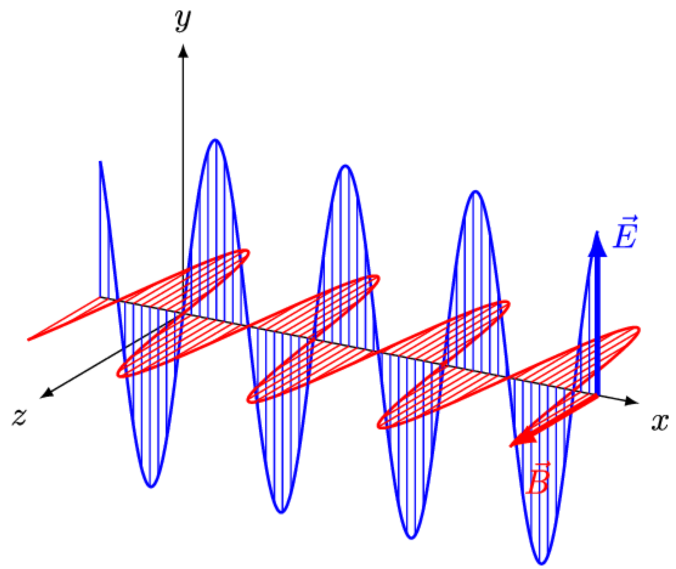


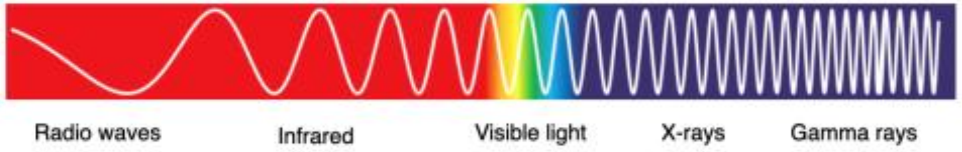


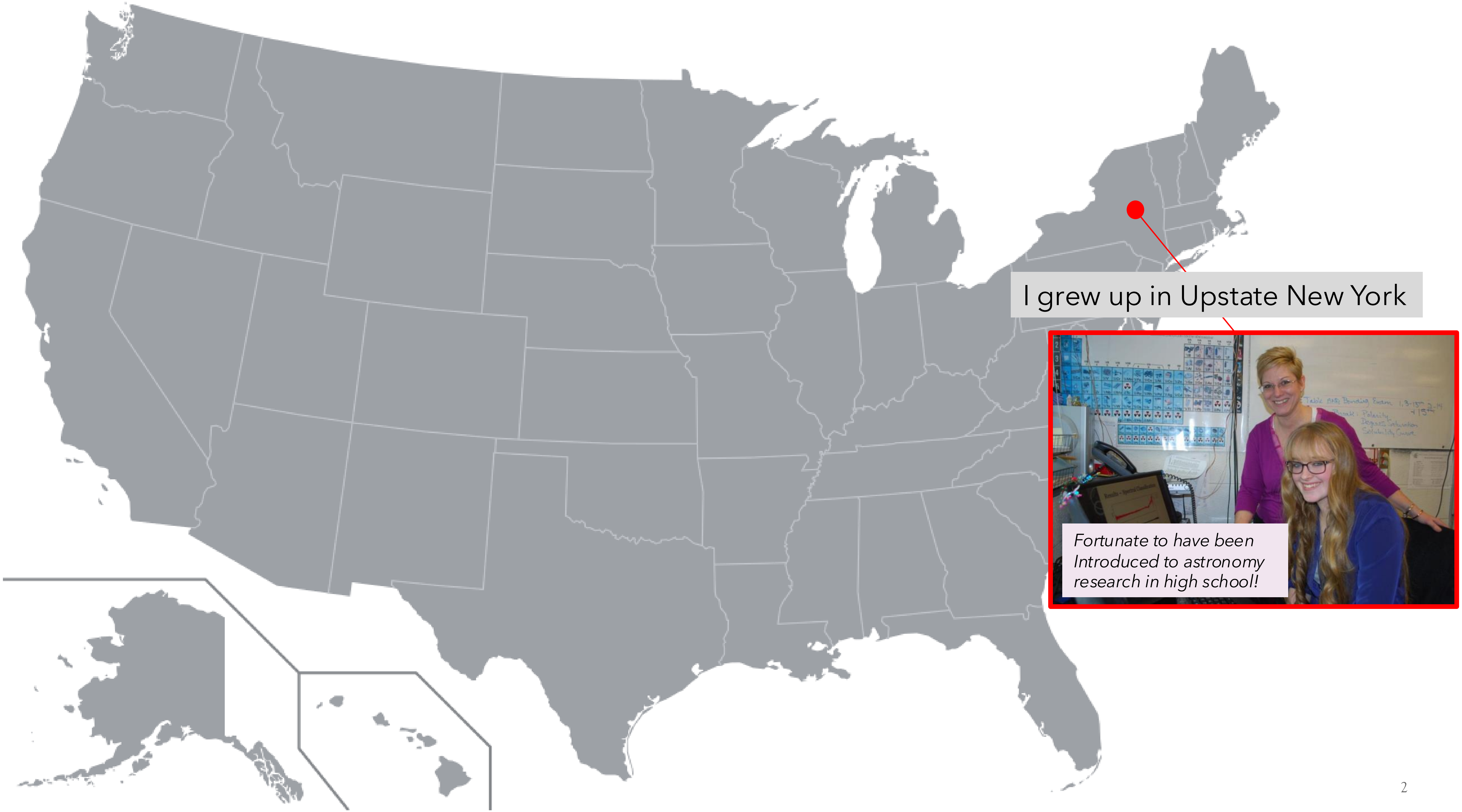
Image credit: NASA JPL

An Introduction to Electromagnetic (E&M) Waves

Dr. Samantha Scibelli

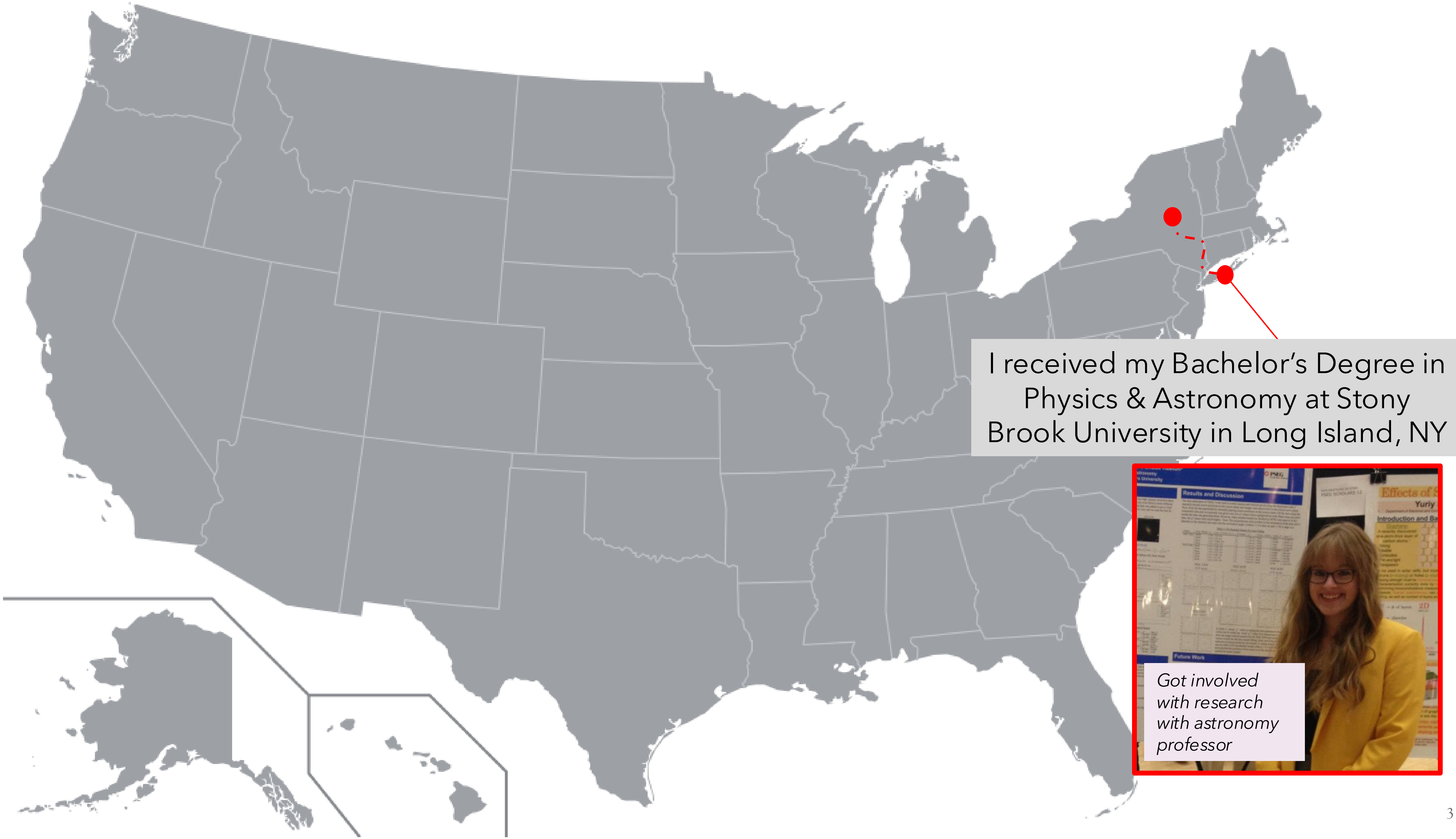
Jansky Fellow at the National Radio Astronomy Observatory (NRAO)

AAA.org Lecture, May 15th, 2024



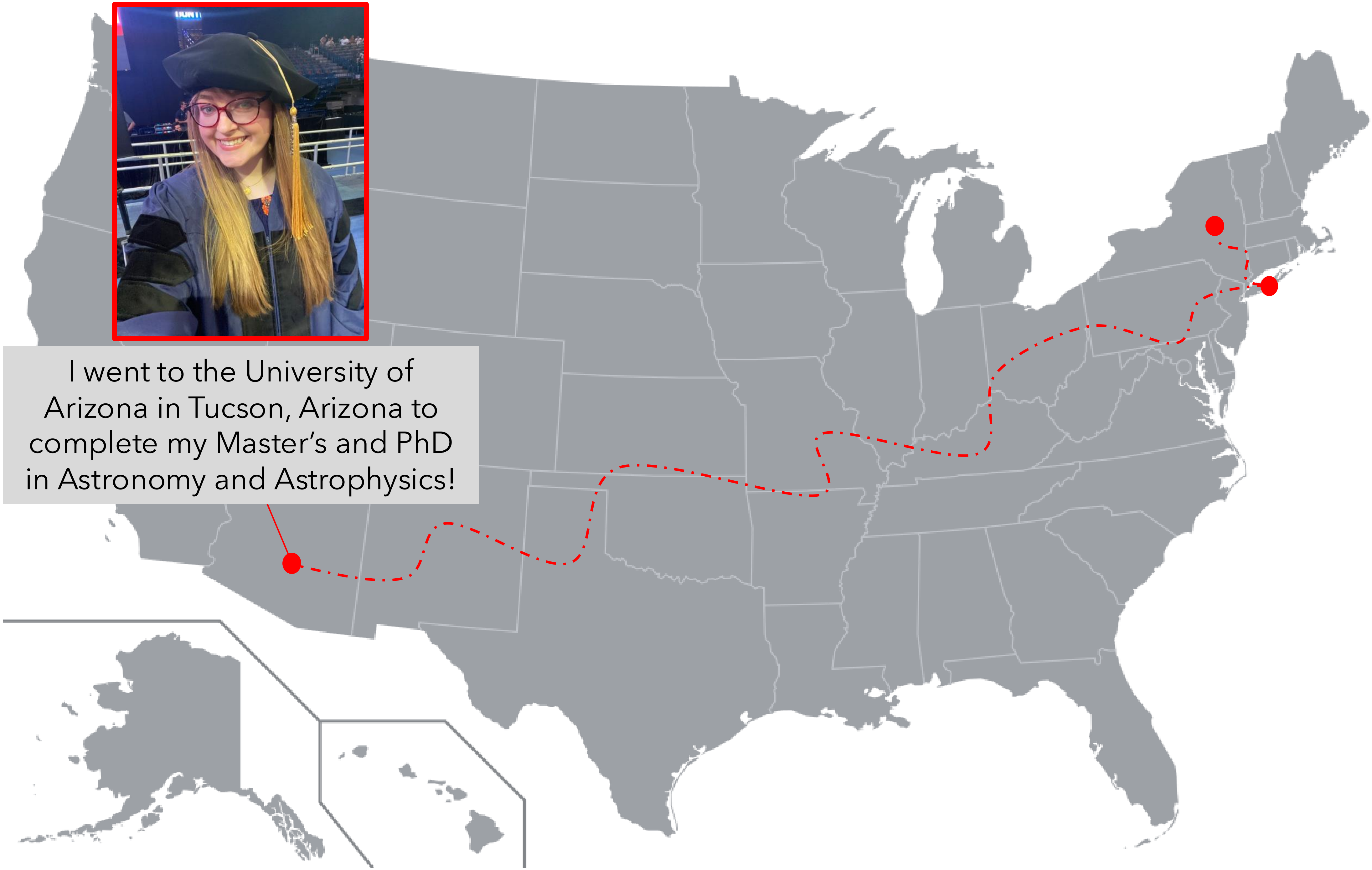
I grew up in Upstate New York

Fortunate to have been Introduced to astronomy research in high school!



I received my Bachelor's Degree in Physics & Astronomy at Stony Brook University in Long Island, NY

Got involved with research with astronomy professor

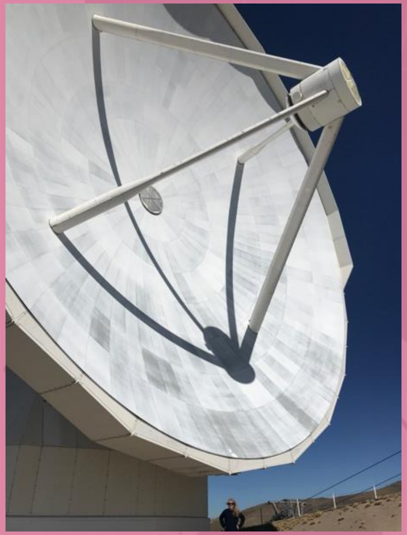


I went to the University of Arizona in Tucson, Arizona to complete my Master's and PhD in Astronomy and Astrophysics!

Currently, I am a Jansky Postdoctoral Fellow at the National Radio Astronomy Observatory (NRAO) here in Charlottesville, VA!

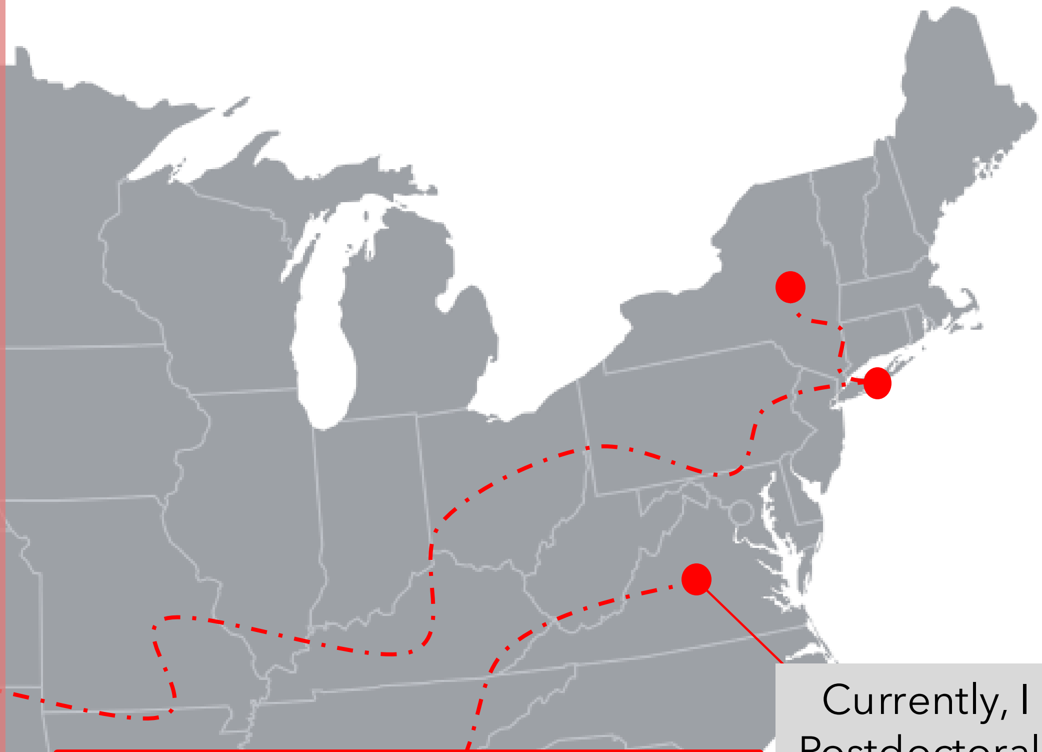
12m Radio Telescope, Kitt Peak, AZ

Control Room @ SMT, Mt. Graham, AZ



IRAM 30m Radio Telescope, Granada, Spain

Green Bank Radio Telescope, 100m, in West Virginia



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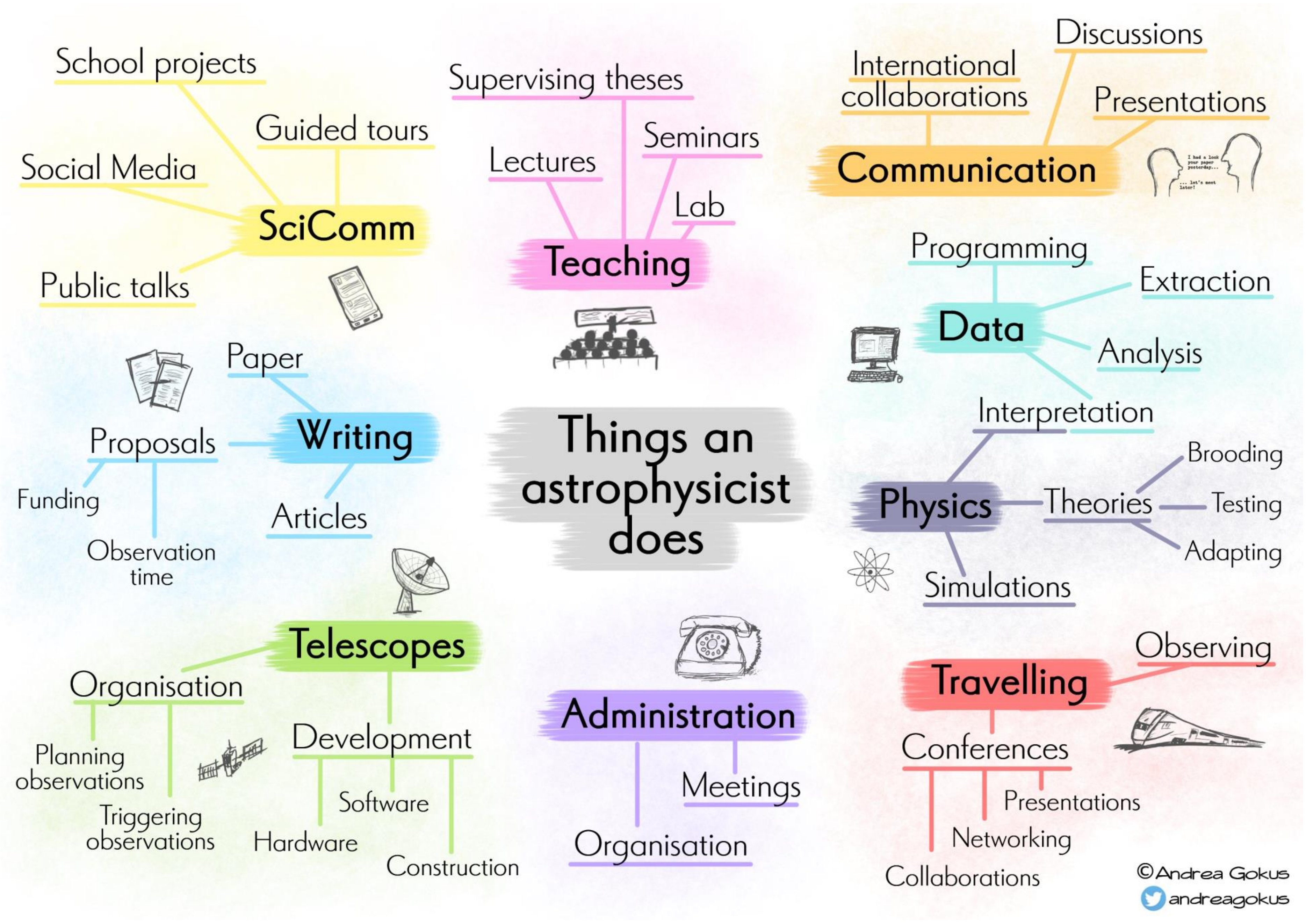

Things an astrophysicist does
SciComm
School projects
Guided tours
Social Media
Public talks
Teaching
Supervising theses
Lectures
Seminars
Lab
Communication
International collaborations
Discussions
Presentations
Data
Programming
Extraction
Analysis
Interpretation
Writing
Paper
Proposals
Funding
Observation time
Articles
Physics
Theories
Brooding
Testing
Adapting
Simulations
Telescopes
Organisation
Planning observations
Triggering observations
Development
Hardware
Software
Construction
Administration
Meetings
Organisation
Travelling
Observing
Conferences
Presentations
Networking
Collaborations
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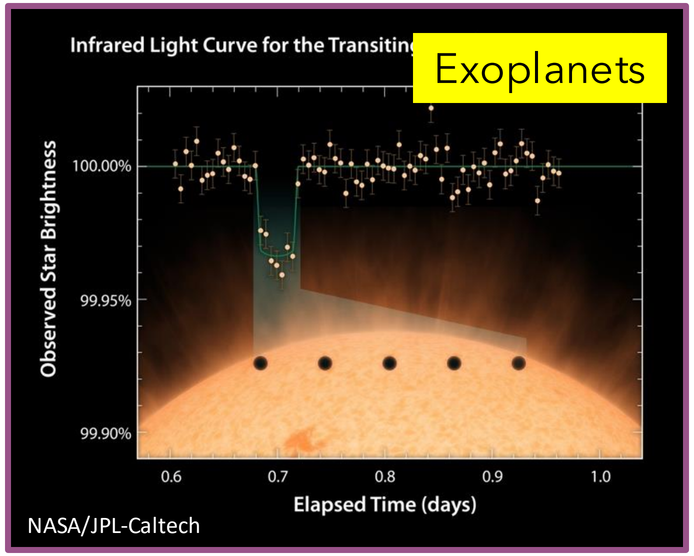
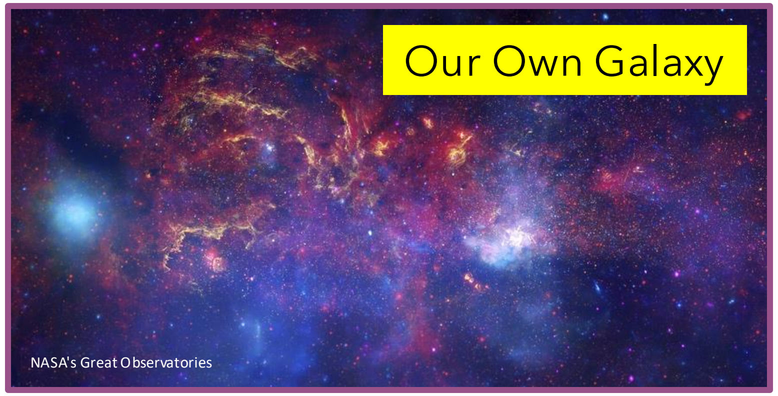
andreagokus

Astronomy relies heavily on observations of Electromagnetic Waves/Electromagnetic Radiation/Light

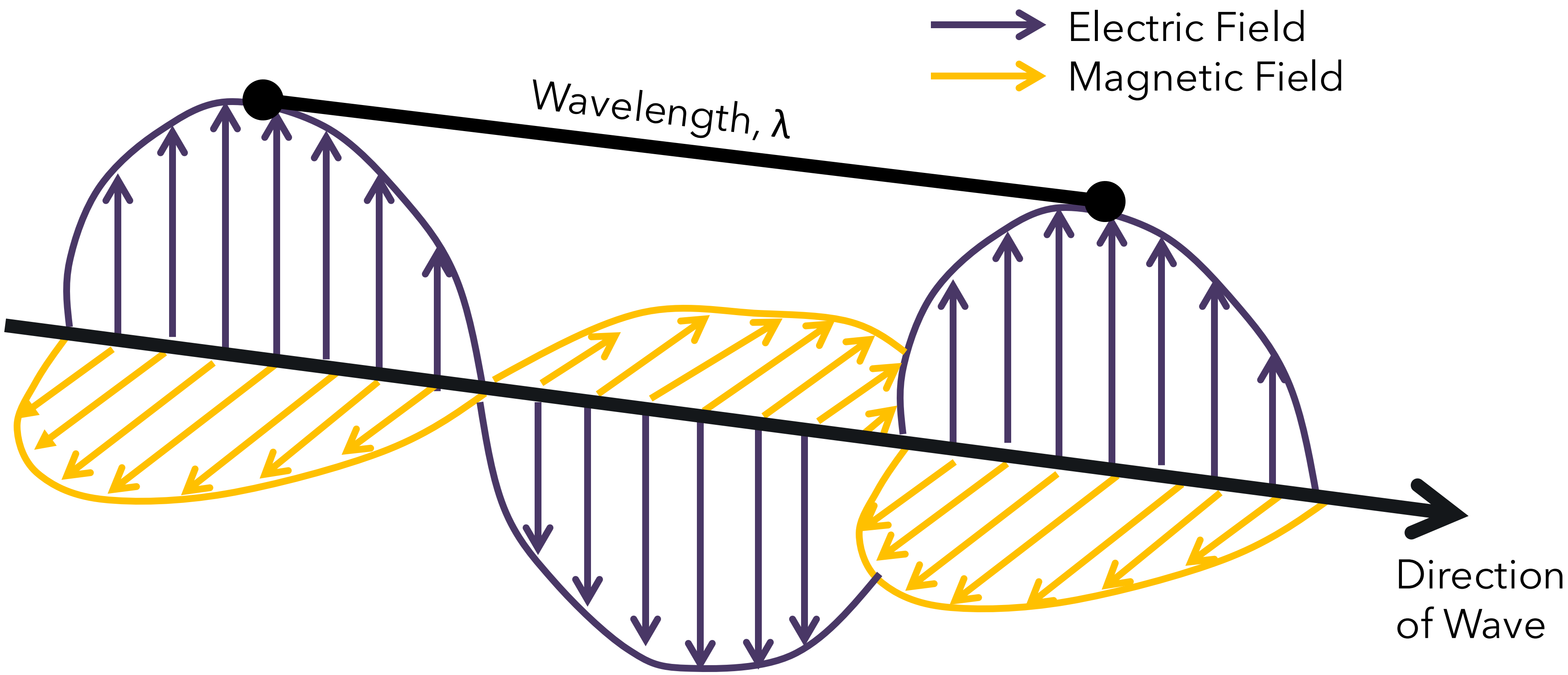




Almost all information about the Universe comes from the study of **light**!

Electromagnetic Waves = Light!

Definition: Electromagnetic Waves, or Electromagnetic Radiation is a type of radiation that has both magnetic fields and electric fields



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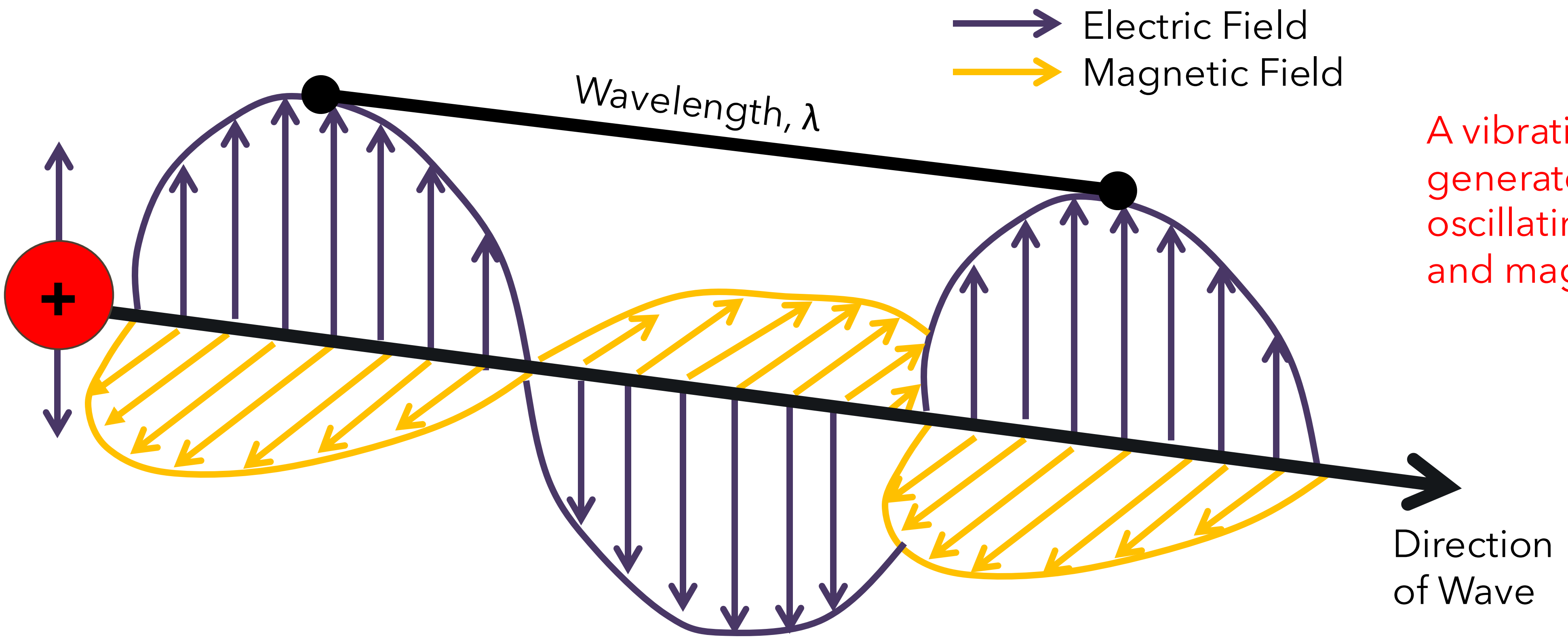
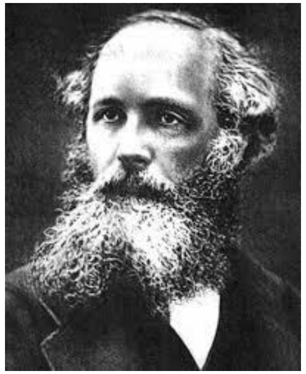


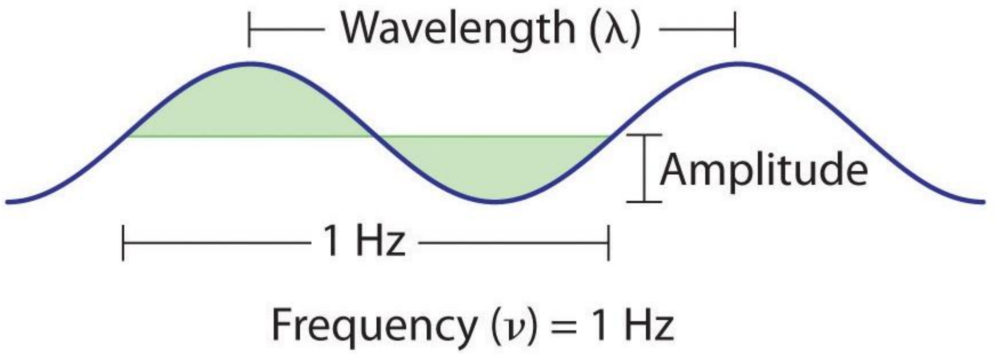
A vibrating charged particle generates the perpendicular, oscillating vibrating electric and magnetic fields

(described by Maxwell's equations)



Electromagnetic Waves = Light!

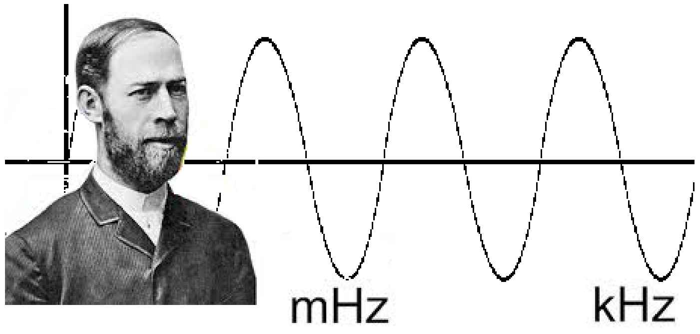
Electromagnetic Waves are characterized by **wavelength** and **frequency**



Wavelength, λ: described as the distance between wave 'crests' or rather the corresponding points of adjacent waves. Usually measured in meters (m).

Frequency, ν: described as the number of waves that pass a fixed point in a given amount of time. One wave, or cycle, per second (1/s) is called a Hertz (Hz)

Speed (m/s) = Frequency (1/s) x wavelength (m)



Electromagnetic Waves = Light!

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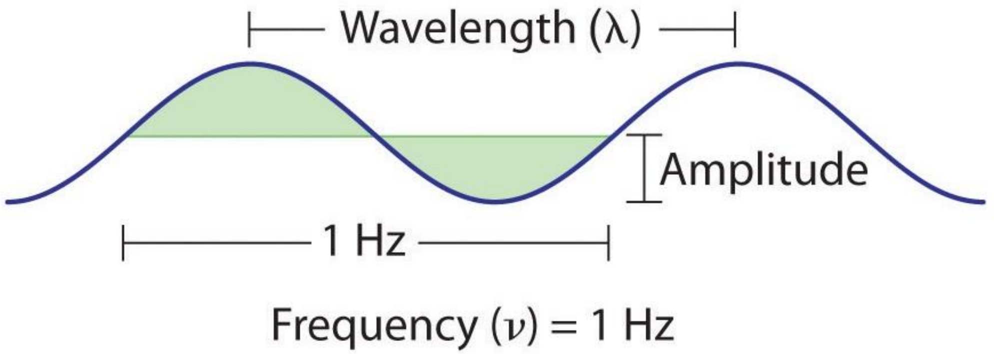

Both inversely related by the speed of light,

$$c = \lambda \nu = 2.99 \times 10^8 \text{ m/s}$$

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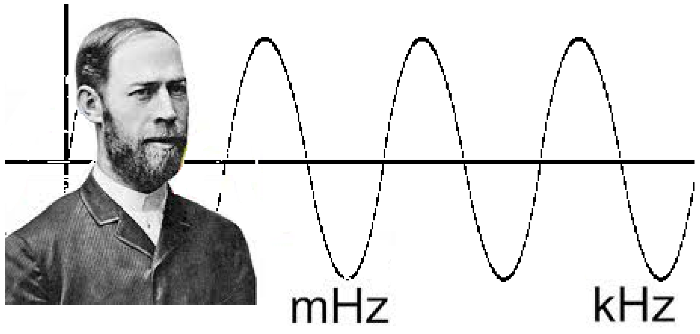
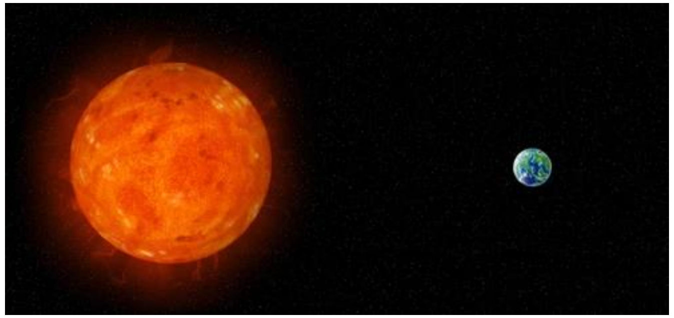


Powers of 10

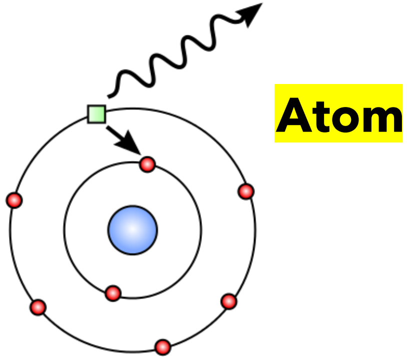
sciencenotes.org

Prefix	Exponent	Number	Scientific Notation	Name
Exa (E)	18	1,000,000,000,000,000,000	10^{18}	quintillion
Peta (P)	15	1,000,000,000,000,000	10^{15}	quadrillion
Tera (T)	12	1,000,000,000,000	10^{12}	trillion
Giga (G)	9	1,000,000,000	10^{9}	billion
Mega (M)	6	1,000,000	10^{6}	million
kilo (k)	3	1,000	10^{3}	thousand
hecto (h)	2	100	10^{2}	hundred
deca (da)	1	10	10^{1}	ten
	0	1	10^{0}	one
deci (d)	-1	0.1	10^{-1}	one tenth
centi (c)	-2	0.01	10^{-2}	one hundredth
milli (m)	-3	0.001	10^{-3}	one thousandth
micro (μ)	-6	0.000001	10^{-6}	one millionth
nano (n)	-9	0.000000001	10^{-9}	one billionth
pico (p)	-12	0.000000000001	10^{-12}	one trillionth
femto (f)	-15	0.000000000000001	10^{-15}	one quadrillionth
atto (a)	-18	0.000000000000000001	10^{-18}	one quintillionth



~ 10^{11} meters

~ a few x 10^{0} meters



~ 10^{-10} meters

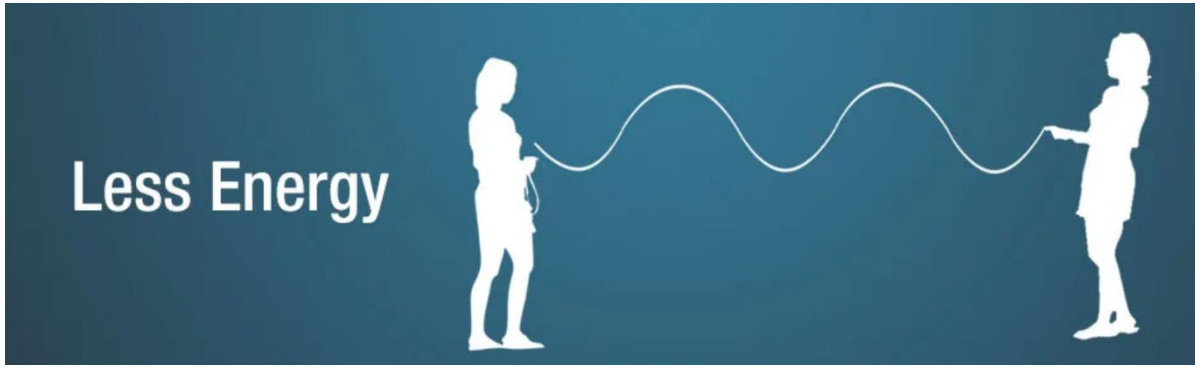
Speed of light, $c = \lambda\nu = 2.99 \times 10^{8}$ m/s

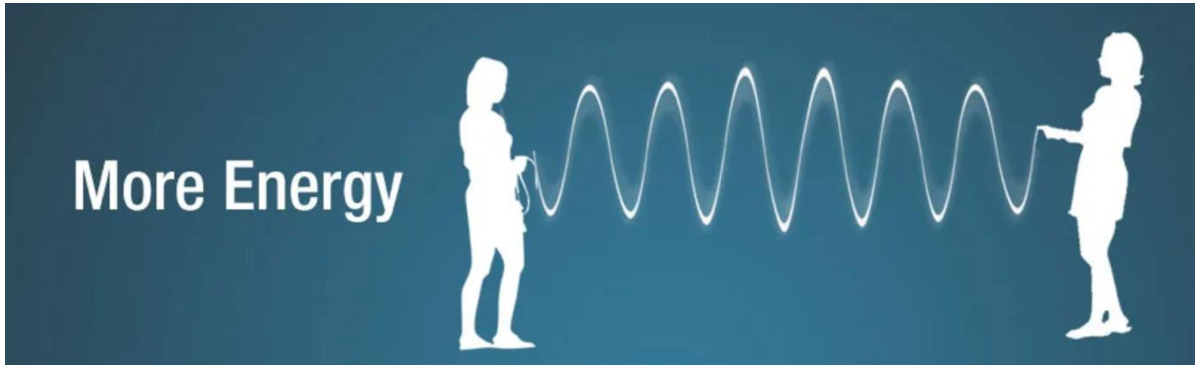
Electromagnetic Waves = Light!

The **wavelength** and **frequency** of the Electromagnetic Wave determines its **energy**:

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

h – Planck constant [6.62×10^{-34} J = kg m^2 s^{-2}]
c – Speed of light [2.99×10^{8} m/s]
ν – frequency [Hz or 1/s]
λ – wavelength [m]





REF: https://science.nasa.gov/ems/02_anatomy/

Light: A Wave and Particle

The wavelength and frequency of the Electromagnetic Wave determines its **energy**:

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

h – Planck constant [6.62 x 10^{-34} J = kg m^2 s^{-2}]
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The fact that energy and frequency are linearly related is a consequence of quantum mechanics!

Light behaves like both a wave and particle

Light: A Wave and Particle

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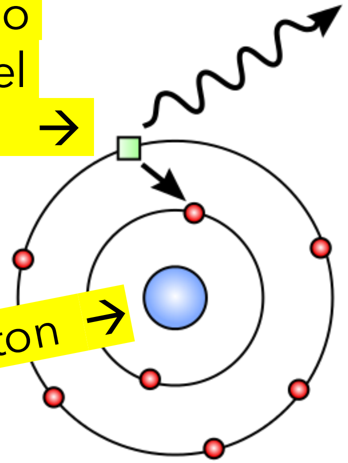
Light behaves like both a wave and particle

Electron returns to lower energy level and releases a packet of energy →



← Photon

Proton →

Atom

A "packet" of energy, E, is called a **photon**

Light: A Wave and Particle

The wavelength and frequency of the Electromagnetic Wave determines its **energy**:

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

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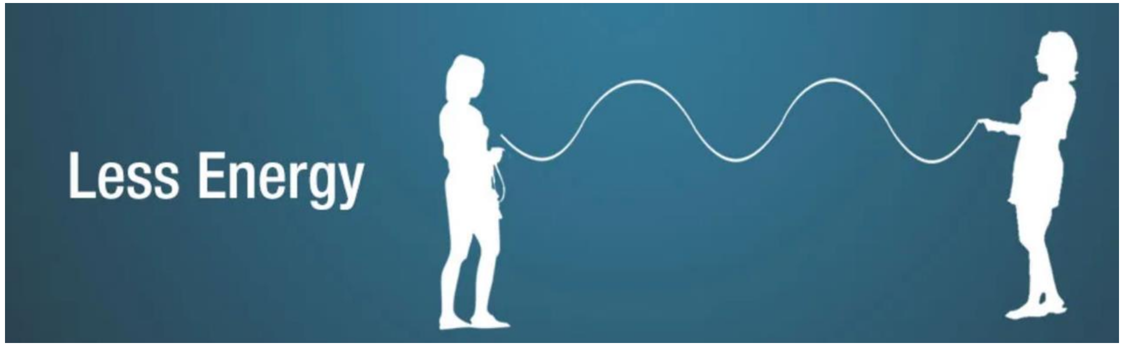
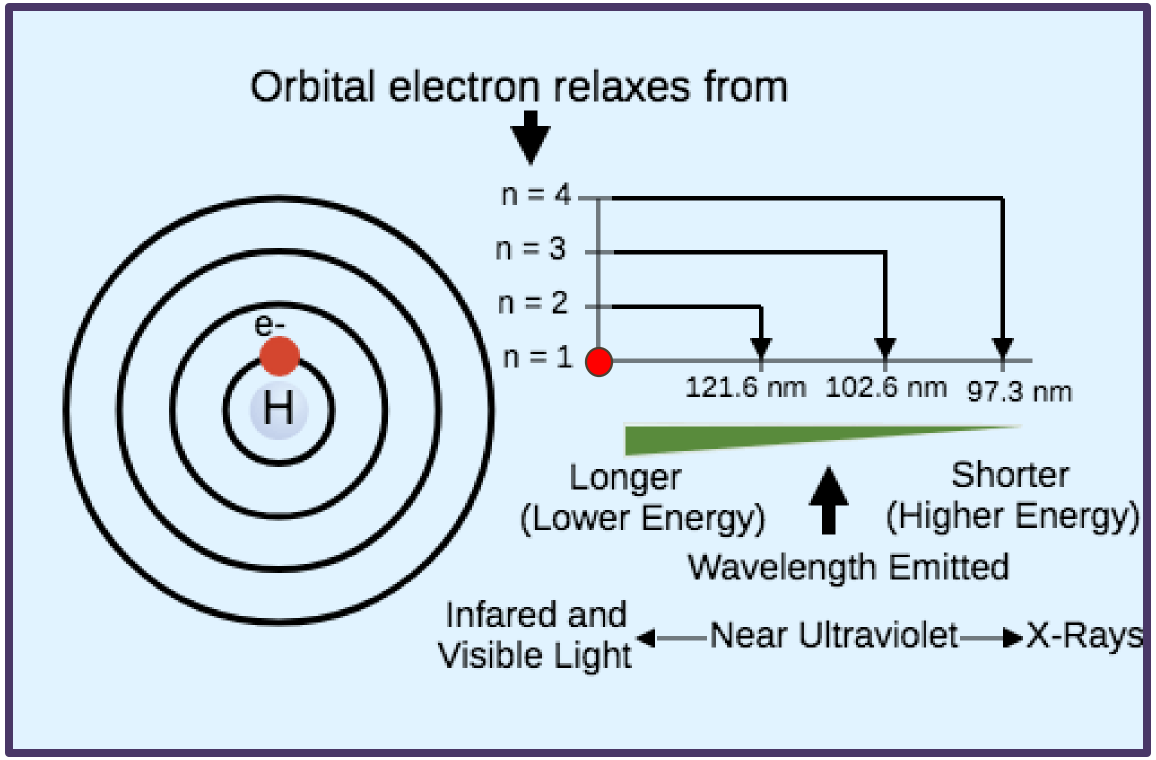


You can think of **lower energy light** not only as **longer wavelength light**, but also as **low energy photons** released by lower orbital electron returning to its lower energy level

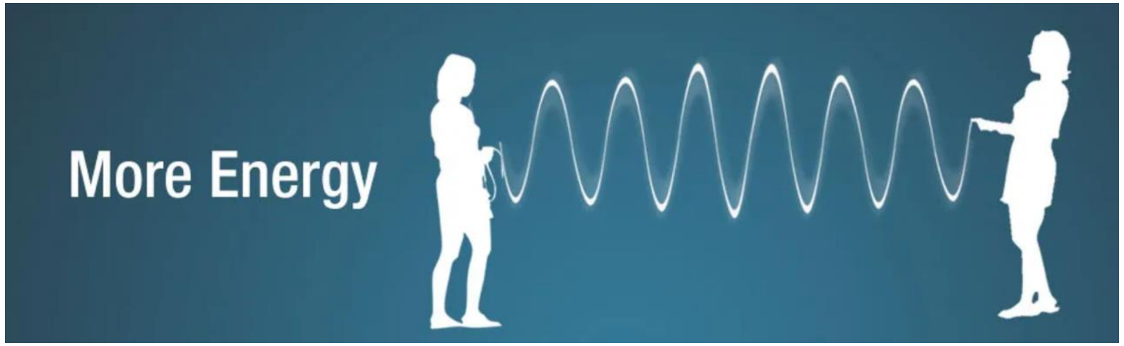


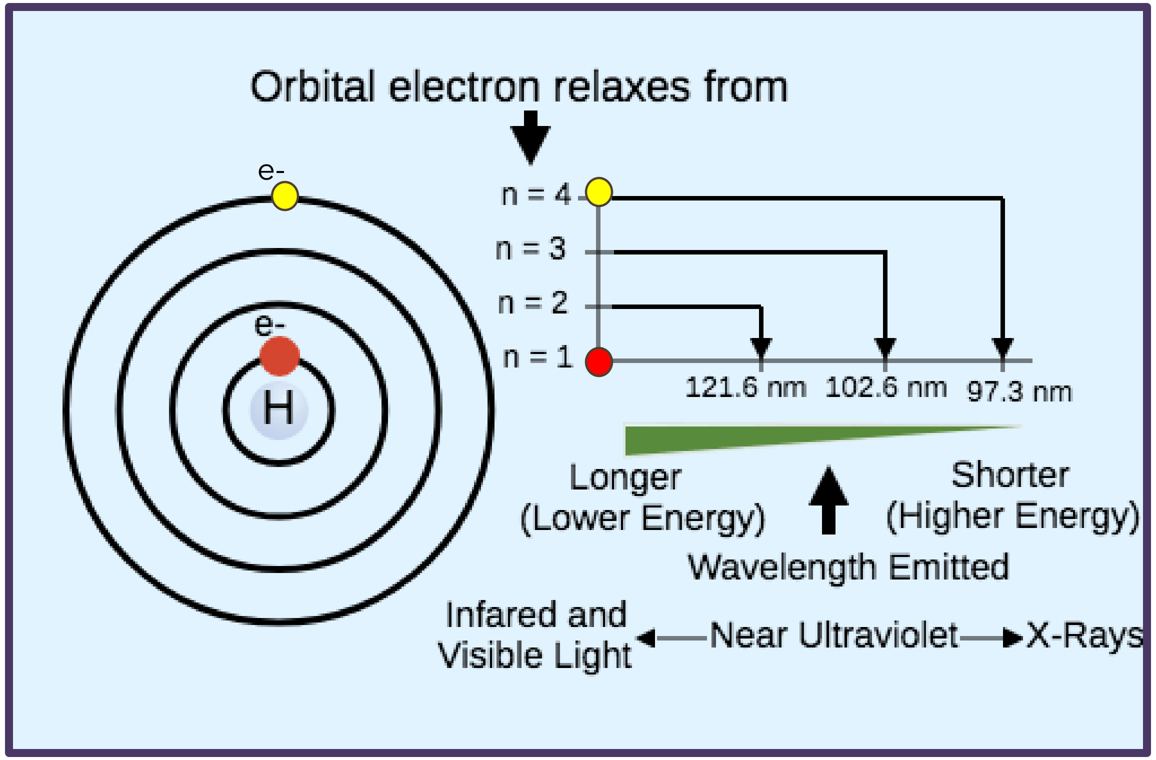
Light: A Wave and Particle

The wavelength and frequency of the Electromagnetic Wave determines its **energy**:

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

h – Planck constant [6.62×10^{-34} J = kg m^2 s^{-2}]
c – Speed of light [2.99×10^8 m/s]
ν – frequency [Hz or 1/s]
λ – wavelength [m]

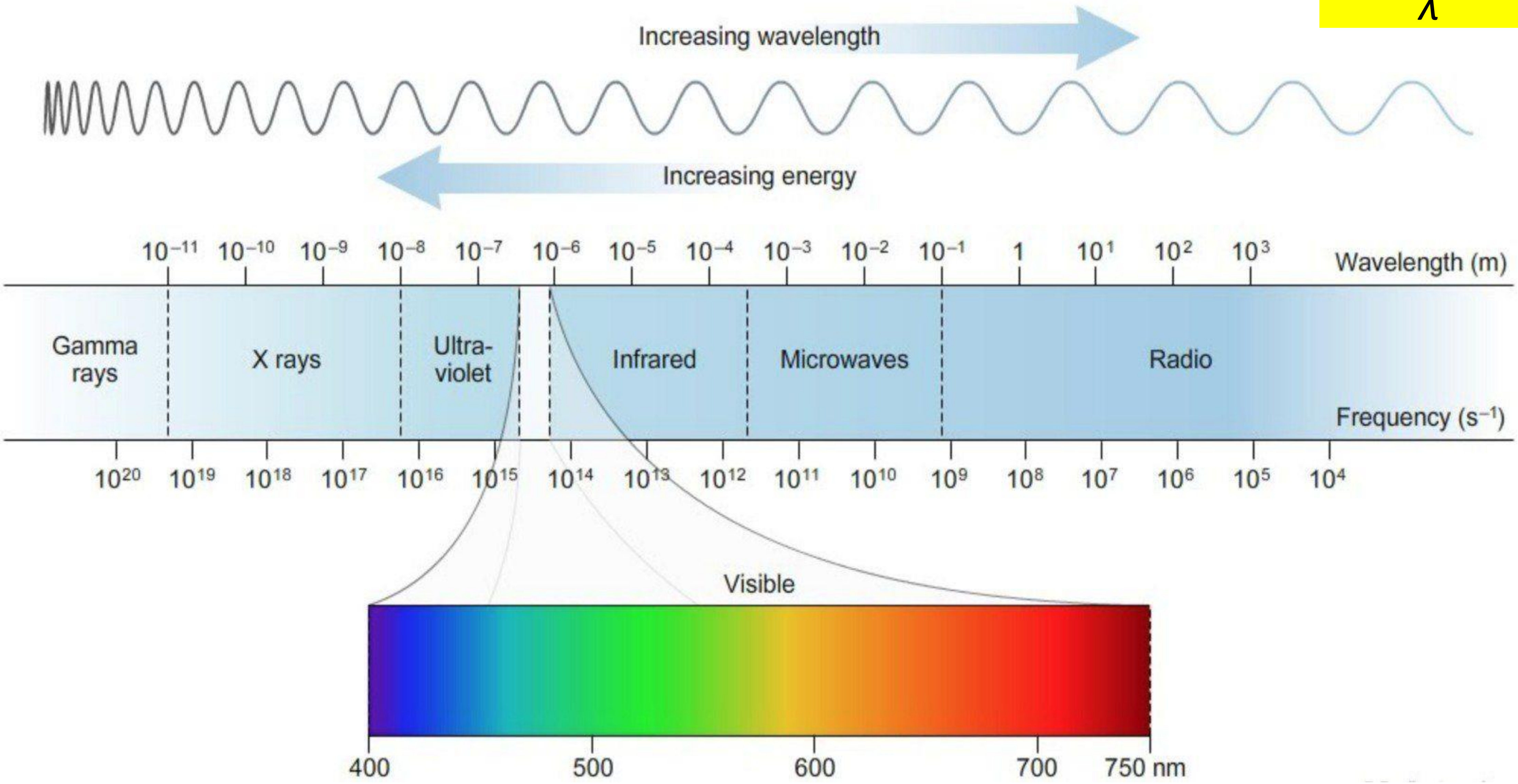




You can think of **higher energy light** not only as **shorter wavelength light**, but also as **higher energy photons** released by a higher orbital electron returning to a lower energy level

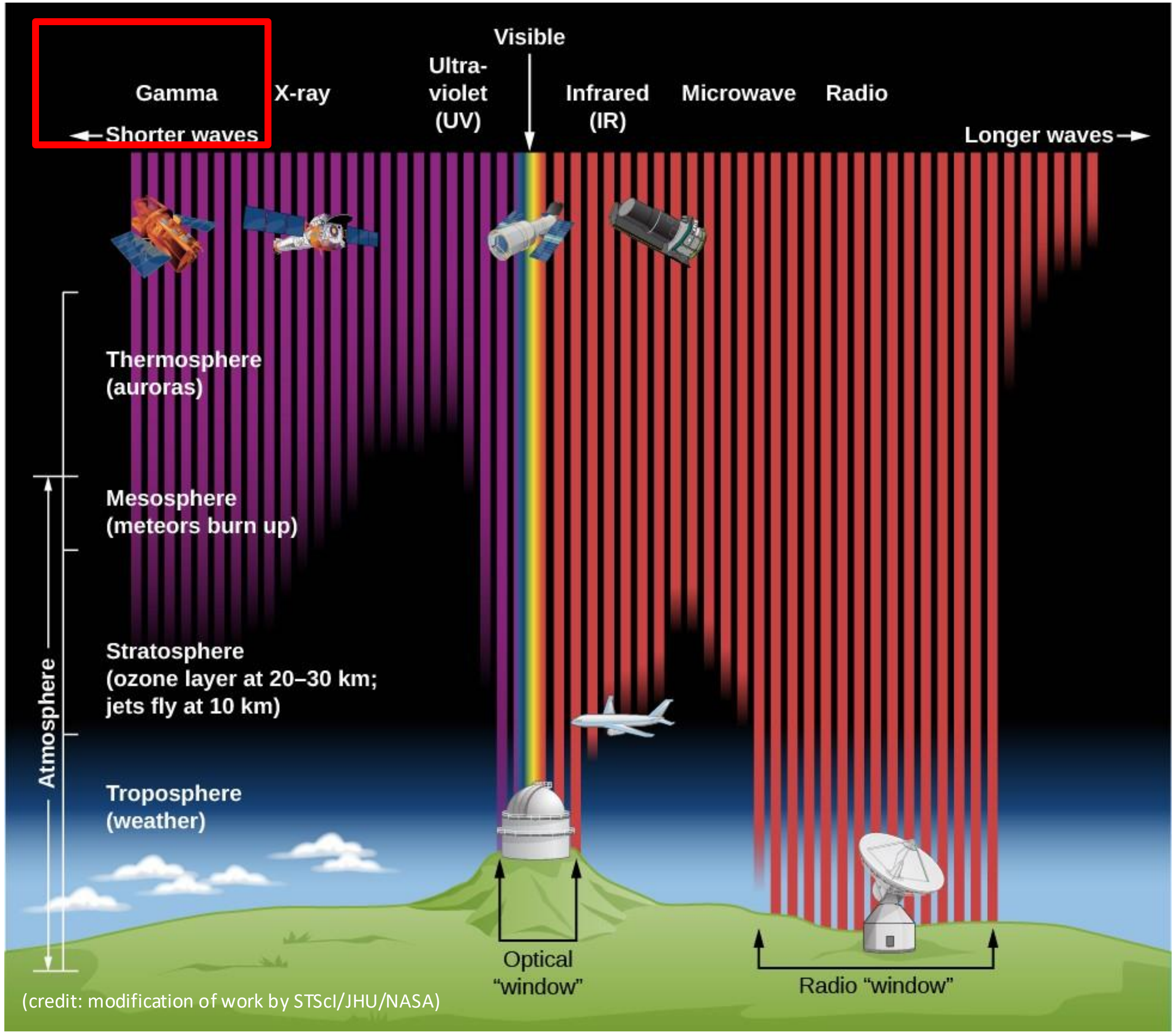
The Electromagnetic Spectrum

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



Gamma Rays

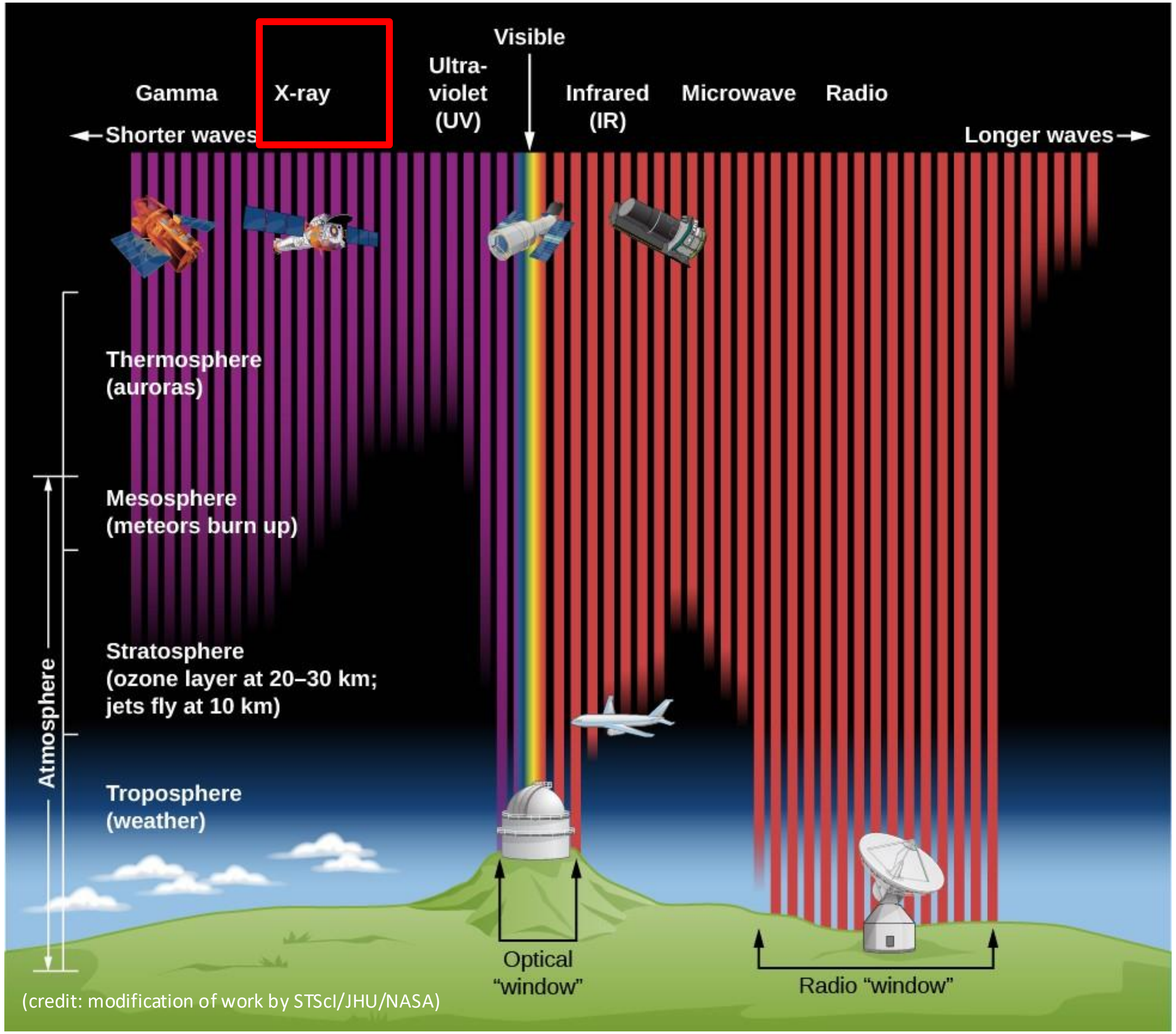
- Shortest wavelength light, no longer than 0.01 nanometers (1 nanometer = 10^{-9} meters)
- Gamma rays carry a lot of energy, they can be dangerous for living tissues
- Gamma rays coming to Earth are absorbed by our atmosphere before they reach the ground and thus can only be using using instruments in space
- Gamma radiation is generated deep in the interior of stars, as well as by the death of stars and the merging of later stage stars, such as neutron stars



(credit: modification of work by STScI/JHU/NASA)

X-Rays

- Wavelengths ~ between 0.01 nanometer and 20 nanometers (1 nanometer = 10^{-9} meters)
- Allow us to penetrate soft tissues but not bones, and so allow us to make images of the shadows of the bones inside us
- From space, they are stopped by the large number of atoms in Earth's atmosphere with which they interact
- X-rays are used to study exploding stars (supernova) and the Sun's corona (the outermost part of its atmosphere)



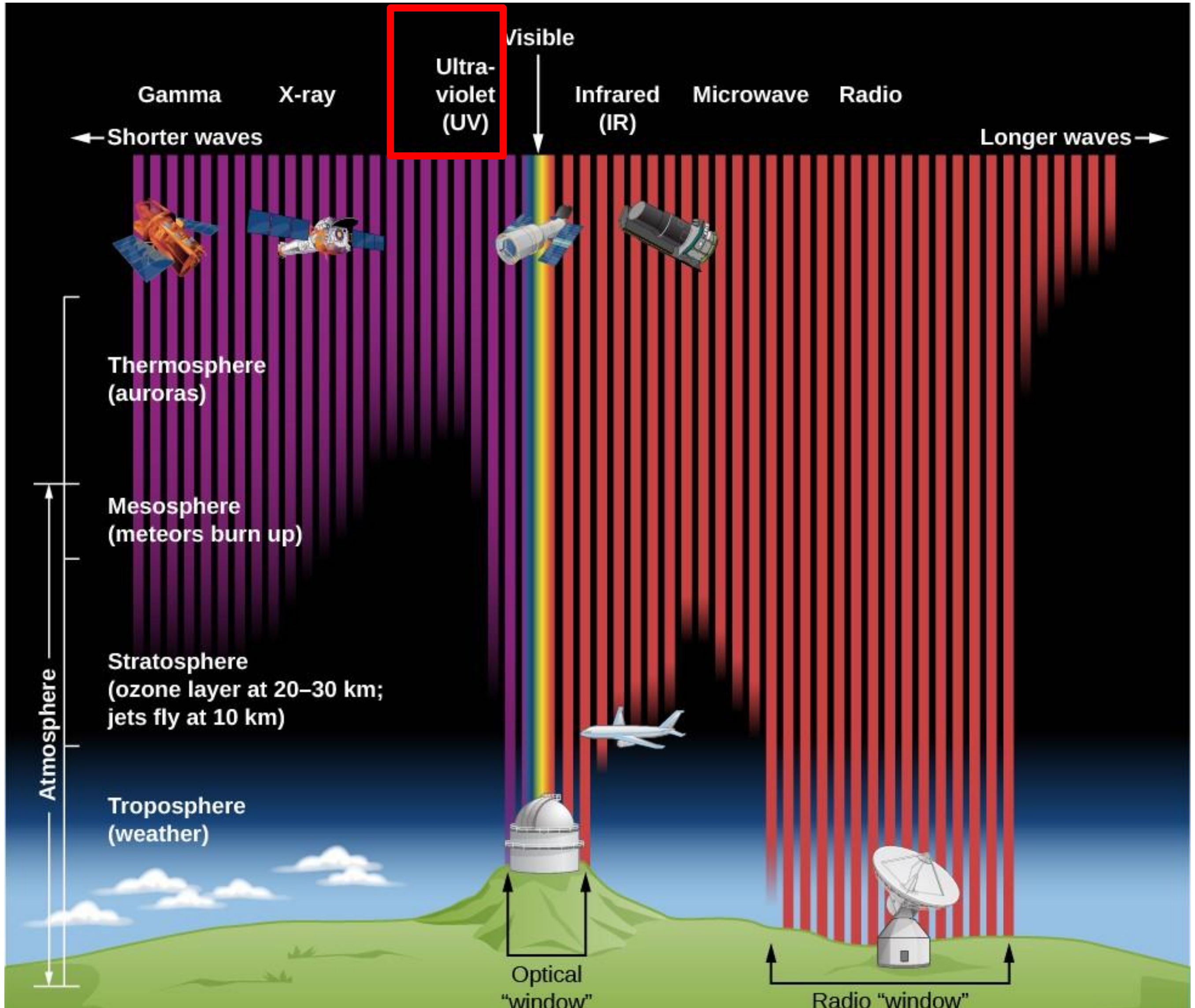
(credit: modification of work by STScI/JHU/NASA)

Ultraviolet Light

- Blocked by the ozone layer of Earth's atmosphere, but a small fraction of ultraviolet rays from the Sun do penetrate to cause sunburn, or, in extreme cases, skin cancer

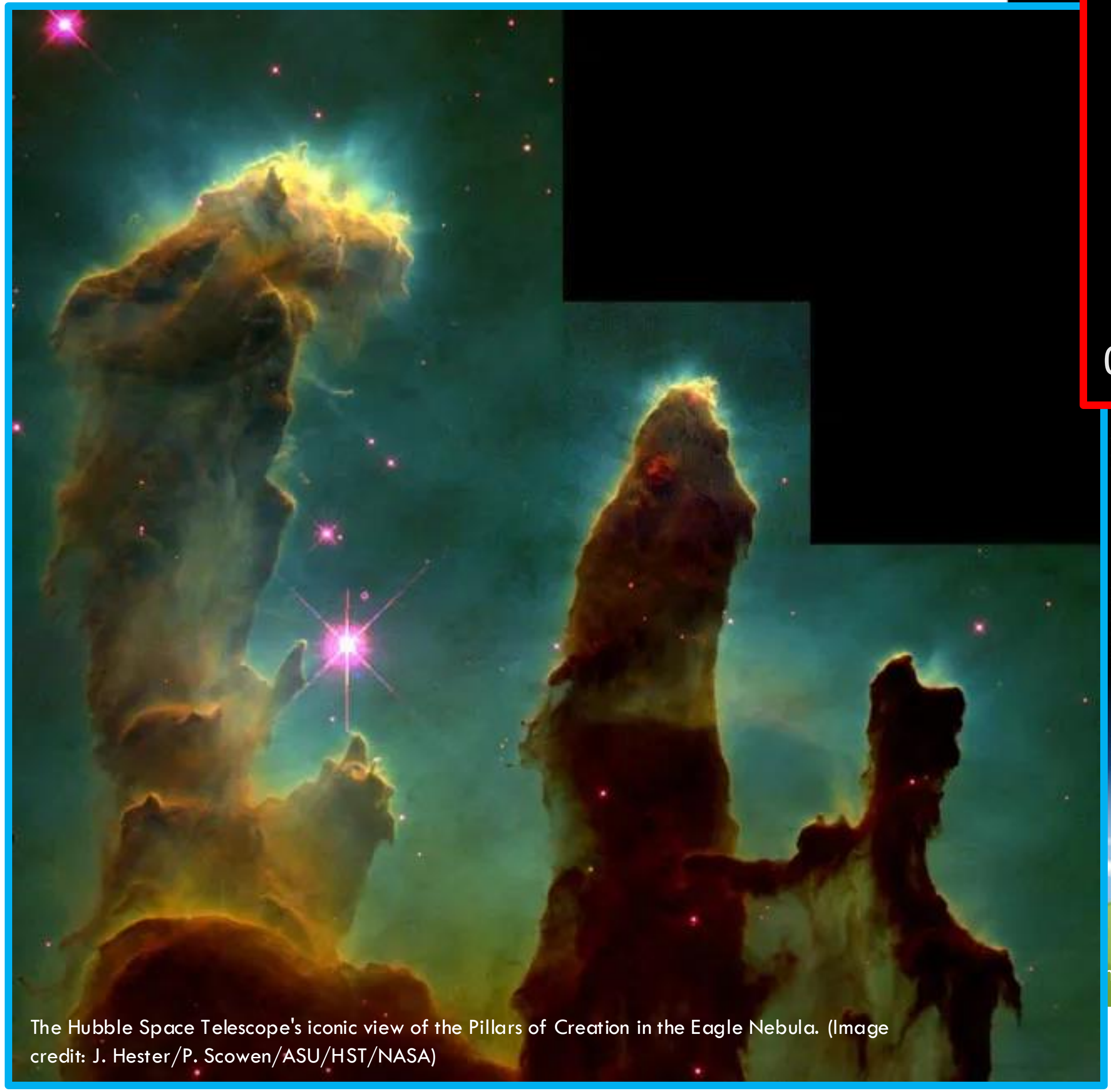
- Like Gamma and X-Rays, UV science is also best done in space

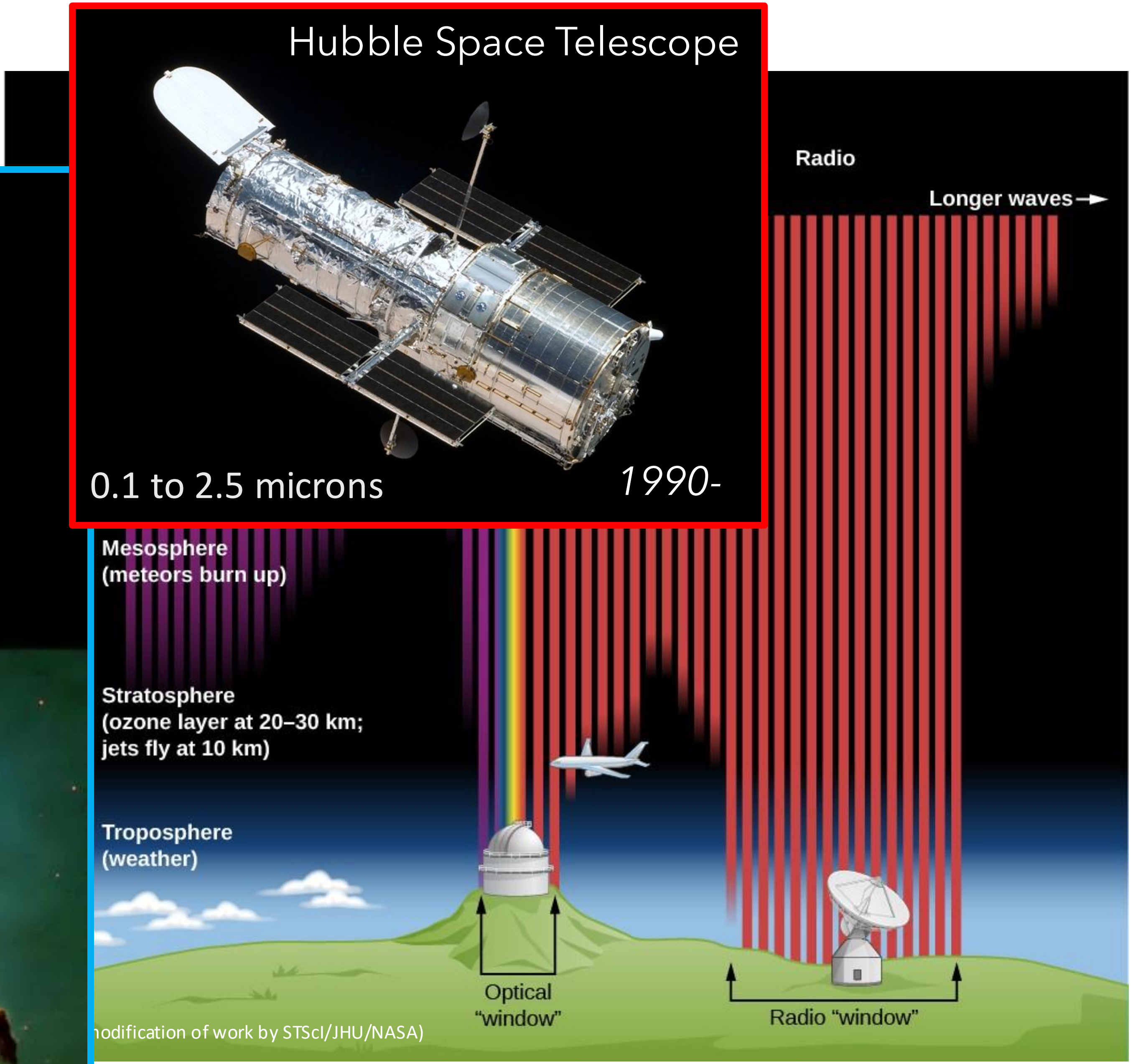
- The Hubble Space telescope can observe in the ultra-violet and visible parts of the spectrum from 0.1 to 0.8 microns (1 micron = 10^{-6} meters)



(credit: modification of work by STScI/JHU/NASA)

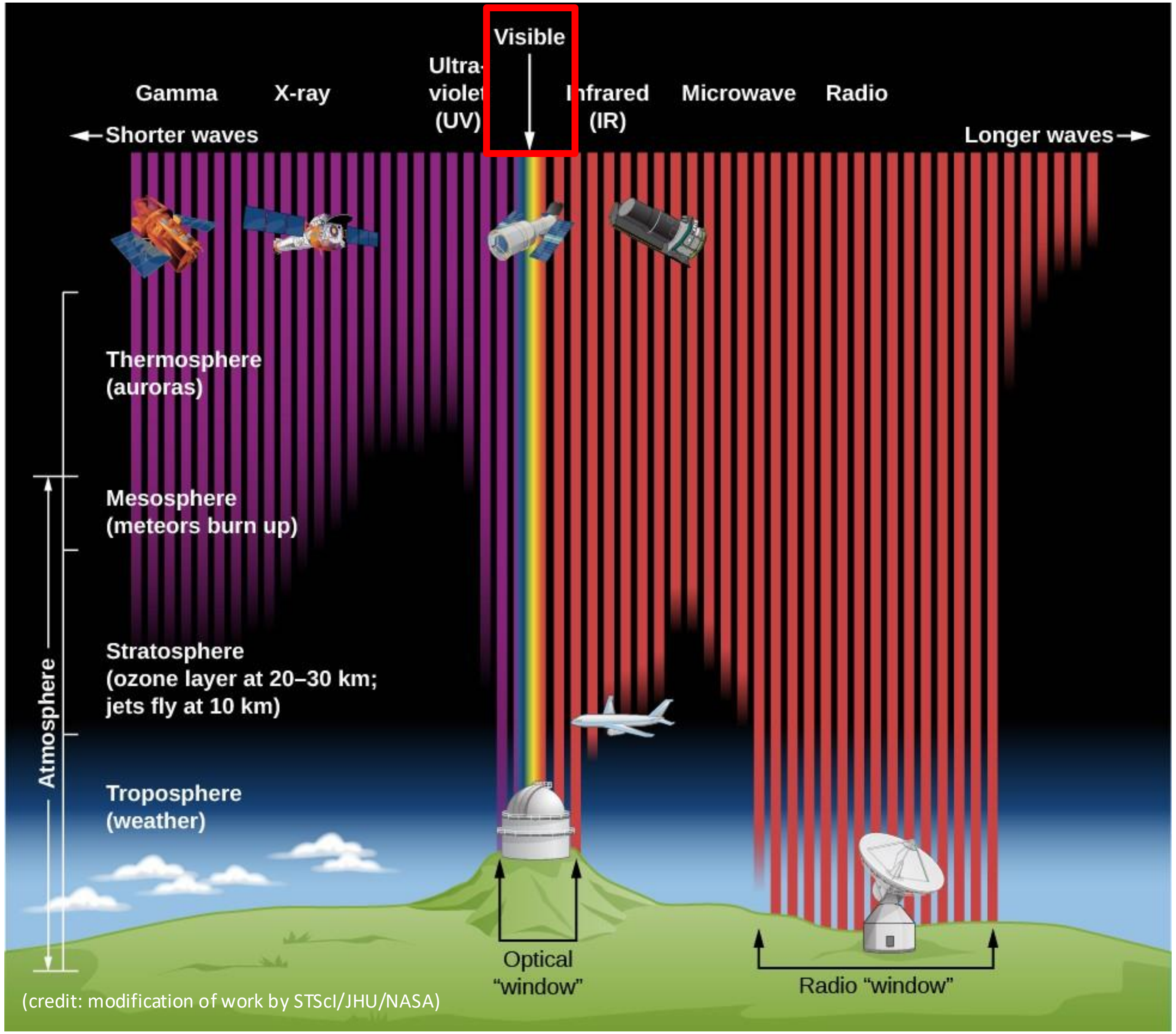
Ultraviolet Light


The Hubble Space Telescope's iconic view of the Pillars of Creation in the Eagle Nebula. (Image credit: J. Hester/P. Scowen/ASU/HST/NASA)



Visible Light

- Wavelengths between 400 and 700 nm
  (1 nanometer = 10^{-9} meters)
- This is the band that most readily reaches Earth's surface
- Human eyes have evolved to see the kinds of waves that arrive from the Sun most effectively
- The light that our eyes can see is only a tiny fraction of the broad range of waves generated in the universe!



(credit: modification of work by STScI/JHU/NASA)

Visible Light

Credit: Brett A. McGuire

Visible Light

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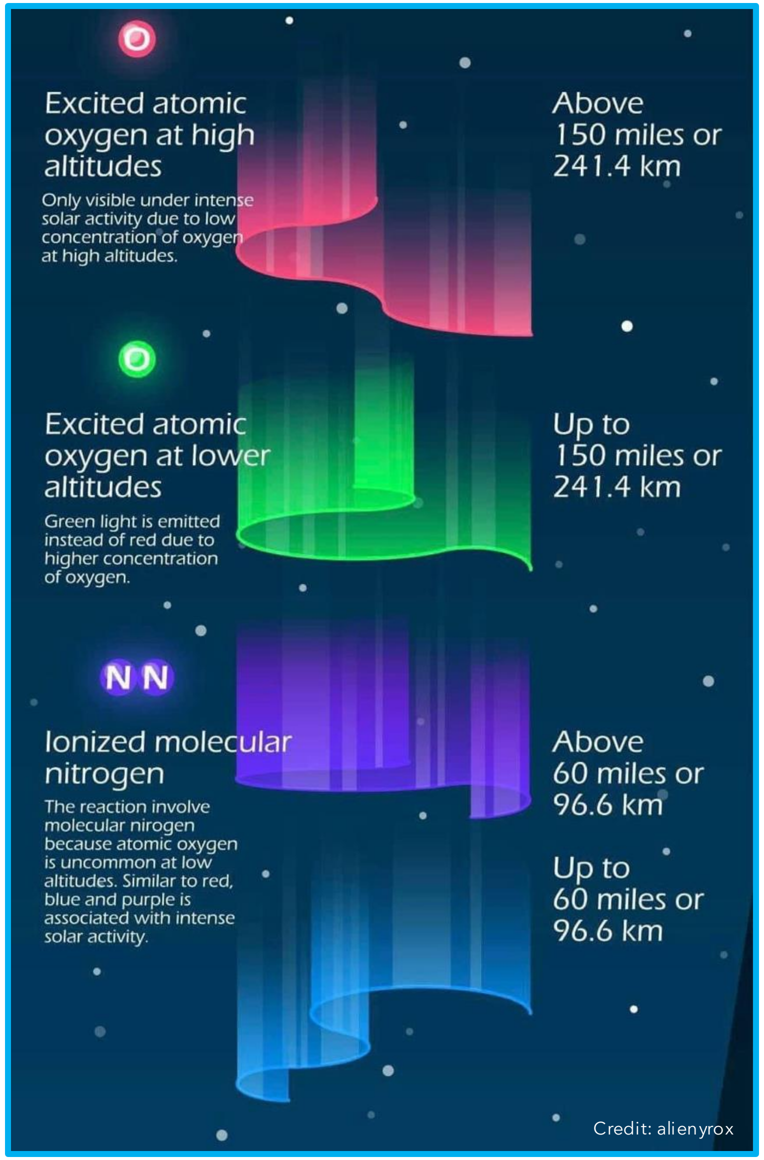
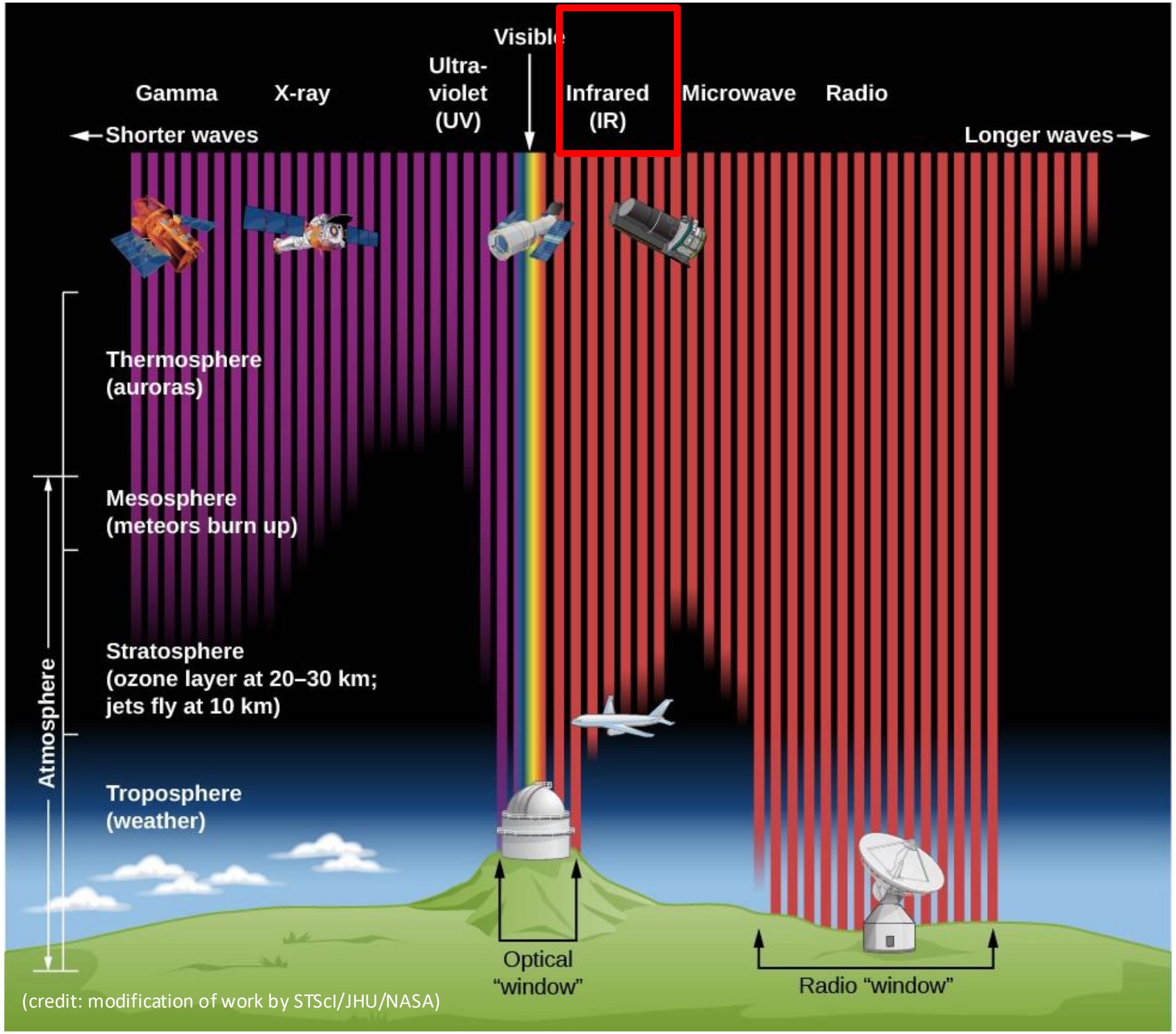


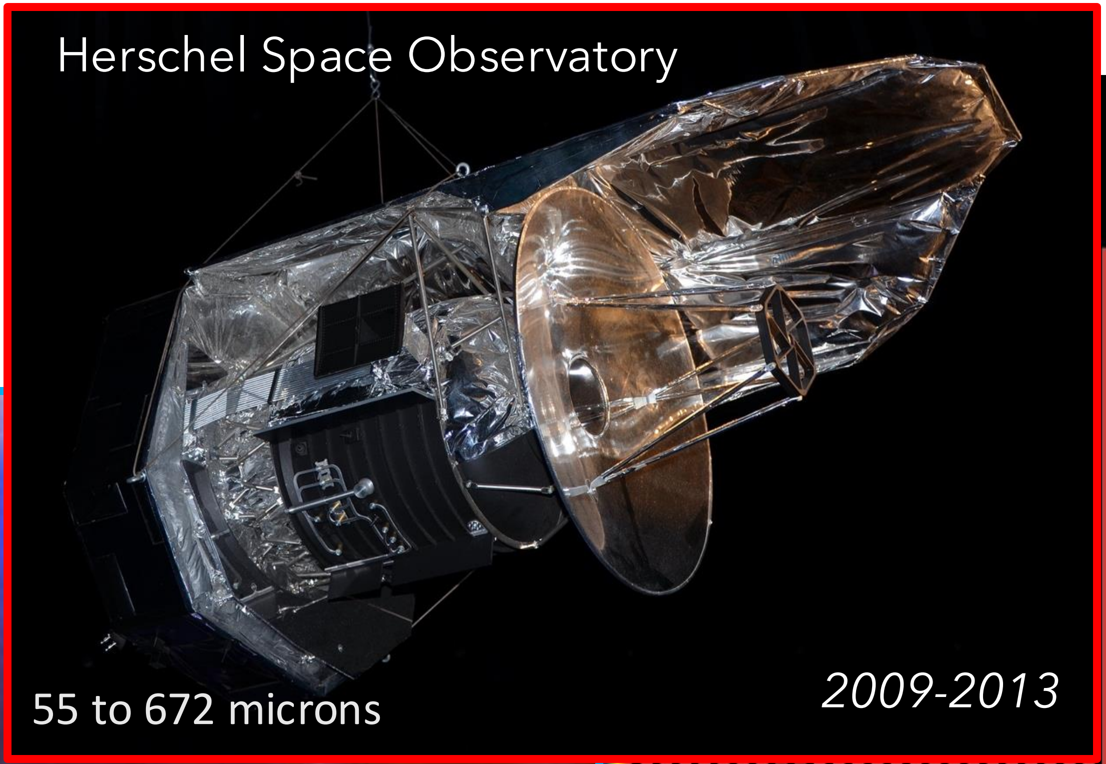
Infrared (IR) Light

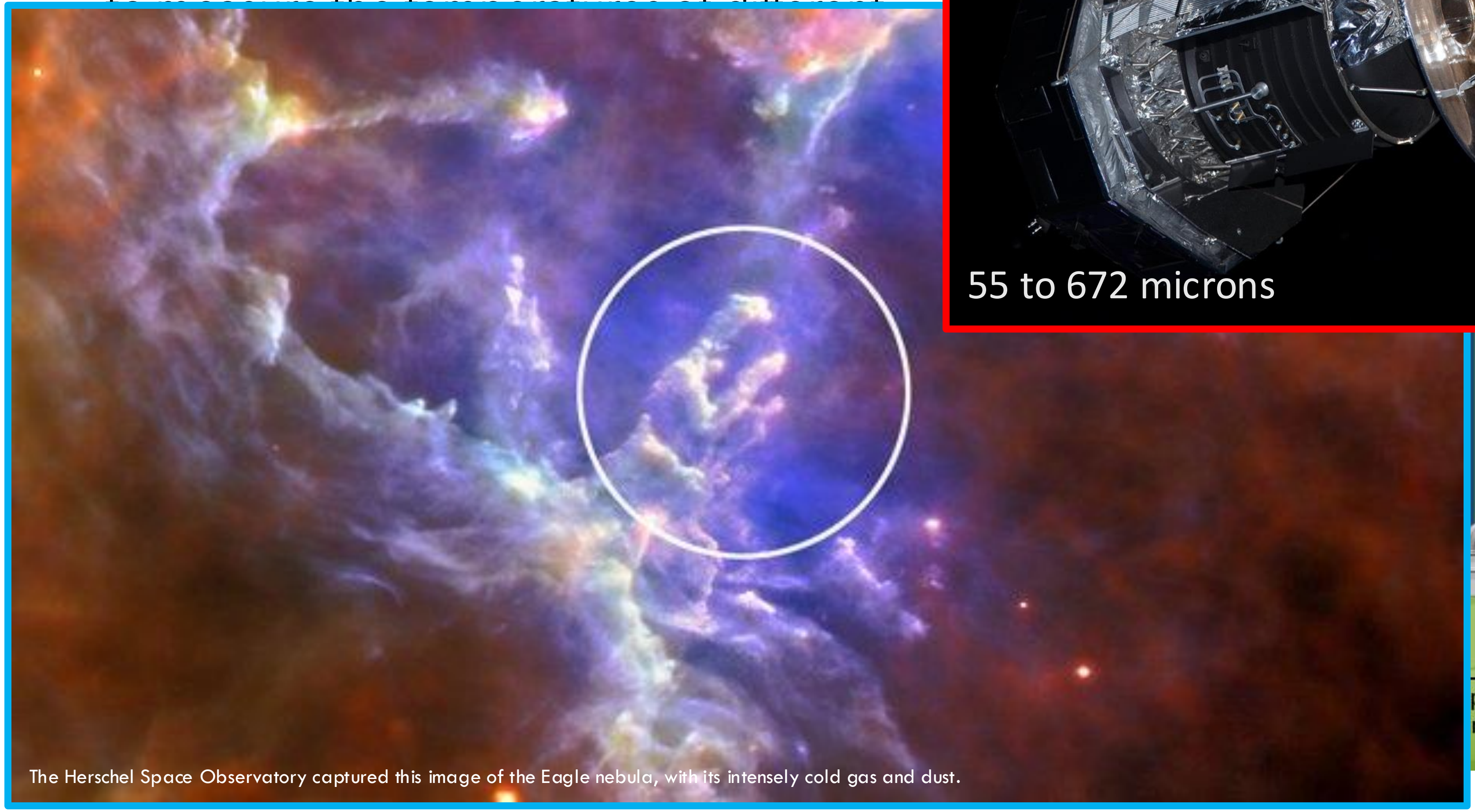
- Astronomer William Herschel first discovered infrared in 1800 while trying to measure the temperatures of different colors of sunlight spread out into a spectrum
  - He noticed when we positioned his thermometer beyond the reddest color, it still registered heating!
- Heat lamps radiate mostly infrared radiation and the nerve endings in our skin are sensitive to this band
- IR waves are absorbed by water and carbon dioxide (CO_2) in our atmosphere and must be observed at high mountaintops, spacecrafts (Herschel, JWST!) or high-flying airplanes (SOFIA)!



Infrared (IR) Light

- Astronomer William Herschel first discovered infrared in 1800 while trying

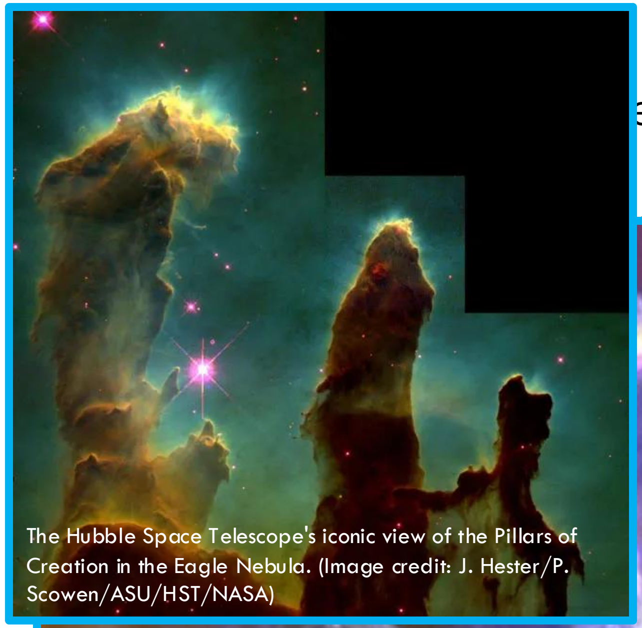




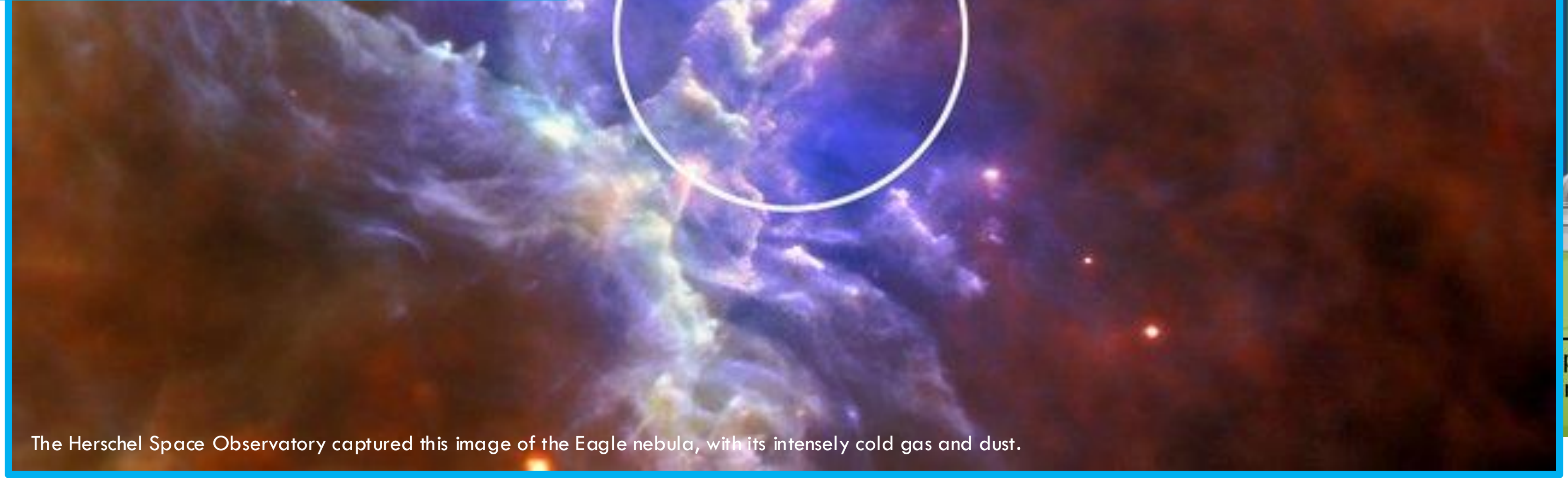
The Herschel Space Observatory captured this image of the Eagle nebula, with its intensely cold gas and dust.

Infrared (IR) Light

erschel first
1800 while trying



The Hubble Space Telescope's iconic view of the Pillars of Creation in the Eagle Nebula. (Image credit: J. Hester/P. Scowen/ASU/HST/NASA)



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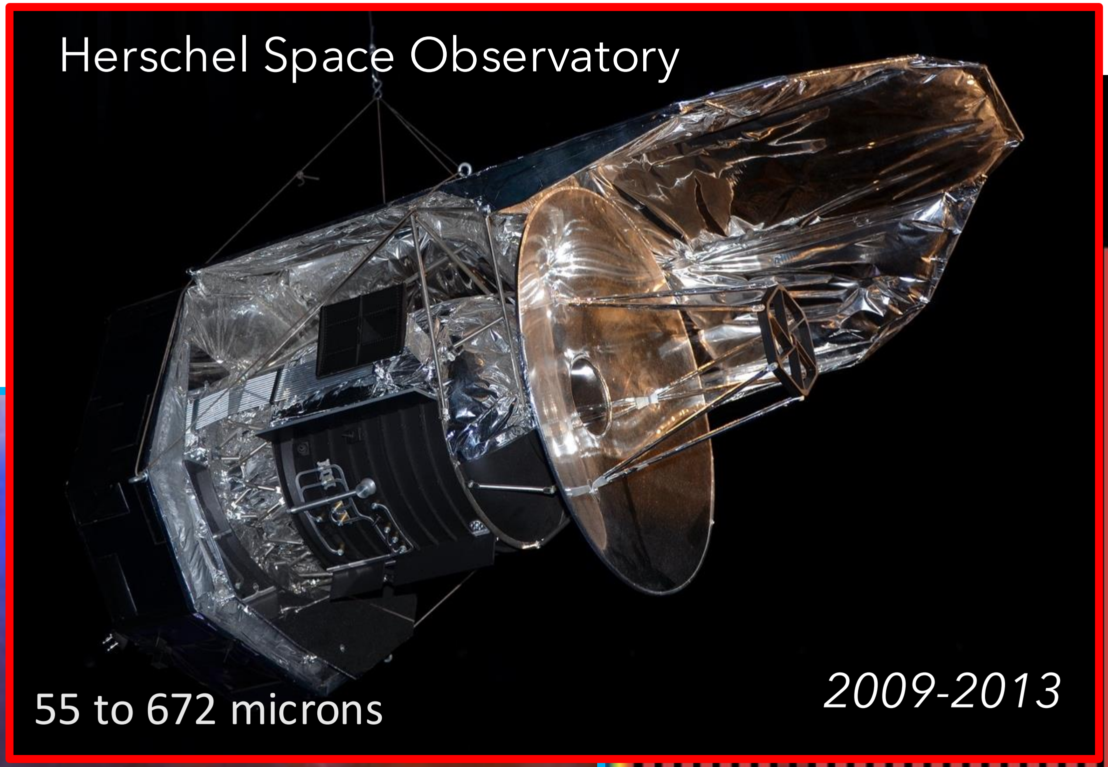
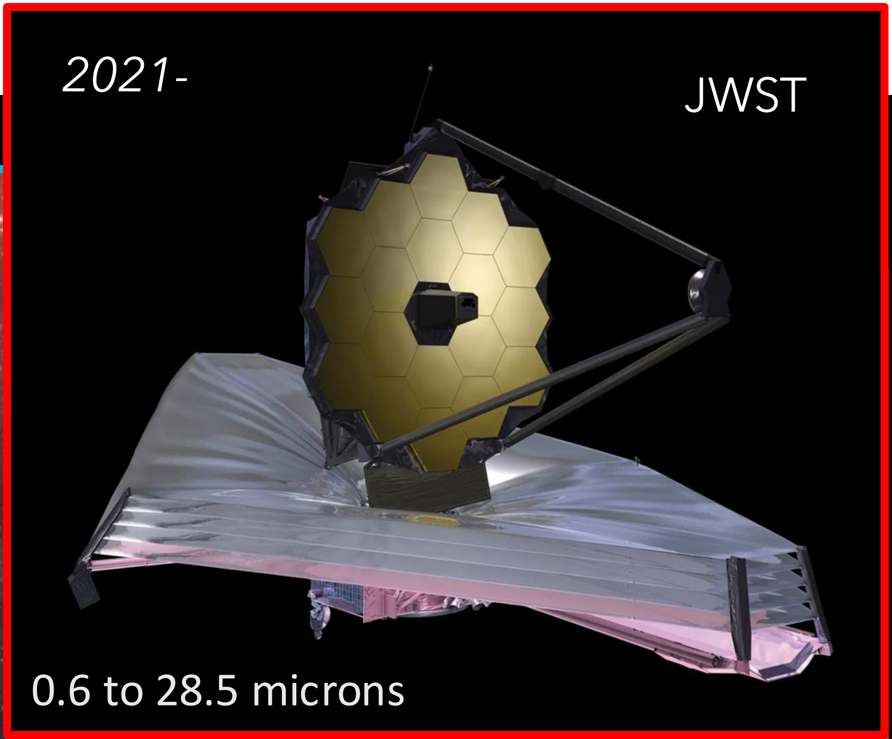
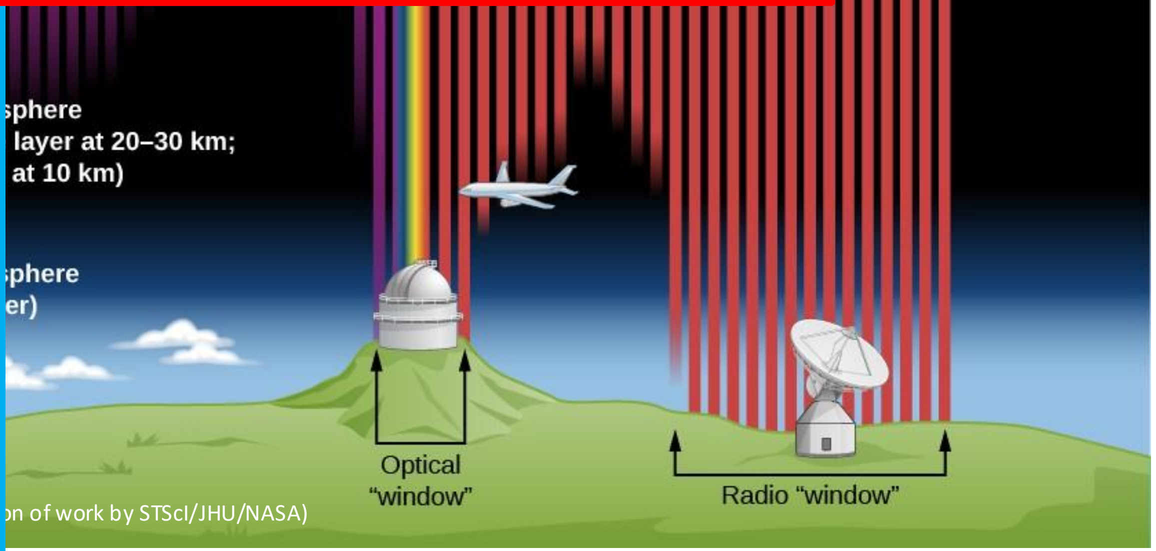
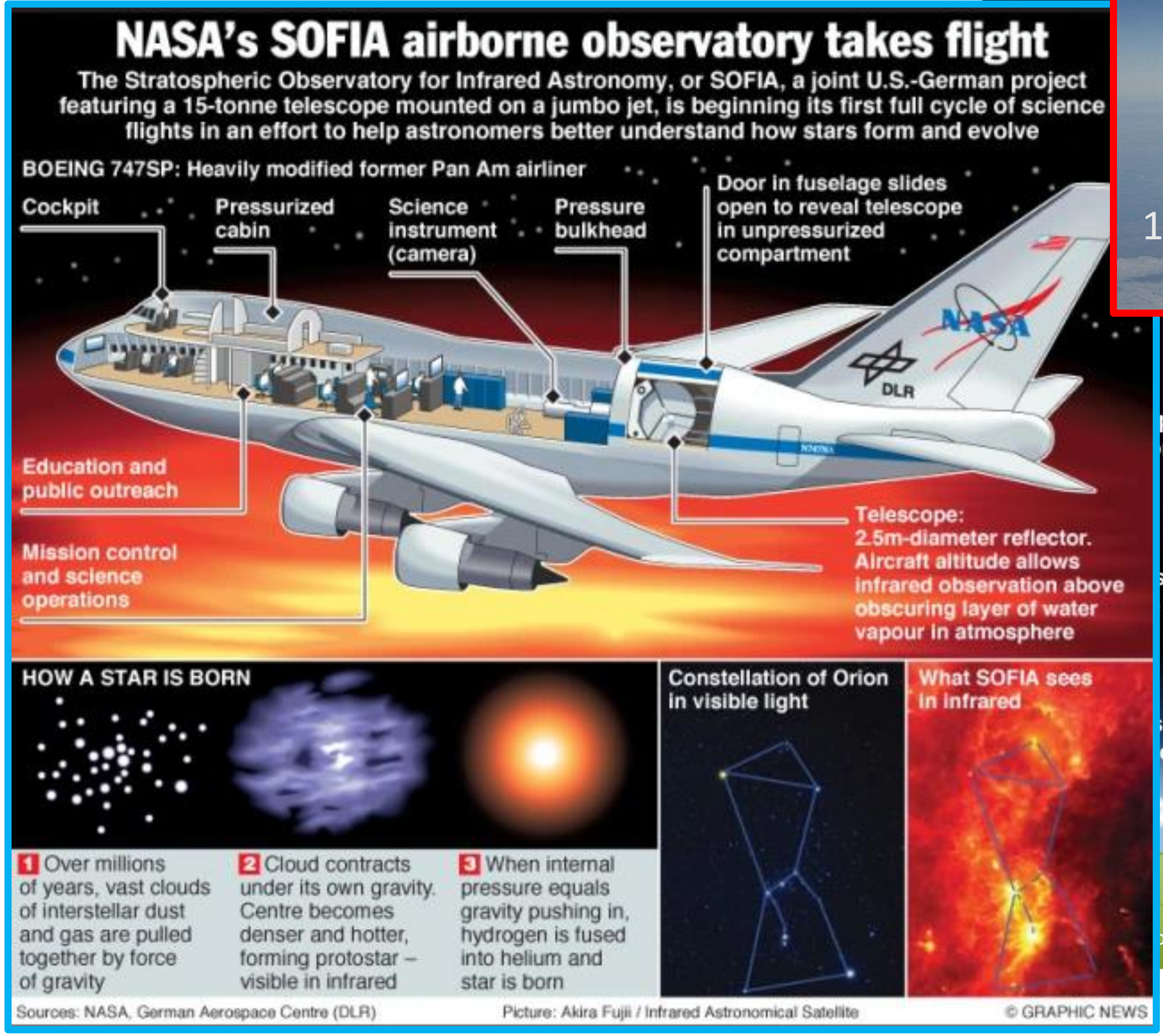


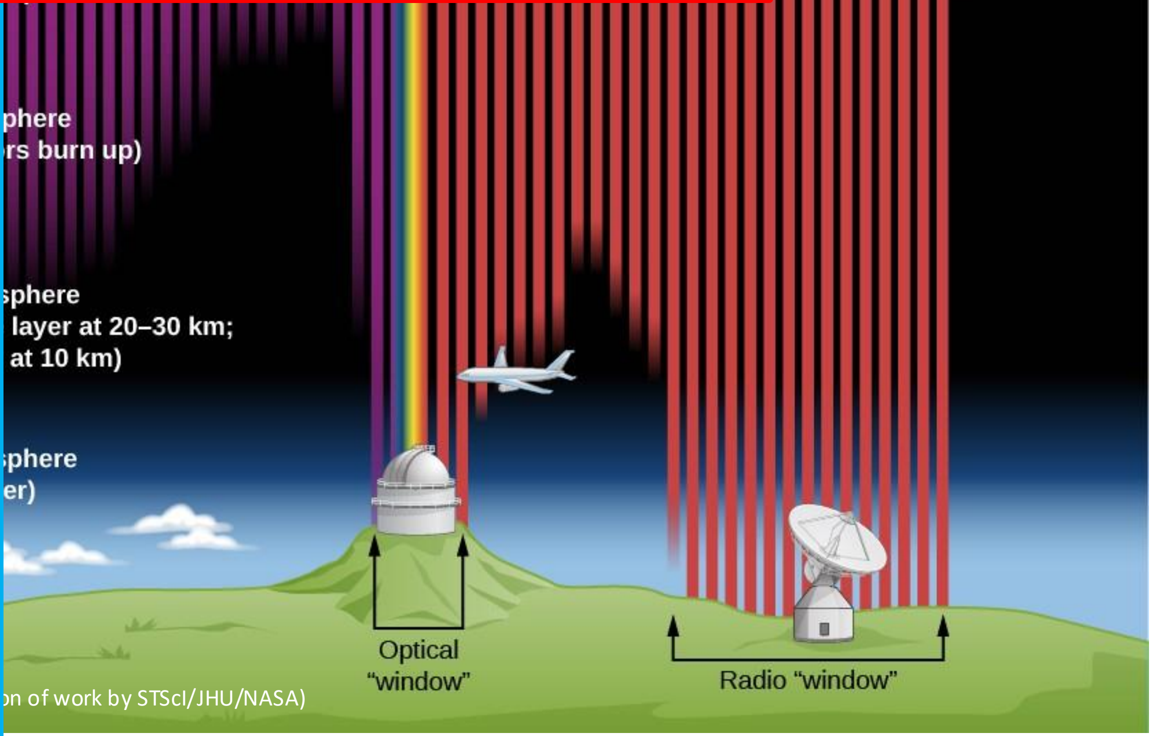
Infrared (IR) Light

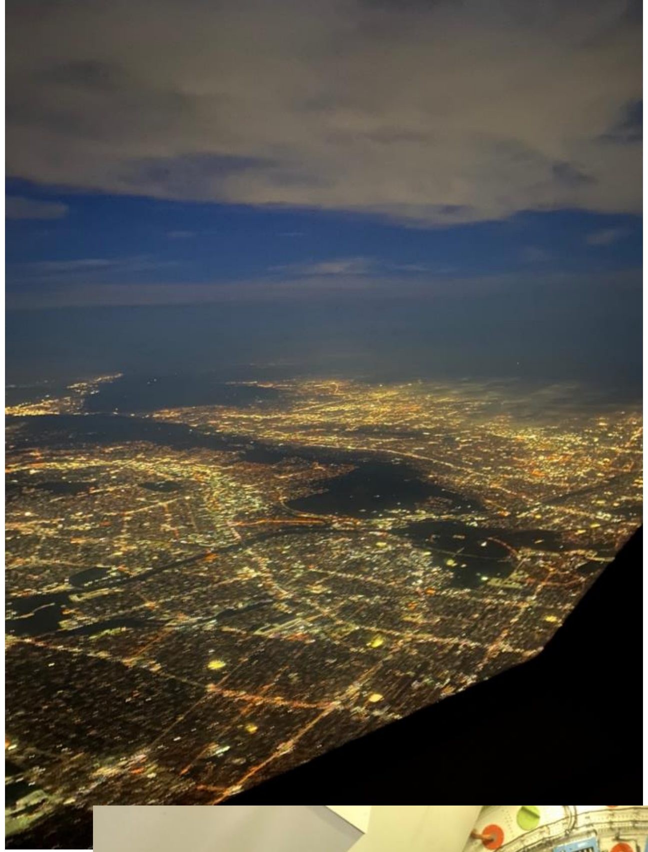


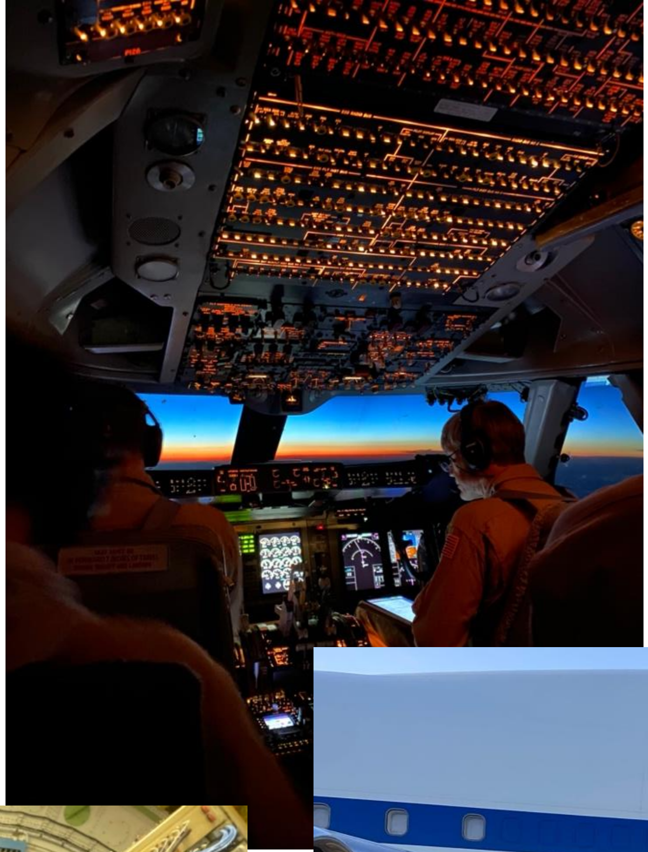


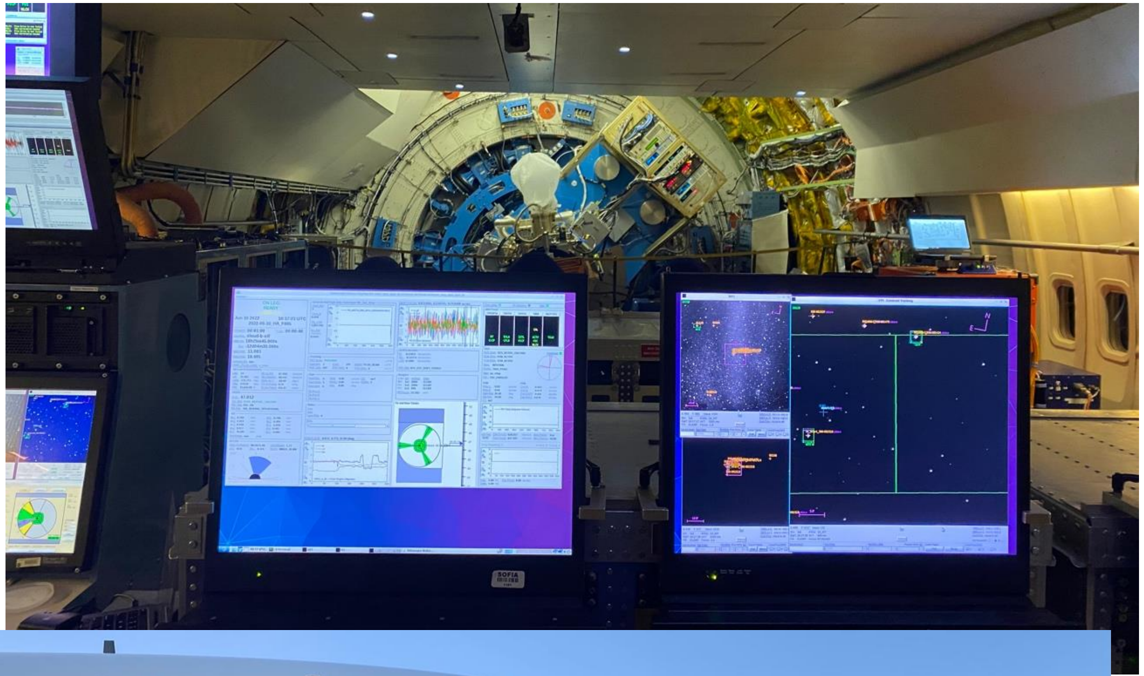
Infrared (IR) Light

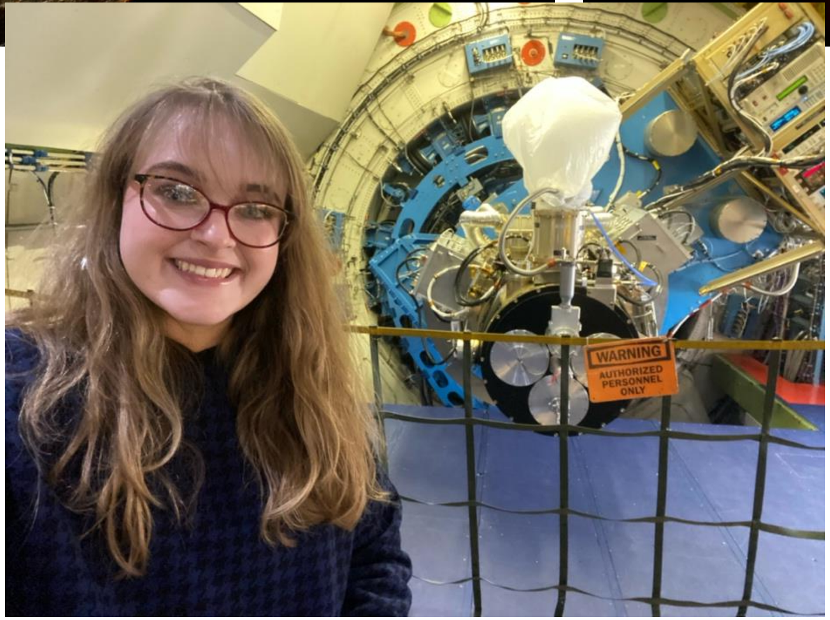








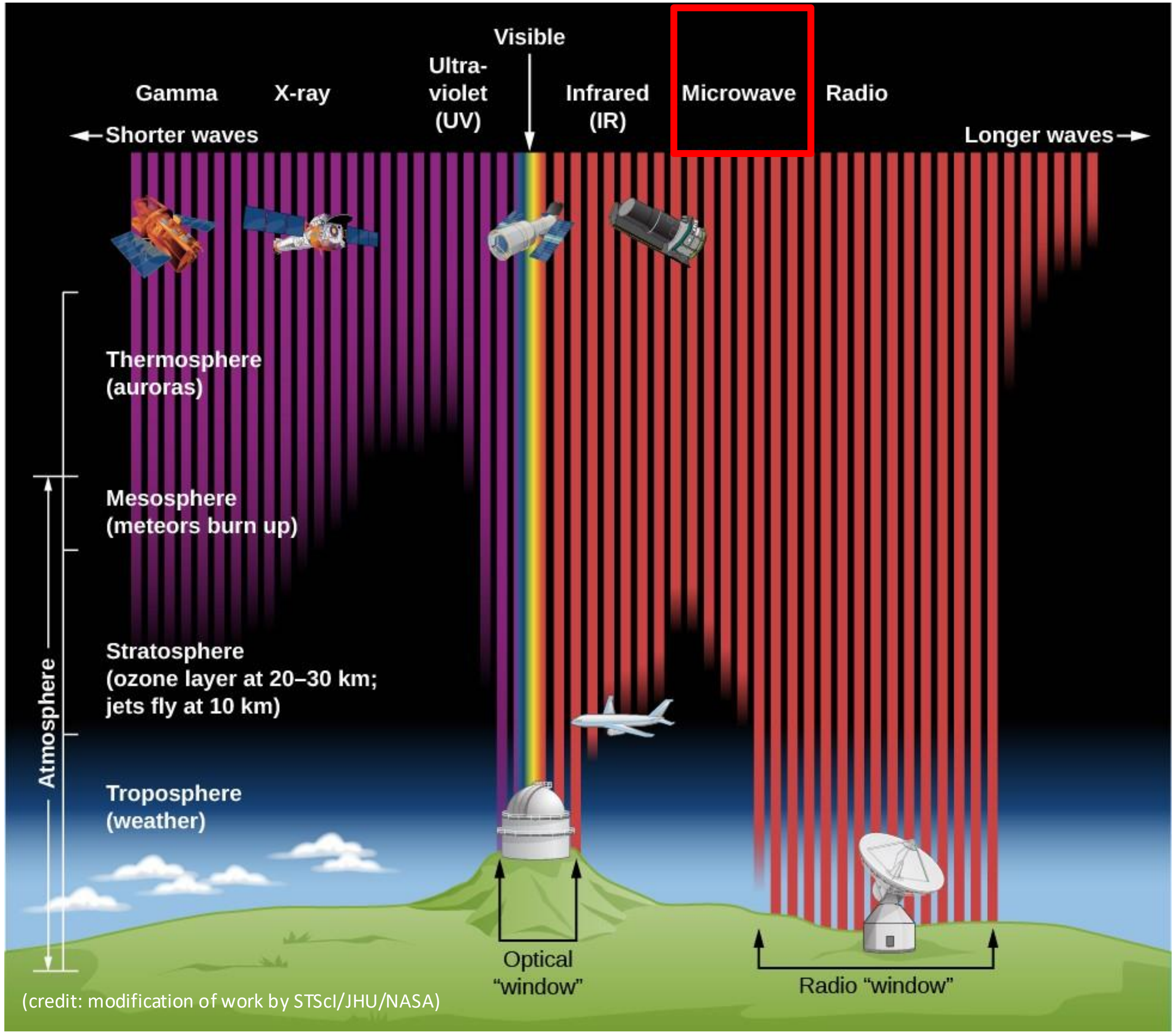



WARNING
AUTHORIZED PERSONNEL ONLY


SOFIA
STRATOSPHERIC OBSERVATORY FOR INFRARED ASTRONOMY

Microwaves*
(Millimeter Radio Waves)

- Wavelengths between ~1mm to 1m
- Used in short-wave communication and in microwave ovens
- Absorbed by water vapor (making them effective in heating foods!)
- The prefix 'micro-' refers to the fact that microwaves are small in comparison to longer radio waves
- *It is in this regime where many *rotational lines lie of **molecules** of interest to astrochemists!*



Microwaves*
(Millimeter Radio Waves)

- Wavelengths between ~1mm to 1m
- Used in short-wave communication and in microwave ovens
- Absorbed by water vapor (making them effective in heating foods!)
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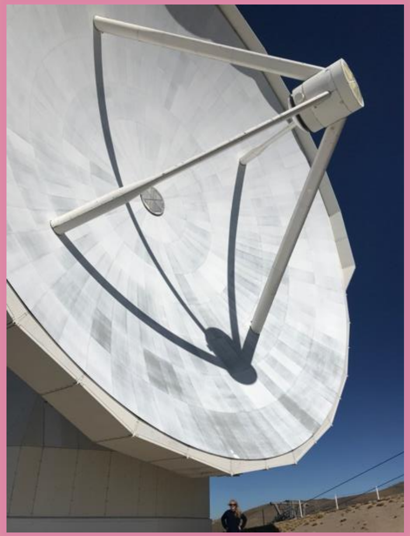
12m Radio Telescope, Kitt Peak, AZ

Control Room @ SMT, Mt. Graham, AZ



IRAM 30m Radio Telescope, Granada, Spain

Green Bank Radio Telescope, 100m, in West Virginia

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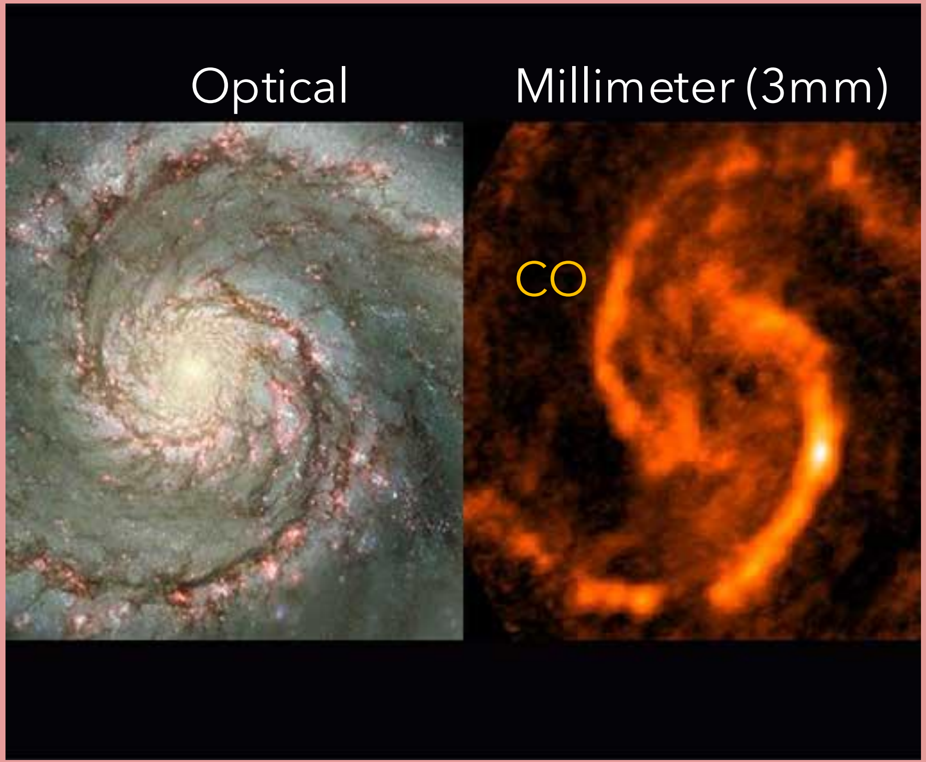
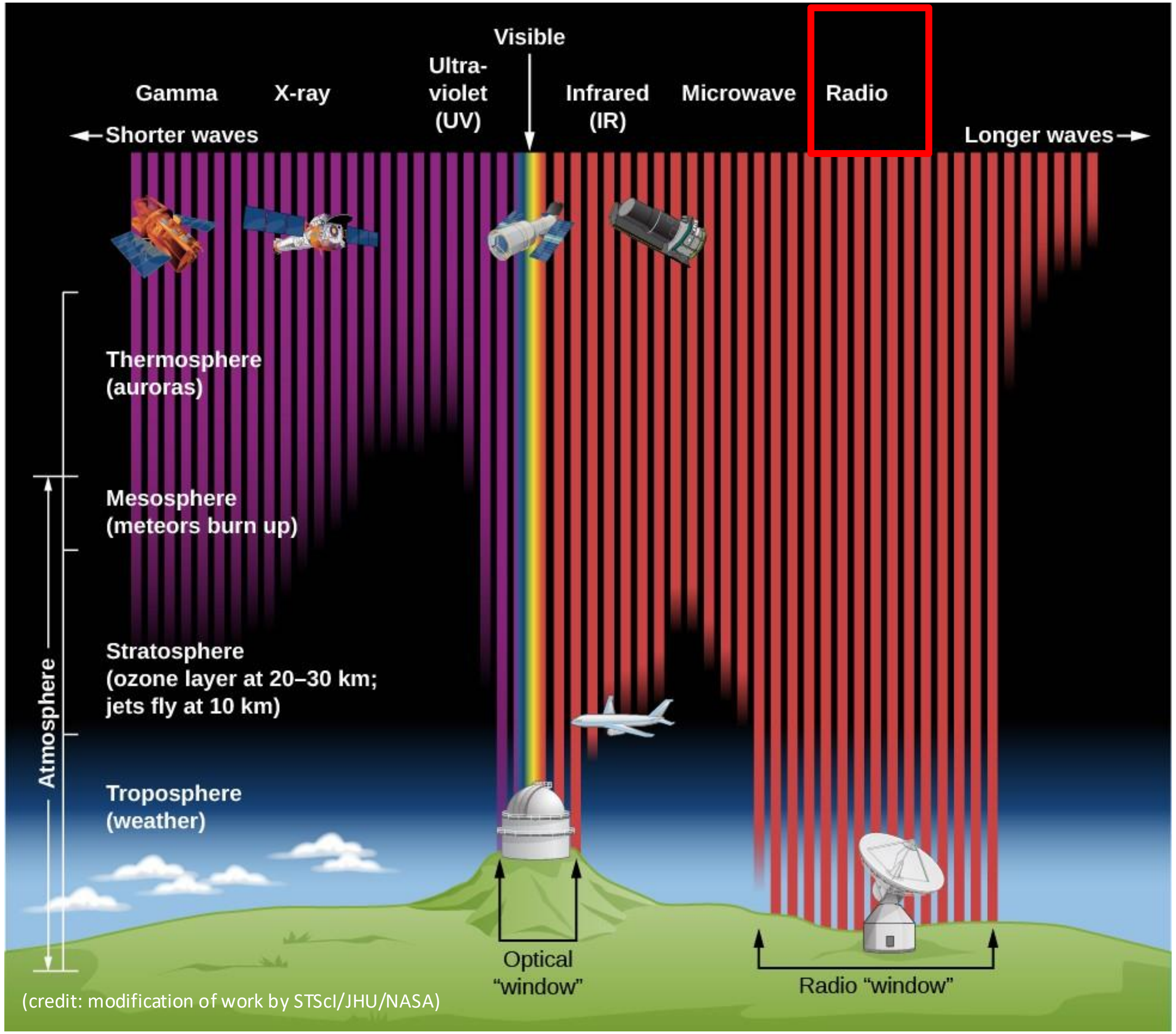


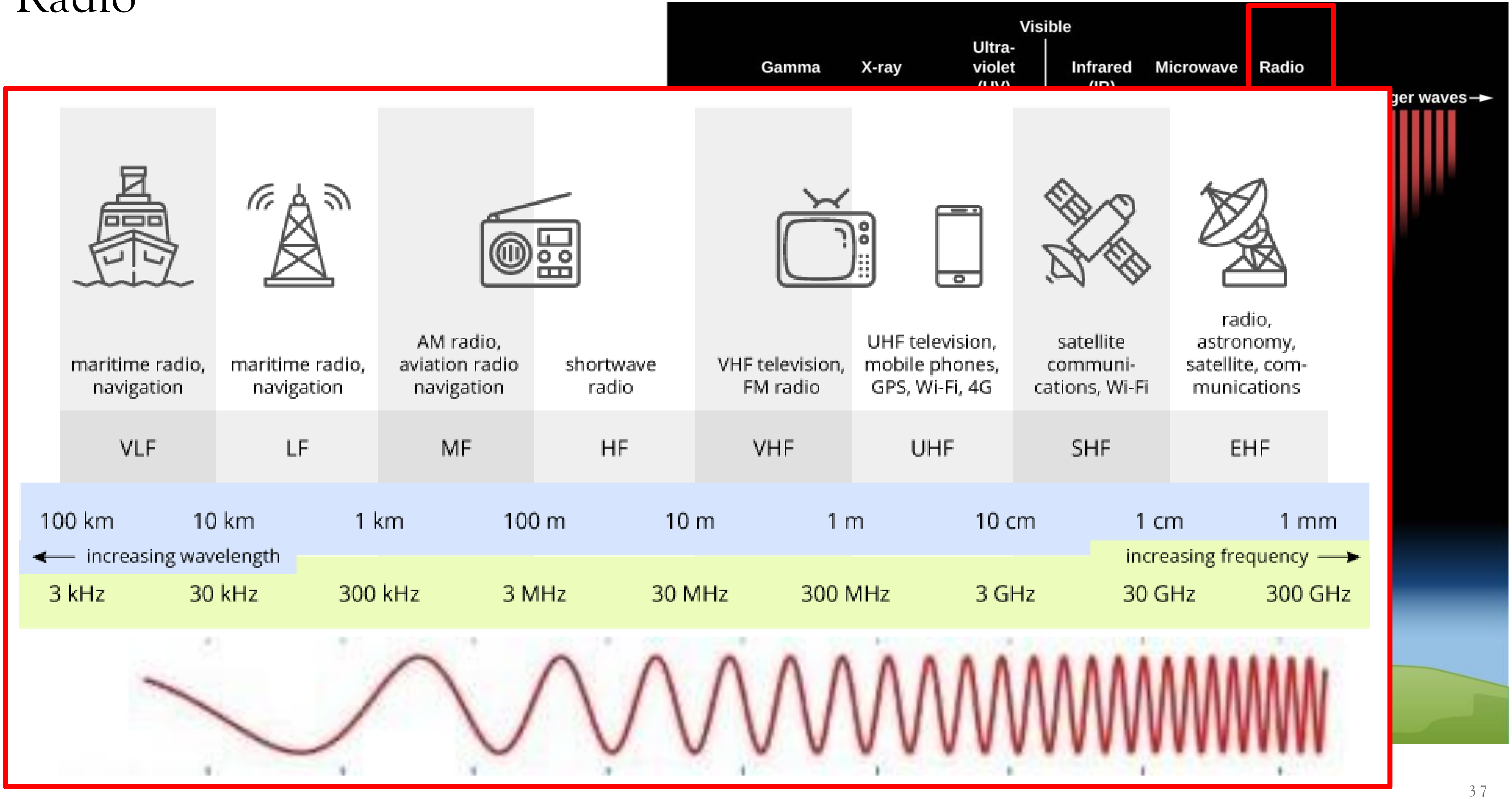
Radio

- All electromagnetic waves longer than microwaves are called radio waves
- E.g., radar waves are used in radar guns by traffic officers to determine vehicle speeds, and AM radio waves that were the first to be developed for broadcasting – range from over a meter to hundreds of meters!
- Note: not all radio waves interact with Earth's atmosphere in the same way! FM (88-108 MHz) and TV waves can travel easily through the atmosphere, but AM waves are absorbed or reflected by a layer in Earth's atmosphere called the ionosphere



(credit: modification of work by STScI/JHU/NASA)

Radio


Visible
Ultra-violet
Gamma
X-ray
Infrared
Microwave
Radio
maritime radio, navigation
maritime radio, navigation
AM radio, aviation radio navigation
shortwave radio
VHF television, FM radio
UHF television, mobile phones, GPS, Wi-Fi, 4G
satellite communi-cations, Wi-Fi
radio, astronomy, satellite, com-munications
VLF
LF
MF
HF
VHF
UHF
SHF
EHF
100 km
10 km
1 km
100 m
10 m
1 m
10 cm
1 cm
1 mm
increasing wavelength
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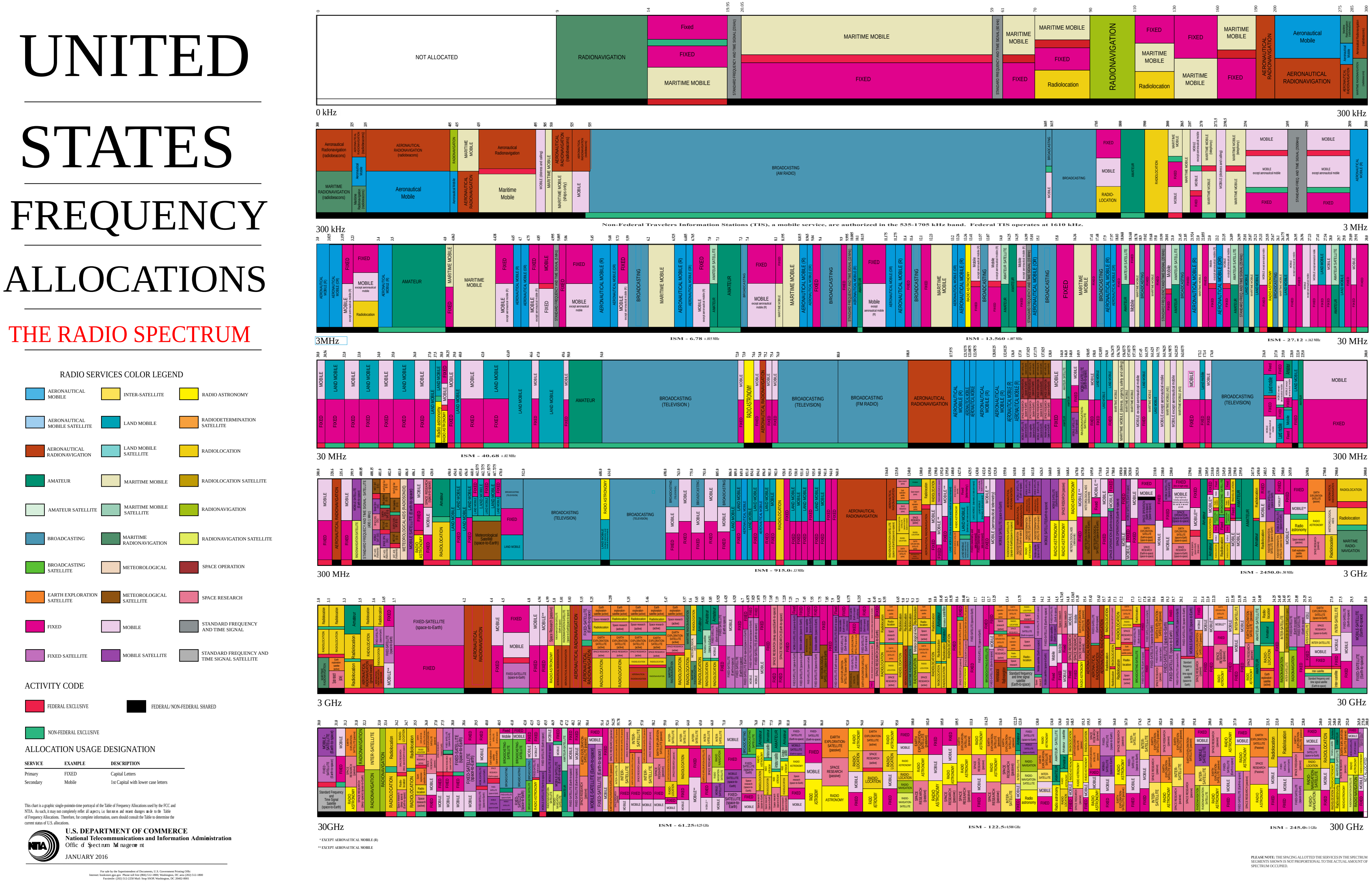
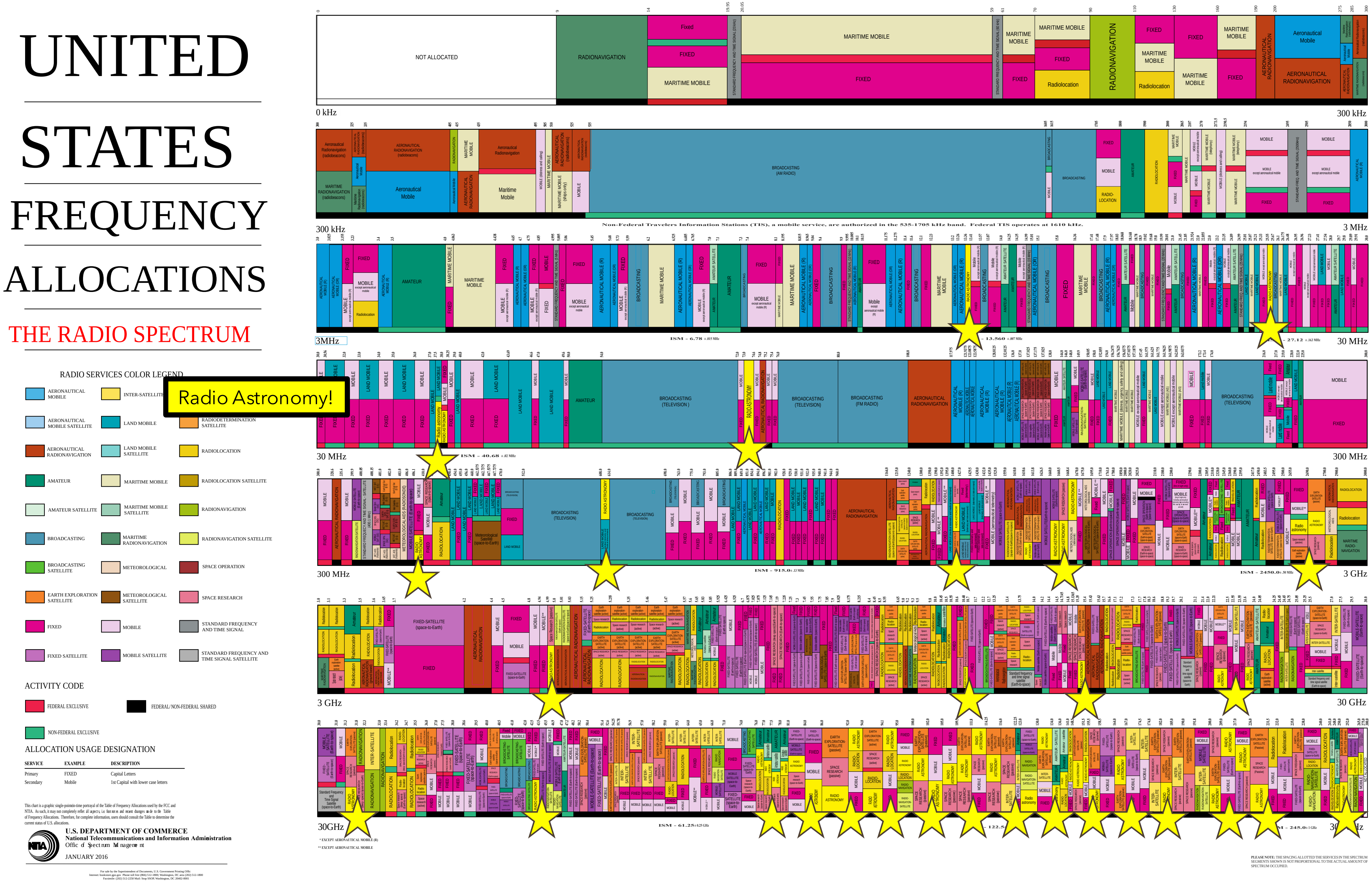


Lots of uses!
Overlapping allocations!

6kHz – 300 GHz

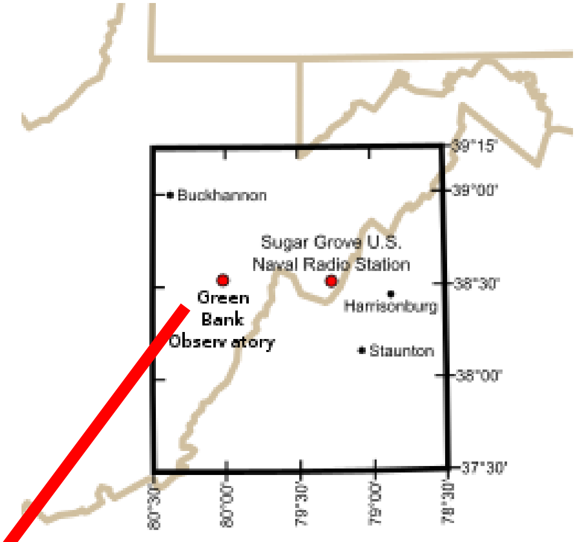


Lots of uses!
Overlapping allocations!

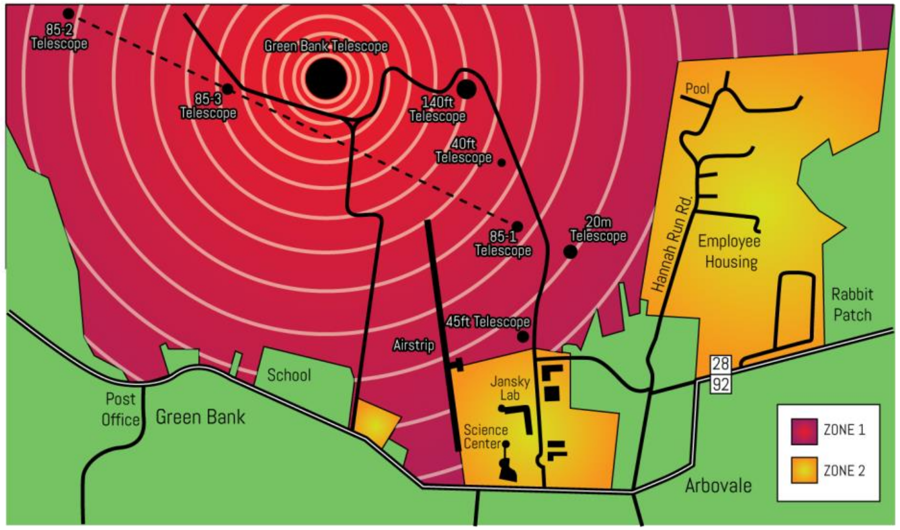
6kHz – 300 GHz

Radio

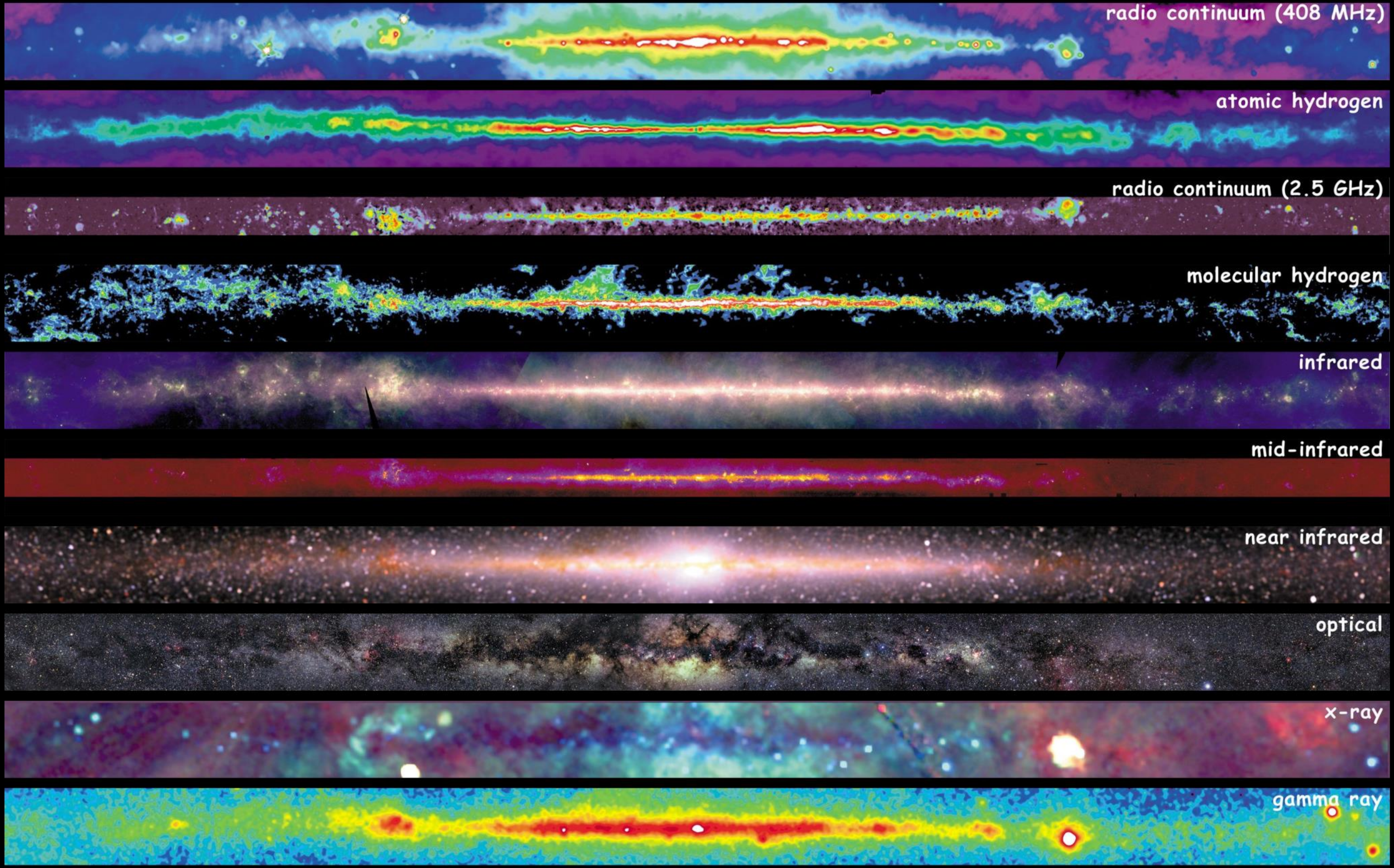
- The National Radio Quiet Zone (NRQZ) was set aside by the federal government to provide a geographical region to protect sensitive instrumentation from Radio Frequency Interference (RFI).
- The Federal Communications Commission (FCC) created the Quiet Zone in 1958 to protect the radio telescopes at Green Bank and Sugar Grove from harmful interference



Green Bank Radio Telescope, 100m, in West Virginia



The Milky Way at different wavelengths



Click images to select or deselect

Decreasing wavelength

Our Galaxy across the E&M Spectrum!

What determines the ***type*** of **electromagnetic radiation** emitted by astronomical objects?

A) Its size
B) Its temperature
C) Its distance
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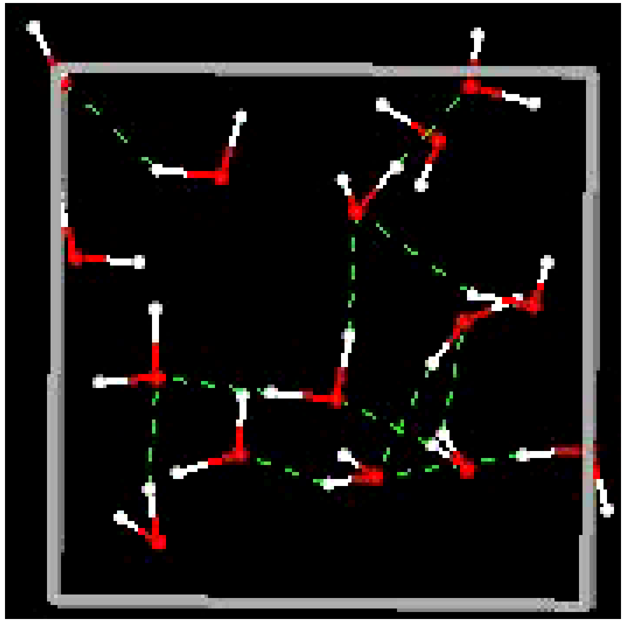
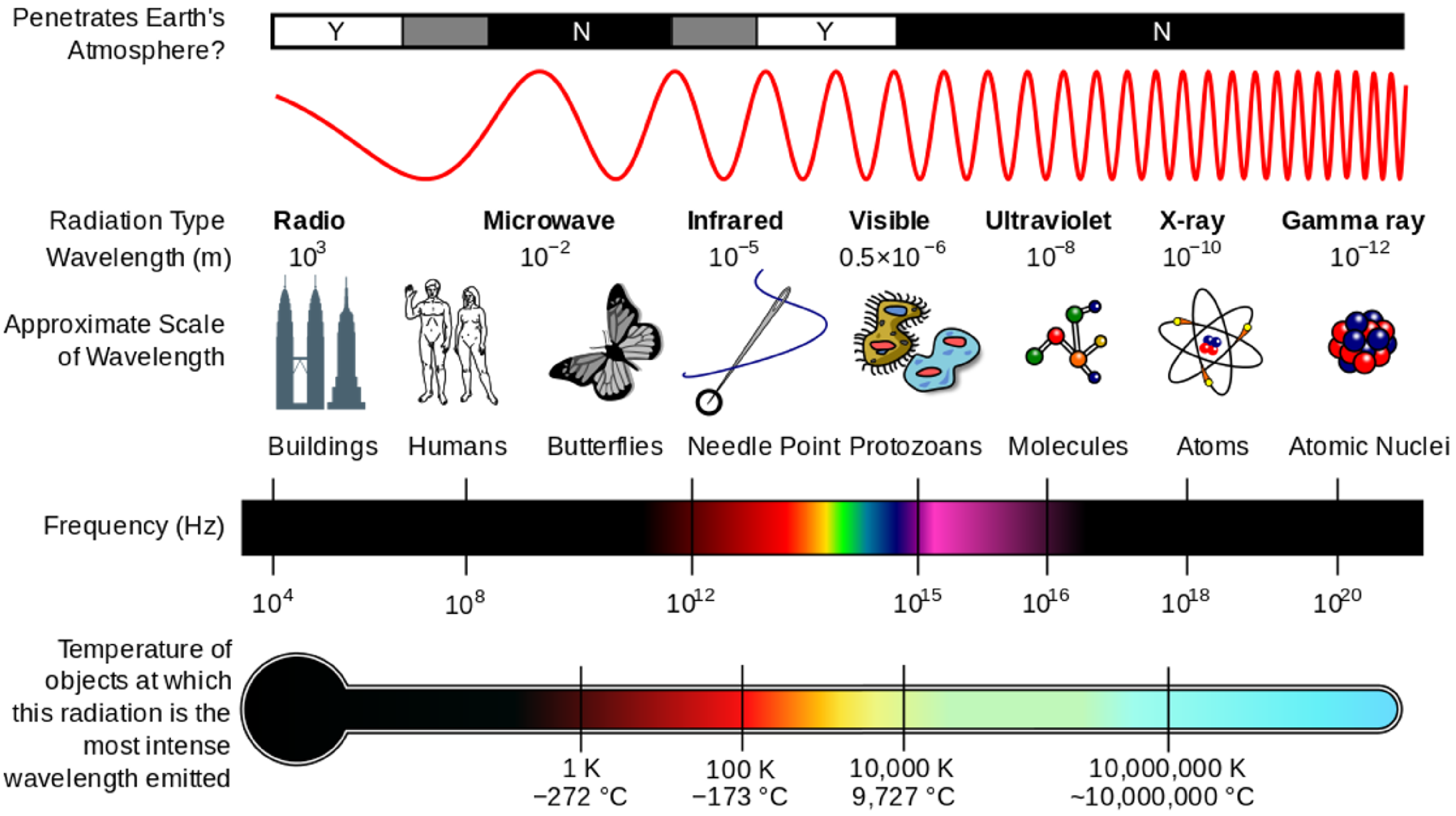


Temperature is a measure of the average energy of the stuff in a material

The Electromagnetic Spectrum

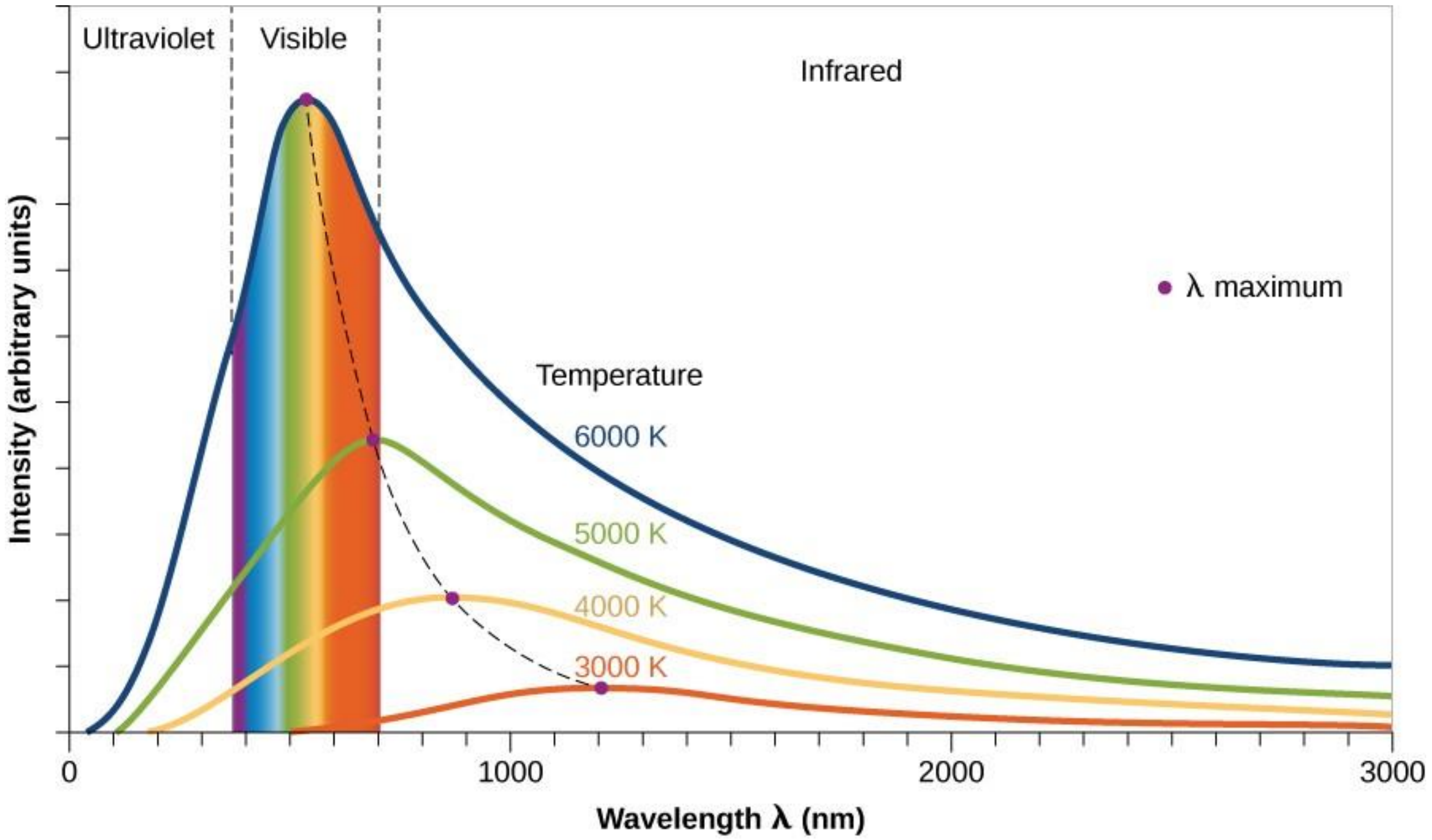


*1 K = - 457.87 °F, 10^6 K ~ 10^6 °F

Blackbody Radiation

Definition: An object that absorbs all radiation falling on it, at all wavelengths, is called a blackbody

When a blackbody is at a uniform temperature, its emission has a **characteristic frequency distribution** that depends on the **temperature**



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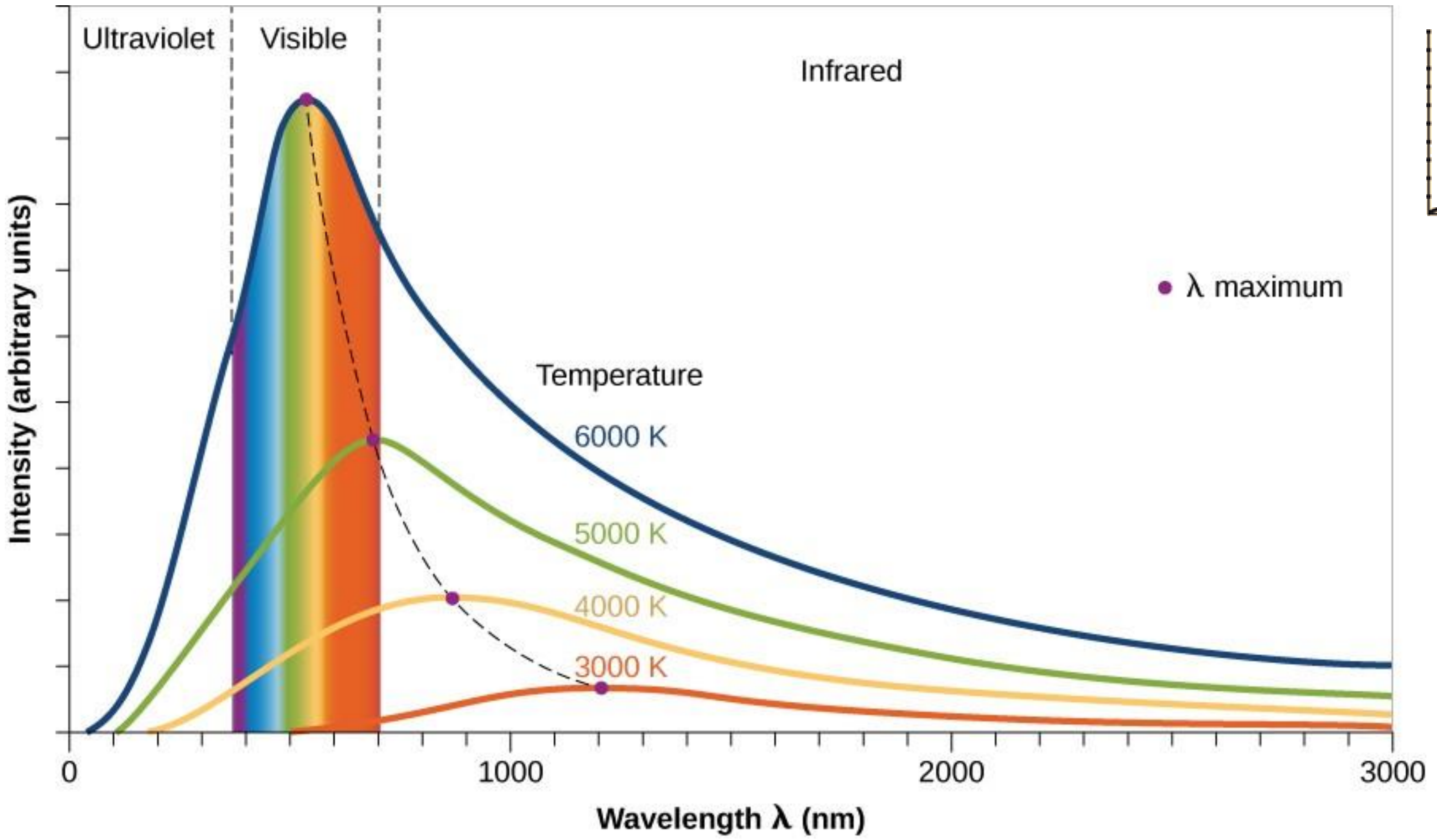

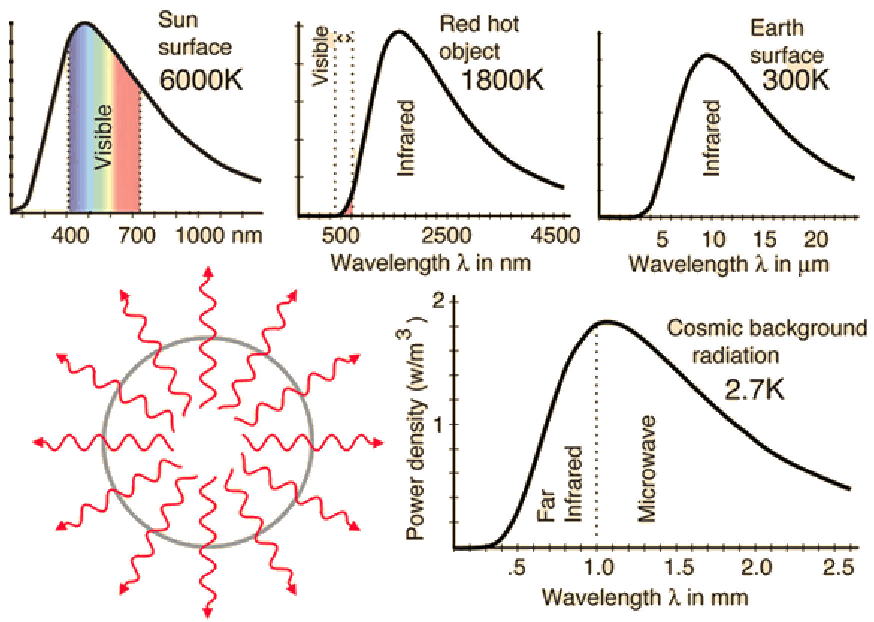

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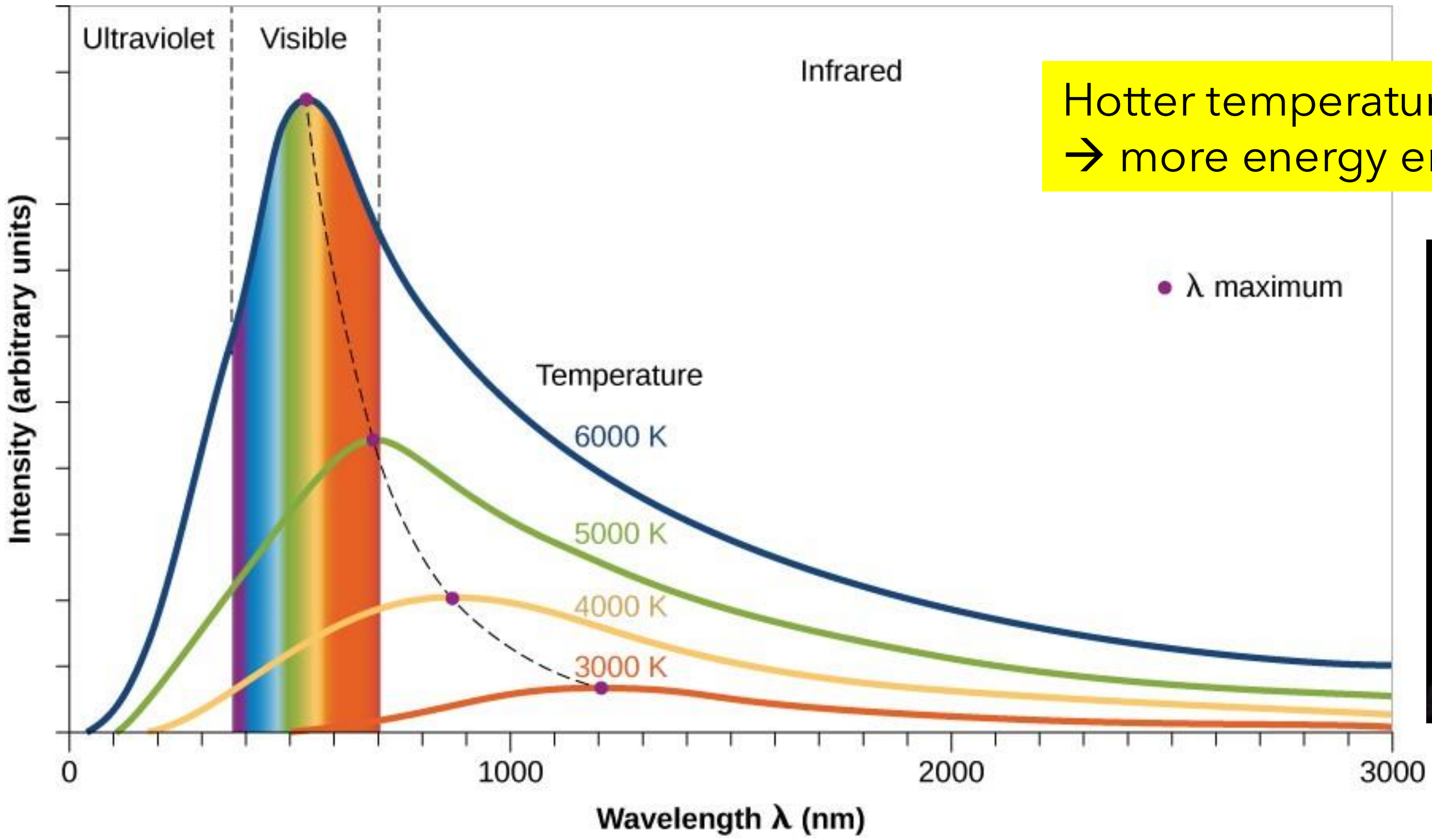

Hotter temperature → peaks at shorter wavelengths
→ more energy emitted at all wavelengths

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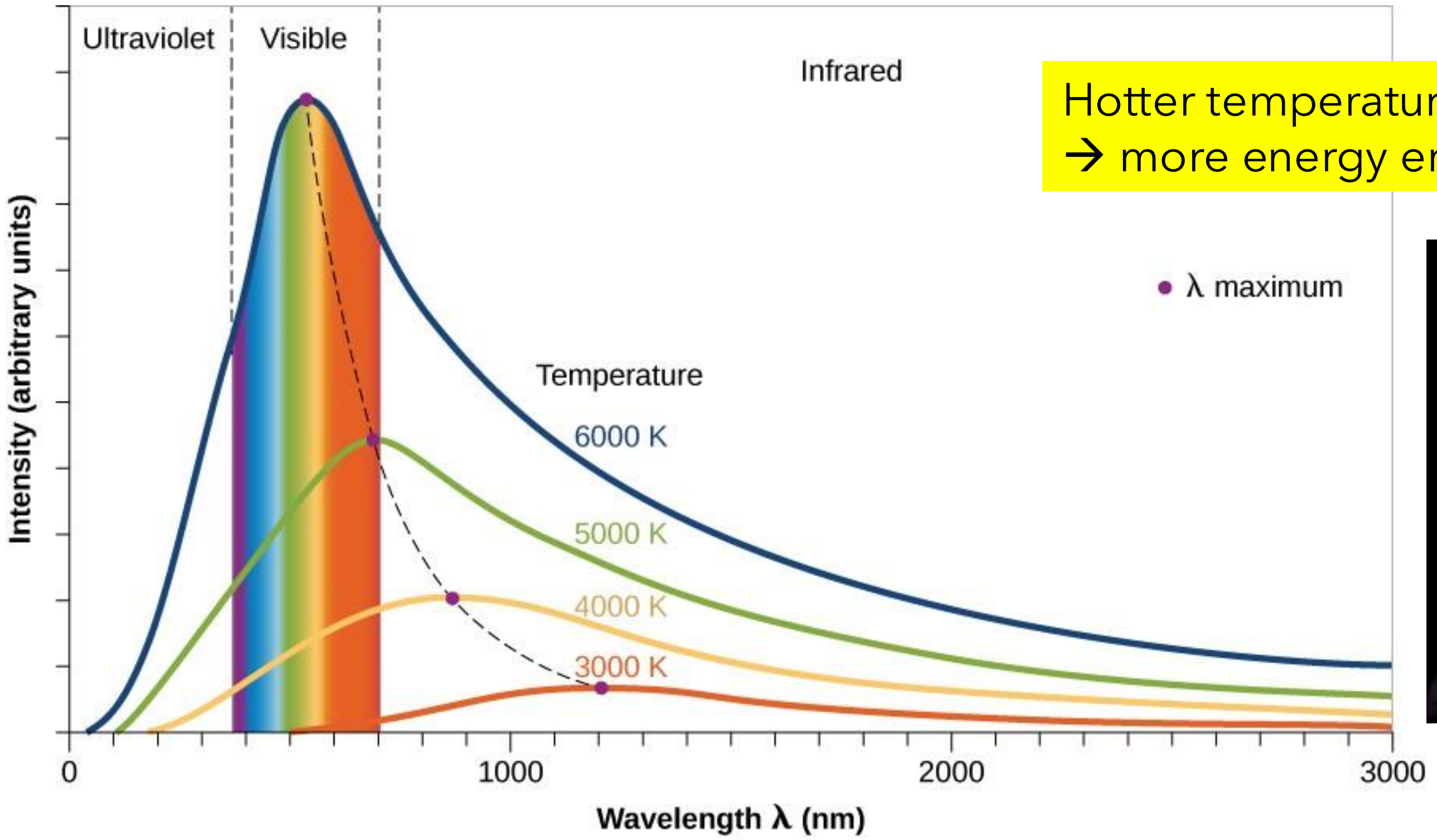

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Wien's law:
λ_{max} [nm] = $(3 \times 10^6)/T$ [K]

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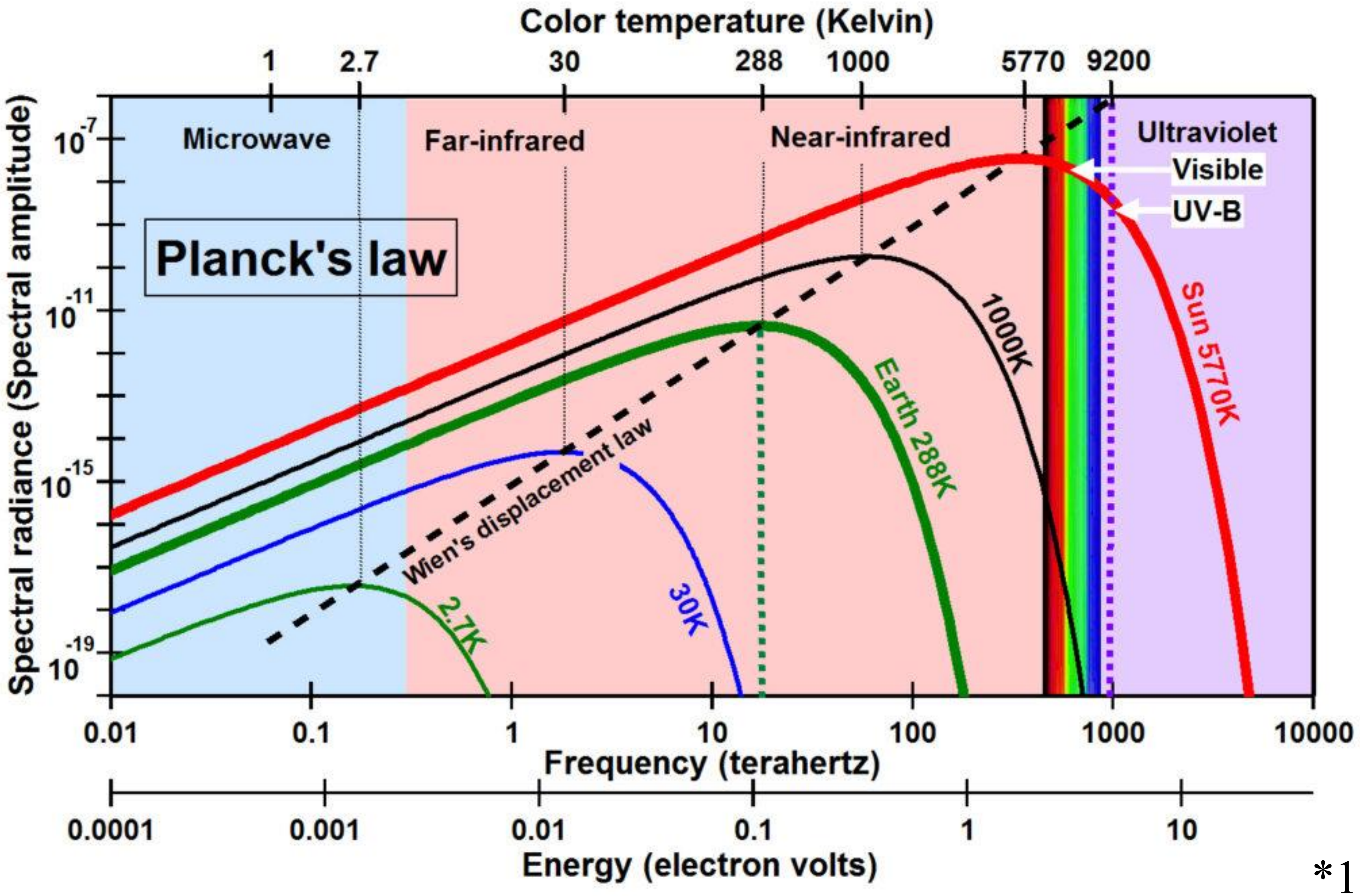

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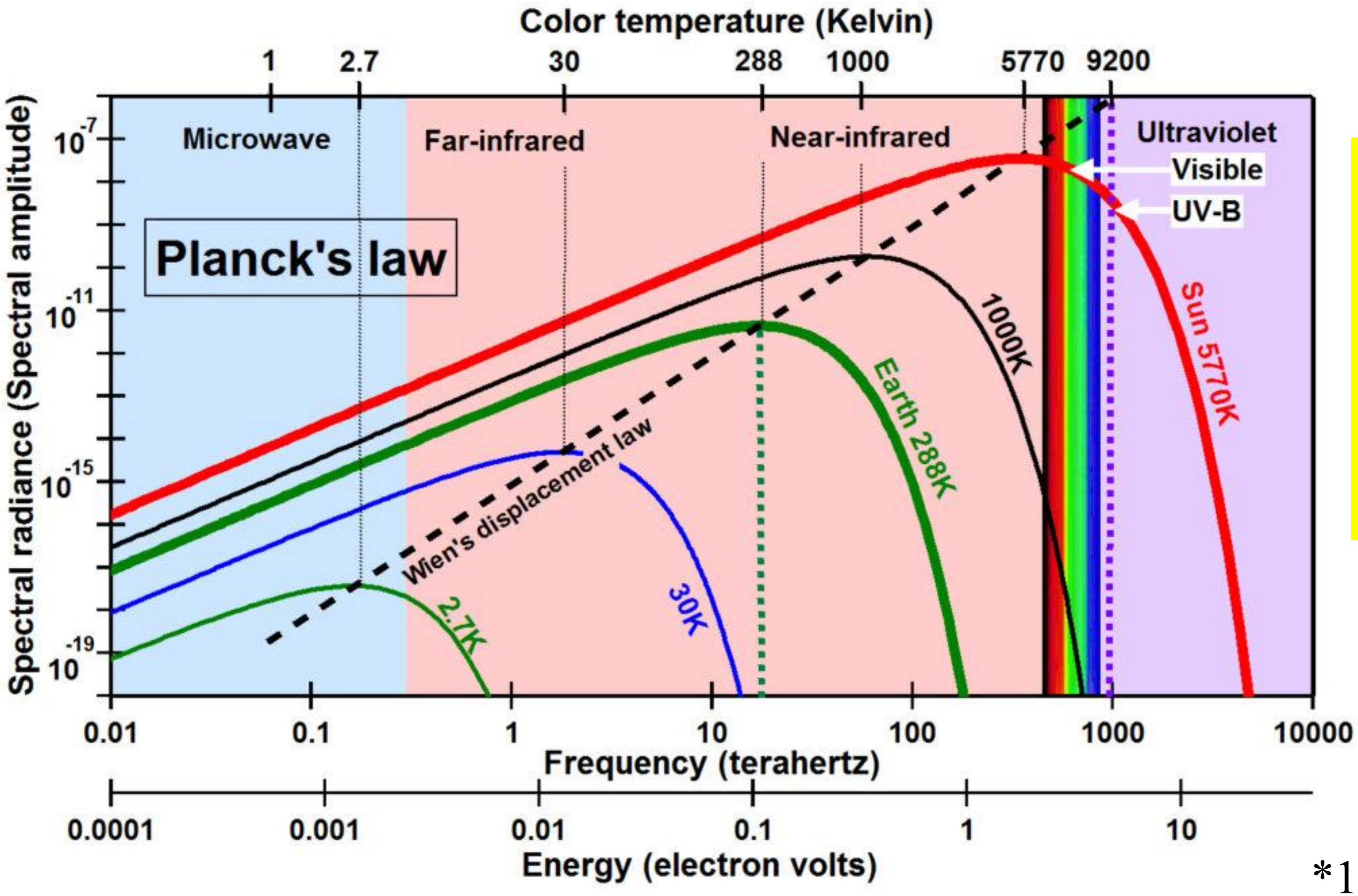

Remember E =hv !

Where,

h is **Planck** constant

[6.62 x 10^{-34} J = kg m^2 s^{-2}]

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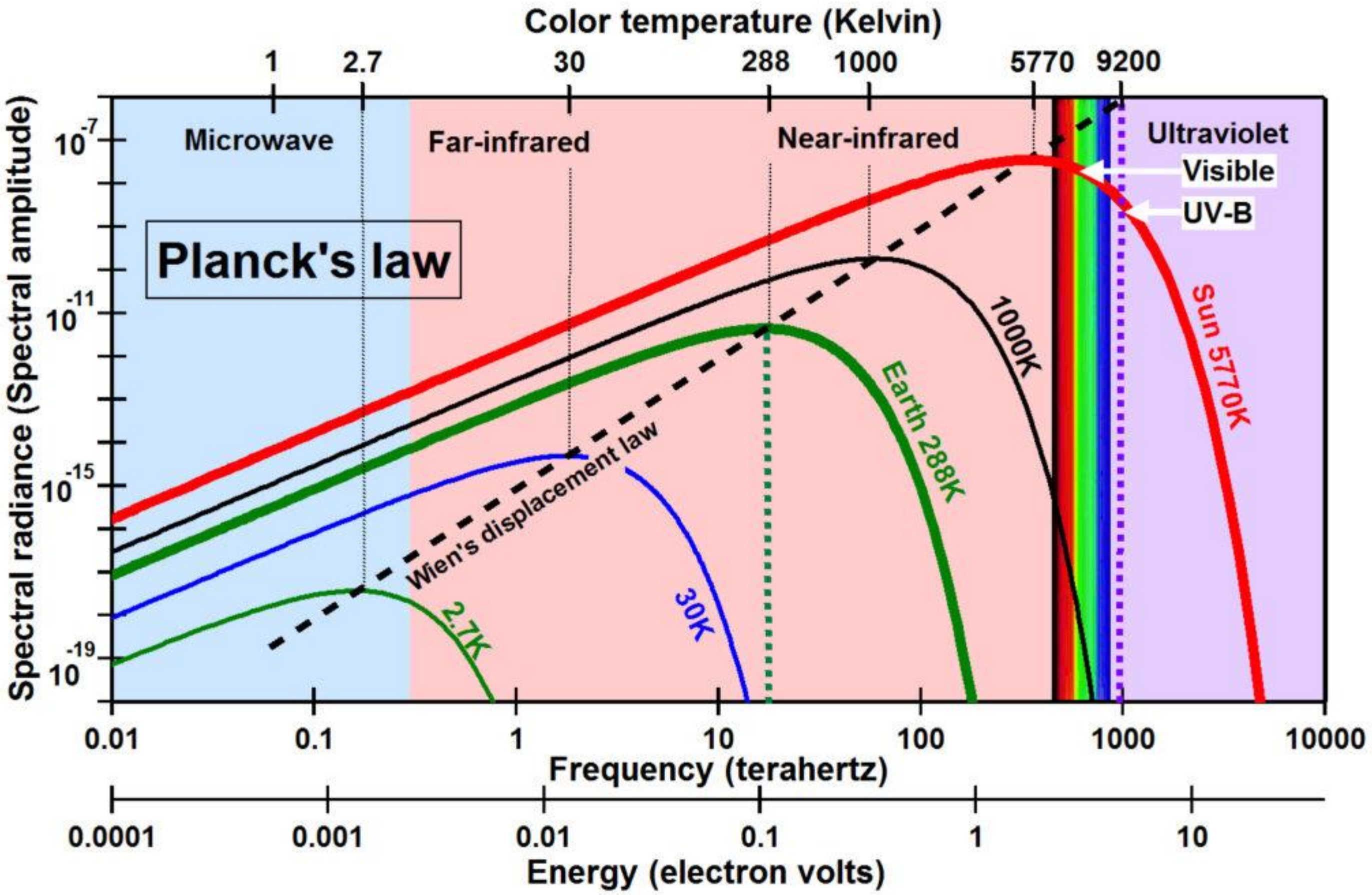


Planck showed that the actual energy distribution per volume per unit frequency is,

$E = 8\pi h\nu^3/c^3 \times 1/(e^{h\nu/kT}-1)$

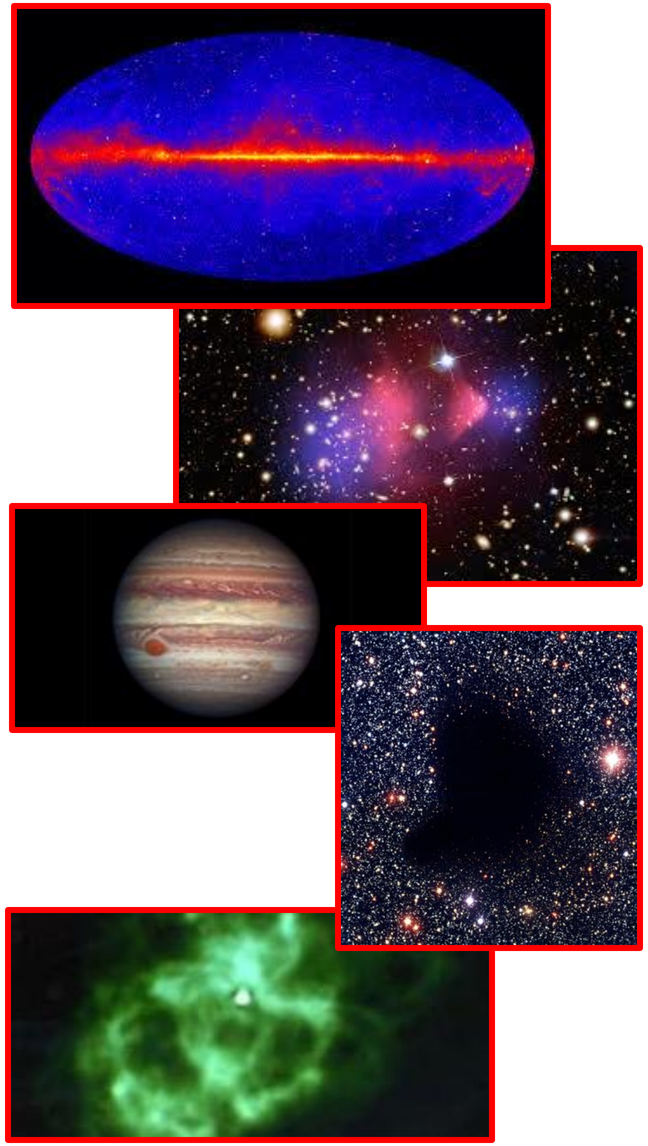
where c is the speed of light, *k* is the Boltzmann constant, *T* is the absolute temperature, and *v* is the frequency.

This equation is called Planck's radiation law.

Planck's theory matched experimental results so well that, in 1918, he was awarded the Nobel Prize for Physics!

Emission of E&M Radiation Deeply Connected to the Temperature of the Source!

Types of Radiation	Radiated by Objects at this Temperature	Typical Sources
Gamma-rays	> 10^8 Kelvin (K)	accretion disks around black holes
X-rays	10^6-10^8 K	Gas in clusters of galaxies; supernova remnants; stellar corona
Ultraviolet	10^4-10^6 K	Supernova remnants; very hot stars
Visible	10^3-10^4 K	Planets, stars, some satellites
Infrared	10-10^3 K	cool clouds of dust and gas; planets
Microwave	1-10 K	Cool clouds of gas; newly formed stars; cosmic microwave background
Radio	< 1 K	Radio emission produced by electrons moving in magnetic fields



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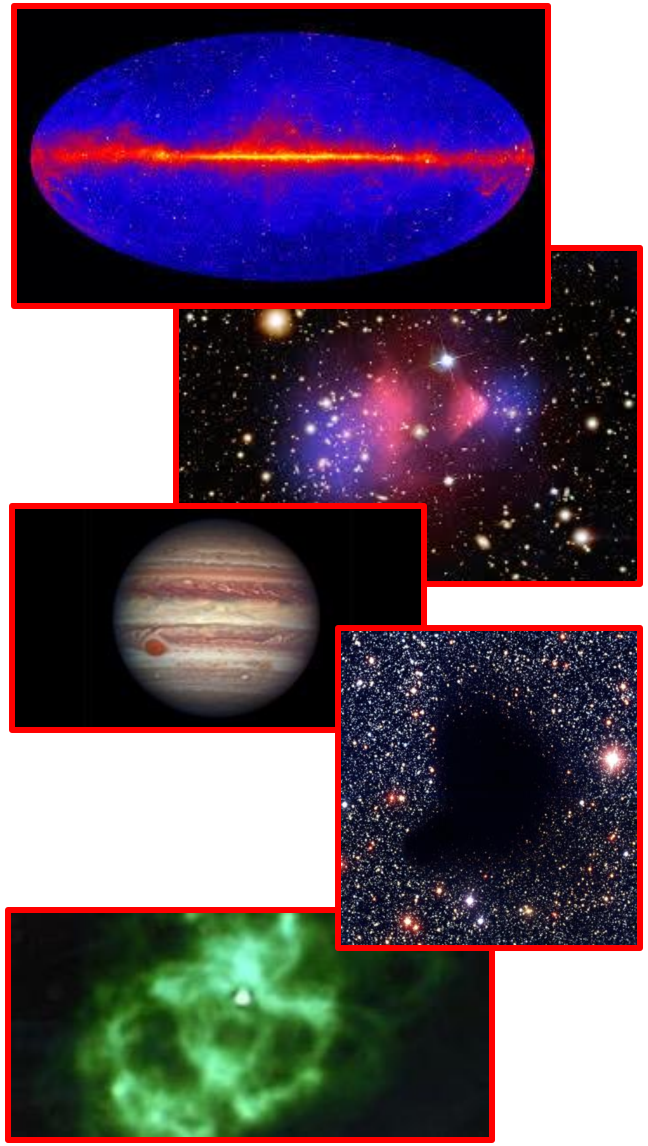

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The Electromagnetic Spectrum

*By observing different regions of the electromagnetic spectrum, we can also learn about different aspects of a singular source

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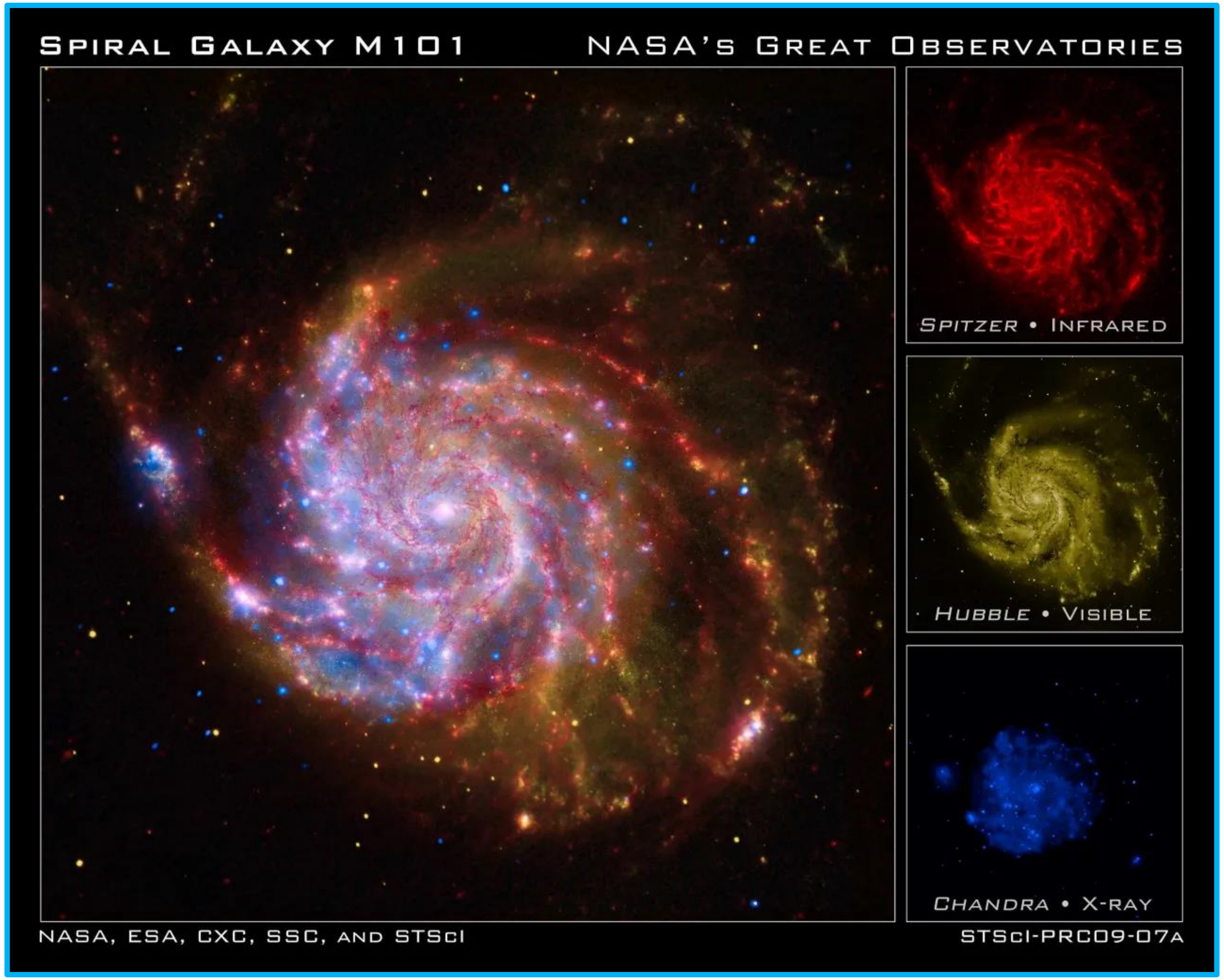
We can create a 'Composite' or 'False Color' Image →



The Electromagnetic Spectrum

*By observing different regions of the electromagnetic spectrum, we can also learn about different aspects of a singular source

We can create a 'Composite' or 'False Color' Image →

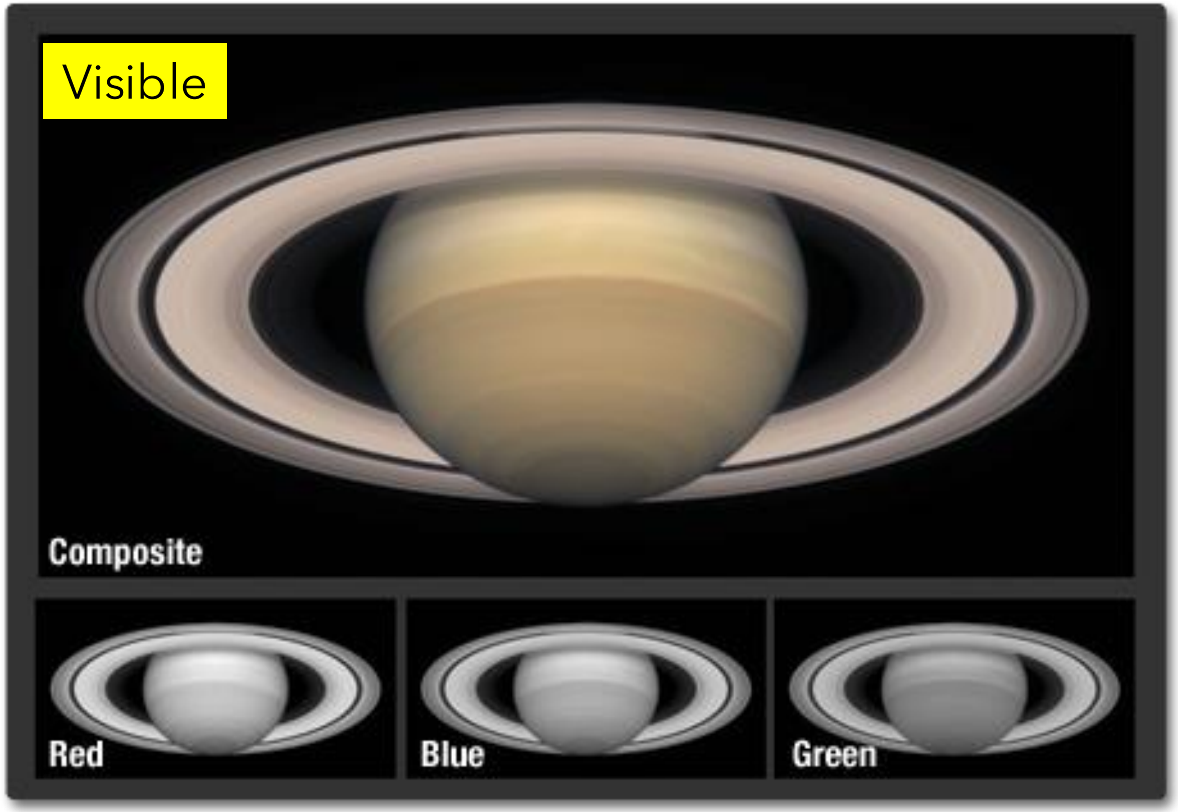
Observations from 5 telescopes were used to make this image!

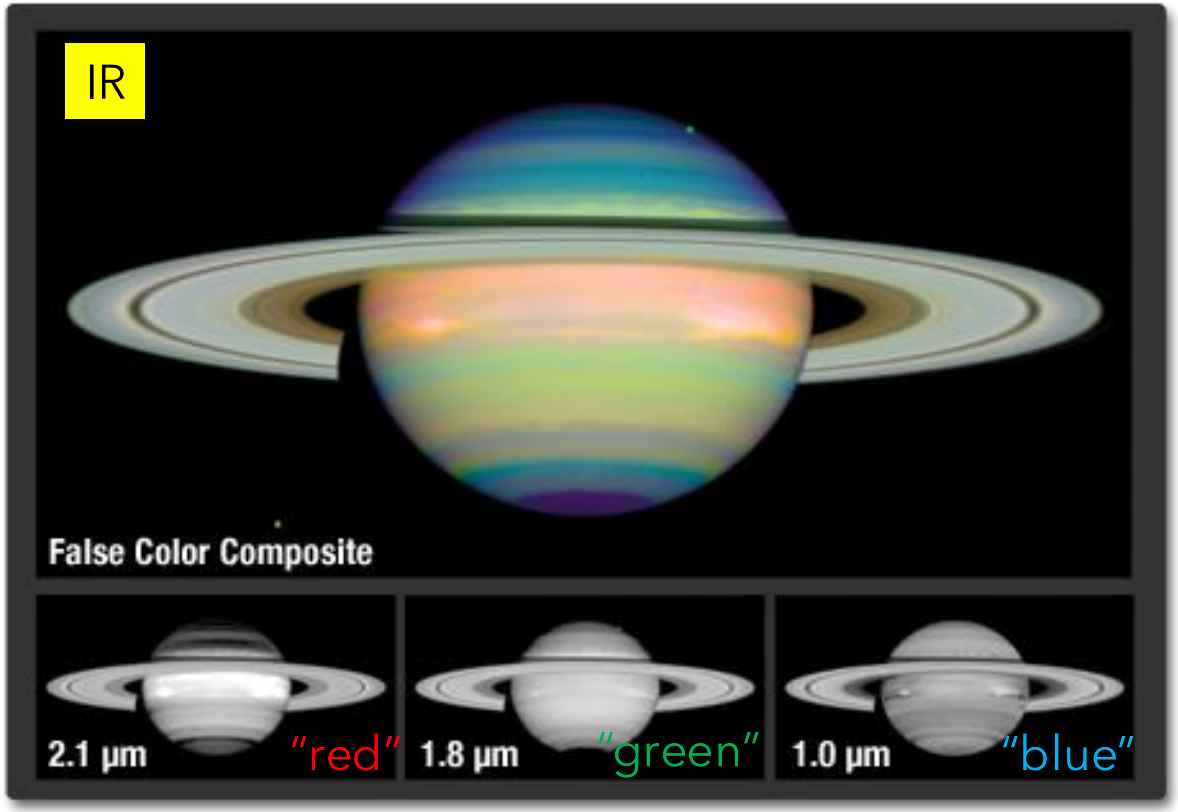
The VLA (radio) in red; Spitzer Space Telescope (infrared) in yellow; Hubble Space Telescope (visible) in green; XMM-Newton (ultraviolet) in blue; and Chandra X-Ray Observatory (X-ray) in purple

Image credit: NASA JPL

The Electromagnetic Spectrum

*By observing different regions of the electromagnetic spectrum, we can also learn about different aspects of a singular source





Electromagnetic Waves/Light let us study the **Composition** of Astronomical Objects!

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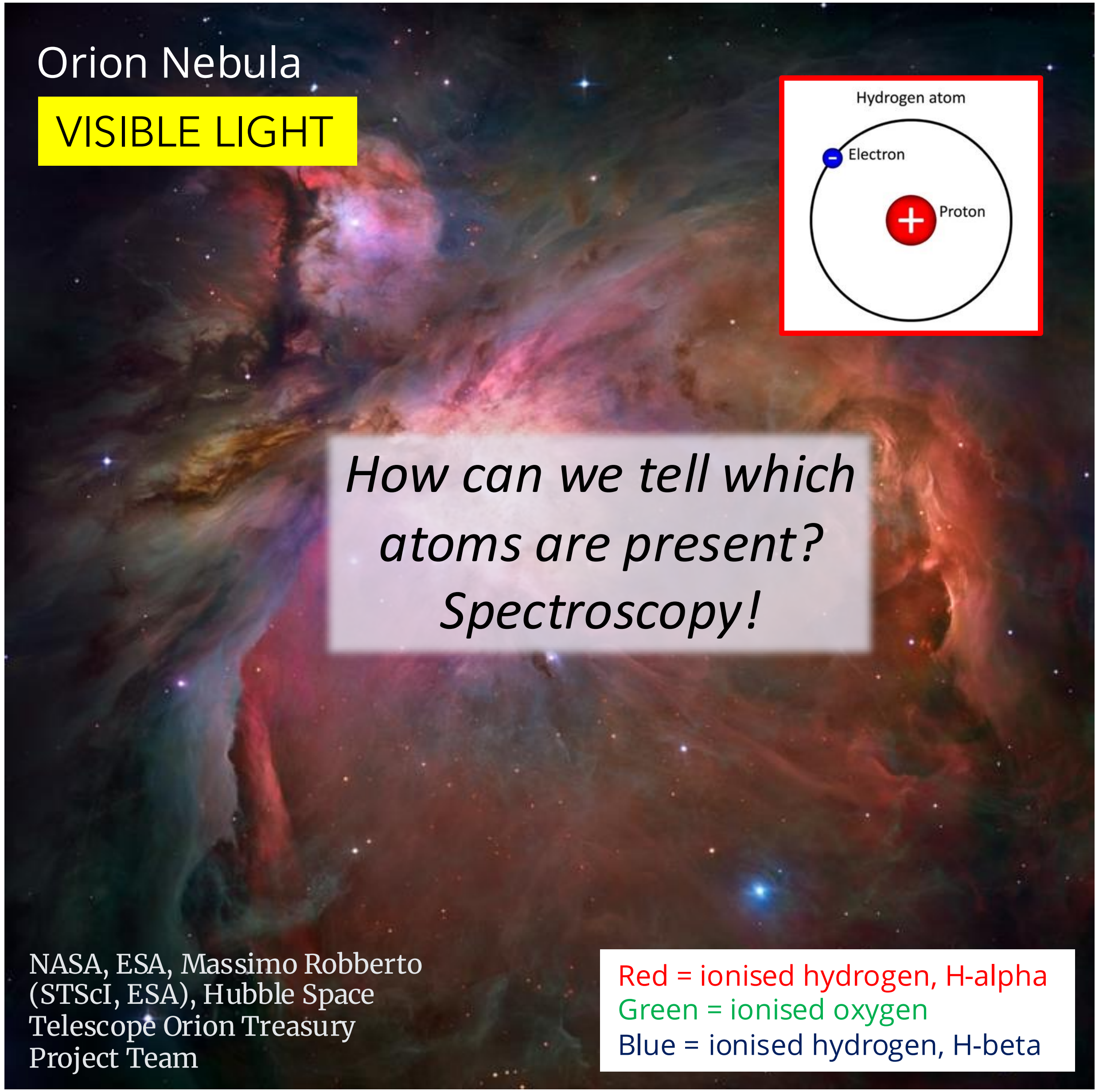
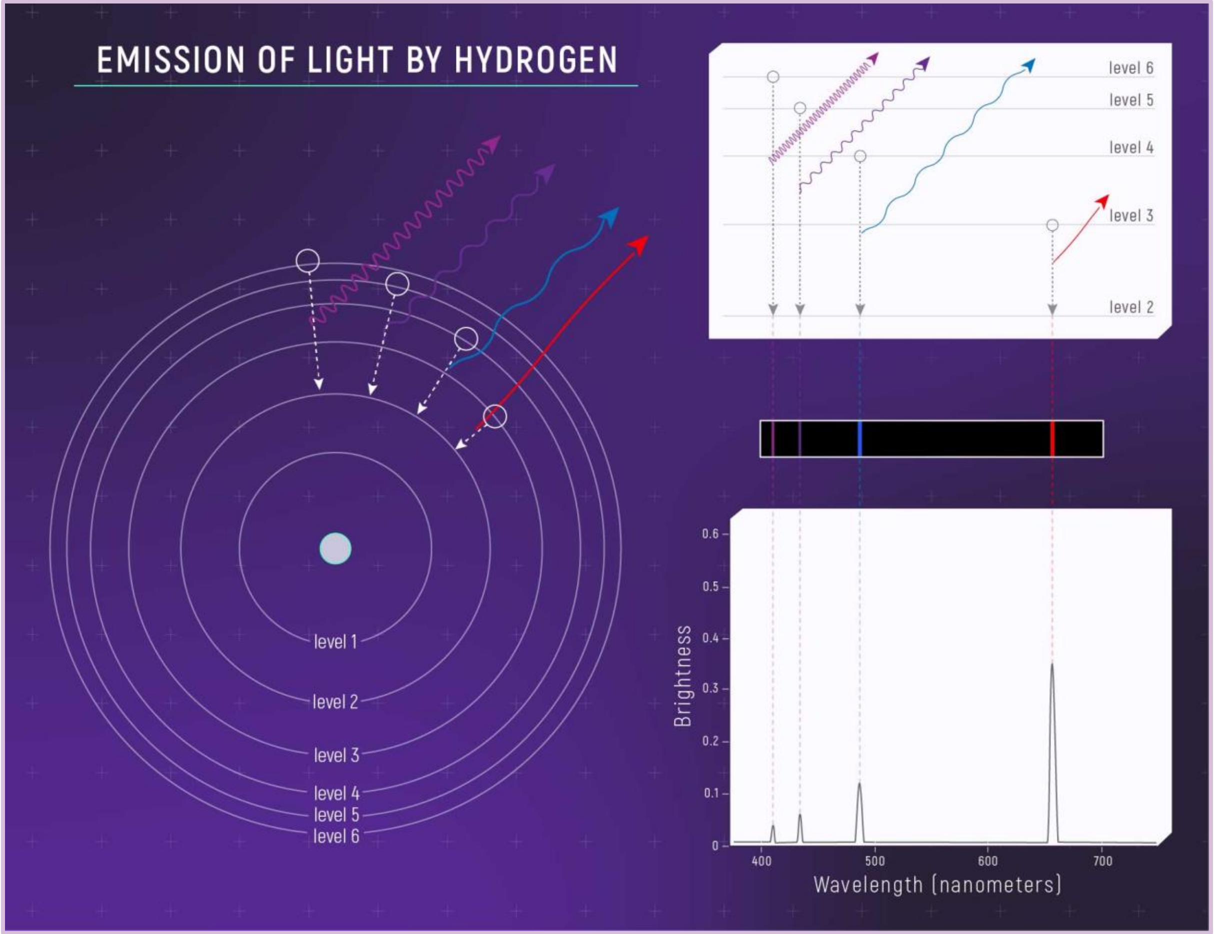
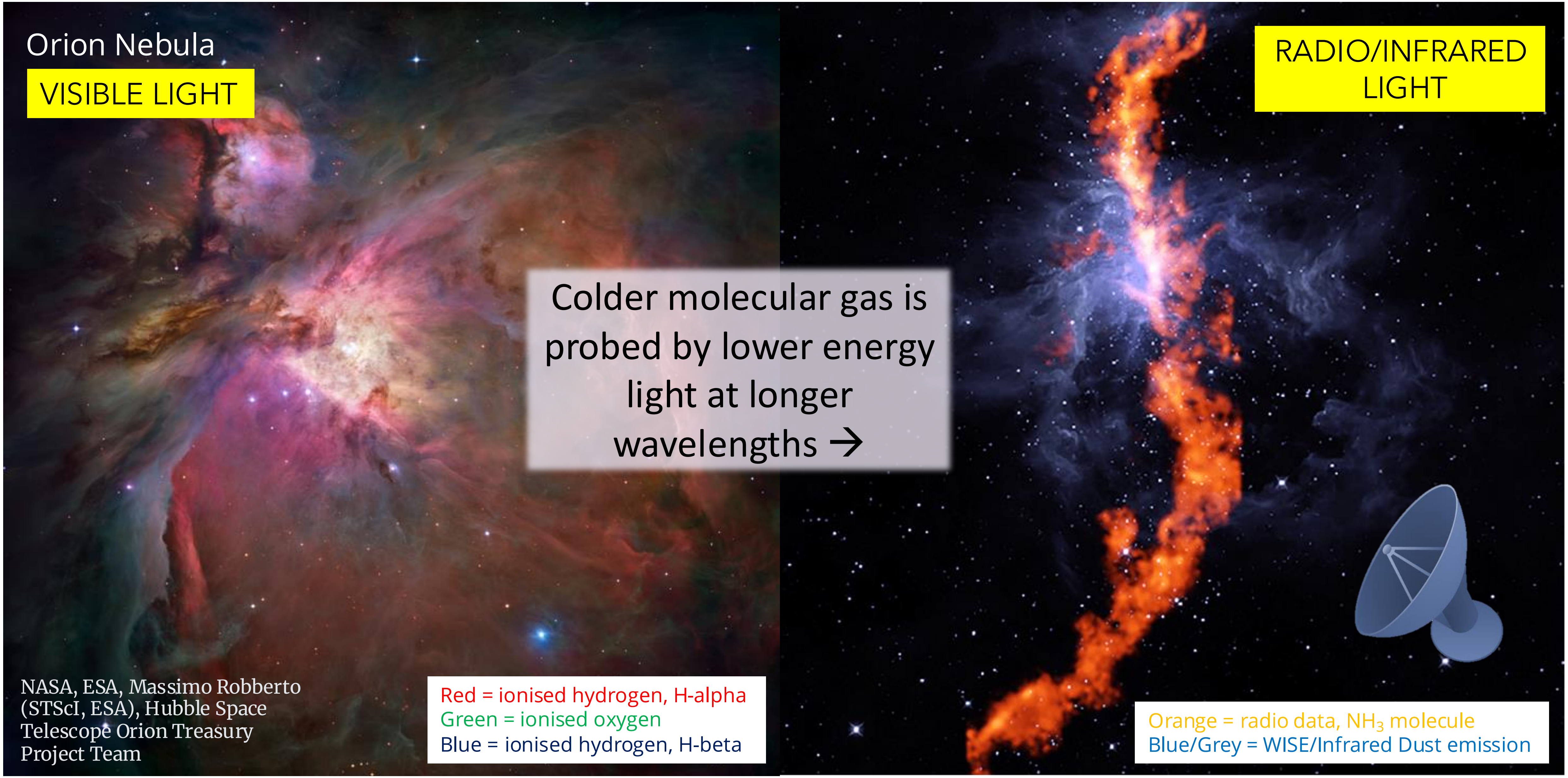


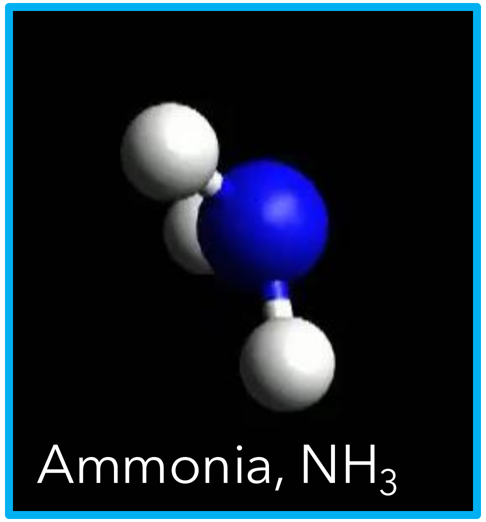


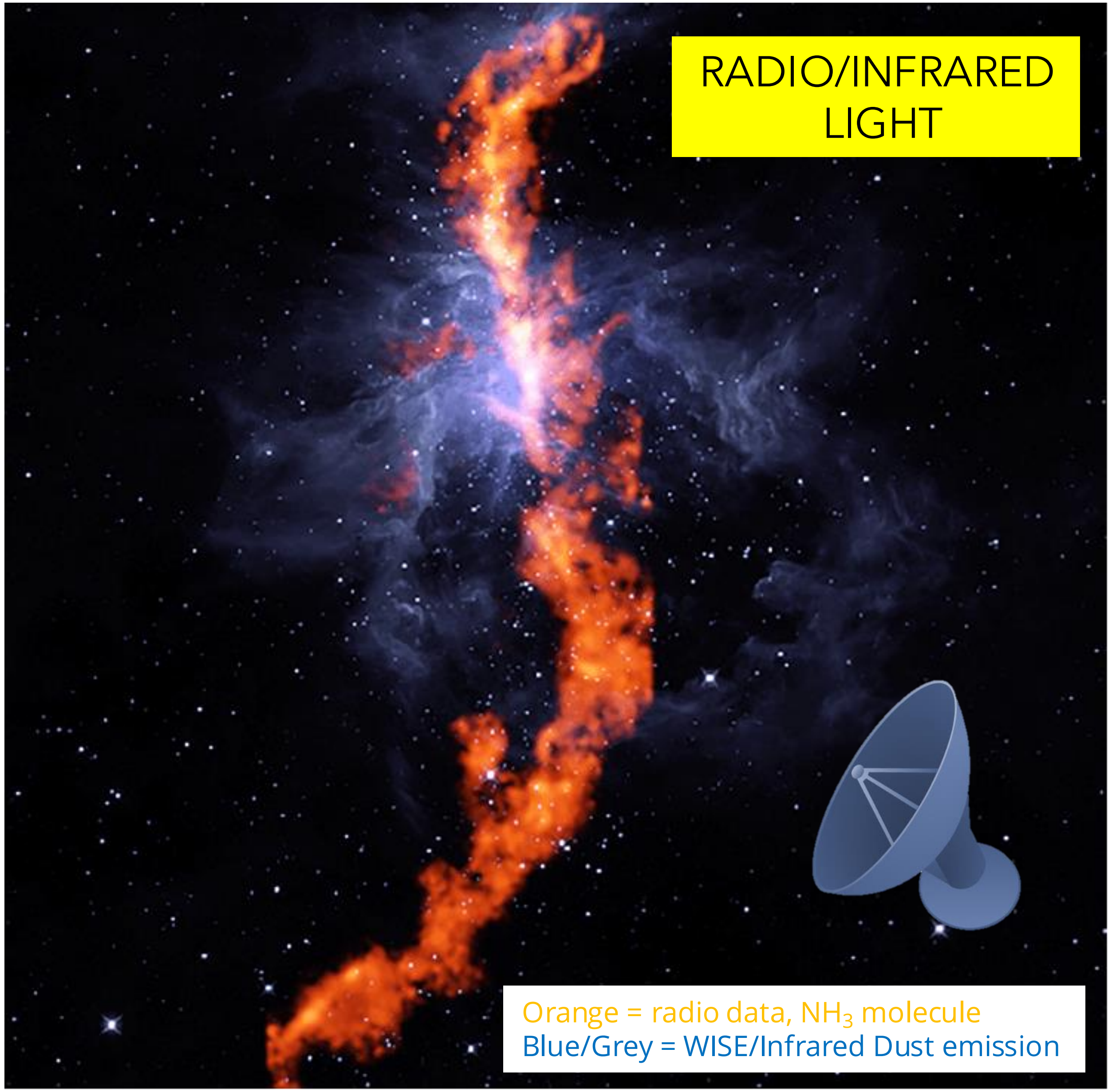
Clouds of gas will emit spectral lines at specific wavelengths corresponding to energy transitions of certain atoms and/or molecules!

Electromagnetic Waves/Light let us study the **Composition** of Astronomical Objects!

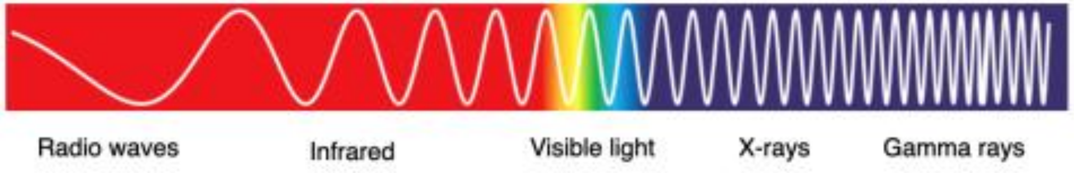


Fundamental to **Astrochemistry** is the study of Molecules with Millimeter Radio Telescopes!





SUMMARY: Electromagnetic Waves



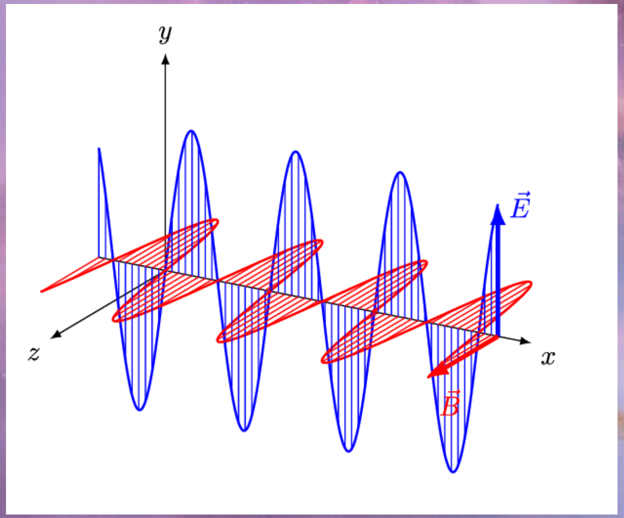
- Electromagnetic Waves/Electromagnetic Radiation/Light is a type of radiation that has both magnetic fields and electric fields and can be **described by its wavelength and frequency, inversely related by the speed of light**, $c = \lambda v = 3.8 \times 10^8$ m/s

- Light is also described as a particle or 'photons' represented by 'packets of energy' that follows a simply linear relation ($E = hv$) where **higher frequency (or shorter wavelength) light is higher energy**

- The **emission of electromagnetic radiation is intimately connected to the temperature of the source**, and the higher the temperature of an idealized emitter of electromagnetic radiation (i.e., a blackbody), the shorter is the wavelength at which the maximum amount of radiation is emitted

*__Longer wavelength millimeter radio observations let us study cold molecular gas__ where interesting **chemistry** is taking place, hidden at other wavelengths *(more to come in next week's lecture!)*

Astronomy relies heavily on observations of light! We can study the universe across the E&M spectrum, from gamma rays to radio waves!


y
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Questions?


ROBERT C. BYRD
GREEN BANK TELESCOPE
Dedicated August 25, 2000