Statement of Solidarity by MSU faculty and staff with respect to students and immigrants at MSU:

We the faculty and staff of MSU, stand in agreement with President Simon's calls for support of all students and our values of diversity. President Simon stated: "Our students and scholars come from around the world to become Spartans, and then return to the world to make it better. We must not allow fear to change the nature of who we are." We declare our solidarity with all our students, including those who are immigrants, refugees, or children of immigrants. We will not collaborate with federal forces or agencies seeking to establish the legal immigration status of students or facilitate their apprehension or deportation. We support completely their attempts to remain here as students pursuing a higher education and their drive to make a better life for themselves and contribute to the future of our country and the world.

734 MSU faculty and I are signatories.

hi

Lecture 21, 28.03.2017

Quantum Mechanics 1

housekeeping

Question about anything?

I'll make a movie for you:

Marie Curie movie anyone?

March 29: 6:30pm, BPS 1400

penultimate pizza poll pace peaked & pegged

FakeFacebook is due April Fools Day. tee hee

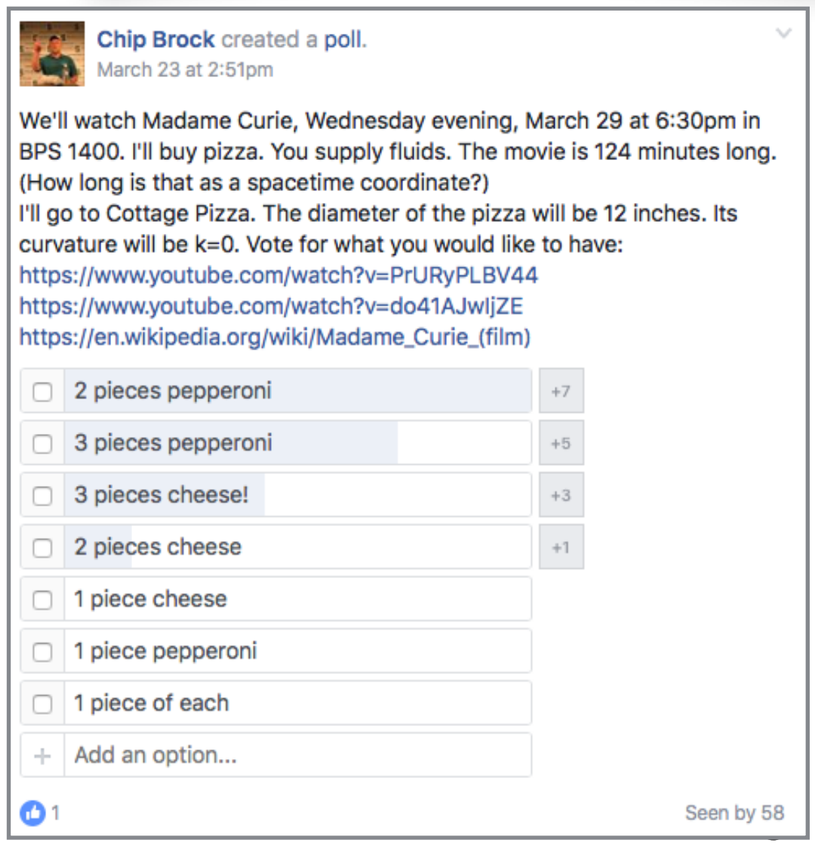
Blog read-reflect project has started. it stinks

Next week's homework: back to MasteringPhysics

Manuscript chapters:

man_waves_up and man_quantum1_up in

`http://www.pa.msu.edu/~brock/file_sharing/QSandBB/QS&BB_manuscript/`



Honors Project

has begun. First milestone was last Friday.

Read the Second of two sets of instructions:

`MinervaInstructions2_2017.pdf` in

www.pa.msu.edu/~brock/file_sharing/QSandBB/2017homework/honors_project_2017/

one more tool

waves

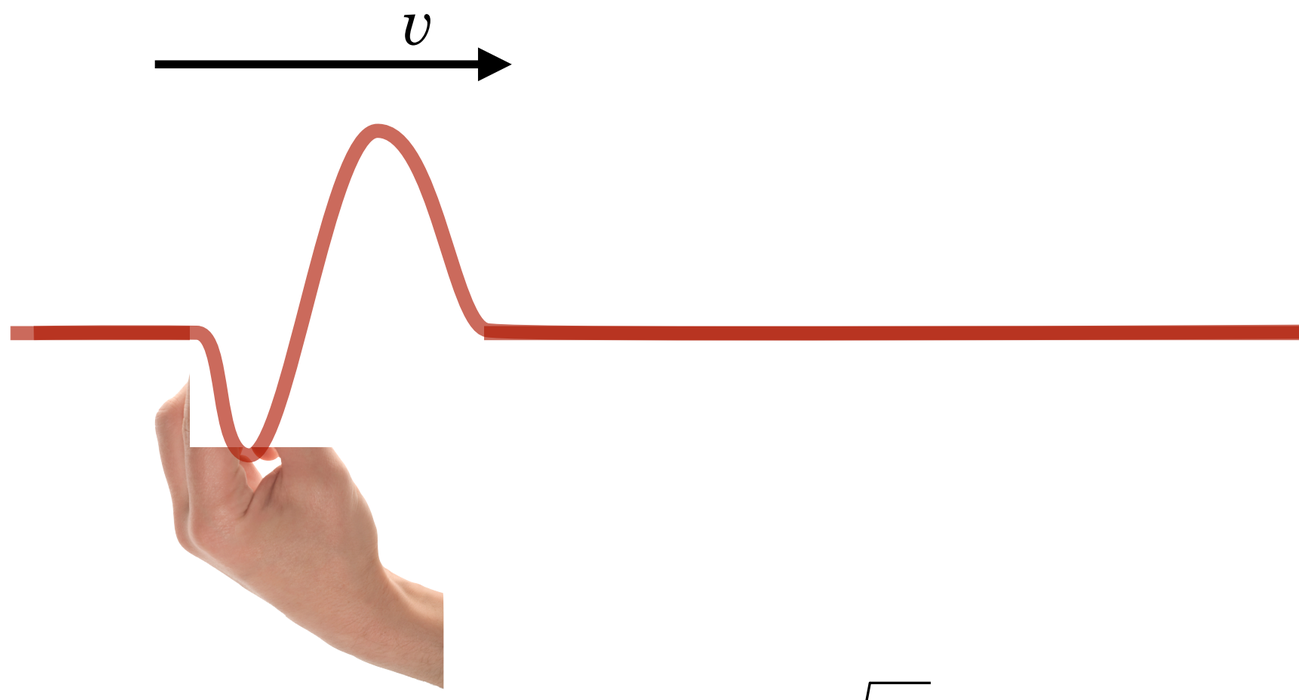
a wave is

a disturbance.

a way to transmit energy

without transmitting matter

one part is stretched, but the rope's tension restores it - and K is passed on to an adjacent part



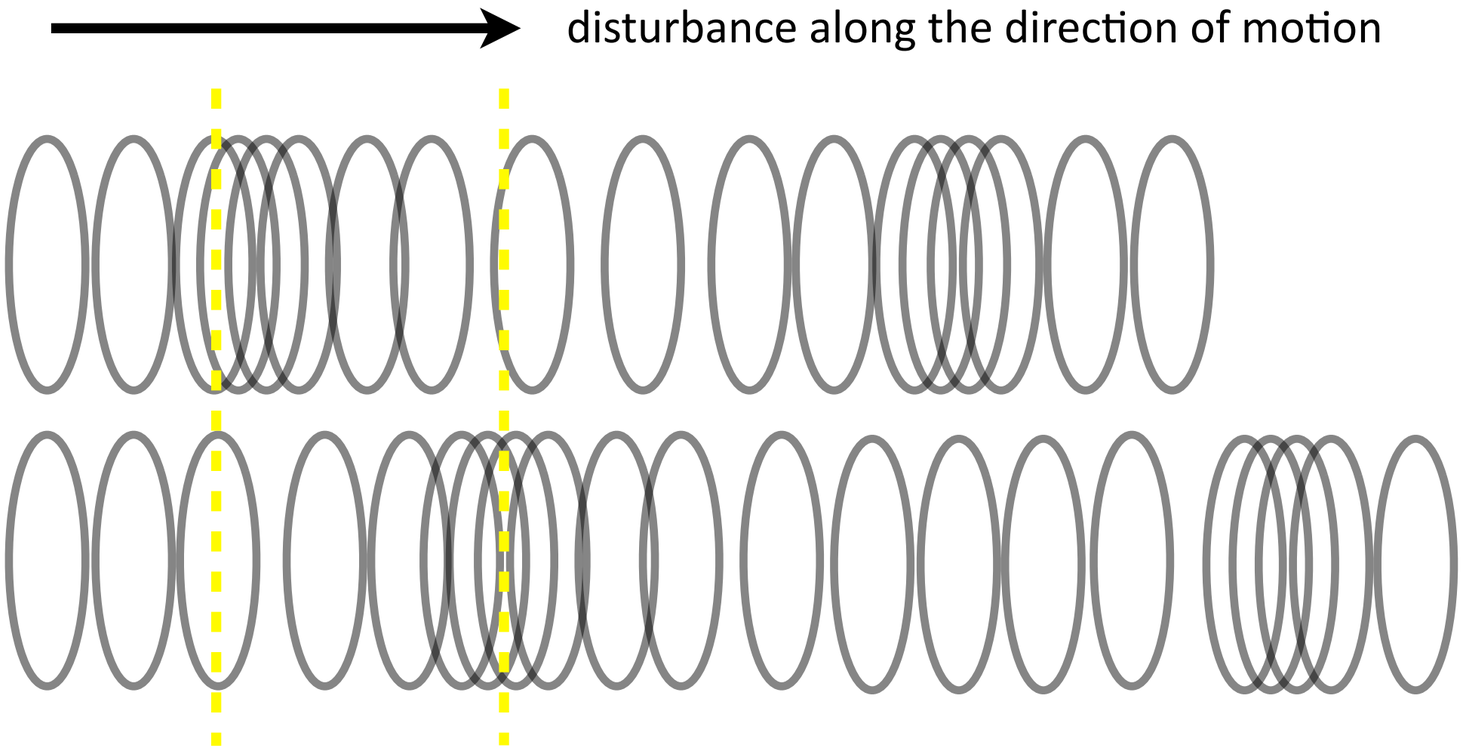
the *disturbance* moves with velocity $v = \sqrt{\frac{T}{\rho}}$

stiffer - faster

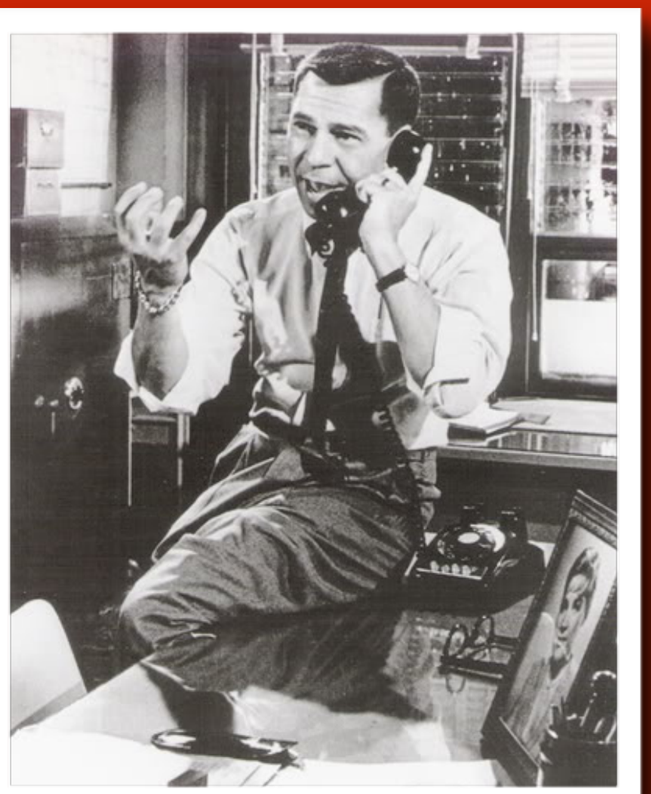
lighter - faster

2 kinds of waves

Longitudinal ***SOUND***

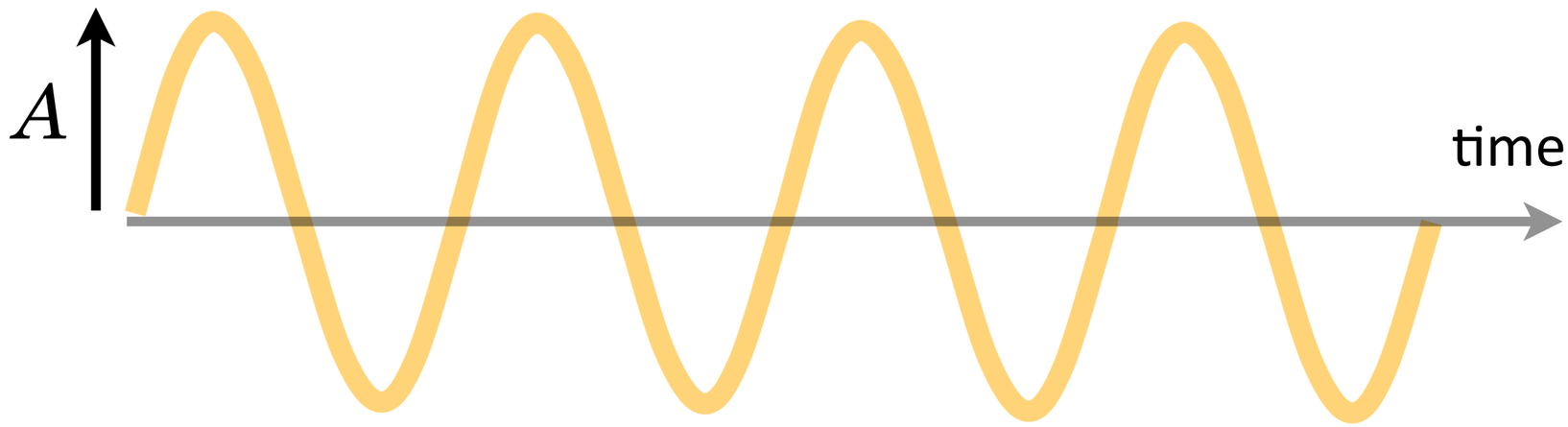


just some facts, Ma’am



maximum height of the disturbance: “Amplitude,” A.

“Intensity” is ~ A^2



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:

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

what characterizes a wave?

different from a material body?

a material object is

here.

a wave is

everywhere.

a material bounces

doesn’t pass through.

?

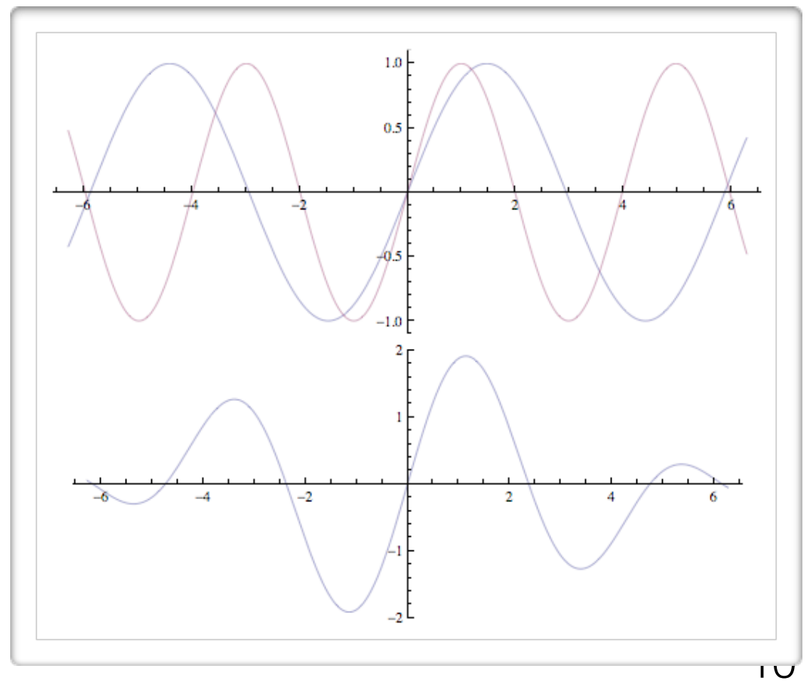
!

waves go right through

one another

blue or red

blue + red

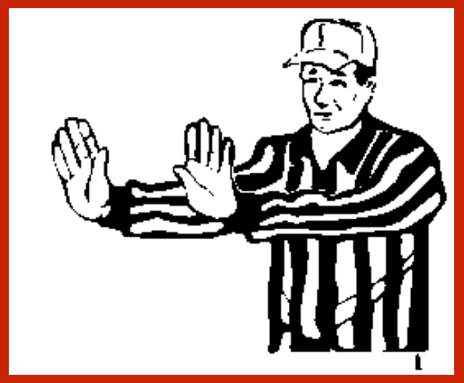


the

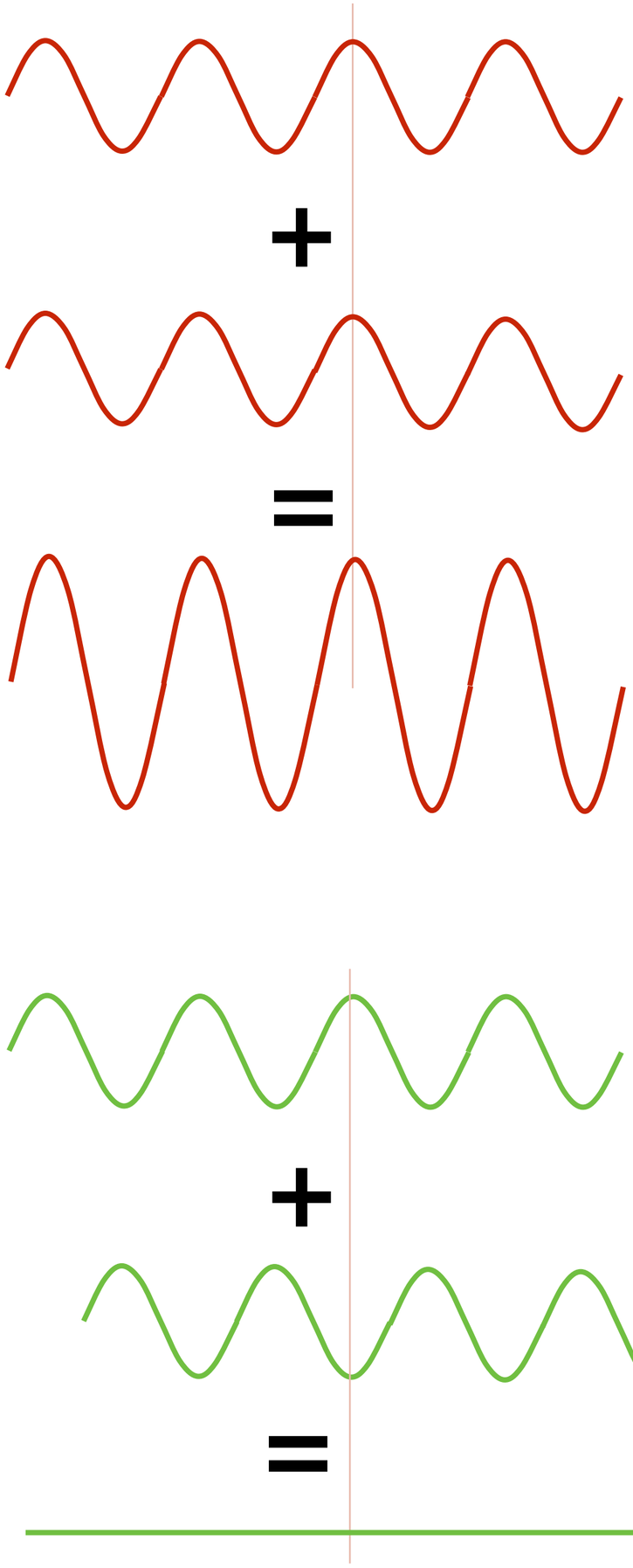
for waves?

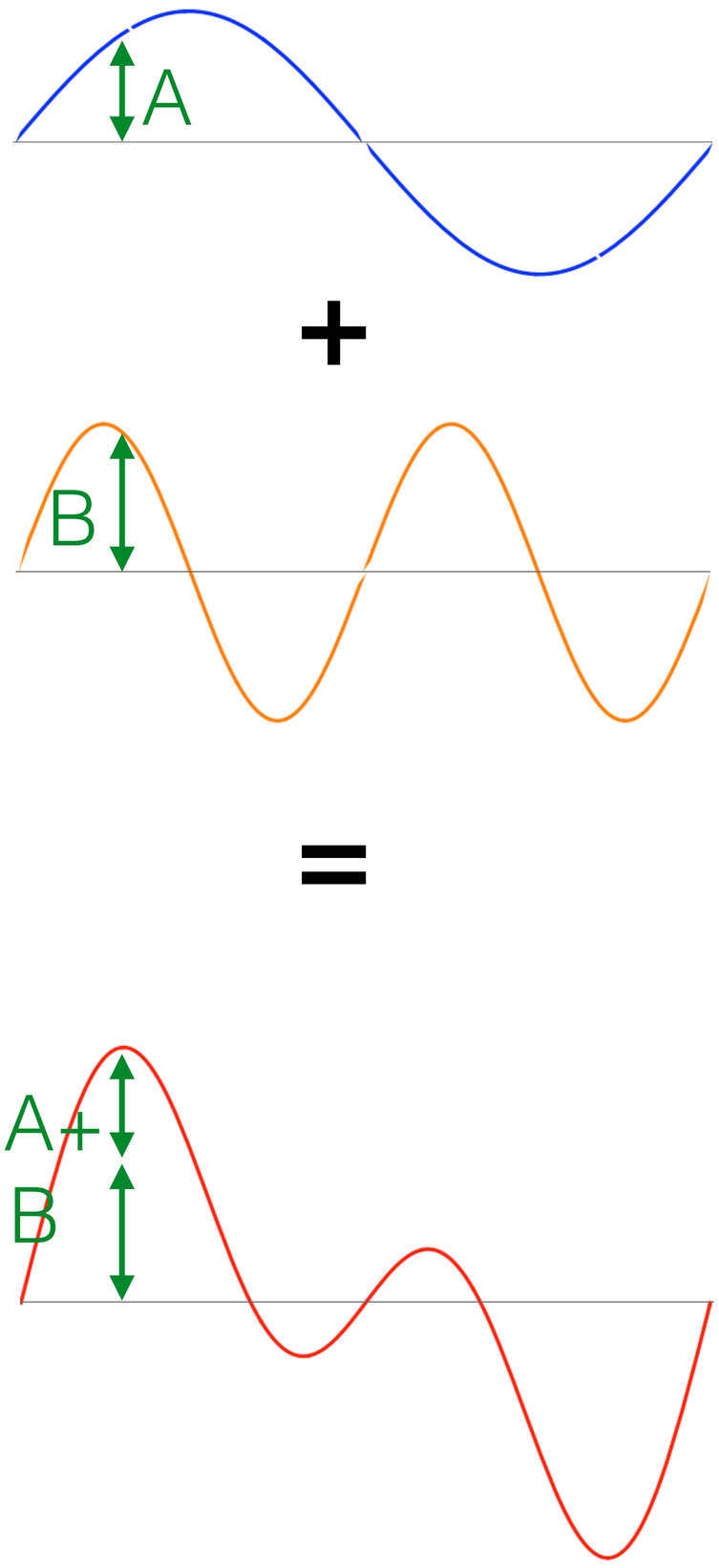
that's right

interference



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





for us, two kinds

traveling waves

the disturbance translates

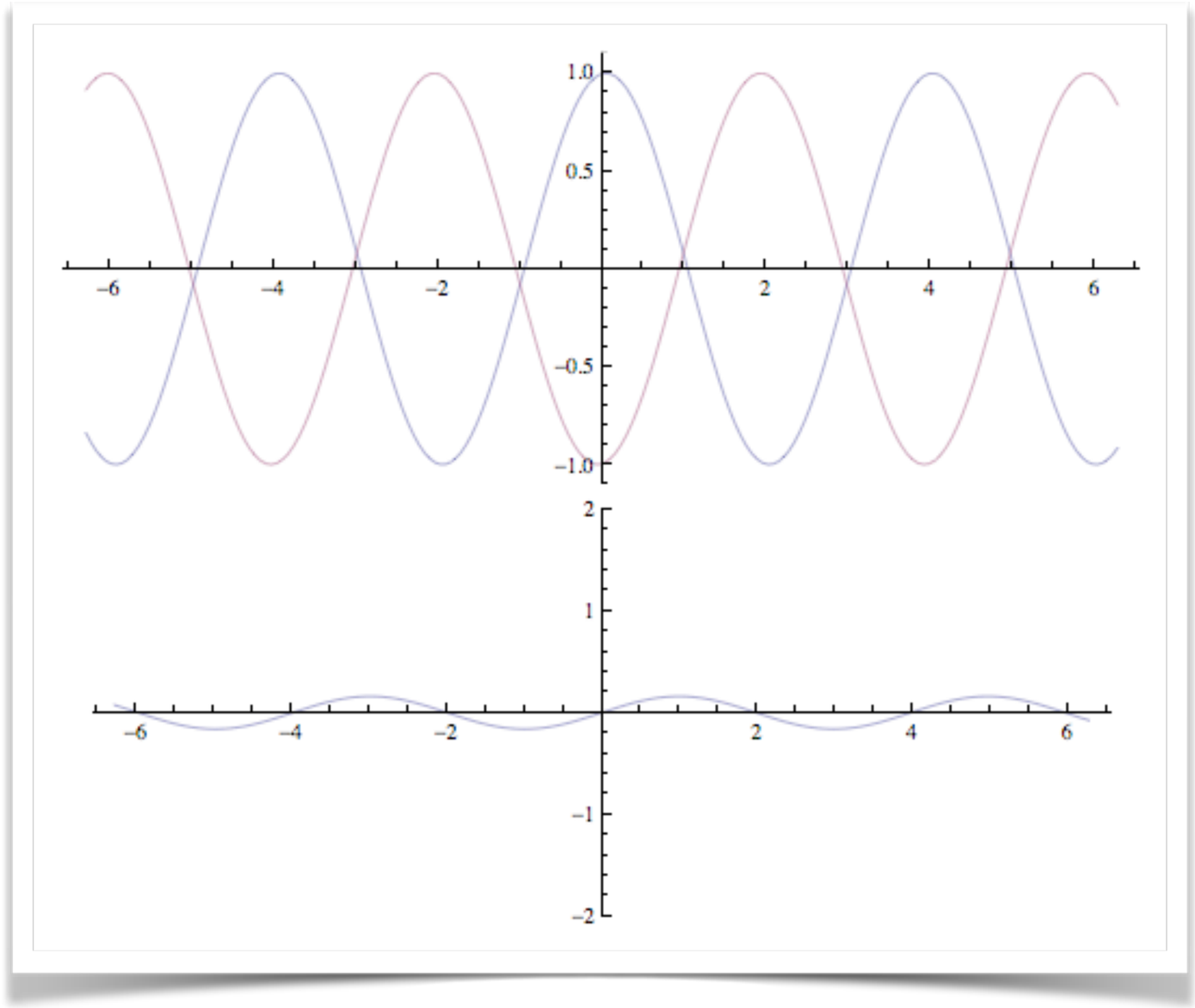
standing waves

the disturbance marches in place

Standing room only

"standing wave"

the sum of two traveling waves moving in opposite directions



Quantum Mechanics

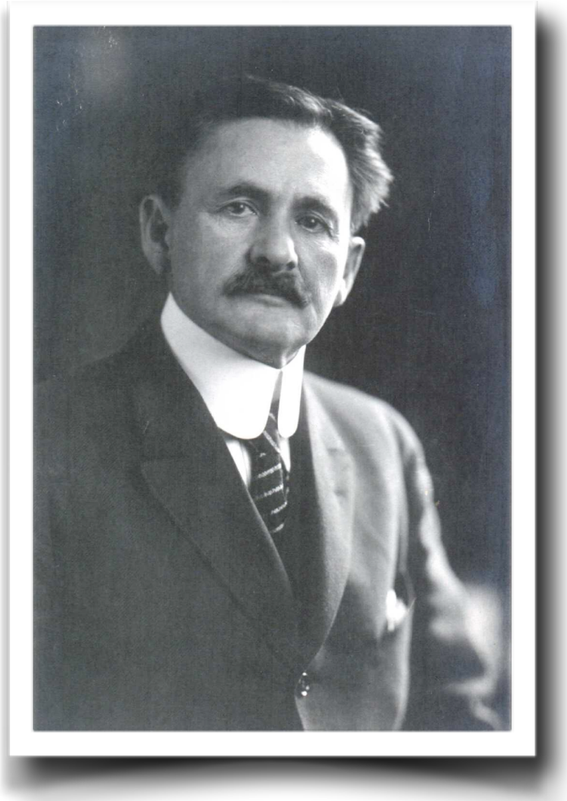
so...all tied up in a nice package, Mr Michelson?

notsomuch

we got matter falling apart in radioactivity

we got the Michelson Morley Experiment showing no Ether

we got Blackbody radiation all messed up



The more important fundamental laws and facts of physical science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote.

– A.A. Michelson
Light Waves and Their Uses (1903

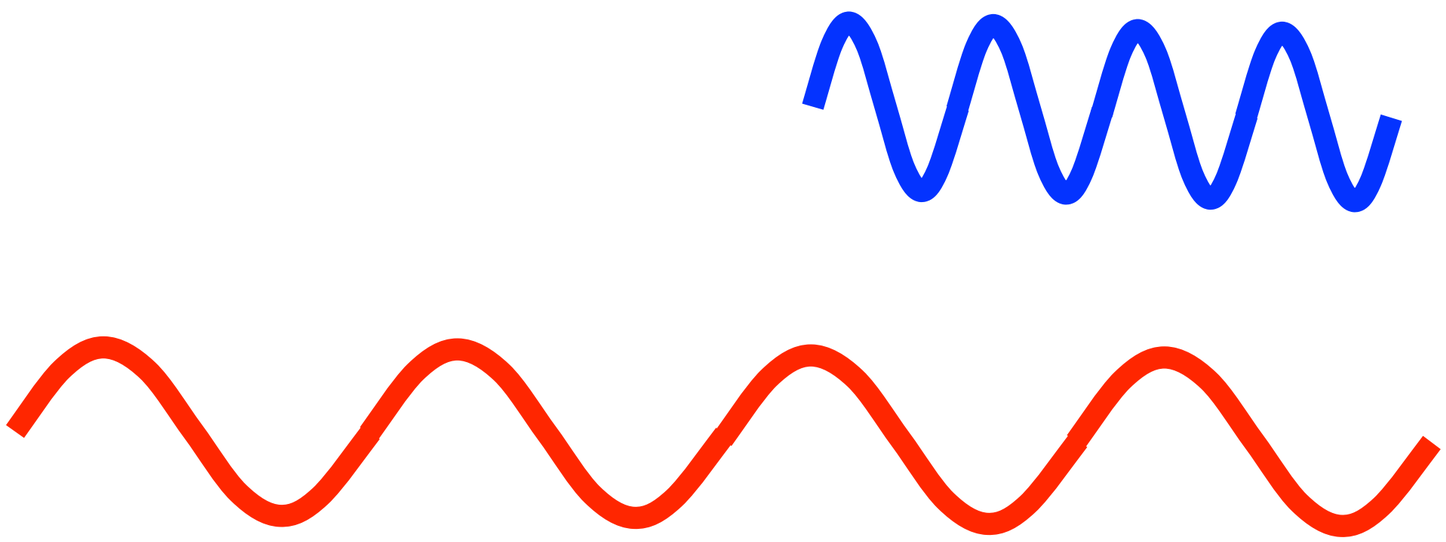
in the 1890's things were heating up

I mean, literally.

color = temperature

why?

Gassan Sadatoshi

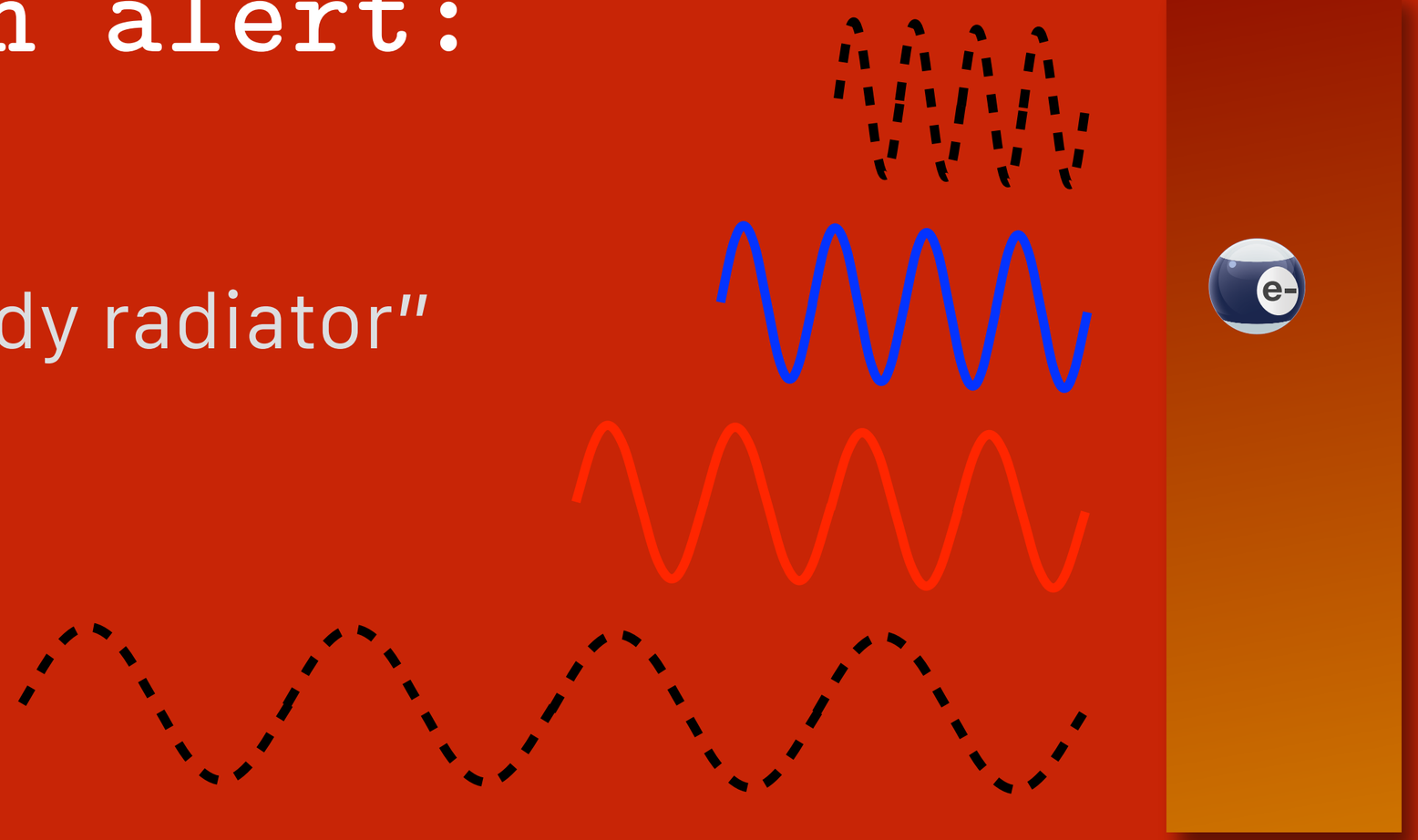


http://www.howstuffworks.com/sword-making.htm/printable

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:

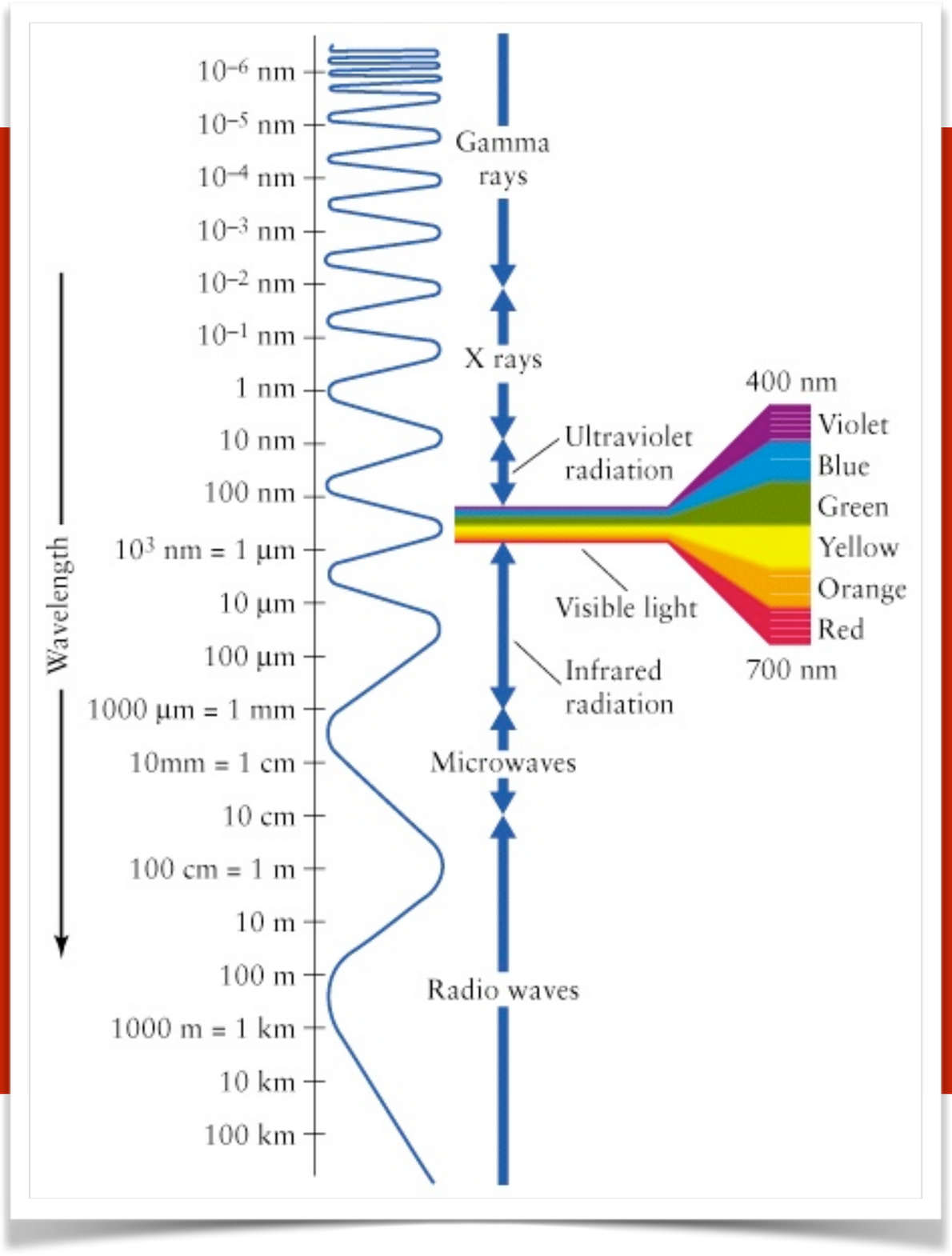
A cavity with a hole, a near-black object, a star...

everything radiates

everything.

Many objects approximate Blackbody radiators:

- stars
- you, me
- heated metal
- stuff...



temperature scales

water freezing - boiling - absolute zero

The US go-it-alone scale: Fahrenheit

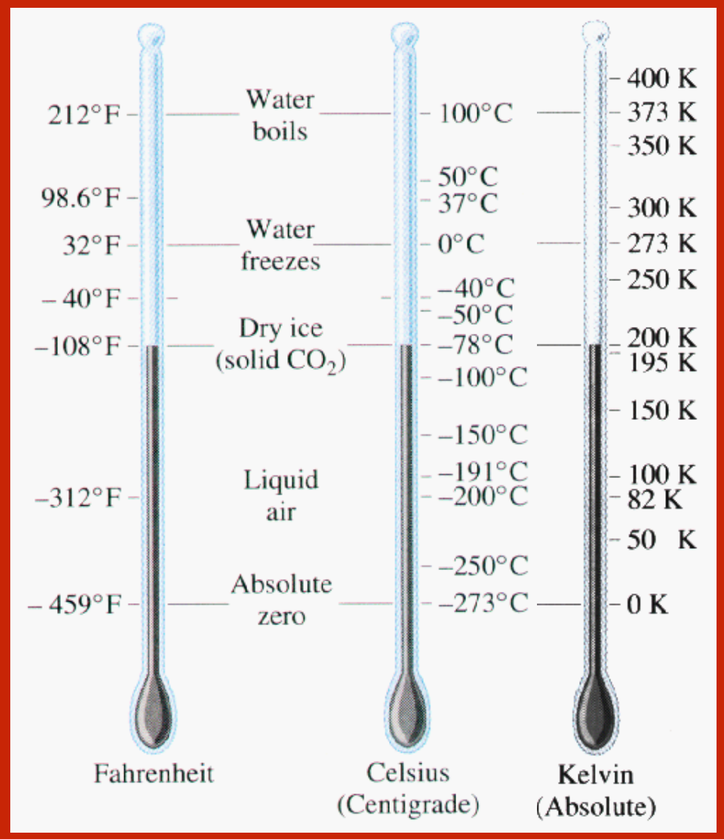
- (32°F - 212°F - —459°F)

The rest of the world: Celsius (or Centigrade)

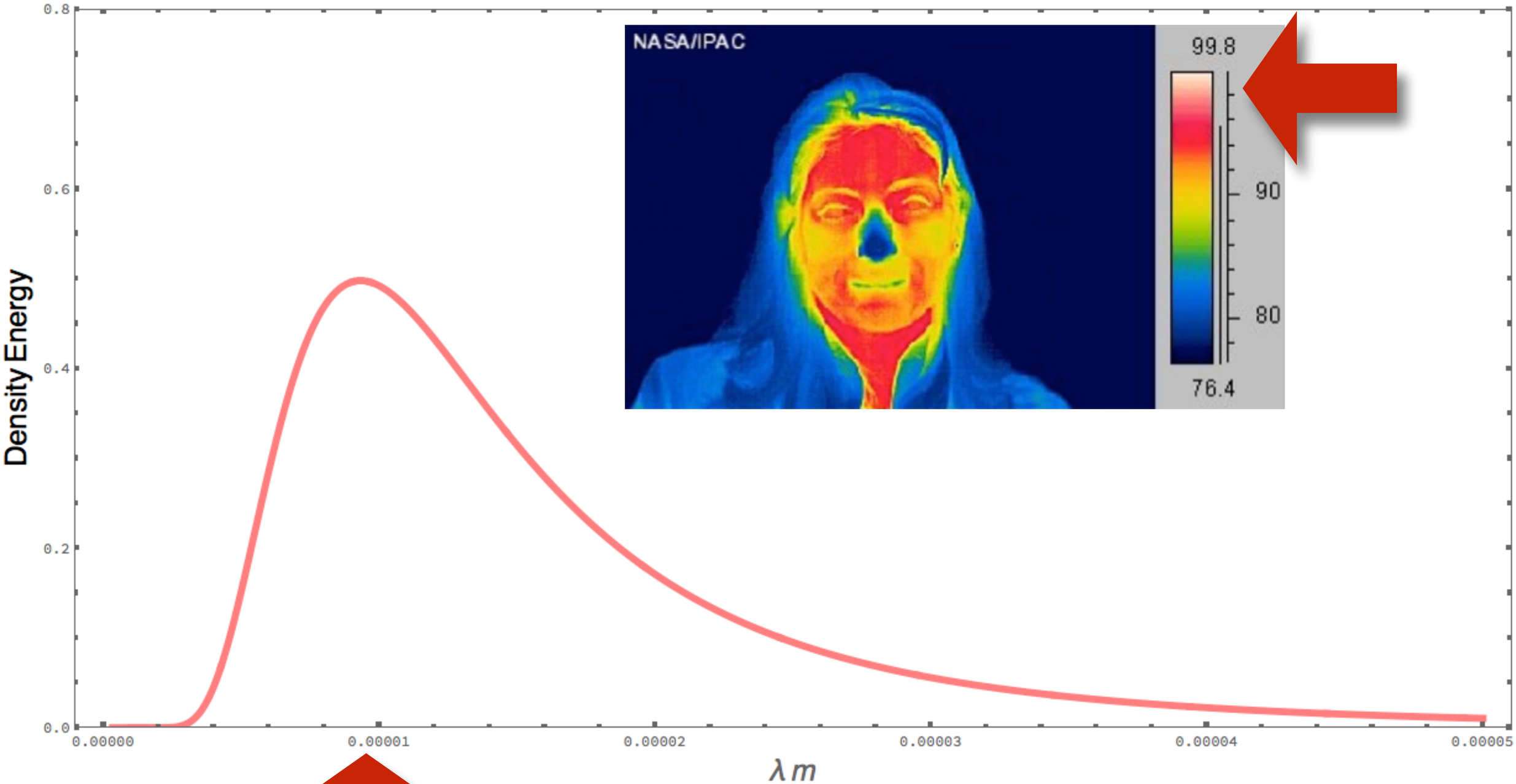
- (1°C - 100°C - —273°C)

The scientific community: Kelvin

- (273 K - 373 K - 0 K)

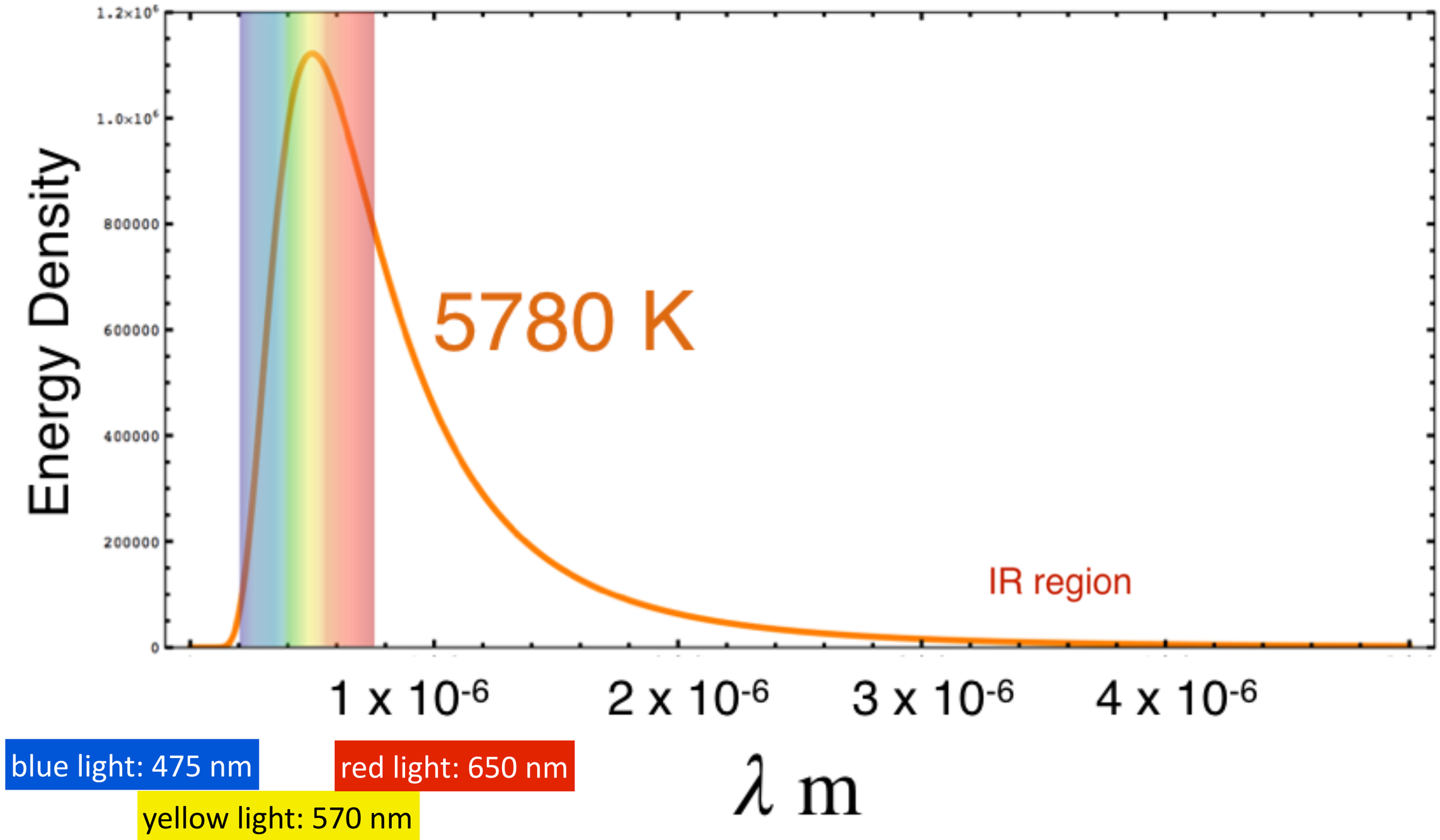


everything with a temperature radiates electromagnetic waves



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

sun

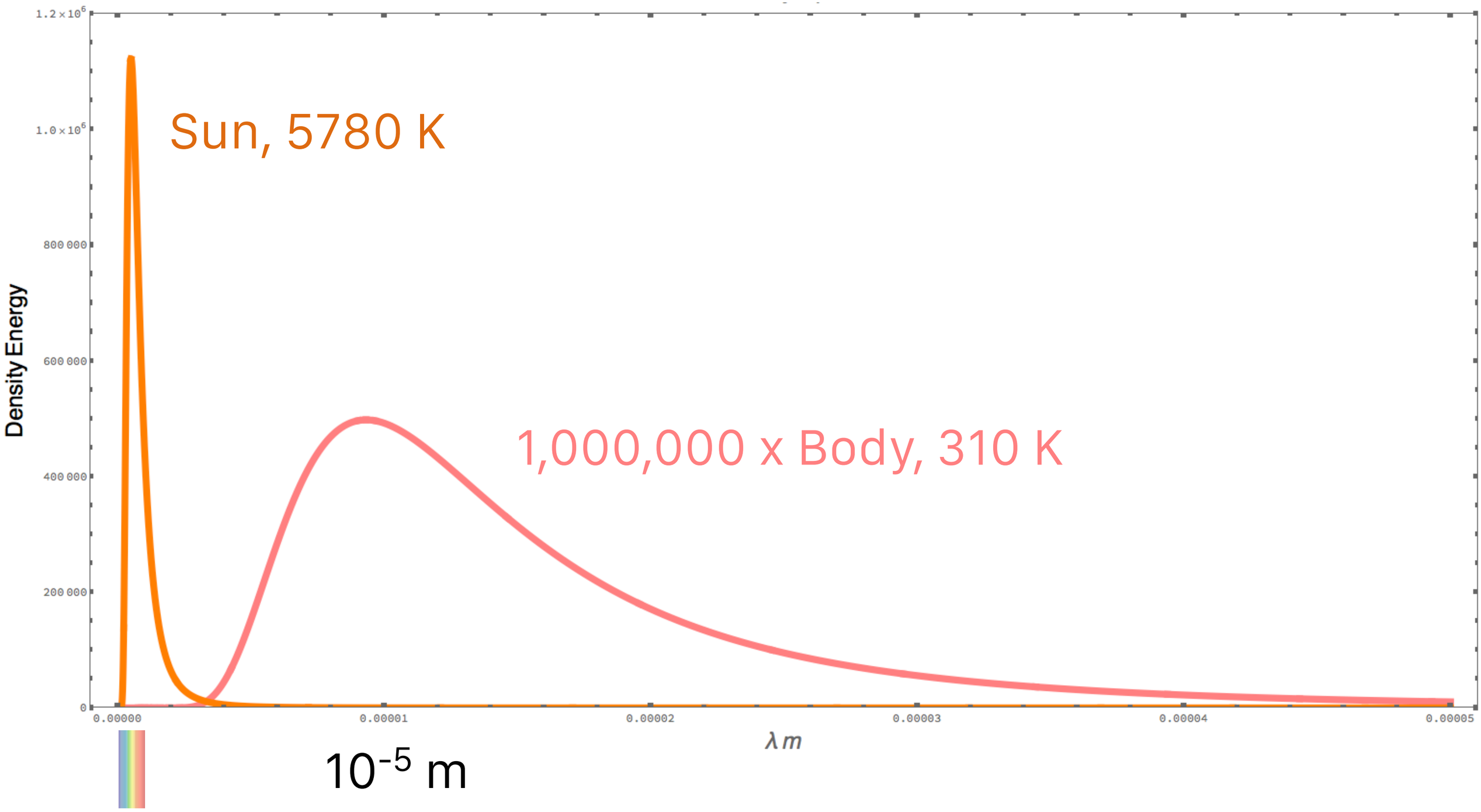


blue light: 475 nm

red light: 650 nm

yellow light: 570 nm

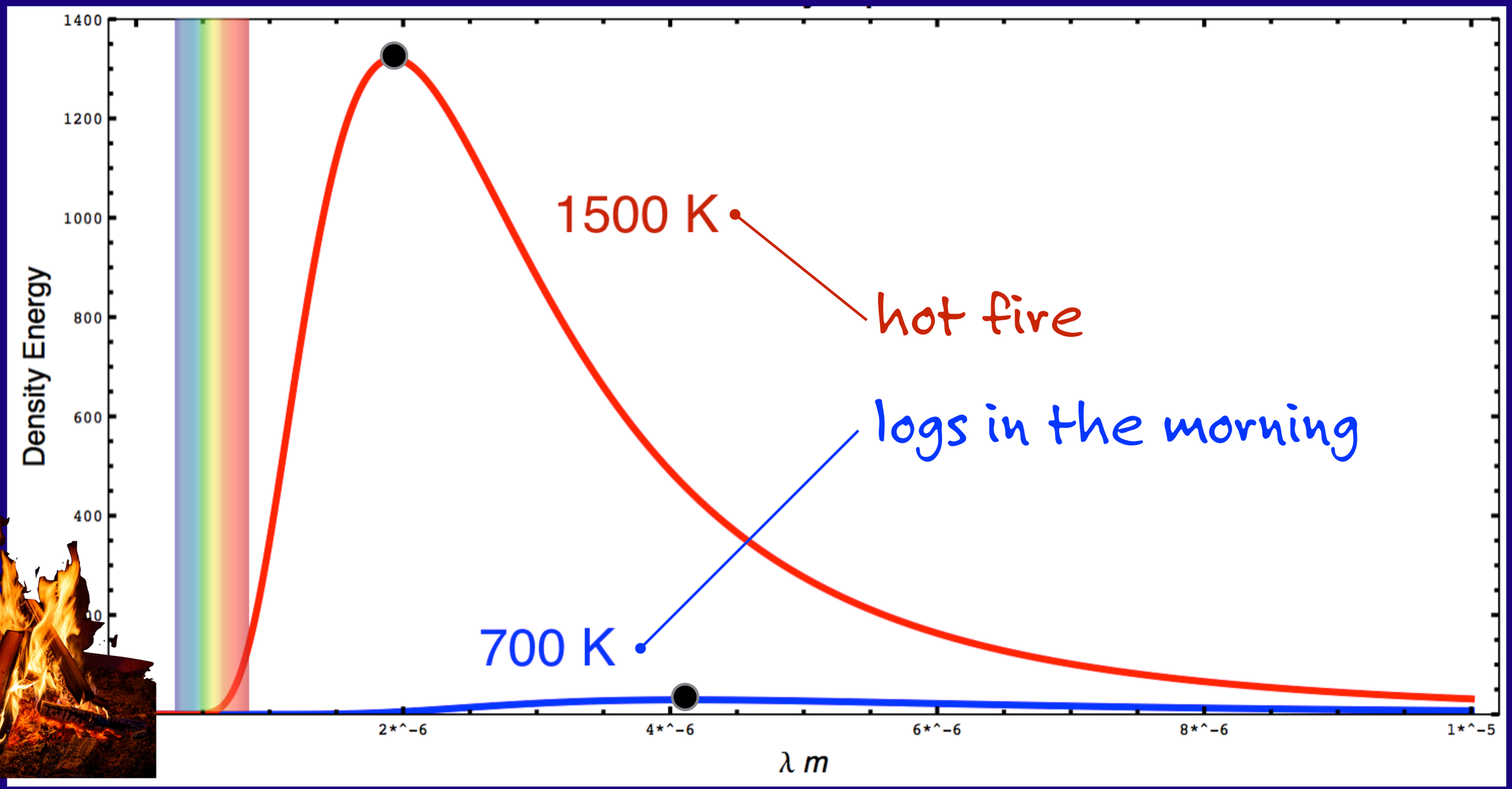
Sun’s warmth? notsomuch

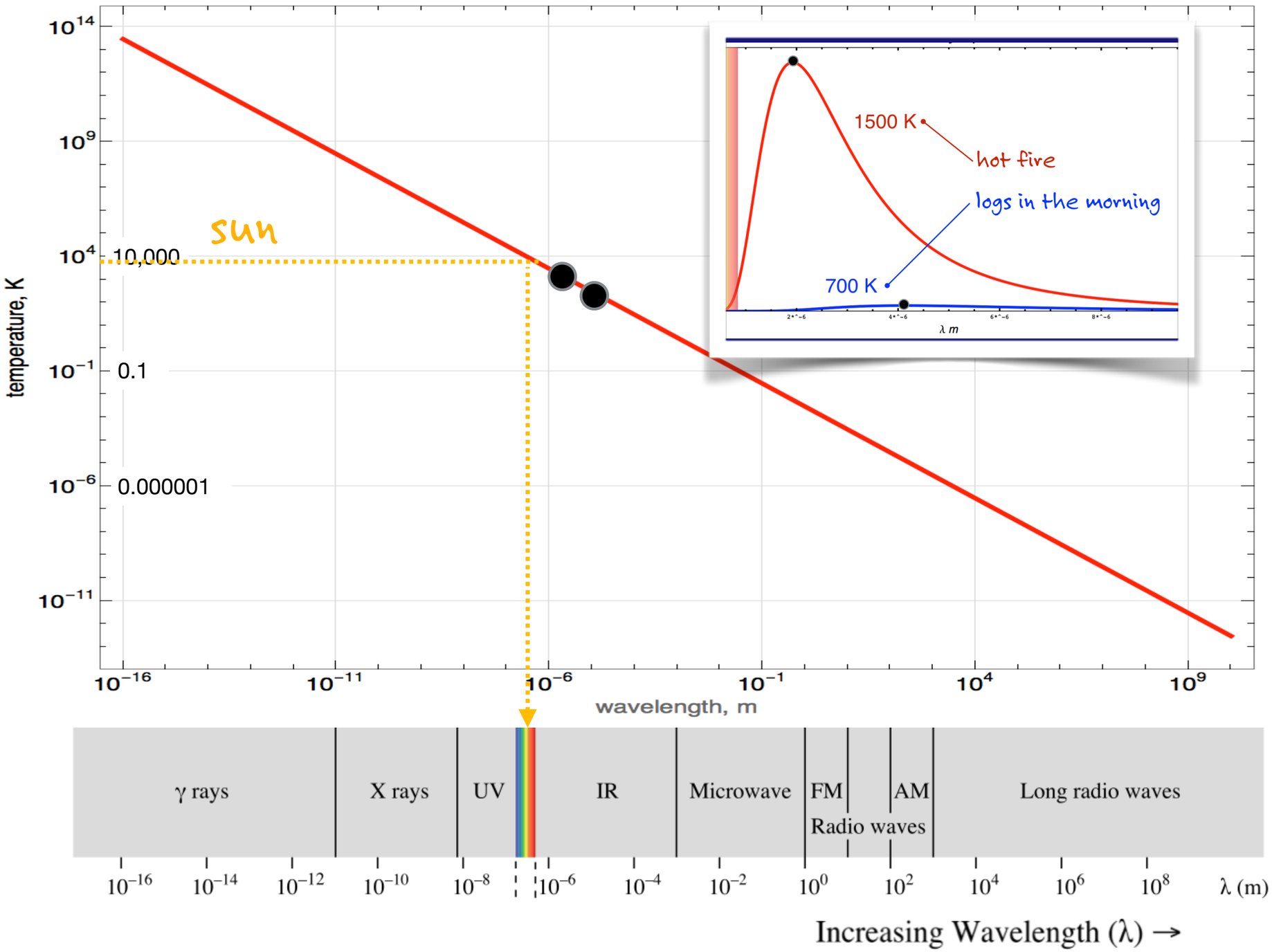


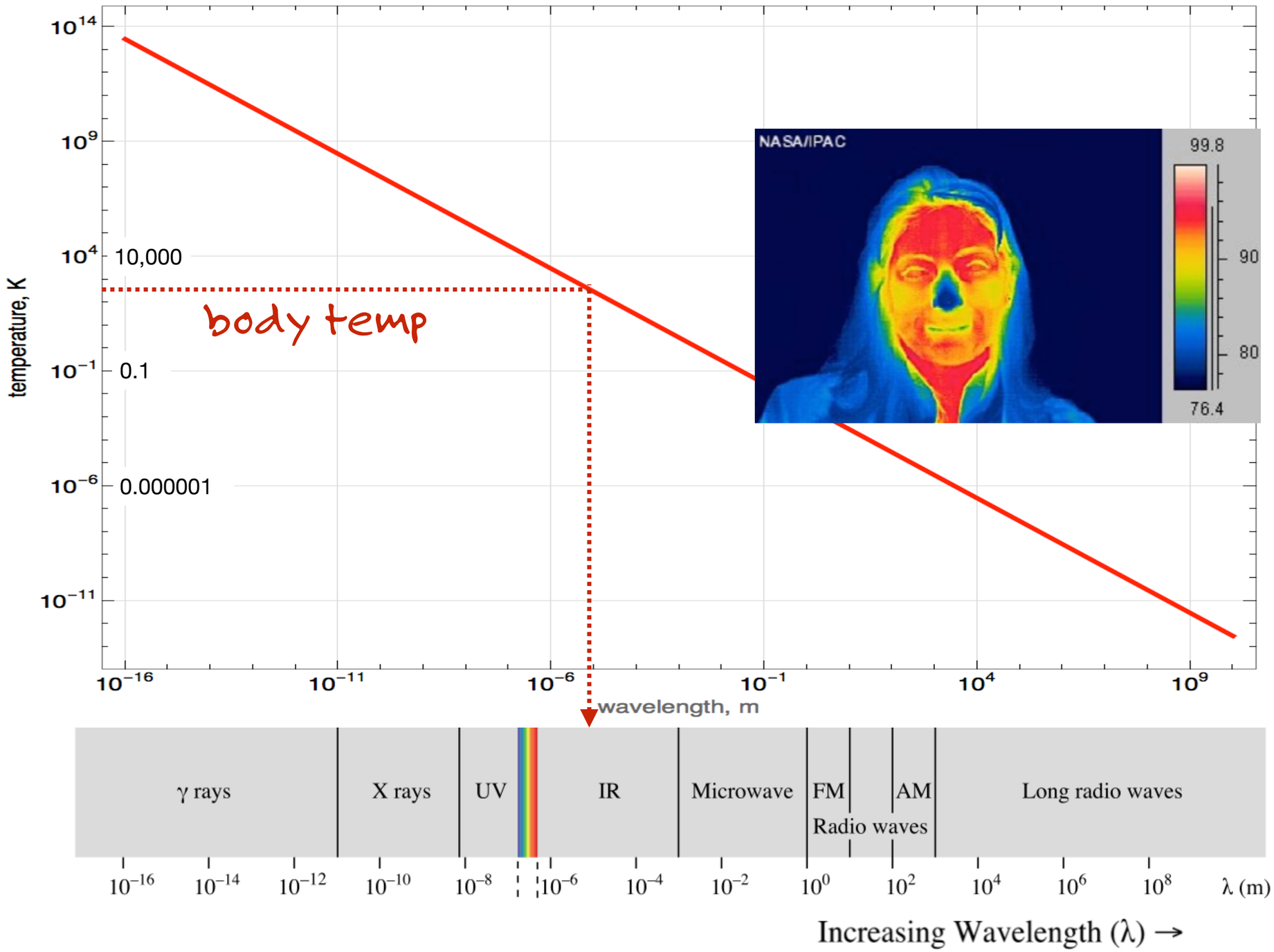
10^{-5} m

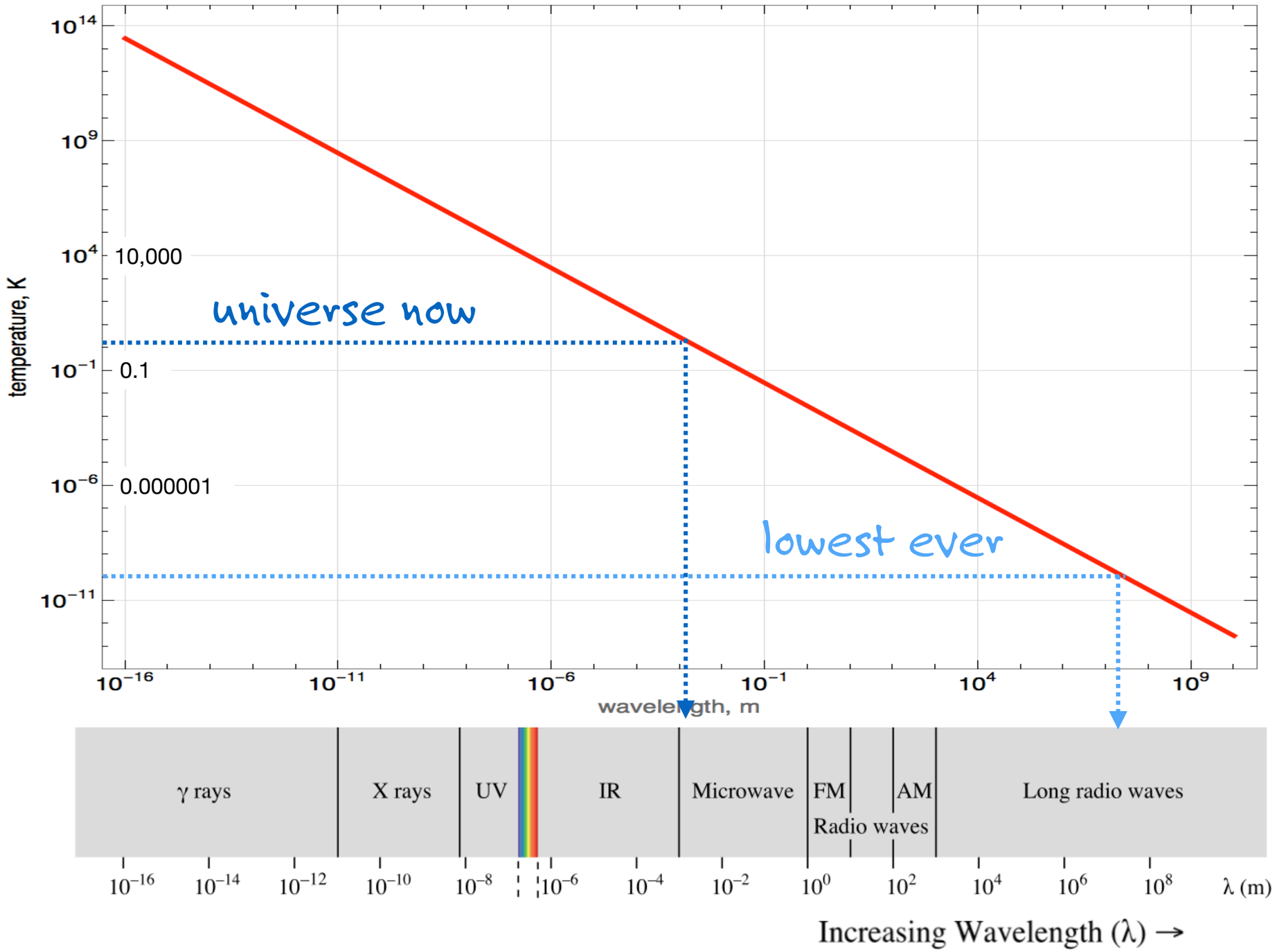
a range

of wavelengths for each temperature




temperature, K
10^{14}
10^{9}
10^{4}
10,000
10^{-1}
0.1
10^{-6}
0.000001
10^{-11}
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) →


temperature, K
10^{14}
10^{9}
10^{4}
10,000
body temp
10^{-1}
0.1
10^{-6}
0.000001
10^{-11}
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^{14}
10^{9}
10^{4}
10,000
universe now
10^{-1}
0.1
10^{-6}
0.000001
lowest ever
10^{-11}
10^{-16}
10^{-11}
10^{-6}
10^{-1}
10^{4}
10^{9}
wavelength, 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) →

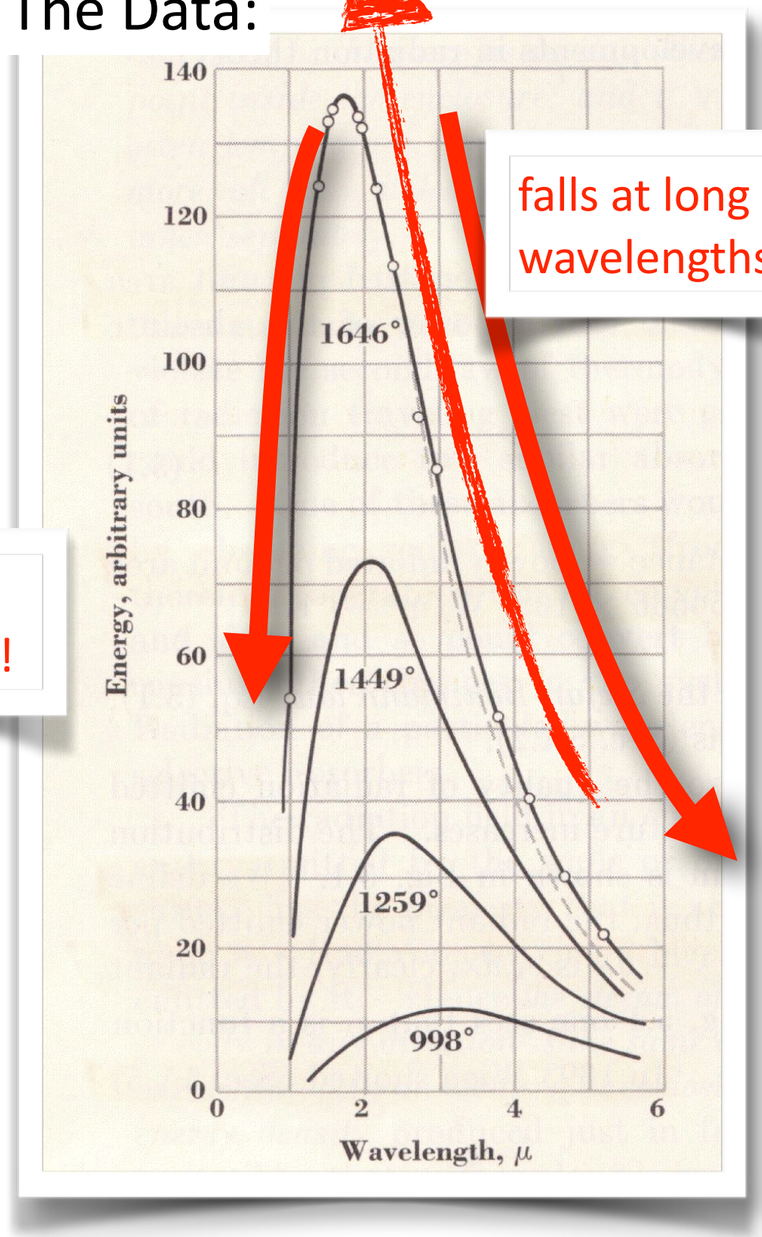
what would Maxwell's theory say?

nonsense.

a major problem.

imagine a cavity with radiation inside

The Data:

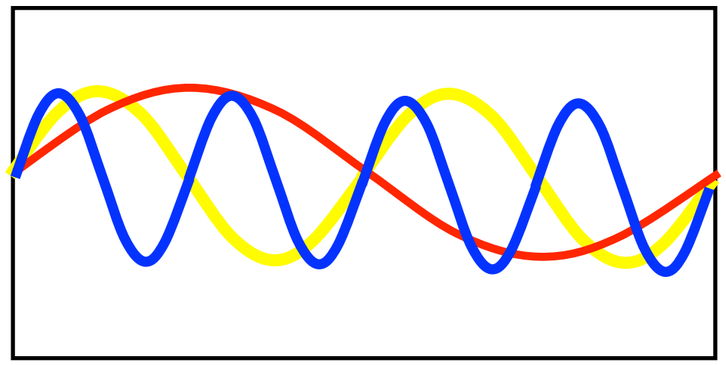


falls at short wavelengths!

falls at long wavelengths

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?

Heat seems to be related to Electromagnetism...independent of the material.

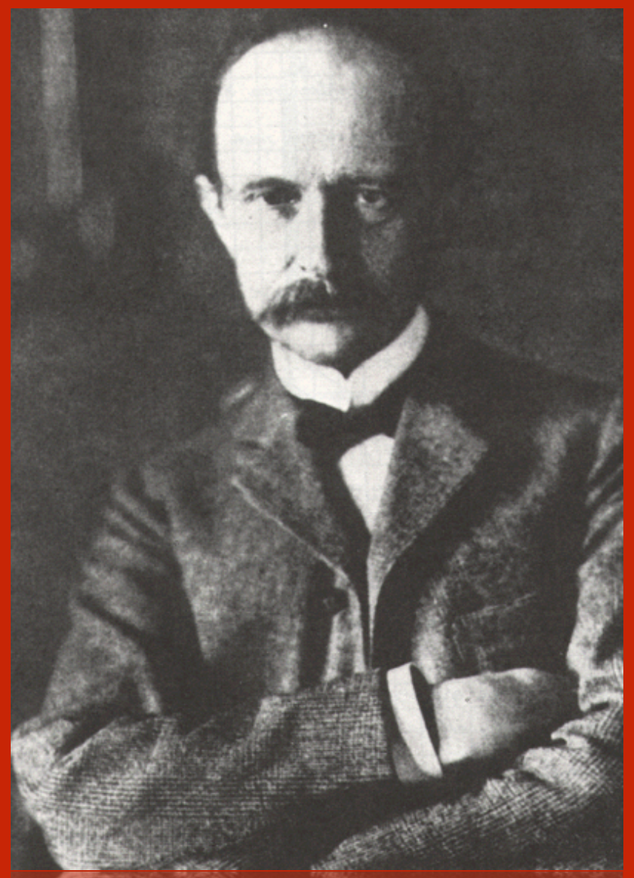
Why?

Was a major late 19th century question.

the solution to heat radiation

came in 1900

and then expanded in 1905



Max Planck
1858-1947

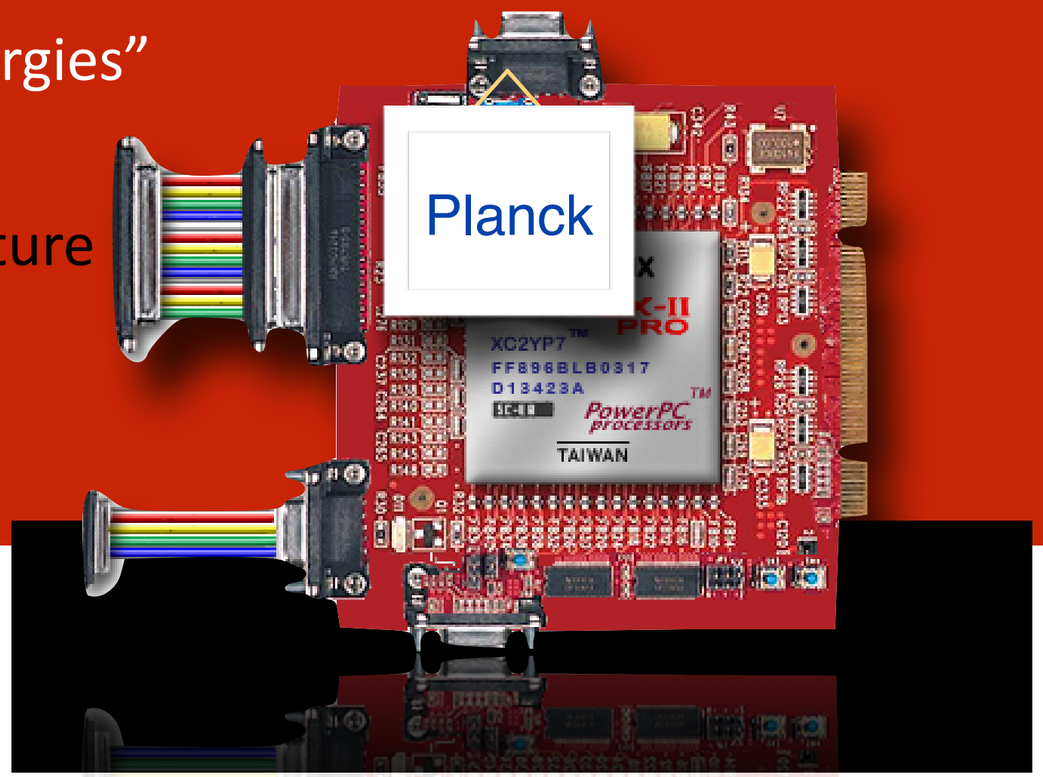
one of the good guys

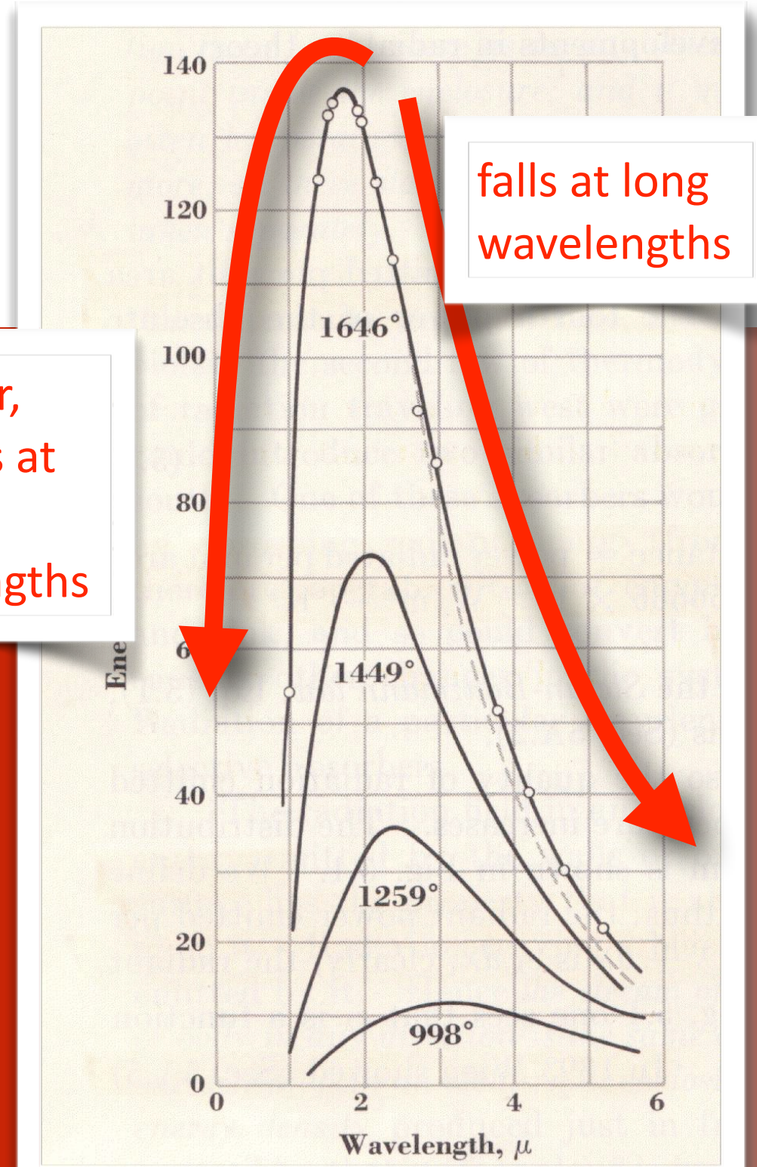
Planck could only get a solution

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"

Before Planck:

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

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

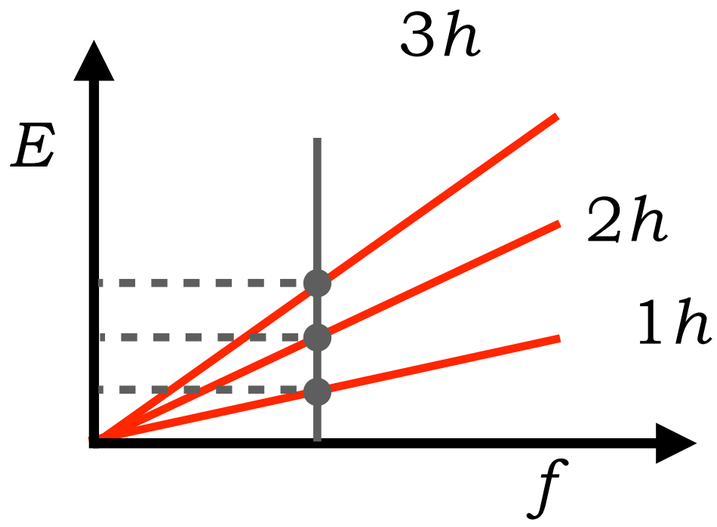
2 "E's" going on...this one's **Electric Field** vector

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: $h = 6.62606896(33)\times10^{-34}$ 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

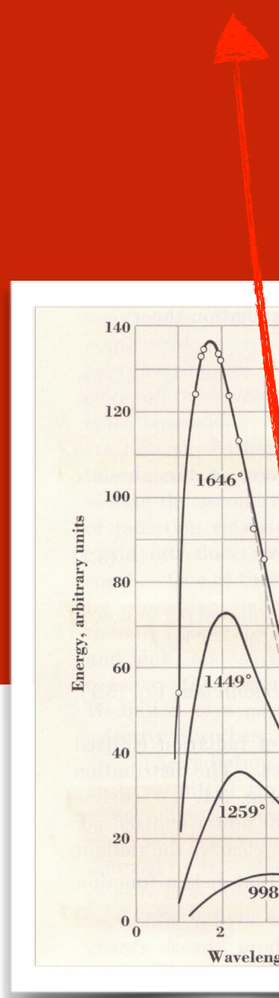
it’s as if

no matter how hard you pump

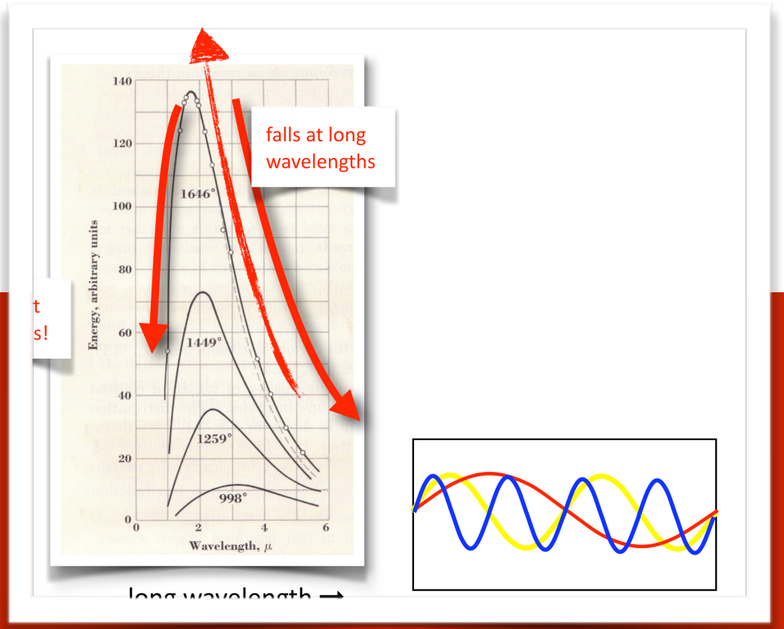
your amplitude is choppy

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”



a maximum E, depending on temperature

Energy

classically,
all frequencies are probable

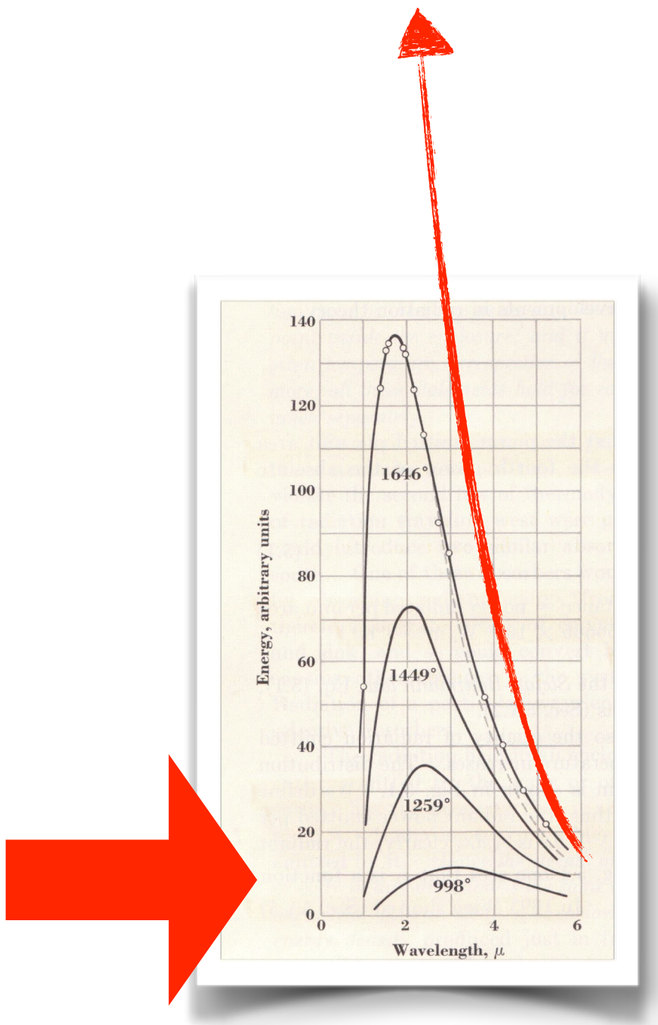
frequency

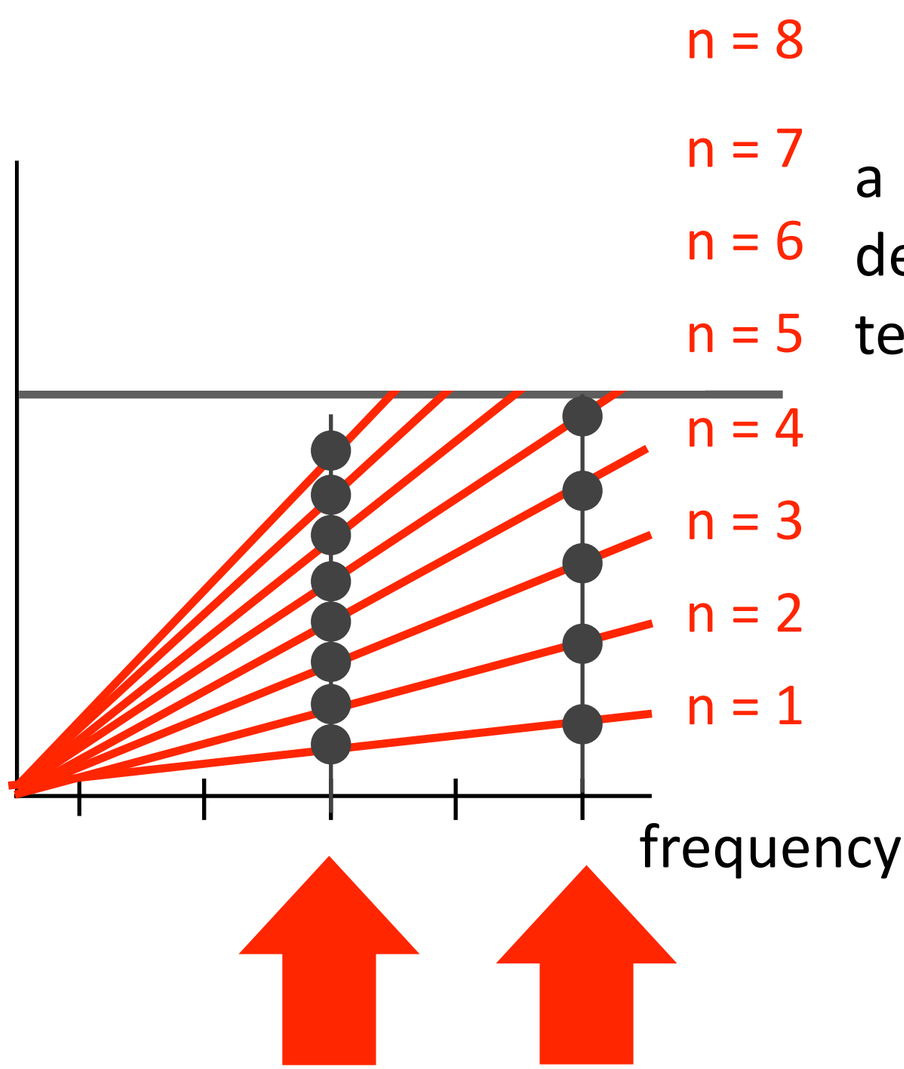
the lack of light at the short wavelengths

= high frequencies?

But, for Planck:

$$E = nhf$$





a maximum E, depending on temperature

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

each quantum has more energy...but there are fewer of them.

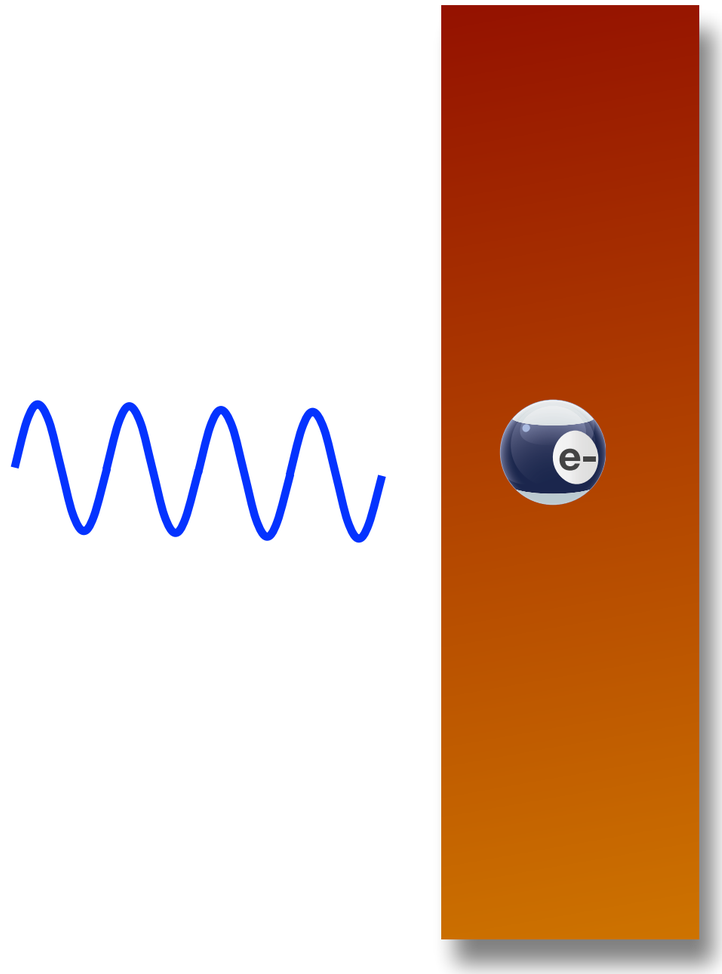
for Planck

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!

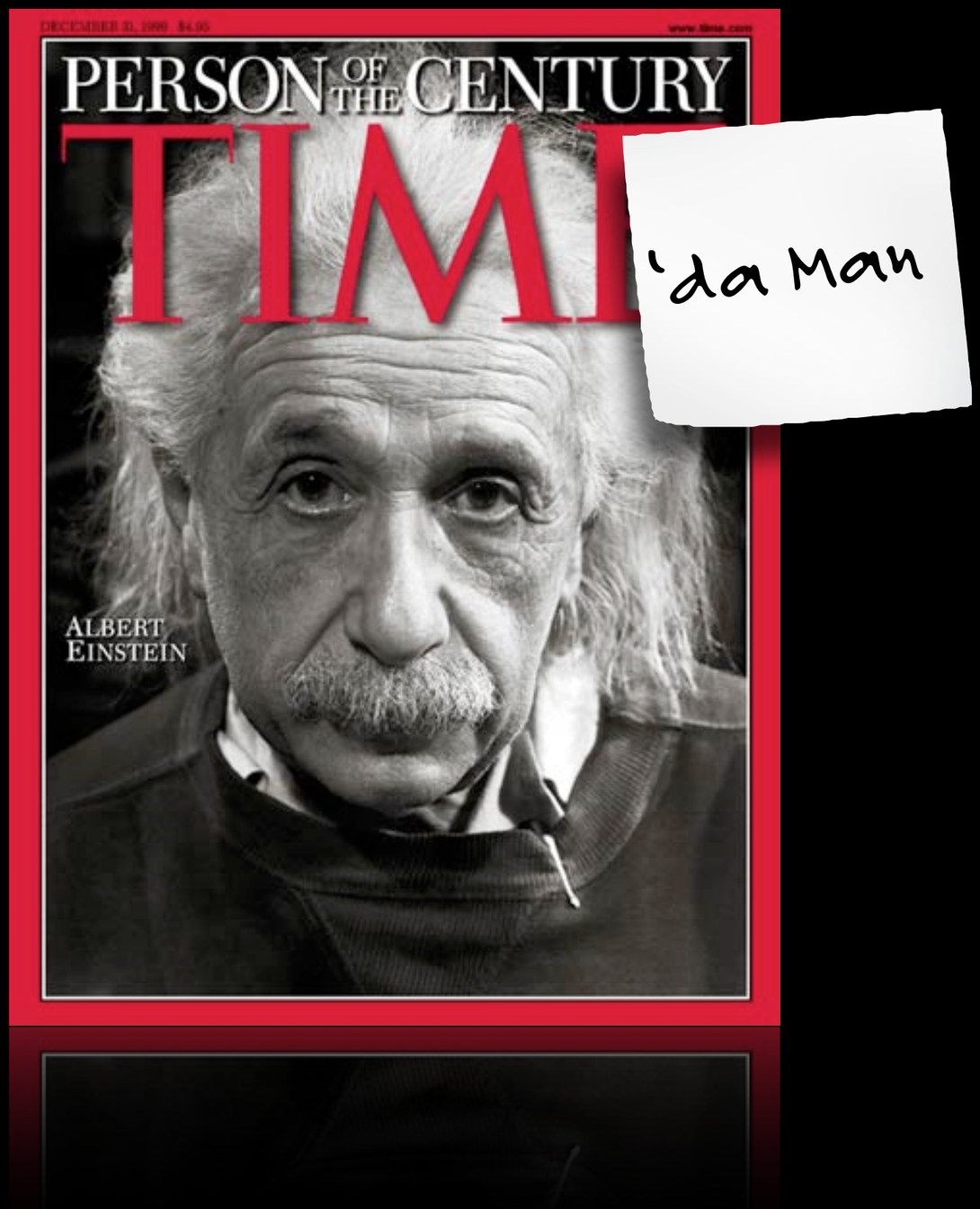
perfect analogy

sound

piano

sound can be any frequency
piano can produce only particular frequencies

Not a statement about sound!
A statement about pianos!



'da Man

He's Back

perfect analogy

sound

piano

sound can be any frequency

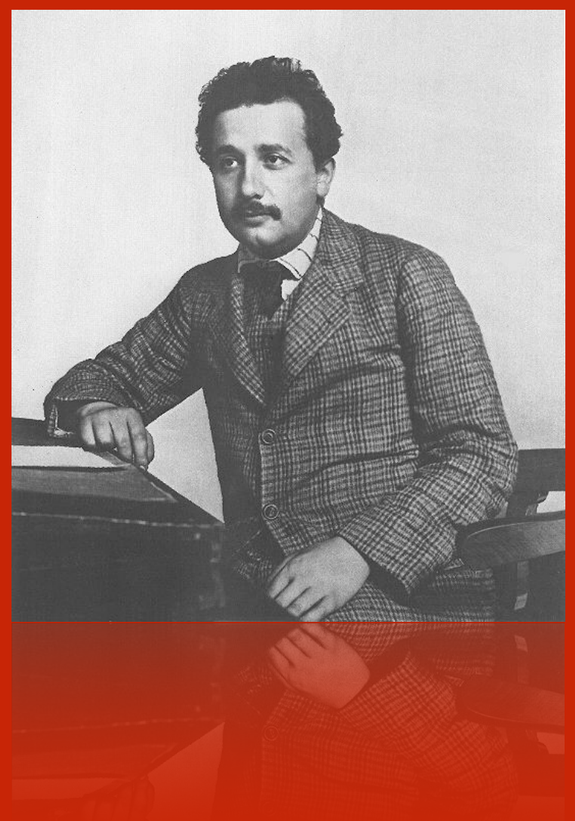
piano can produce only particular frequencies

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

It is a statement about light (electromagnetism)

Light is itself "quantized"

....as particles:

these particles are called:

"photons," γ

they have no mass

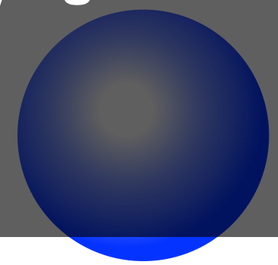
hold the phone.

A wave is EVERYWHERE

& light is a wave!

How could things so opposite be combined into one reality?

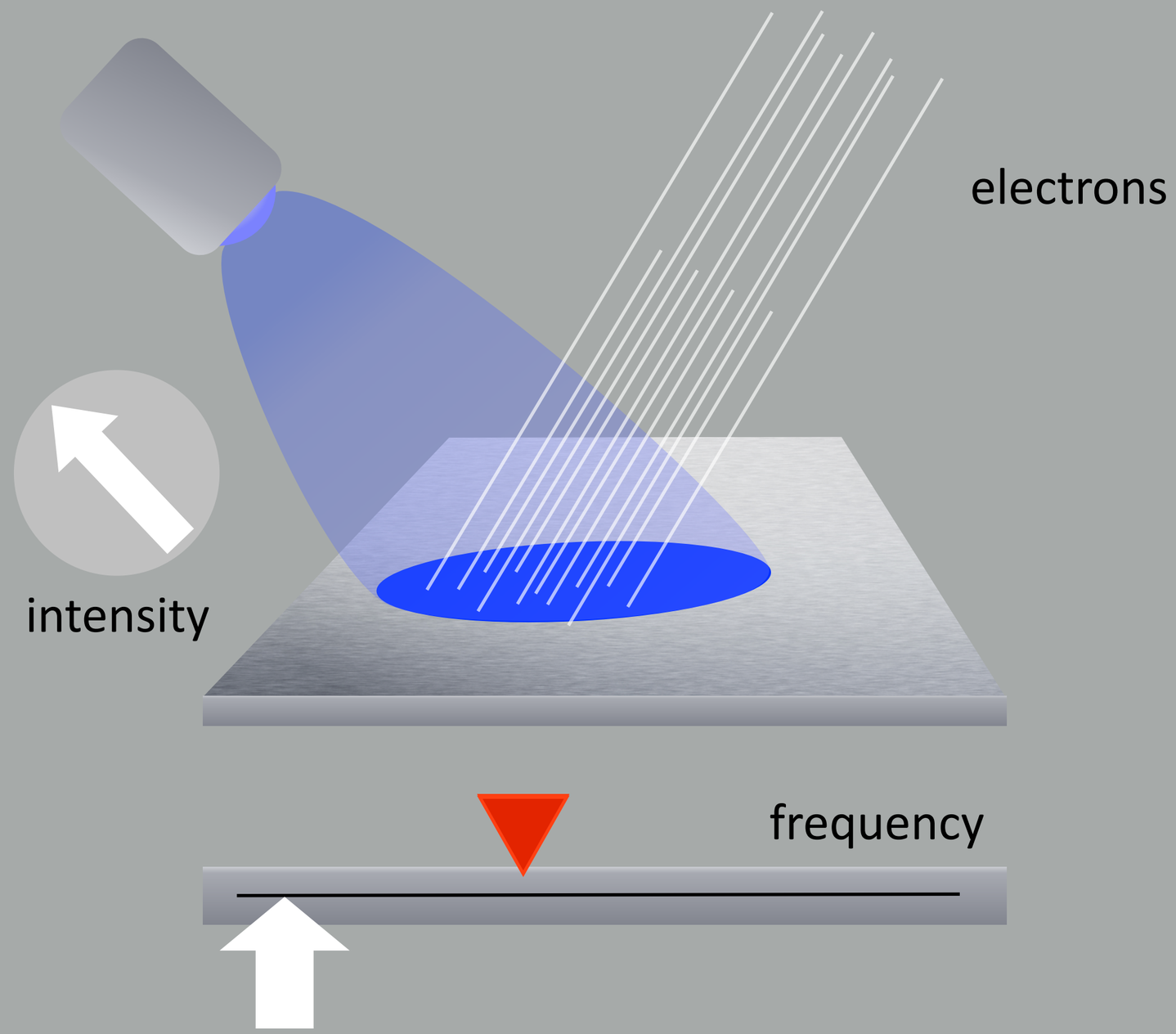
A particle is HERE:



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 <u>until a particular frequency</u> *then, with higher frequency they come out with more energy*	huh?
2. raise the intensity...get <u>more</u> electrons	expect <u>higher energy</u> electrons

Using Planck's formula

E = hf

it makes sense.

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

The intensity is just more and more photons kicking more and more electrons

photoelectric effect

everywhere:

photodiodes

smoke detectors, CD players, remote controls...

photocells

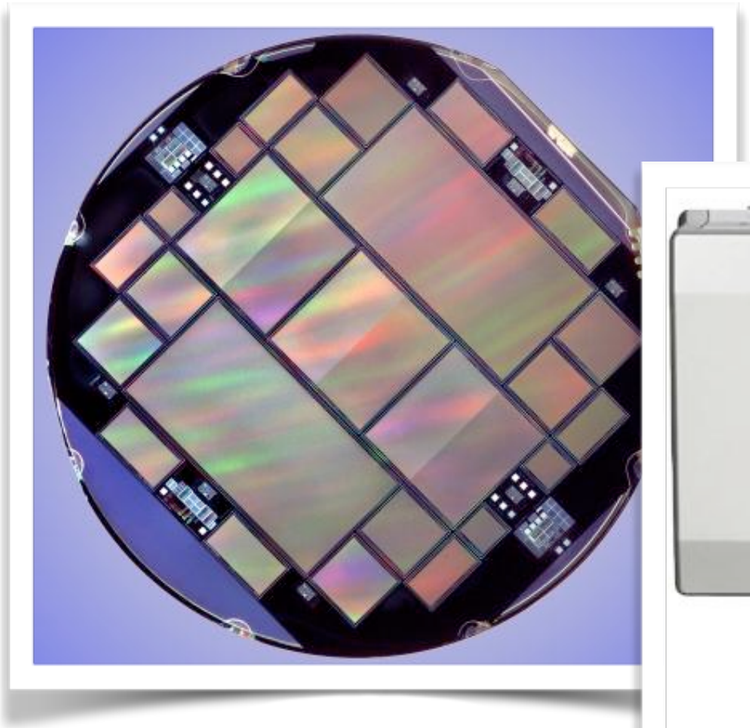
packed into "pixels" and arrays of pixels:

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

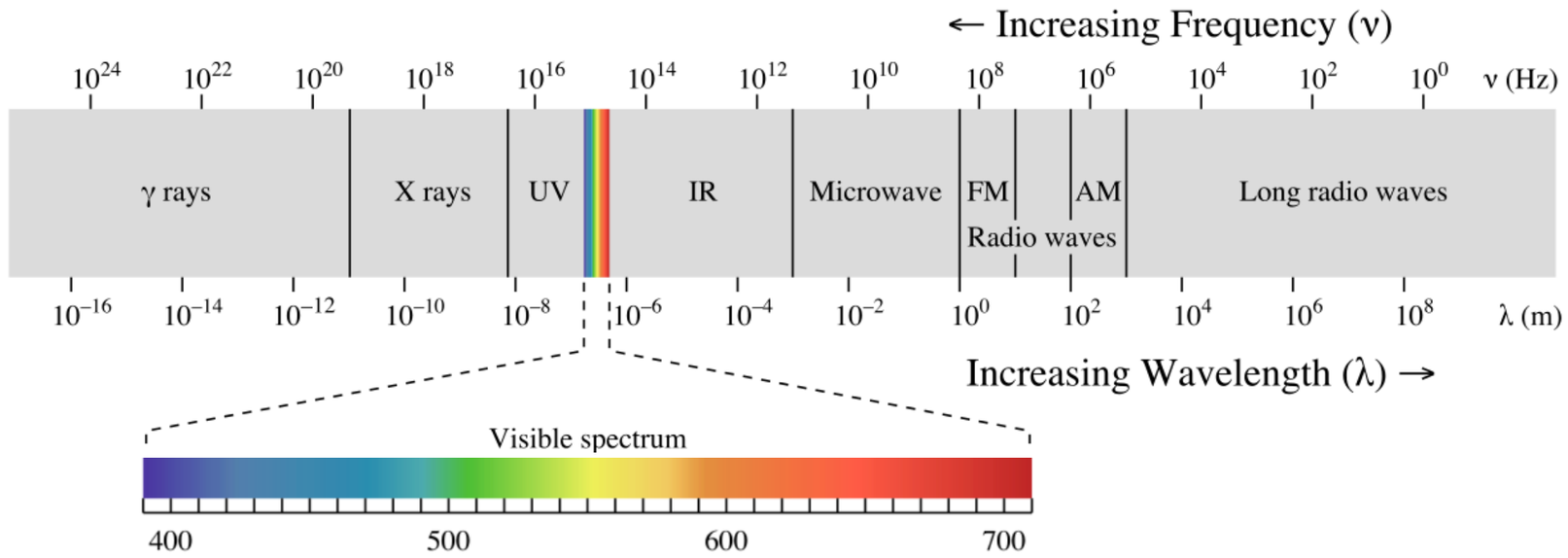
$$E = hf$$

the higher the frequency

the higher the energy

the lower the energy

the lower the frequency



remember about waves: $v = \lambda f$

$$f = \frac{v = c}{\lambda}$$ for light

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

the larger the wavelength

the smaller the energy

the larger the energy

the smaller the wavelength

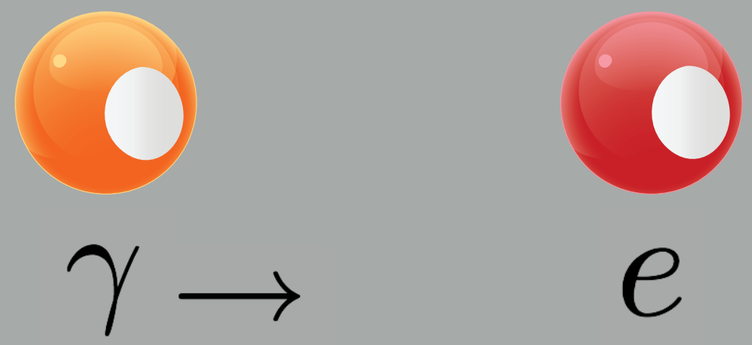
Einstein made a prediction: treat light like billiard-balls

and cause collisions

like particles

the photon loses energy γ

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



$\gamma \rightarrow$ e

the electron gains energy e

this seals the deal

"Compton Effect"

measured in 1923

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

longer wavelength - lower energy

E_A

E_B

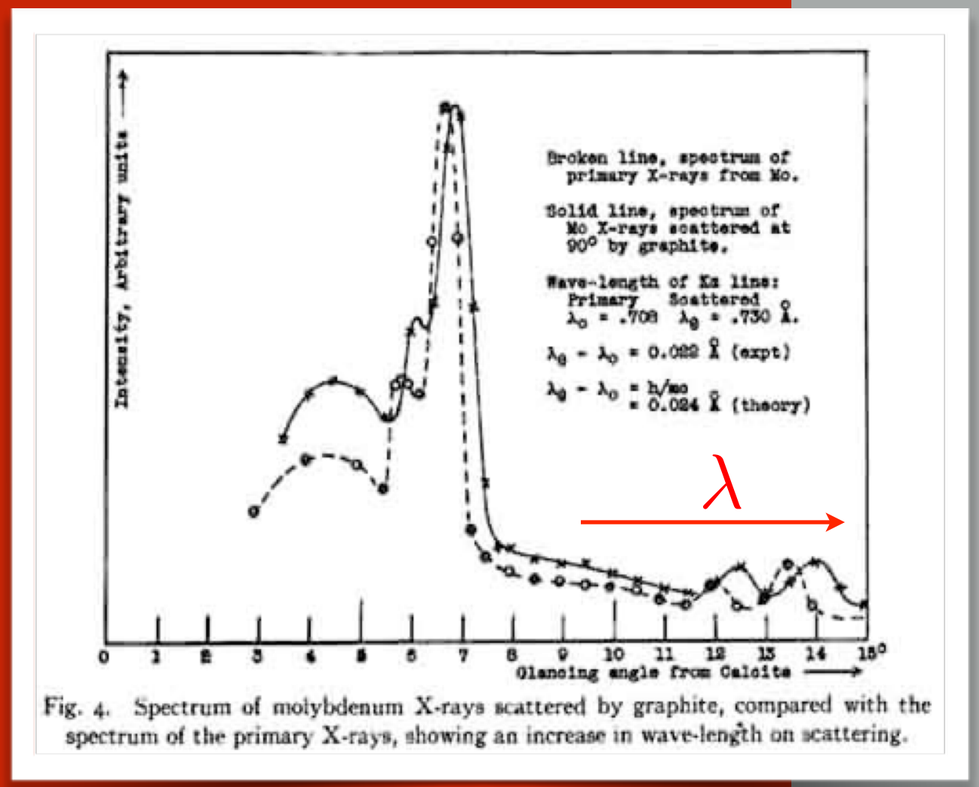


Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

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

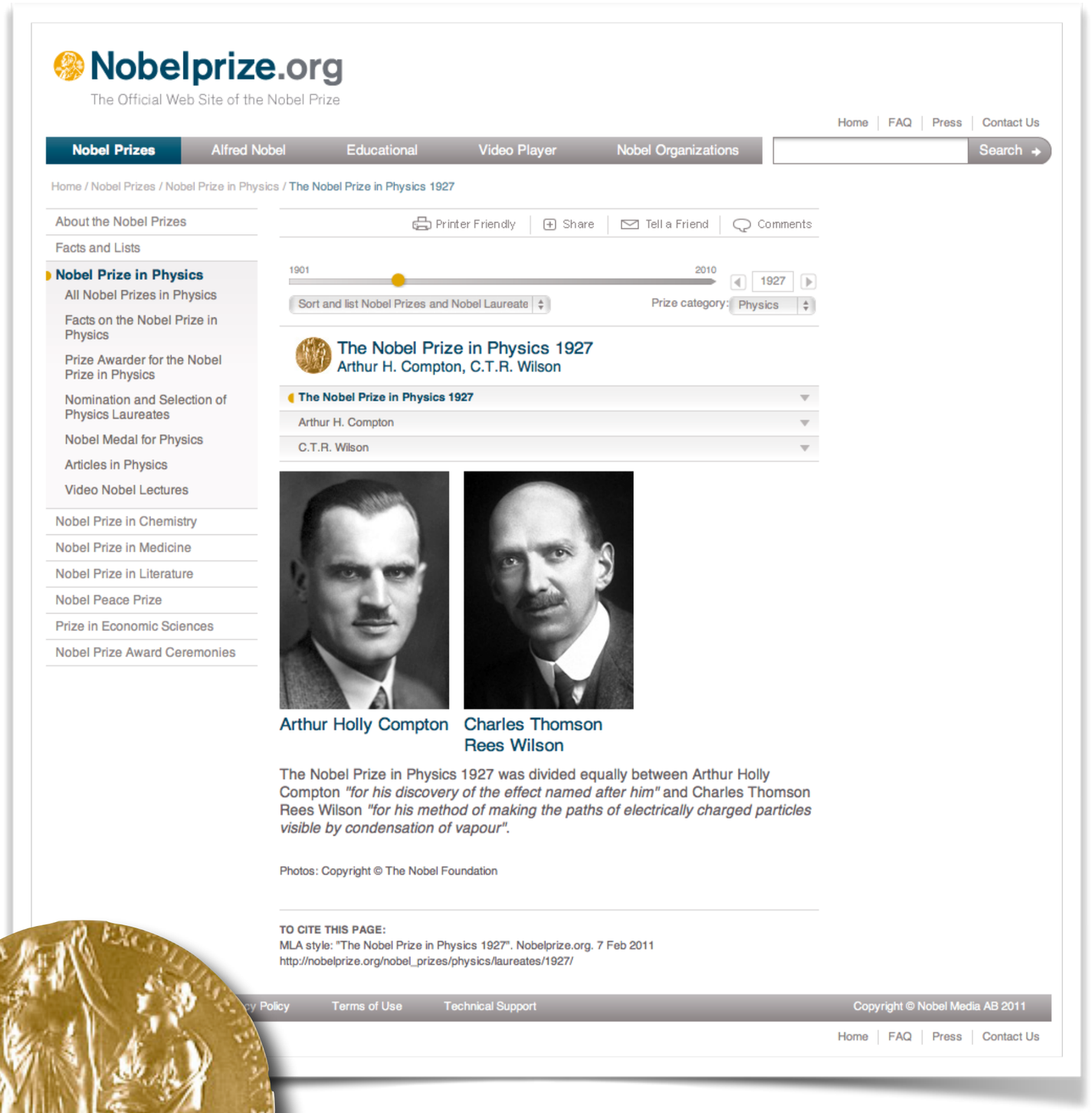
Called: Compton Scattering

E_A should be < E_B so $\lambda_A > \lambda_B$

‘‘Compy’’

I played with his grandson as a kid

which I find absolutely bizarre



our second elementary particle, 1923

the photon (aka “gamma”)

γ

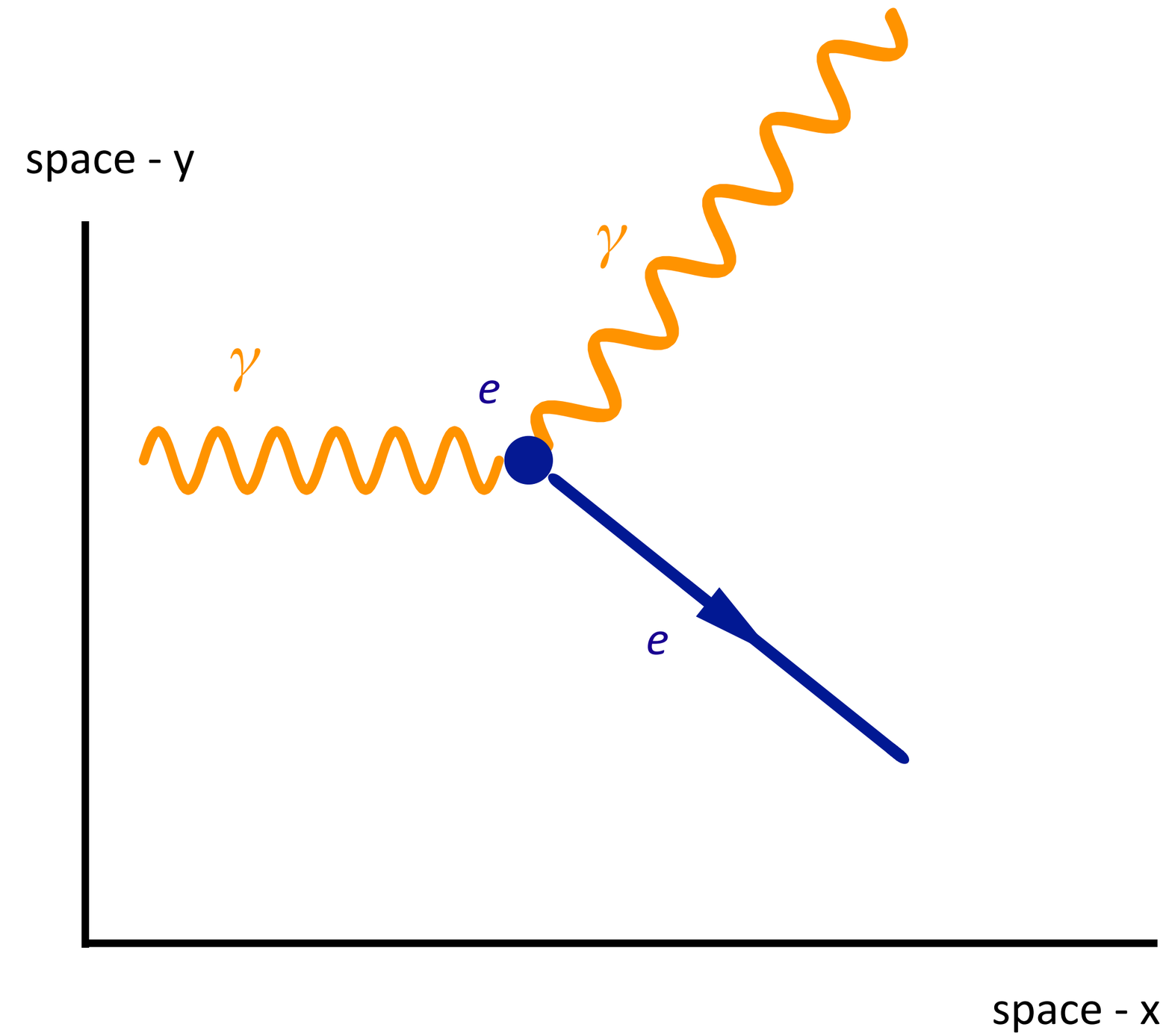
massless

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

Compton scattering

Space diagram

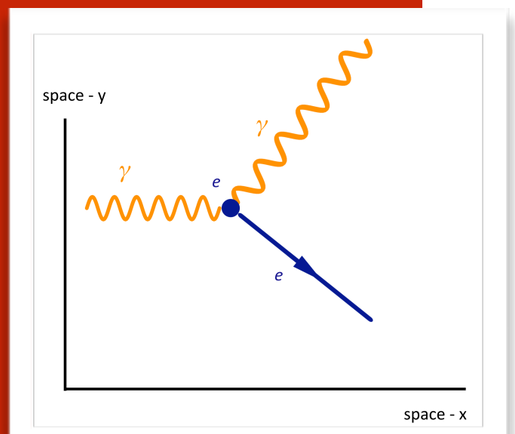
$$\gamma + e \rightarrow \gamma' + e'$$



Compton scattering

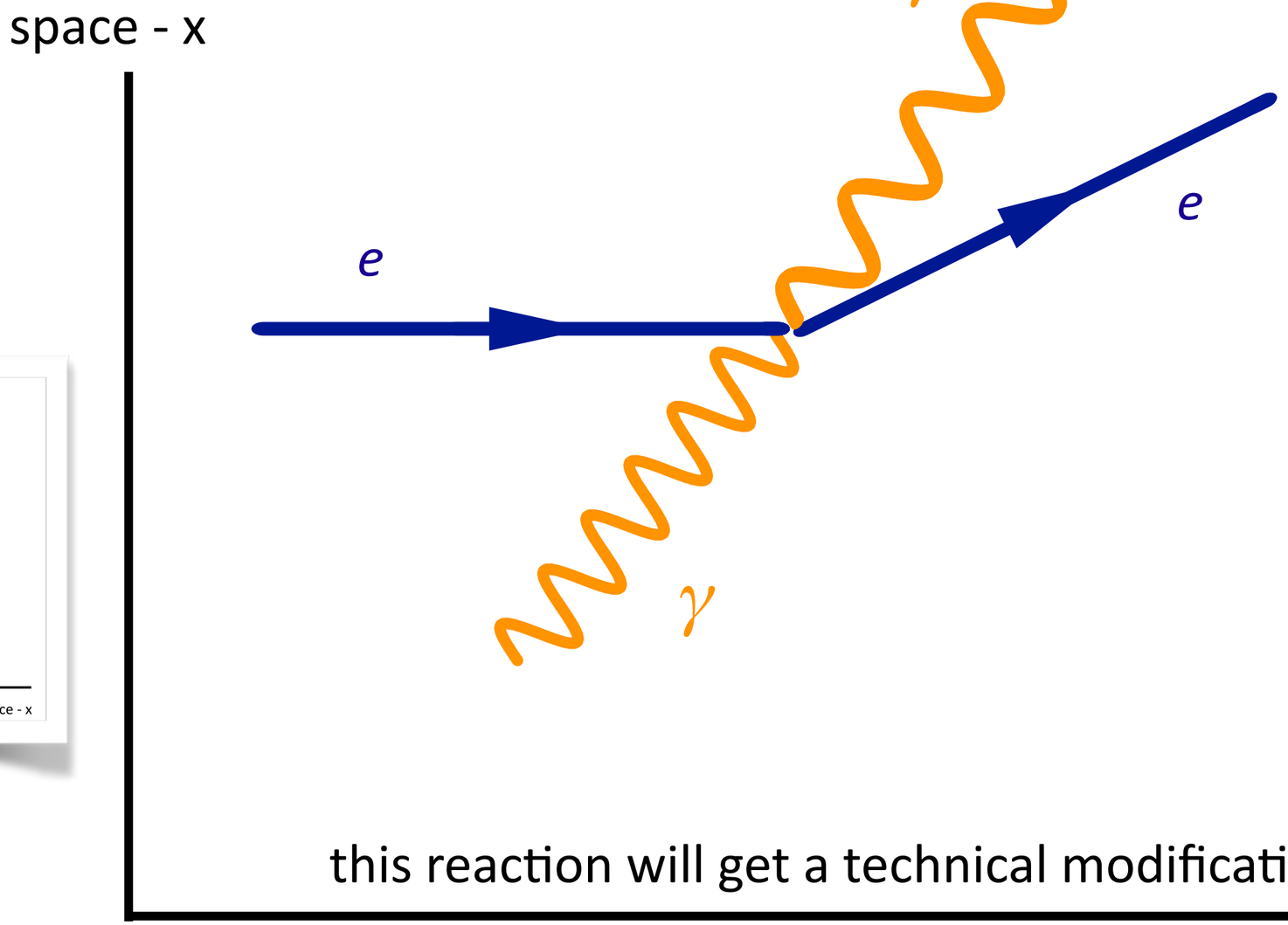
spacetime diagram

aka, *Feynman* diagram



draw the Feynman diagram for Compton Scattering

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



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.

the wavelength is the key

look at the relative sizes of openings and barriers compared to the wavelength

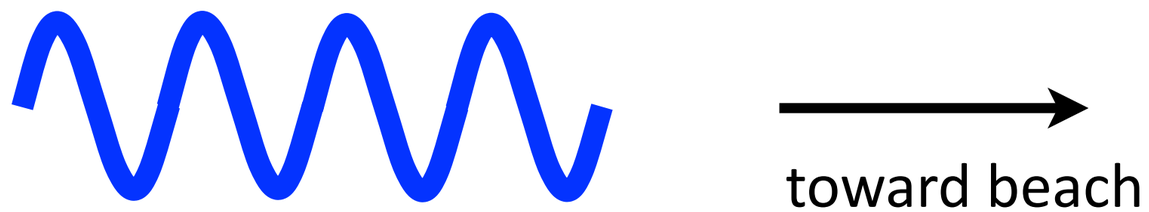
First, think about water waves, then about light waves.

imagine two shapes of waves

on water

“plane wave”

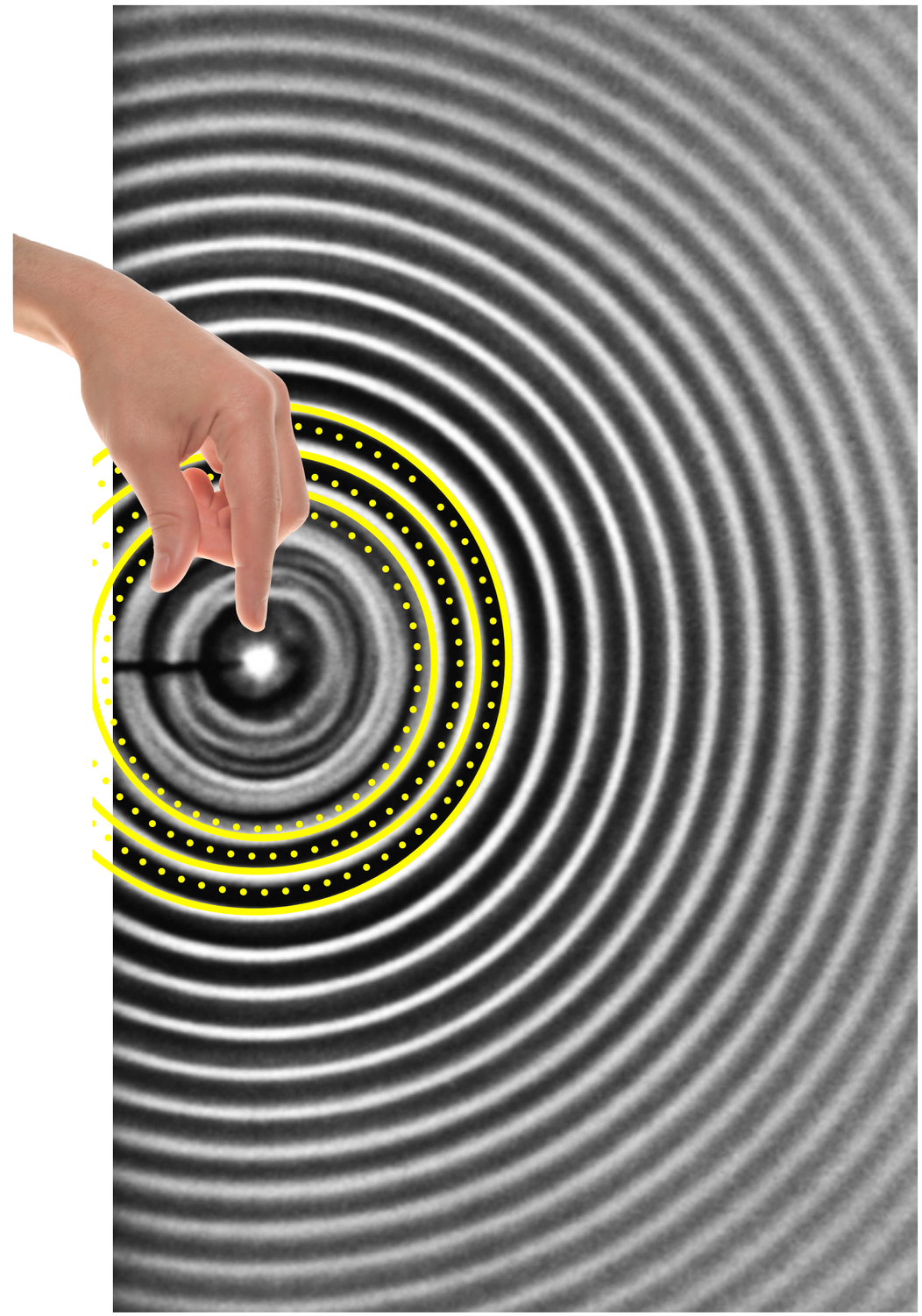
from side:



“circular wave”

waves

one tap



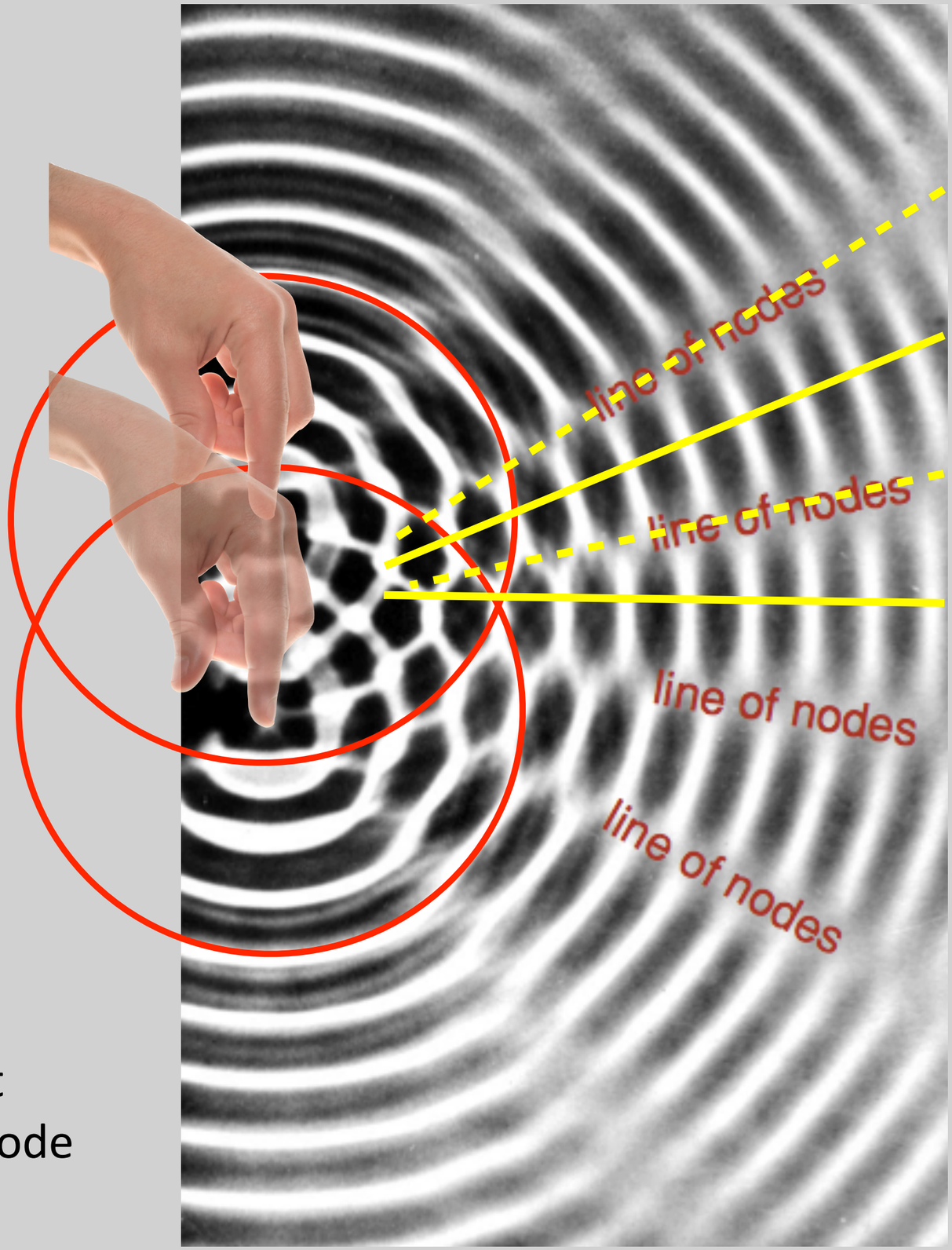
solid- crest
dashed - trough

interference again

two taps

"node": a trough

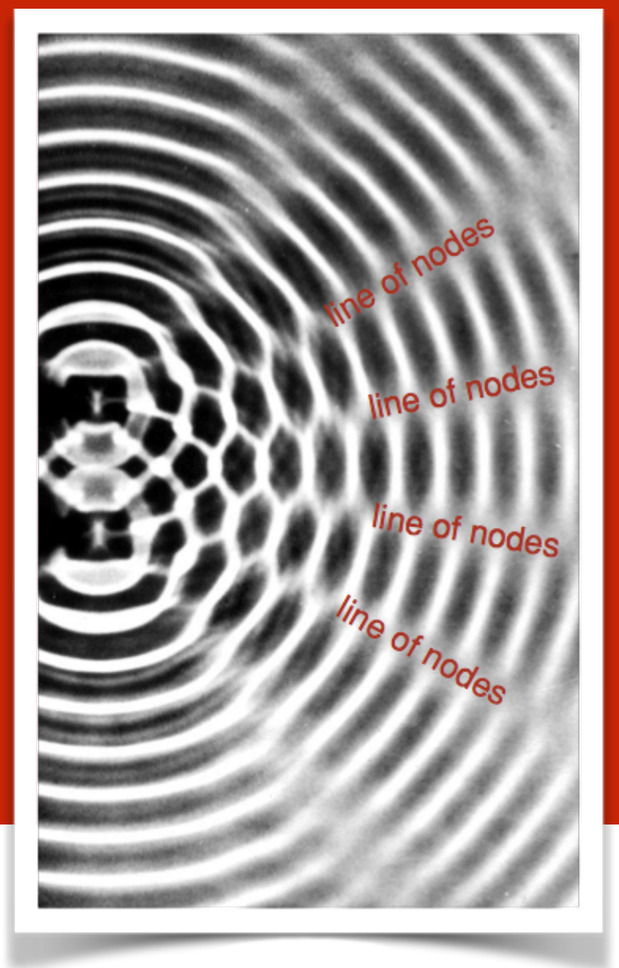
"crest": a peak



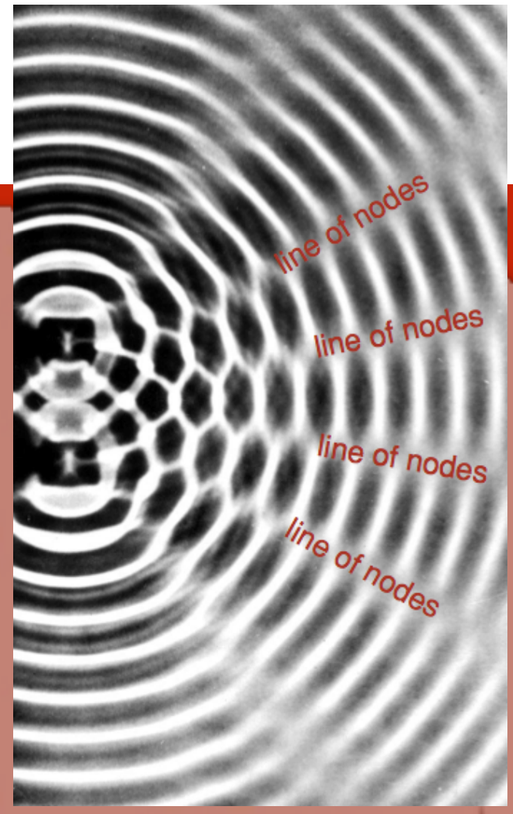
solid- crest
dashed - node

this is it

THE smoking gun of wave behavior:
interference



keep those in mind



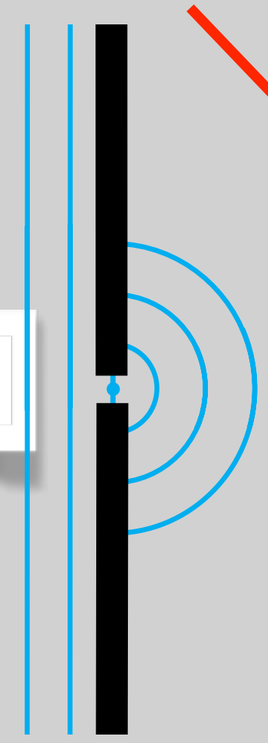
1 and 2 taps

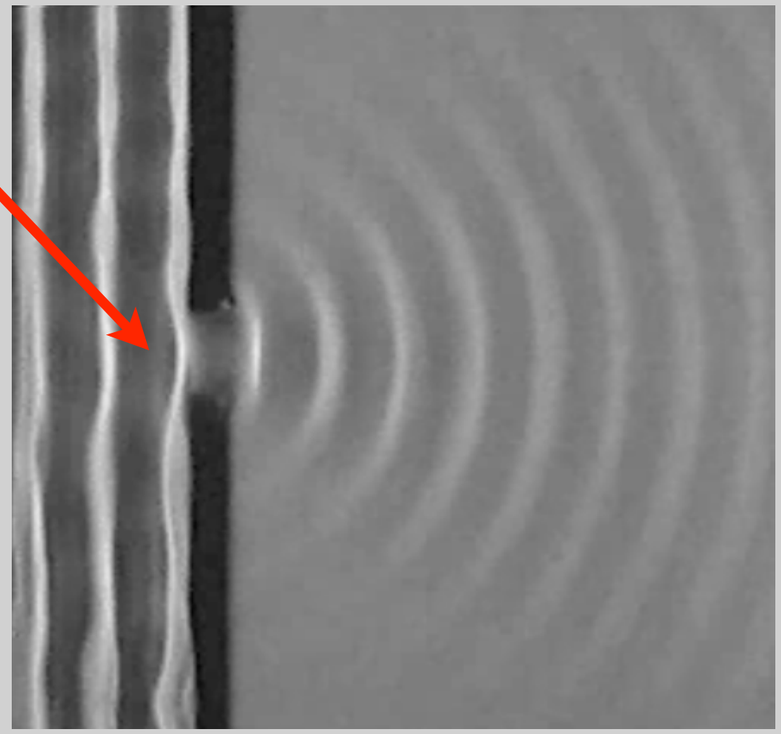
a plane wave impinging on a gap

like 1 "tap"

a gap of about a wavelength-width

plane waves





like the 1-tap image

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

This is diffraction

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

dramatic images from oceans

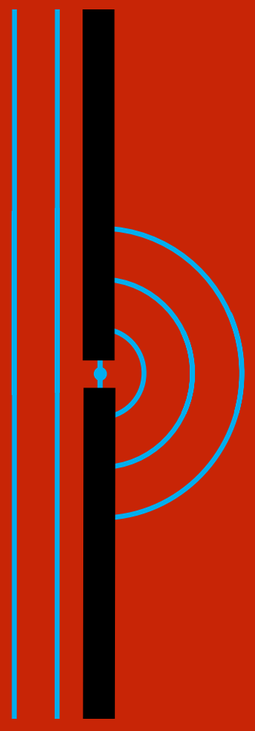
now we know the answer

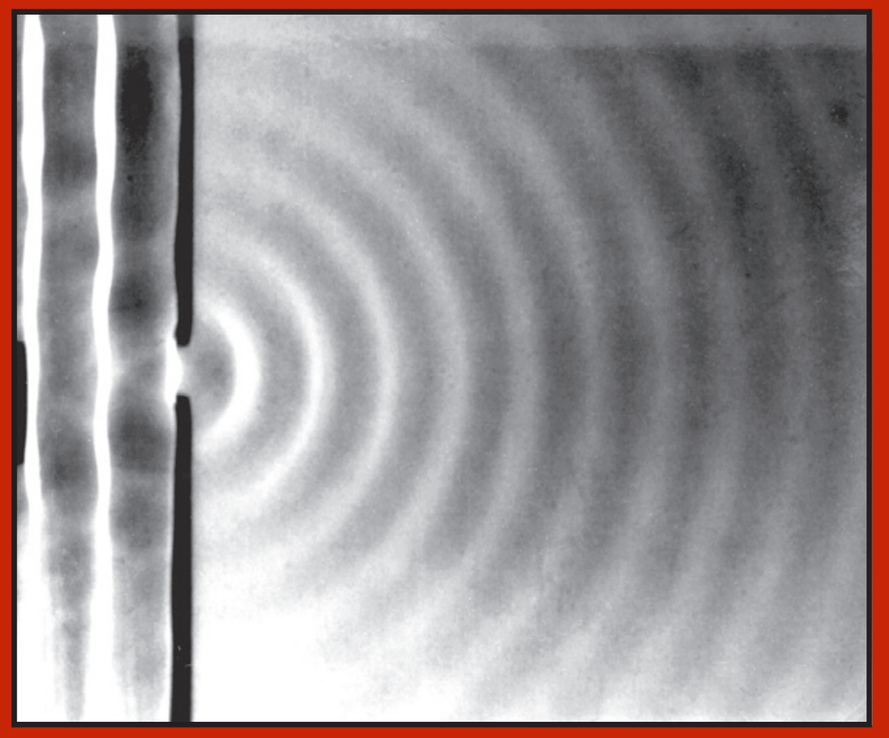
about hearing around corners

wavelength of sound? about 1m

middle C, f = 256 Hz

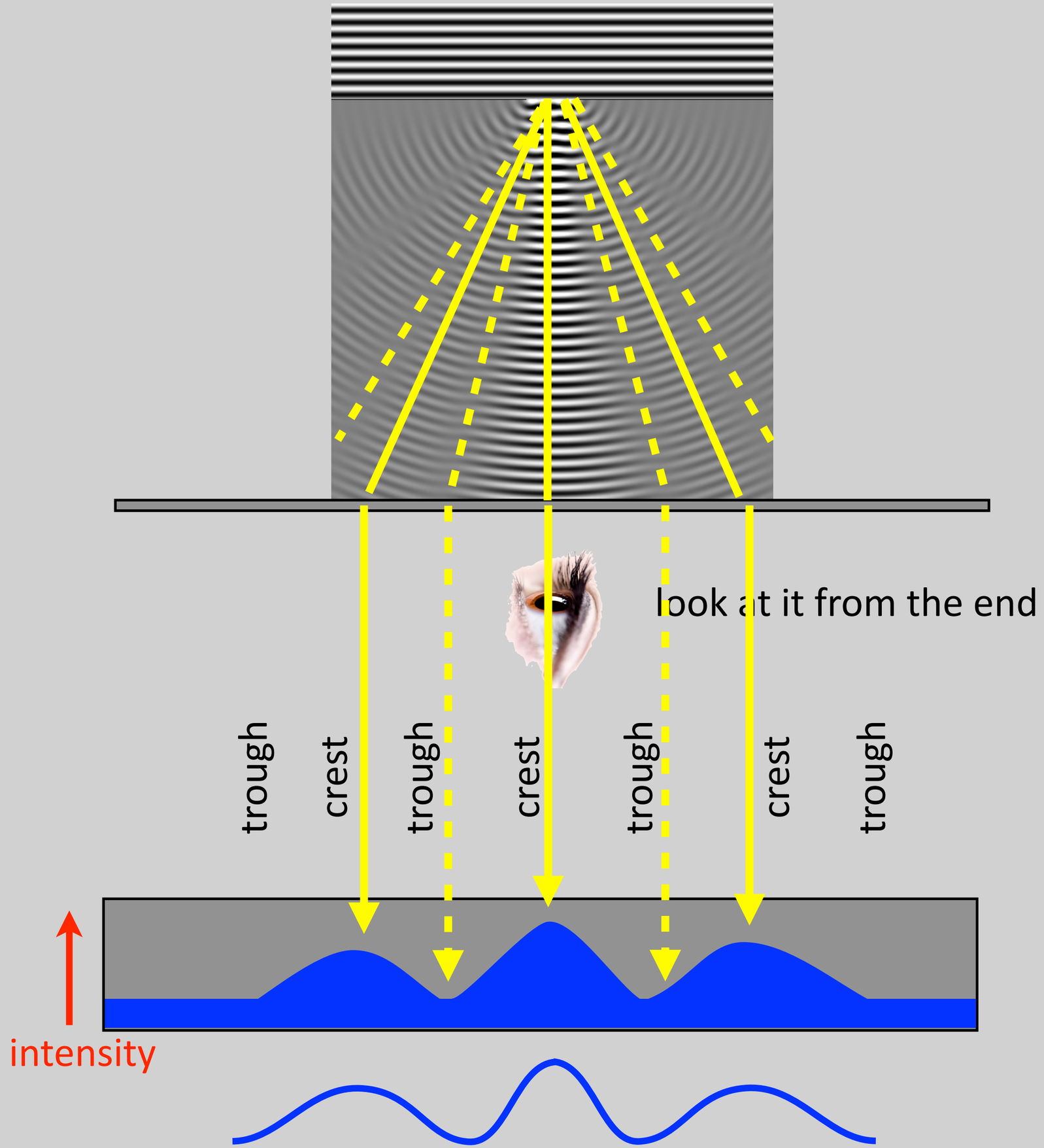
which is about door-sized





look at it from:

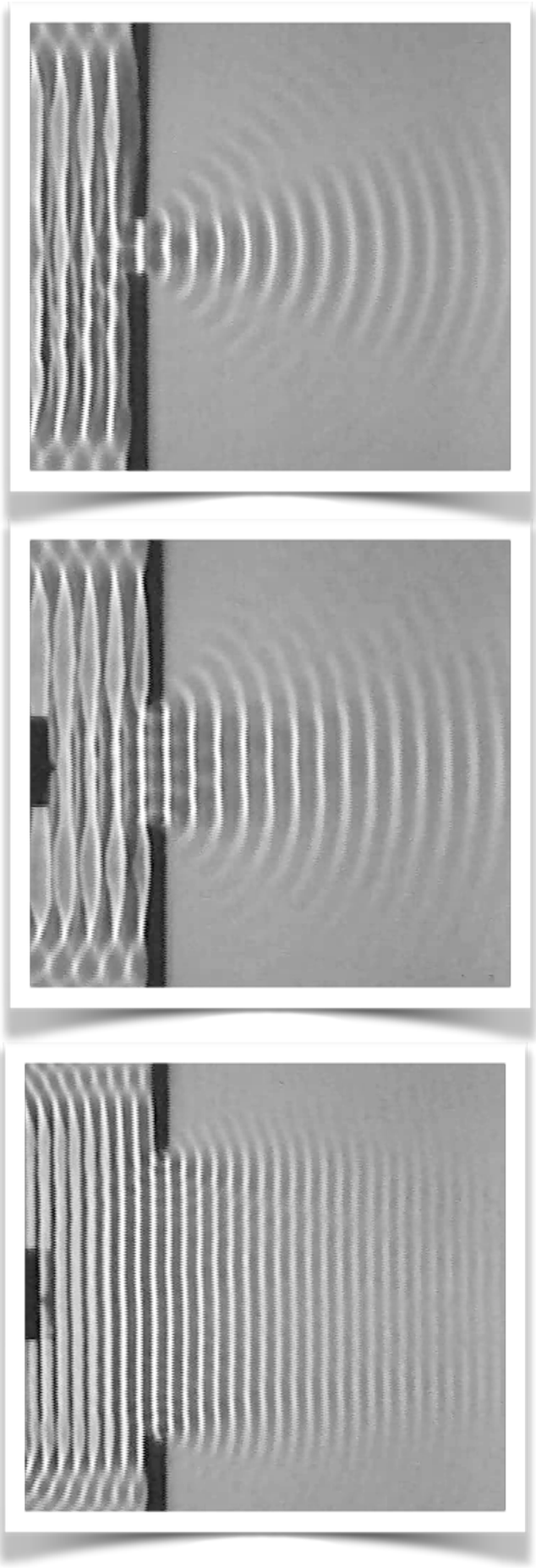
the side where the waves are coming at you



the relative size of the gap

determine the apparent diffraction amount

increasing gap relative to wavelength

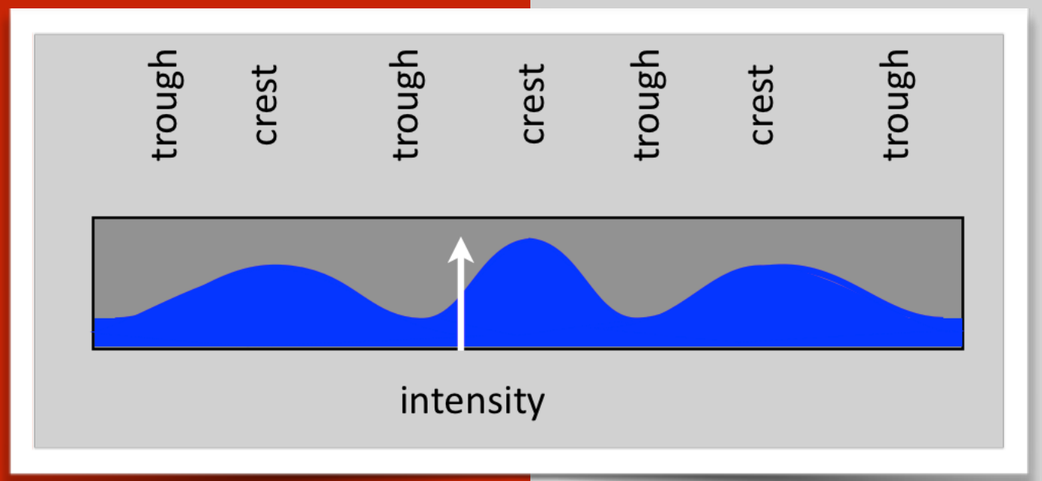


that’s why you can’t see around doors

this is for water

close to the slits

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



diffraction

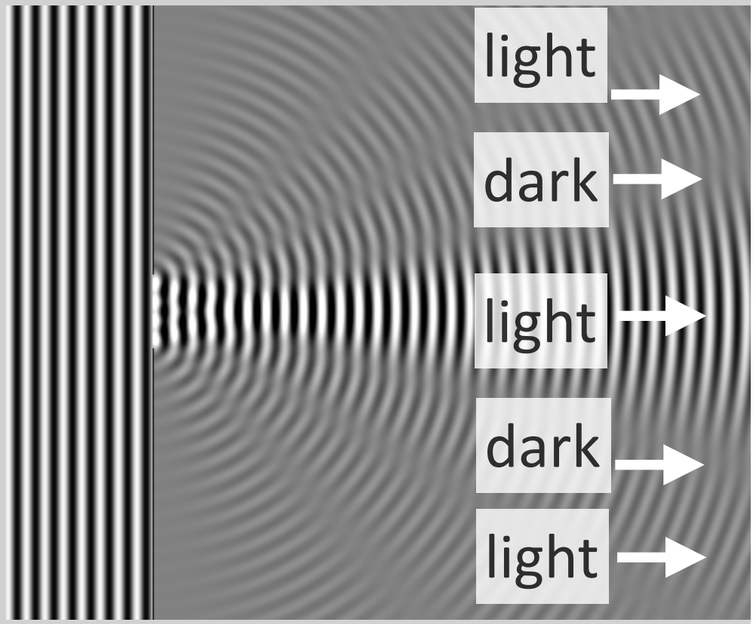
with light

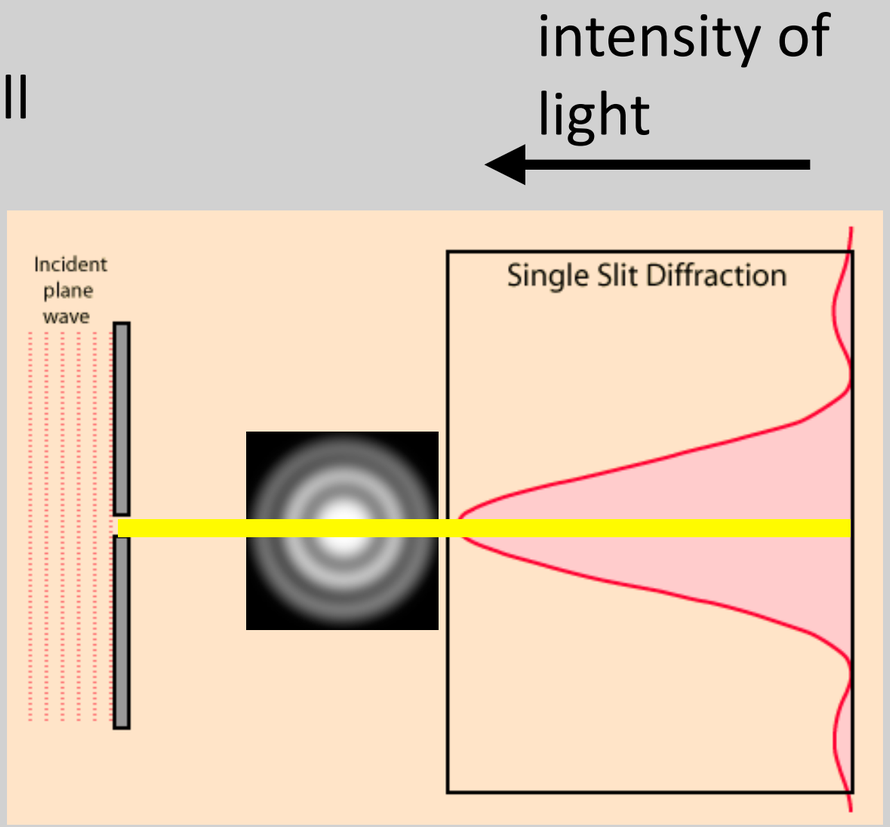
like that of water

wave height like brightness

crest: bright

trough: dark





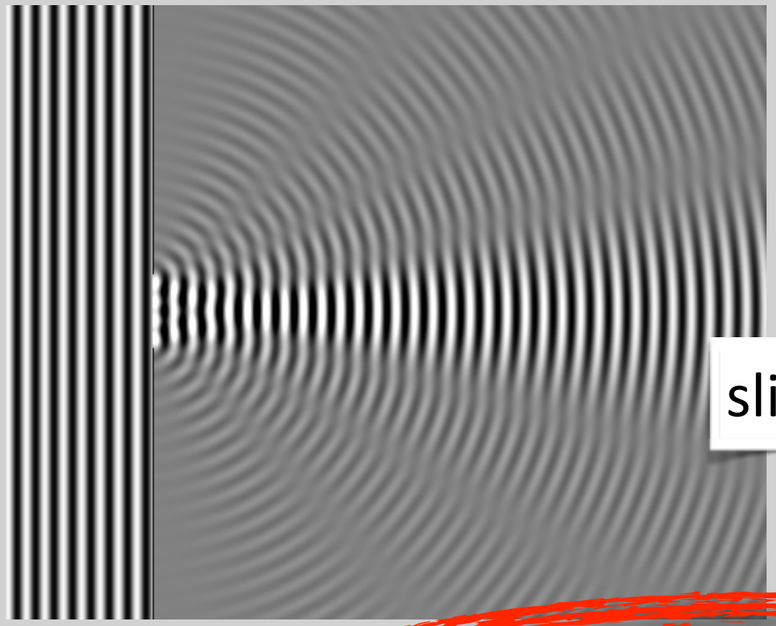
all across the width of the gap is light on the projected wall

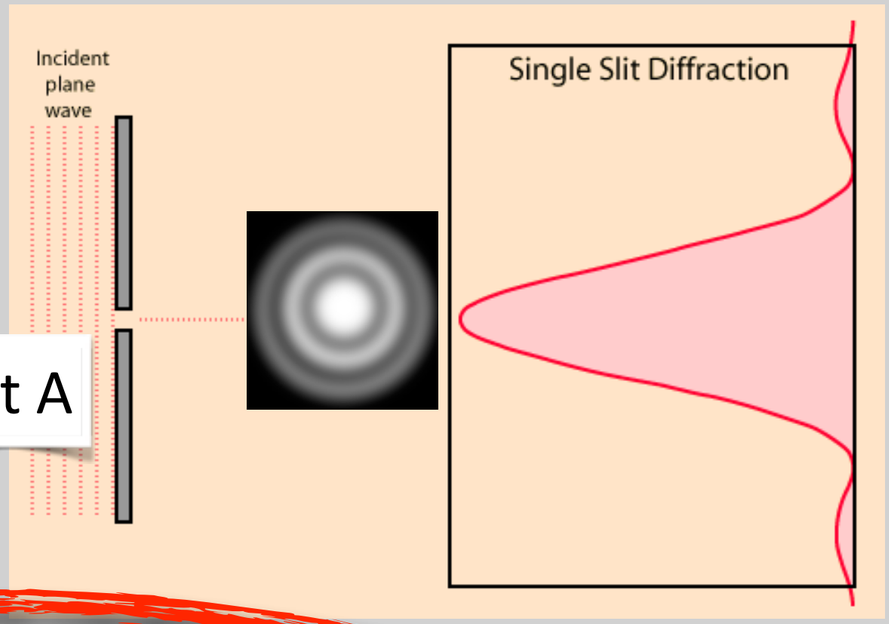
now do something strange.

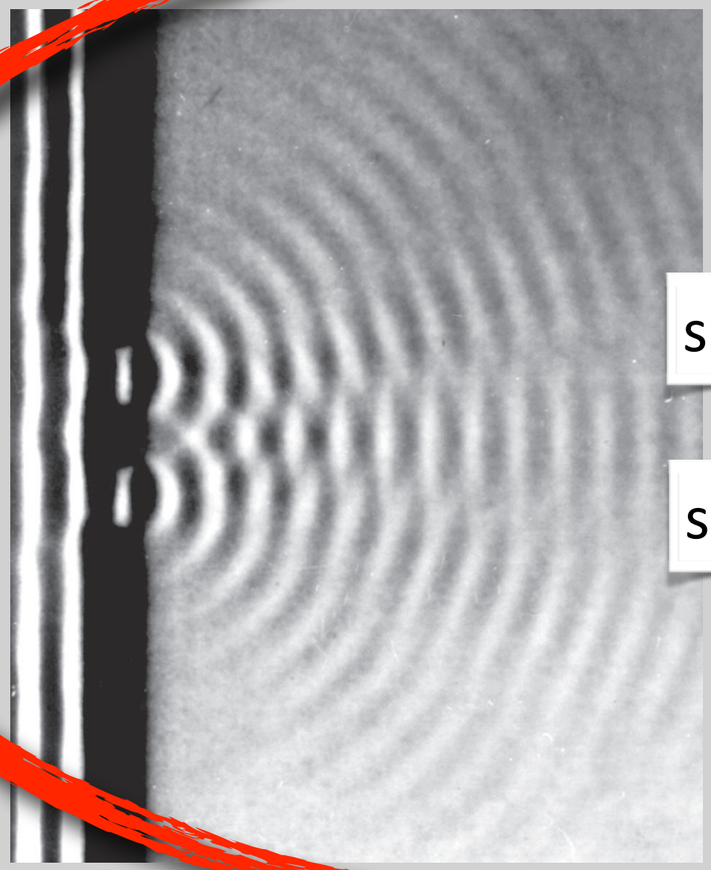
add light by opening another gap

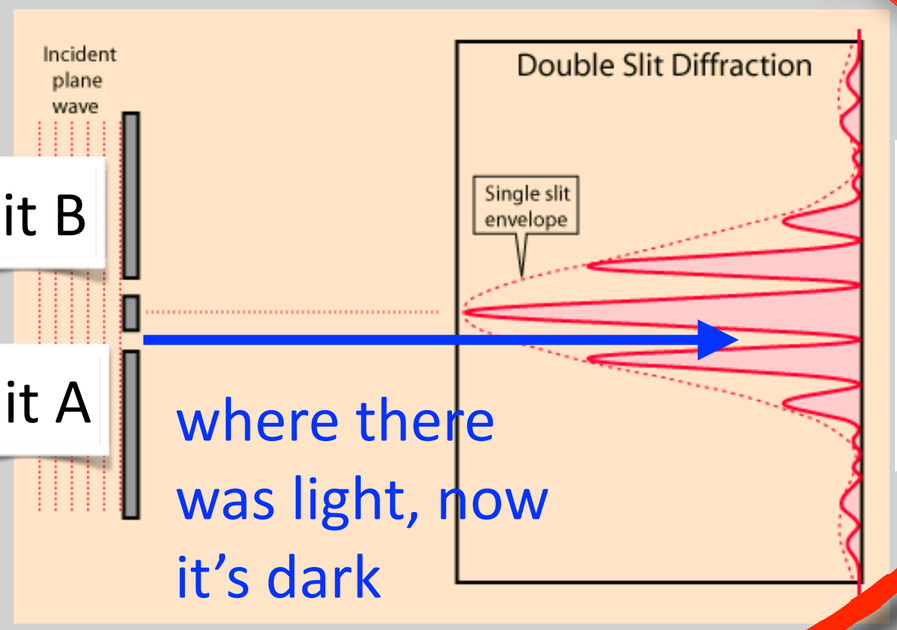
interference of light

and diffraction at the same time







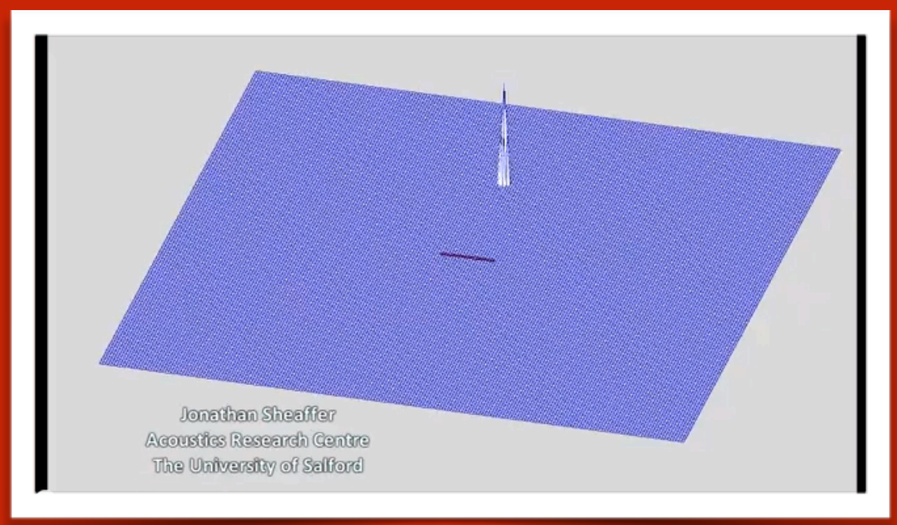


bottom line:

waves interfere…and they bend - they creep around edges

that’s diffraction

particles don’t do this!



yet, Einstein suggested that waves and particles are spookily connected together in one object - a particle of light

how’s that work?