3. Experimental Basis of Quantum Physics, 2

lecture 14, October 2, 2017

housekeeping

exam 1 was last friday ;)

- actually, next one is scheduled for Friday, 3 Nov
- I may make it a week early

Homework, chapter 3 in Thornton and Rex:

- I moved some problems into the following week
- I remembered - all by myself - to unlock the dropbox

Shameless plug:

- ISP220

Honors option

- we're good.
- I'm slow: this week

Derivations:

- pep talk

unravelling

the 19th Century

11 catastrophes

1. specific heats of gases and solids
2. atomic spectra
3. photoelectricity
4. ether
5. electron theory
6. discovery of electron
7. x-rays
8. radioactivity
9. radioactive elements
10. nuclear radiations
11. blackbody radiation

Albert Michelson
from his book, *Light Waves and Their Uses*, 1903

"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...Many other instances [of 'apparent exceptions'] might be cited, but these will suffice to justify the statement that our future discoveries must be looked for in the sixth place of decimals.

very famous quote which he lived to regret

the pace picks up

The decade of 1888-1898 was the warm-up to rapidly changing circumstances

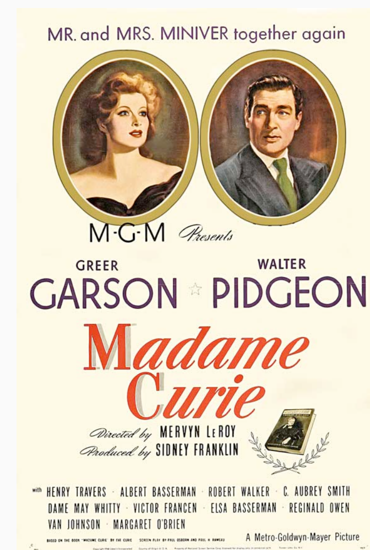
We’ll barrel through 11 separate catastrophes from this one decade

- then, I’ll come back to some of the details

1898 Marie Skodowska Curie

1857-1934

believe it or not
true-love stories in physics are rare!



10. nuclear radiations

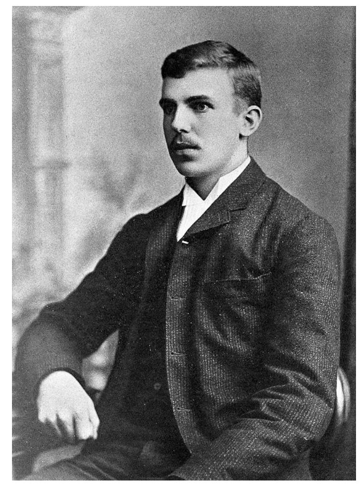
a force of nature

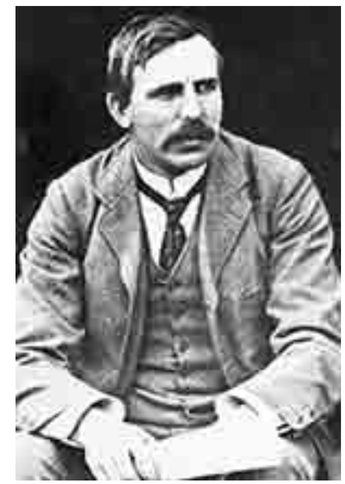
a transplanted New Zealander

- JJ student at Cambridge 1897
  - aggressive, fun, and driving, commanded respect and received affection from everyone who worked with him - interested only in discovery
    - “There is always someone, somewhere, without ideas of his own, who will measure that accurately.”

X-rays and Becquerel rays ionized gases to the same degree

- actually concentrated on radioactivity, making quantitative measurements





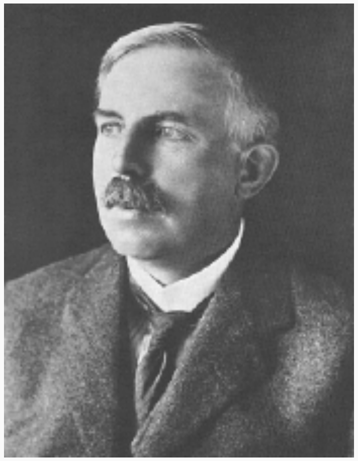
Ernest Rutherford 1871-1937

1899

Ernest Rutherford

1871 – 1937

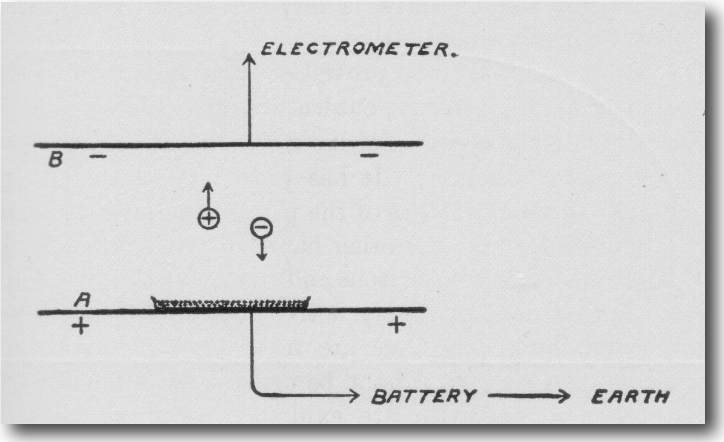
the nuclear physics' 800 lb gorrilla



“

I have to keep going, as there are always people on my track. The best sprinters in this road are Becquerel and the Curies.

The epitome of the aggressive scientist... but I mean that in a good way.



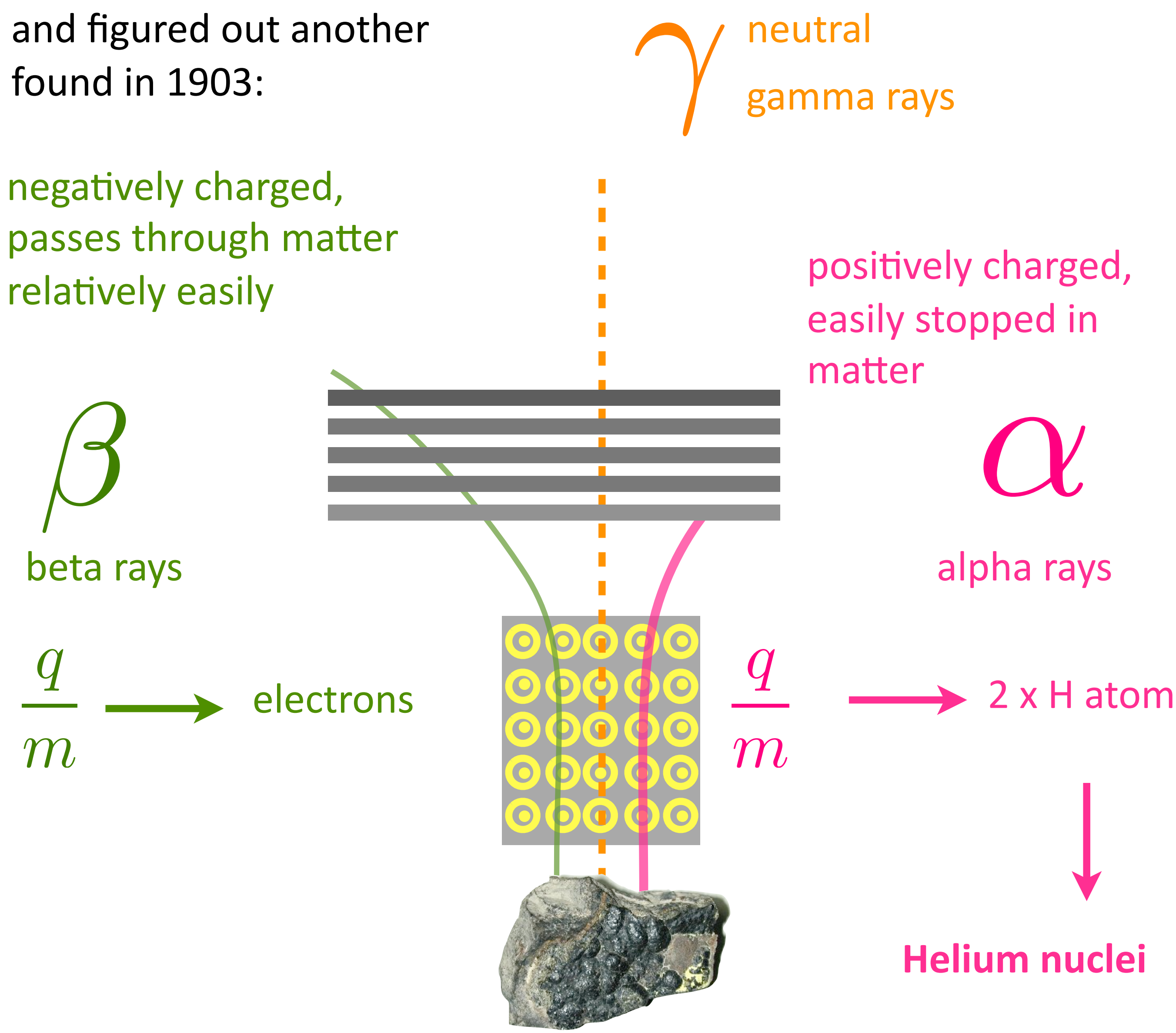
He measured the actual current from radioactive decays.

1899: he carefully isolated 2 components of radiation:

one stopped by thin aluminum

one highly penetrating

and one more



then, it gets really strange.

11. blackbody radiation

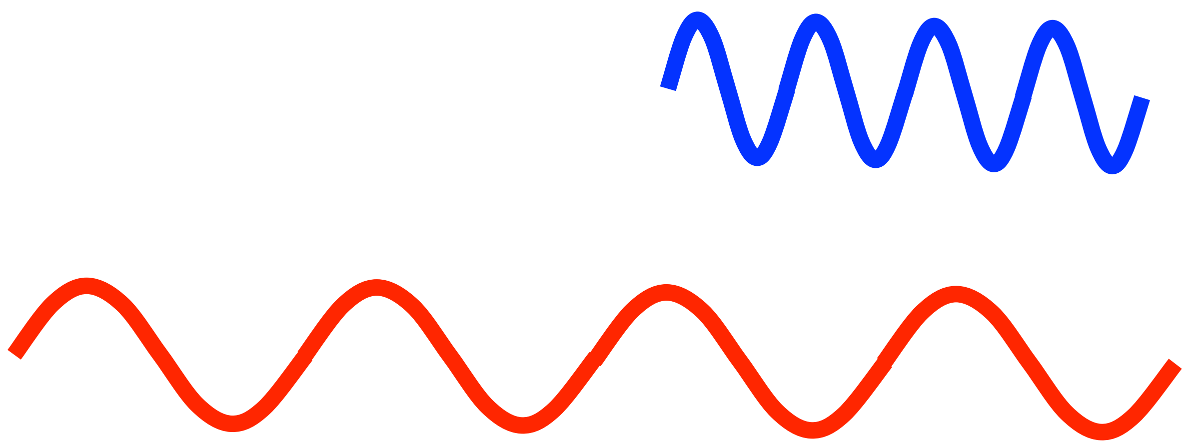
in the 1890's things were heating up

I mean, literally.

color = temperature

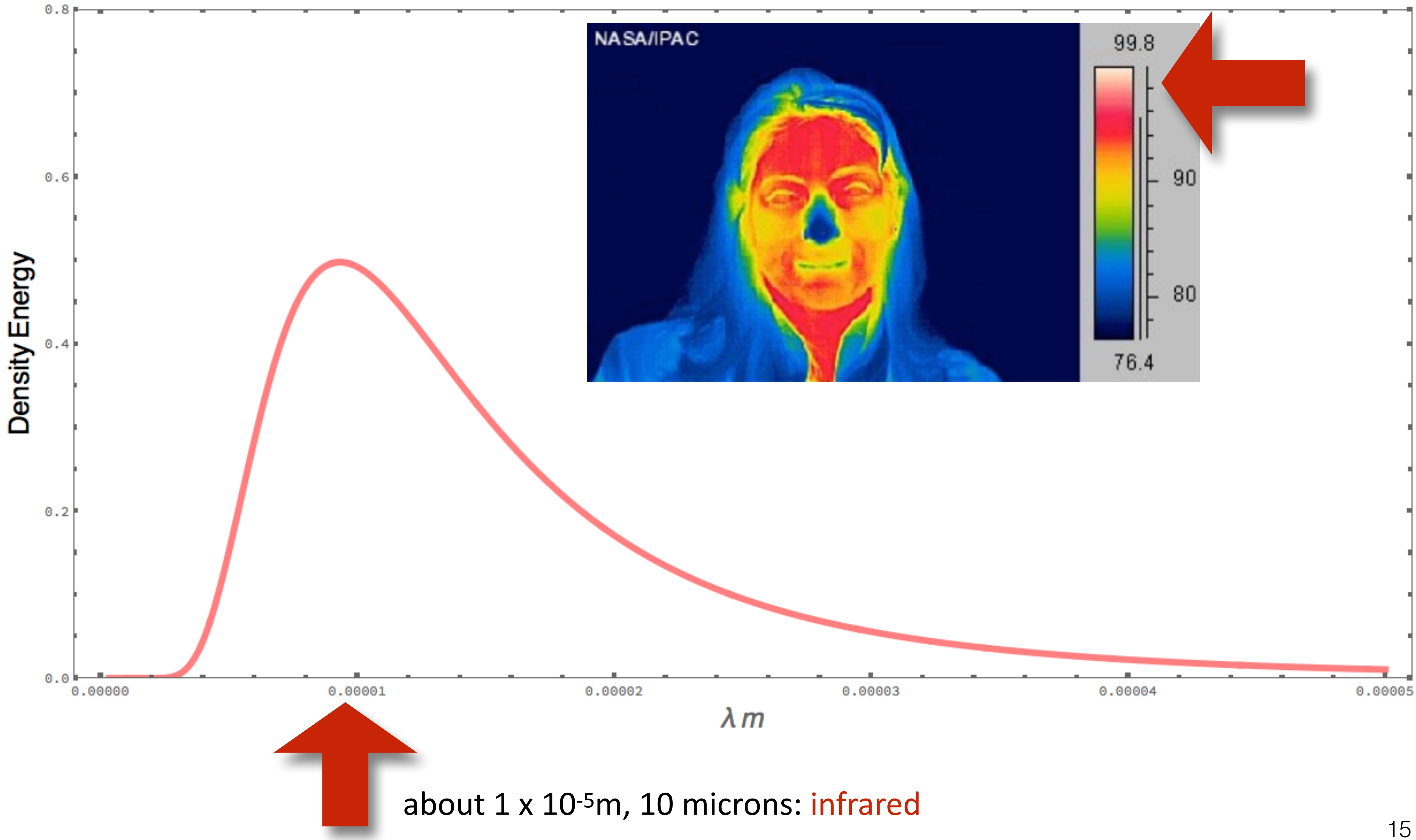
why?

Gassan Sadatoshi



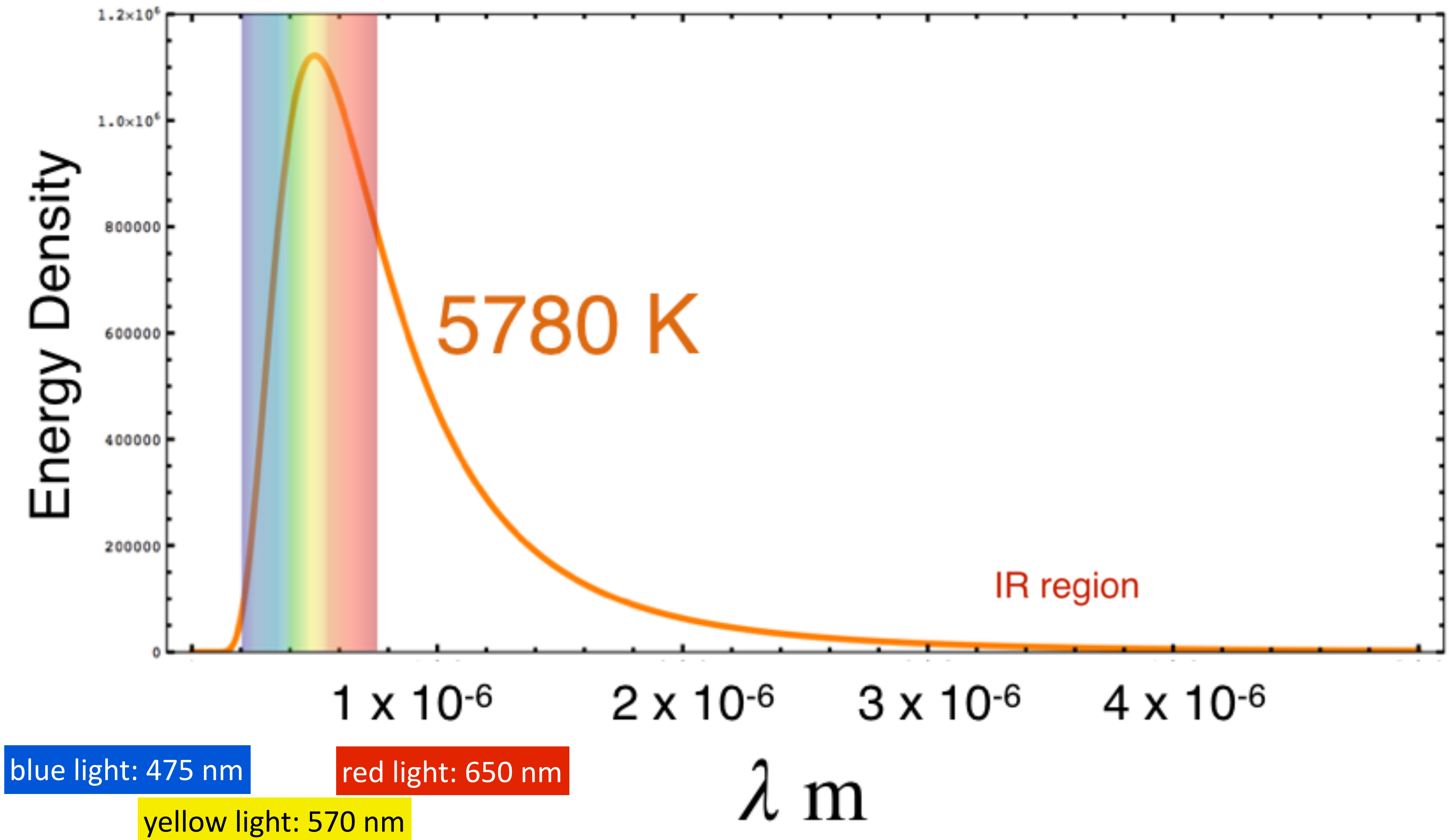
http://www.howstuffworks.com/sword-making.htm/printable

everything with a temperature radiates electromagnetic waves



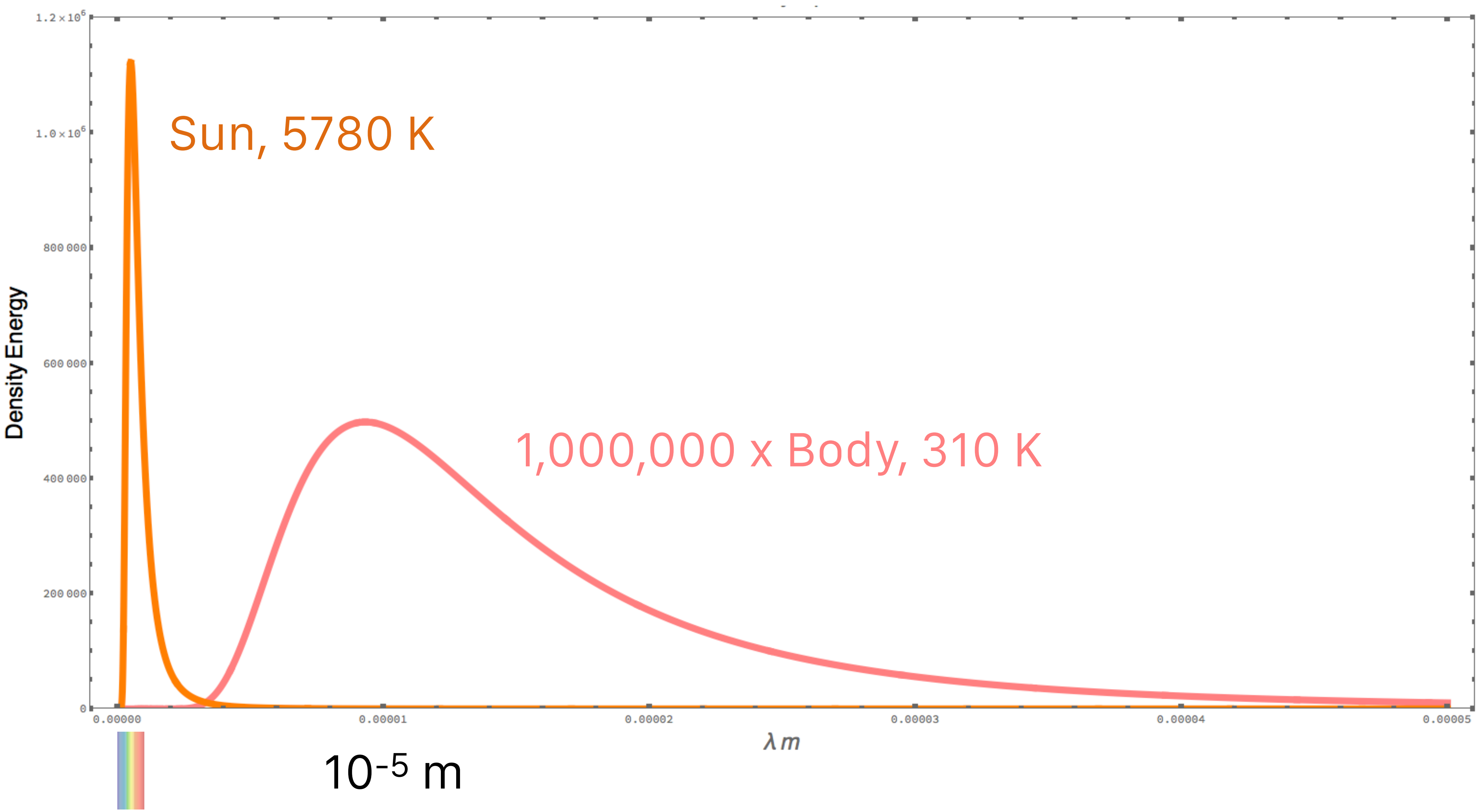
about 1 x 10^{-5}m, 10 microns: infrared

sun



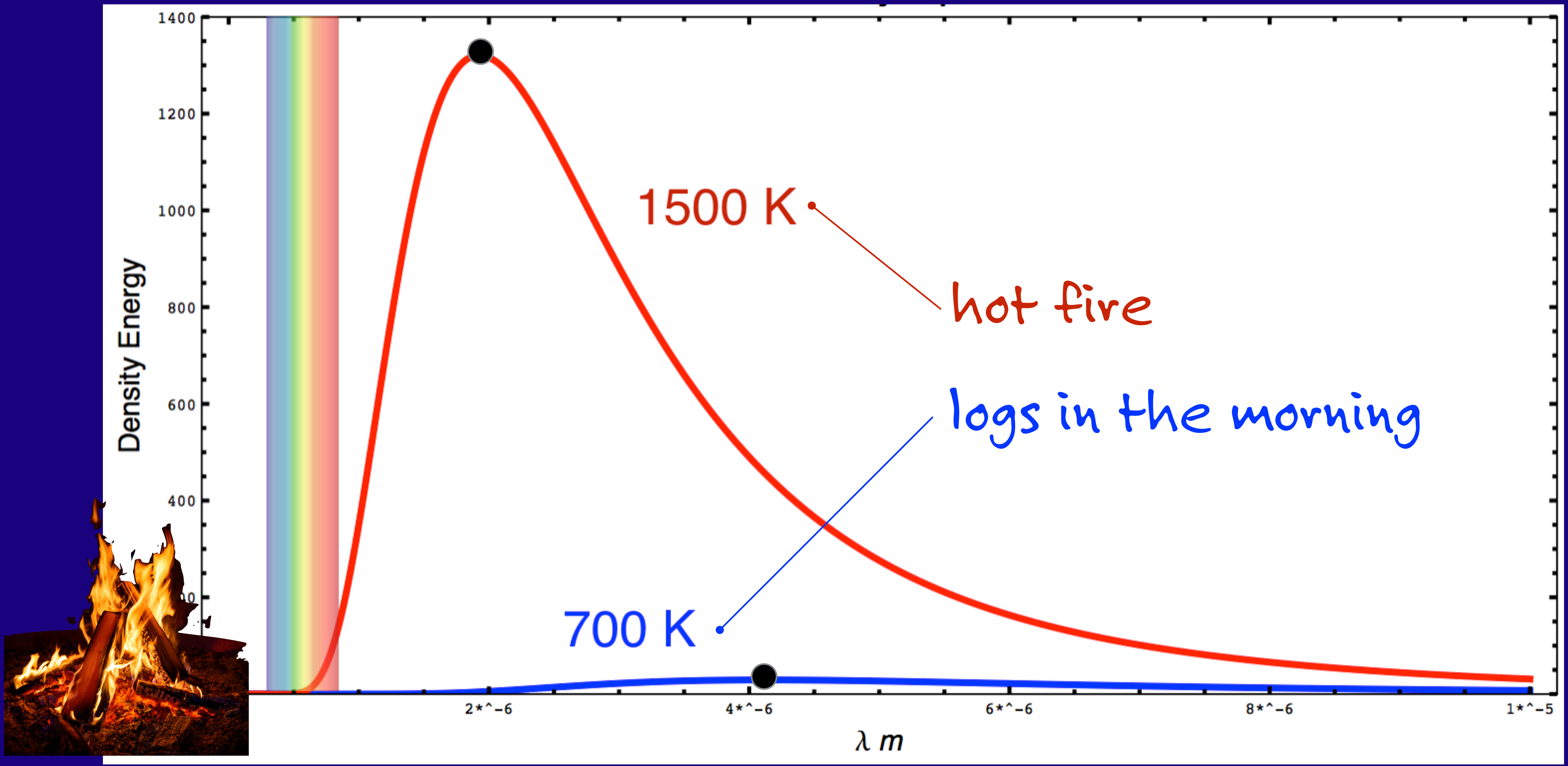
Energy Density
1.2×10⁶
1.0×10⁶
800000
600000
400000
200000
0
5780 K
IR region
1 x 10-6
2 x 10-6
3 x 10-6
4 x 10-6
λ m
blue light: 475 nm
red light: 650 nm
yellow light: 570 nm

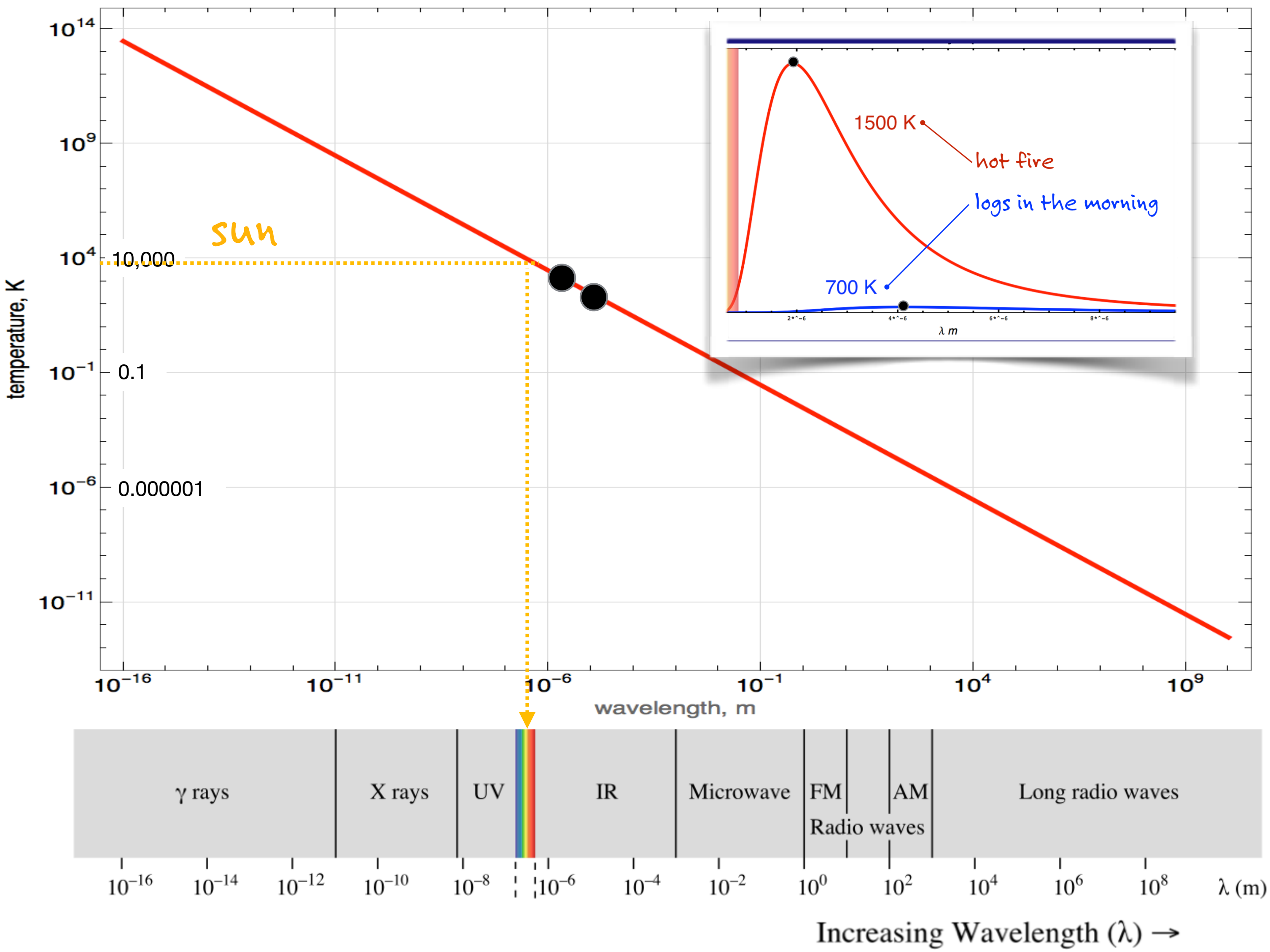
Sun's warmth? notsomuch



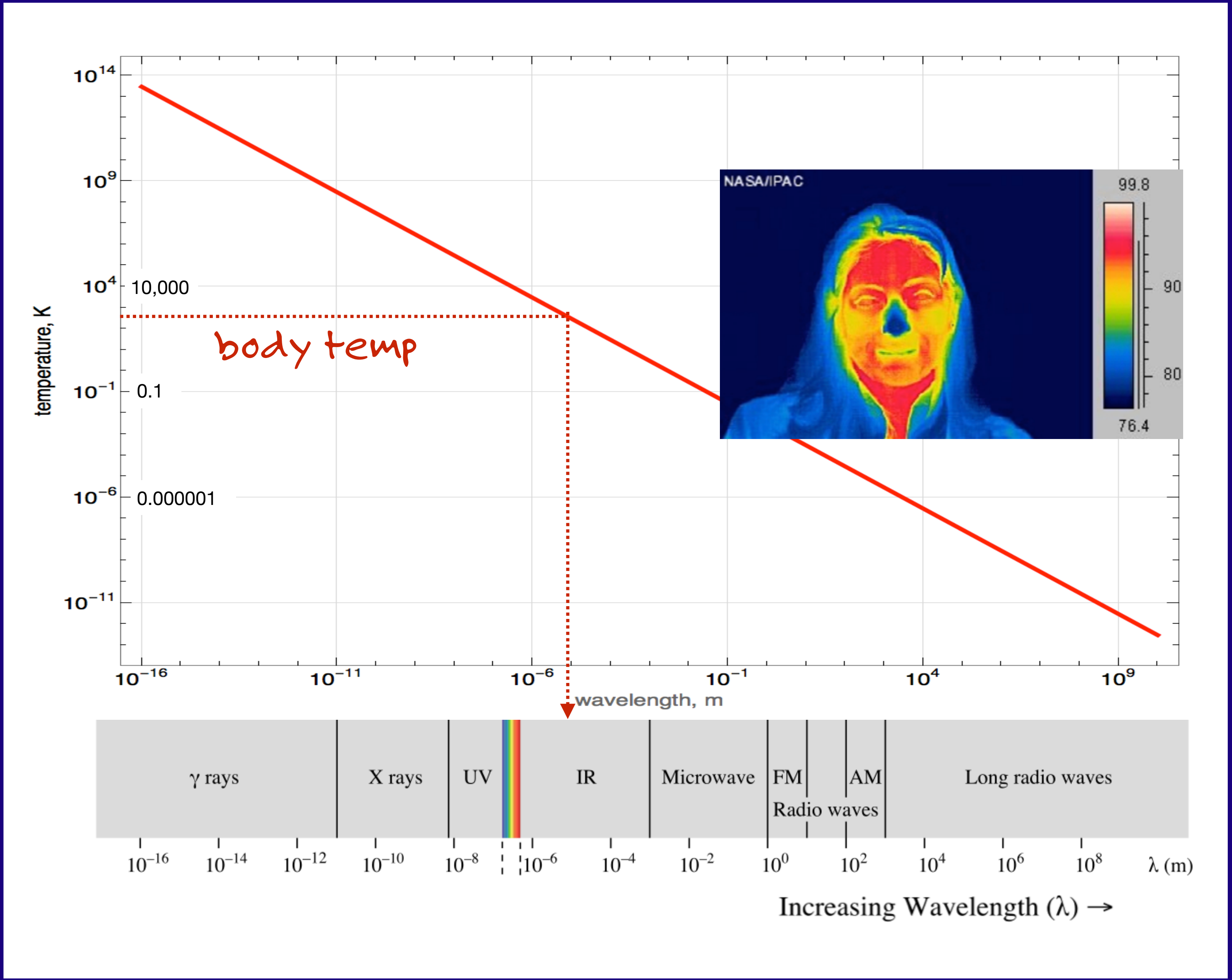
a range

of wavelengths for each temperature

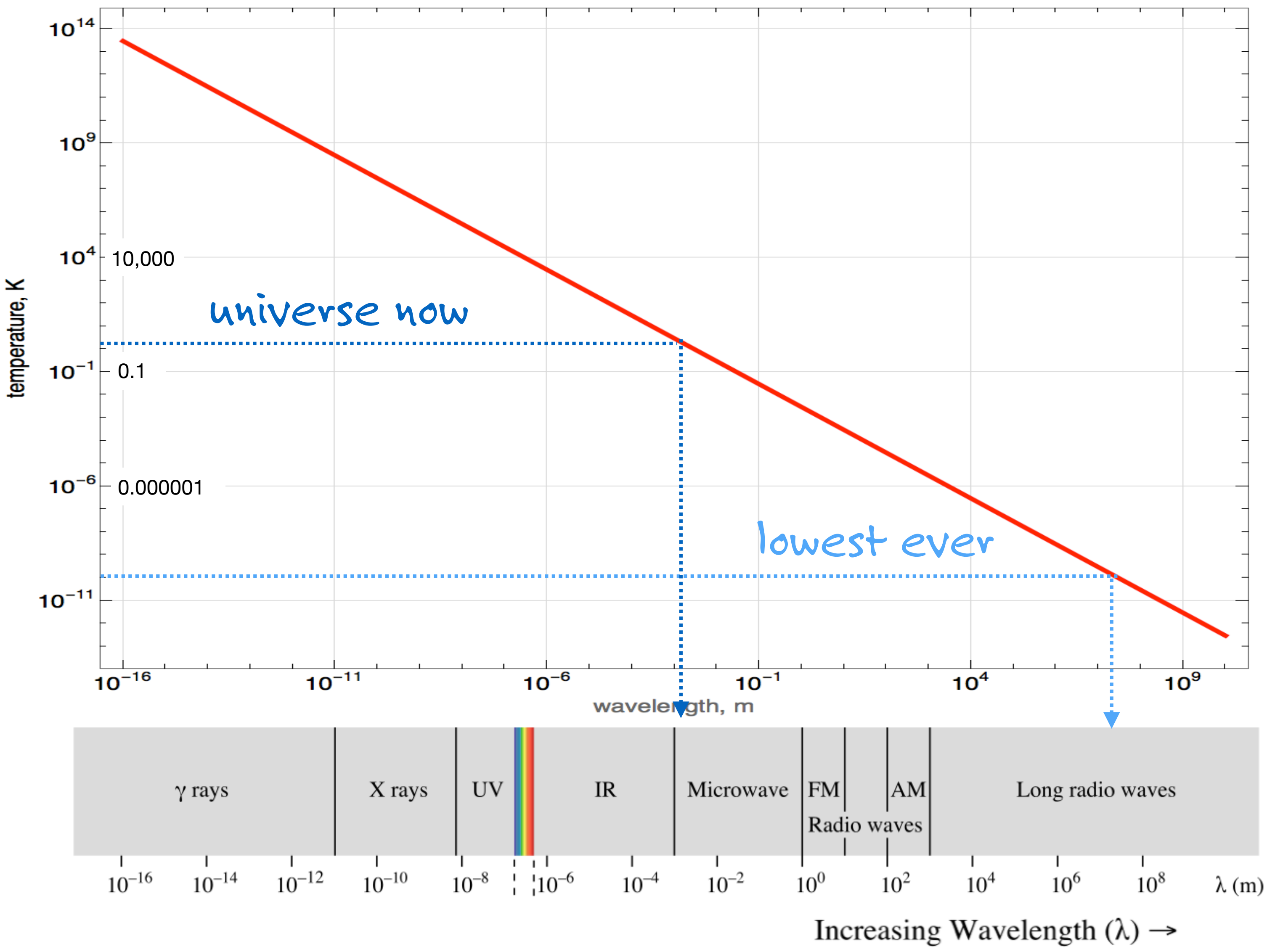




sun
10,000
0.1
0.000001
temperature, K
wavelength, m
1500 K
hot fire
logs in the morning
700 K
λ m
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
λ (m)
Increasing Wavelength (λ) →



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

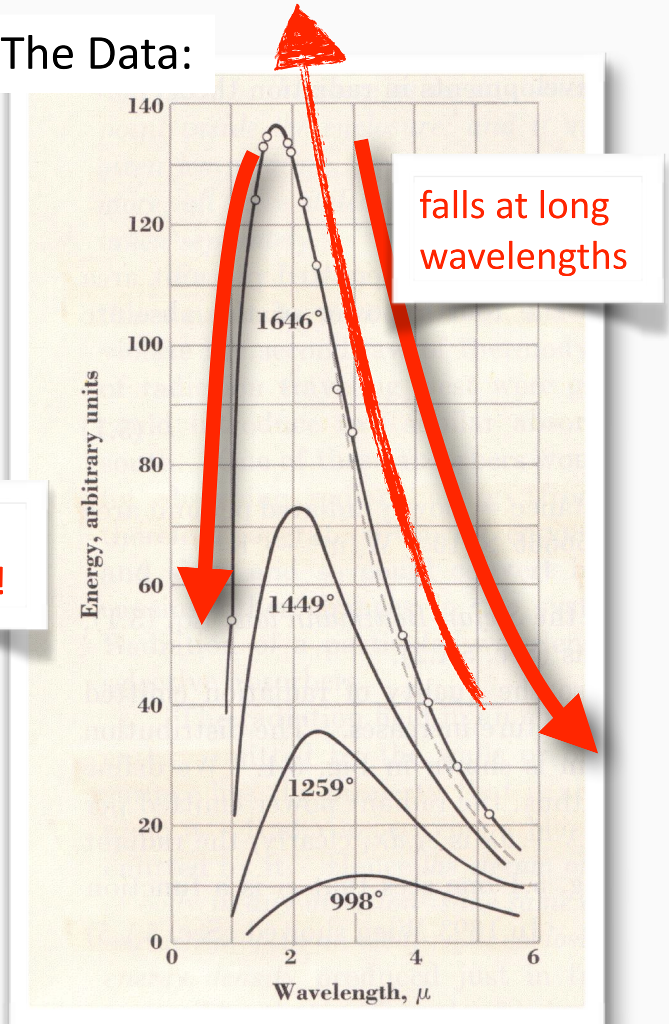


temperature, K
10^14
10^9
10^4
10,000
10^−1
0.1
10^−6
0.000001
10^−11
universe now
lowest ever
10^−16
10^−11
10^−6
10^−1
10^4
10^9
wavelength, m
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^−16
10^−14
10^−12
10^−10
10^−8
10^−6
10^−4
10^−2
10^0
10^2
10^4
10^6
10^8
λ (m)
Increasing Wavelength (λ) →

what would Maxwell's theory say?

falls at short wavelengths!

The Data:



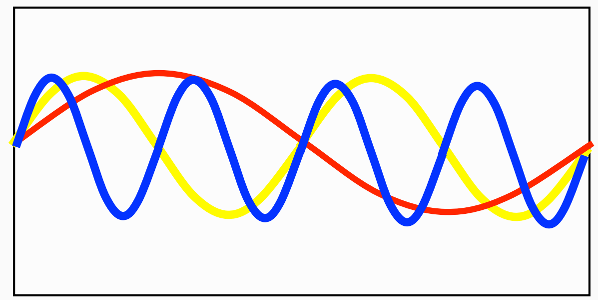
long wavelength →

← high frequency

nonsense.

a major problem.

imagine a cavity with radiation inside



Maxwell-like theory:
<u>no limit</u> 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?

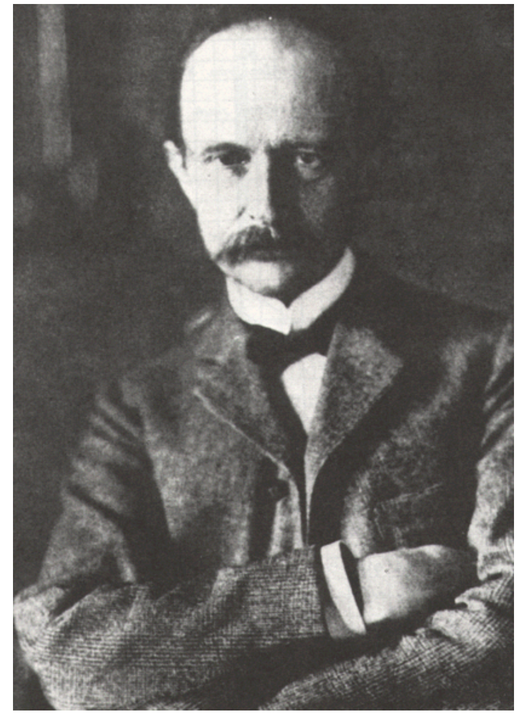
Heat seems to be related to Electromagnetism...independent of the material.

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

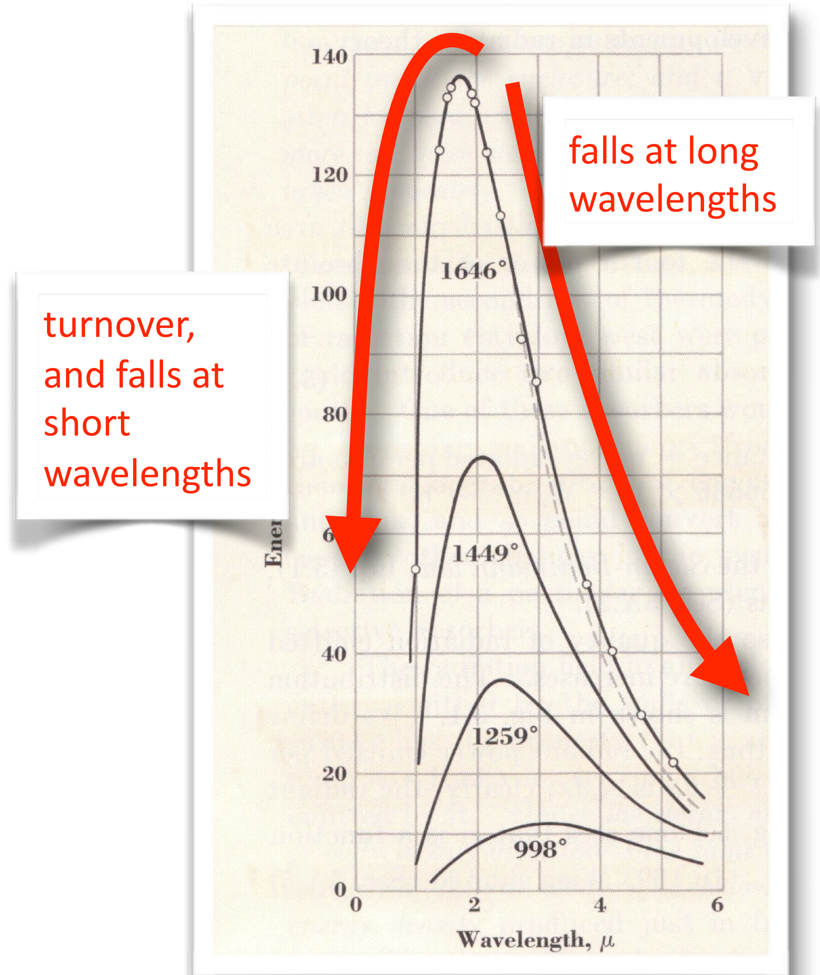
one of the good guys

remember the Data:

Planck could only get a solution

if he restricted energies of emitted electromagnetic radiation

into bundles



long wavelength ⟶

⟵ high frequency

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:

$$E = nhf$$

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

Planck’s Constant - itsy bitsy…n is an integer

energy of an electromagnetic wave

classically

and

Planck

Before Planck:

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

2 “E’s” going on...this one’s “**energy**”

2 “E’s” going on...this one’s **Electric Field** vector

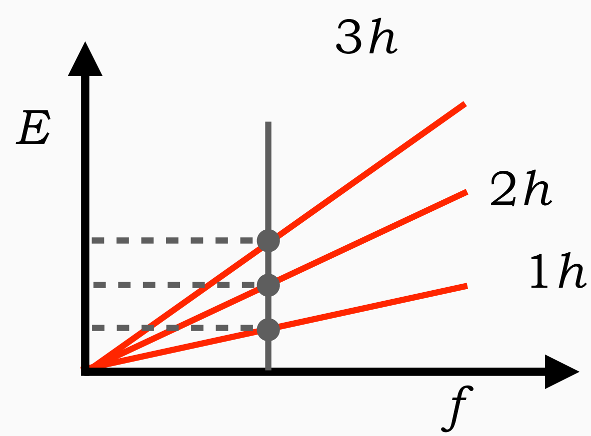
before 1905 physics is often called “classical physics”

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

After Planck:

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

1 “E” going on...just “**energy**”



$$c = \lambda f$$

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

for a given frequency (wavelength)

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

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

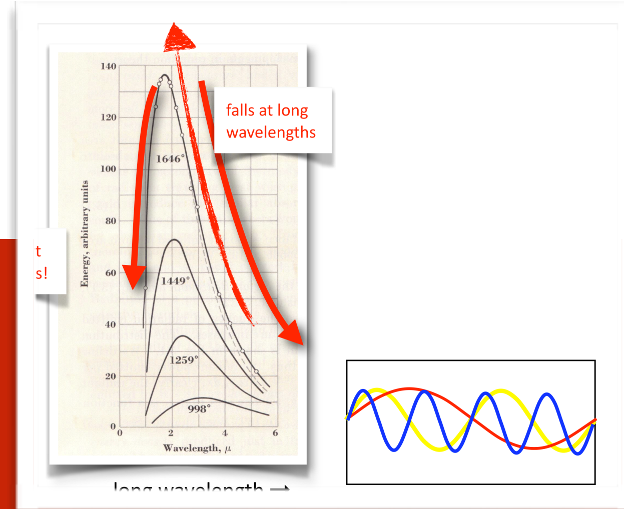
it's as if

no matter how hard you pump

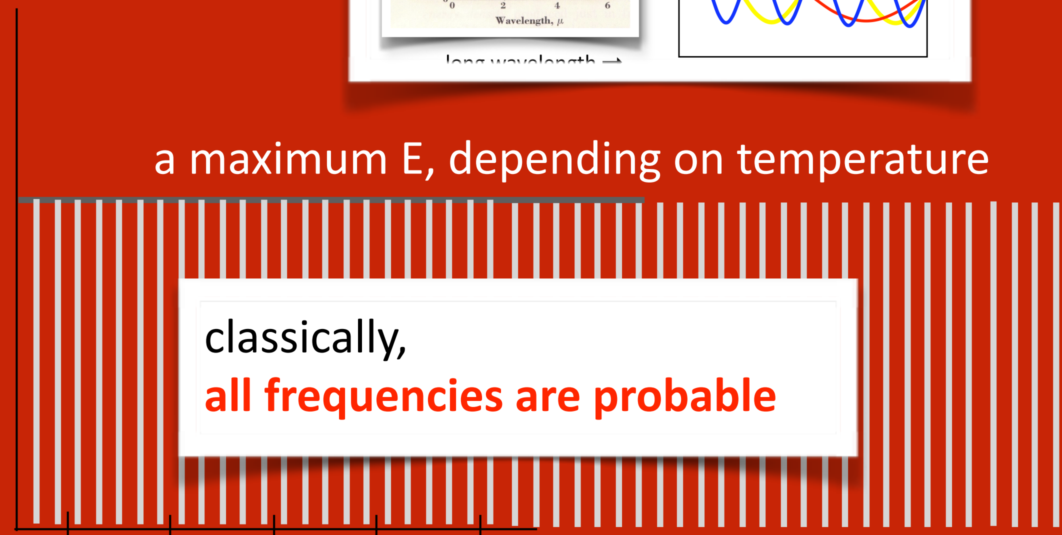
your amplitude is choppy

the lack of light at the short wavelengths

= high frequencies?

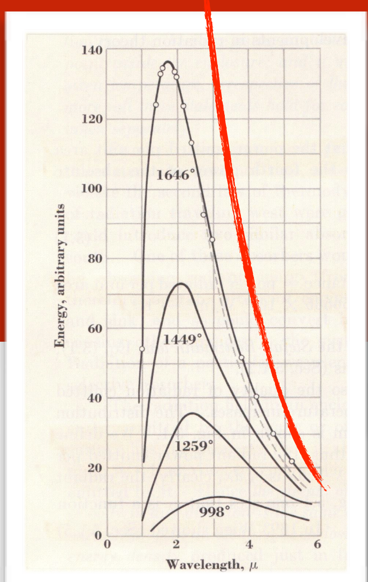


Energy



classically,
all frequencies are probable

frequency



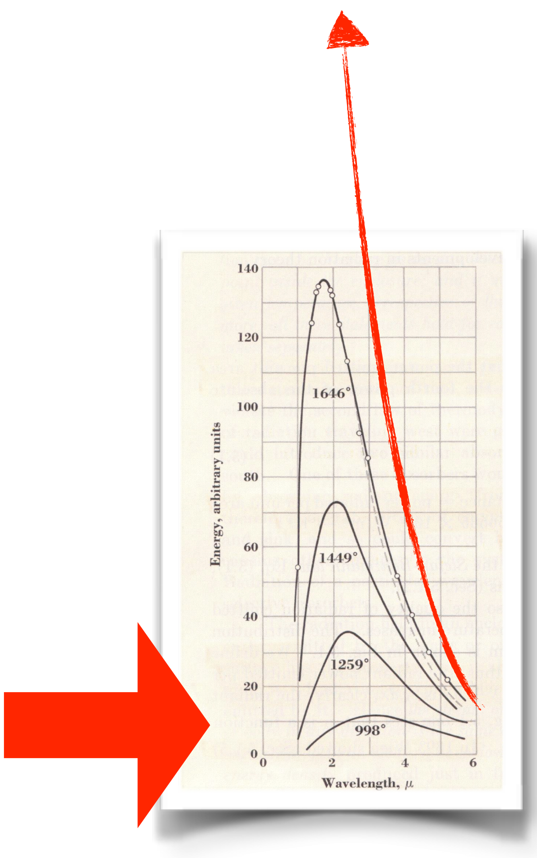
Classical radiation theory predicted an infinite amount of energy at high frequencies....the "Ultraviolet Catastrophe"

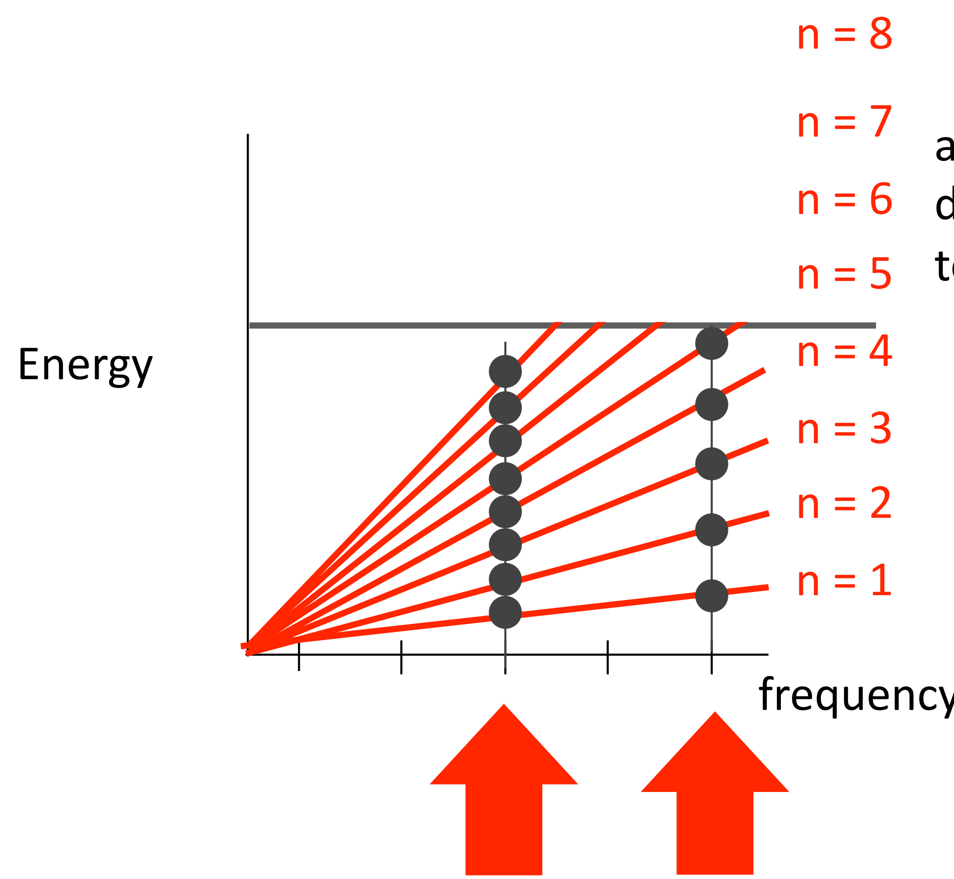
the lack of light at the short wavelengths

= high frequencies?

But, for Planck:

$E = nhf$





a maximum E, depending on temperature

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

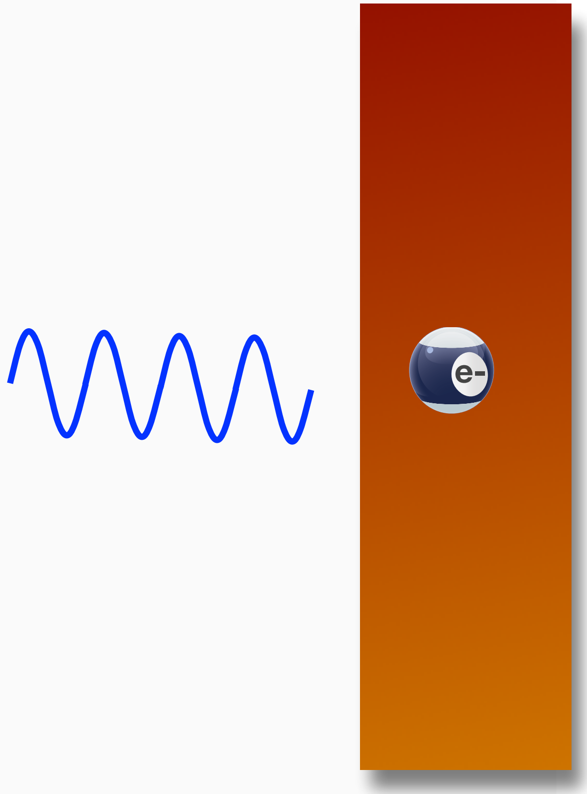
each quantum has <u>more energy</u>...but there are <u>fewer of them</u>.

for Planck

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

electromagnetic waves

- can still be anything
- the radiator walls "quantize" emission



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

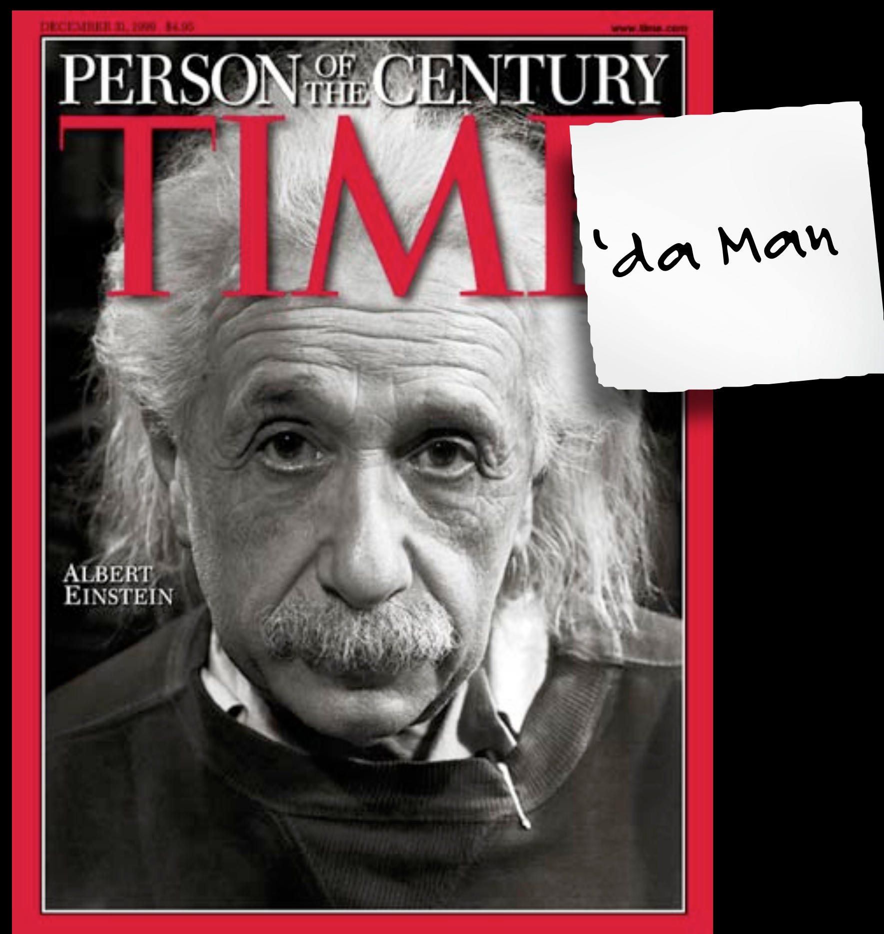
perfect analogy

sound can be any frequency
piano can produce only particular frequencies

sound

piano

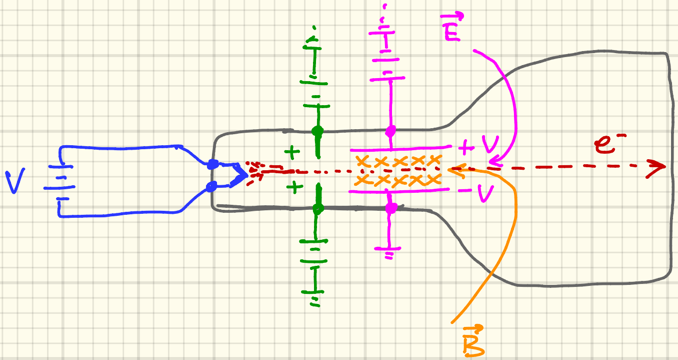
Not a statement about sound!
A statement about pianos!



He’s Back

Dig Into the Historical Intro

ELECTRON DISCOVERY



$$\vec{F} = -q\vec{E} - q\vec{v} \times \vec{B}$$

↑ particulate

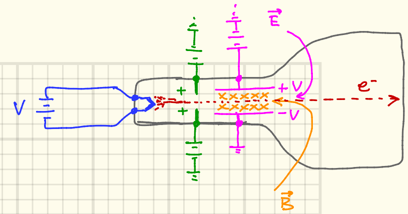
assumed ^ negative charge.

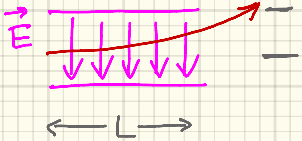
- Adjust $\vec{E}$ & $\vec{B}$ to create zero deflection of beam → determine v.

$$F = 0 = -qE - q v_x B$$

$$\cancel{q}E = \cancel{q} v_x B$$

$$v_x = E/B$$





d deflection

$\uparrow F = qE$

$= a_y m$

$$\begin{cases} a_y = \dfrac{F}{m} = \dfrac{qE}{m} = \dfrac{qV}{md} \\ t = \dfrac{L}{v_x} \end{cases}$$

$v_y = a_y t$

$\tan\theta = \dfrac{v_y}{v_x}$

$$v_y = \frac{qV}{md}\,\frac{L}{v_x}$$

$$\frac{v_y}{v_x} = \tan\theta = \frac{qVL}{md\,v_x^2} \longrightarrow \theta = \frac{VL}{v_x^2 d}\left(\frac{q}{m}\right)$$

from ∅ deflection
$E/B = \dfrac{V}{Bd}$

so

$$\left(\frac{q}{m}\right) = \frac{V\theta}{B^2 L d}$$

he found $\frac{q}{m} = 2 \times 10^{-11}$ C/kg.

He did H^+ ions (protons!) $\frac{q}{m} \cong 10^{-14}$ C/kg.

He found charge from bending.

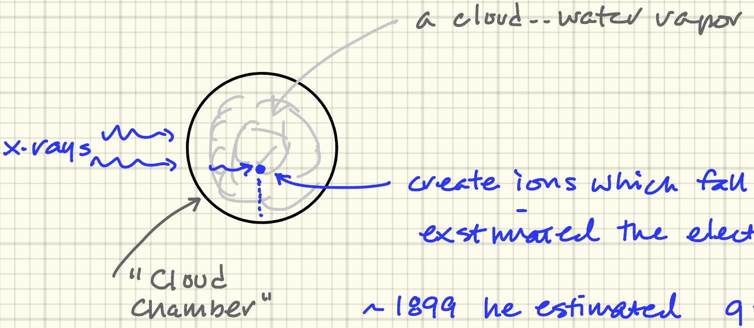
... an the v? ⟶ used fr the m(v) measurements

Why JJ?

- vacuum
- mind-set

q/m is neither "q" nor "m"

JJ:



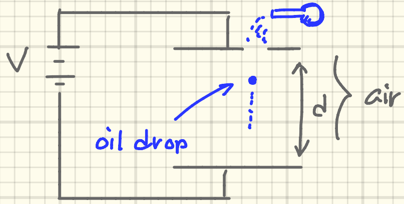
estimated the electrical conductivity

~1899 he estimated $q \cong -1.1 \times 10^{-19}\,C$ -- $-2.3 \times 10^{-19}\,C$

"crude"

Robert Millikan 1906

extreme precision



Adjust $\vec{E}$ to counteract gravity

each drop: many electrons

$$QE = mg$$

total charge on drop

$$E = V/d$$

$$Q = \frac{mgd}{V}$$

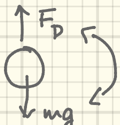
mass of drop

↳ watching them fall

Stokes' Law:

$$F_D = 6\pi a \eta v$$

- radius of drop (a)
- viscosity of air (η)
- terminal velocity of drop (v)



equilibrium

↳ ρ, mass density of drops

Table after table of Q's

looked for common divisor

"e" $= 1.60217733 \times 10^{-19}$ C

Millikin ... within 1%