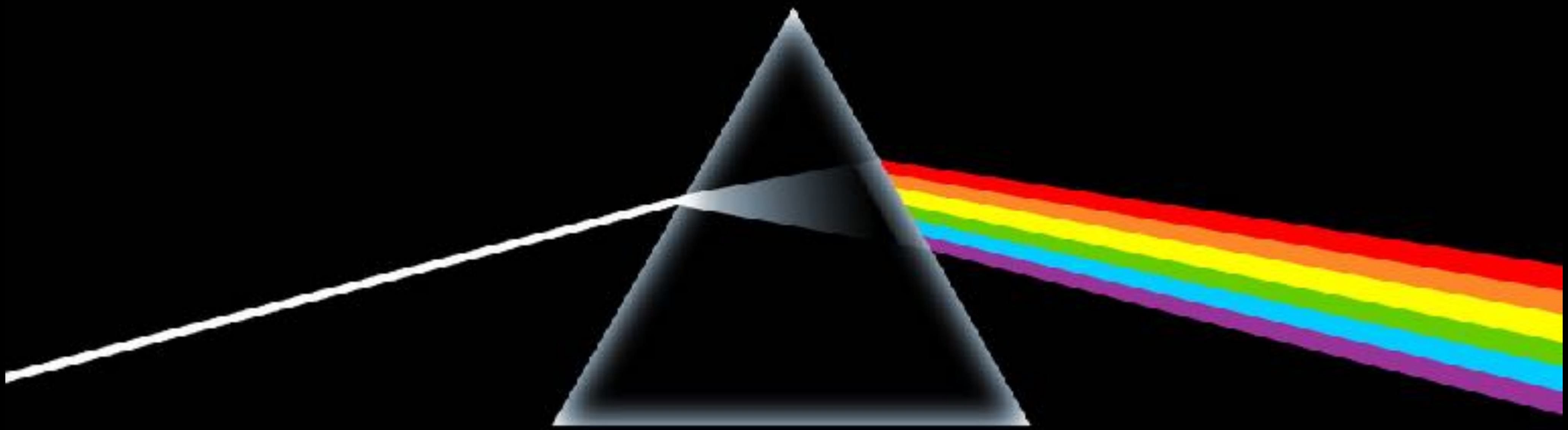
Astronomy 503
Observational Astronomy



Prof. Gautham Narayan

Lecture 02: Light & Radiation

Announcements

- Read Longair 2009 *History of Astronomical Discoveries* to discuss on Teams over the weekend (reading will be on GitHub for convenience)

Exp Astron (2009) 25:241–259
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REVIEW ARTICLE

History of astronomical discoveries

Malcolm Longair

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Abstract The wide diversity of routes to astronomical, astrophysical and cosmological discovery is discussed through a number of historical case studies. Prime ingredients for success include new technology, precision observation, extensive databases, capitalising upon discoveries in cognate disciplines, imagination and luck. Being in the right place at the right time is a huge advantage. The changing perspectives on the essential tools for tackling frontier problems and astronomical advance are discussed.

Keywords Astronomy · Astrophysics · Cosmology · Discovery · History

M31

Andromeda

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Andromeda


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Andromeda

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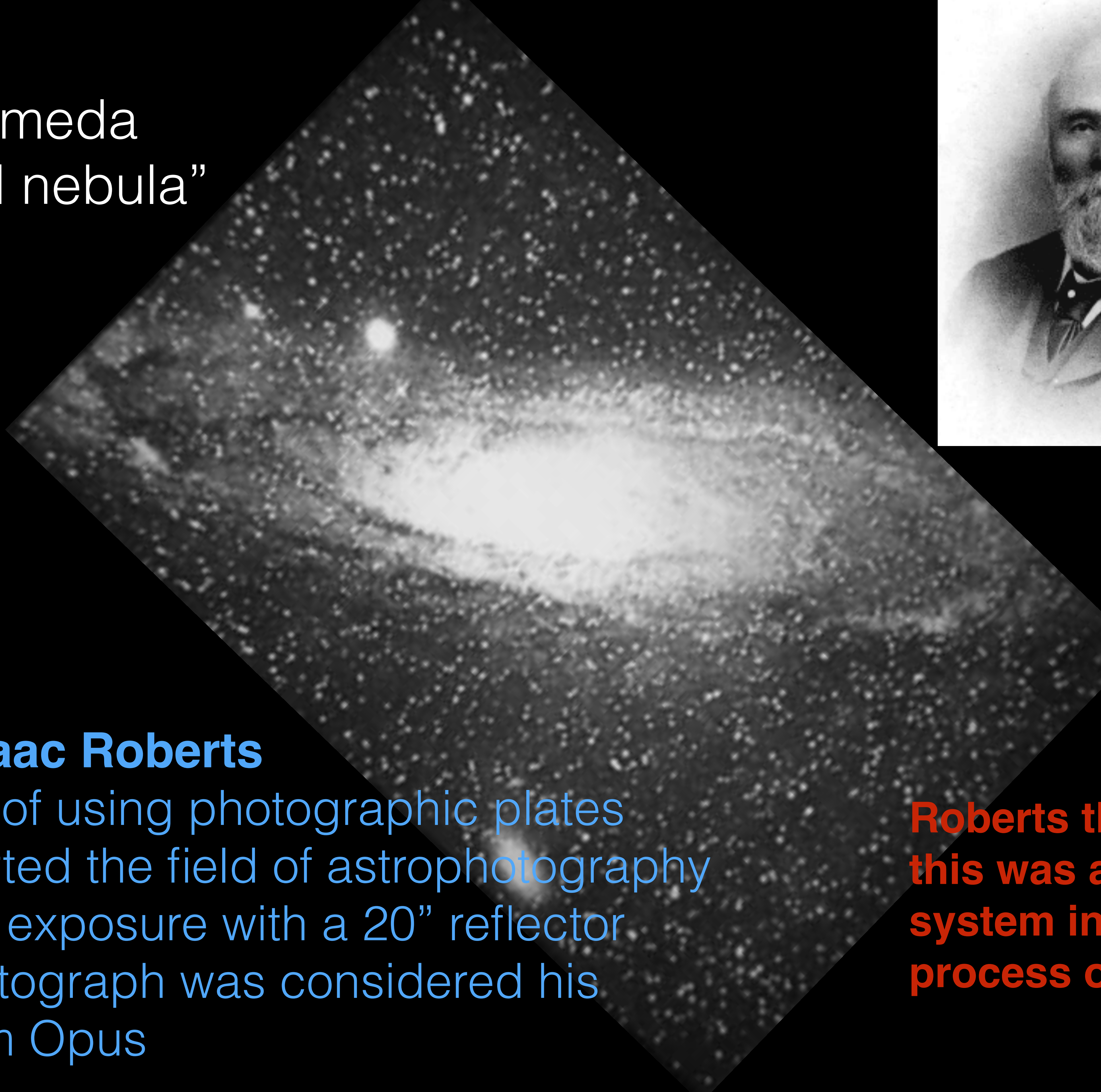
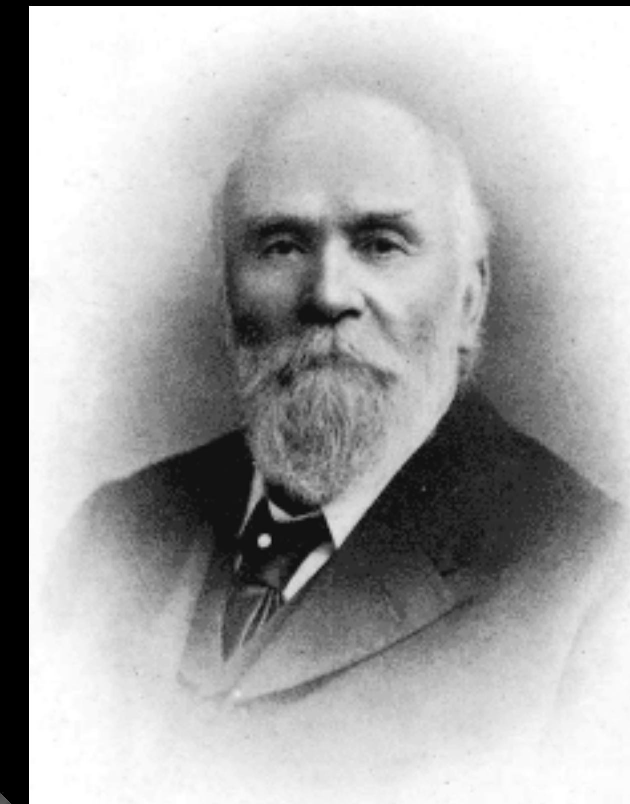
Andromeda
“spiral nebula”





1899 Isaac Roberts
pioneer of using photographic plates
and started the field of astrophotography
~1 hour exposure with a 20” reflector
this photograph was considered his
Magnum Opus

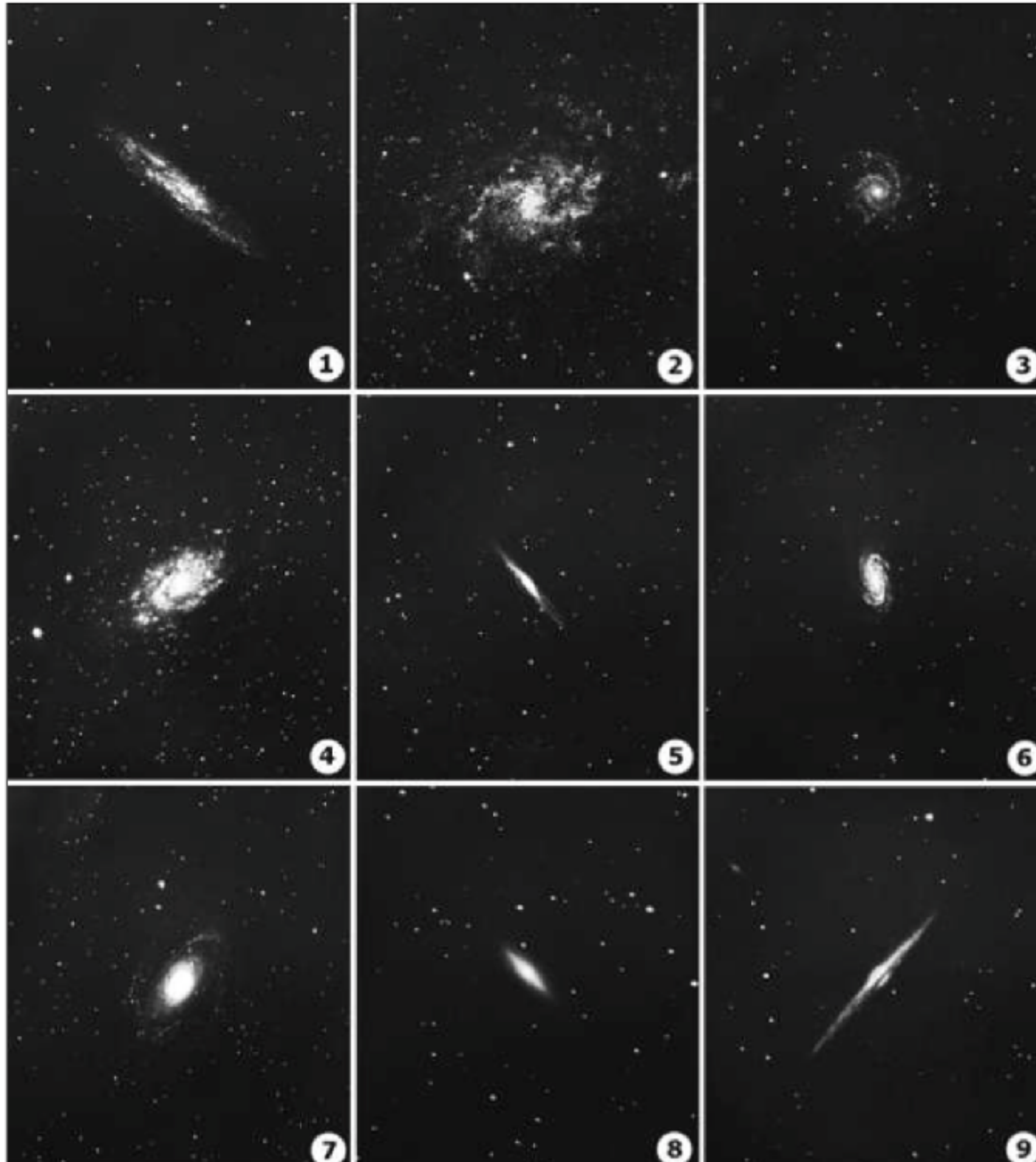
Roberts thought this was a solar system in the process of forming

Photographs obtained by Keeler with the Crossley 36-inch reflector ~1899–1901

Typical exposures ~3 hours. (Lick Director Keeler died in 1900.)

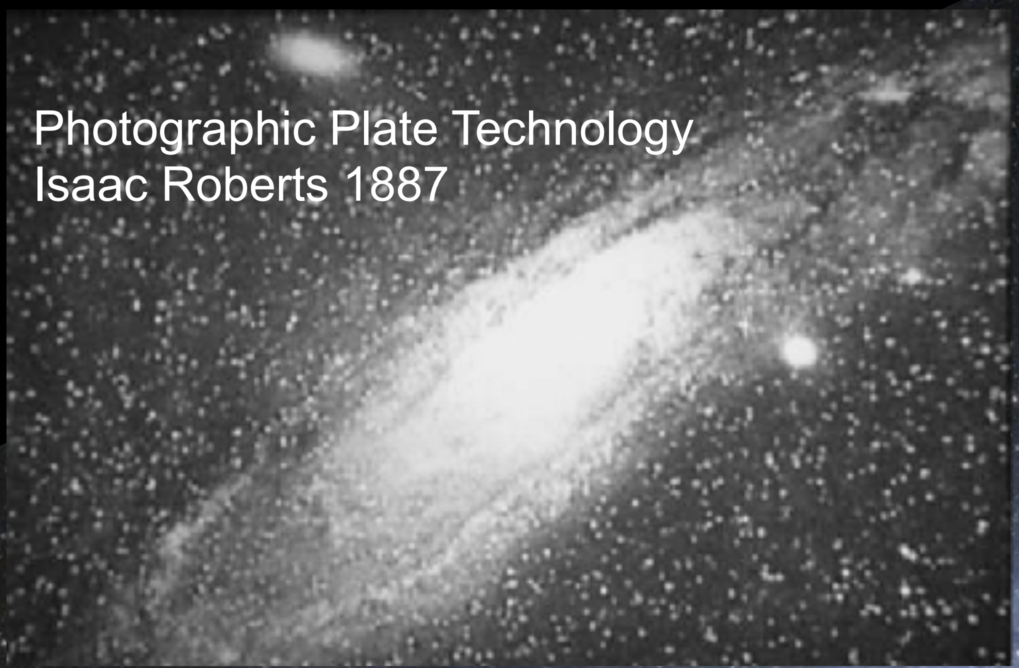
Between 1912—1923 Herber Curtis began arguing that these nebulae were island universes.

This led to the famous Great Debate in 1920 with Harlow Shapley

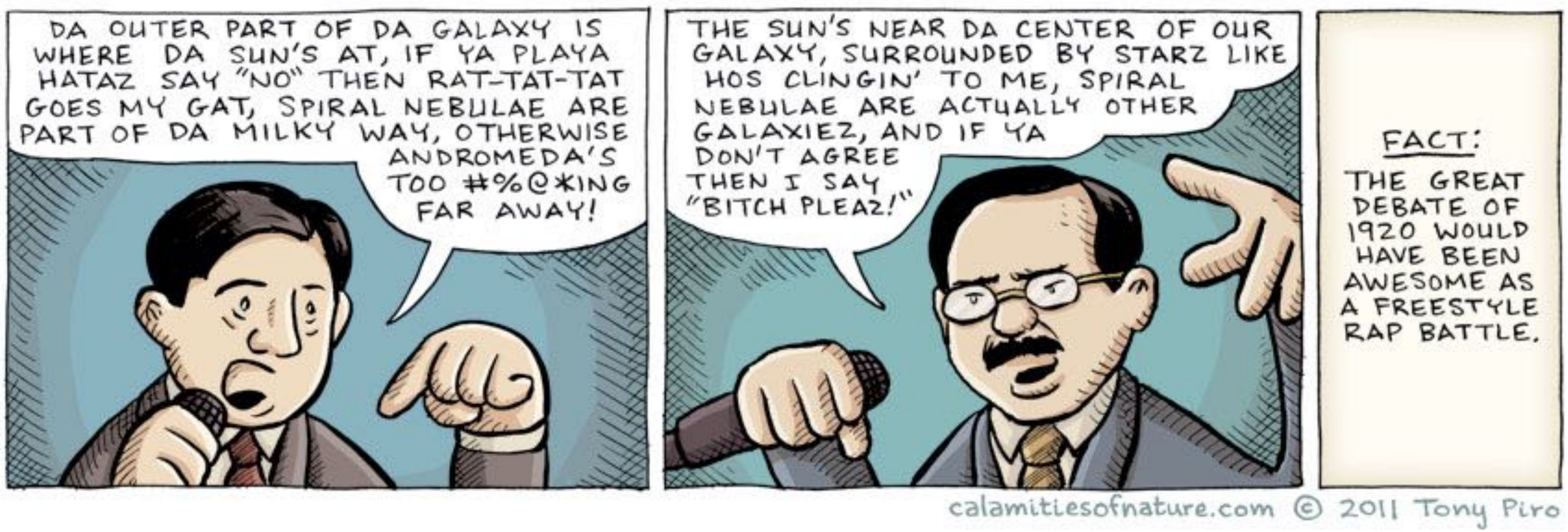


The Great Debate of 1920

- In the early 1900s, scientists argued whether “spiral nebulae” were entire galaxies, or just collections of stars within the Milky Way
- In 1920 a debate was held at the US National Academy of Sciences between eminent astronomers Harlow Shapley and Heber Curtis
- Harlow: Milky Way was the entire Universe. Andromeda would have to be millions of light years from earth.
- Heber: Nebulae are "Island Universes"



Lil' Harlow Heber Dawg

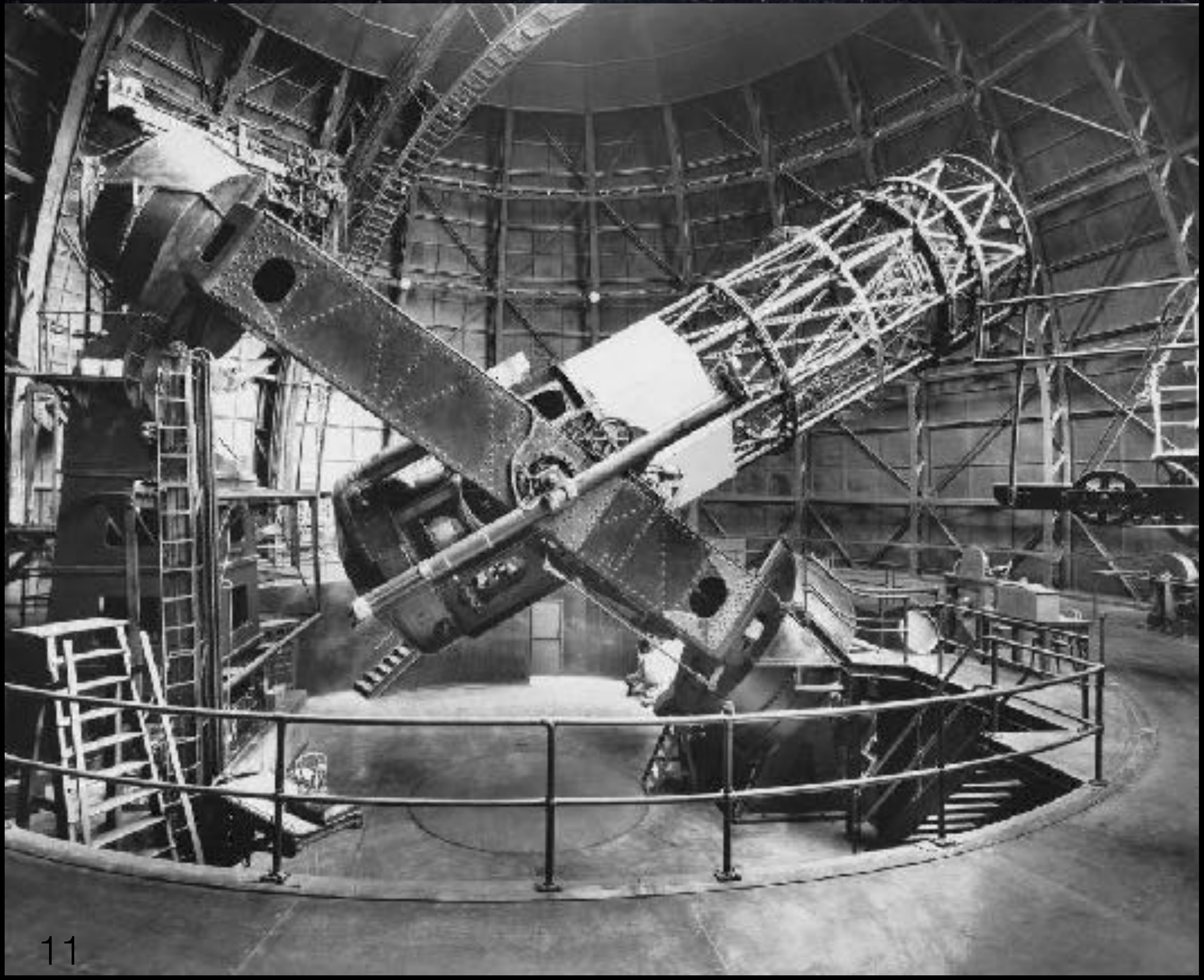


Hubble Discovers the Universe

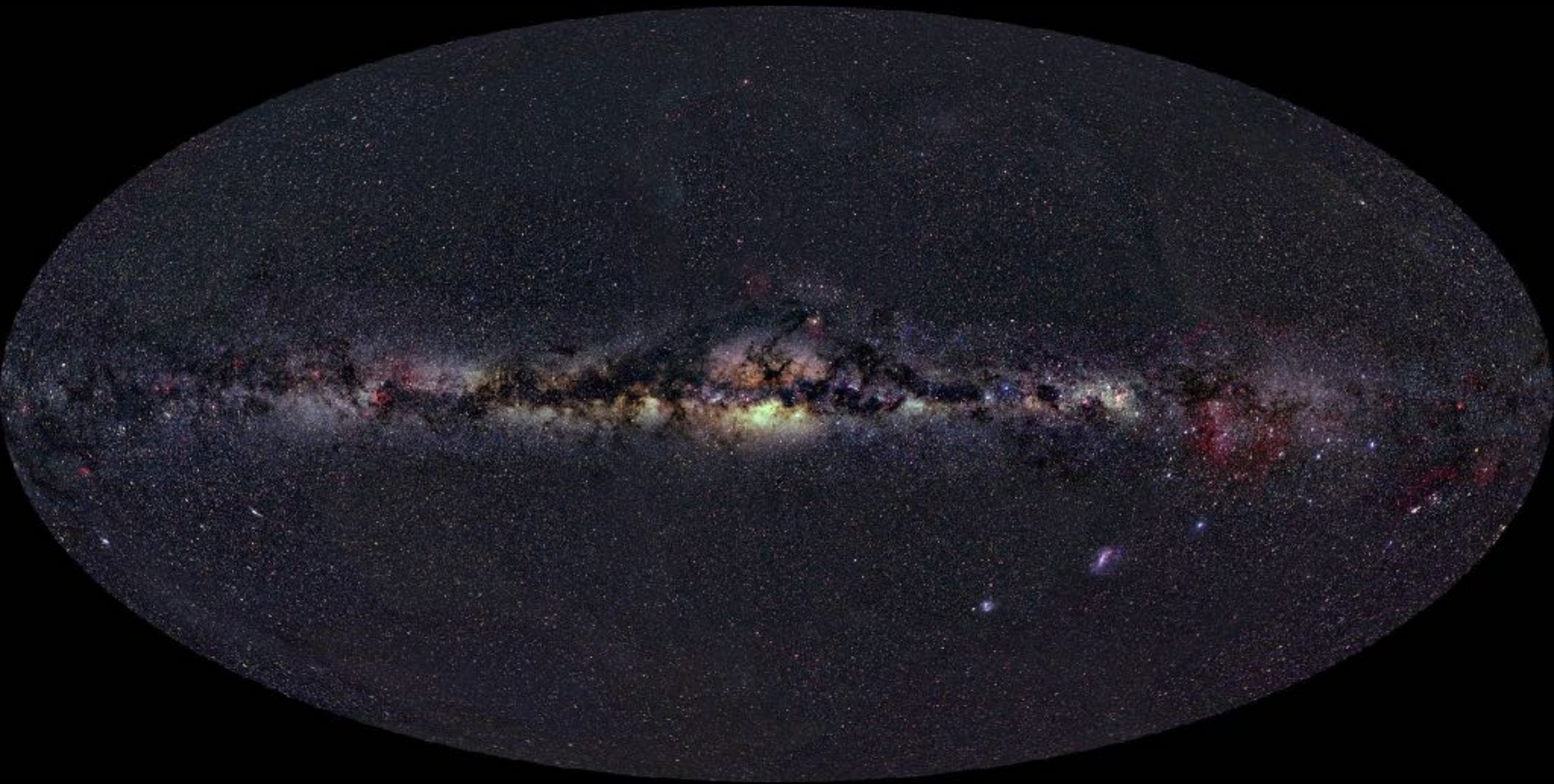
- In 1917 the 100” (2.5m) Hooker Telescope on Mt Wilson was completed. It was the largest and most powerful telescope in the world until1949.

- In 1923 Edwin Hubble used it to measure the distance to Andromeda. (1 million light years away)

- This completely revolutionized our understanding of the Universe.



The Milky Way



M31

Andromeda

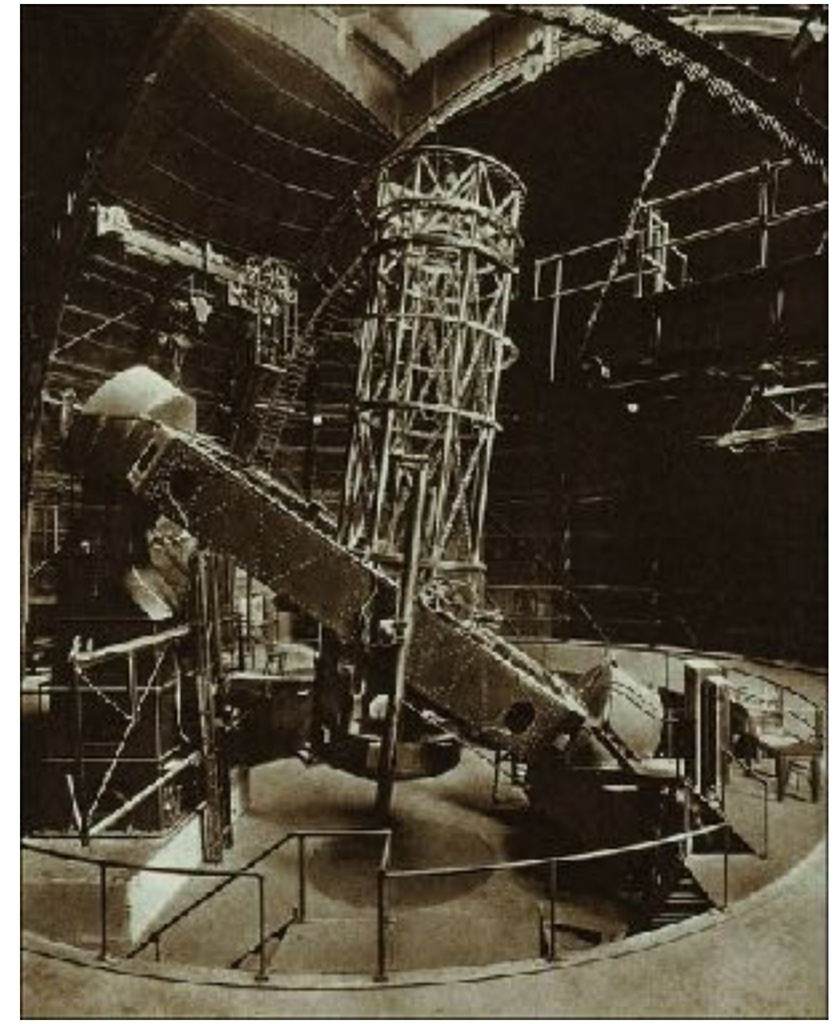
The closest spiral galaxy to the Milky Way

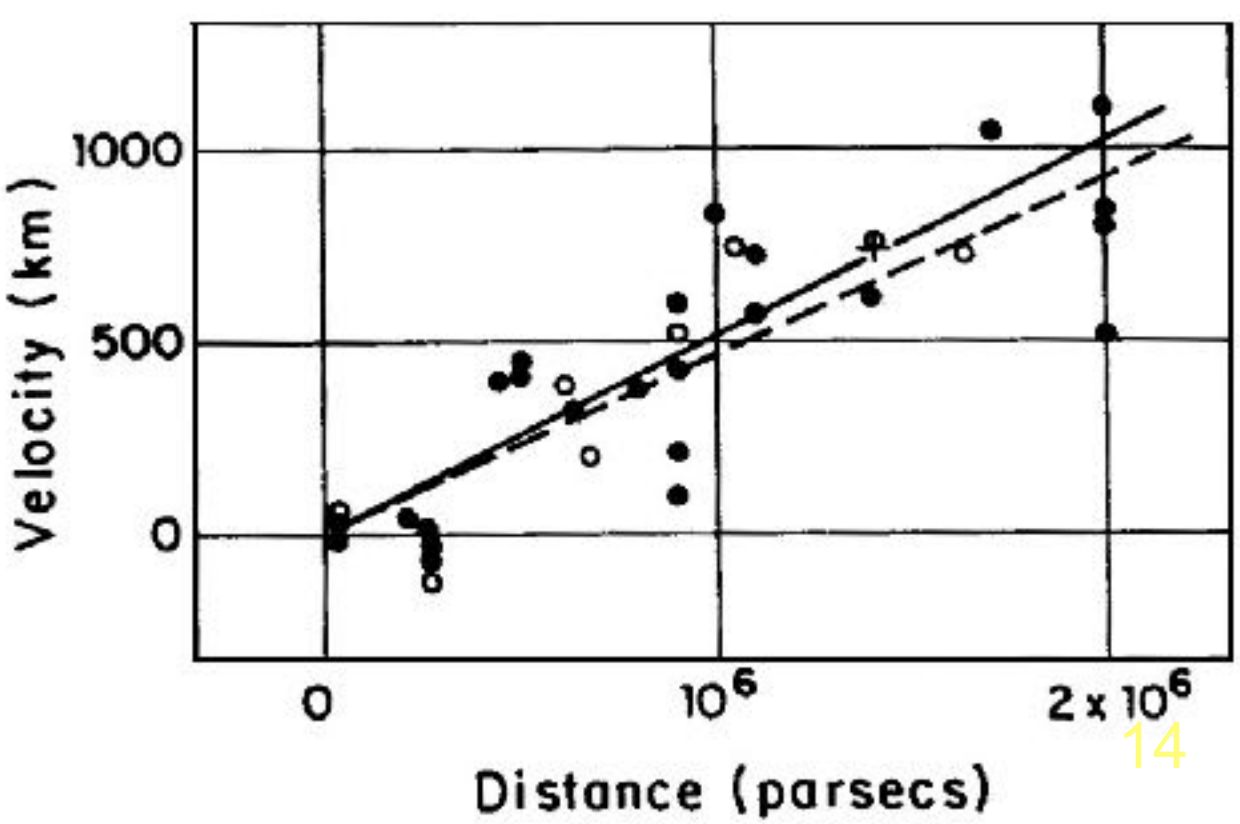
1.2 trillion M_{sun}

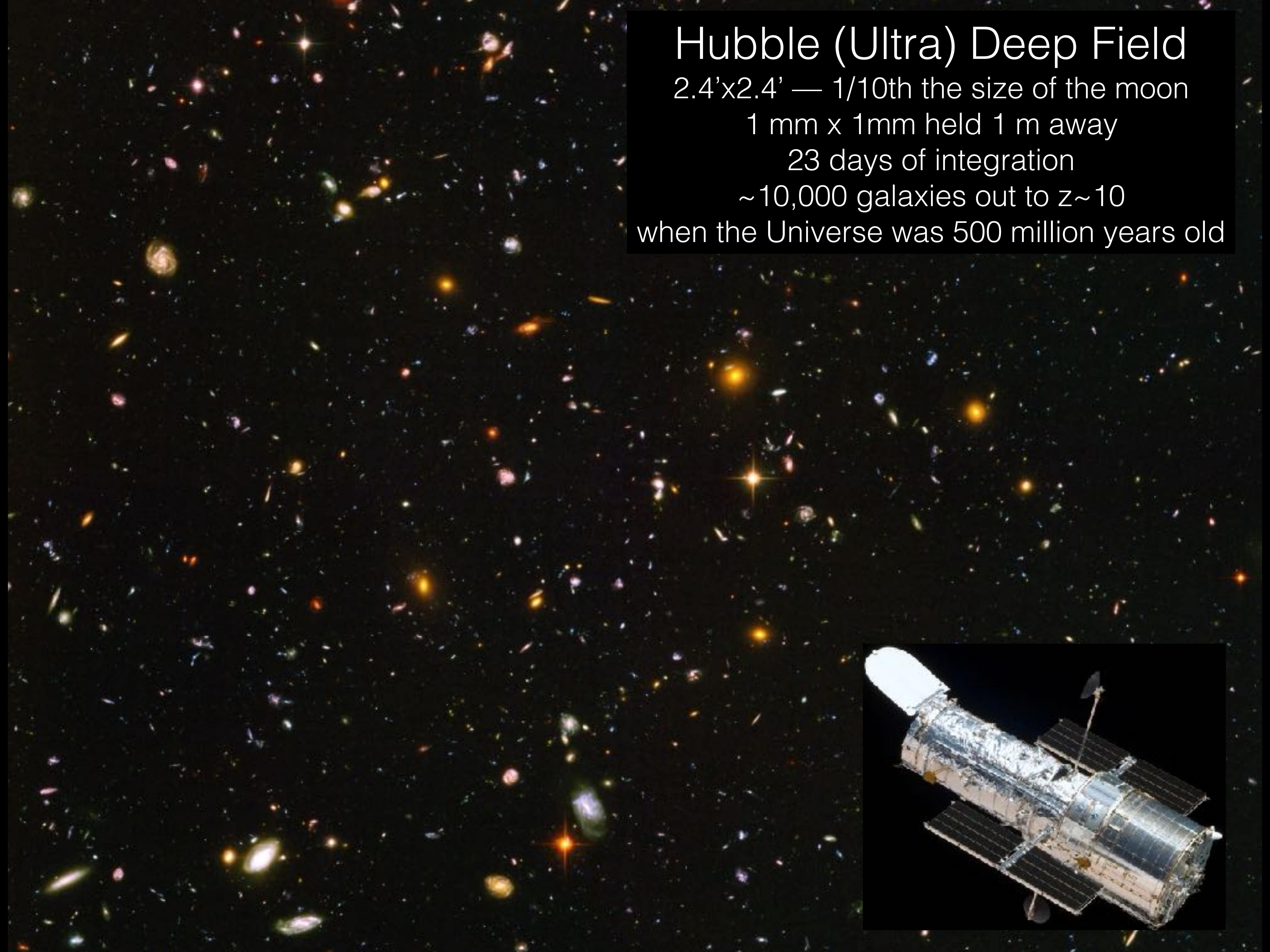
2.5 Mly away

The Universe is Expanding

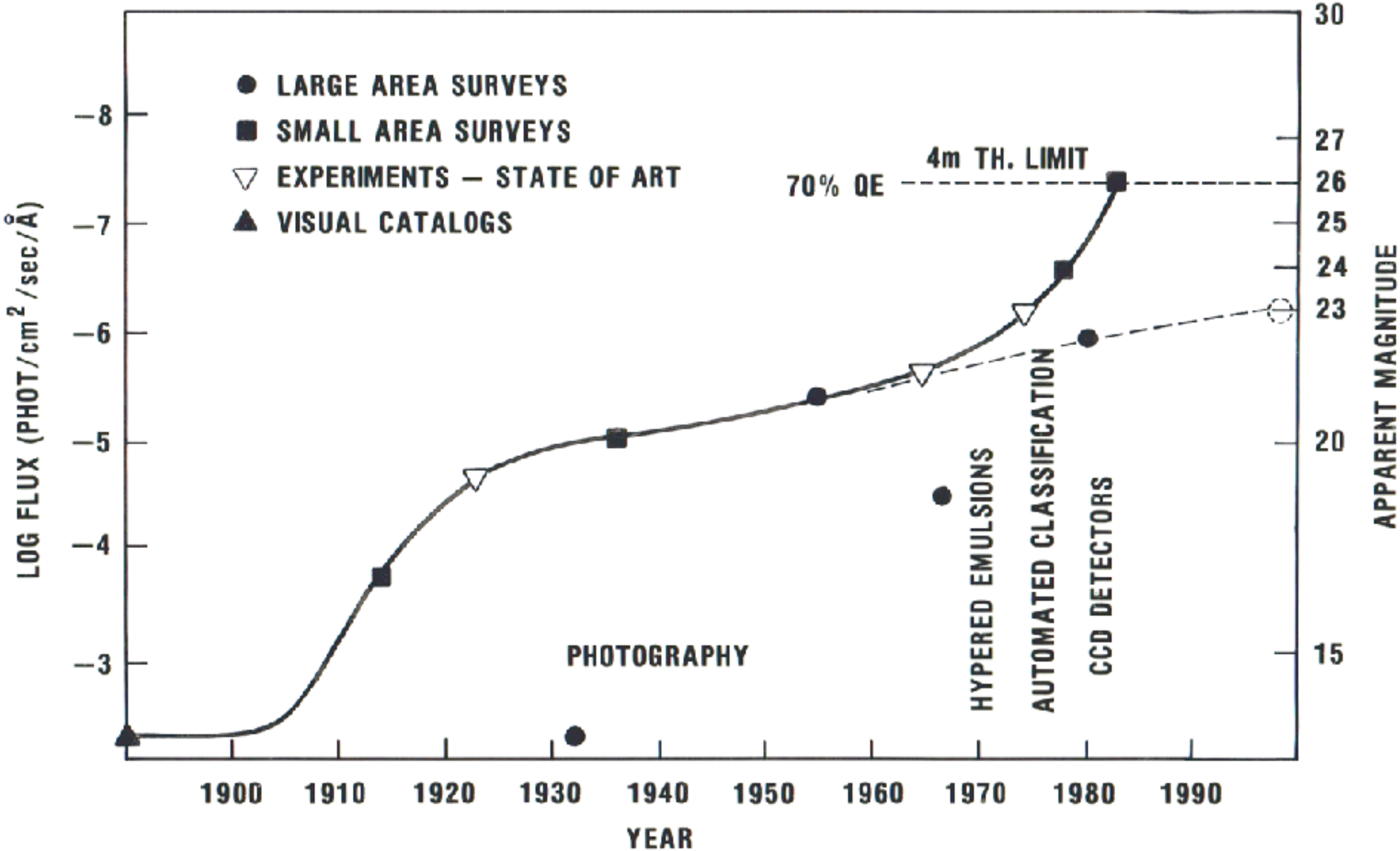
- In 1922 Edwin Hubble determined the distance to the nebulae by observing cepheid variable stars.
- He used the 100-inch Hooker Telescope on Mt. Wilson, which was the most powerful telescope on Earth from 1917—1948
- In 1929 he reported the "redshift distance law of galaxies" thereby demonstrating that the Universe, once assumed to be unchanging, was expanding



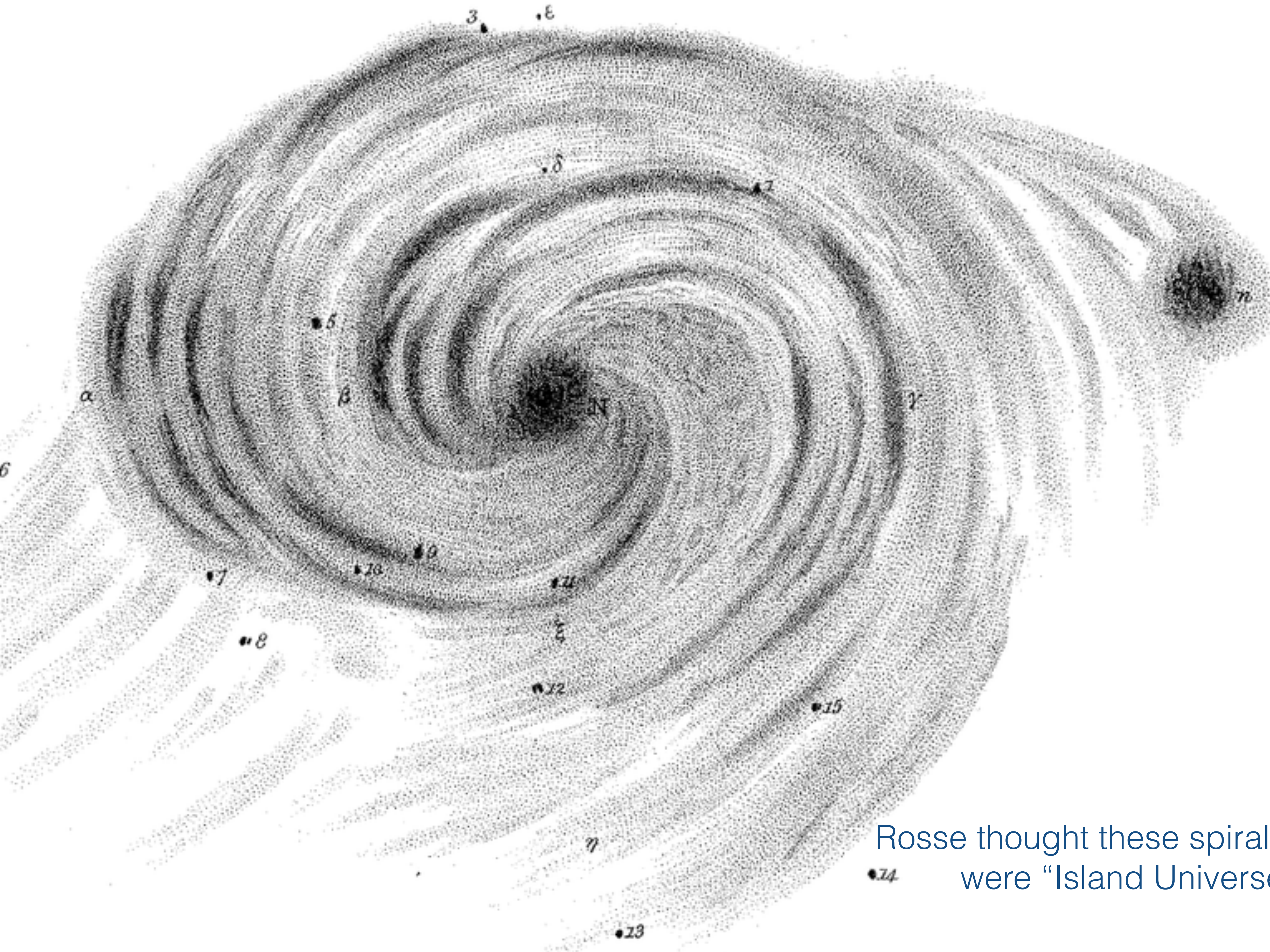



Hubble (Ultra) Deep Field
2.4’x2.4’ — 1/10th the size of the moon
1 mm x 1mm held 1 m away
23 days of integration
~10,000 galaxies out to z~10
when the Universe was 500 million years old

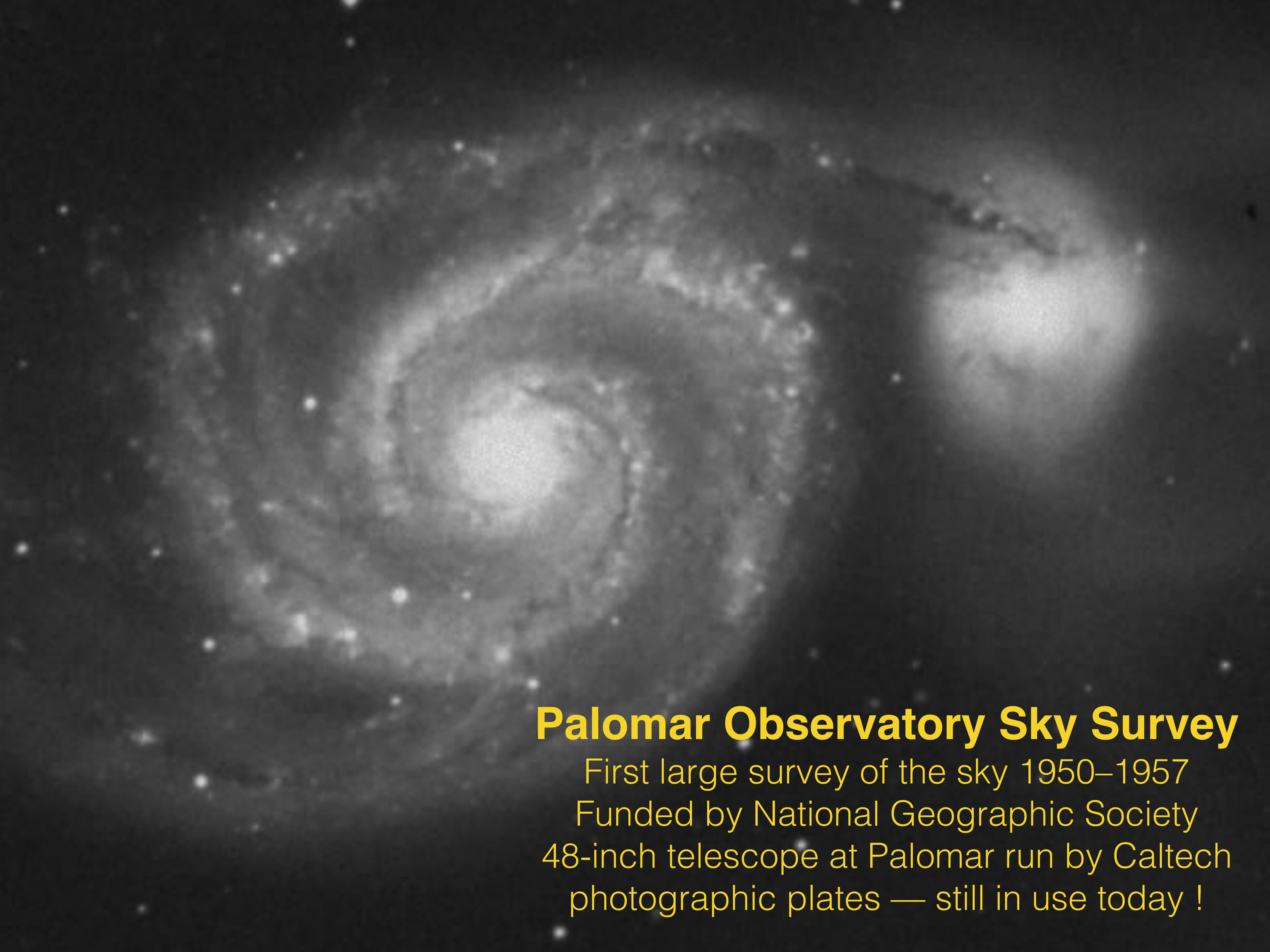
MODERN LIMITS FOR GALAXY PHOTOMETRY



Sketch of M51 by Lord Rosse in 1845



Rosse thought these spiral nebulae were “Island Universes”



Palomar Observatory Sky Survey

First large survey of the sky 1950–1957
Funded by National Geographic Society
48-inch telescope at Palomar run by Caltech
photographic plates — still in use today !

Sloan Digital Sky Survey (SDSS)

digital survey of the 35% of the sky 2000–2005

2.5m telescope in New Mexico

Final lab is with this data!

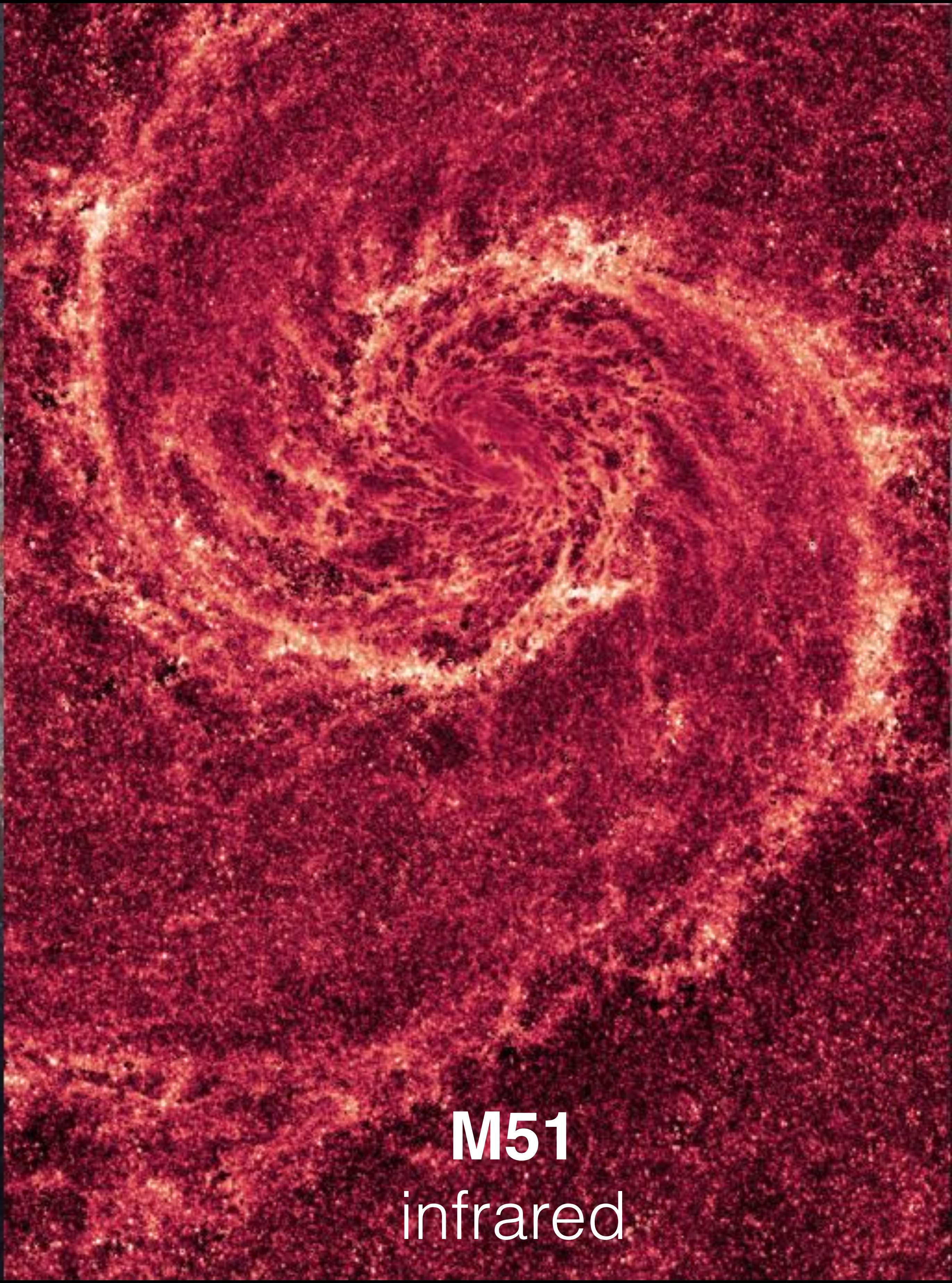

Hubble Space Telescope
2.4 m
ACS camera 2005

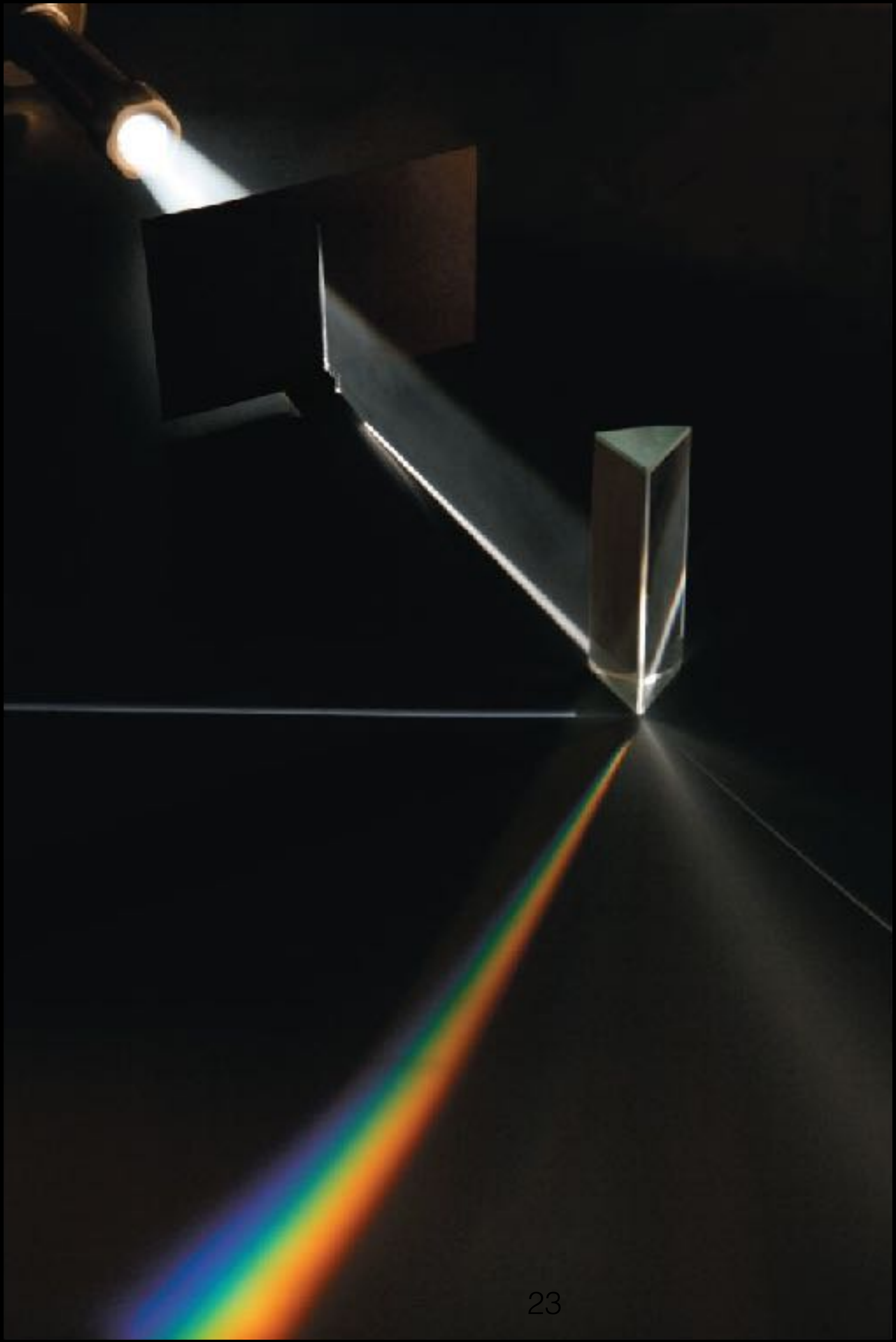
M51

NGC 5194
Whirlpool Galaxy
spiral galaxy
160 billion M_{sun}
AGN in center
23 M ly away

M51b

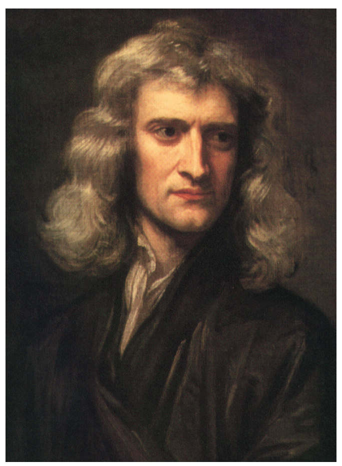
NGC 5195
Dwarf Galaxy
Getting eaten up by M51
passed through the center
600 m years ago, and again
100 M years ago
Interaction cause a burst of
star formation in M51


M51
optical

M51
infrared

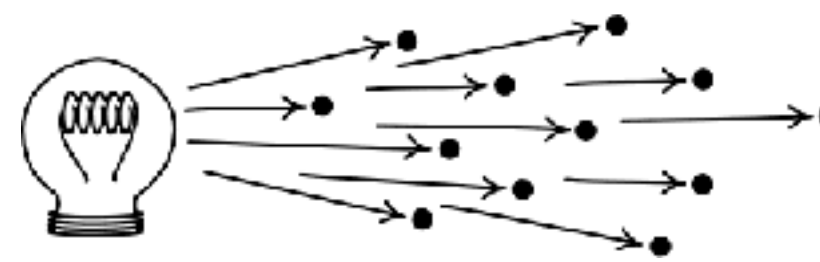


What is light made of?

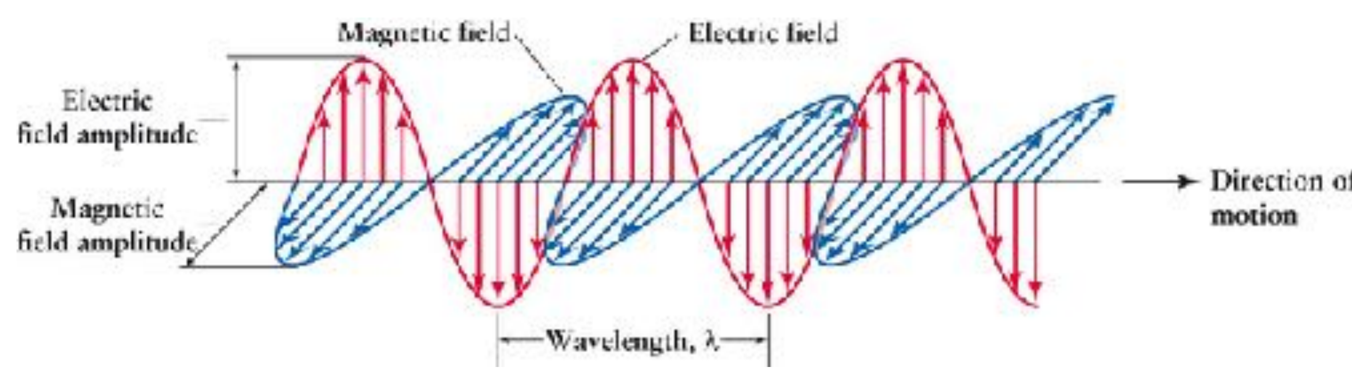
- Huygens (1629–1695): **Waves** !



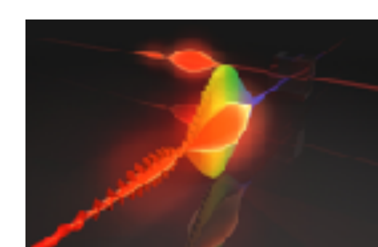
- Newton (1642–1727): **Particles**!



- Maxwell (1831–1879): Oscillating electric and magnetic **fields** !

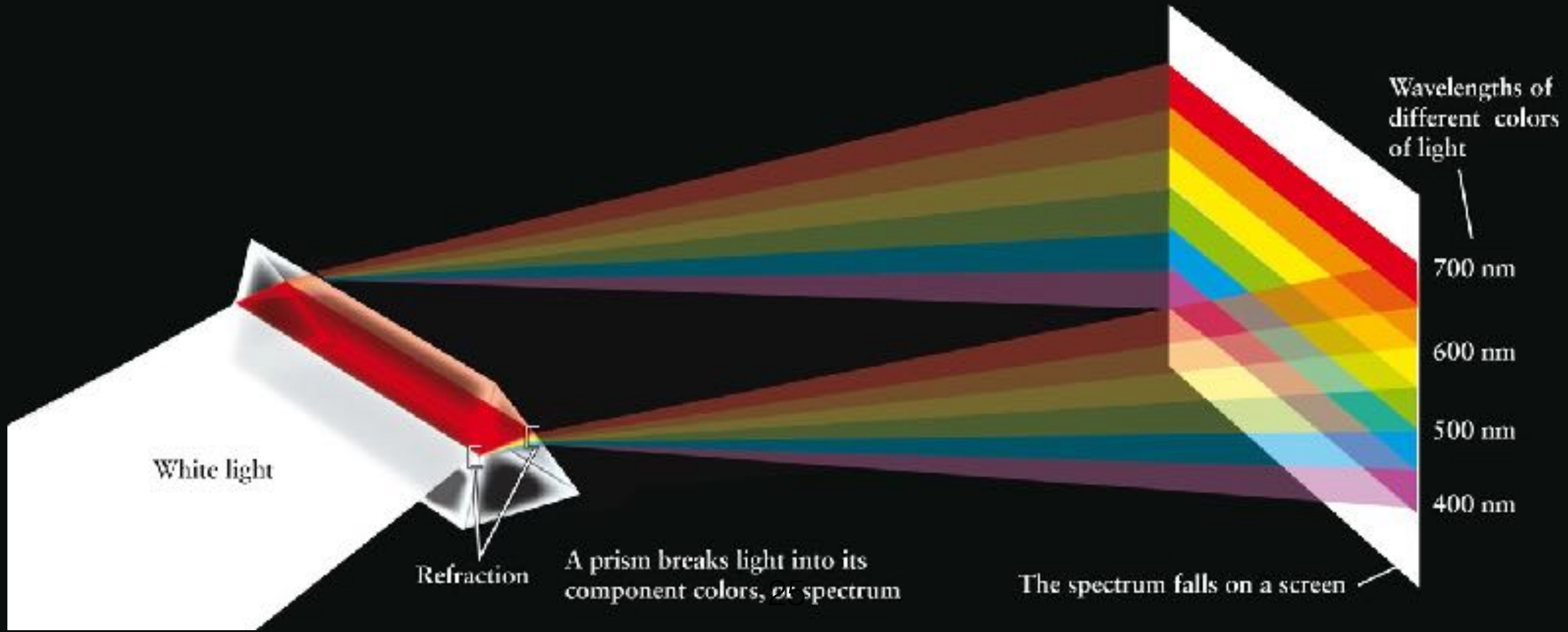


- Einstein (1879–1955): Quanta of **energy** !



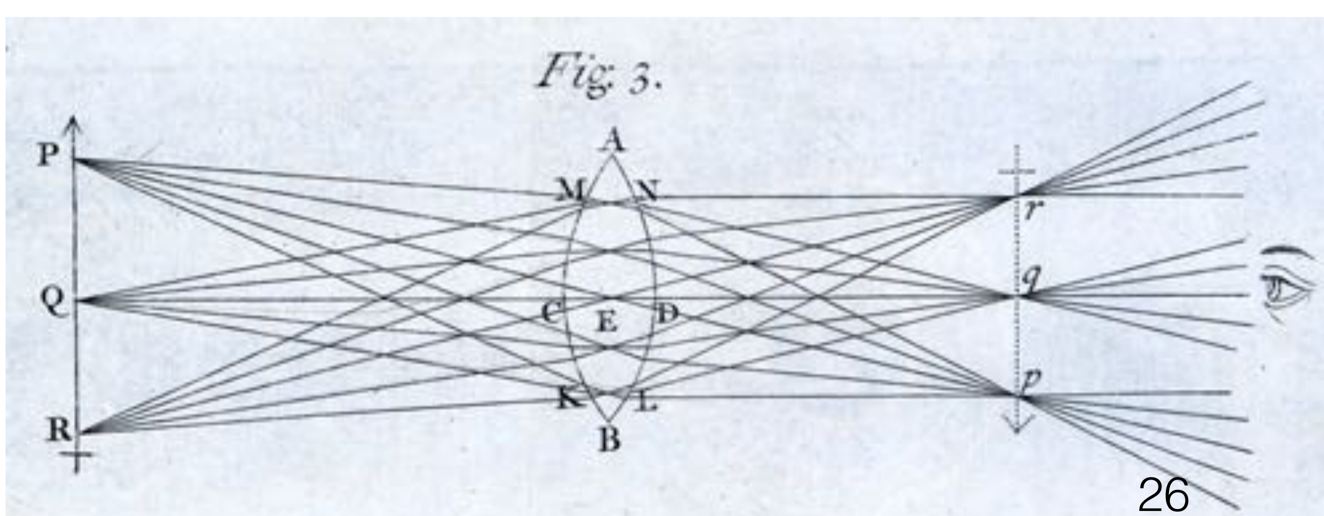
magic crystals, rainbows, & dispersion

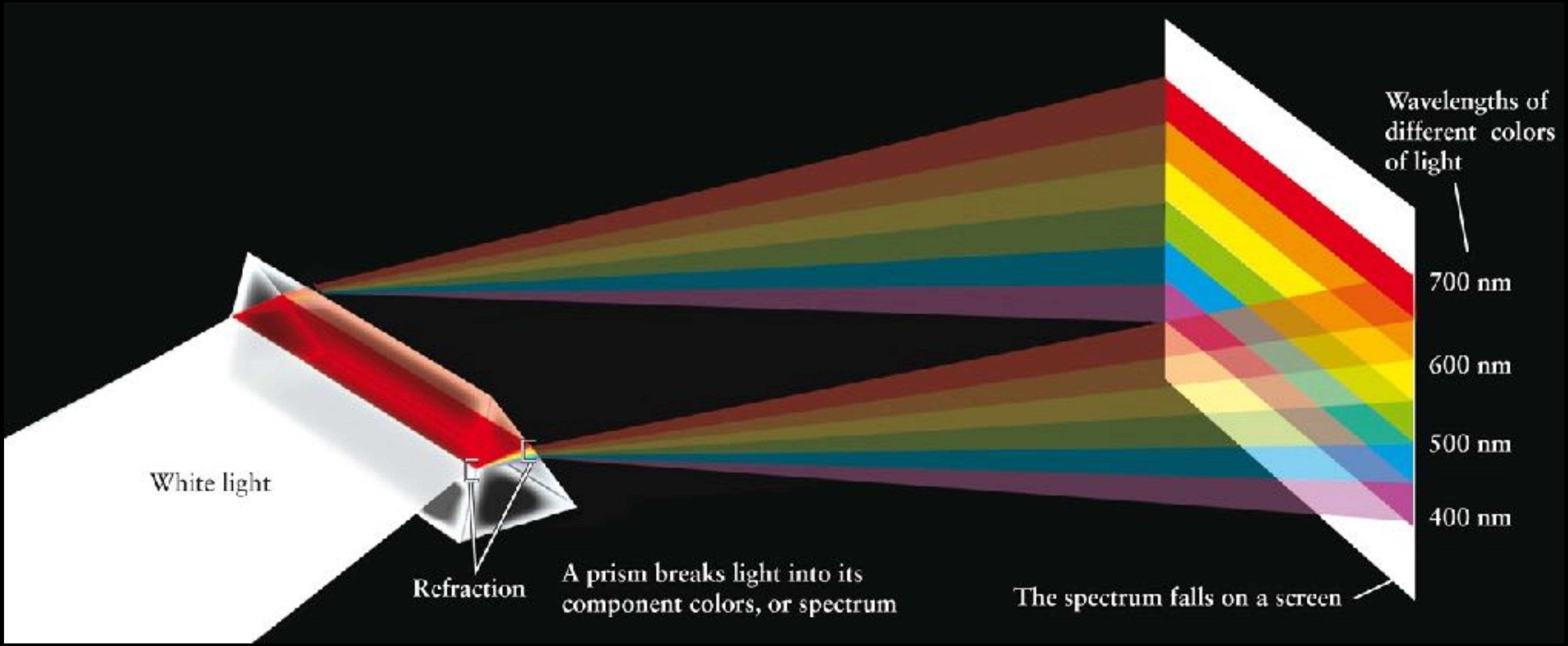
- Before Newton, it was believed that white light was colorless, and that the prism itself produced the color. Newton's experiments demonstrated that all the colors already existed in the white light and that “particles" of light were fanned out because particles with different colors traveled with different speeds through the prism.
- Newton arrived at his conclusion by passing the red color from one prism through a second prism and found the color unchanged. From this, he concluded that the colors must already be present in the incoming light — thus, the prism did not create colors, but merely separated colors that are already there. He also used a lens and a second prism to recompose the spectrum back into white light. This experiment has become a classic example of the methodology introduced during the scientific revolution.
- It was only later that Young and Fresnel combined Newton's particle theory with Huygens' wave theory to show that color is the visible manifestation of light's wavelength.
- Light changes speed as it moves from one medium to another (for example, from air into the glass of the prism). The speed of light is related by the index of refraction, $v = c/n$, where $n=1$ in vacuum and $n(\lambda)\sim 1.6$ in glass.
- This speed change causes the light to be refracted and to enter the new medium at a different angle, with the degree of bending depending on the angle that the incident beam of light makes with the surface, and on the ratio between the refractive indices of the two media (Snell's law).
- This can be used to separate a beam of white light into its constituent spectrum of colors (**spectroscopy**). The most familiar example of dispersion is probably a **rainbow**, in which dispersion causes the spatial separation of a white light into components of different wavelengths (different colors).



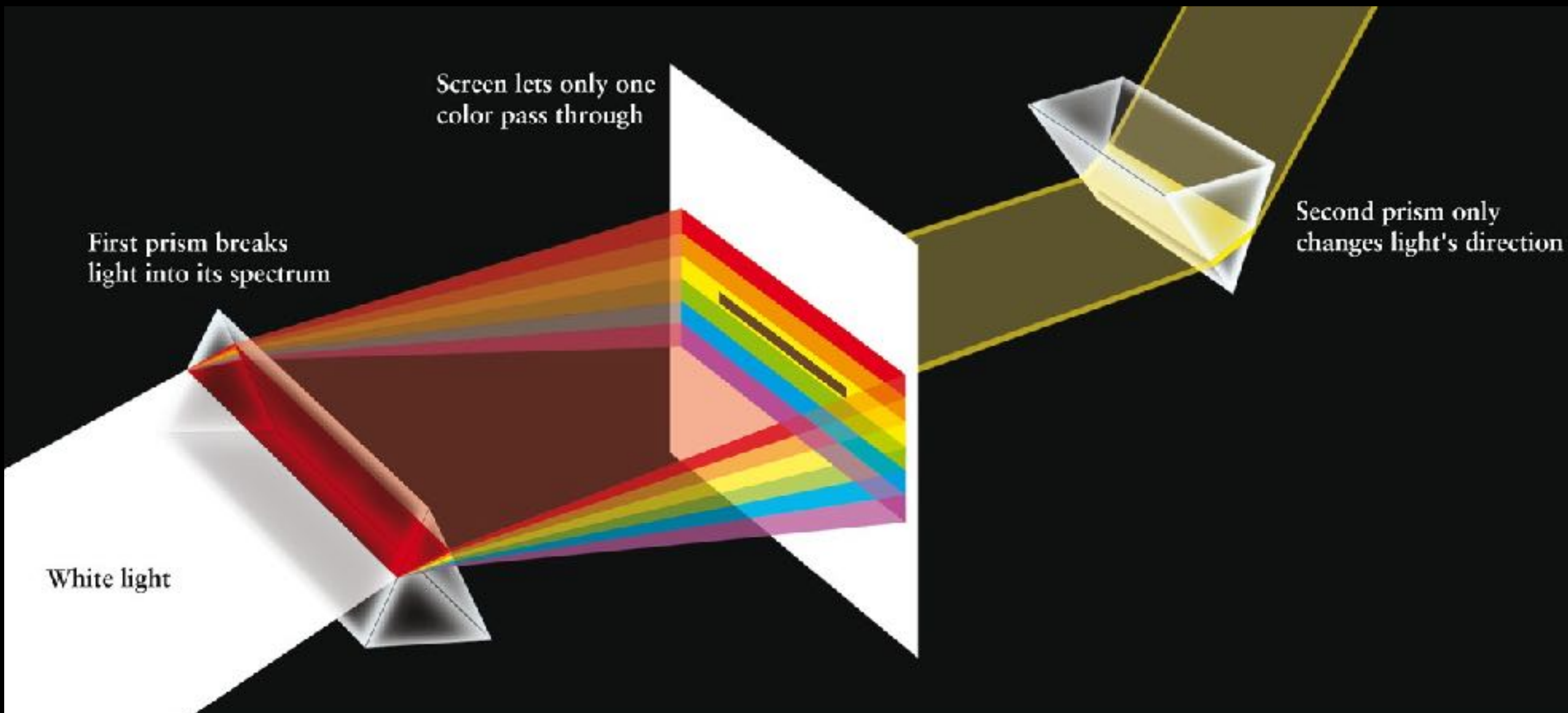
Light behaves like a particle

- Newton's view (1642–1726)
- light travels in straight lines
- light behaves discretely, e.g. photoelectric effect
- allowed calculation of optics —> In 1668 built first reflecting telescope
- In 1704 Newton published *Optiks*
- Newton's view prevailed until Maxwell largely based on reputation.
- failed to explain: diffraction, interference, polarization.
- think: x-rays



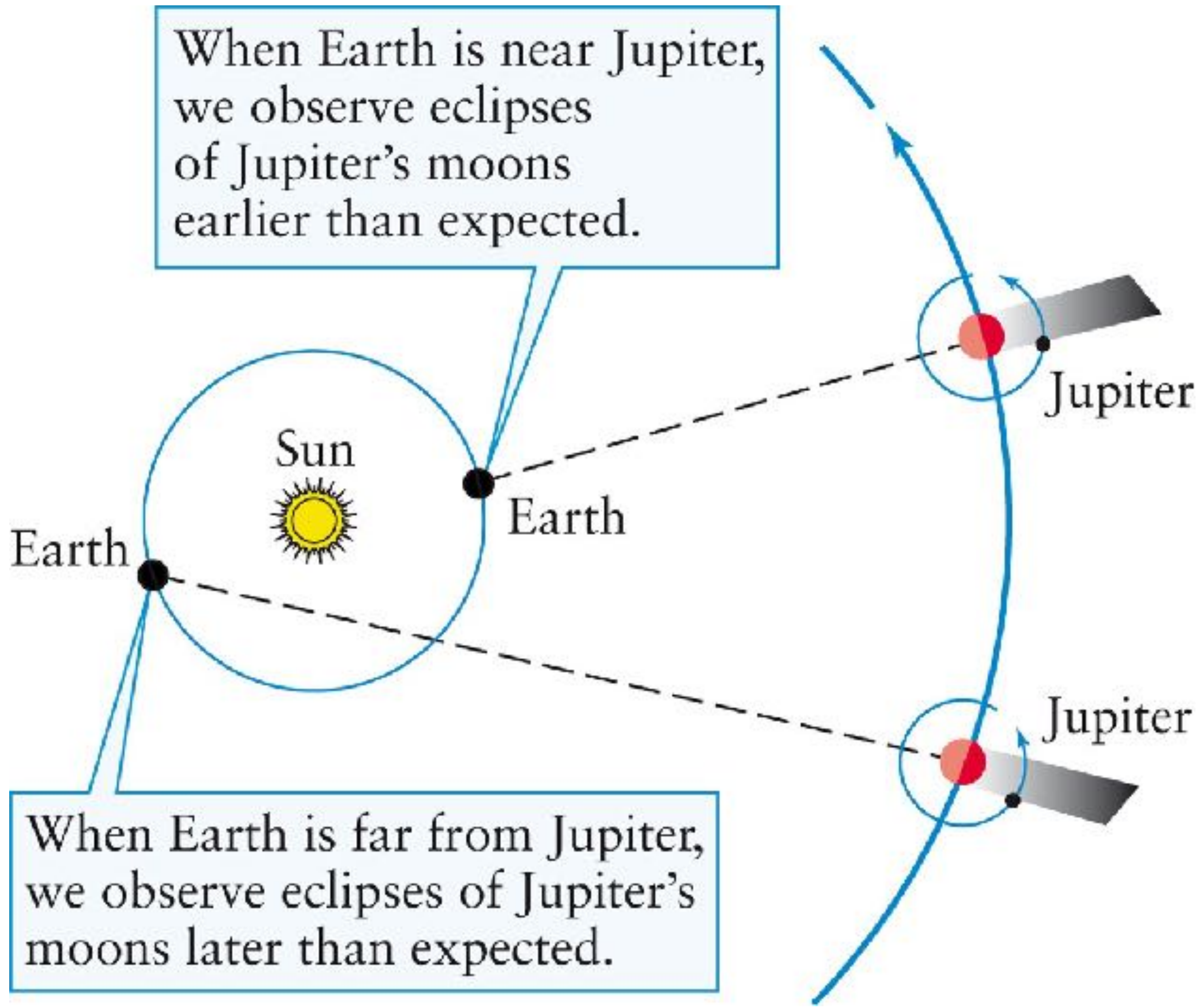

Wavelengths of different colors of light
700 nm
600 nm
500 nm
400 nm
White light
Refraction
A prism breaks light into its component colors, or spectrum
The spectrum falls on a screen

Newton’s experiment:

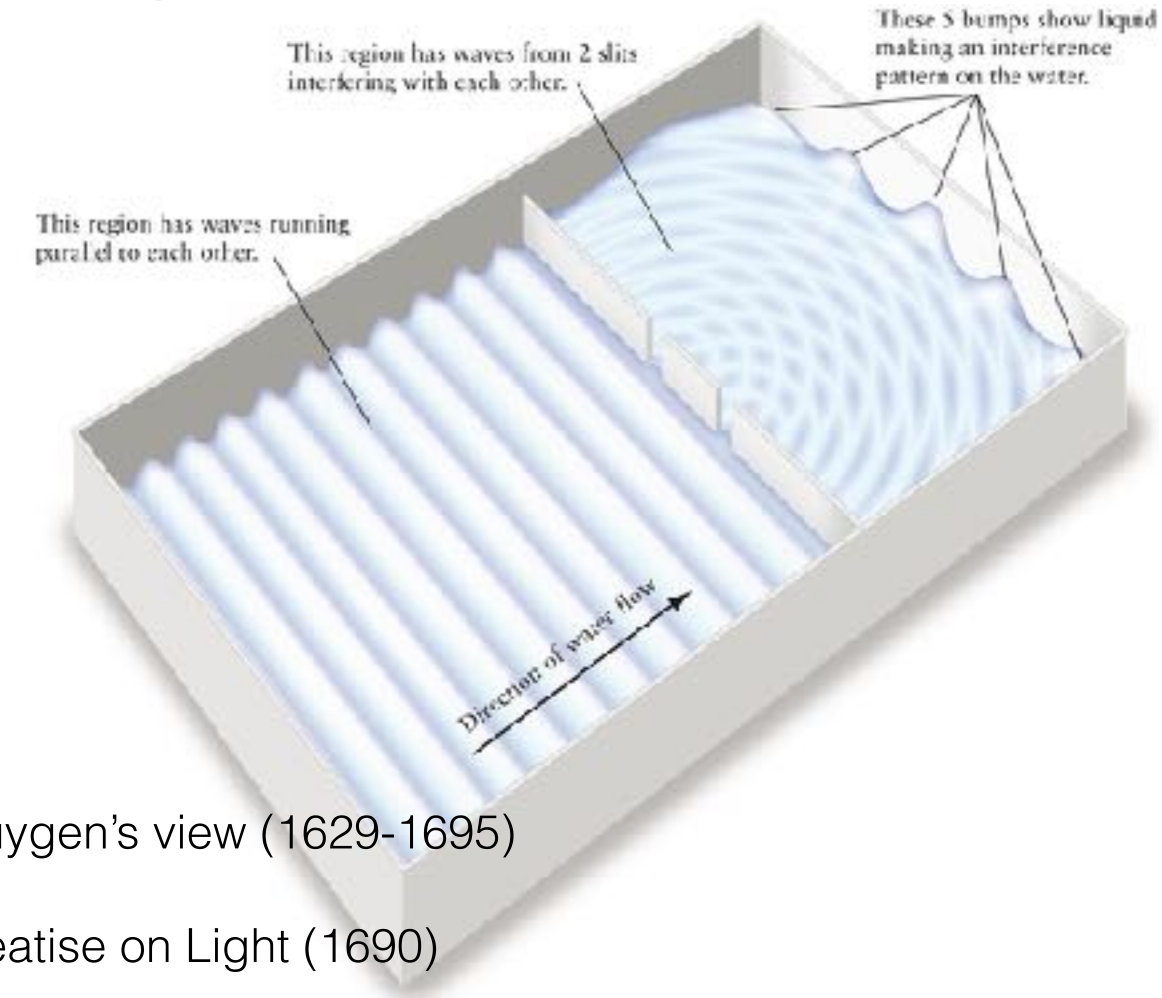


Ole Roemer (1644-1710) measures the Speed of Light

Roemer noticed that on average, Io (42.5 hour orbital period) took took an *extra* 3.5 minutes to pass behind Jupiter when the Earth was moving *away* from Jupiter, and 3.5 minutes *less* when the Earth was moving *towards* Jupiter.

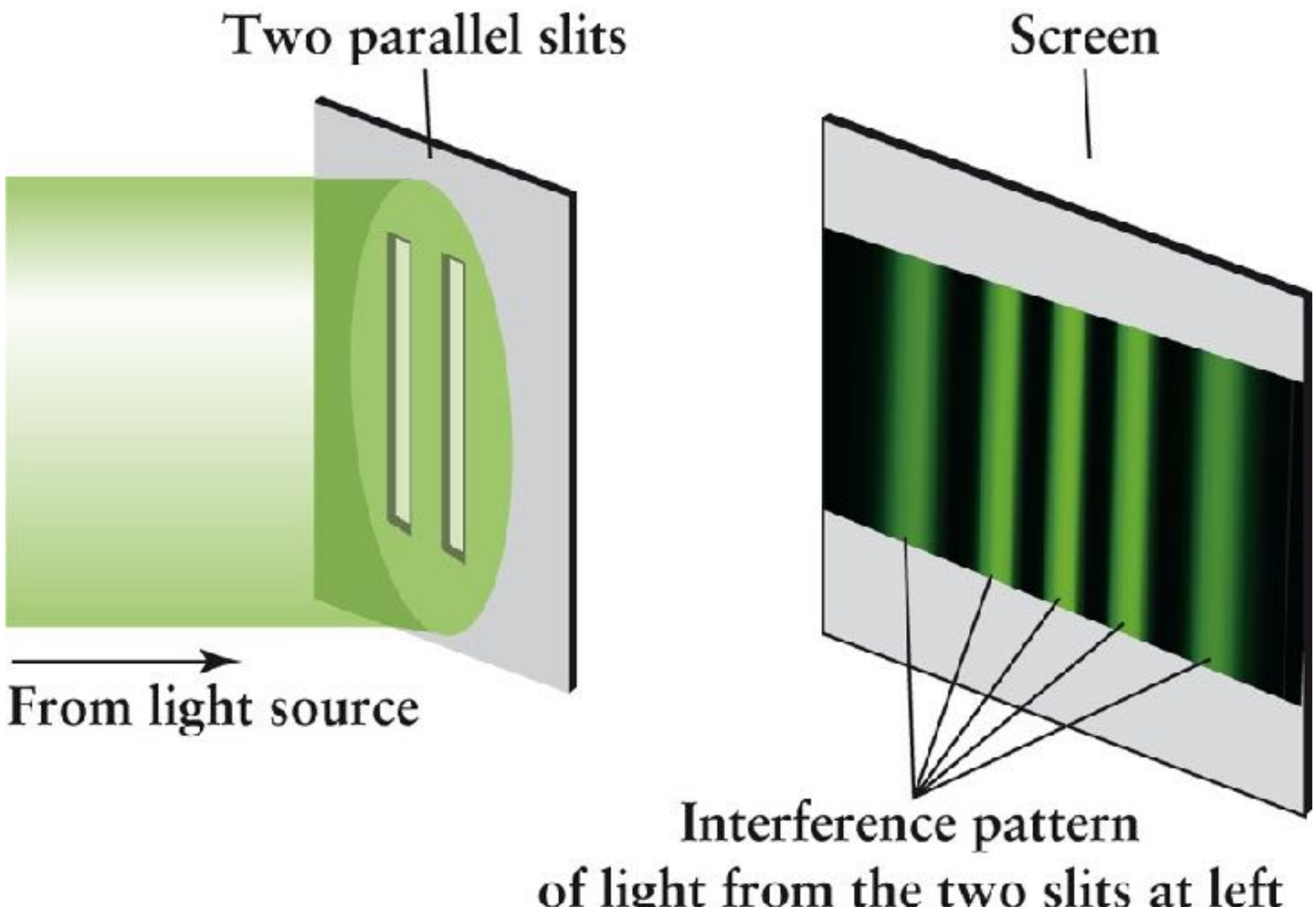


Light behaves like a wave



- Huygen’s view (1629-1695)
- Treatise on Light (1690)
- Evidence: refraction, diffraction, interference, polarization, birefringence
- Newton’s view prevailed until Maxwell largely based on reputation.
- Maxwell’s equations confirmed this view, joined infrared, optical, and UV radiation.
- think: radio waves

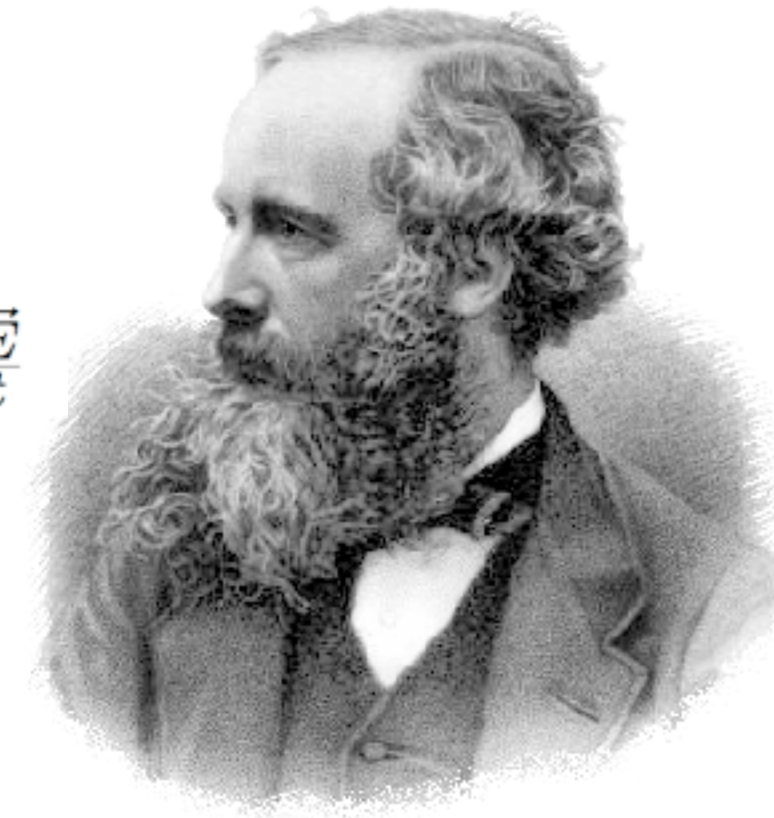
Young’s (1773-1829) double-slit experiment (1801)



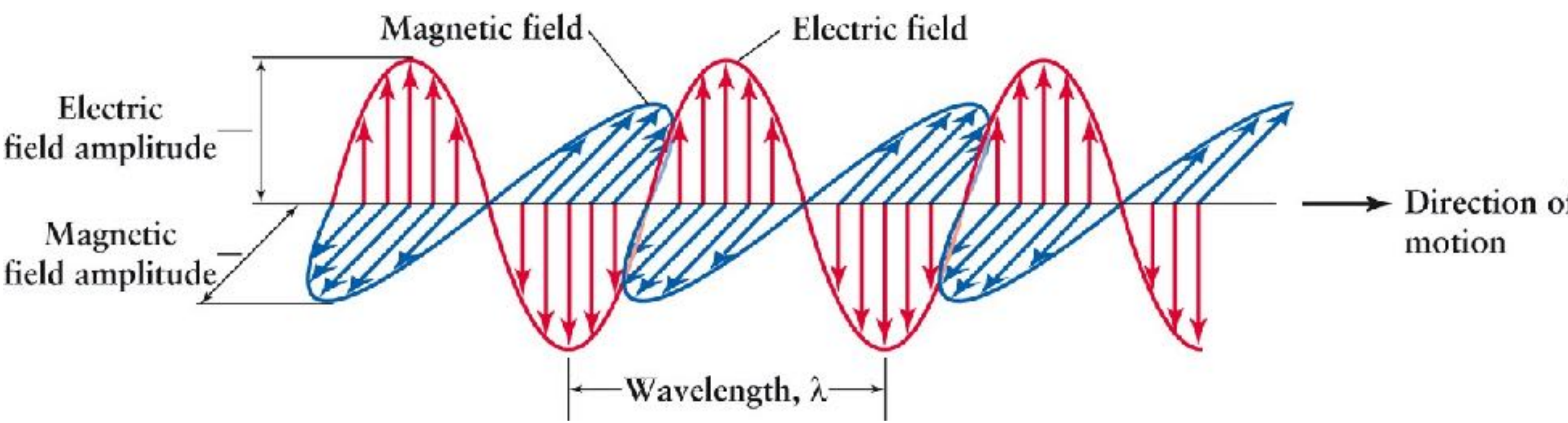
Maxwell's view of light:

James Clerk Maxwell
1831–1879
Bridged Newton and Einstein

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0}$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$\nabla \times \vec{B} = \mu_0 \vec{J} + \frac{1}{c^2}\frac{\partial \vec{E}}{\partial t}$$



Maxwell's equations (1862) confirmed wave-like view and joined infrared, optical, and UV radiation.

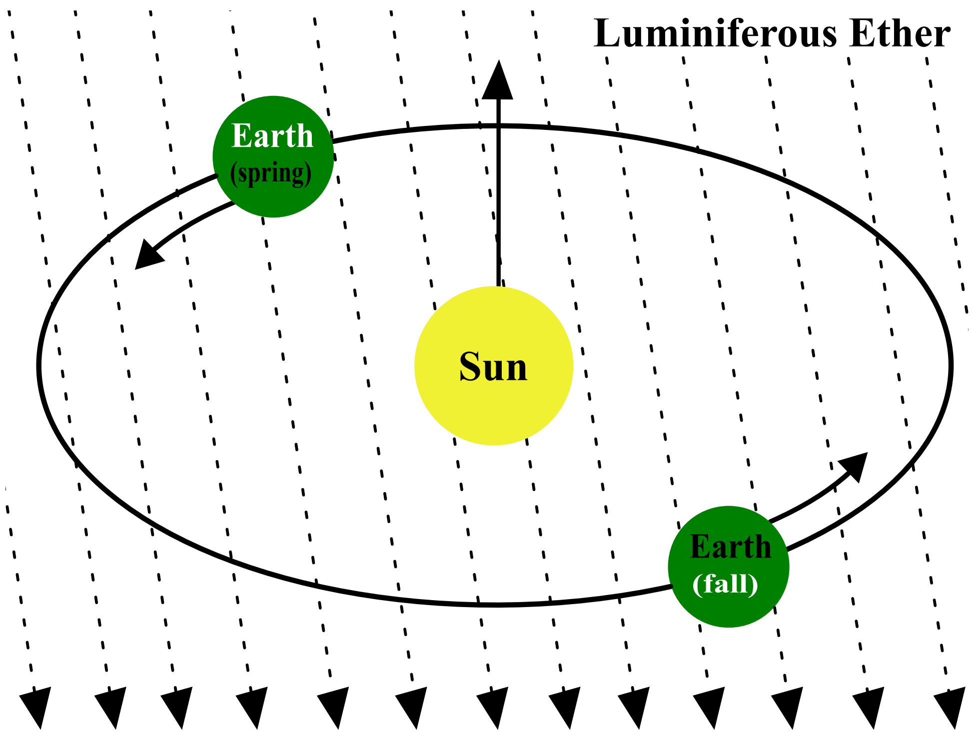


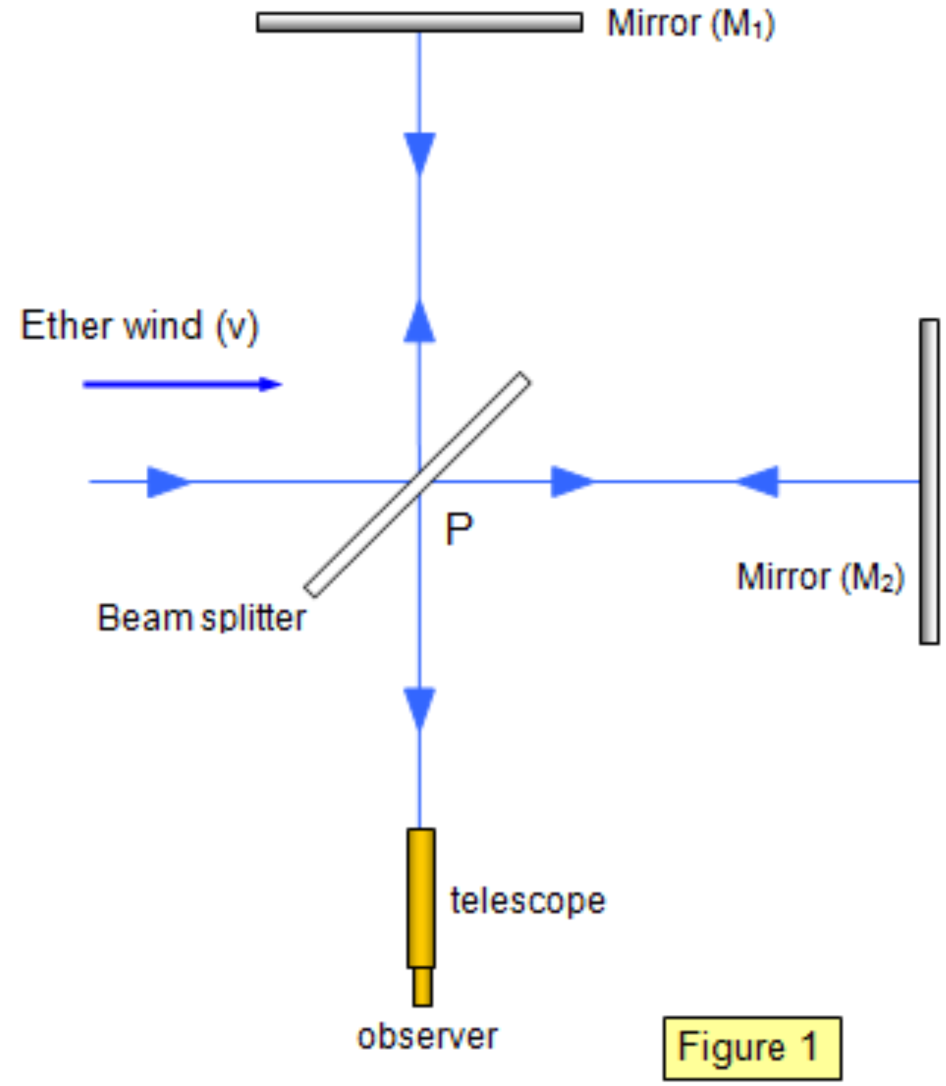
$$E(t) = E_o cos(wt + \phi) = E_o e^{-iwt}$$

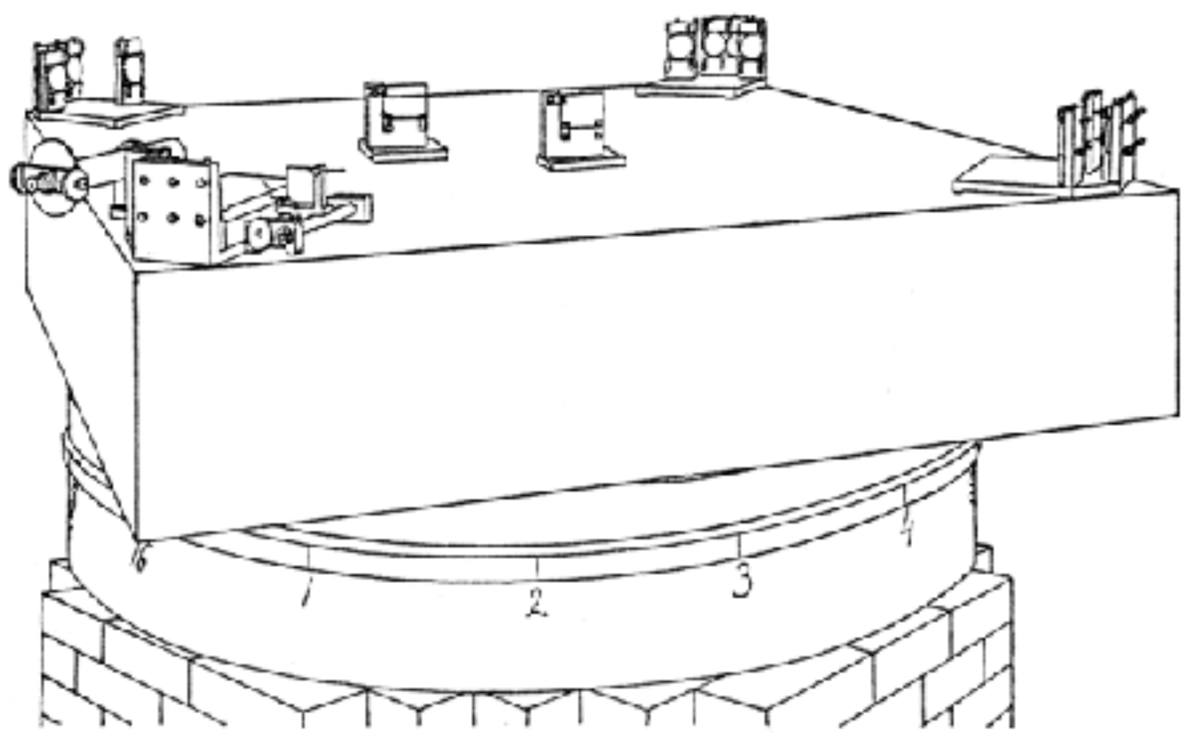
$$c = \nu\lambda$$

Michelson-Moreley Experiment — 1887

the most famous failed experiment in history

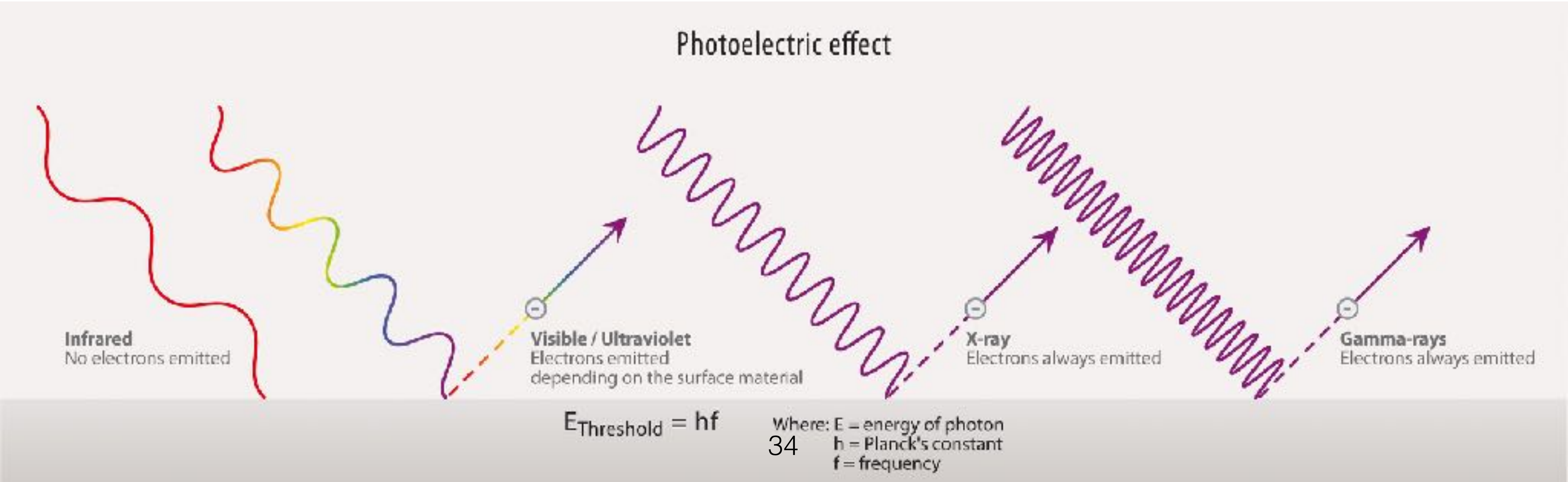




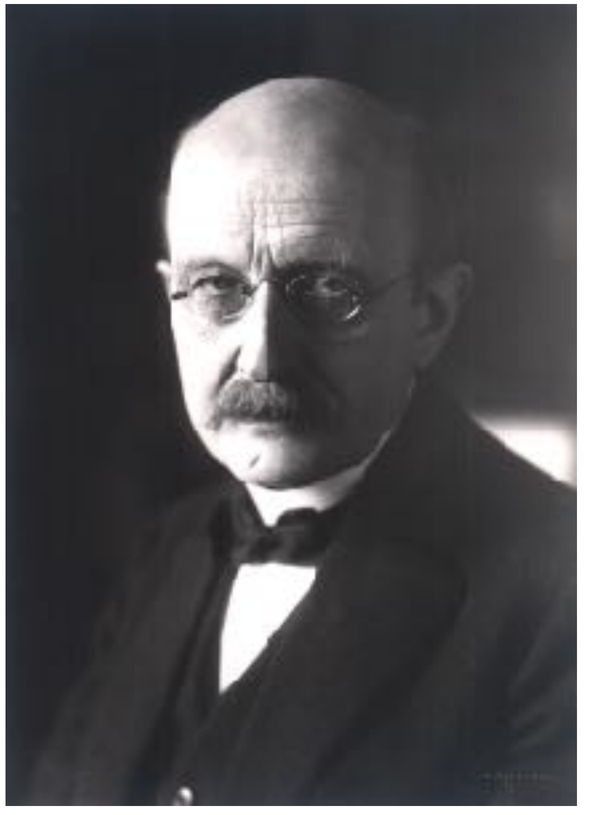


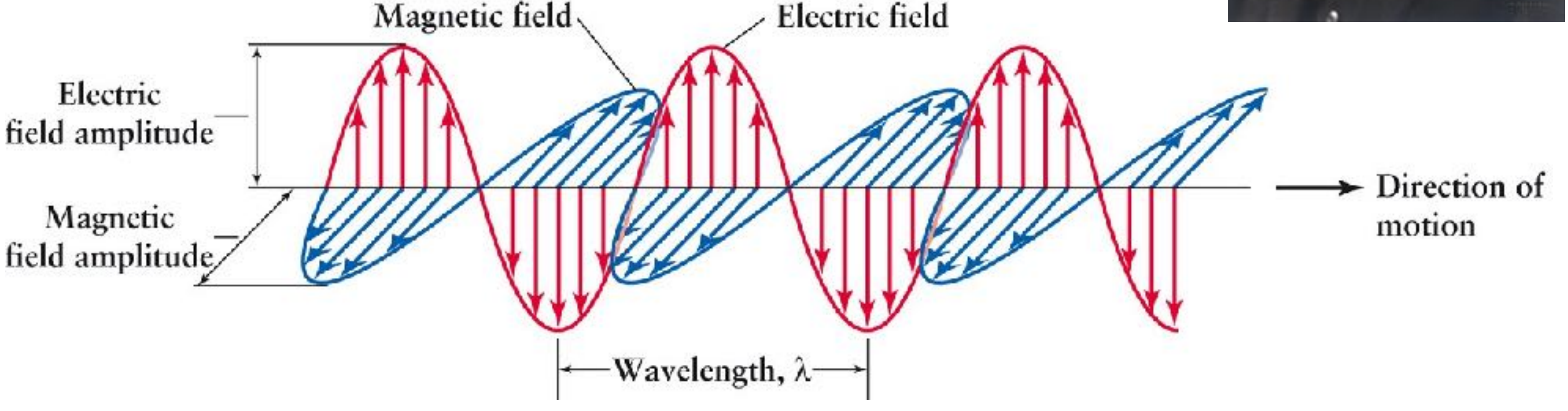
The photoelectric effect

- In 1887 Hertz and Hallwachs noticed that light shined on a charged surface could emit charged particles.
- Only worked for light above a given threshold wavelength, e.g. UV light.
- Shine a light on a material (or gas). As frequency increases into UV, electrons are released. Gas is ionized. Measure electrons.
- This light discharged charged particles with the same nature as cathode rays
- In 1899 J.J. Thompson discovered these were the same thing as electrons
- In 1902 Leonard observed that the energy of the electrons was proportional to the wavelength of light.
- This was at odds with Maxwell's theory which said $E_e \propto$ intensity, not λ
- In 1905, Einstein proposed quanta of light ("photons") and won the nobel prize in 1921



Planck's Picture:





$$E_\gamma = h\nu = \frac{hc}{\lambda} \qquad h = 6.626 \times 10^{-34} J \cdot s$$

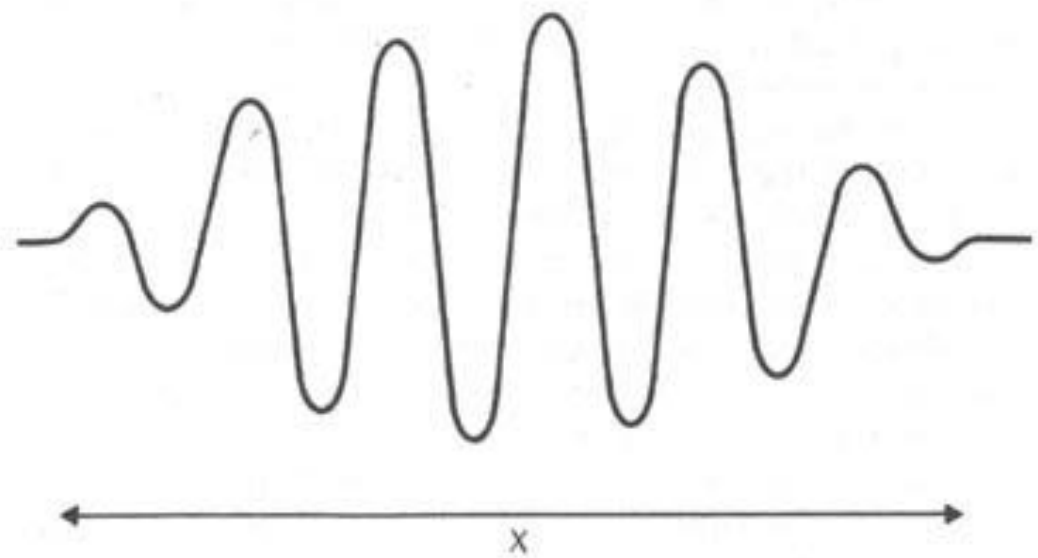
Planck's constant, "quantum of action" *c.* 1900

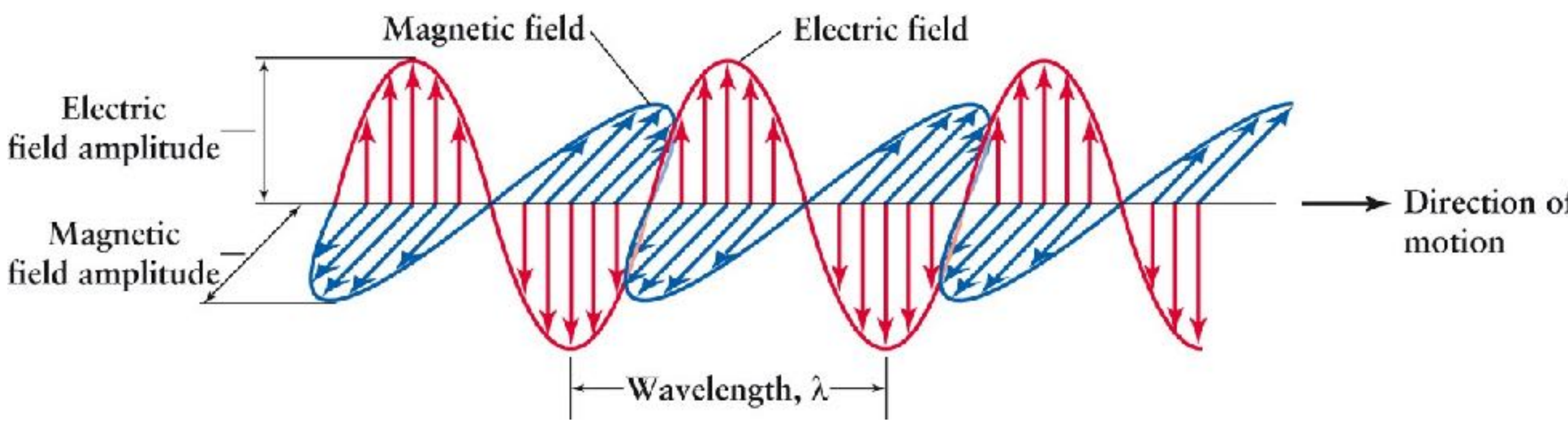
Einstein 1905

26 year old patent office clerk
and amateur physicist
wrote 4 papers:

- light is made of photons, which are discrete packets of energy (quantum mechanics)
- random motion of particles is due to molecular action which supported the atomic theory (atomic physics)
- special relativity says that light always travels at the same finite speed (relativity)
- $E=mc^2$ matter is interchangeable with energy (nuclear age)

Modern Picture:





Photons have:

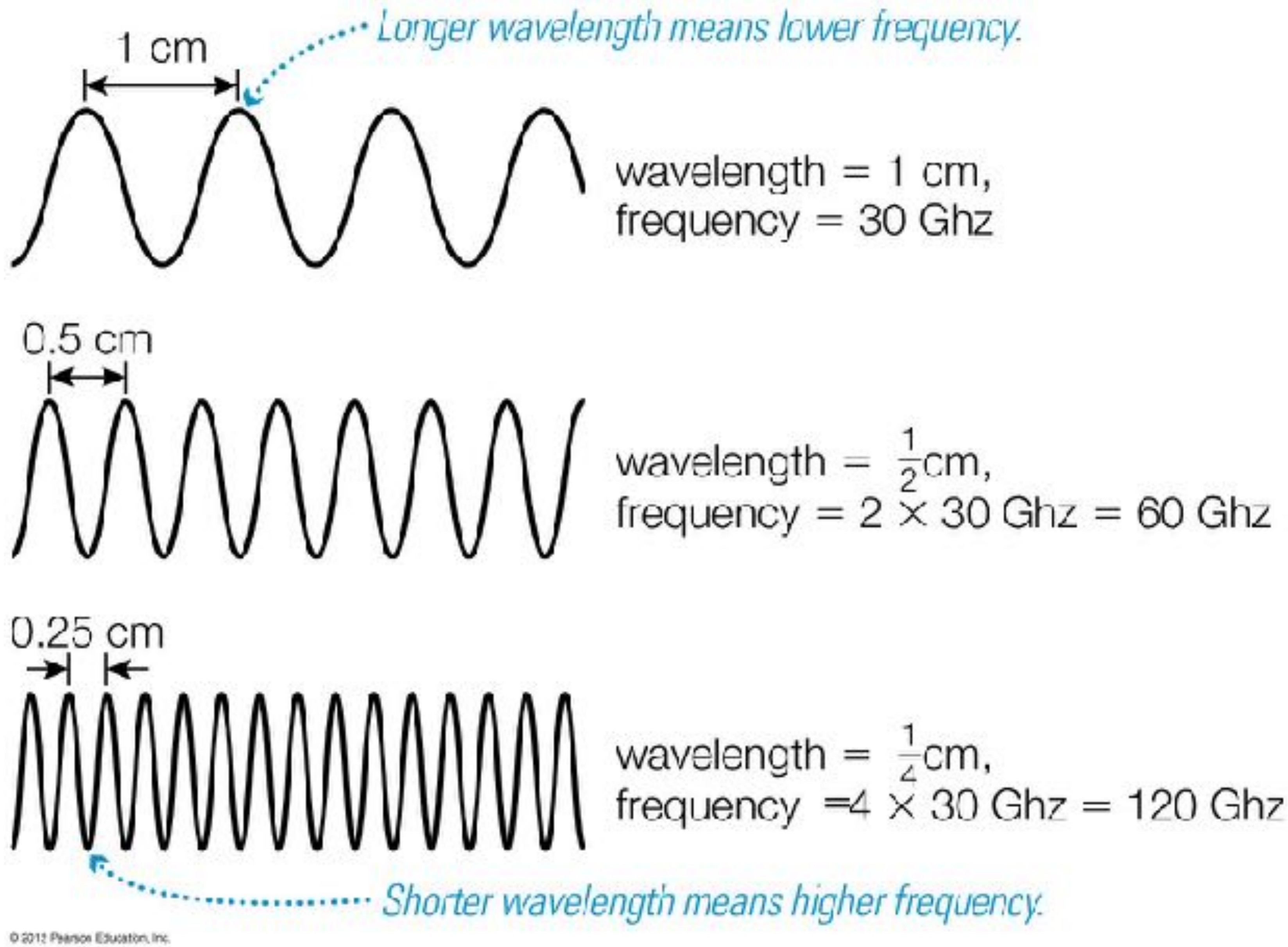
- direction
- wavelength
- amplitude
- phase
- polarization

$$E(t) = E_o cos(wt + \phi) = E_o e^{-iwt}$$

$$c = \nu\lambda$$

$$E_\gamma = h\nu = \frac{hc}{\lambda}$$

don't forget: $dE_\nu = \frac{\lambda^2}{c} dE_\lambda$

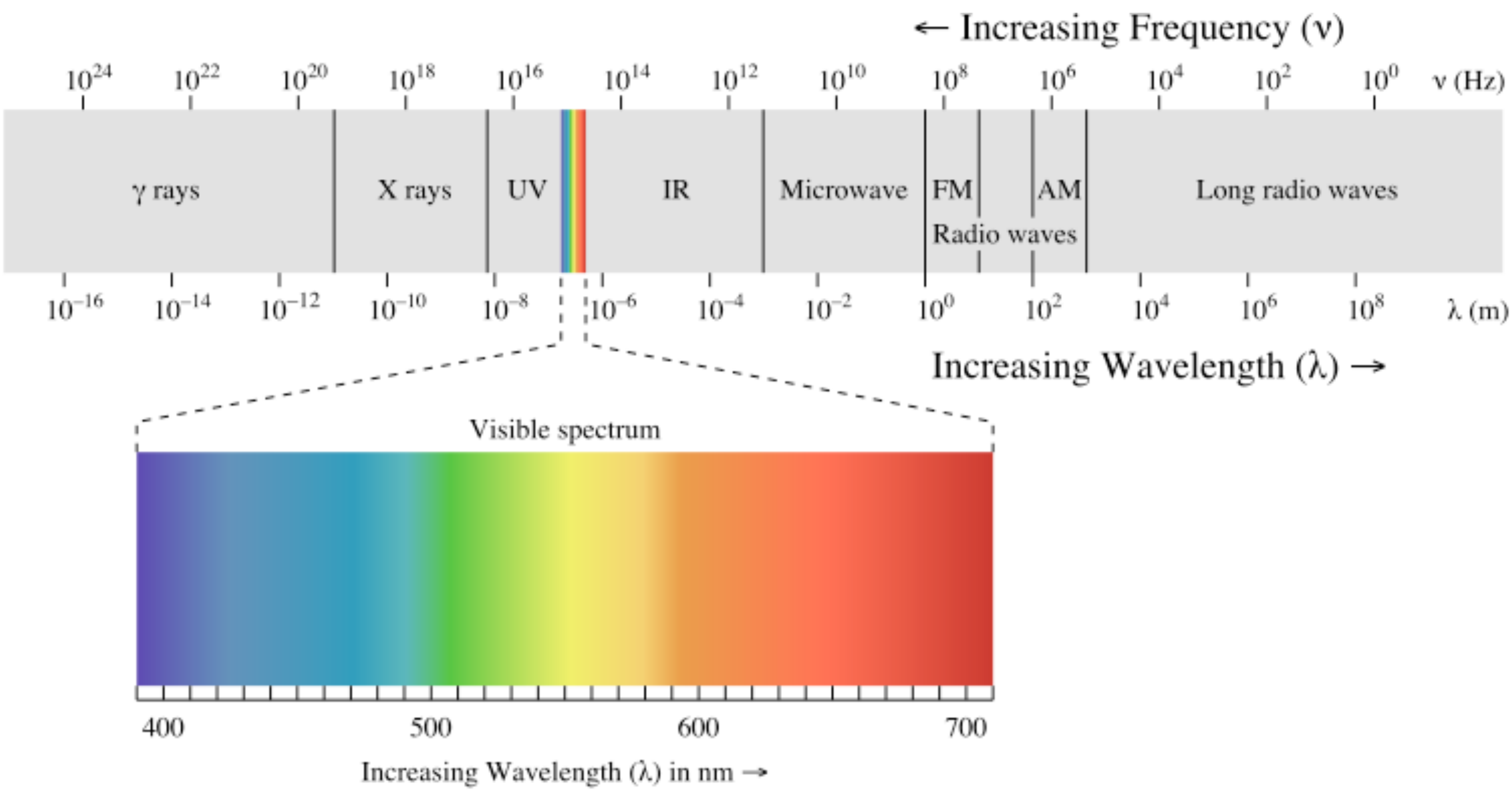


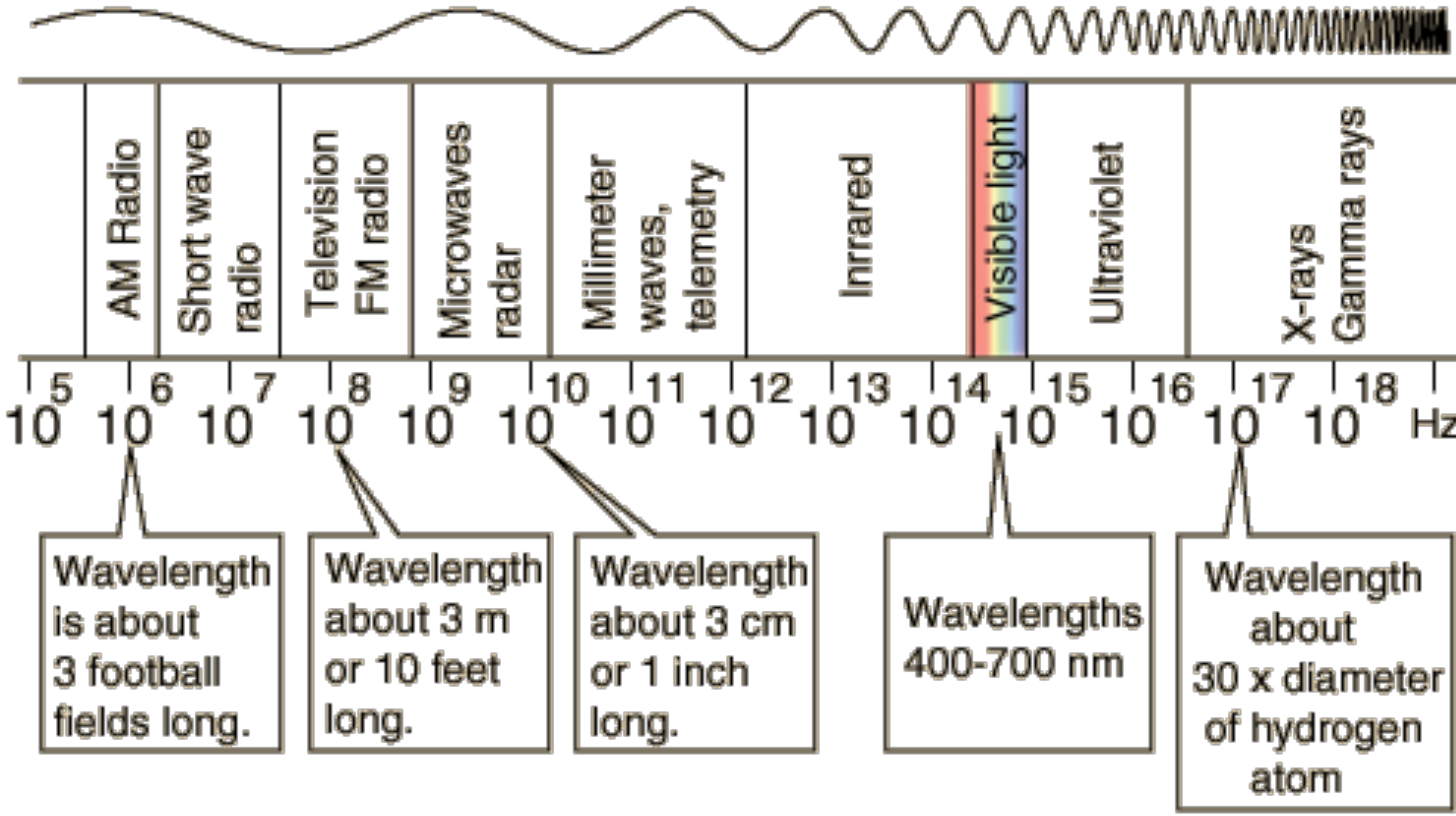
Light can be described by three interchangeable quantities:

- Frequency (ν): how often light wave peaks pass a given point in space
- Wavelength (λ): Separation between peaks of a light wave
- Energy: Proportional to frequency

More energy → higher frequency → shorter wavelength

Visible light is only a small part of the *electromagnetic spectrum*





AM Radio
Short wave radio
Television FM radio
Microwaves radar
Millimeter waves, telemetry
Inrrared
Visible light
Ultraviolet
X-rays Gamma rays
10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 Hz
Wavelength is about 3 football fields long.
Wavelength about 3 m or 10 feet long.
Wavelength about 3 cm or 1 inch long.
Wavelengths 400-700 nm
Wavelength about 30 x diameter of hydrogen atom

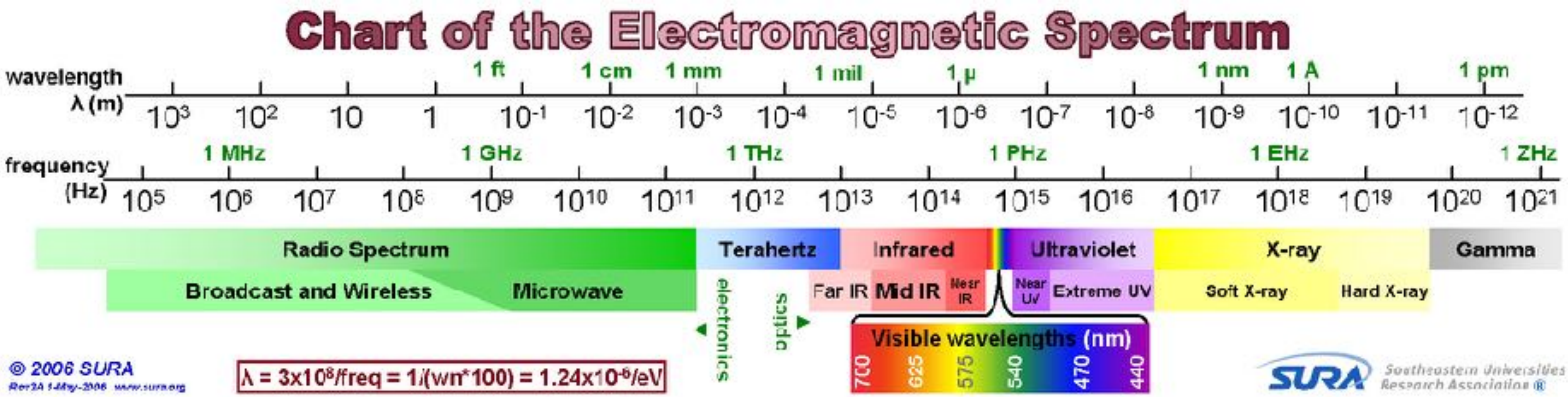
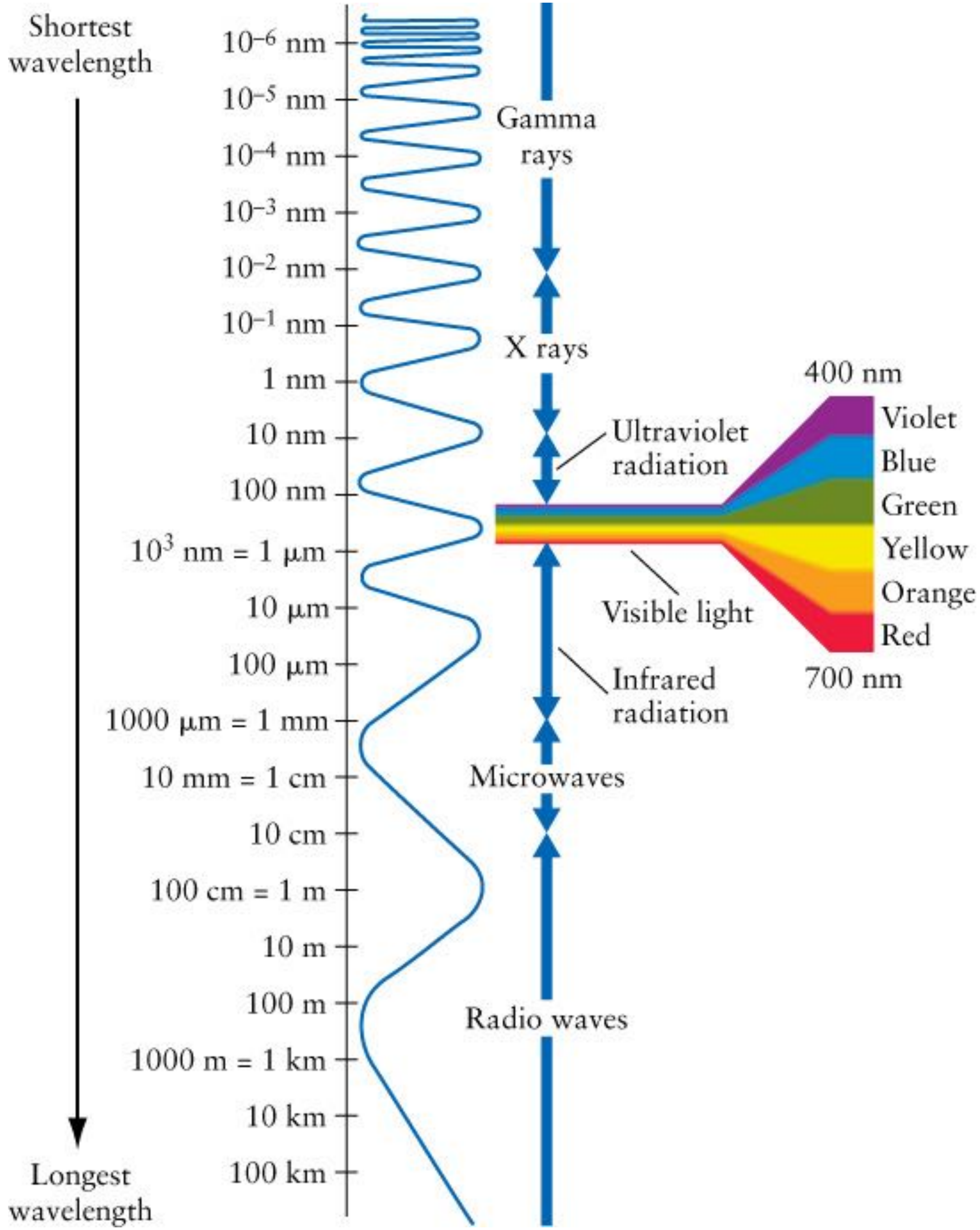
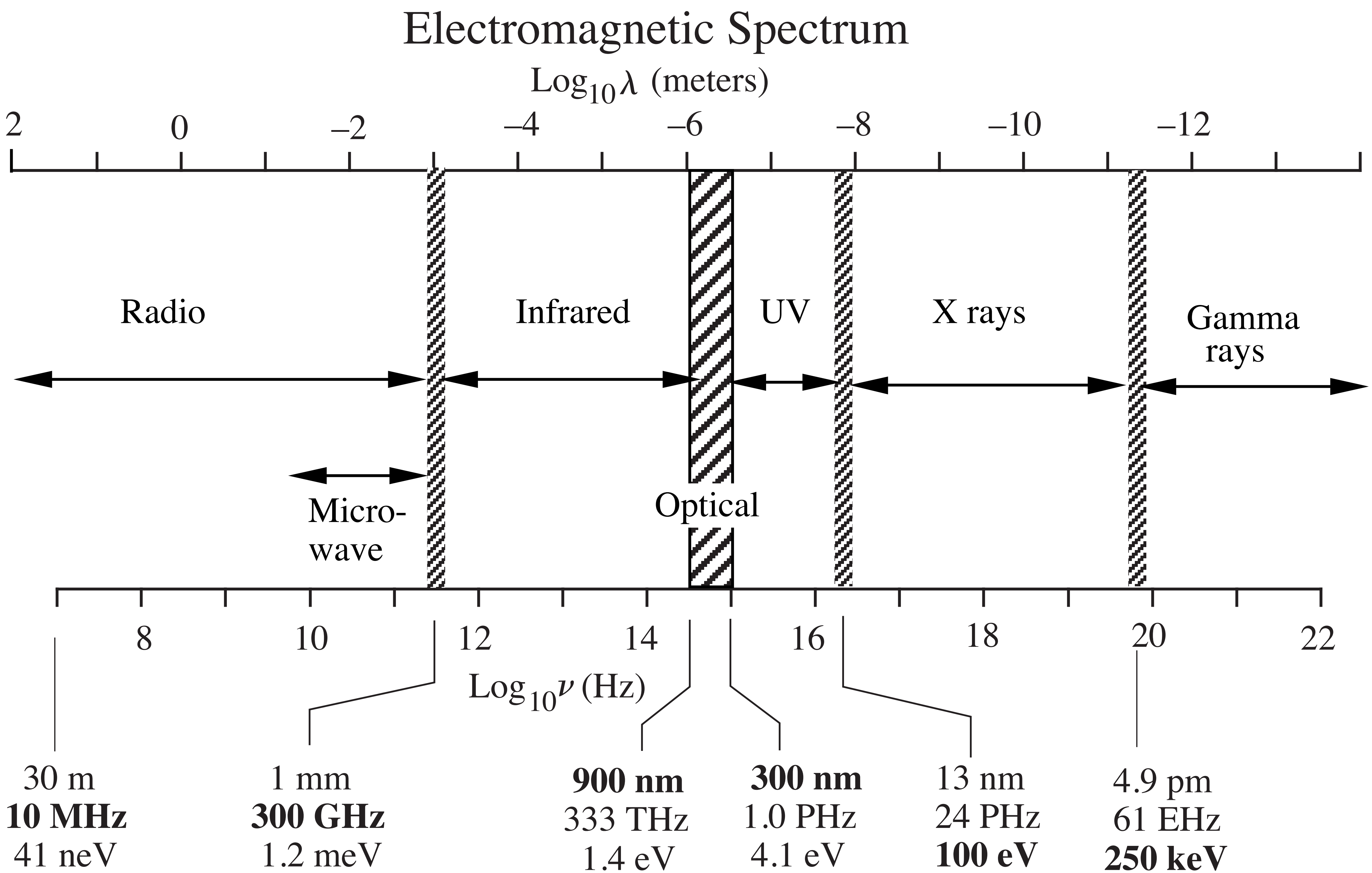
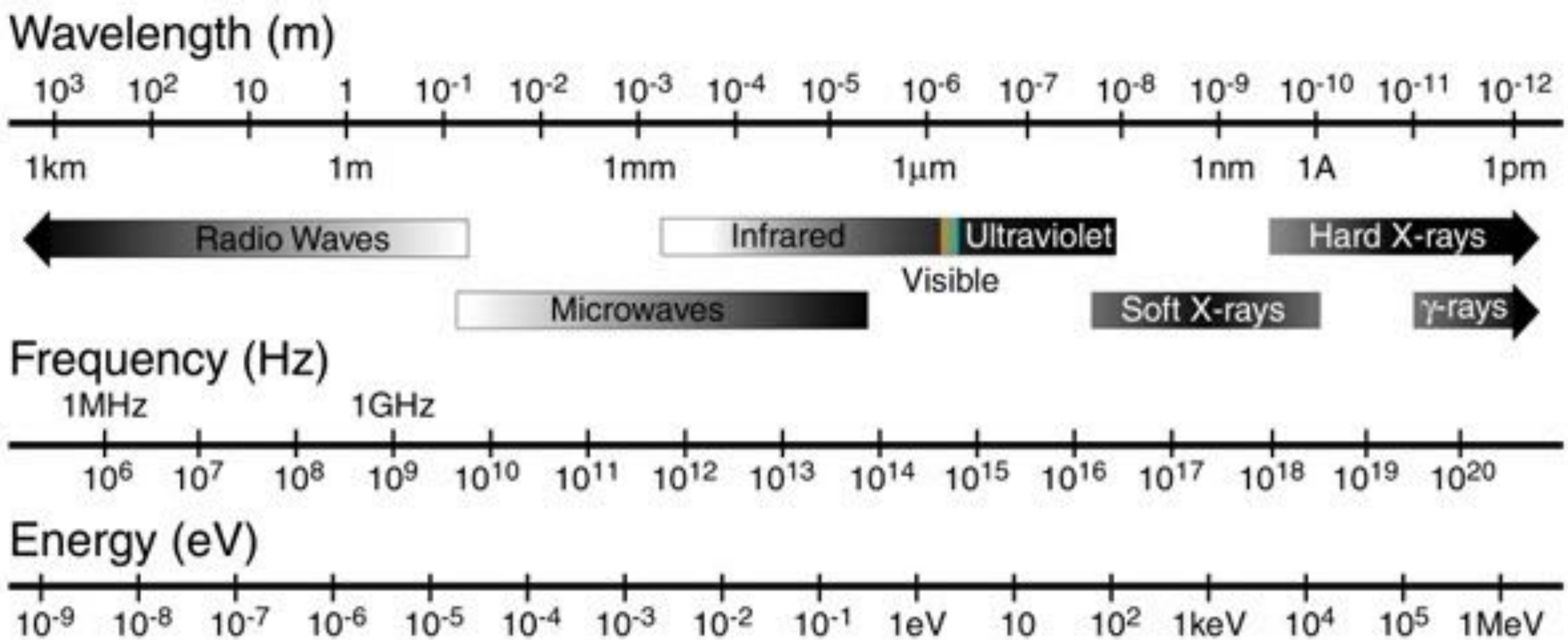


Chart of the Electromagnetic Spectrum
wavelength λ (m)
1 ft
1 cm
1 mm
1 mil
1 μ
1 nm
1 Å
1 pm
10^3 10^2 10 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
frequency (Hz)
1 MHz
1 GHz
1 THz
1 PHz
1 EHz
1 ZHz
10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20 10^21
Radio Spectrum
Terahertz
Infrared
Ultraviolet
X-ray
Gamma
Broadcast and Wireless
Microwave
electronics
optics
Far IR
Mid IR
Near IR
Near UV
Extreme UV
Soft X-ray
Hard X-ray
Visible wavelengths (nm)
700
625
575
540
470
440
© 2006 SURA
λ = 3x10^8/freq = 1/(wn*100) = 1.24x10^-6/eV
SURA
Southeastern Universities Research Association


Shortest wavelength
10^{-6} nm
10^{-5} nm
10^{-4} nm
10^{-3} nm
10^{-2} nm
10^{-1} nm
1 nm
10 nm
100 nm
10^{3} nm = 1 μm
10 μm
100 μm
1000 μm = 1 mm
10 mm = 1 cm
10 cm
100 cm = 1 m
10 m
100 m
1000 m = 1 km
10 km
100 km
Longest wavelength
Gamma rays
X rays
Ultraviolet radiation
Visible light
Infrared radiation
Microwaves
Radio waves
400 nm
Violet
Blue
Green
Yellow
Orange
Red
700 nm


Electromagnetic Spectrum
$\mathrm{Log}_{10}\lambda$ (meters)
2
0
–2
–4
–6
–8
–10
–12
Radio
Infrared
UV
X rays
Gamma rays
Micro-wave
Optical
8
10
12
14
16
18
20
22
$\mathrm{Log}_{10}\nu$ (Hz)
30 m
10 MHz
41 neV
1 mm
300 GHz
1.2 meV
900 nm
333 THz
1.4 eV
300 nm
1.0 PHz
4.1 eV
13 nm
24 PHz
100 eV
4.9 pm
61 EHz
250 keV



Wavelength (m)
10³ 10² 10 1 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹²
1km 1m 1mm 1μm 1nm 1A 1pm
Radio Waves
Infrared
Ultraviolet
Hard X-rays
Visible
Microwaves
Soft X-rays
γ-rays
Frequency (Hz)
1MHz 1GHz
10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
Energy (eV)
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1eV 10 10² 1keV 10⁴ 10⁵ 1MeV

photon	energy	λ	ν	T	natural unit	scale
	[eV]	[m]	[Hz]	[K]		
γ-ray	10^{5}	10^{-15}	10^{20}	1^{12}	MeV	nuclear
x-ray	10^{3}	10^{-10}	10^{18}	1^{6}	keV	atomic
UV	10	10^{-8}	10^{16}	10,000	eV, Å	electronic
visible	1	10^{-7}	10^{15}	3,000	nm	stars
IR	0.1	10^{-6}	10^{13}	100	μm	hot thermal
μ-wave	10^{-3}	10^{-2}	10^{11}	3	mm, GHz	cold thermal
radio	10^{-6}	1	10^{9}	1	cm, GHz	synchrotron, hyperfine

Neutrinos

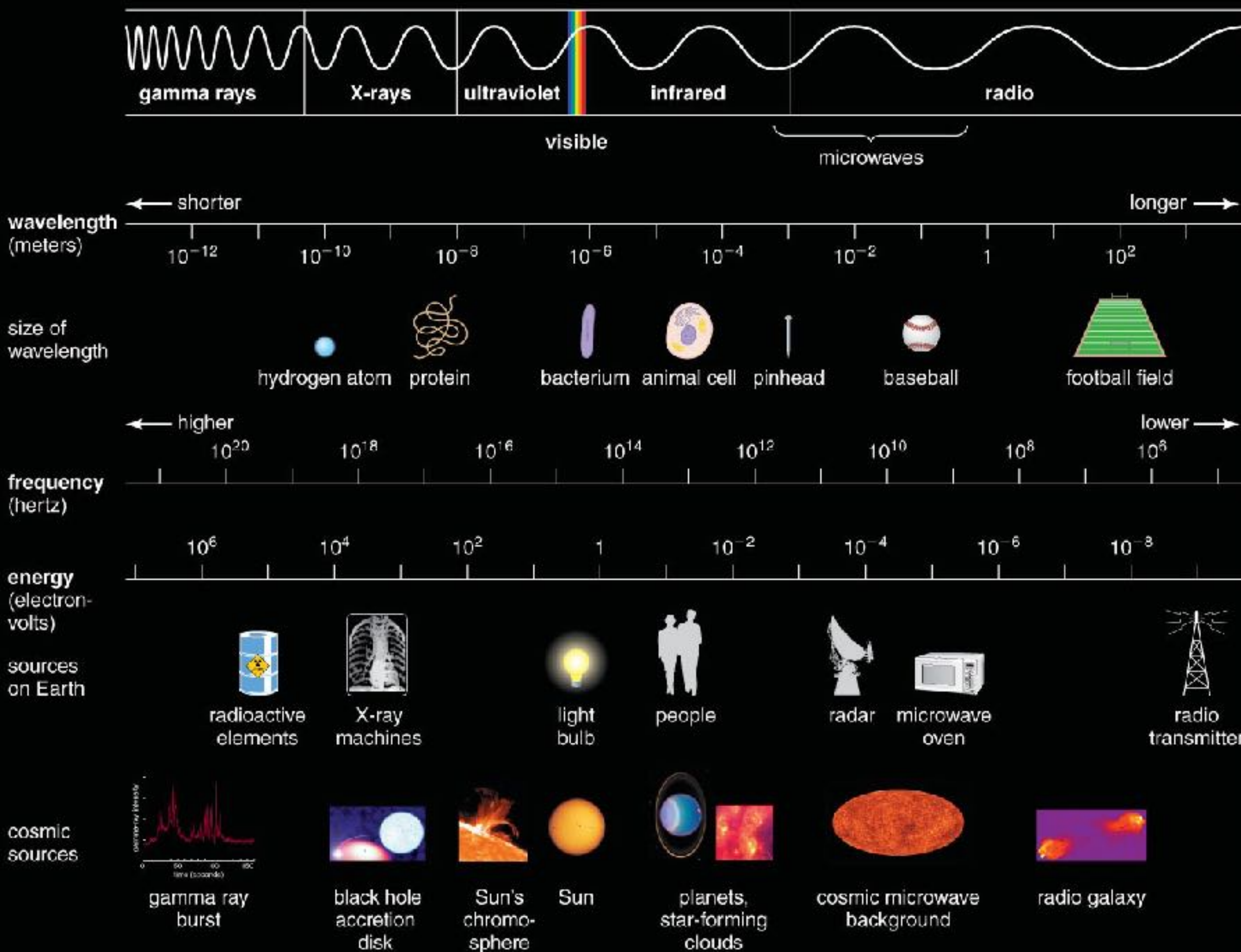
photon	energy	λ	ν	T	natural unit	scale
	[eV]	[m]	[Hz]	[K]		
γ-ray	10^5	10^{-15}	10^{20}	1^{12}	MeV	nuclear
solar ν's	10^5					
SN ν's	10^7					
IceCube ν's	10^{15}					

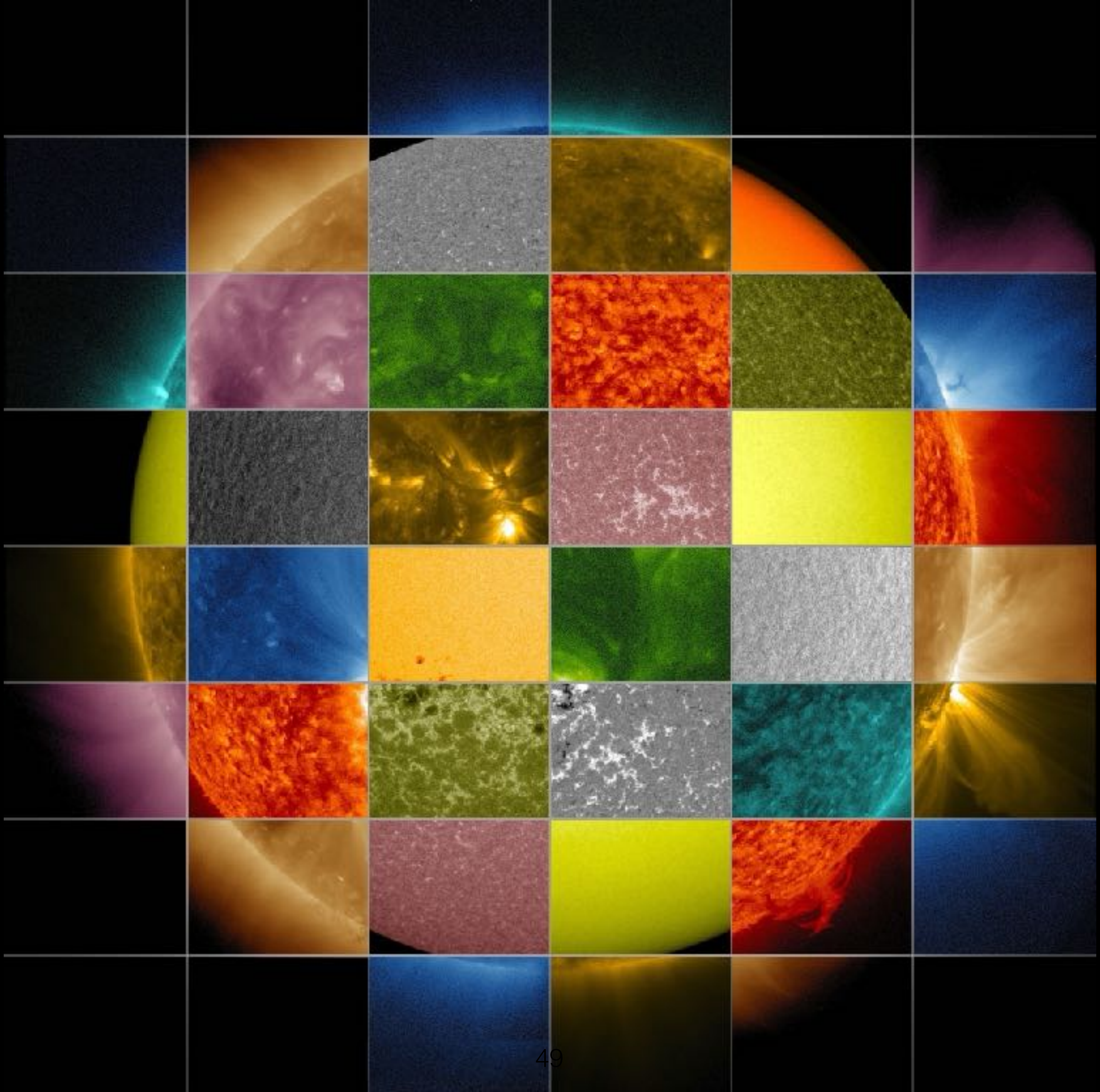
Thermal Blackbody Temperatures

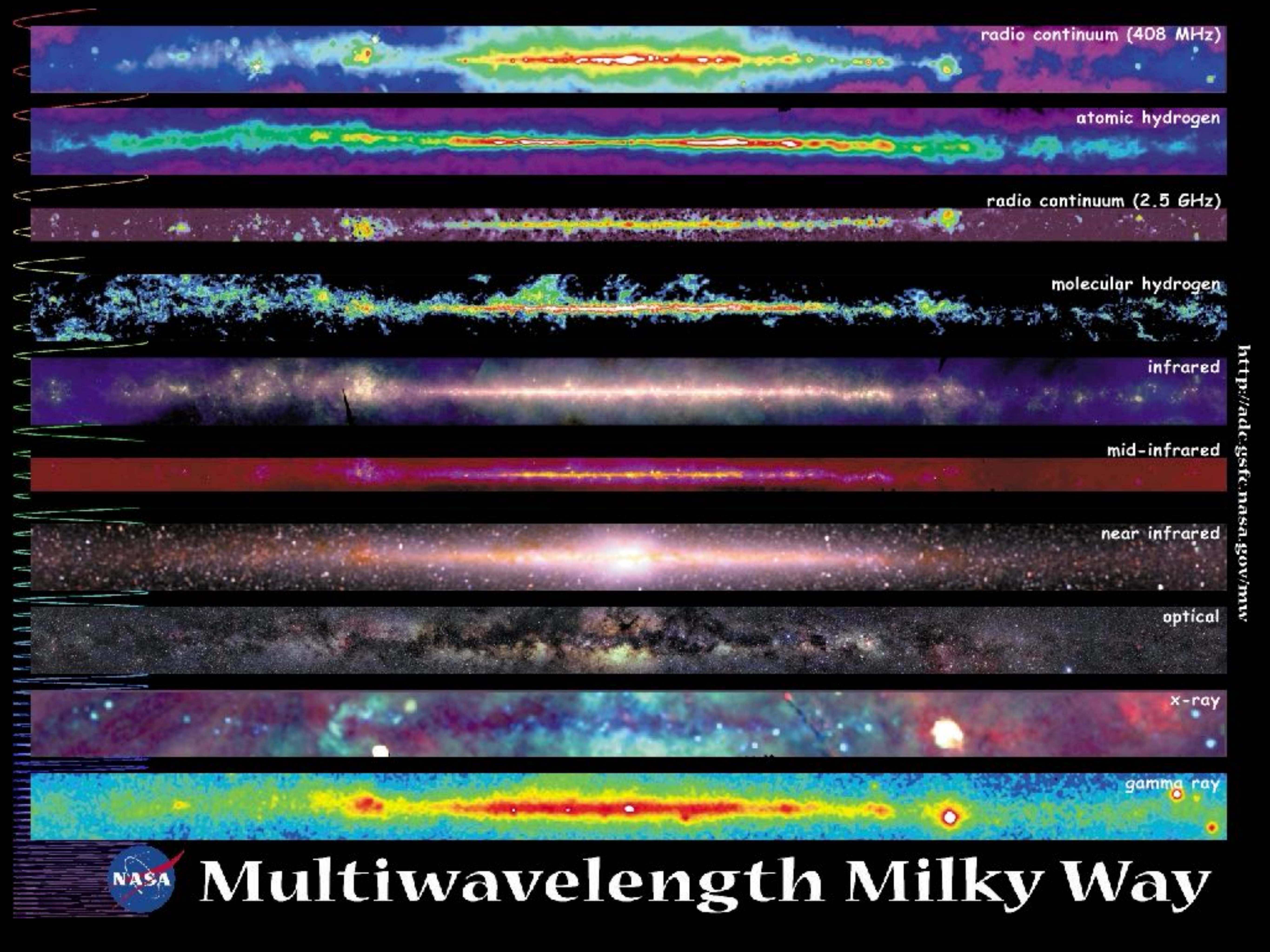
photon	energy	λ	v	T	natural unit	scale
	[eV]	[m]	[Hz]	[K]		
γ-ray	10^5	10^{-15}	10^{20}	1^{12}	MeV	nuclear
x-ray	10^3	10^{-10}	10^{18}	1^6	keV	atomic
UV	10	10^{-8}	10^{16}	10,000	eV, Å	electronic
visible	1	10^{-7}	10^{15}	3,000	nm	stars
IR	0.1	10^{-6}	10^{13}	100	μm	hot thermal
μ-wave	10^{-3}	10^{-2}	10^{11}	3	mm, GHz	cold thermal
radio	10^{-6}	1	10^9	1	cm, GHz	synchrotron, hyperfine

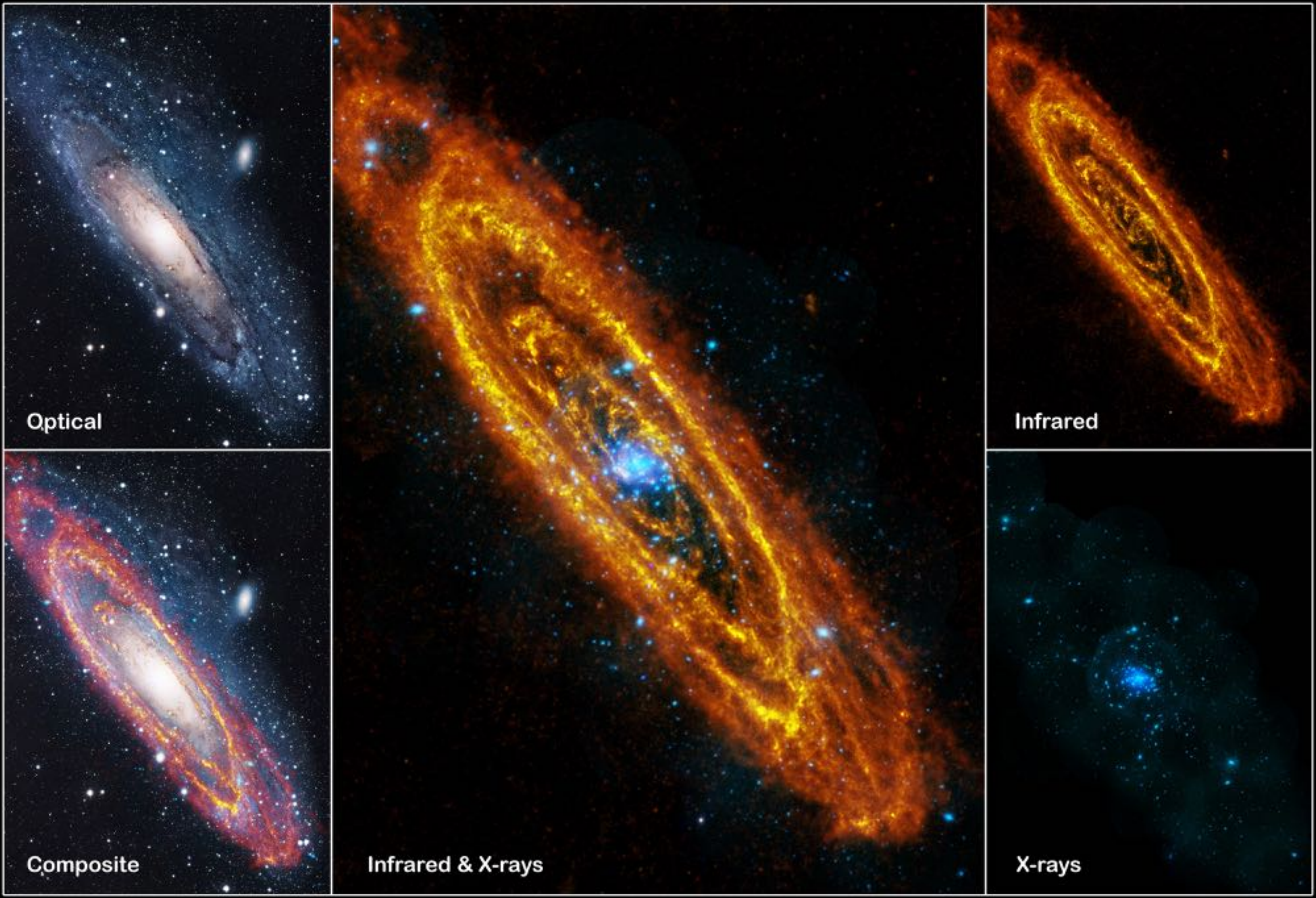
photon	energy	λ	v	T	peak
	[eV]	[m]	[Hz]	[K]	
CMB	10^{-3}	10^{-2}	10^{11}	2.7	150 GHz
Galaxy	10^{-2}	10^{-4}	10^{13}	30	100 μm
Earth	0.1	10^{-5}	10^{14}	287	10 μm
Star	1	10^{-8}	10^{16}	5,000	1 μm
ICM	10^3	10^{-7}	10^{15}	10^6	*x*-ray

The Electromagnetic Spectrum





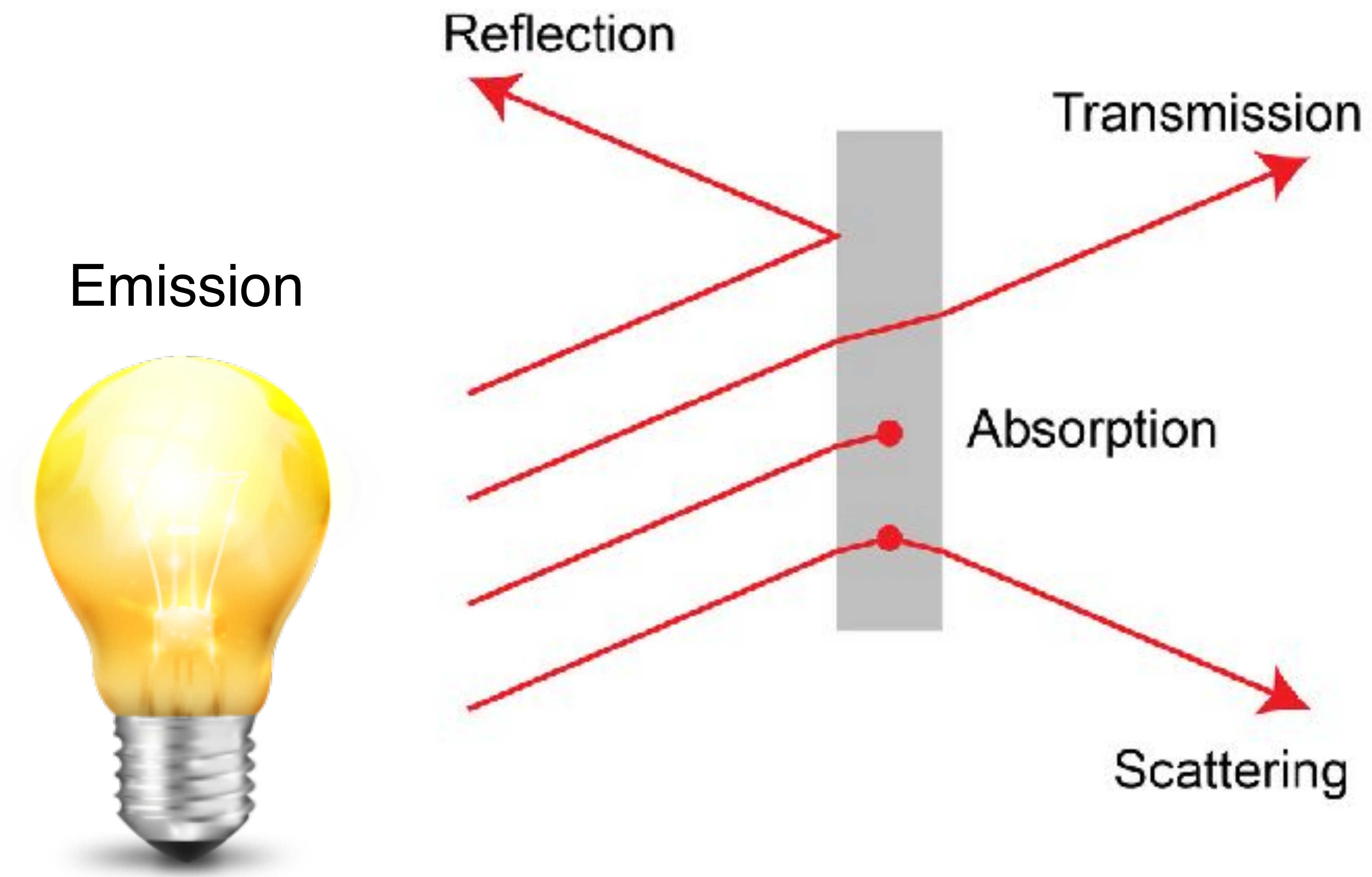

radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

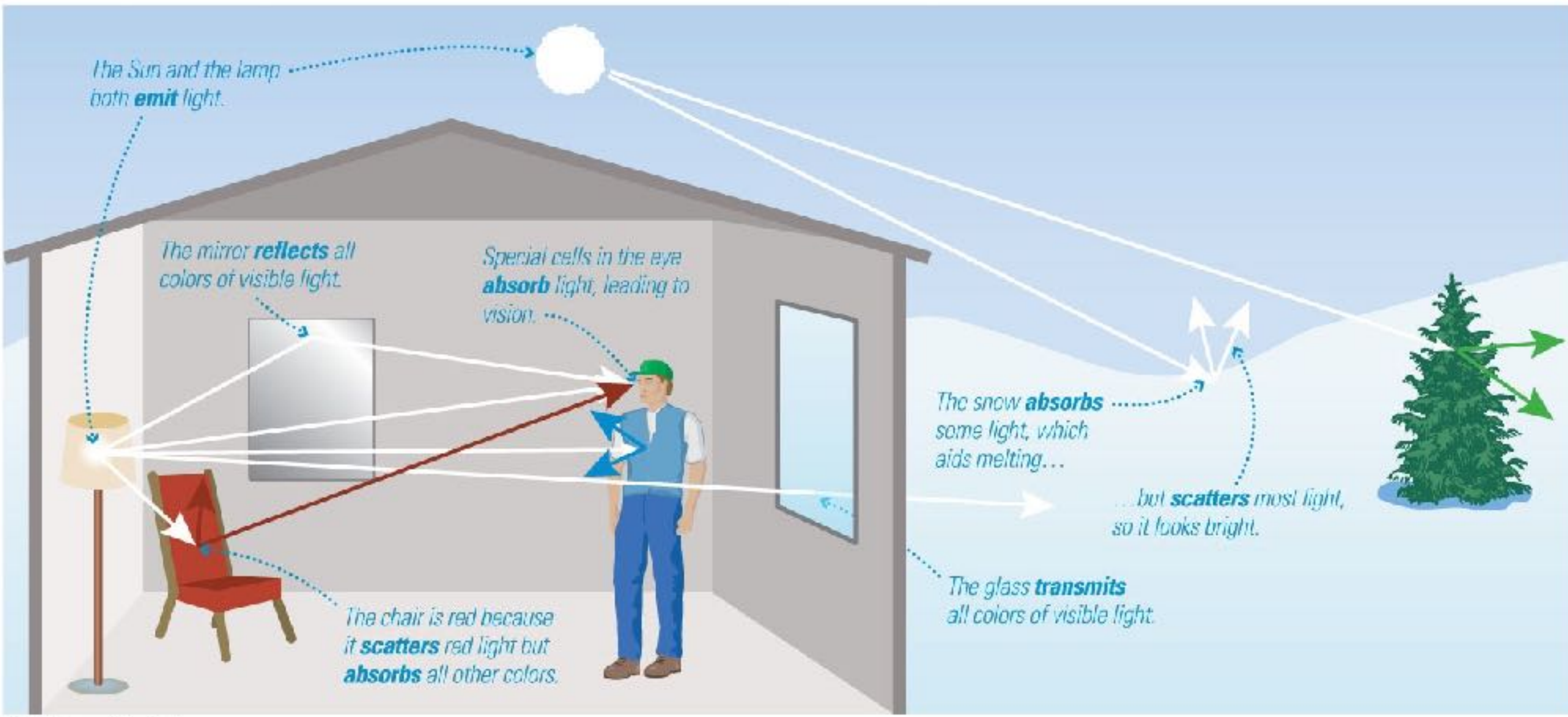


Optical
Composite
Infrared & X-rays
Infrared
X-rays

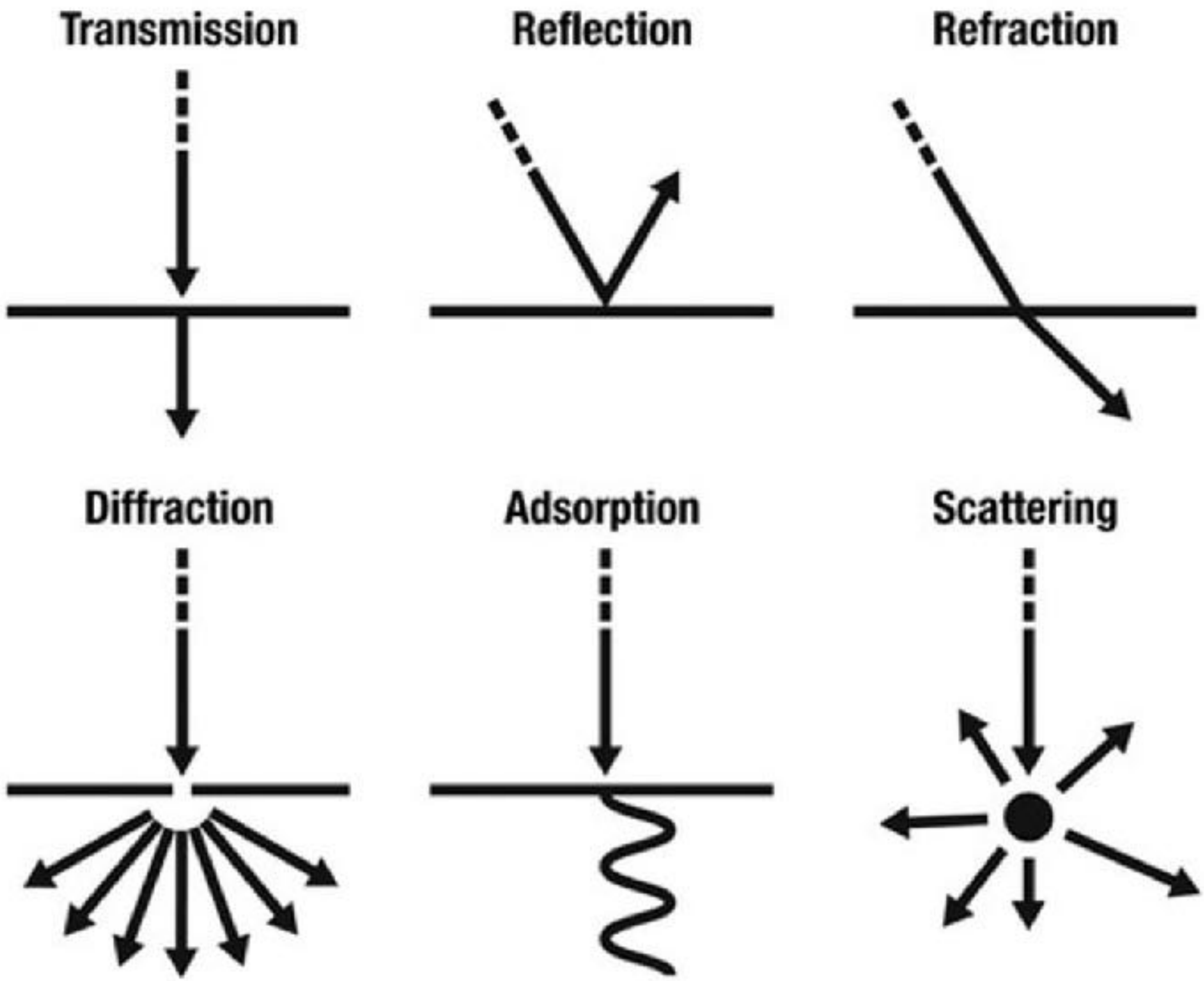
Light-Matter Interactions

- **Emission**: Light given off by matter, as in a light bulb
- **Absorption**: Energy of light deposited in matter.
- **Reflection/Scattering**: Light bounces off some materials
- **Transmission**: Light may pass through some types of matter

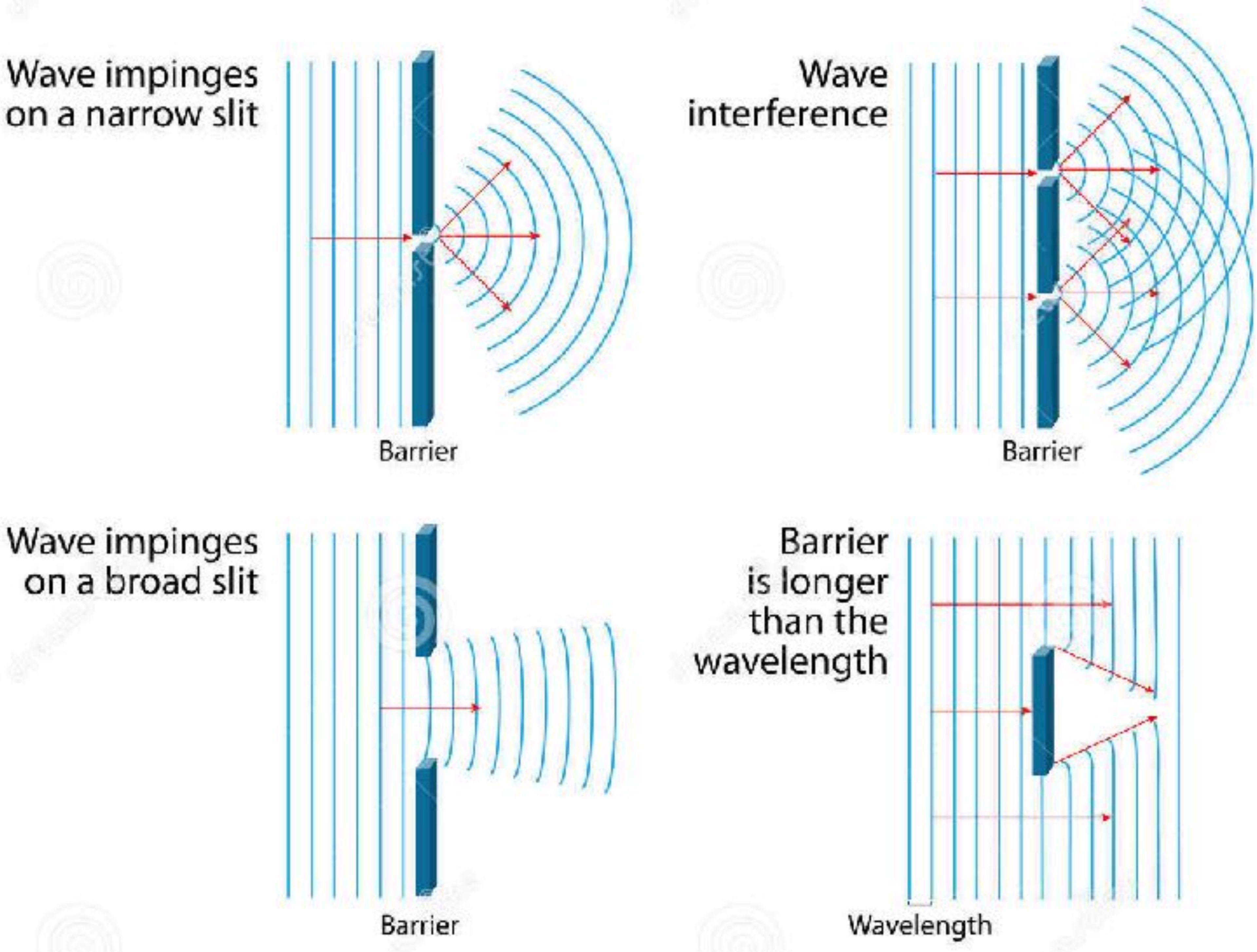


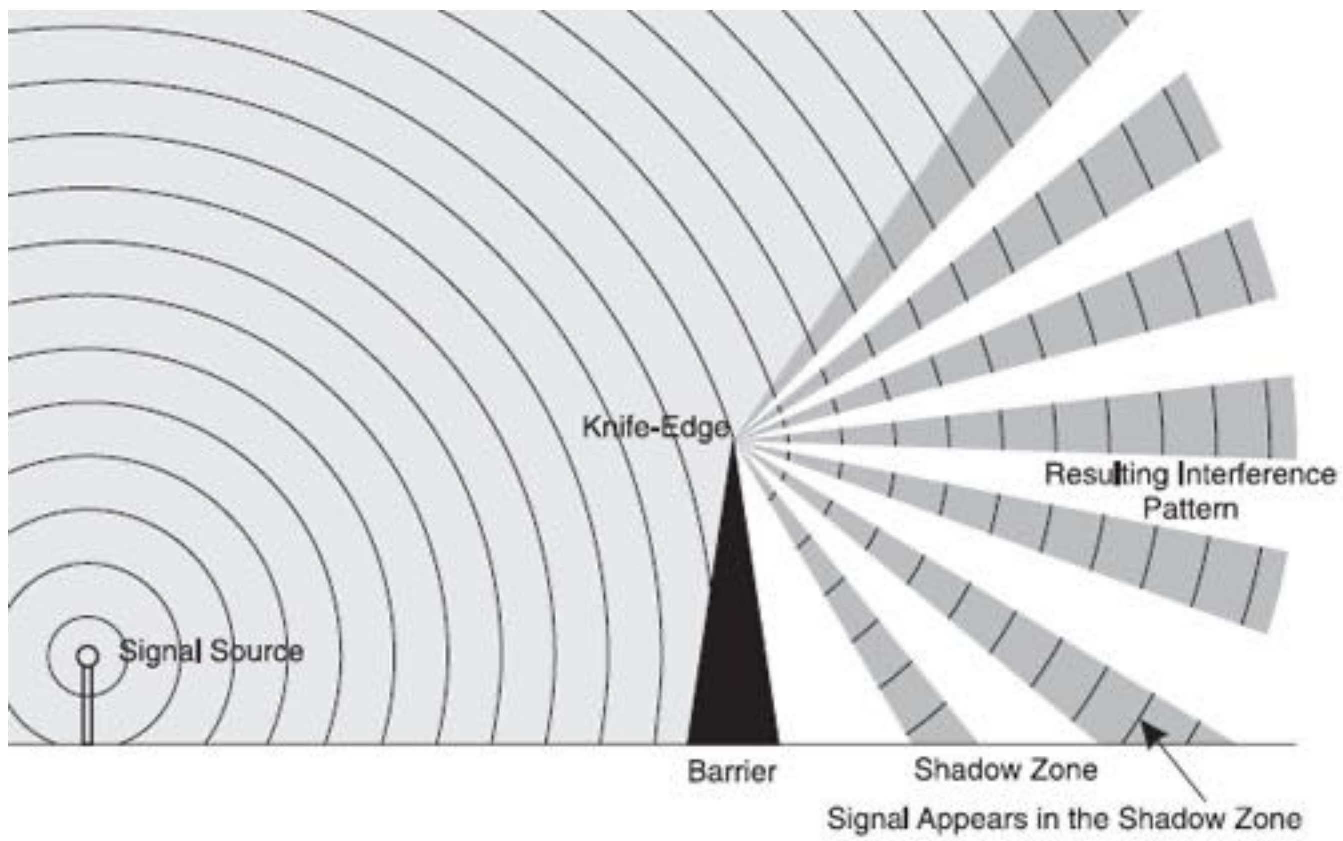

The Sun and the lamp both **emit** light.
The mirror **reflects** all colors of visible light.
Special cells in the eye **absorb** light, leading to vision.
The snow **absorbs** some light, which aids melting…
…but **scatters** most light, so it looks bright.
The glass **transmits** all colors of visible light.
The chair is red because it **scatters** red light but **absorbs** all other colors.

Wave Interactions

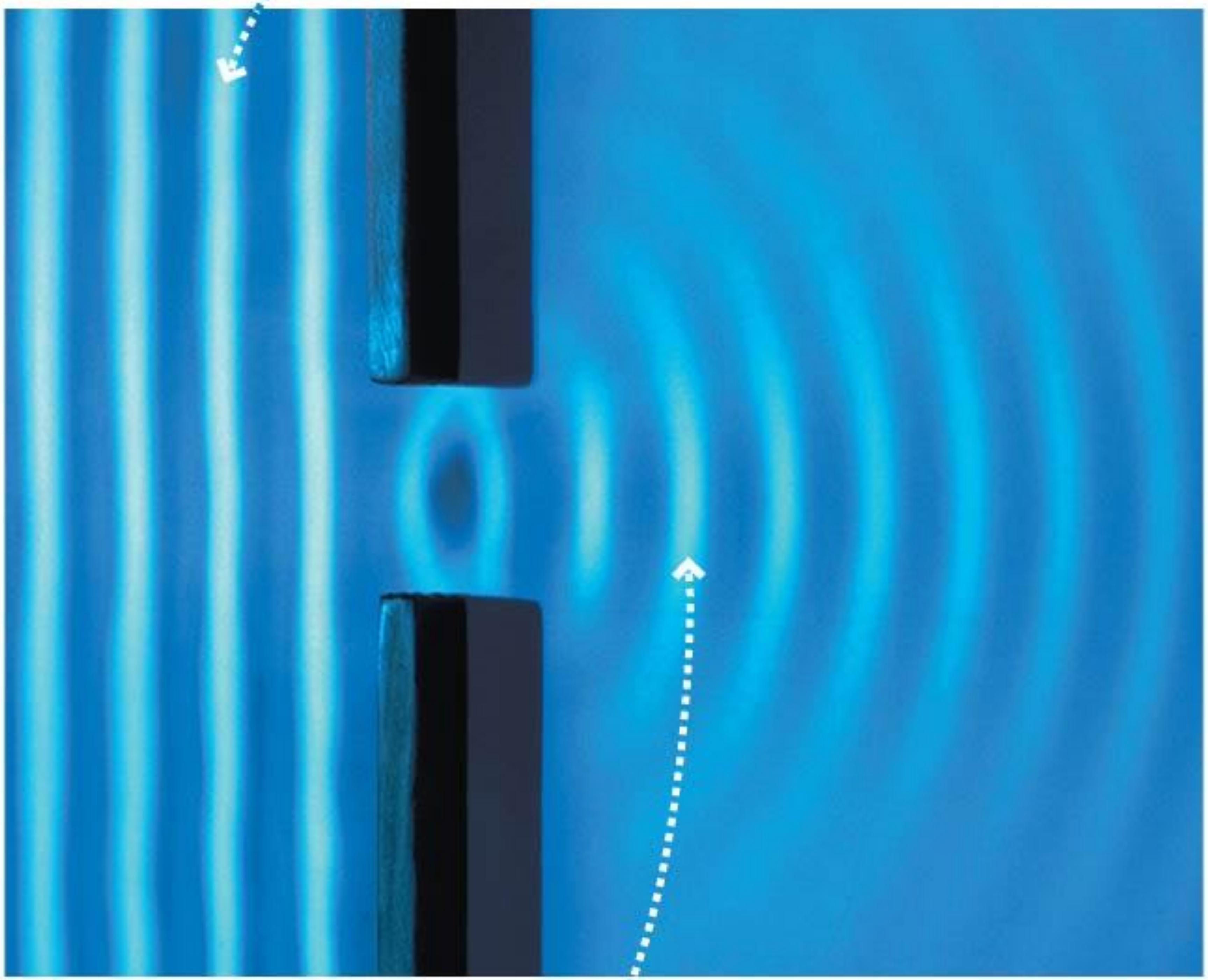


DIFFRACTION OF WAVES

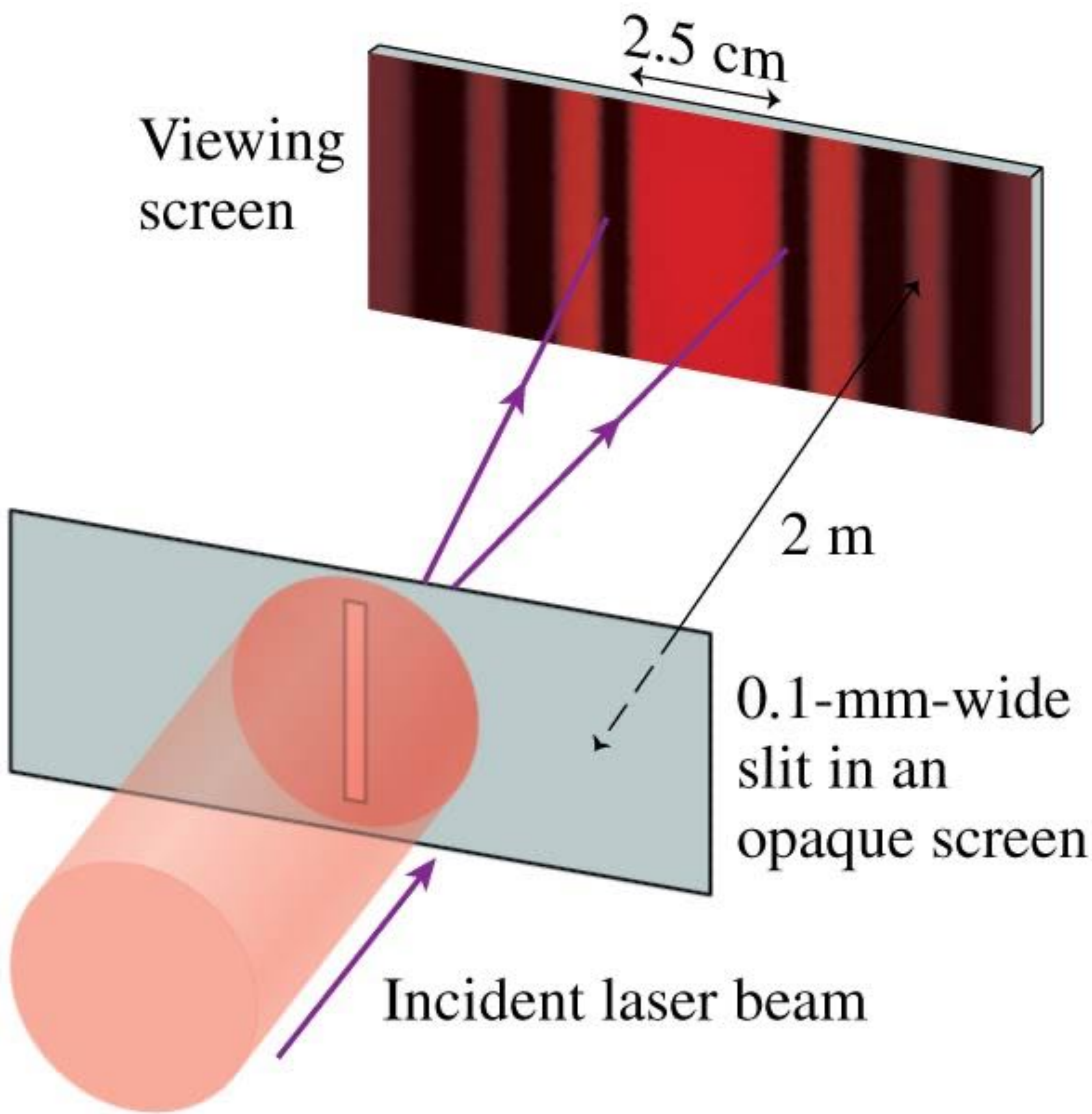



Knife-Edge
Resulting Interference Pattern
Signal Source
Barrier
Shadow Zone
Signal Appears in the Shadow Zone

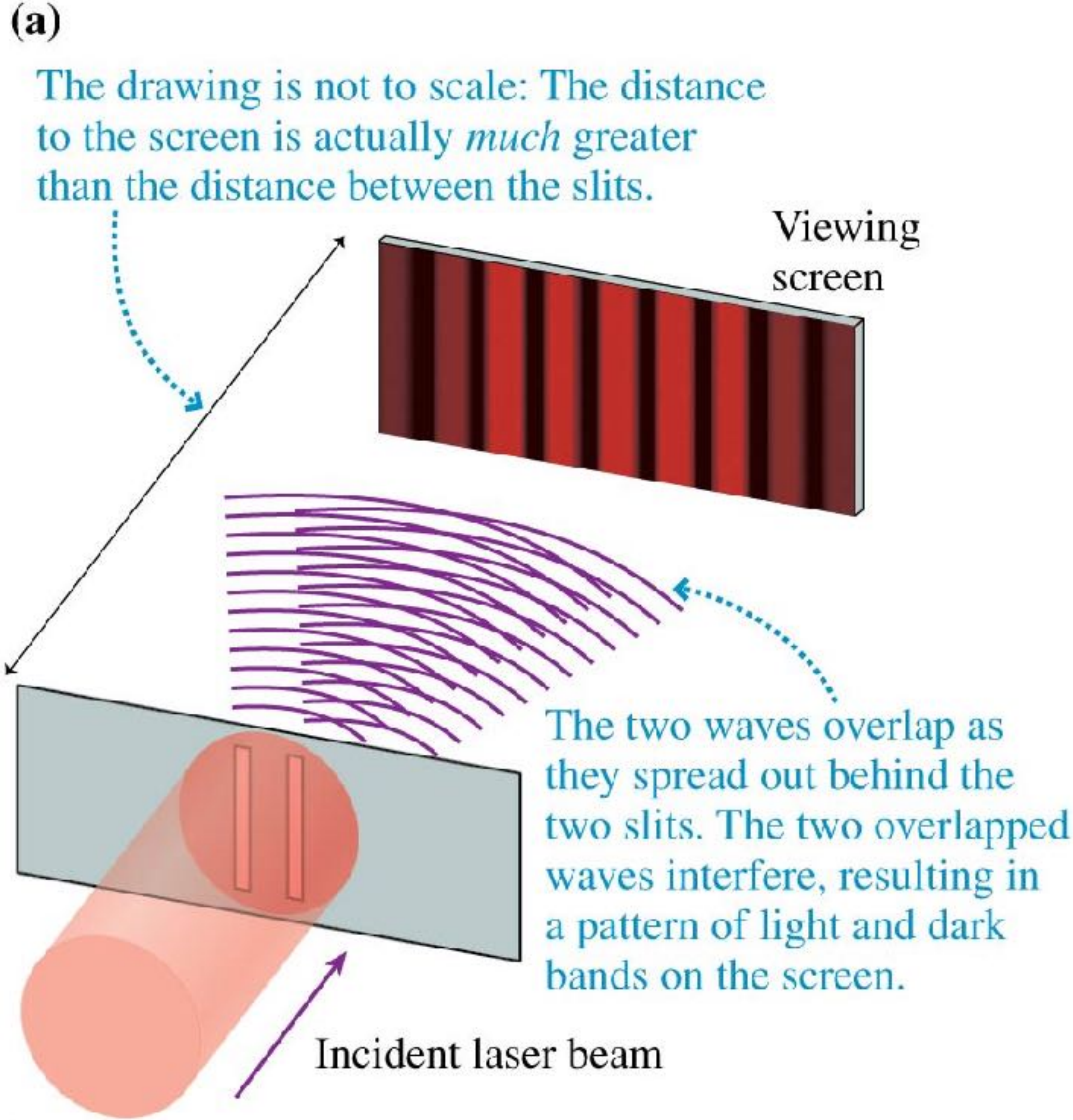
(a) Plane waves approach from the left.



Circular waves spread out on the right.

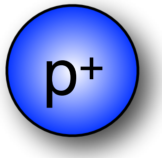


2.5 cm
Viewing
screen
2 m
0.1-mm-wide
slit in an
opaque screen
Incident laser beam

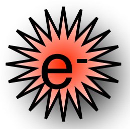

(a)
The drawing is not to scale: The distance to the screen is actually *much* greater than the distance between the slits.
Viewing screen
The two waves overlap as they spread out behind the two slits. The two overlapped waves interfere, resulting in a pattern of light and dark bands on the screen.
Incident laser beam

Light can be treated as
discrete wavelengths
or a
continuous spectrum.

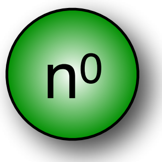
The simplest atom
Hydrogen H



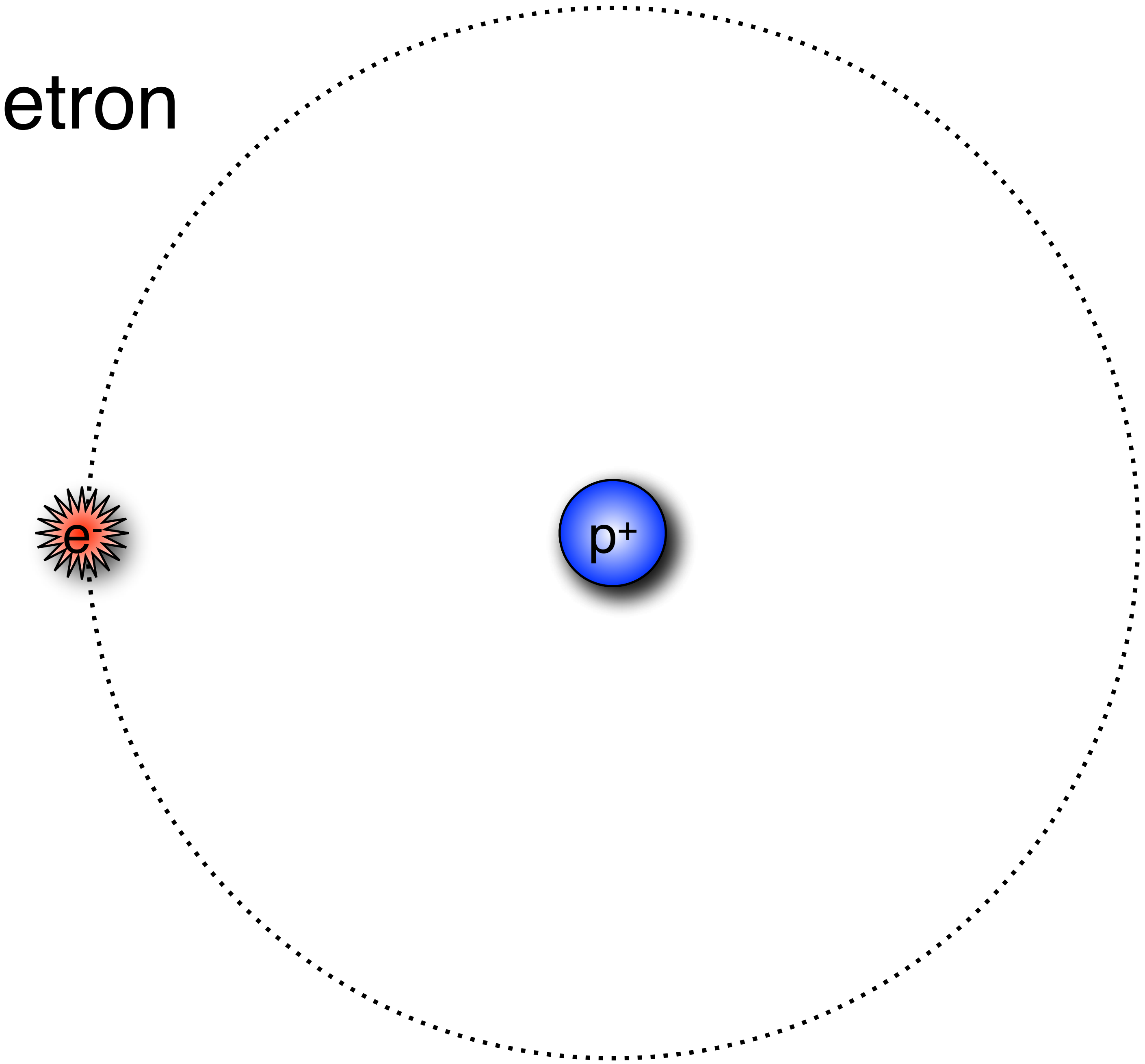
= proton

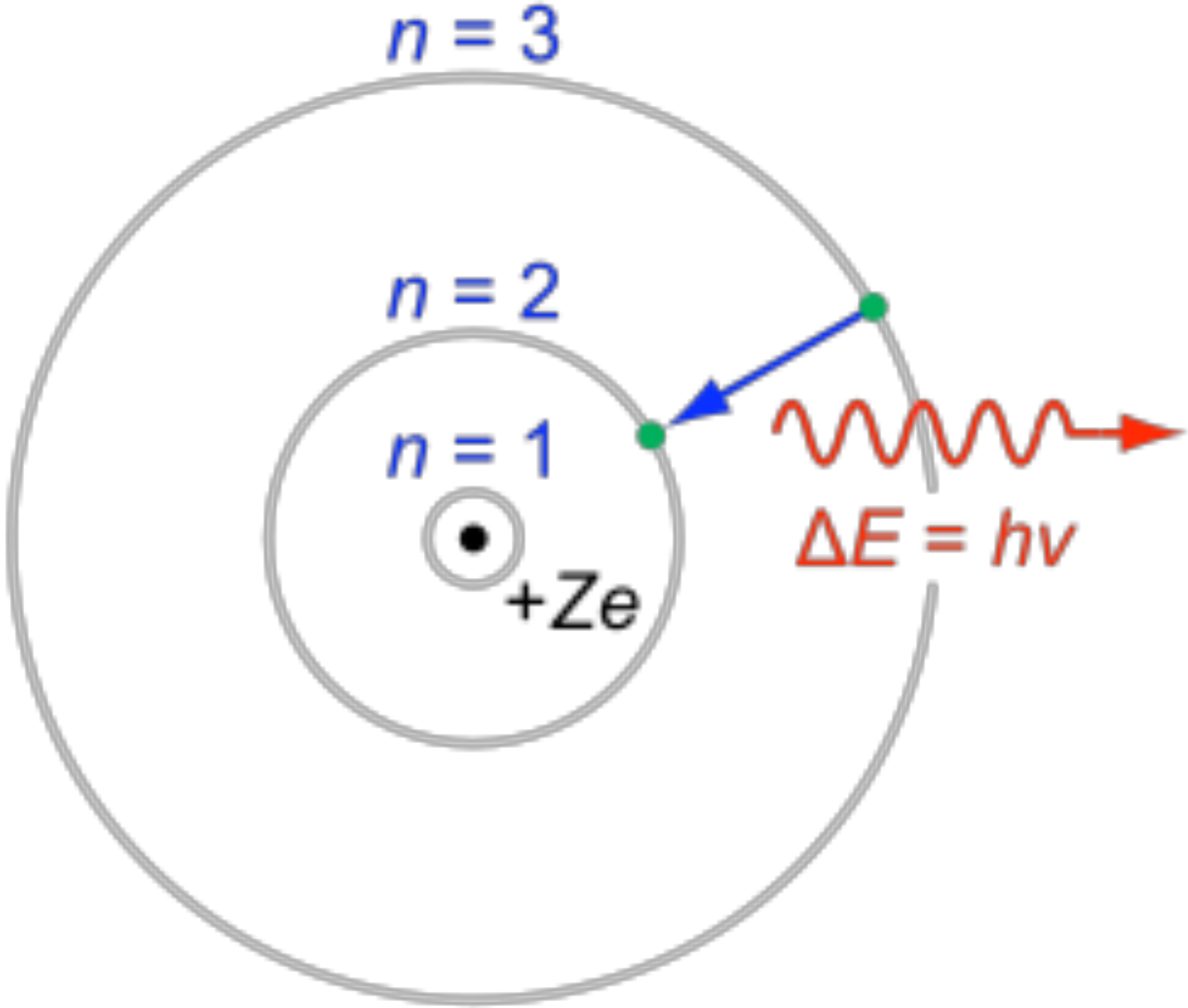


= electron

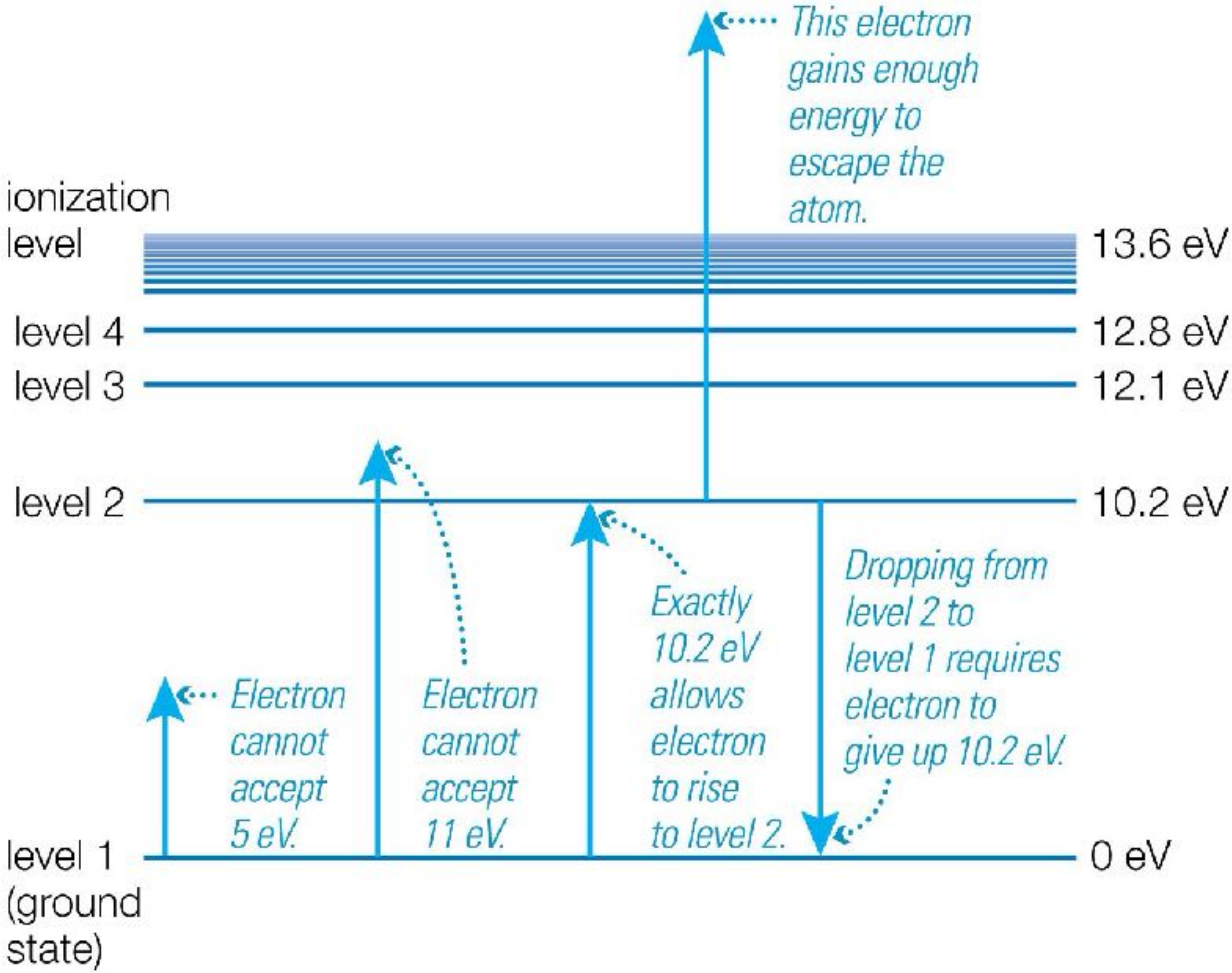


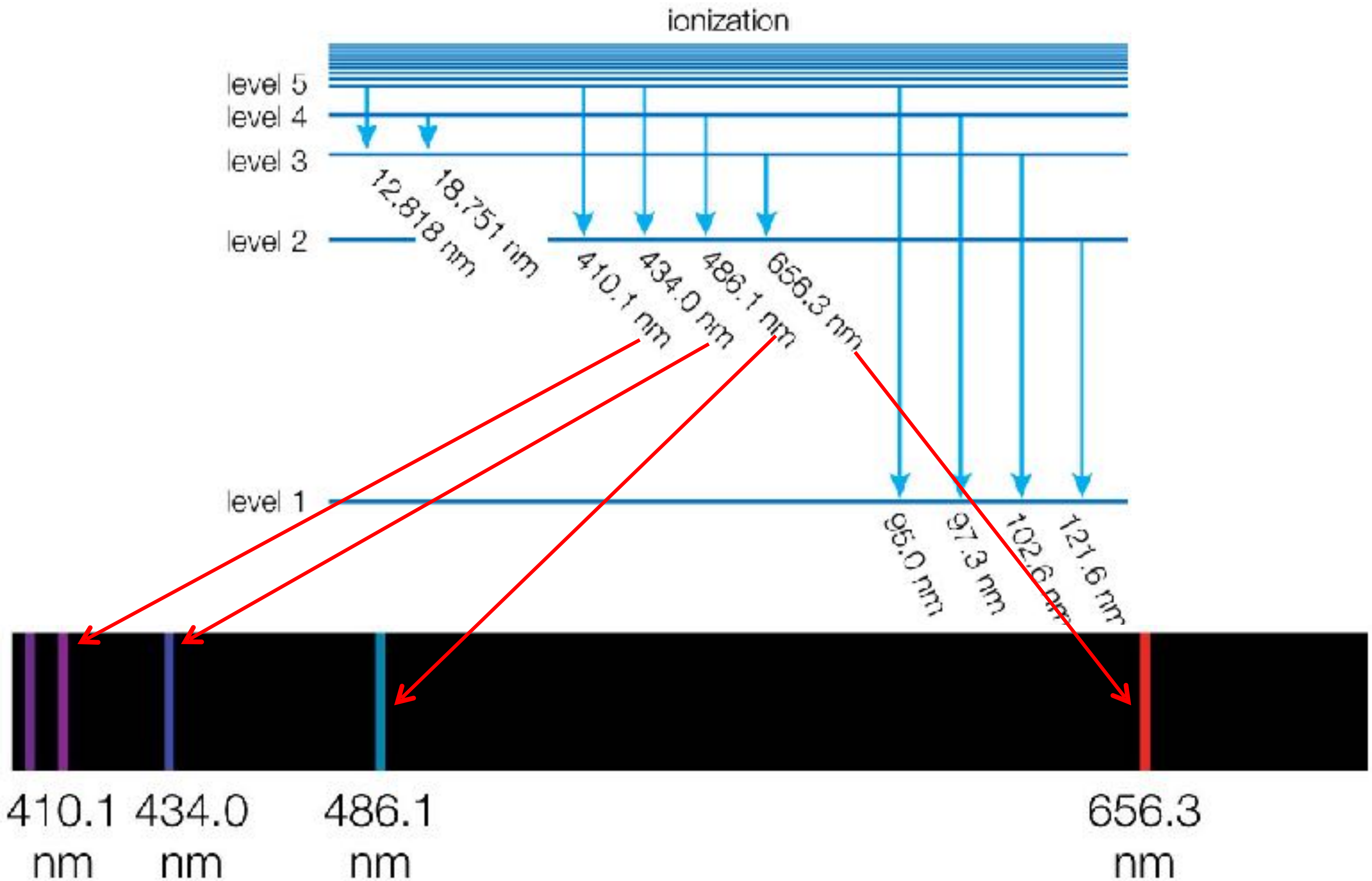
= nuetron



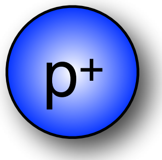


$n = 3$
$n = 2$
$n = 1$
$+Ze$
$\Delta E = h\nu$


This electron gains enough energy to escape the atom.
ionization level
13.6 eV
level 4
12.8 eV
level 3
12.1 eV
level 2
10.2 eV
Exactly 10.2 eV allows electron to rise to level 2.
Dropping from level 2 to level 1 requires electron to give up 10.2 eV.
Electron cannot accept 5 eV.
Electron cannot accept 11 eV.
level 1 (ground state)
0 eV

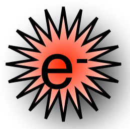


ionization
level 5
level 4
level 3
level 2
level 1
12,818 nm
18,751 nm
410.1 nm
434.0 nm
486.1 nm
656.3 nm
95.0 nm
97.3 nm
102.6 nm
121.6 nm
410.1 nm
434.0 nm
486.1 nm
656.3 nm

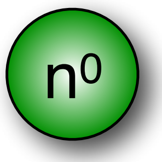


= proton

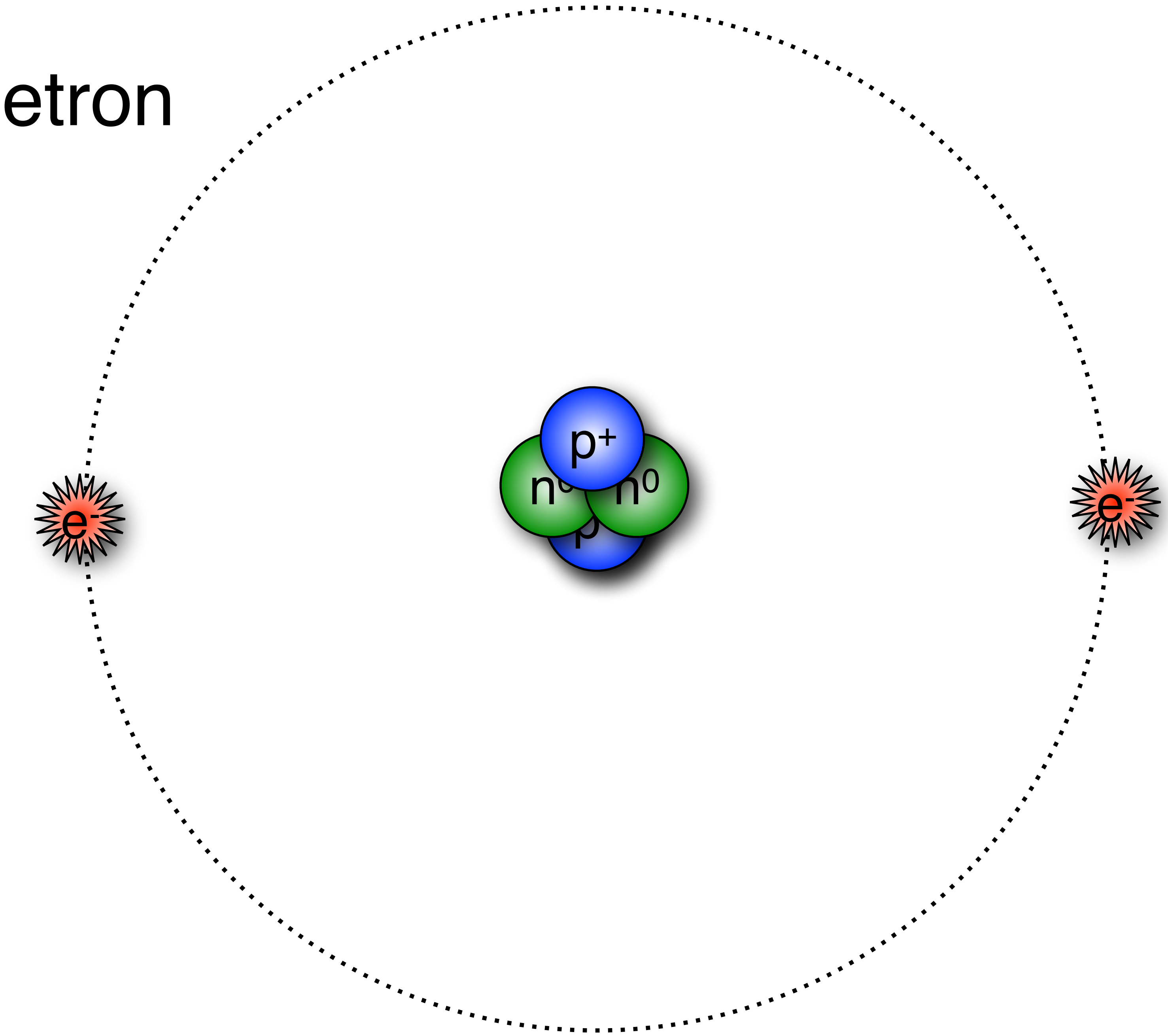
Helium He

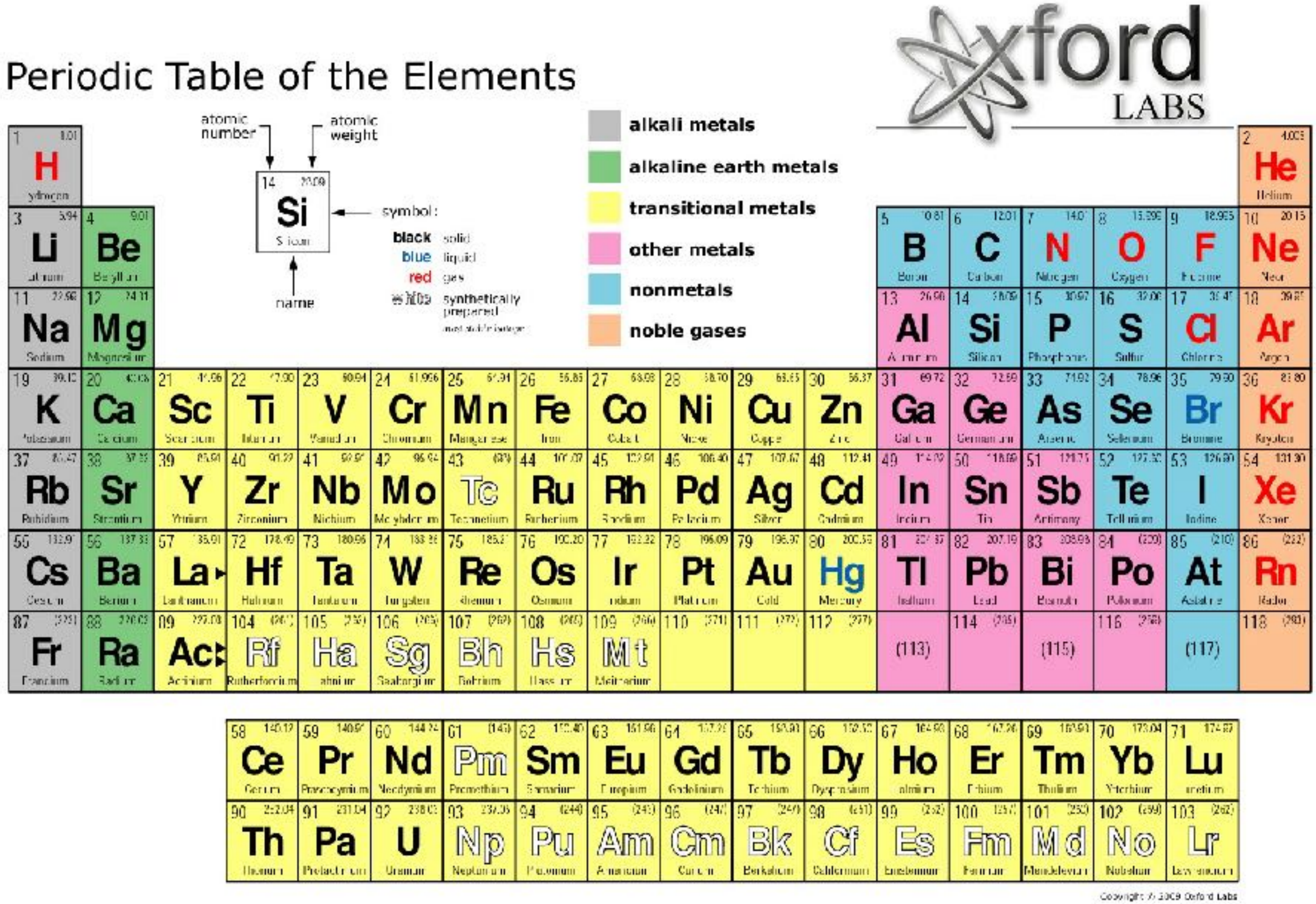


= electron



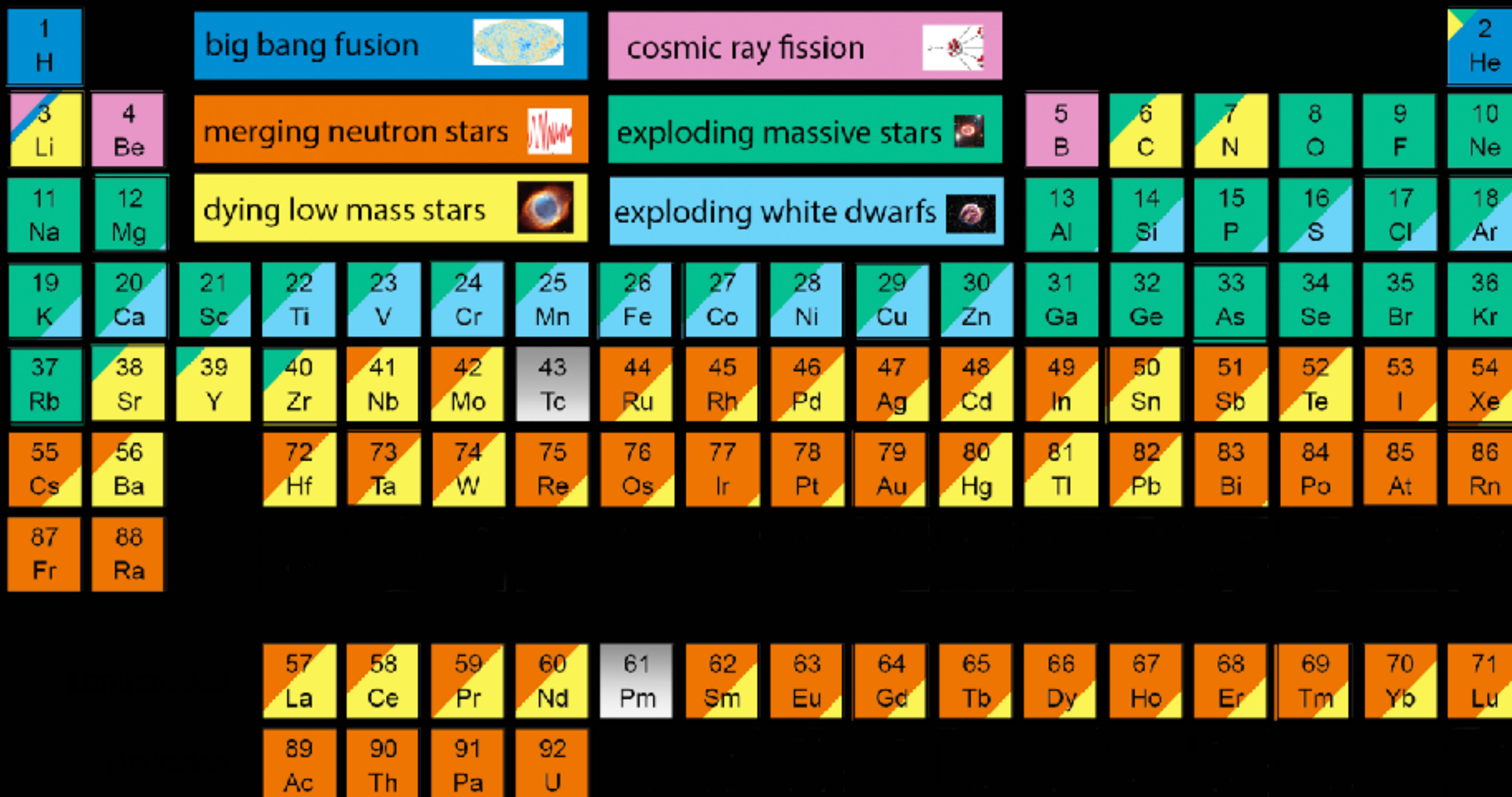
= nuetron





Periodic Table of the Elements
Oxford LABS
atomic number
atomic weight
symbol:
name
black solid
blue liquid
red gas
synthetically prepared
alkali metals
alkaline earth metals
transitional metals
other metals
nonmetals
noble gases
1 H
2 He Helium
3 Li
4 Be
5 B
6 C Carbon
7 N Nitrogen
8 O Oxygen
9 F
10 Ne
11 Na Sodium
12 Mg
13 Al
14 Si Silicon
15 P Phosphorus
16 S Sulfur
17 Cl Chlorine
18 Ar Argon
19 K
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br Bromine
36 Kr
37 Rb Rubidium
38 Sr
39 Y Yttrium
40 Zr Zirconium
41 Nb
42 Mo
43 Tc Technetium
44 Ru
45 Rh
46 Pd
47 Ag Silver
48 Cd Cadmium
49 In
50 Sn
51 Sb
52 Te
53 I Iodine
54 Xe
55 Cs
56 Ba Barium
57 La
72 Hf
73 Ta
74 W Tungsten
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg Mercury
81 Tl
82 Pb Lead
83 Bi
84 Po
85 At
86 Rn
87 Fr
88 Ra
89 Ac Actinium
104 Rf Rutherfordium
105 Ha
106 Sg
107 Bh
108 Hs
109 Mt
110
111
112
(113)
114
(115)
116
(117)
118
58 Ce
59 Pr
60 Nd
61 Pm
62 Sm
63 Eu
64 Gd
65 Tb
66 Dy
67 Ho
68 Er
69 Tm
70 Yb
71 Lu
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
98 Cf
99 Es
100 Fm
101 Md
102 No
103 Lr

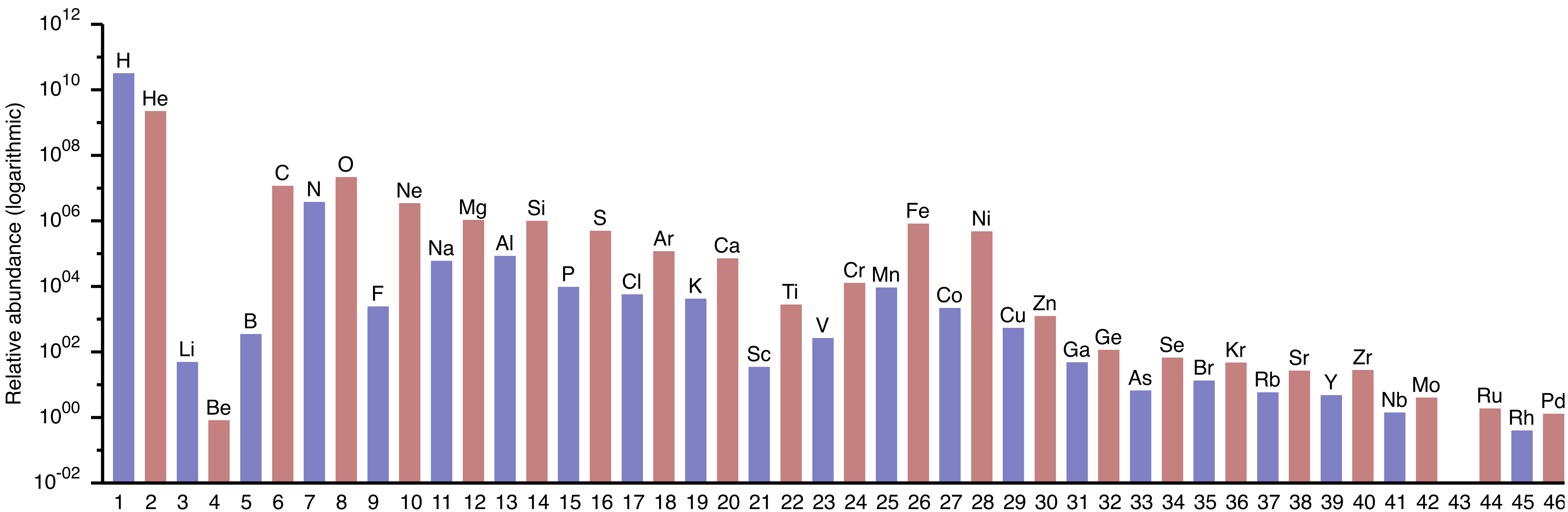
The Origin of the Solar System Elements

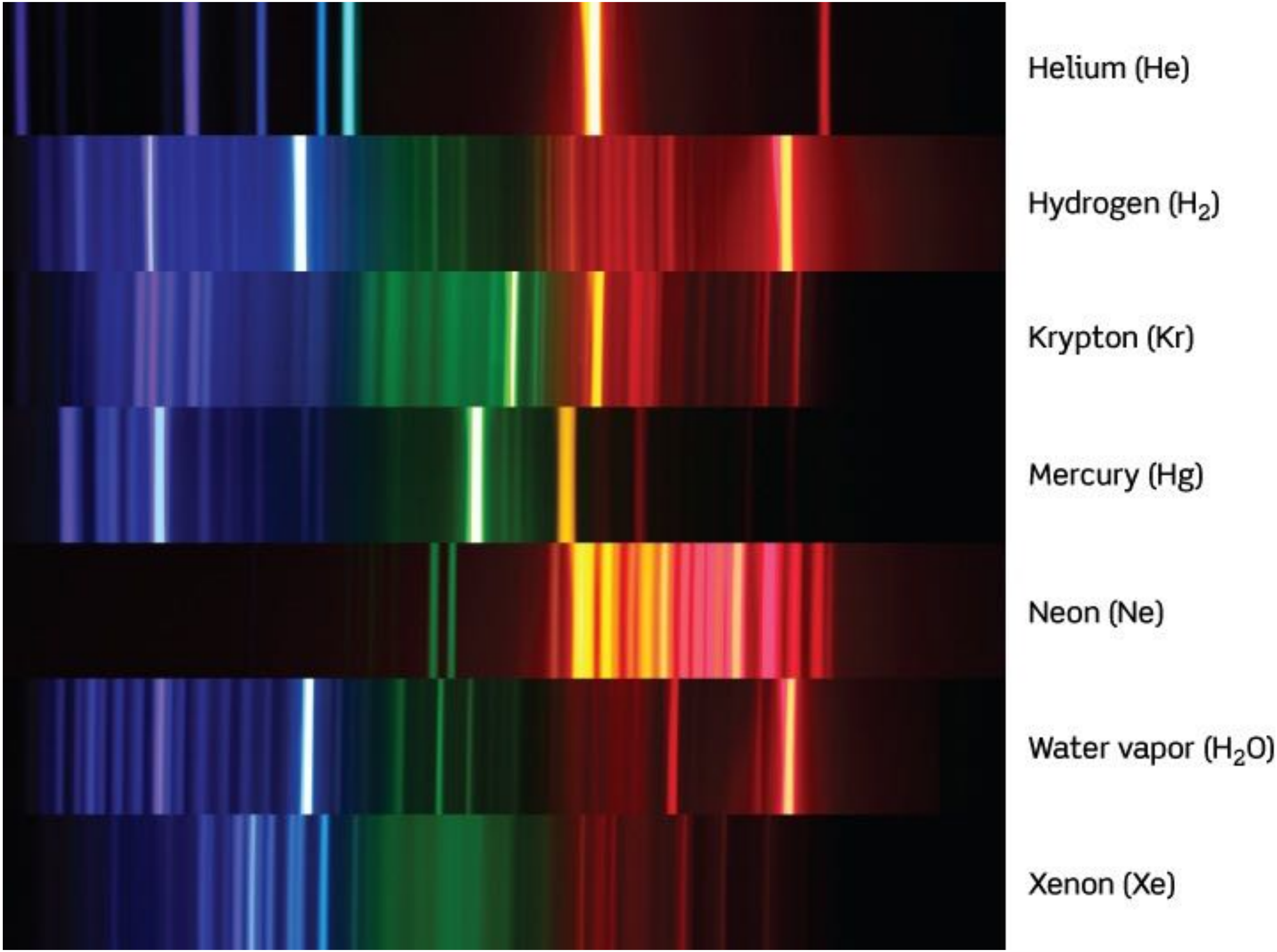


Astronomical Image Credits:
ESA/NASA/AASNova

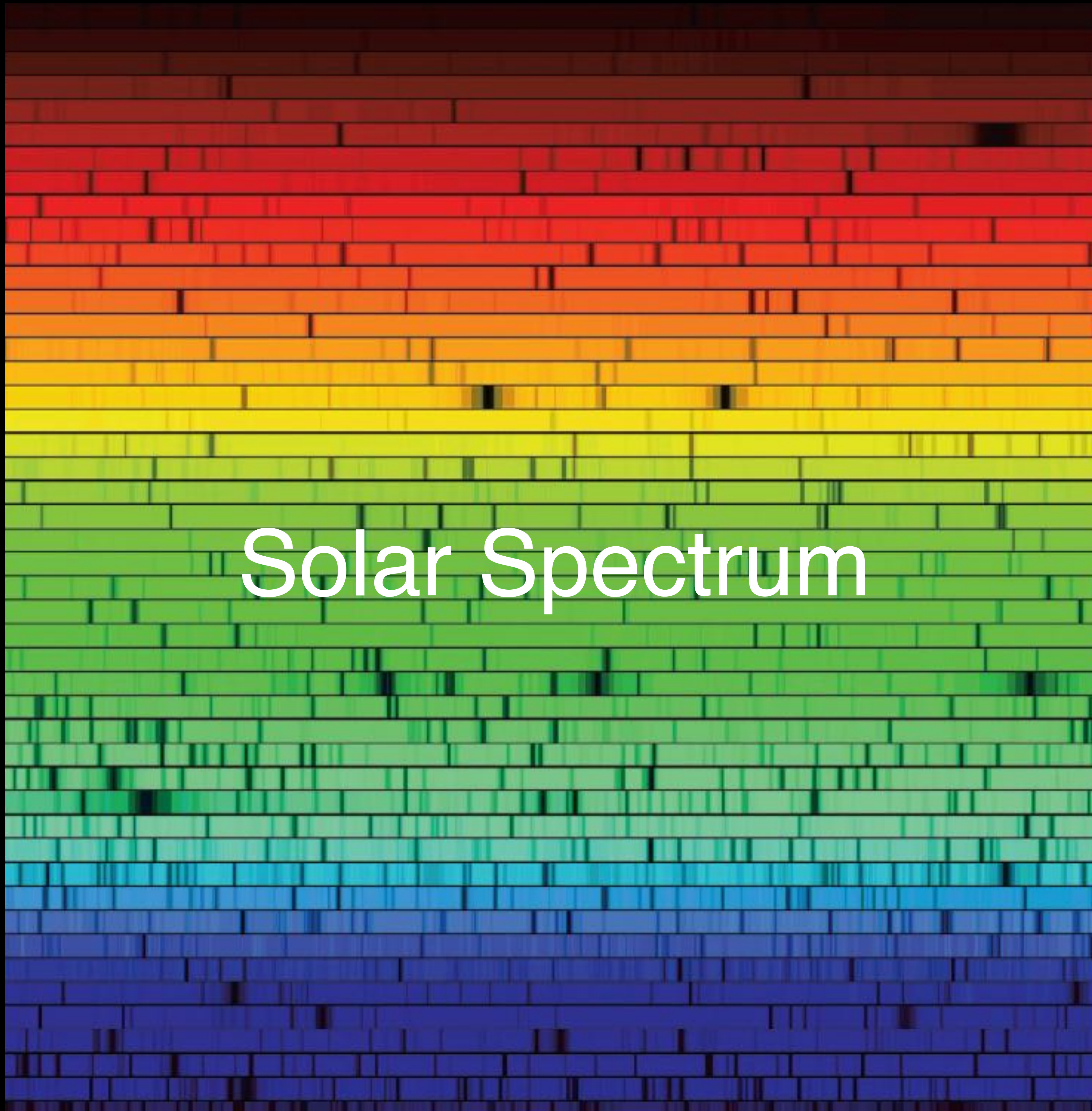
Graphic created by Jennifer Johnson

Relative Abundances of the Elements

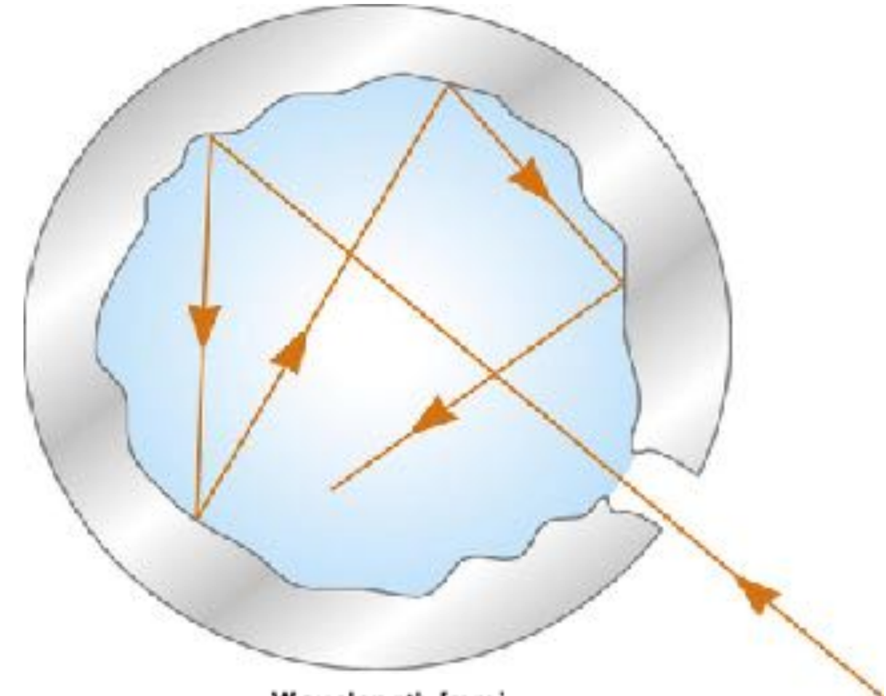



Helium (He)
Hydrogen (H_2)
Krypton (Kr)
Mercury (Hg)
Neon (Ne)
Water vapor (H_2O)
Xenon (Xe)

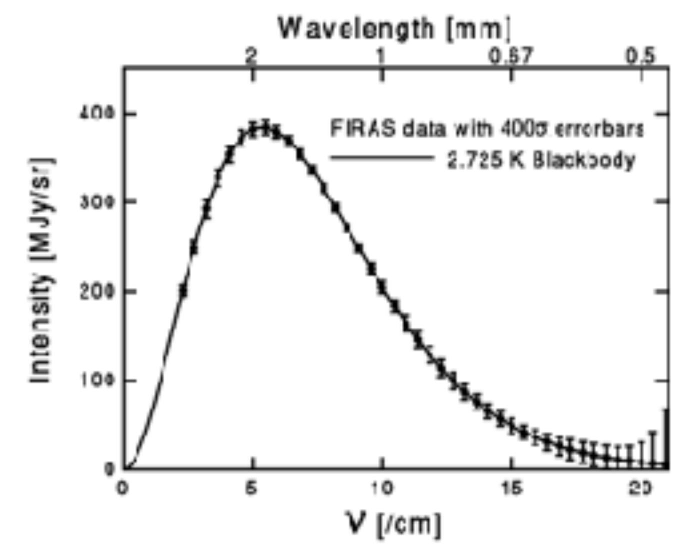
Solar Spectrum



Blackbody Radiation

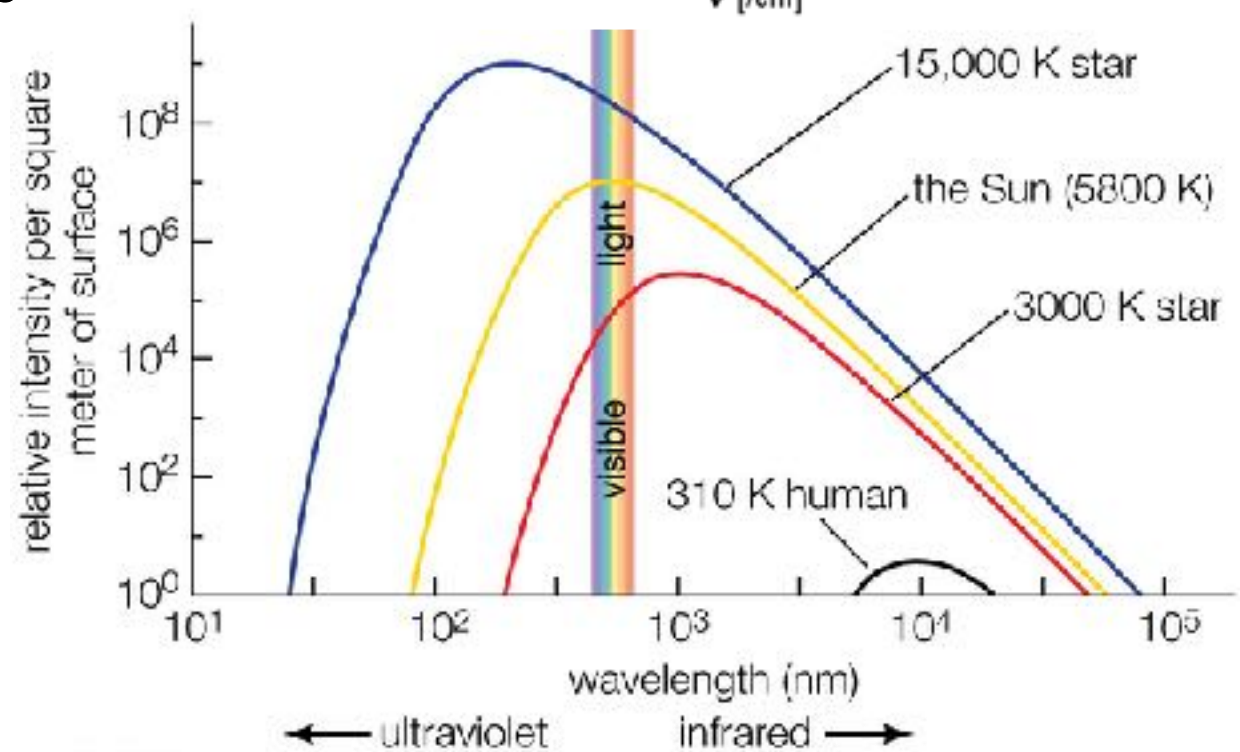


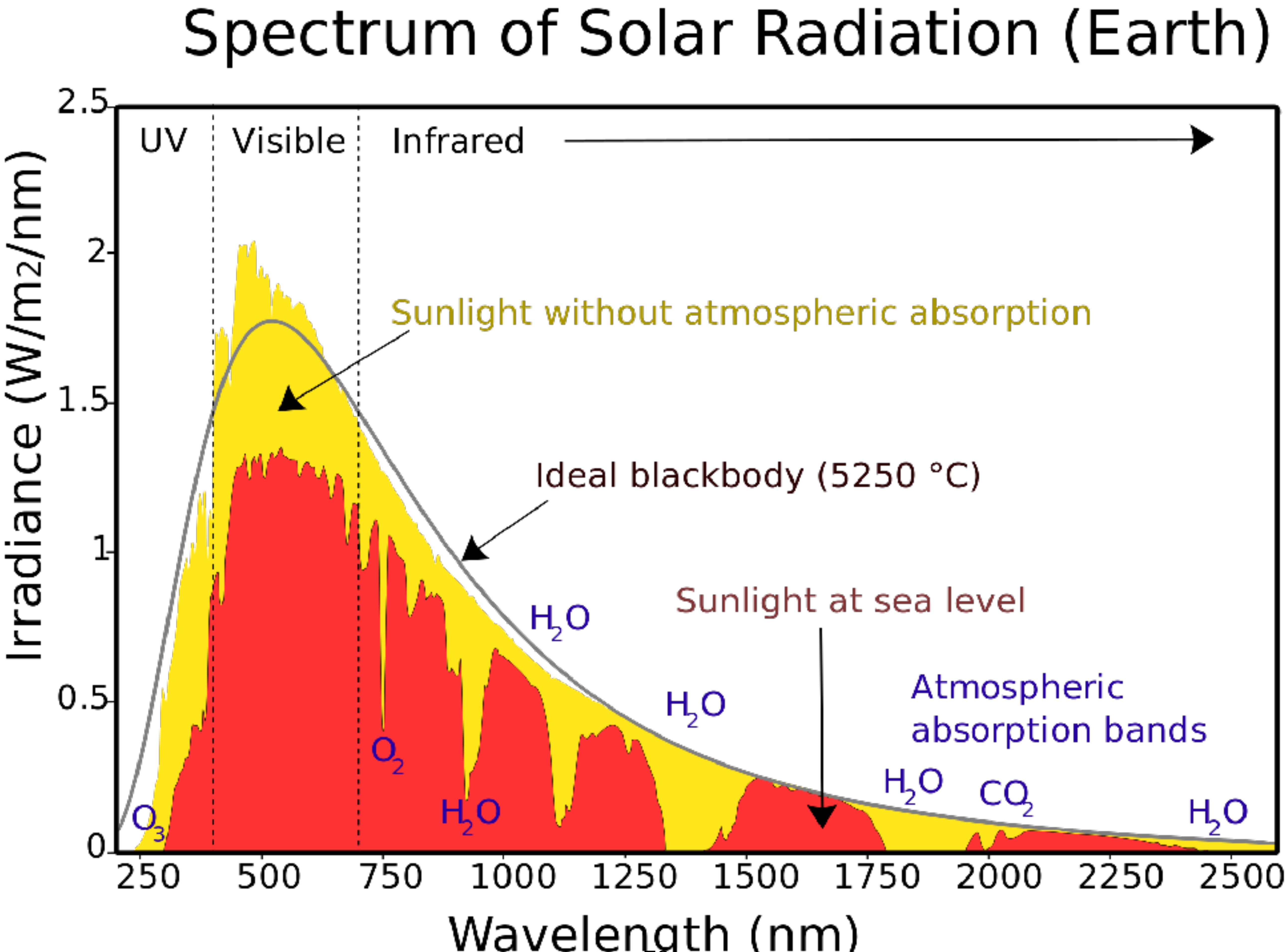
- A perfect blackbody is an idealized material that absorbs all radiation incident upon it, and emits at all wavelengths with a characteristic shape, completely characterized by it's temperature. (Planck's Law)
- Wien's Law gives us a quick way to convert temperature to peak frequency.
- Stefan-Boltzmann Law: the power emitted per unit area of the surface of a black body is directly proportional to T^4
- No blackbody is actually perfect.
- The CMB (3K) is the most perfect blackbody in the Universe.

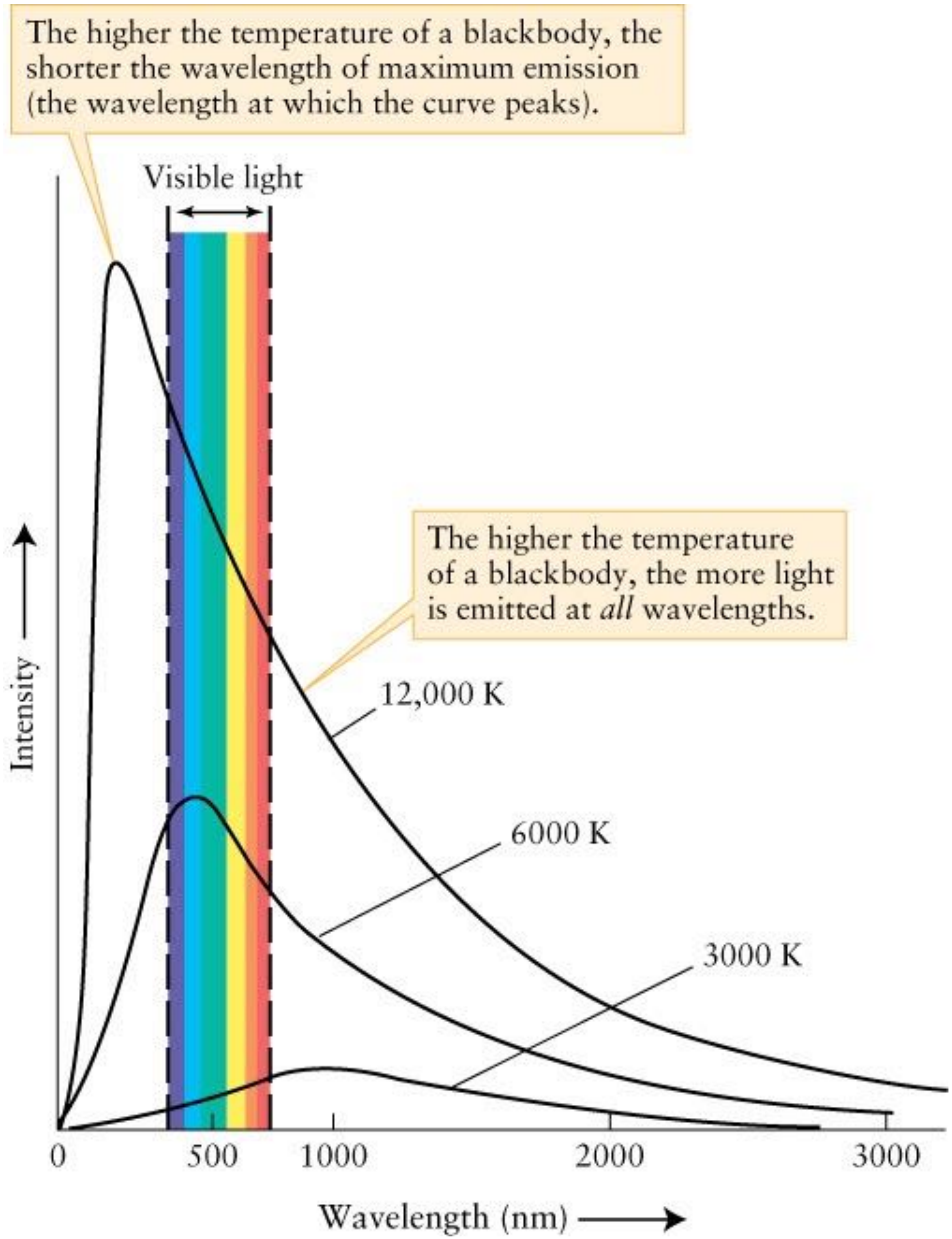


$$\nu_{\max} = T \times 60 \frac{\mathrm{GHz}}{\mathrm{K}}$$

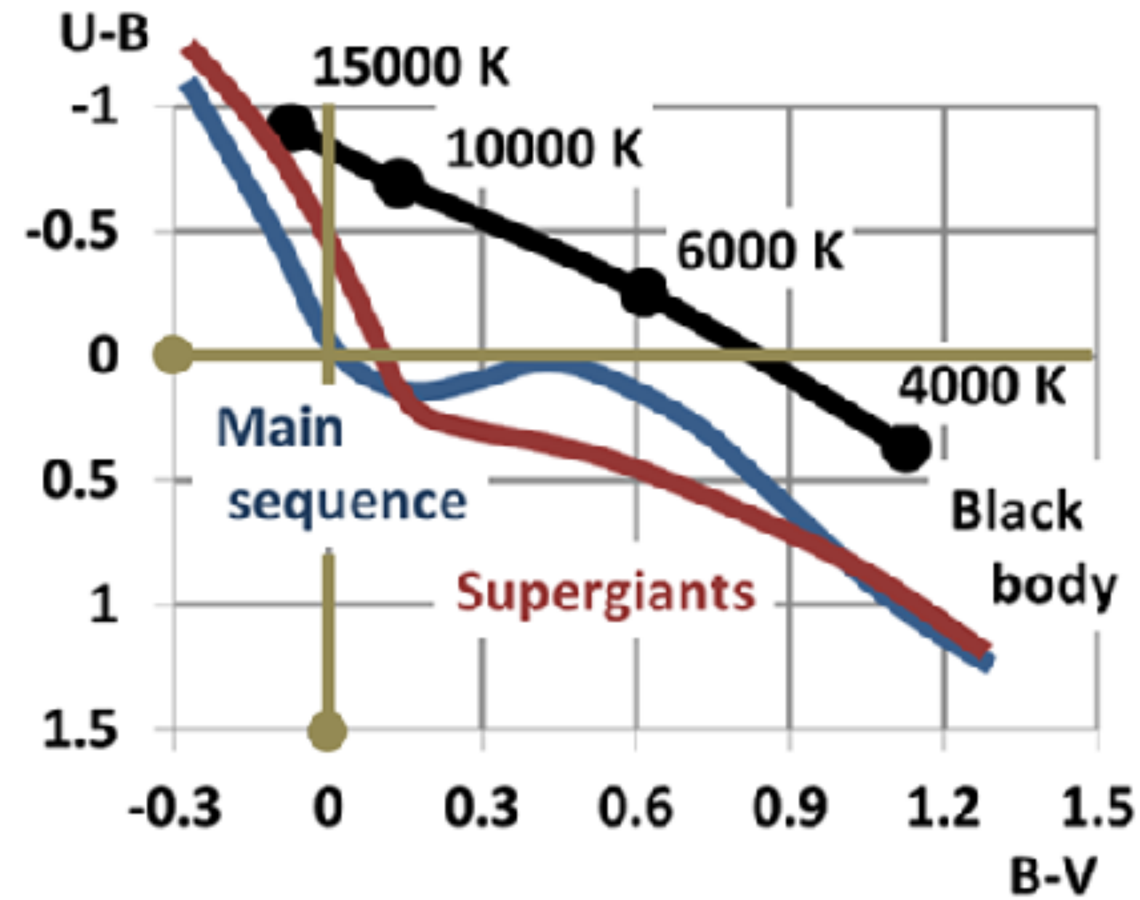
$$j = \sigma T^4$$

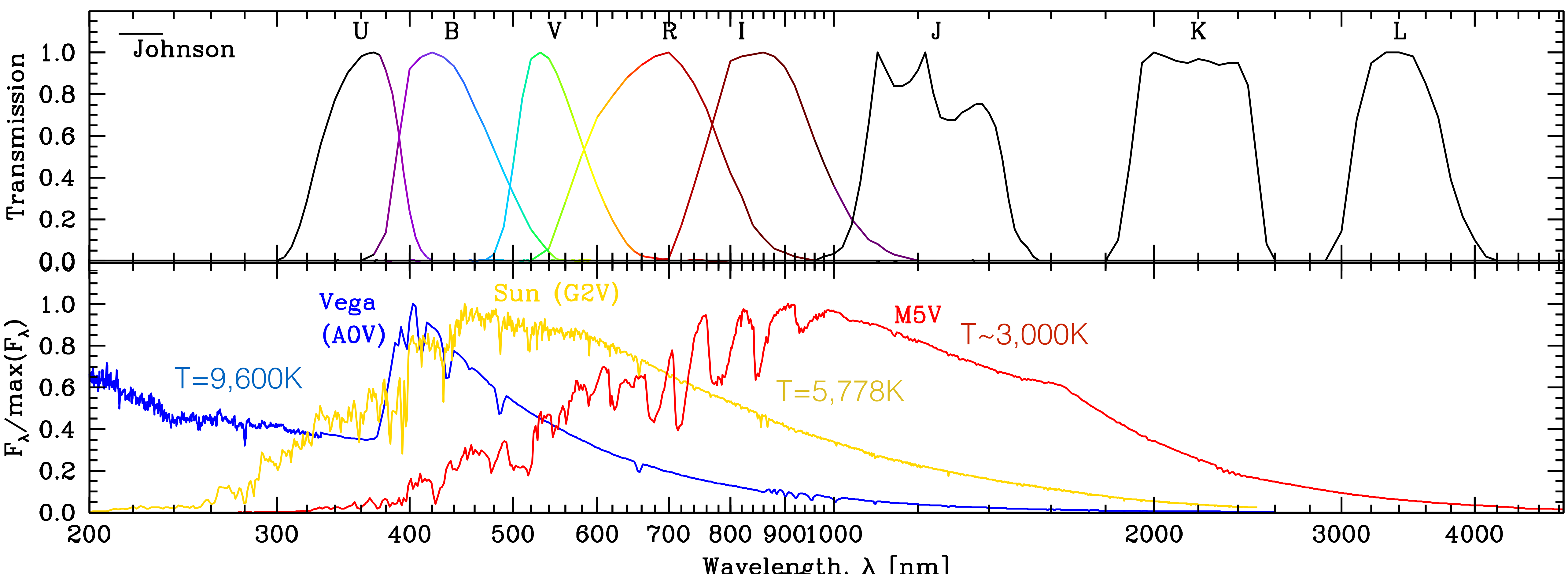


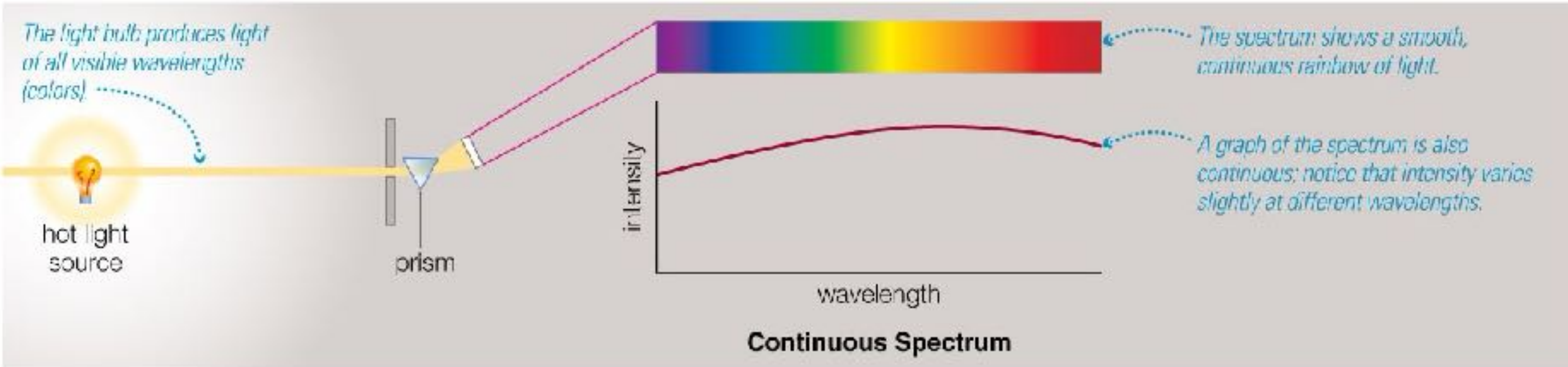

Spectrum of Solar Radiation (Earth)
UV
Visible
Infrared
Sunlight without atmospheric absorption
Ideal blackbody (5250 °C)
Sunlight at sea level
Atmospheric absorption bands
O_3
O_2
H_2O
H_2O
H_2O
H_2O
CO_2
H_2O
Irradiance (W/m₂/nm)
Wavelength (nm)
2.5
2
1.5
1
0.5
0
250
500
750
1000
1250
1500
1750
2000
2250
2500


The higher the temperature of a blackbody, the shorter the wavelength of maximum emission (the wavelength at which the curve peaks).
Visible light
The higher the temperature of a blackbody, the more light is emitted at *all* wavelengths.
12,000 K
6000 K
3000 K
Intensity
0
500
1000
2000
3000
Wavelength (nm)

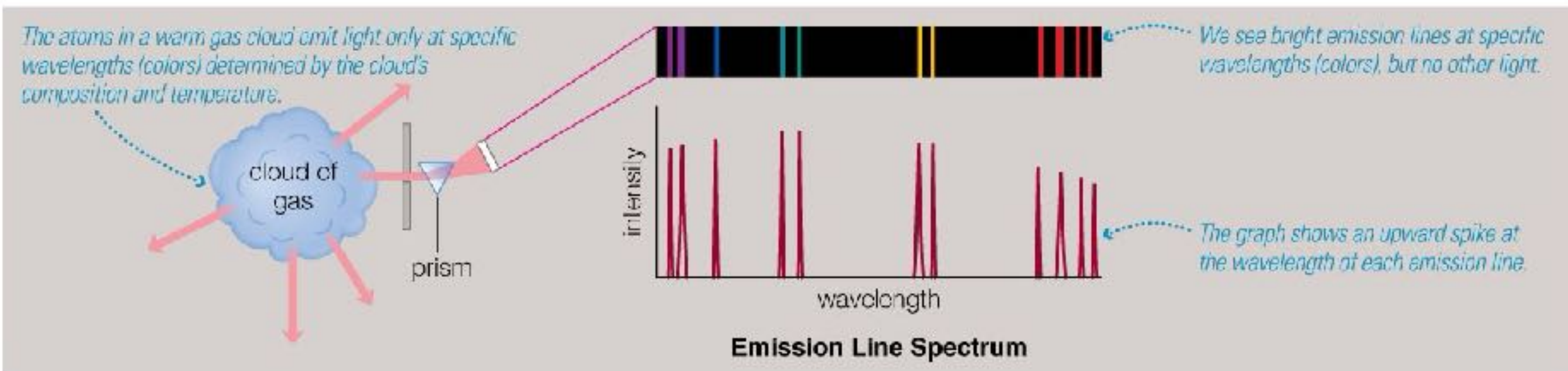
Blackbodies and stars



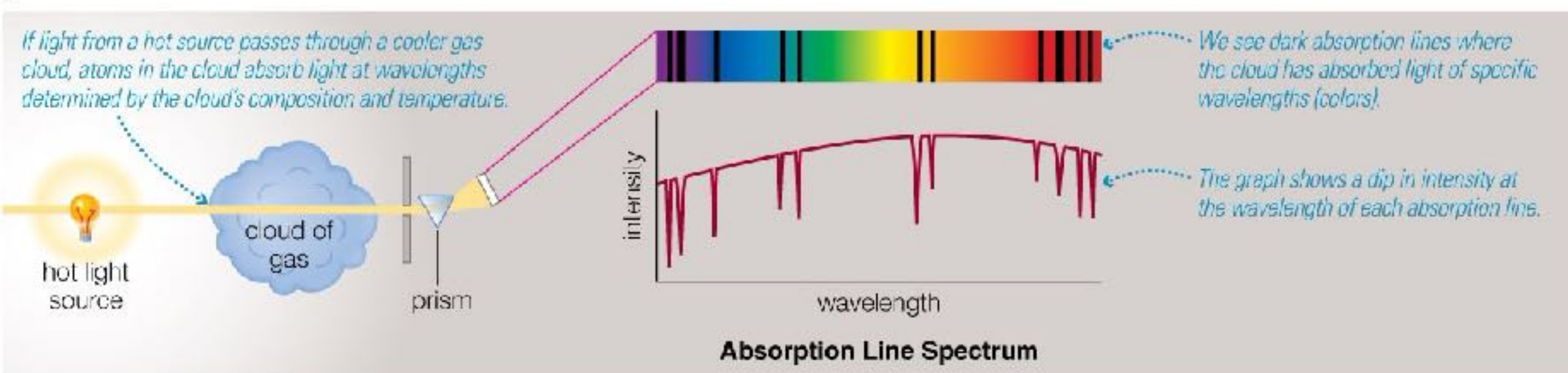



The light bulb produces light of all visible wavelengths (colors).
hot light source
prism
The spectrum shows a smooth, continuous rainbow of light.
intensity
wavelength
A graph of the spectrum is also continuous; notice that intensity varies slightly at different wavelengths.
Continuous Spectrum

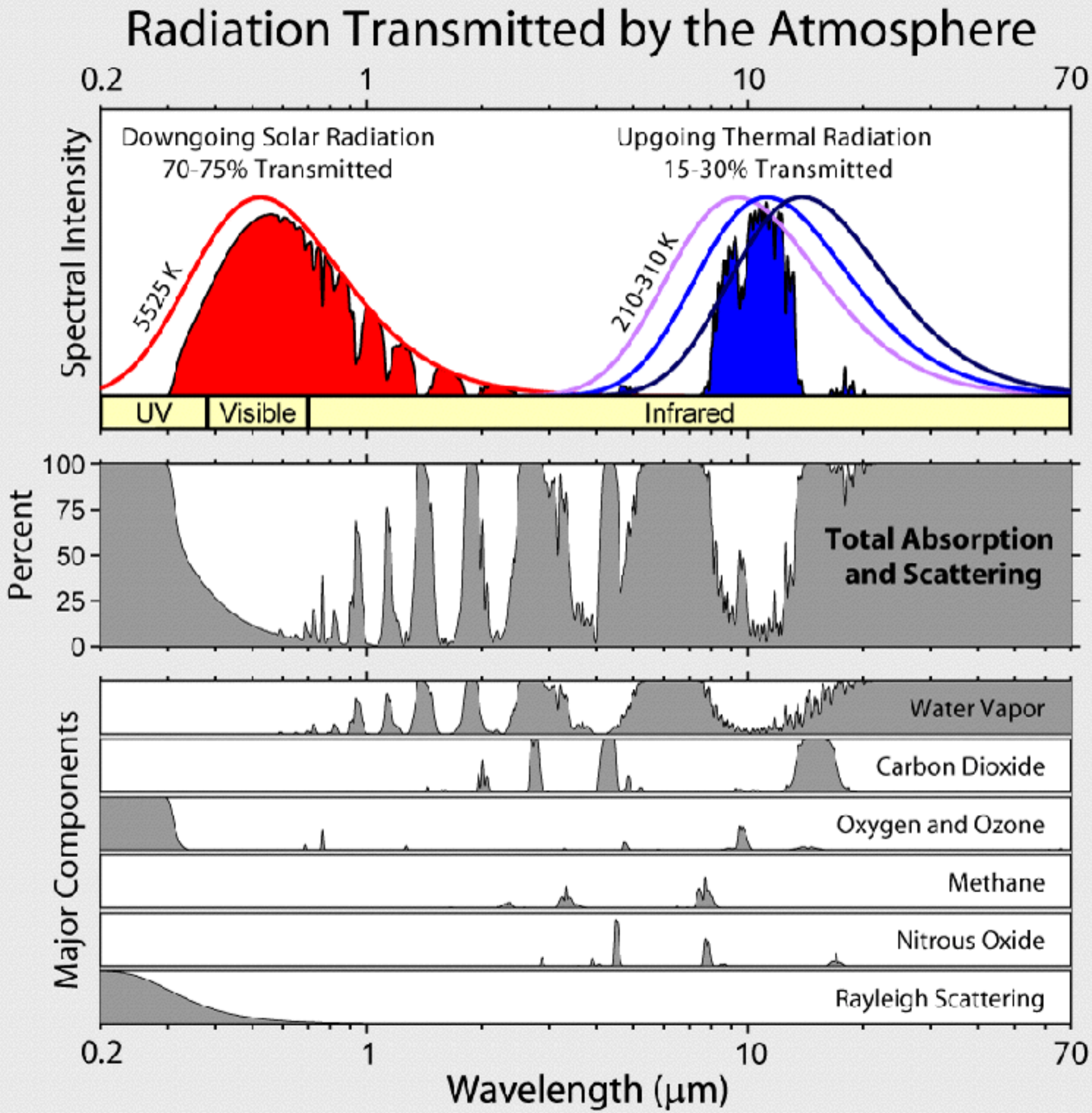
a


The atoms in a warm gas cloud emit light only at specific wavelengths (colors) determined by the cloud's composition and temperature.
cloud of gas
prism
We see bright emission lines at specific wavelengths (colors), but no other light.
intensity
wavelength
The graph shows an upward spike at the wavelength of each emission line.
Emission Line Spectrum

b


If light from a hot source passes through a cooler gas cloud, atoms in the cloud absorb light at wavelengths determined by the cloud's composition and temperature.
hot light source
cloud of gas
prism
We see dark absorption lines where the cloud has absorbed light of specific wavelengths (colors).
intensity
wavelength
The graph shows a dip in intensity at the wavelength of each absorption line.
Absorption Line Spectrum

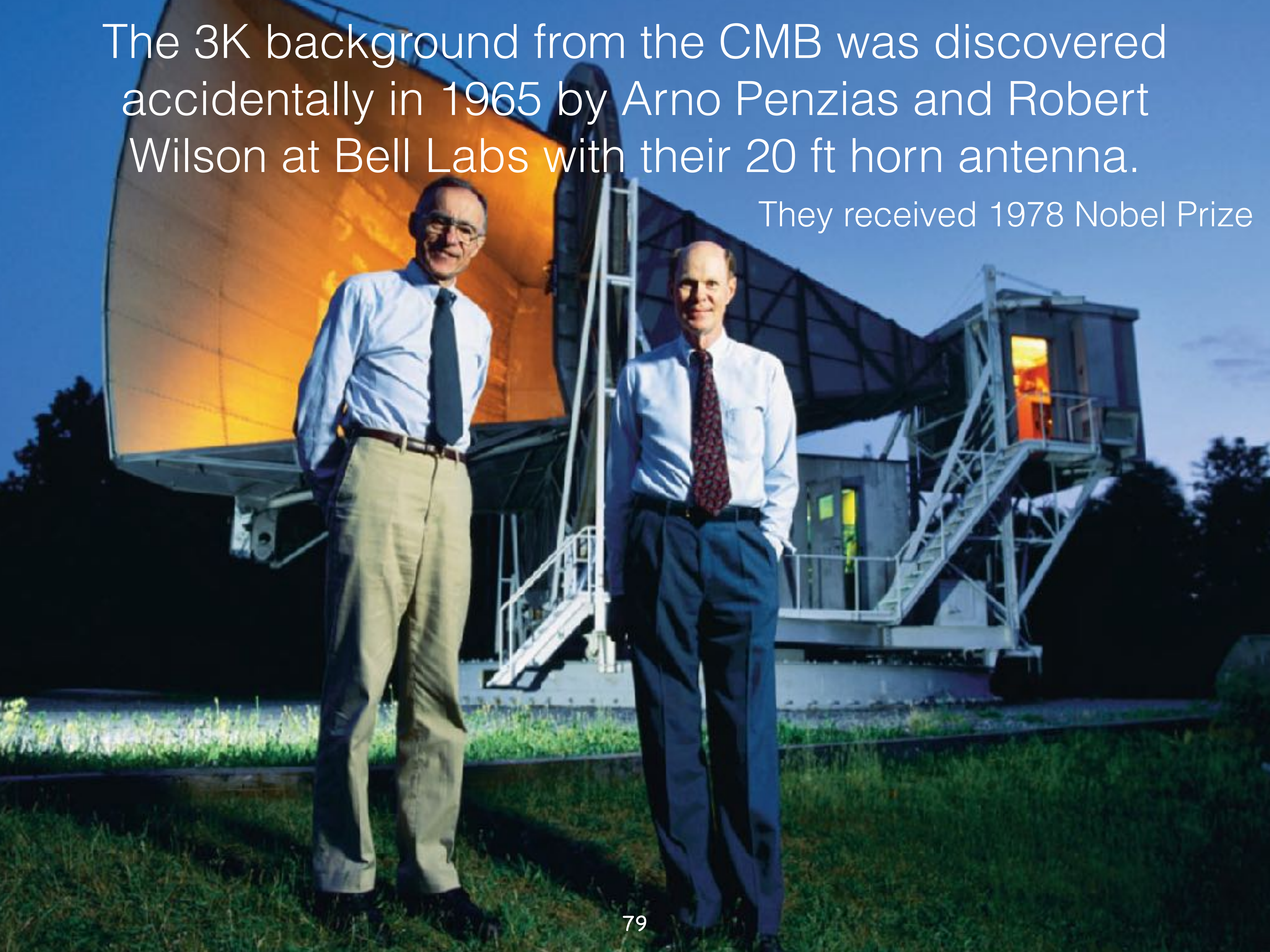
c



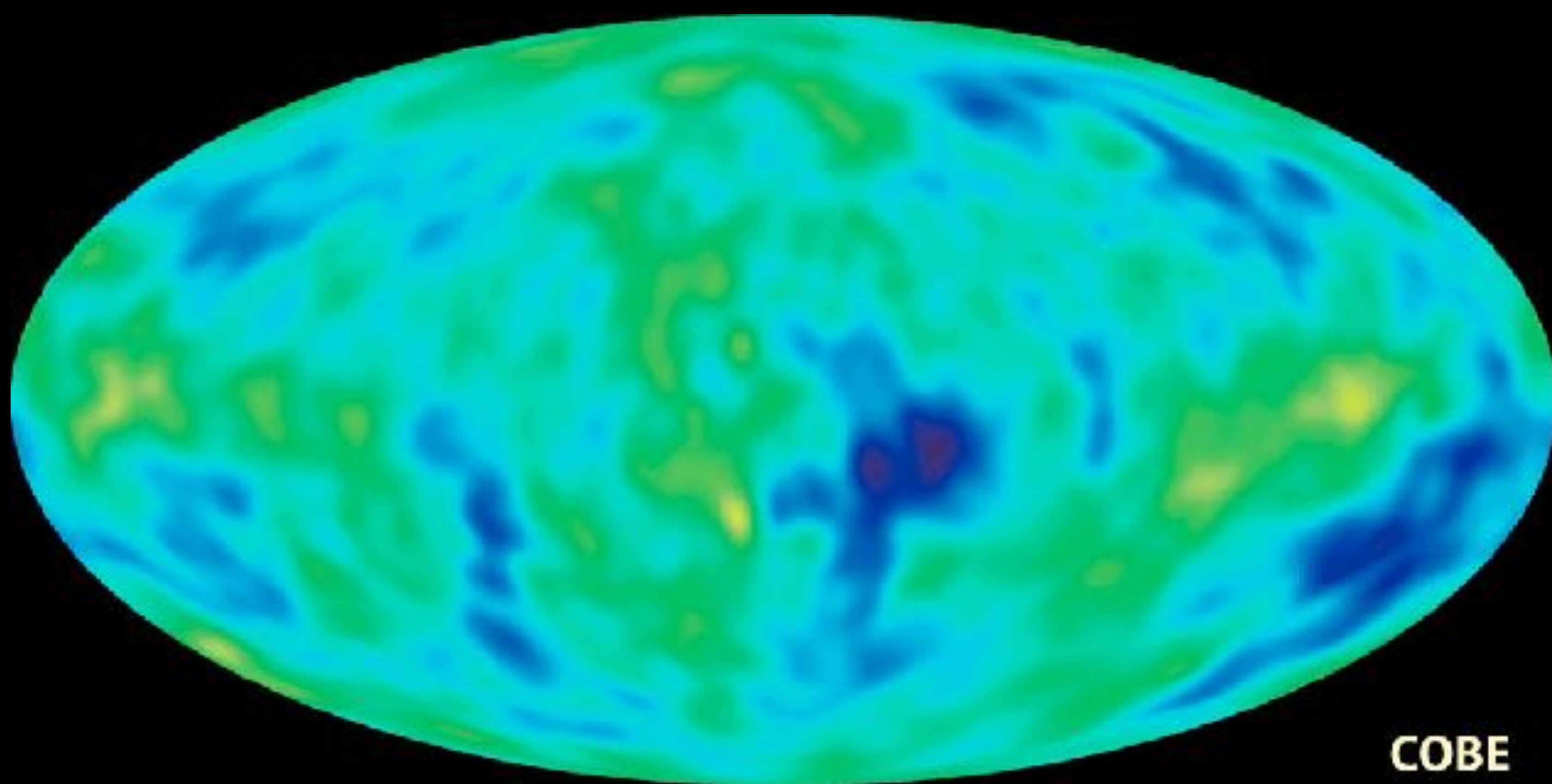
Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (μm)

The 3K background from the CMB was discovered accidentally in 1965 by Arno Penzias and Robert Wilson at Bell Labs with their 20 ft horn antenna.

They received 1978 Nobel Prize

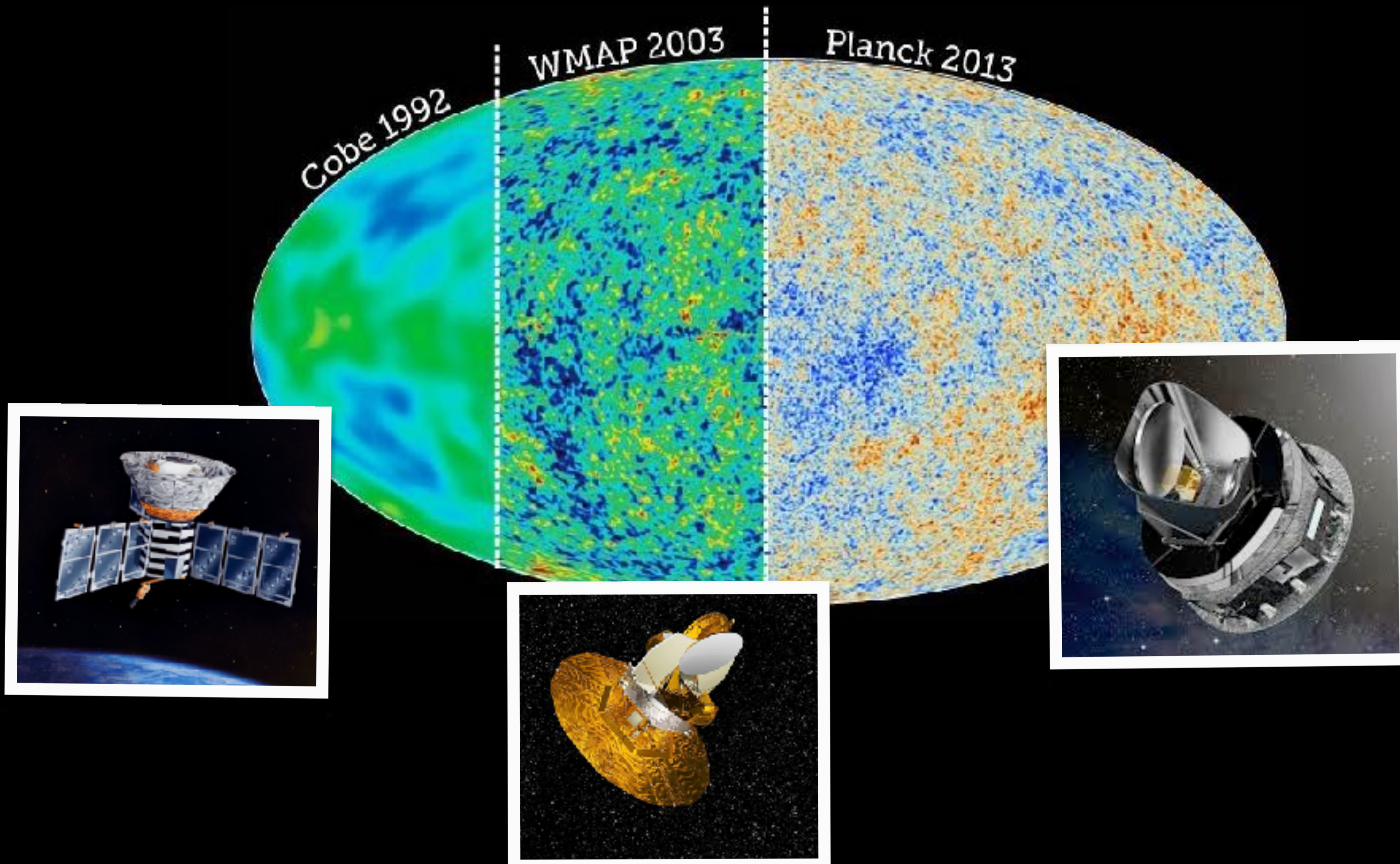


The CMB is a "Baby" Picture of the Universe



- COBE Satellite launched 1987
- FIRAS precisely measured T_{CMB}=2.7255±0.0006 K
- DMR measured fluctuations at 10^{-5}, which are the seeds of structure in the universe today
- Stephen Hawking: "It is the discovery of the century, if not of all time."
- COBE team leaders John Mather & George Smoot received 2006 Nobel Prize

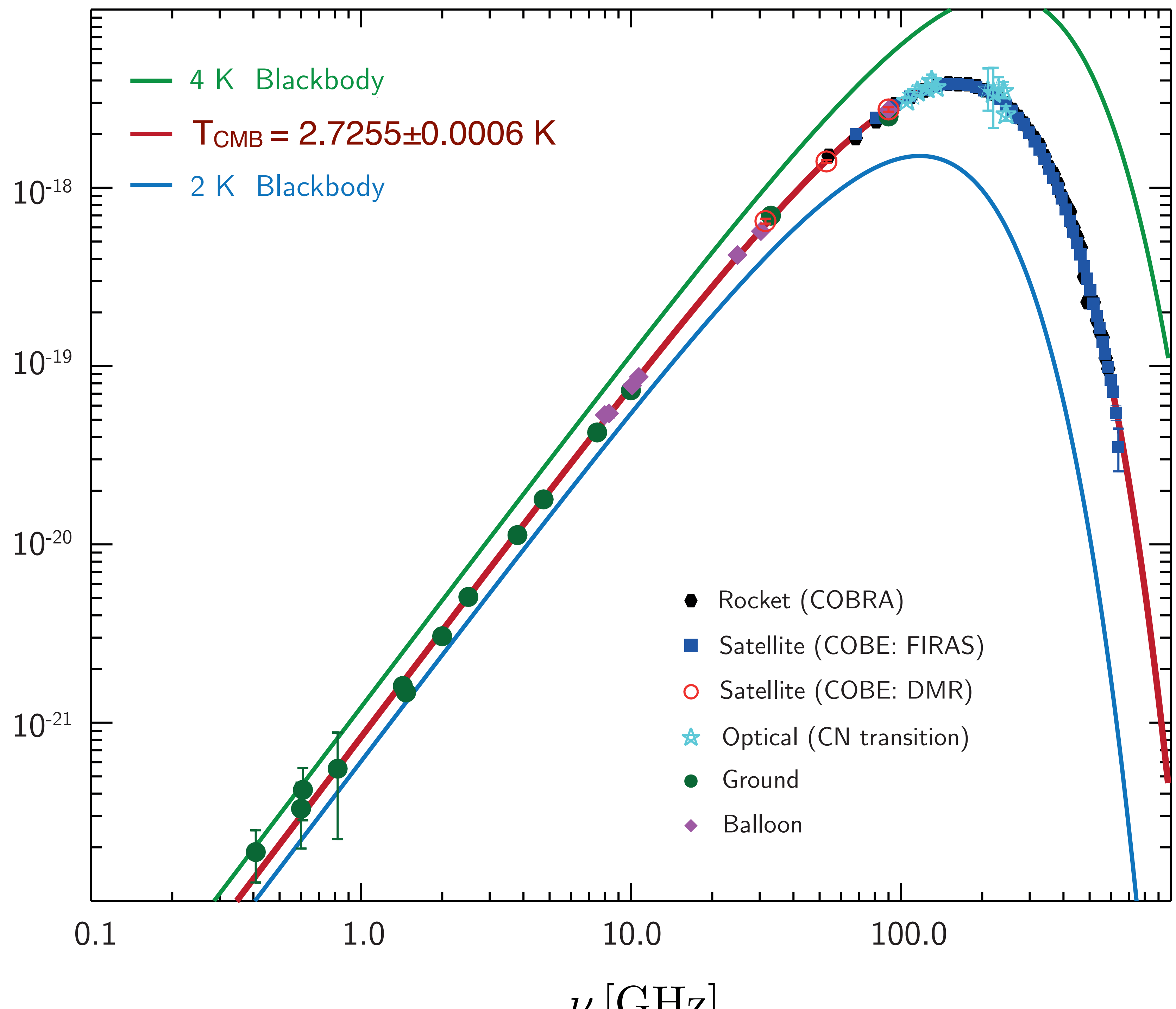
Over time, the measurements of the CMB became more and more precise:



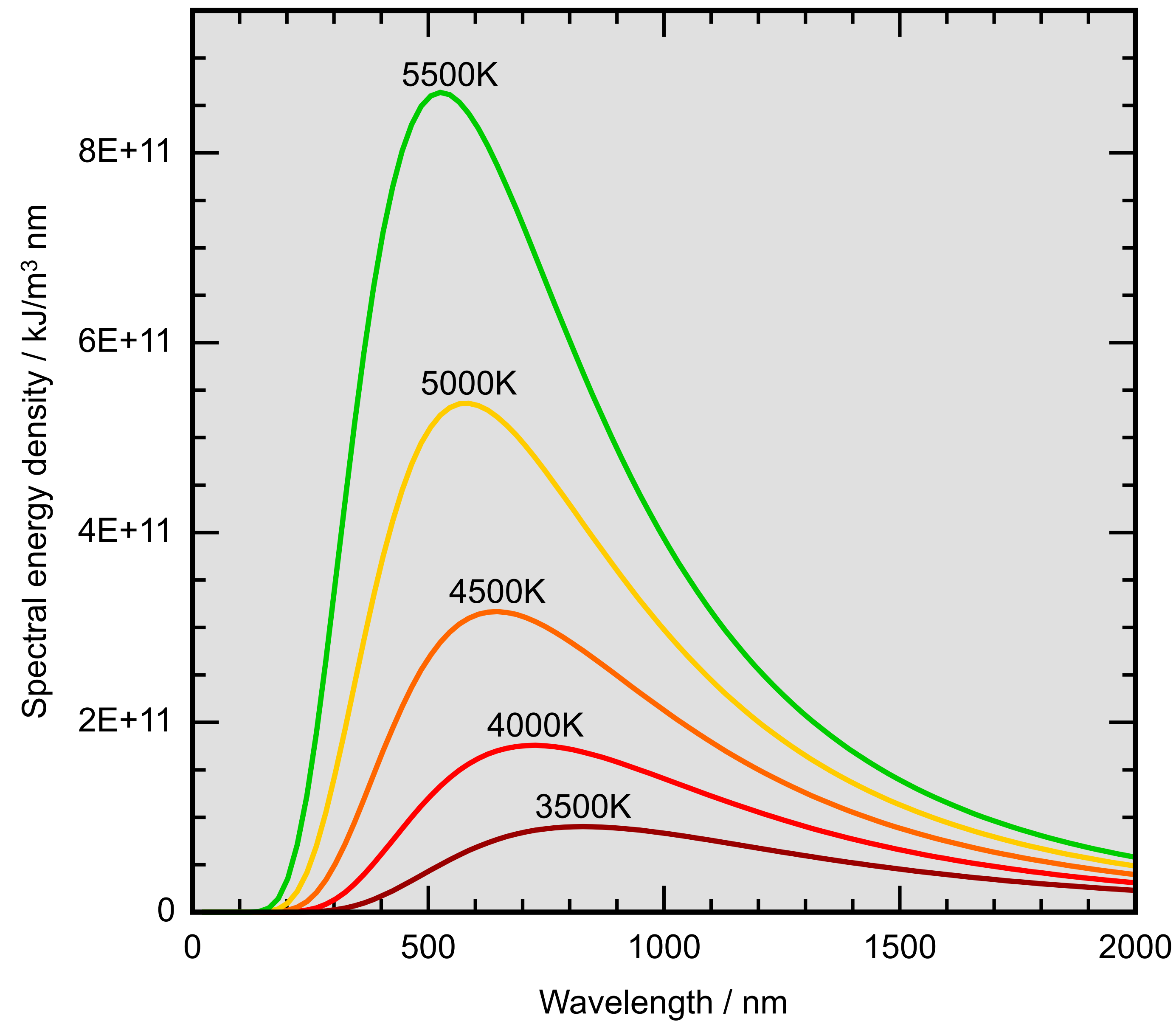
The CMB is the most perfect blackbody ever observed

$$I_\nu = \frac{2h\nu^3}{c^2} f(\nu)$$

intensity



Planck's Law



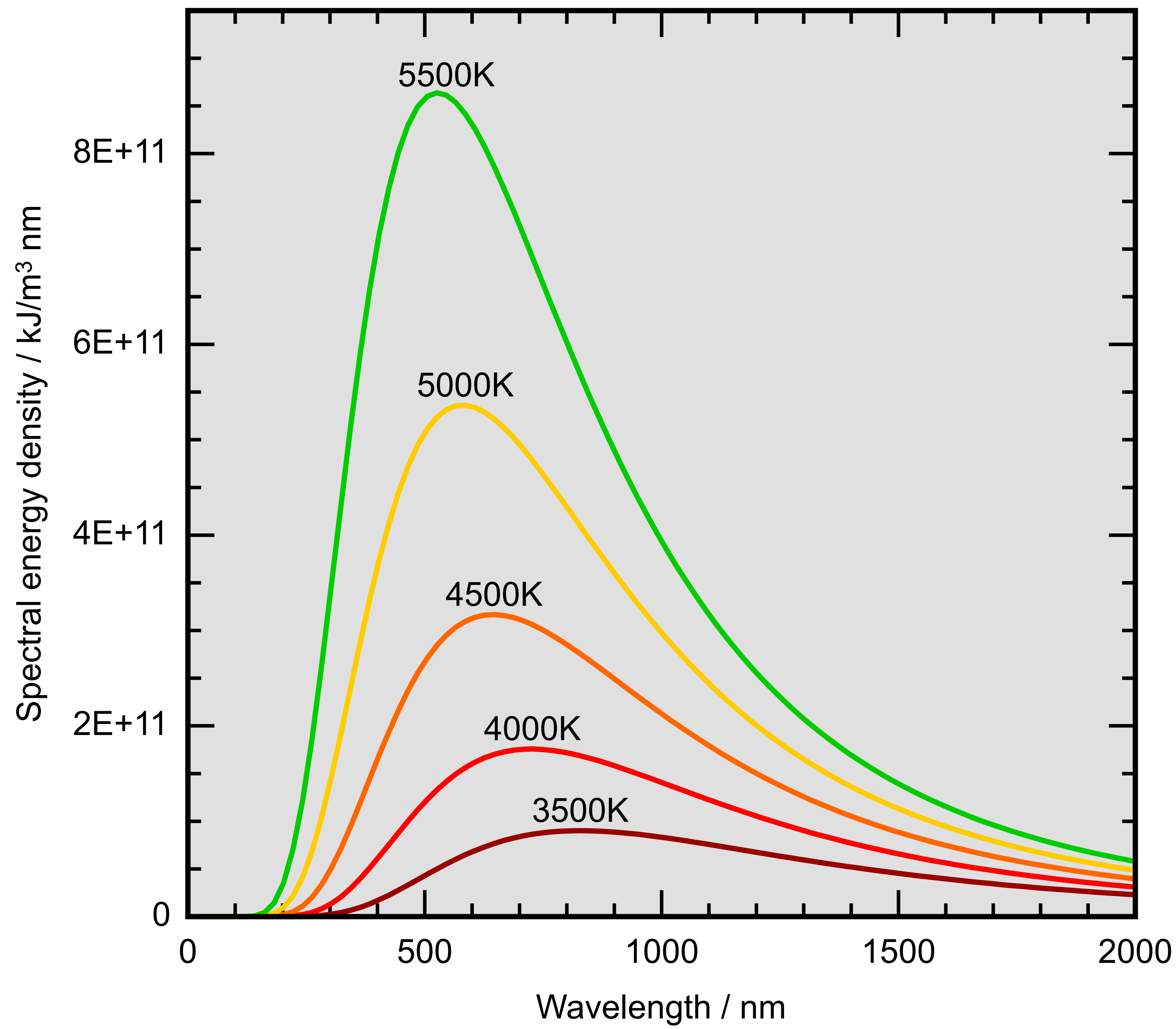
Stefan-Boltzmann law (1878,1884)

$$s = \sigma T^4$$

The total energy radiated per unit surface area of a black body across all wavelengths per unit time
(also known as the black-body radiant exitance or emissive power, j),
is directly proportional to the
fourth power of the black body's thermodynamic temperature, T

$$\sigma = \frac{2\pi^3 k_B^4}{15h^2c^2} = 5.67 \times 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}\ \text{Stefan-Boltmann constant}$$

Planck's Law



Wien's displacement law (1893)

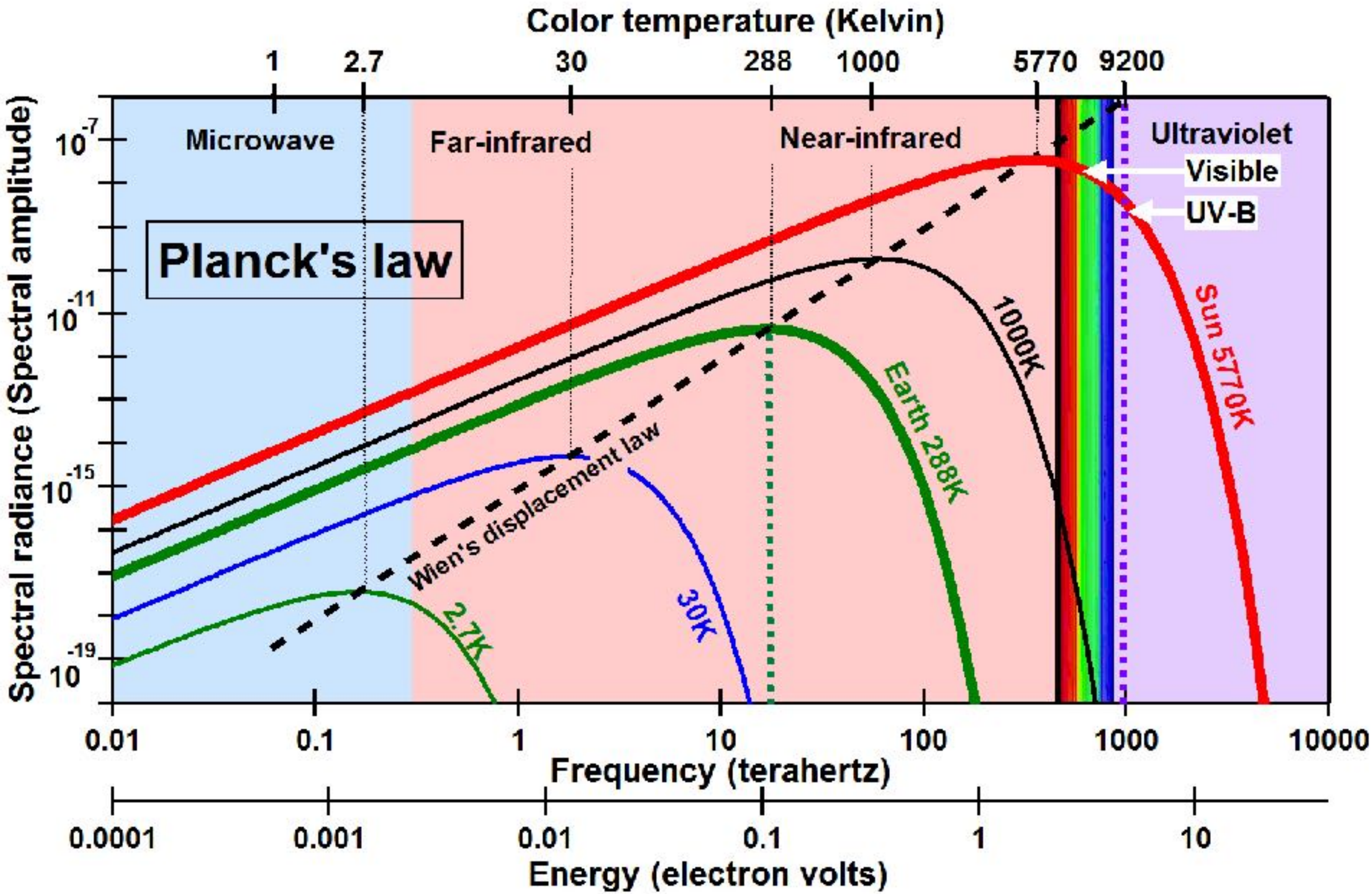
$$\lambda_{\max} = \frac{b}{T}$$

b is a constant of proportionality called Wien's displacement constant
$b = 2.897 \times 10^{-3}$ m K, or b≈2900 μm·K

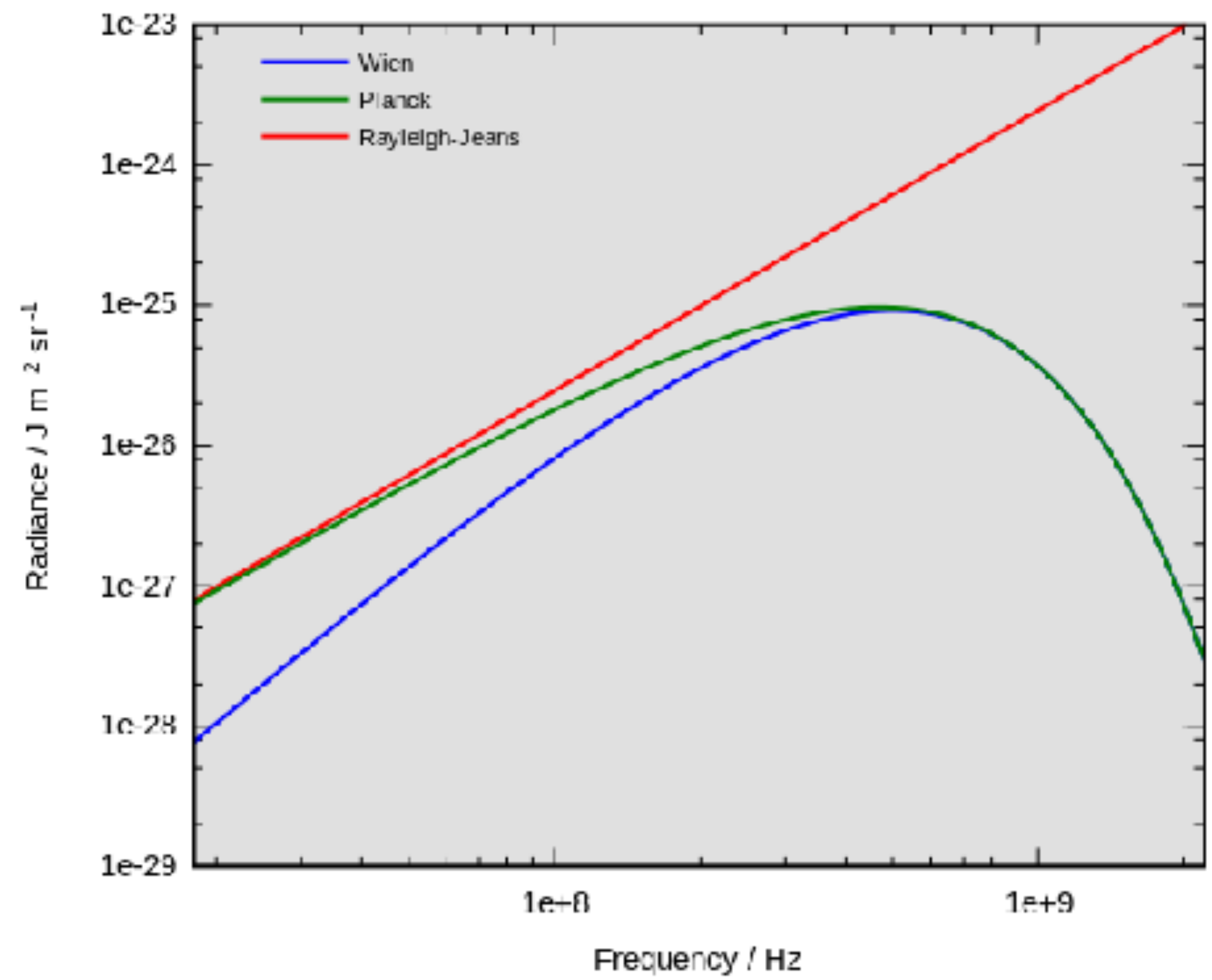
$$T(\nu_{max}) = 1.7344 \times 10^{-11} \ \frac{K}{\nu} \ [\nu \text{ in Hz}]$$

or

$$T(\lambda_{max}) = 2.8979 \times 10^{-3} \ \lambda \cdot K \ [\lambda \text{ in m}]$$


Color temperature (Kelvin)
1
2.7
30
288
1000
5770
9200
Microwave
Far-infrared
Near-infrared
Ultraviolet
Visible
UV-B
Planck's law
Spectral radiance (Spectral amplitude)
10^{-7}
10^{-11}
10^{-15}
10^{-19}
Sun 5770K
1000K
Earth 288K
30K
2.7K
Wien's displacement law
0.01
0.1
1
10
100
1000
10000
Frequency (terahertz)
0.0001
0.001
0.01
0.1
1
10
Energy (electron volts)

Planck's Law



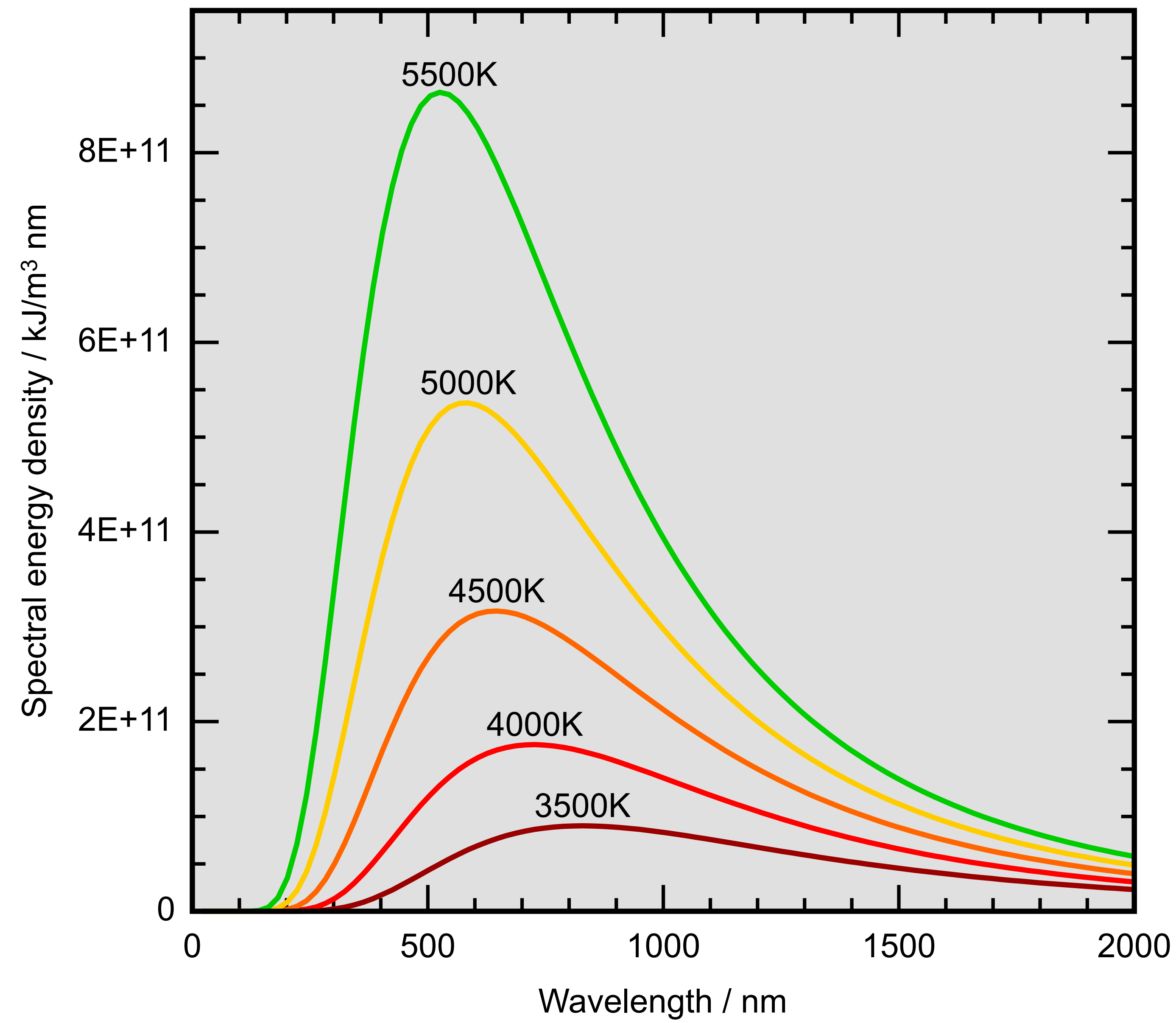
Rayleigh-Jeans Law (1900)

$$B(\nu, T) = 2kT\frac{\nu^2}{c^2}$$

$$B(\lambda, T) = \frac{2ckT}{\lambda^4}$$

led to UV catastrophe

Planck's Law

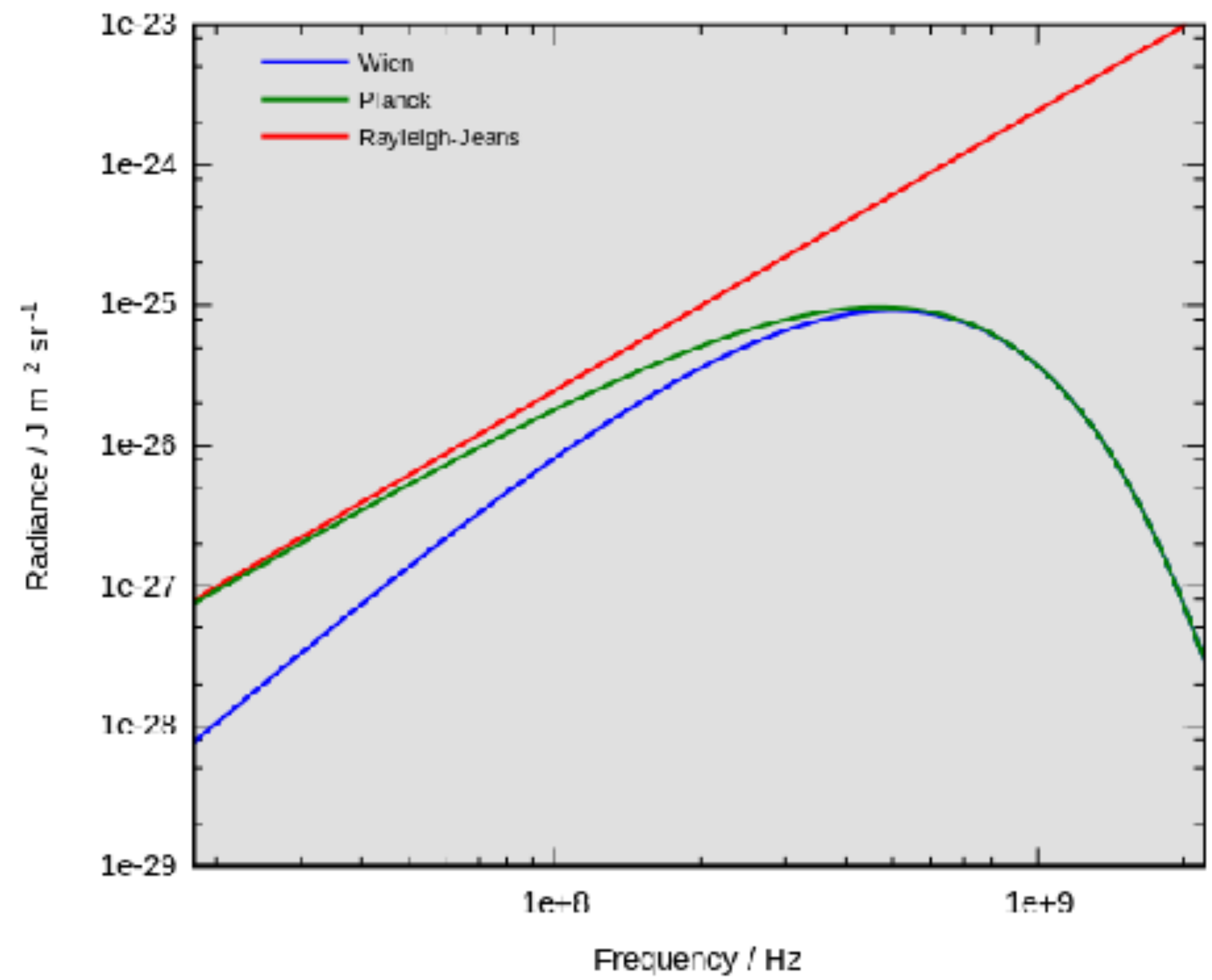


Planck's Law 1900

$$B(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{exp(\frac{h\nu}{kT})-1}$$

$$B(\lambda, T) = \frac{2hc^2}{\lambda^5}\frac{1}{exp(\frac{hc}{\lambda kT})-1}$$

Planck's Law



Rayleigh-Jeans approximation

For low ν or long λ when $h\nu << kT$

exponential can be Taylor expanded

$$exp(\frac{h\nu}{kT}) - 1 = \frac{h\nu}{kT} + ...$$

then ...

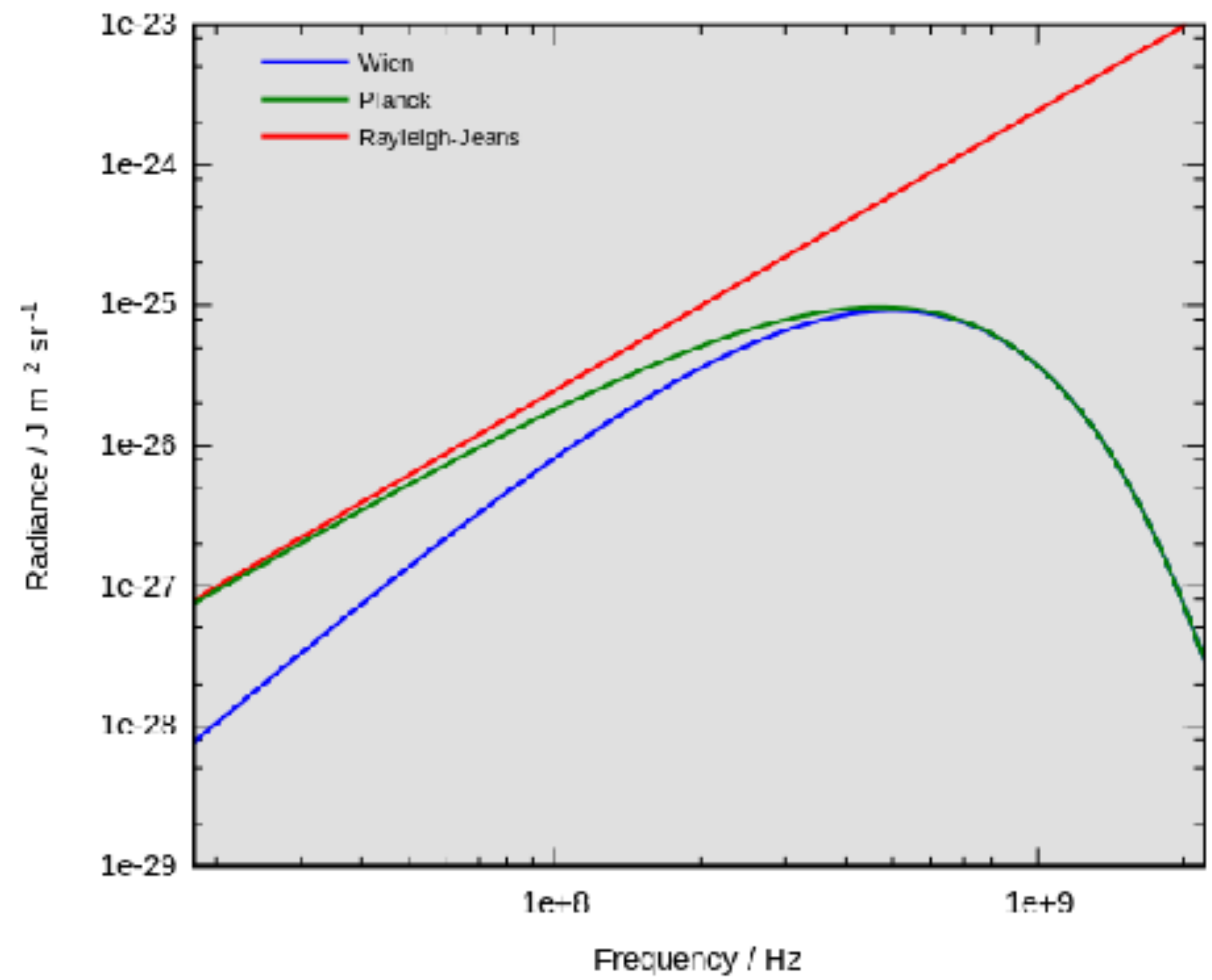
$$B(\nu, T) = 2kT\frac{\nu^2}{c^2}$$

$$B(\lambda, T) = \frac{2ckT}{\lambda^4}$$

So, for a fixed T, $B(\nu) \propto \nu^2$

So, for a fixed ν, $B(T) \propto T$

Planck's Law

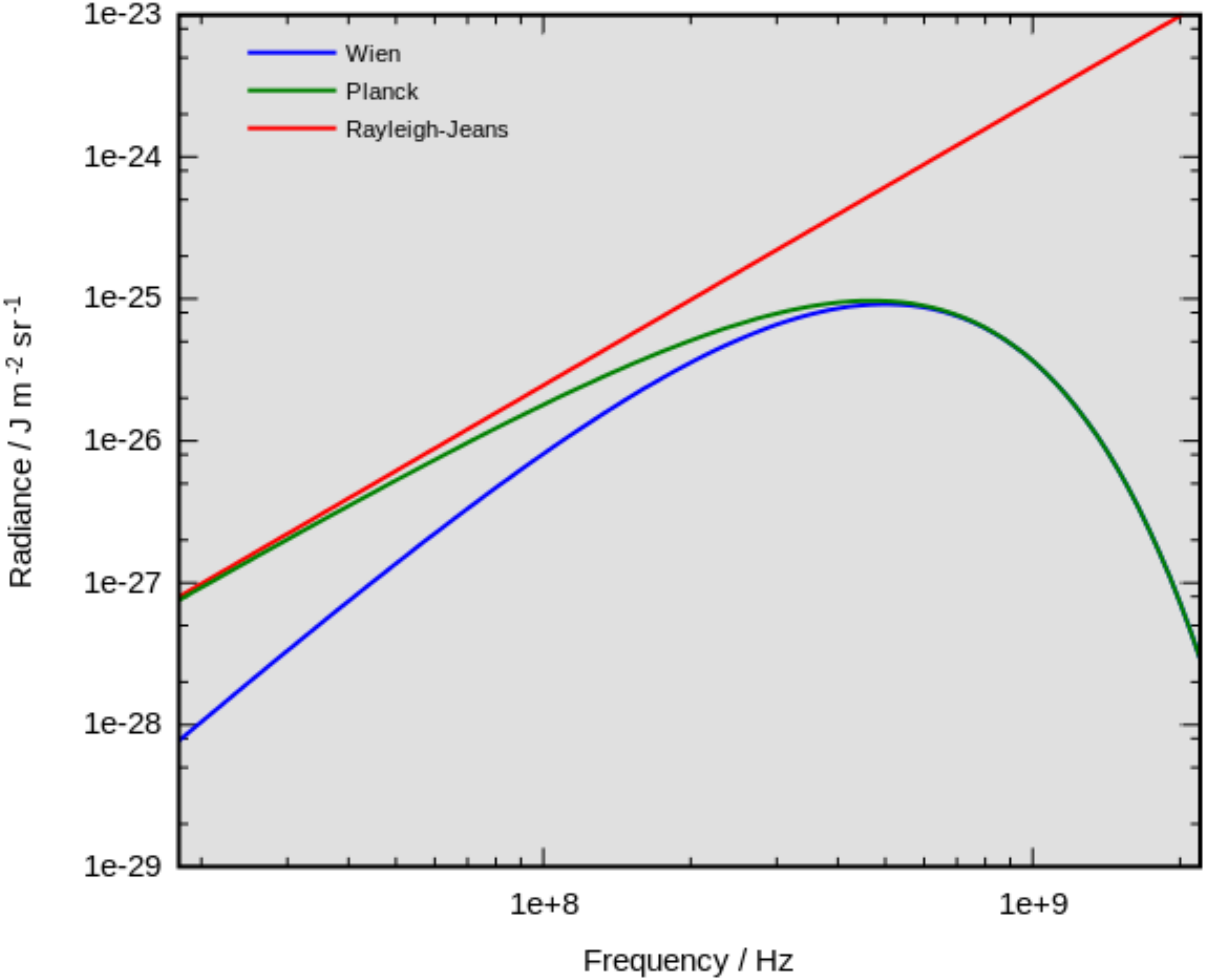


Wien Approximation

For high ν or short λ when $h\nu >> kT \Rightarrow exp(\frac{h\nu}{kT}) \rightarrow 1$

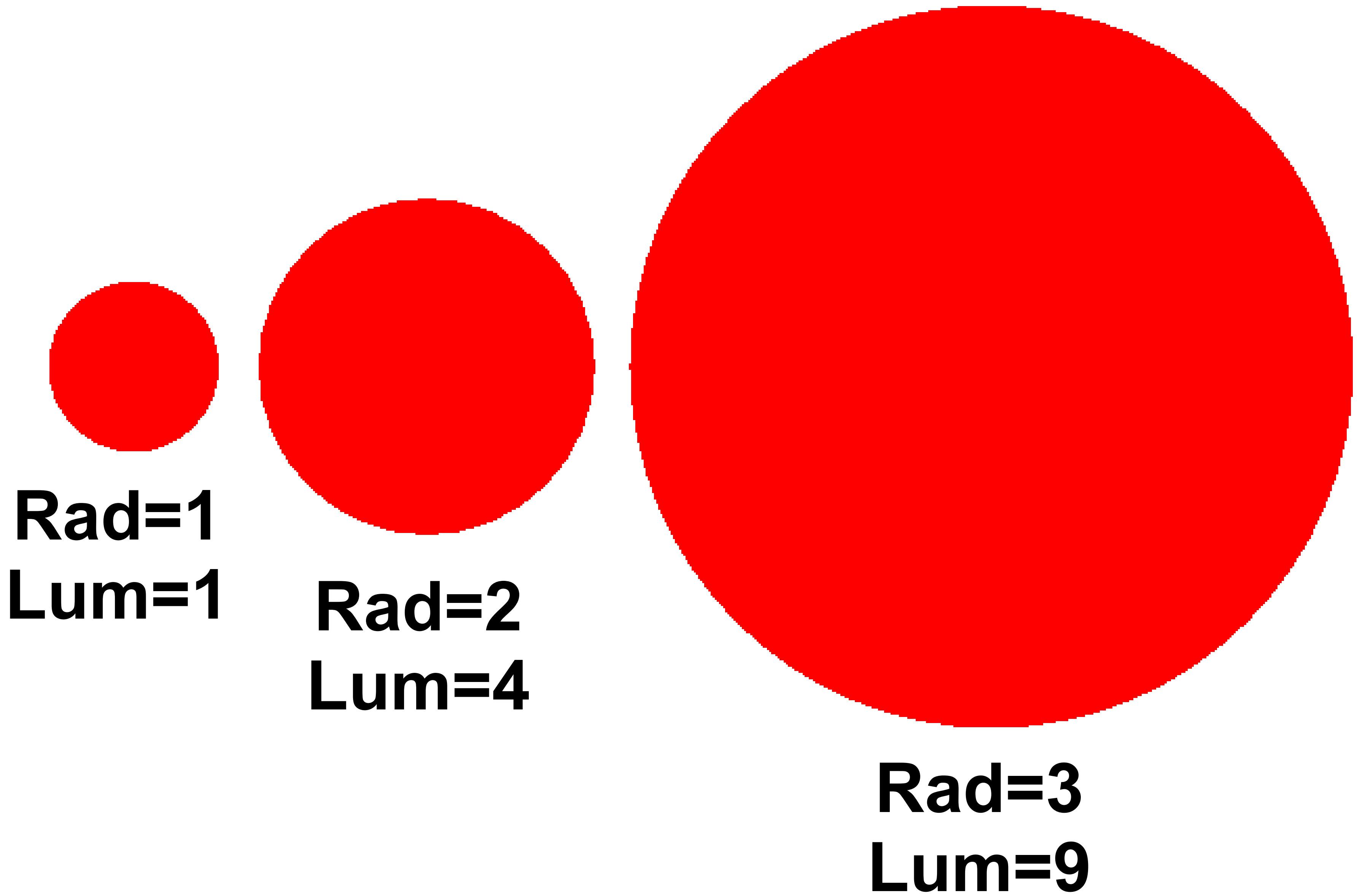
$$B(\nu, T) = \frac{2h\nu^3}{c^2} exp(\frac{-h\nu}{kT})$$

So, for a fixed T, $B(\nu) \propto \nu^3 e^{-\nu}$ at high ν, $B(\nu)$ falls off exponentially once the maximum is reached.



Wien
Planck
Rayleigh-Jeans
1e-23
1e-24
1e-25
1e-26
1e-27
1e-28
1e-29
1e+8
1e+9
Frequency / Hz
Radiance / J m -2 sr -1

Bigger objects are brighter



For stars of the same temperature, the larger the star, the greater the luminosity

sizes from blackbodies

- How to measure a star's size? Stars are too far away to resolve, so we can't directly measure their sizes.
- However, we can use the Stefan-Boltzmann Law and solve for it !

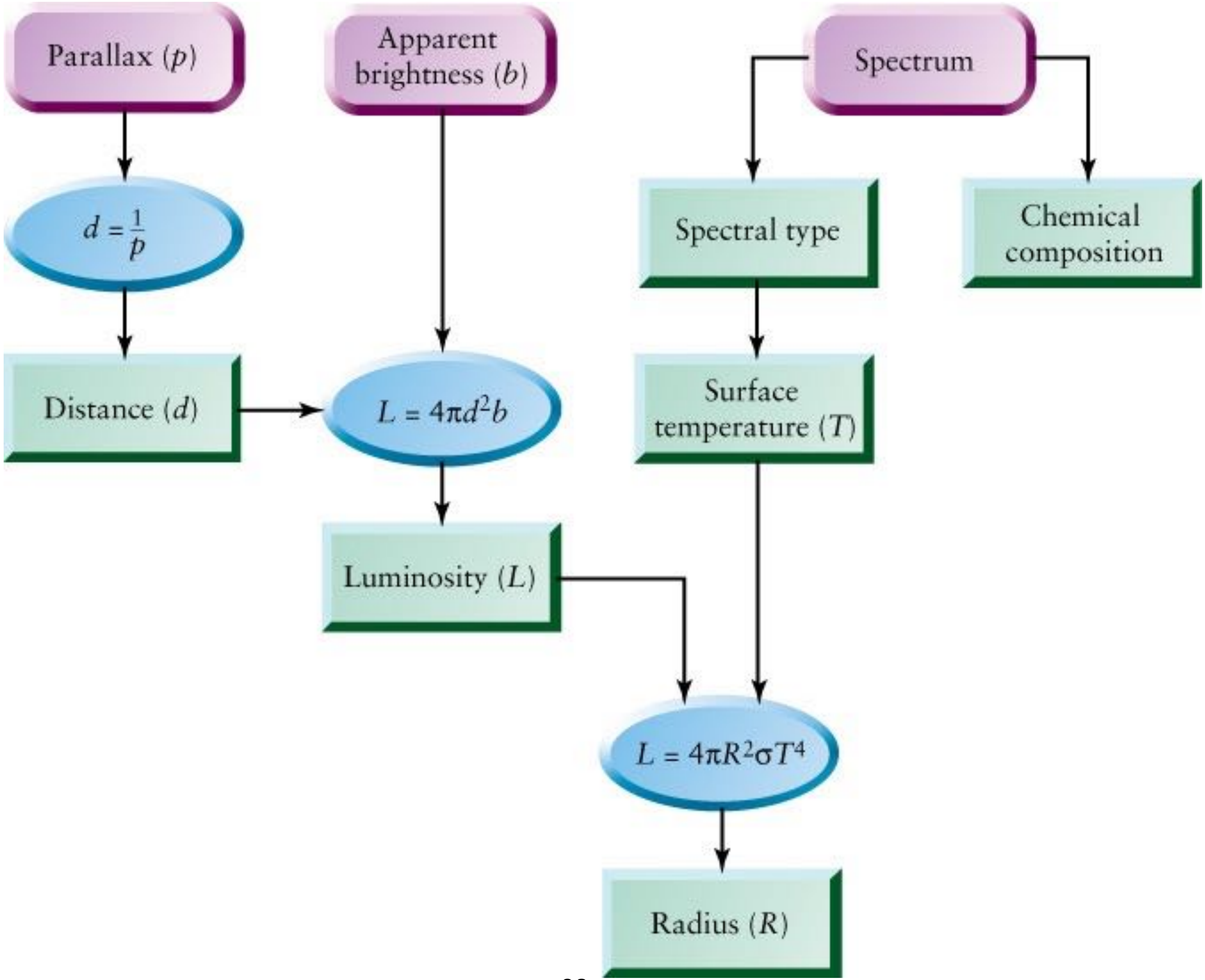
$$L = 4\pi R^2 \sigma T^4$$

$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67 \times 10^{-8} J s^{-1} m^{-2} K^{-4}$$

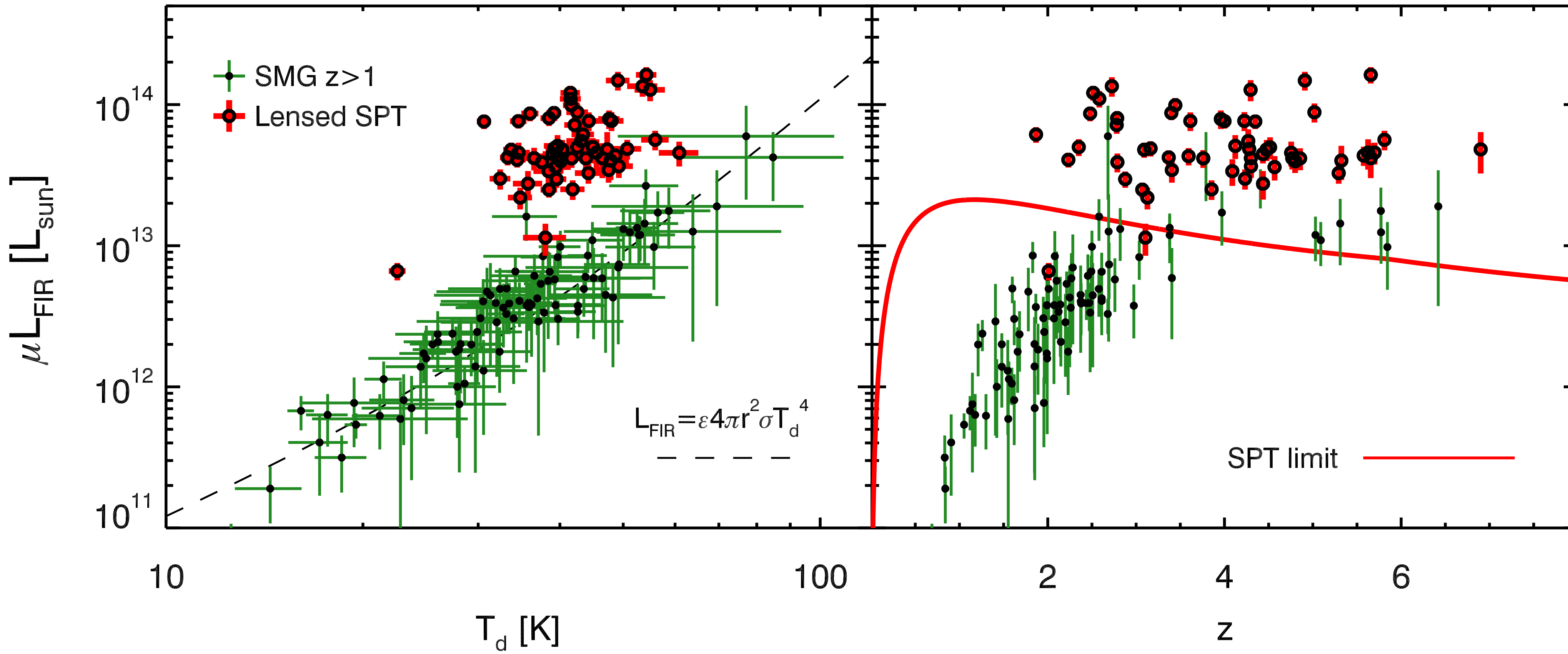
pi = ratio of a circle's circumference to it's diameter
c = the speed of light
k = Boltzmann constant relates a particle's energy to the temperature
h = Planck constant is a quantum mechanical unit of energy

$$L \propto R^2 T^4$$

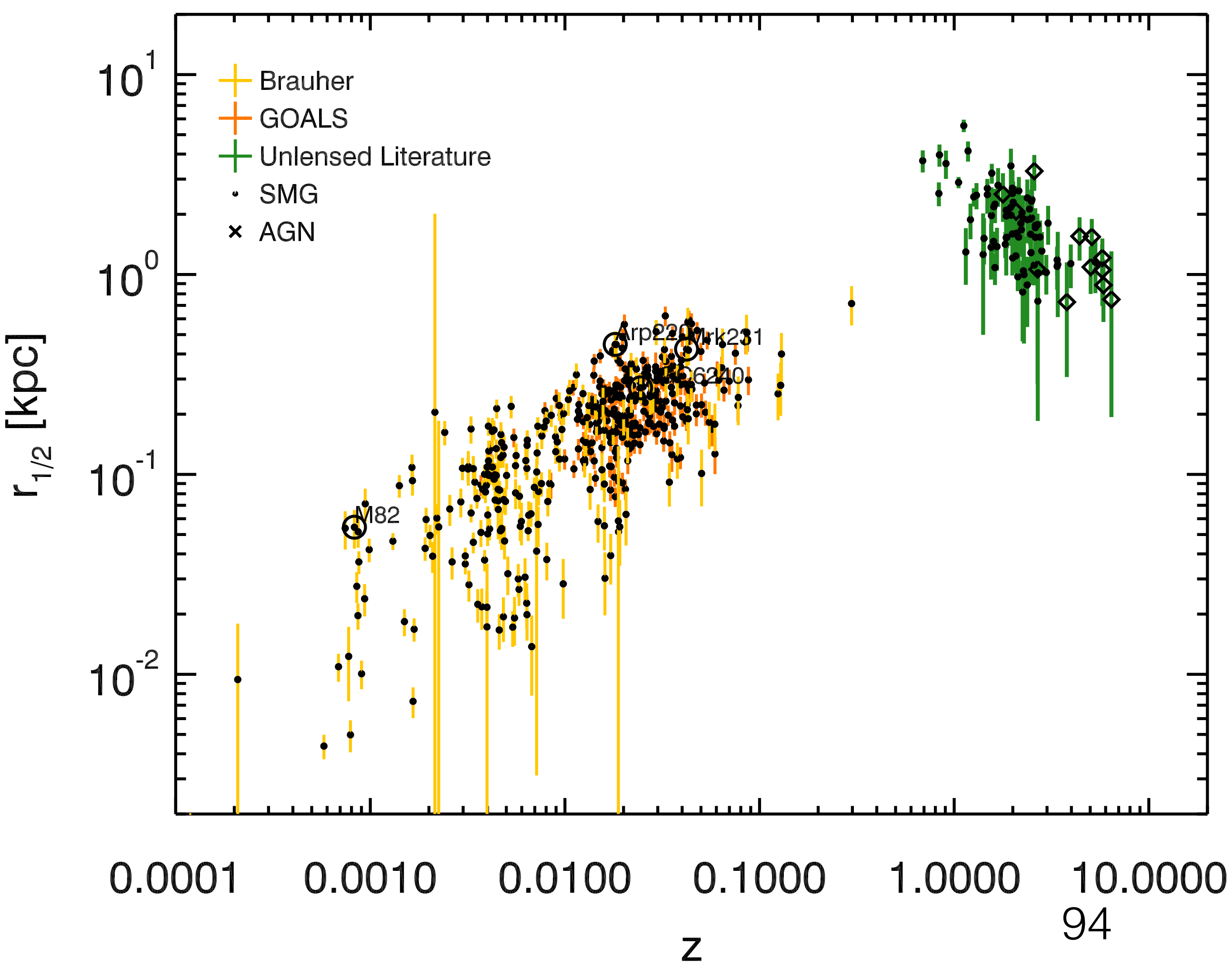
$$R \propto \frac{\sqrt{L}}{T^2}$$



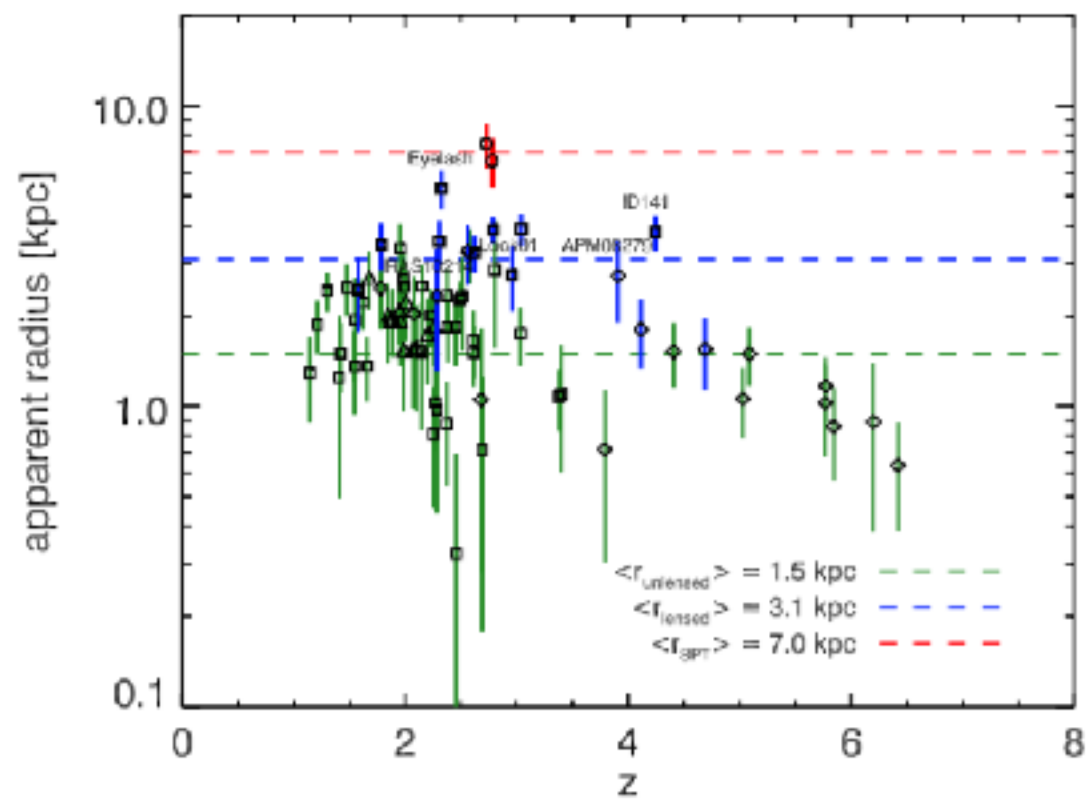
Parallax (p)
Apparent brightness (b)
Spectrum
$d = \frac{1}{p}$
Spectral type
Chemical composition
Distance (d)
$L = 4\pi d^2 b$
Surface temperature (T)
Luminosity (L)
$L = 4\pi R^2 \sigma T^4$
Radius (R)



SMG z>1
Lensed SPT
μL_{FIR} [L_{sun}]
$L_{FIR}=\epsilon 4\pi r^2 \sigma T_d^4$
SPT limit
T_d [K]
z



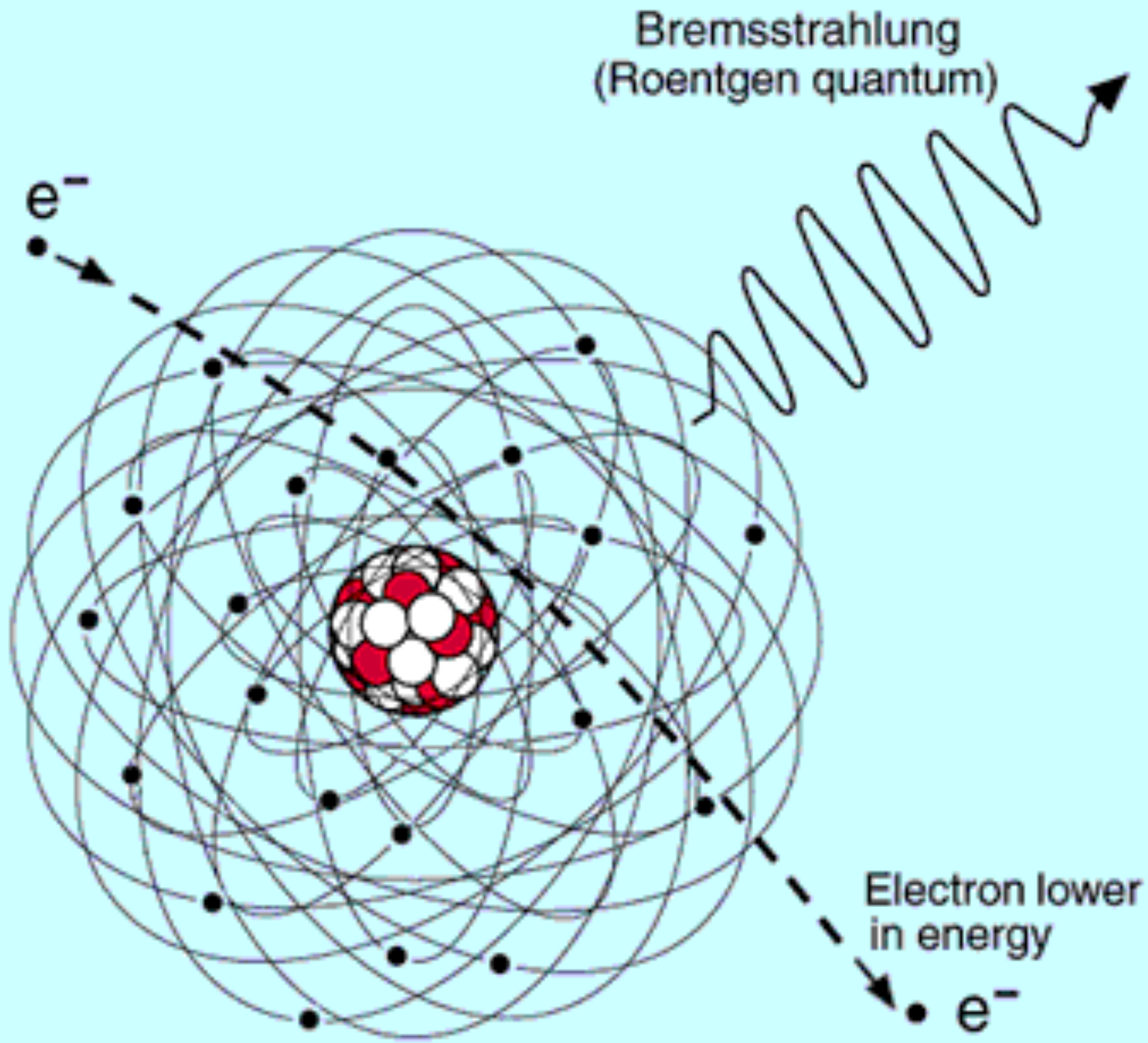
Brauher
GOALS
Unlensed Literature
SMG
AGN
M82
Arp220
Mrk231
$r_{1/2}$ [kpc]
z



ID141
apparent radius [kpc]
$<r_{unlensed}>$ = 1.5 kpc
$<r_{lensed}>$ = 3.1 kpc
$<r_{SPT}>$ = 7.0 kpc
z

Bremsstrahlung “Braking Radiation”

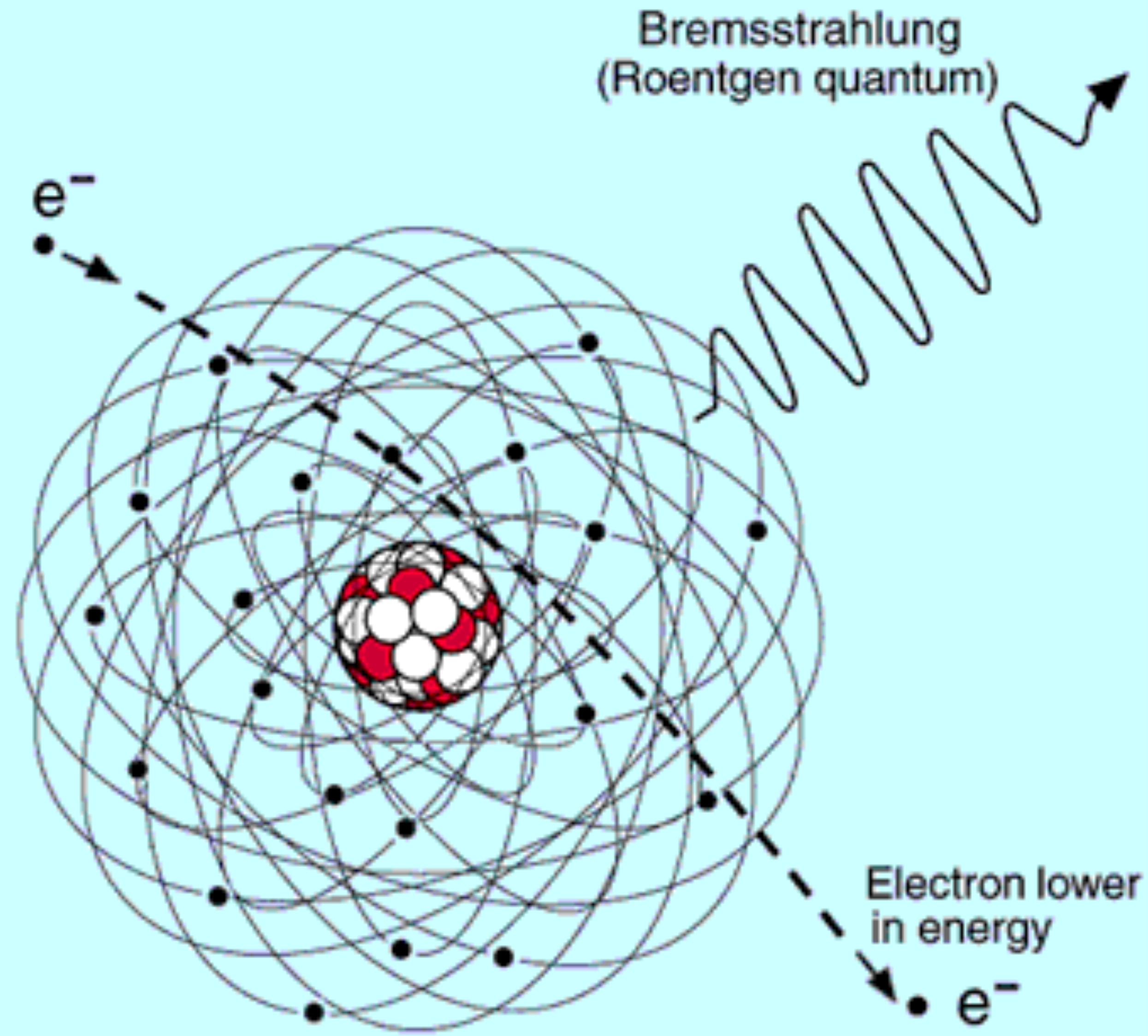
E_1



E_2

$$h\nu = E_1 - E_2$$

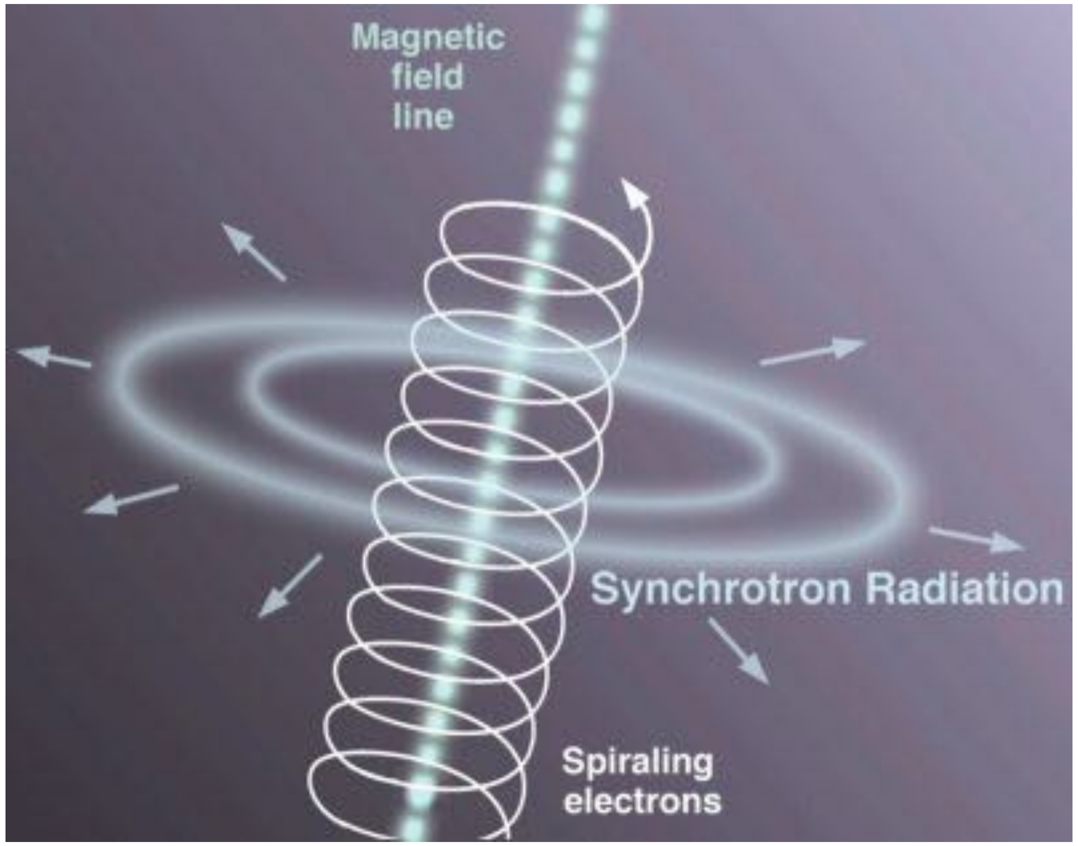
free-free emission

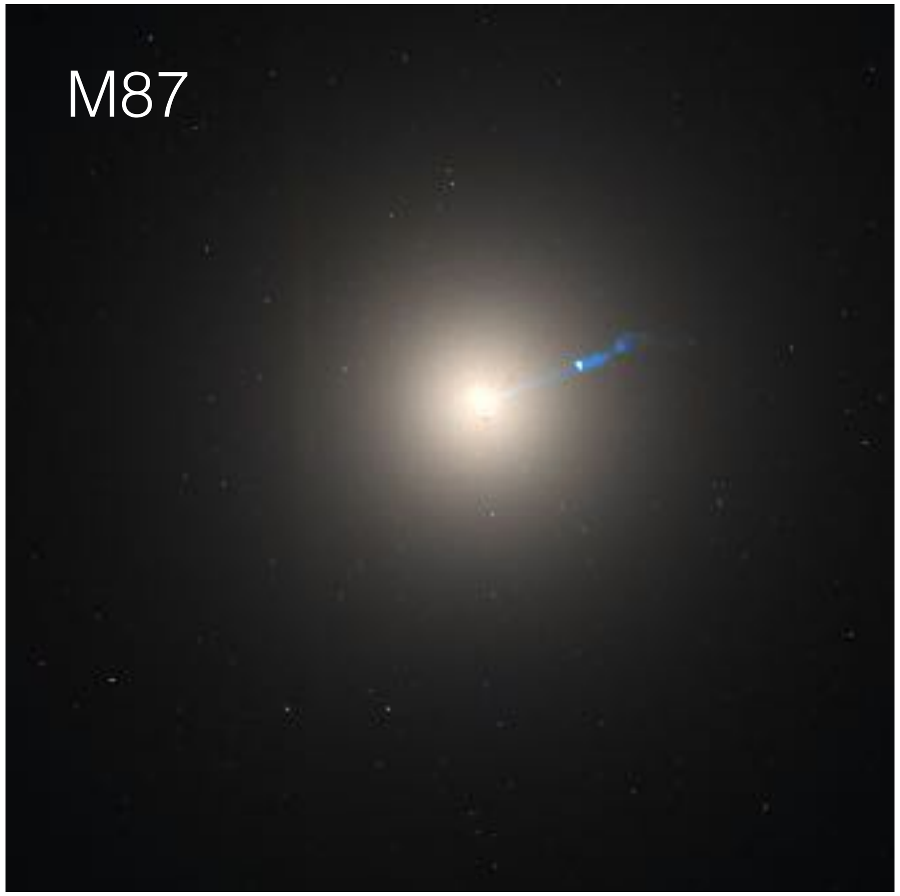


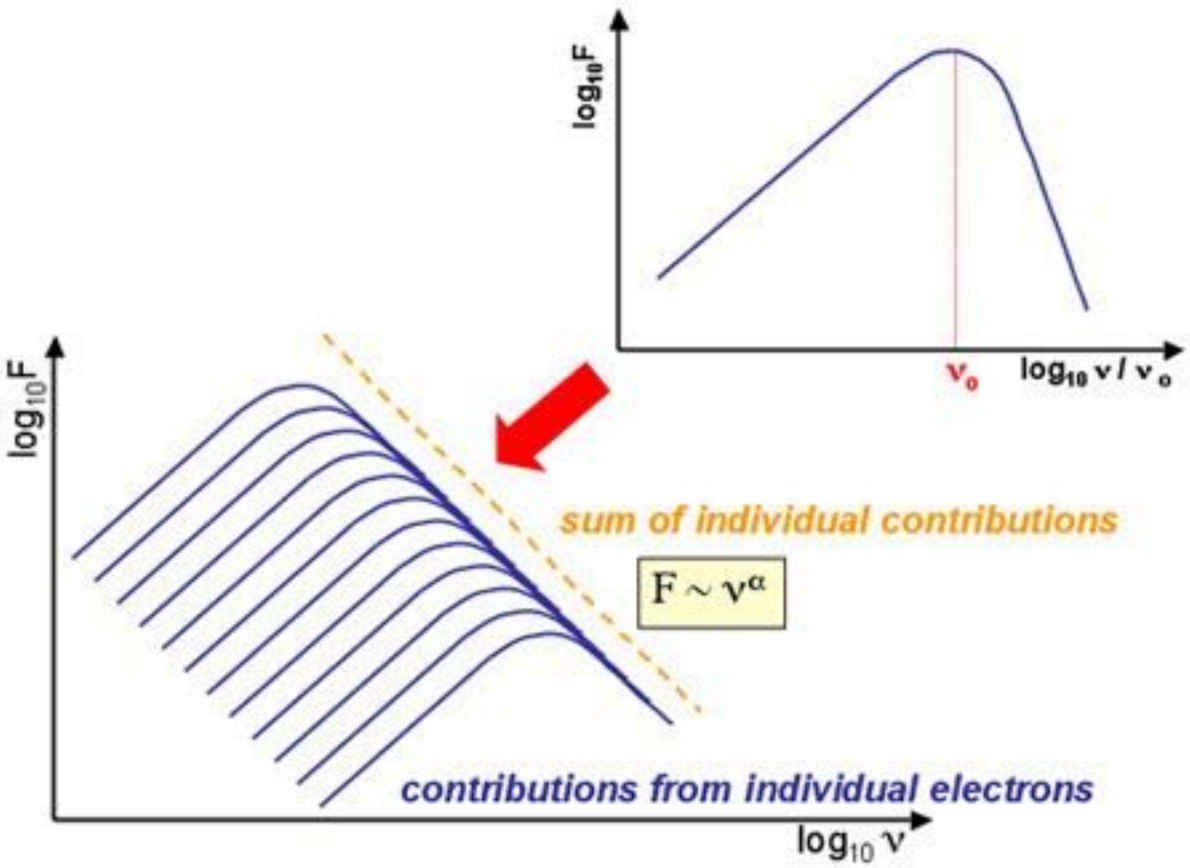
- thermal bremsstrahlung
- free electrons scattering off ions
- free before, free after
- HII regions, star formation, proportional to thermal energy
- unpolarized

Synchrotron emission

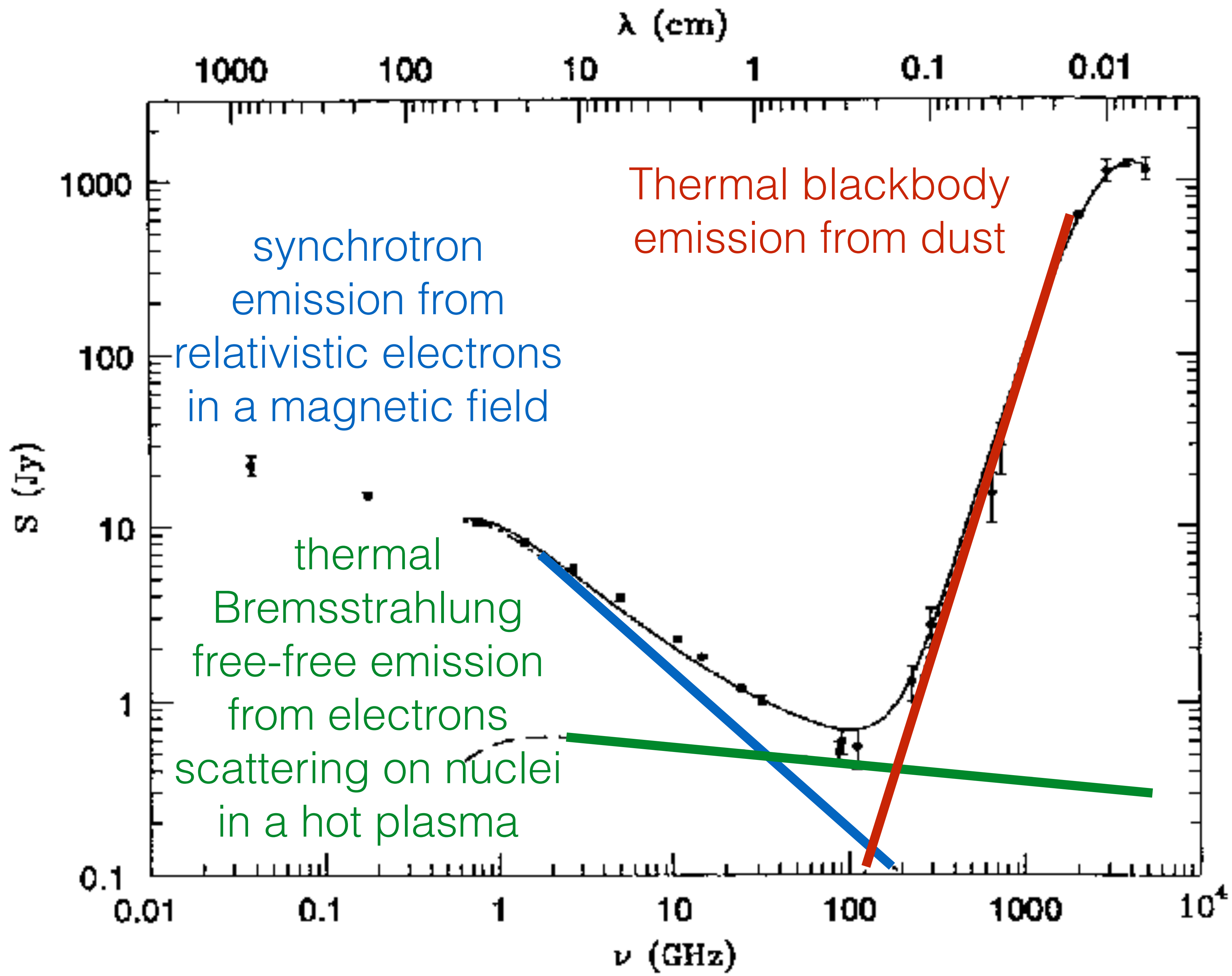
- Charged particles moving through magnetic fields
- Electrons produce broad spectrum, polarized light
- First detected in 1956 by Burbidge in M87



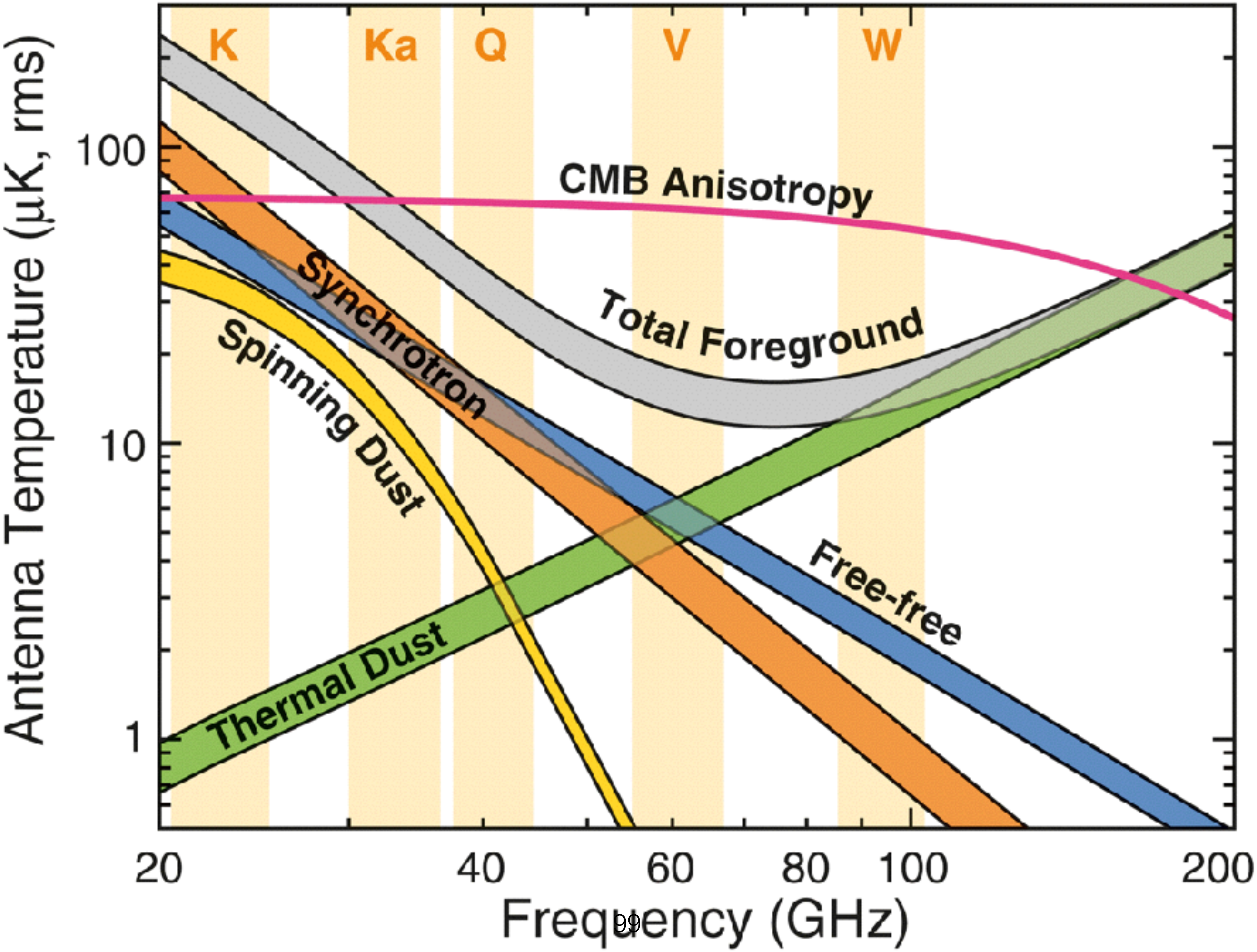




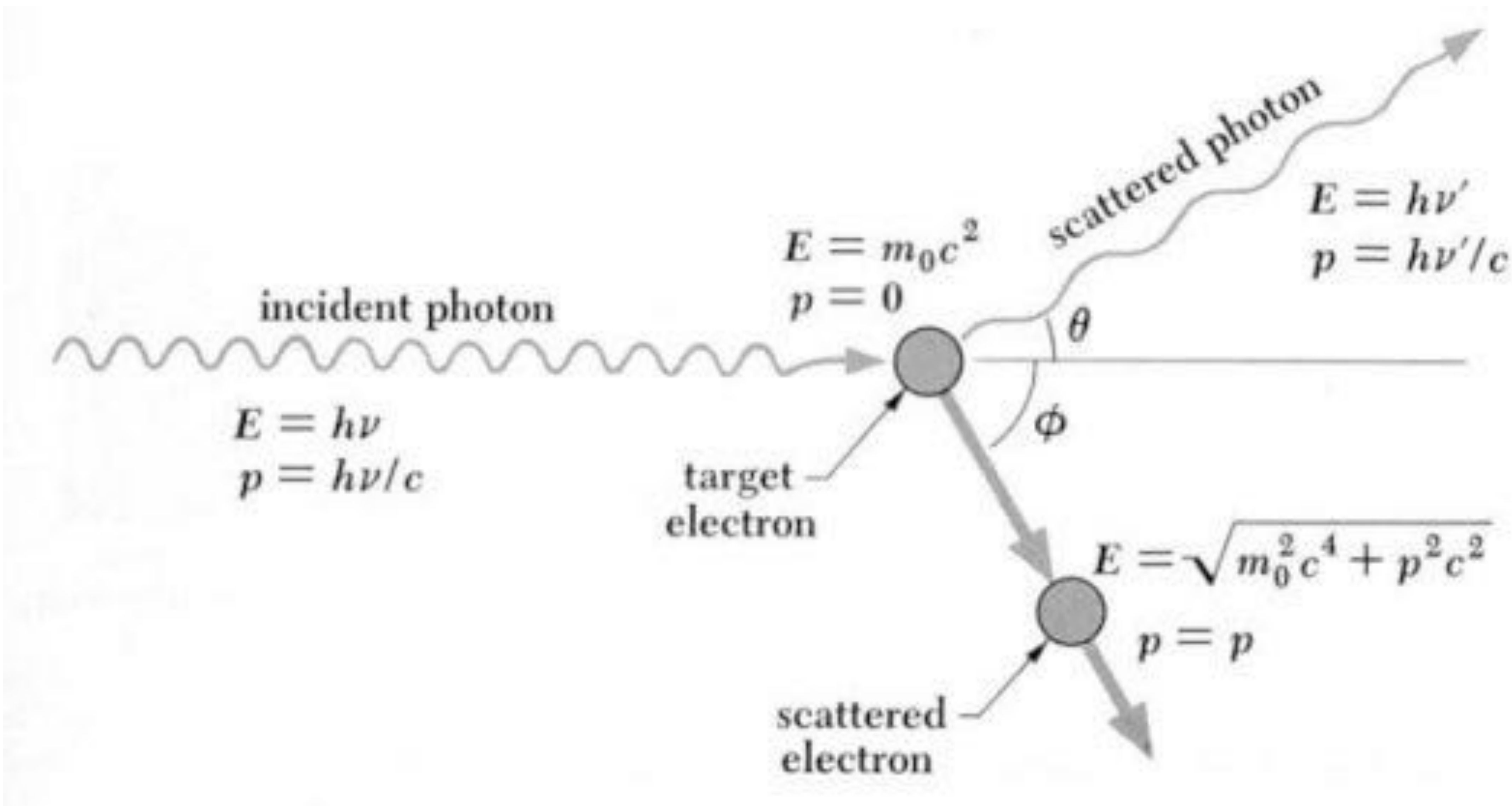
M82


λ (cm)
1000
100
10
1
0.1
0.01
1000
100
10
1
0.1
S (Jy)
0.01
0.1
1
10
100
1000
10^4
ν (GHz)
Thermal blackbody emission from dust
synchrotron emission from relativistic electrons in a magnetic field
thermal Bremsstrahlung free-free emission from electrons scattering on nuclei in a hot plasma

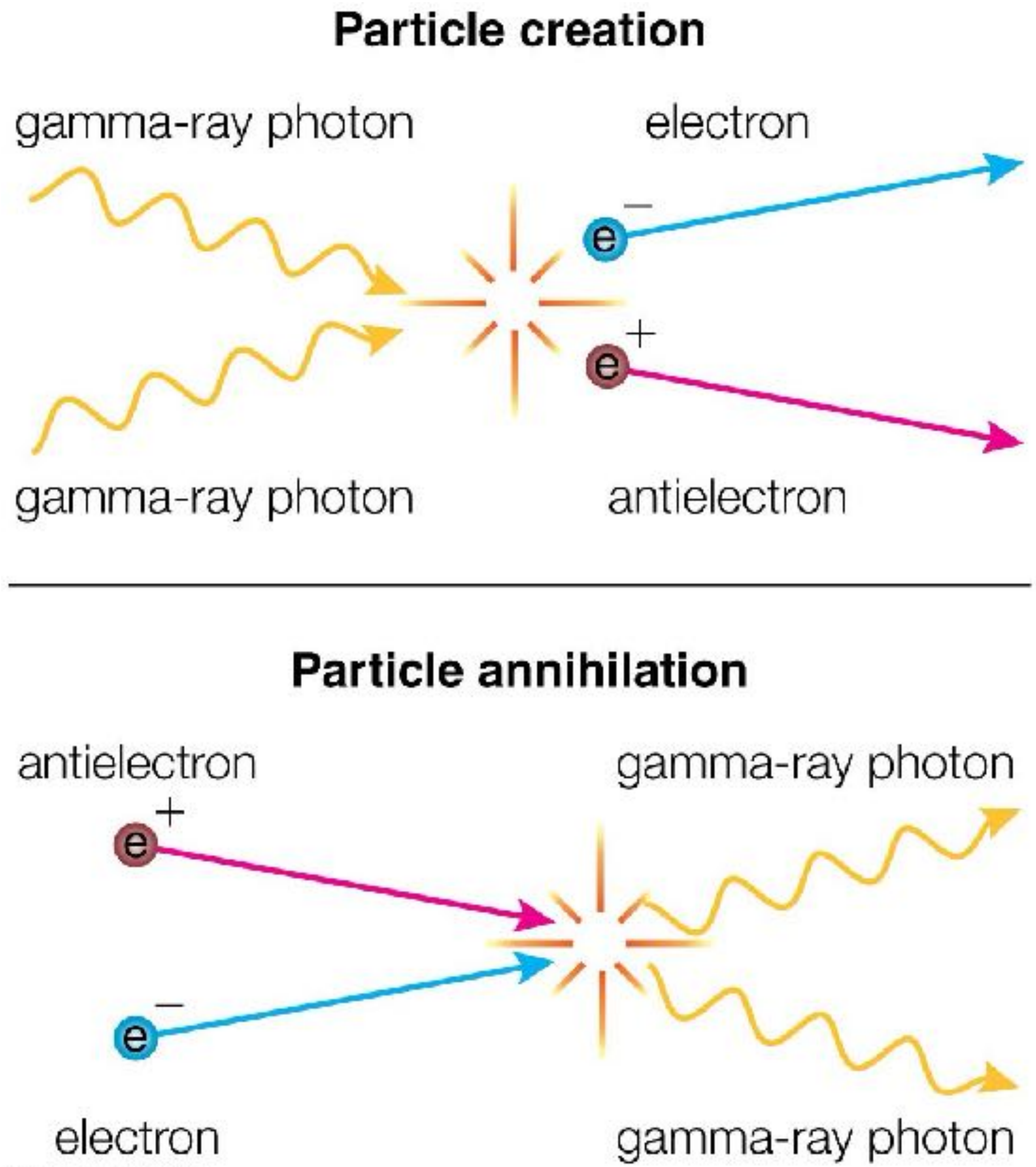
Galactic Foregrounds and CMB

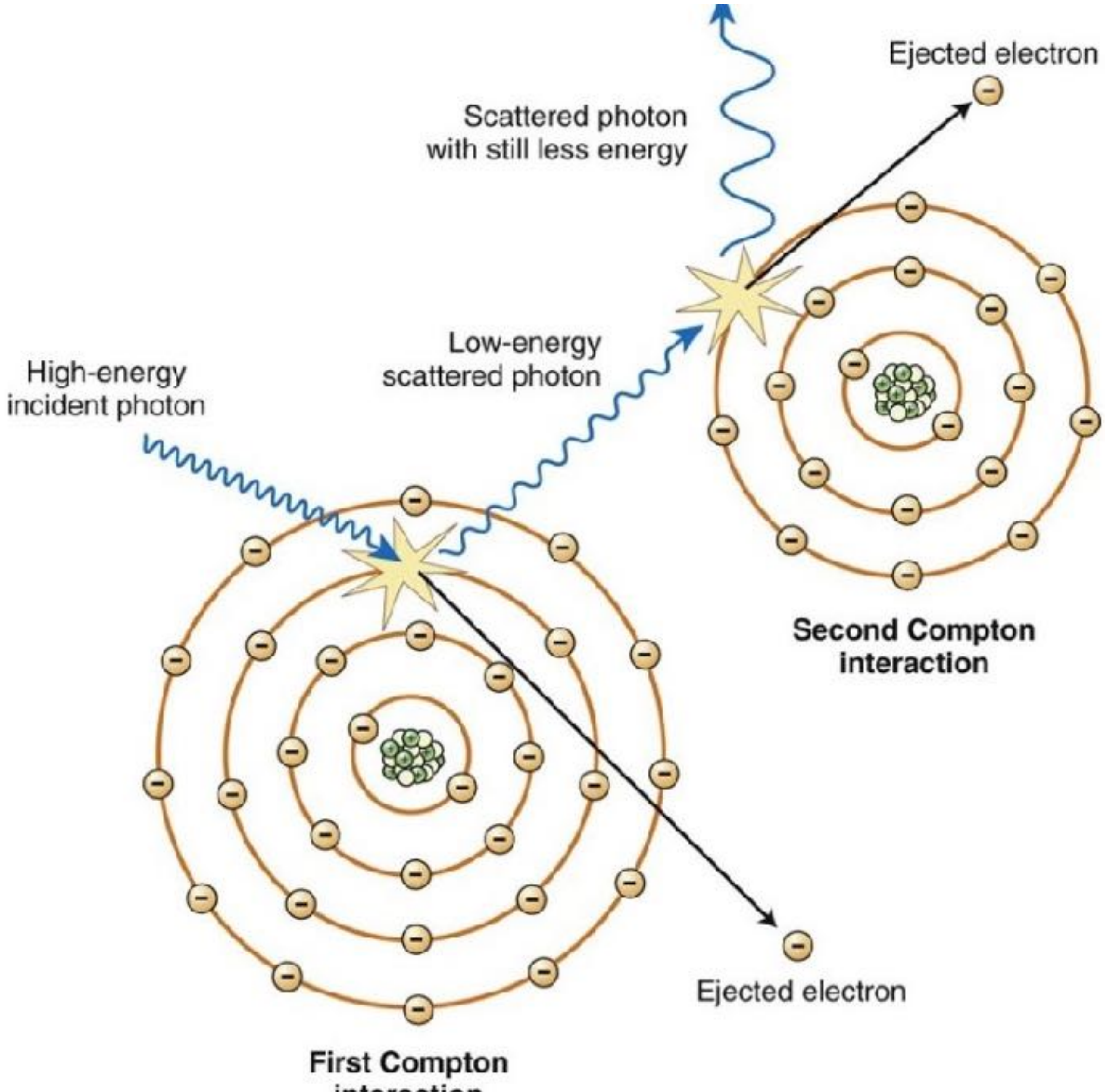


Compton Scattering

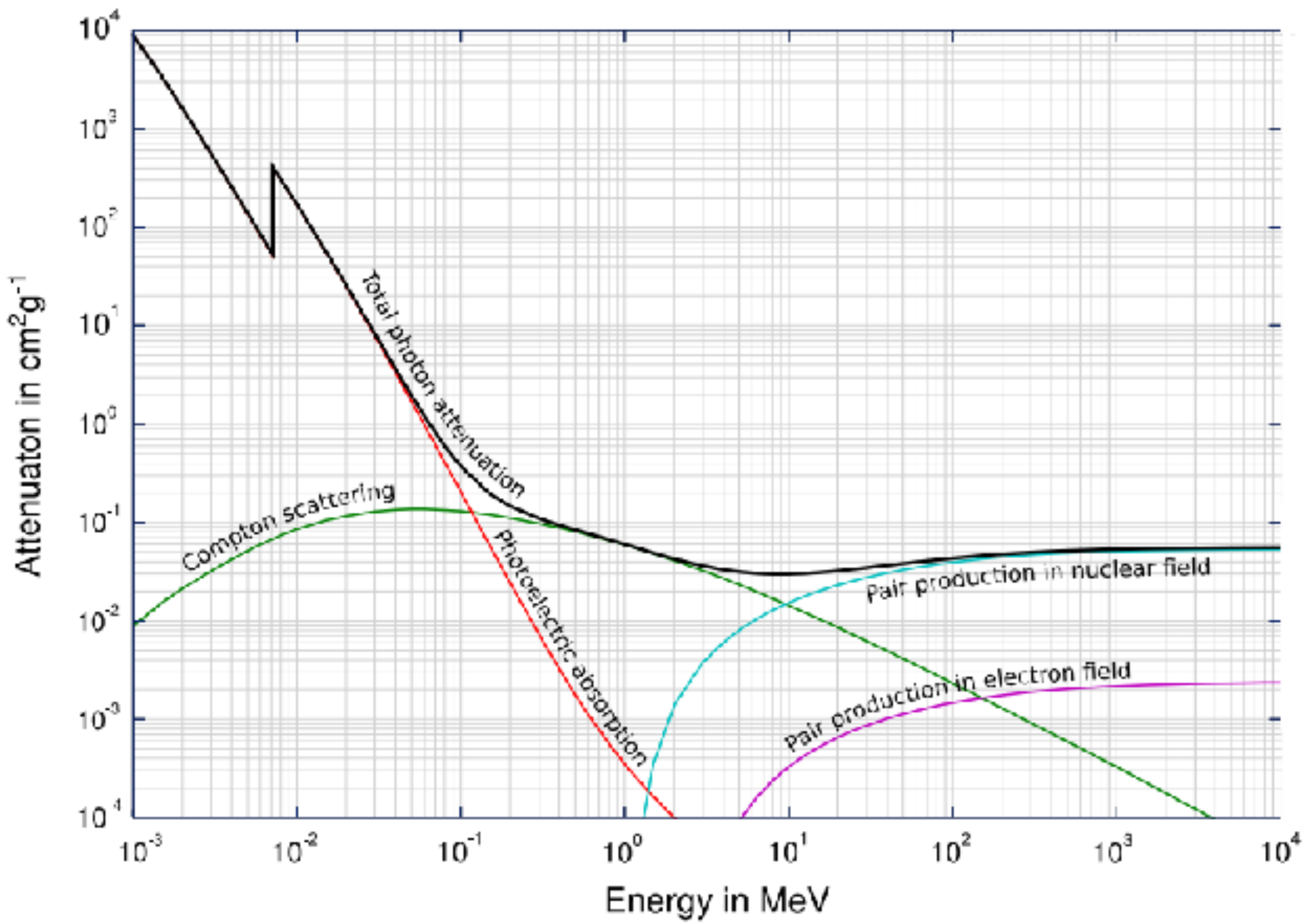


Pair production



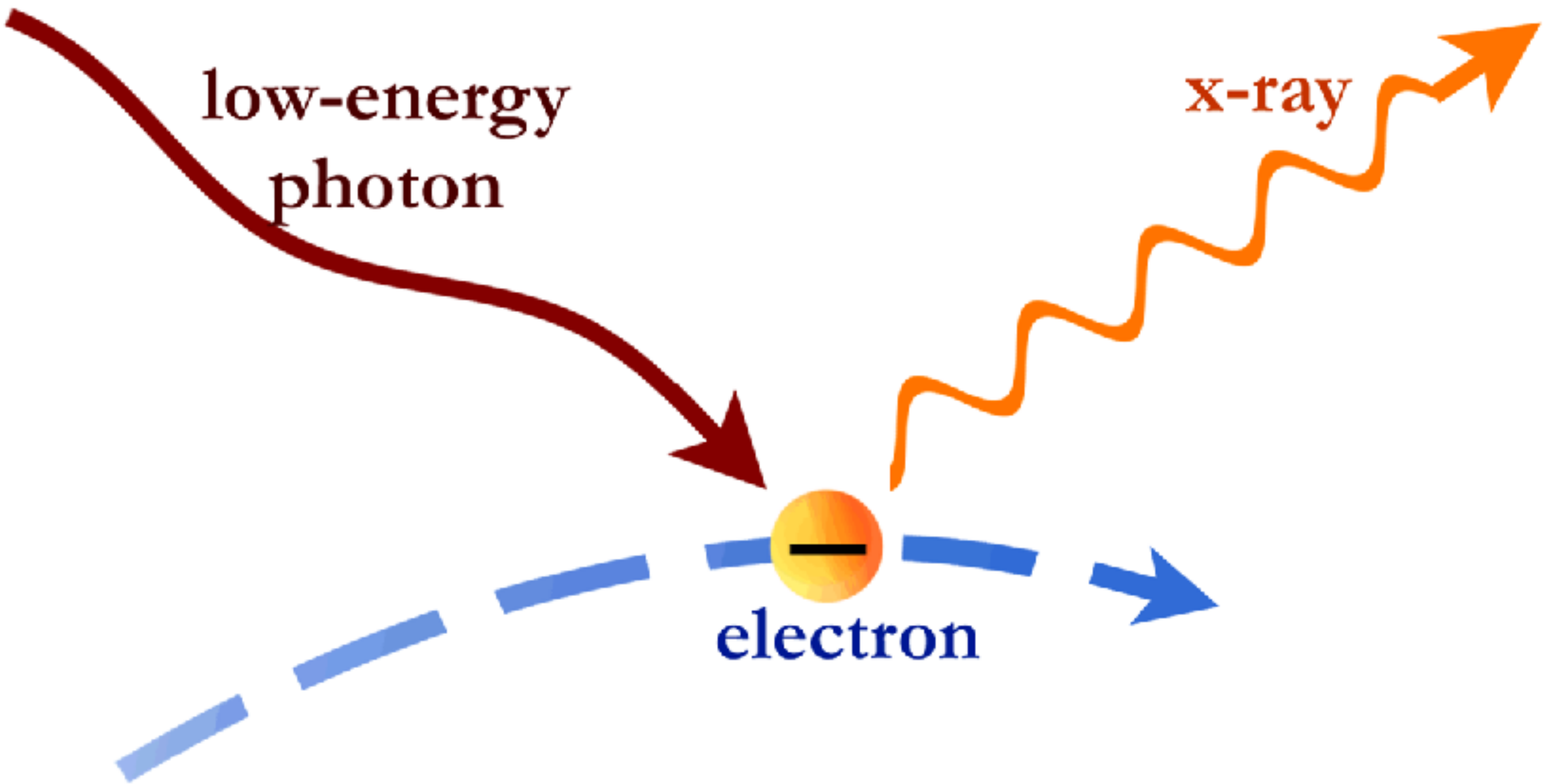

Ejected electron
Scattered photon
with still less energy
Low-energy
scattered photon
High-energy
incident photon
Second Compton
interaction
Ejected electron
First Compton
interaction

Gamma Ray Cross Sections

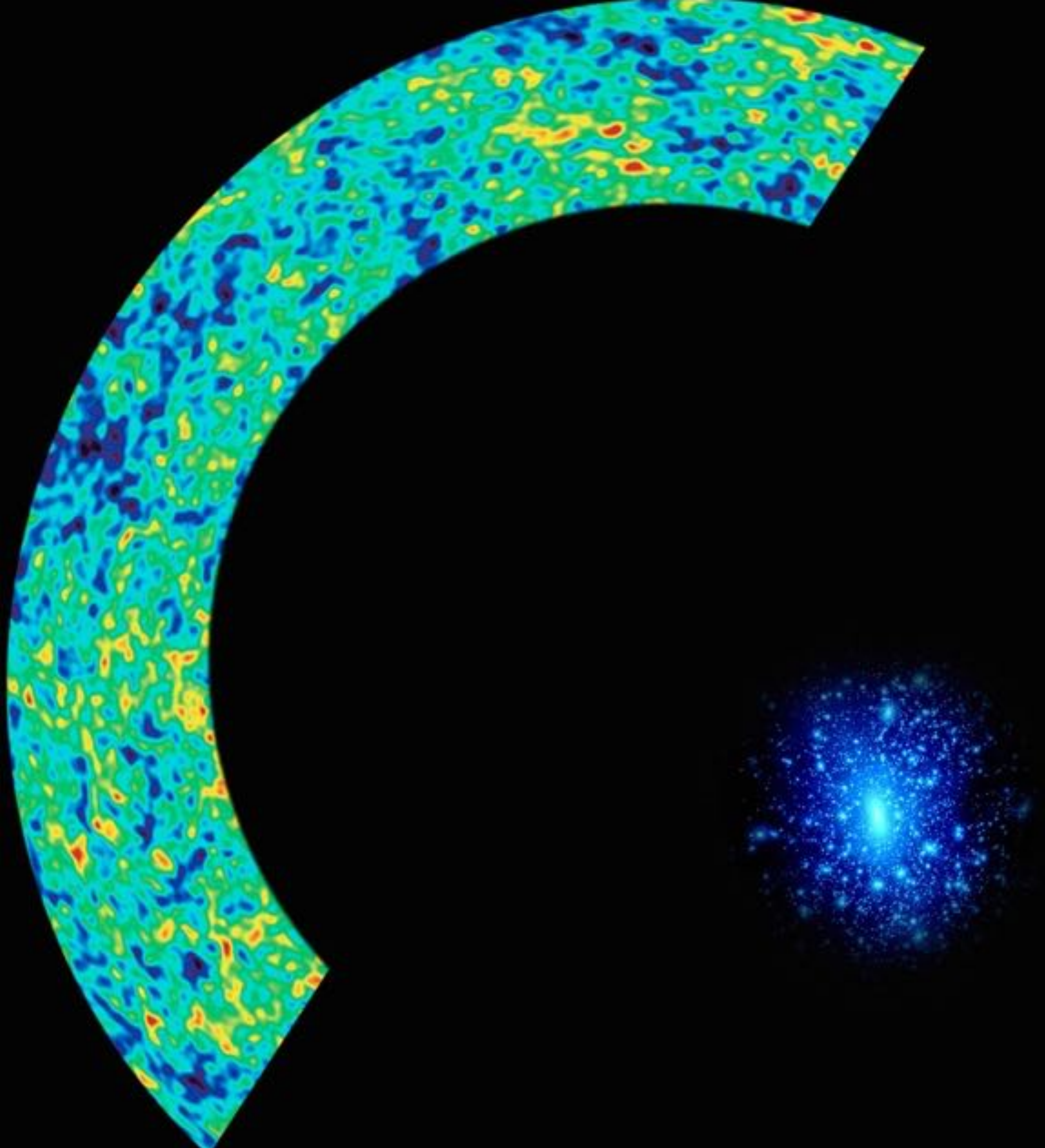


At low energies, lots of scattering events, but low energy loss

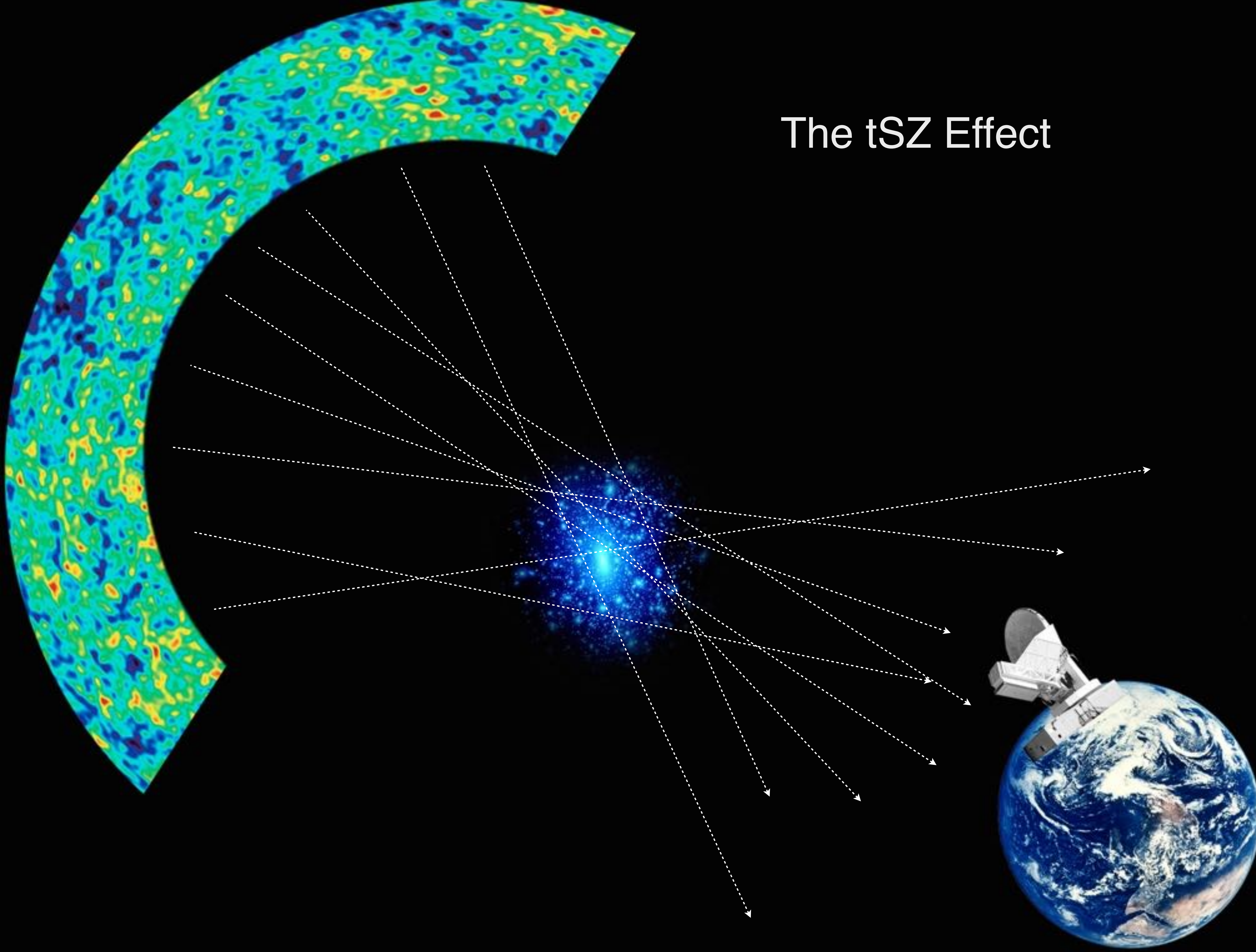
Inverse Compton Scattering



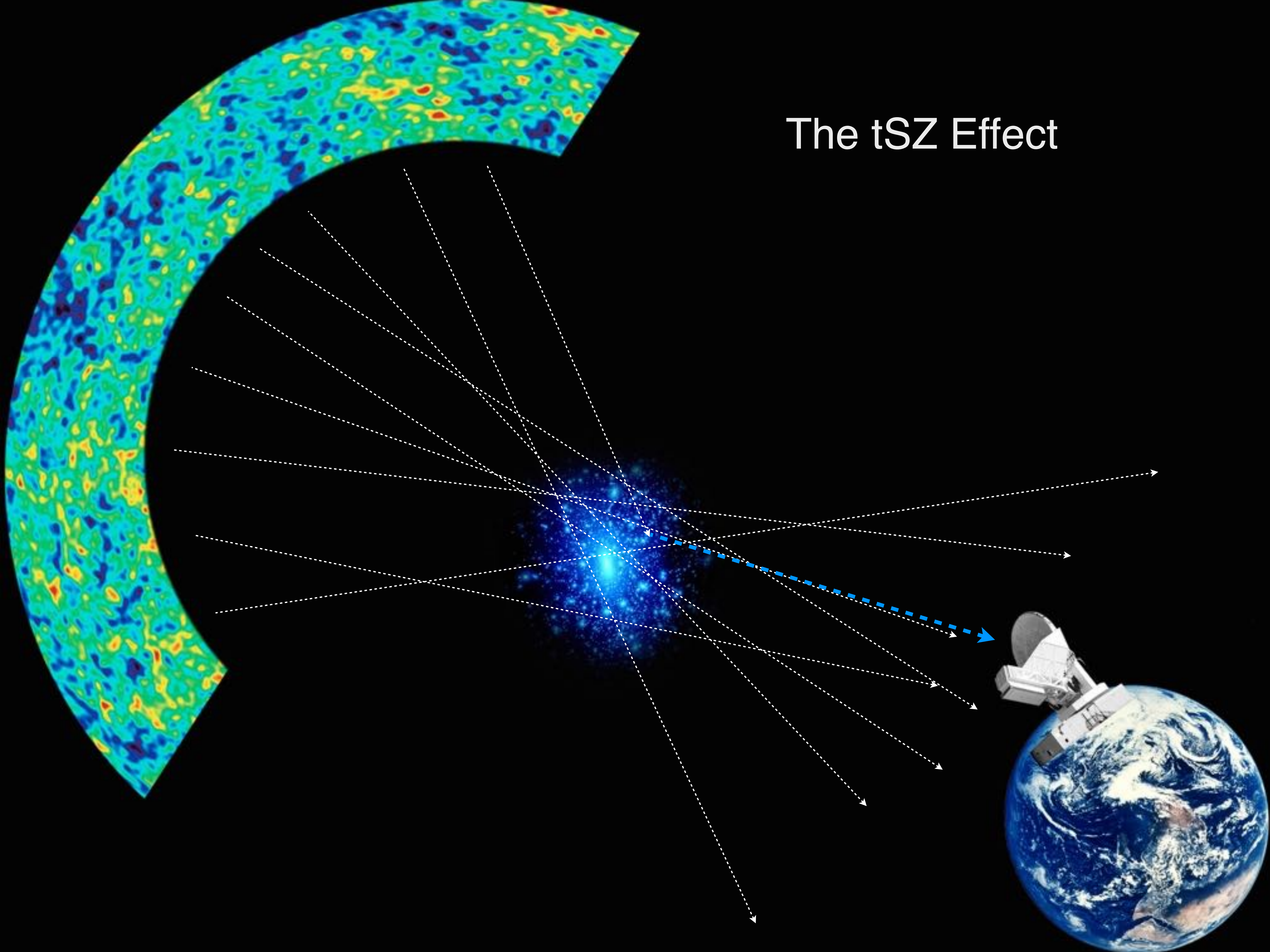
The tSZ Effect



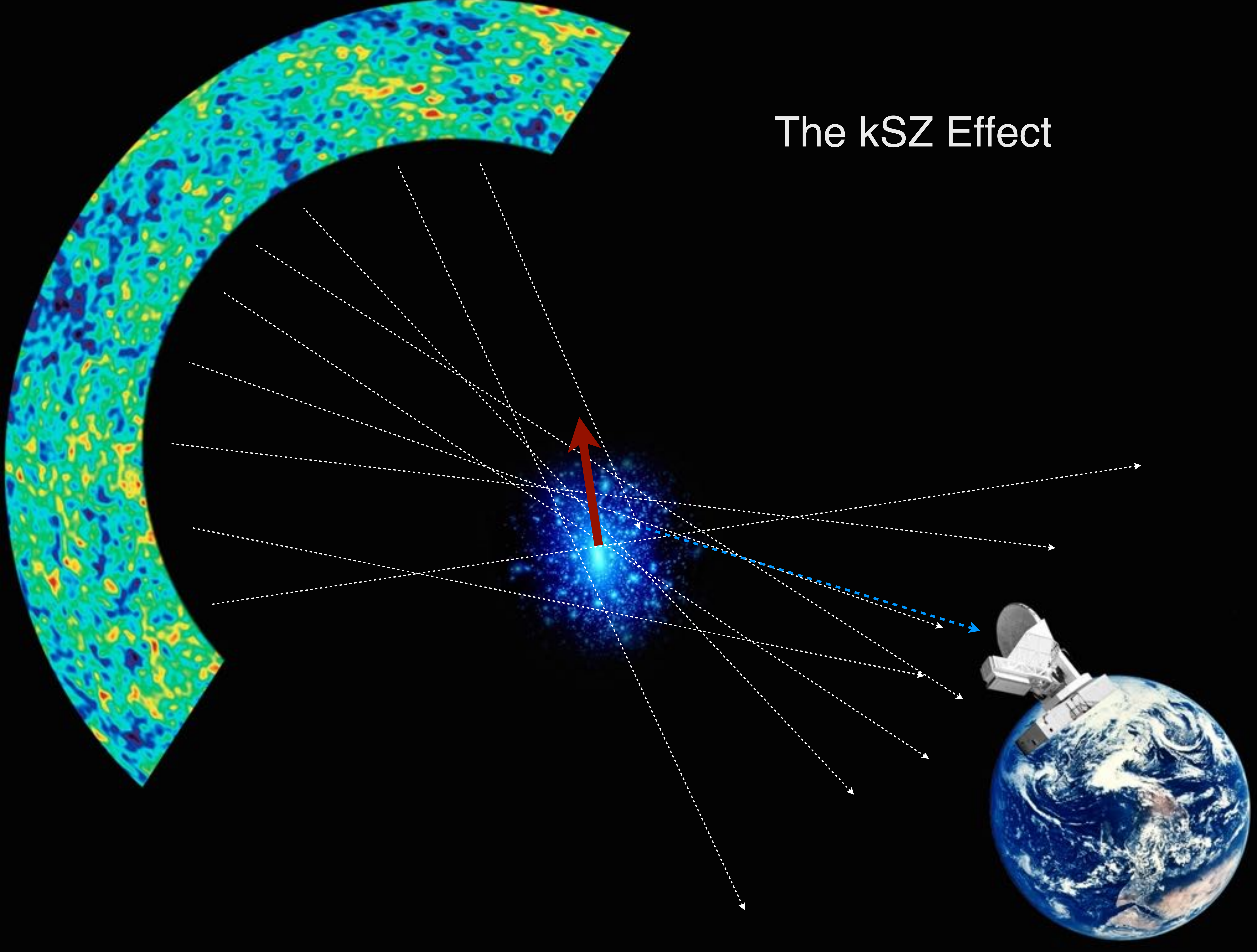
The tSZ Effect



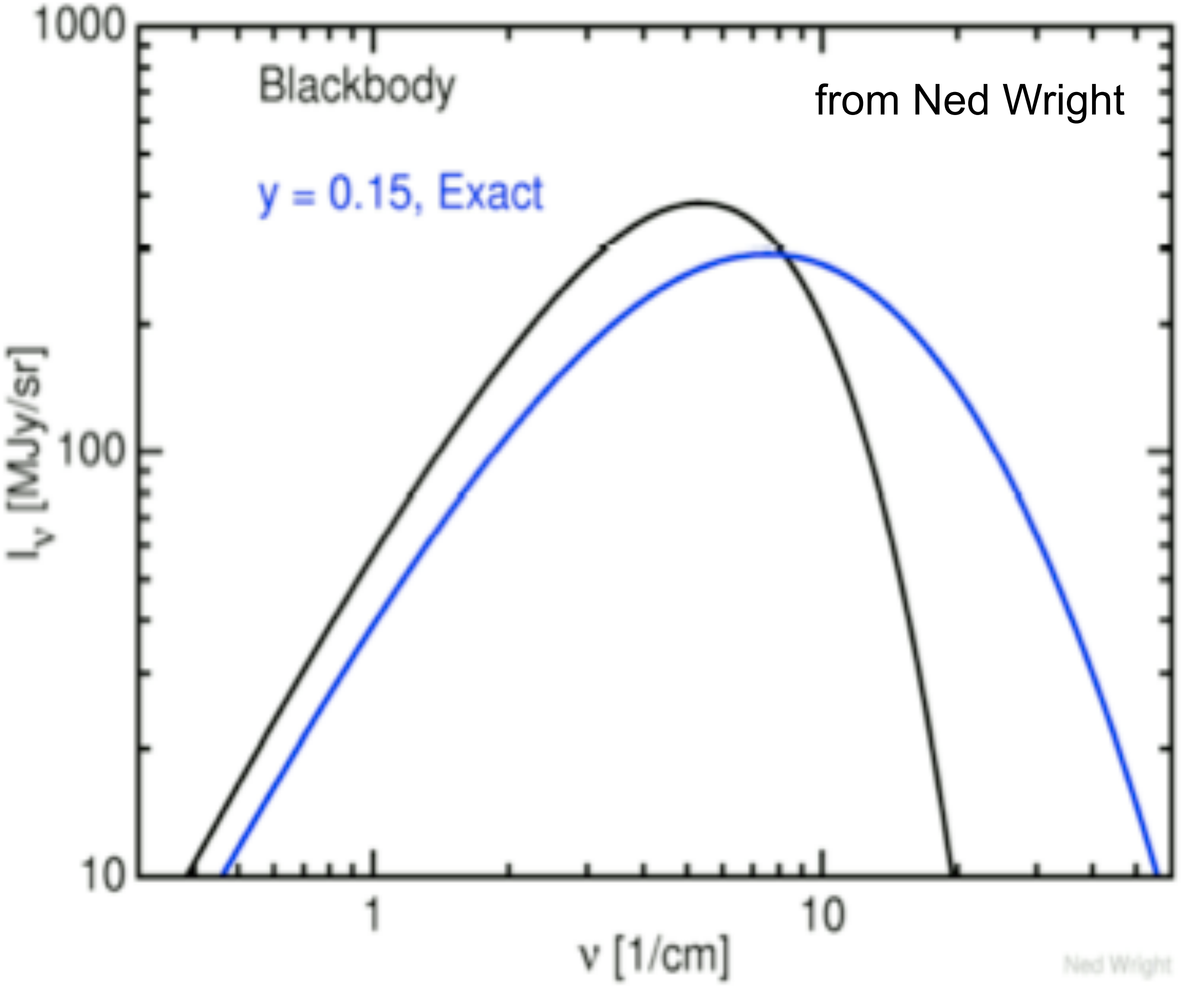
The tSZ Effect

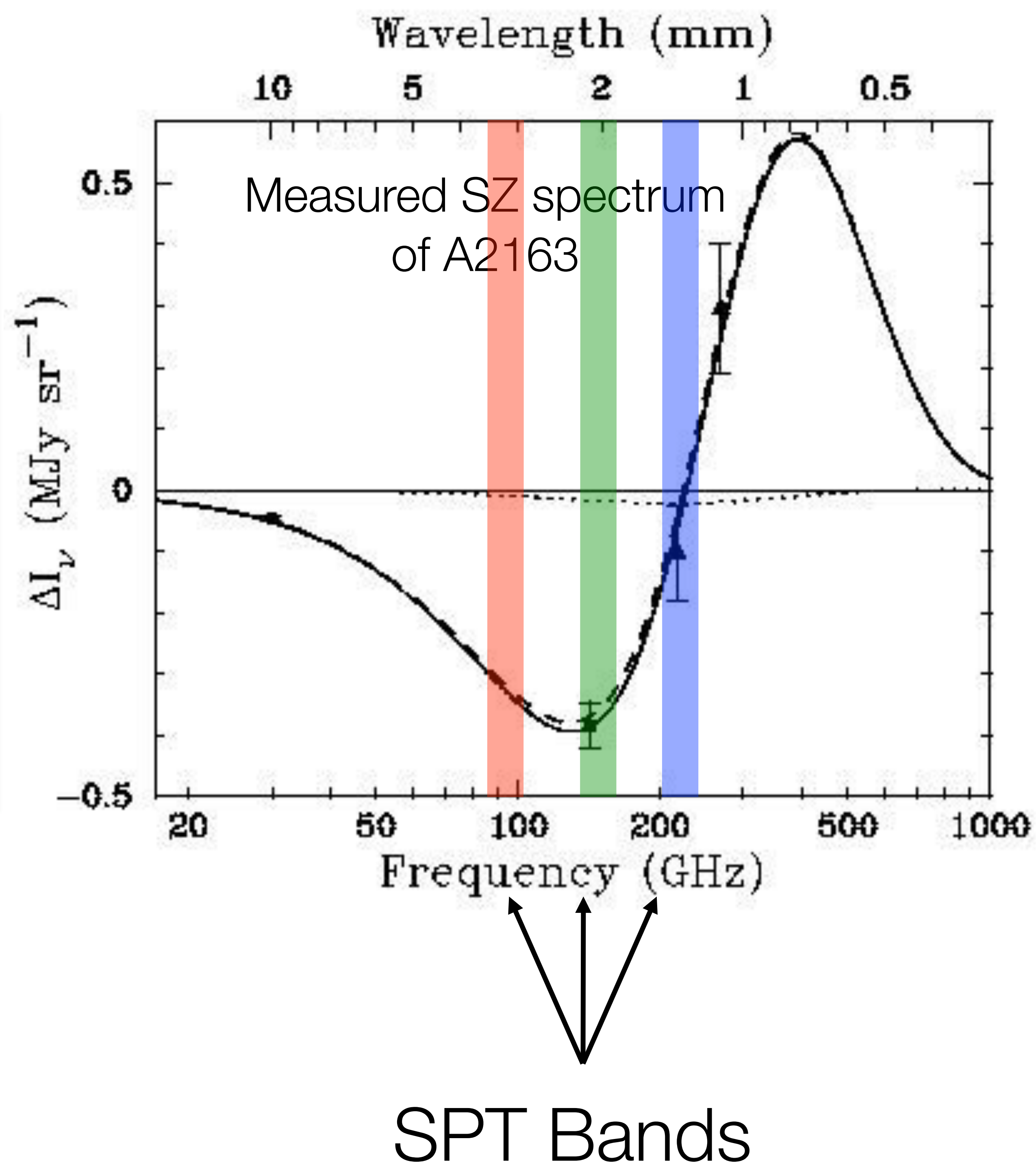


The kSZ Effect

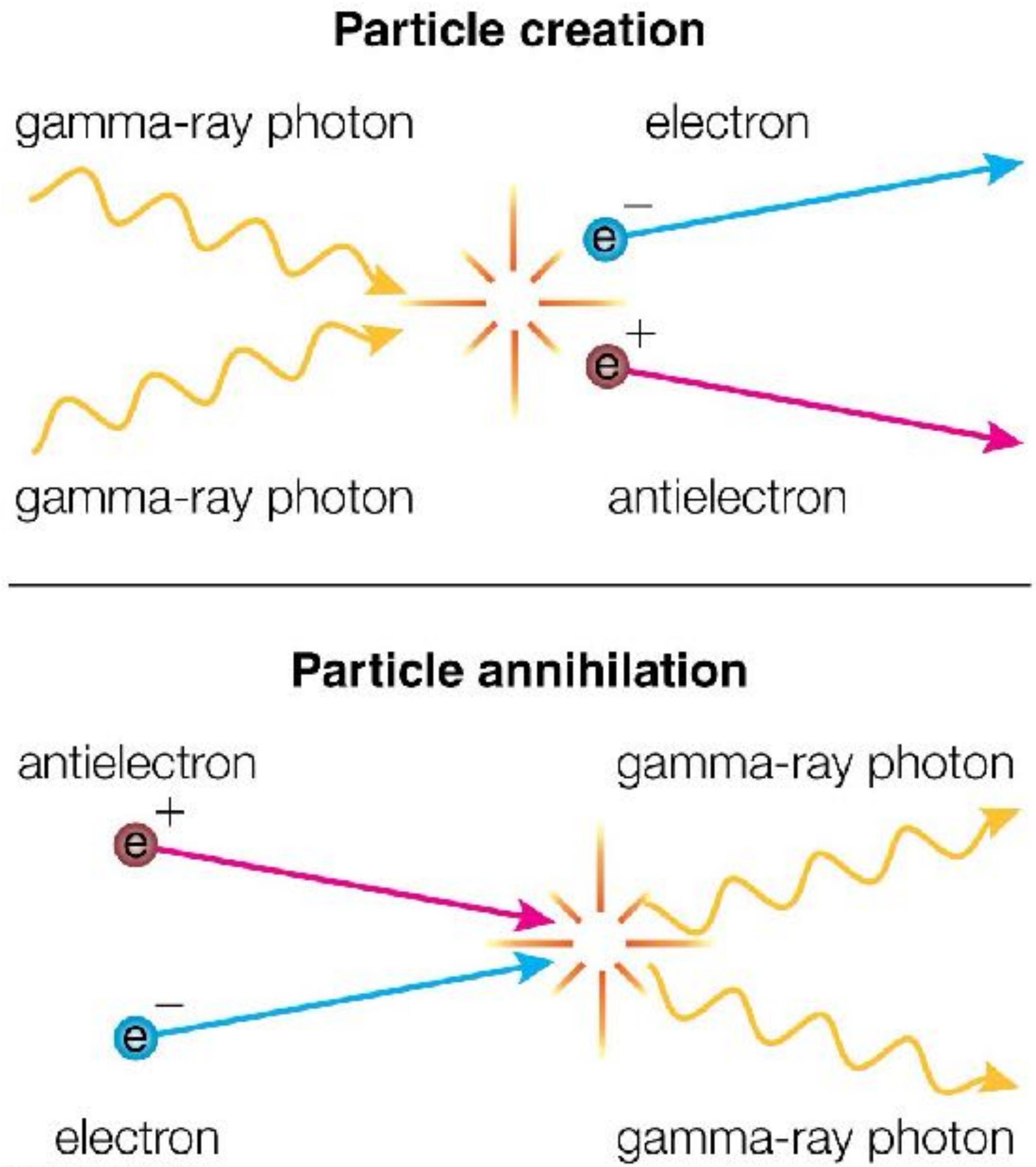


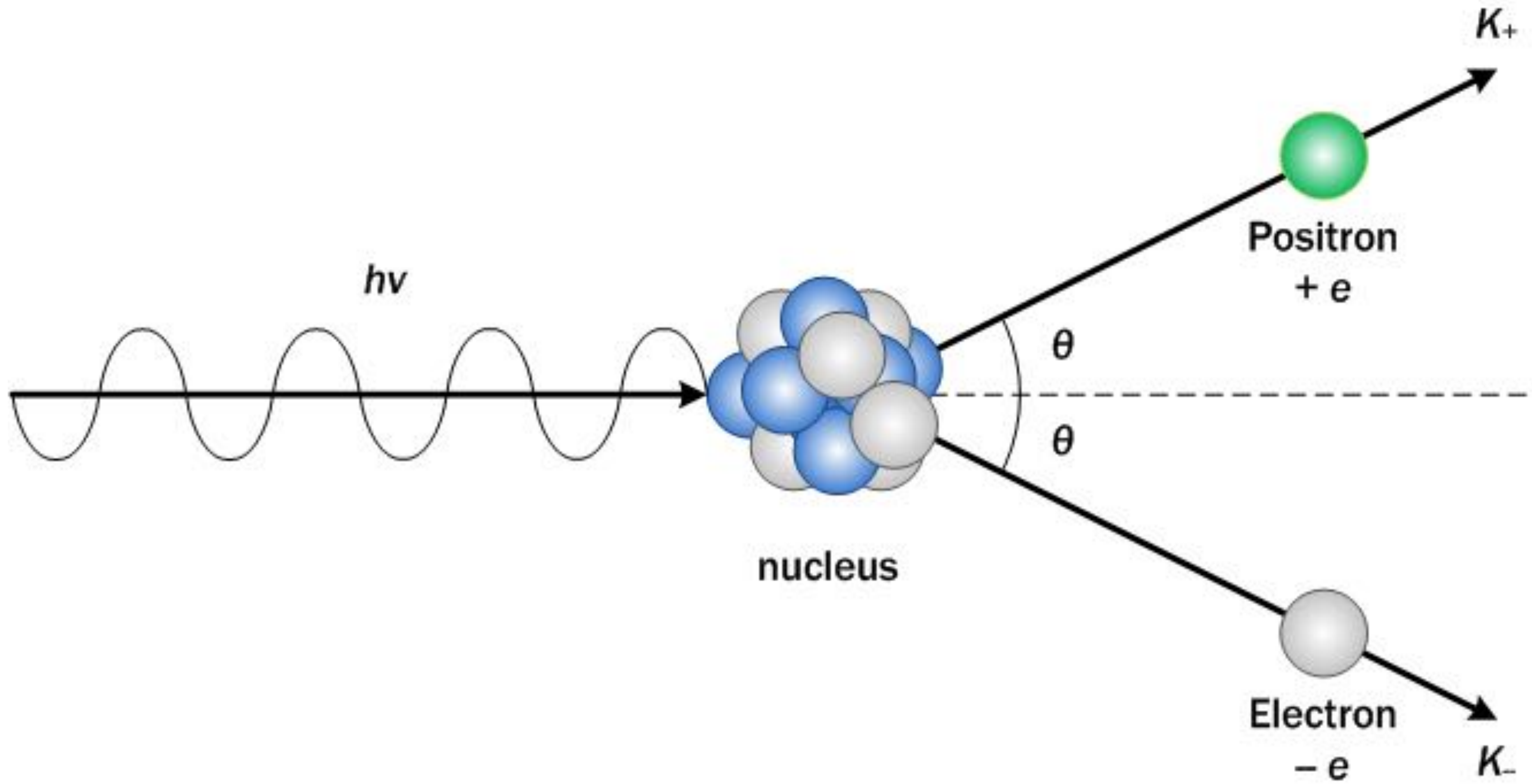
Sunyaev-Zel'dovich Effect





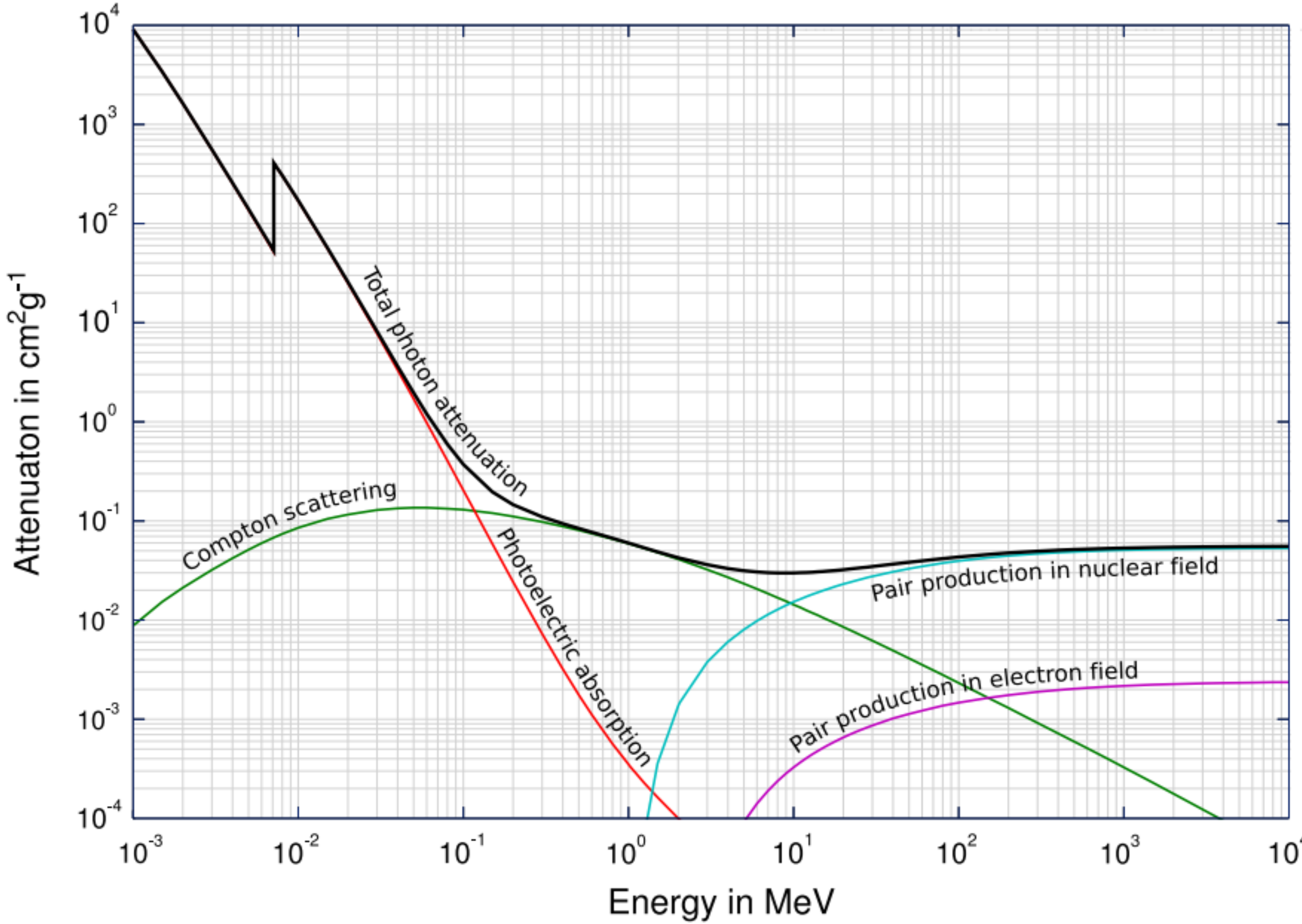
Pair production



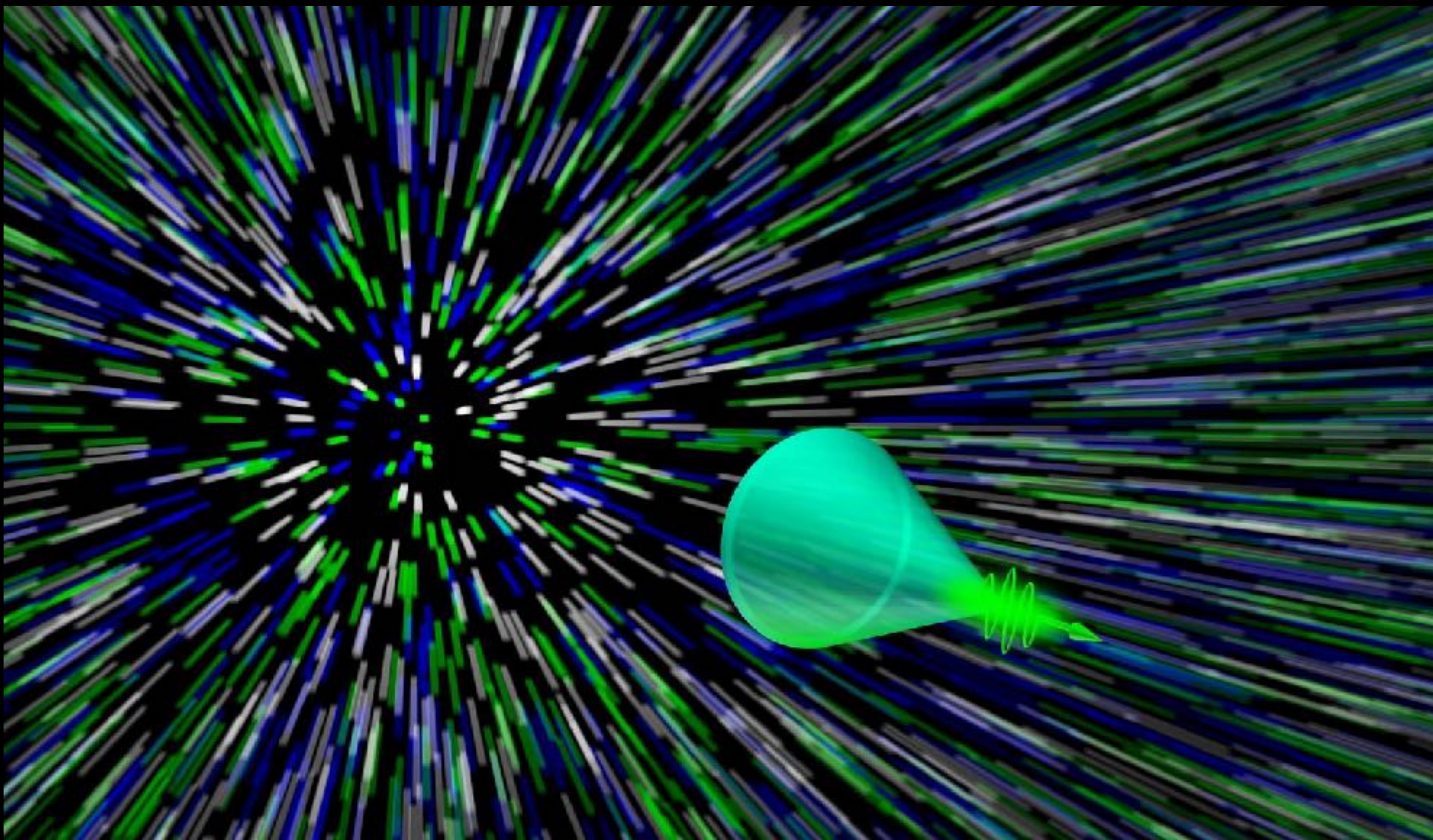


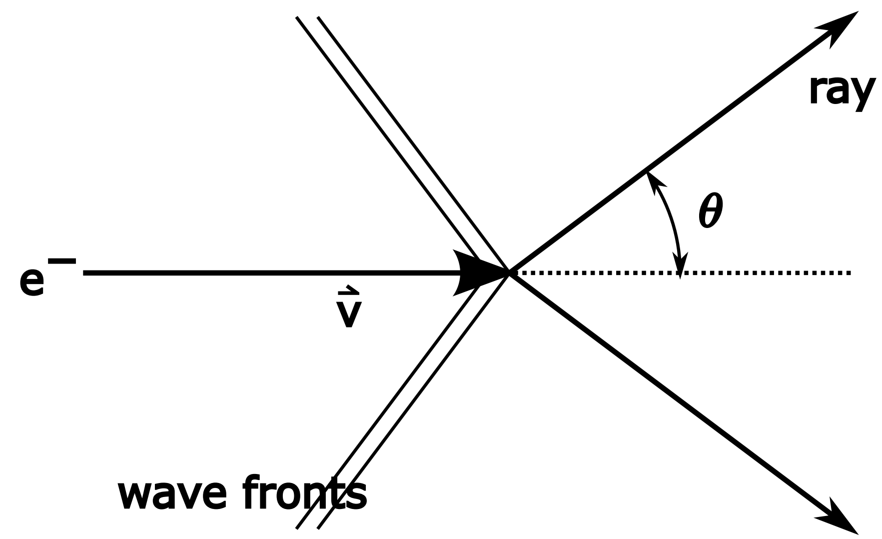
hv
nucleus
θ
θ
Positron
+ e
K+
Electron
− e
K−

Gamma Ray Cross Sections



Cherenkov





Cerenkov light and Super Kamiokande

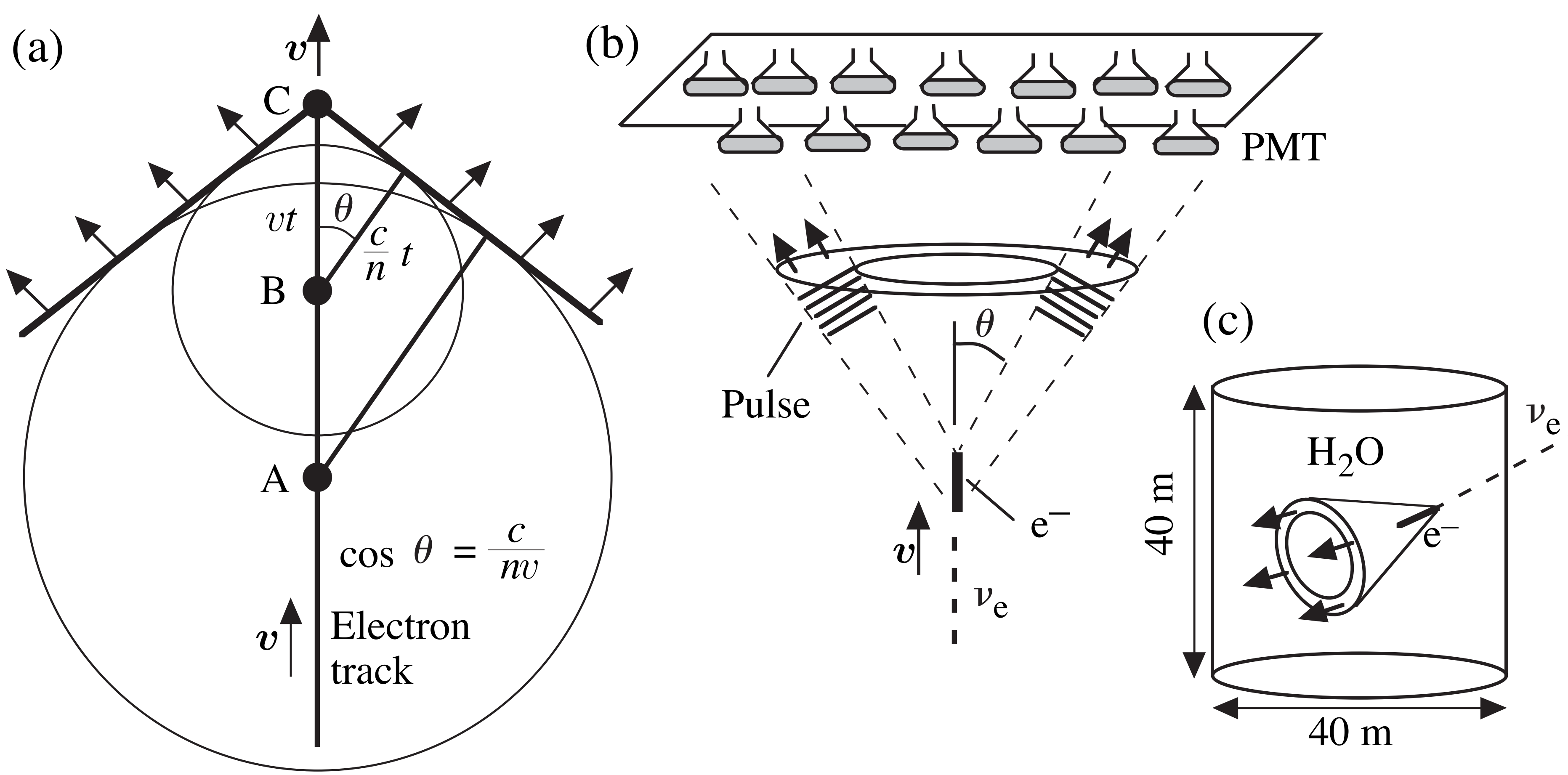
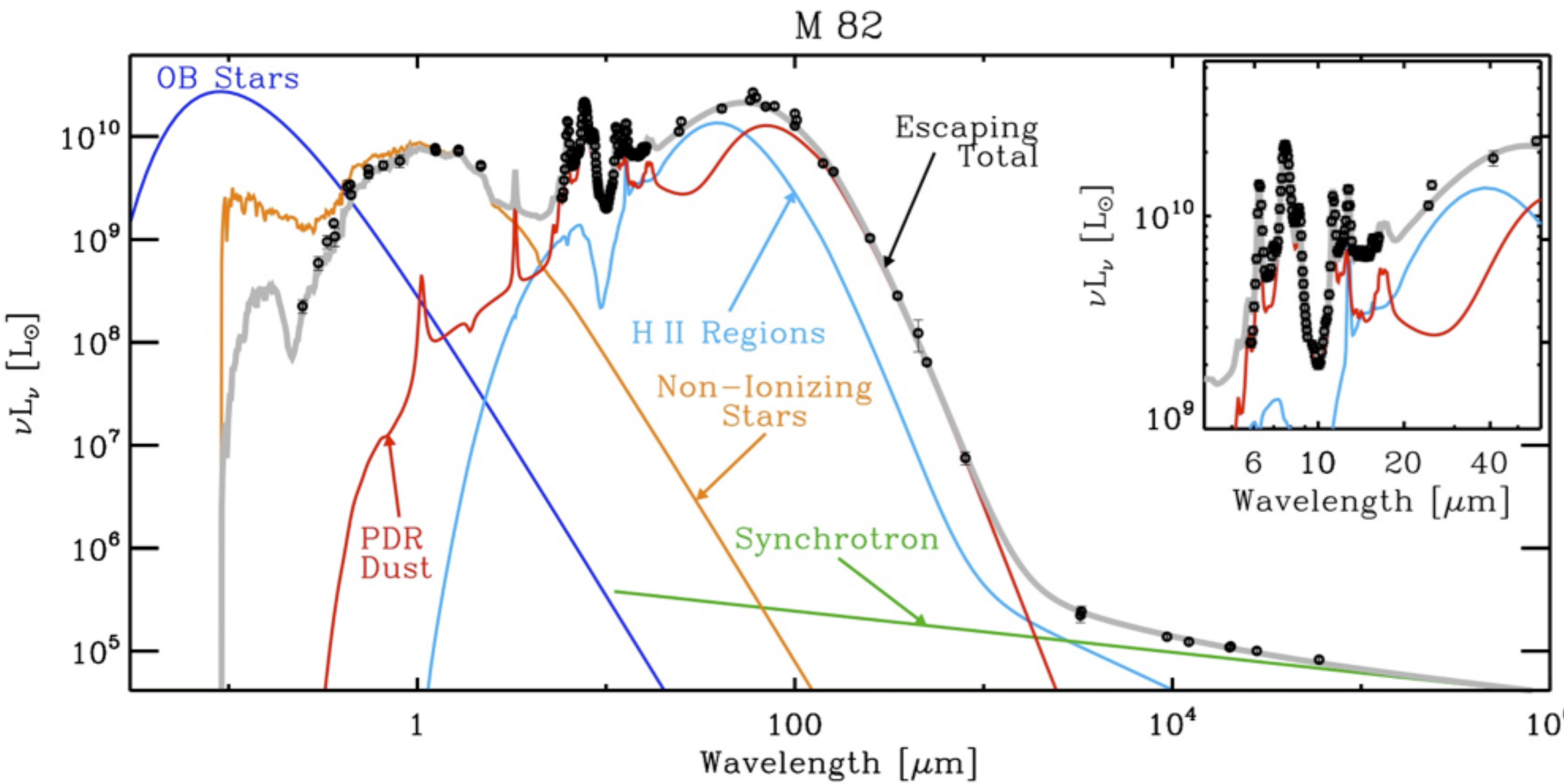


Fig. 12.2: Astronomy Methods (CUP), ©H. Bradt 2004

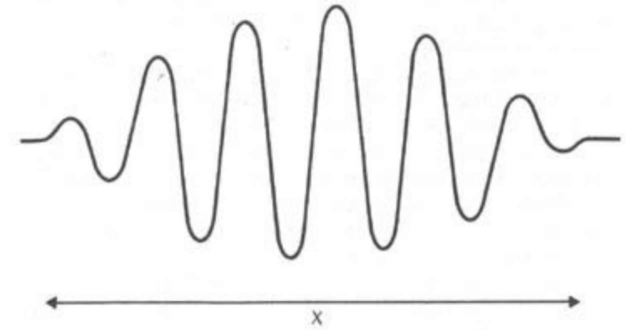


Galliano, Dwek & Chanial 2008

review of radiation processes:

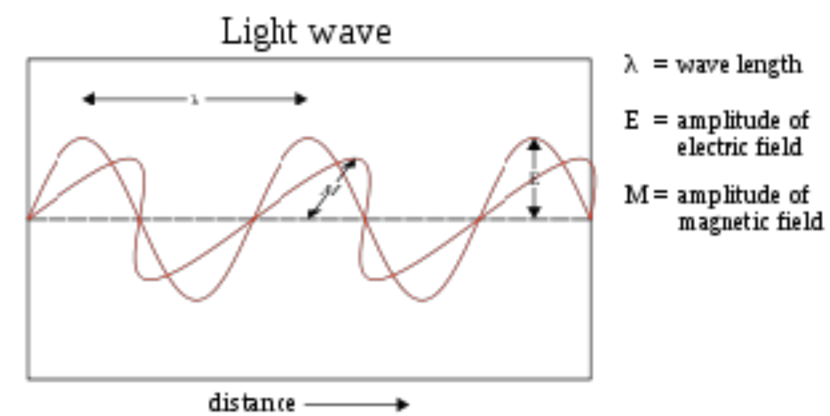
- blackbody
- free-free
- synchrotron
- compton-scattering
- pair-production
- Cherenkov

What to remember?

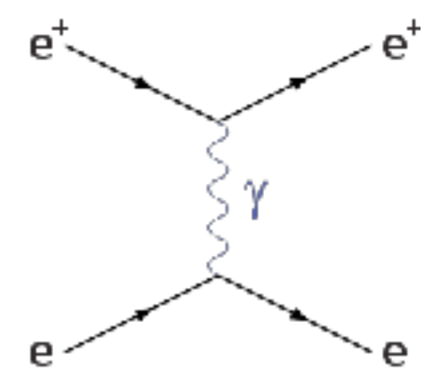


- Light is a **particle** and a **wave**
- The energy of light is characterized perfectly by its **wavelength**

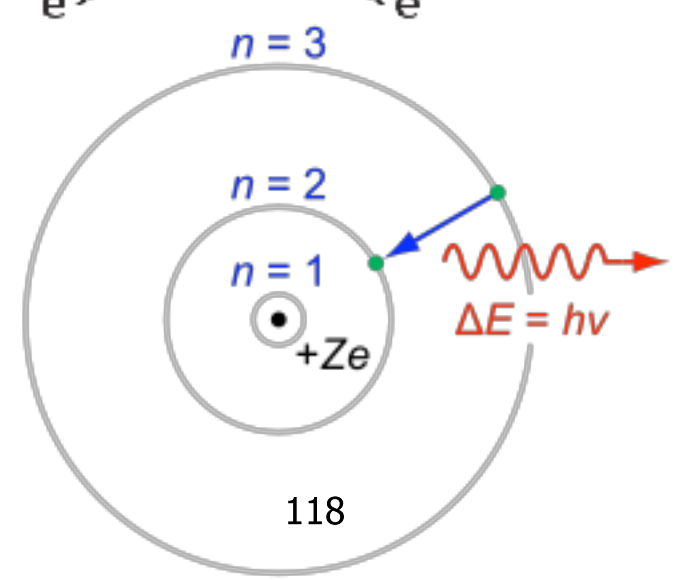
$$E_\gamma = h\nu = \frac{hc}{\lambda}$$



- Light is a quanta of **energy**
- Light moves at the **speed of light** … ALWAYS !
- The different **processes** of light are: emission, absorption, scattering, transmission.



- All **atoms** have a specific spectroscopic signature.
- Dissecting the **spectra** of light from astronomical objects we understand most things in astronomy.
- Because light moves at a finite speed, looking at objects far away is a way of looking **back in time**.



Flux and Luminosity

- **Flux** = the amount of power falling within a given area [W/m^2]
- **Luminosity** = the brightness of an object (like wattage of a lightbulb) [W]