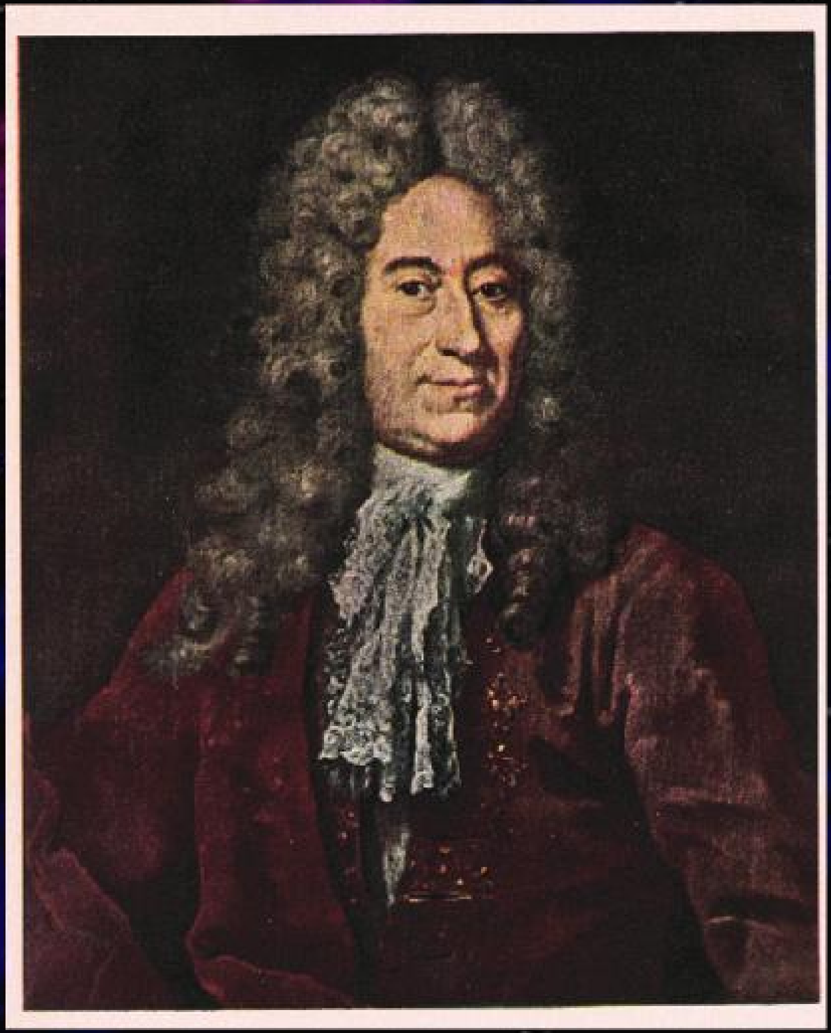
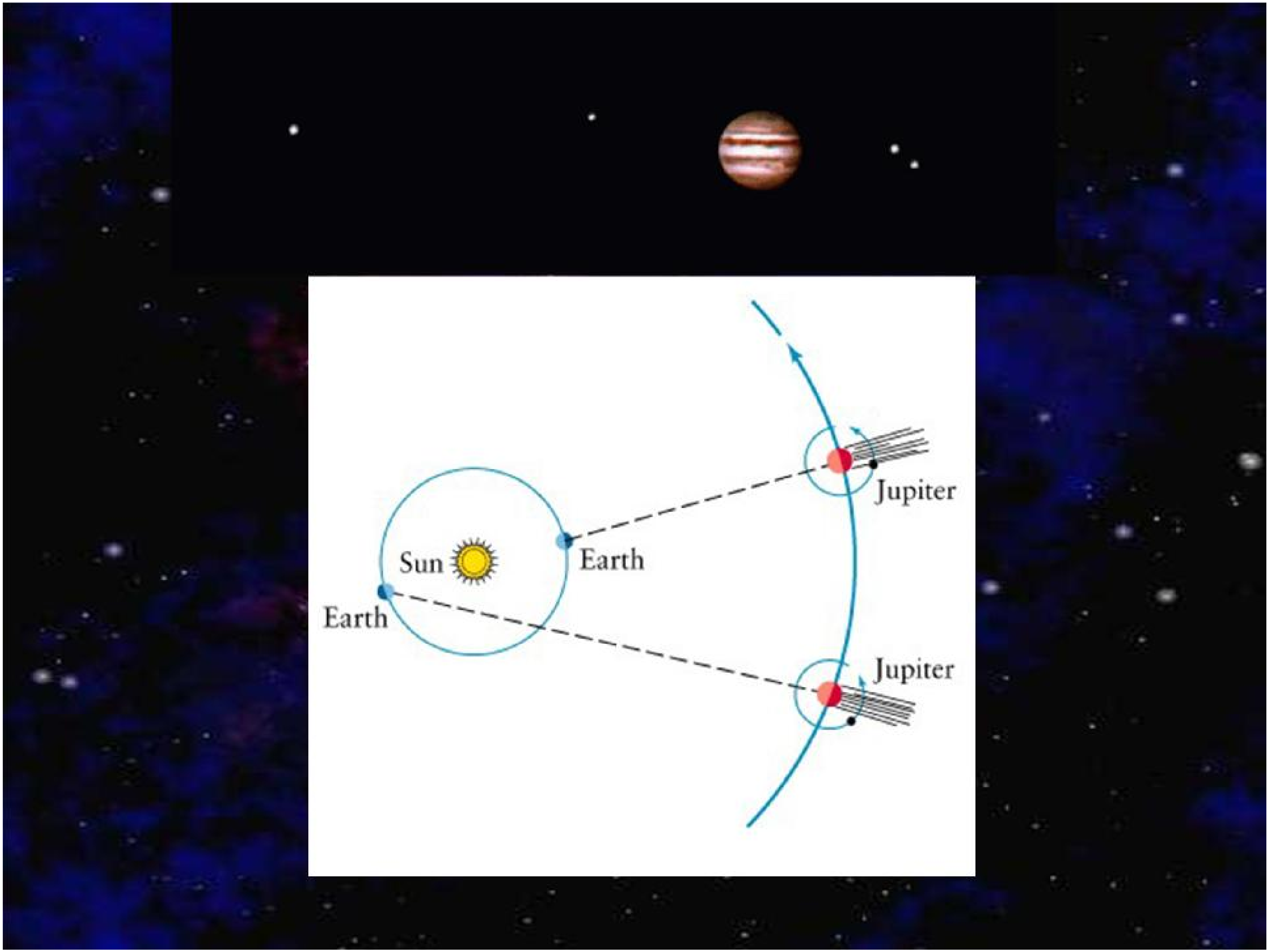
# The Nature of Light

# Ole Roemer (1676)




Jupiter
Sun
Earth
Earth
Jupiter

# The Speed of Light

- Accurately measured in a vacuum:

**186,282 miles per *<u>second!</u>***

11 million miles per minute

671 million miles per hour

5.9 trillion miles per year

**Betelgeuse:**

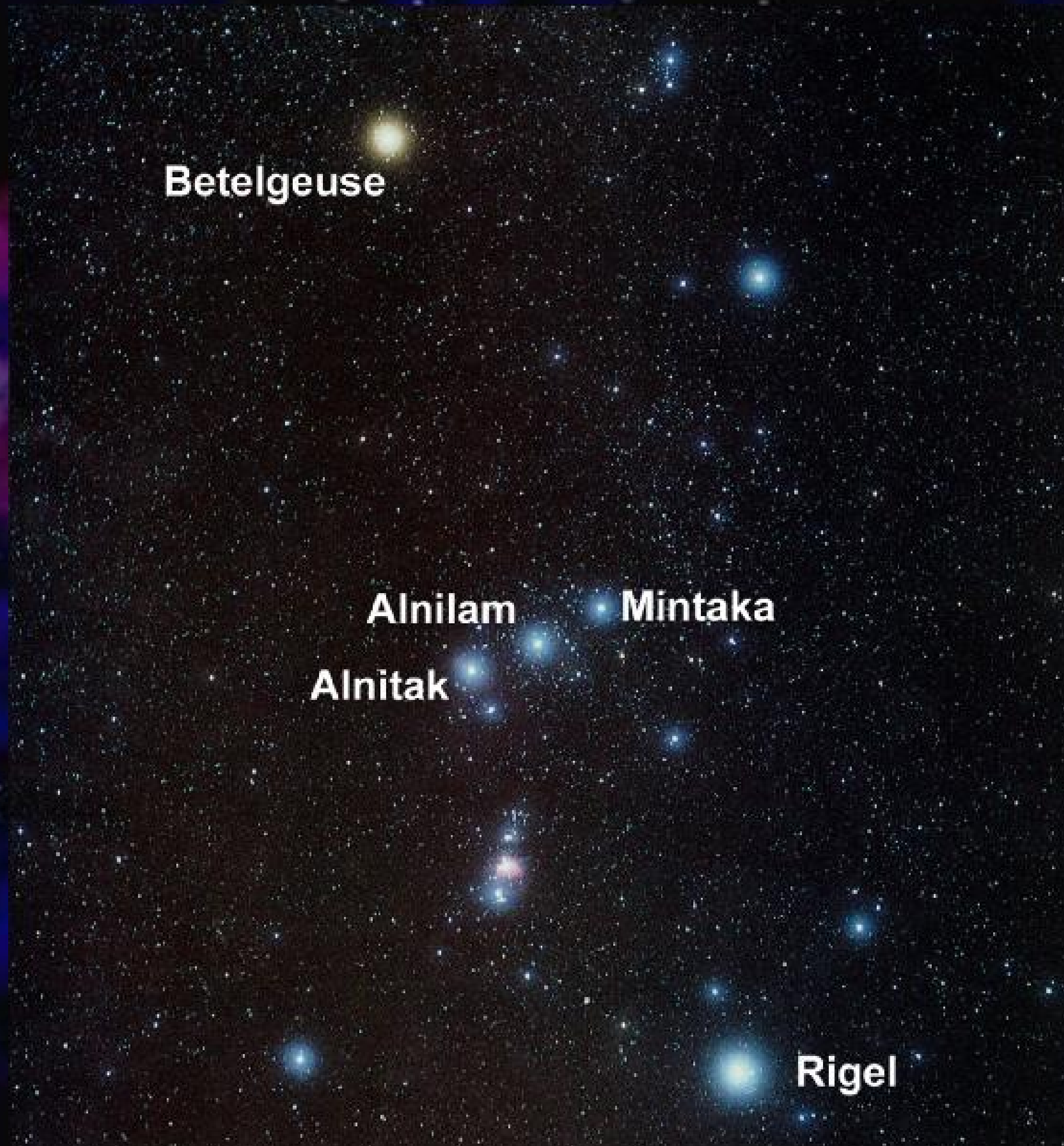
427 years

**Rigel:**

773 years

**Orion Nebula:**

1600 years



# Light year

The distance a beam of light will travel in one years time.

5.9 **T**rillion miles

5,900,000,000,000 miles

**Betelgeuse:**

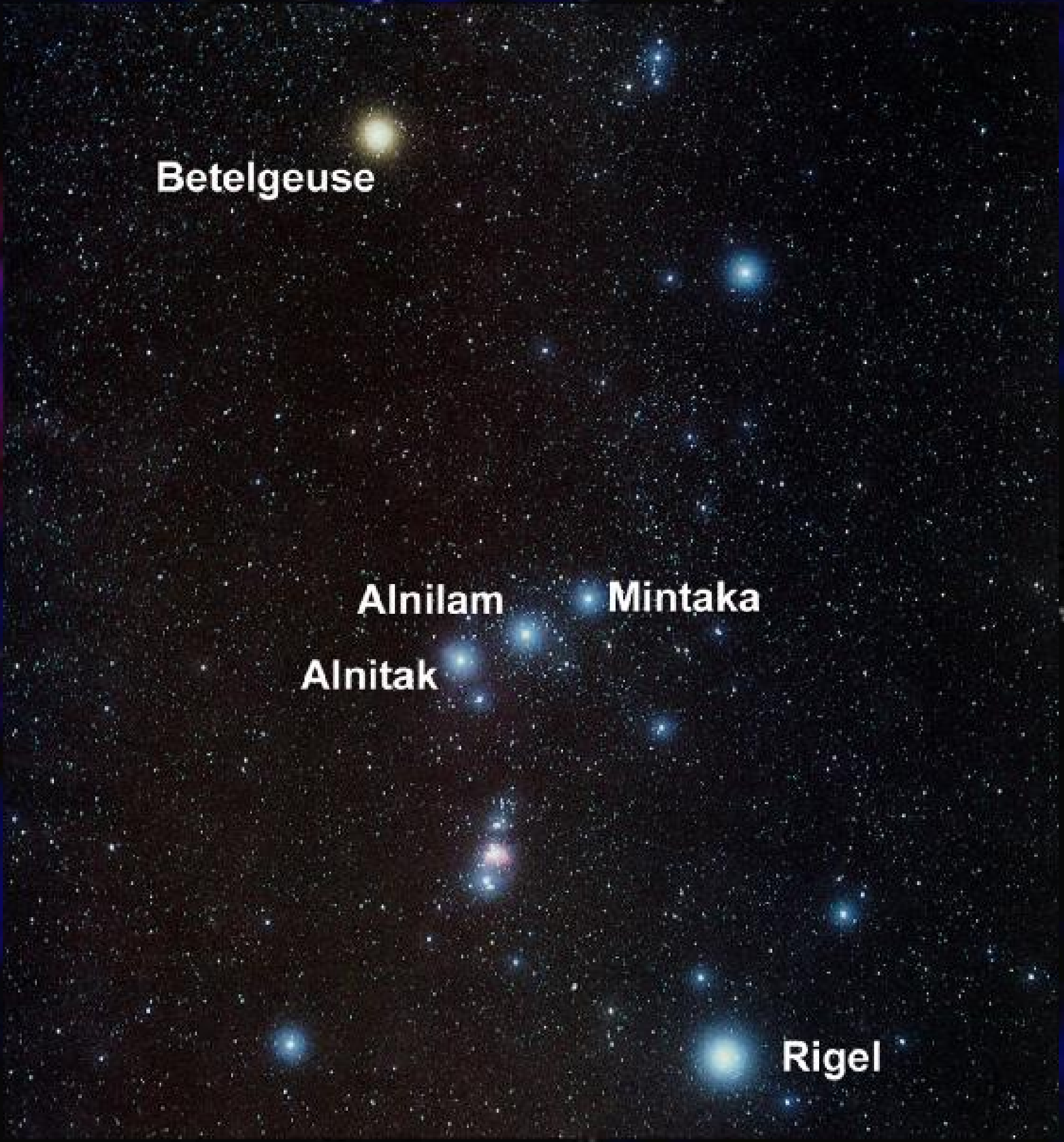
427 *light years*

**Rigel:**

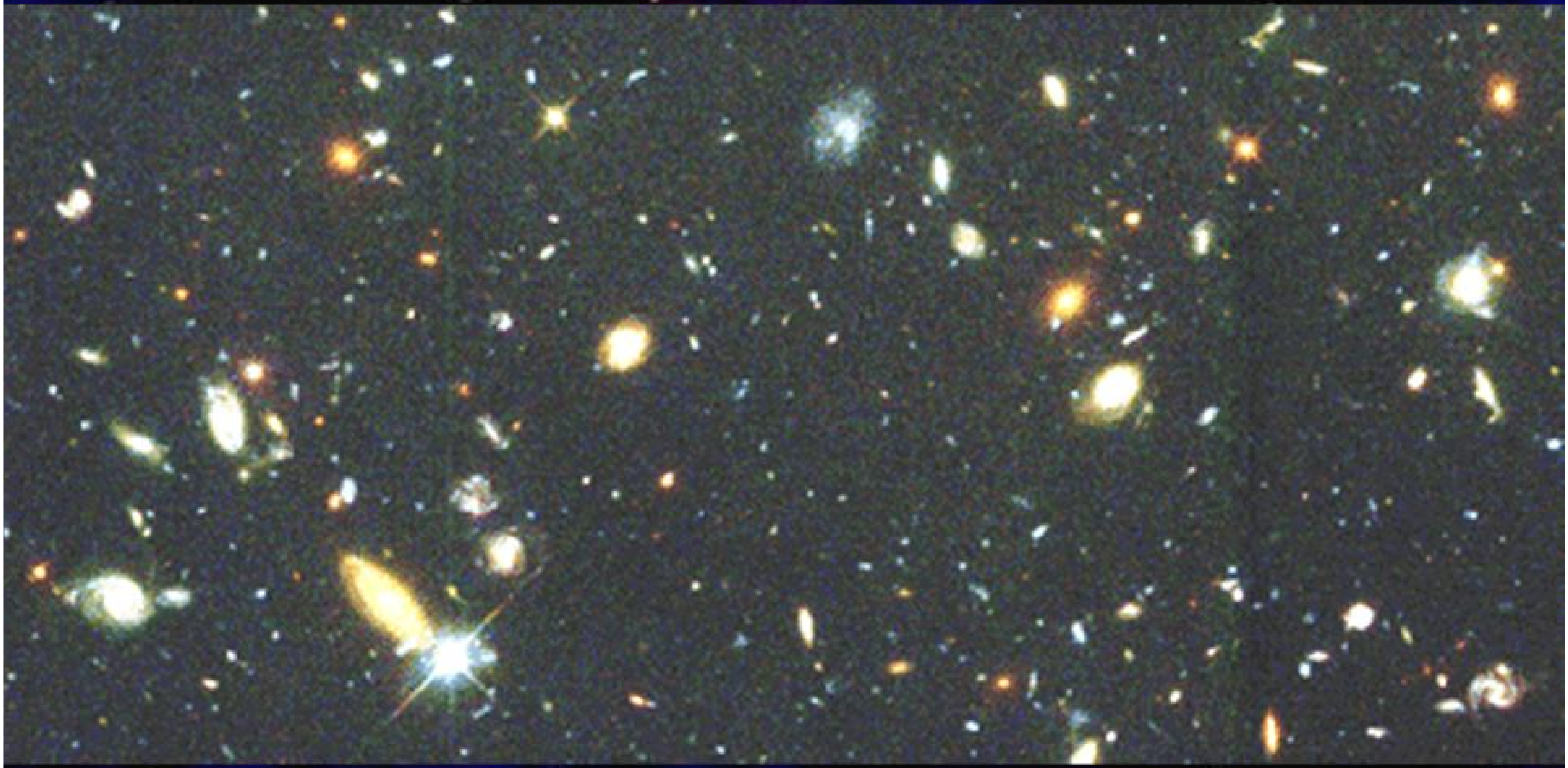
773 *light years*

**Orion Nebula:**

1600 *light years*

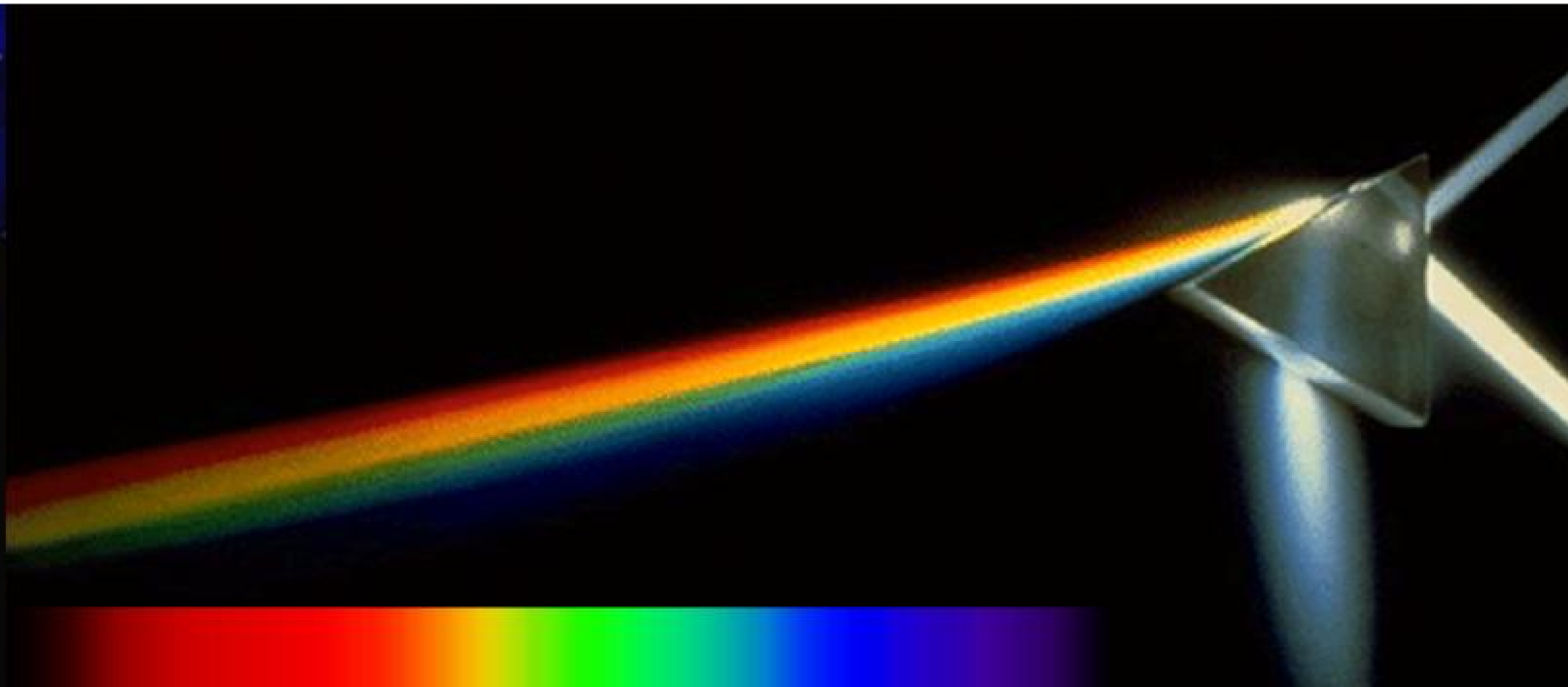


# Thus, looking into space is to travel in a time machine



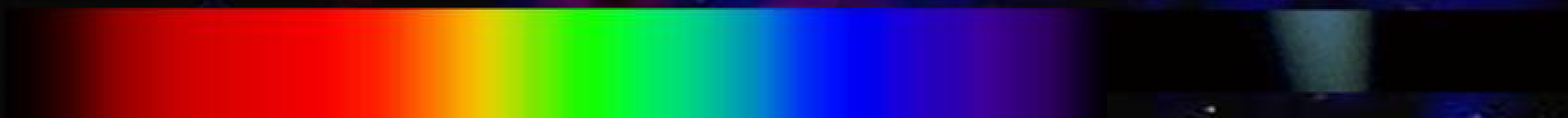
# How does light ***travel*** ?

Isaac Newton



**ROY G. BiV**

Light must behave as a *packet* of energy...

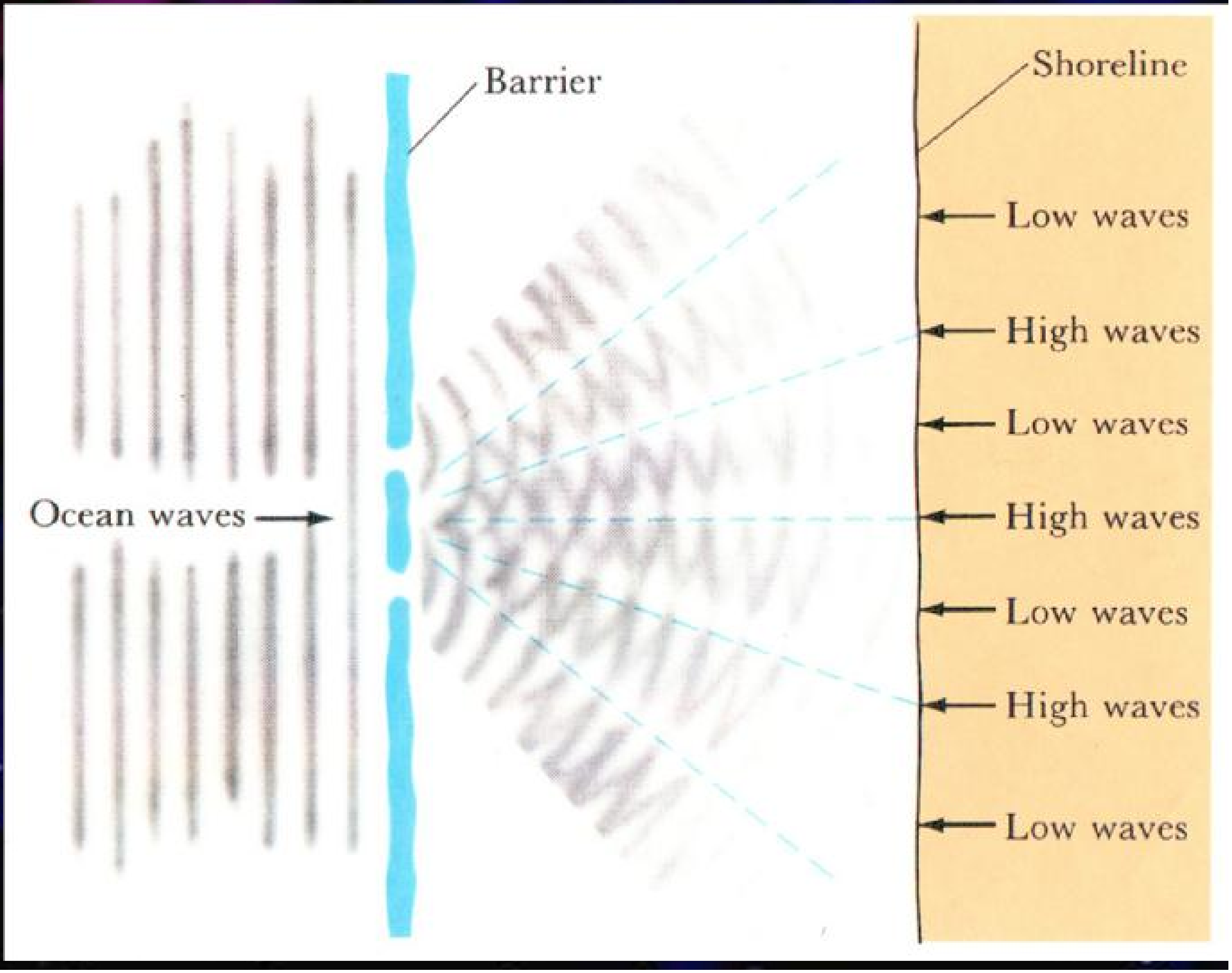


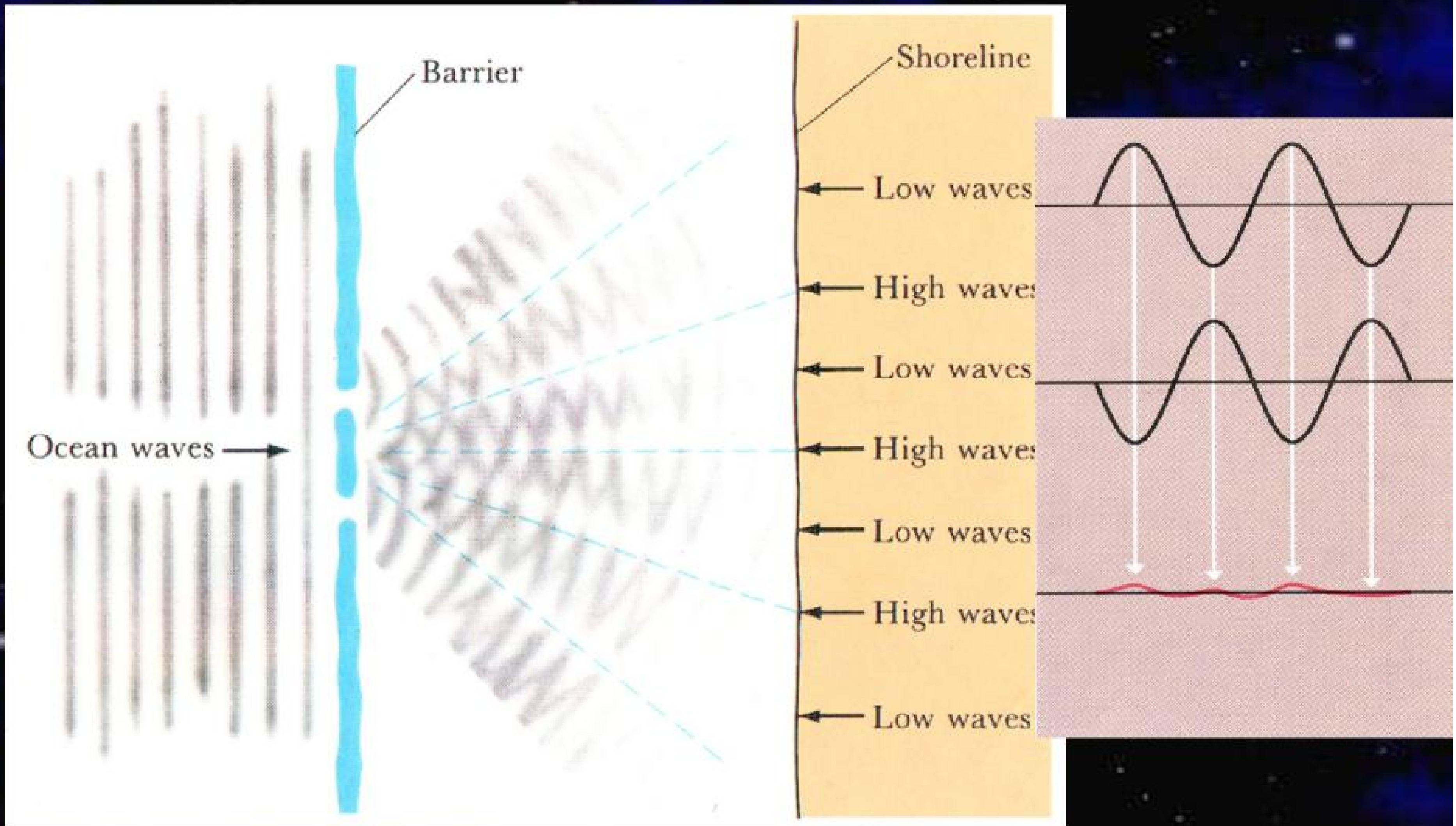
**ROY G. BiV**

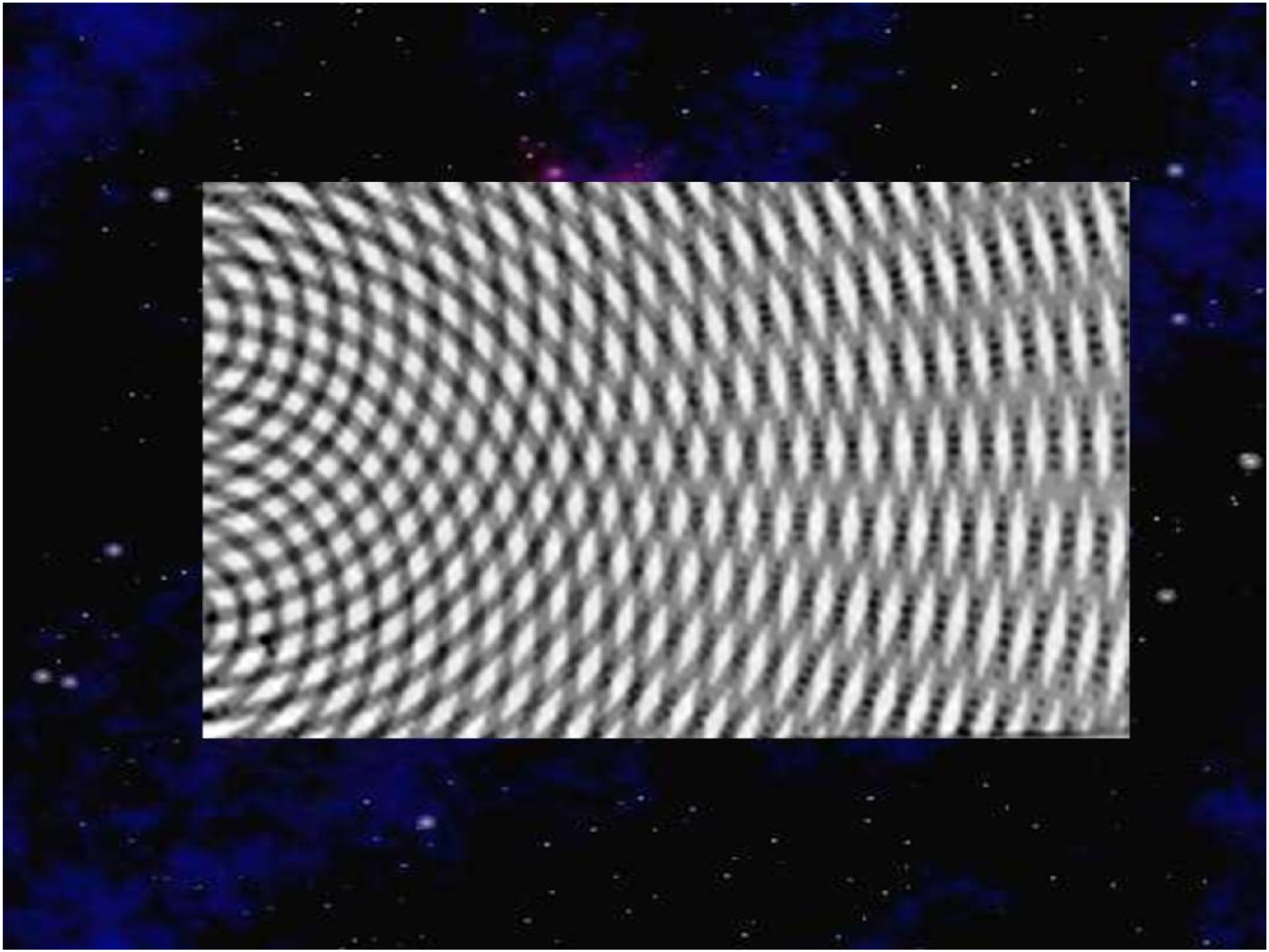
Light must behave as a *packet* of energy...

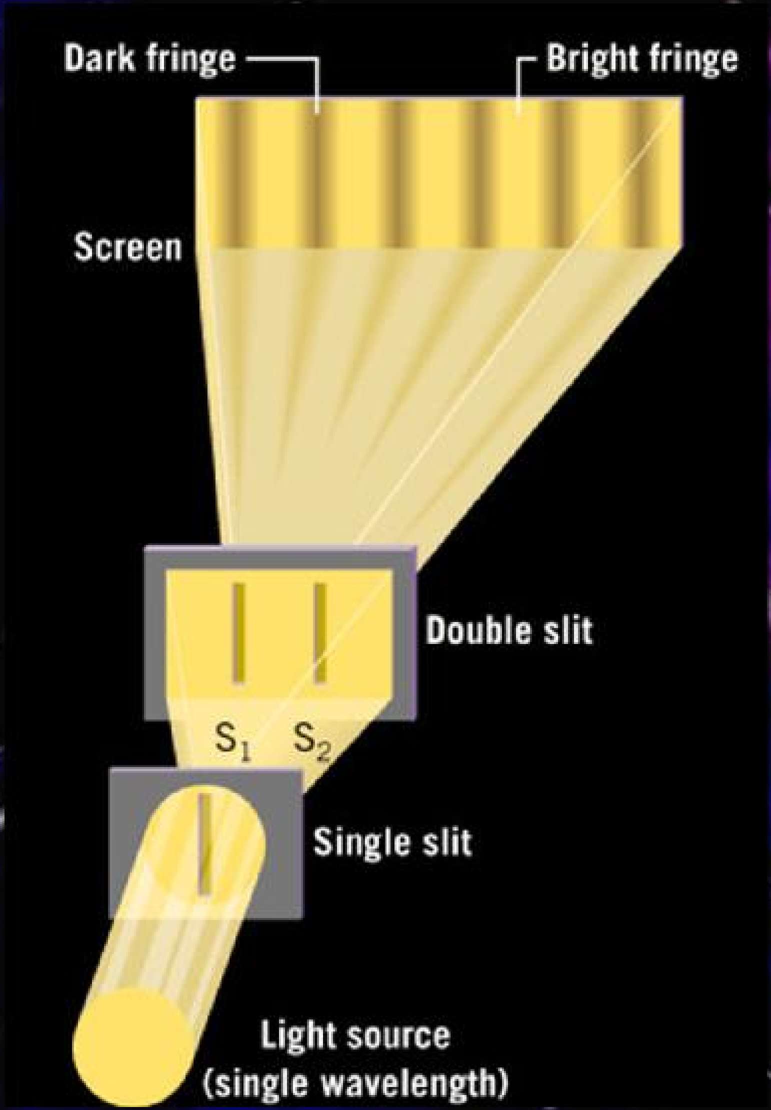
# How does light *behave*?

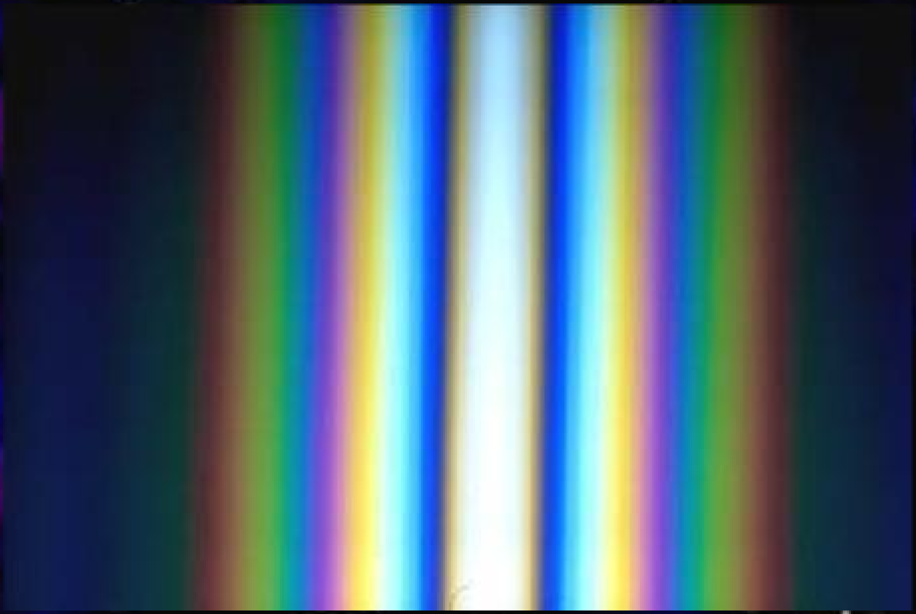
Thomas Young




Barrier
Shoreline
Ocean waves
Low waves
High waves
Low waves
High waves
Low waves
High waves
Low waves

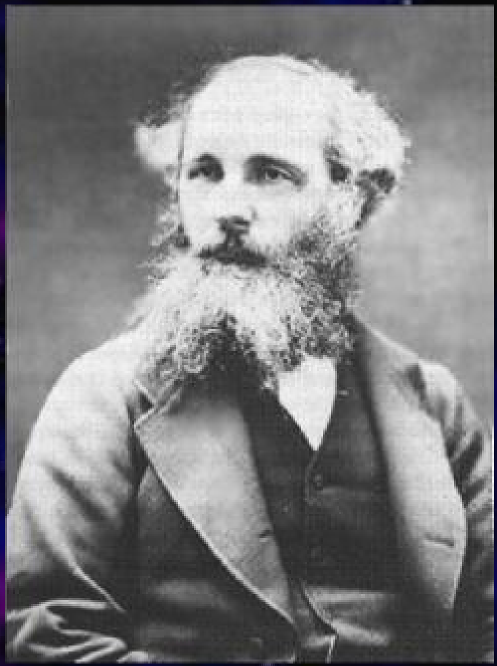




Light must behave like a *wave* of energy...

# What ***is*** light?



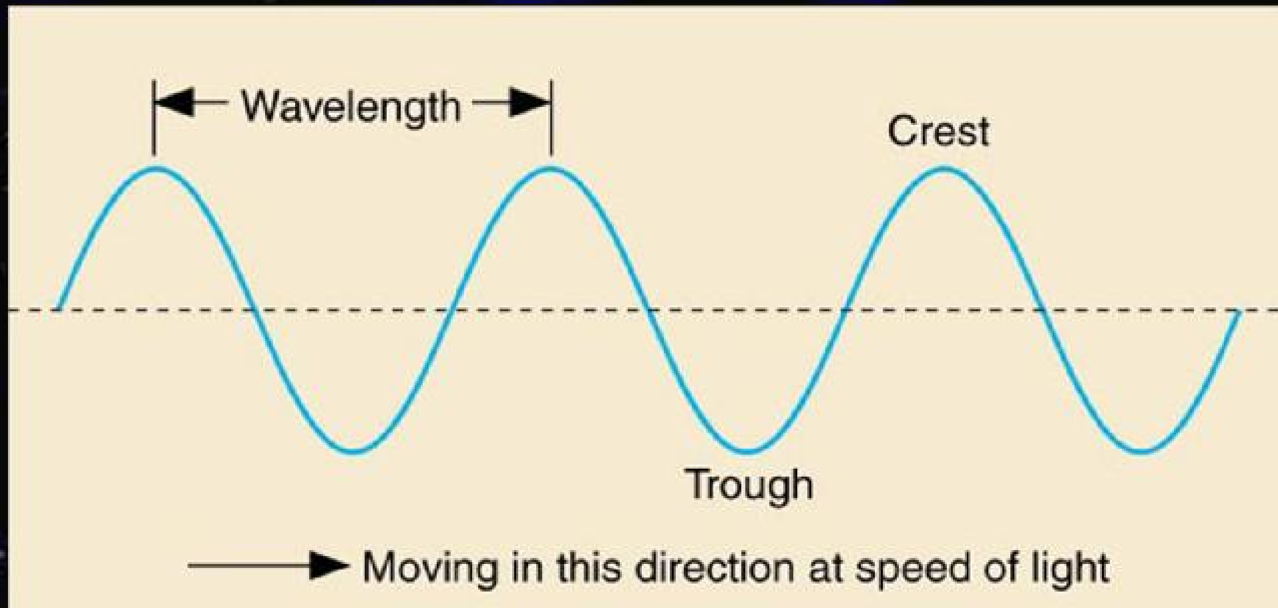
James Clerk Maxwell

What we commonly refer to as "light" is actually the combination of *electricity* and *magnetism*.

ELECTRO*MAGNETIC* ENERGY

**ELECTROMAGNETIC RADIATION**

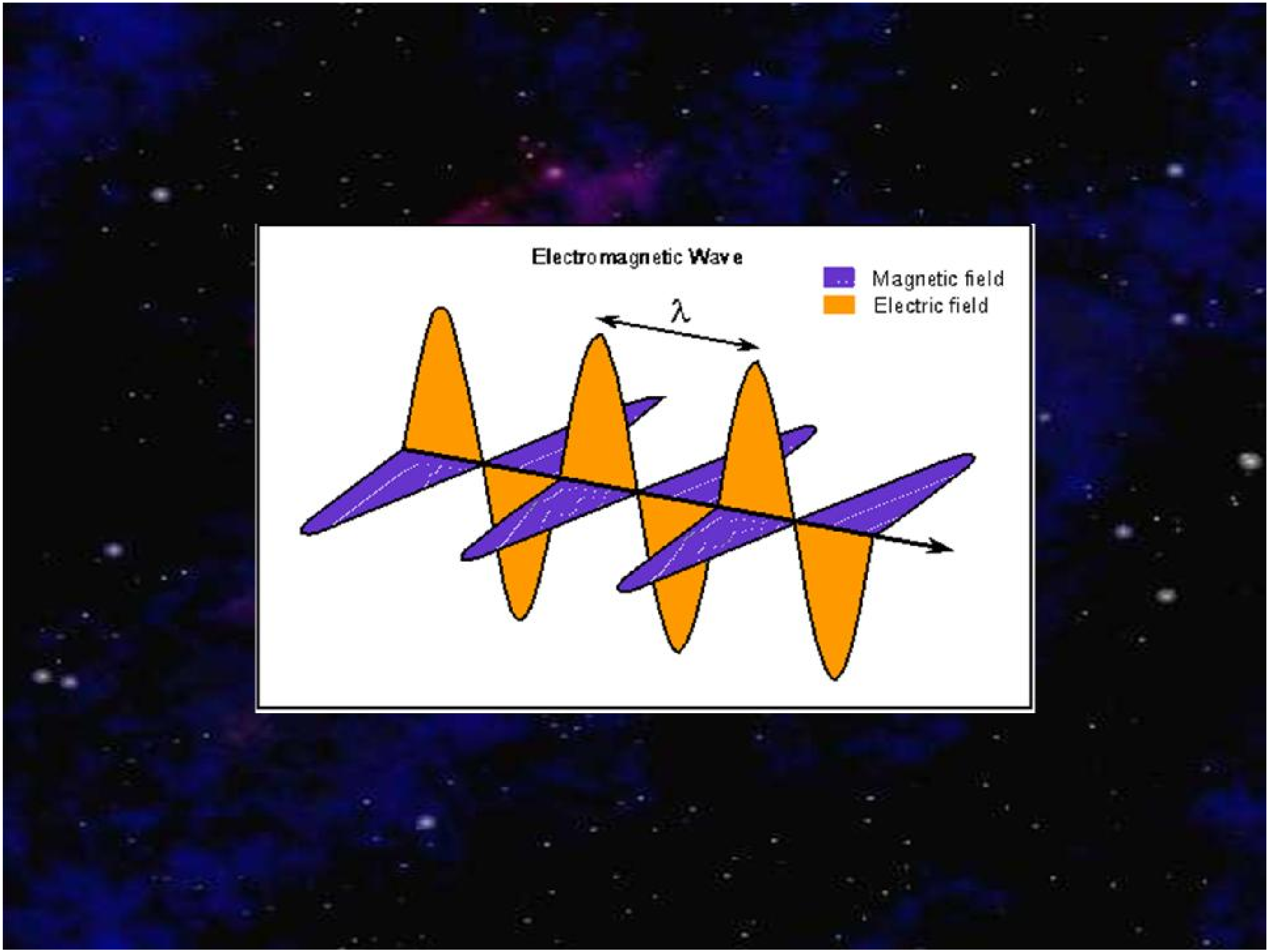
# Wave Mechanics

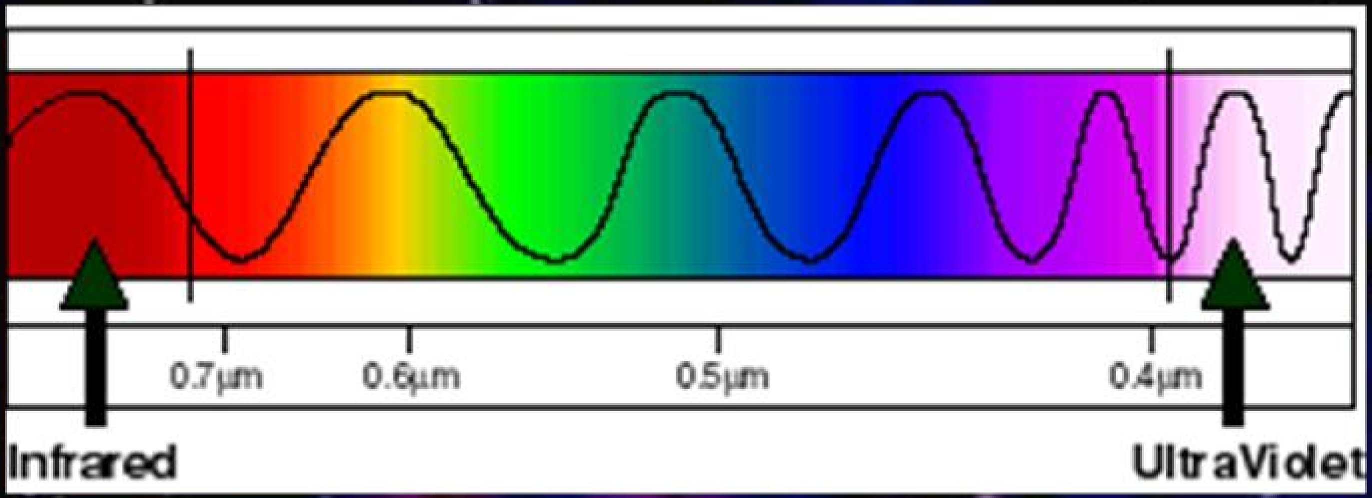



**Wavelength (l)**

- The distance between two successive wave peaks or valleys
- Wavelength for light is measured in **Ångstroms**

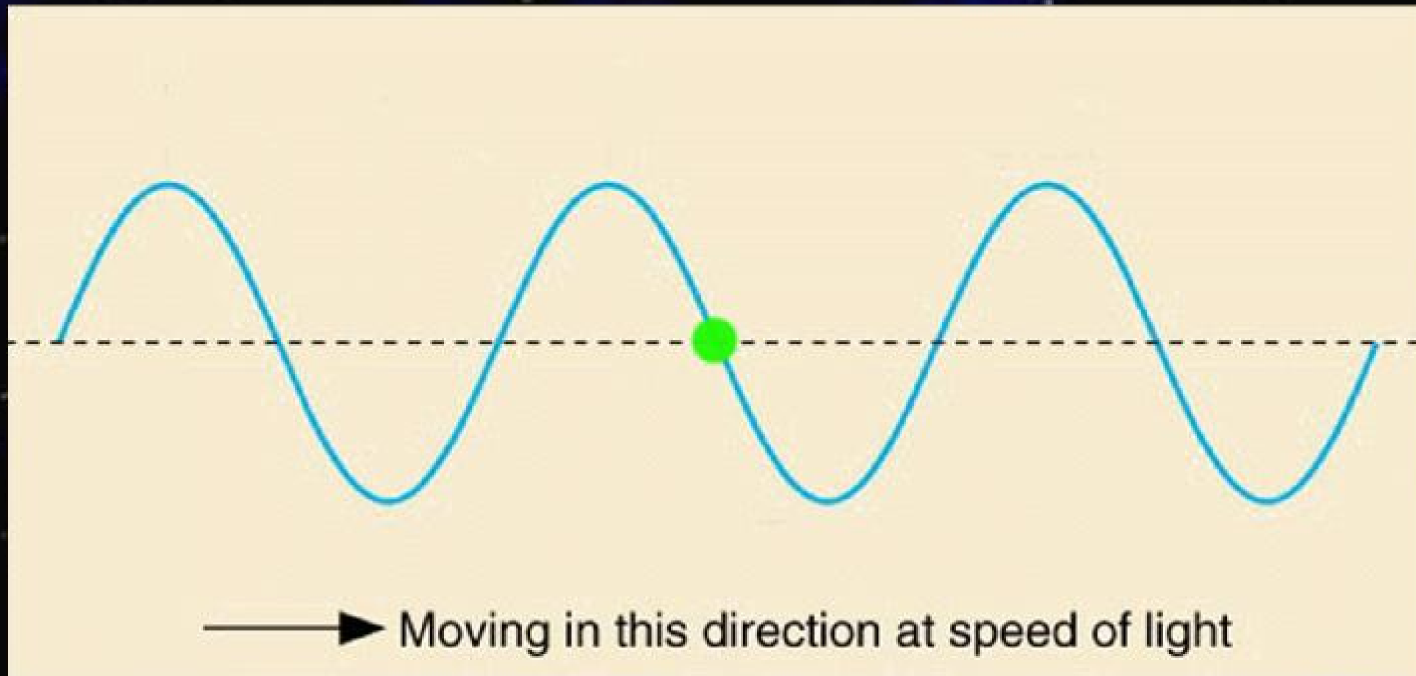
**where 1Å = $10^{-10}$ meters**


Electromagnetic Wave
Magnetic field
Electric field
λ




Range of wavelengths for visible light:

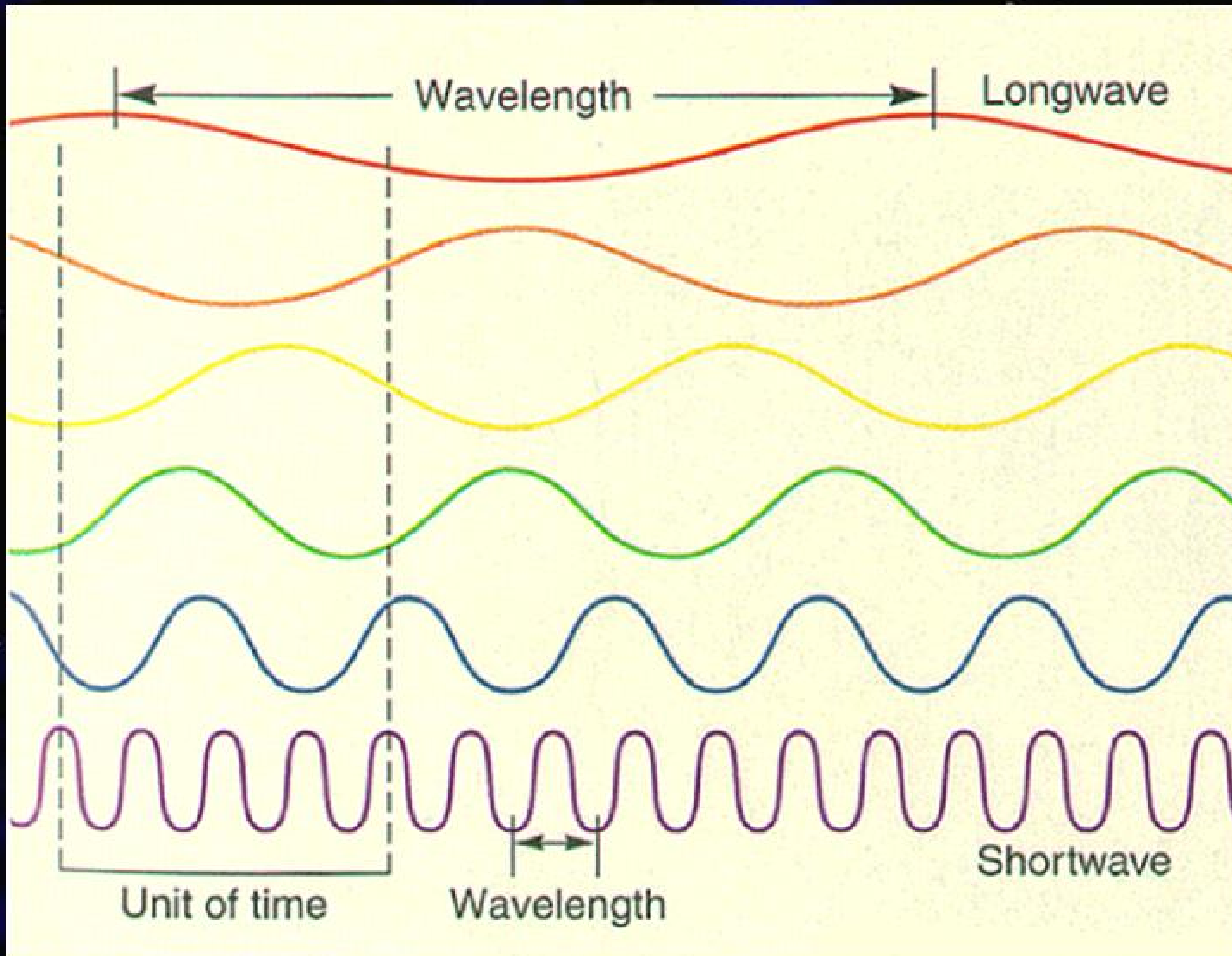
**7000 Å – 4000 Å**

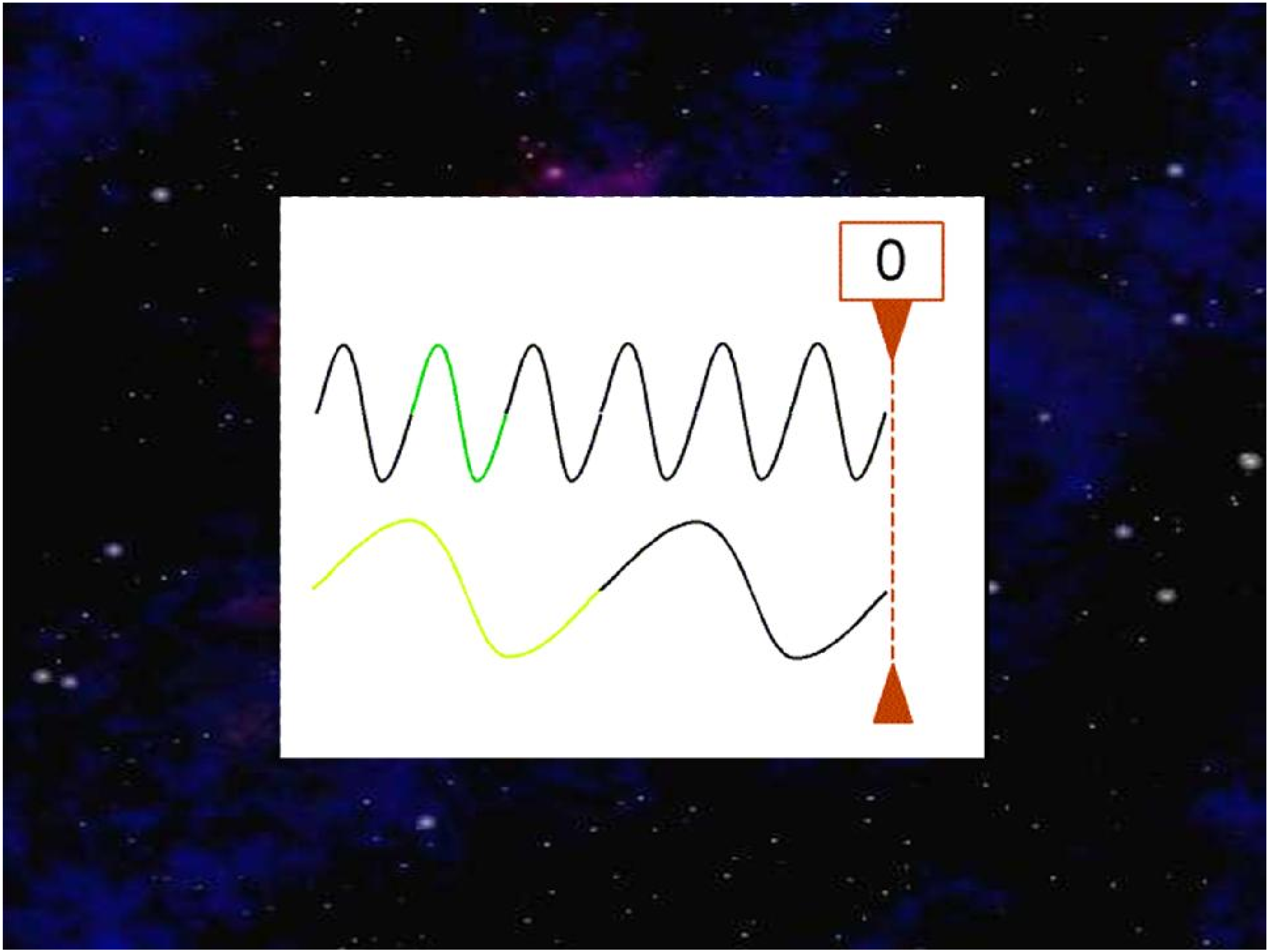



**Frequency (n)**

The number of cycles per second that pass a given point.

Hertz (Hz) where 1Hz = 1 cycle/second


Wavelength
Longwave
Shortwave
Unit of time
Wavelength


0

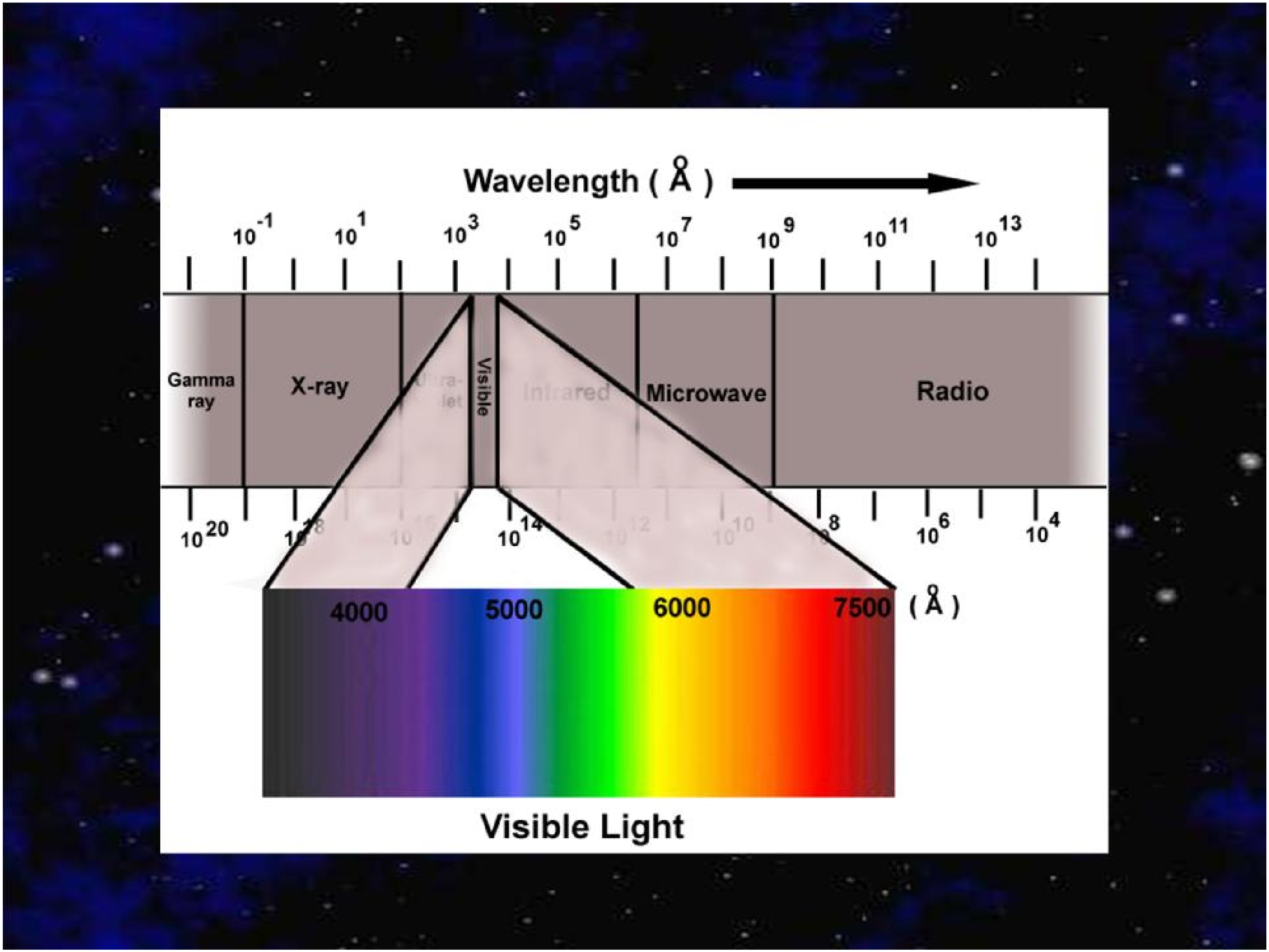
# How are wavelength and frequency related?

Speed = wavelength x frequency

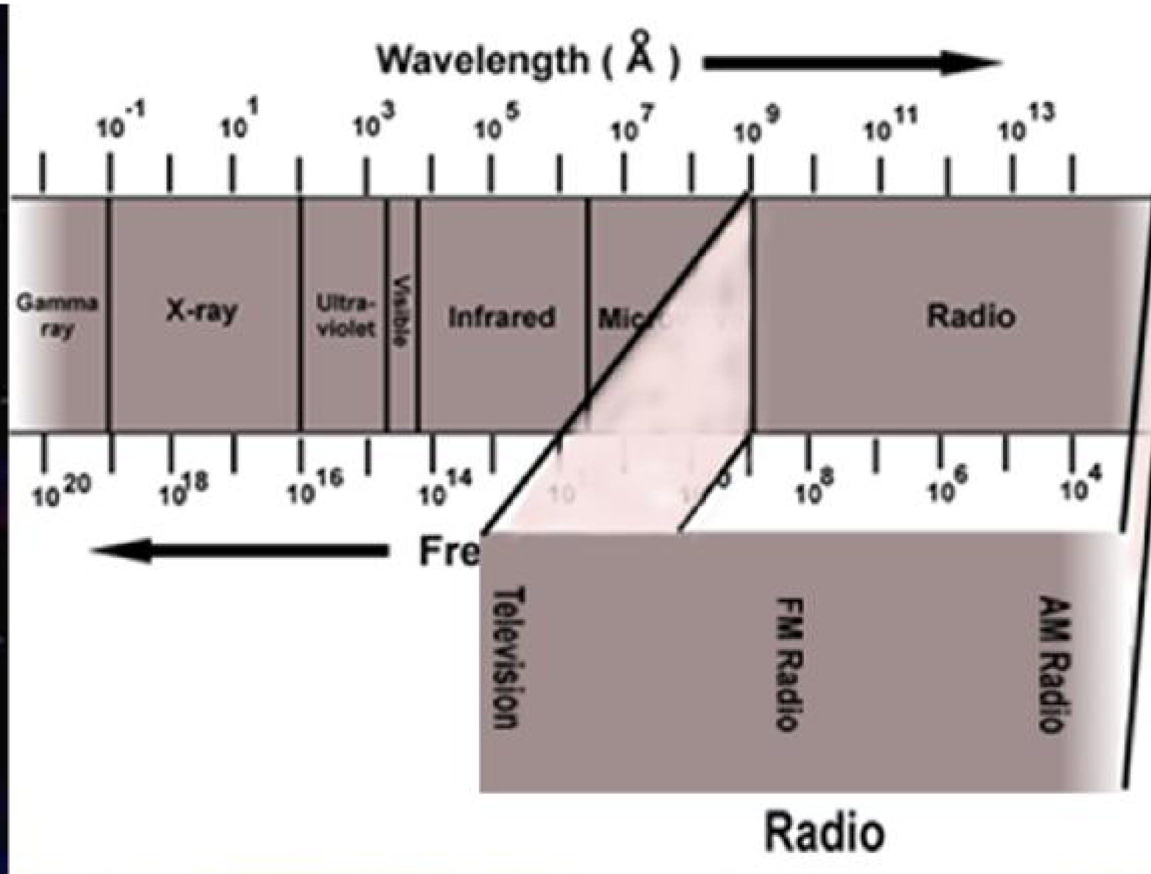
$$c = l\ u$$

$$u = \frac{c}{l}$$

$$l = \frac{c}{u}$$



Wavelength ( Å )
$10^{-1}$
$10^{1}$
$10^{3}$
$10^{5}$
$10^{7}$
$10^{9}$
$10^{11}$
$10^{13}$
Gamma ray
X-ray
Visible
Microwave
Radio
$10^{20}$
$10^{14}$
$10^{6}$
$10^{4}$
4000
5000
6000
7500
( Å )
Visible Light




FM Radio

88 MHz – 108 MHz

11.2 ft – 9.2 ft

AM Radio

540 KHz – 1650 KHz

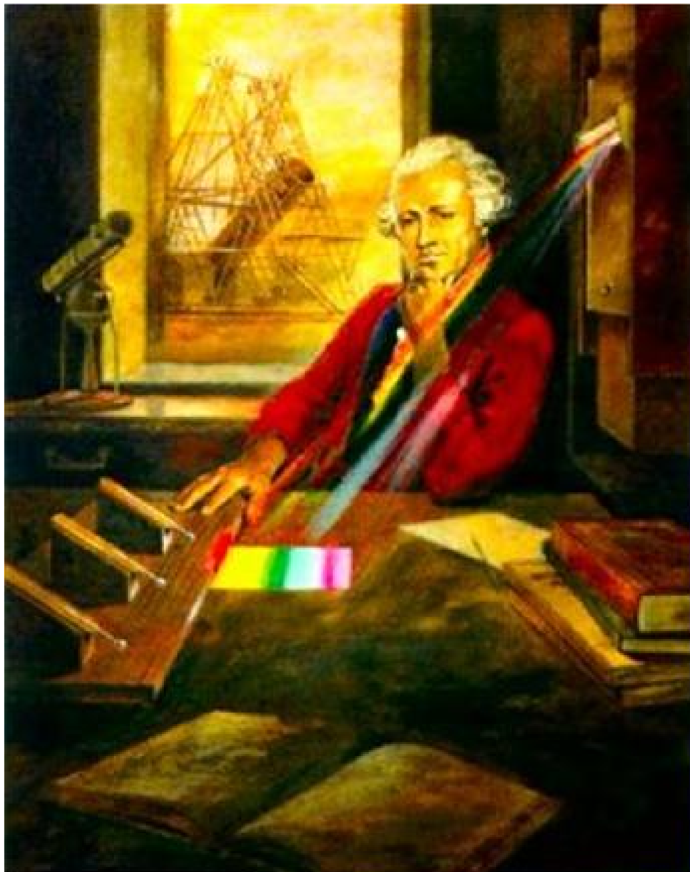
1825 ft – 598 ft

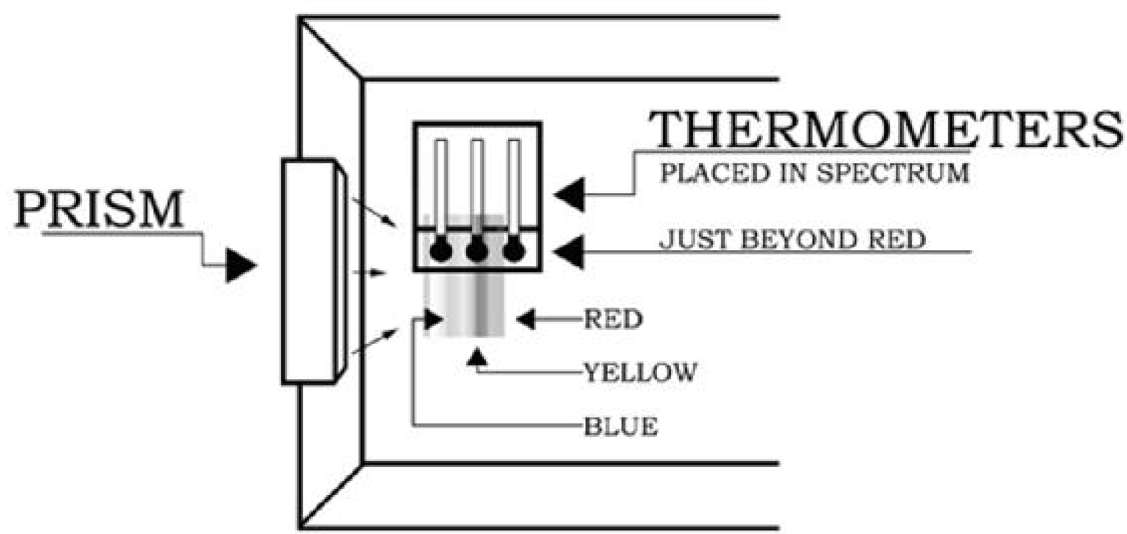
Television

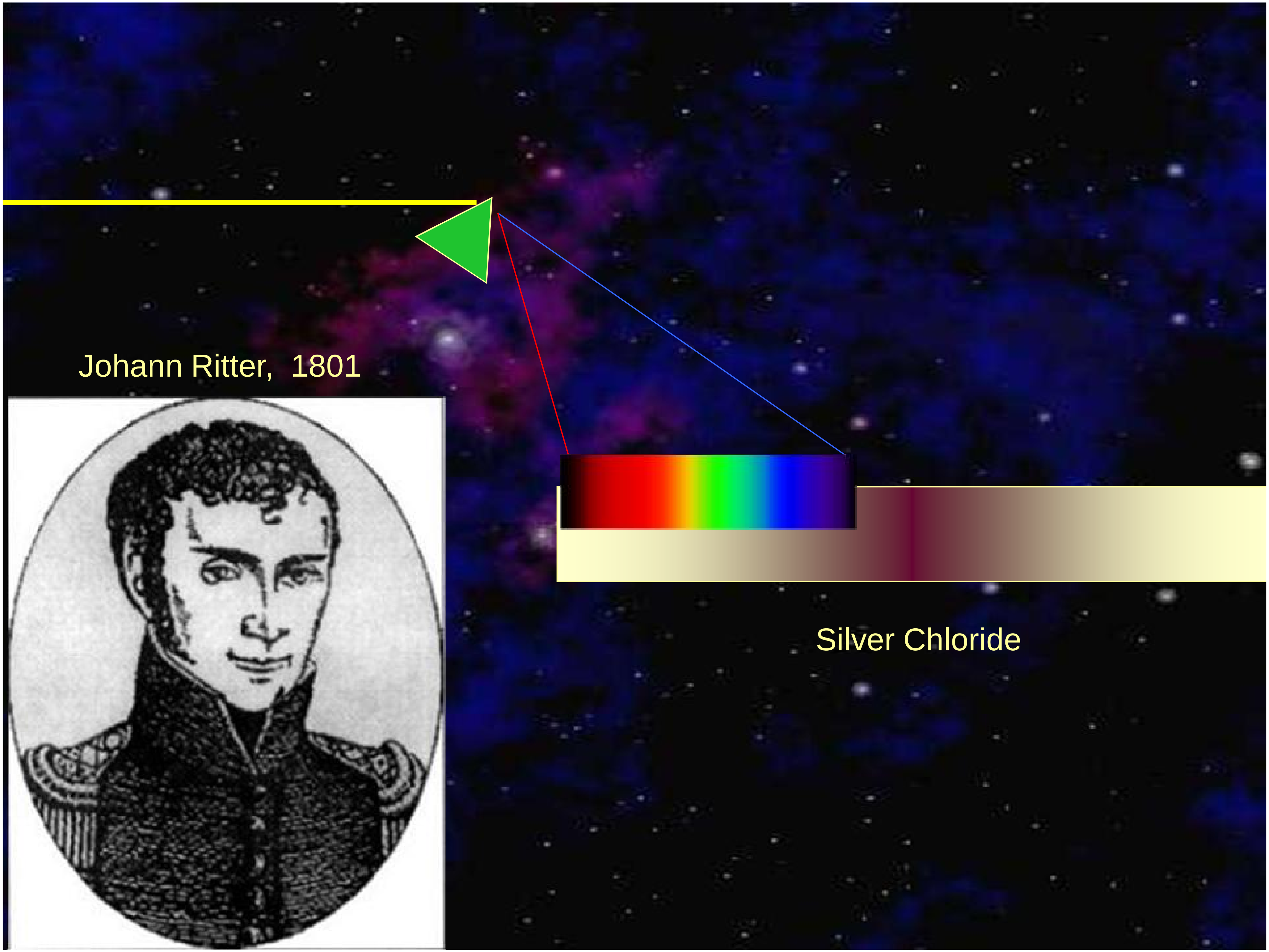
1 GHz – 100 GHz

1 ft – 1/10 inch

Sir Frederick William Herschel, 1800

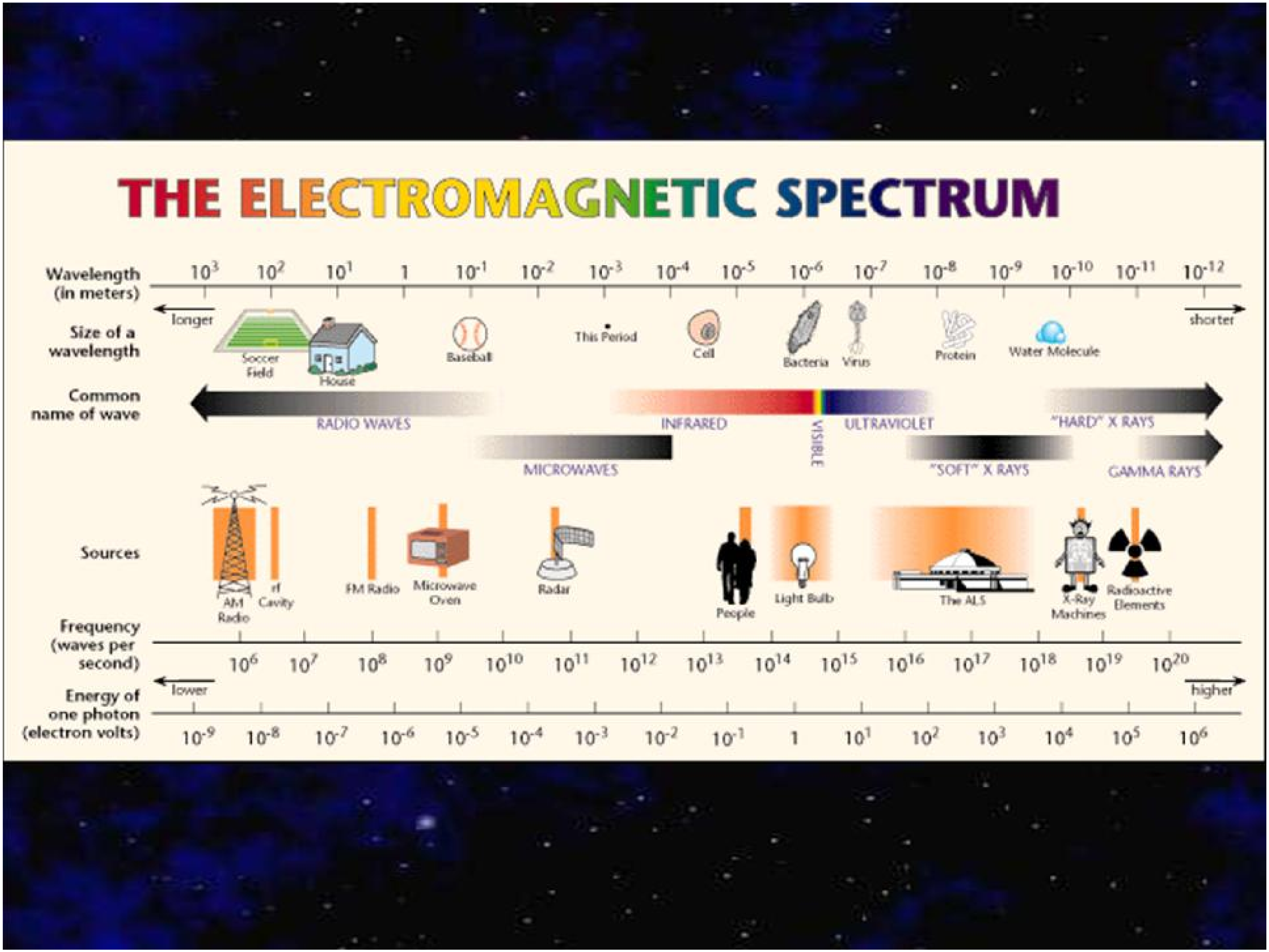





Johann Ritter, 1801
Silver Chloride

**Long l = Low n**

**Short l = High n**


THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10³ 10² 10¹ 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
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
lower
higher
Energy of one photon (electron volts)
10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶

# How are Wavelength, Frequency and Energy Related?

"Light is composed of packets of energy (particles) called *PHOTONS* "

Each photon carries an associated energy with it

$$E = \frac{hc}{l} \quad OR \quad E = hu$$

Example:

Photon energy for red light:

E=0.00012 calories

Photon energy for blue light:

E=0.00021 calories

**Short l = High Energy**

**Long l = Low Energy**

Example:

Photon energy for red light:

E=0.00012 calories

Photon energy for blue light:

E=0.00021 calories

1 Calorie = amount of energy needed to raise temperature of 1 gram (~ 1 teaspoon) of water 1 degree C

red light = 8333 photons
blue light = 4761 photons

# James Clerk Maxwell

# Maxwell's Equations

$$\nabla \cdot \mathbf{D} = \rho \qquad \oint_S \mathbf{D} \cdot d\mathbf{A} = \int_V \rho dV$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \oint_S \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad \oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt} \int_S \mathbf{B} \cdot d\mathbf{A}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \qquad \oint_C \mathbf{H} \cdot d\mathbf{l} = \int_S \mathbf{J} \cdot d\mathbf{A} + \frac{d}{dt} \int_S \mathbf{D} \cdot d\mathbf{A}$$

Michael Faraday

# Electromagnetic Radiation and Temperature

***<u>Everything</u>*** in the Universe has a temperature associated with it.

Temperature can be thought of as a measure of the average velocity of atoms or molecules.

## TEMPERATURE SCALES:

FAHRENHEIT (°F)

32° = freezing point of water

212° = boiling point of water

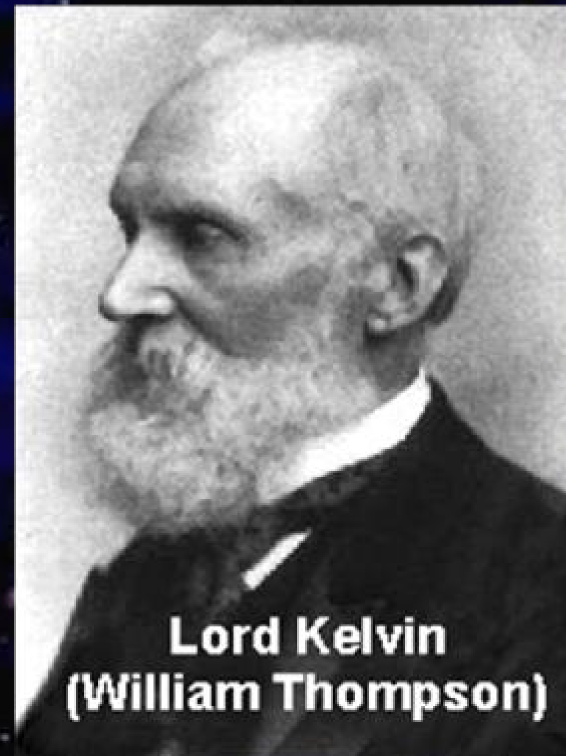
CENTEGRADE (°C)

0° = freezing point of water

100° = boiling point of water

$$T_F = (\tfrac{9}{5} T_C) + 32 \qquad T_C = (T_F - 32)\tfrac{5}{9}$$

# Absolute Scale

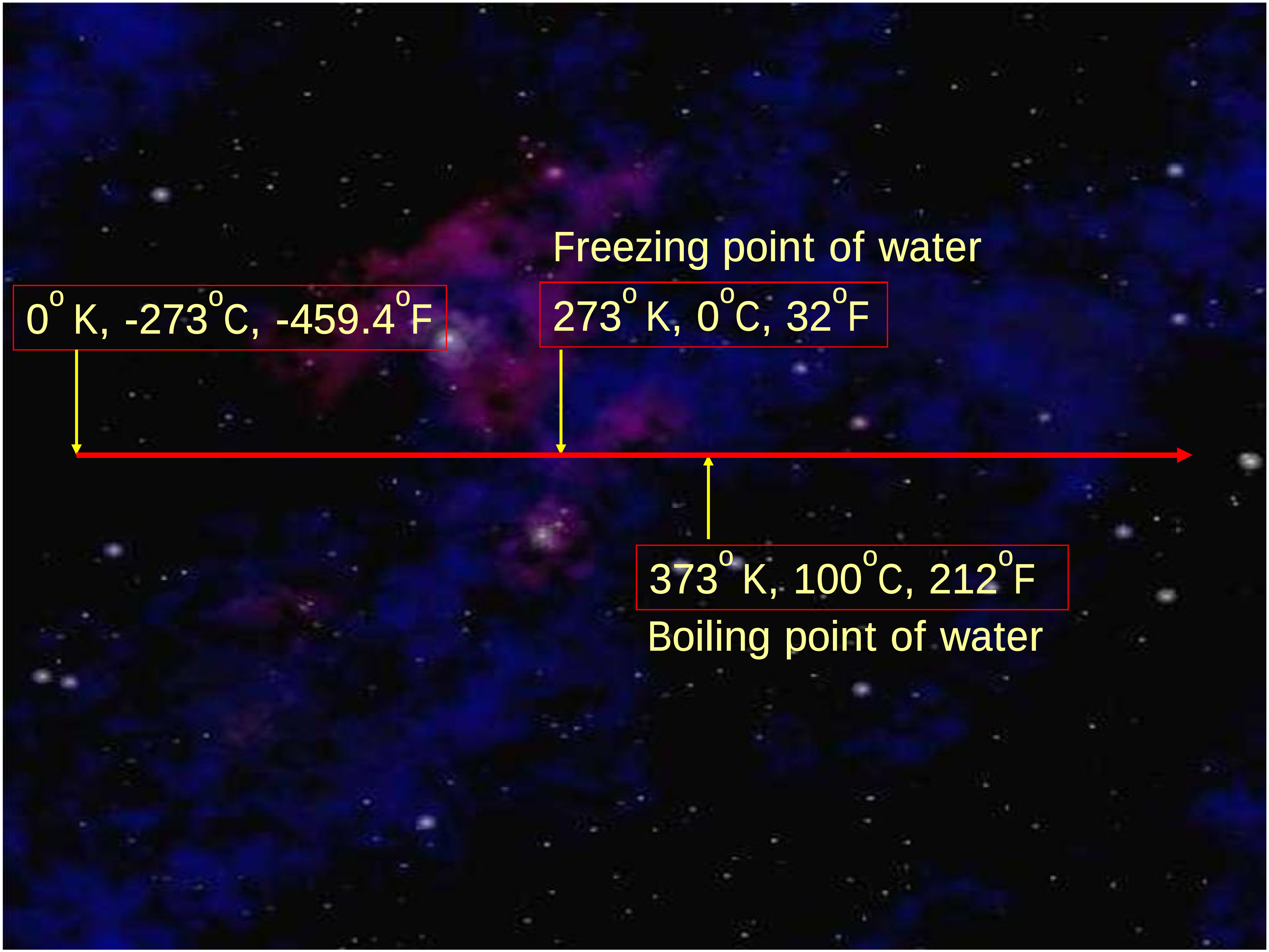



KELVINS (K)

<u>Based on theoretical limit for temperature</u>

**Absolute Zero Ø 0 K**

Uses same increment as CENTIGRADE

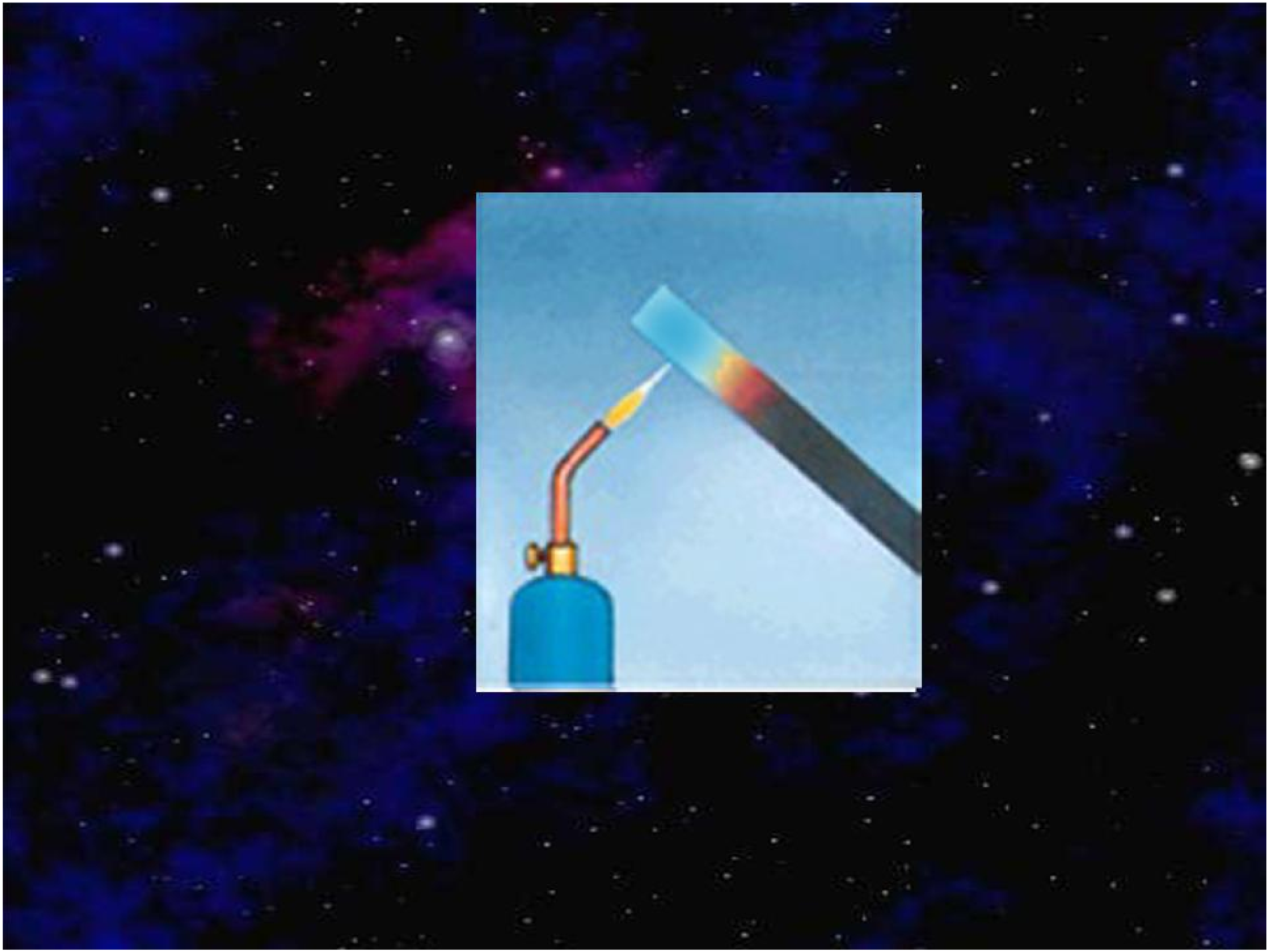

Freezing point of water
0° K, -273°C, -459.4°F
273° K, 0°C, 32°F
373° K, 100°C, 212°F
Boiling point of water

# Josef Stefan (1879)

$$E \propto T^4$$

Everything in the Universe has a temperature associated with it.

Objects in nature will emit energy based upon their temperature.



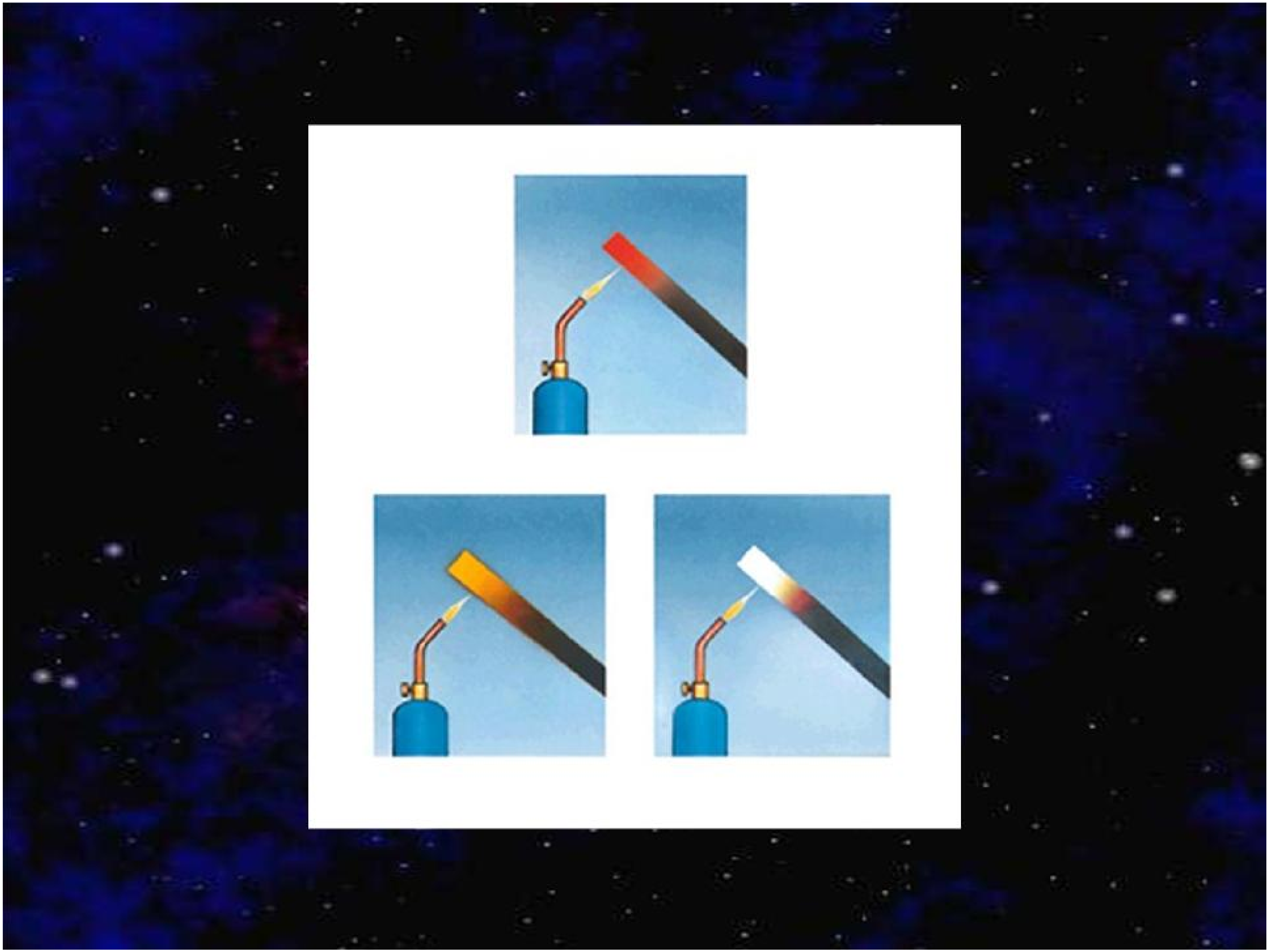
# BLACKBODY RADIATION

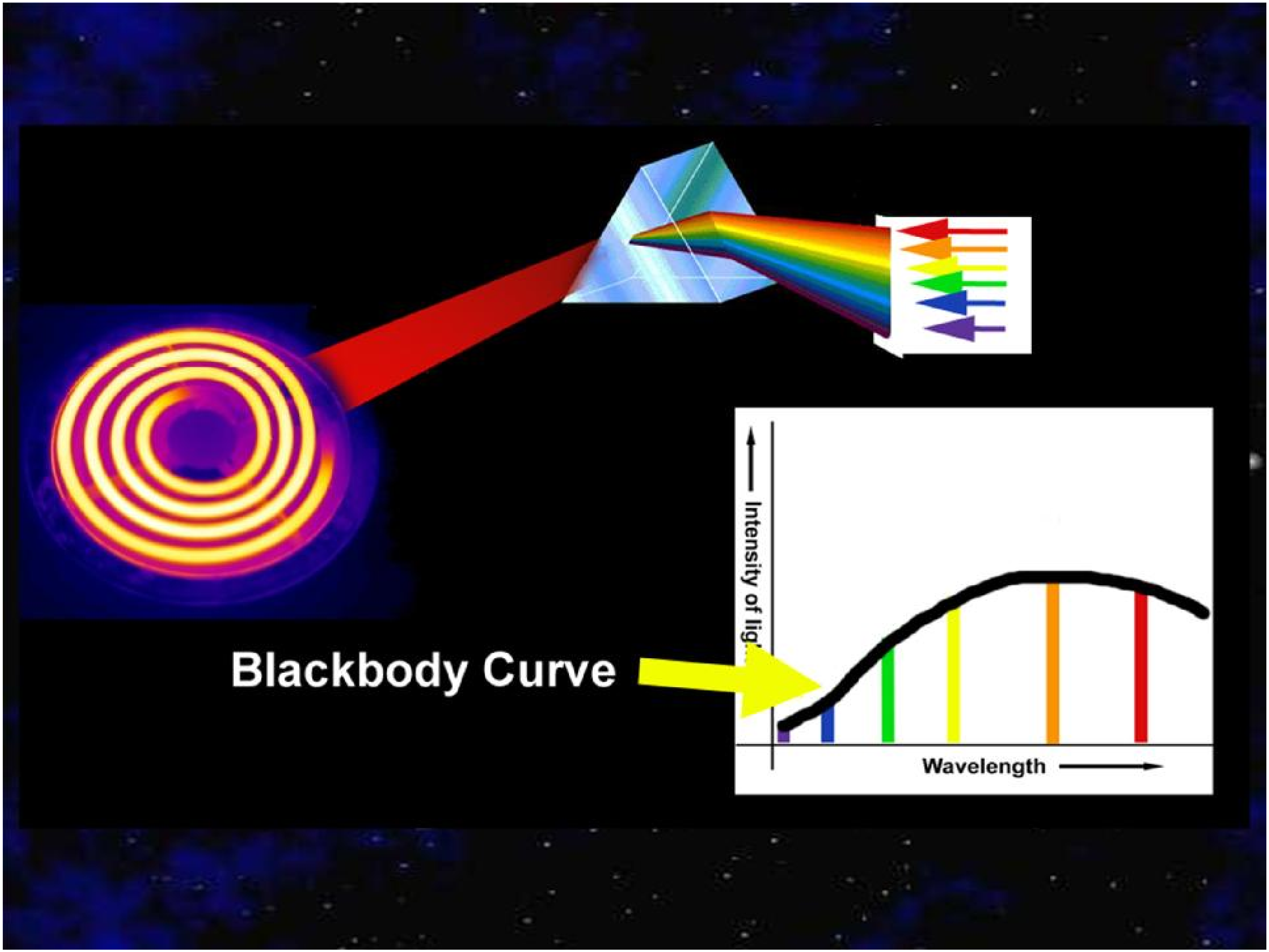
**Thermodynamic Rules for Blackbodies**:

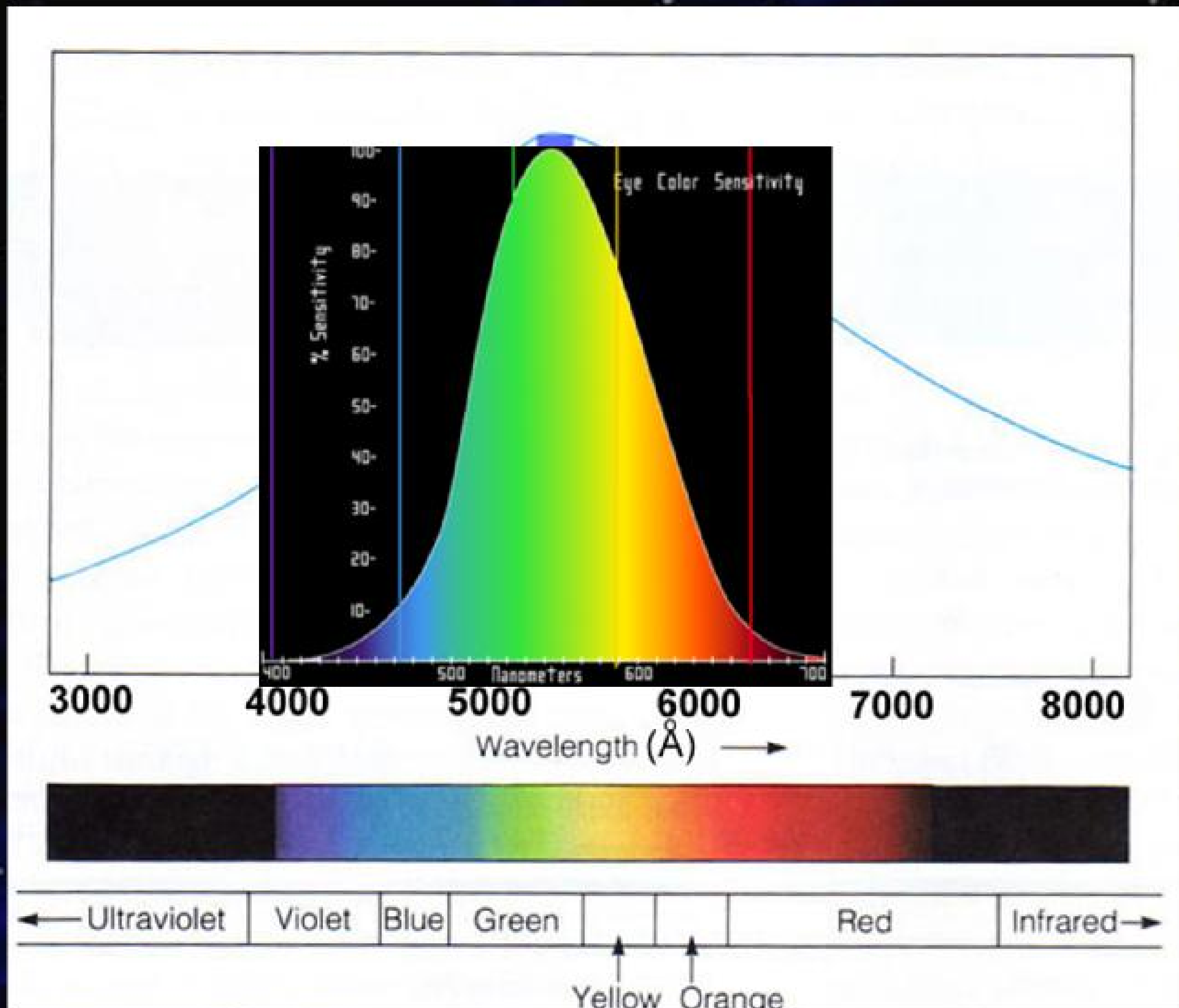
1. An object that reflects ***NO*** light.

2. An object that absorbs ***ALL*** light that falls upon it.

3. An object that emits light as a result of its temperature ***only***.

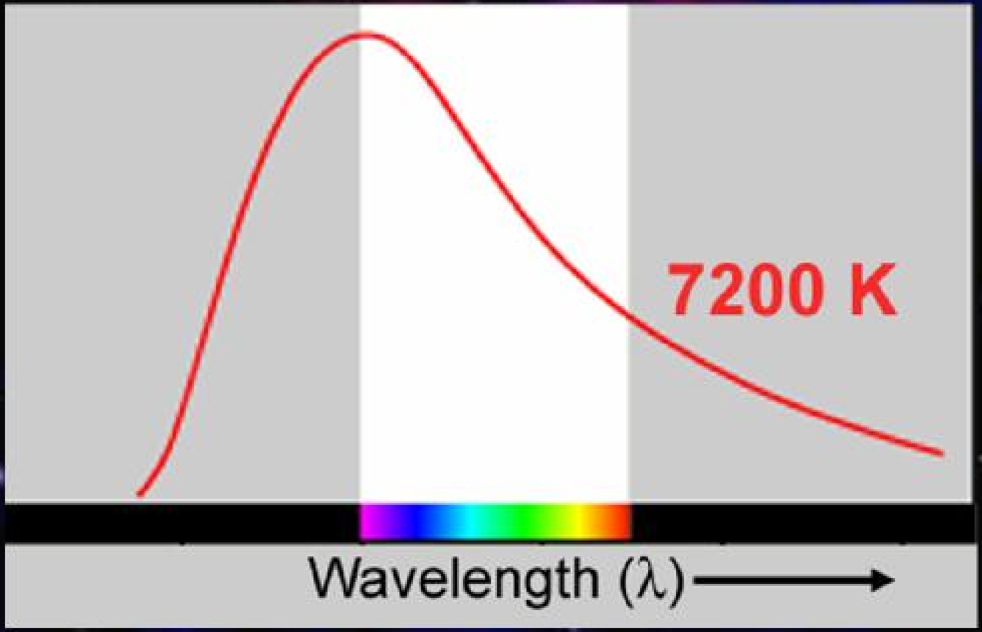



Blackbody Curve
Intensity of lig
Wavelength



Eye Color Sensitivity
% Sensitivity
100
90
80
70
60
50
40
30
20
10
400
500
Nanometers
600
700
3000
4000
5000
6000
7000
8000
Wavelength (Å)
Ultraviolet
Violet
Blue
Green
Red
Infrared
Yellow
Orange

# Wilhelm Wien (1897)




# Wilhelm Wien (1897)

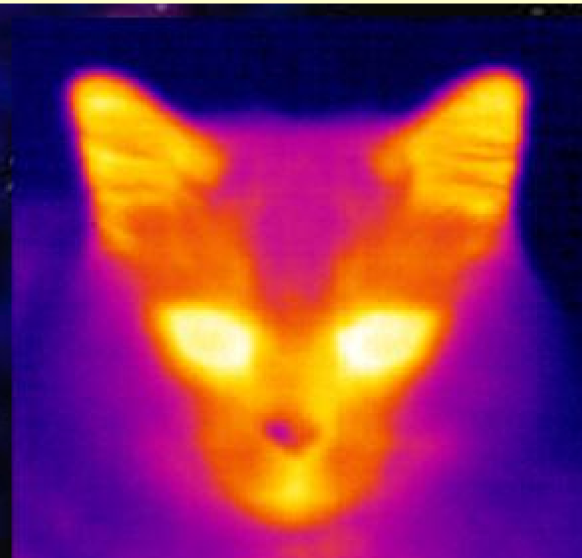
$$l_{max} = \frac{2.9 \times 10^7}{T}$$

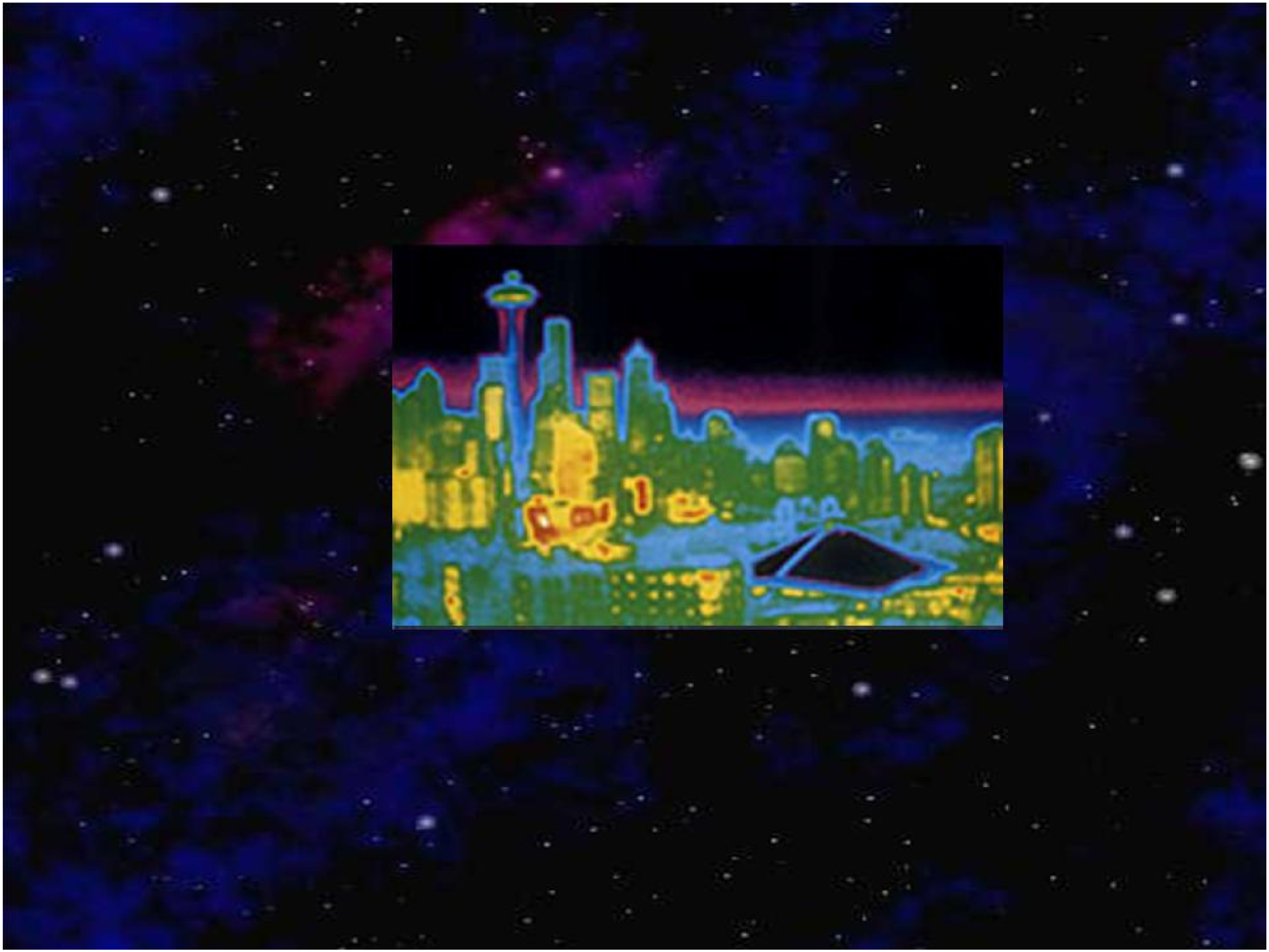
$$T = \frac{2.9 \times 10^7}{l_{max}}$$

# Example of Wien's Law:

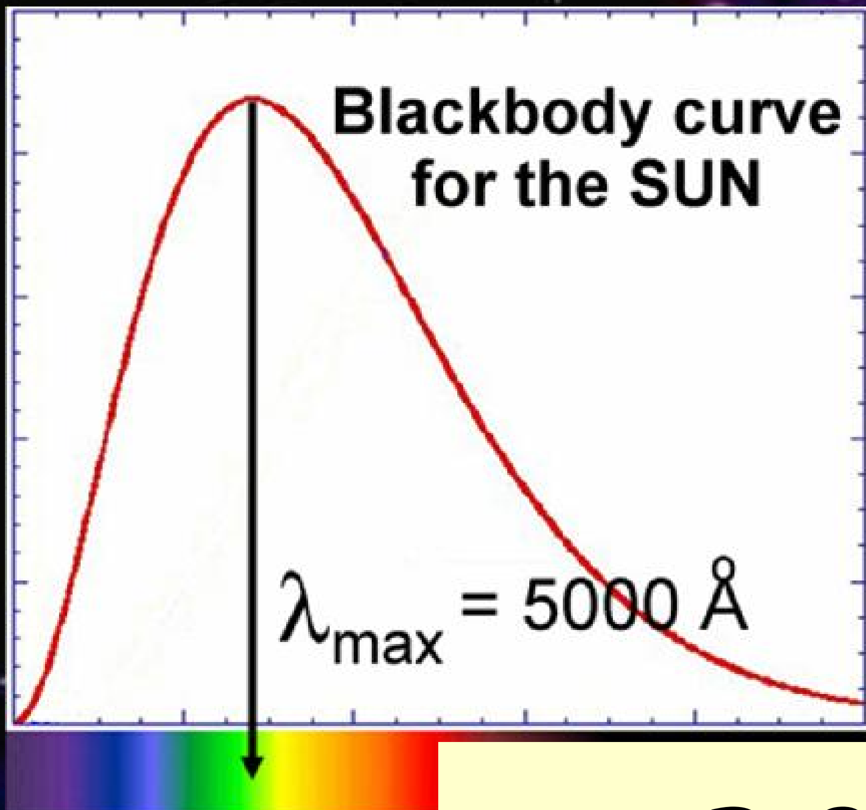
How to find the cat in the dark...

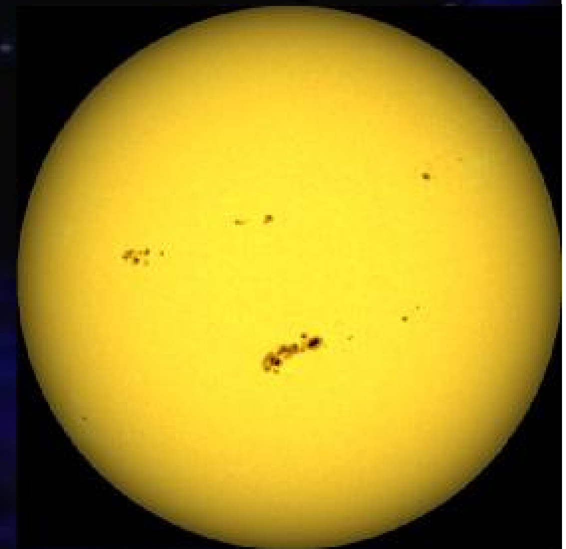
$$l_{\max} = \frac{2.9\times10^{7}}{T} = \frac{2.9\times10^{7}}{311} = 93247\ A$$





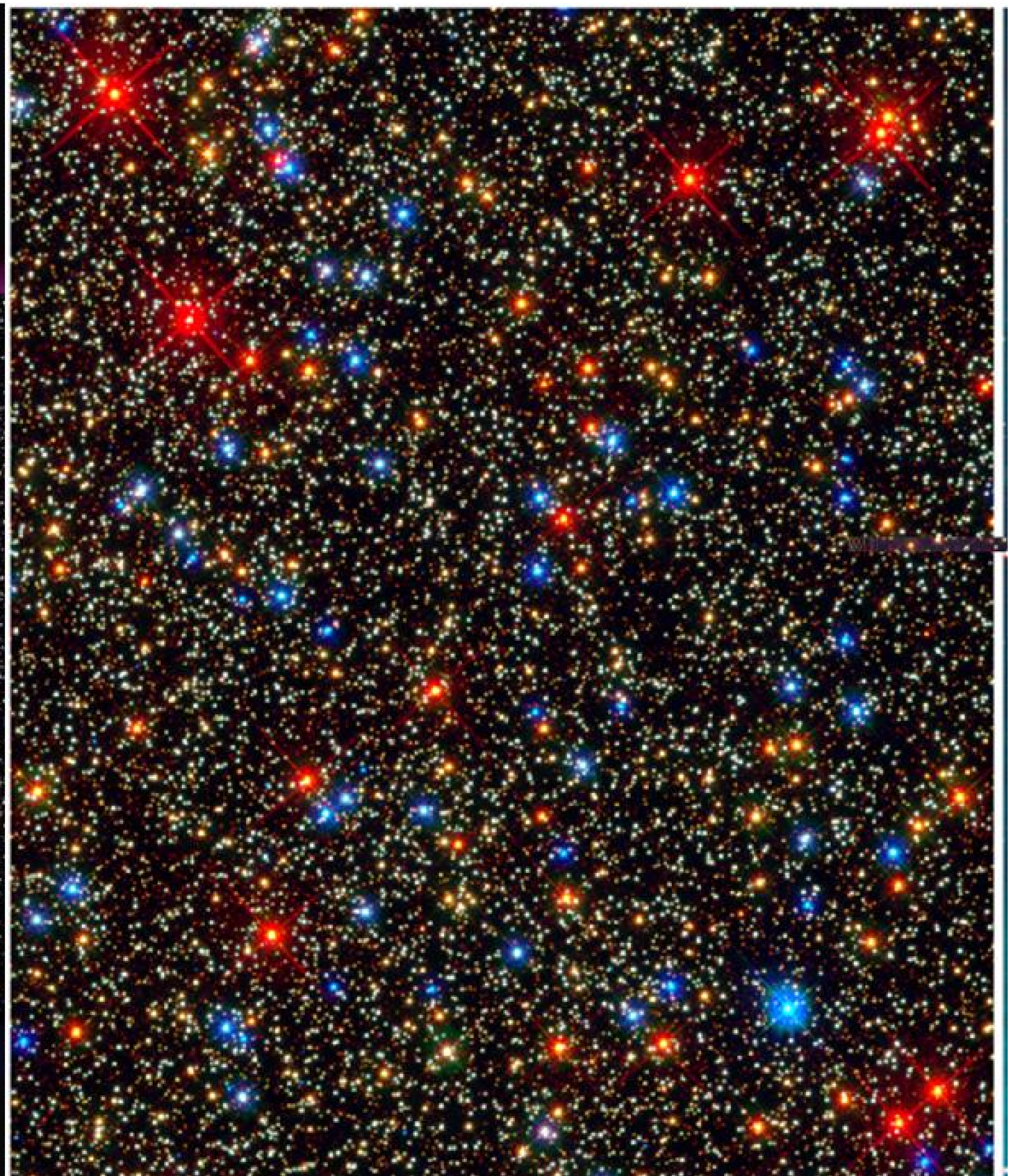
# Temperature of the Sun



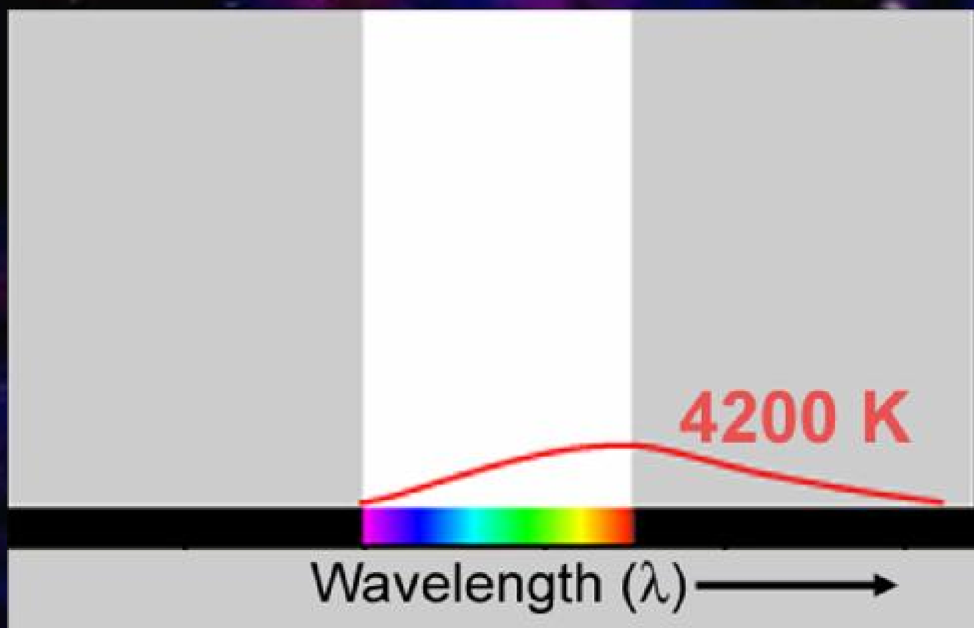



$$T = \frac{2.9\times10^7}{5000A} = 5800K$$

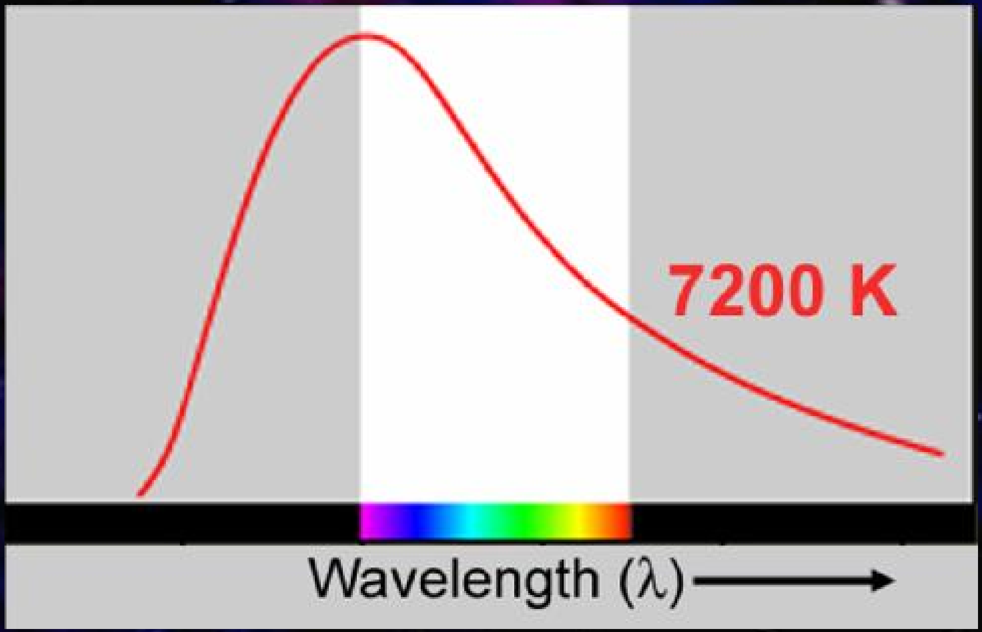
# Star Colors

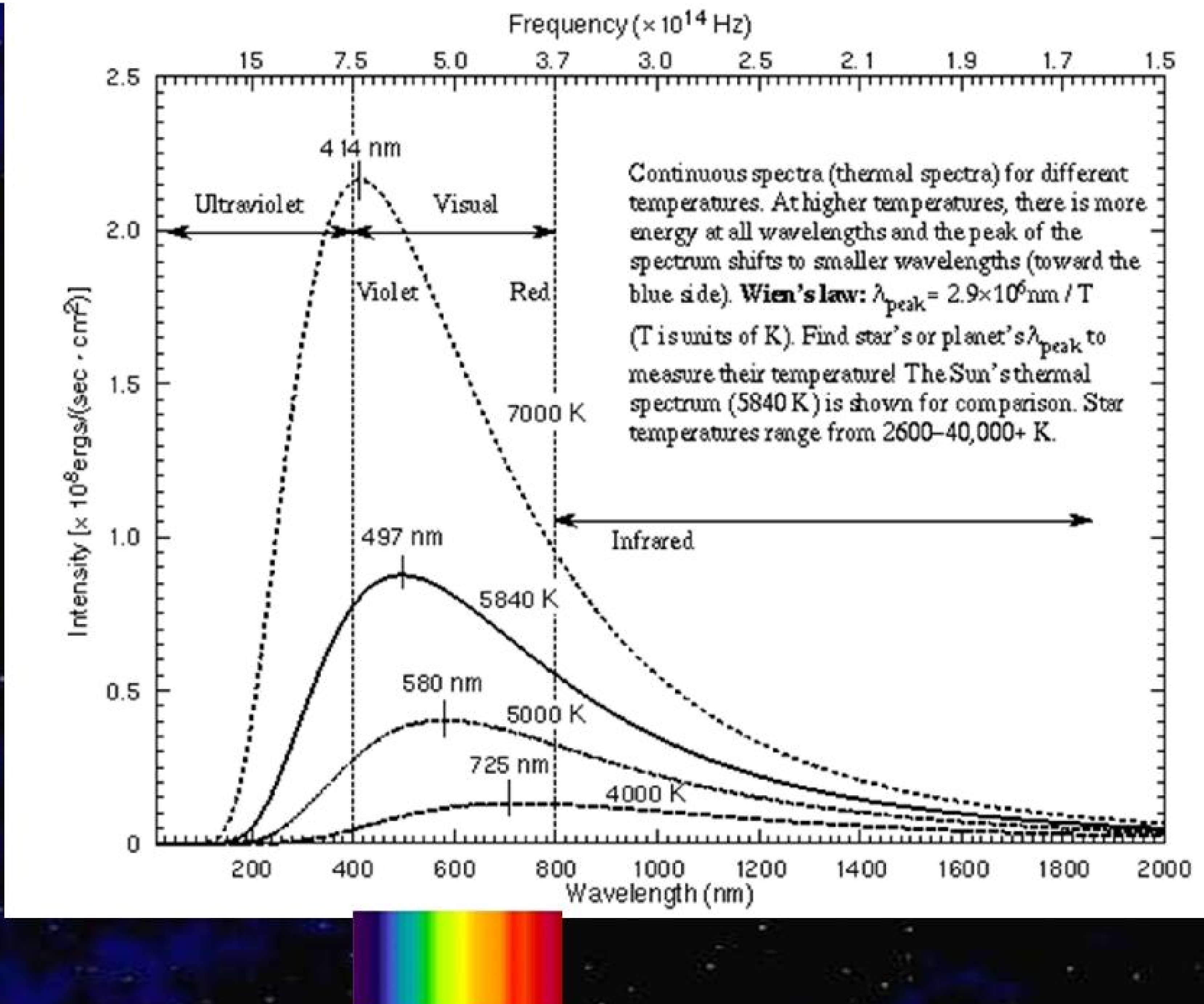


# Star Colors

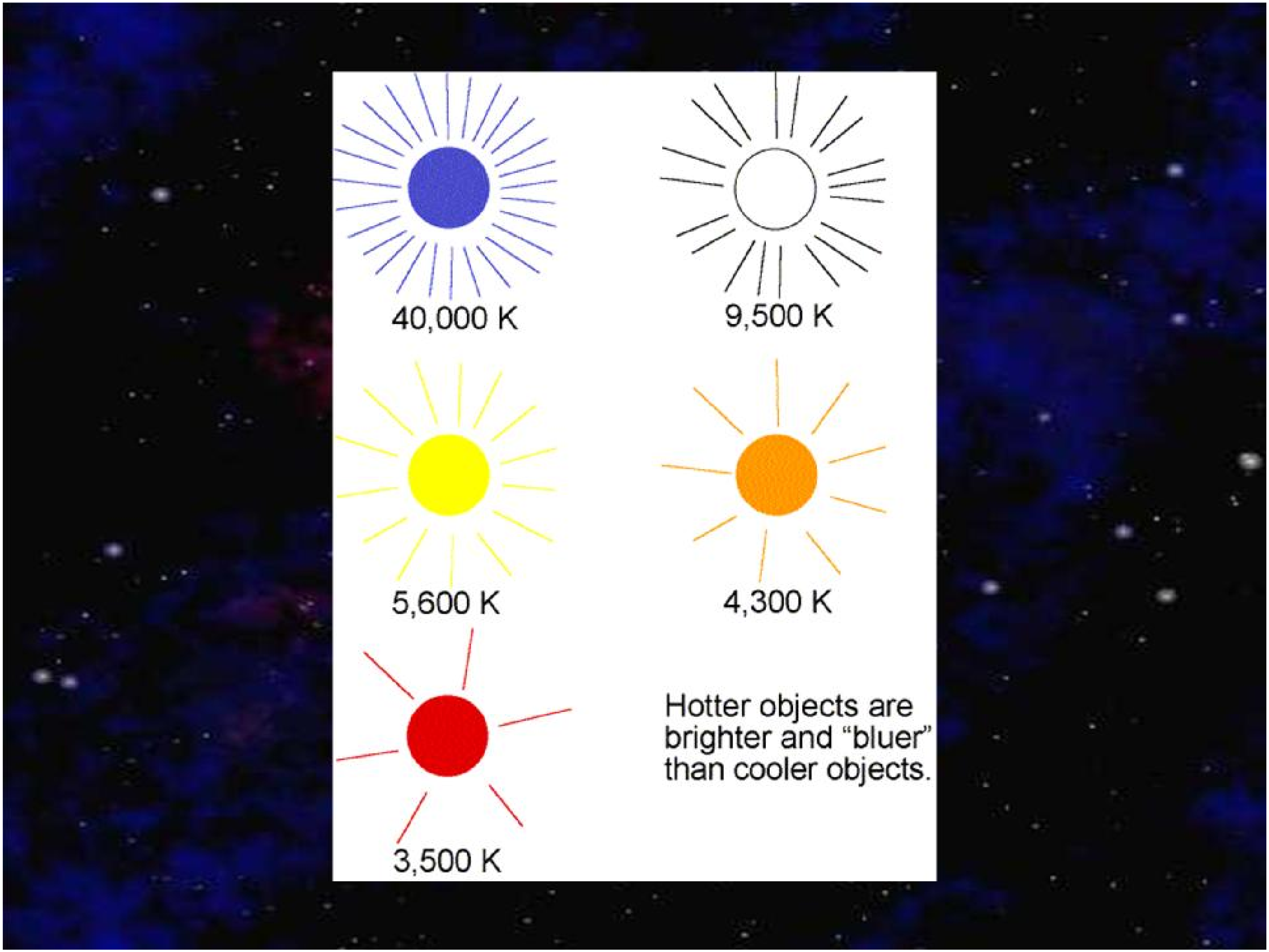



# Star Colors

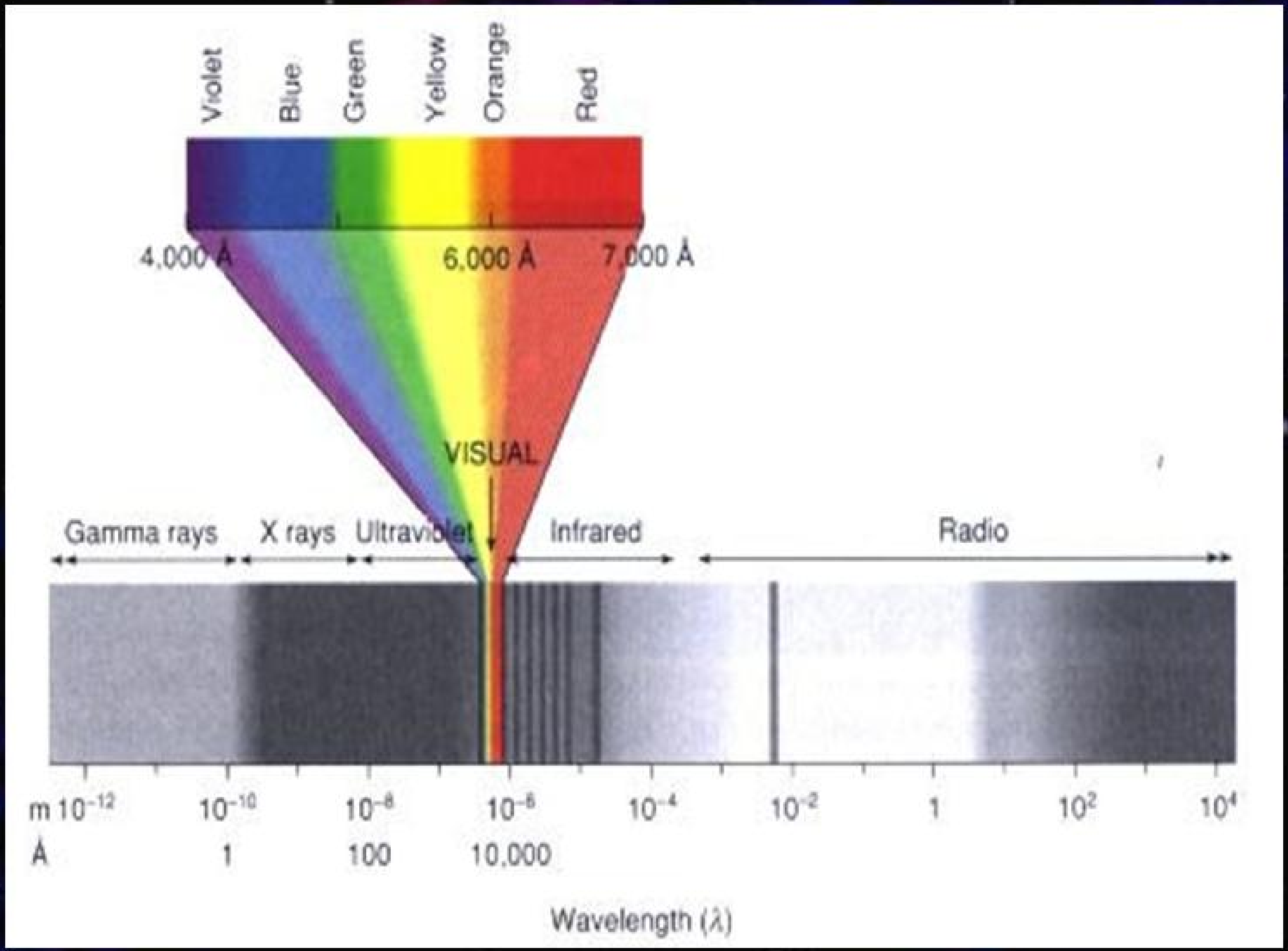



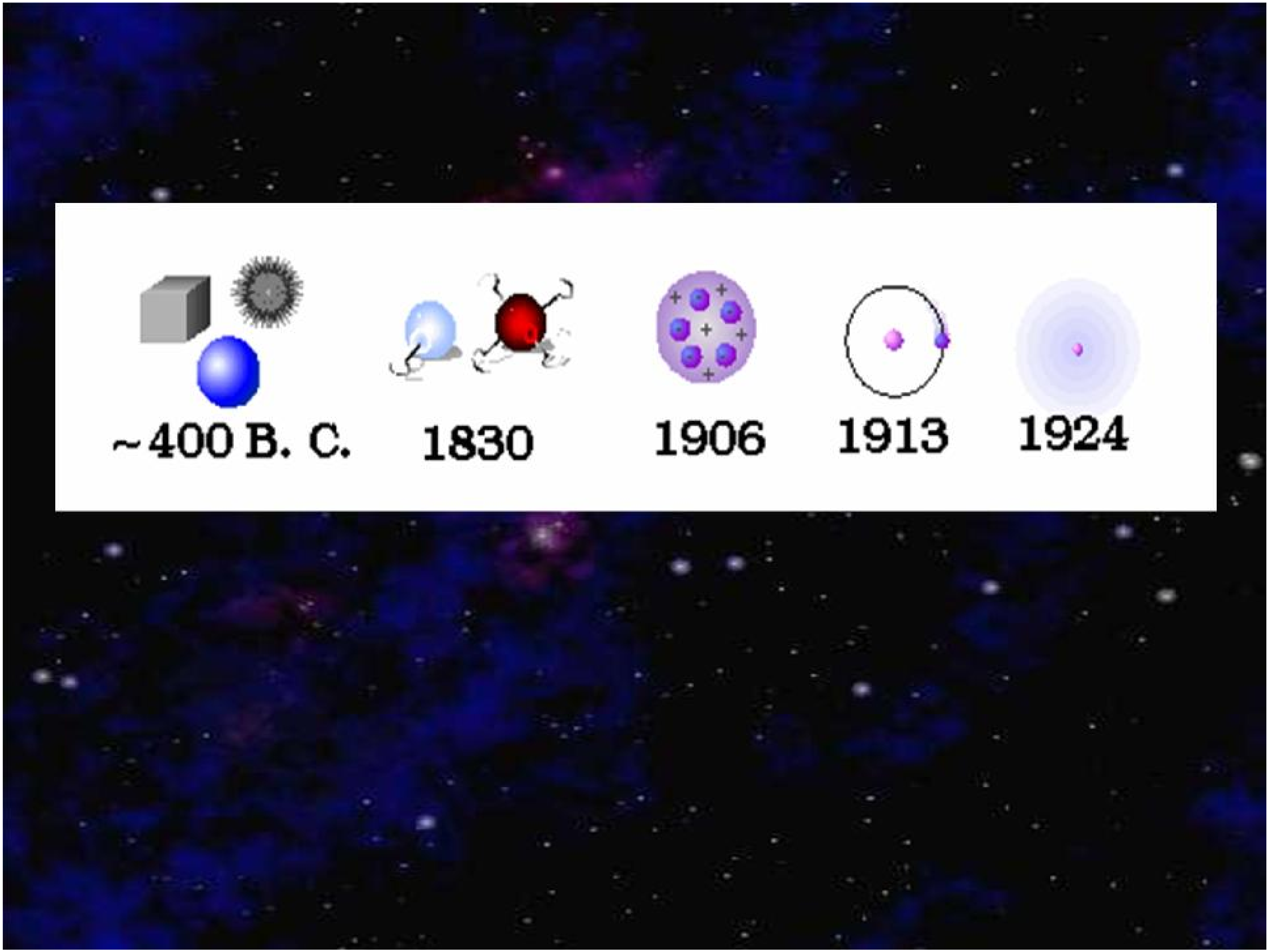


Frequency (× 10^14 Hz)
15
7.5
5.0
3.7
3.0
2.5
2.1
1.9
1.7
1.5
2.5
2.0
1.5
1.0
0.5
0
Intensity [× 10^8 ergs/(sec · cm^2)]
414 nm
Ultraviolet
Visual
Violet
Red
7000 K
Infrared
497 nm
5840 K
580 nm
5000 K
725 nm
4000 K
200
400
600
800
1000
1200
1400
1600
1800
2000
Wavelength (nm)
Continuous spectra (thermal spectra) for different temperatures. At higher temperatures, there is more energy at all wavelengths and the peak of the spectrum shifts to smaller wavelengths (toward the blue side). **Wien's law:** $\lambda_{peak} = 2.9\times10^6 nm / T$ (T is units of K). Find star's or planet's $\lambda_{peak}$ to measure their temperature! The Sun's thermal spectrum (5840 K) is shown for comparison. Star temperatures range from 2600–40,000+ K.

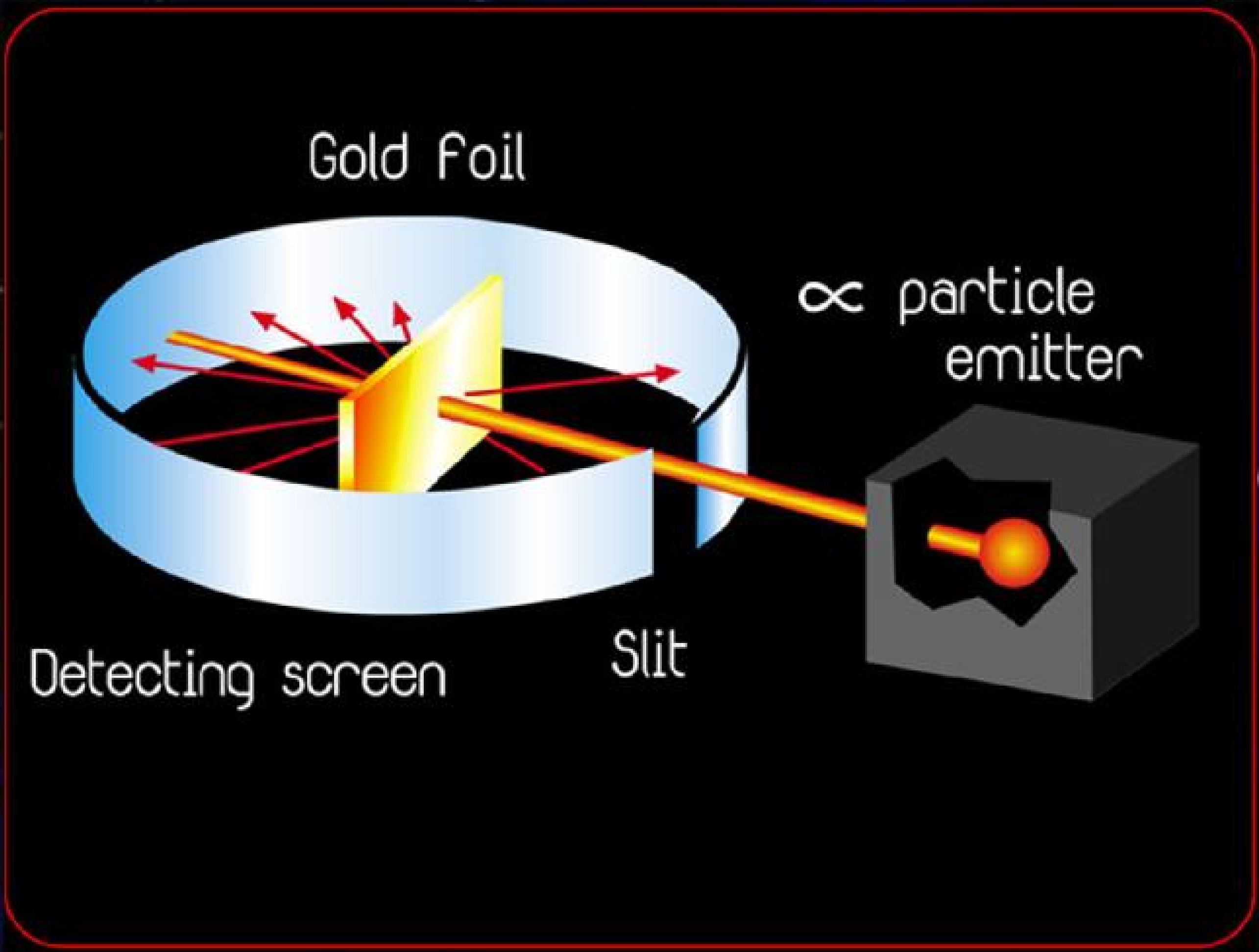

40,000 K
9,500 K
5,600 K
4,300 K
3,500 K
Hotter objects are brighter and "bluer" than cooler objects.

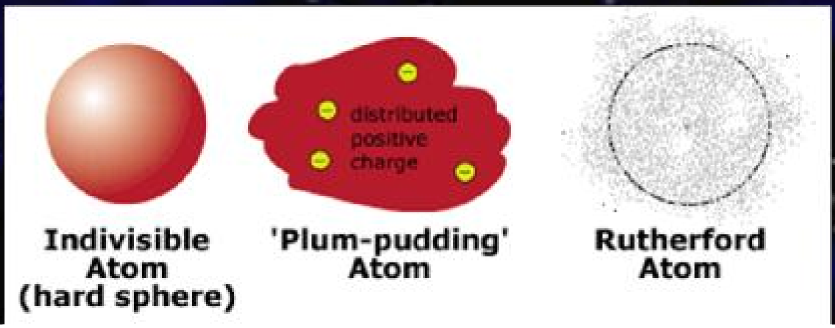
# *The Electromagnetic Spectrum*



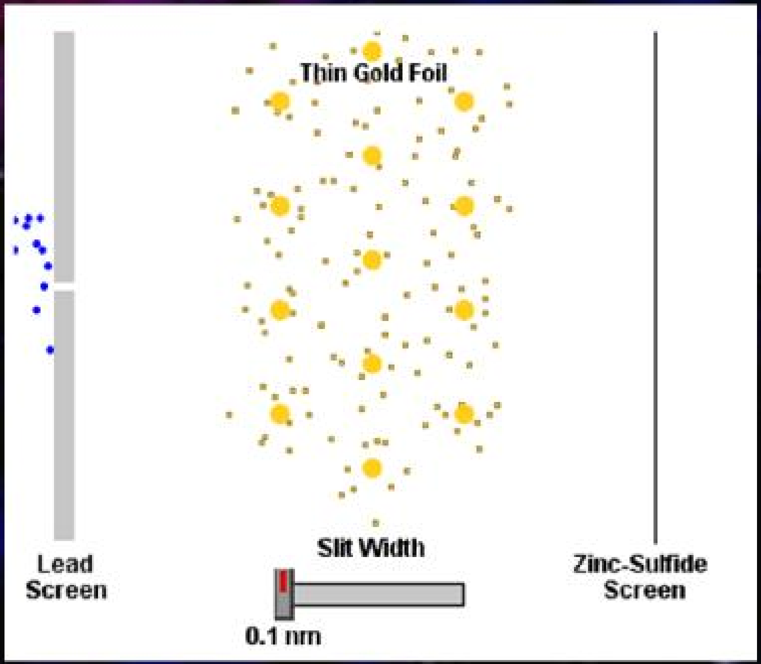

~400 B. C.
1830
1906
1913
1924

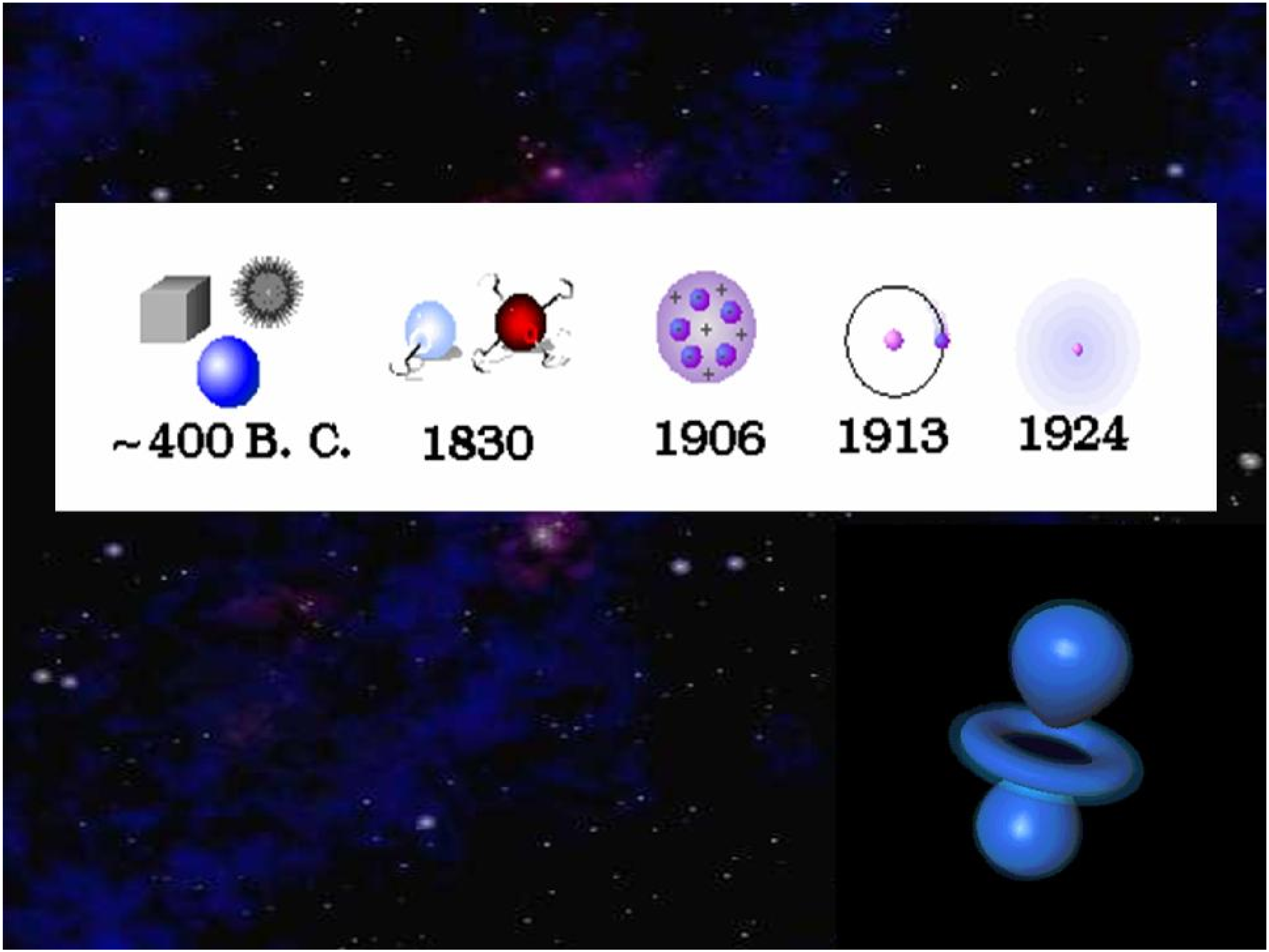
# *Ernest Rutherford, 1911*

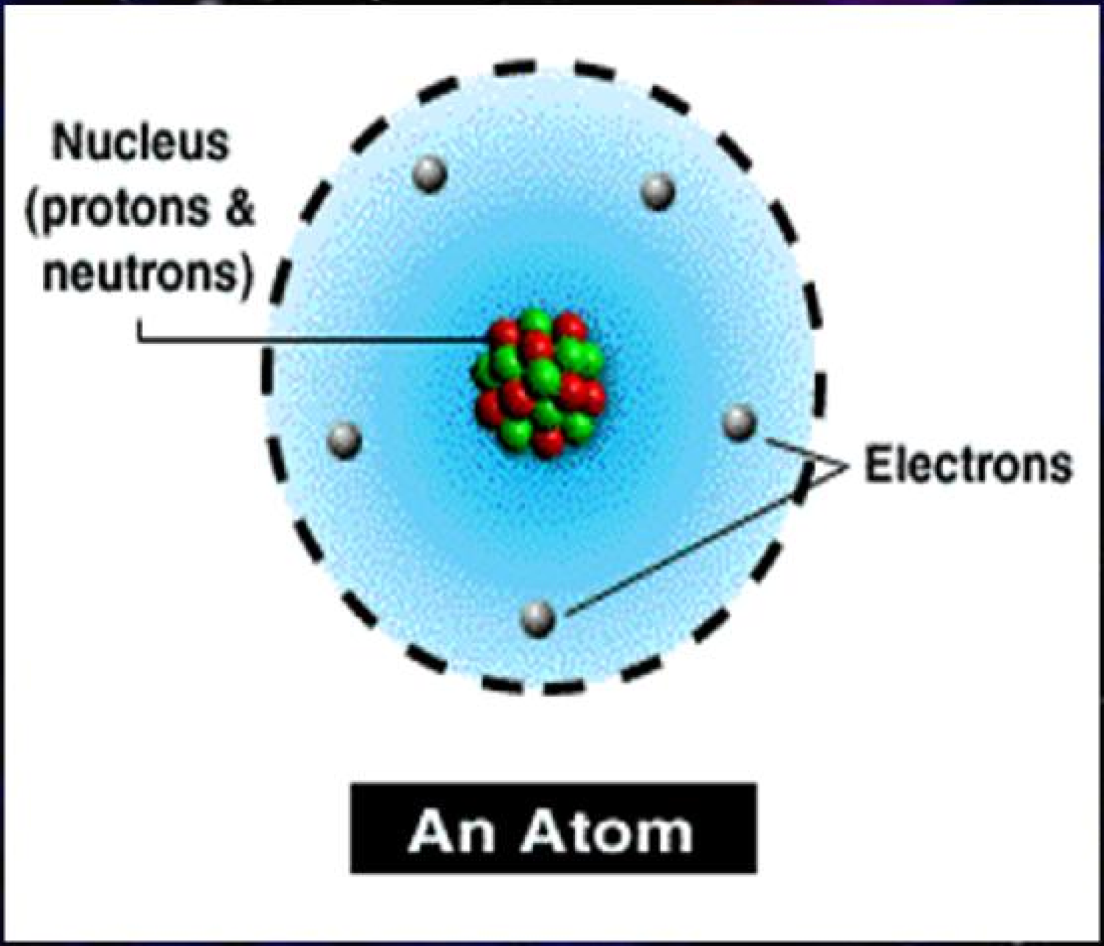


# *Ernest Rutherford, 1911*





~400 B. C.
1830
1906
1913
1924

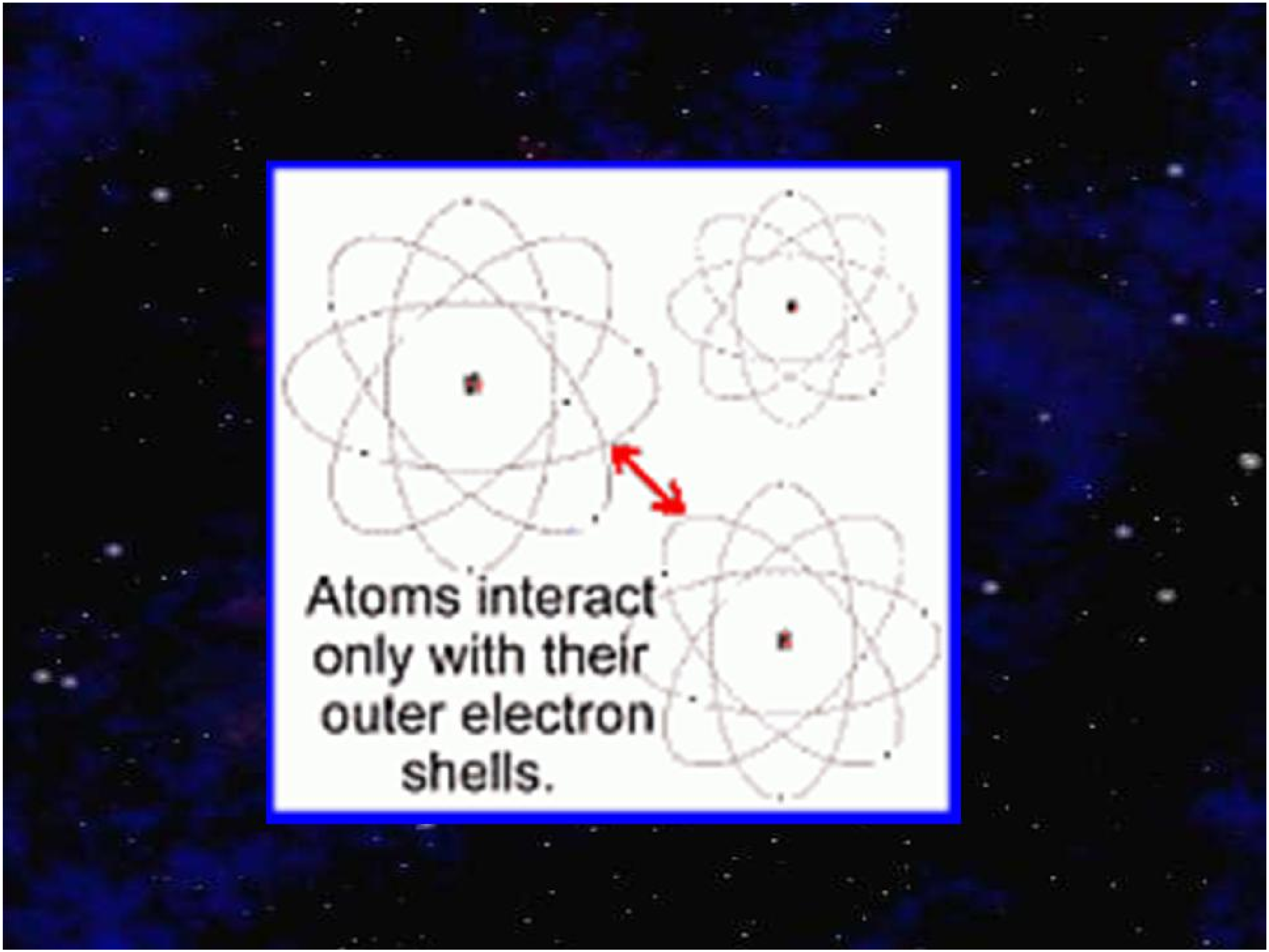



**Protons:** + charge
determines chemistry

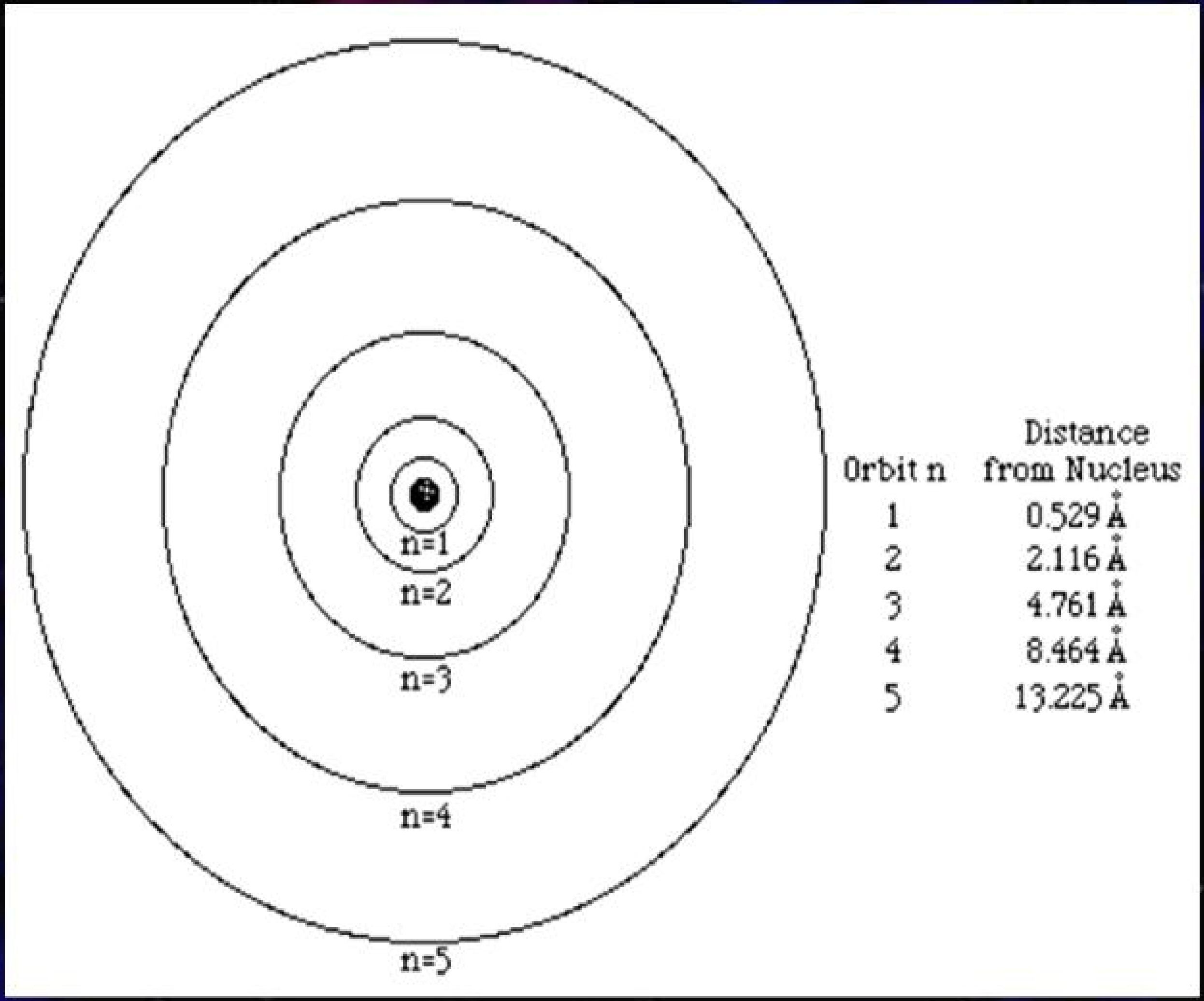
**Neutrons:** no charge
adds stability
adds mass

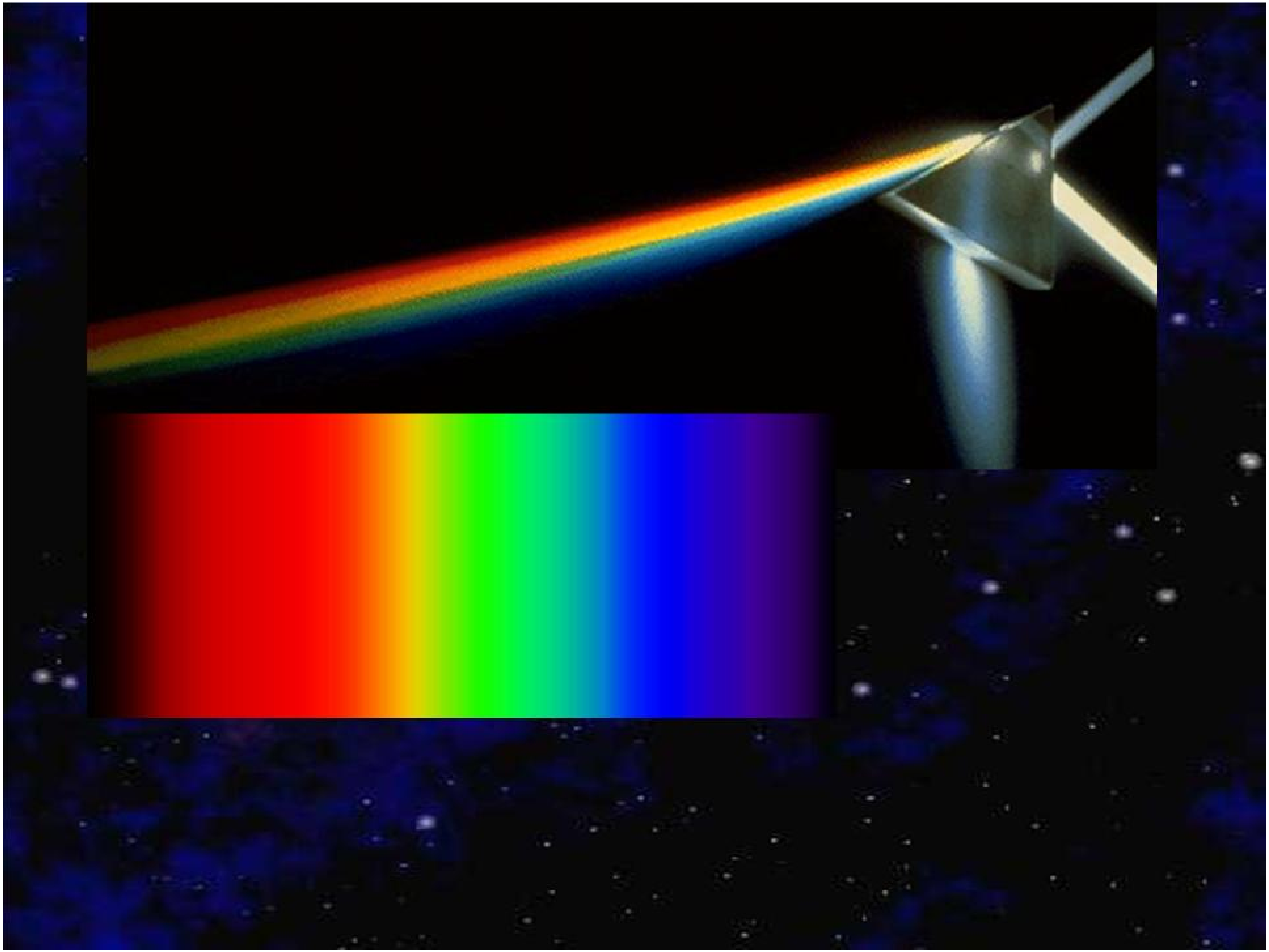
**Electrons:** - charge
interacts with rest of
world interacts with
light

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 H 1.008 | 2 IIA 2A | | | | | | | | | | | 13 IIIA 3A | 14 IVA 4A | 15 VA 5A | 16 VIA 6A | 17 VIIA 7A | 2 He 4.003 |
| 3 Li 6.941 | 4 Be 9.012 | | | | | | | | | | | 5 B 10.81 | 6 C 12.01 | 7 N 14.01 | 8 O 16.00 | 9 F 19.00 | 10 Ne 20.18 |
| 11 Na 22.99 | 12 Mg 24.31 | 3 IIIB 3B | 4 IVB 4B | 5 VB 5B | 6 VIB 6B | 7 VIIB 7B | 8 | 9 ------- VIII ------- 8 ------- | 10 | 11 IB 1B | 12 IIB 2B | 13 Al 26.98 | 14 Si 28.09 | 15 P 30.97 | 16 S 32.07 | 17 Cl 35.45 | 18 Ar 39.95 |
| 19 K 39.10 | 20 Ca 40.08 | 21 Sc 44.96 | 22 Ti 47.88 | 23 V 50.94 | 24 Cr 52.00 | 25 Mn 54.94 | 26 Fe 55.85 | 27 Co 58.47 | 28 Ni 58.69 | 29 Cu 63.55 | 30 Zn 65.39 | 31 Ga 69.72 | 32 Ge 72.59 | 33 As 74.92 | 34 Se 78.96 | 35 Br 79.90 | 36 Kr 83.80 |
| 37 Rb 85.47 | 38 Sr 87.62 | 39 Y 88.91 | 40 Zr 91.22 | 41 Nb 92.91 | 42 Mo 95.94 | 43 Tc (98) | 44 Ru 101.1 | 45 Rh 102.9 | 46 Pd 106.4 | 47 Ag 107.9 | 48 Cd 112.4 | 49 In 114.8 | 50 Sn 118.7 | 51 Sb 121.8 | 52 Te 127.6 | 53 I 126.9 | 54 Xe 131.3 |
| 55 Cs 132.9 | 56 Ba 137.3 | 57 La* 138.9 | 72 Hf 178.5 | 73 Ta 180.9 | 74 W 183.9 | 75 Re 186.2 | 76 Os 190.2 | 77 Ir 190.2 | 78 Pt 195.1 | 79 Au 197.0 | 80 Hg 200.5 | 81 Tl 204.4 | 82 Pb 207.2 | 83 Bi 209.0 | 84 Po (210) | 85 At (210) | 86 Rn (222) |

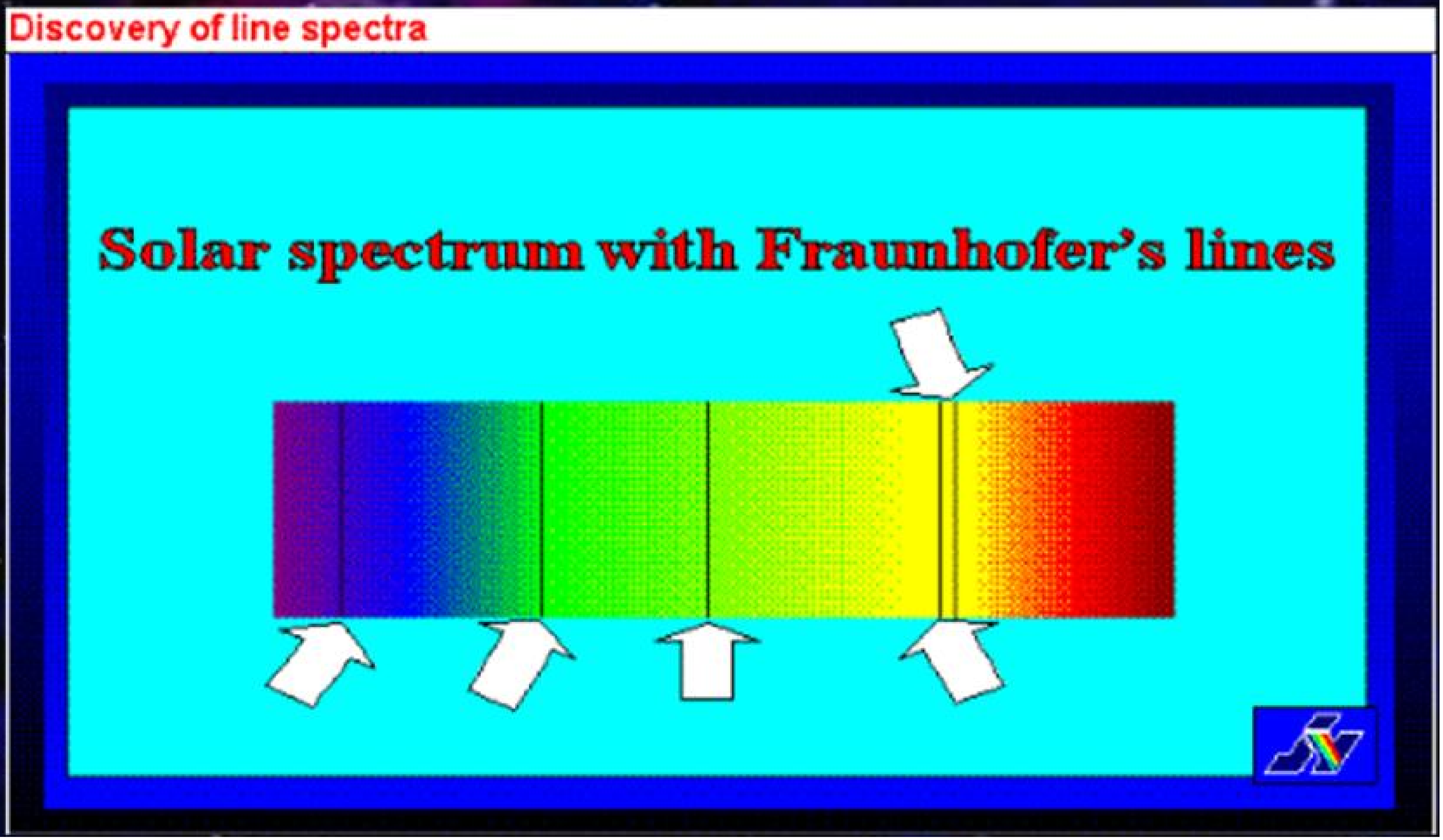

Atoms interact only with their outer electron shells.

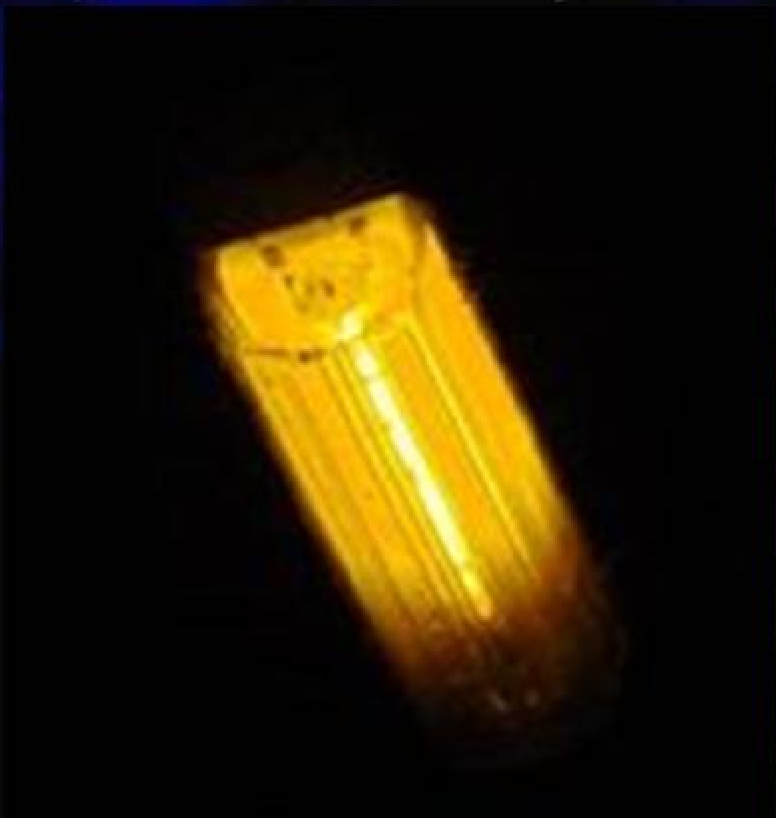
# *The Simplest: Hydrogen*



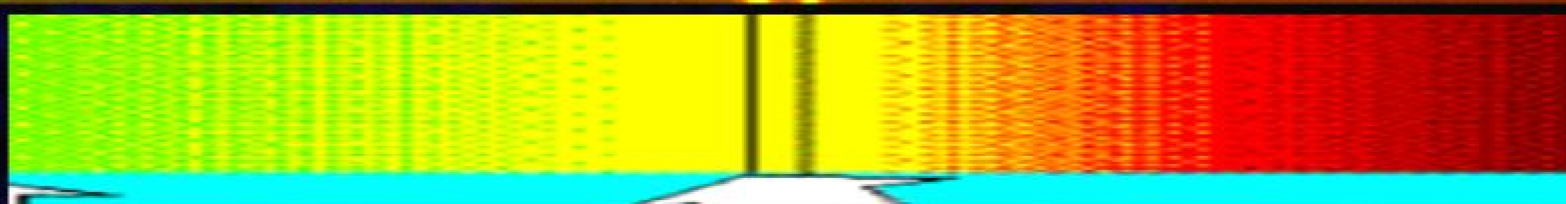


# Josef Fraunhofer, 1787-1826





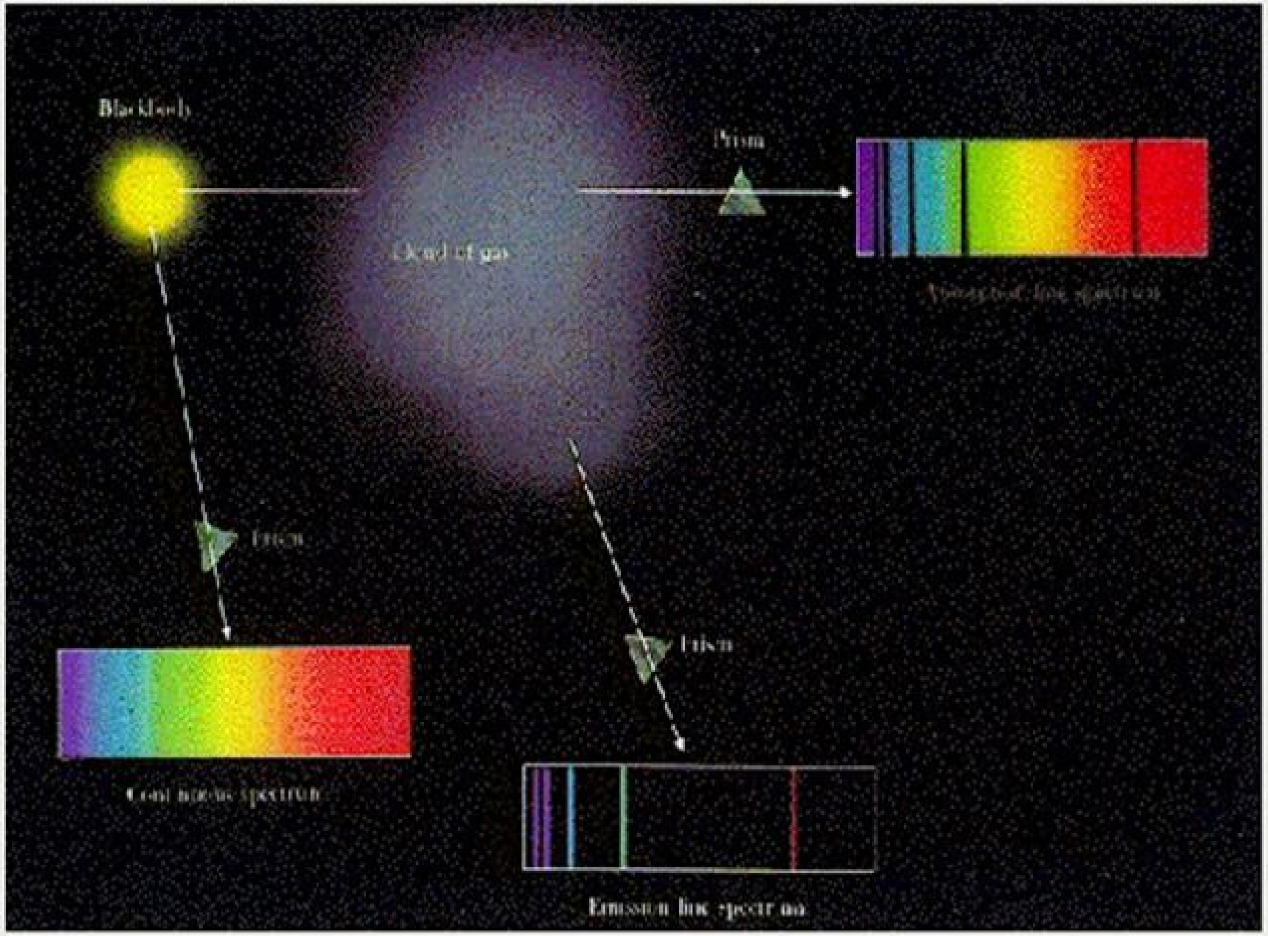
# The Sodium Story



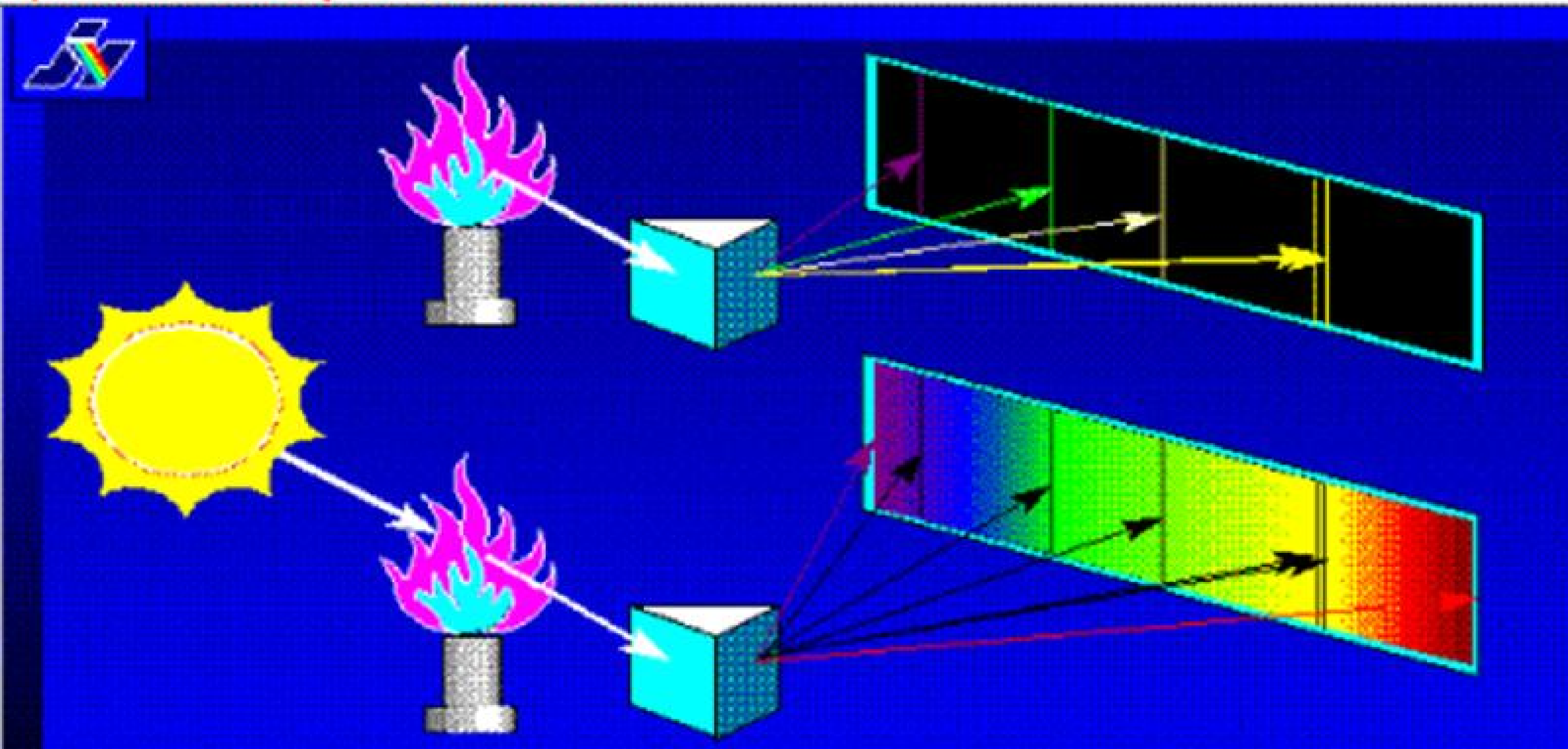
# Kirchhoff's Laws

Bunsen

Kirchhoff

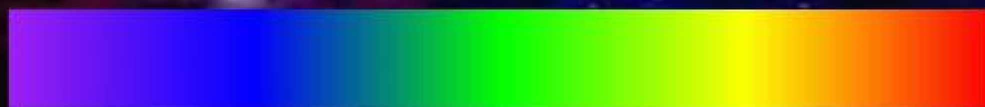


Spectrochemistry fundamentals

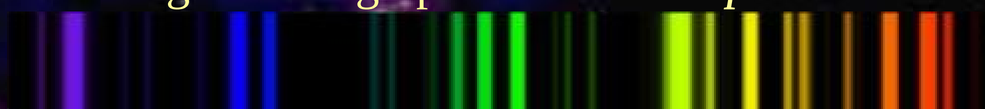


**Kirchhof and Bunsen experiment diagram**

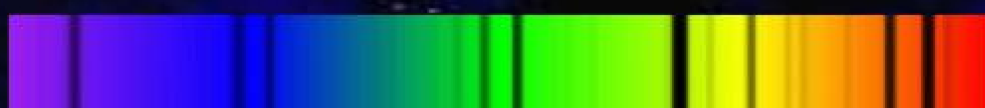
•from hot objects are *continuous*, like a rainbow



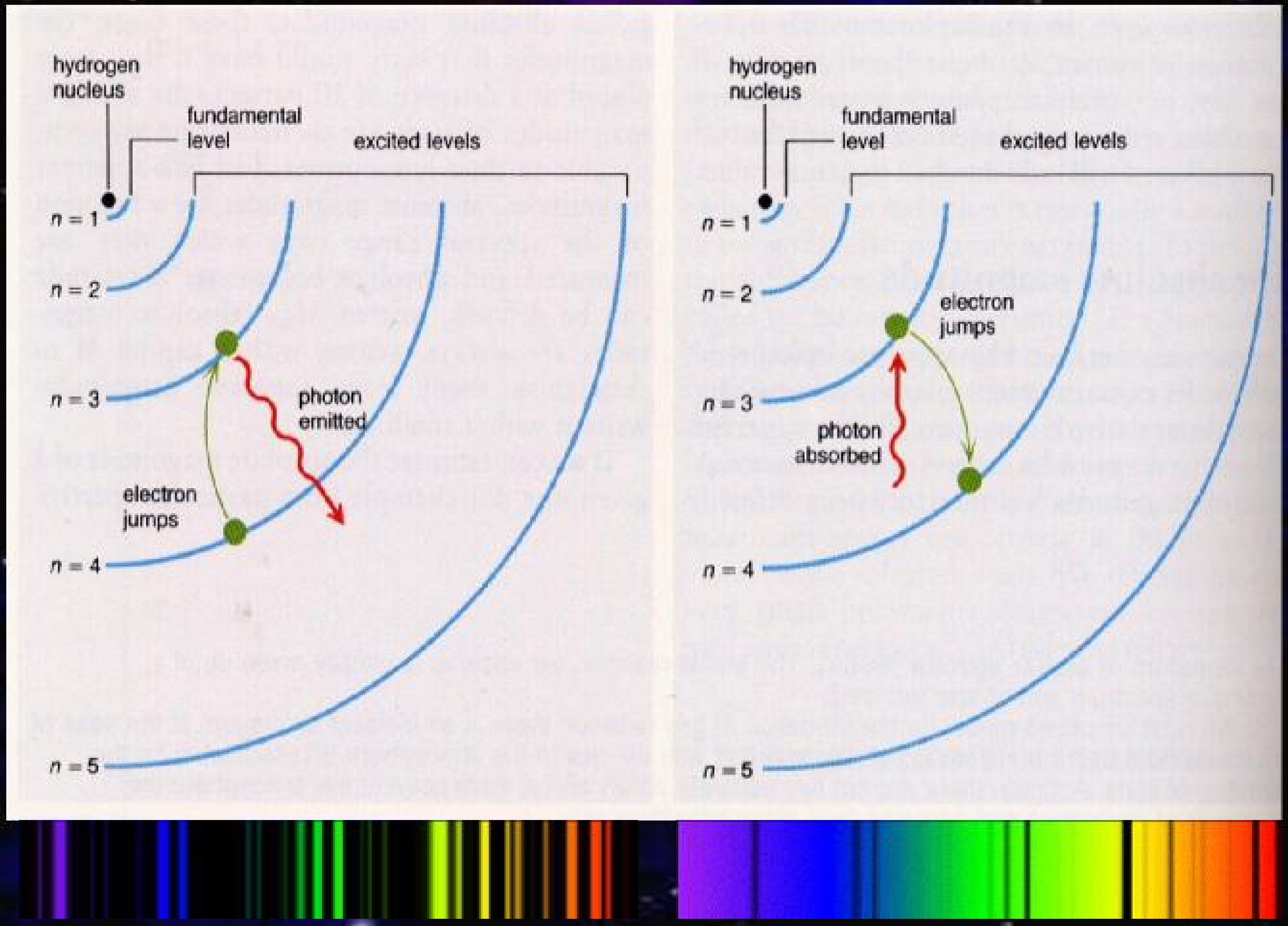
•atoms only emit light of specific colours, revealing their fingerprints as a *line spectrum*



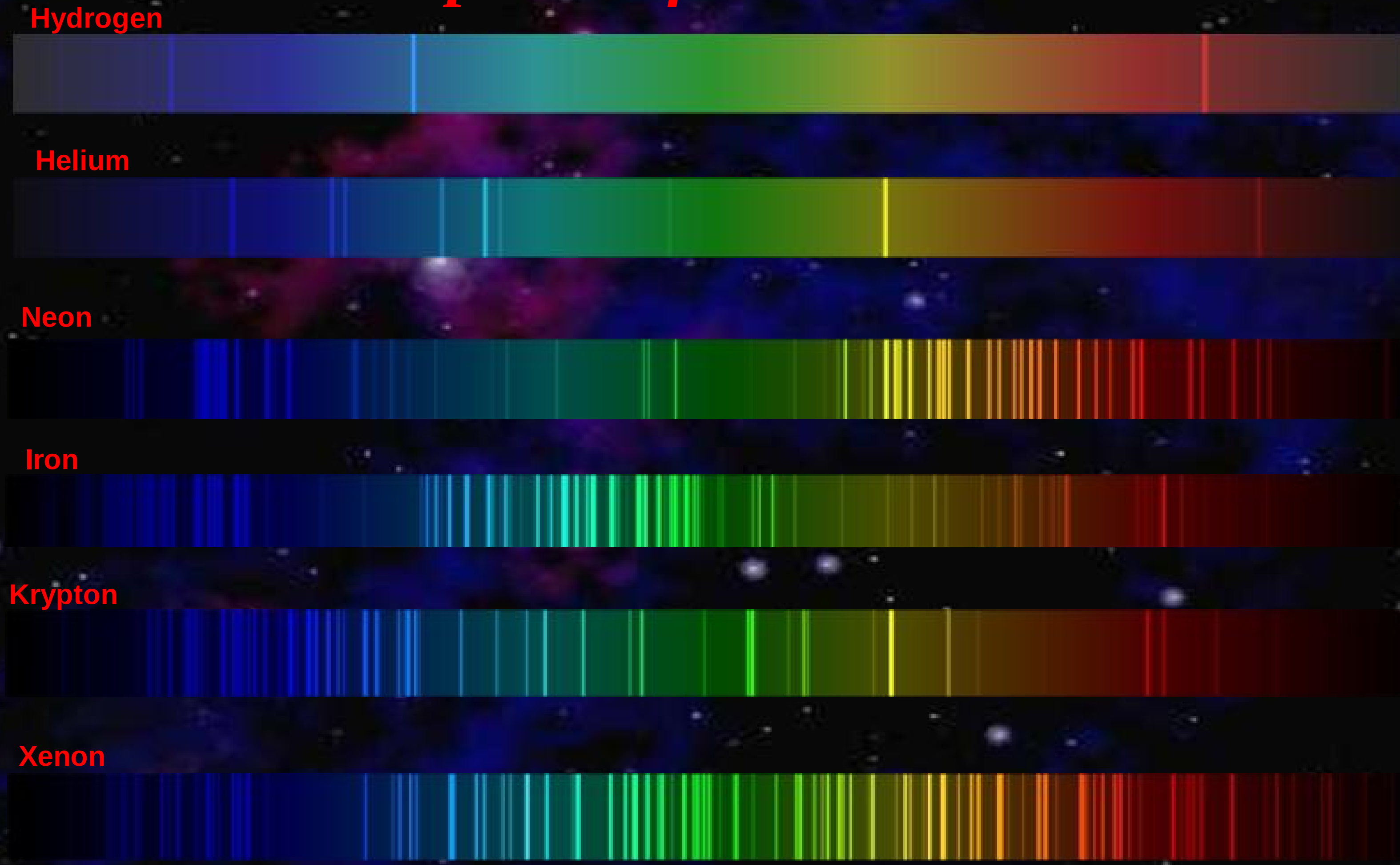
•atoms in front of a hot object absorb light at these colours, giving an *absorption spectrum*

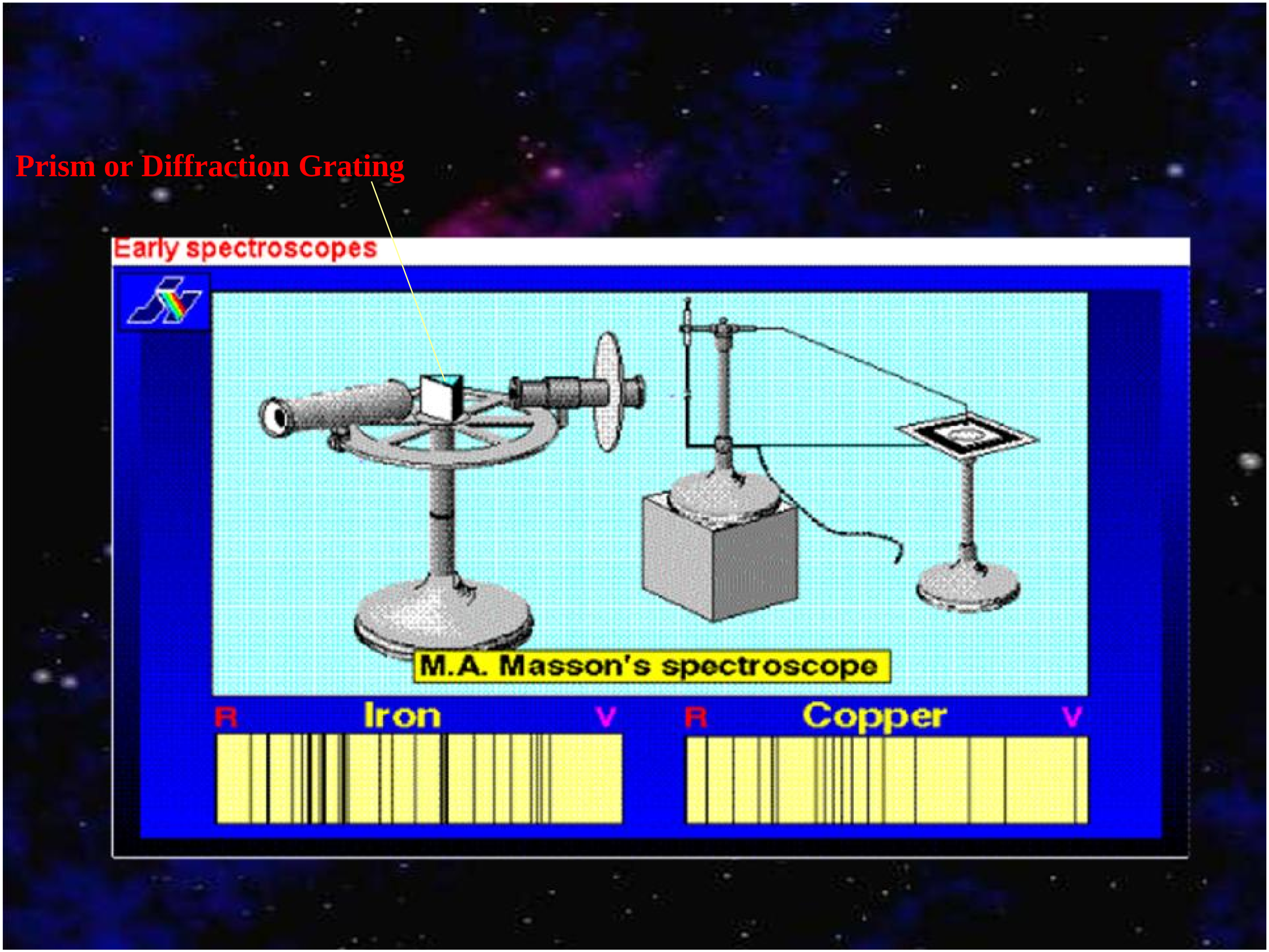


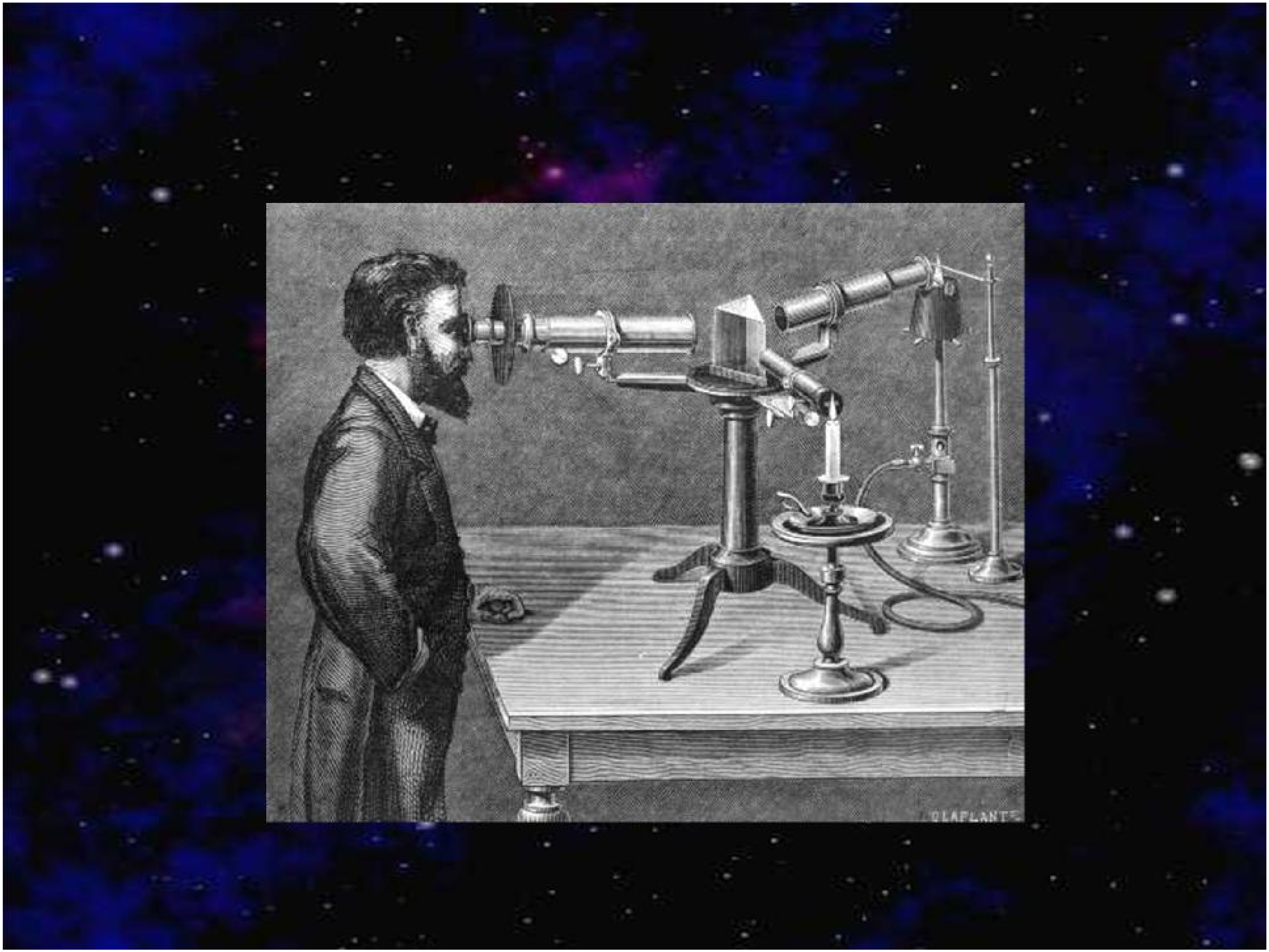
# *Generation of Emission or Absorption Line Spectrum*



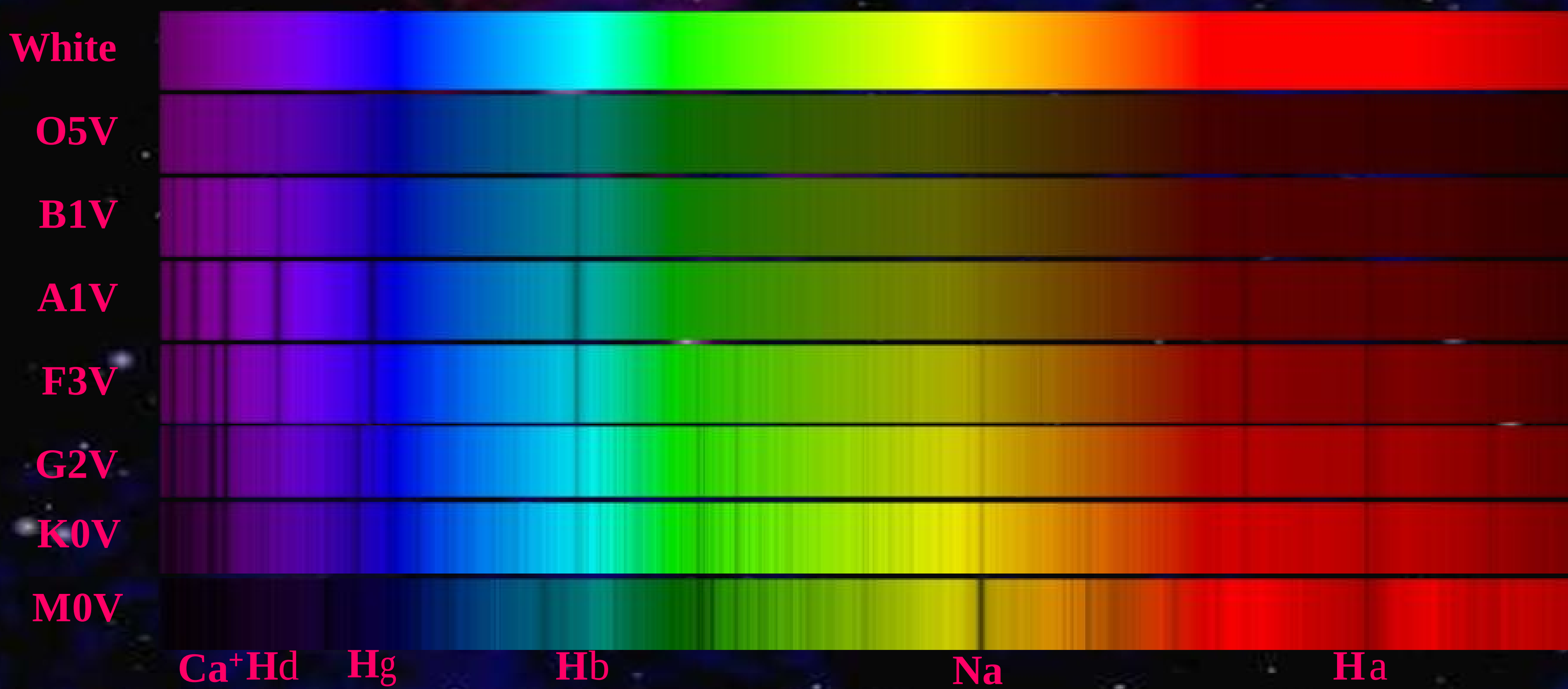
# *Visible Spectra of common Elements*

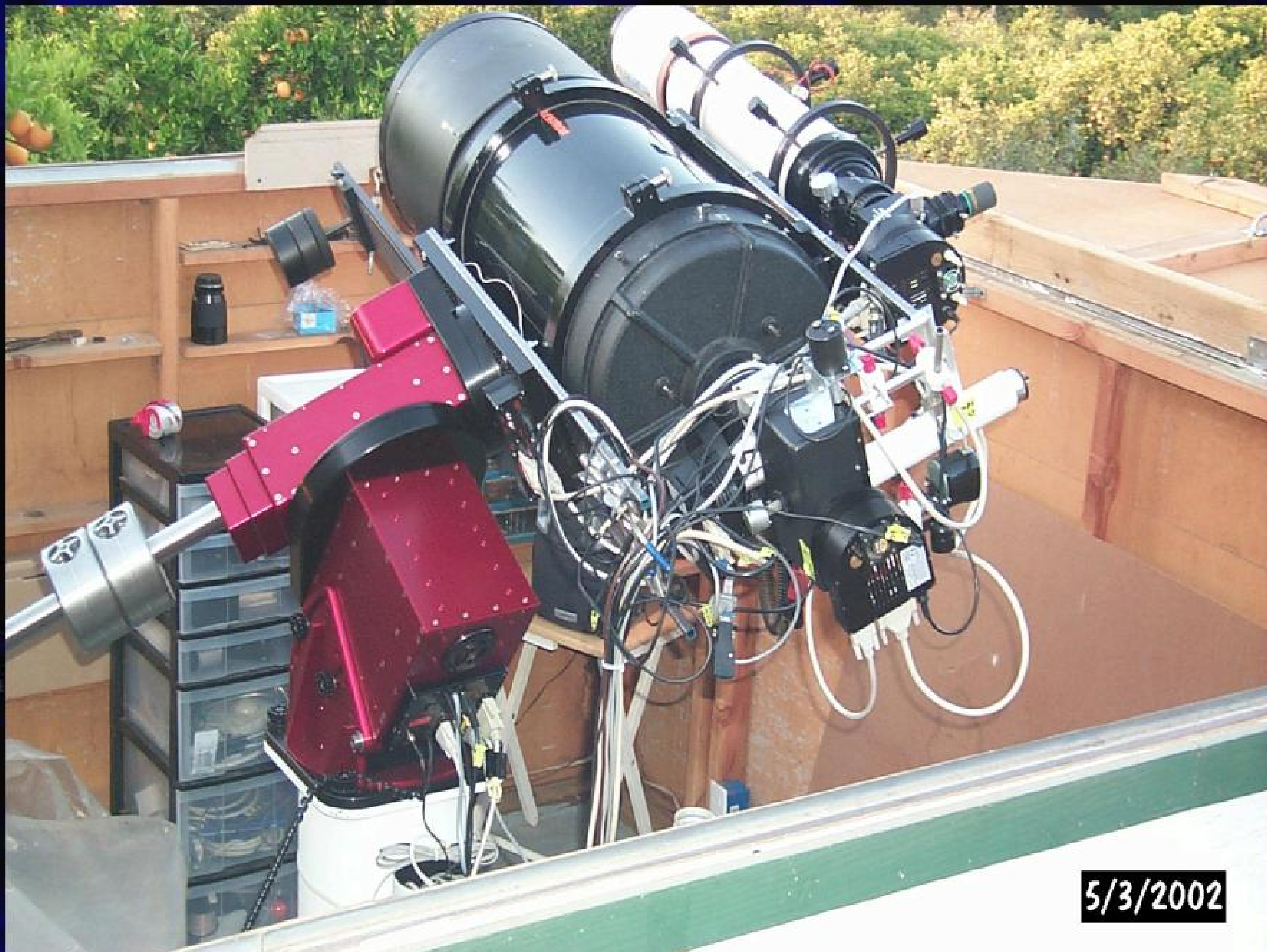


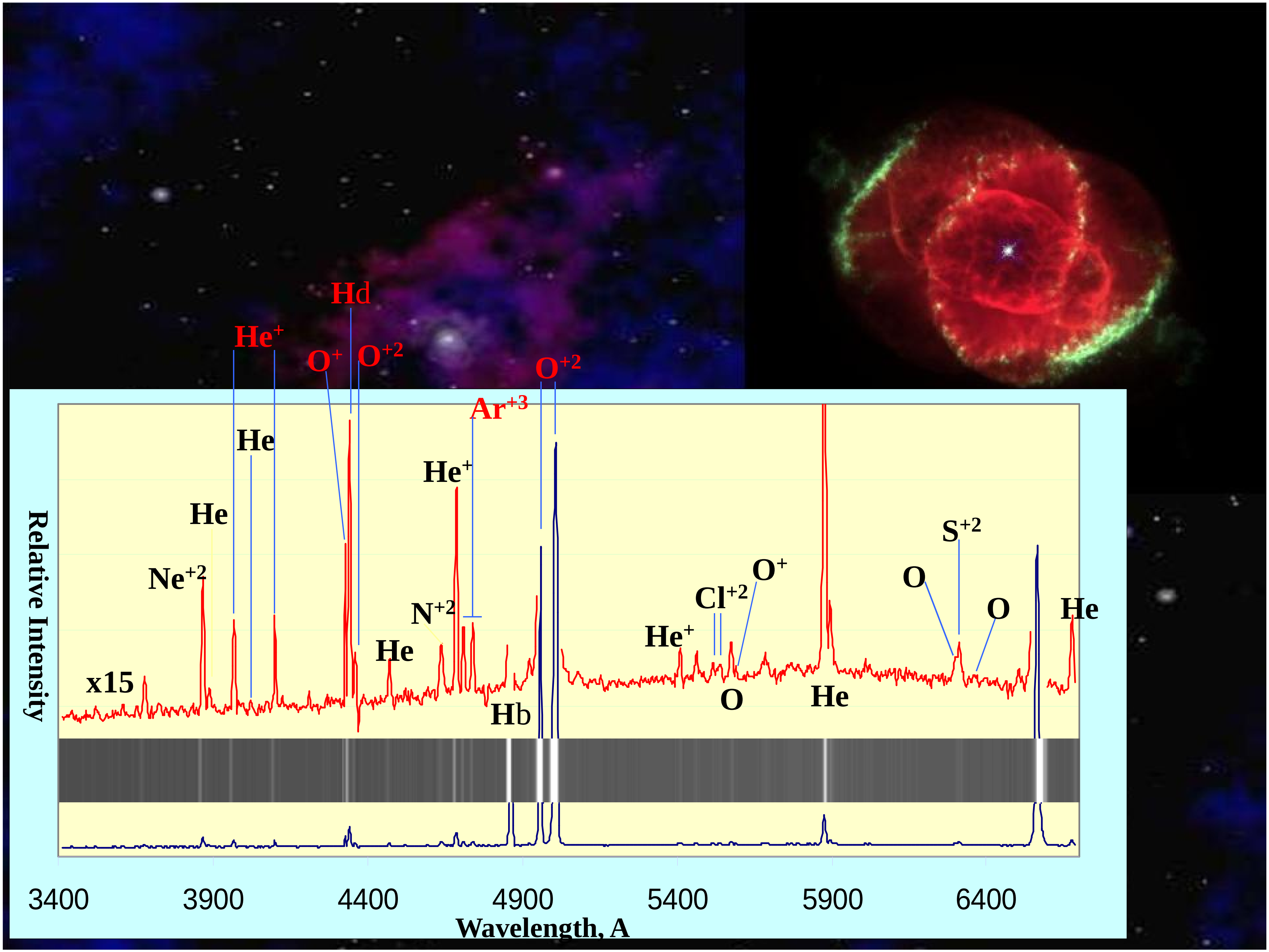

Prism or Diffraction Grating
Early spectroscopes
M.A. Masson's spectroscope
R
Iron
V
R
Copper
V



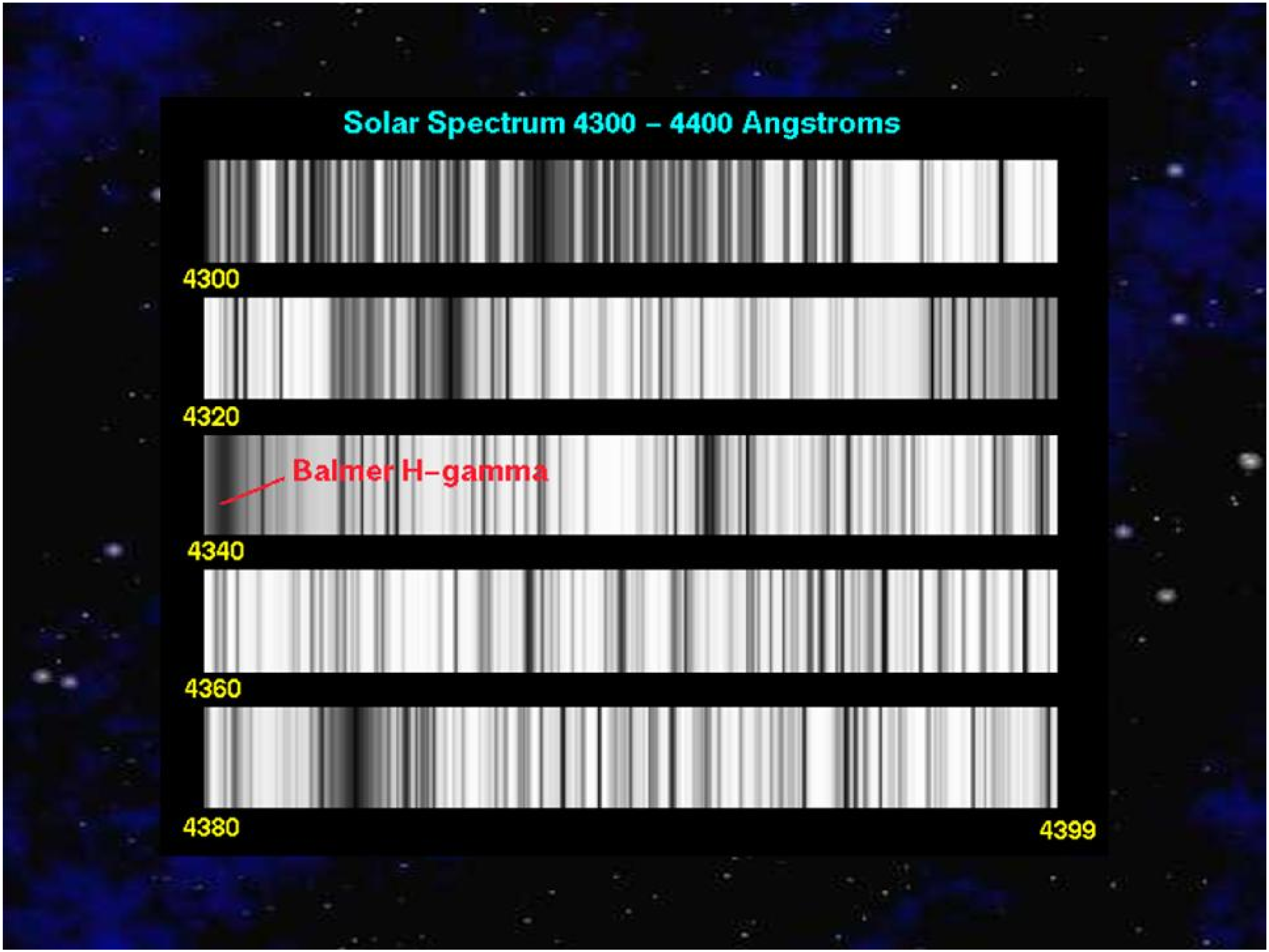
# *Spectral Sequence in Color*



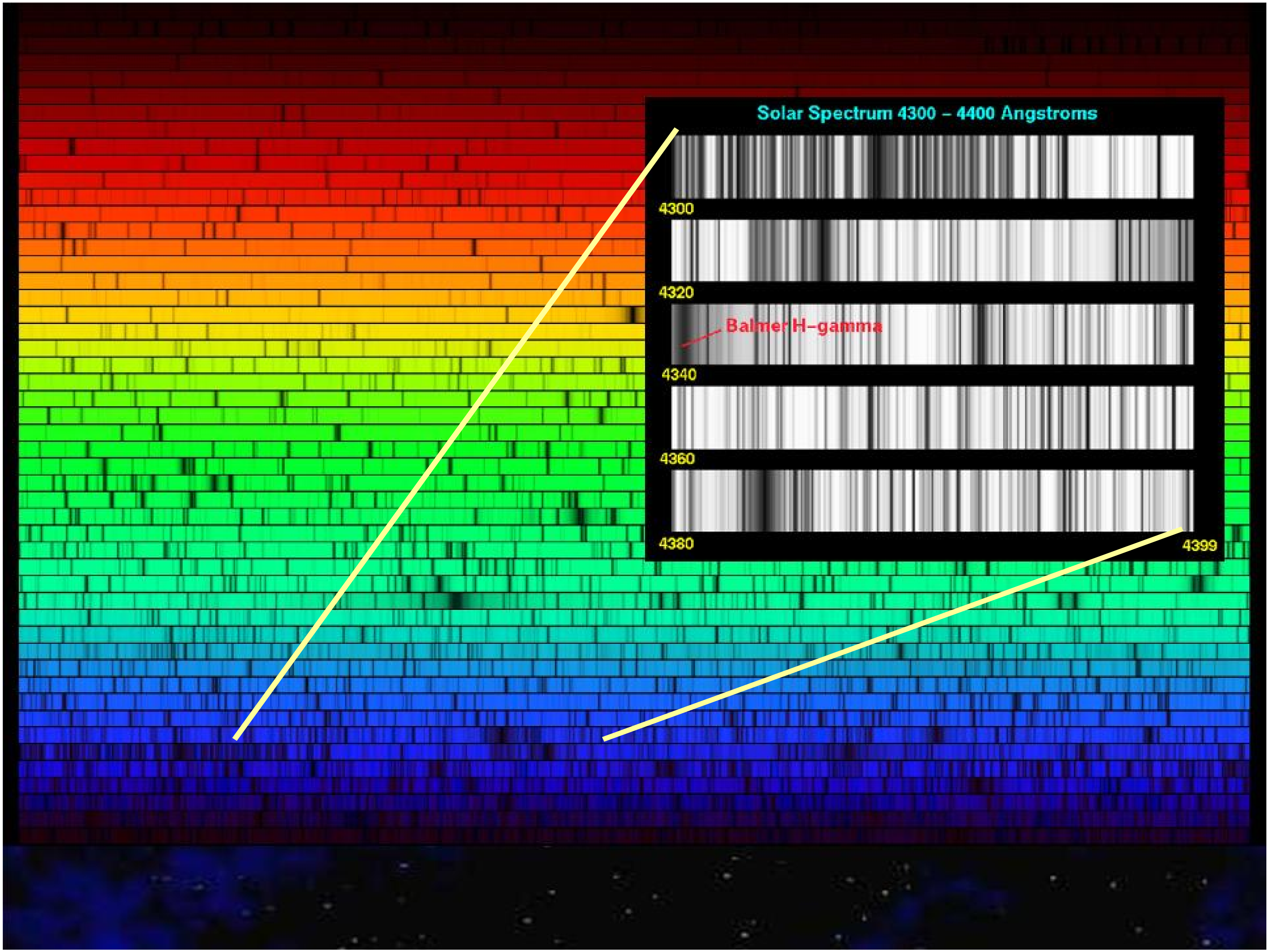

5/3/2002



Hd
He+
O+
O+2
O+2
Ar+3
He
He+
He
Ne+2
N+2
He
x15
Hb
He+
Cl+2
O+
O
He
O
S+2
O
He
Relative Intensity
3400
3900
4400
4900
5400
5900
6400
Wavelength, A



Solar Spectrum 4300 – 4400 Angstroms
4300
4320
Balmer H-gamma
4340
4360
4380
4399



Solar Spectrum 4300 – 4400 Angstroms
4300
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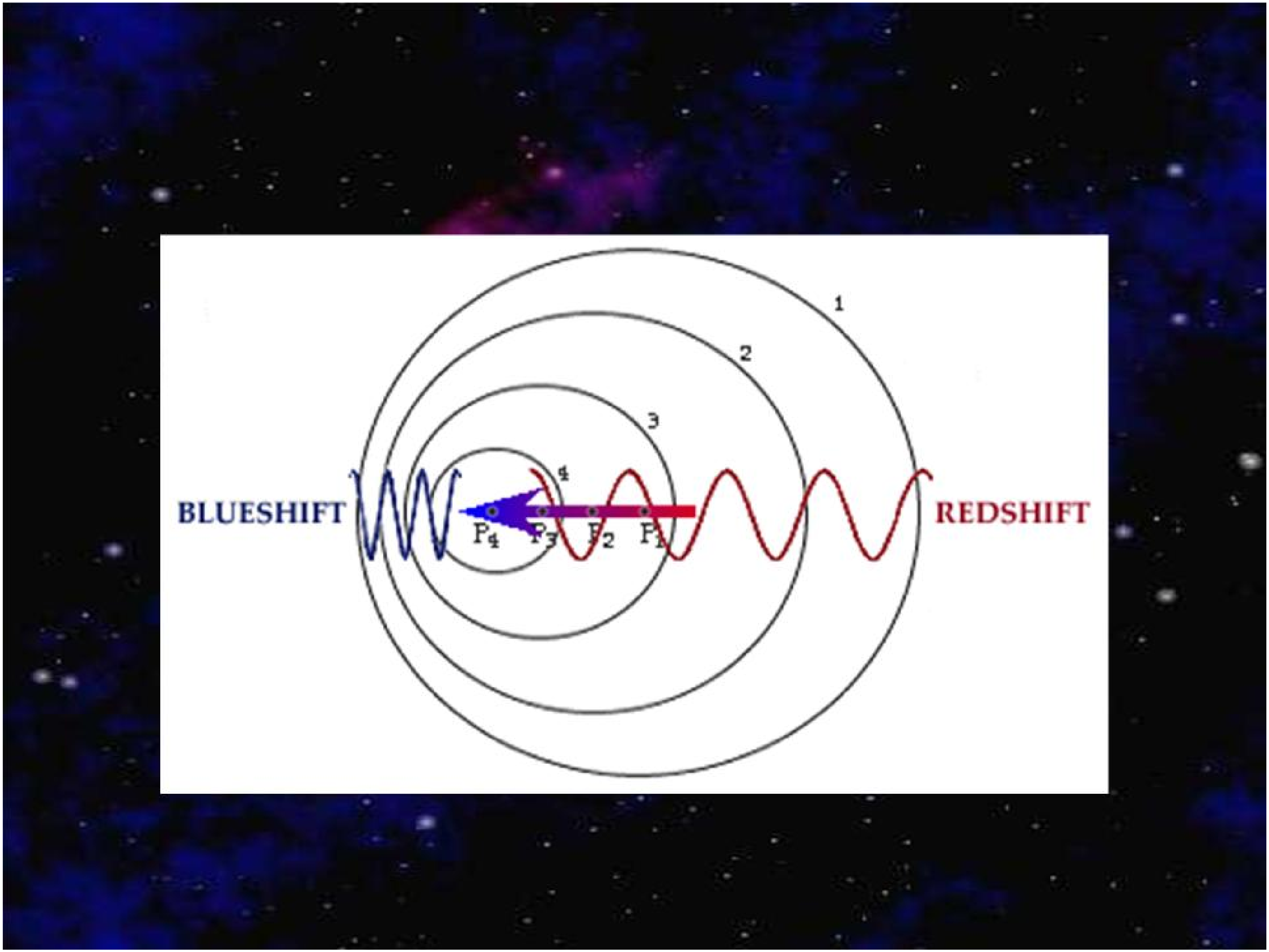
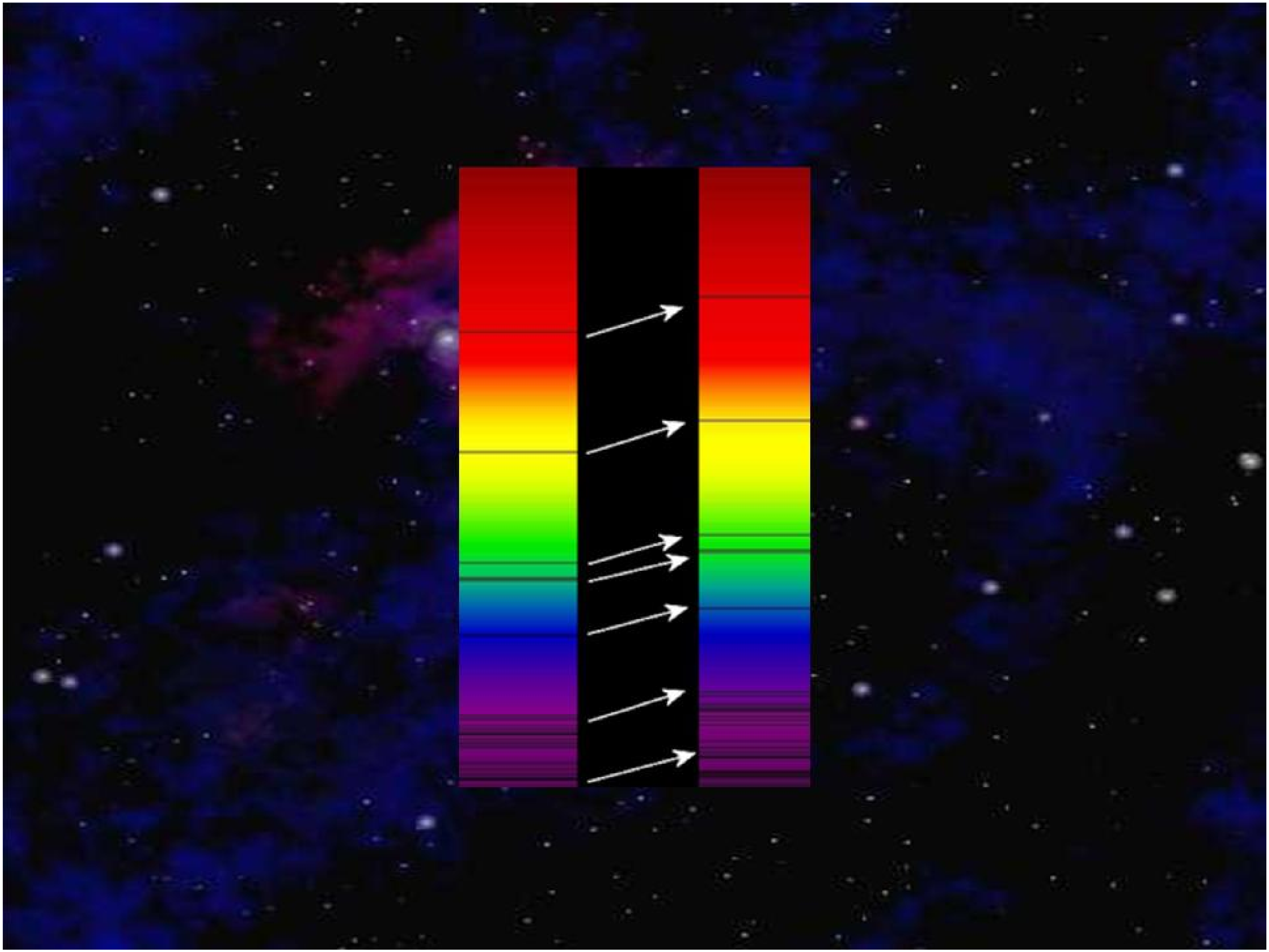
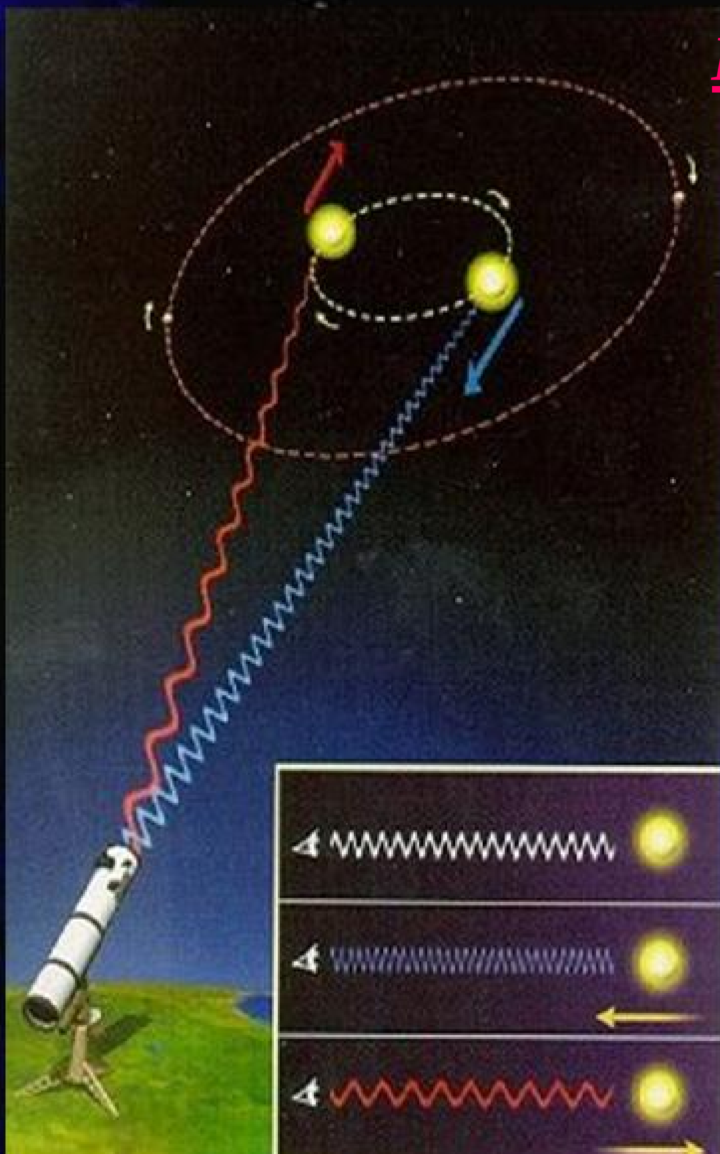
4399



BLUESHIFT
REDSHIFT
1
2
3
4

www.spacetelescope.org

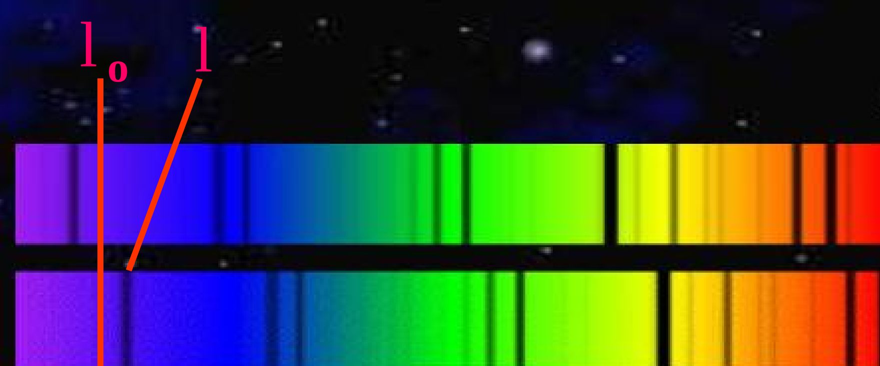




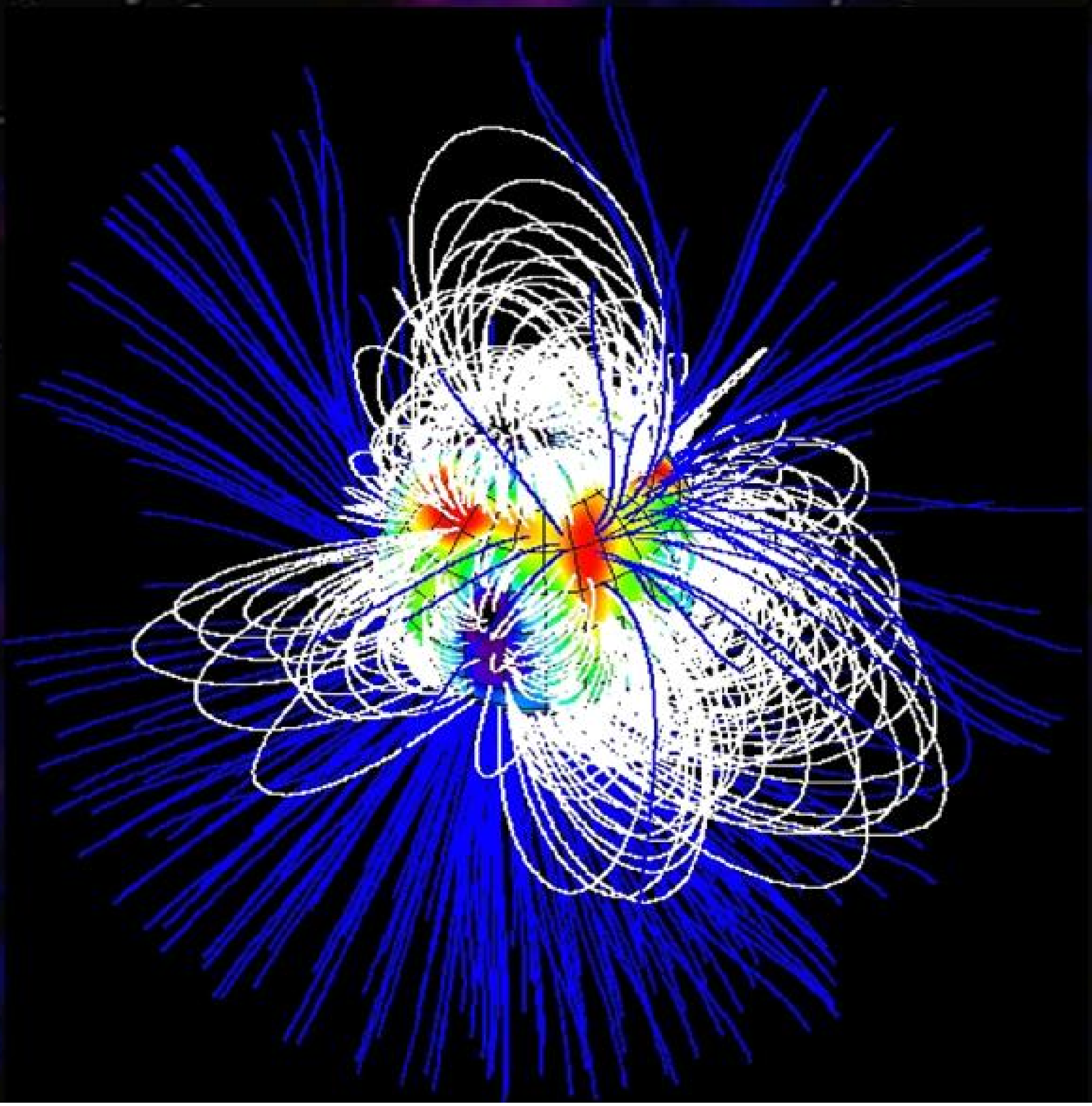
## *Doppler Shift of Light: measuring the speed of objects*

$$z = v/c = (l - l_o)/\, l_o$$

**v = velocity of object**
**c = velocity of light (300,000 km/sec)**
**$l_o$ = rest wavelength**
**l = measured wavelength**



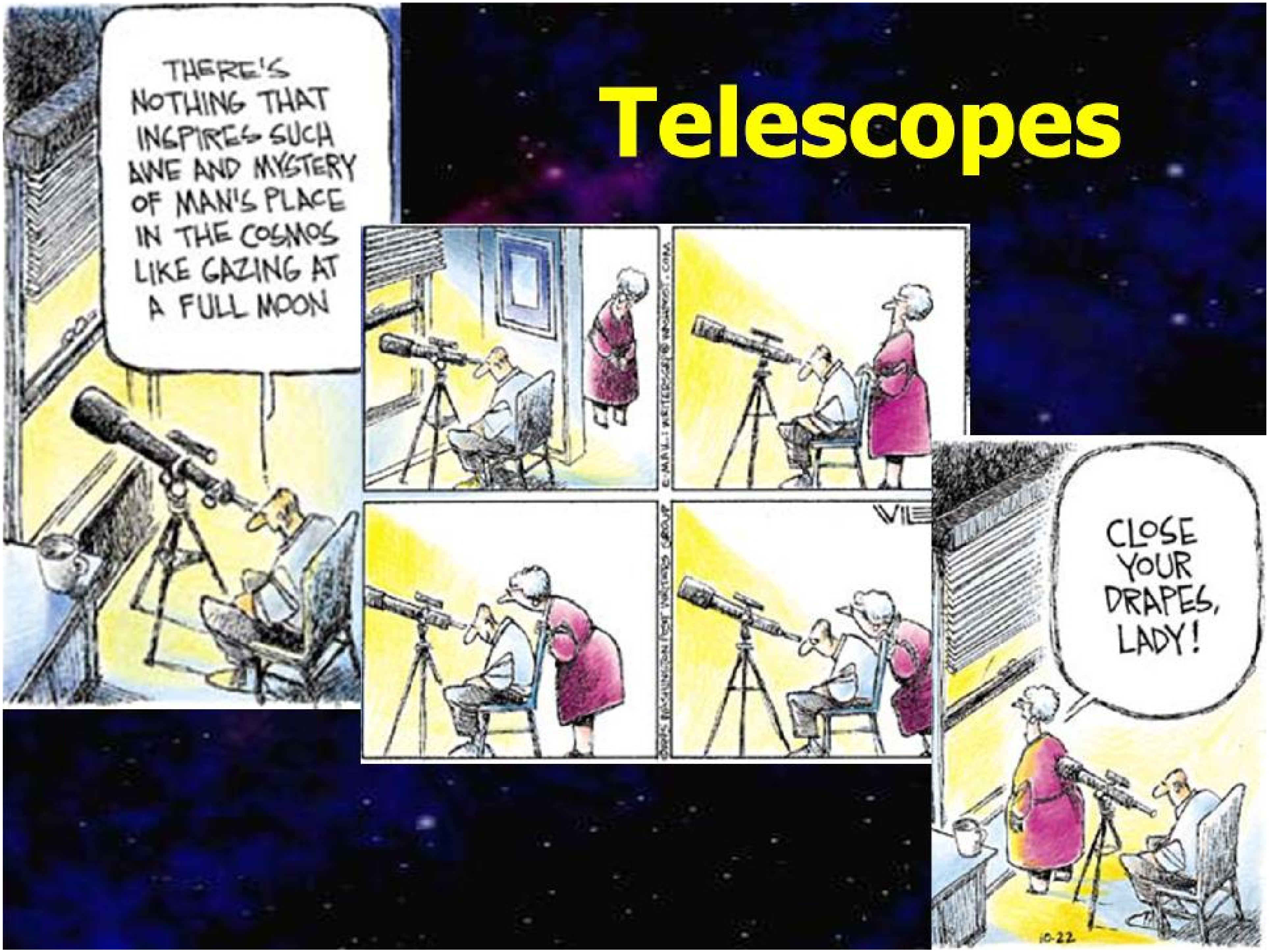
# Magnetic Field Map of star FU Aurigae



In 1835, Auguste Comte, the French philosopher and founder of sociology, said of the stars:

"We shall never be able to study, by any method, their chemical composition or their mineralogical structure... Our positive knowledge of stars is necessarily limited to their geometric and mechanical phenomena".

# Telescopes


THERE'S NOTHING THAT INSPIRES SUCH AWE AND MYSTERY OF MAN'S PLACE IN THE COSMOS LIKE GAZING AT A FULL MOON
CLOSE YOUR DRAPES, LADY!

**Why do astronomers use telescopes?**

**How do telescopes work?**

**Which telescopes do astronomers prefer?**

# Why do astronomers use telescopes?

1. **Light Gathering Power**

Gathering more light makes faint objects appear brighter.

Objects that are normally too distant and faint to be seen with the eye can be seen with a telescope.

**Human Eye**:

Area of pupil = $\pi r^2$

Area of pupil = $\pi\ (0.15\text{cm})^2$

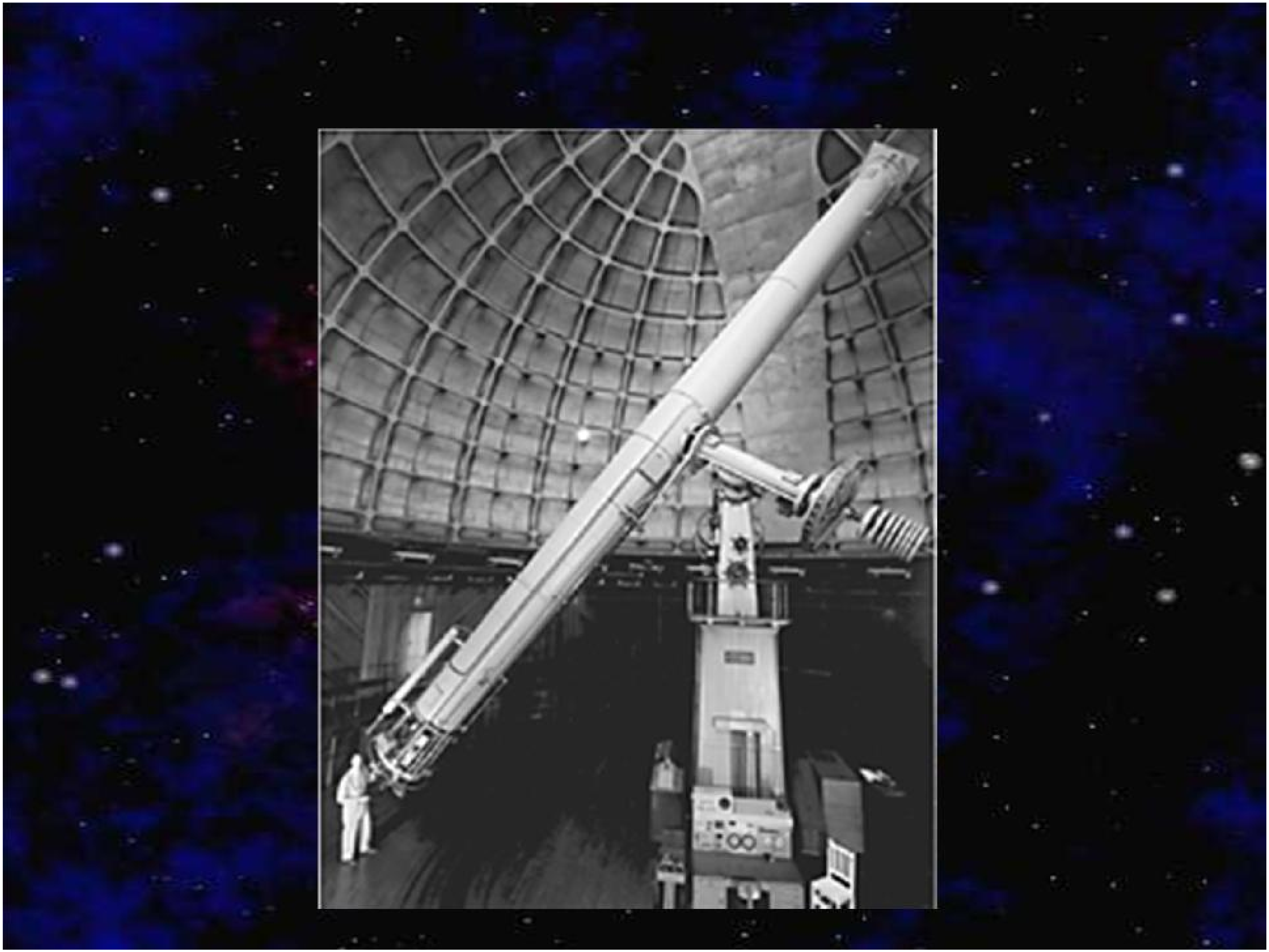
Area of pupil = $0.07\text{cm}^2$

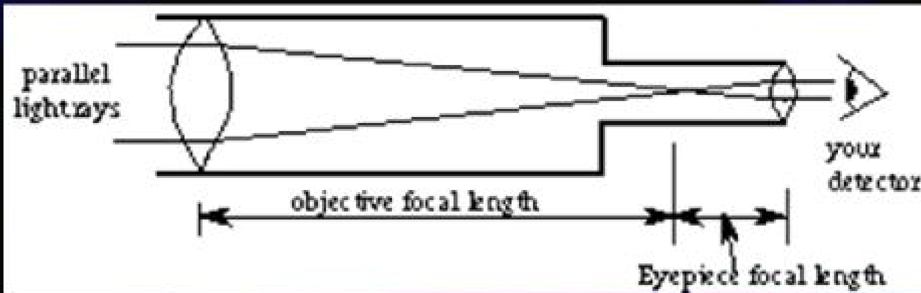
**Modest sized telescope** (MLO 40inch):

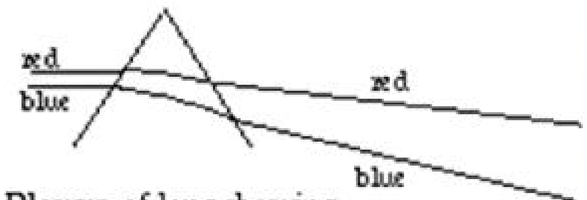
Area of telescope opening = $\pi r^2$

Area = $\pi$ (50 cm)$^2$ = 7,800 cm$^2$

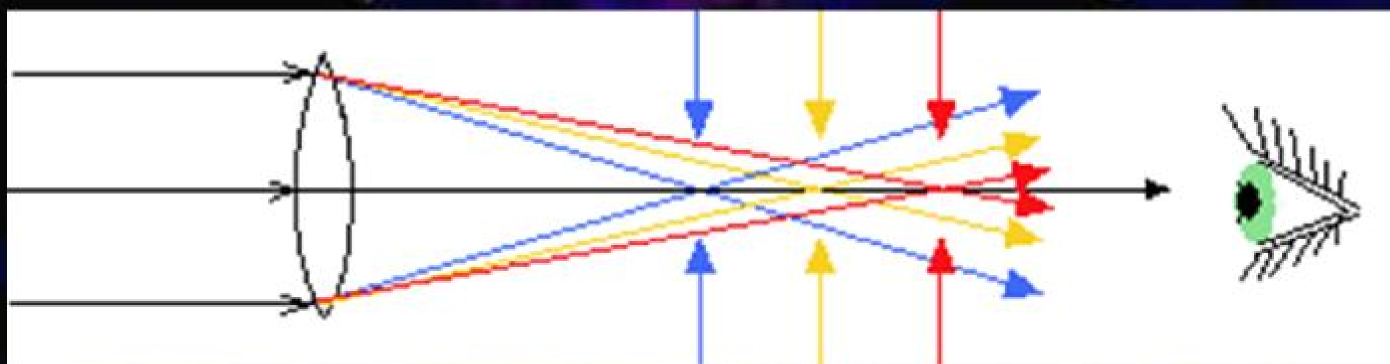
**RATIO = 7,800/0.07 = 111,000**

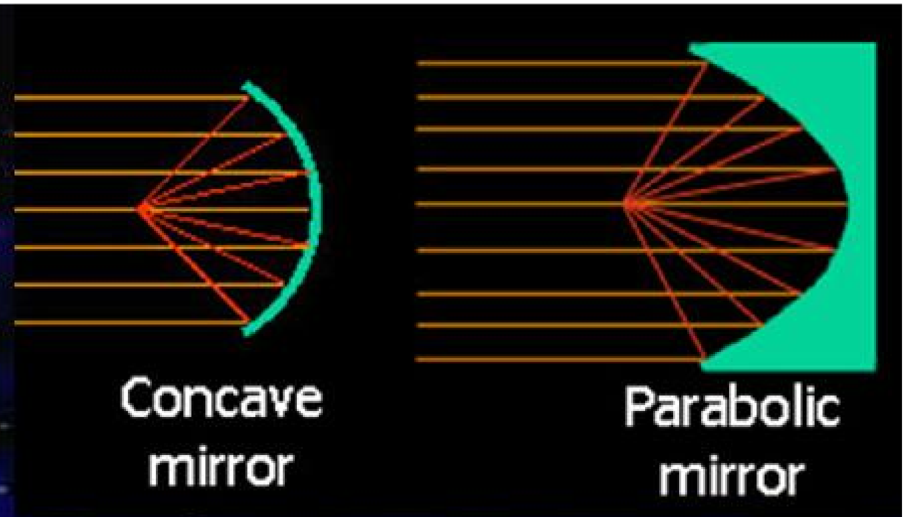


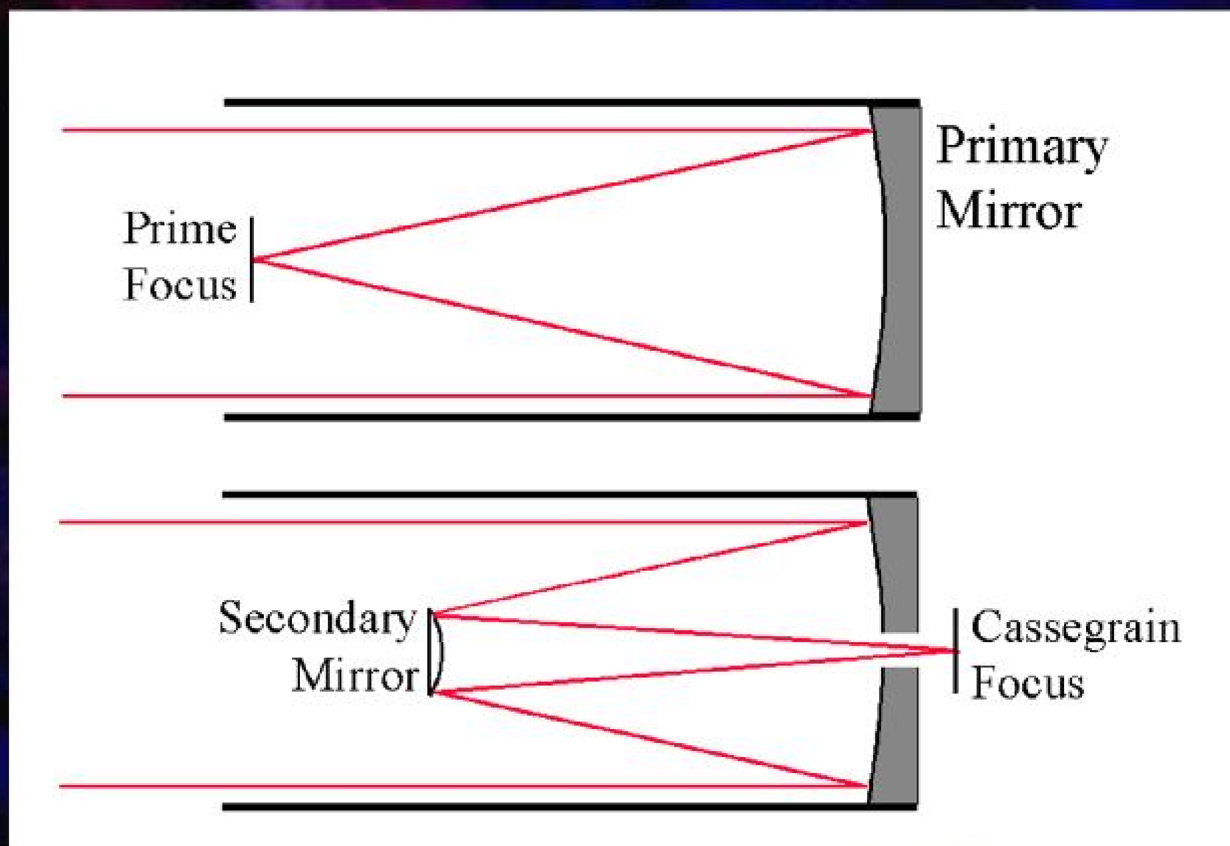


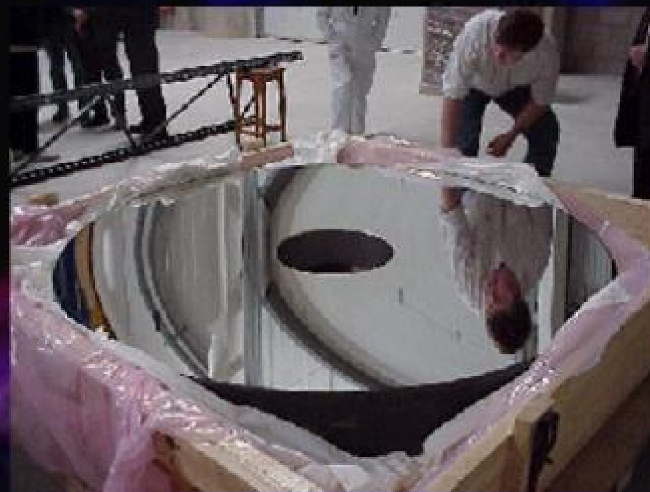




Blowup of lens showing
chromatic aberration

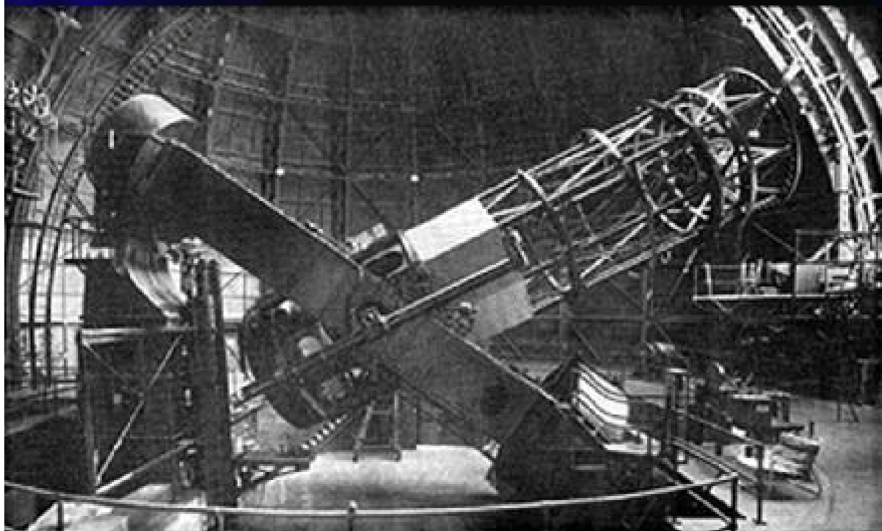


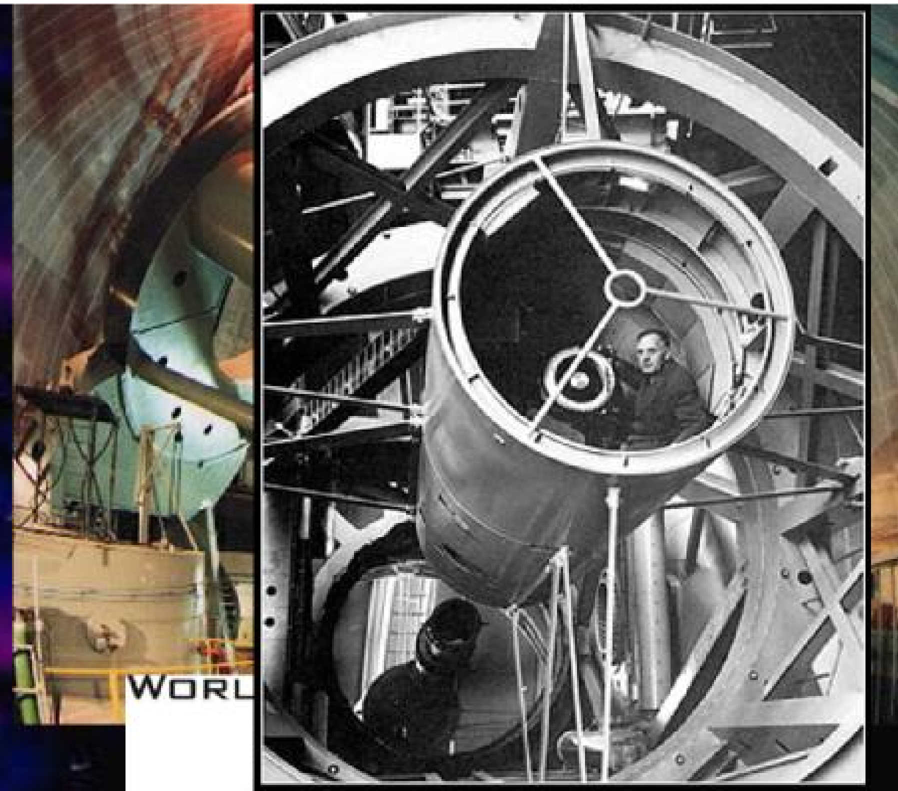

Concave mirror
Parabolic mirror

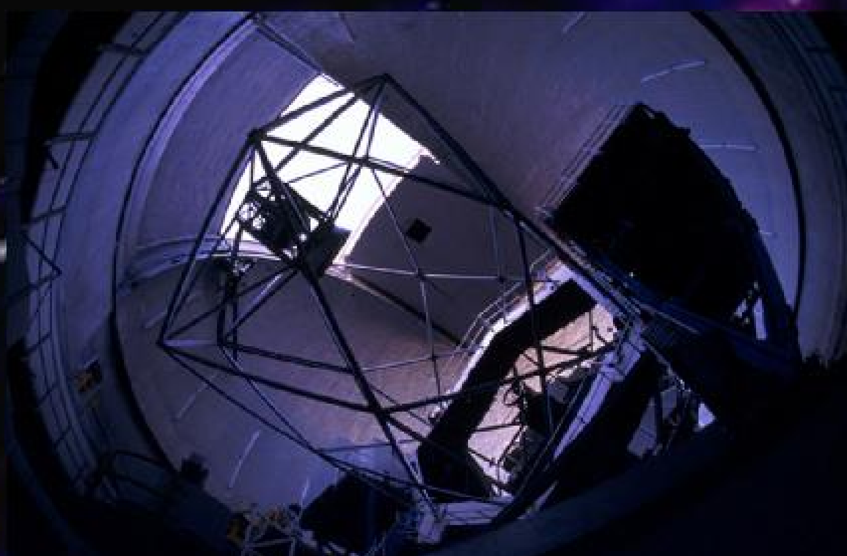

Primary Mirror
Prime Focus
Secondary Mirror
Cassegrain Focus

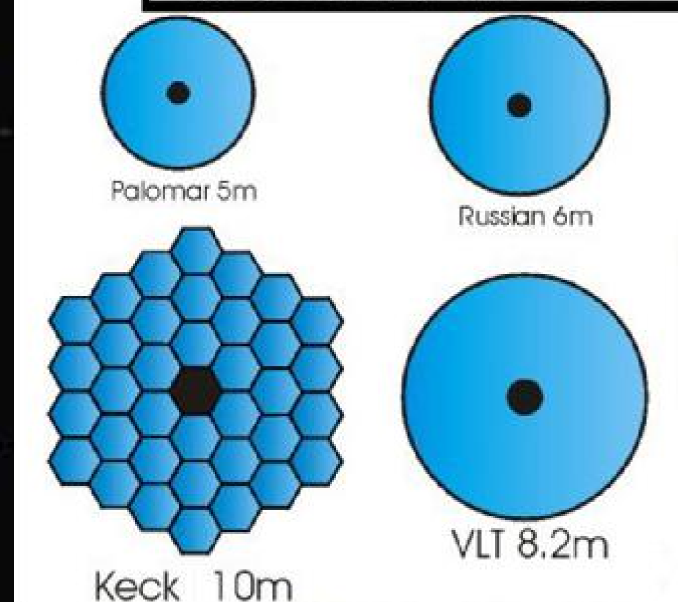


# Bigger is better!









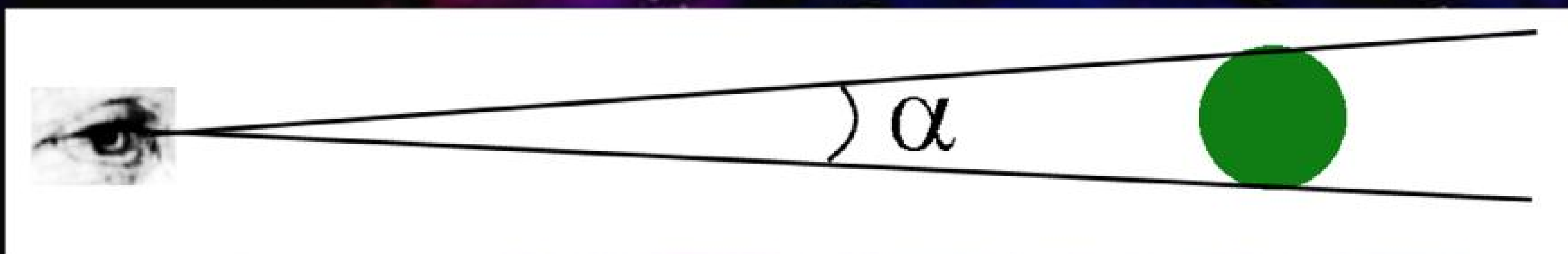
## 2. Increased Resolution

Resolution:

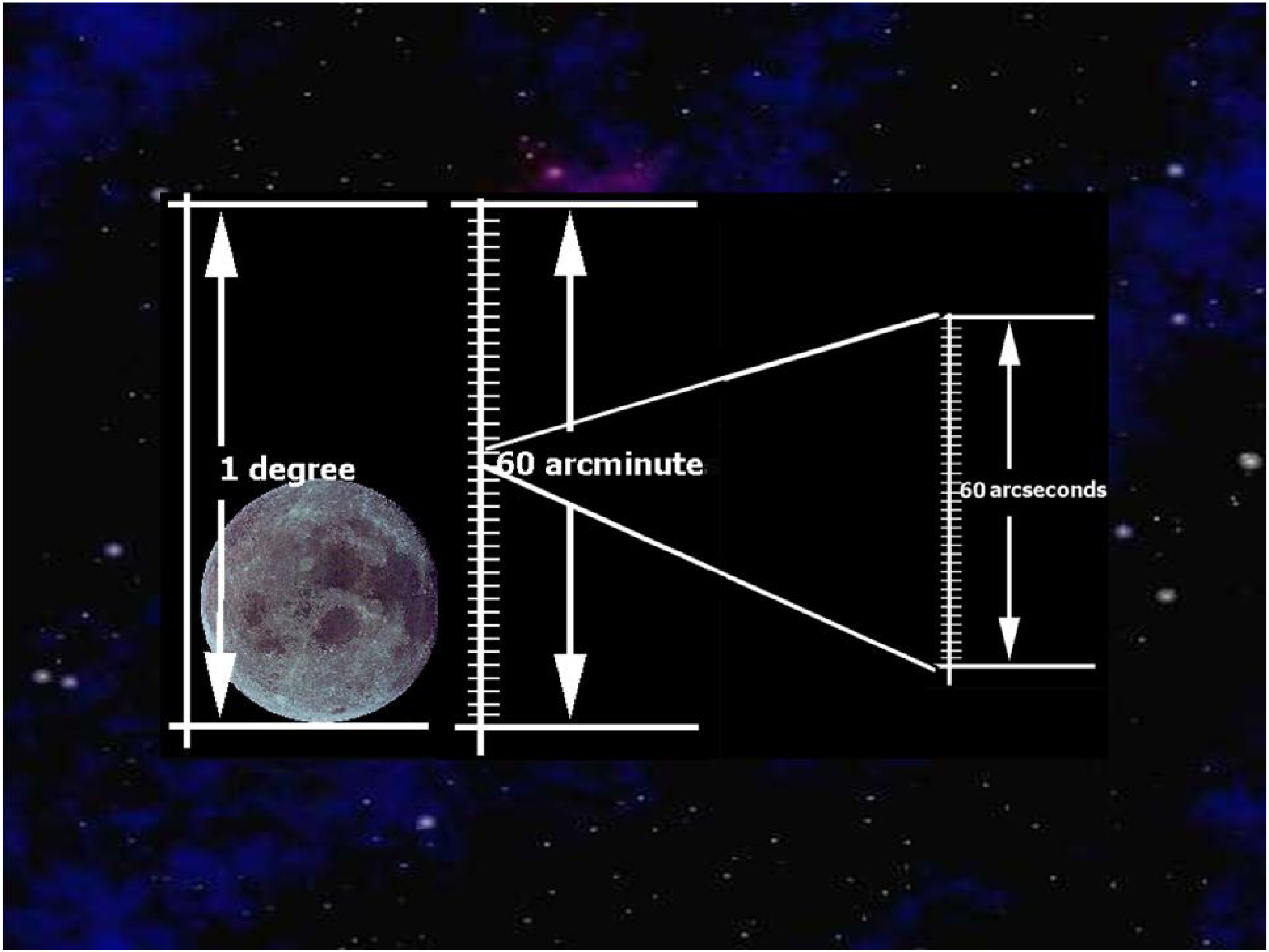
The ability to see fine details in small objects.

Angular Resolution:

α = the minimum angle that can be resolved.




$$a \propto \frac{l}{D}$$


1 degree
60 arcminute
60 arcseconds

# Example (human eye vs. MLO):

Choose $\lambda$ = 5000 Å or 0.00005 cm

$$a'' = \frac{\left(2.5\times10^{5}\right)\left(5\times10^{-5}\right)}{0.3cm} = 42''$$

$$a'' = \frac{\left(2.5\times10^{5}\right)\left(5\times10^{-5}\right)}{100cm} = 0.13''$$

# So you're thinking "build 'em really huge"?

Not so fast!

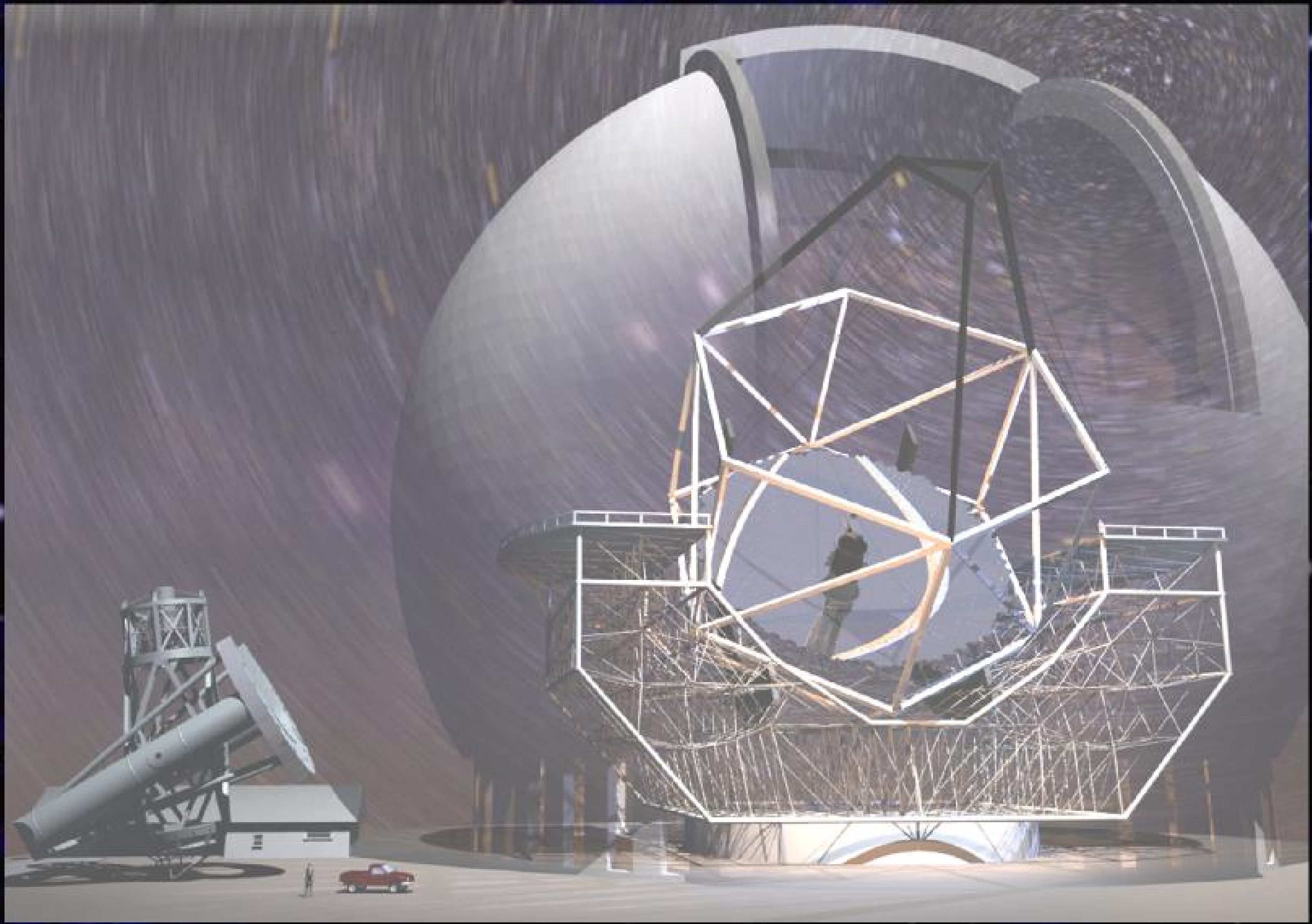
The atmosphere limits the resolution of any telescope.

**SEEING:**

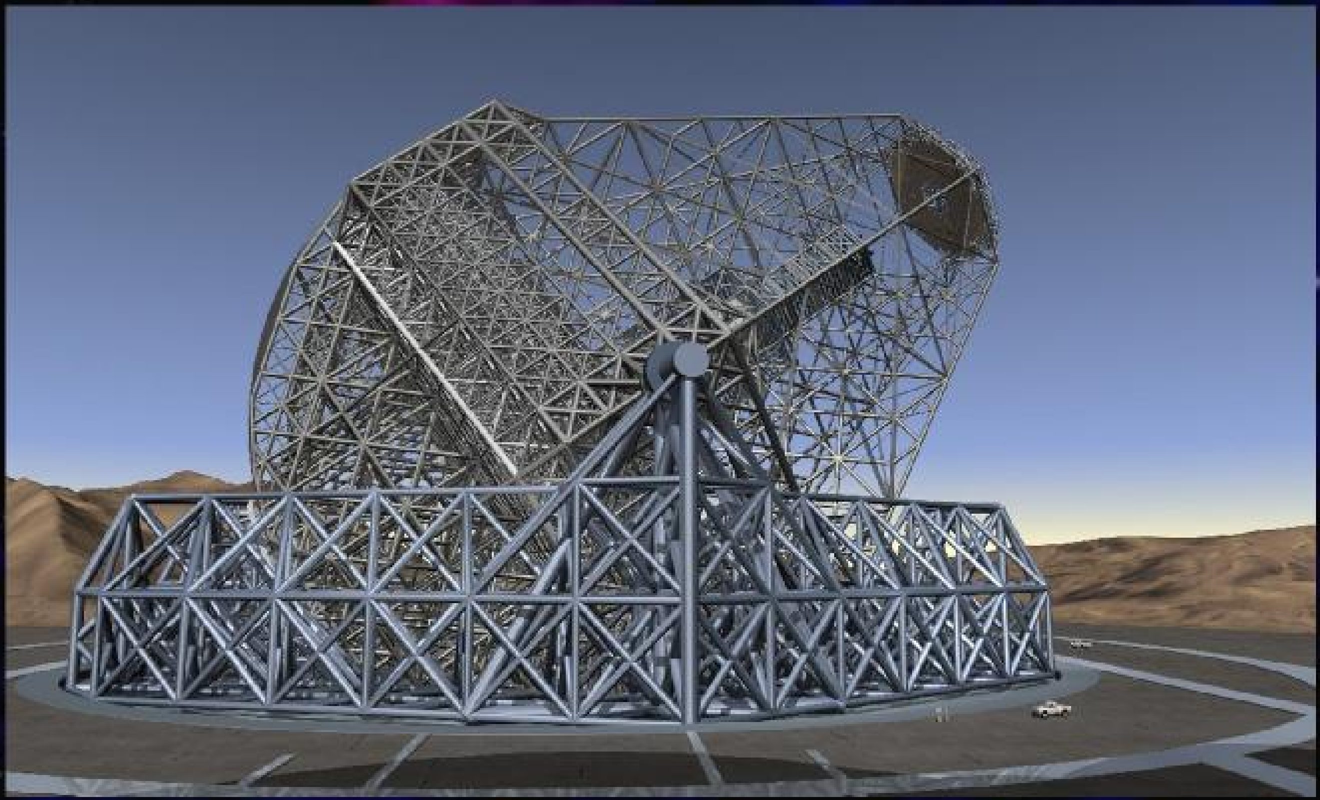
The smearing of an image seen with the telescope due to the turbulance of the Earth's atmosphere.

**1" ® 0.25" at the *__very__* best!**

# Hale 5-meter versus the 30-meter telescope



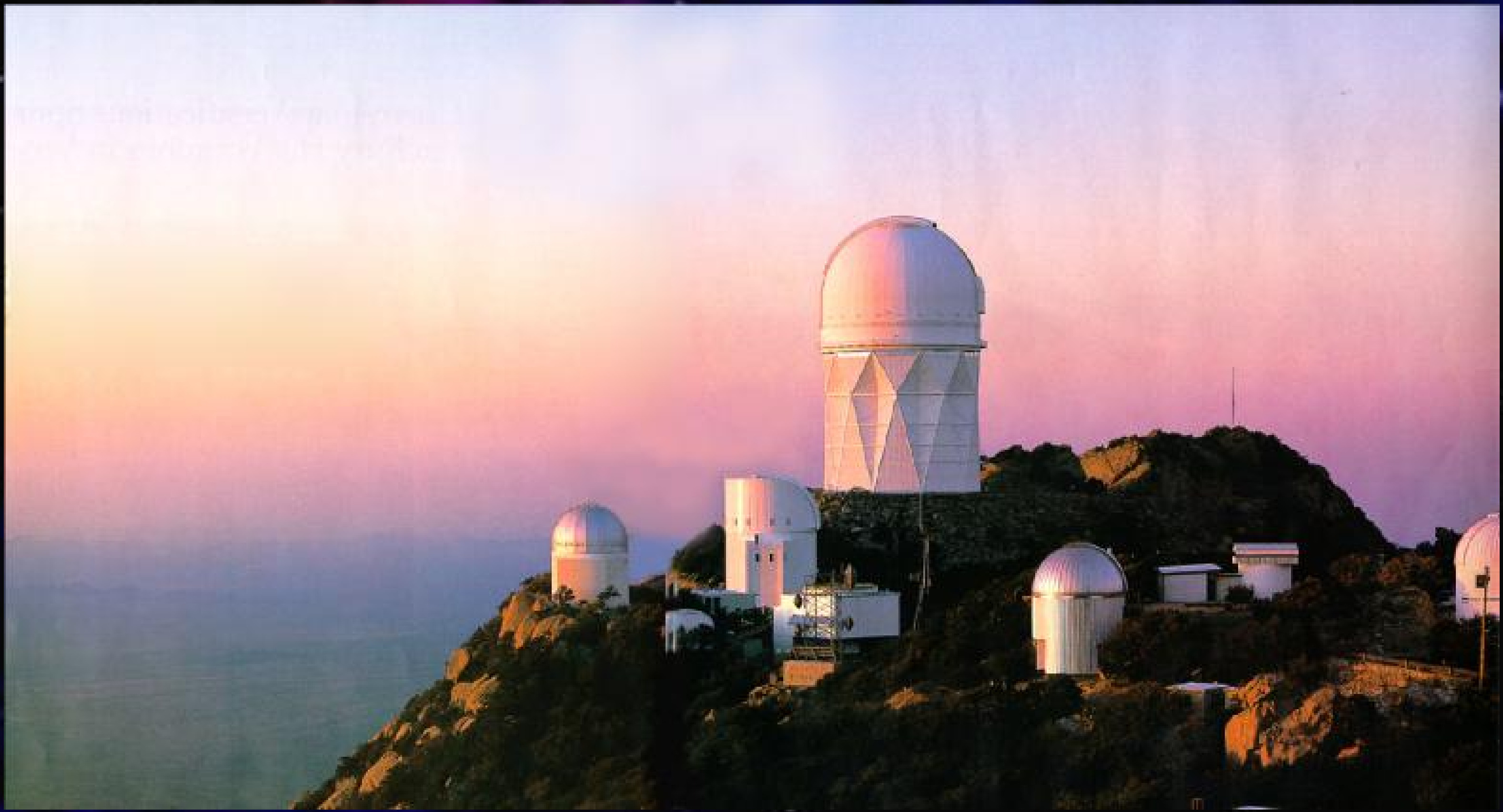
# OWL Telescope 100-meter!!



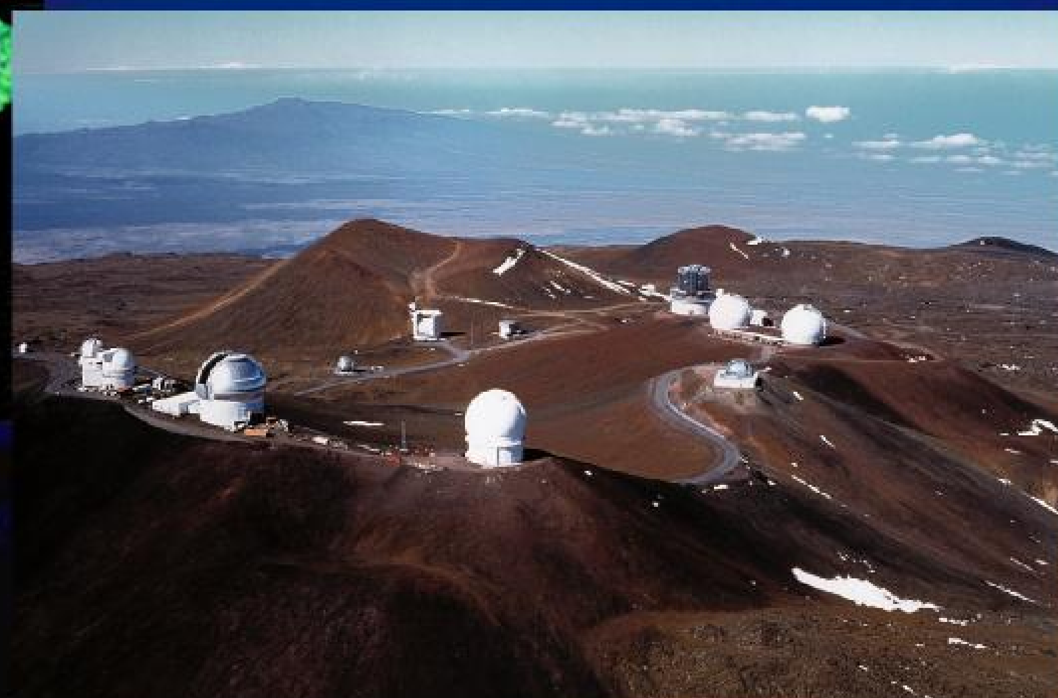
Comparison of the sizes!

# Other atmospheric problems?

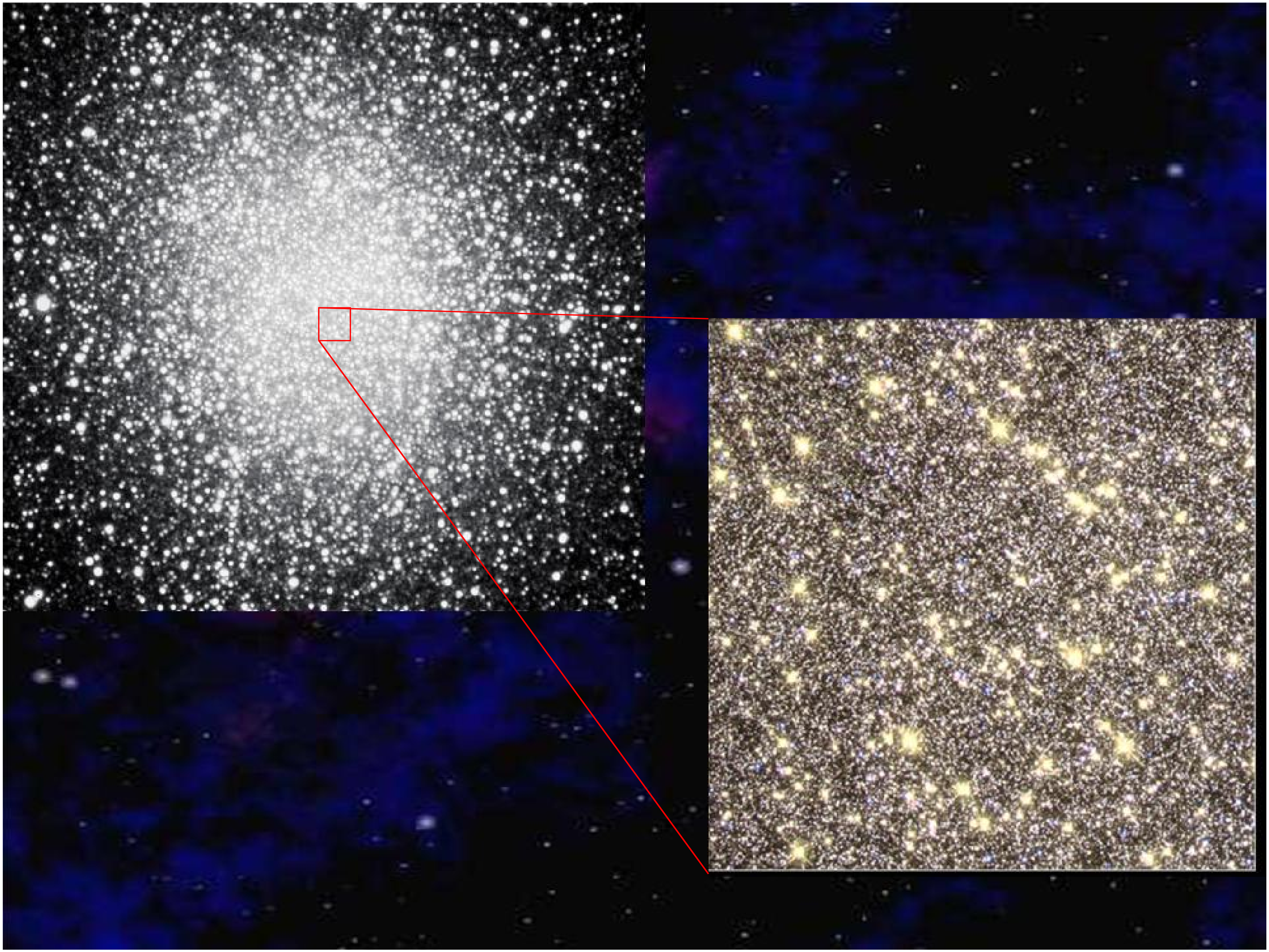
# So where do we put telescopes to minimize the problems?




Mauna Kea



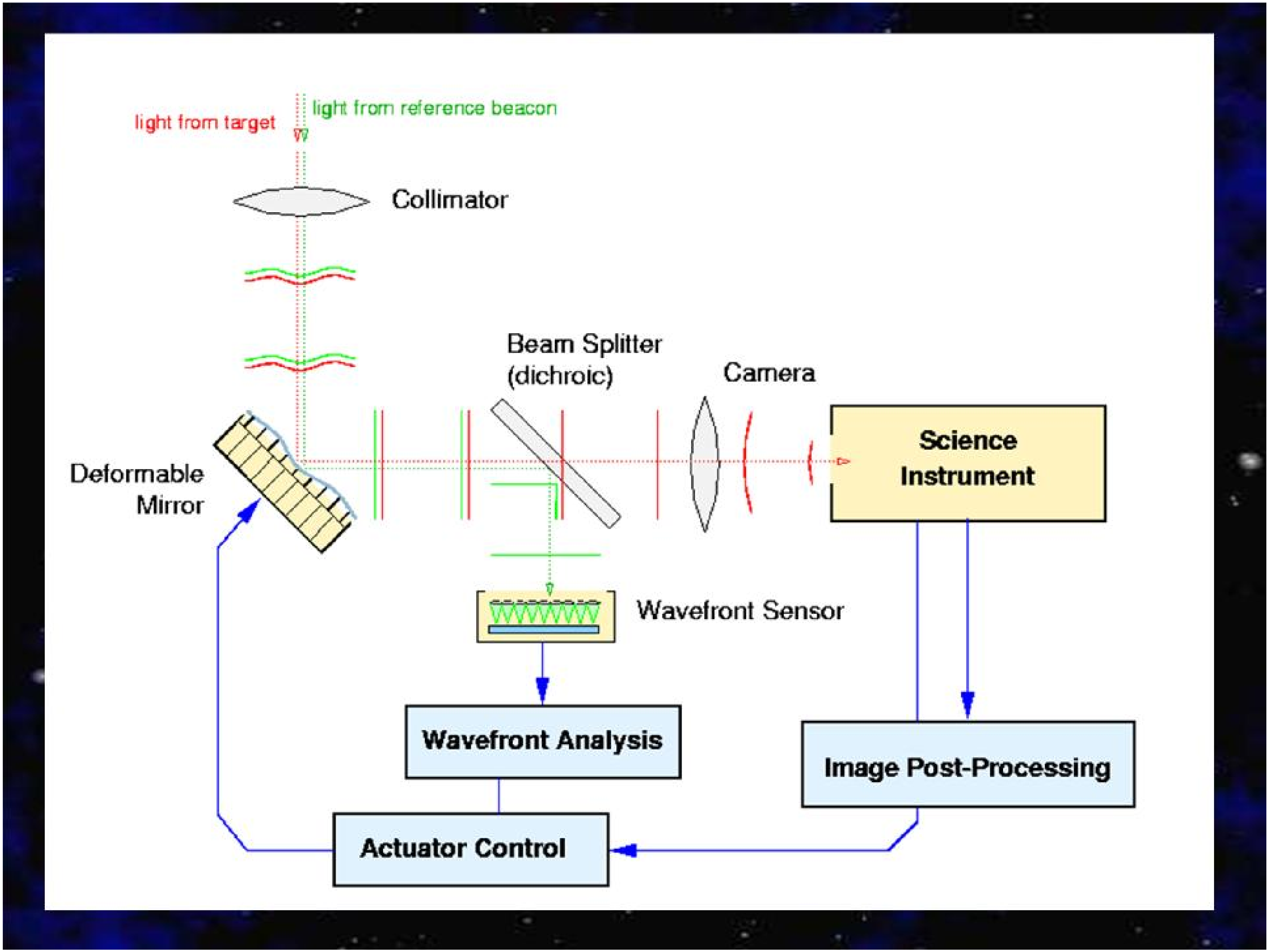
# Where is the ULTIMATE place to put a telescope?



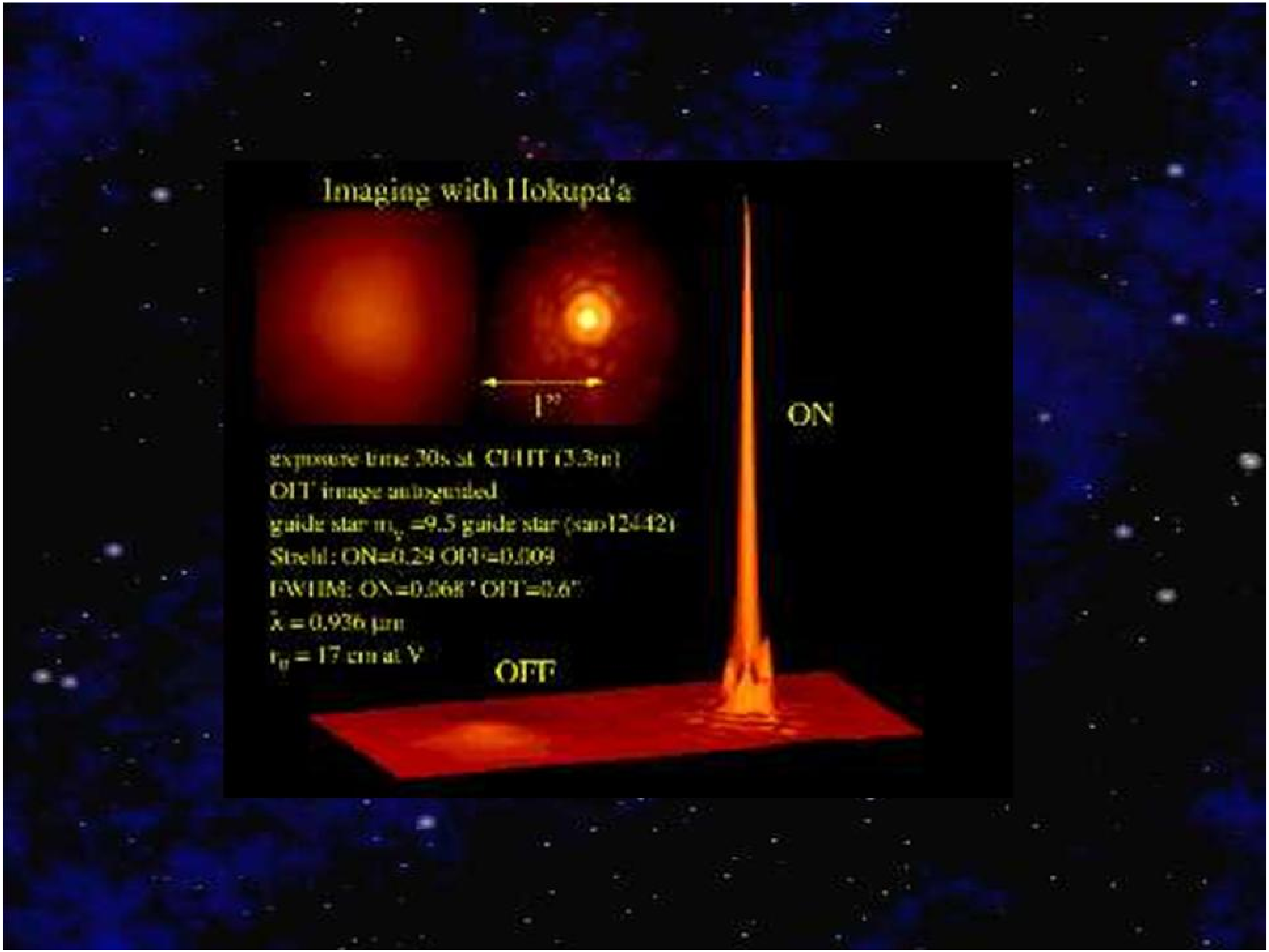
In the 1960's and 70's as space telescopes were being advanced

Unforeseen technology advances were occurring with with ground based telescopes

- Adaptive optics: the ability to compensate for the blurring effect of earths atmosphere



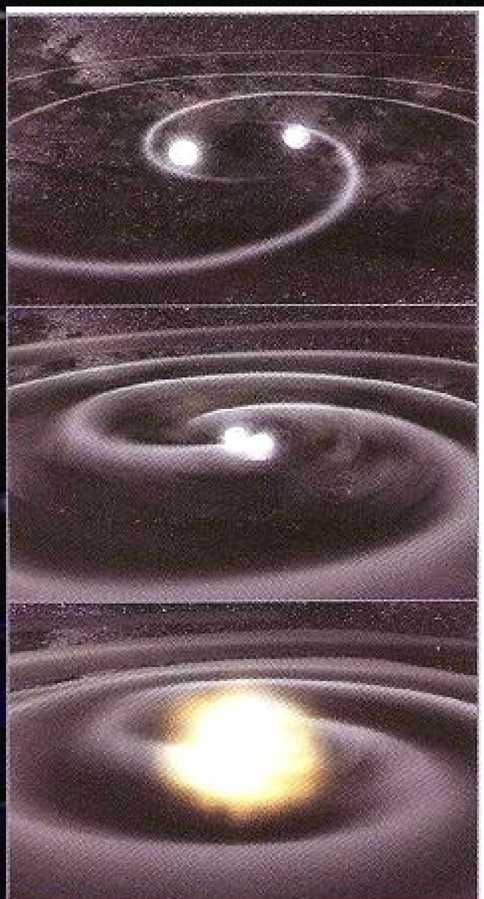
light from target
light from reference beacon
Collimator
Beam Splitter
(dichroic)
Camera
Deformable
Mirror
Science
Instrument
Wavefront Sensor
Wavefront Analysis
Image Post-Processing
Actuator Control

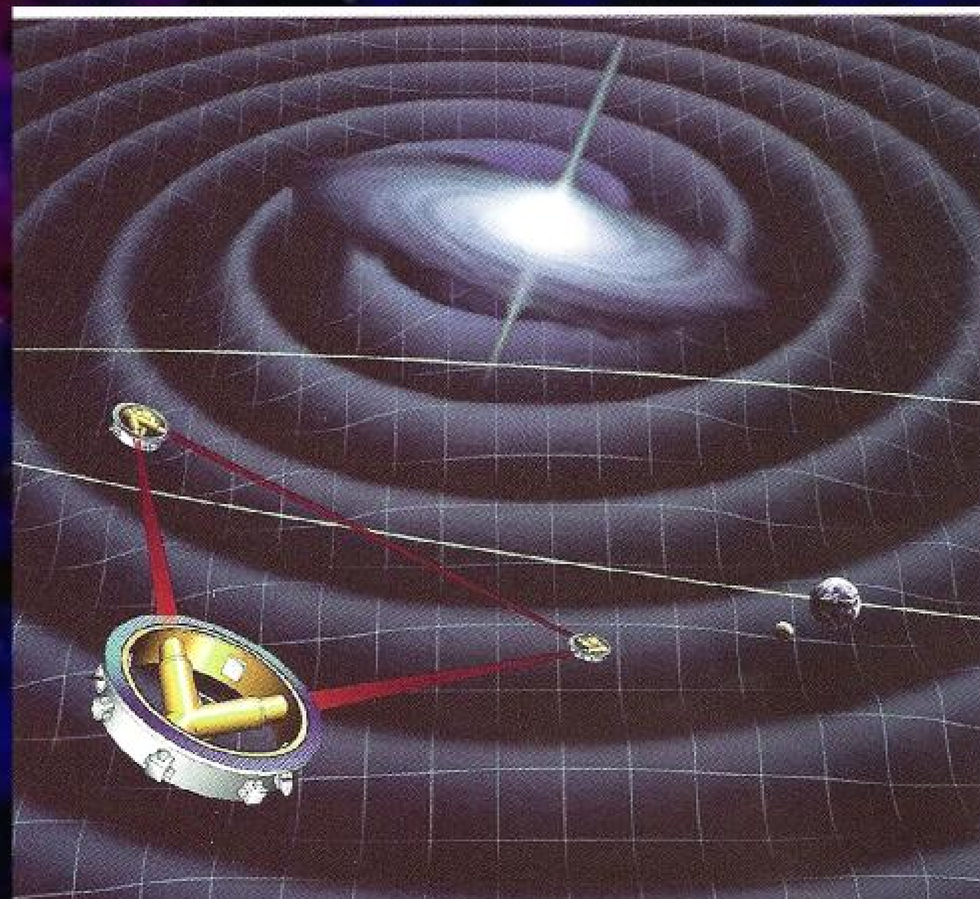

Imaging with Hokupa'a
1"
ON
exposure time 30s at CFHT (3.3m)
OFF image autoguided
guide star m_v =9.5 guide star (sao12442)
Strehl: ON=0.29 OFF=0.009
FWHM: ON=0.068" OFF=0.6"
λ = 0.936 μm
r_0 = 17 cm at V
OFF

Chandra X-Ray Telescope/Observatory

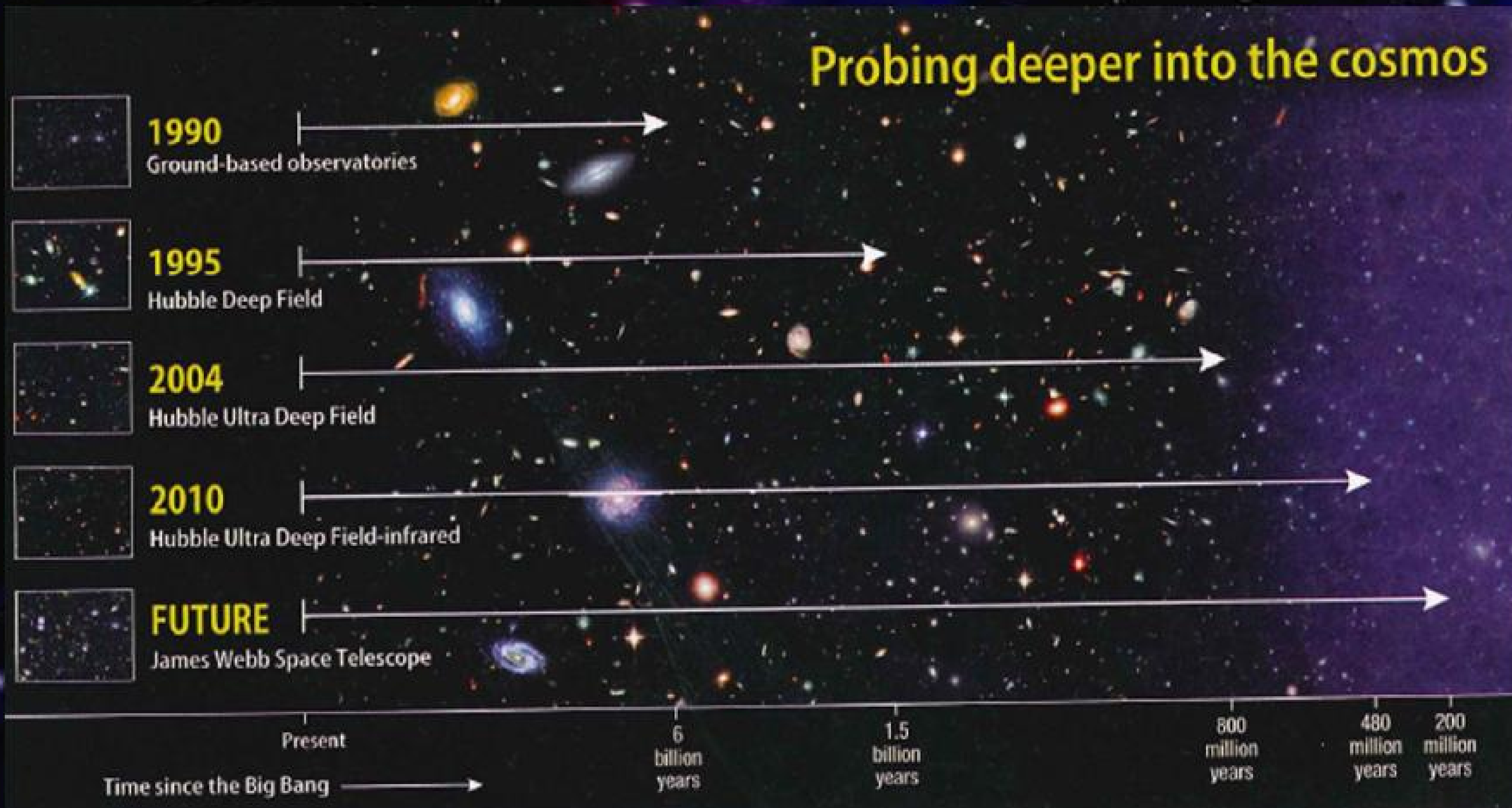
# Kepler’s Star:  Super nova remnant in X-rays

# Gravity Wave Telescope: LISA





# Probing ever Deeper into Space and the Past



# Probing ever Deeper into Space and the Past

esa

www.spacetelescope.org

# James Webb Space Telescope