The Dual Nature of Light

Particle: photon w/ E (ergs)

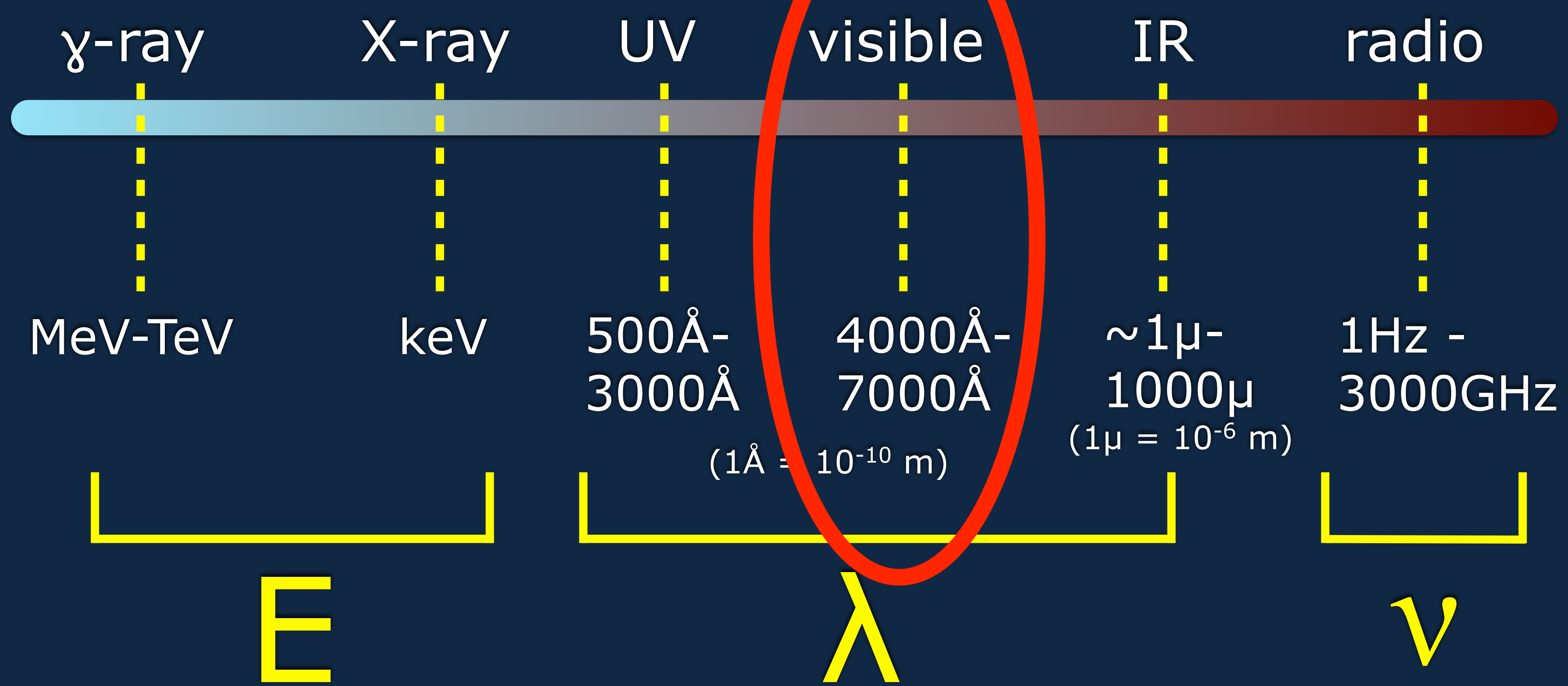
Wave: wavelength λ, frequency ν, velocity c

$$\lambda = c/\nu$$

$$E = h\nu = hc/\lambda \text{ ergs}$$

(higher energy =
higher frequency =
shorter wavelength)

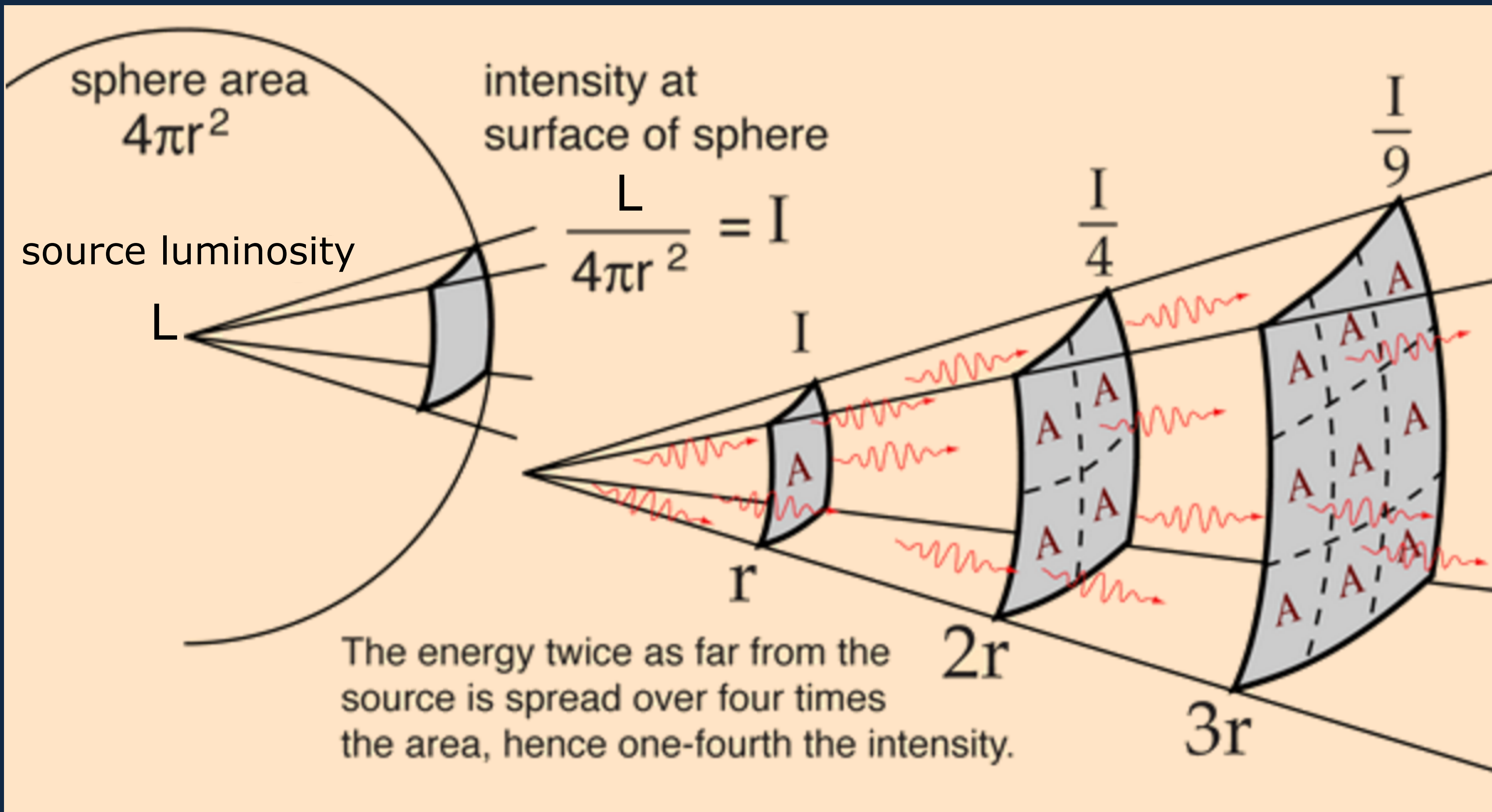
The E&M Spectrum



Basic Properties of Light

Inverse Square Law

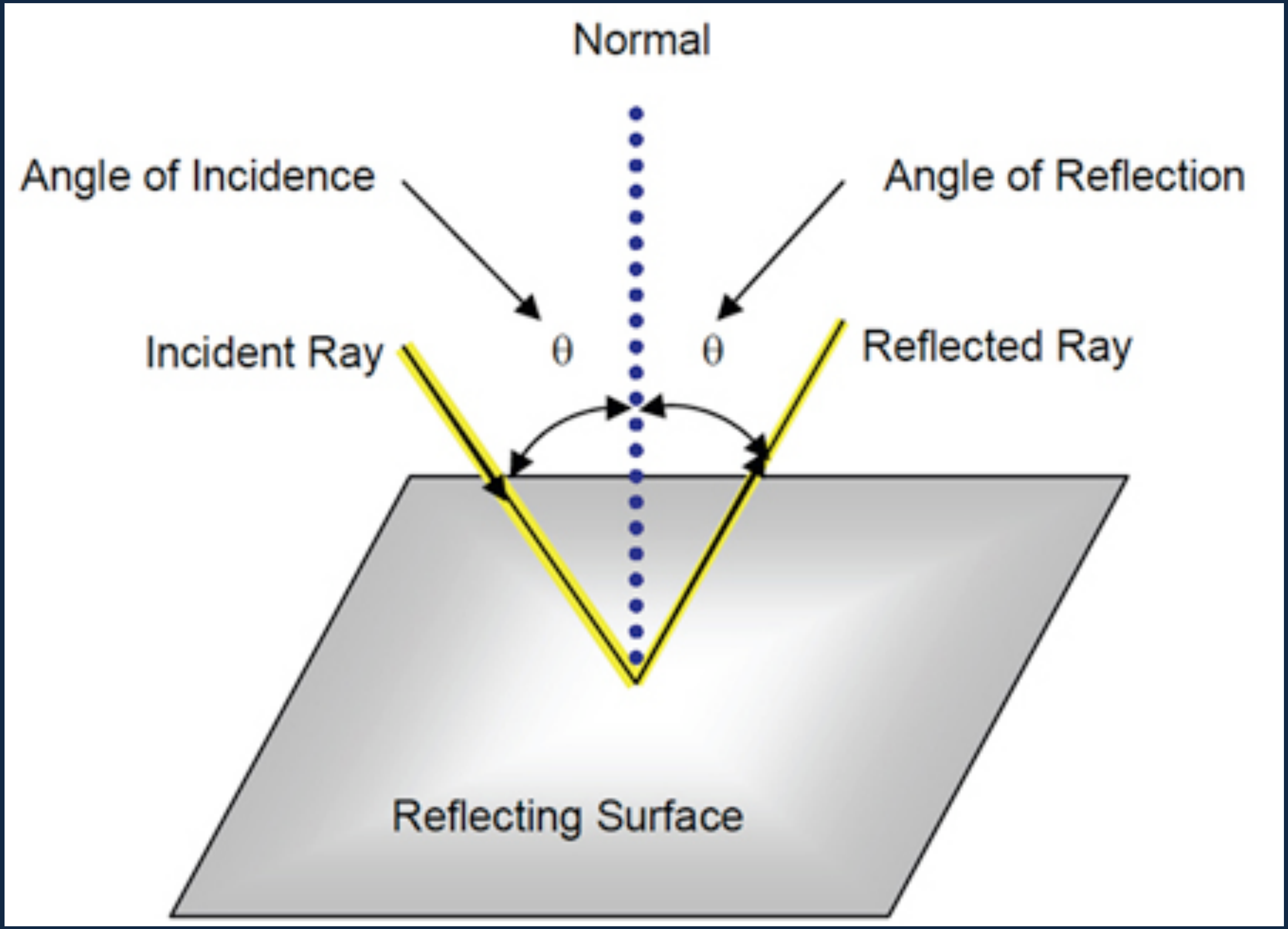
$$I = L/4\pi r^2$$



Basic Properties of Light

Reflection

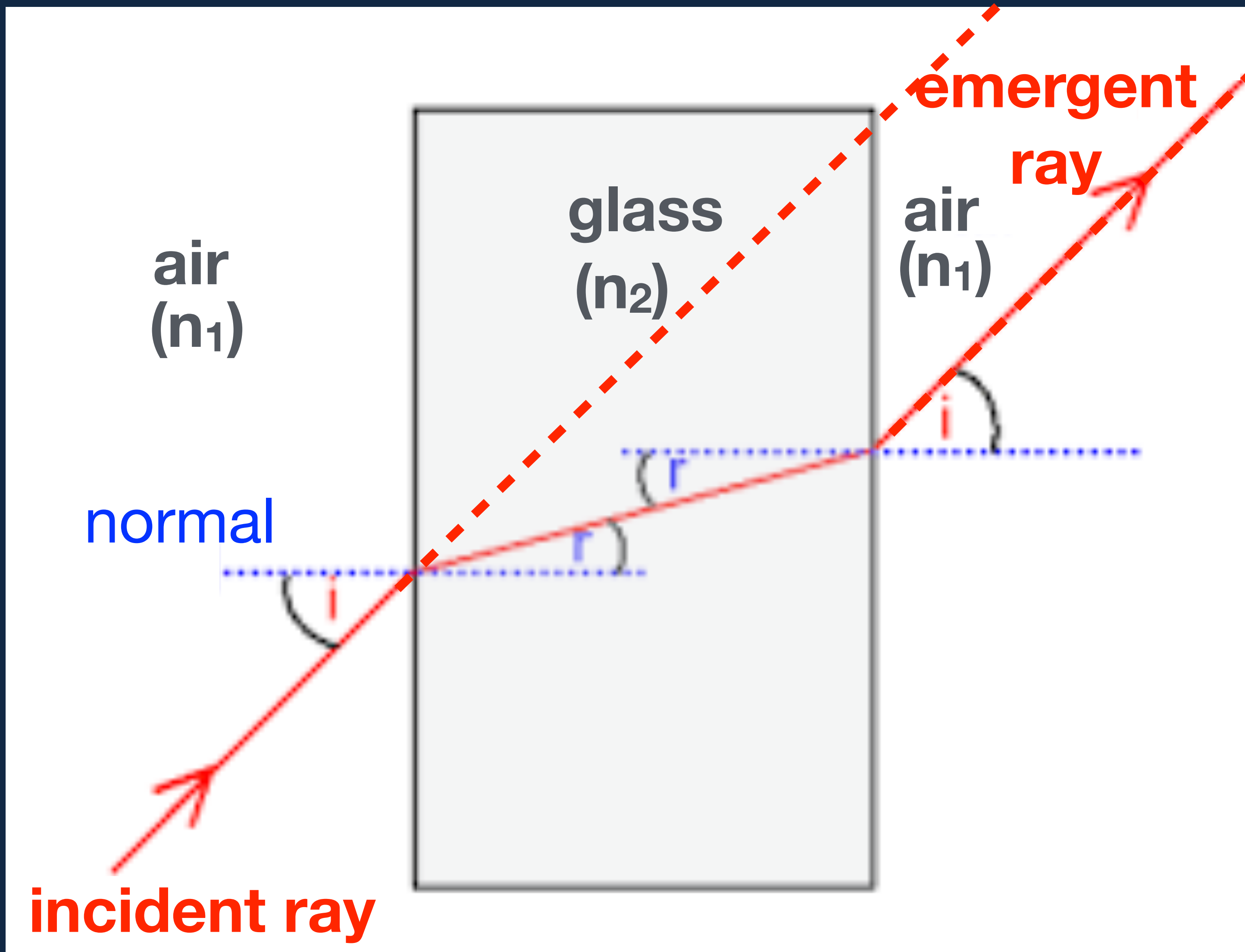
$$\theta_i = \theta_r$$



Basic Properties of Light

<u>Refraction</u>

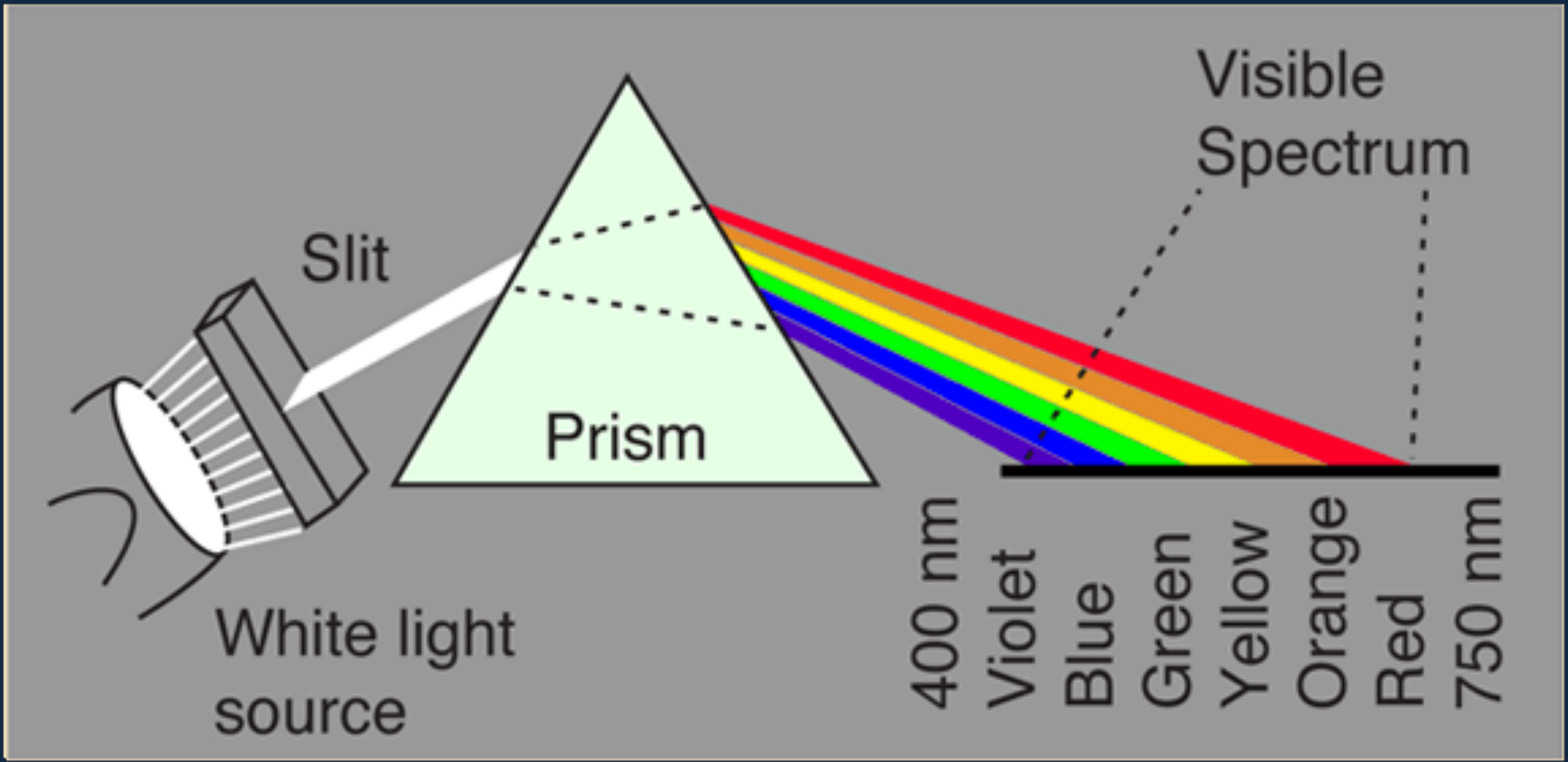
$$n_1 \sin i = n_2 \sin r$$



Basic Properties of Light

Dispersion

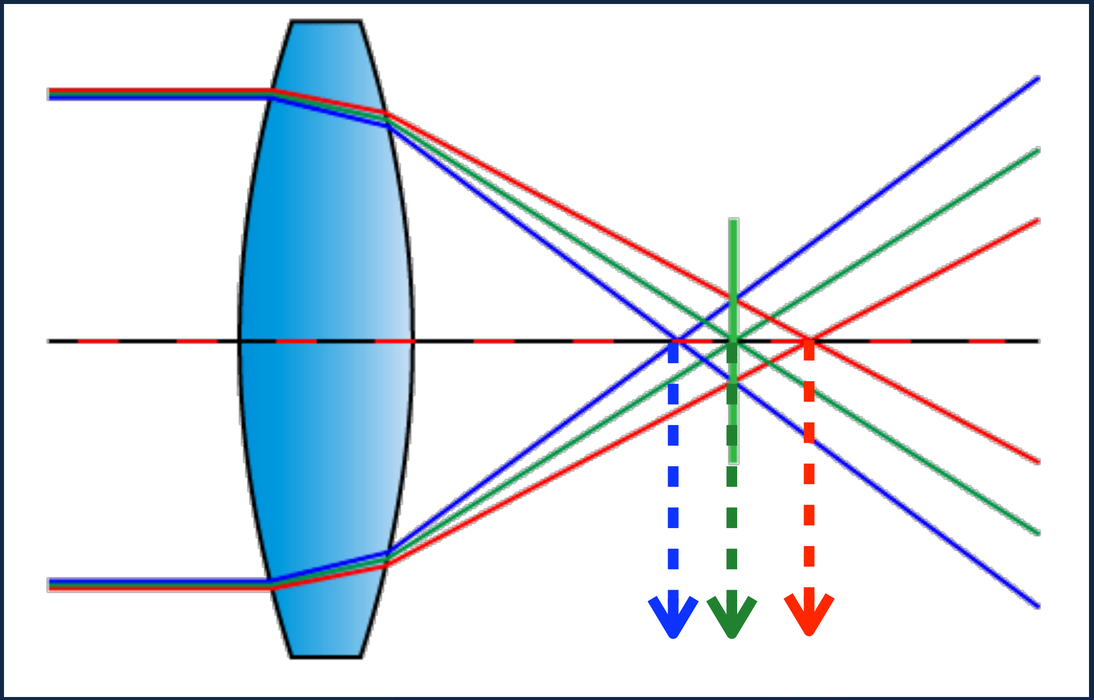
The index of refraction is λ-dependent: n(λ)



Basic Properties of Light

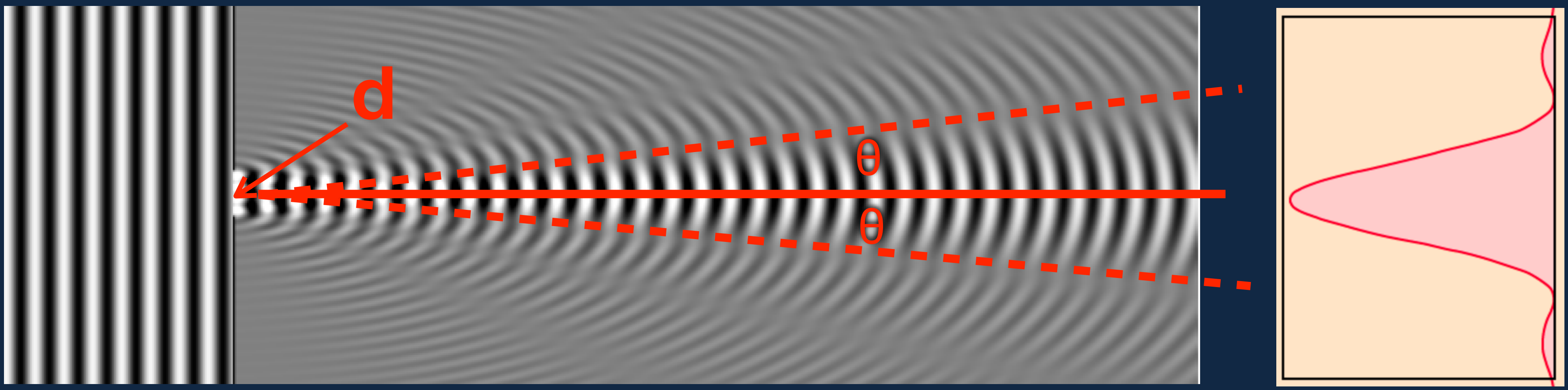
Dispersion

Reason for **chromatic aberration**



Basic Properties of Light

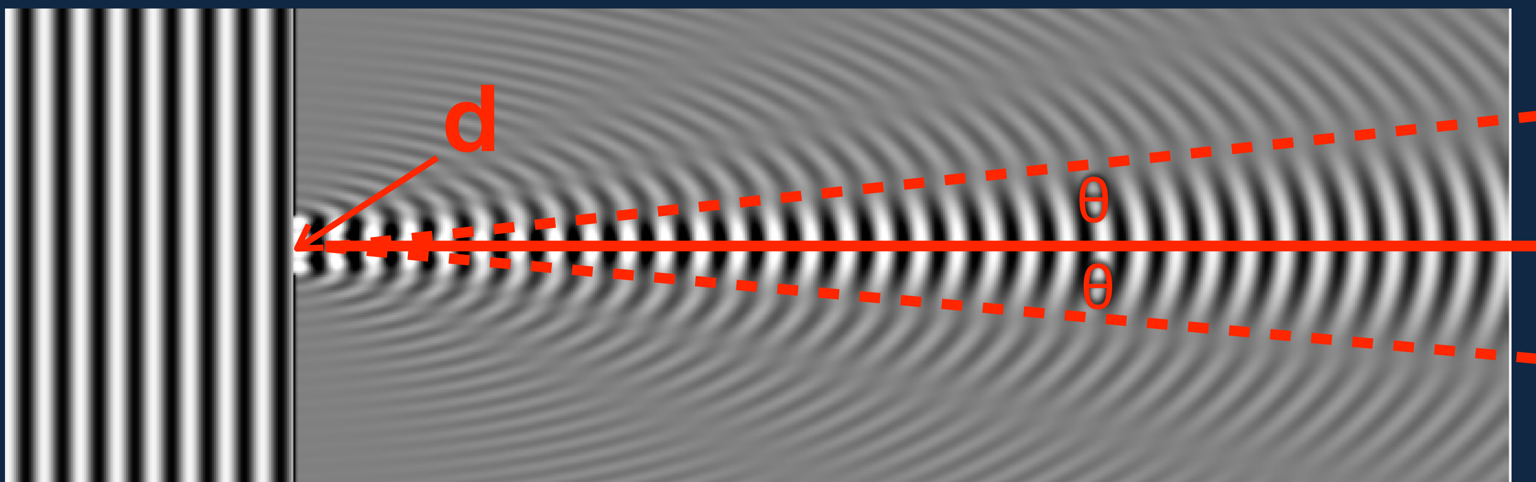
Diffraction

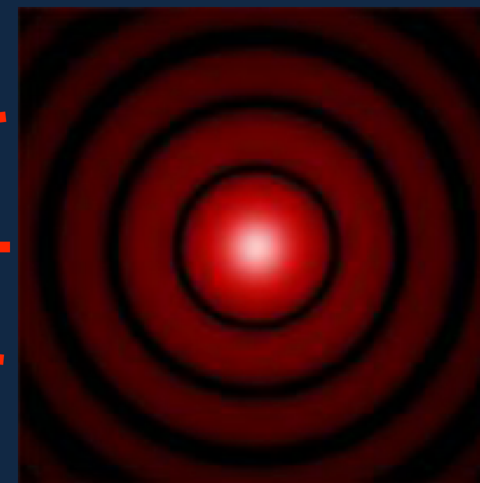


For an aperture of width d, θ (radians) ~ λ/d

Basic Properties of Light

Diffraction





For an aperture of width d, θ (radians) ~ λ/d

1 radian = 206265″ (arcsec)

resolution (α) = 206265″x λ/d x 1.22

A 10cm telescope at λ=5000A has α = ~1″

Basic Properties of Light

QUICK QUESTION

$$\alpha = 206265'' \times \lambda/d \times 1.22$$

A 10cm telescope has α = ~1″ at λ=5000A. The Keck 10m telescopes in Hawaii each have a resolution of:

A) α = ~.01″
B) α = ~.1″
C) α = ~1″
D) α = ~10″

A 10cm telescope at λ=5000A has α = ~1

Basic Properties of Light

Diffraction

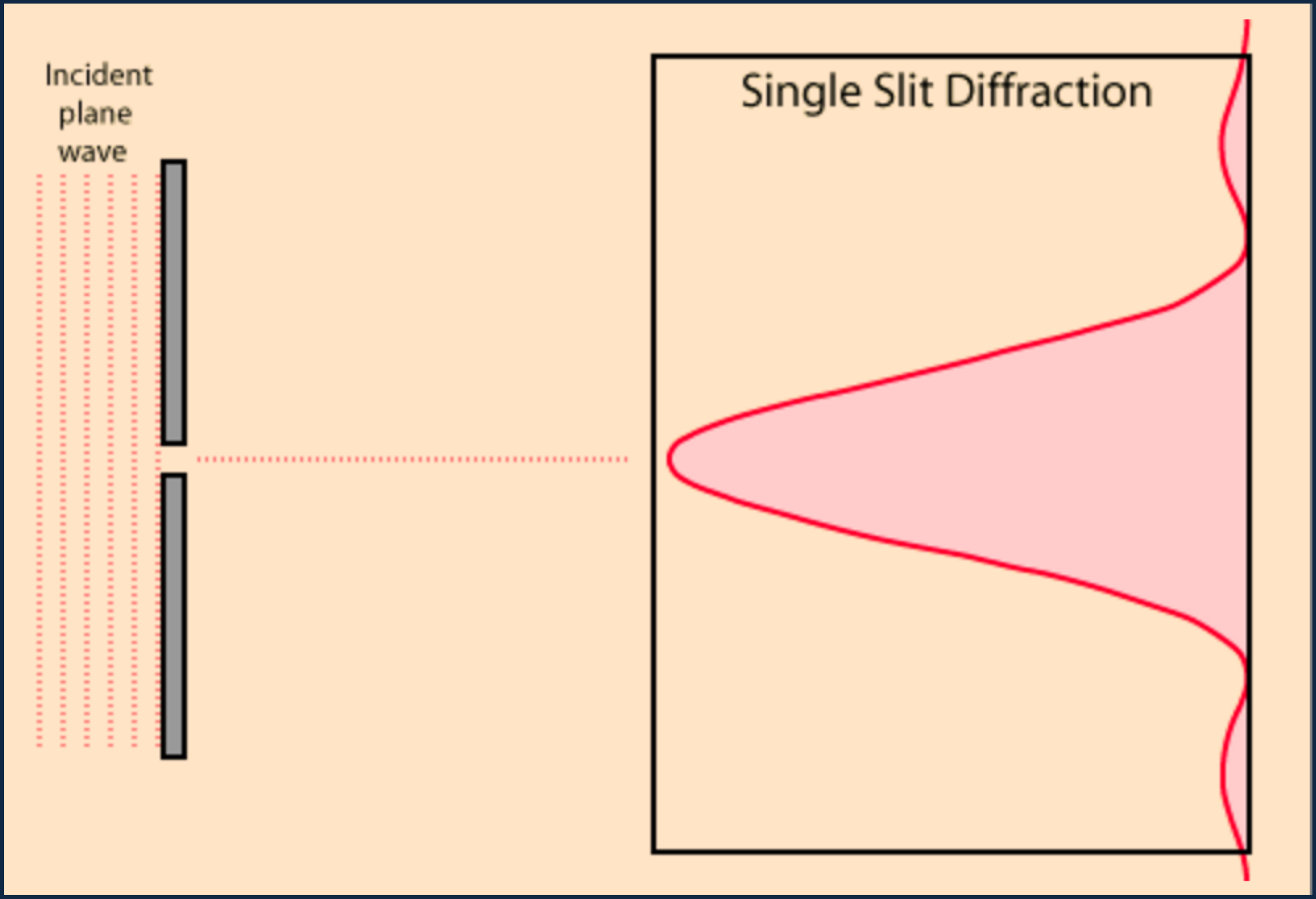
"**Diffraction-limited astronomy**" means we're getting images at the telescope's resolution α - we're limited only by the laws of physics.

This is practically impossible from the ground because of atmospheric "**seeing**".

Solution:

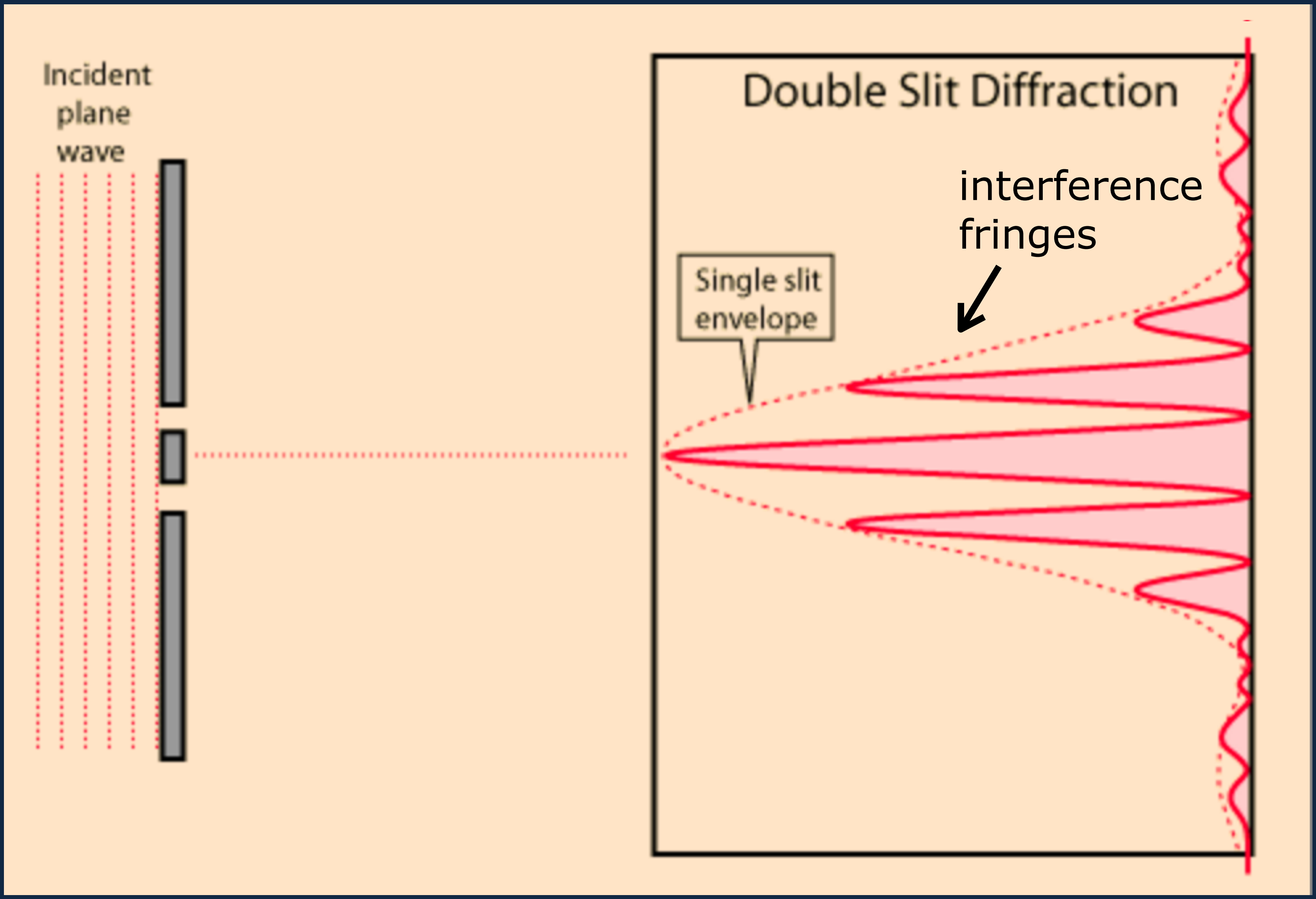
Basic Properties of Light

Diffraction



Basic Properties of Light

Interference



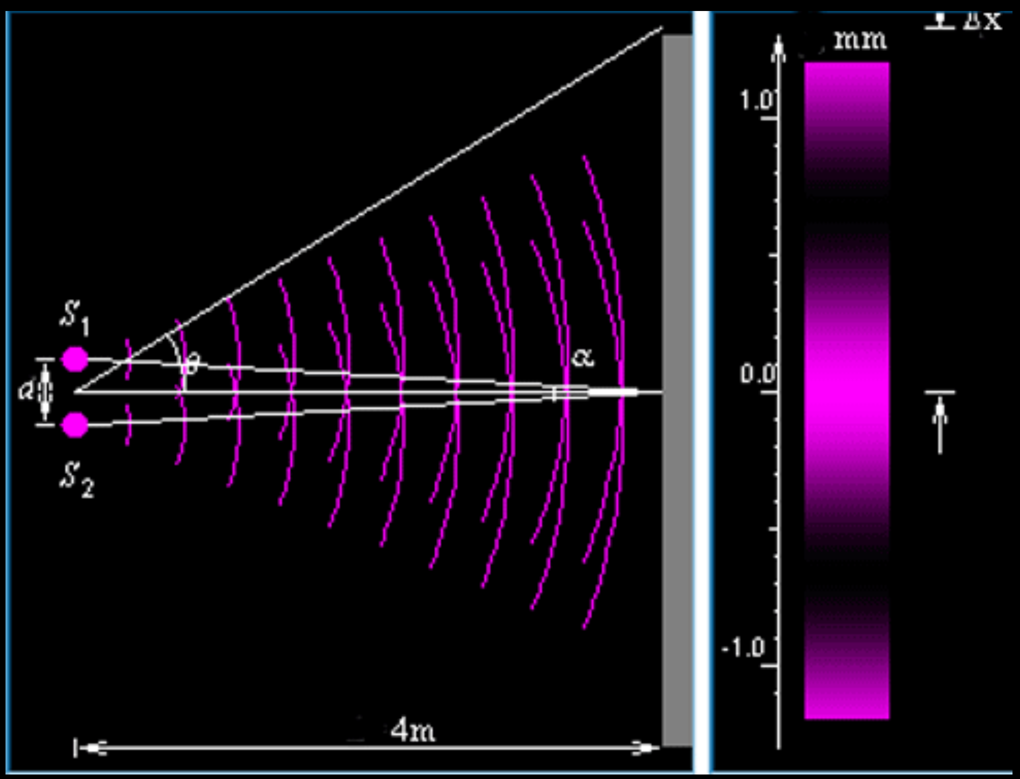
Basic Properties of Light

Discussion Question

If the distance between slits increases, the distance between fringes…

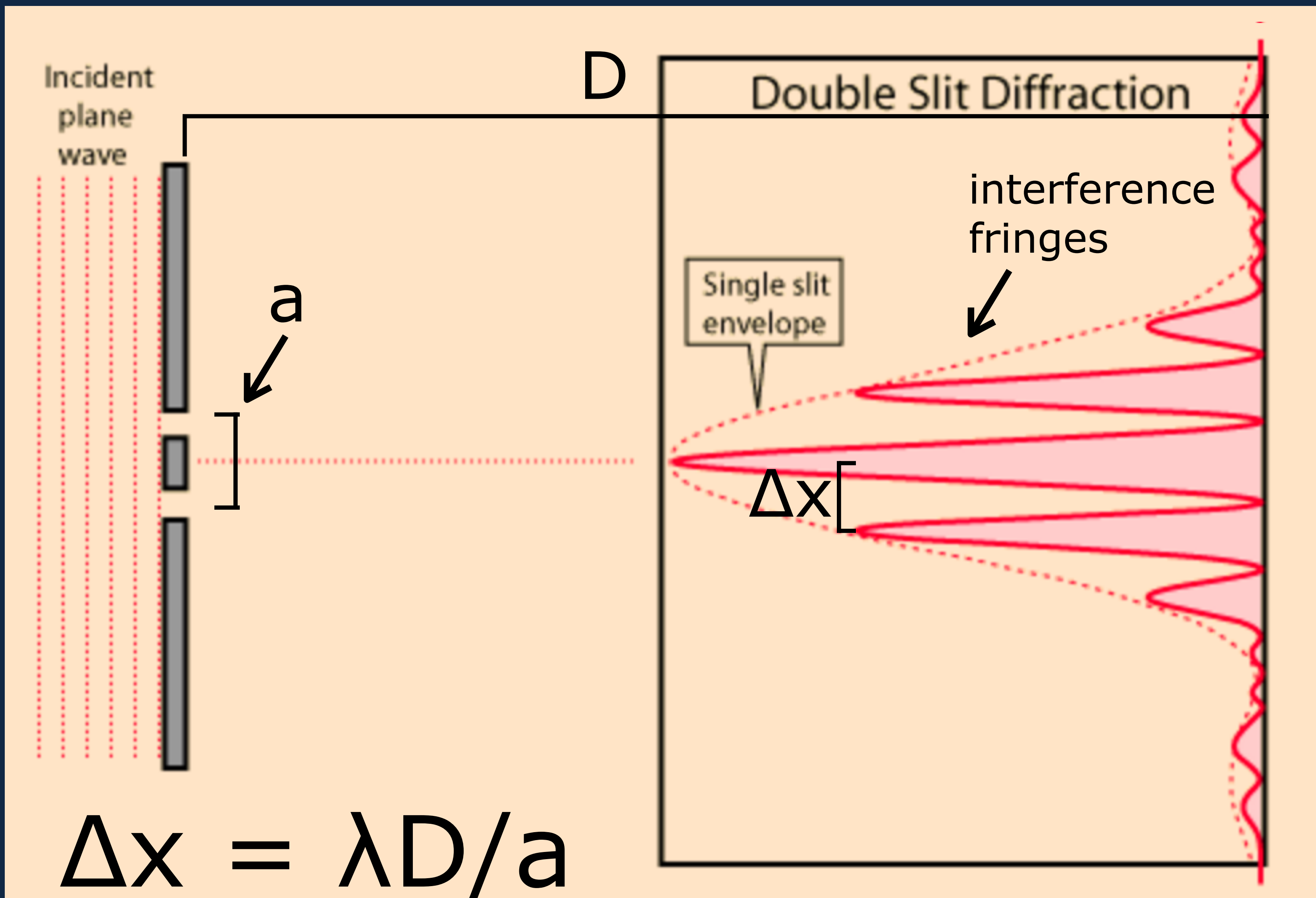
A) increases
B) decreases
C) stays the same
D) depends on λ

$$\Delta x = \lambda D/a$$



Basic Properties of Light

Interference



$$\Delta x = \lambda D/a$$

Basic Properties of Light

Quick Question

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A) increases

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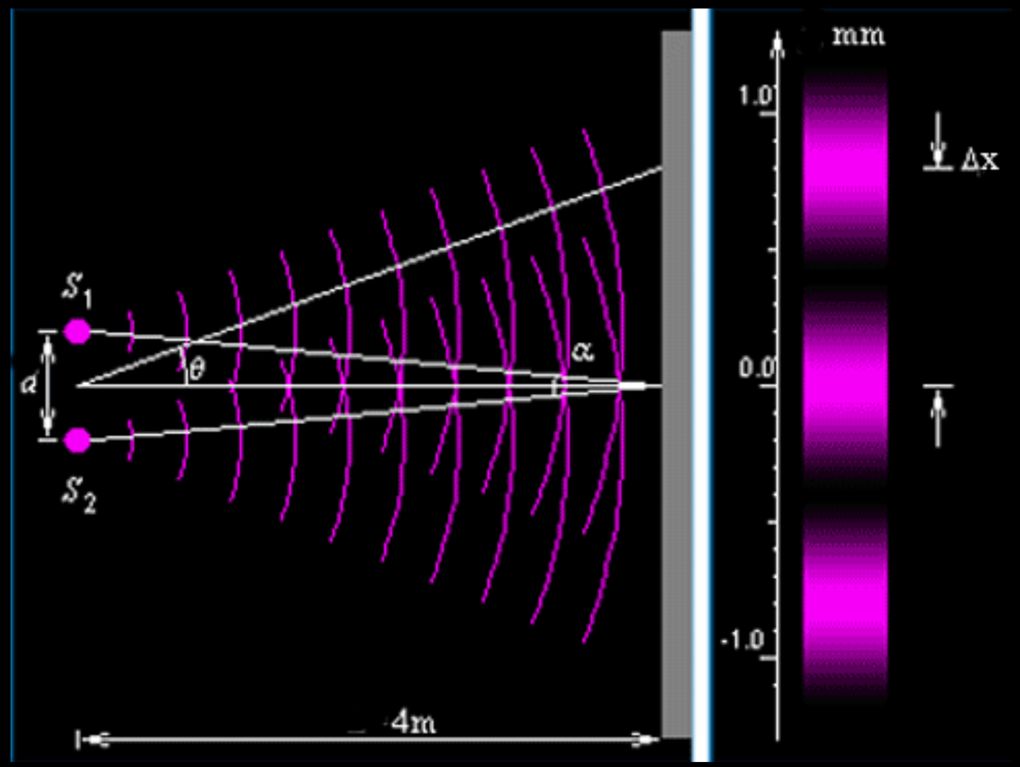
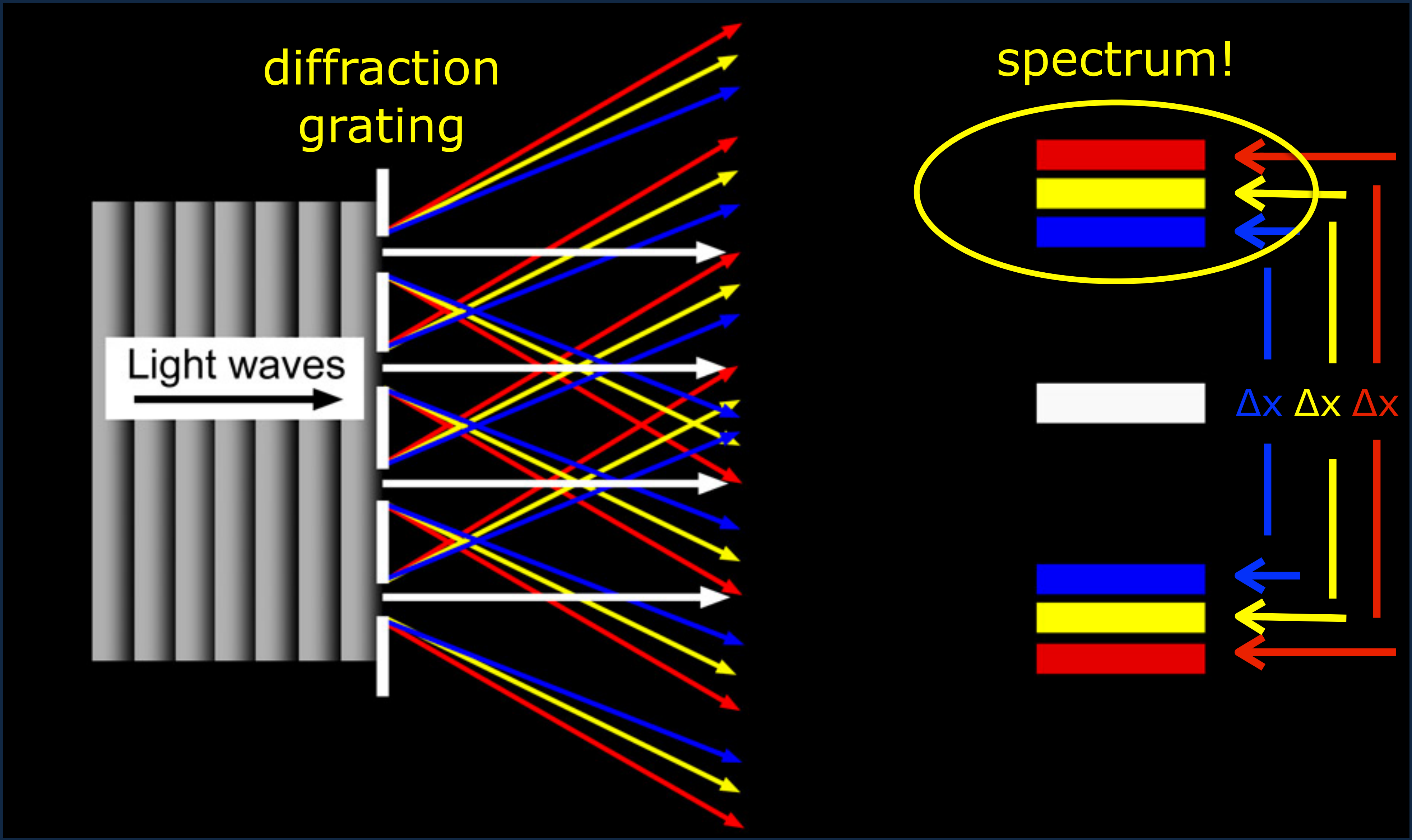


Basic Properties of Light

Interference



Basic Properties of Light

$$\lambda = c/\nu$$

$$E = h\nu = hc/\lambda \text{ ergs}$$

Inverse Square Law: $I = L/4\pi r^2$

Reflection: $\theta_i = \theta_r$

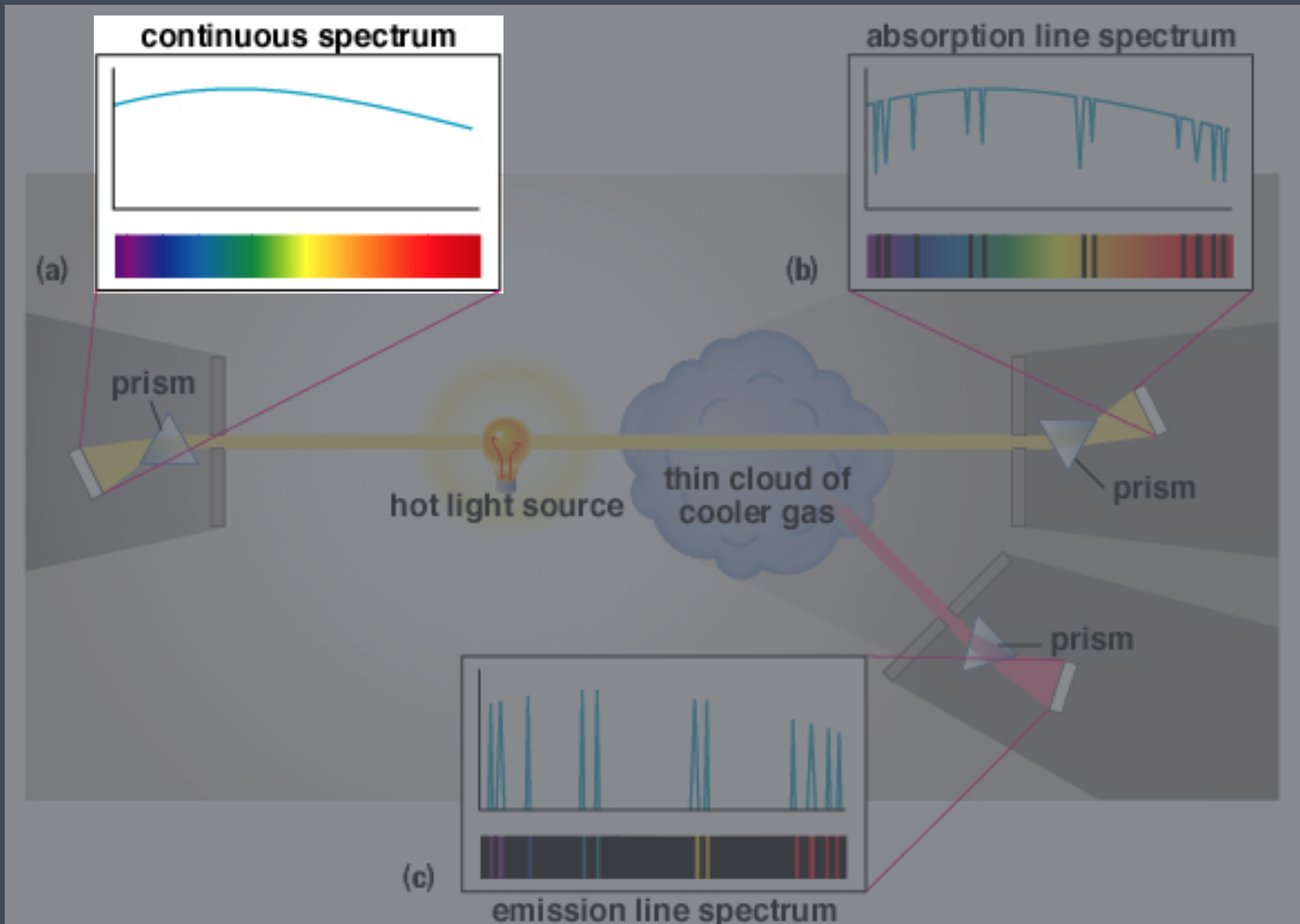
Refraction: $n_1 \sin i = n_2 \sin r$

Disperson: $n(\lambda)$

Diffraction: $\theta \sim \lambda/d$

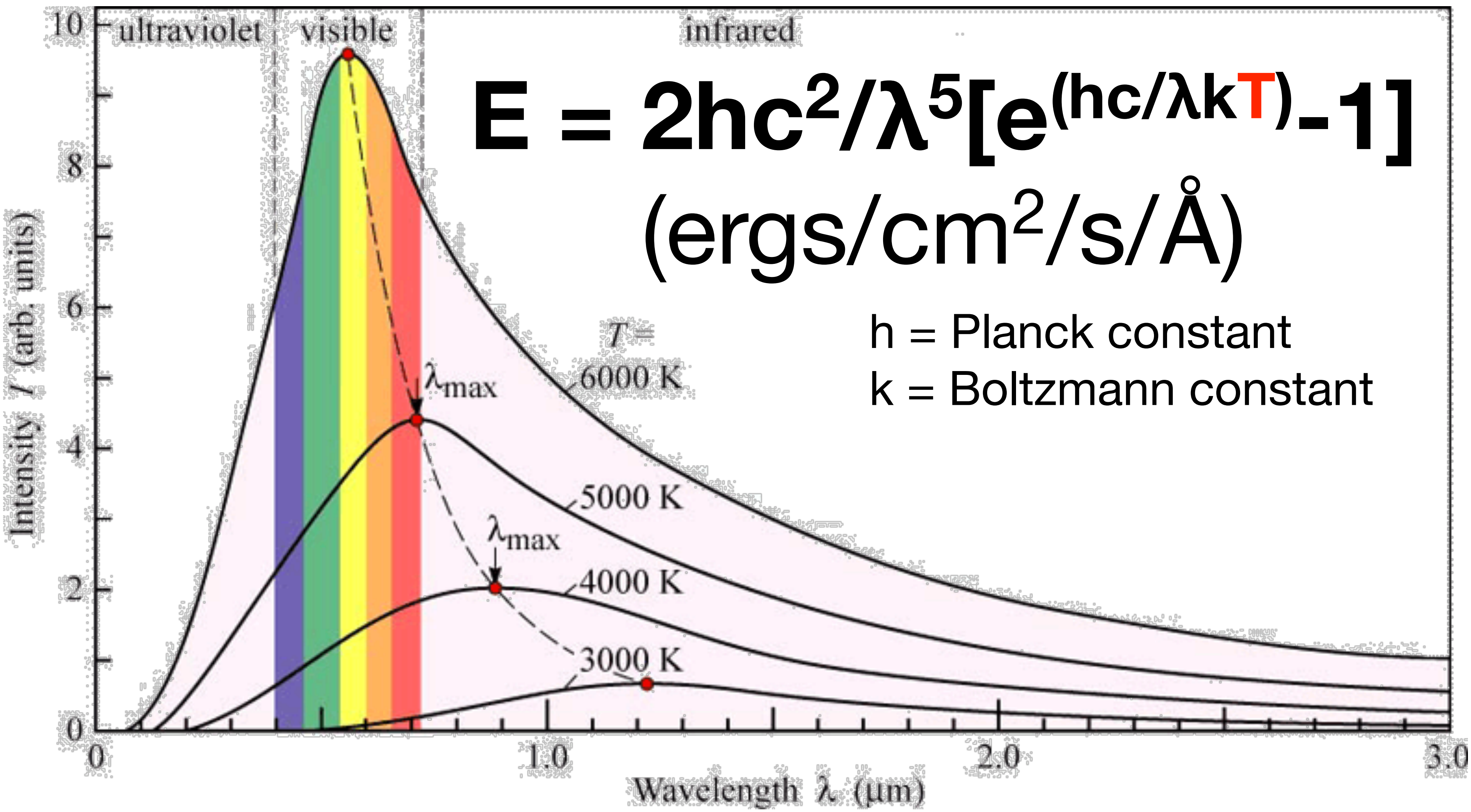
Interference: $\Delta x = \lambda D/a$

Making a Spectrum - Continuum



Making a Spectrum - Continuum

Continuum radiation is approximated by a **blackbody**; energy given by Planck function



$$E = 2hc^2/\lambda^5[e^{(hc/\lambda kT)}-1]$$

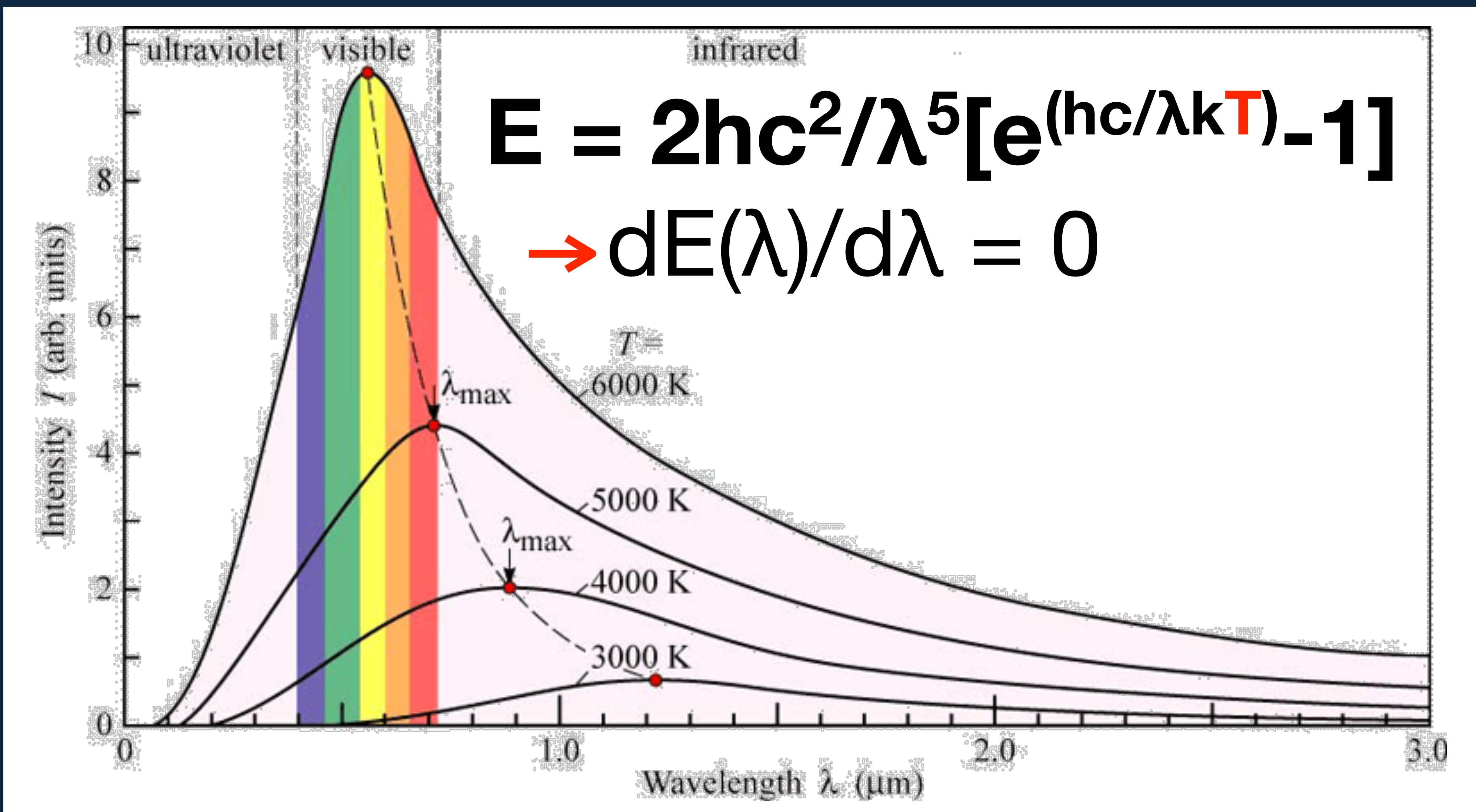
(ergs/cm^2/s/Å)

h = Planck constant

k = Boltzmann constant

Making a Spectrum - Continuum

Continuum radiation is approximated by a **blackbody**; energy given by Planck function



$$E = 2hc^2/\lambda^5[e^{(hc/\lambda kT)}-1]$$

$$\rightarrow dE(\lambda)/d\lambda = 0$$

Making a Spectrum - Continuum

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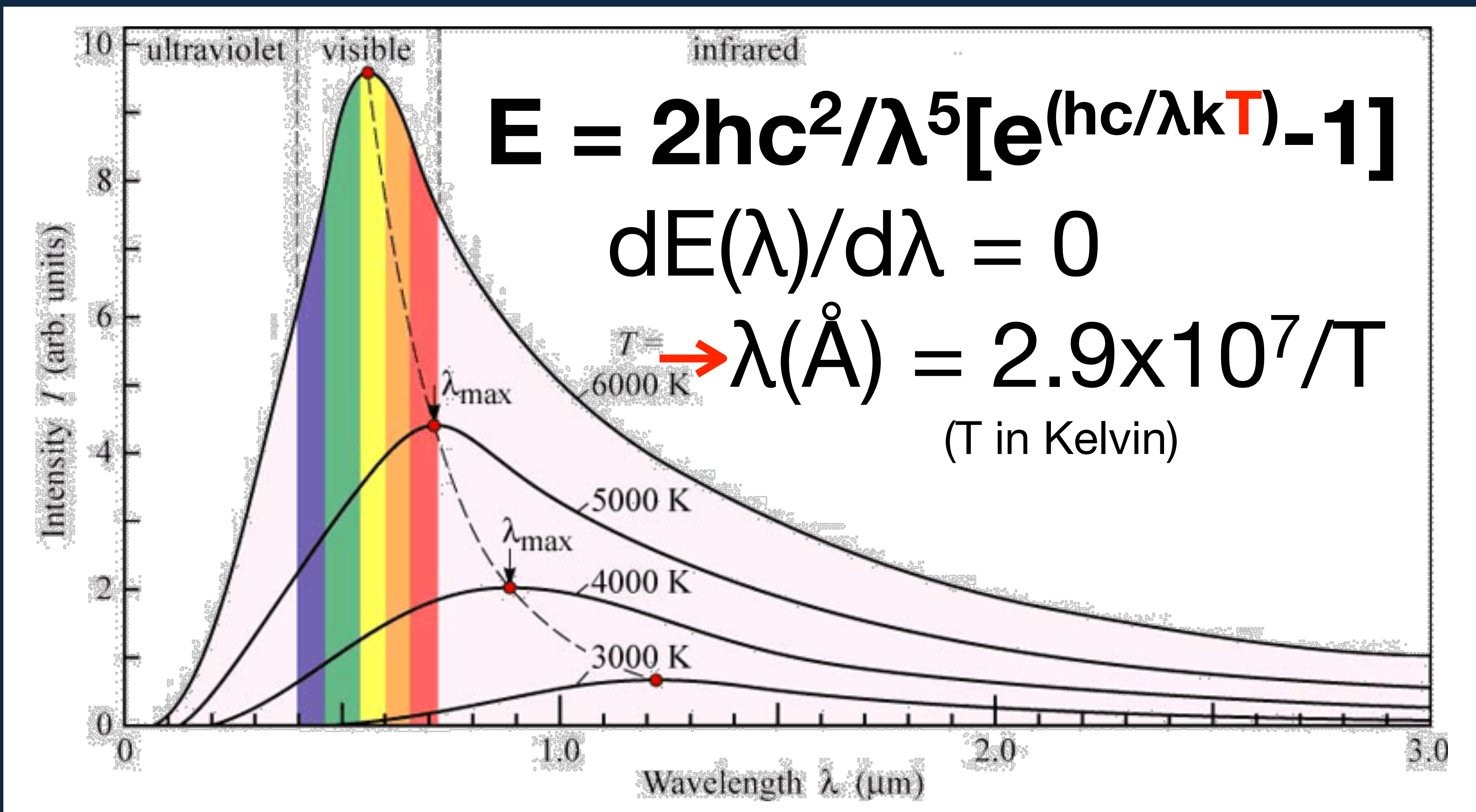


$$E = 2hc^2/\lambda^5[e^{(hc/\lambda kT)}-1]$$

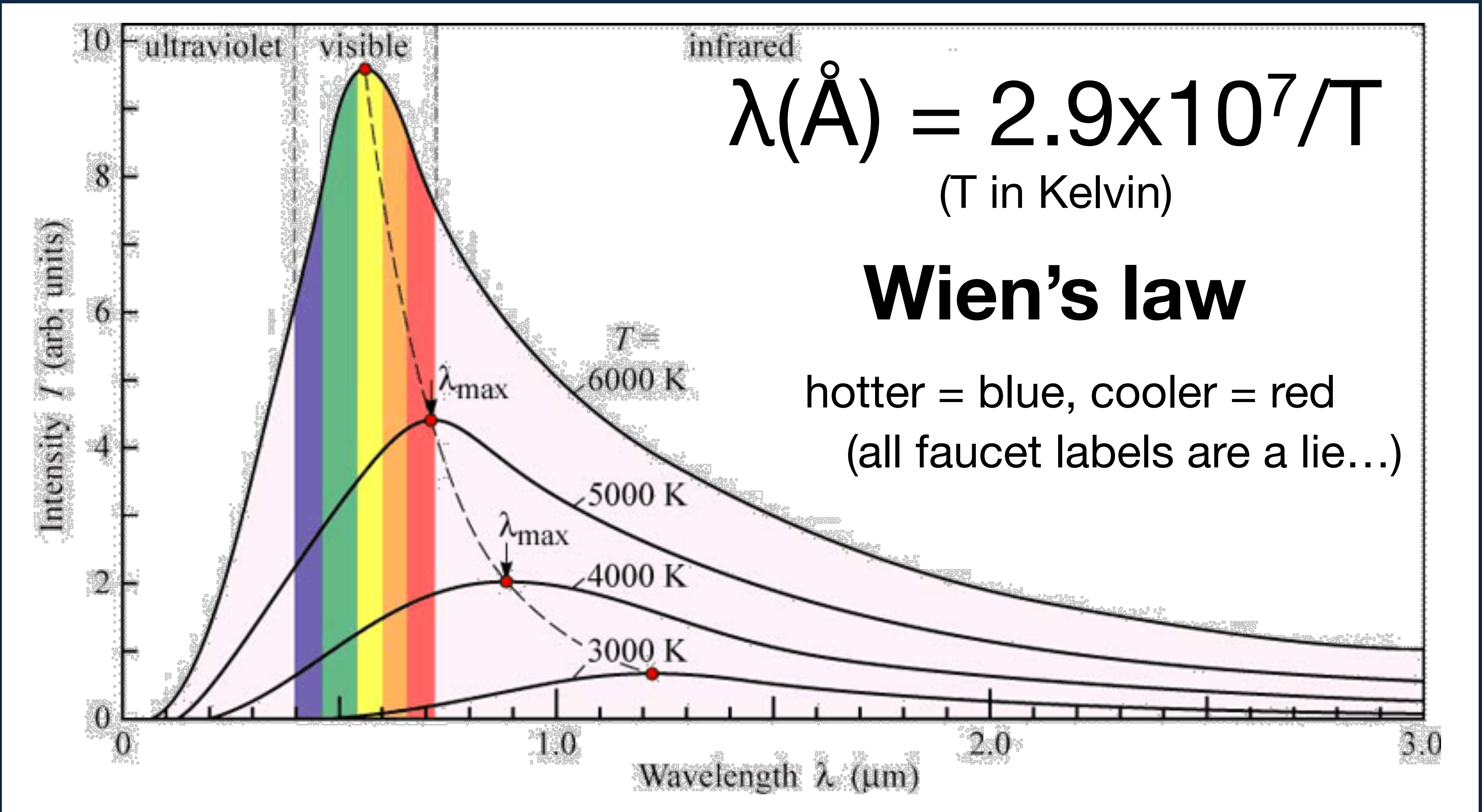
$$dE(\lambda)/d\lambda = 0$$

$$\rightarrow \lambda(\text{Å}) = 2.9\times10^7/T$$

(T in Kelvin)

Making a Spectrum - Continuum

Continuum radiation is approximated by a **blackbody**; energy given by Planck function



Making a Spectrum - Continuum

Continuum radiation is approximated by a

QUICK QUESTION

You want to observe two stars that are identical in size. Star X is 60,000K; Star Y is 3,500 K. Sadly, you only have access to an infrared telescope.
To get similar-quality observations, which star should you observe for longer and why?

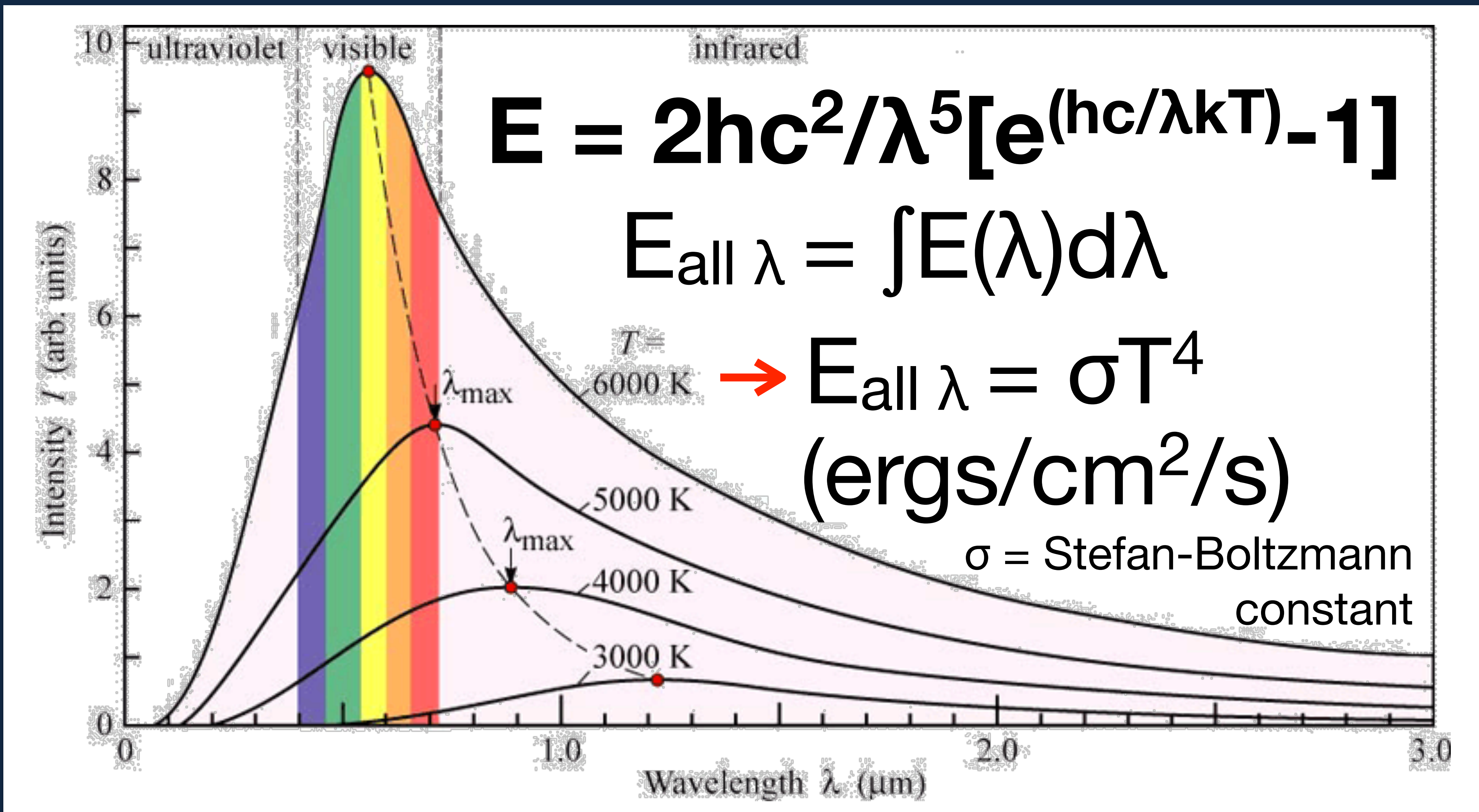
A) Star X; it's hotter and ∴ dimmer in the IR

B) Star Y; it's cooler and ∴ dimmer in the IR

C) Doesn't matter; they're the same size

Making a Spectrum - Continuum

Continuum radiation is approximated by a **blackbody**; energy given by Planck function



$$E = 2hc^2/\lambda^5[e^{(hc/\lambda kT)}-1]$$

$$E_{\text{all }\lambda} = \int E(\lambda)d\lambda$$

$$\rightarrow E_{\text{all }\lambda} = \sigma T^4$$

$(ergs/cm^2/s)$

σ = Stefan-Boltzmann constant

Making a Spectrum - Continuum

Continuum radiation is approximated by a

Discussion Question

E= σT^4 gives us ergs/s/cm^2 , the ergs per second emitted by each square centimeter of a star. Luminosity (L) is defined as the total ergs per second emitted by the ENTIRE star.

Assume stars are spheres with radius R. If a star's luminosity stays the same and its temperature decreases, the star will:

A) get denser
B) get bigger
C) get smaller
D) this is impossible

Making a Spectrum - Continuum

Continuum radiation is approximated by a

DISCUSSION QUESTION

$E = \sigma T^4$ gives us $ergs/s/cm^2$, the ergs per second emitted by each square centimeter of a star. Luminosity (L) is defined as the total ergs per second emitted by the ENTIRE star.

Surface area of a sphere A is $4\pi R^2$. L = E*A, so

$$L = 4\pi R^2 \sigma T^4$$

A) get denser
B) get bigger
C) get smaller
D) this is impossible

Making a Spectrum - Continuum

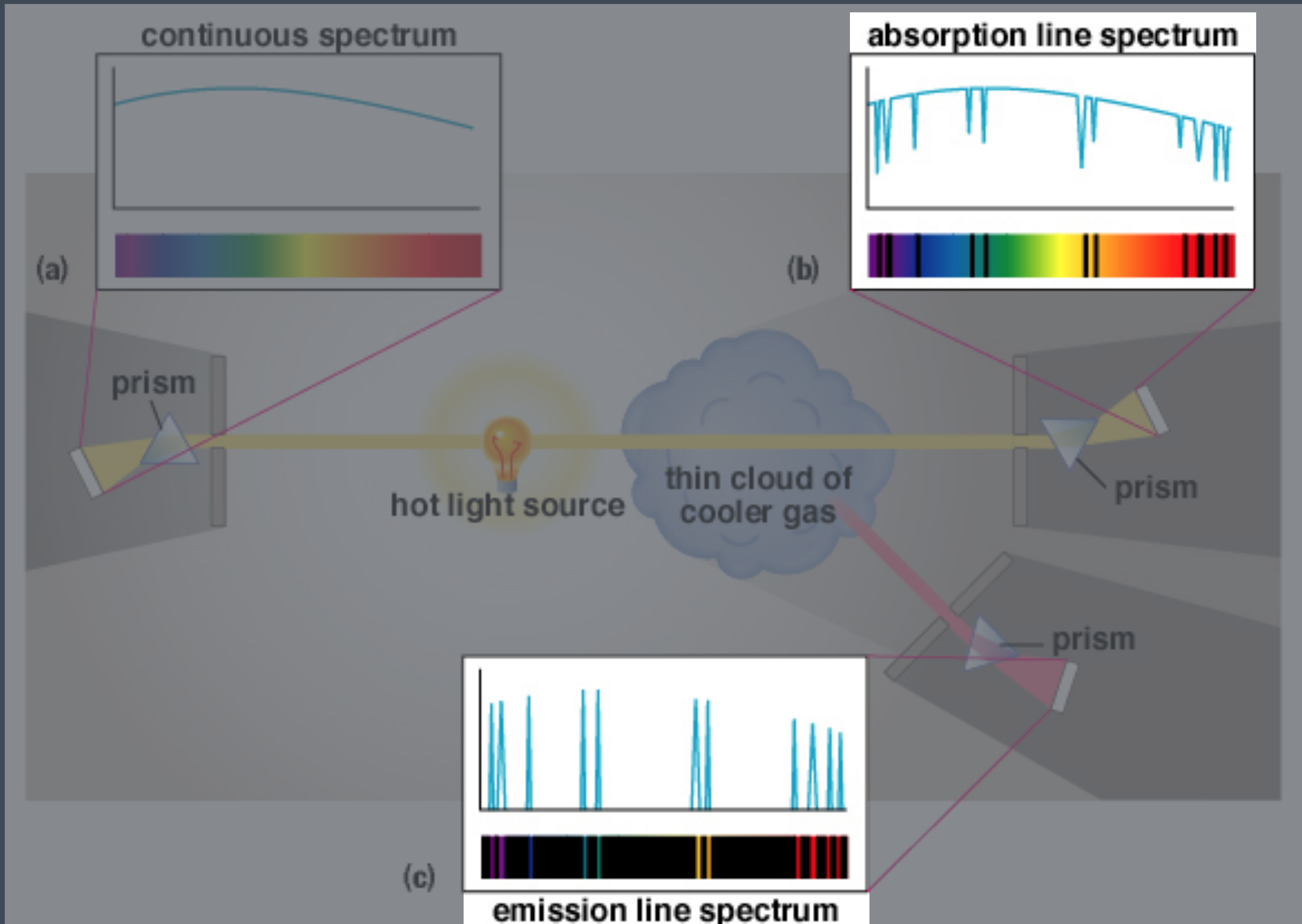
<u>Planck Function</u>: $E = 2hc^2/\lambda^5[e^{(hc/\lambda kT)}-1]$
(ergs/cm^2/s/Å)

<u>Stefan-Boltzmann Law</u>: $E_{all\ \lambda} = \sigma T^4$
(ergs/cm^2/s)

<u>Luminosity</u>: $L = 4\pi R^2 \sigma T^4$

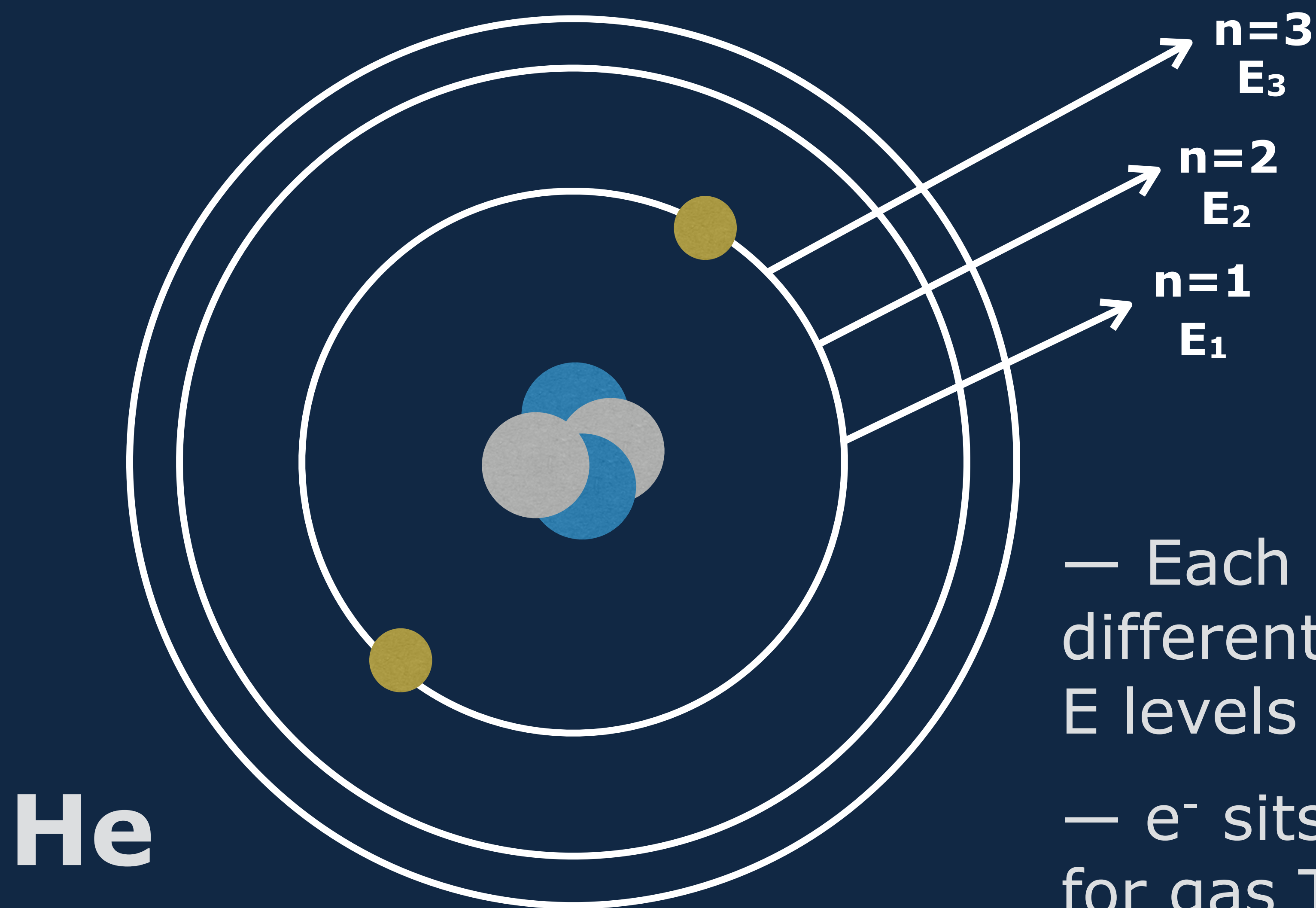
<u>Wien's Law</u>: $\lambda(\text{Å}) = 2.9\text{x}10^7/T$

Making a Spectrum - Lines



Making a Spectrum - Lines

Lines in spectra can be approximated by the Bohr model…

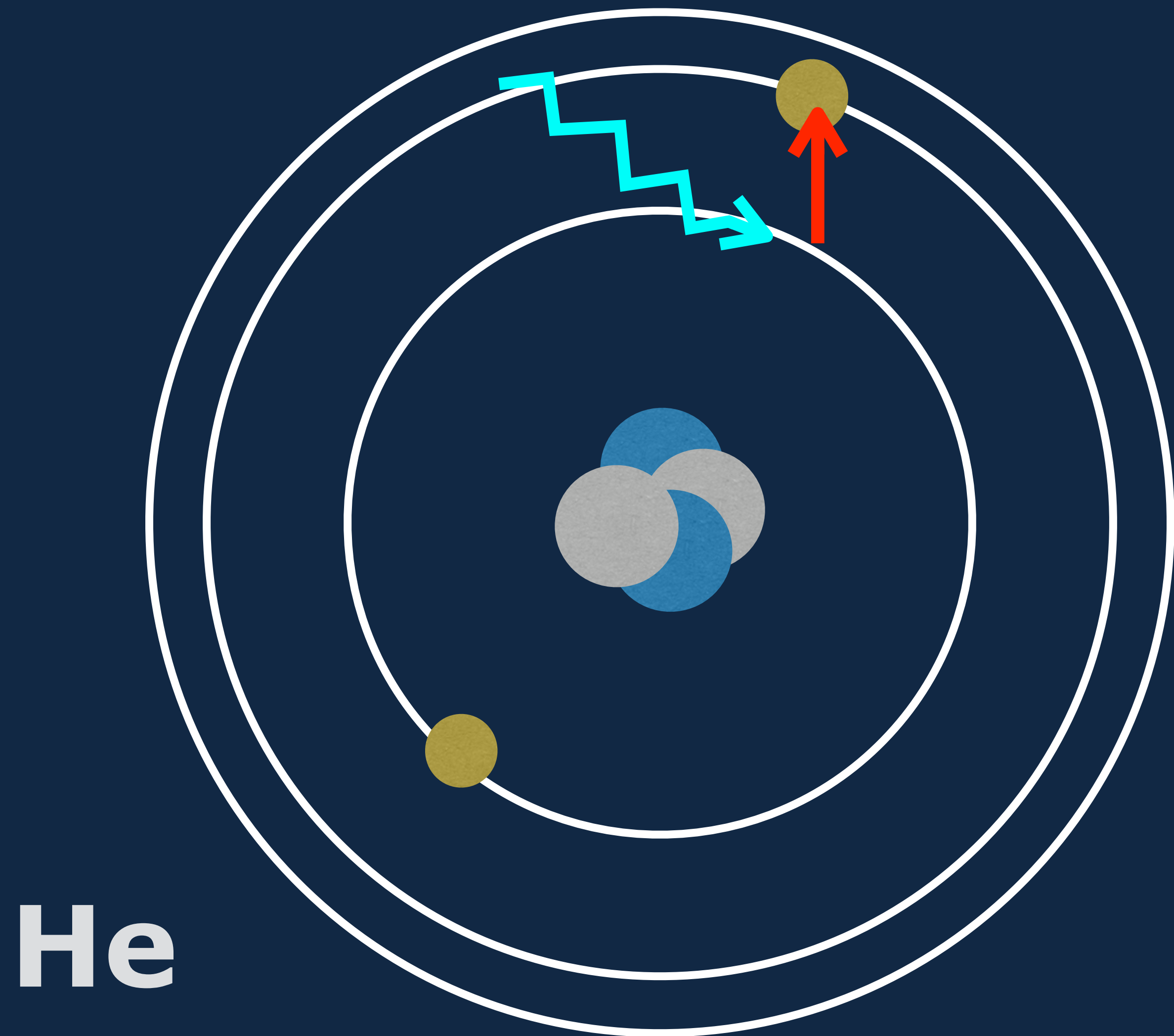


— Each element has different p, e^-, n, E levels

— e^- sits at lowest E for gas T

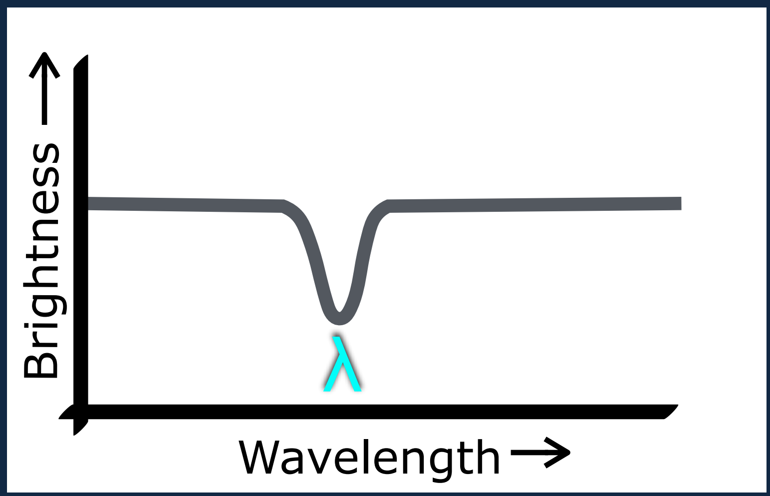
Making a Spectrum - Lines

Lines in spectra can be approximated by the Bohr model…



Absorption line

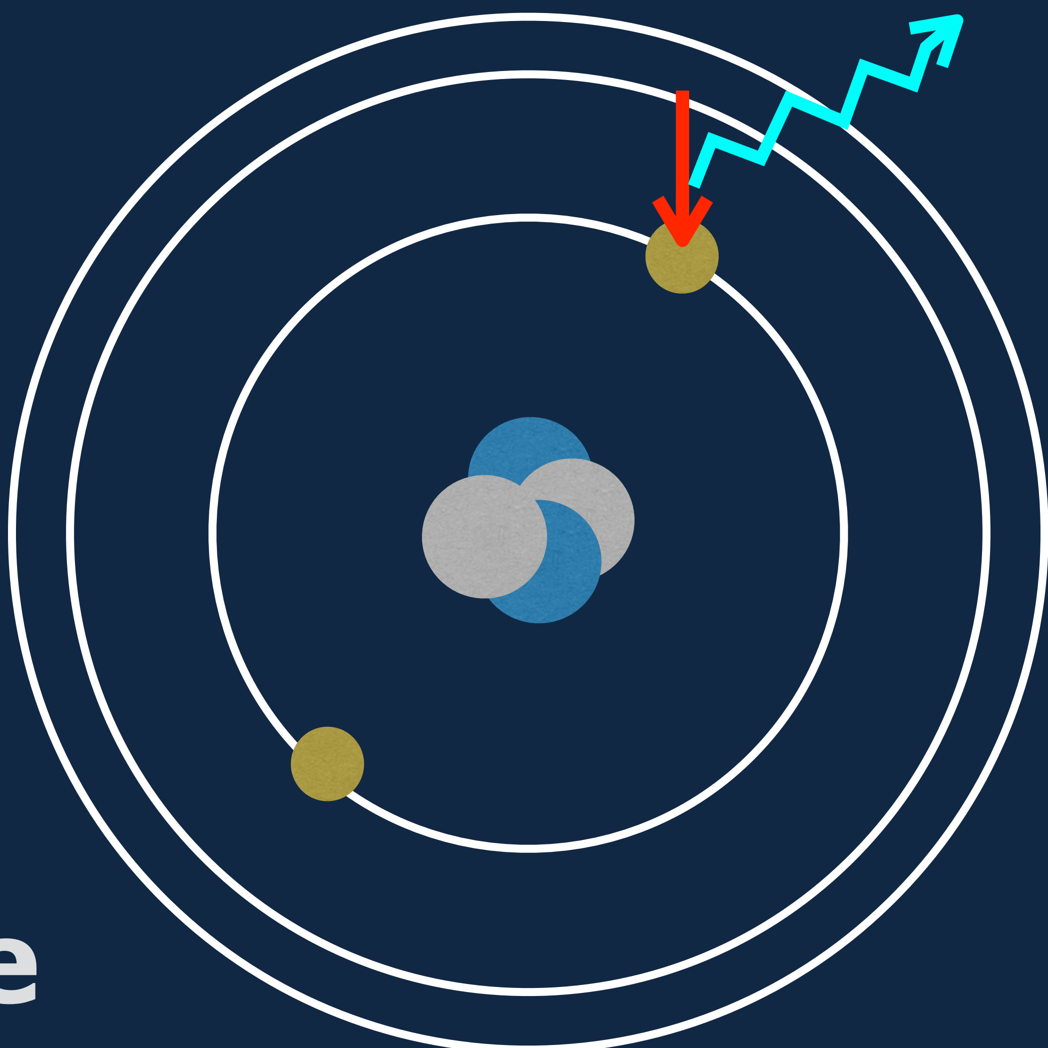
e^- absorbs photon and moves to higher E level (n=2)



$\Delta E = hc/\lambda$

Making a Spectrum - Lines

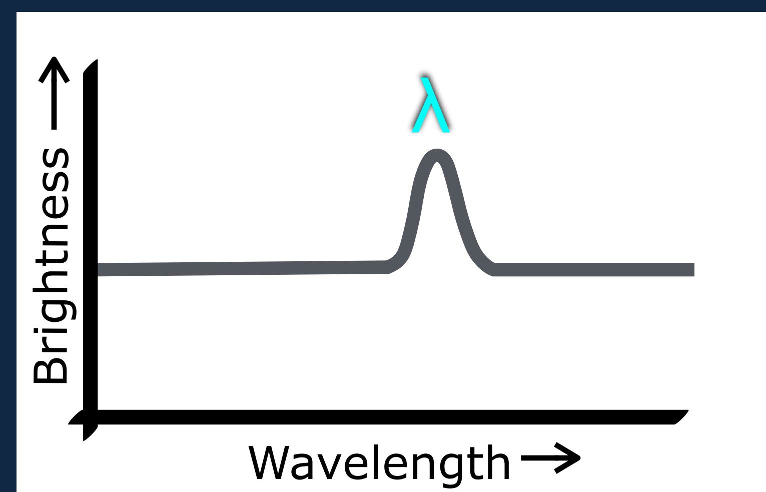
Lines in spectra can be approximated by the Bohr model…



He

Emission line

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



$$\Delta E = hc/\lambda$$

Making a Spectrum - Lines

We start by assuming that the electron is held in a circular orbit by electrostatic attraction, so:

$$\frac{m_e v^2}{r} = \frac{Z k_e e^2}{r^2}$$

centripetal force = Coulomb's force

Z = atomic number, k_e = Coulomb's const
m_e = mass of electron, e = charge of electron

Making a Spectrum - Lines

We start by assuming that the electron is held in a circular orbit by electrostatic attraction, so:

$$\frac{m_e v^2}{r} = \frac{Z k_e e^2}{r^2} \rightarrow v = \sqrt{\frac{Z k_e e^2}{m_e r}}$$

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Making a Spectrum - Lines

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$$\frac{m_e v^2}{r} = \frac{Z k_e e^2}{r^2}$$

$$v = \sqrt{\frac{Z k_e e^2}{m_e r}} \rightarrow E = \frac{1}{2} m_e v^2 - \frac{Z k_e e^2}{r} = -\frac{Z k_e e^2}{2r}$$

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$$m_e v r = n\hbar$$

Z = atomic number, k_e = Coulomb’s const, n = energy level
m_e = mass of electron, e = charge of electron, $\hbar$ = reduced Planck

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$$r_n = \frac{n^2 \hbar^2}{Z k_e e^2 m_e}$$

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+

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Making a Spectrum - Lines

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$$m_e v r = n\hbar$$

$$r_n = \frac{n^2 \hbar^2}{Z k_e e^2 m_e}$$

$$E = -\frac{Z^2 (k_e e^2)^2 m_e}{2\hbar^2 n^2} \approx \frac{-13.6 Z^2}{n^2} \mathrm{eV}$$

→ R_E, the Rydberg unit of energy

Z = atomic number, k_e = Coulomb’s const, n = energy level
m_e = mass of electron, e = charge of electron, $\hbar$ = reduced Planck

Making a Spectrum - Lines

$R_E = hcR$

$$\frac{1}{\lambda_{\mathrm{vac}}} = RZ^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

R = Rydberg constant, Z = atomic number, n = energy levels

Making a Spectrum - Lines

$R_E = hcR$

$$\frac{1}{\lambda_{\mathrm{vac}}} = RZ^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$$

$R \sim 0.001$ Å^{-1}

Quick Question

Given the information to the left, the n=2-1 transition of hydrogen falls into which wavelength regime?

A) radio
B) infrared
C) optical
D) UV

R = Rydberg constant, Z = atomic number, n = energy levels

Making a Spectrum - Lines

$R_E = hcR$

$$\frac{1}{\lambda_{vac}} = RZ^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

R ~ 0.001 Å^{-1}

Quick Question

Given the information to the left, the n=2-1 transition of hydrogen falls into which wavelength regime?

Z = 1 ; ( ) = 3/4 ; R = 1/1000

λ = 1000Å * 4/3 ~ 1333Å

A) radio
B) infrared
C) optical
D) UV

R = Rydberg constant, Z = atomic number, n = energy levels

Making a Spectrum - Lines

$R_E = hcR$

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R ~ ~~0.001~~ $Å^{-1}$

0.00109678...

QUICK QUESTION

Given the information to the left, the n=2-1 transition of hydrogen falls into which wavelength regime?

Z = 1 ; ( ) = 3/4 ; R = 1/1000

λ = ~~1000Å~~ * 4/3 ~ ~~1333Å~~

912Å 1216Å

A) radio

B) infrared

C) optical

D) UV

R = Rydberg constant, Z = atomic number, n = energy levels

Making a Spectrum - Lines

$R_E = hcR$

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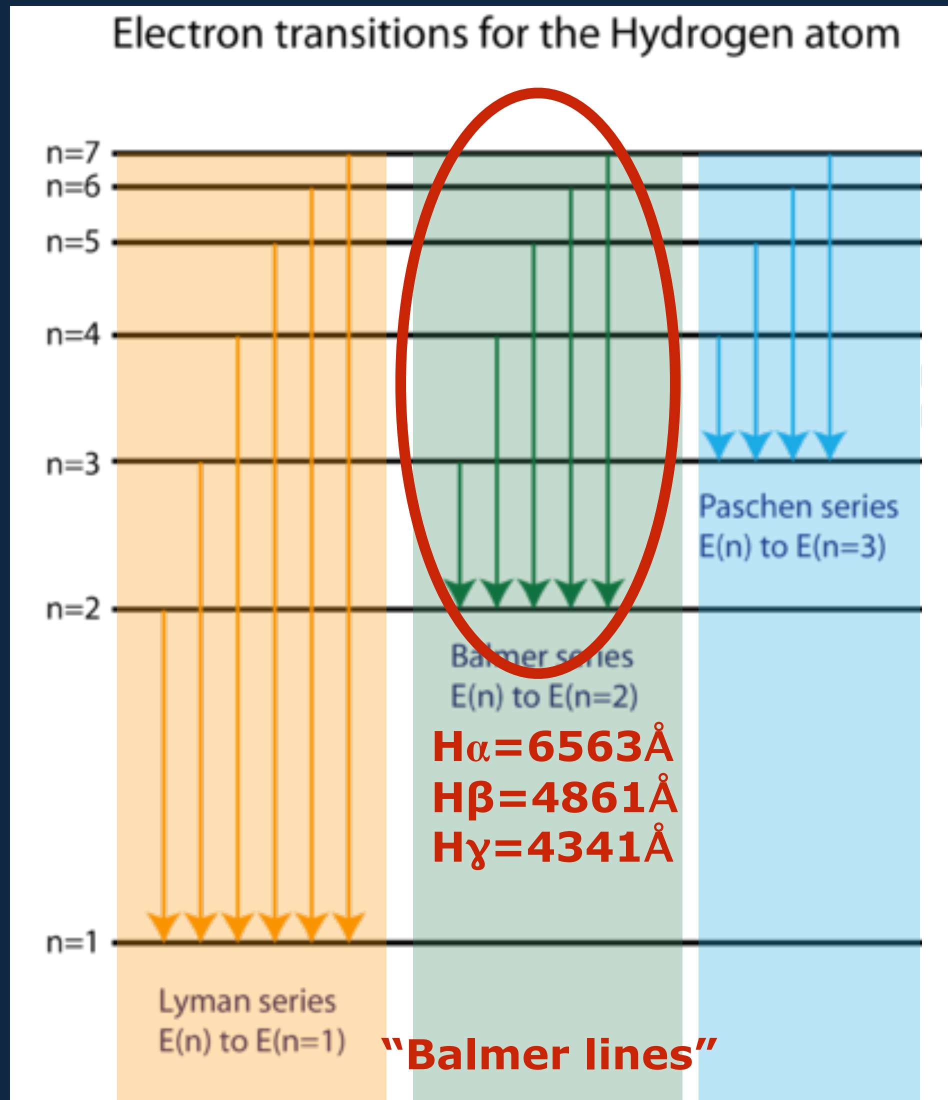
0.00109678...

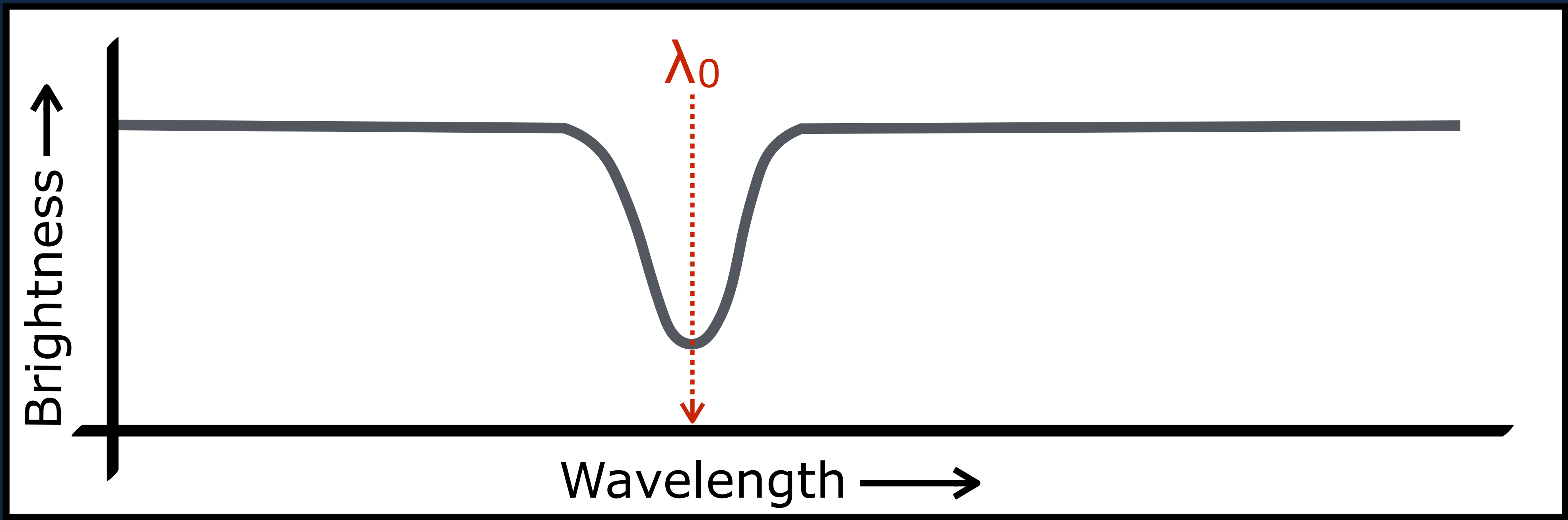


γ-ray X-ray UV visible IR radio

Making a Spectrum - Lines

Anatomy of a spectral line

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

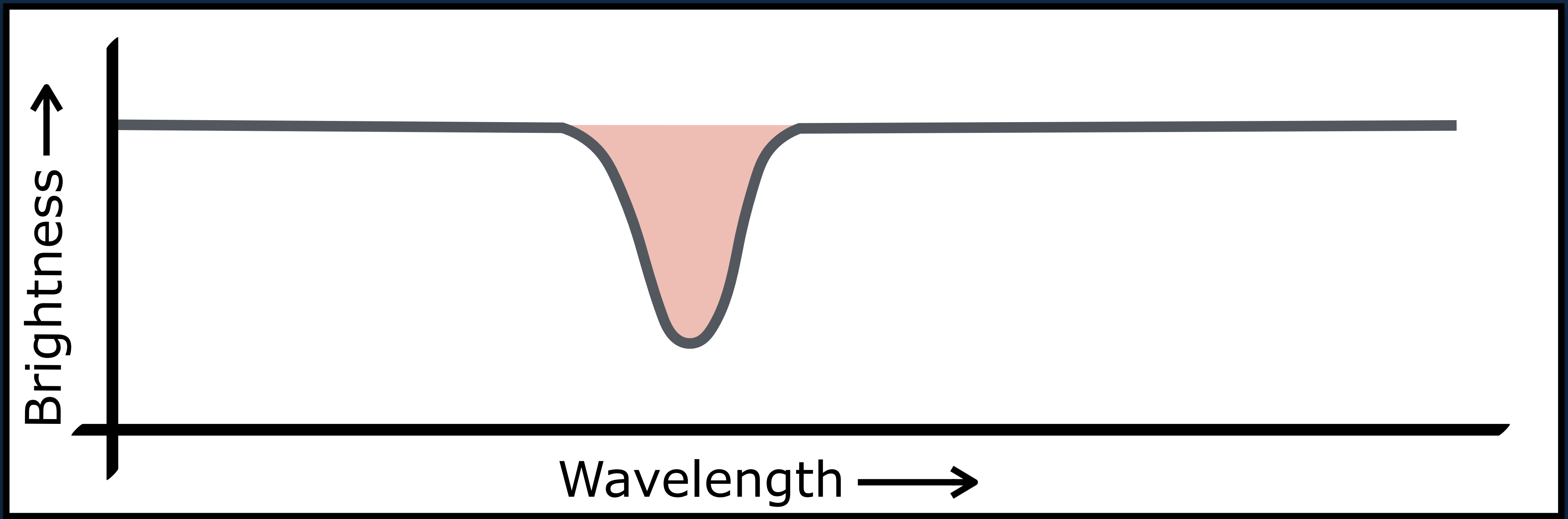


Making a Spectrum - Lines

Anatomy of a spectral line

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

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



Making a Spectrum - Lines

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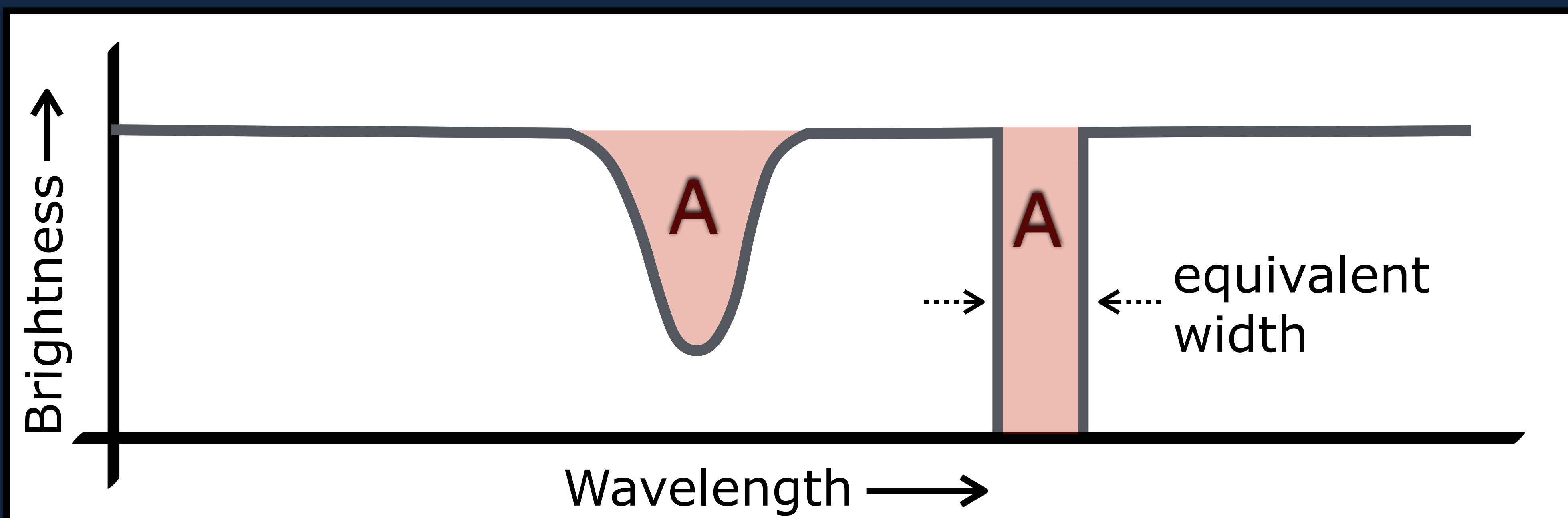
Width: ?



Making a Spectrum - Lines

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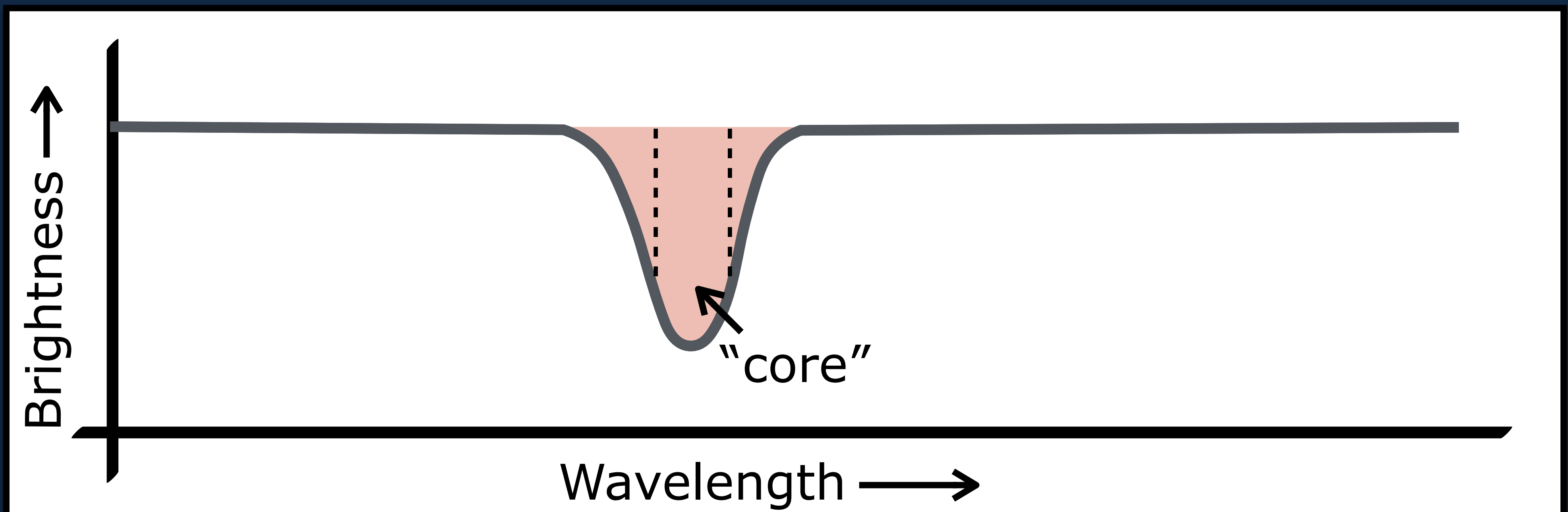

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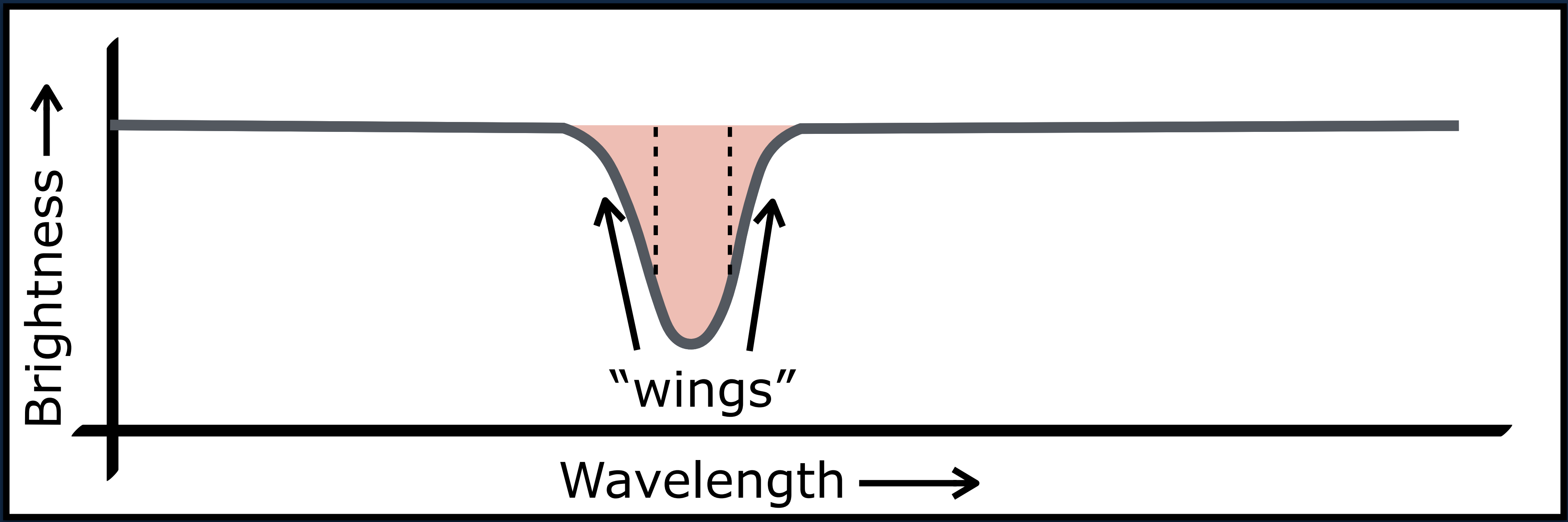

Making a Spectrum - Lines

Anatomy of a spectral line

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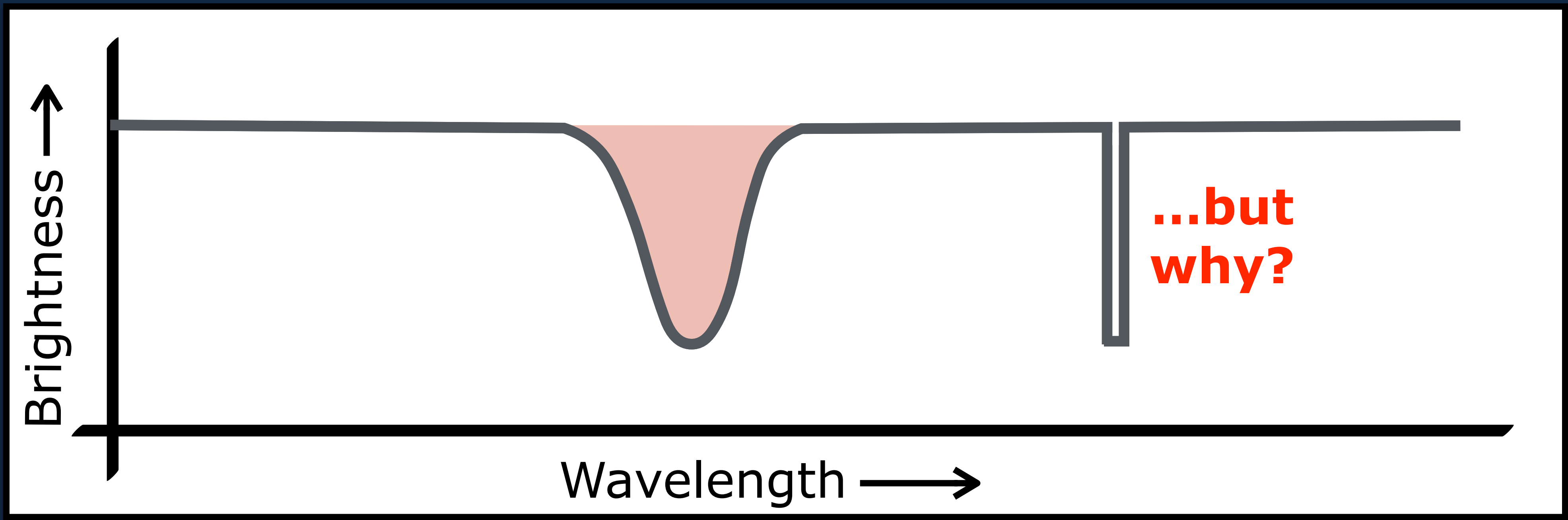
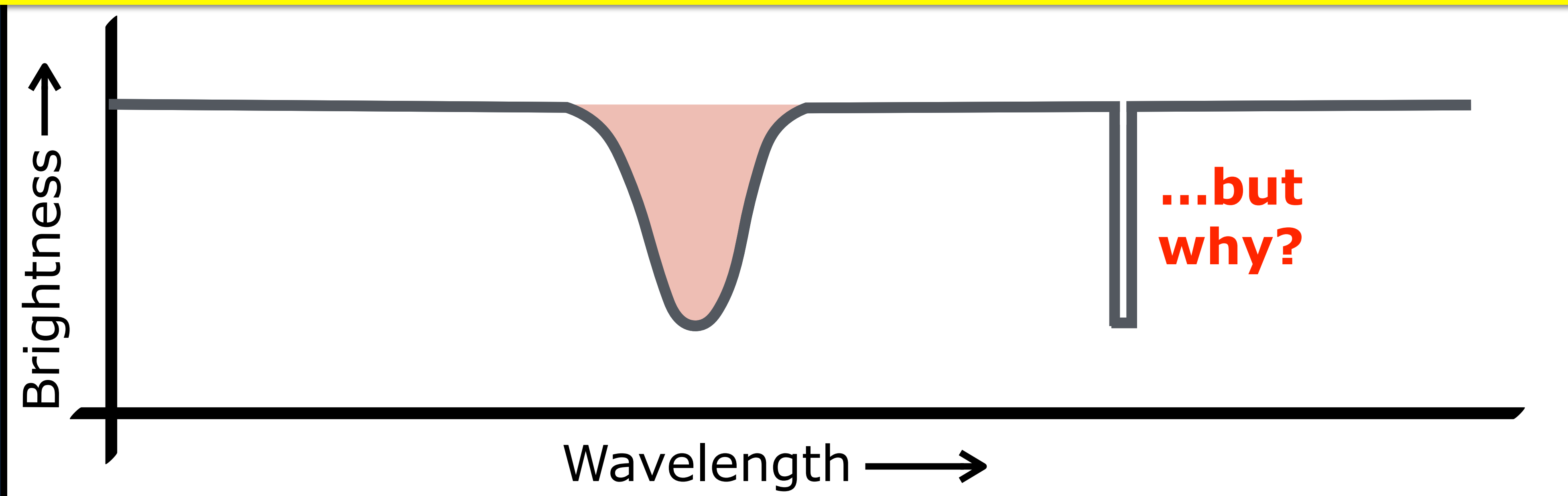


Making a Spectrum - Lines

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

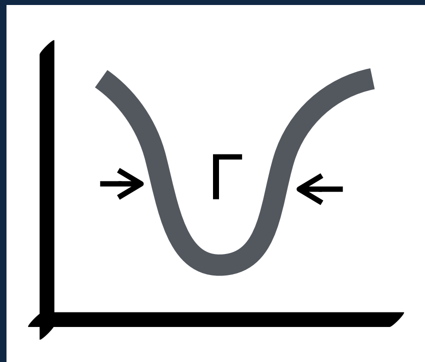
Sources of Line Broadening

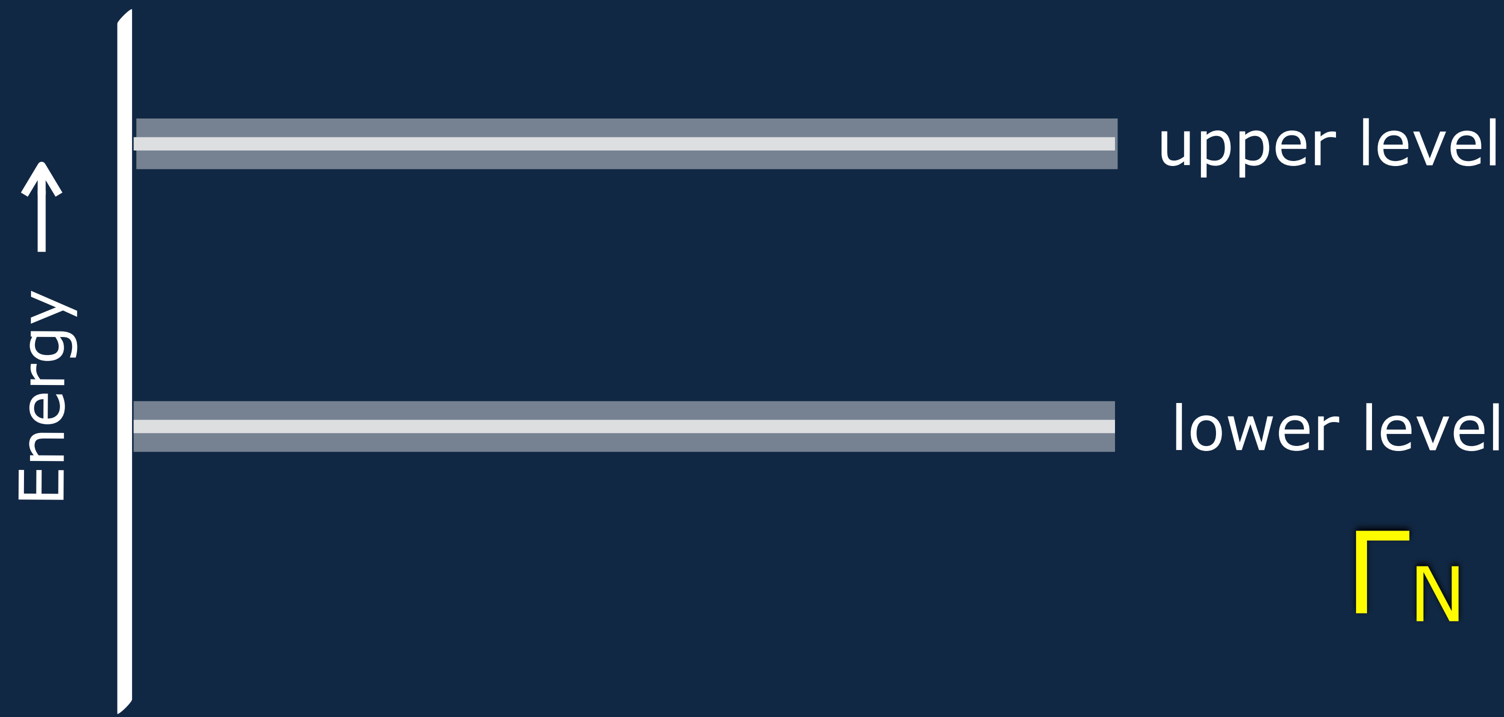
1) Heisenberg: $\Delta E \Delta t > \hbar/2$

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

equation for a damped oscillator $\rightarrow$

Lorentzian





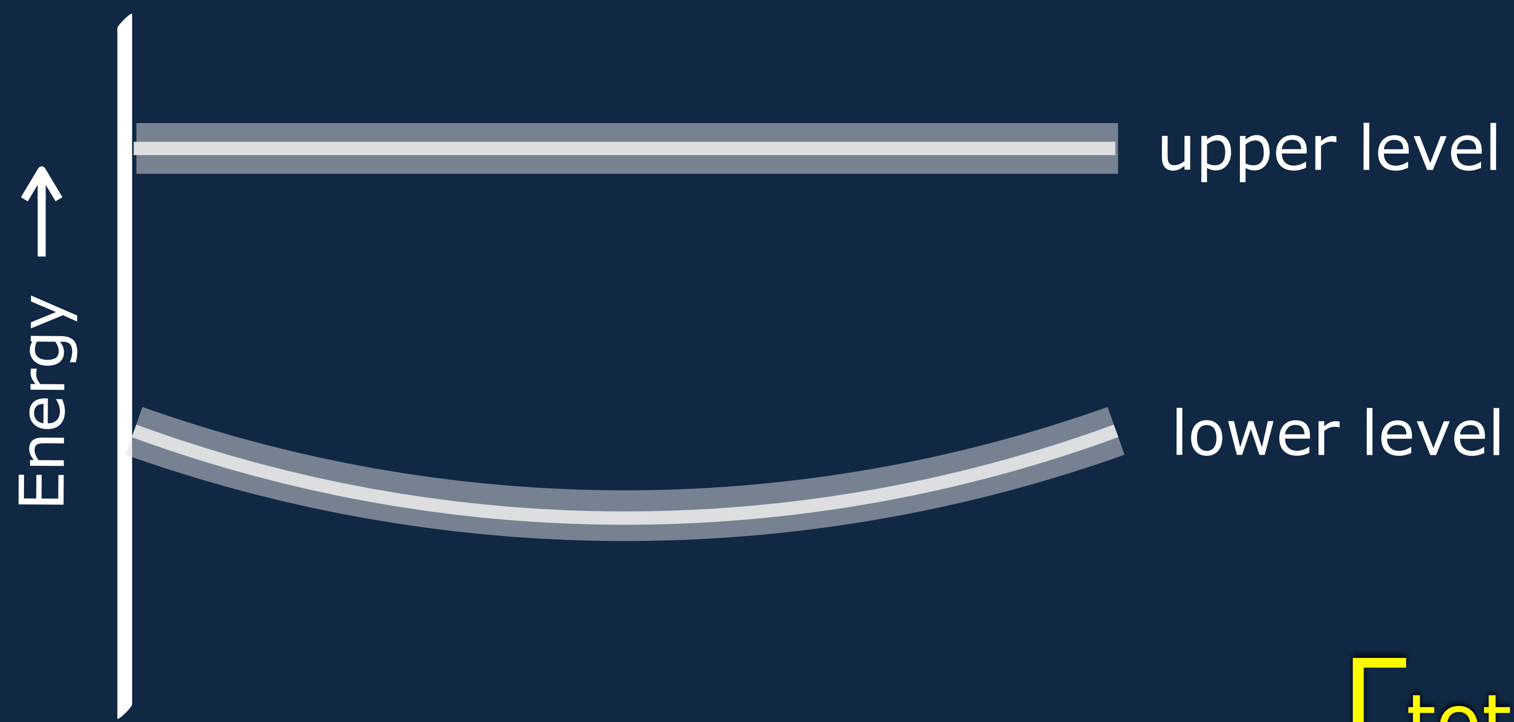
$$\Gamma_N = \Gamma_u + \Gamma_l$$

Making a Spectrum - Lines

Sources of Line Broadening

1) Heisenberg (Lorentzian)

2) Pressure (also Lorentzian)



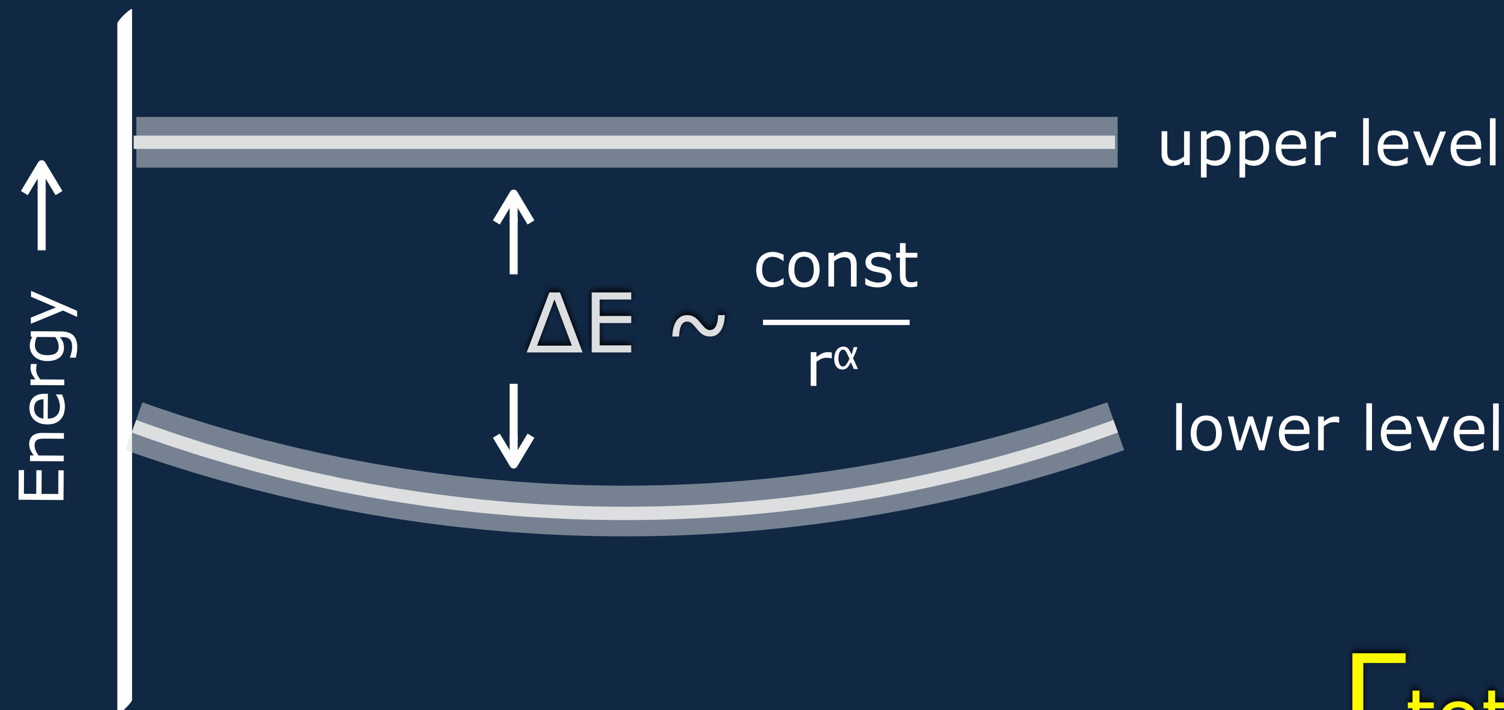
$$\Gamma_P$$

$$\downarrow$$

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

Making a Spectrum - Lines

Sources of Line Broadening



Γ_P

$\downarrow$

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

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

Making a Spectrum - Lines

Sources of Line Broadening

1) Heisenberg (Lorentzian)

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3) Thermal (Gaussian)

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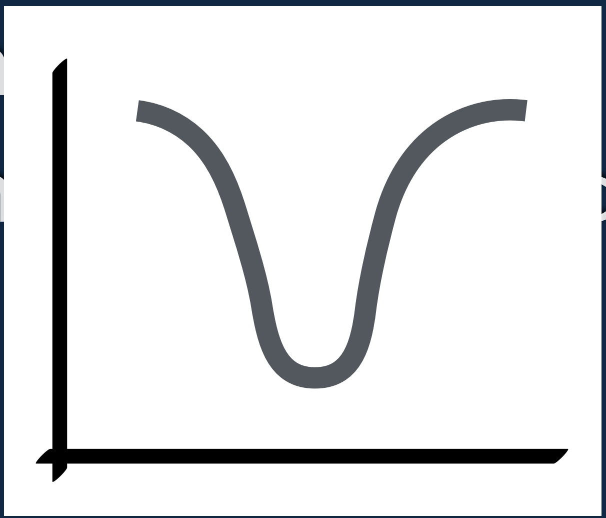
total distribution is a Gaussian

Gaussian



Making a Spectrum - Lines

Sources of Line Broadening

1) Heisenberg (Lorentzian)
2) Pressure (also Lorentzian)
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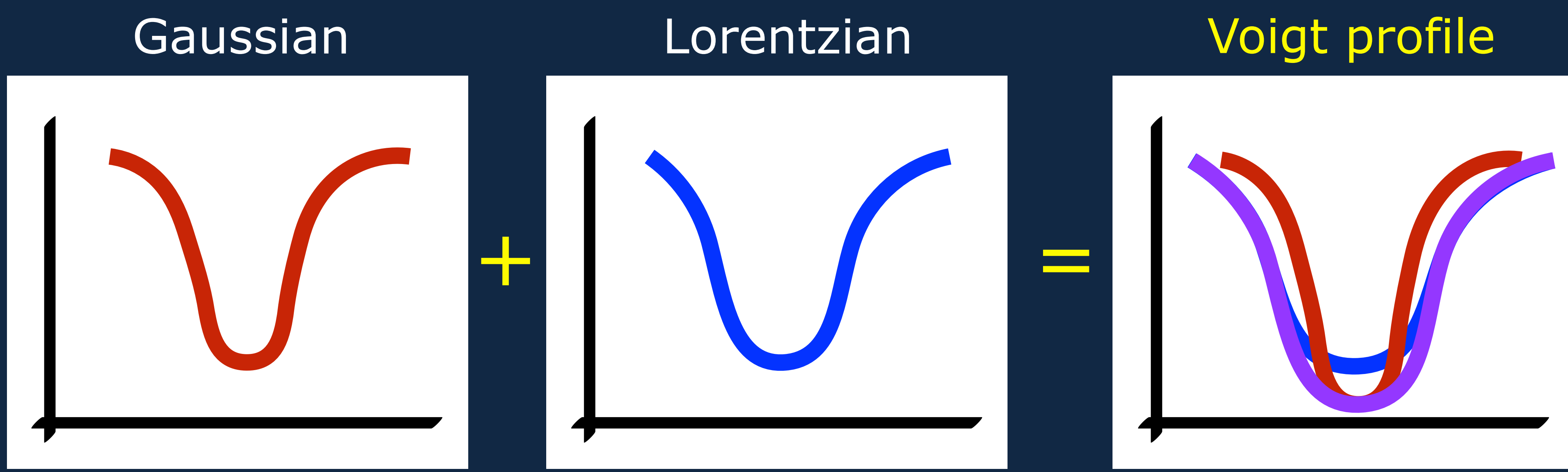


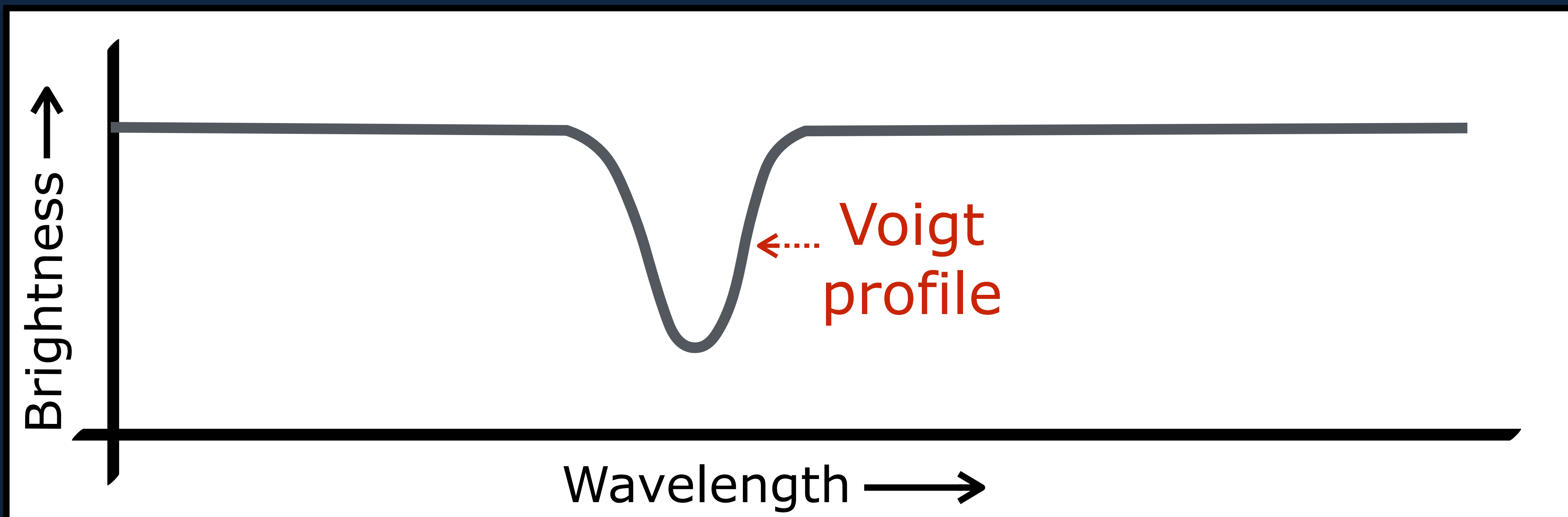
Making a Spectrum - Lines

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

source at rest

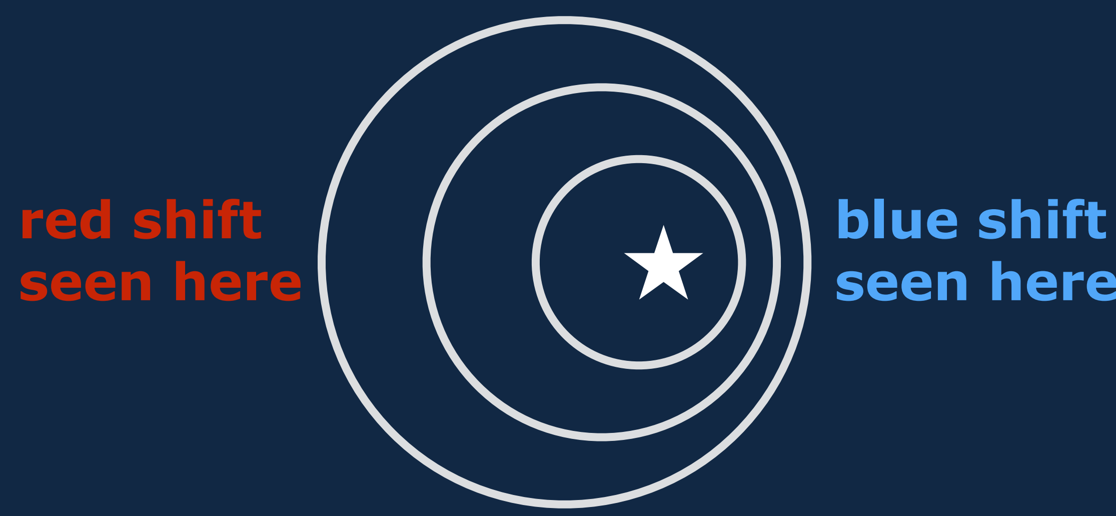
Making a Spectrum - Lines

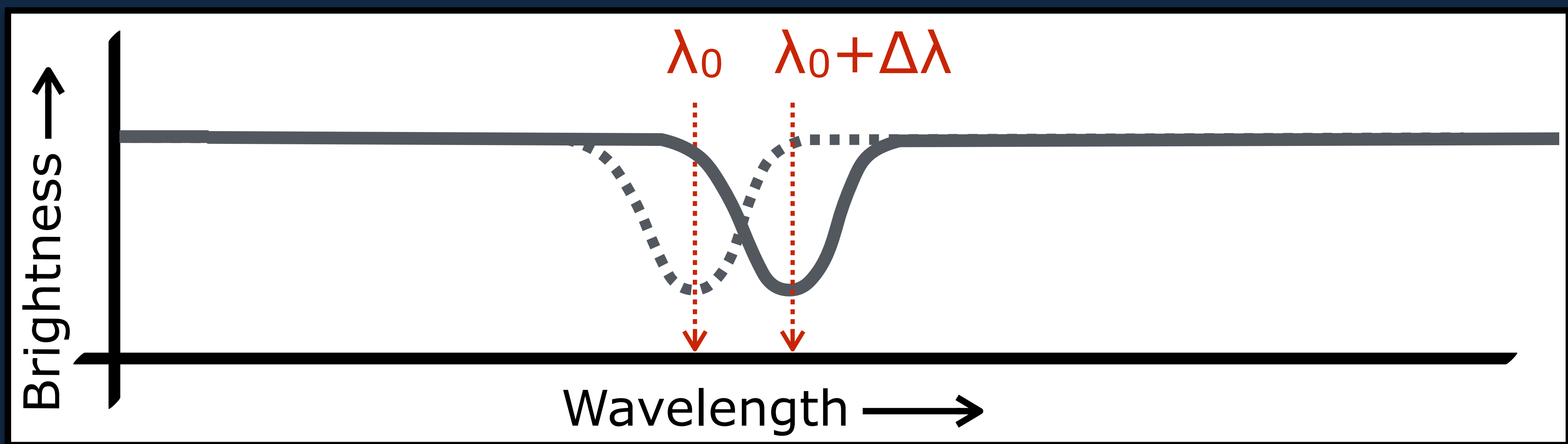
Doppler shift

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.

Br

Wavelength ⟶

Making a Spectrum - Lines

Doppler shift

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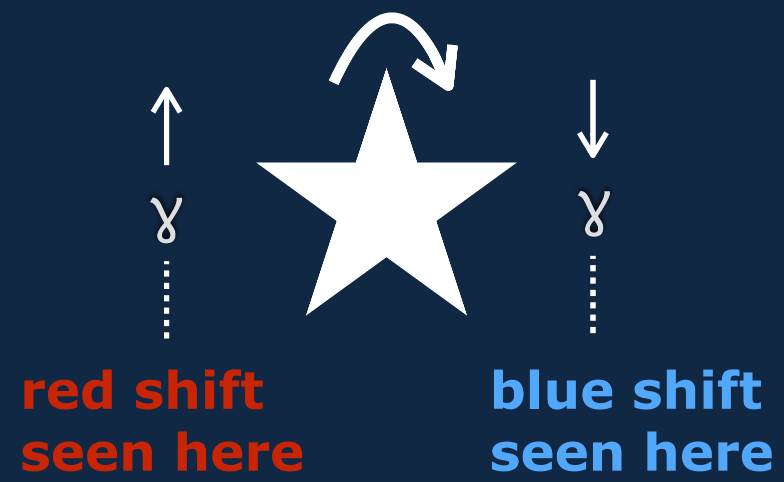

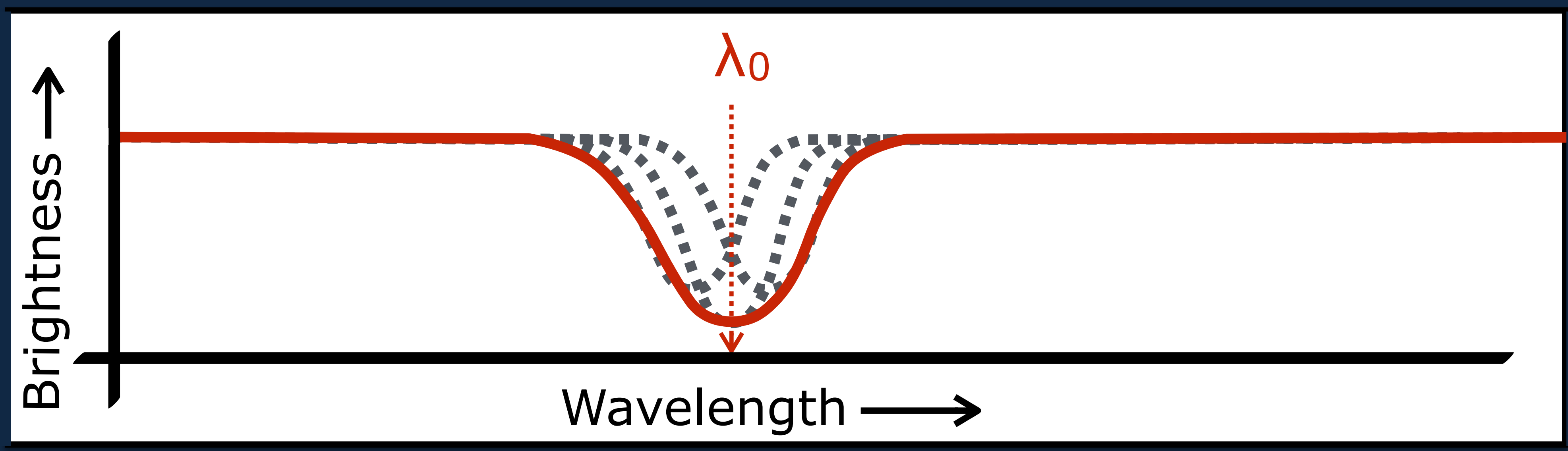

Making a Spectrum - Lines

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red shift seen here

blue shift seen here

Uses in astronomy:

1) find motion 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
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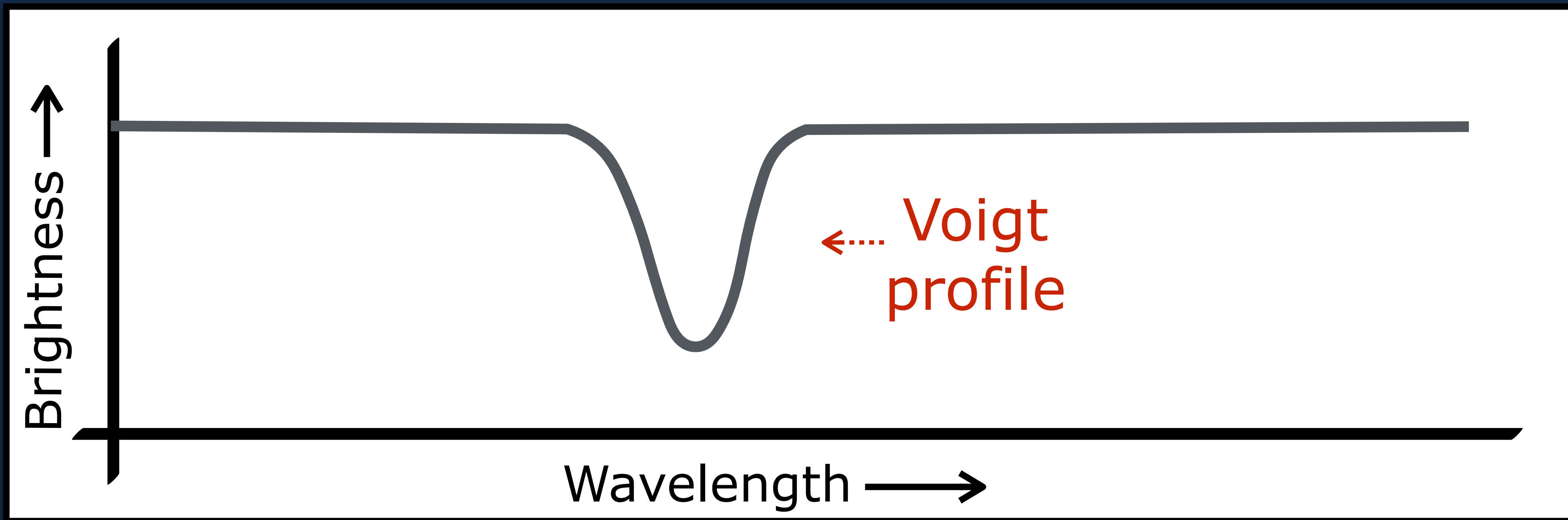
Strength/flux: # of e^- in that level; composition/abundance

Width: intrinsic broadening; rotation; abundance

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



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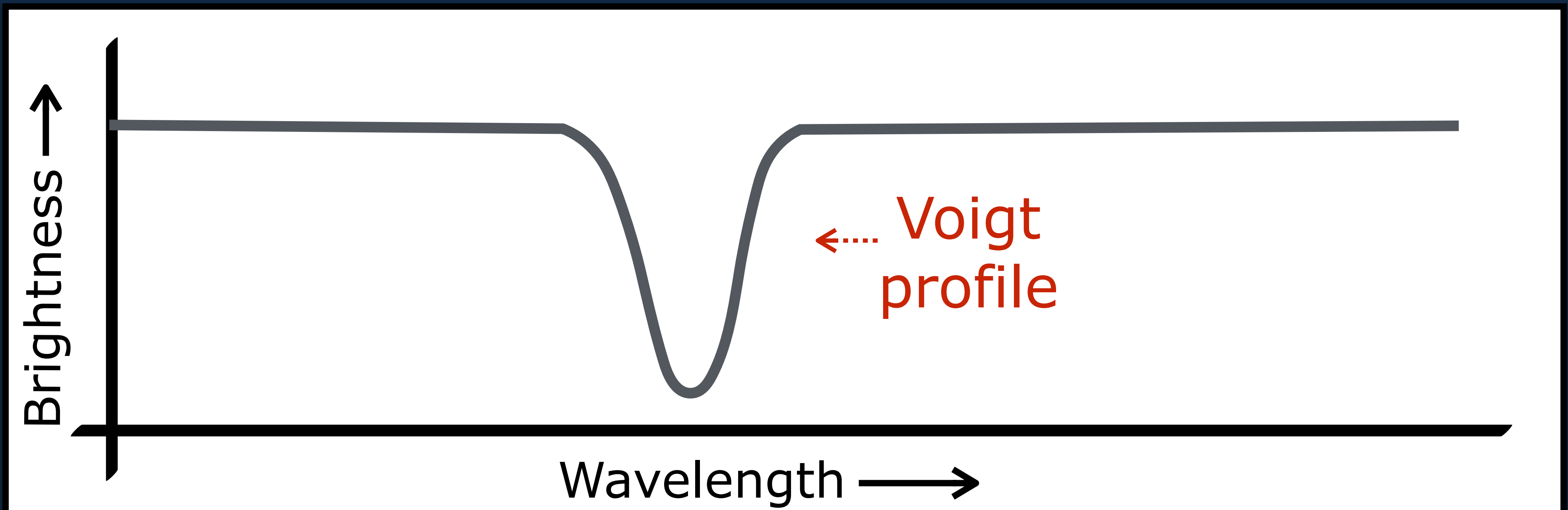

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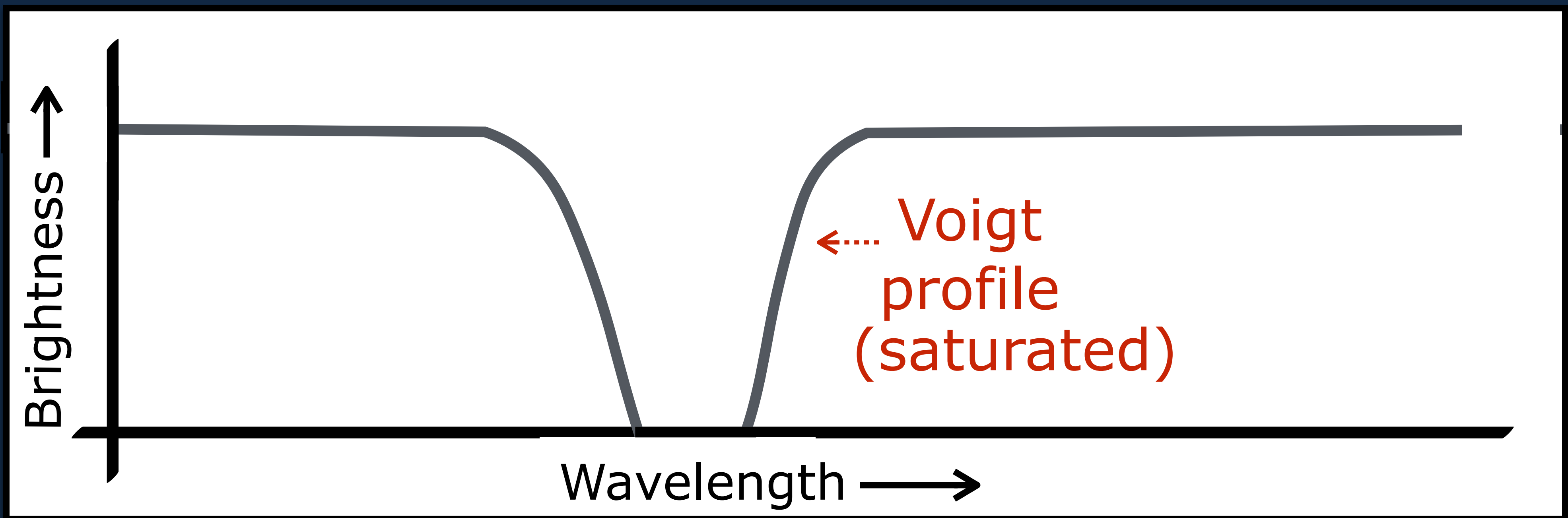

Making a Spectrum - Lines

Sources of Line Broadening

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

Making a Spectrum - Lines

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(most important: instrumentation/resolution!)

Making a Spectrum - Lines

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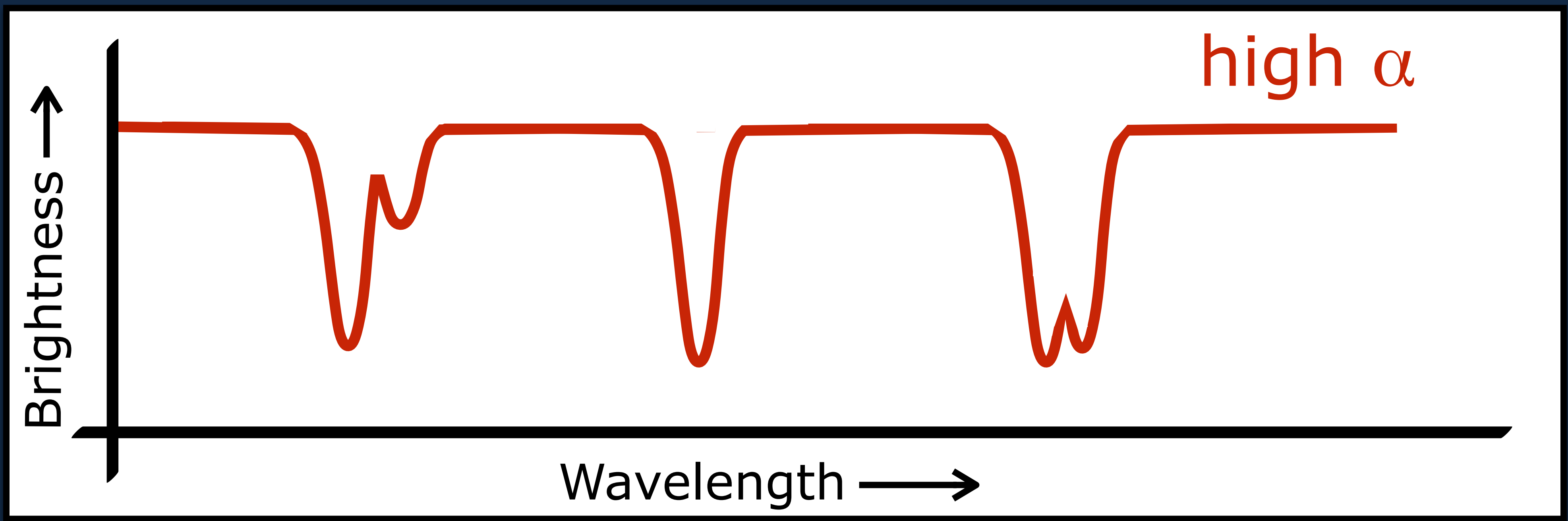

Making a Spectrum - Lines

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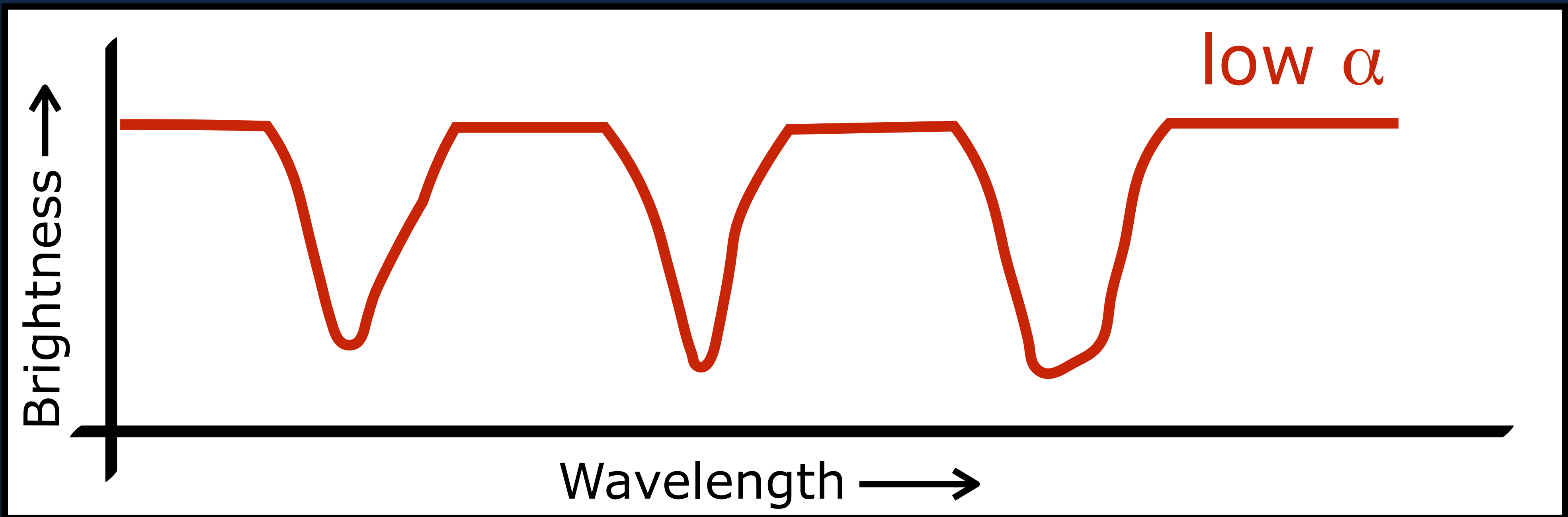


Spectra in Astronomy

Anatomy of a spectrum

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

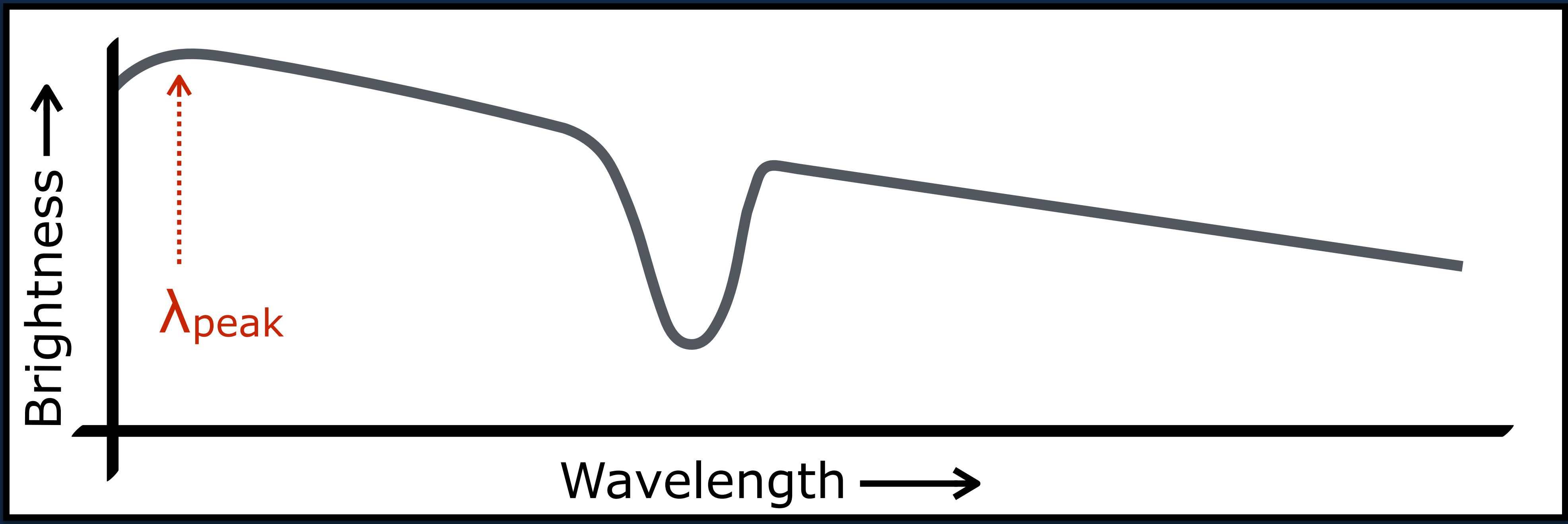
Strength/flux: # of e$^-$ in that level; composition/abundance

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

lines

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

continuum



Spectra in Astronomy

Anatomy of a spectrum

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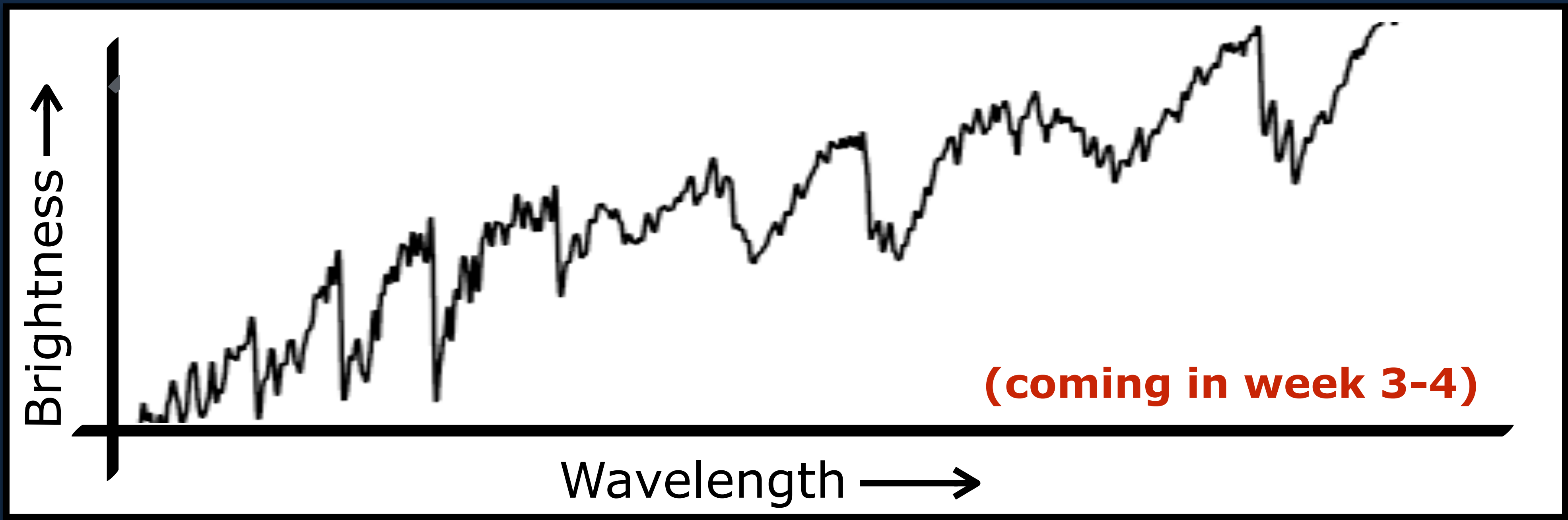
Strength/flux: # of e^- in that level; composition/abundance

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

lines

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



Spectra in Astronomy

Anatomy of a spectrum

A star's spectrum can give us its…

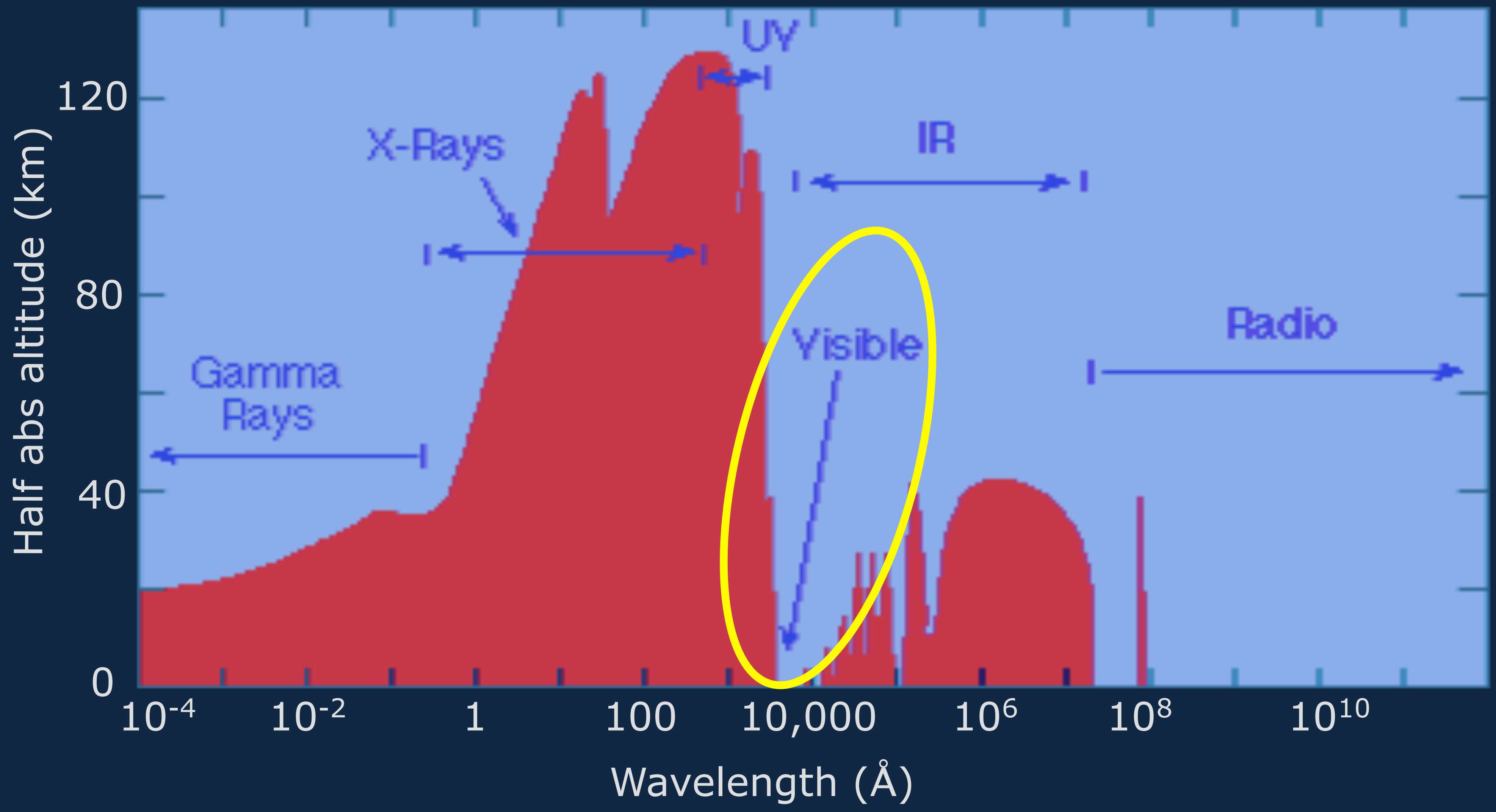
1) Distance
2) Velocity
3) Brightness
4) Temperature
5) Mass
6) Radius

(coming in week 3-4)

Spectra in Astronomy

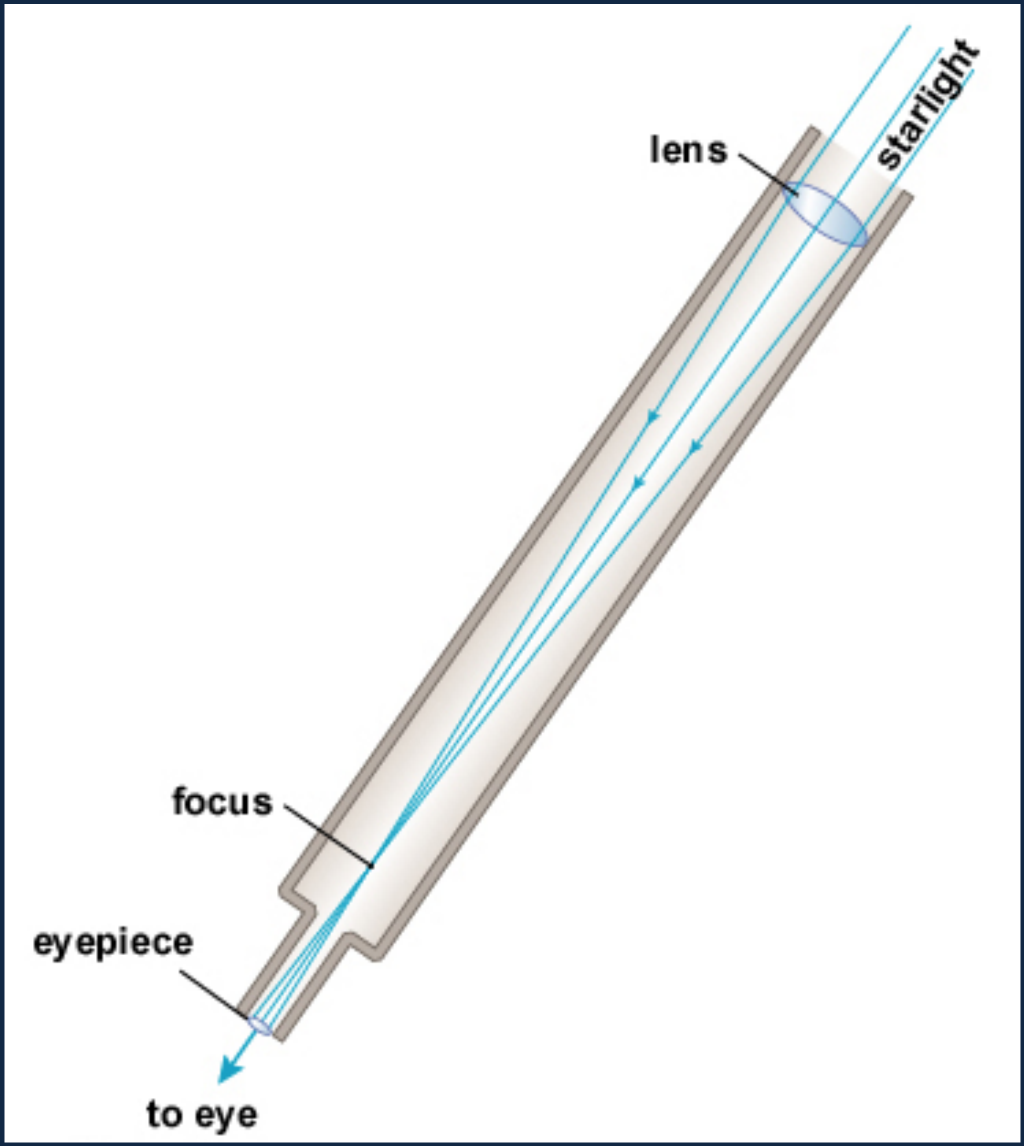
γ-ray	X-ray	UV	visible	IR	radio
MeV-TeV	keV	500Å-3000Å	4000Å-7000Å	~1μ-1000μ	1Hz - 3000GHz
GRB, SNe	XRBs, SN remnants	hot stars	most stars	cool stars, planets	molecular clouds

Spectra in Astronomy



Telescopes - Optical

Early telescopes were refractors…



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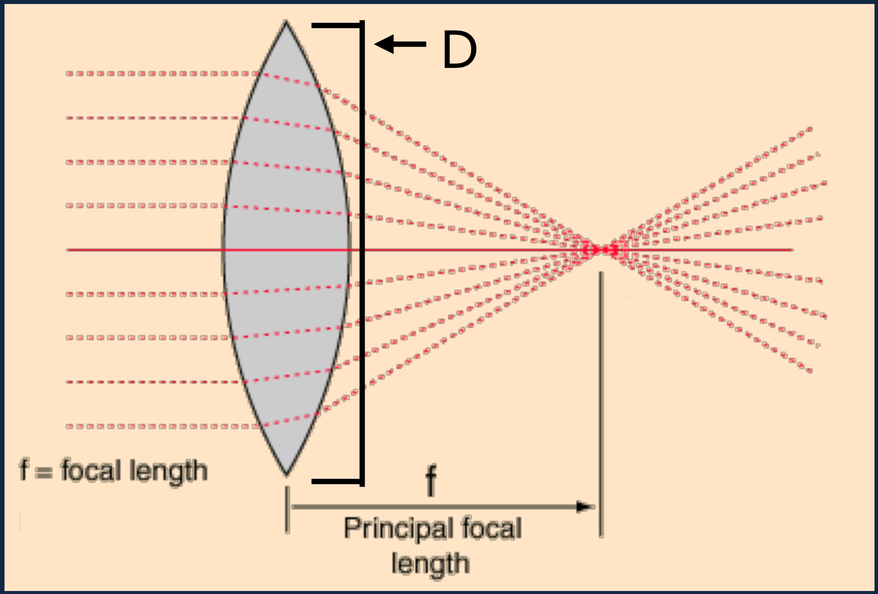
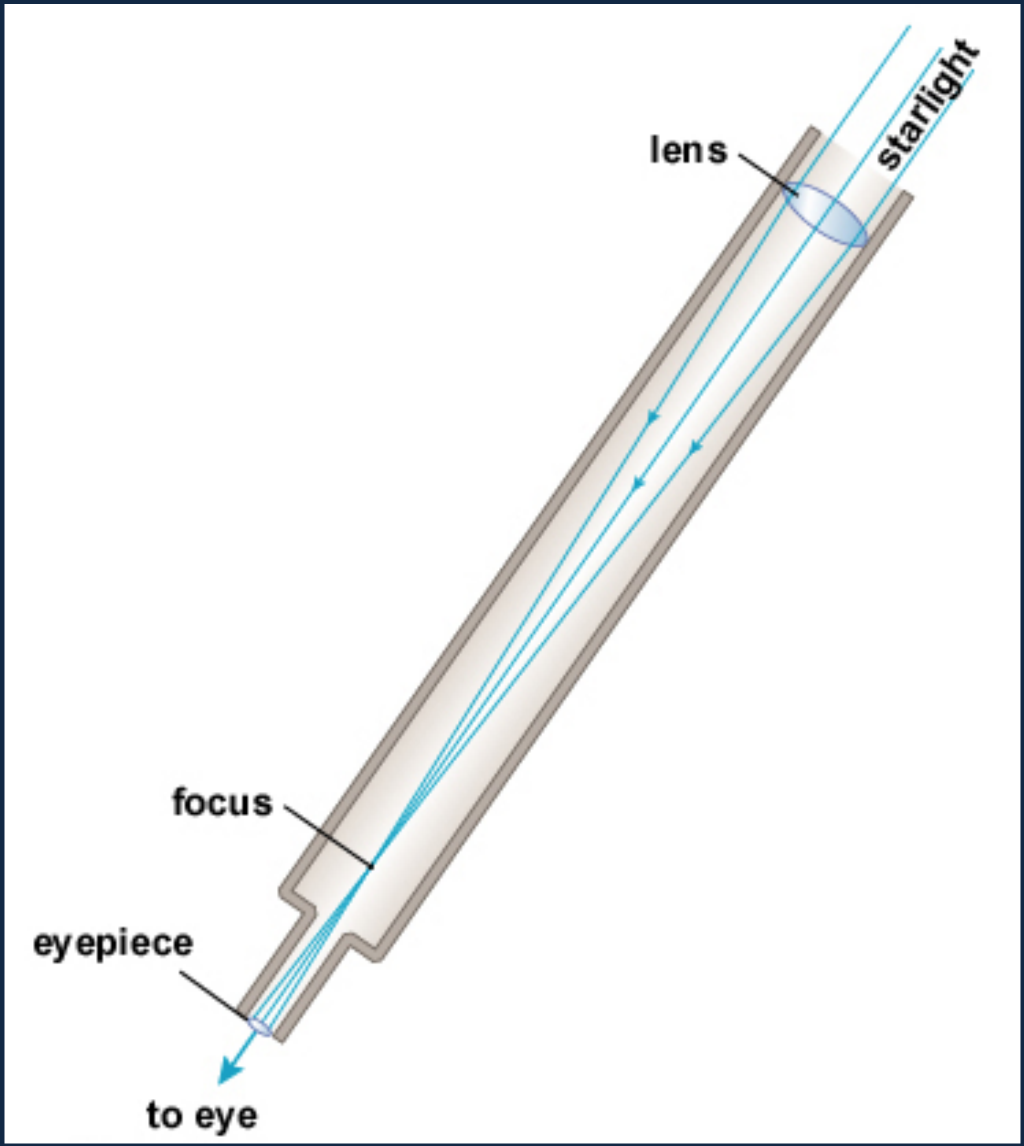




f-ratio = f/D

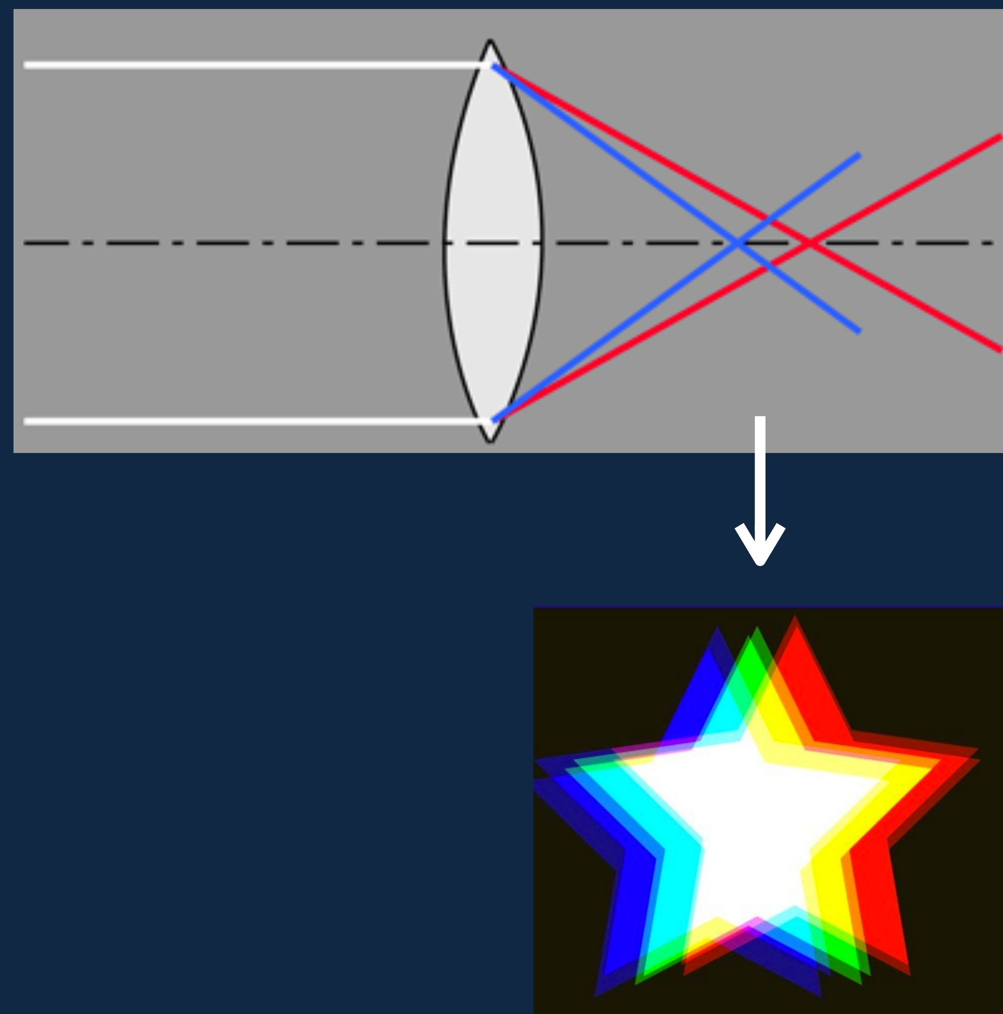
(smaller f-ratio = brighter image)

Telescopes - Optical

Early telescopes were refractors…

…but there were problems.

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



Telescopes - Optical

Early telescopes were refractors…

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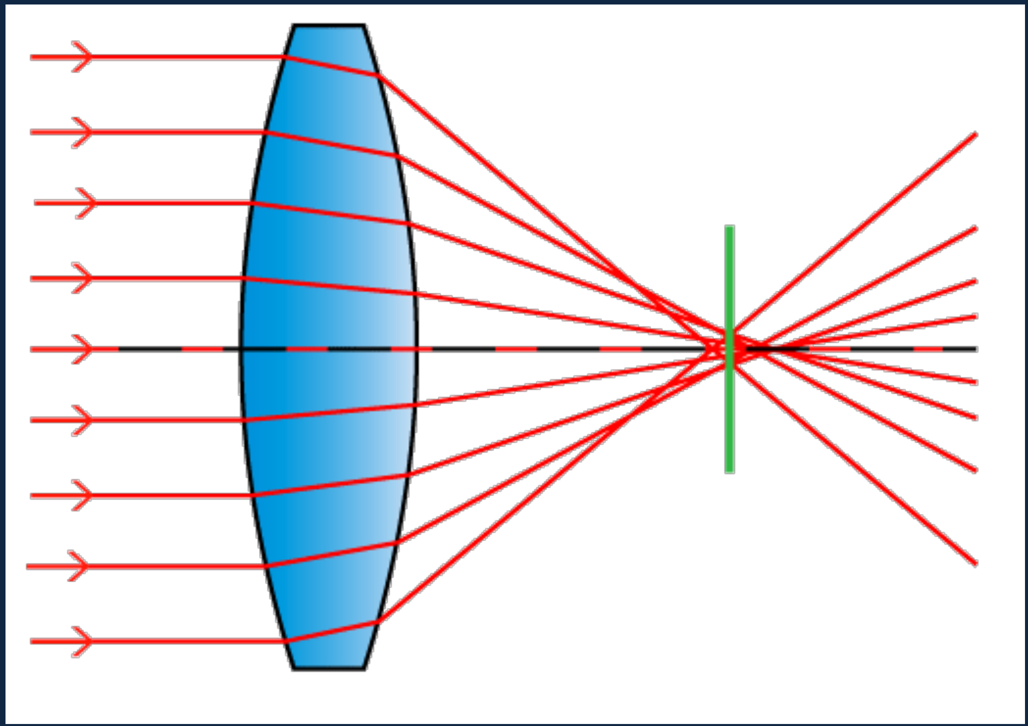
2) Spherical aberration
(light entering a spherical lens at different apertures has different focal points)



Telescopes - Optical

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

Telescopes - Optical

Discussion Question

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

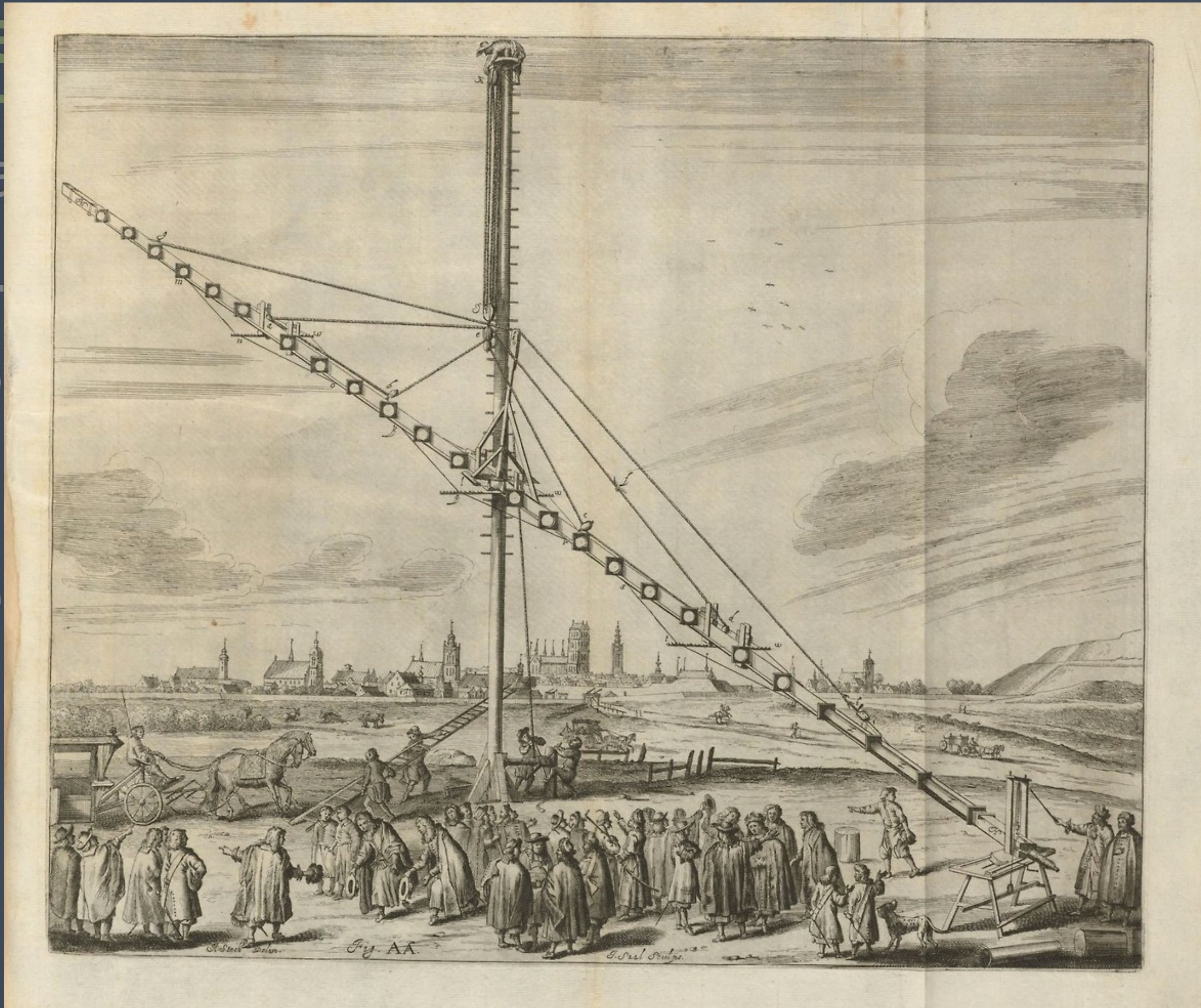
A) Increase the focal length (higher f-ratio, so less aberration)
B) Increase the lens diameter (lower f-ratio, so brighter image)
C) Decrease the lens diameter (higher f-ratio, so less aberration)
D) Sell it and buy a mirror for a reflecting telescope

Te

Ea

1)

2)



Hevelius 150 ft. long telescope, 1673

Telescopes - Optical

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 - Optical

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…

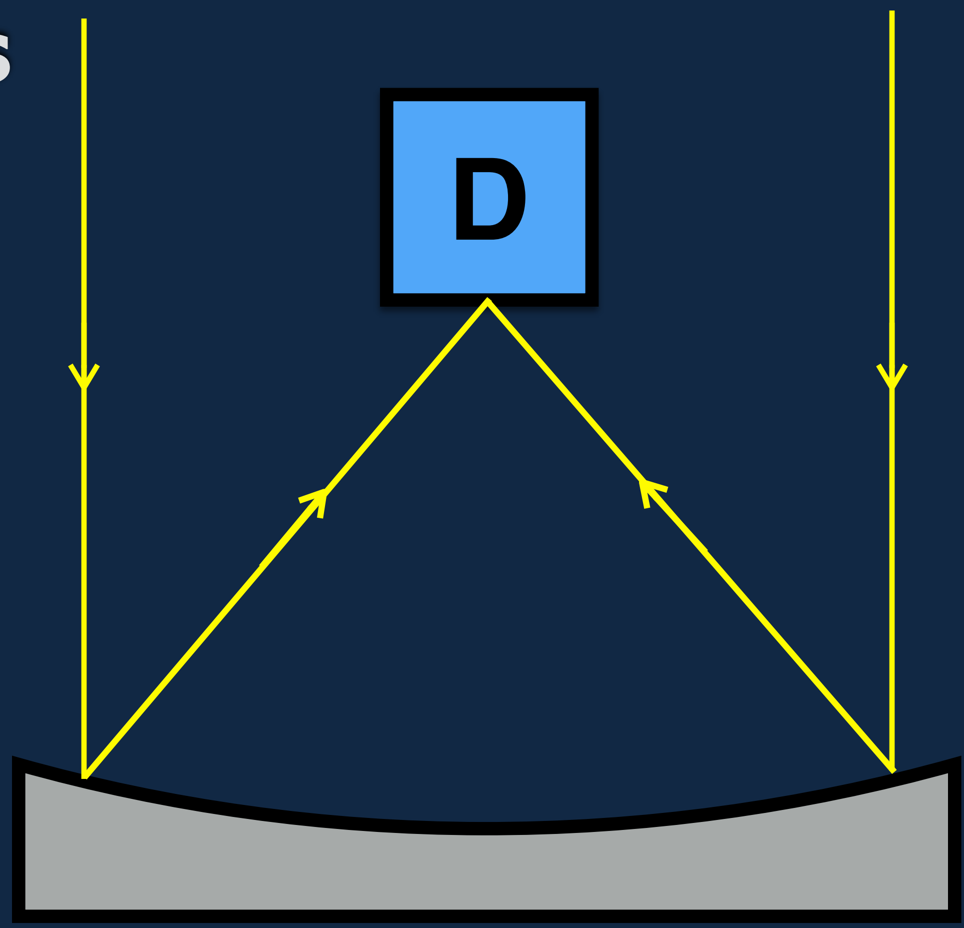
~~a) Lens sag~~ easily fixed!

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

Telescopes - Optical

<u>Refracting Telescope Designs</u>

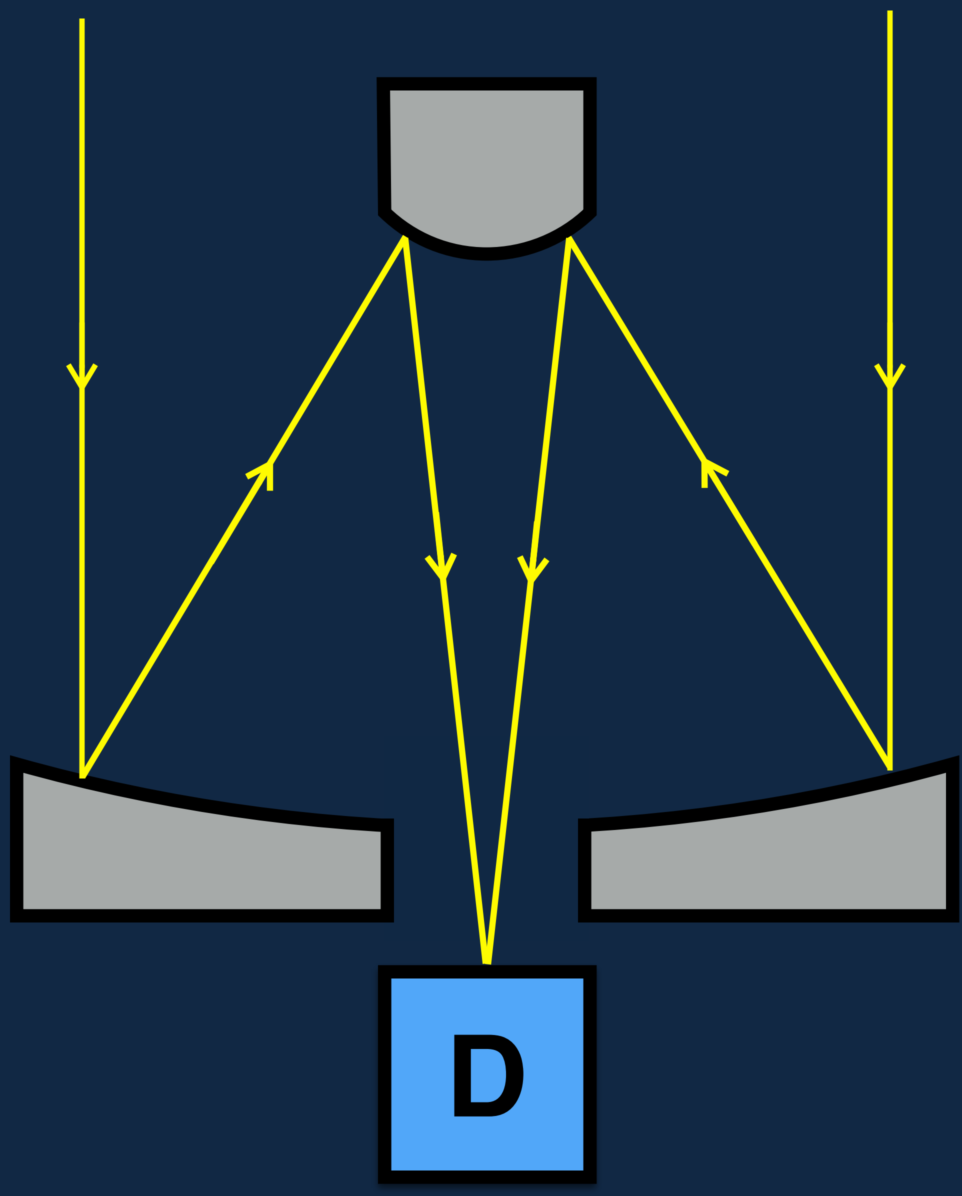
Prime focus



Telescopes - Optical

Refracting Telescope Designs

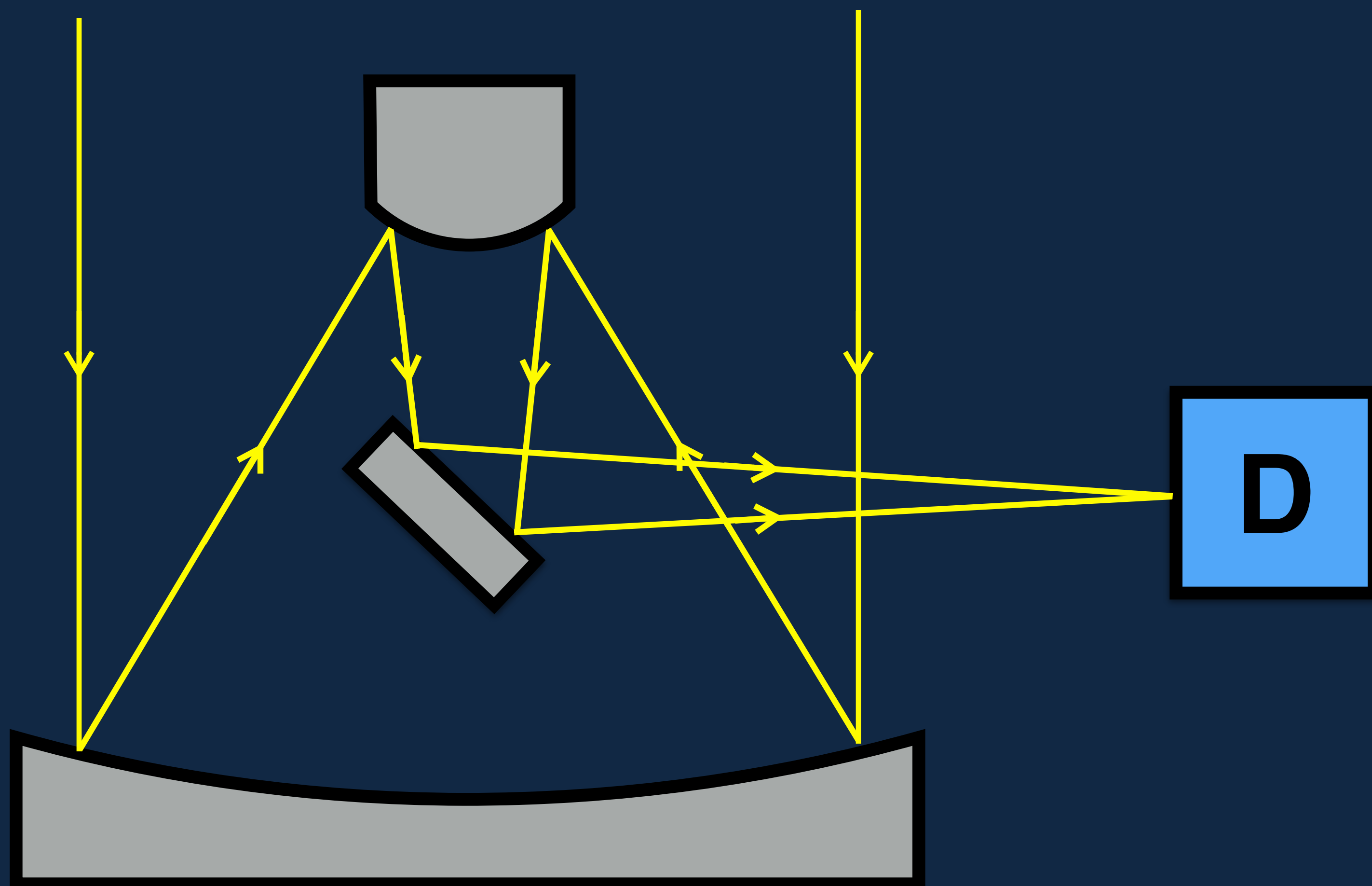
Cassegrain



Telescopes - Optical

Refracting Telescope Designs

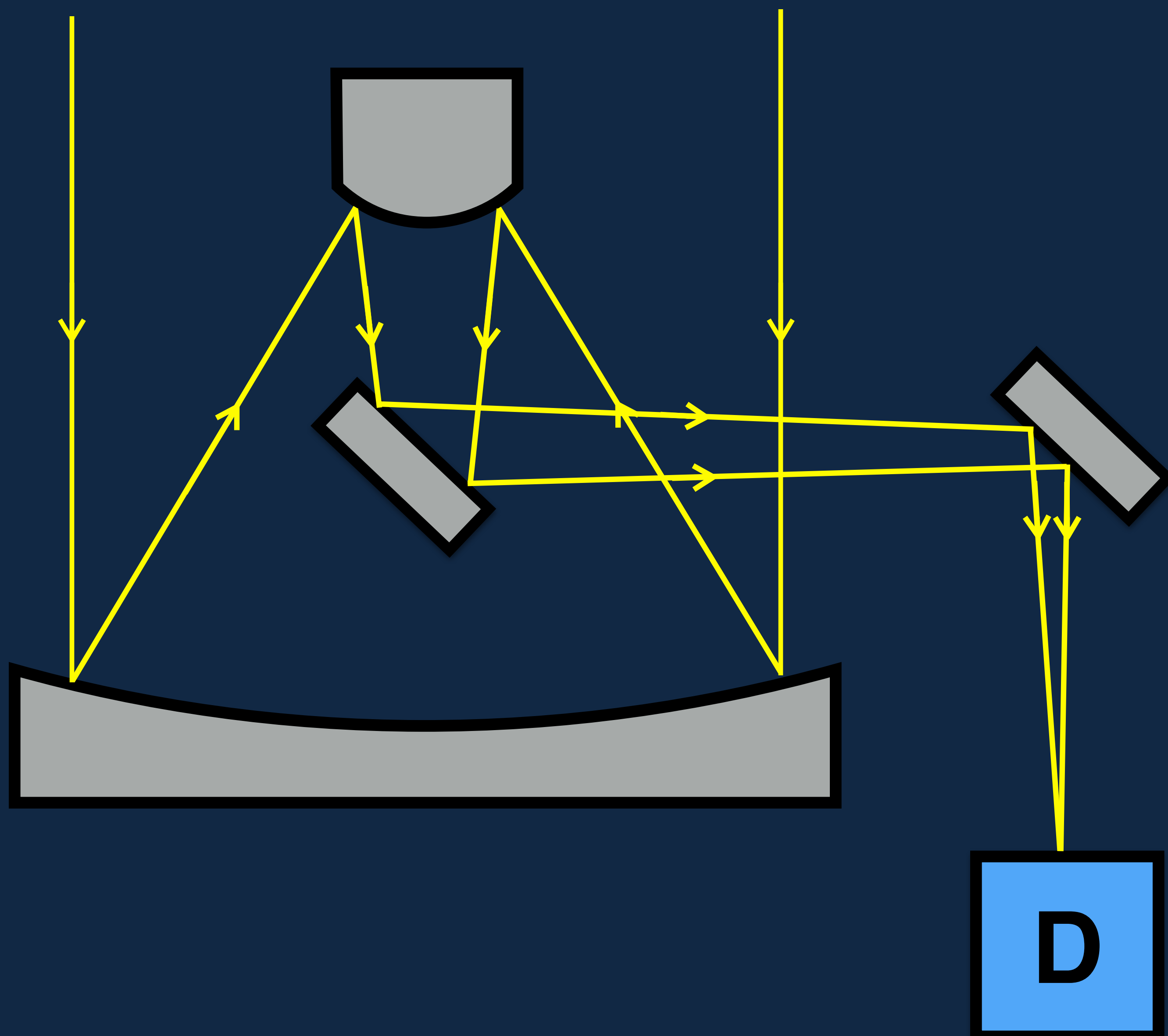
Nasmyth



Telescopes - Optical

Refracting Telescope Designs

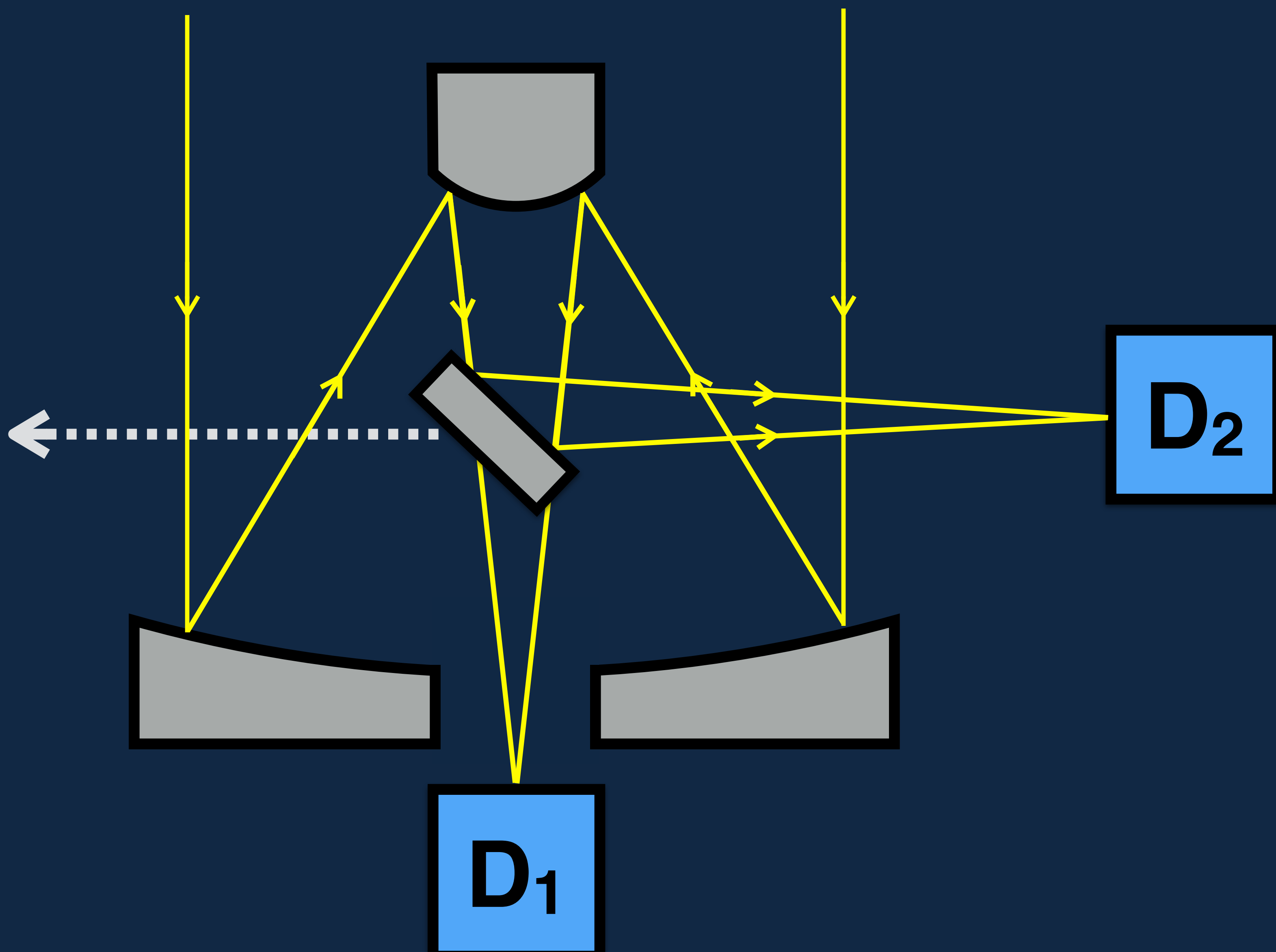
Coudé



Telescopes - Optical

Refracting Telescope Designs

Reality: multiple

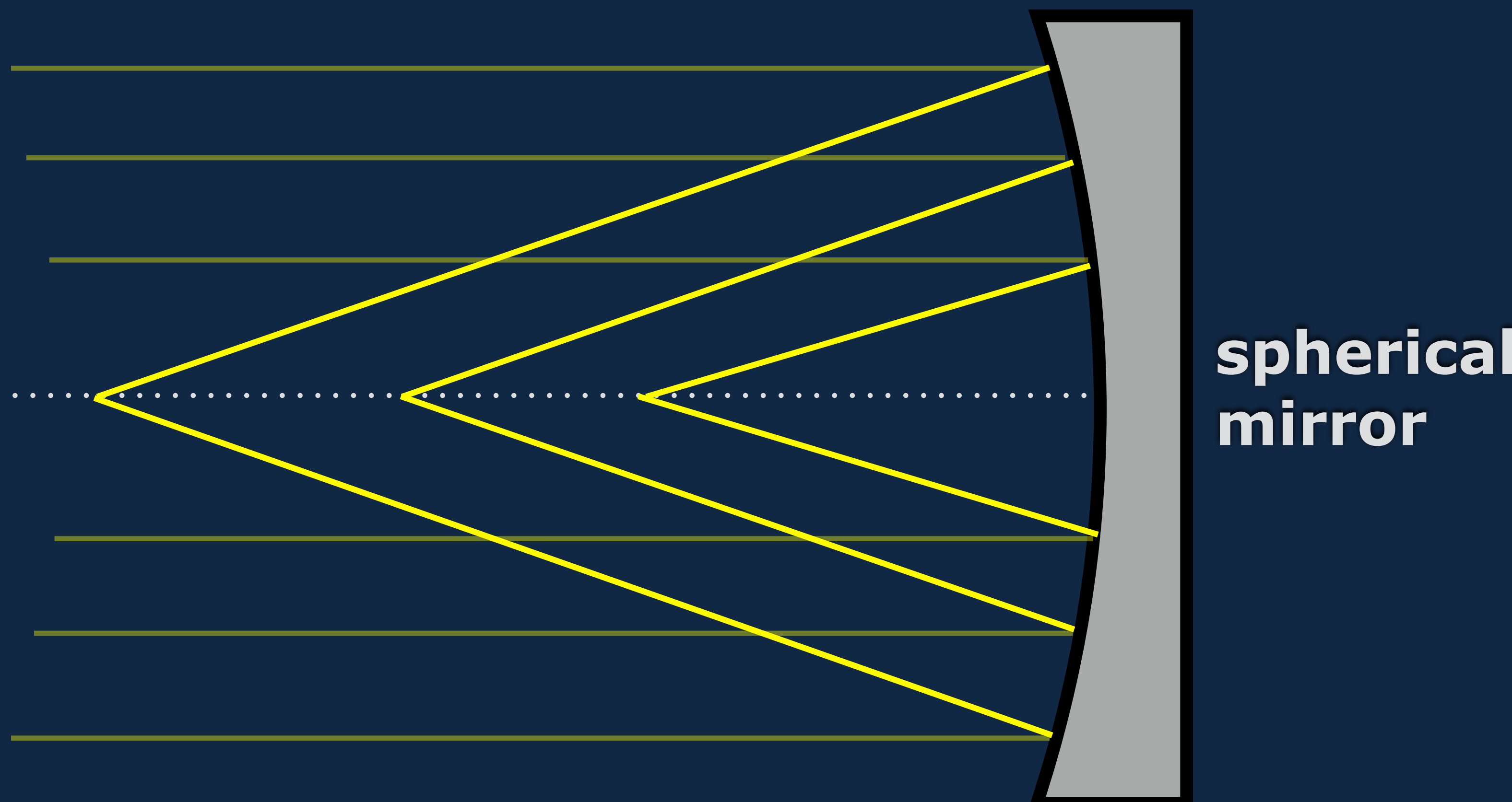


Telescopes - Optical

<u>Refracting Telescope Designs</u>

There are still a few issues…

1) Spherical aberration



Telescopes - Optical

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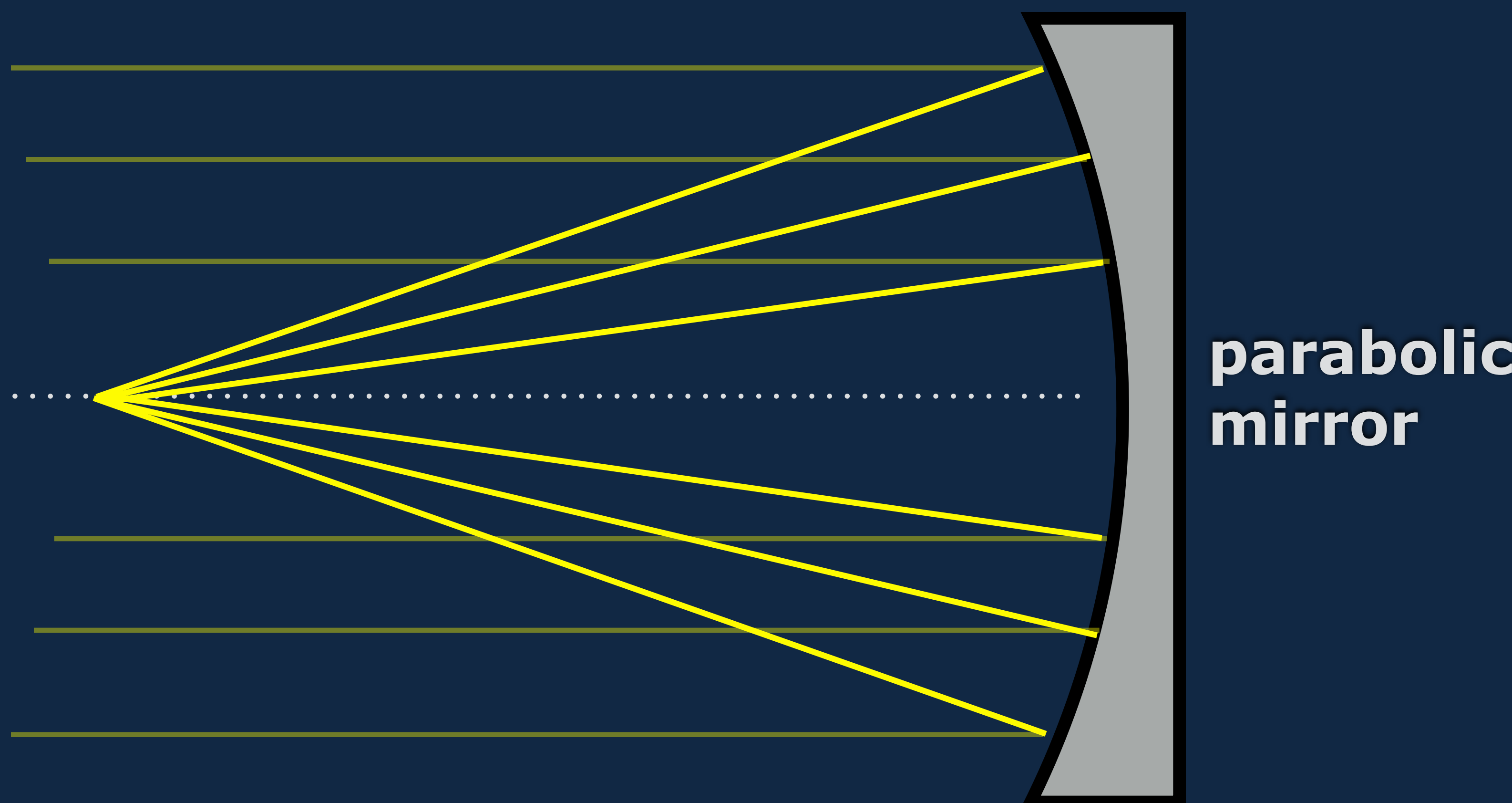


Telescopes - Optical

mirror oven, University of Arizona Mirror Lab

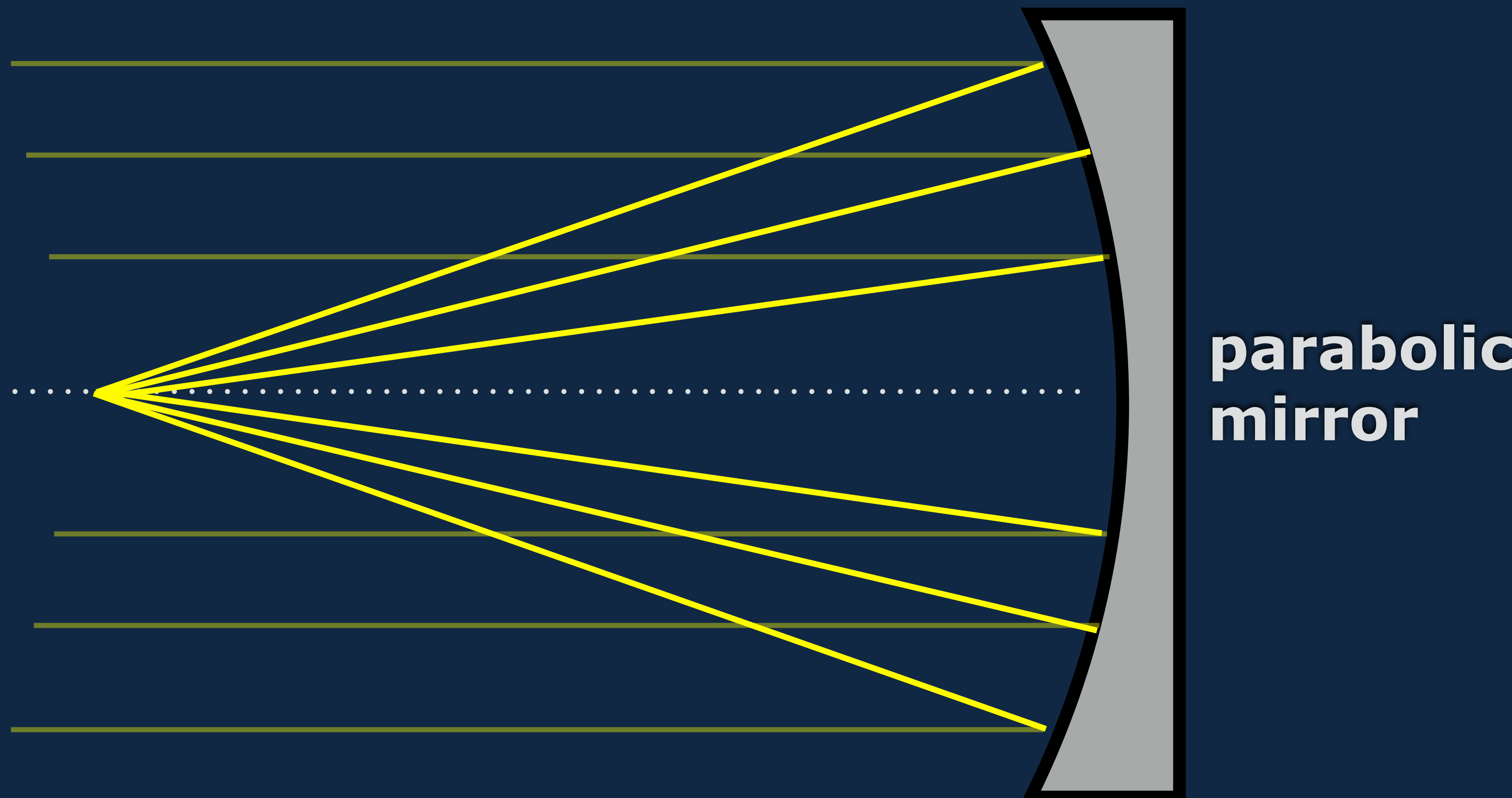
Telescopes - Optical

<u>Refracting Telescope Designs</u>

There are still a few issues…

1) Spherical aberration

Required precision ~ 0.05λ → 20nm for visible light



Next time

The most famous case of spherical aberration…