hi

Day 19, 28.03.2019

Quantum Mechanics 1.5

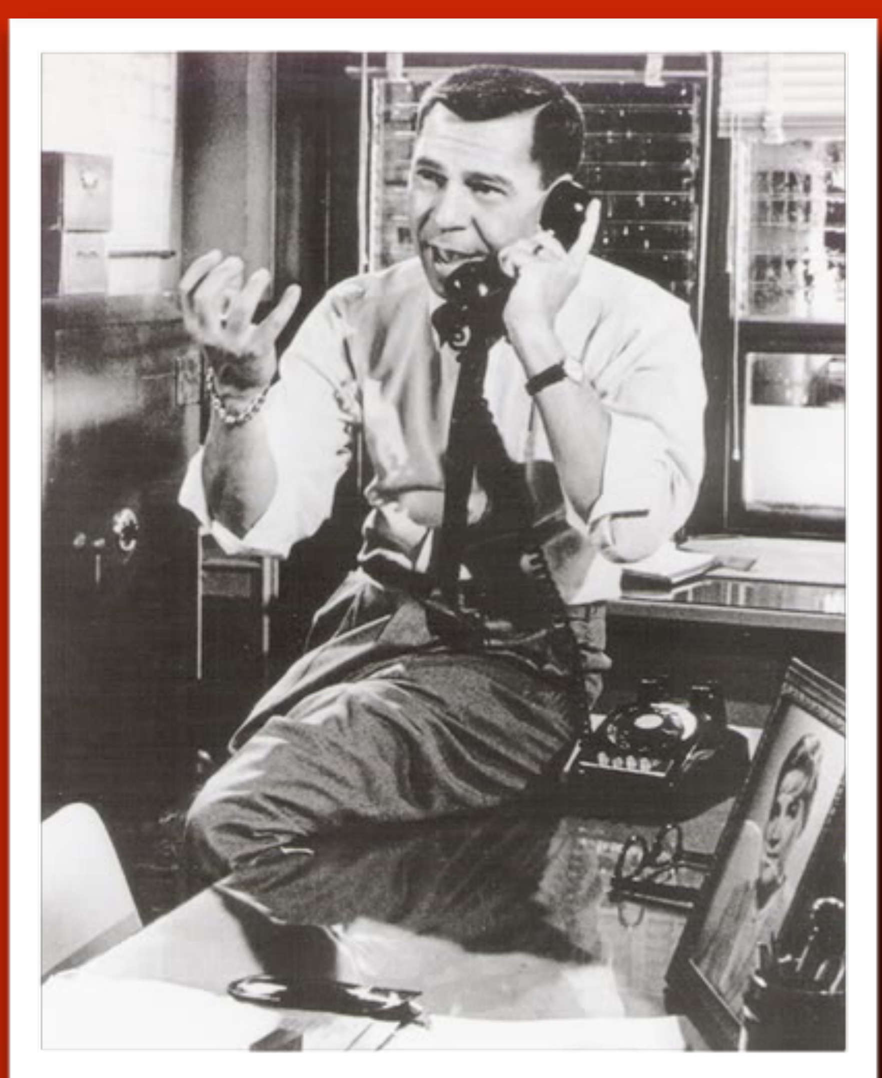
today is opening day

Ray Brown week

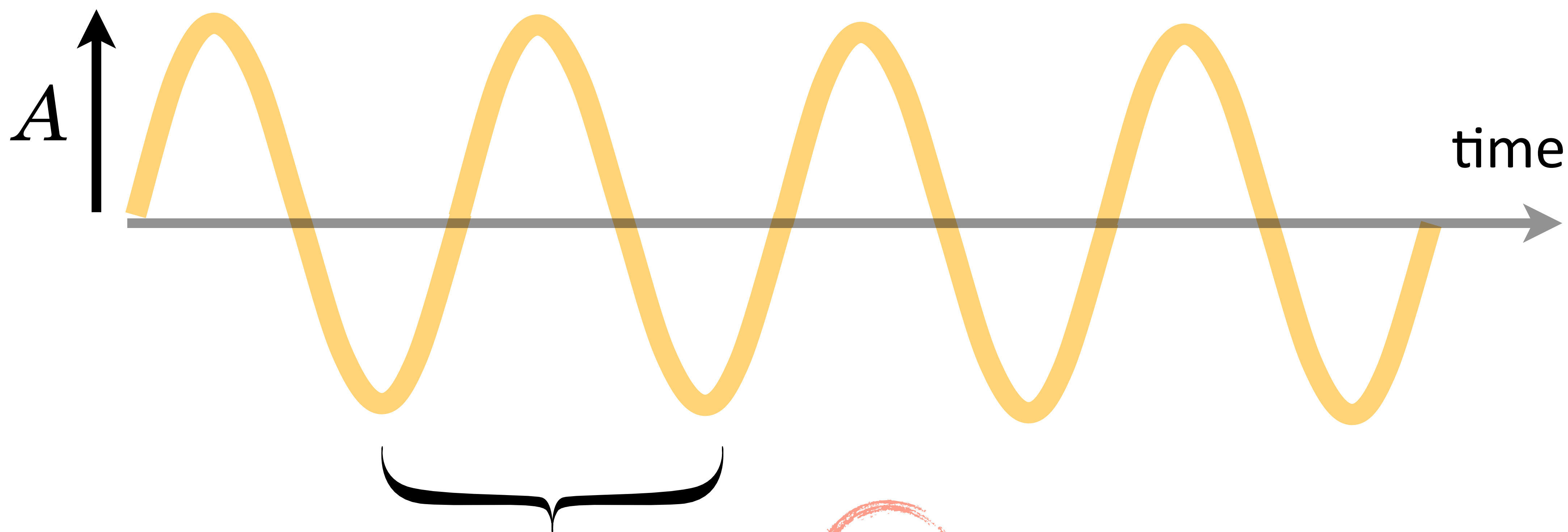
remember”

waves?

just some facts, Ma'am

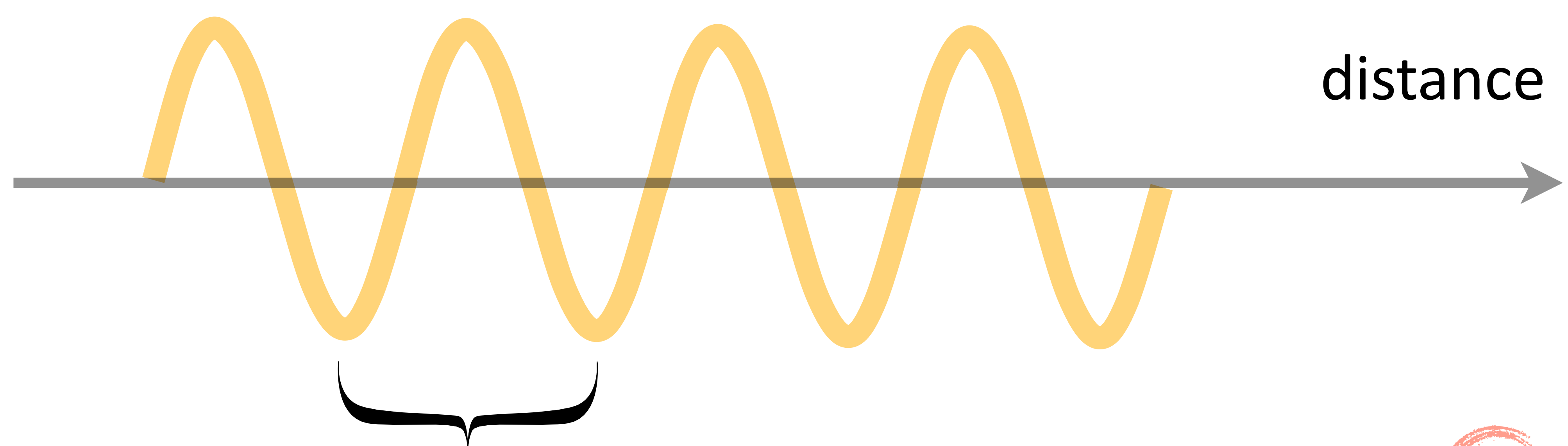


maximum height of the disturbance: "Amplitude," A.
"Intensity" is ~ A^2



time to repeat: "Period," T. seconds

rate of repetition: "Frequency," f. (Hz) $f = \frac{1}{T}$



distance through which it repeats: "Wavelength," λ m

$v = \frac{\lambda}{T}$ $v = \lambda f$

relation alert: **speed of a wave**

refers to: $v = \lambda f$

example:

middle C ~ 4 ft (=1.2 m) wavelength

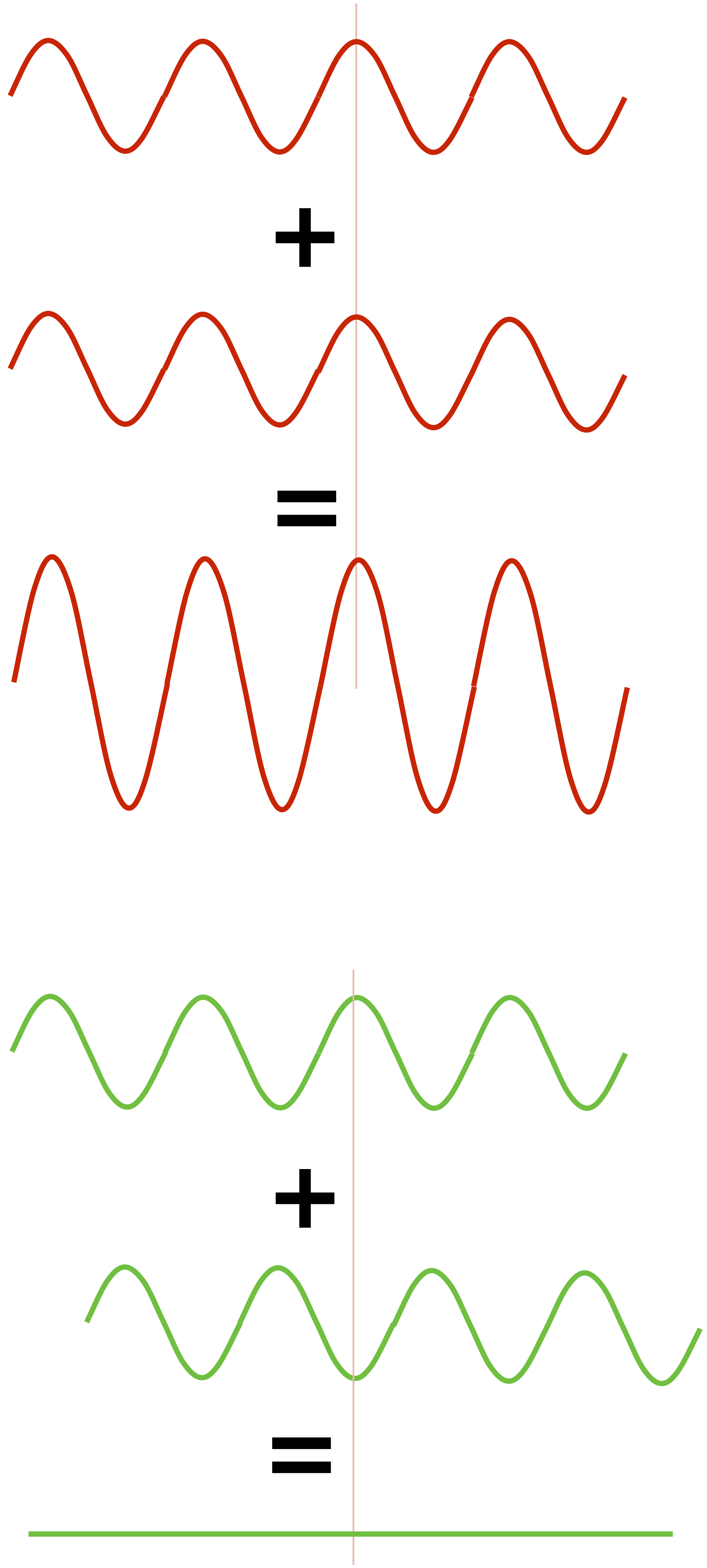
f = 262 Hz, so speed of sound:

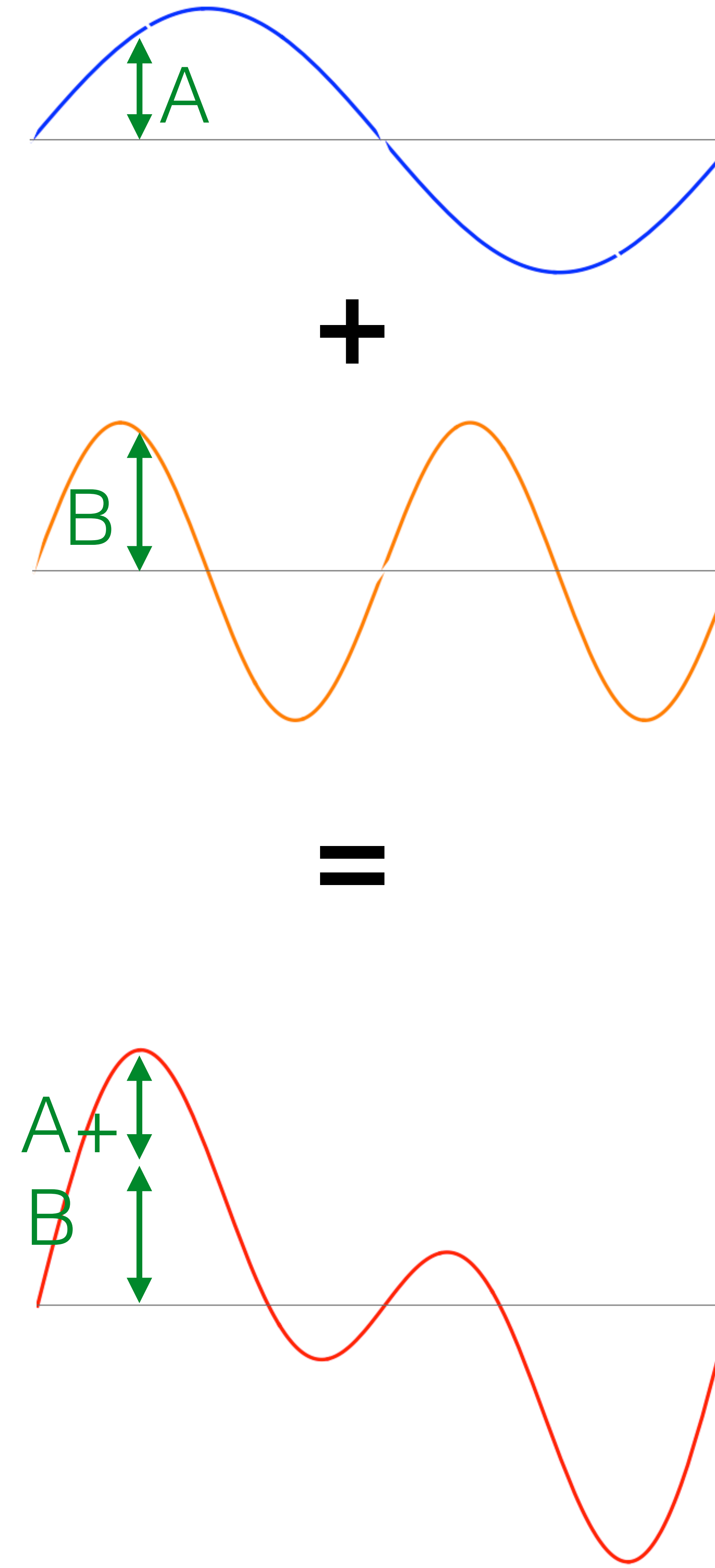
$$v = 1.2 \times 262 = 314 \text{ m/s}$$

that's right

interference

can always make a third wave out of the sum of two waves





for us, two kinds

traveling waves

the disturbance translates

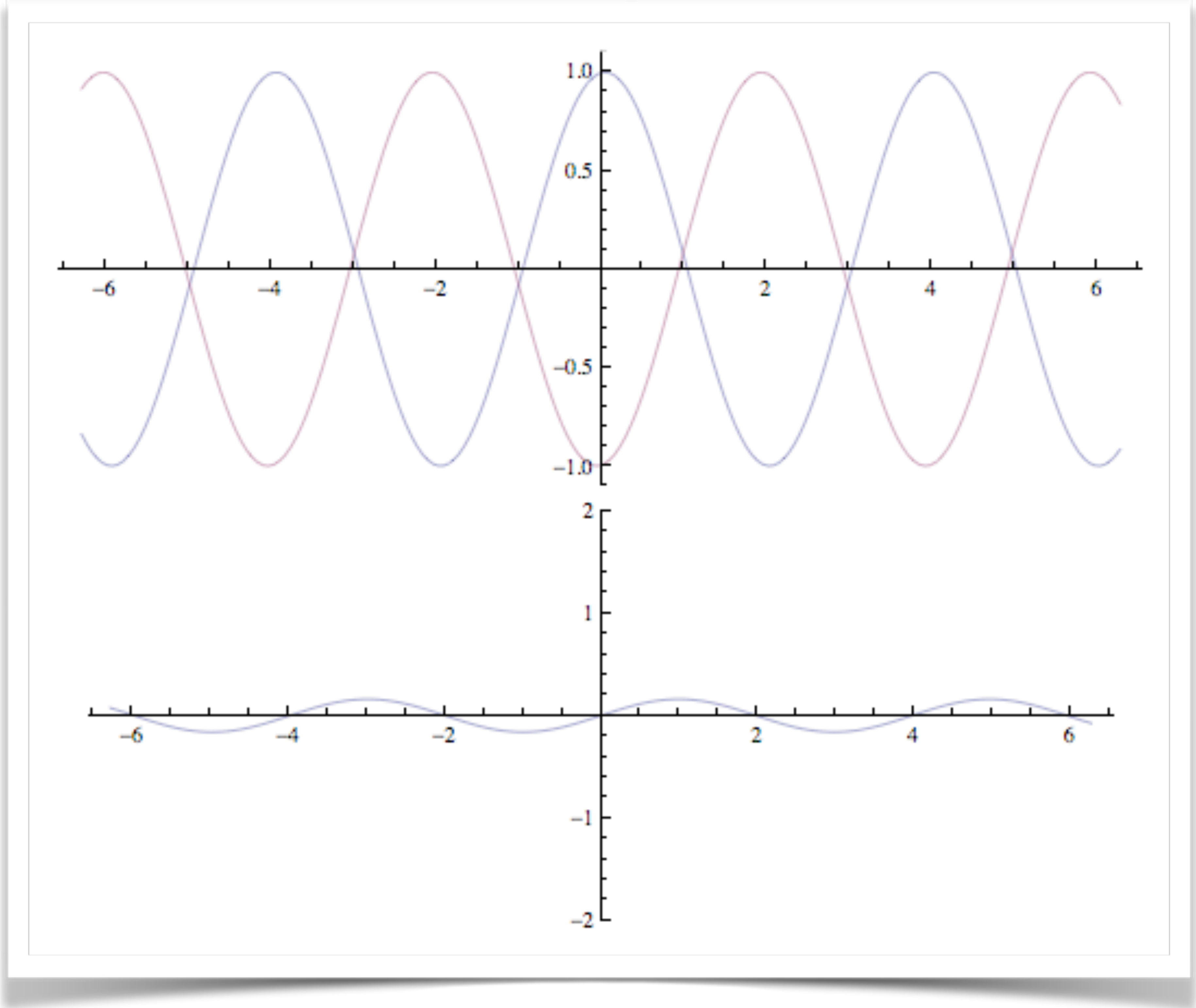
standing waves

the disturbance marches in place

Standing room only

"standing wave"

the sum of two traveling waves moving in opposite directions



Quantum Mechanics

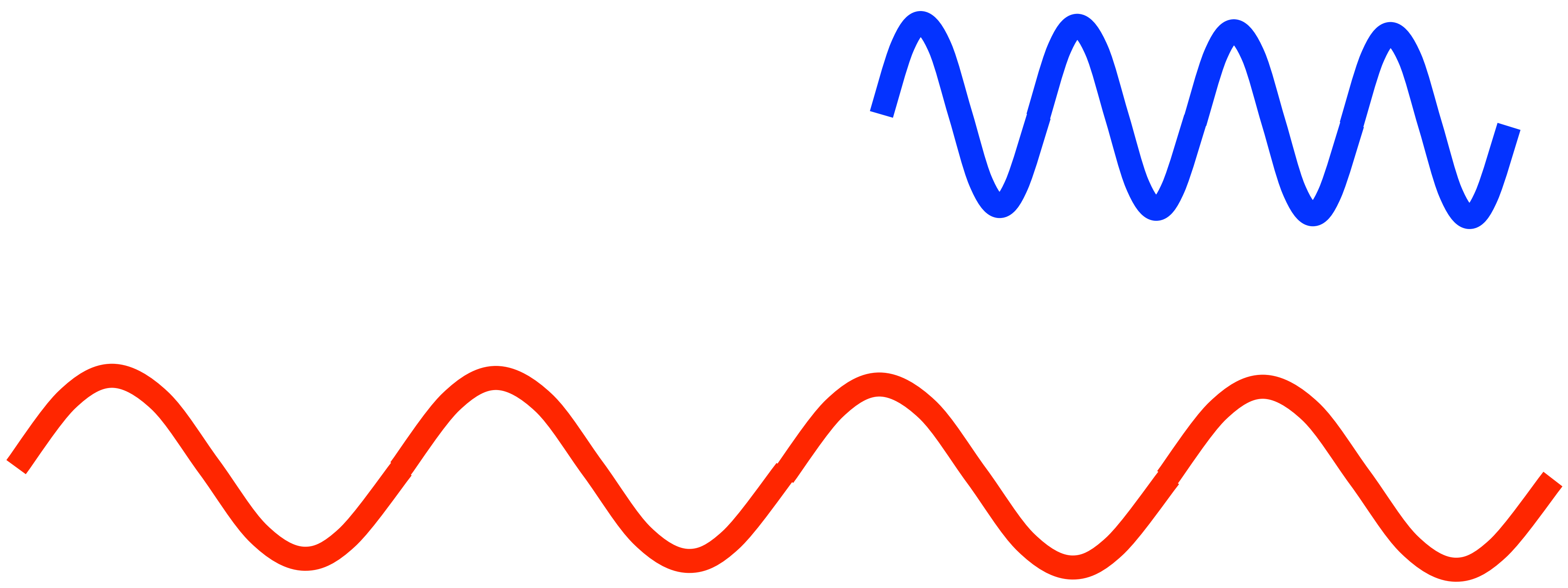
in the 1890's things were heating up

I mean, literally.

color = temperature

why?

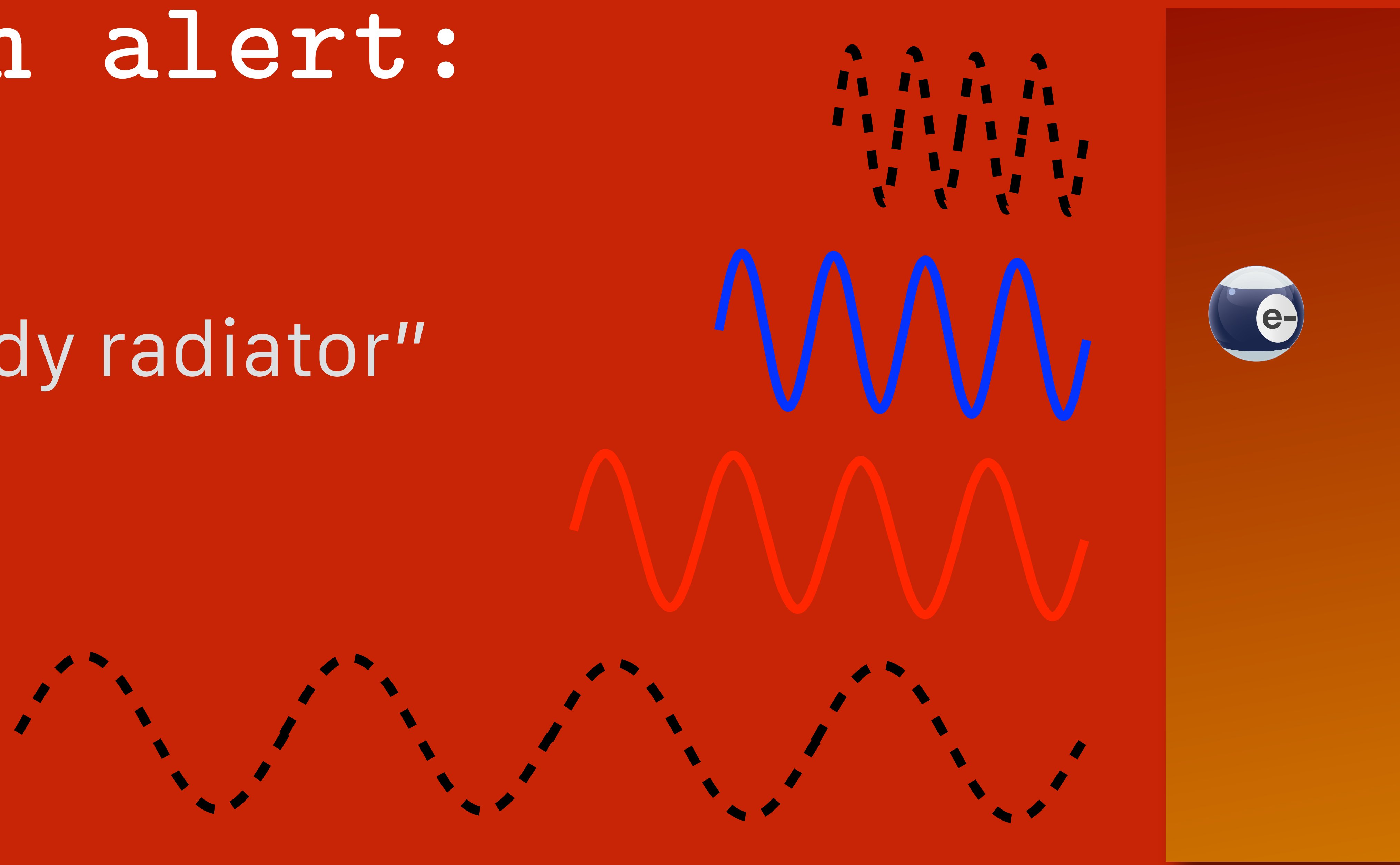
Gassan Sadatoshi



http://www.howstuffworks.com/sword-making.htm/printable amount of each wavelength: depends **ONLY** on temperature

jargon alert:

"Blackbody radiator"



A little more complicated - glass, metals, soot...all behave differently

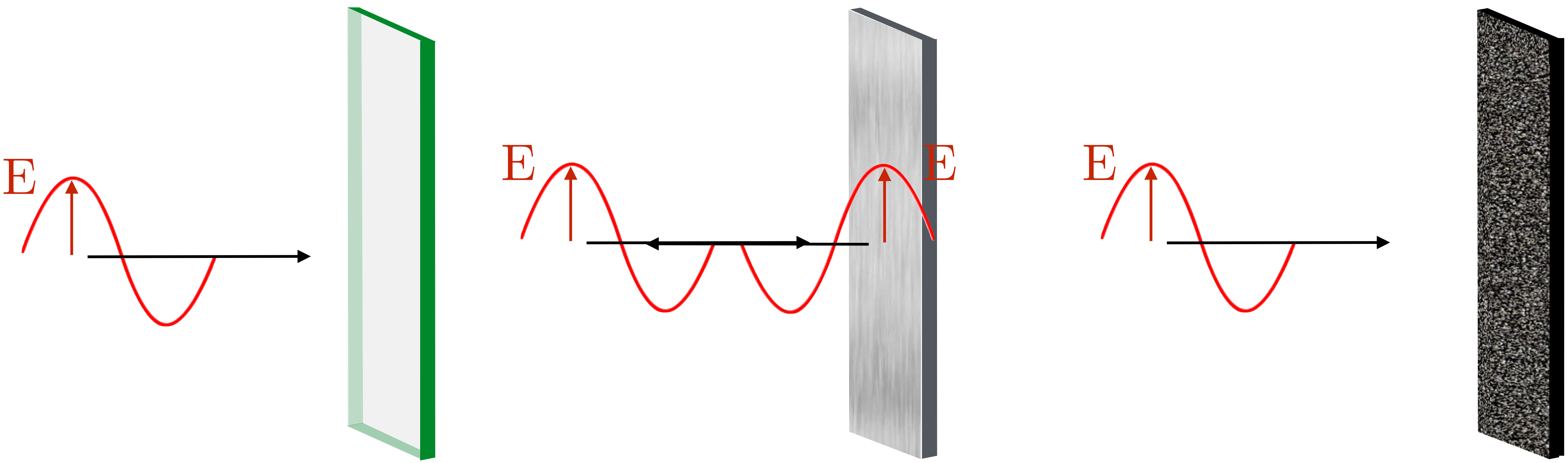
Basically think of a "Blackbody Radiator" as a perfectly absorbing, perfectly radiating substance.

jargon alert:

Black Body Radiation

refers to:	A thermal absorber that perfectly absorbs all wavelengths of EM radiation and emits according to its temperature
entomology:	"black" in the sense of a perfect absorber...no reflection
example:	A cavity with a hole, a near-black object, a star...

three materials

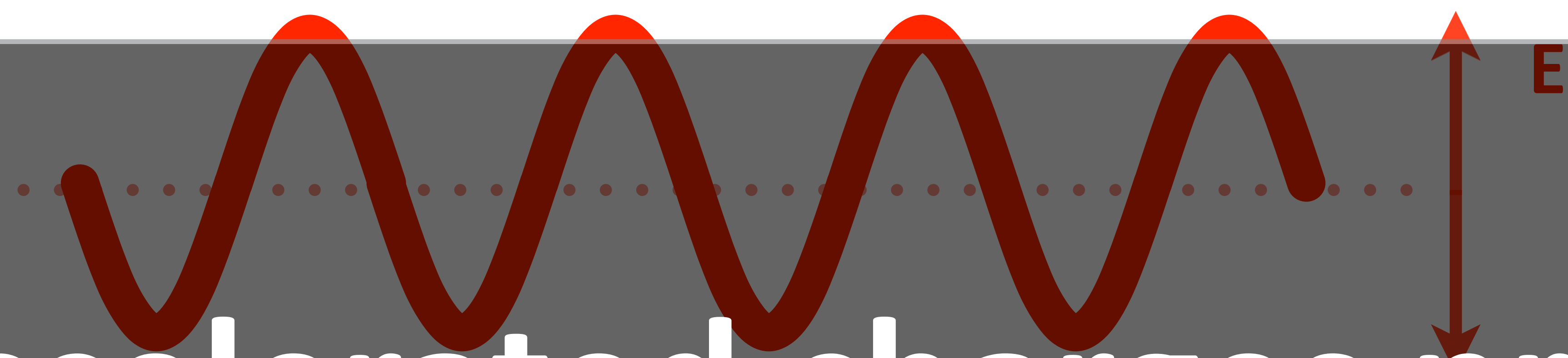


glass	metal	soot
full transmission	full reflection	full absorption

why? ...remember this from February:

E applies a force on any Q

E field for example:



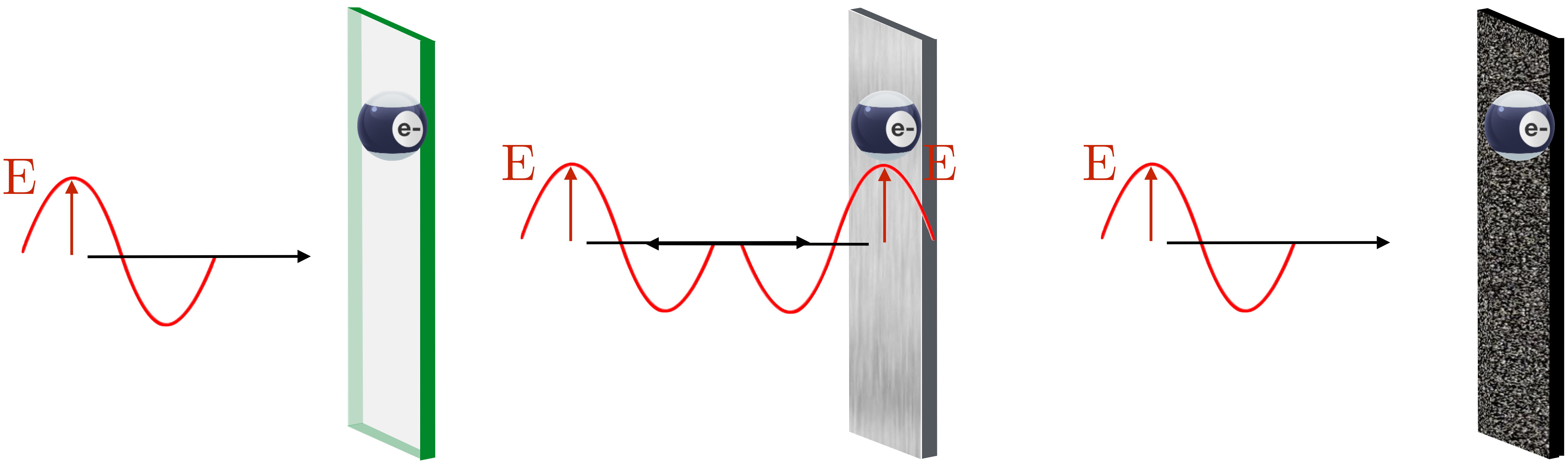
the *value of the strength* of the field oscillates in time and **accelerates a charge**

accelerated charges produce

Electromagnetic radiation

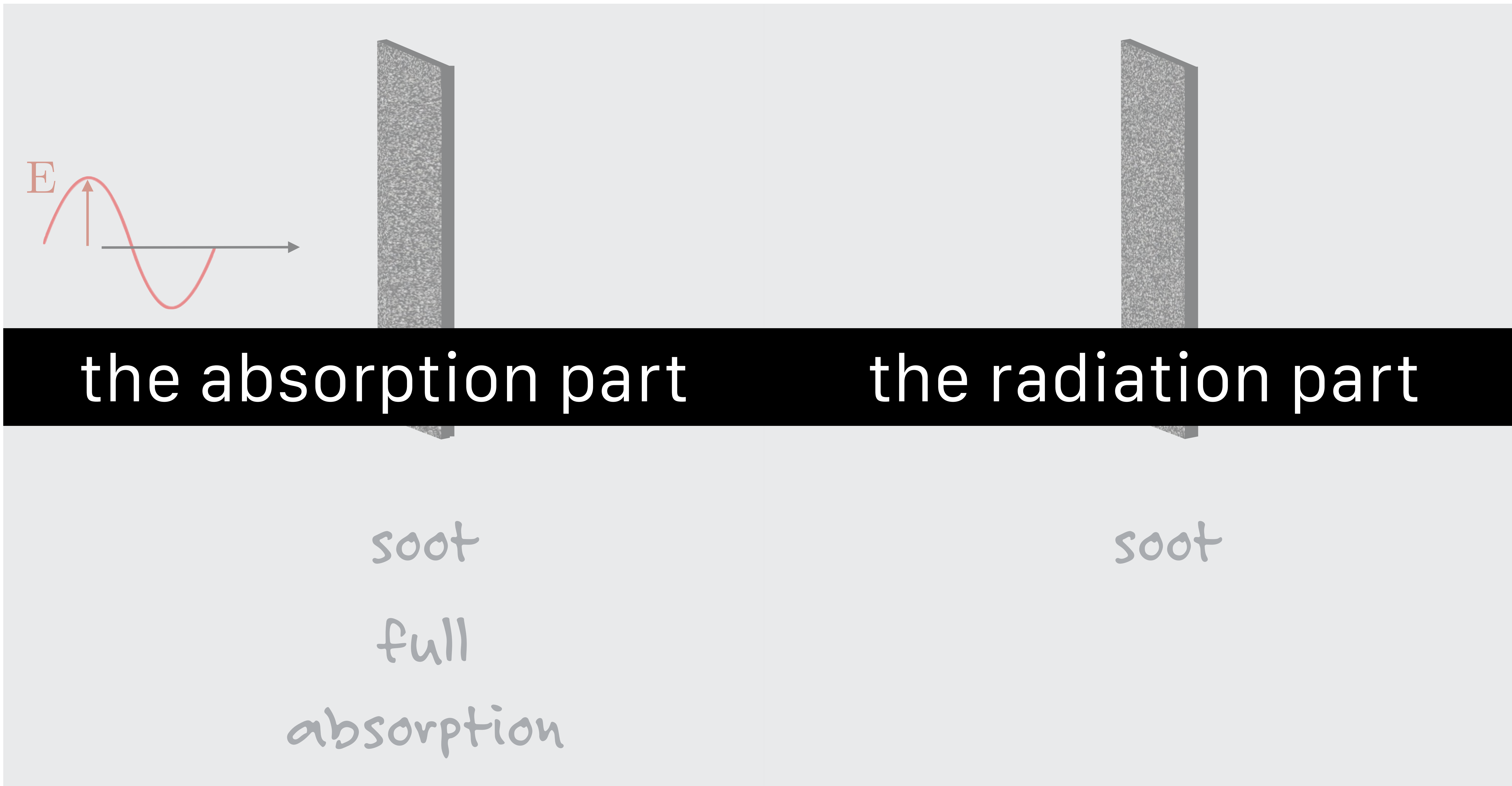
three materials

the electrons are bound differently



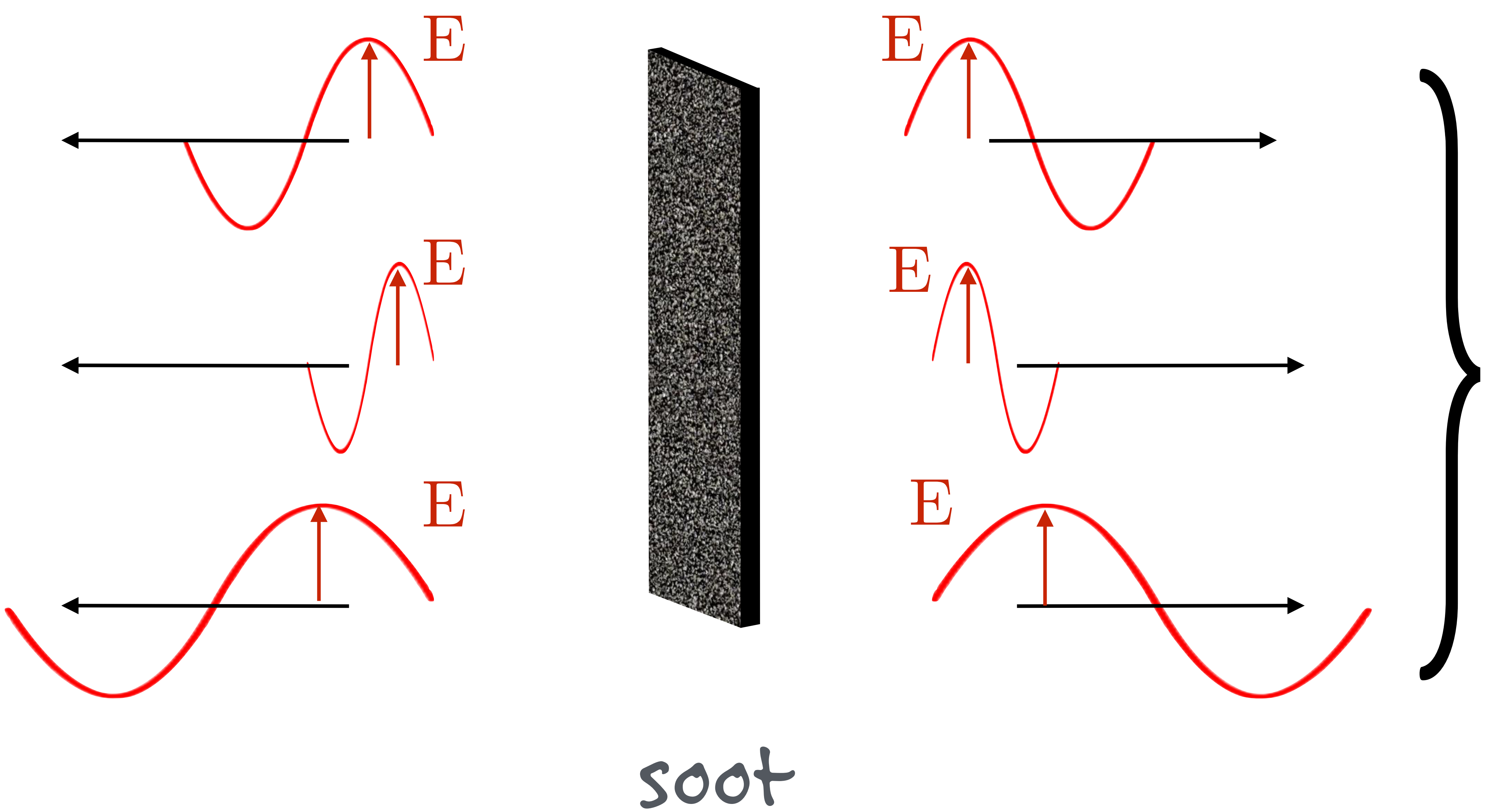
glass	metal	soot
full transmission	full reflection	full absorption

two aspects to the idea of a “black body”



it's still radiating

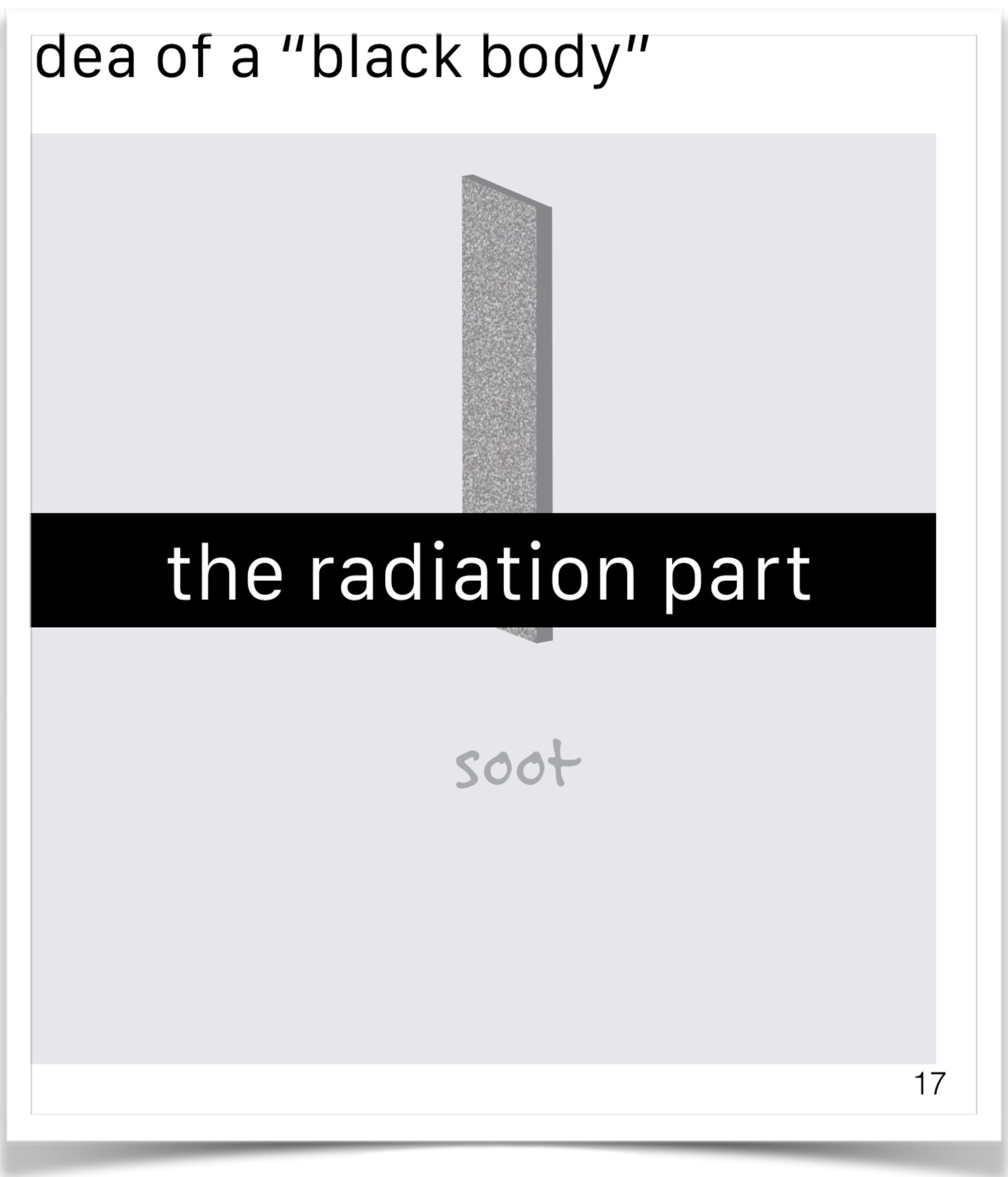
absorbs all radiation and emits particular radiation



the amount at each wavelength:

- depends on temperature
- universal for all materials

blackbody radiators



many objects radiate like nearly perfect blackbody radiators

furnaces

you, me

stars

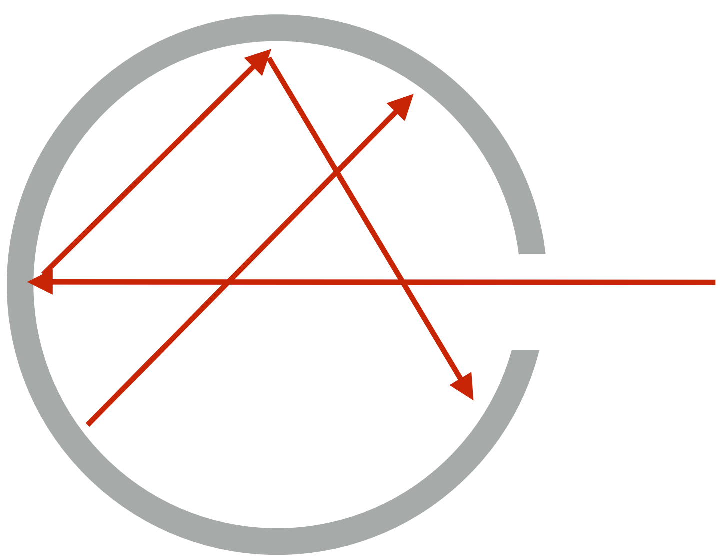
the universe

...

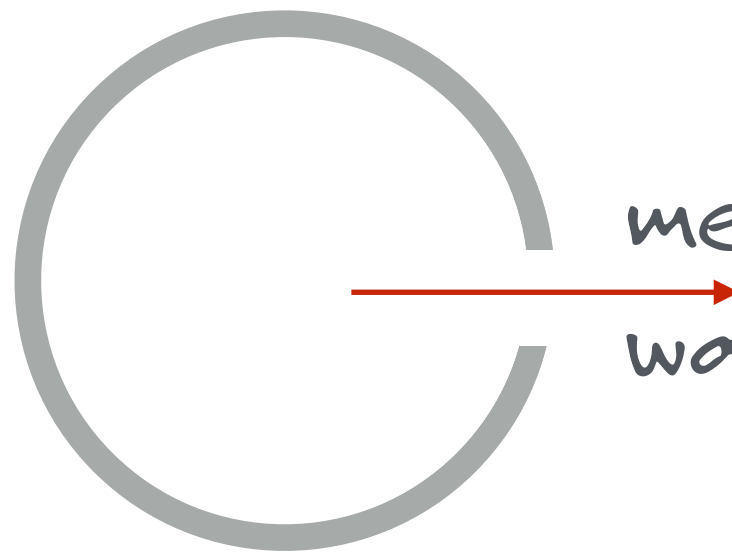
an experimental blackbody radiator

an empty volume with a small hole

like a perfect absorber



plays the role of a perfect radiator

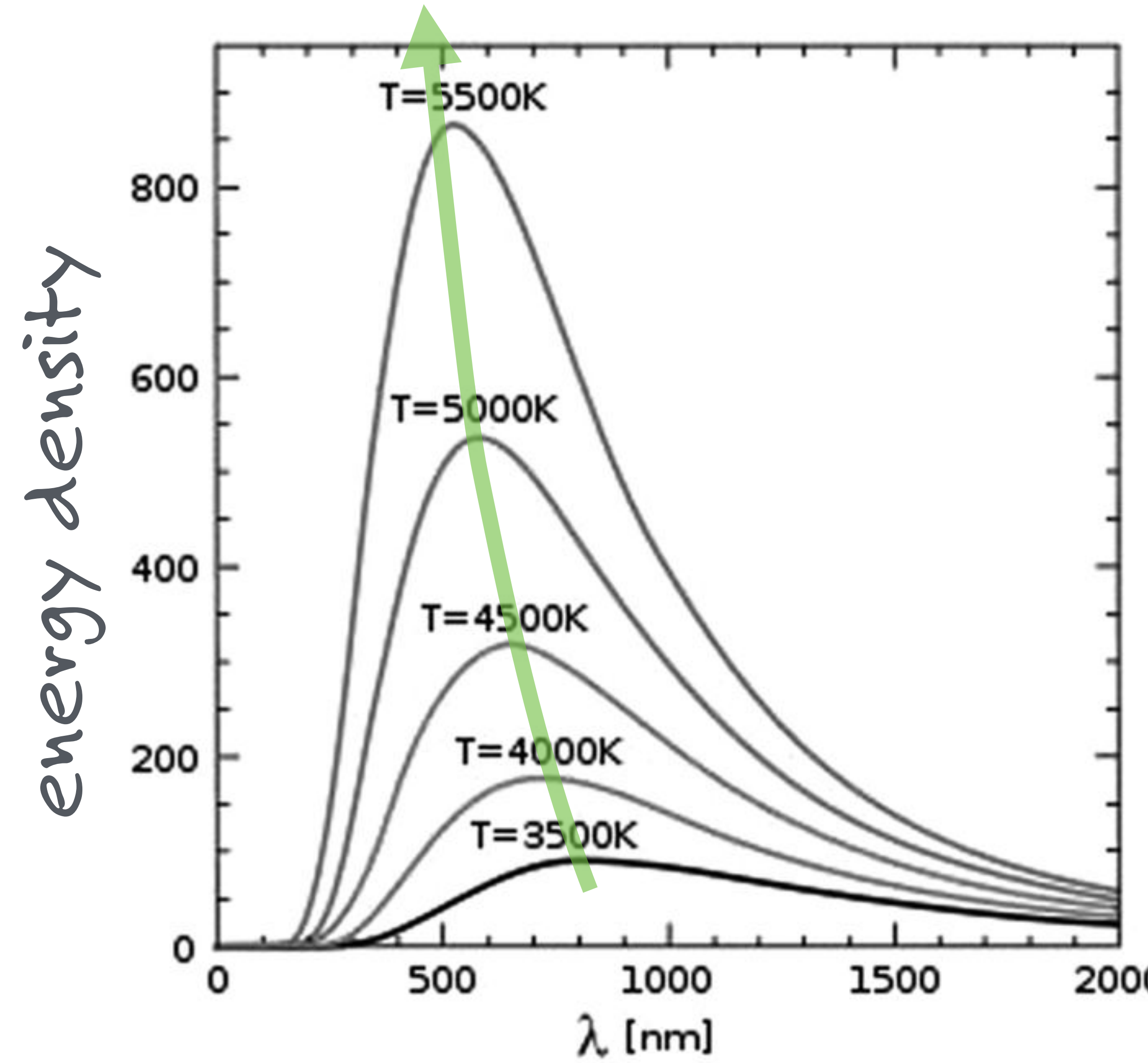


measure wavelengths

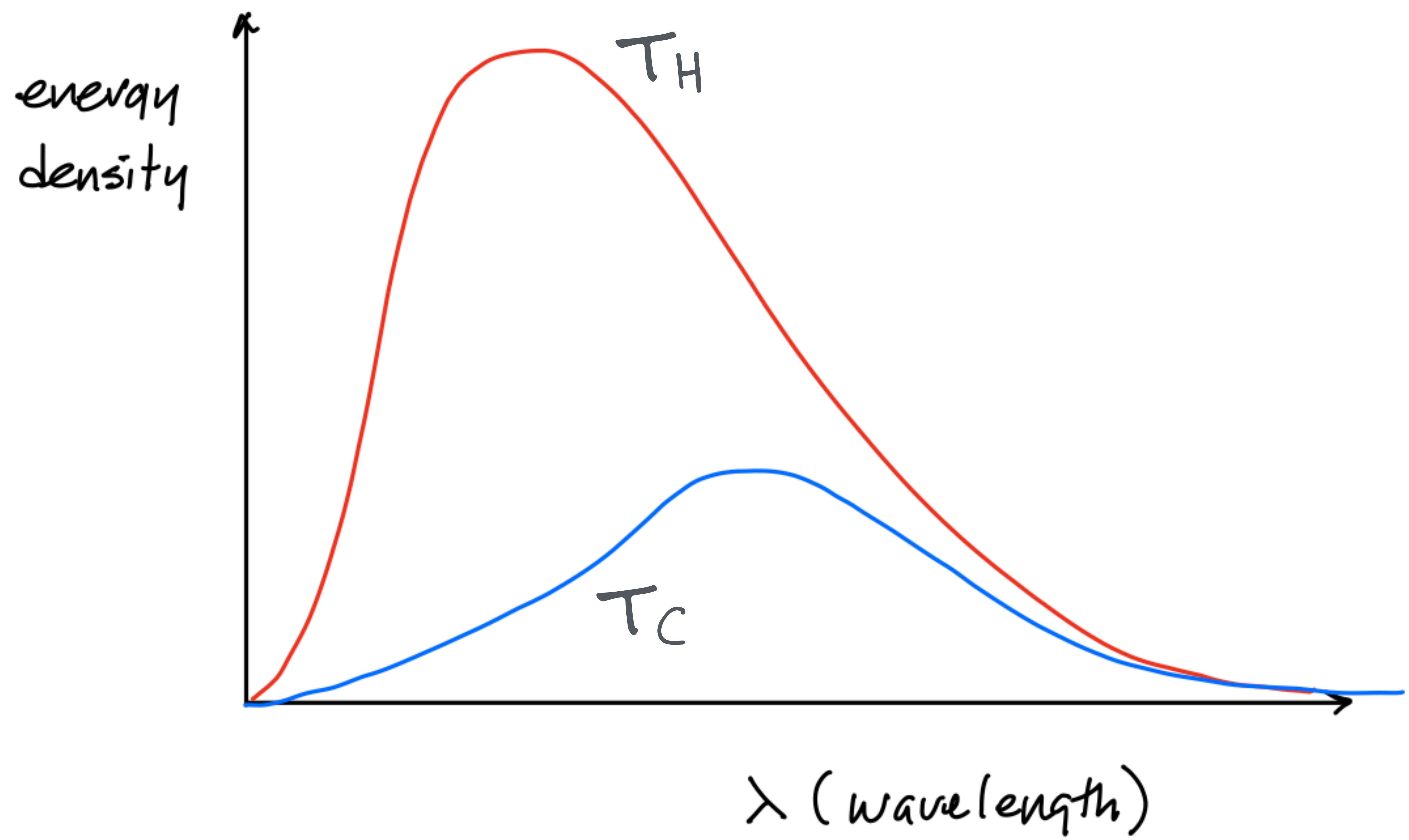
control its temperature

universal shape

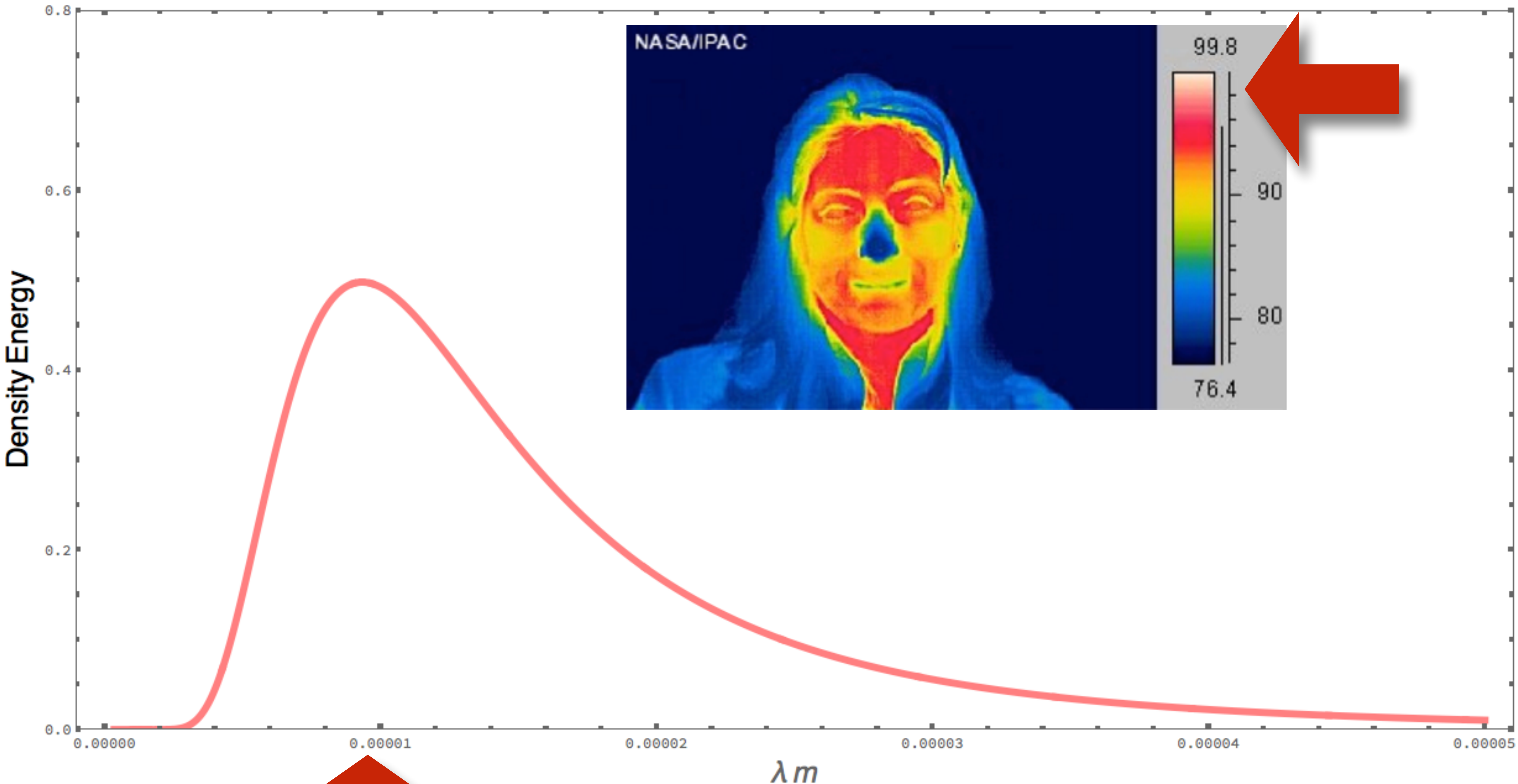
peak λ↓ T↑



make your fingers think

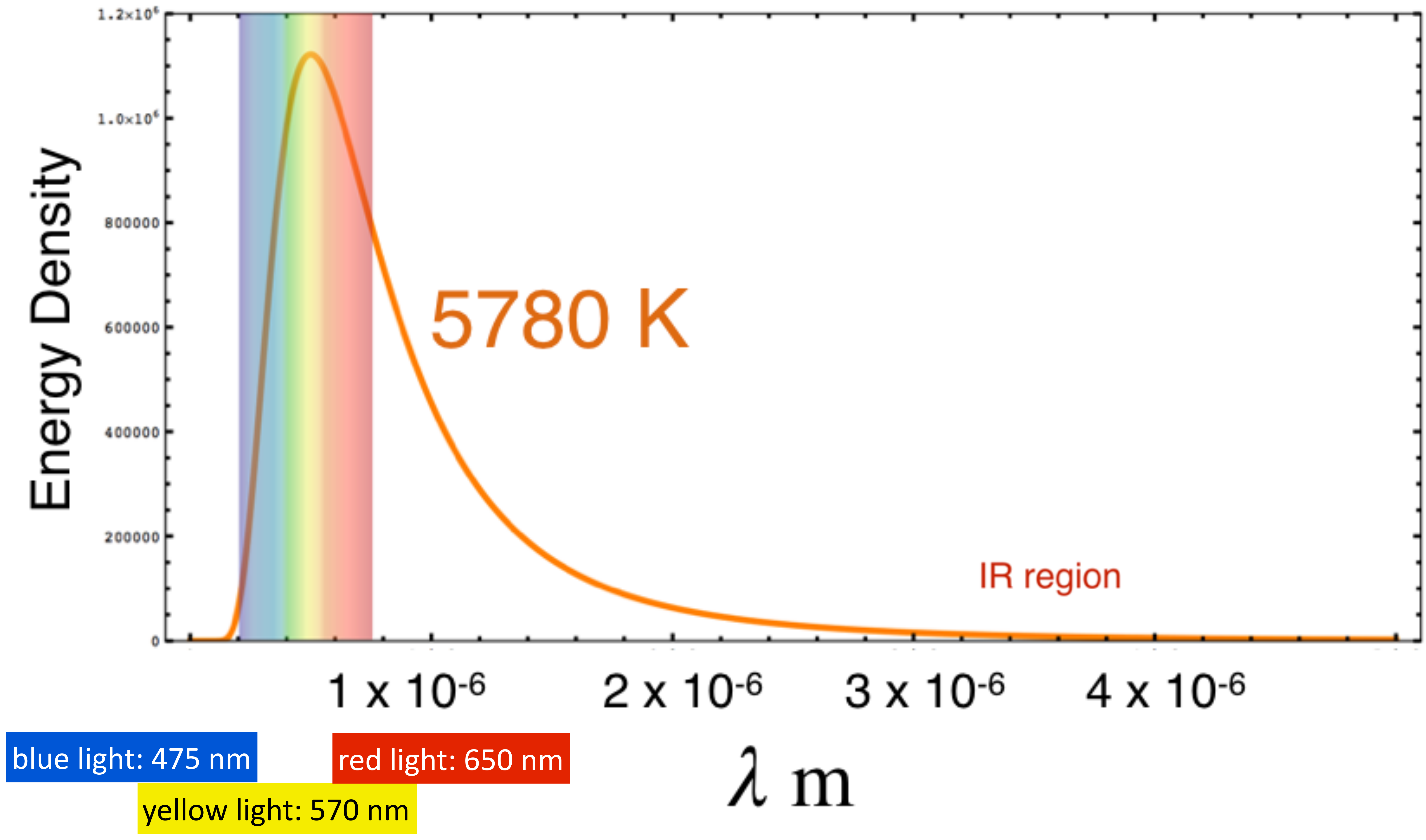


everything with a temperature radiates electromagnetic waves

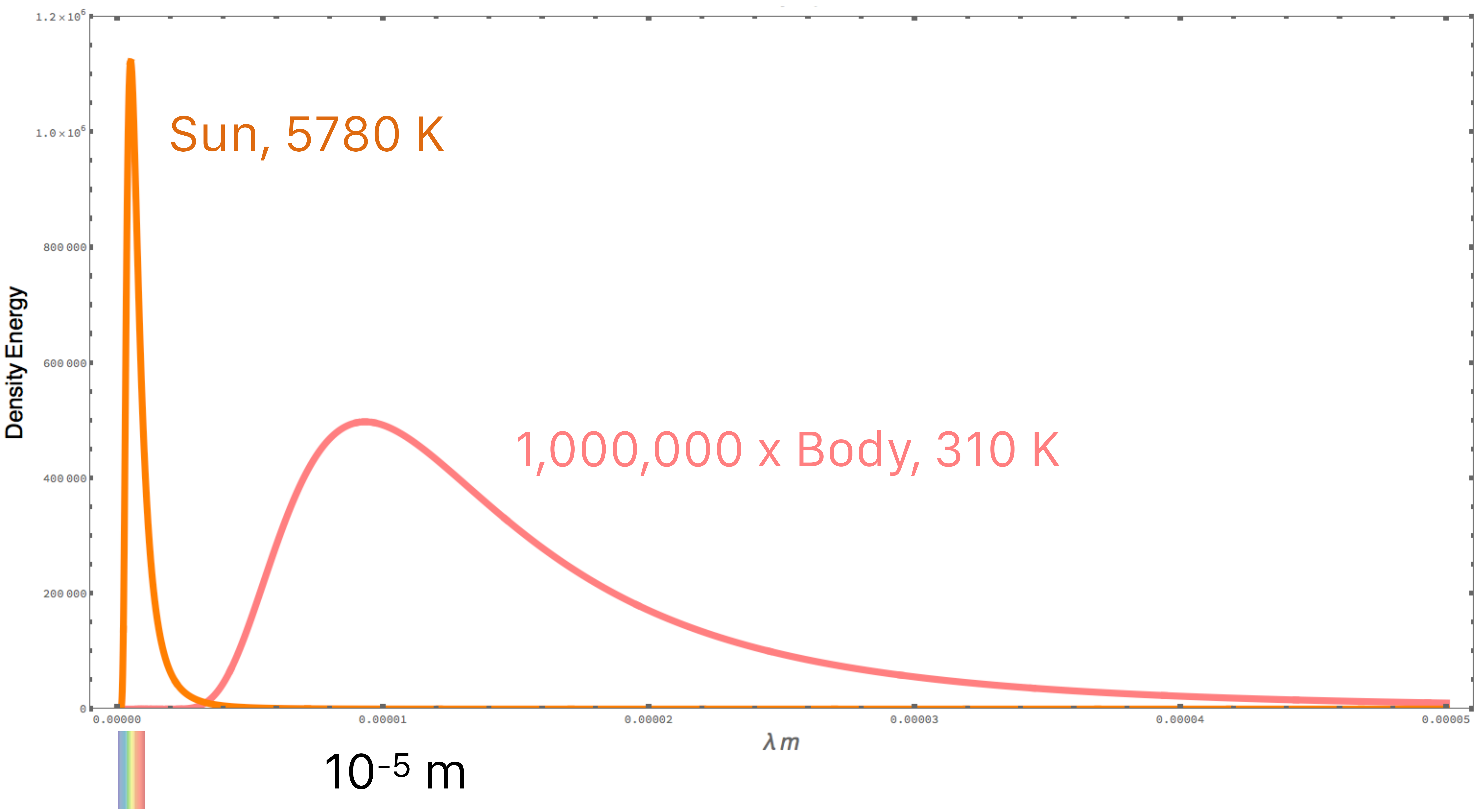


about 1 x 10^{-5}m, 10 microns: infrared

sun

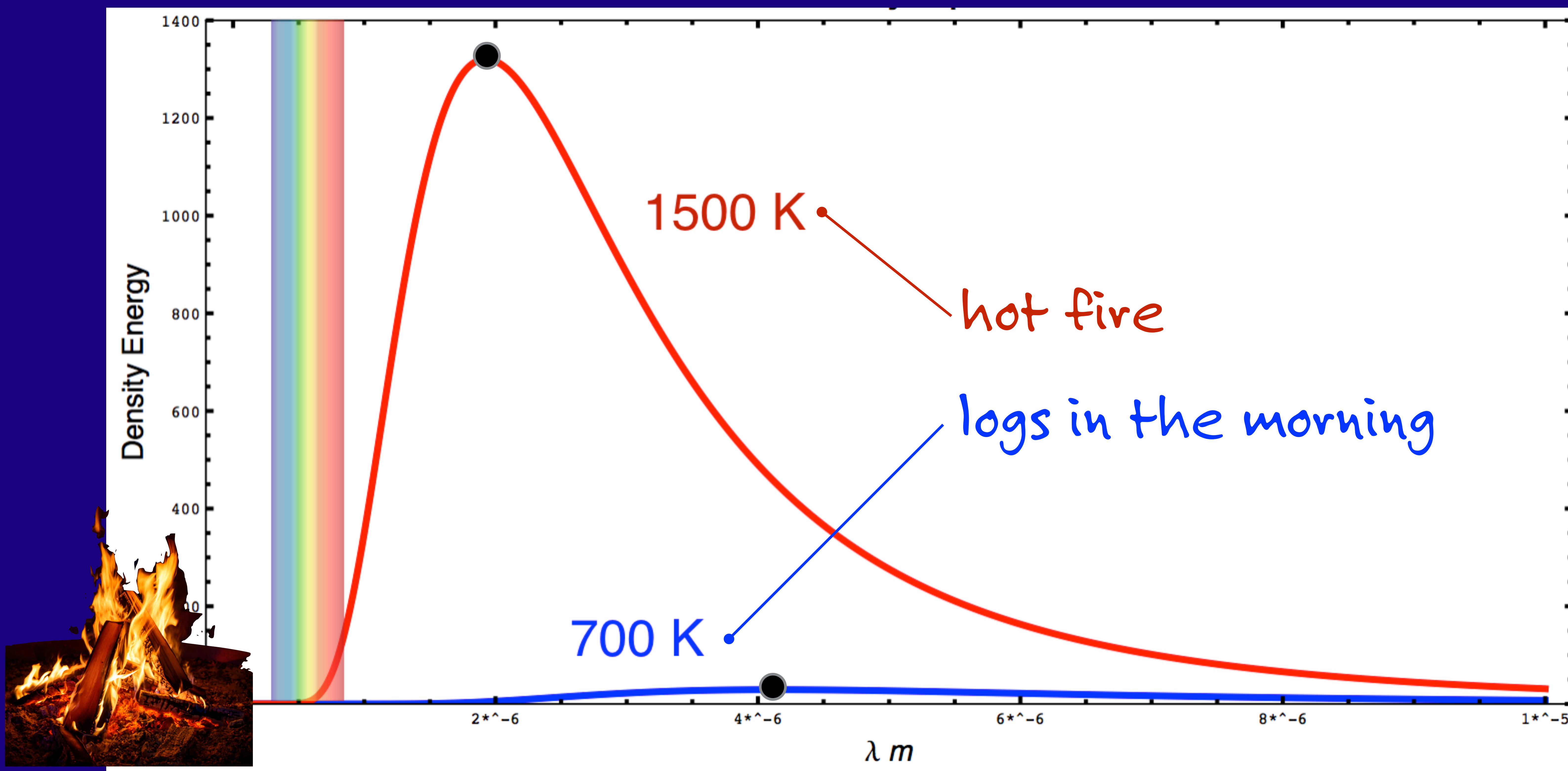

Energy Density
1.2×10⁶
1.0×10⁶
800000
600000
400000
200000
0
5780 K
IR region
1 x 10-6
2 x 10-6
3 x 10-6
4 x 10-6
λ m
blue light: 475 nm
red light: 650 nm
yellow light: 570 nm

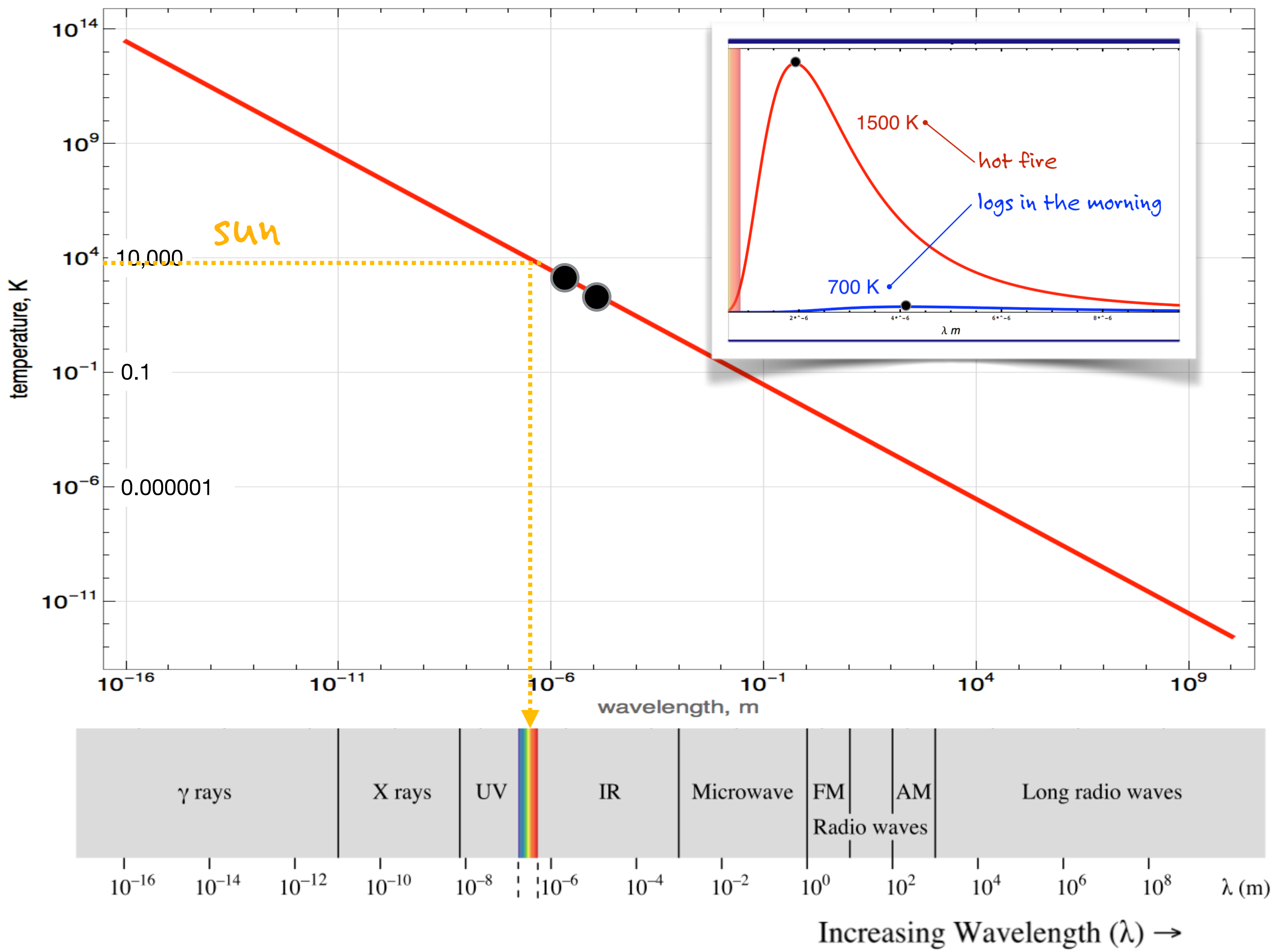
Sun's warmth? notsomuch

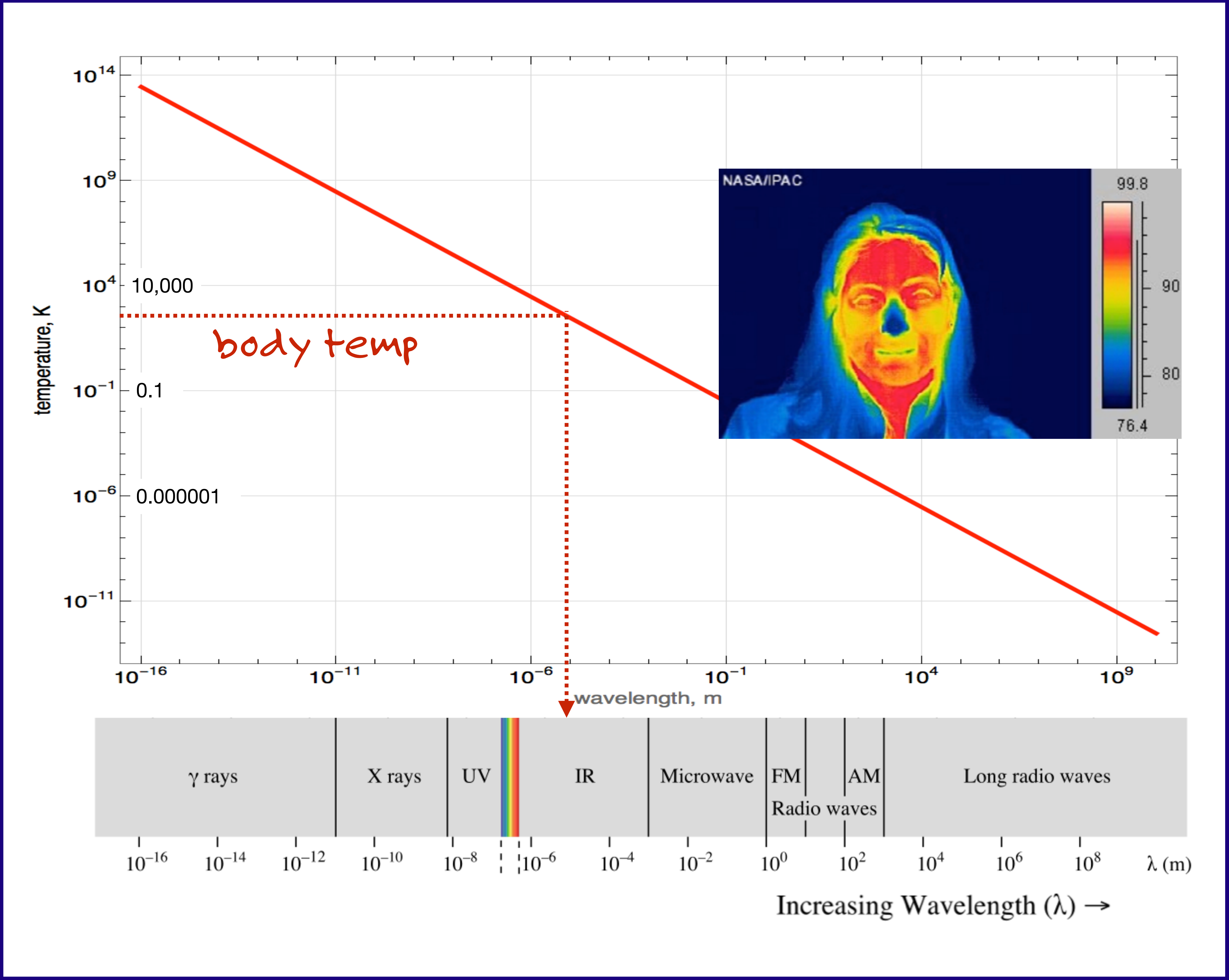


a range

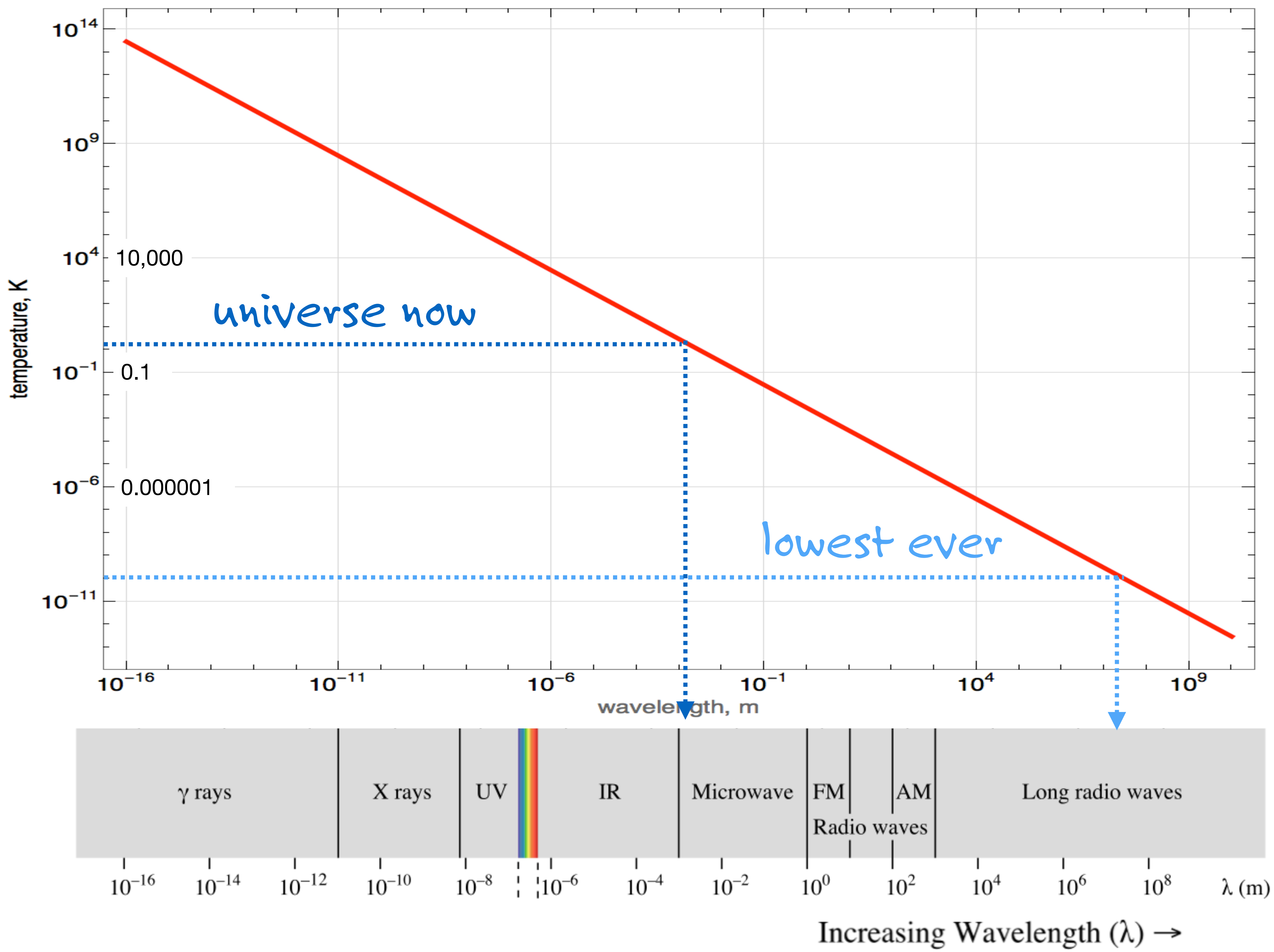
of wavelengths for each temperature




10^14
10^9
10^4 10,000
10^−1 0.1
10^−6 0.000001
10^−11
temperature, K
sun
10^−16
10^−11
10^−6
10^−1
10^4
10^9
wavelength, m
1500 K
hot fire
logs in the morning
700 K
λ m
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^−16
10^−14
10^−12
10^−10
10^−8
10^−6
10^−4
10^−2
10^0
10^2
10^4
10^6
10^8
λ (m)
Increasing Wavelength (λ) →



10^{14}
10^{9}
10^{4} 10,000
10^{-1} 0.1
10^{-6} 0.000001
10^{-11}
temperature, K
body temp
10^{-16} 10^{-11} 10^{-6} 10^{-1} 10^{4} 10^{9}
wavelength, m
NASA/IPAC
99.8
90
80
76.4
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} λ (m)
Increasing Wavelength (λ) →



temperature, K
10,000
0.1
0.000001
universe now
lowest ever
wavelength, m
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
λ (m)
Increasing Wavelength (λ) →

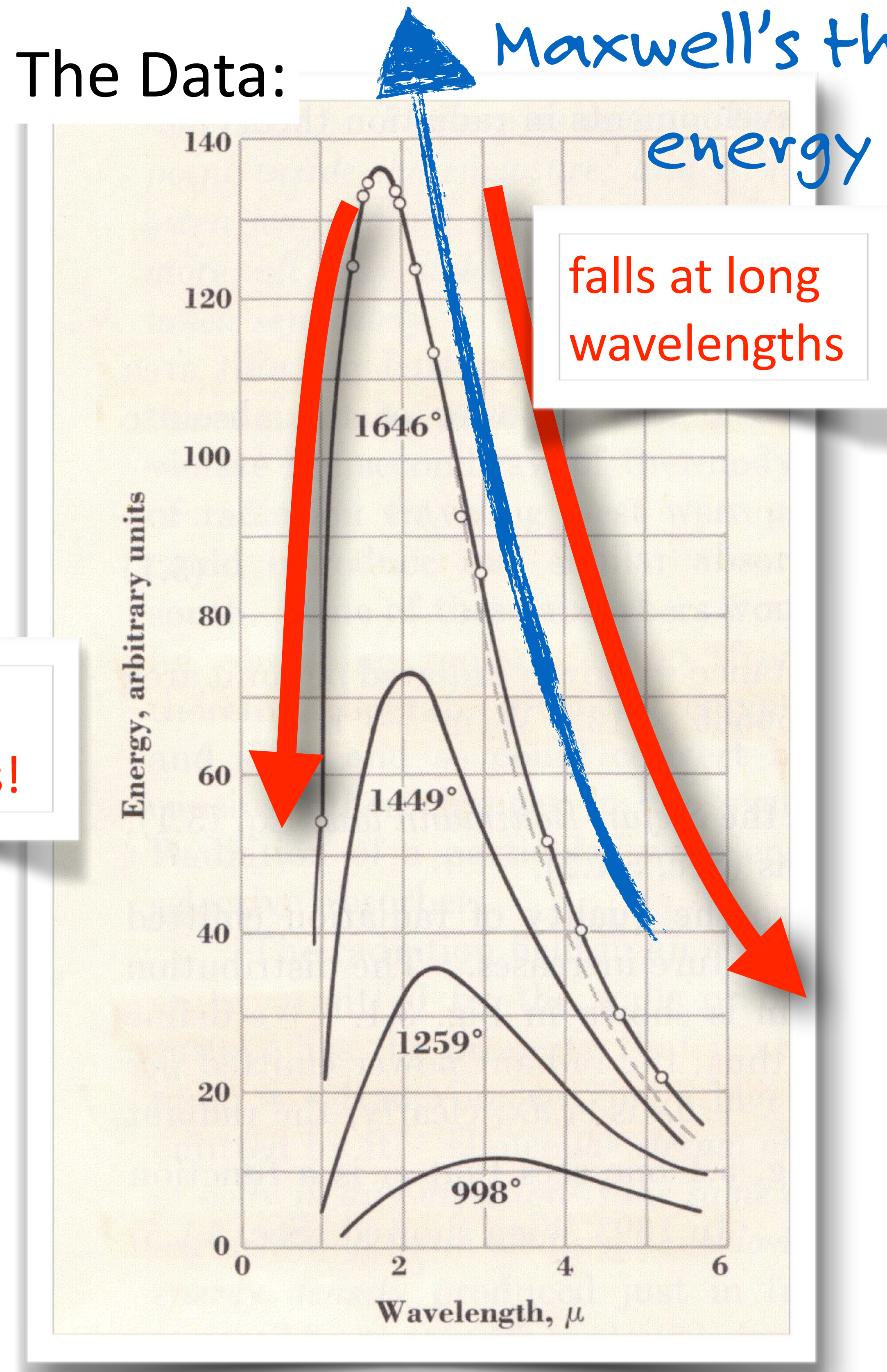
what would Maxwell's theory say?

nonsense.

a major problem.

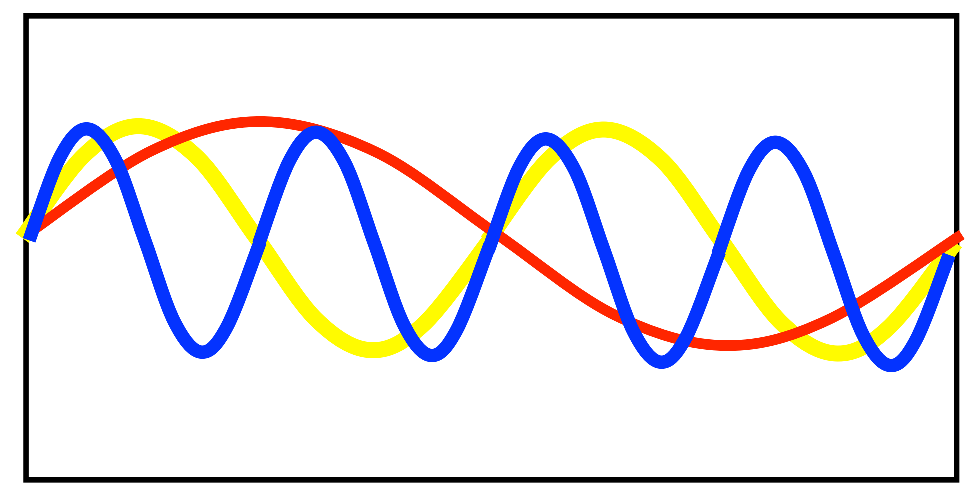
imagine a cavity with radiation inside

The Data:



long wavelength →

← high frequency



Maxwell-like theory:
no limit to the number of different short wavelengths (= high frequencies) that could fit

a universal phenomenon...

Why is there such a strict relationship between temperature and color?

a problem in electromagnetism & thermodynamics

Why?
Was a major late 19th century question.

the solution to heat radiation

came in 1900

and then expanded in 1905

Max Planck
1858-1947

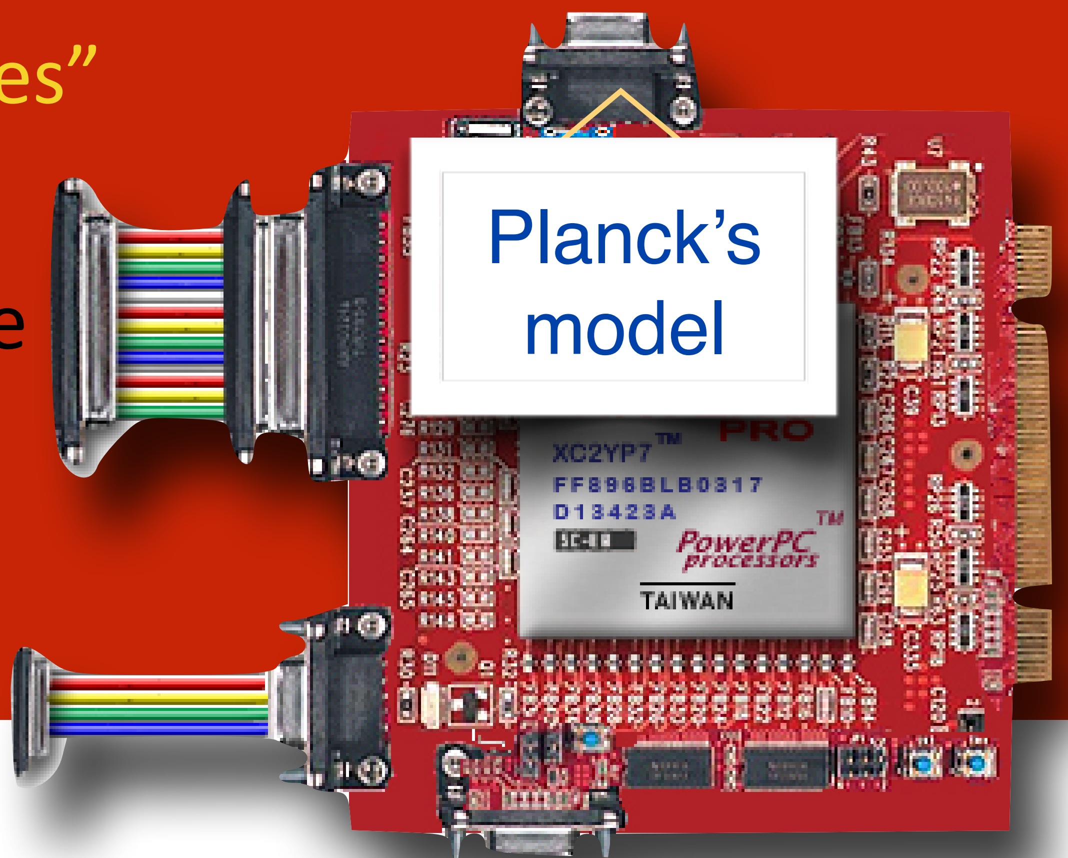
one of the good guys

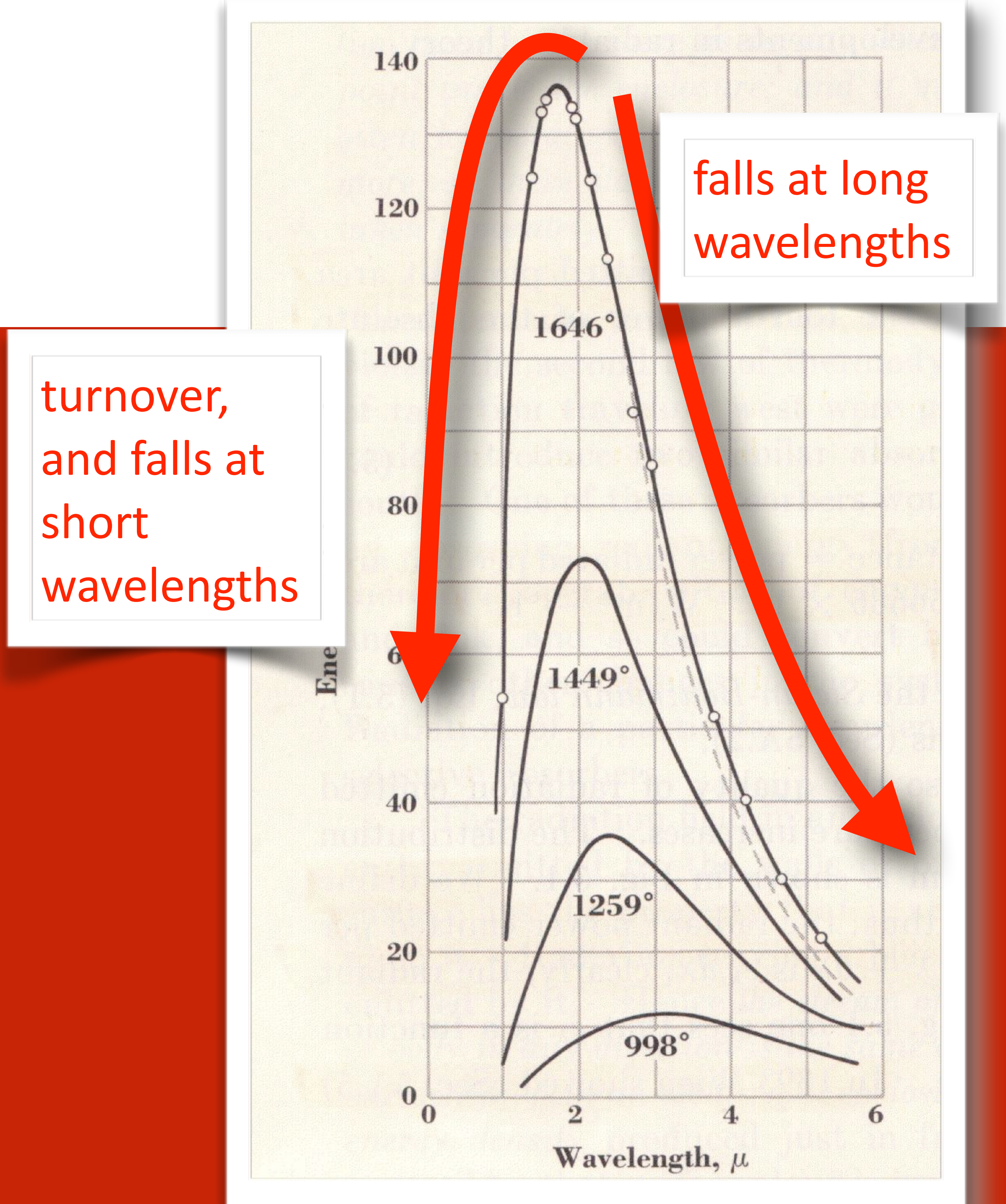
Planck could only get a solution

if he restricted energies of emitted electromagnetic radiation

"**bundled** energies"

temperature





long wavelength ➞

← high frequency

$$v = \lambda f$$

what in the world does that mean?

Good question:

“It was an act of desperation. For six years I had struggled with the blackbody theory. I knew the problem was fundamental and I knew the answer. I had to find a theoretical explanation at any price...”

Energy of radiation is parceled in particular amounts

Planck: "bundles"

Philip Lenard 1902: "quanta"

Planck's Law: $E = nhf$

$h = 6.62606896(33) \times 10^{-34}$ J-sec

Planck's Constant - itsy bitsy...n is an integer

energy of an electromagnetic wave

classically

and

Planck

before 1905 physics is often called "classical physics"

Maxwellian:

2 "E's" going on...this one's "**energy**"

$$E(\text{classical}) \sim \mathbf{E}^2$$

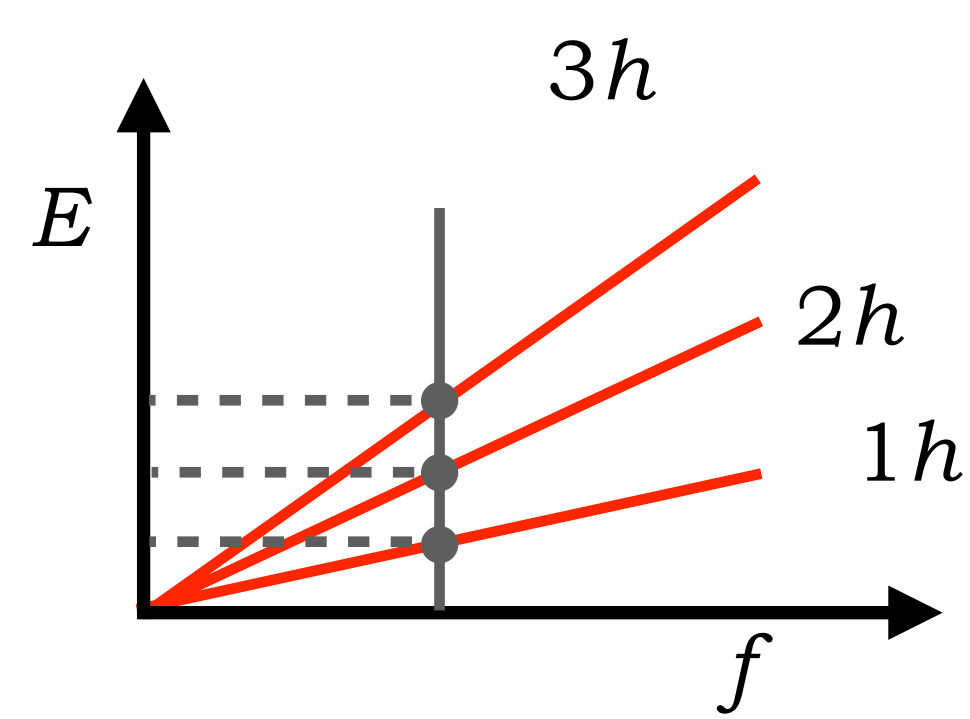
2 "E's" going on...this one's **Electric Field** vector

electric field vector magnitude $\mathbf{E}$ could be any amount

After Planck:

1 "E" going on...just "**energy**"

$$E(\text{modern}) = nhf$$



relation alert: **Planck's Law**

refers to:

$$E = hf$$

Energy of radiation comes in a discrete amount for each frequency

example: photoelectric effect

constant of nature:

Planck's Constant, h

value:	$h = 6.62606896(33) \times 10^{-34}$ J-sec
units:	Energy - time
usage:	everything at atomic and smaller sizes

$$c = \lambda f$$

$$f = \frac{c}{\lambda}$$

for a given frequency (wavelength)

$$E = nhf$$

the only energies that can be radiated:

1hf, 2hf, 3hf, 4hf....

So, for 10 micron infrared wave, E = n(3 x 10^{-13}J)

E's must be = 3 x 10^{-13} J, 6 x 10^{-13} J, 9 x 10^{-13} J...

that is: 5 x 10^{-13} J, 7.8 x 10^{-13} J, etc are not possible

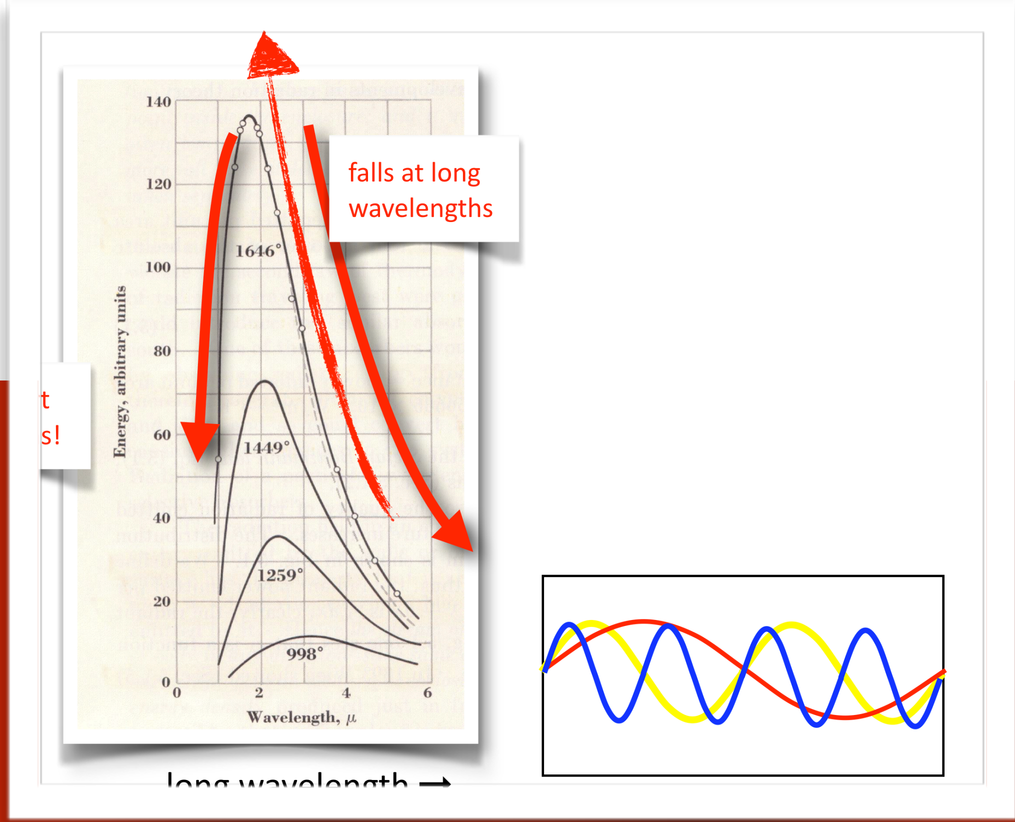
it’s as if

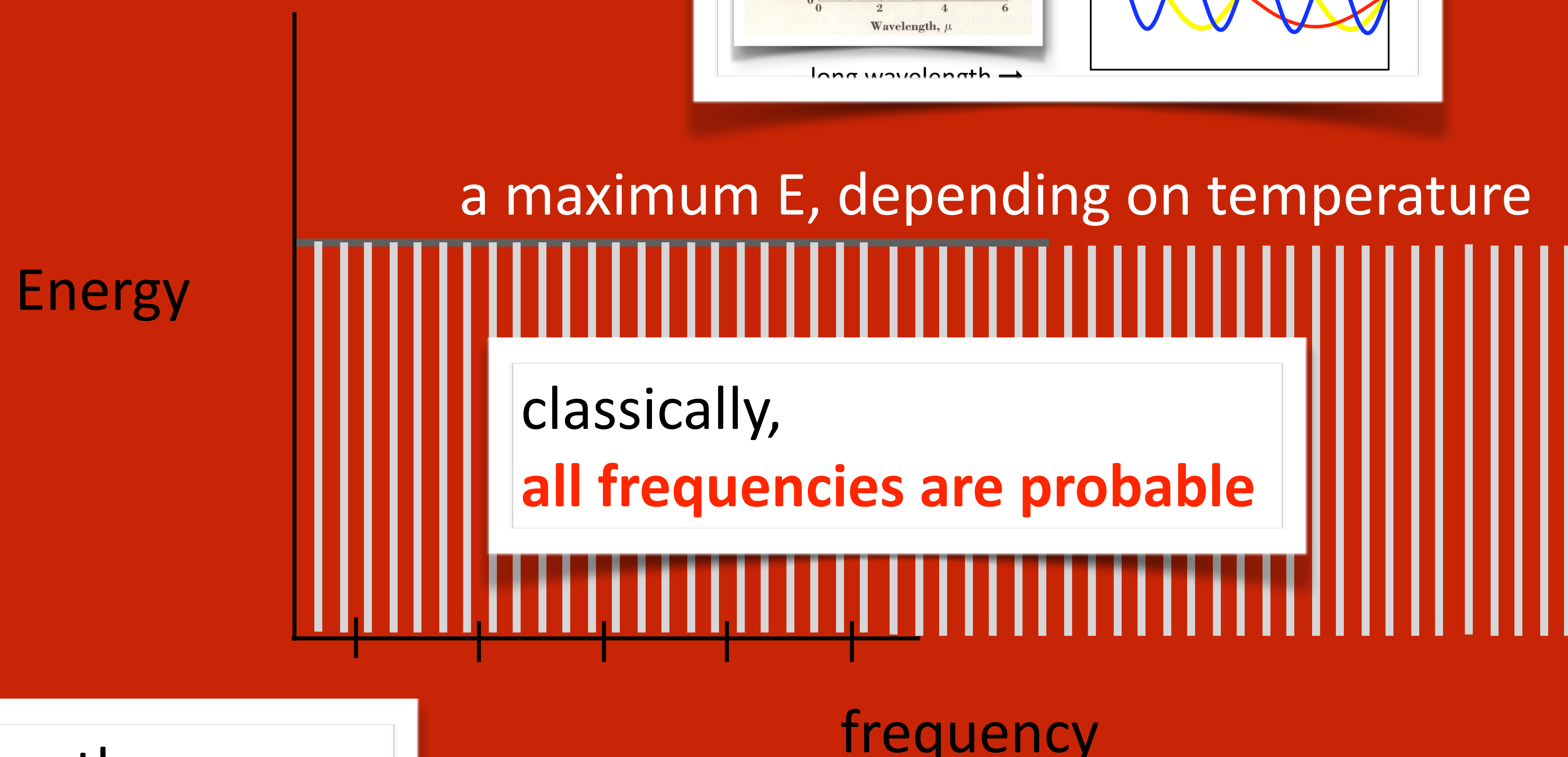
no matter how hard you pump

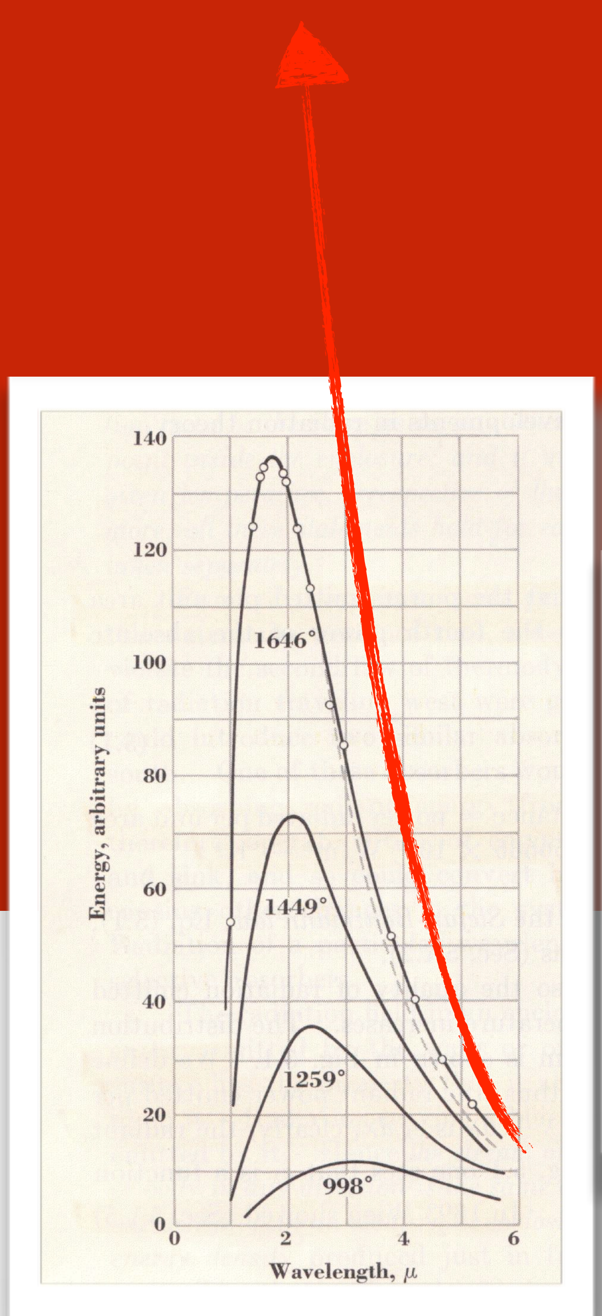
your amplitude is choppy

the lack of light at the short wavelengths

= high frequencies?







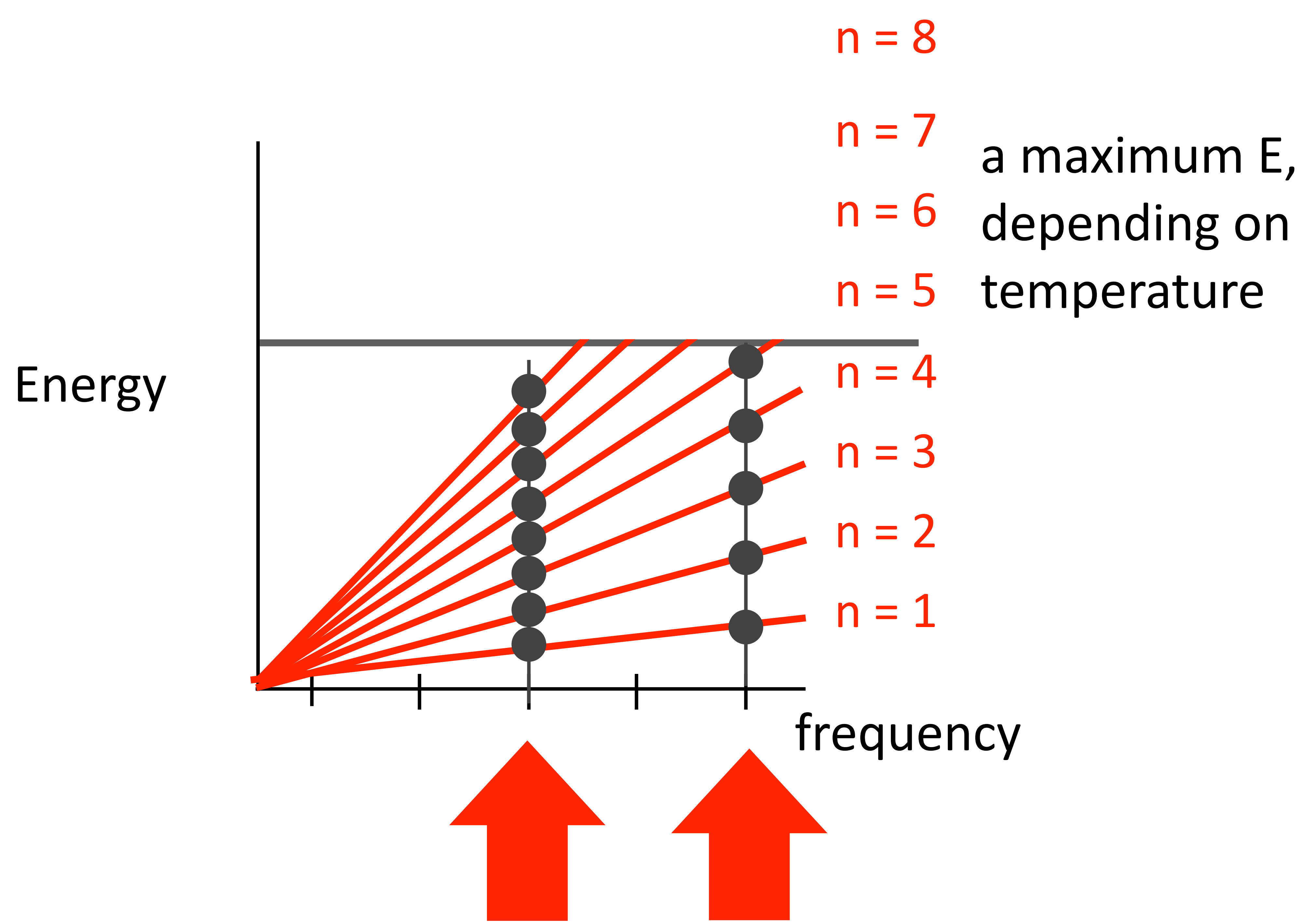
Classical radiation theory predicted an infinite amount of energy at high frequencies....the “Ultraviolet Catastrophe”

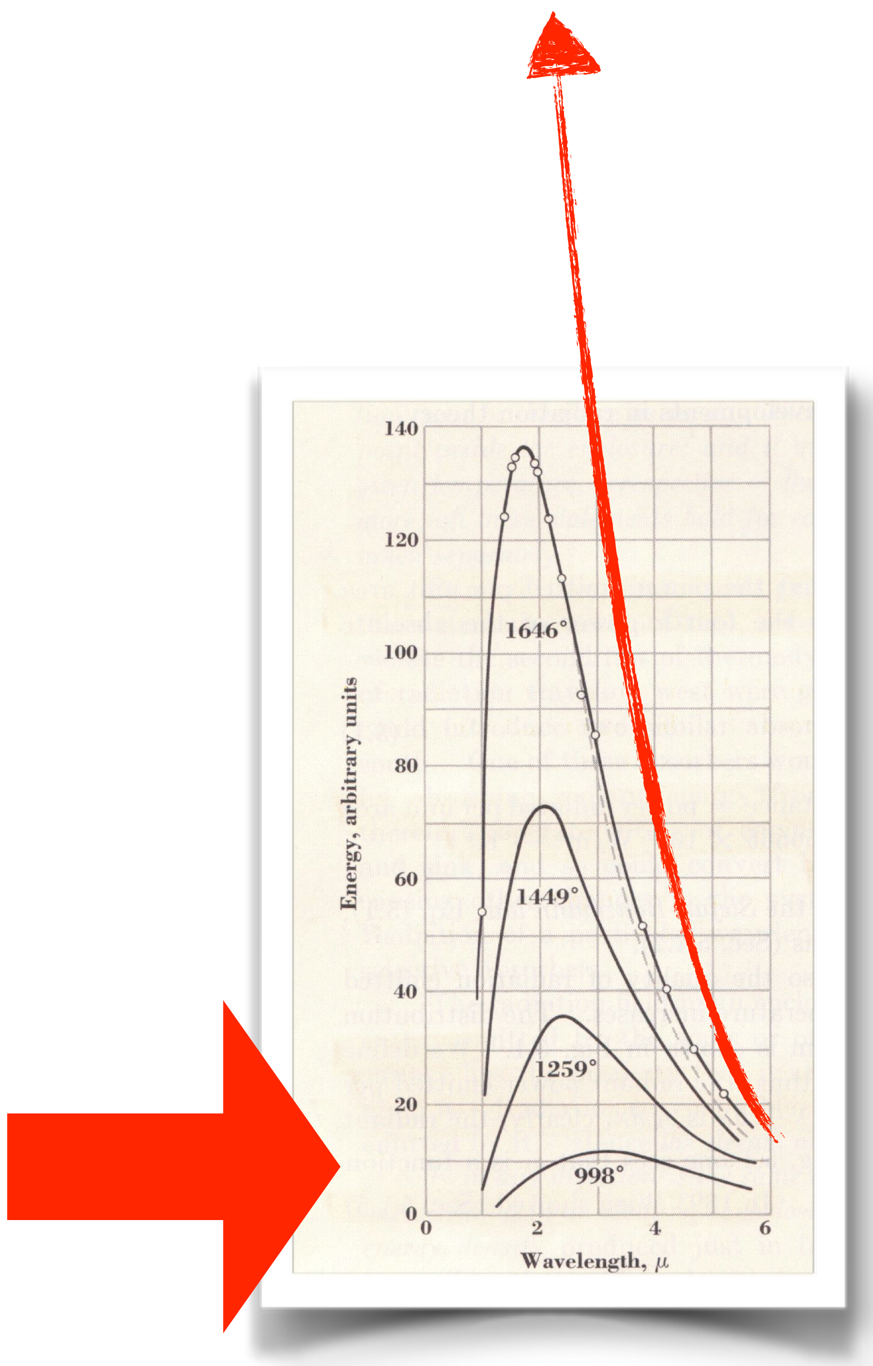
the lack of light at the short wavelengths

= high frequencies?

But, for Planck:

$$E = nhf$$





The number of high frequency oscillations are much fewer than low frequencies:

each quantum has <u>more</u> <u>energy</u>...but there are <u>fewer of them</u>.

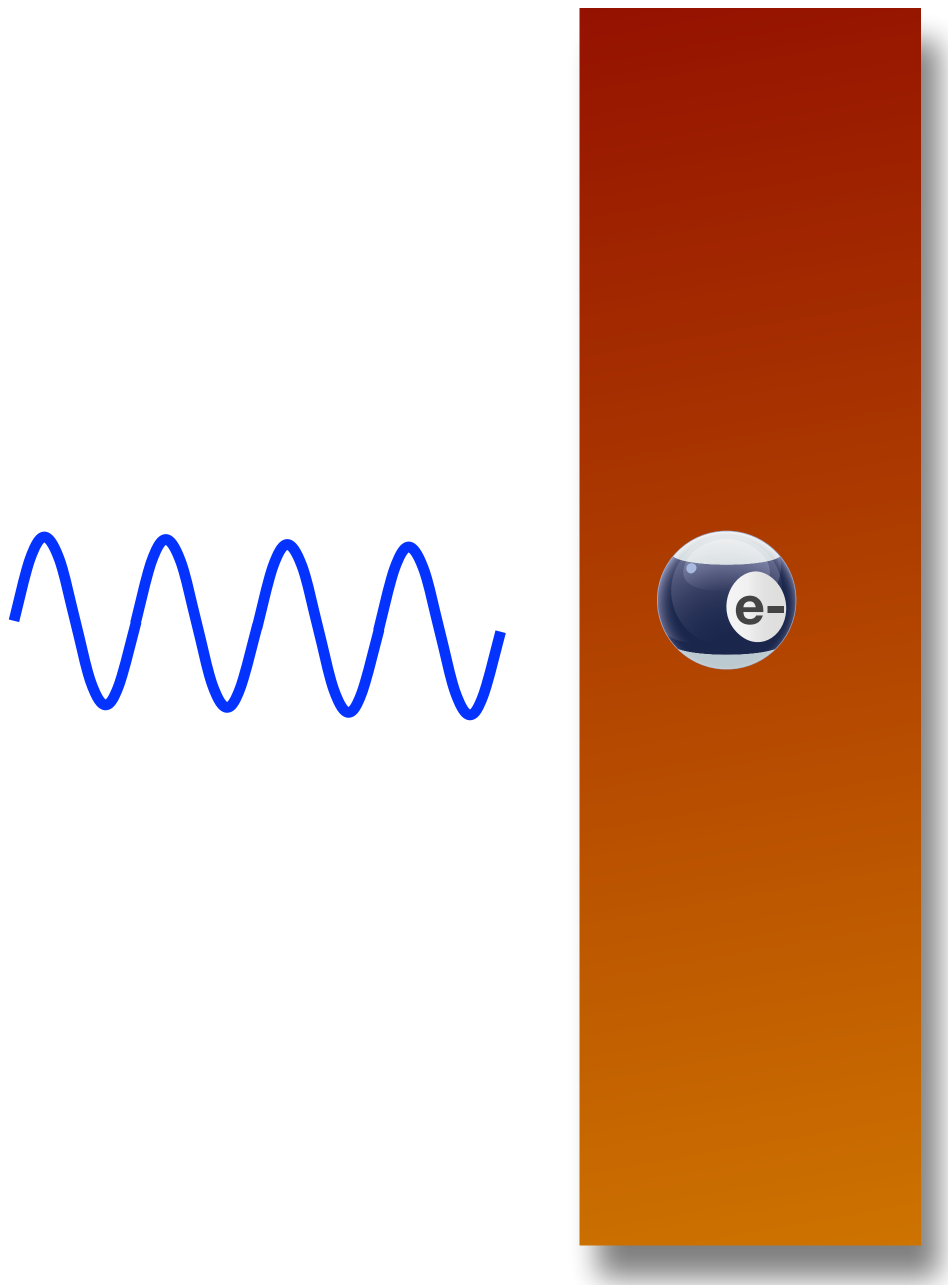
for Planck

electromagnetic waves

can still be anything

the radiator walls "quantize" emission

EM can be any frequency radiator (the container wall) can produce only particular frequencies



Not a statement about EM!
A statement about the material radiators of energy!

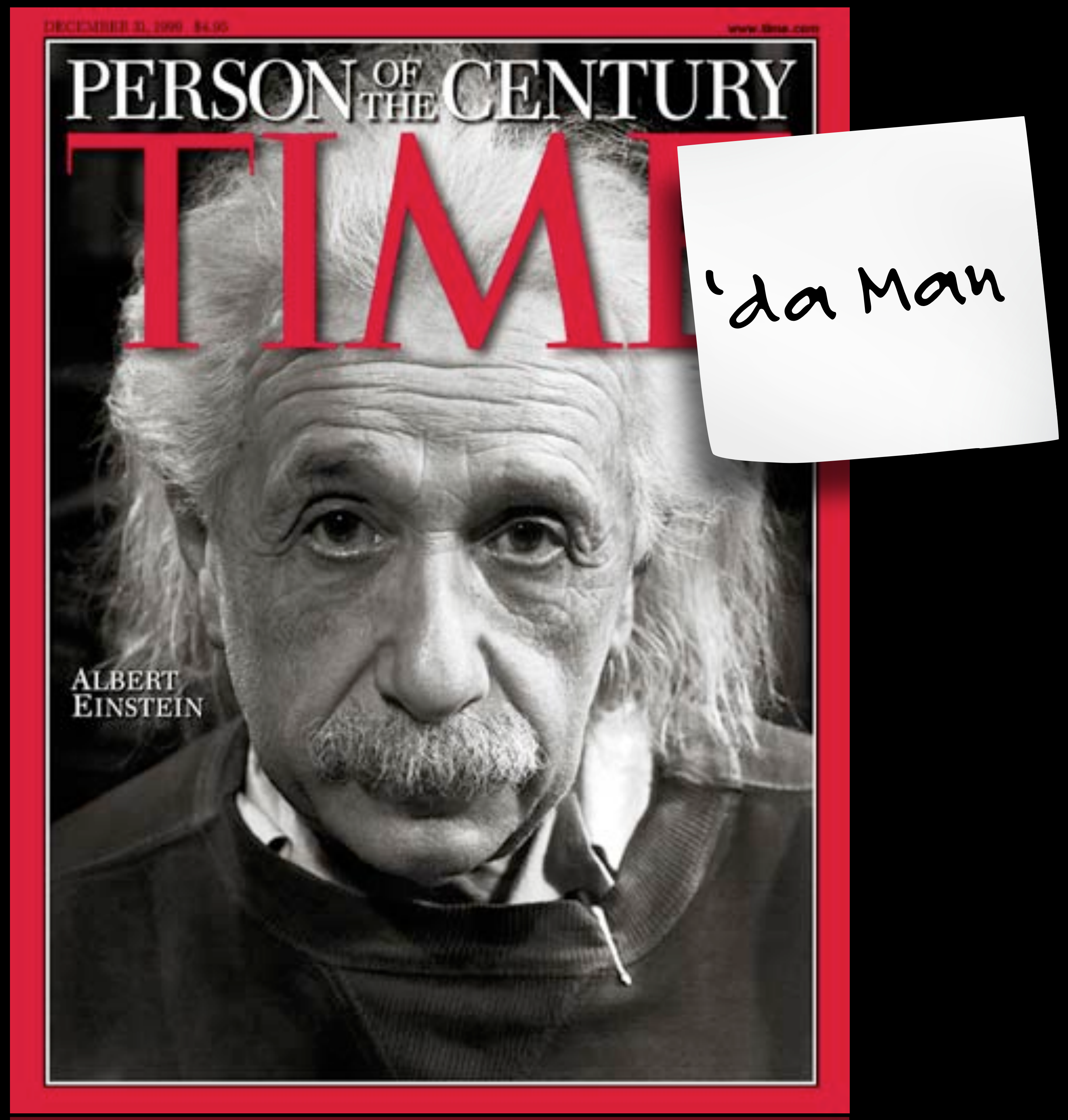
perfect analogy

sound

piano

sound can be any frequency
piano can produce only particular frequencies

Not a statement about sound!
A statement about pianos!



He’s Back

perfect analogy

sound

piano

sound can be any frequency
piano can produce only particular frequencies

Not a statement about sound!
A statement about pianos!

Einstein said:

in that famous 1905 year

Planck's bundles are not about the walls...the radiators

<u>**It is**</u> a statement about light (electromagnetism)

Light is itself "quantized"

....as particles:

these particles are now called: "photons," γ

they have no mass

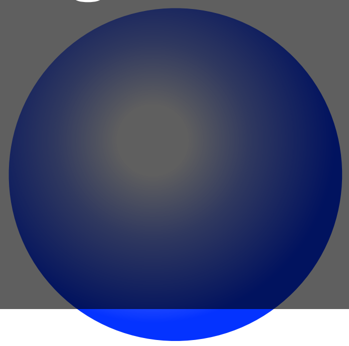
hold the phone.

A wave is EVERYWHERE

& light is a wave:

How could things so opposite be combined into one reality?

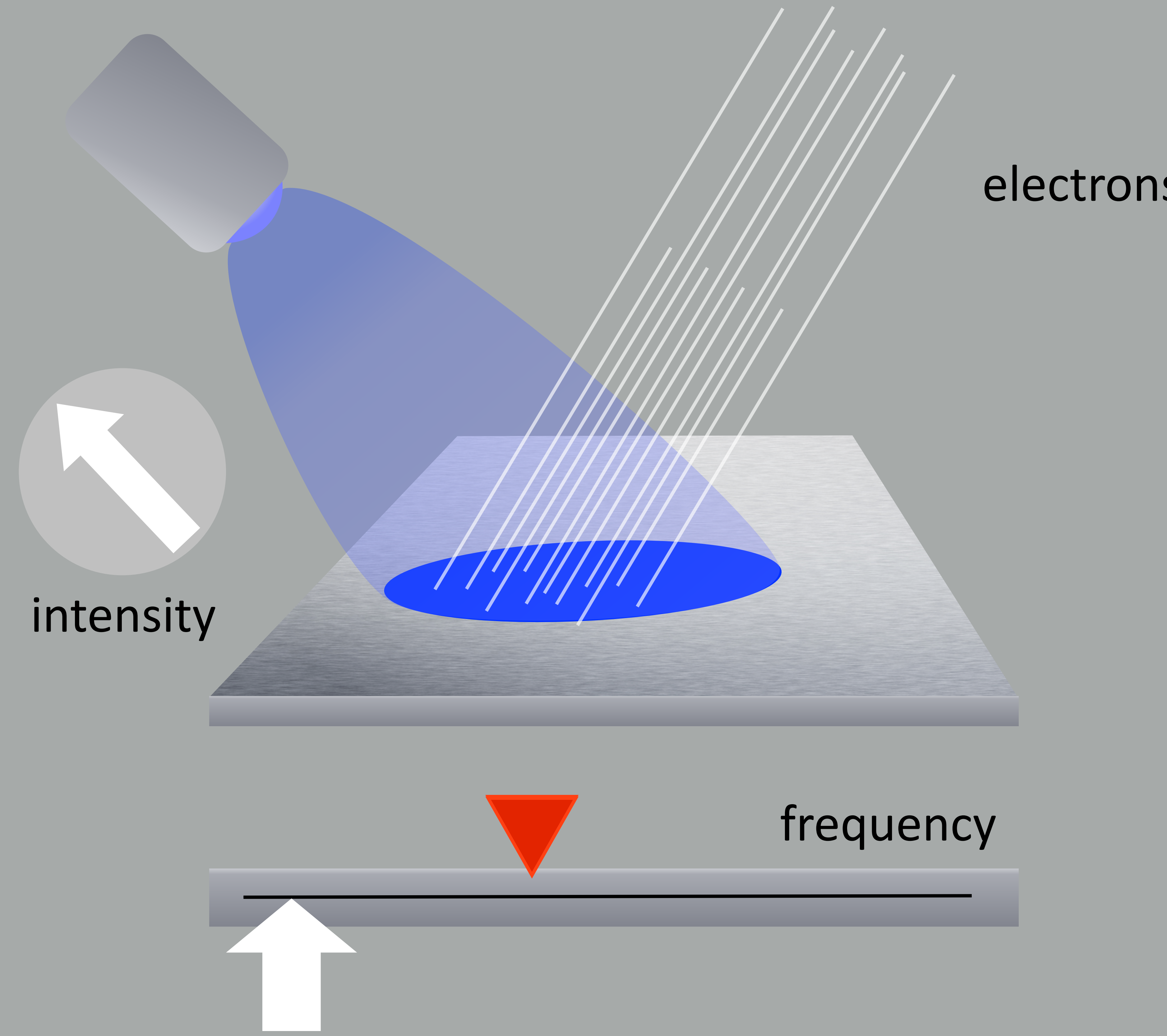
A particle is HERE:



Einstein was motivated by experiment: “Photoelectricity”

found by Hertz in his confirmation of Maxwell’s waves

Ultraviolet light causes electrons to stream from surface of some metals



The facts:	The light-wave expectation:
1. no electrons until a particular frequency *then, with higher frequency they come out with more energy*	huh?
2. raise the intensity...get more electrons	expect higher energy electrons

Using Planck's formula

$$E = hf$$

the "Photoelectric Effect" makes sense.

the electrons are bound a little...so, they get released above a particular frequency, f so a particular E is required

Intensity is just more and more photons in the light

kicking out more and more electrons

photoelectric effect

everywhere:

photodiodes

smoke detectors, CD players, remote controls...

photocells

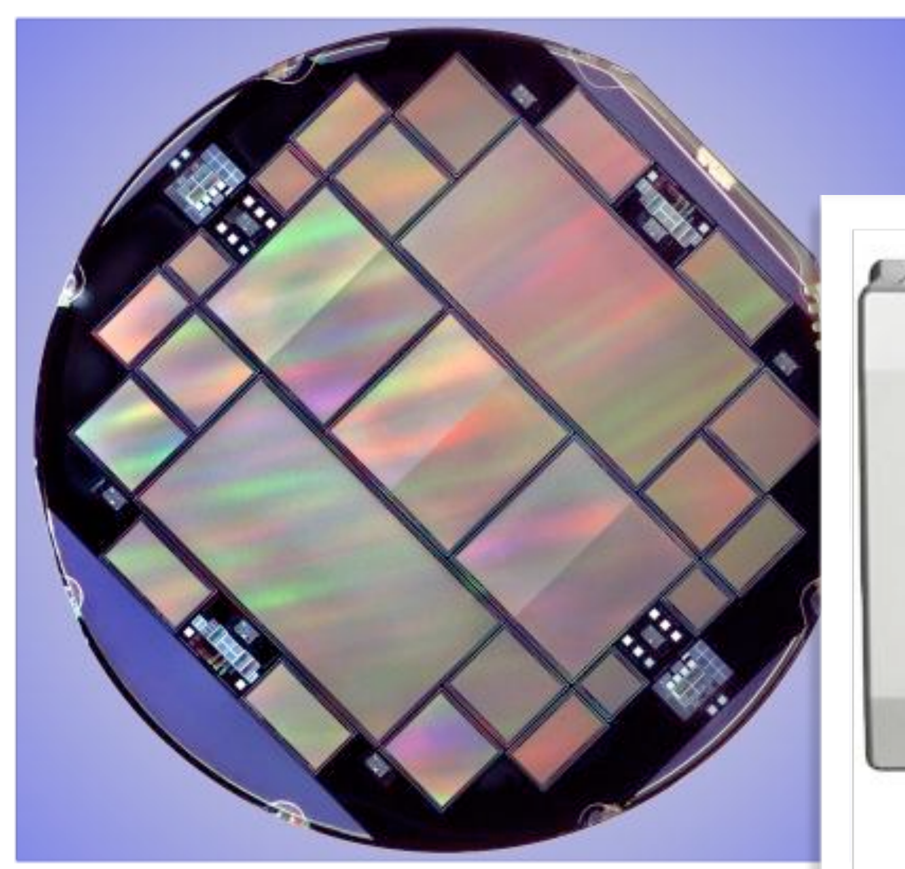
packed into "pixels" and arrays of pixels:

CCDs (charged coupled devices)

The facts:	The light-wave expectation:
1. no electrons until a particular frequency *then, with higher frequency they come out with more energy*	huh?
2. raise the intensity...get more electrons	expect higher energy electrons

53

that's a current



remember the formula

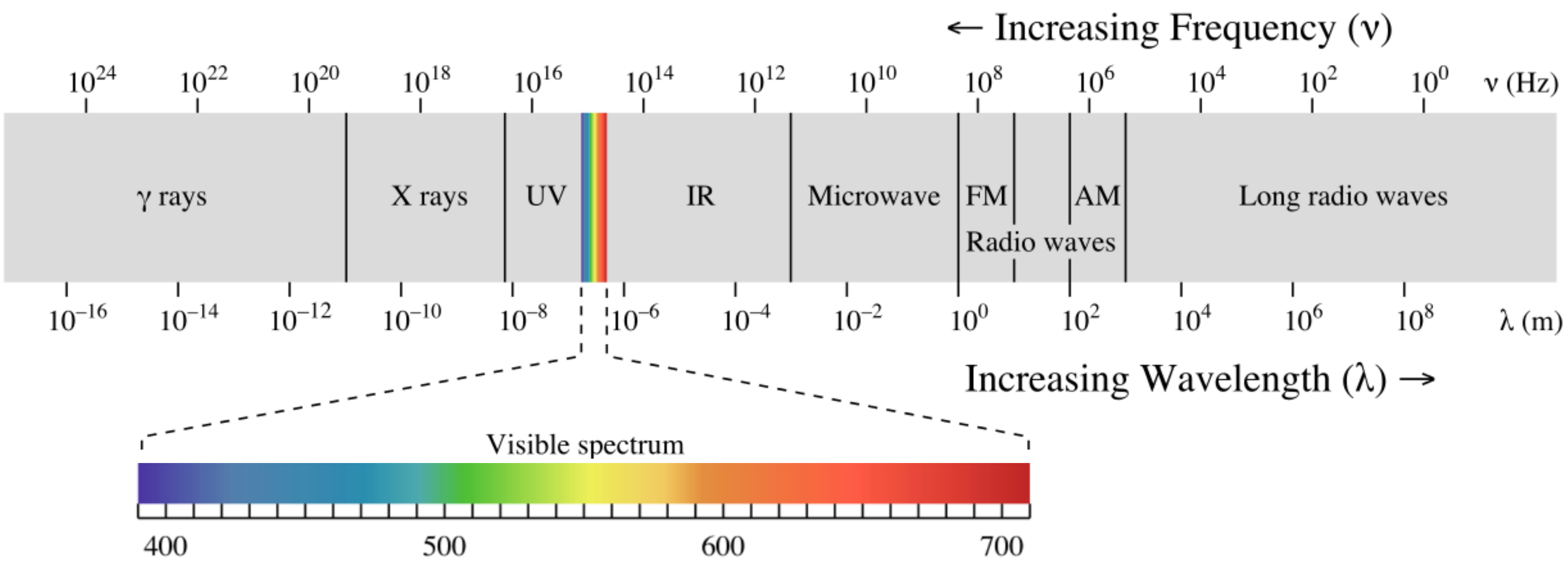
$$E = hf$$

the higher the frequency

the higher the energy

the lower the energy

the lower the frequency



remember about waves: $v = \lambda f$

$$f = \frac{v}{\lambda} \quad v = c$$

for light

$$E = \frac{hc}{\lambda}$$

the larger the wavelength

the smaller the energy

the larger the energy

the smaller the wavelength

Einstein made a prediction: treat light like billiard-balls

and cause collisions

like particles

$$\gamma + e \rightarrow \gamma' + e'$$

the photon loses energy γ'

$\gamma \rightarrow$ e

the electron gains energy e'

Einstein made a prediction: treat light like billiard-balls

and cause collisions

like particles

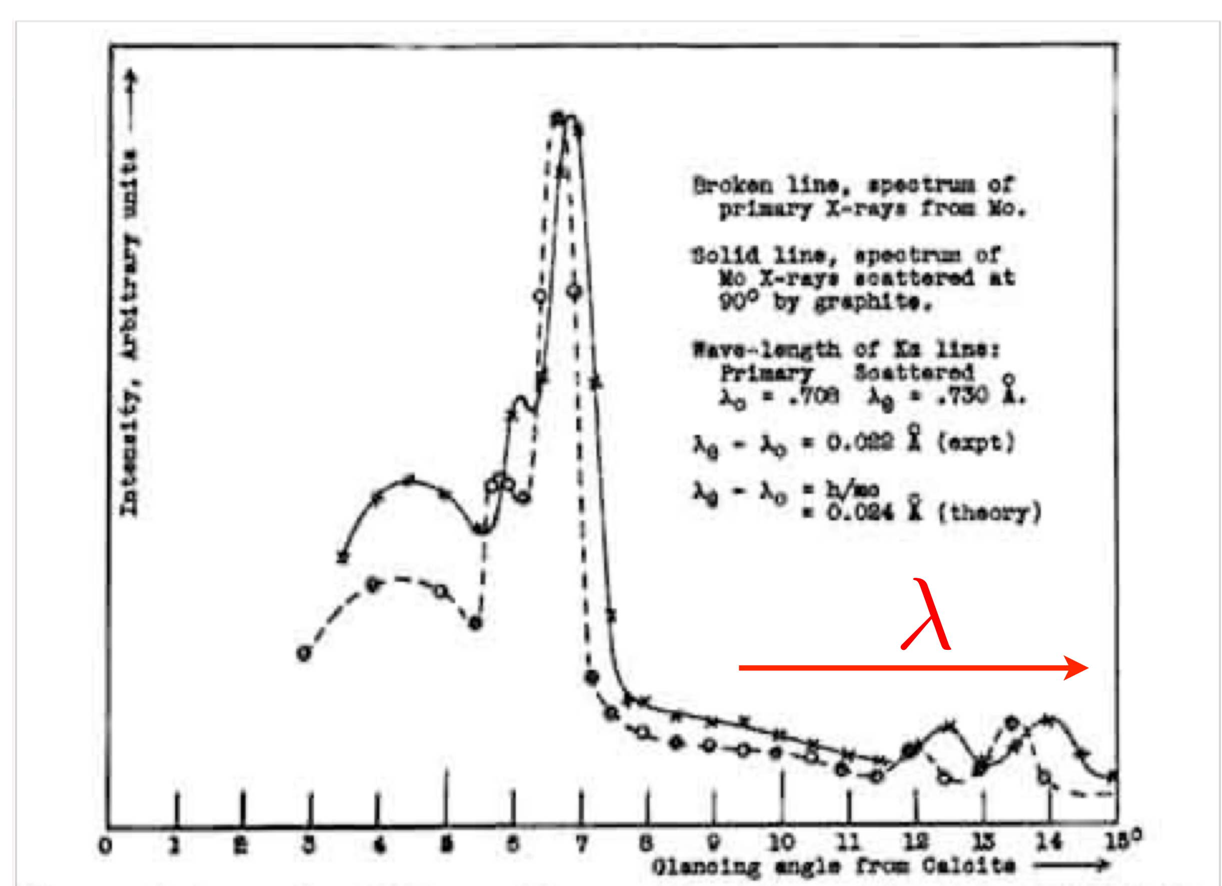
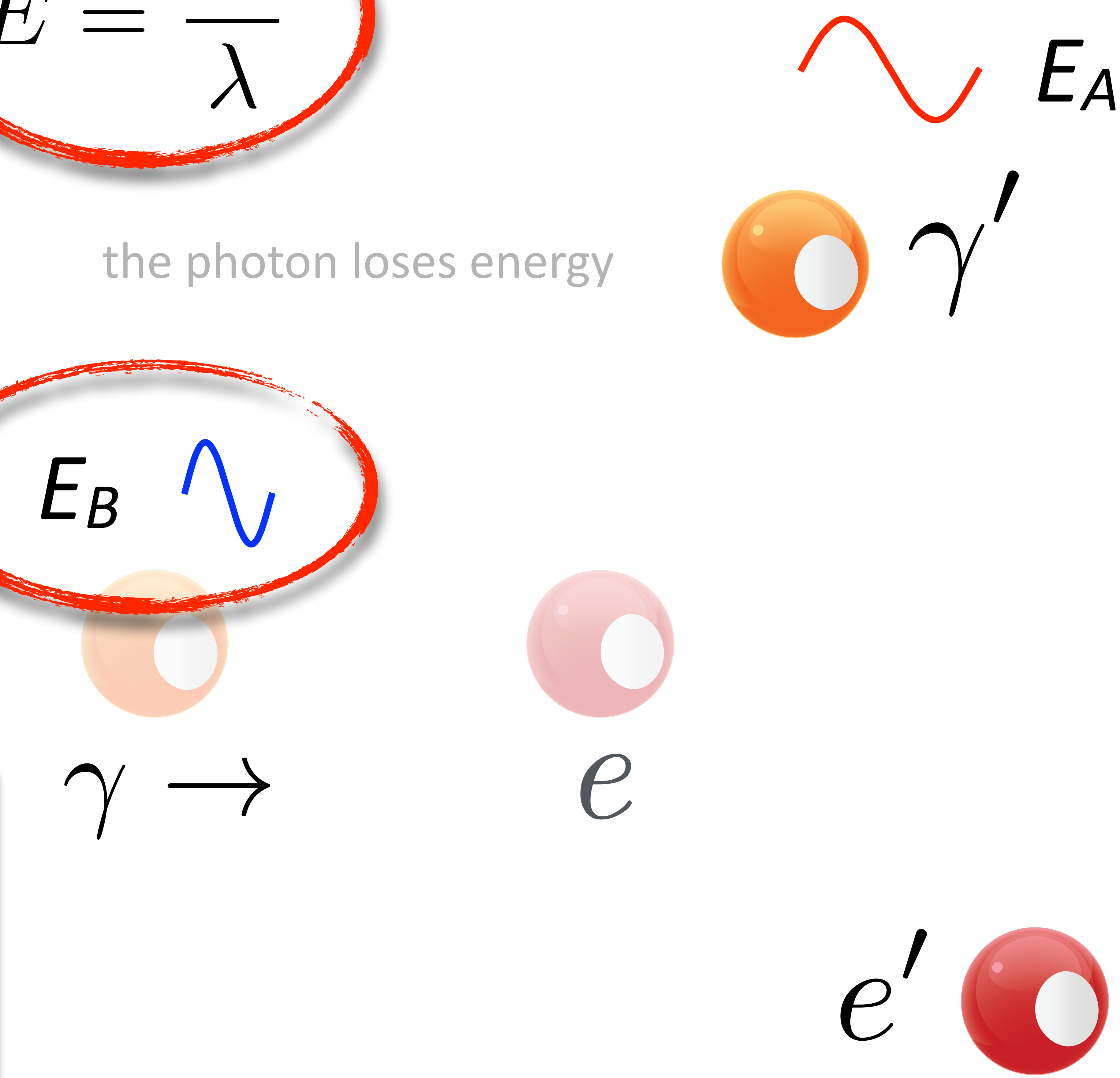


Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

$$E = \frac{hc}{\lambda}$$

longer wavelength - lower energy

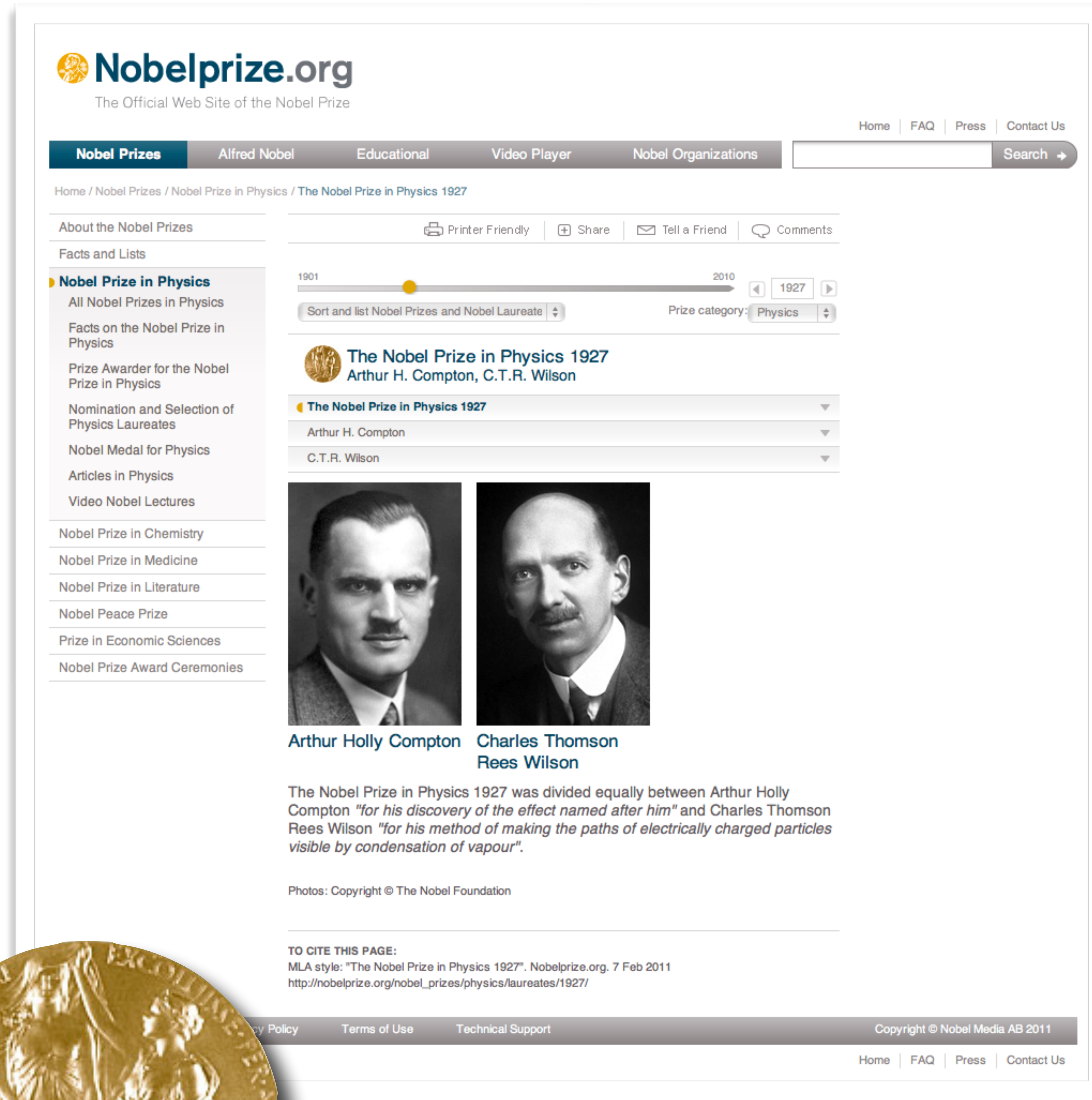


The "Compton Effect"

"Compy"

I played with his grandson as a kid

which I find absolutely bizarre



The "Compton Effect" or "Compton Scattering"

our second elementary particle, 1923

the photon (aka “gamma”)

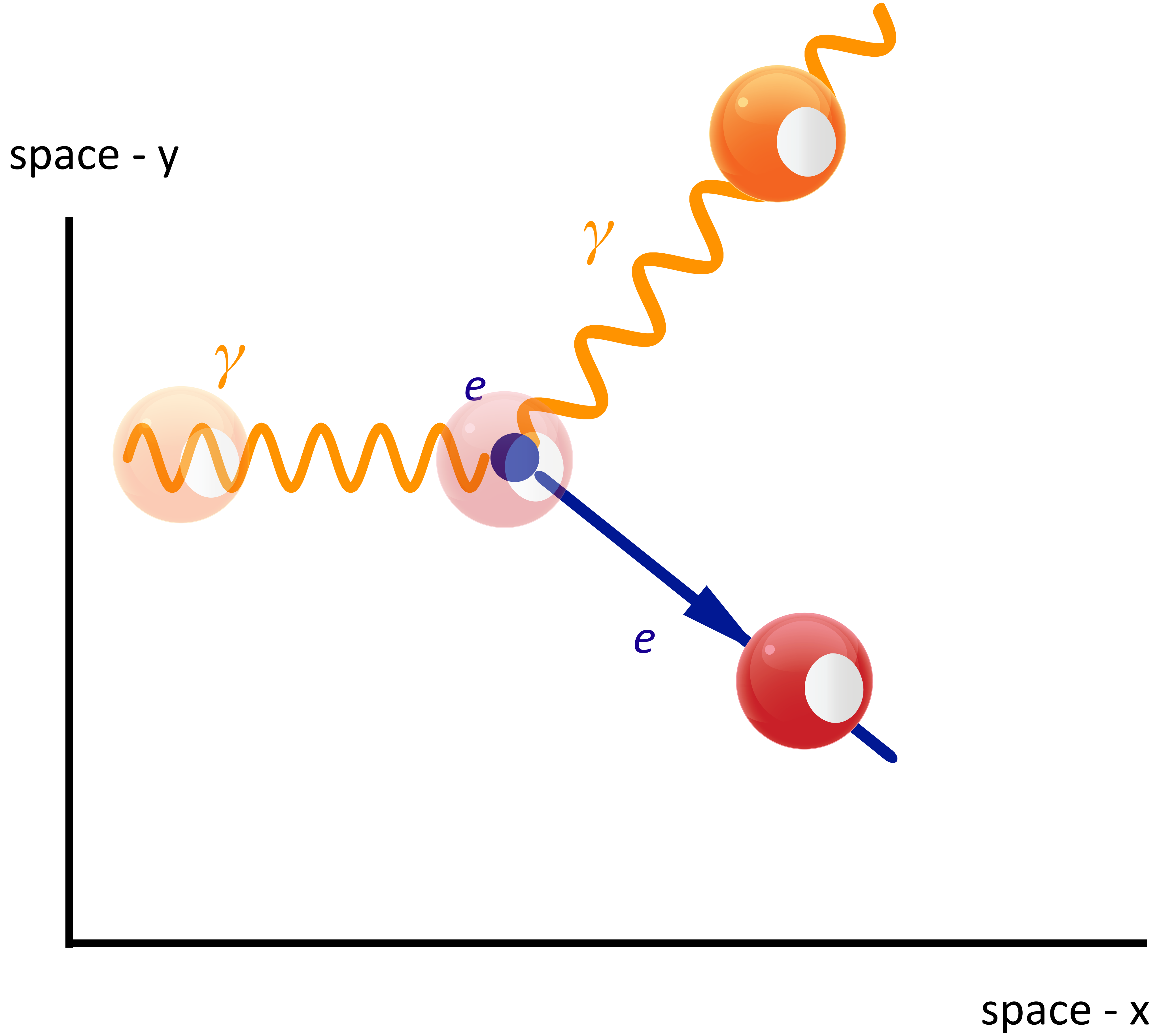
particle: **photon, γ**

symbol:	γ
charge:	0
mass:	0
spin:	1
category:	an intermediate vector boson, a messenger particle

Compton scattering

Space diagram

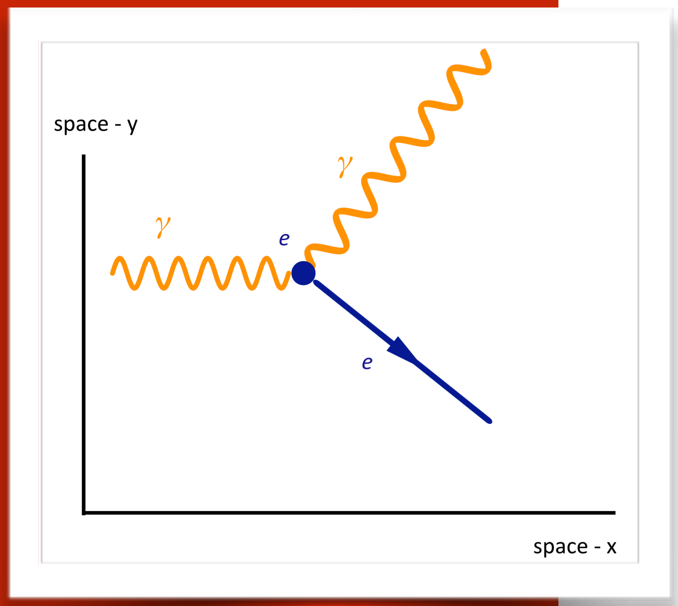
$$\gamma + e \rightarrow \gamma' + e'$$



Compton scattering

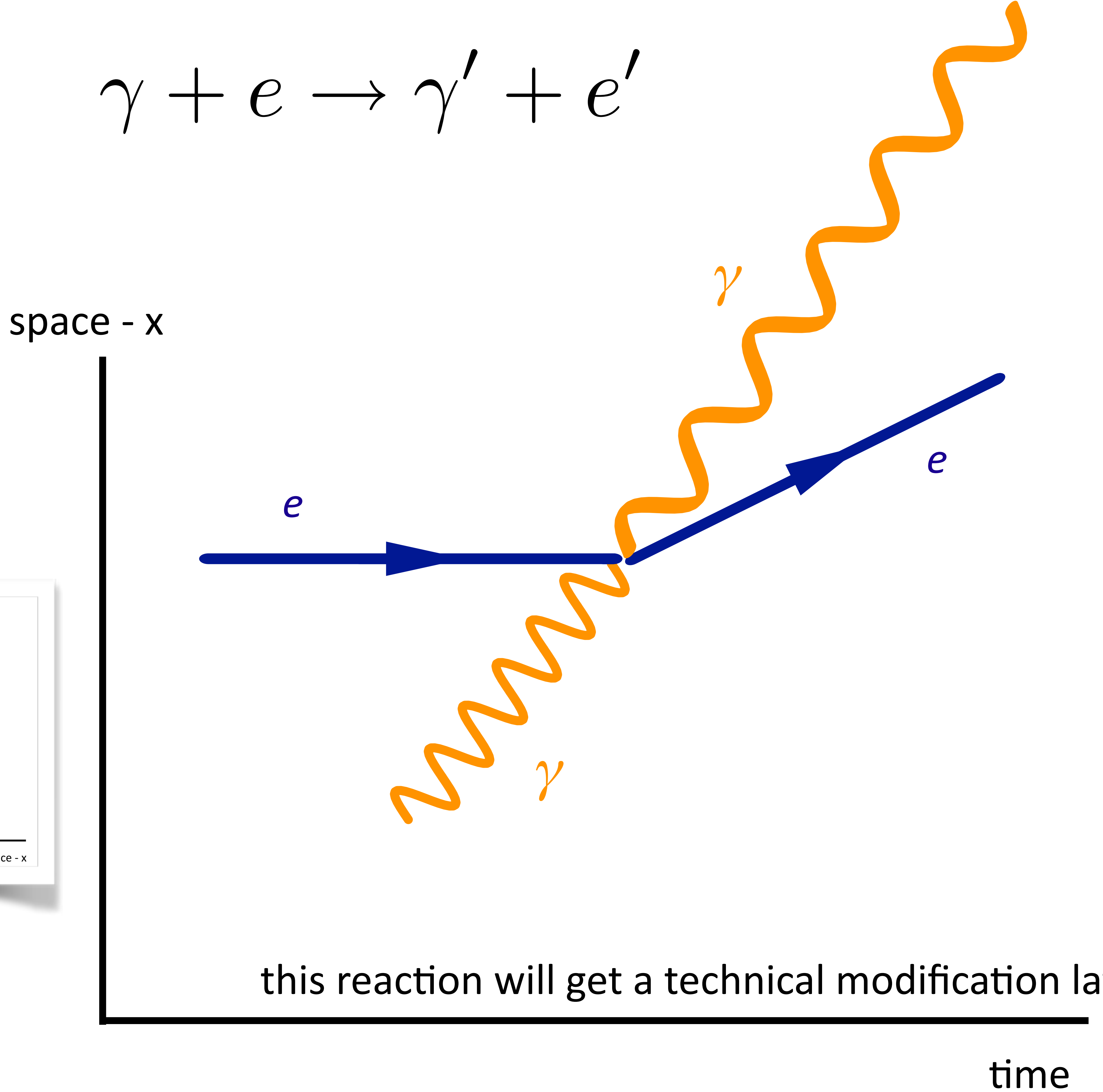
spacetime diagram

aka, *Feynman* diagram



draw the Feynman diagram for Compton Scattering

$$\gamma + e \rightarrow \gamma' + e'$$



this reaction will get a technical modification later

the definitive proof that light acts like

a particle.

How is that possible?

Particles come in whole sizes - no parts, no fractions.

Remember what "makes" a wave...

Waves **interfere** with one another.

What makes wave behavior in your life?

How about hearing around corners?

Stay tuned...as it will become weird.

wavelength is the key

look at the relative sizes of openings and barriers

compared to the wavelength

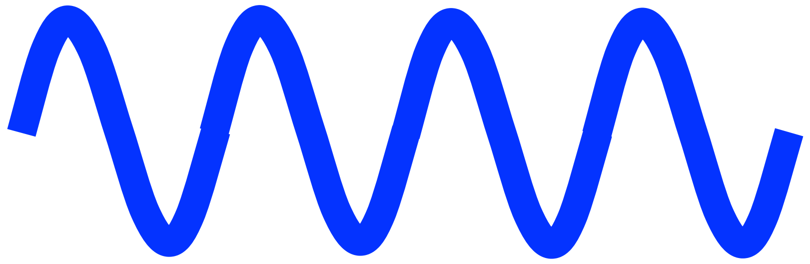
First, think about water waves, then about light waves.

imagine two shapes of waves

on water

"plane wave"

from side:

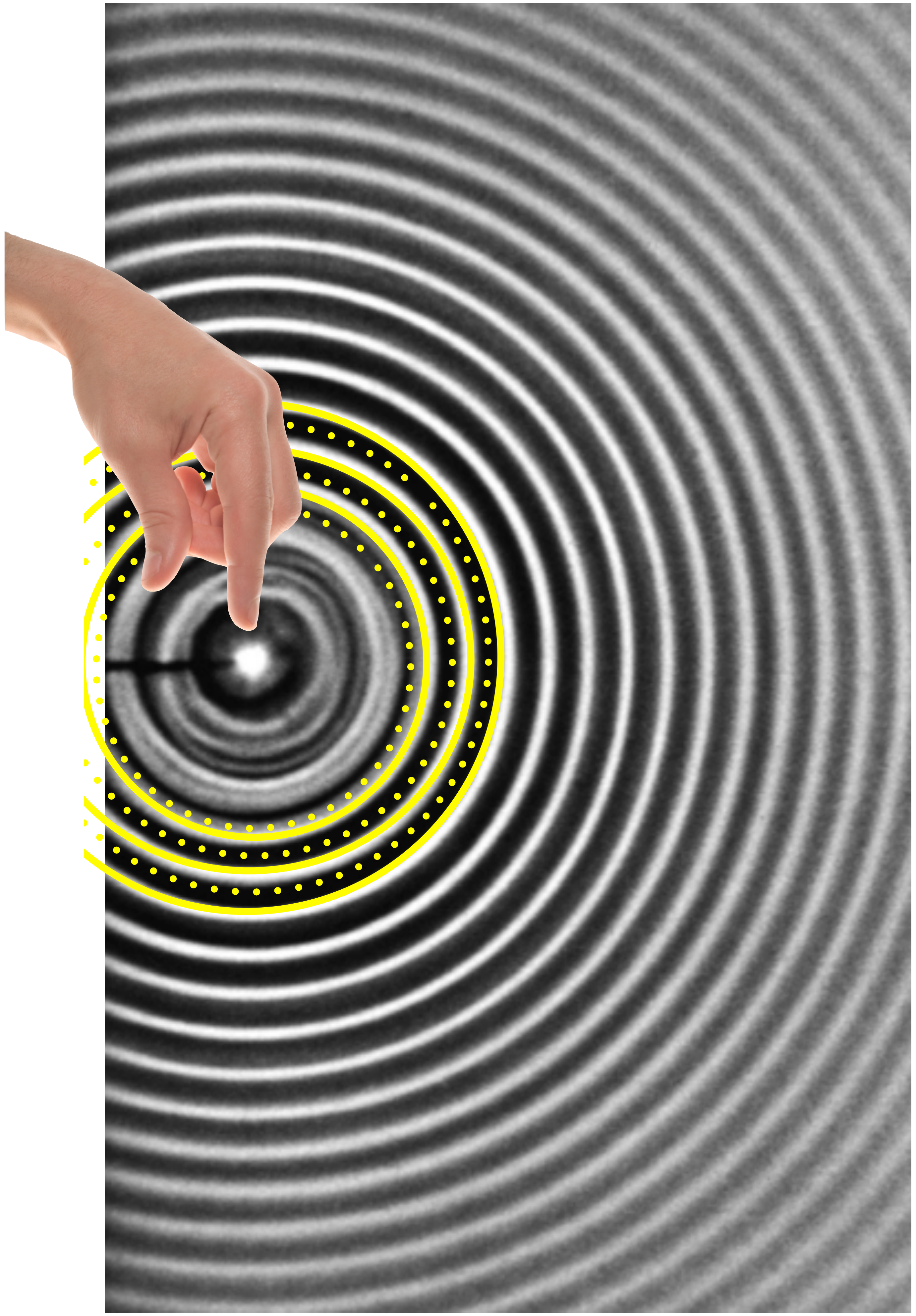


toward beach

"circular wave"

waves

one tap



solid- crest
dashed - trough

interference again

two taps

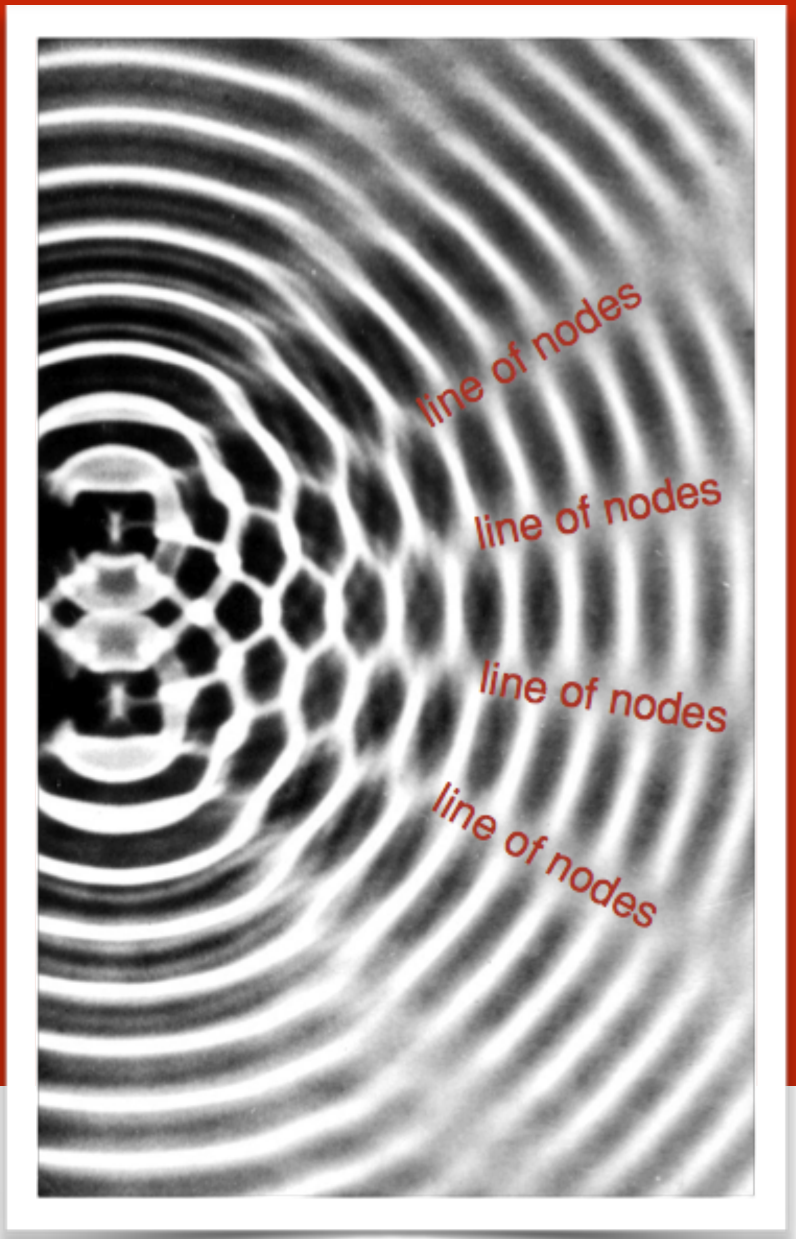
"node": a trough

"crest": a peak

solid- crest
dashed - node

this is it

THE smoking gun of wave behavior: interference



keep those in mind

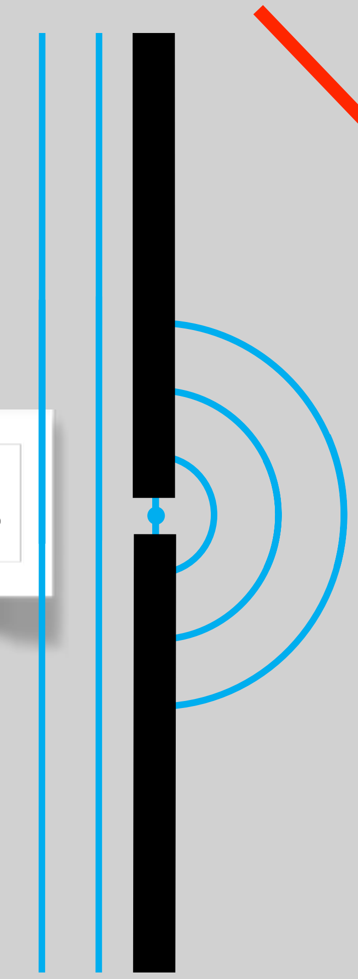
1 and 2 taps

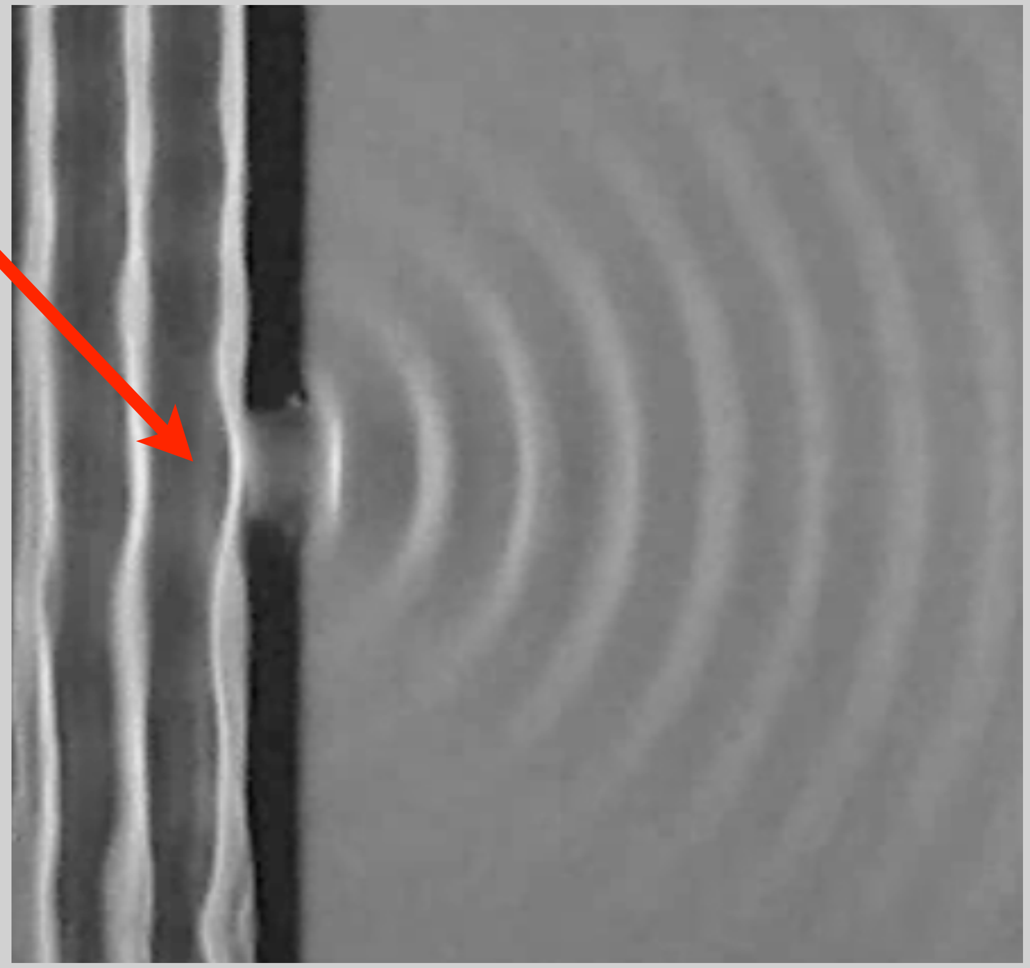
a plane wave impinging on a gap

like 1 "tap"

a gap of about a wavelength-width

plane waves





like the 1-tap image

This is diffraction

...the bending of the wave around the opening.

Another smoking gun of wave-behavior (as opposed to particle behavior)

dramatic images from oceans

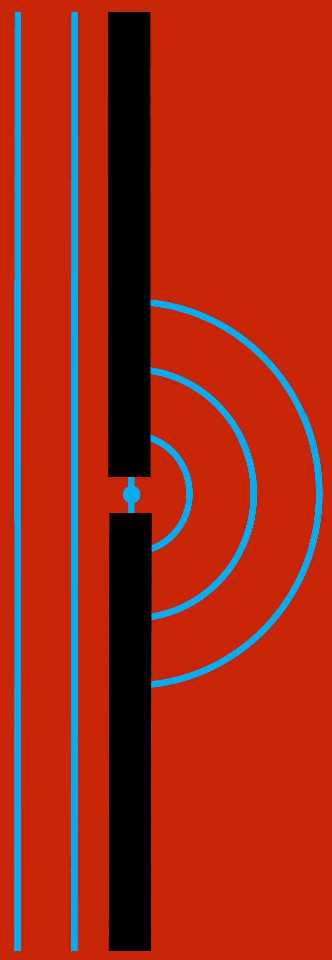
now we know the answer

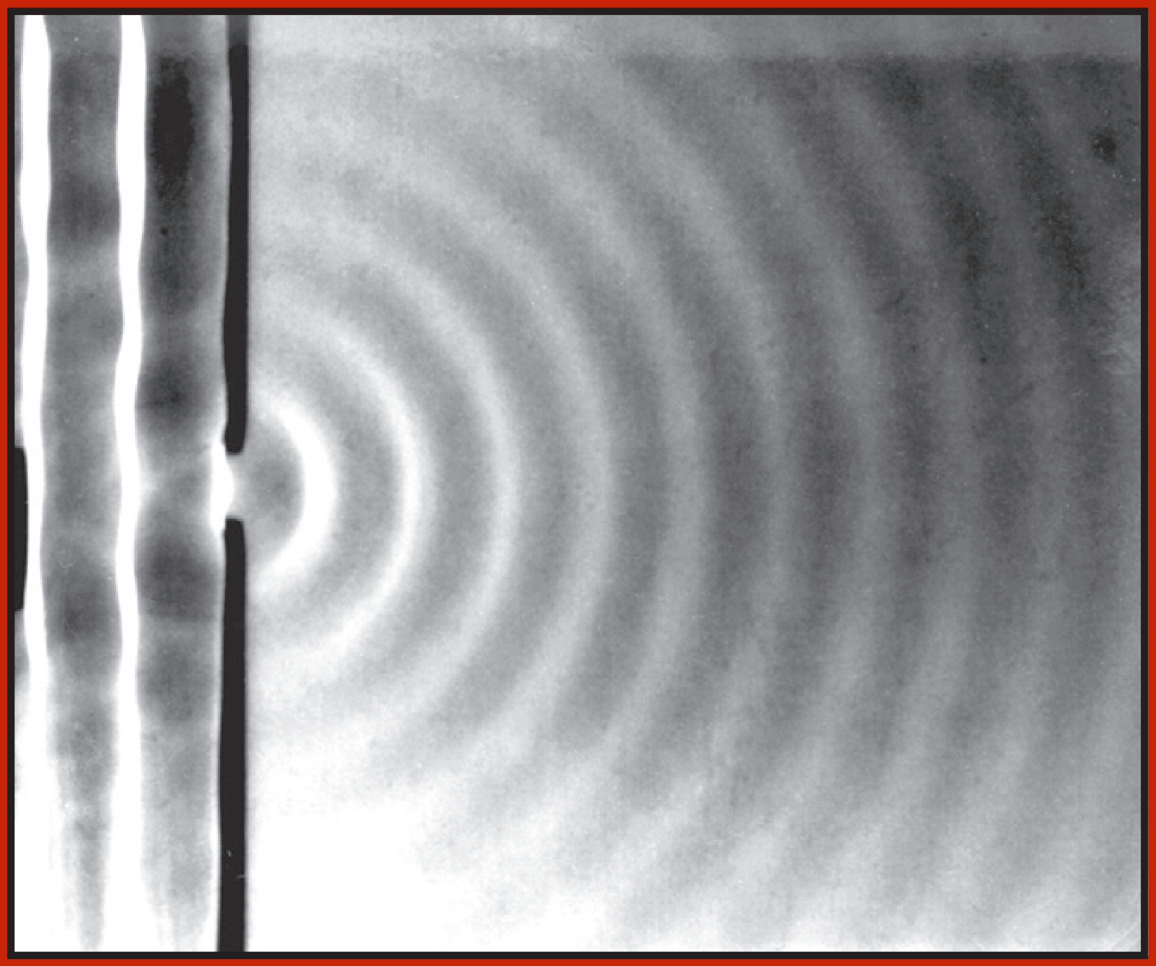
about hearing around corners

wavelength of sound? about 1m

middle C, f = 256 Hz

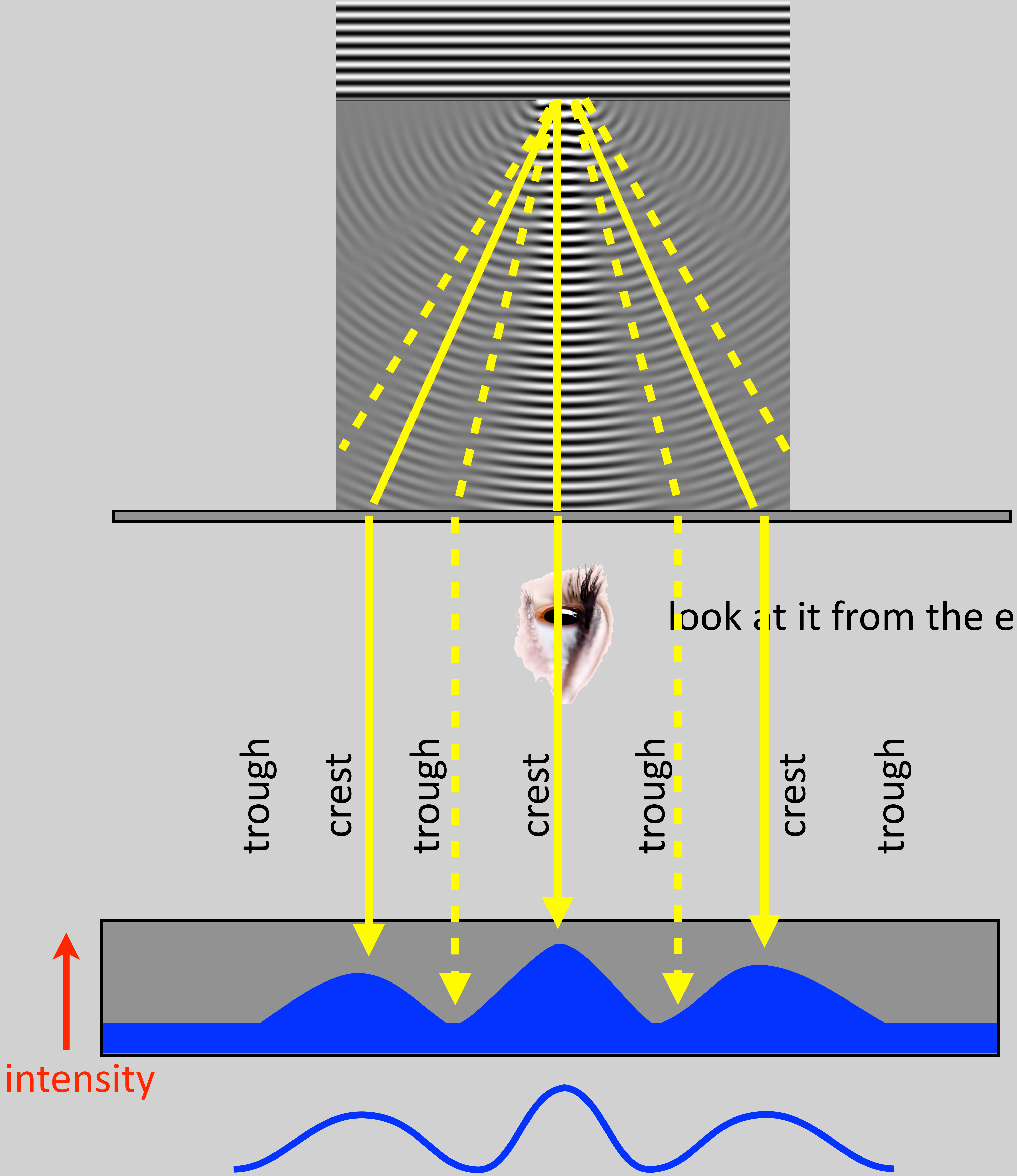
which is about door-sized





look at it from:

the side where the waves are coming at you

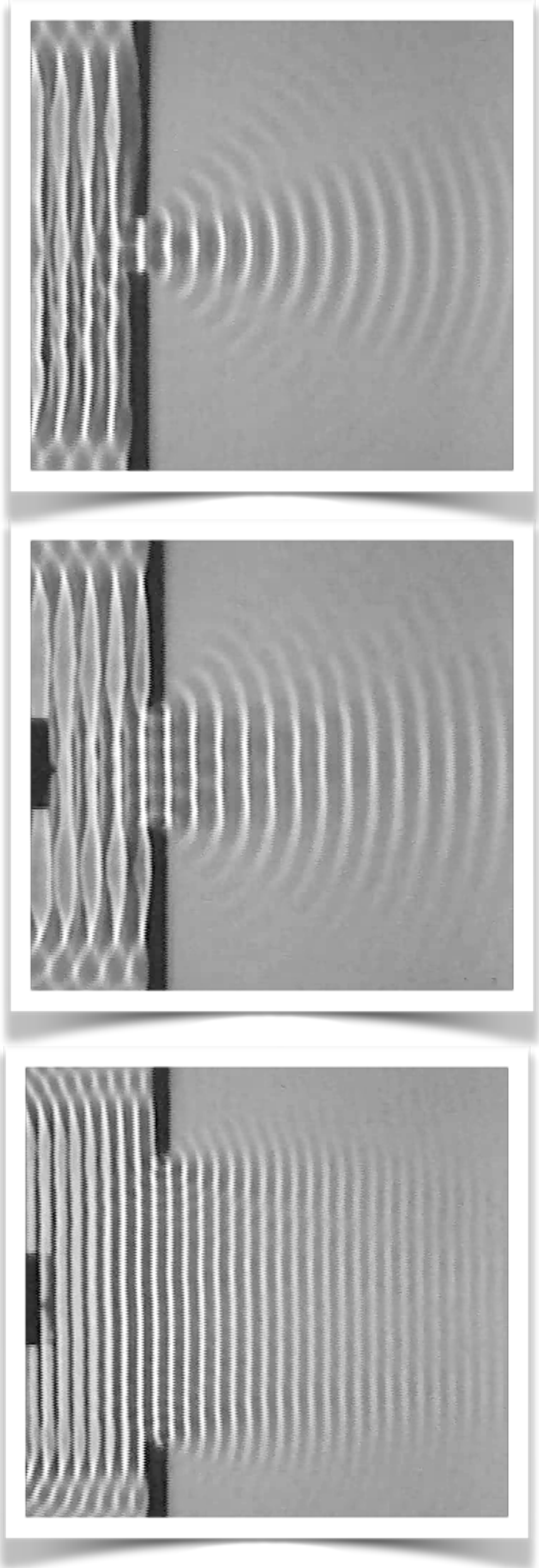


the relative size of the gap

determine the apparent diffraction amount

increasing gap relative to wavelength

that’s why you can’t see around doors



this is for water

close to the slits

for light...many, many wavelengths away from the slits...stuff happens