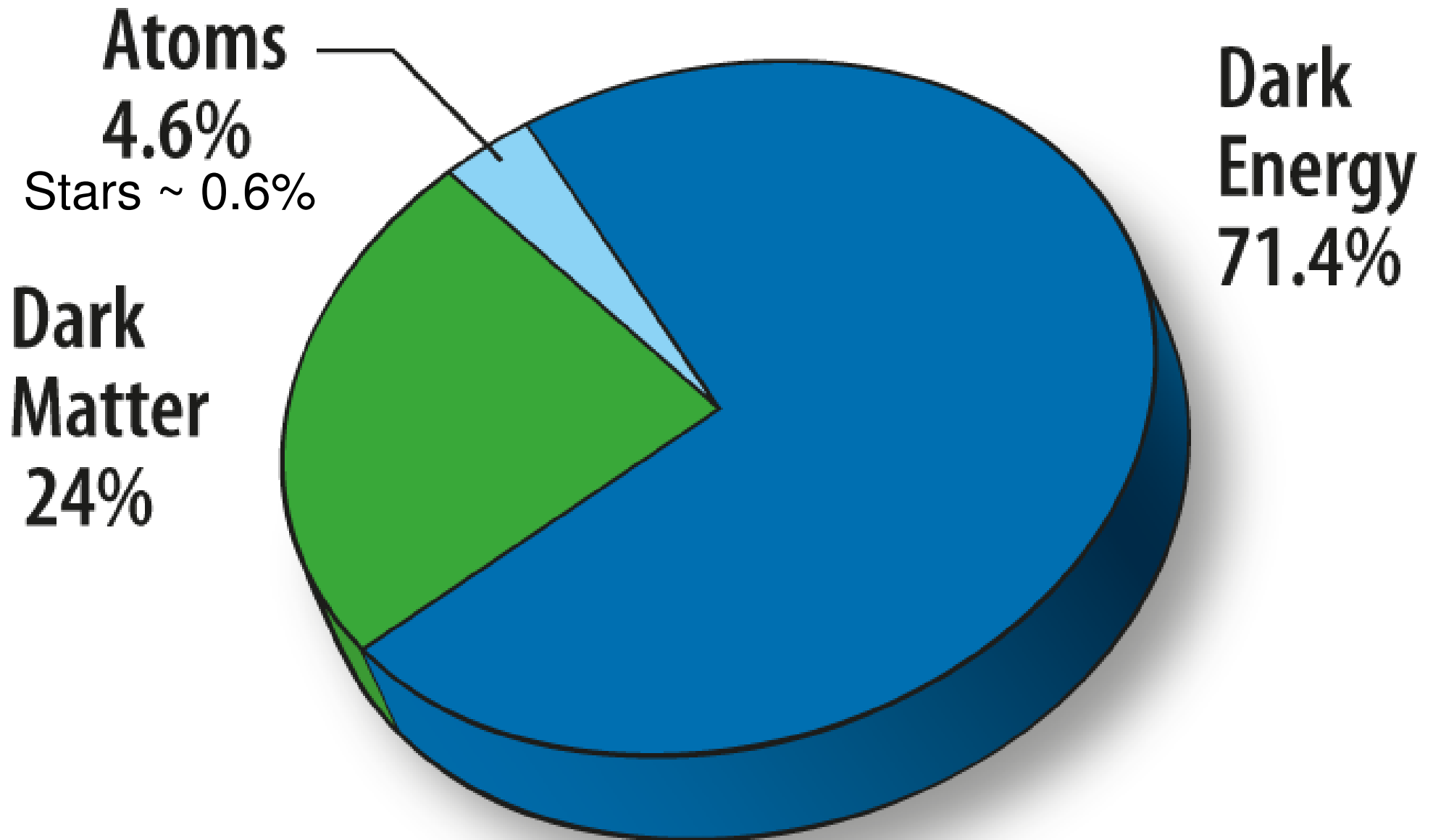


Lectures 1 - 2

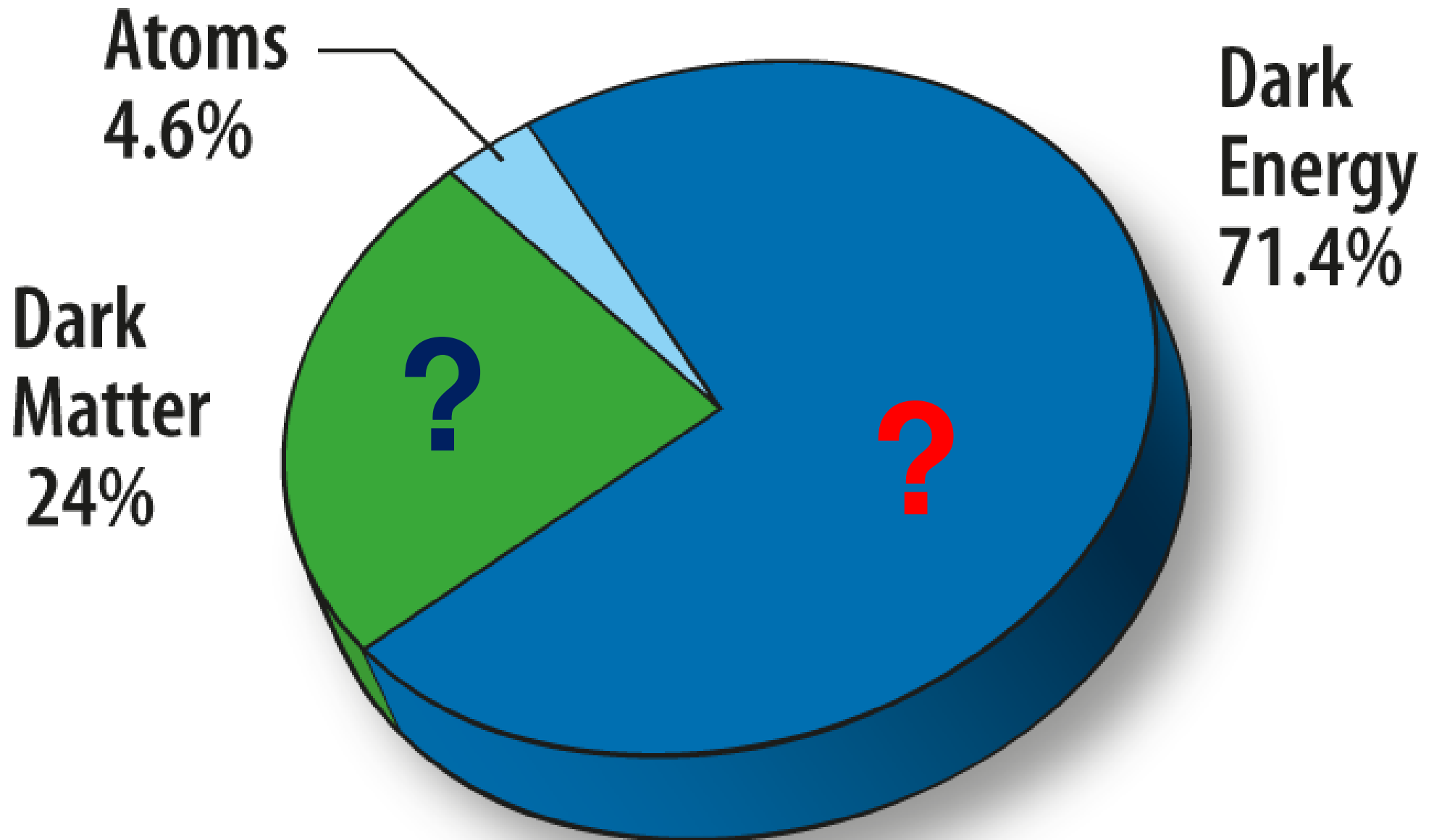
What is the Universe made of?

The puzzle of dark matter.

What is the Universe made of?



What is the Universe made of?



**Dark matter and dark energy:
We don't know what it is.**

“ORDINARY MATTER”: People, Stars, Molecules, Atoms

PERIODIC TABLE
Atomic Properties of the Elements

NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Group
1
IA

1
H
Hydrogen
1.00794
1s
13.5984

2
IIA

3
IIIB

4
IVB

5
VB

6
VIB

7
VIIB

8
VIII

9
VIII

10
VIII

11
IB

12
IIB

13
IIIA

14
IVA

15
VA

16
VIA

17
VIIA

18
VIIIA

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ¹³³Cs

speed of light in vacuum	<i>c</i>	299 792 458 m s ⁻¹	(exact)
Planck constant	<i>h</i>	6.6261 × 10 ⁻³⁴ J s	(<i>h</i> = <i>h</i> /2π)
elementary charge	<i>e</i>	1.6022 × 10 ⁻¹⁹ C	
electron mass	<i>m_e</i>	9.1094 × 10 ⁻³¹ kg	
	<i>m_ec²</i>	0.5110 MeV	
proton mass	<i>m_p</i>	1.6726 × 10 ⁻²⁷ kg	
fine-structure constant	<i>α</i>	1/137.036	
Rydberg constant	<i>R_∞</i>	10 973 732 m ⁻¹	
	<i>R_∞c</i>	3.289 842 × 10 ¹⁵ Hz	
	<i>R_∞hc</i>	13.6057 eV	
Boltzmann constant	<i>k</i>	1.3807 × 10 ⁻²³ J K ⁻¹	

Physics Laboratory
physics.nist.gov

Standard Reference Data Group
www.nist.gov/srd

Solids
 Liquids
 Gases
 Artificially Prepared

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	H Hydrogen 1.00794 1s 13.5984																	He Helium 4.002602 1s ² 24.5874	
2	Li Lithium 6.941 1s ² 2s 5.3917	Be Beryllium 9.012182 1s ² 2s ² 9.3227											B Boron 10.811 1s ² 2s ² 2p 8.2980	C Carbon 12.0107 1s ² 2s ² 2p ² 11.2603	N Nitrogen 14.0067 1s ² 2s ² 2p ³ 14.5341	O Oxygen 15.9994 1s ² 2s ² 2p ⁴ 13.6181	F Fluorine 18.9984032 1s ² 2s ² 2p ⁵ 17.4228	Ne Neon 20.1797 1s ² 2s ² 2p ⁶ 21.5645	
3	Na Sodium 22.989770 [Ne]3s 5.1391	Mg Magnesium 24.3050 [Ne]3s ² 7.6462											Al Aluminum 26.981538 [Ne]3s ² 3p 5.9858	Si Silicon 28.0855 [Ne]3s ² 3p ² 8.1517	P Phosphorus 30.973761 [Ne]3s ² 3p ³ 10.4867	S Sulfur 32.065 [Ne]3s ² 3p ⁴ 10.3600	Cl Chlorine 35.453 [Ne]3s ² 3p ⁵ 12.9676	Ar Argon 39.948 [Ne]3s ² 3p ⁶ 15.7596	
4	K Potassium 39.0983 [Ar]4s 4.3407	Ca Calcium 40.078 [Ar]4s ² 6.1132	Sc Scandium 44.955910 [Ar]3d ¹ 4s ² 6.5615	Ti Titanium 47.867 [Ar]3d ² 4s ² 6.8281	V Vanadium 50.9415 [Ar]3d ³ 4s ² 6.7462	Cr Chromium 51.9961 [Ar]3d ⁵ 4s 6.7665	Mn Manganese 54.938049 [Ar]3d ⁵ 4s ² 7.4340	Fe Iron 55.845 [Ar]3d ⁶ 4s ² 7.9024	Co Cobalt 58.933200 [Ar]3d ⁷ 4s ² 7.8810	Ni Nickel 58.6934 [Ar]3d ⁸ 4s ² 7.6398	Cu Copper 63.546 [Ar]3d ¹⁰ 4s 7.7264	Zn Zinc 65.409 [Ar]3d ¹⁰ 4s ² 9.3942	Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p 5.9993	Ge Germanium 72.64 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994	As Arsenic 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7886	Se Selenium 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524	Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138	Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996	
5	Rb Rubidium 85.4678 [Kr]5s 4.1771	Sr Strontium 87.62 [Kr]5s ² 5.6949	Y Yttrium 88.90585 [Kr]4d ¹ 5s ² 6.2173	Zr Zirconium 91.224 [Kr]4d ² 5s ² 6.6339	Nb Niobium 92.90638 [Kr]4d ⁴ 5s 6.7589	Mo Molybdenum 95.94 [Kr]4d ⁵ 5s 7.0924	Tc Technetium (98) [Kr]4d ⁵ 5s ² 7.28	Ru Ruthenium 101.07 [Kr]4d ⁷ 5s 7.3605	Rh Rhodium 102.90550 [Kr]4d ⁸ 5s 7.4589	Pd Palladium 106.42 [Kr]4d ¹⁰ 8.3369	Ag Silver 107.8682 [Kr]4d ¹⁰ 5s 7.5762	Cd Cadmium 112.411 [Kr]4d ¹⁰ 5s ² 8.9938	In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p 5.7954	Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ² 7.3439	Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³ 8.6084	Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴ 9.0096	I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵ 10.4513	Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶ 12.1298	
6	Cs Cesium 132.90545 [Xe]6s 3.8939	Ba Barium 137.327 [Xe]6s ² 5.2117		Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ² 6.8251	Ta Tantalum 180.9479 [Xe]4f ¹⁴ 5d ³ 6s ² 7.5496	W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ² 7.8640	Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ² 7.8335	Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ² 8.4382	Ir Iridium 192.217 [Xe]4f ¹⁴ 5d ⁷ 6s ² 8.9670	Pt Platinum 195.078 [Xe]4f ¹⁴ 5d ⁹ 6s 8.9588	Au Gold 196.96655 [Xe]4f ¹⁴ 5d ¹⁰ 6s 9.2255	Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	Tl Thallium 204.3833 [Hg]6p 6.1082	Pb Lead 207.2 [Hg]6p ² 7.4167	Bi Bismuth 208.98038 [Hg]6p ³ 7.2855	Po Polonium (209) [Hg]6p ⁴ 8.414	At Astatine (210) [Hg]6p ⁵	Rn Radon (222) [Hg]6p ⁶ 10.7485	
7	Fr Francium (223) [Rn]7s 4.0727	Ra Radium (226) [Rn]7s ² 5.2784		Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ² 6.0 ?	Db Dubnium (262)	Sg Seaborgium (266)	Bh Bohrium (264)	Hs Hassium (277)	Mt Meitnerium (268)	Uun Ununnilium (281)	Uuu Ununnilium (272)	Uub Ununbium (285)		Uuq Ununquadium (289)		Uuh Ununhexium (292)			
				La Lanthanum 138.9055 [Xe]5d ¹ 6s ² 5.5769	Ce Cerium 140.116 [Xe]4f ¹ 5d ¹ 6s ² 5.5387	Pr Praseodymium 140.90765 [Xe]4f ² 6s ² 5.473	Nd Neodymium 144.24 [Xe]4f ³ 6s ² 5.5250	Pm Promethium (145) [Xe]4f ⁵ 6s ² 5.582	Sm Samarium 150.36 [Xe]4f ⁶ 6s ² 5.6437	Eu Europium 151.964 [Xe]4f ⁷ 6s ² 5.6704	Gd Gadolinium 157.25 [Xe]4f ⁷ 5d ¹ 6s ² 6.1498	Tb Terbium 158.92534 [Xe]4f ⁹ 6s ² 5.8638	Dy Dysprosium 162.500 [Xe]4f ¹⁰ 6s ² 5.9389	Ho Holmium 164.93032 [Xe]4f ¹¹ 6s ² 6.0215	Er Erbium 167.259 [Xe]4f ¹² 6s ² 6.1077	Tm Thulium 168.93421 [Xe]4f ¹³ 6s ² 6.1843	Yb Ytterbium 173.04 [Xe]4f ¹⁴ 6s ² 6.2542	Lu Lutetium 174.967 [Xe]4f ¹⁴ 5d ¹ 6s ² 5.4259	
			Ac Actinium (227) [Rn]6d ¹ 7s ² 5.17	Th Thorium 232.0381 [Rn]6d ² 7s ² 6.3057	Pa Protactinium 231.03688 [Rn]5f ² 6d ¹ 7s ² 5.89	U Uranium 238.02891 [Rn]5f ³ 6d ¹ 7s ² 6.1941	Np Neptunium (237) [Rn]5f ⁴ 6d ¹ 7s ² 6.2657	Pu Plutonium (244) [Rn]5f ⁶ 7s ² 6.0260	Am Americium (243) [Rn]5f ⁷ 7s ² 5.9738	Cm Curium (247) [Rn]5f ⁸ 6d ¹ 7s ² 5.9914	Bk Berkelium (247) [Rn]5f ⁹ 7s ² 6.1979	Cf Californium (251) [Rn]5f ¹⁰ 7s ² 6.2817	Es Einsteinium (252) [Rn]5f ¹¹ 7s ² 6.42	Fm Fermium (257) [Rn]5f ¹² 7s ² 6.50	Md Mendelevium (258) [Rn]5f ¹³ 7s ² 6.58	No Nobelium (259) [Rn]5f ¹⁴ 7s ² 6.65	Lr Lawrencium (262) [Rn]5f ¹⁴ 7s ² 7p ¹ 4.9 ?		

Lanthanides
 Actinides

58 ¹G₄
Ce
 Cerium
 140.116
 [Xe]4f¹5d¹6s²
 5.3387
 Ground-state Configuration: [Xe]4f¹5d¹6s²
 Ionization Energy (eV): 5.3387

¹Based upon ¹²C. () indicates the mass number of the most stable isotope. For a description of the data, visit physics.nist.gov/data NIST SP 966 (September 2003)

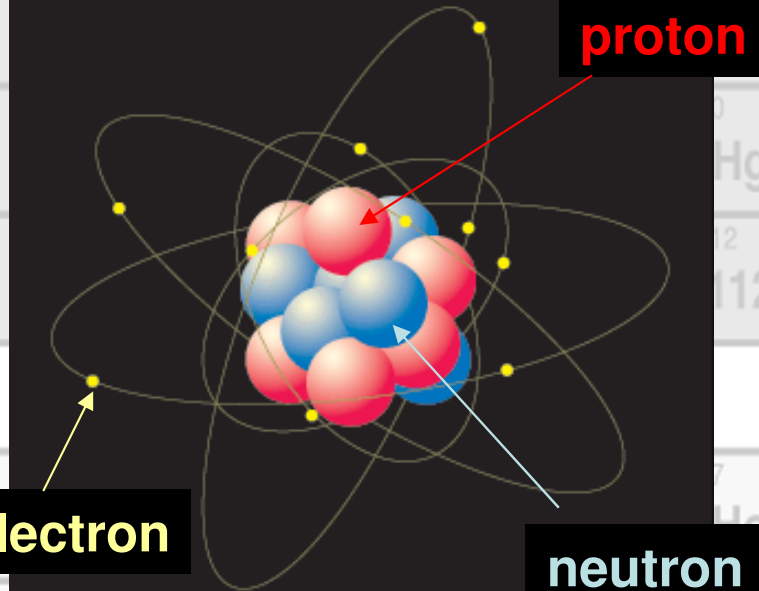
Atoms

Periodic Table

Atoms are all similarly made of:

- protons and neutrons in the nucleus
- electrons orbiting around

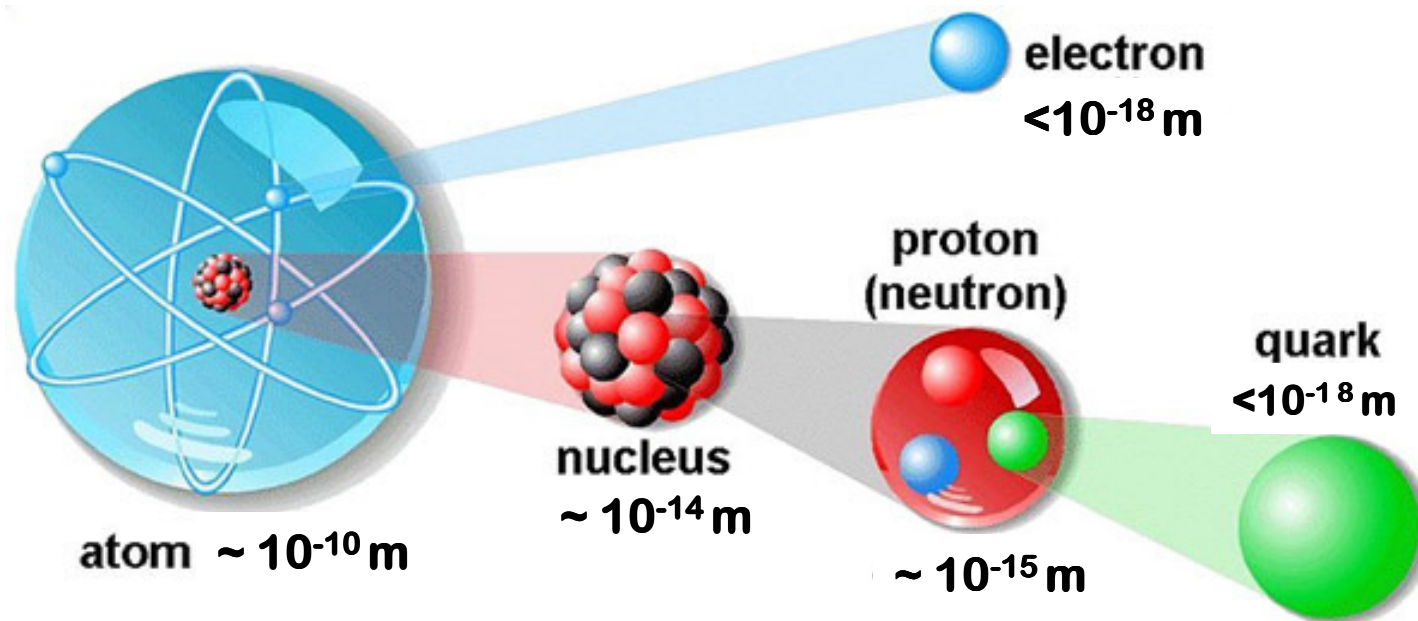
The **electron** was the first elementary particle to be discovered (JJ Thomson 1897)



Protons, neutrons are made up of quarks

From atoms to elementary particles: electrons and quarks

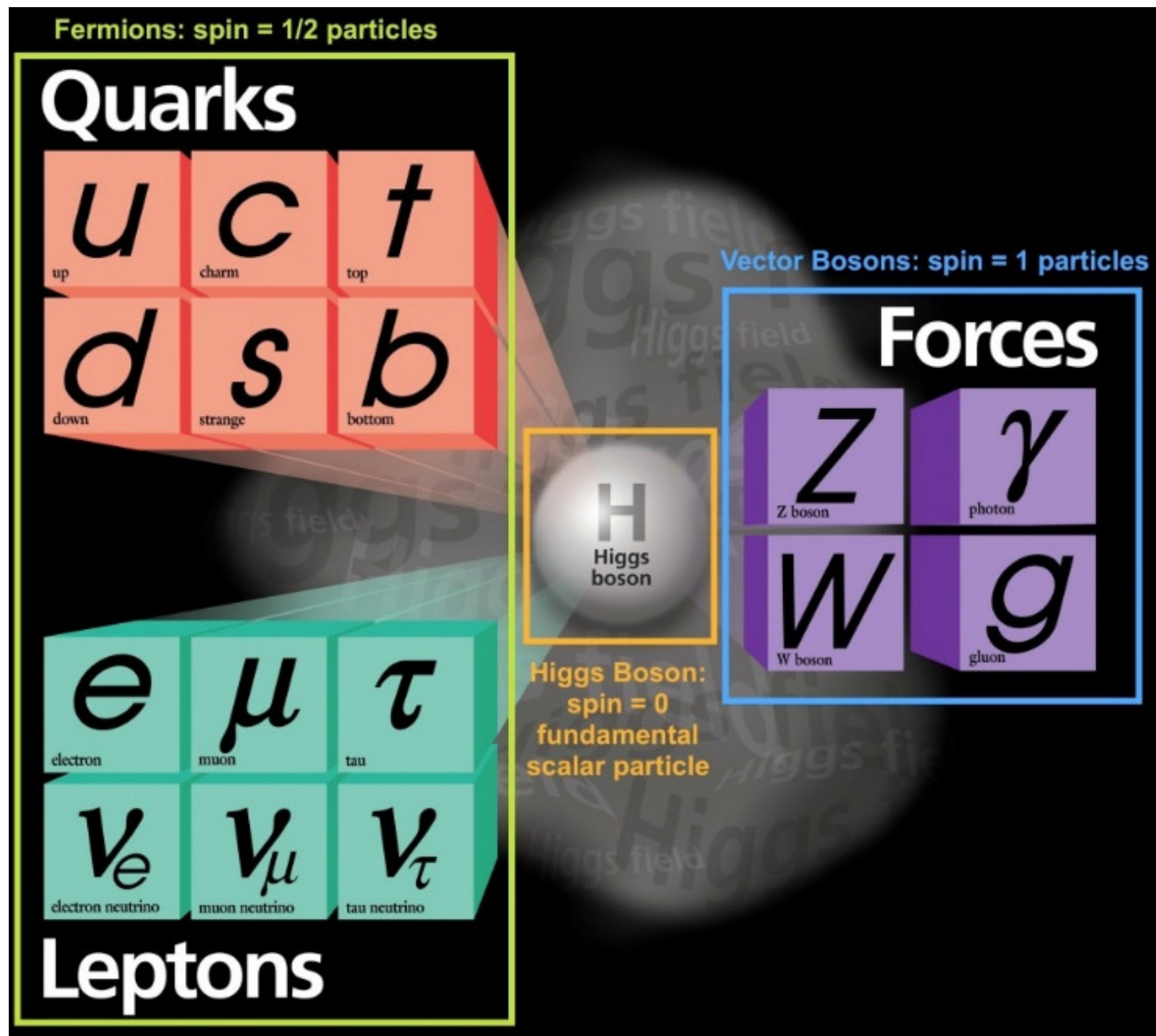
How small are the smallest constituents of matter?



Elementary particles: not consisting from other particles
(to the best of our knowledge)

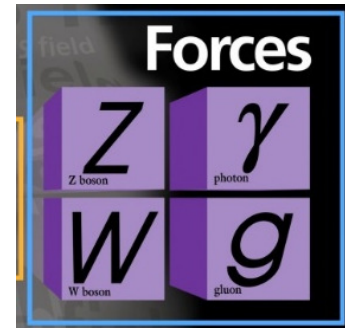
ORDINARY MATTER:

Standard model of Elementary particles



The 4 forces

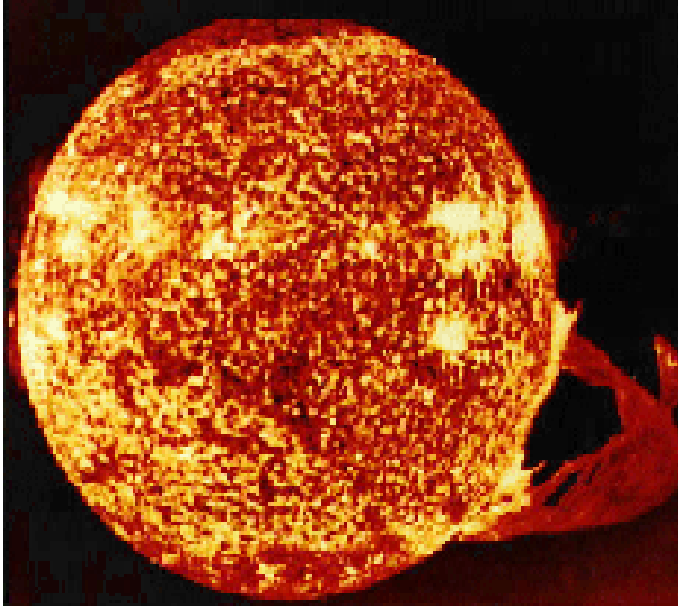
Fundamental interactions



Weak

Beta-decay
pp fusion

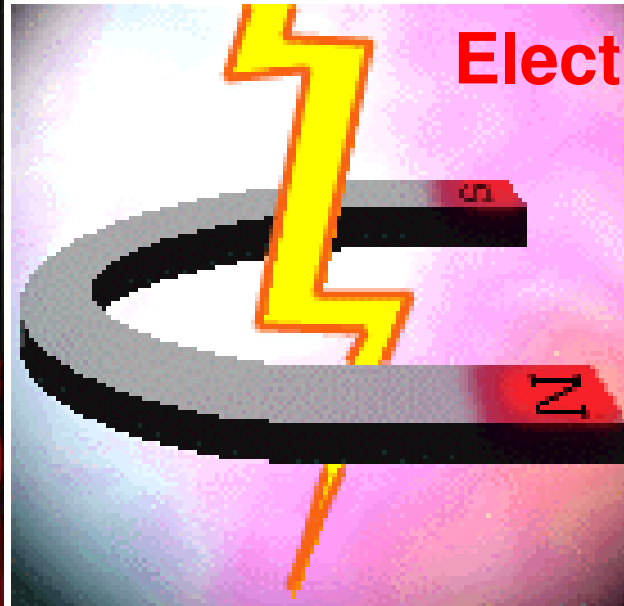
weak
charge



Electromagnetic

Electricity,
lasers,
magnets ...

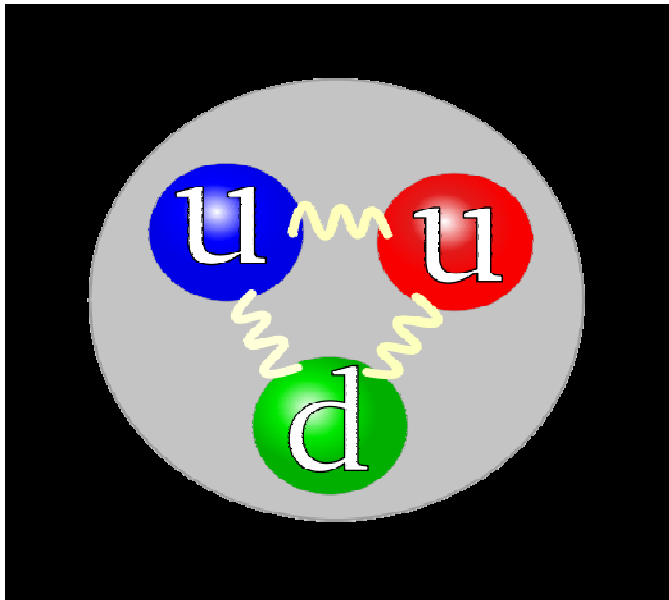
Electric
charge



Strong

Quark
binding

strong
charge



Gravity

Responsible of
keeping us
on Earth

mass



Dark matter and dark energy

Dark Matter: An undetected form of mass that emits little or no photons, but we know it must exist because we observe the effects of its gravity

Dark Energy: An unknown form of energy that is causing the universe to expand faster over time

Part 1

Dark matter:

How do we know that it exists?

Overview of experimental evidence

First evidence for dark matter: 1933



Fritz Zwicky
California Institute of Technology



Coma Cluster: 1000 galaxies
321 million light years away

Fritz Zwicky stumbled across the gravitational effects of dark matter in the early 1930s while studying how galaxies move within the Coma Cluster.

He used the 18 inch telescope to make a survey of all the galaxies in the Coma cluster and used measurements of the **Doppler shift of their spectra** to determine their velocities.

**A few slides on explanation of:
“Doppler shift of their spectra”**

THE ELECTROMAGNETIC SPECTRUM

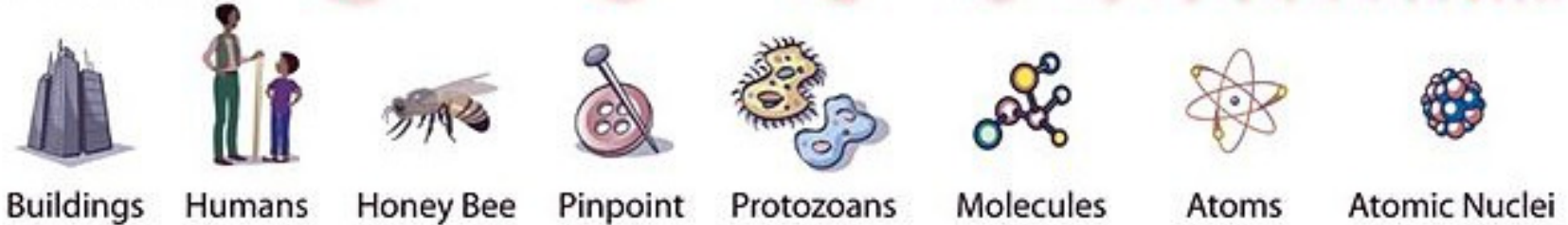
Penetrates Earth Atmosphere?



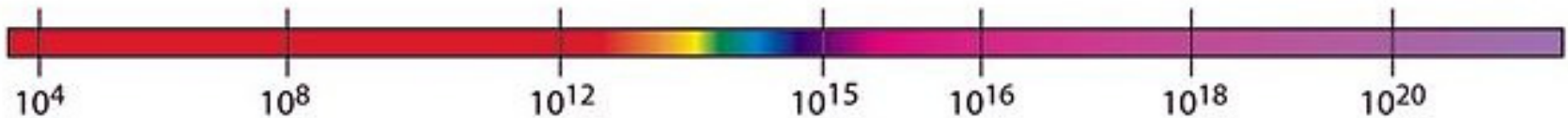
Wavelength (meters)



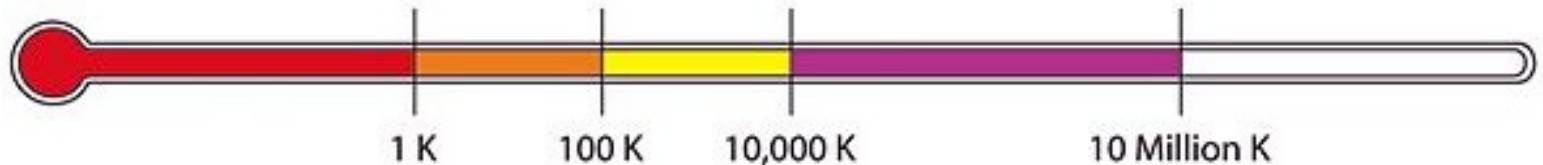
About the size of...



Frequency (Hz)



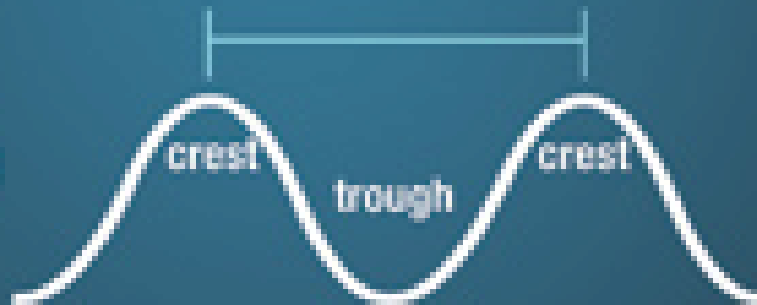
Temperature of bodies emitting the wavelength (K)



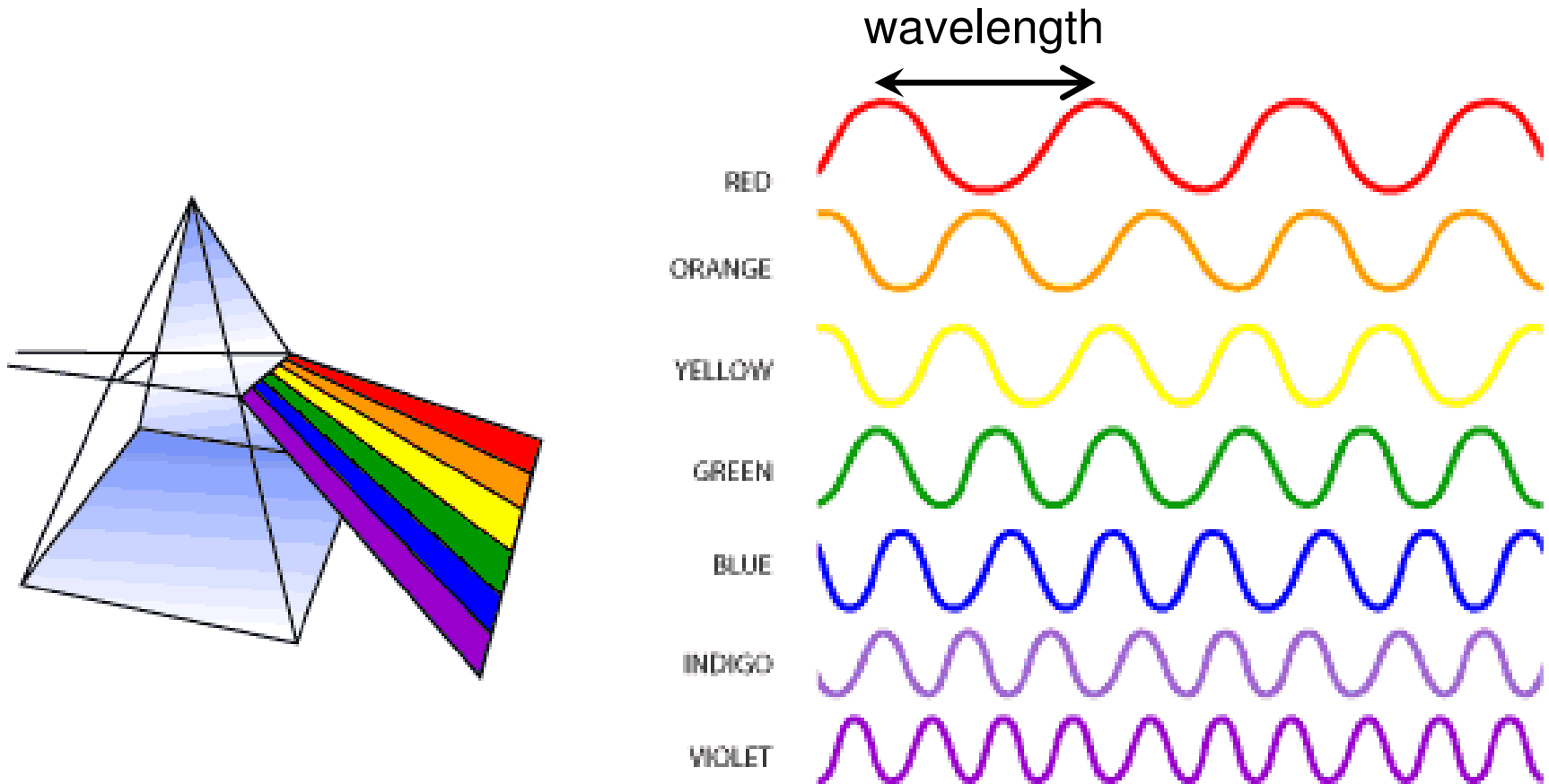
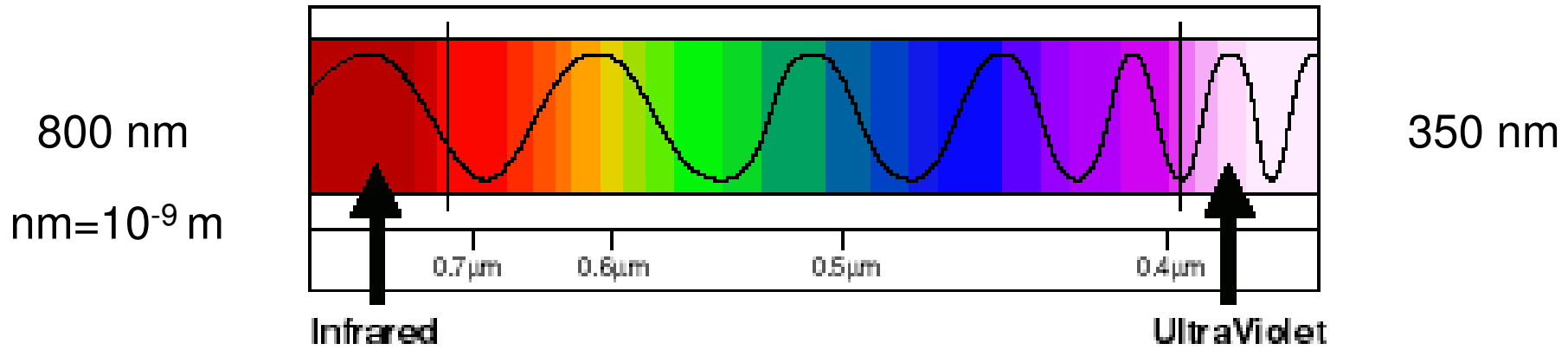
Frequency



Wavelength



Visible Light Region of the Electromagnetic Spectrum

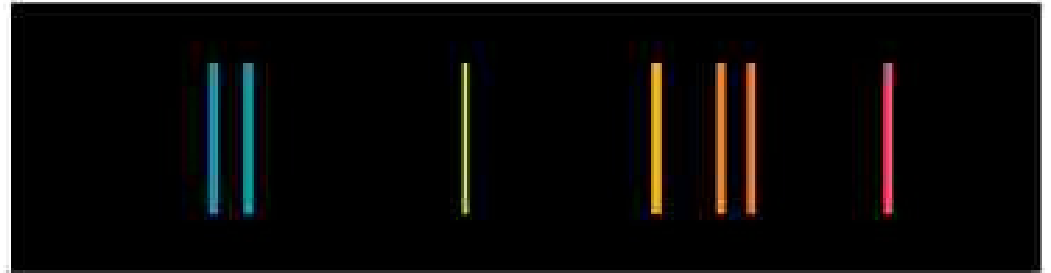


Astronomy and atomic spectral lines

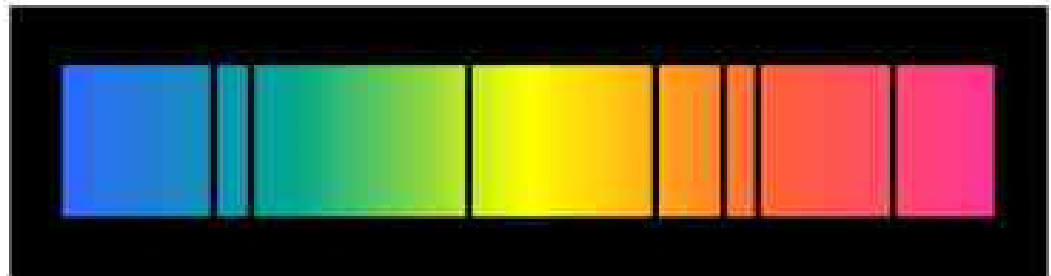
A spectral line is like a fingerprint that can be used to identify the atoms, elements or molecules present in a star, galaxy or cloud of interstellar gas. If we separate the incoming light from a celestial source using a prism, we will often see a spectrum of colors crossed with discrete lines.

[Link: Spectrum Explorer](#)

Emission lines: correspond to specific **wavelengths** of light emitted by an object.



Absorption lines: the result of specific wavelengths being absorbed along the line-of-sight.

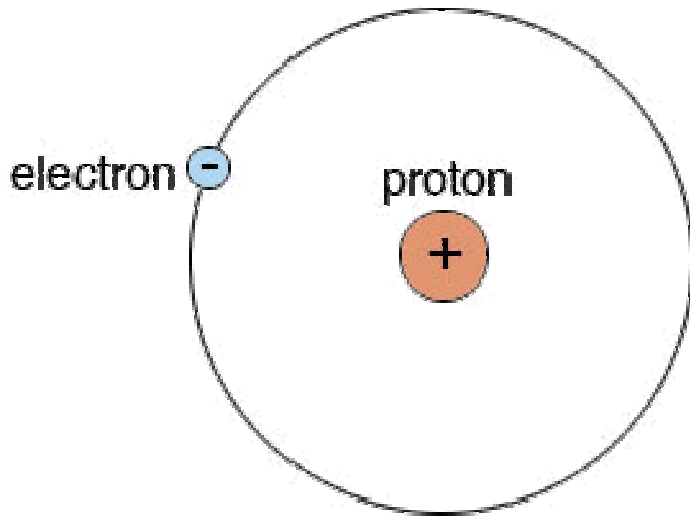


Note that spectral lines can also occur in other regions of the electromagnetic spectrum, although we can no longer use a prism to help identify them.

<http://astronomy.swin.edu.au/cosmos/S/Spectral+Line>

Why atoms emit electromagnetic radiation at specific wavelengths?

Hydrogen Atom

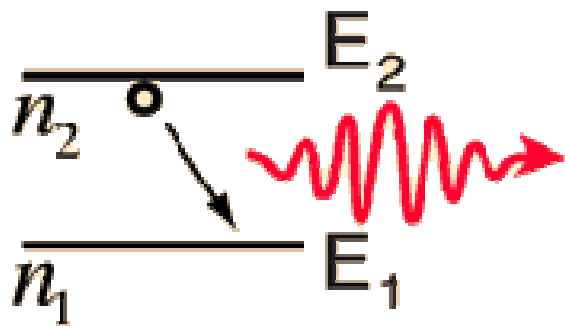


Quantum mechanics:

Electron in a hydrogen atom can only have specific energies: **“energy levels”**.

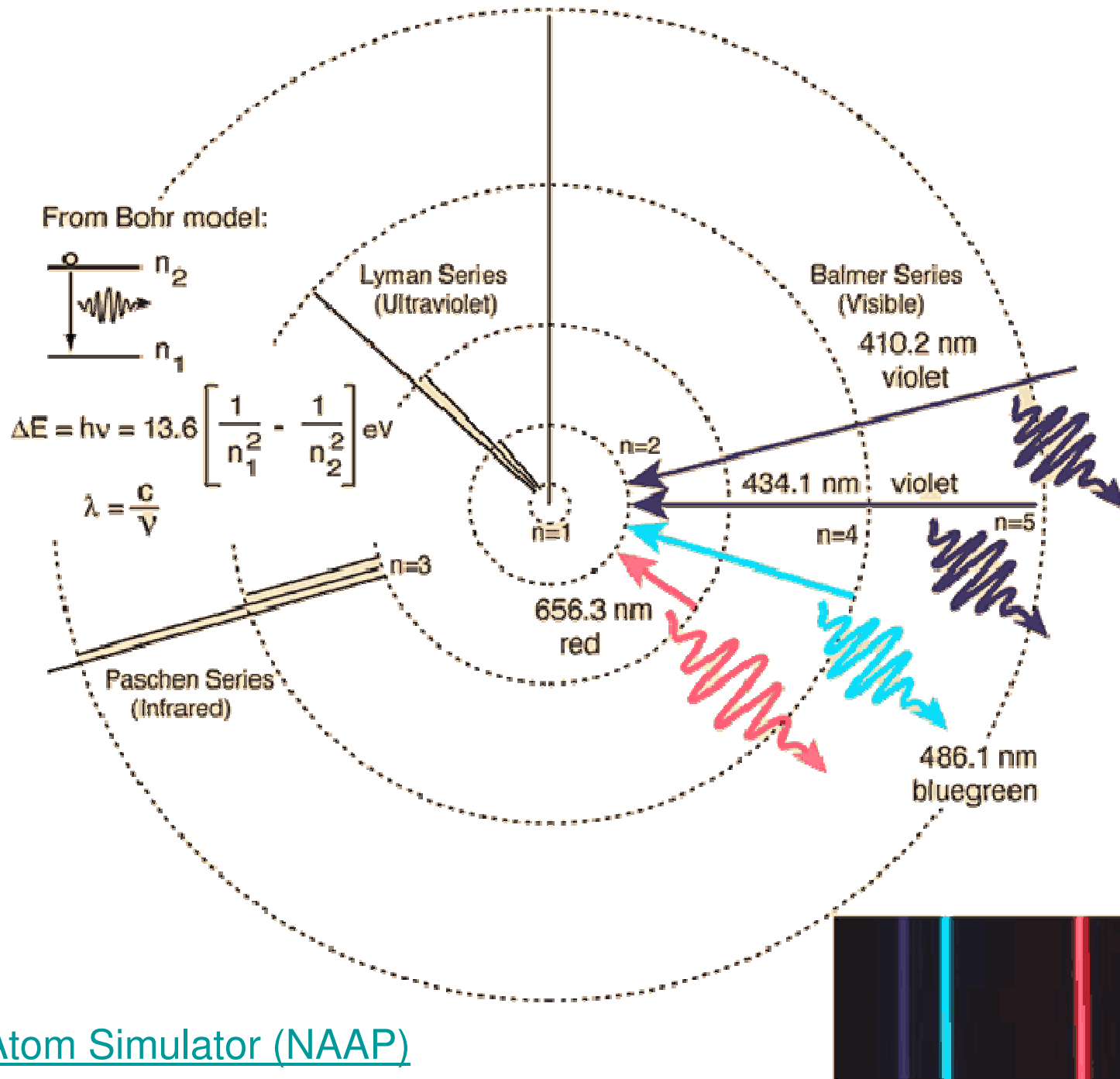
It can “jump” from one level to another by absorbing or emitting electromagnetic radiation of specific wavelength.

The wavelength of such electromagnetic radiation is determined from the **difference between two energy levels**.

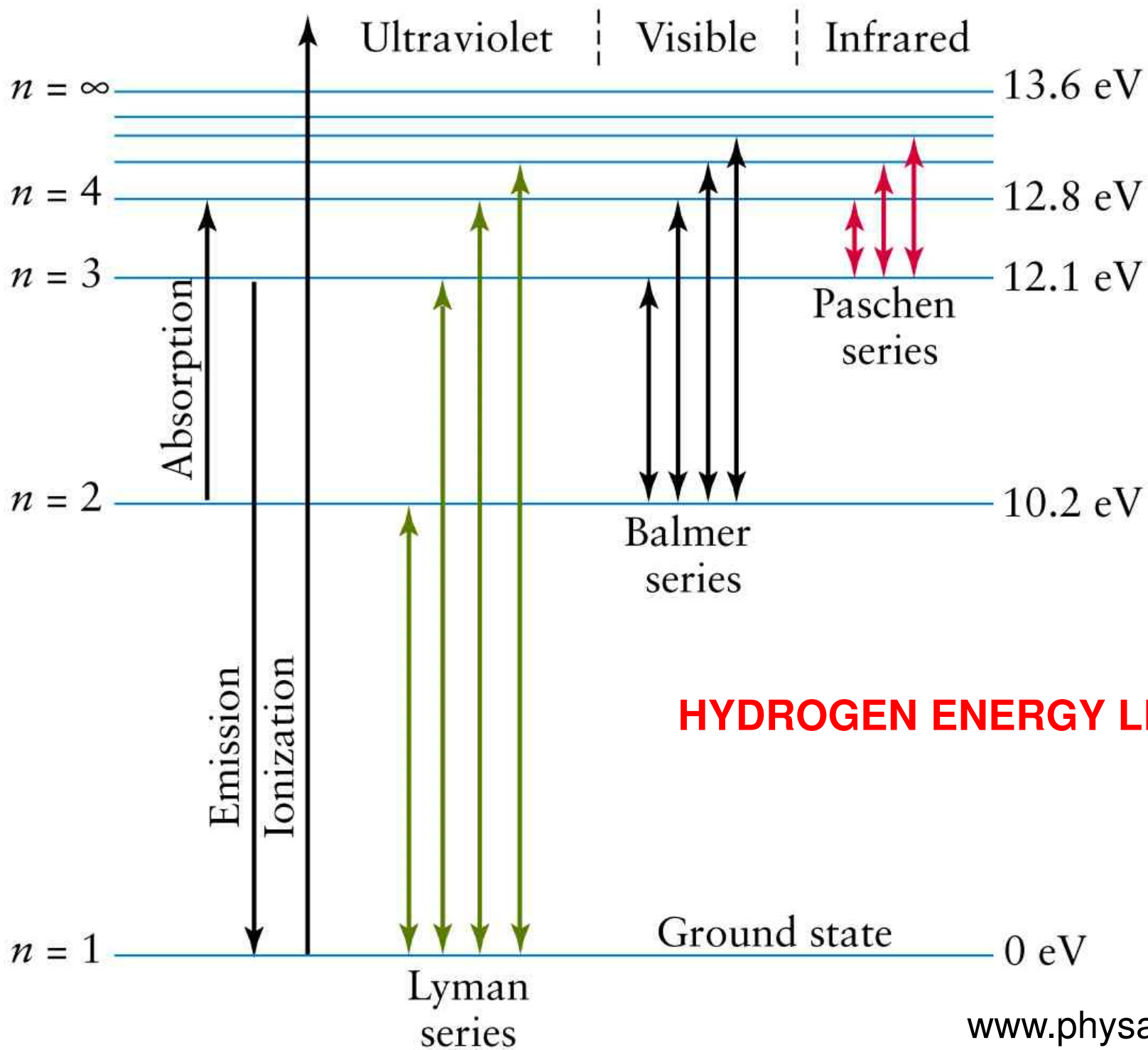


A downward transition involves emission of a photon of energy:

$$E_{\text{photon}} = h\nu = E_2 - E_1$$

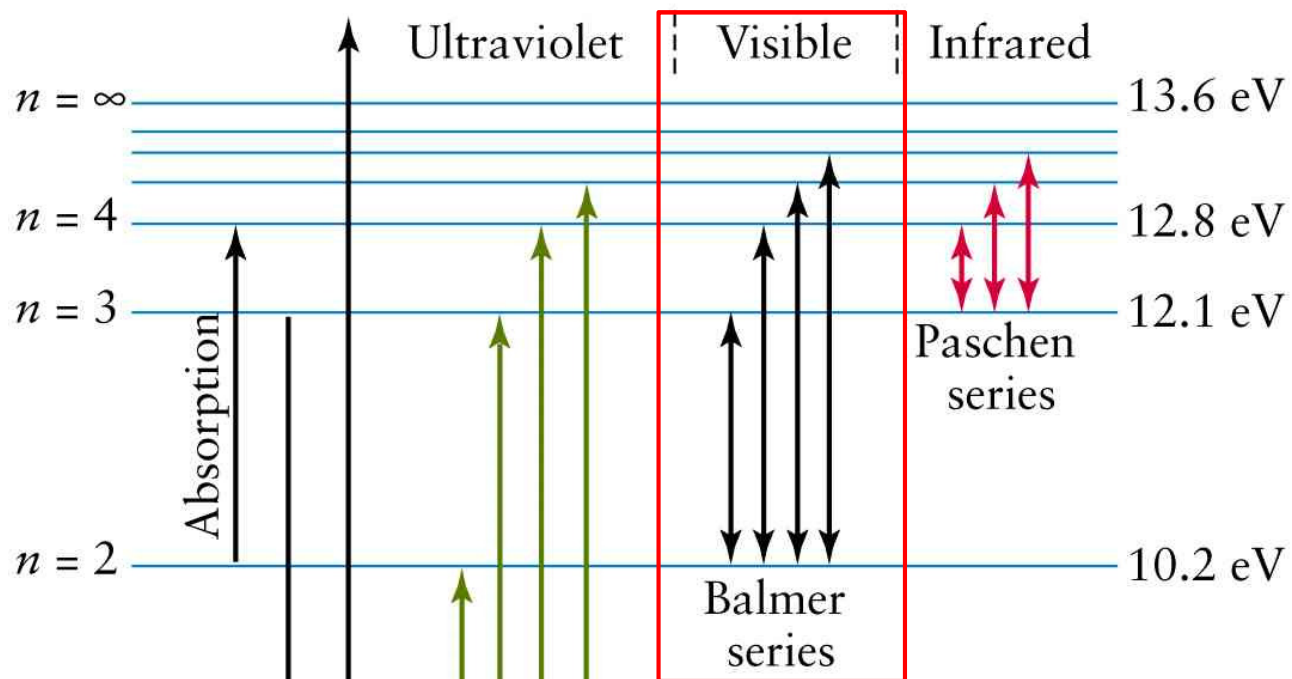
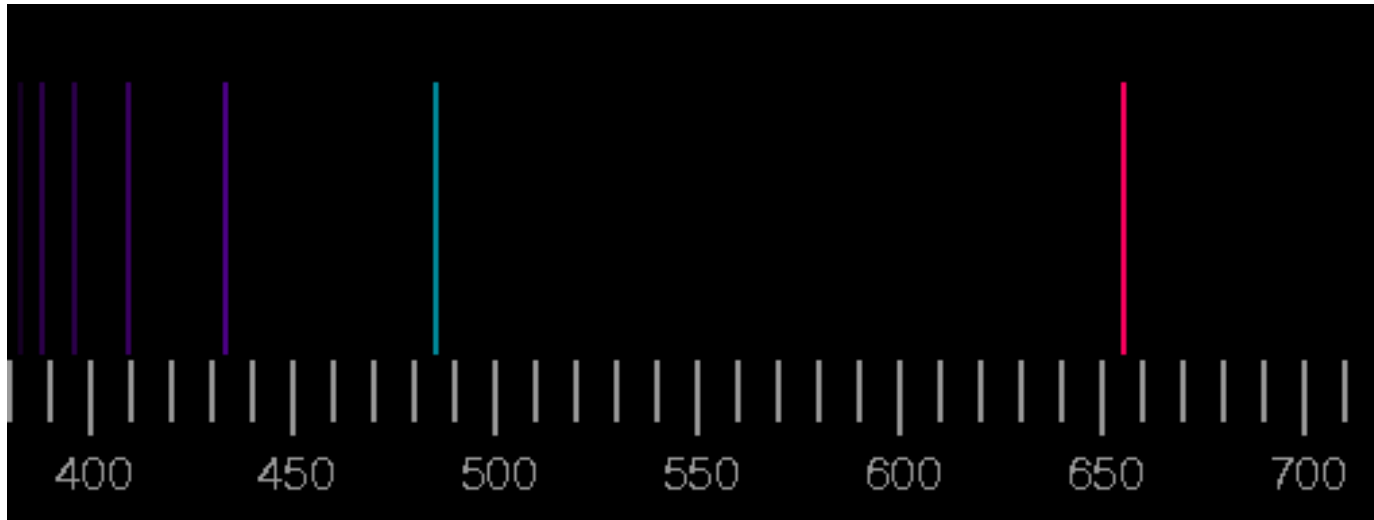


[Hydrogen Atom Simulator \(NAAP\)](http://hyperphysics.phy-astr.gsu.edu/hbase/hyde.html)




HYDROGEN ENERGY LEVELS

Visible part of the hydrogen spectrum

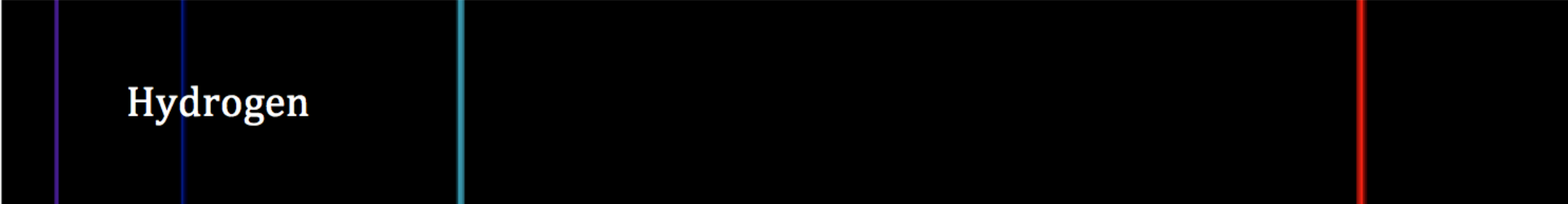


Spectra from different atoms

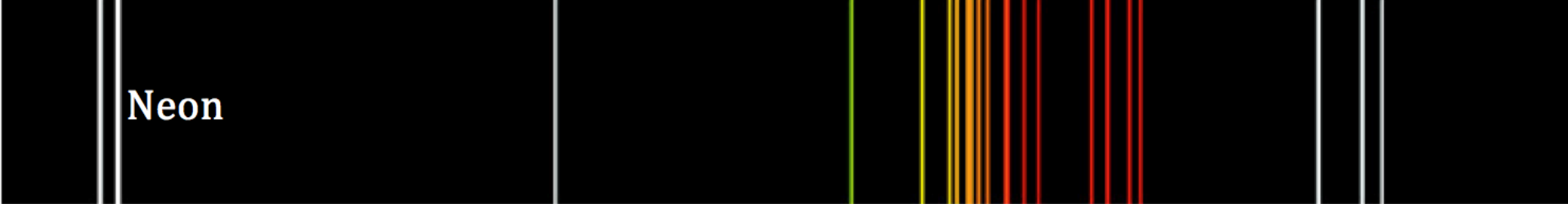
Visible spectrum



Hydrogen



Neon



Iron



[Link: Electromagnetic Spectrum Module](#)

Link: How spectrographs work

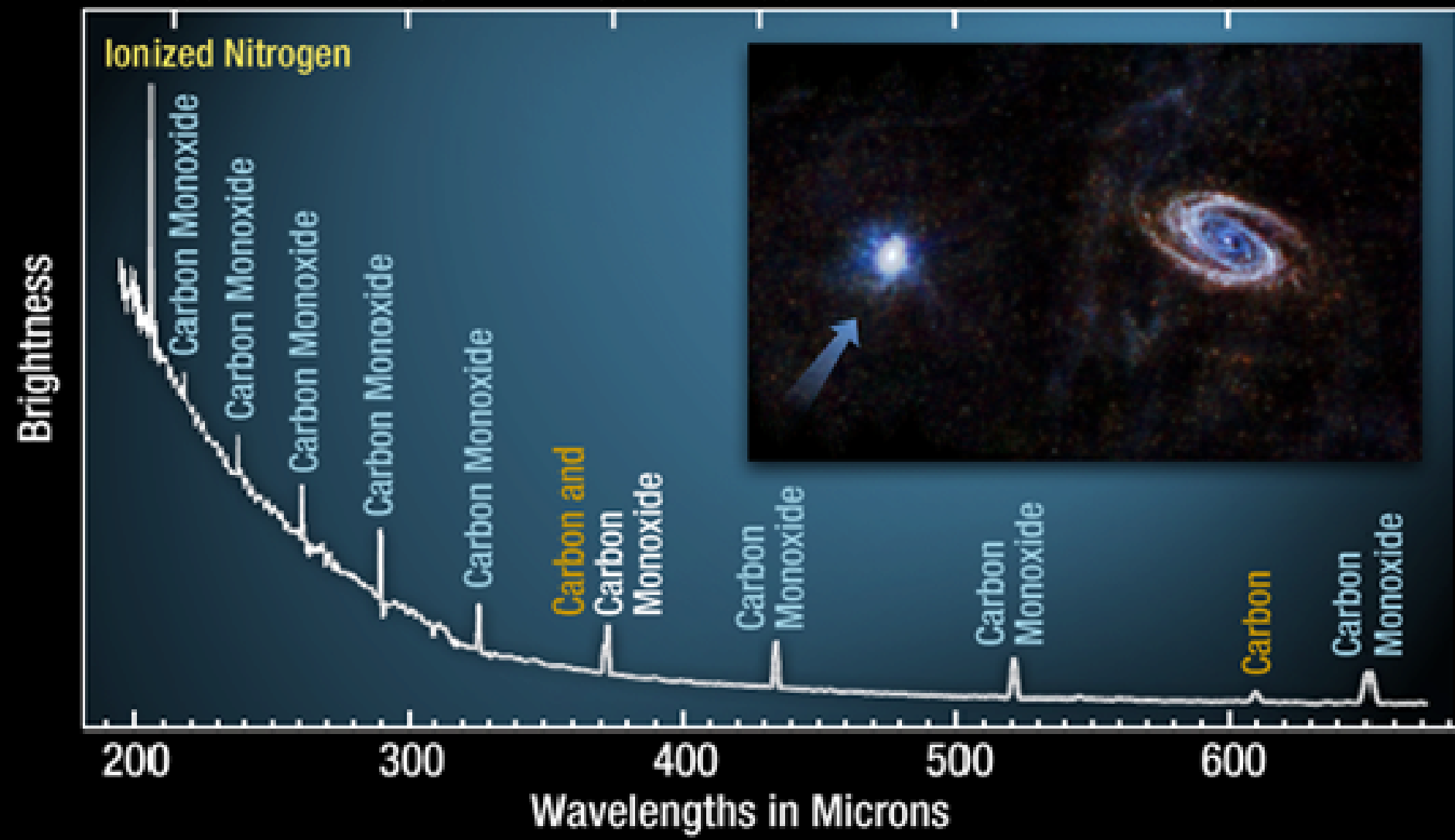
Spectroscopy: Turning Light Into Data

<http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/08.html>

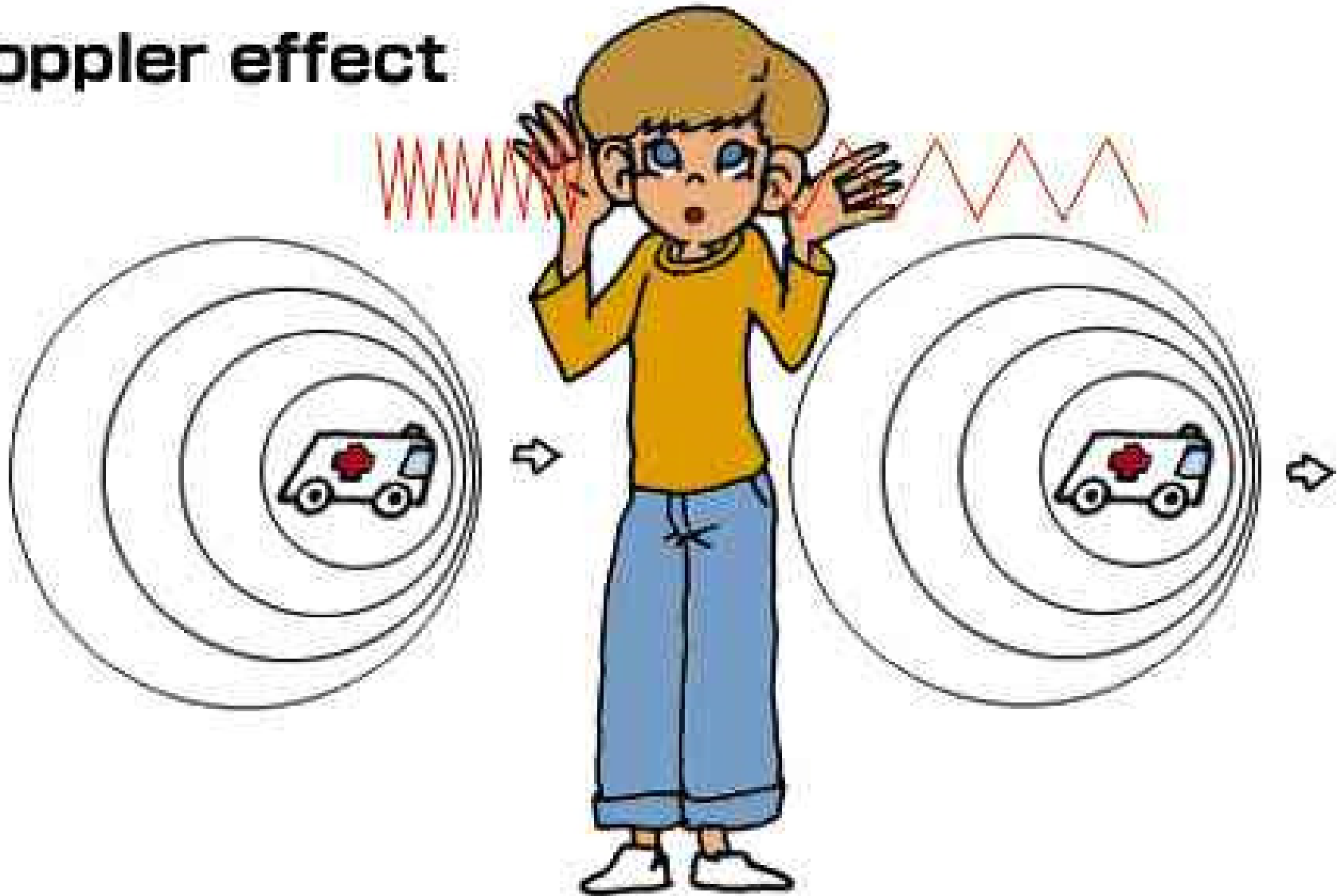
SPECTRAL SIGNATURE OF GALAXY M82

Frequency (GHz)

1400 1000 800 700 600 500

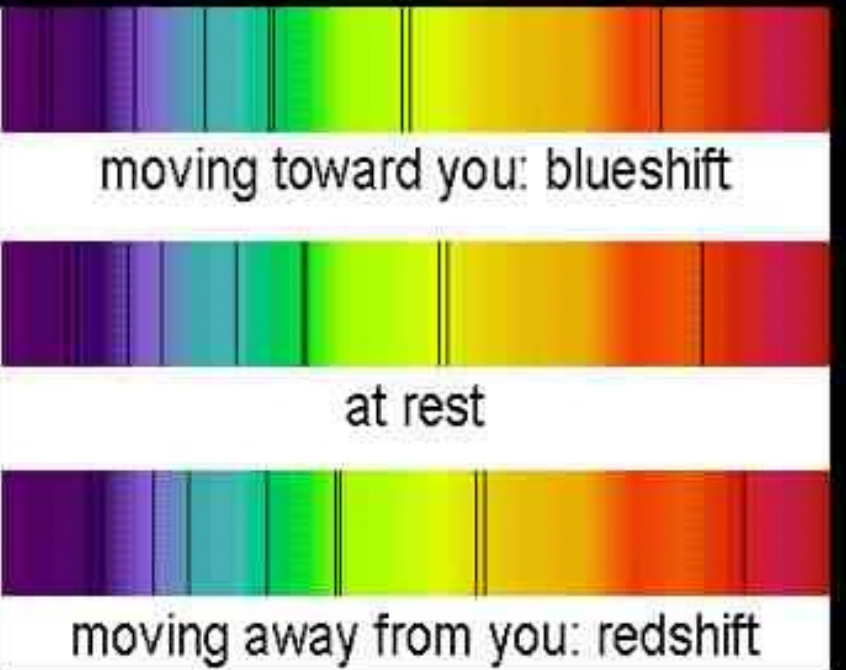
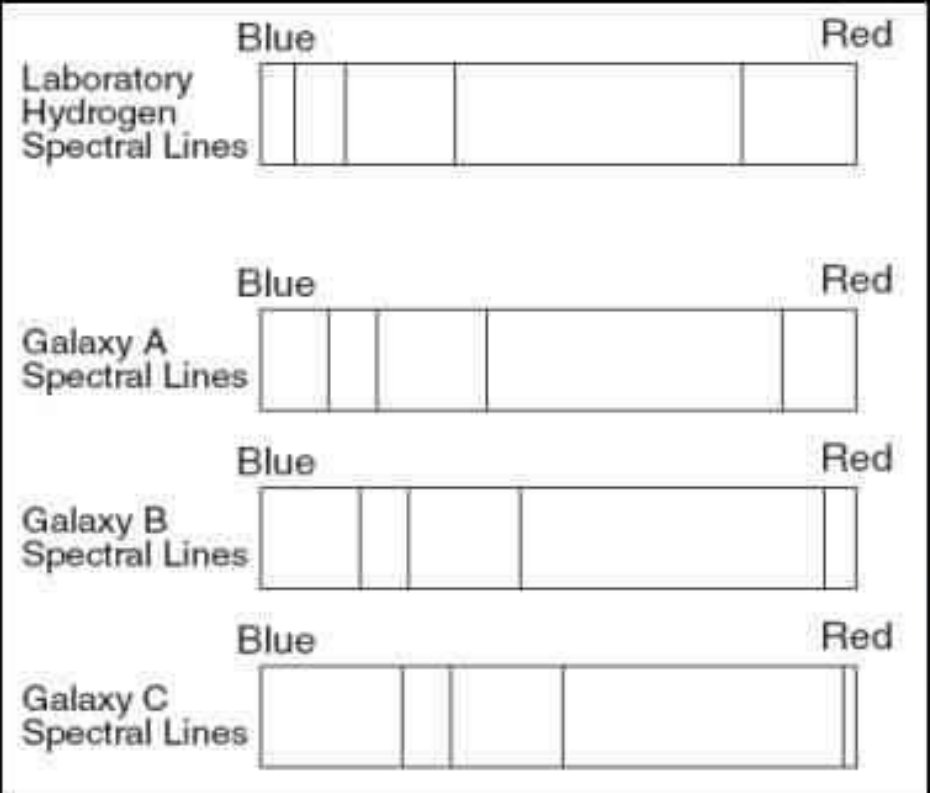
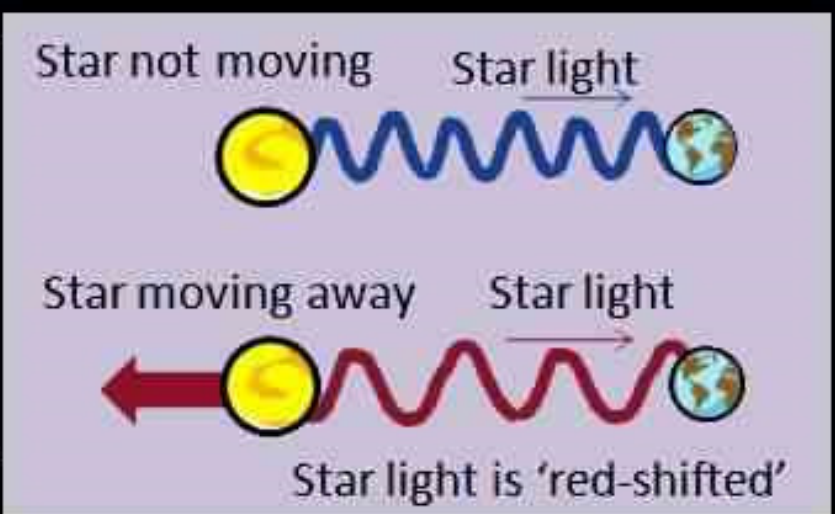
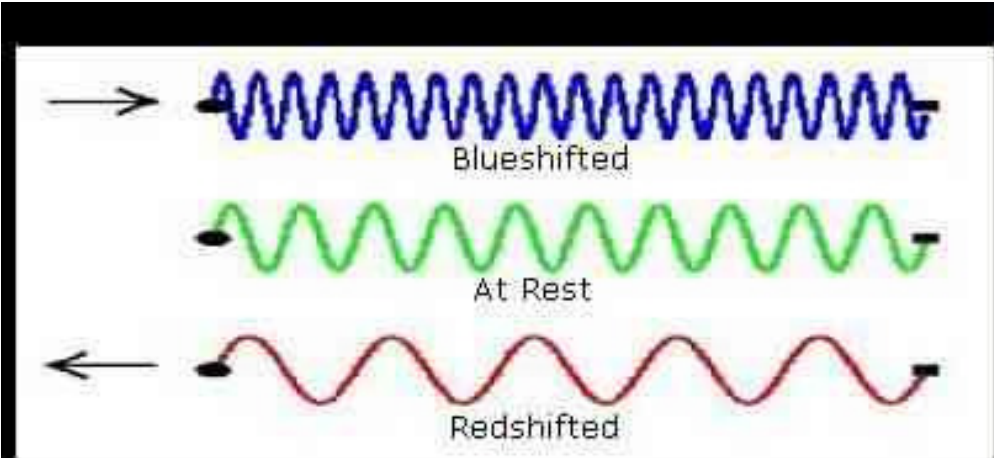


Doppler effect



[Link: Doppler Shift Demonstrator](#)

Doppler effect: measure velocities from shift of spectral lines



Back to dark matter



Fritz Zwicky

California Institute of Technology



Coma Cluster: 1000 galaxies
321 million light years away

Fritz Zwicky used the 18 inch telescope to make a survey of all the galaxies in the Coma cluster and used measurements of the **Doppler shift of their spectra** to determine their velocities.

Dark matter



Fritz Zwicky

California Institute of Technology



Coma Cluster: 1000 galaxies
321 million light years away

He measured the speed with which the galaxies in Coma move. To his surprise, he found enormous speeds—thousands of kilometers per second — **fast enough to rip the cluster apart.**

Why was the cluster not tearing itself up? Zwicky concluded that the cluster must be filled with additional unseen matter that holds the galaxies together with its gravitational force.

Half a century will pass before any
serious considerations of dark matter

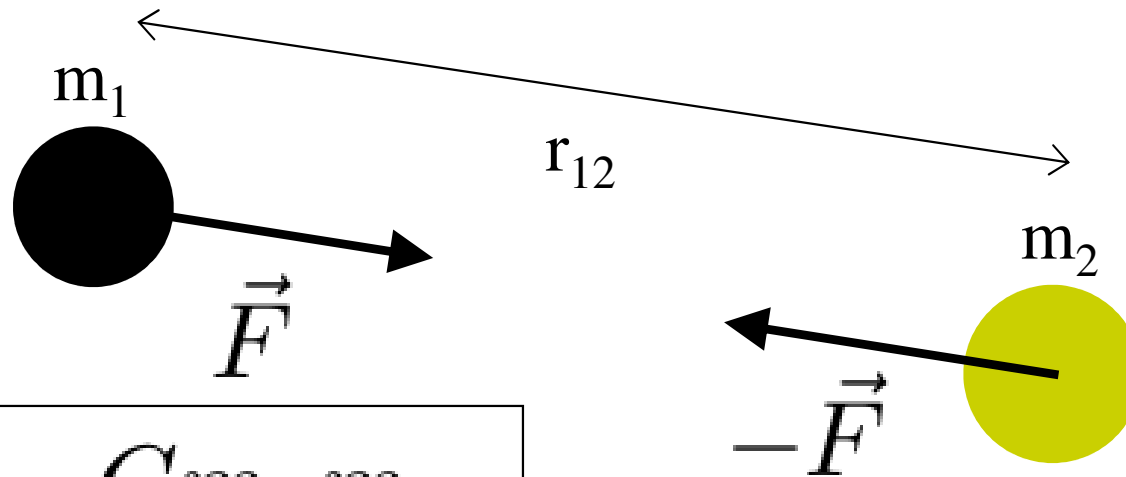
...



Fritz Zwicky

Gravity and detecting Dark Matter

Use the fact that massive objects, even if they emit no light, exert gravitational forces on other massive objects.



$$|\vec{F}| = \frac{Gm_1m_2}{r_{12}^2}$$

Study the motions (dynamics) of visible objects like stars in galaxies, and look for effects that are not explicable by the mass of the other light emitting or absorbing objects around them.

Vera Rubin

Born July 23, 1928



Vera Cooper Rubin
at the Lowell
Observatory.
© Bob Rubin.

PhD thesis: Georgetown University,
Her PhD thesis upon graduation in 1954 concluded that **galaxies clumped together**, rather than being randomly distributed through the universe. The idea that clusters of galaxies existed was not pursued seriously by others until two decades later.

1962: Assistant professor in Georgetown University.
In 1965, she became the first woman allowed to use the instruments at the Palomar Observatory. Prior to this, women had not been authorized to access the facilities.

Wishing to avoid controversy, Rubin moved her area of research to the study of rotation curves of galaxies, commencing with the [Andromeda Galaxy](#).

1970s: Further evidence for dark matter

Rotation curves

Vera Rubin and Kent Ford, Carnegie Institution of Washington



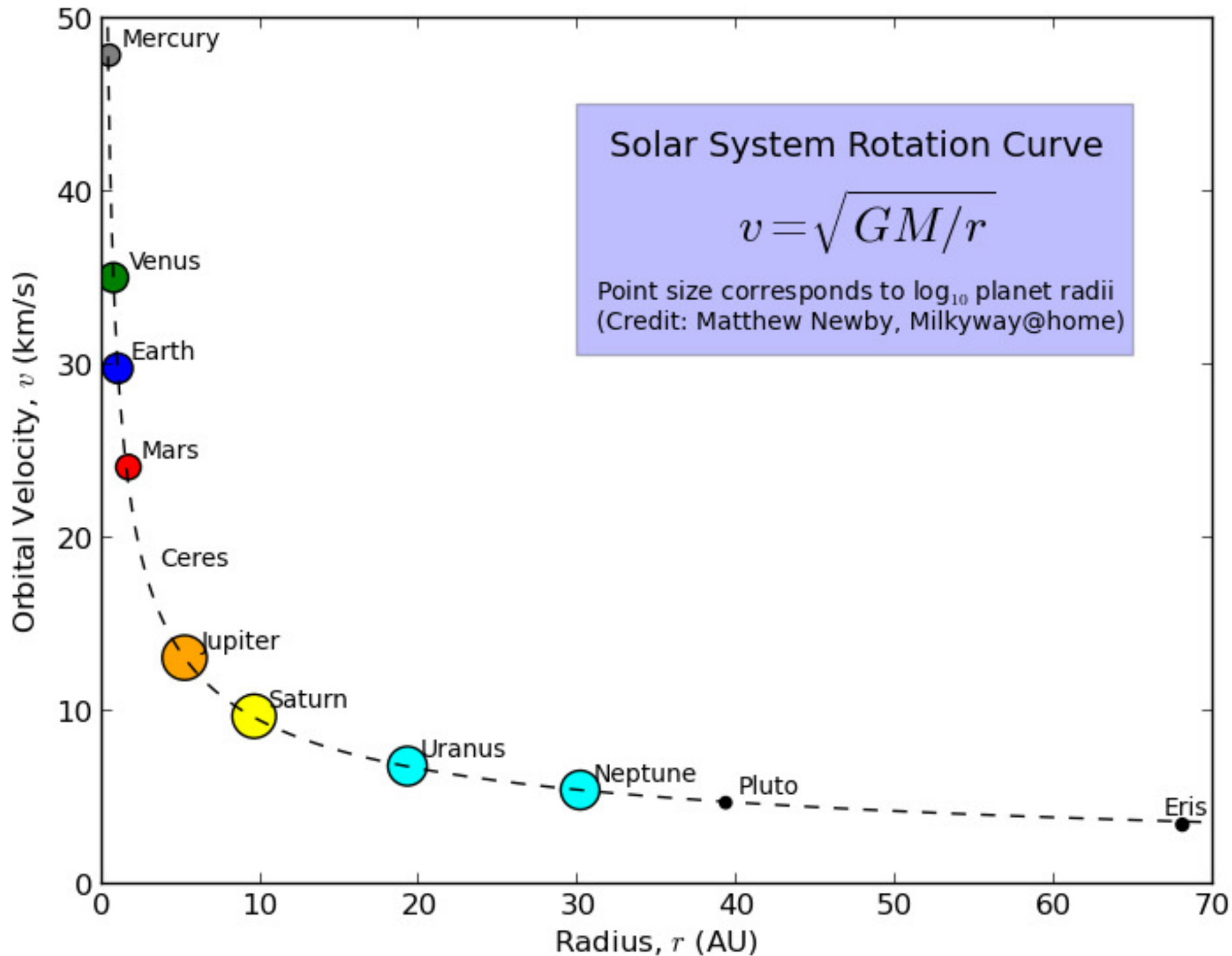
Vera Cooper Rubin at the Lowell Observatory.
© Bob Rubin.

Rubin and Ford measured the velocity of hydrogen gas clouds in and near the Andromeda galaxy.



They expected to find that the hydrogen gas **outside the visible edge of the galaxy would be moving slower** than gas at the edge of the galaxy.

This is what is expected if the mass in the galaxy is concentrated where the galaxy emits light. Instead, they found the opposite: the orbital velocity of the hydrogen clouds **remained constant** outside the visible edge of the galaxy.



Galaxies Rotate

Galaxies are collections of billions of stars.

Most of the light from a galaxy comes from its center.

This indicated that most of the galaxies stars and most of its mass is concentrated at its center.



Under this scenario, we should expect the stars in the outer part of the galaxy to rotate about the center, and this is just what we observe.

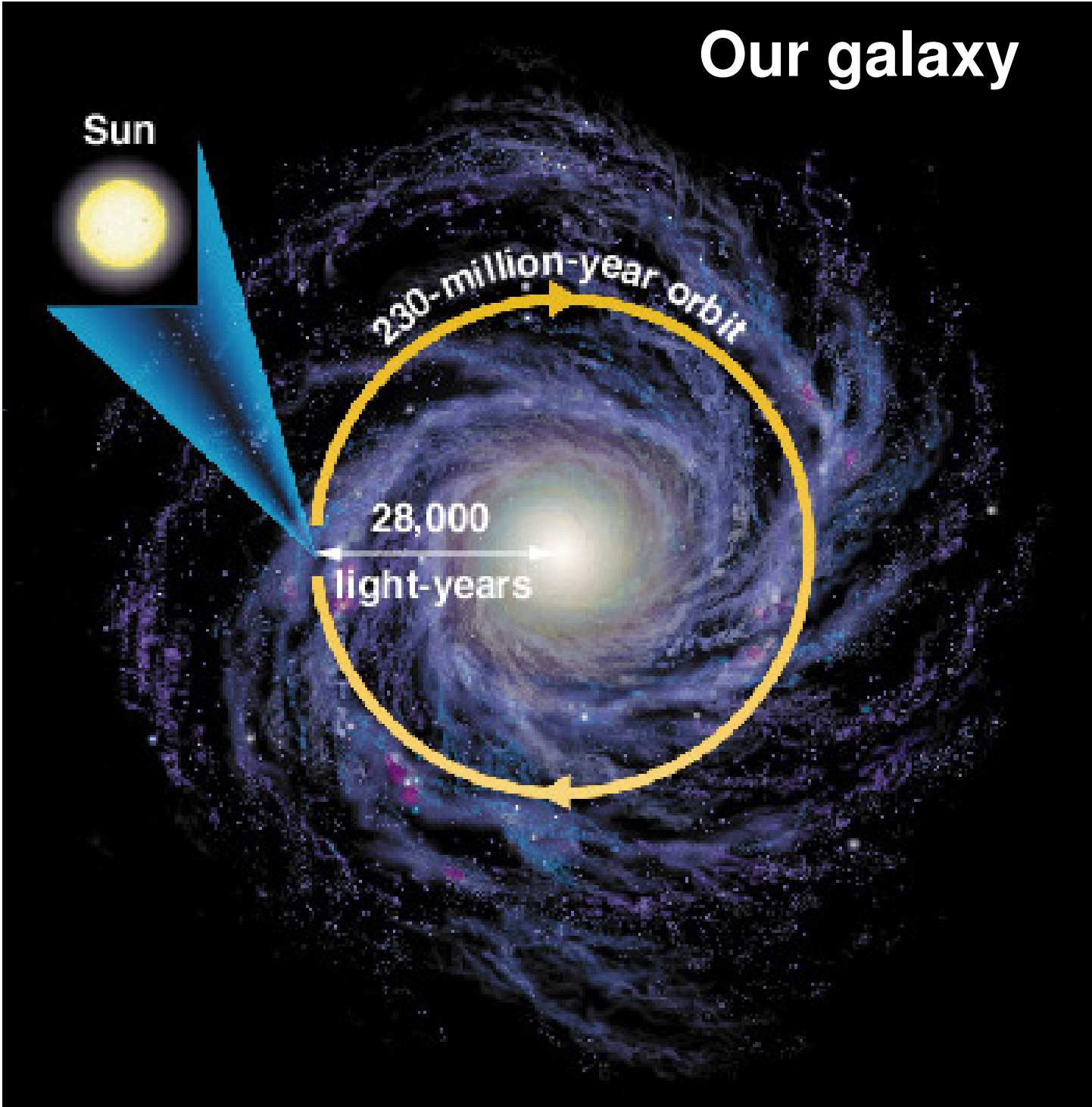
Our galaxy

Sun



230-million-year orbit

28,000
light-years



Rotation of Stars around Galactic Center

We can measure how fast stars rotate around galactic centers by looking at the frequency shift of known spectral lines originating in the stars due to the Doppler effect.



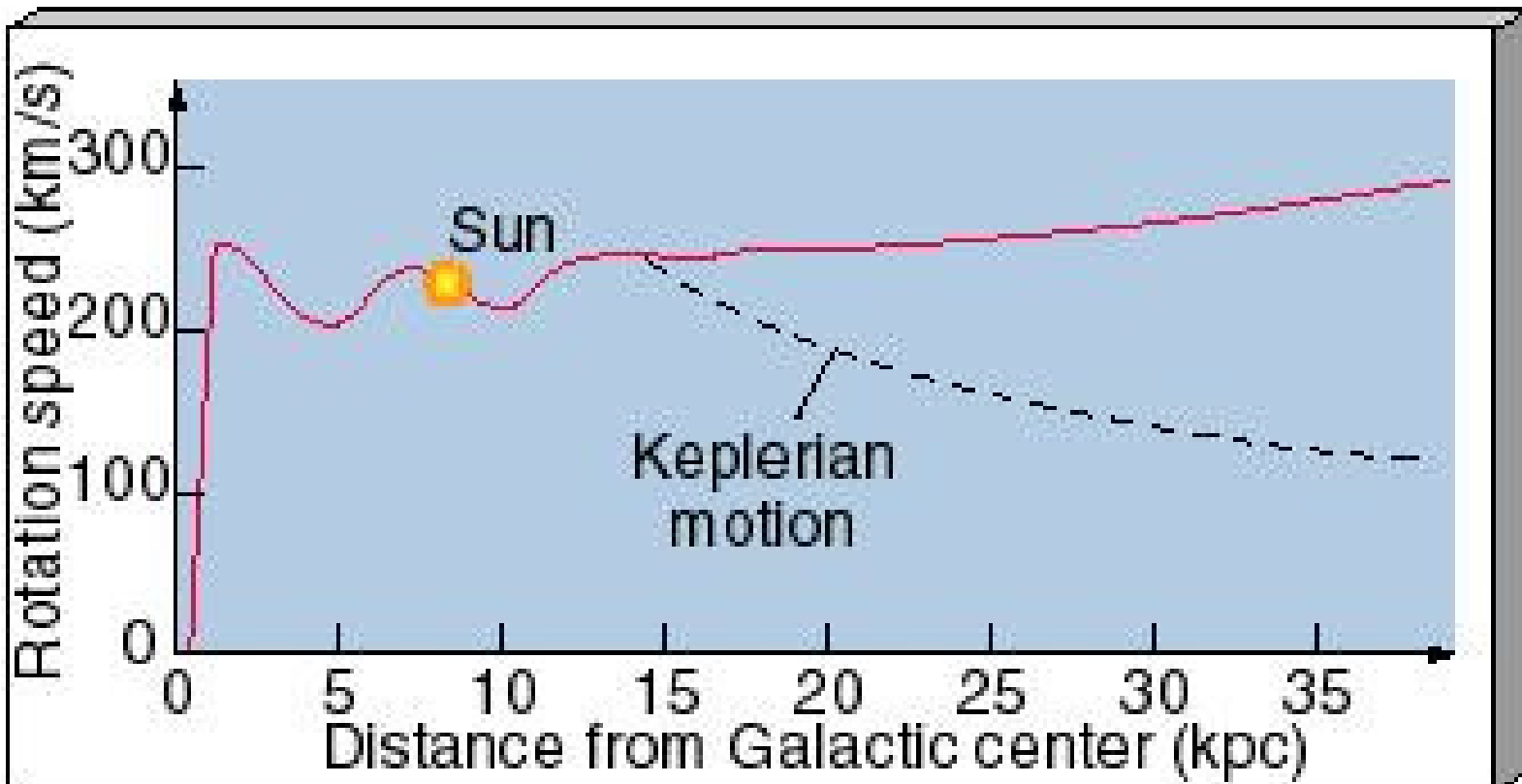
Star's motion towards you, relative to the galactic center alters wavelength of light

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

Problem

Outer stars do not rotate correctly! If gravity causes galaxies to rotate, as we assume it does, then outer stars should behave much like the planets of our solar system. Inner planets rotate faster and outer planets rotate slower (Keplerian motion).

In galaxies, however, **both inner and outer stars rotate at about the same speed.**

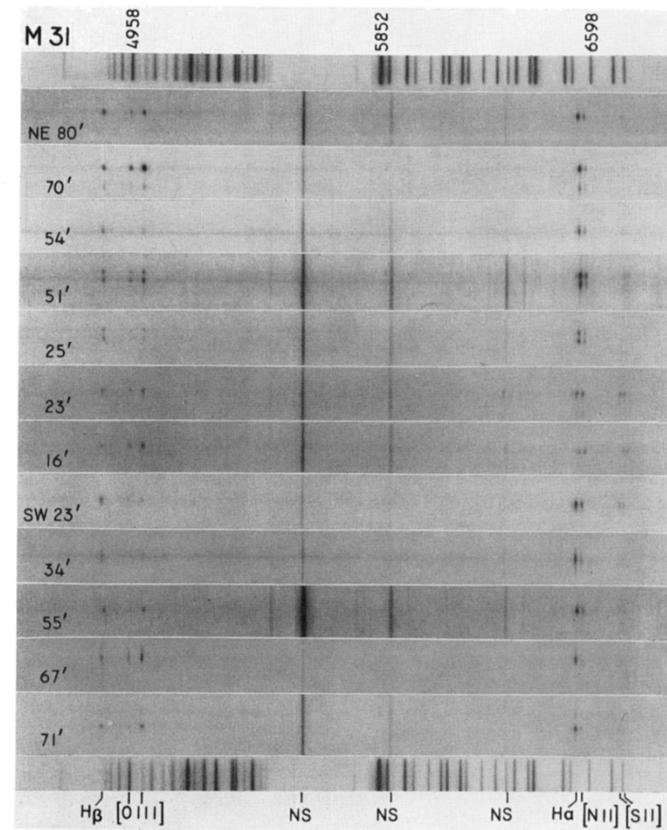
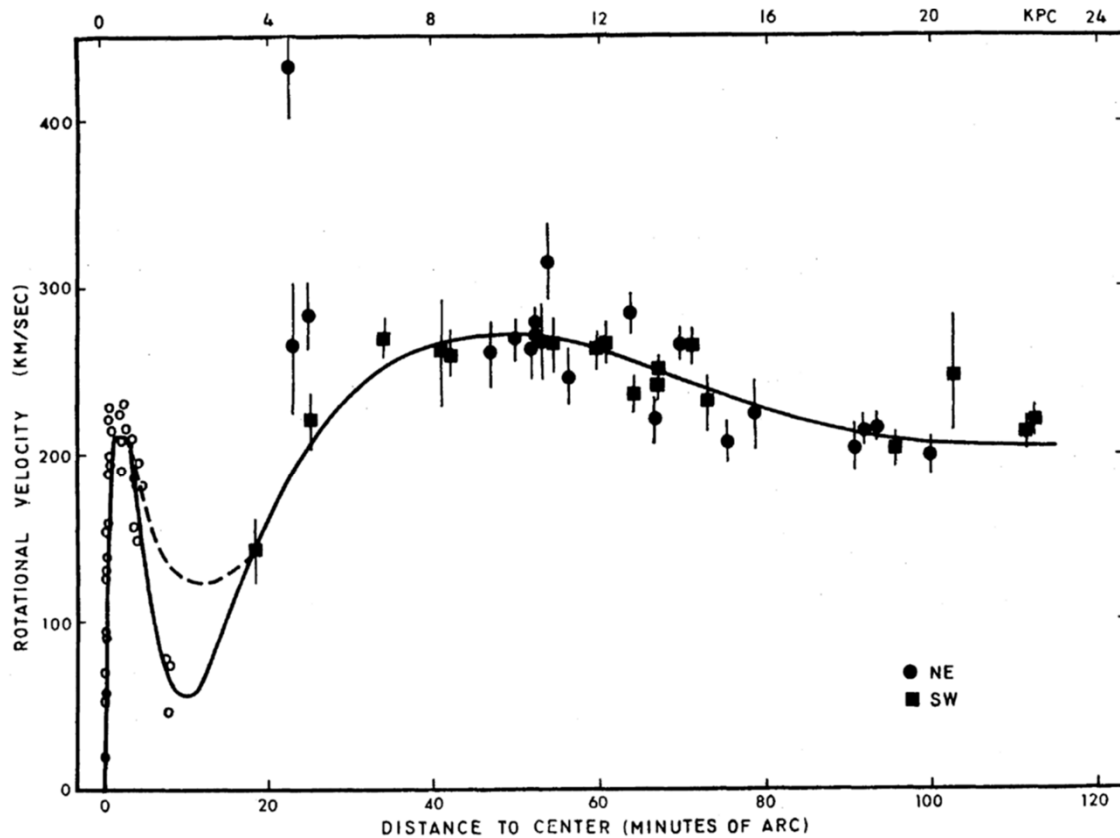


ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†

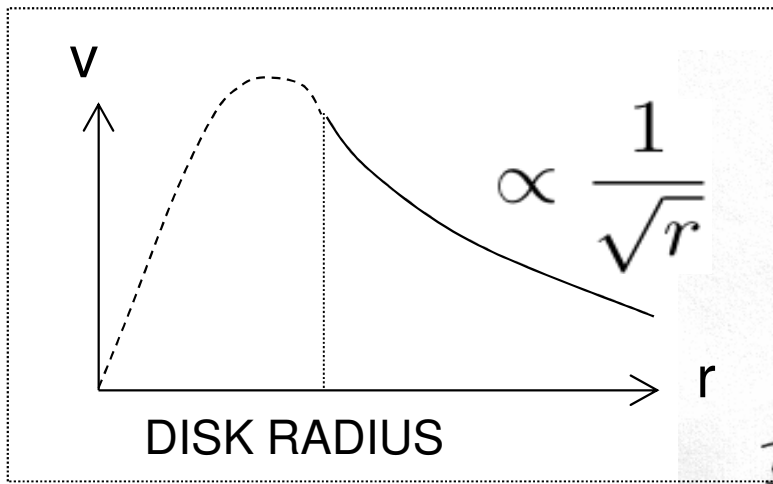
Department of Terrestrial Magnetism, Carnegie Institution of Washington and
Lowell Observatory, and Kitt Peak National Observatory‡

Received 1969 July 7; revised 1969 August 21

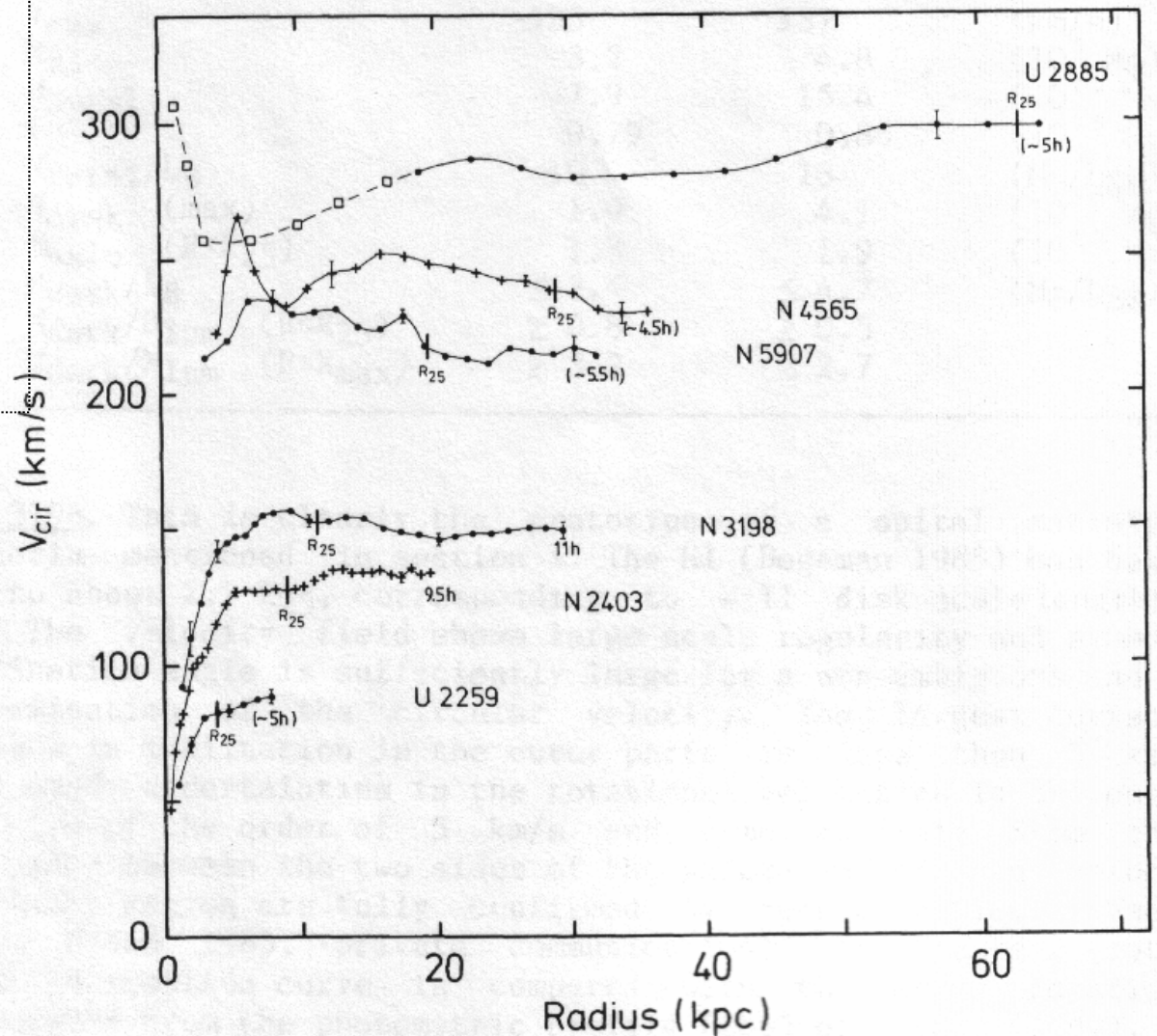


Galactic rotation curves

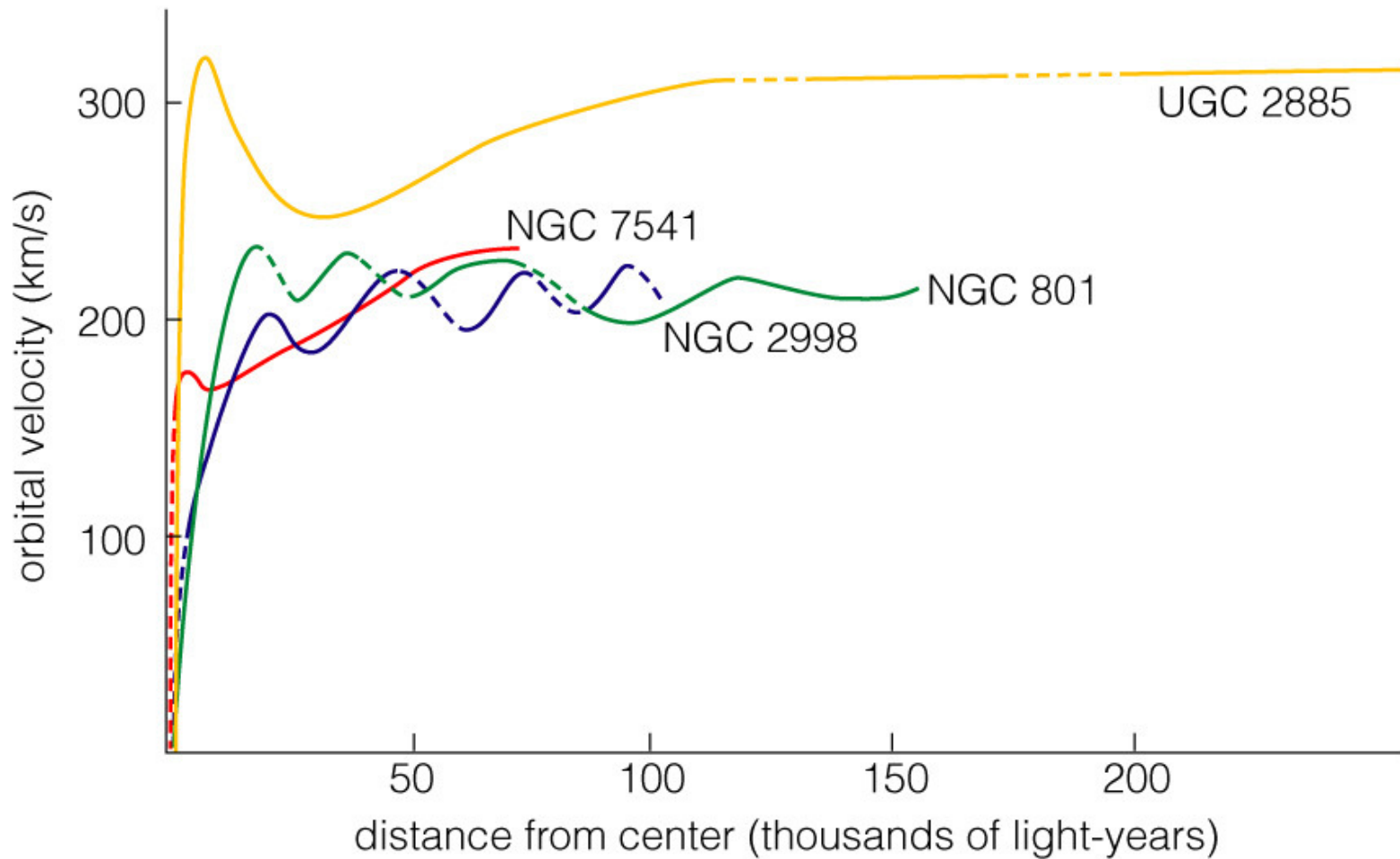
This is what we expect....



...but here are some typical results



Wavelength shifts are about a part in 10^6 . These are hard measurements.



Spiral galaxies all tend to have flat rotation curves indicating large amounts of dark matter.

- [Milky Way Rotational Velocity](#)

Possible Interpretations

-Maybe there is more matter in galaxies that we have not observed.

WHAT MATTER?

Faint stars ? Planets ? Rocks ? Gas ? Dust ?

Exotic Particles ?

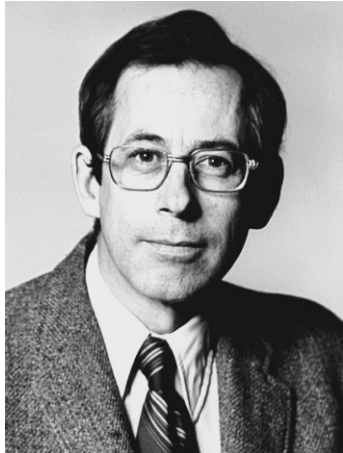
Need about 10 times as much dark matter as visible matter to explain the rotation curve discrepancy !

-Maybe Newton's law of gravitation is wrong for very large distances or very small accelerations?

A alternative theory, **m**odified **N**ewtonian **d**ynamics MOND has been seriously proposed, cannot yet rule tensor-scalar-vector variant ... more later

1973: Further evidence for dark matter

Problem with galactic simulations



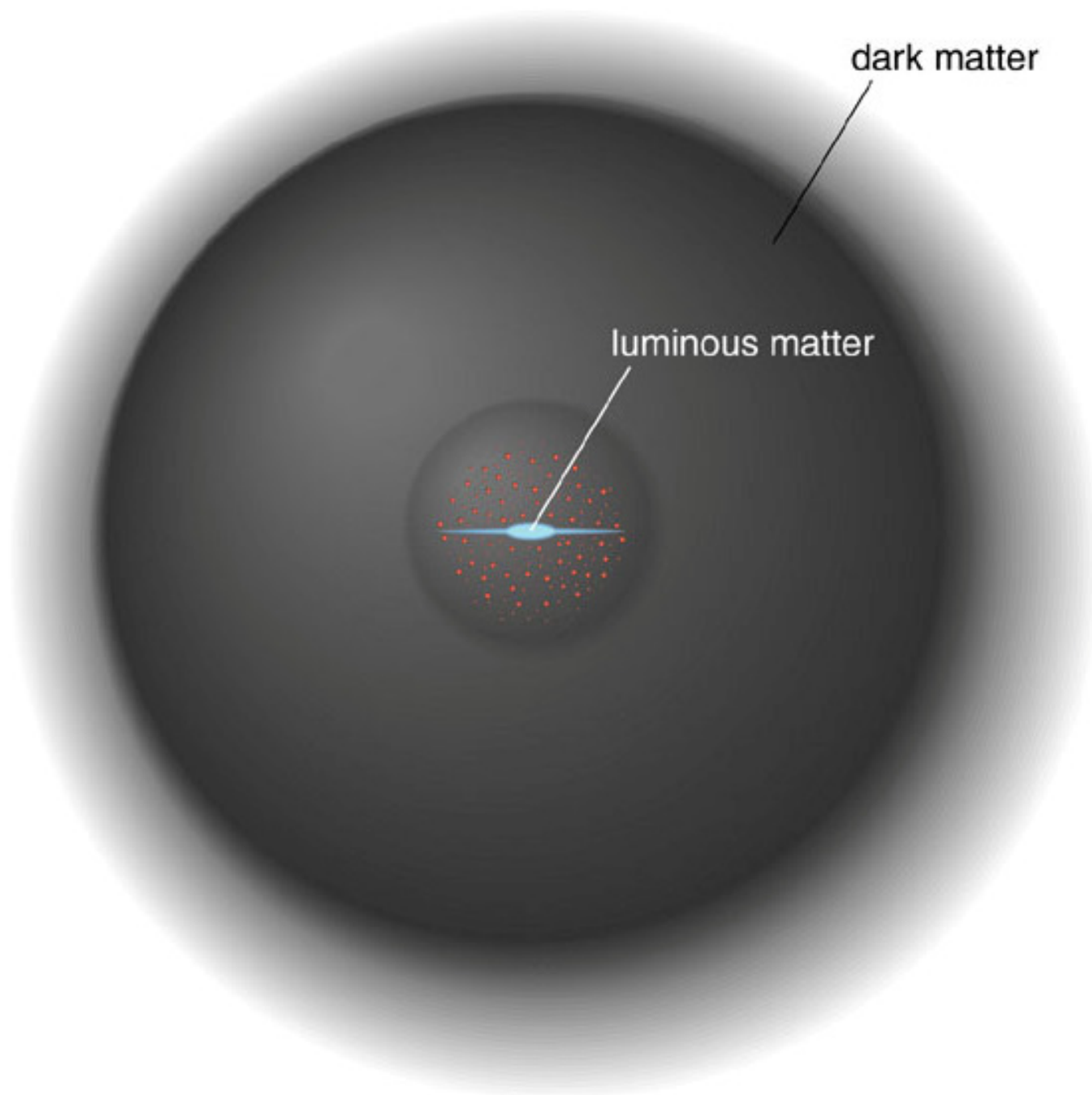
James Peebles Jeremiah Ostriker

Princeton University

Jeremiah Ostriker and James Peebles used numerical simulation to study how galaxies evolve: they programmed 300 mass points into their computer to represent groups of stars in a galaxy rotating about a central point.

Ostriker and Peebles found that in a time less than an orbital period, most of the mass points would collapse to a bar-shaped, dense concentration close to the center of the galaxy with only a few mass points at larger radii.

However, if they added a static, uniform distribution of mass three to 10 times the size of the total mass of the mass points, they found a more recognizable structure would emerge.



The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

1995: the Hubble Space Telescope was able to see farther away (and further back in time) than any other optical telescope in history.

It saw thousands of new galaxies.

Many appeared squashed or stretched out due to
GRAVITATIONAL LENSING



The story of gravitational lensing

1704: Isaac Newton published “Opticks”

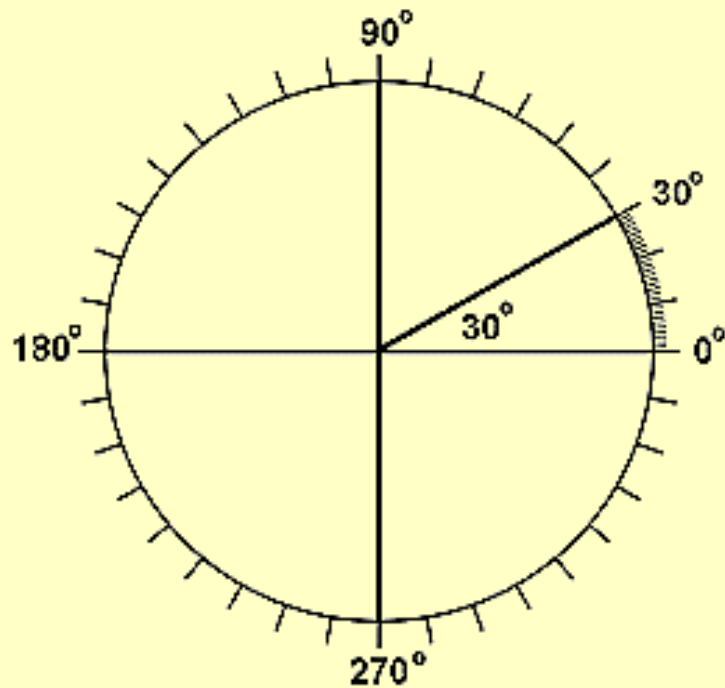
Query:

Do not Bodies act upon Light at a distance and by their action bend its Rays?

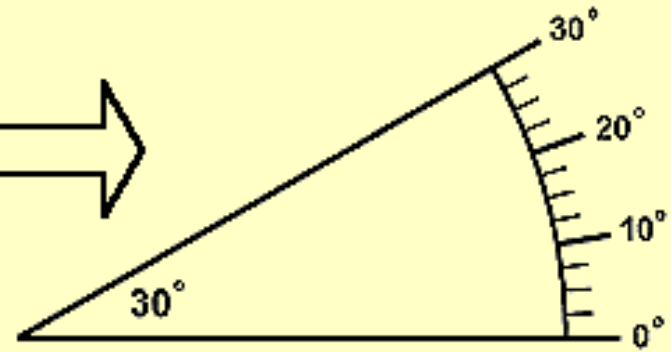
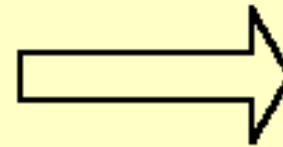
Lets rephrase:

How large is the angle α of bending for the light of distant star passing near the surface of the sun?

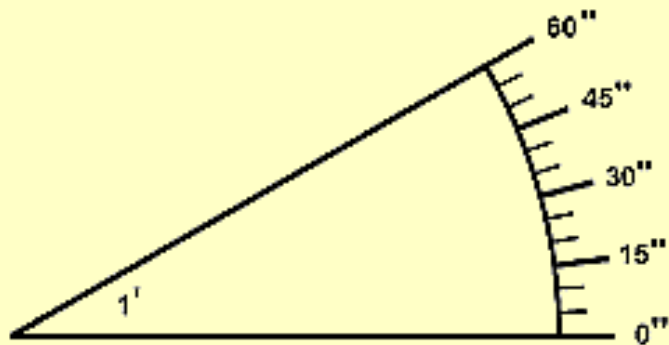
- A. 0 (classical physics, light is a wave with no mass)
- B. $\alpha = 0.87''$ [**arcsecond**] (classical physics, light consists from particles with mass, angle of deflections depends only on velocity)
- C. $\alpha = 1.75''$ (General relativity, no assumptions aabout the nature of light)



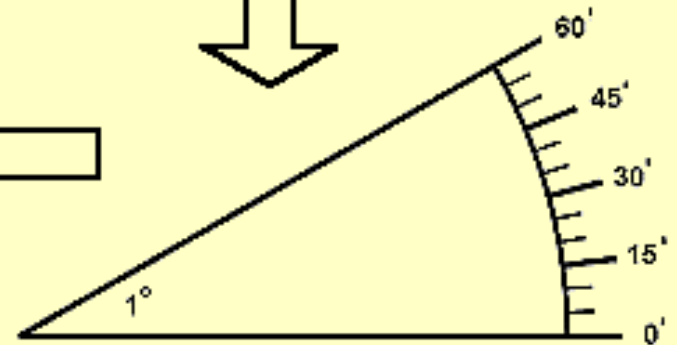
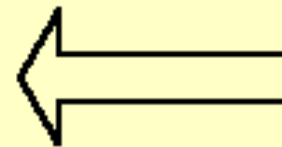
Circle to Degrees



30 Degree Sector

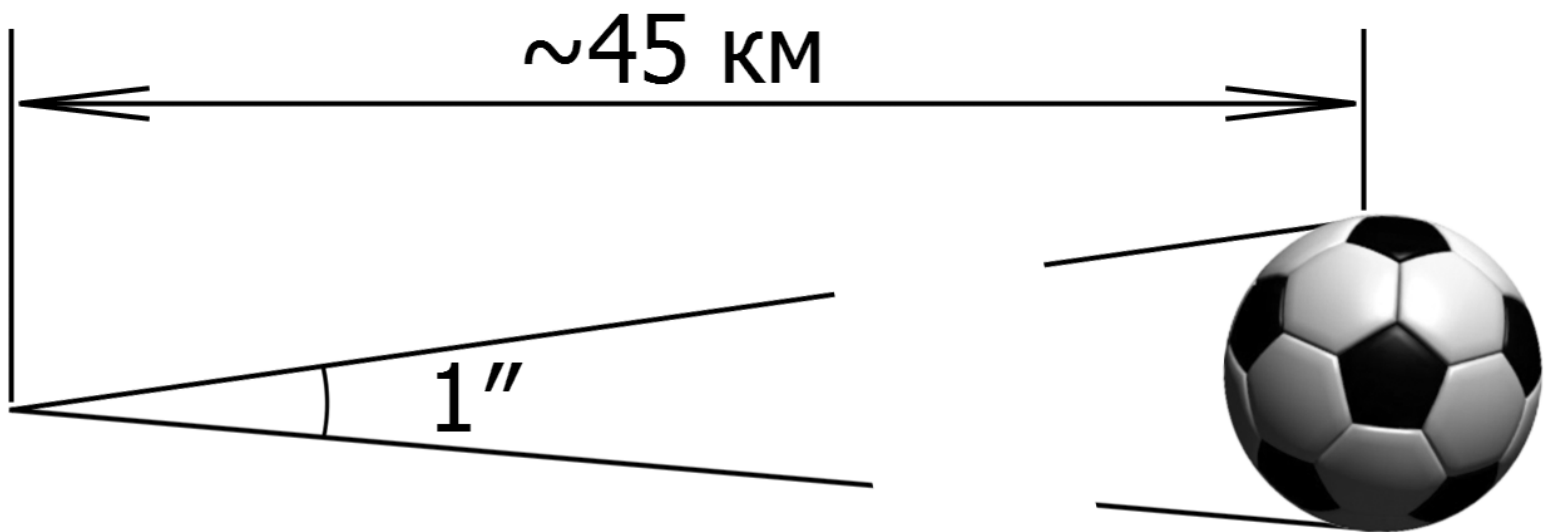
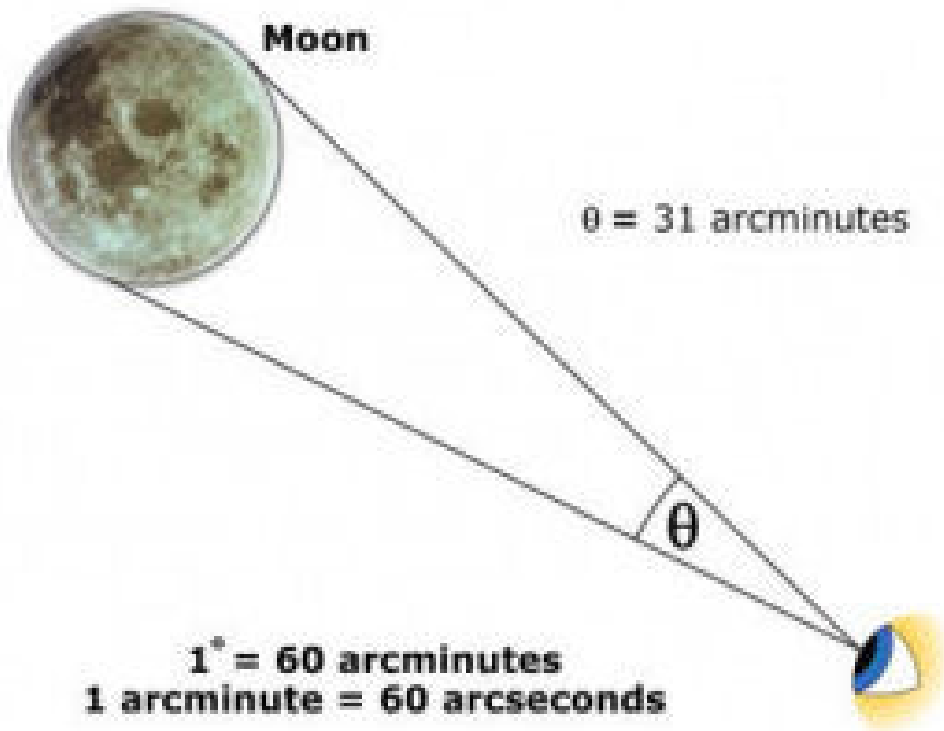


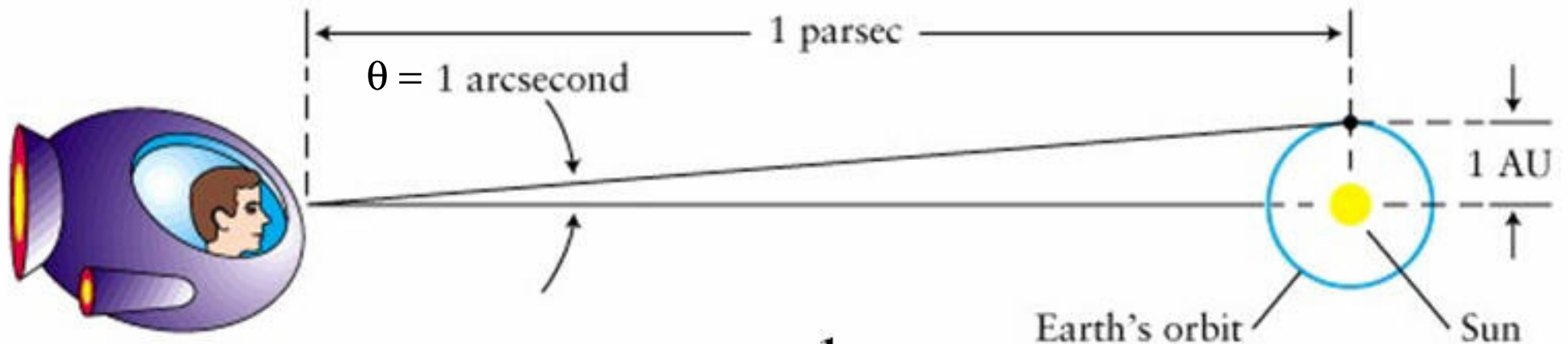
Minute to Seconds



Degree to Minutes

Angle Units Relationships





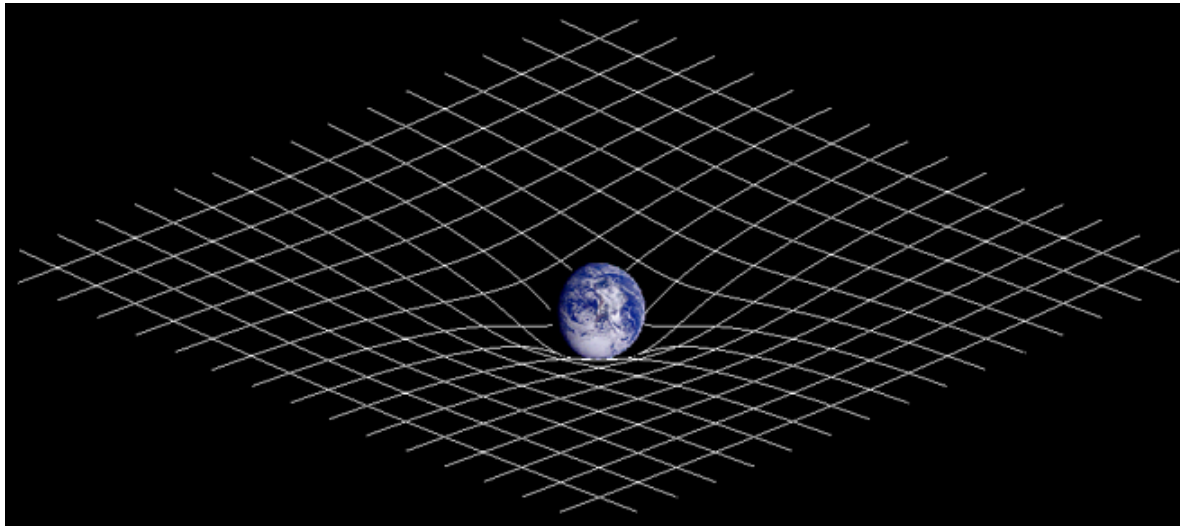
$$d = \frac{1}{p}$$

d is in parsecs when p is in arcseconds

1 parsec = 3.26 light-years

Key ideas of general relativity

- Mass and energy warp spacetime.
- Objects move around in the wrapped spacetime along the “shortest path”.
- The shortest path in a curved space is no longer a straight line.
- Light always moves along this shortest path, and thus light travels through space along a curved path.



Einstein's telescope, Evalin Gates

https://en.wikipedia.org/wiki/Gravitational_lens#/media/File:Spacetime_curvature.png

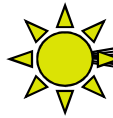
Gravitational Lensing of Light

Bending of light in gravitational fields can make lenses out of massive objects

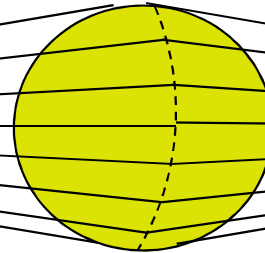
NO
LENS



LENS



SOURCE



LENSING OBJECT



US

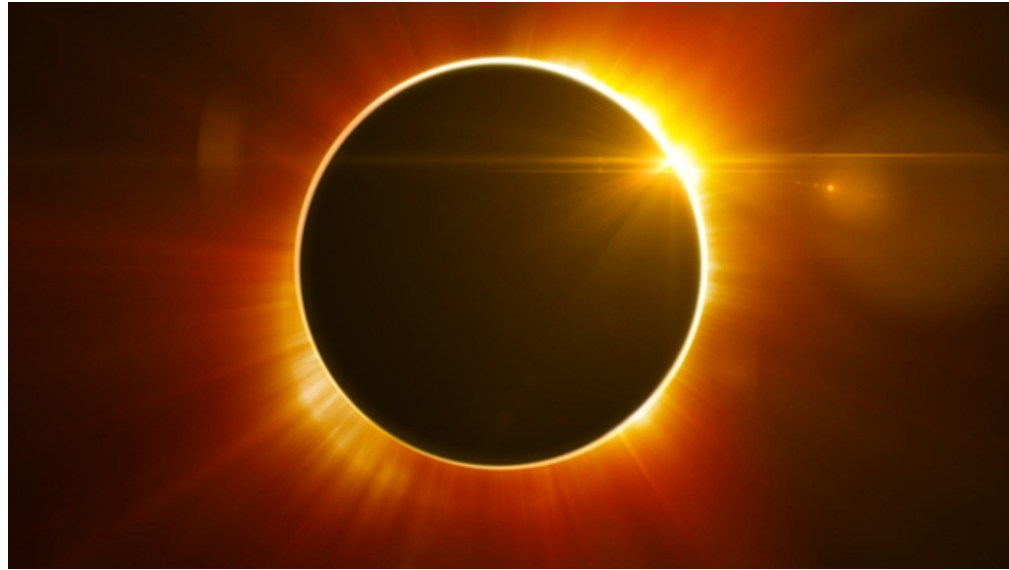
Strong or close lens, expect a ring of light, or a ring of images in the presence of the lens.

When not resolved, expect increased intensity.

Sun, star light, and the general relativity



Erwin Finlay Freundlich



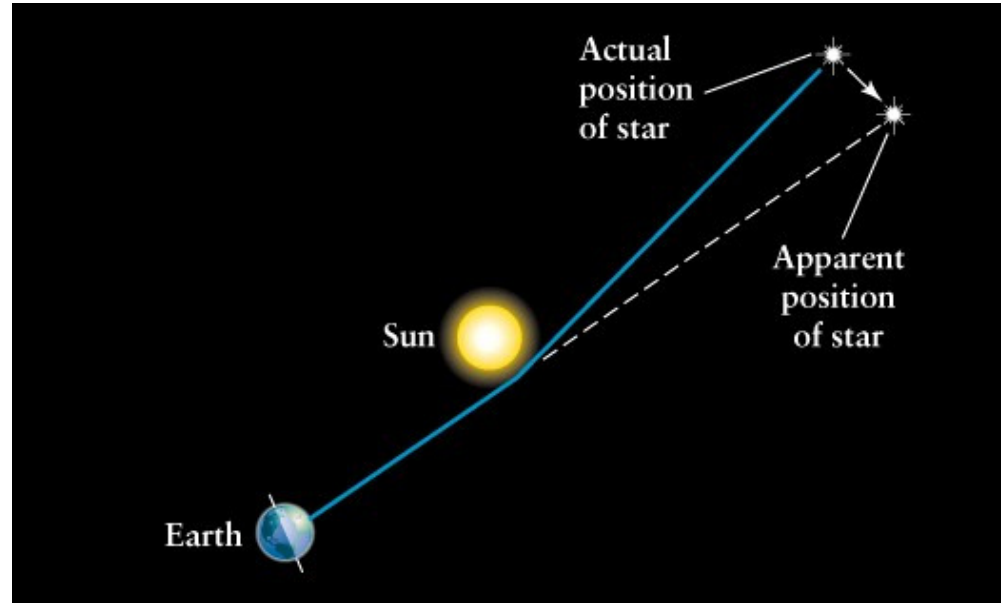
Freundlich was interested in measuring the deflection in a light ray passing close to the sun to test then incomplete Einstein's theory of relativity. The only way to make such measurements at this time was during an eclipse and Freundlich got funding to travel to Crimea in 1914.

World War I broke out before the time for the eclipse and the expedition was abandoned. Freundlich was interned for a while before being able to return to Berlin.

1919 solar eclipse: test of general relativity

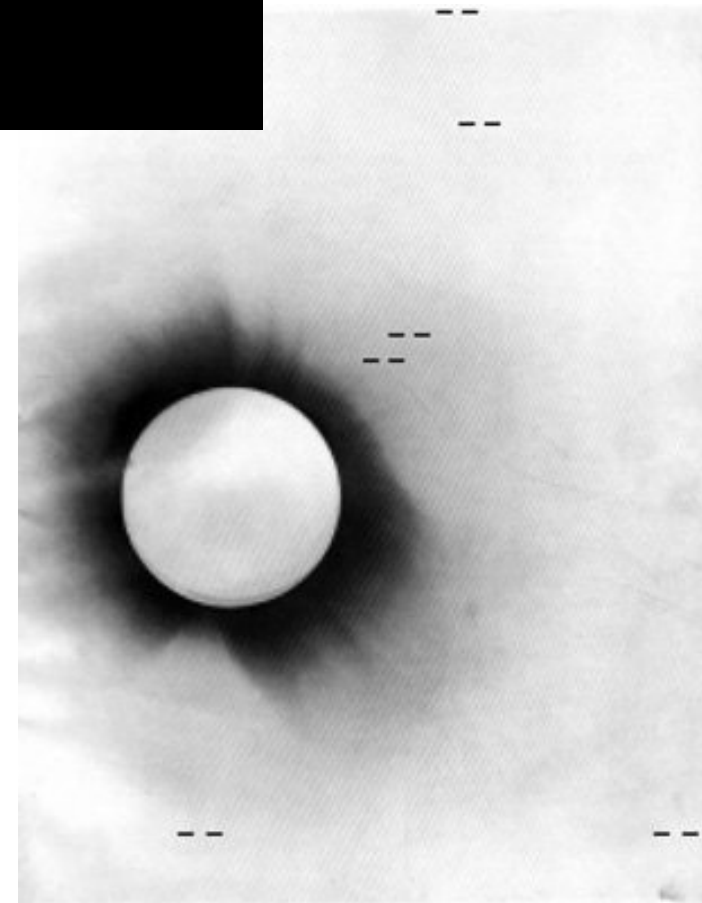


Arthur Stanley
Eddington

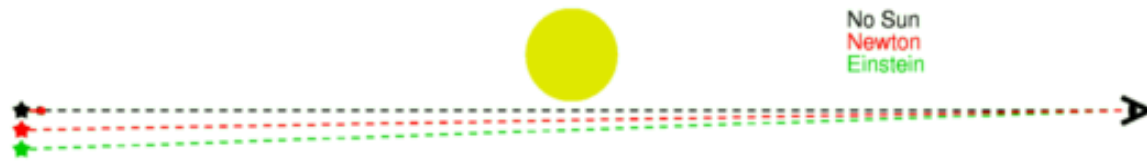


Compare positions of the star near the sun during eclipse with positions of the same stars at other times.

Two simultaneous observations:
Sobral, Brazil and
Island of Principe off the West Africa



Animation by Edward L. Wright

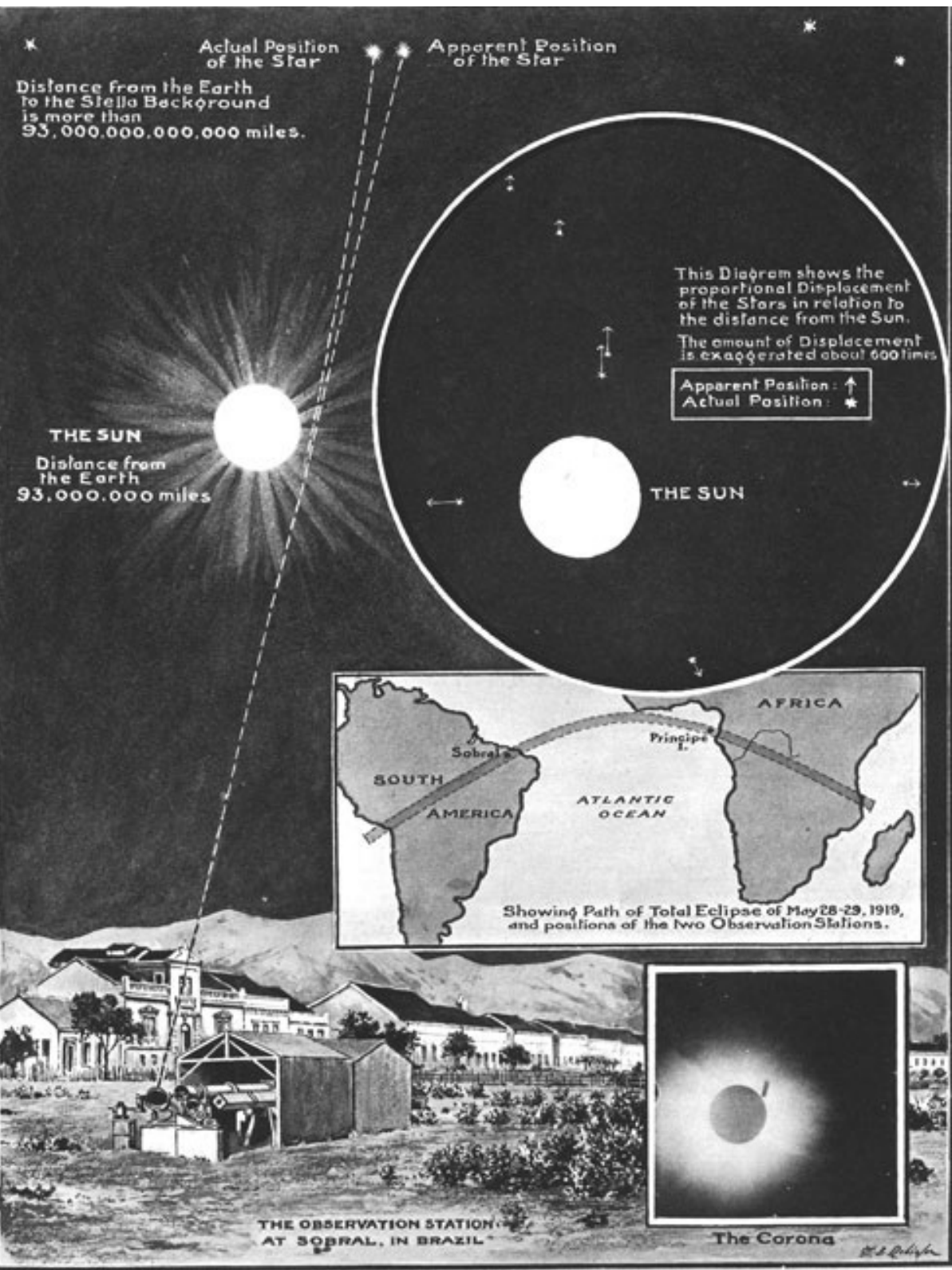


Animation by Edward L. Wright



Ned Wright

22 November 1919
edition of the
Illustrated London News.



<http://community.dur.ac.uk/r.j.massey/Principe/1919eclipse.php>

New York Times

LIGHTS ALL ASKEW IN THE HEAVENS

**Men of Science More or Less
Agog Over Results of Eclipse
Observations.**

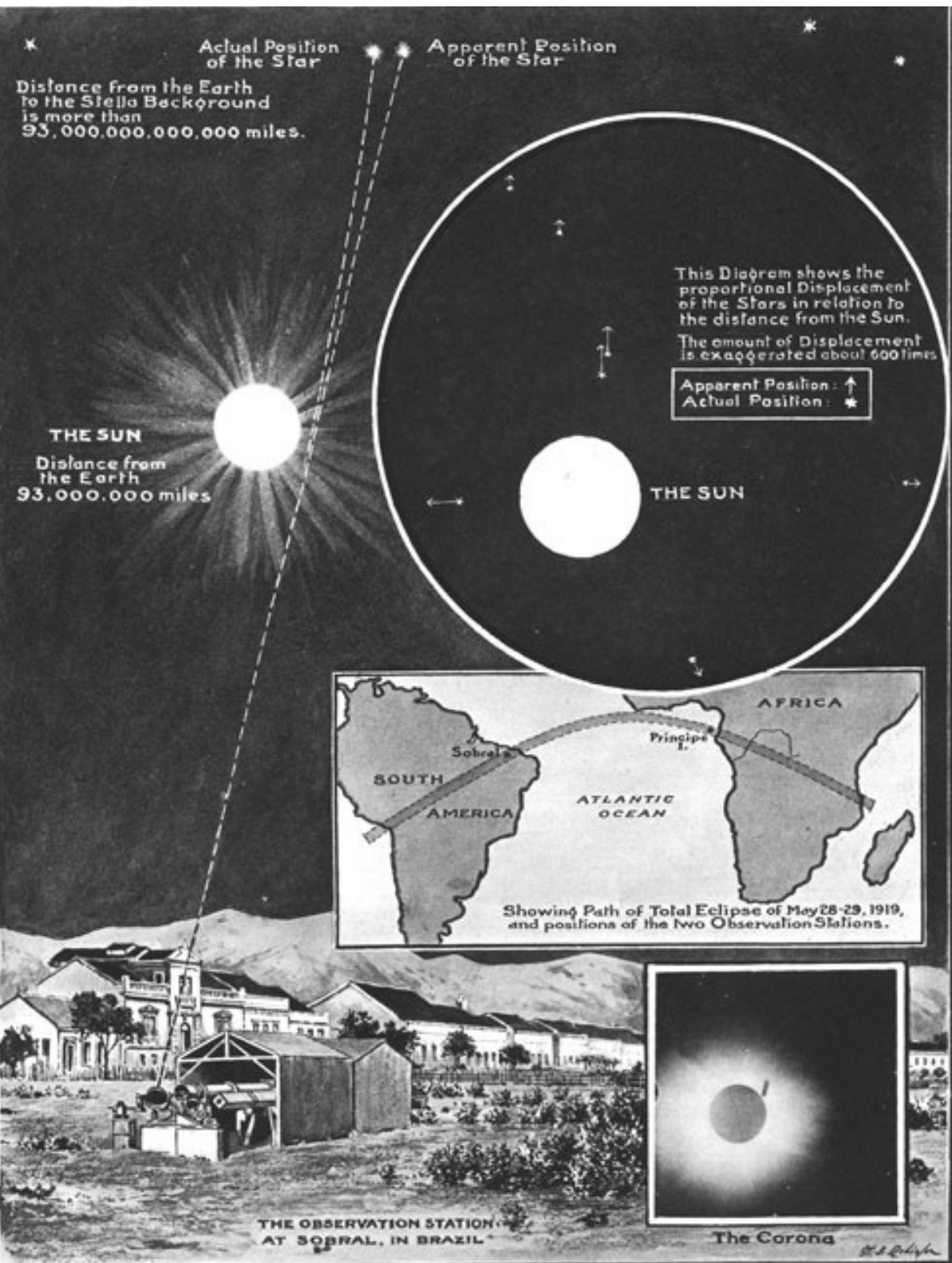
EINSTEIN THEORY TRIUMPHS

**Stars Not Where They Seemed
or Were Calculated to be,
but Nobody Need Worry.**

A BOOK FOR 12 WISE MEN

**No More in All the World Could
Comprehend It, Said Einstein When
His Daring Publishers Accepted It.**

<http://community.dur.ac.uk/r.j.massey/Principe/1919eclipse.php>



1979: Twin quasar

Quasar: “quasi-stellar radio source”:

Quasar: extremely bright source, luminosity can be 100 times greater than that of the Milky Way

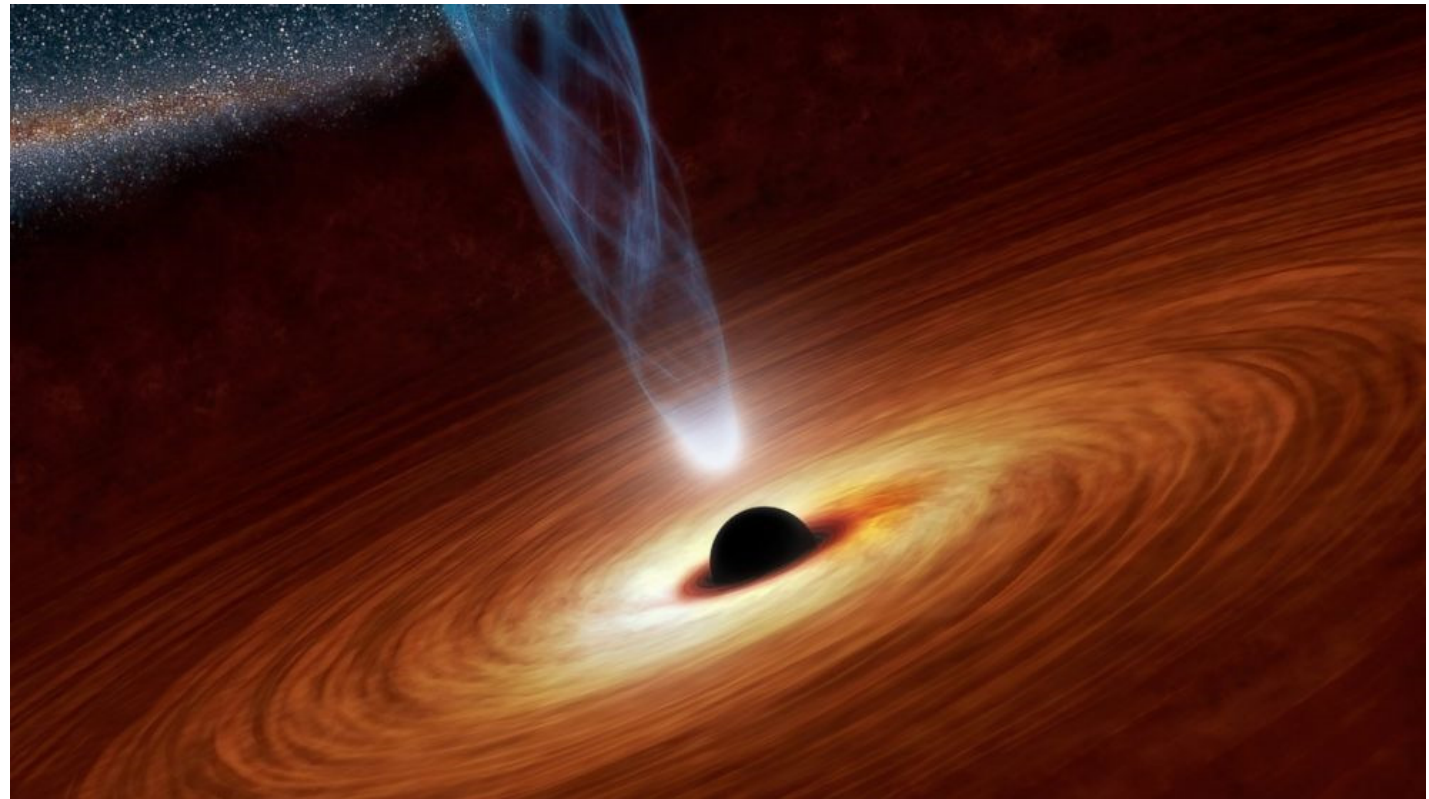
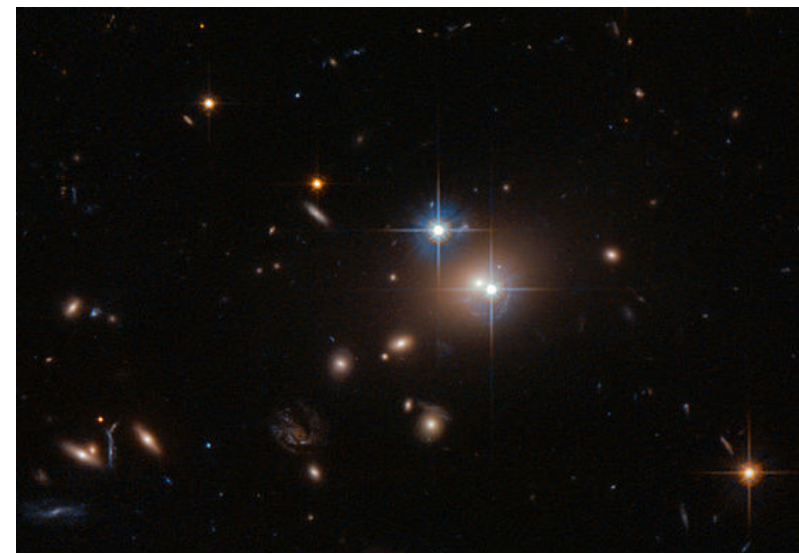
Compact region in the center of a massive galaxy surrounding a central supermassive (hundreds of thousands to billions of solar masses) black hole.



1979: Twin quasar – First identified gravitationally lensed object

Quasar: extremely bright source, luminosity can be 100 times greater than that of the Milky Way

Compact region in the center of a massive galaxy surrounding a central supermassive (hundreds of thousands to billions of solar masses) black hole.

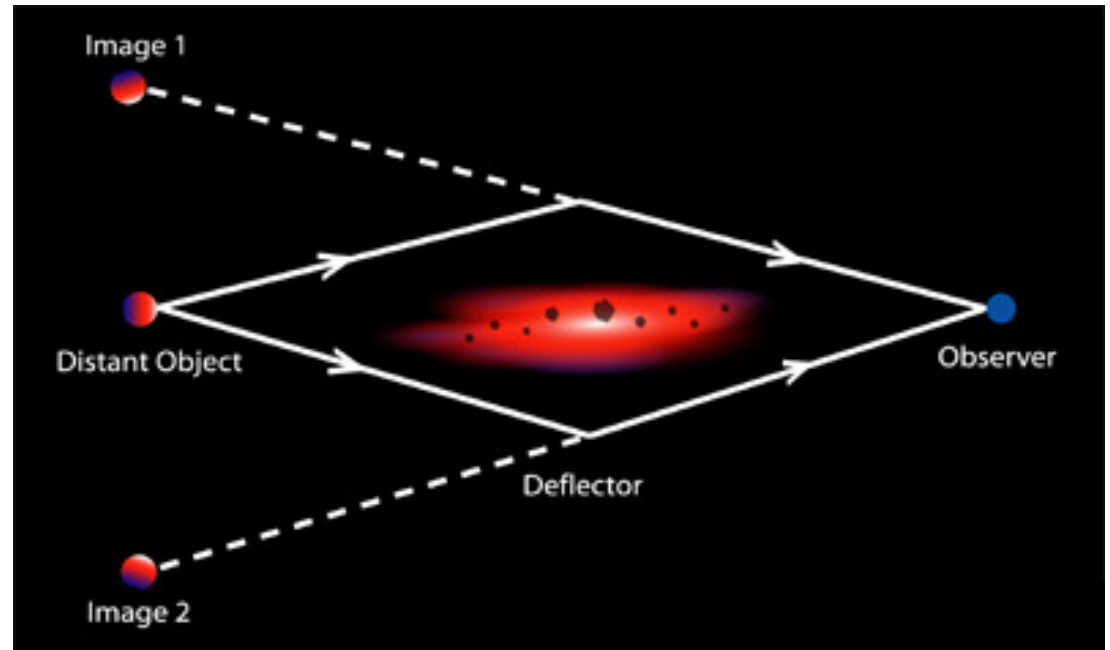


Gravitational Lensing

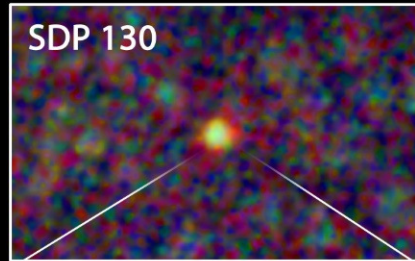
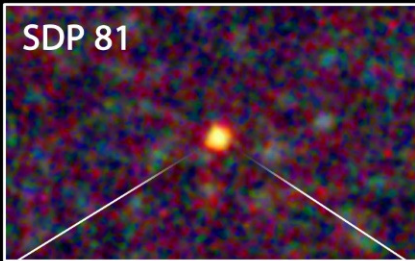
The images of the galaxies were stretched out due to gravity.

The light from these distant galaxies was attracted to mass between the galaxy and the Earth.

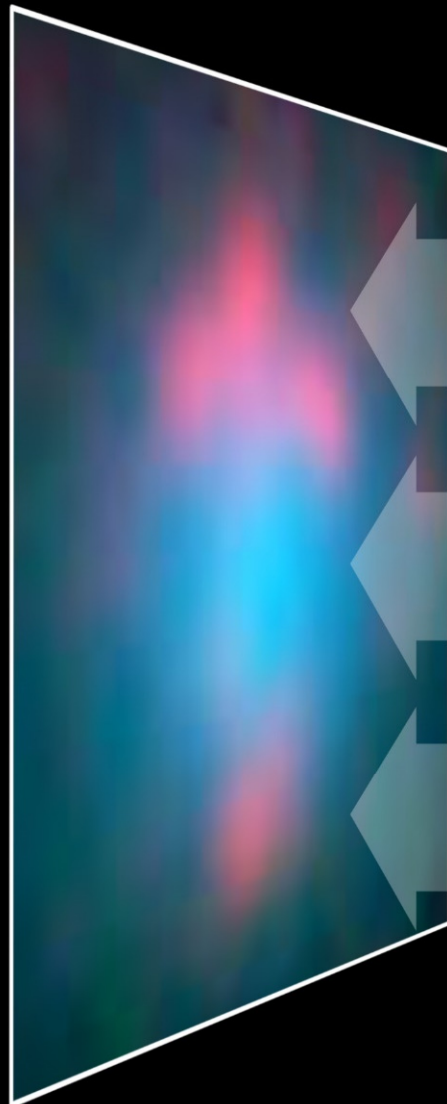
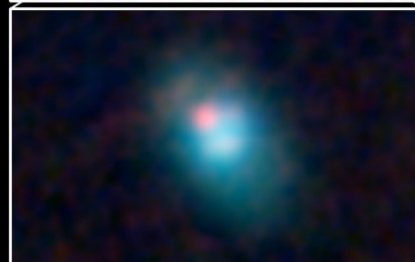
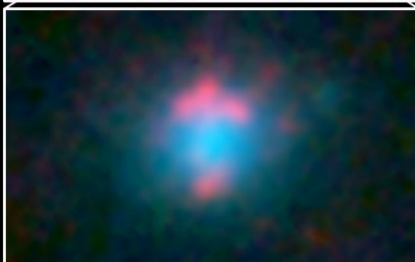
This attraction bent the light and caused the galaxies to look distorted, as if they were being seen through a crooked lens.



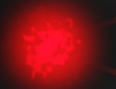
Herschel:



Keck & SMA:



DISTANT GALAXY



FOREGROUND GALAXY

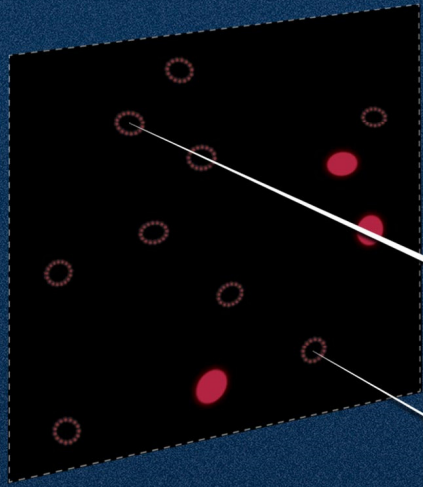


EARTH

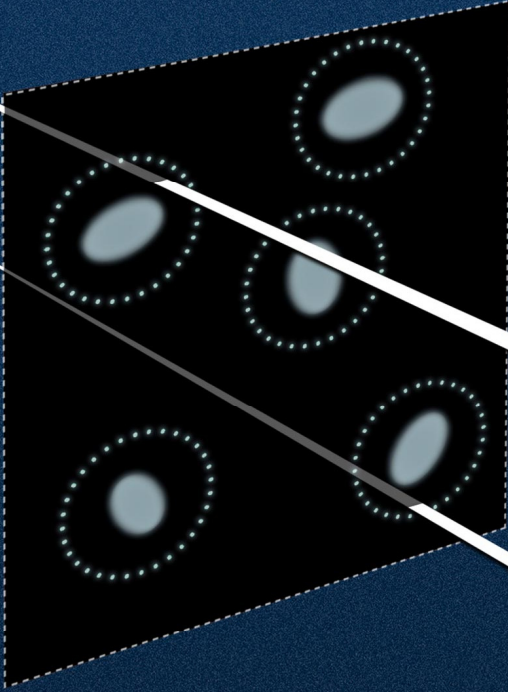
LENSED IMAGES OF DISTANT GALAXY

3 BILLION YEARS

11 BILLION YEARS

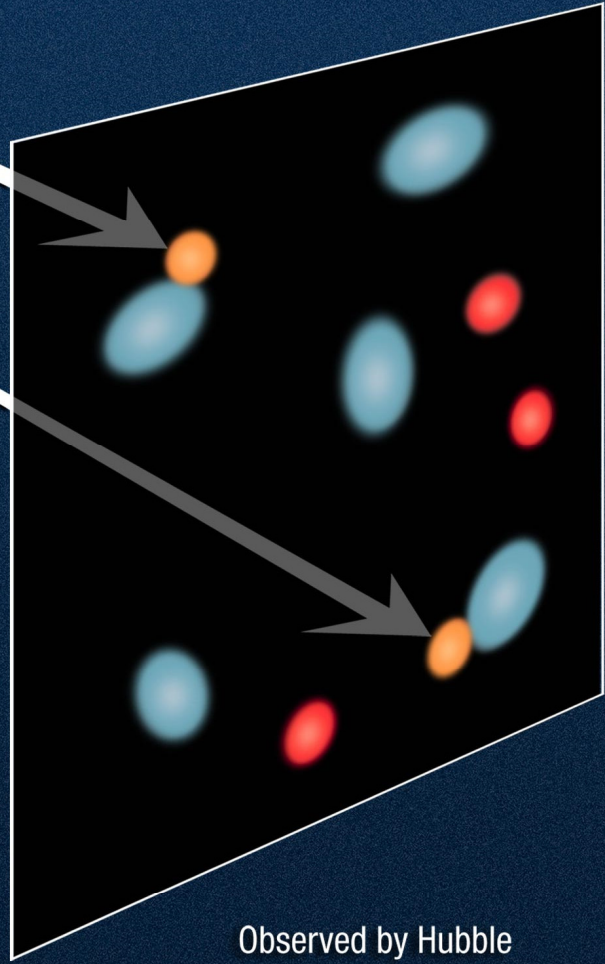


- Observable distant galaxy
- Distant galaxy too faint to detect



- Relatively nearby galaxy
- Gravitational lensing influence of foreground galaxy

Distant galaxies will be biased to appear near foreground galaxies because of gravitational lensing.



Observed by Hubble

[Animation links: https://en.wikipedia.org/wiki/Gravitational lens](https://en.wikipedia.org/wiki/Gravitational_lens)

[Link: https://www.slac.stanford.edu/~kaehler/homepage/visualizations/dark-matter.html](https://www.slac.stanford.edu/~kaehler/homepage/visualizations/dark-matter.html)



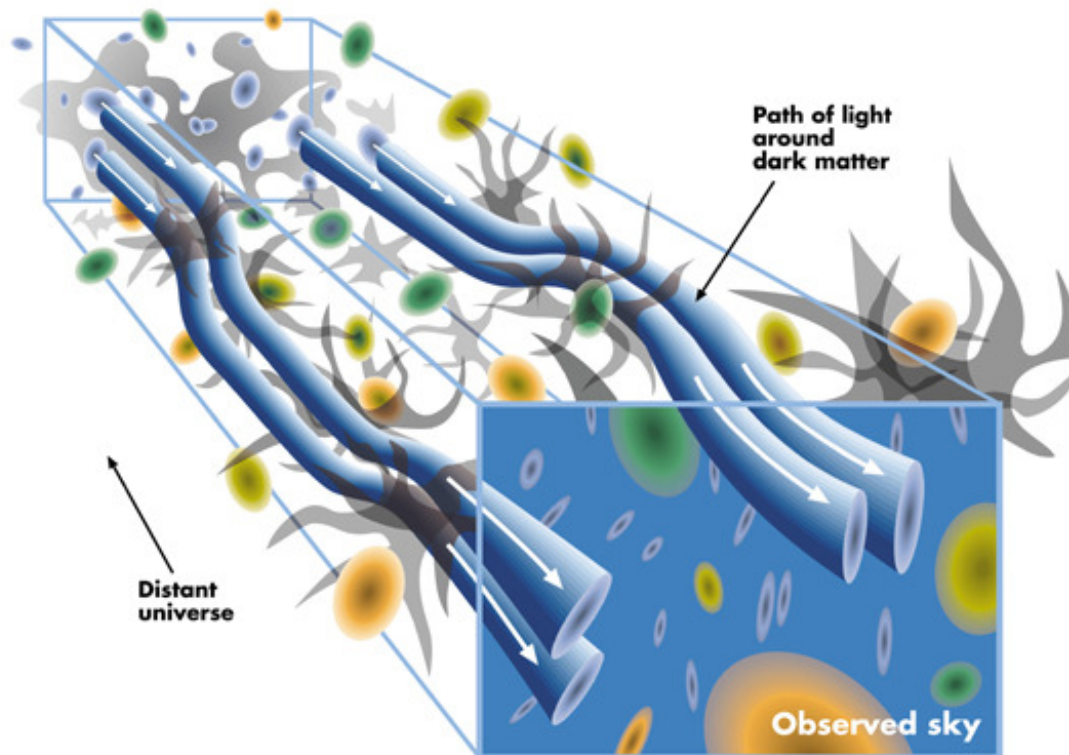
Gravitational lensing by dark matter

Sometimes galaxies are lensed by other galaxies.

Other times they were lensed by invisible objects – dark matter.

By measuring the distortion of the galaxies, scientists were able to “weigh” the dark matter.

They found that it accounts for 90% of the mass of the universe.



Cosmic shear:
the light from
distant
galaxies is
distorted by
dark matter.



Next: redo
Fritz Zwicky
measurements
with much better
instruments.

Measure the
velocities of
galaxies in a
cluster from their
Doppler shifts.

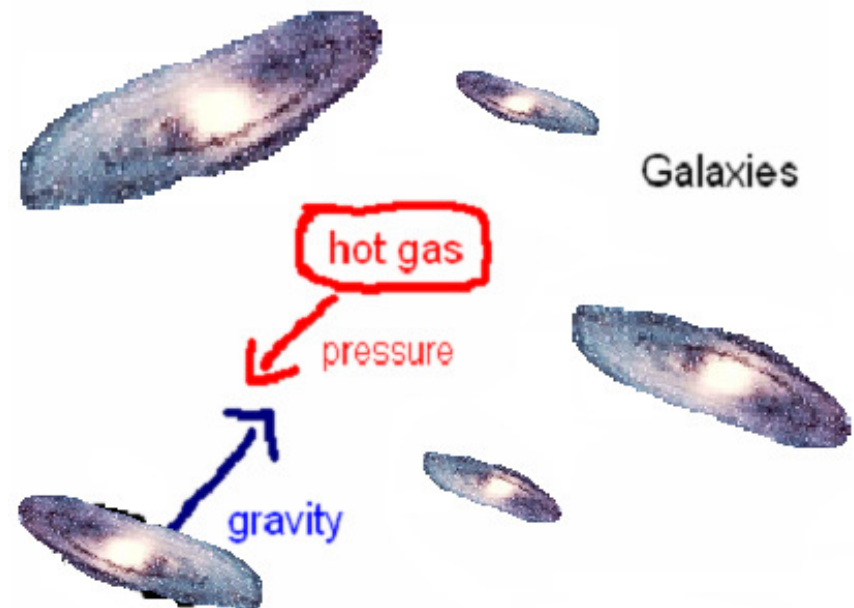
The mass we find
from galaxy
motions in a
cluster is about 50
times larger than
the mass in stars!

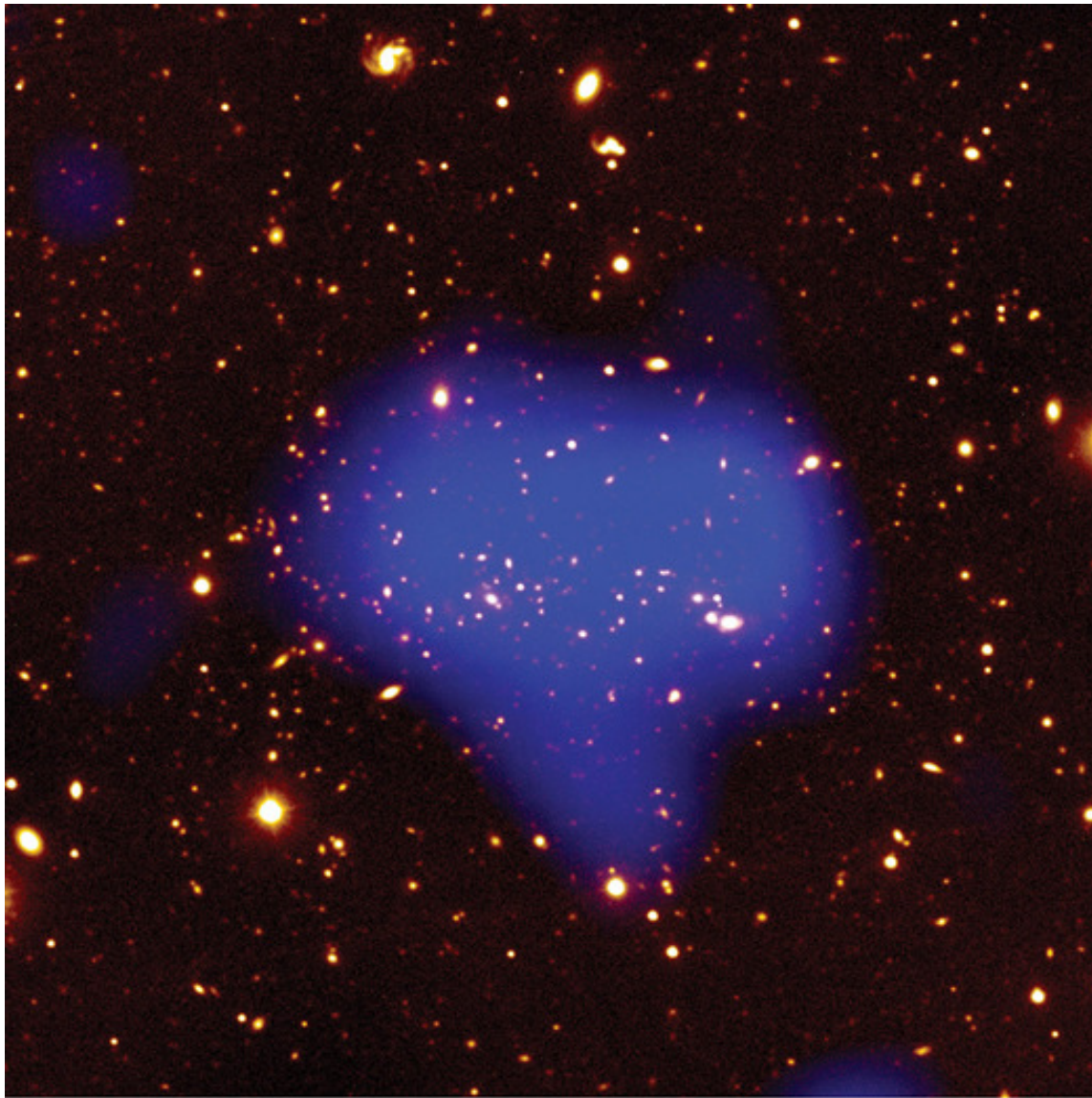
Note on galaxy cluster compositions

Radio astronomers have found hot gas in the space between galaxies in a cluster. This gas produces a pressure that pushes the galaxies apart.

The galaxies' mutual gravitational attraction causes them to cling together. The heavier the galaxies, the stronger the gravitational attraction.

So, are galaxies massive enough to hang together?





Clusters contain large amounts hot gas:
emits **x rays**

Temperature of hot gas tells us cluster mass:

85% dark matter
13% hot gas
1-2% stars

Wavelength
(meters)

Radio

10^3

Microwave

10^{-2}

Infrared

10^{-5}

Visible

$.5 \times 10^{-6}$

Ultraviolet

10^{-8}

X-ray

10^{-10}

Gamma Ray

10^{-12}

Here's one simple way to mass a galaxy

$$\text{Number of stars} = \frac{\text{light emitted by galaxy}}{\text{light emitted by average star}}$$

$$\text{Mass of galaxy} = \text{number of stars} \times \text{average mass of star}$$

It turns out that galaxies do not have enough visible mass to stay grouped in clusters. The extra mass they need must come from dark matter.

2006: Bullet cluster

Dark matter and normal matter have been wrenched apart by the tremendous collision of two large clusters of galaxies. The discovery, using NASA's Chandra X-ray Observatory and other telescopes, gives direct evidence for the existence of dark matter.



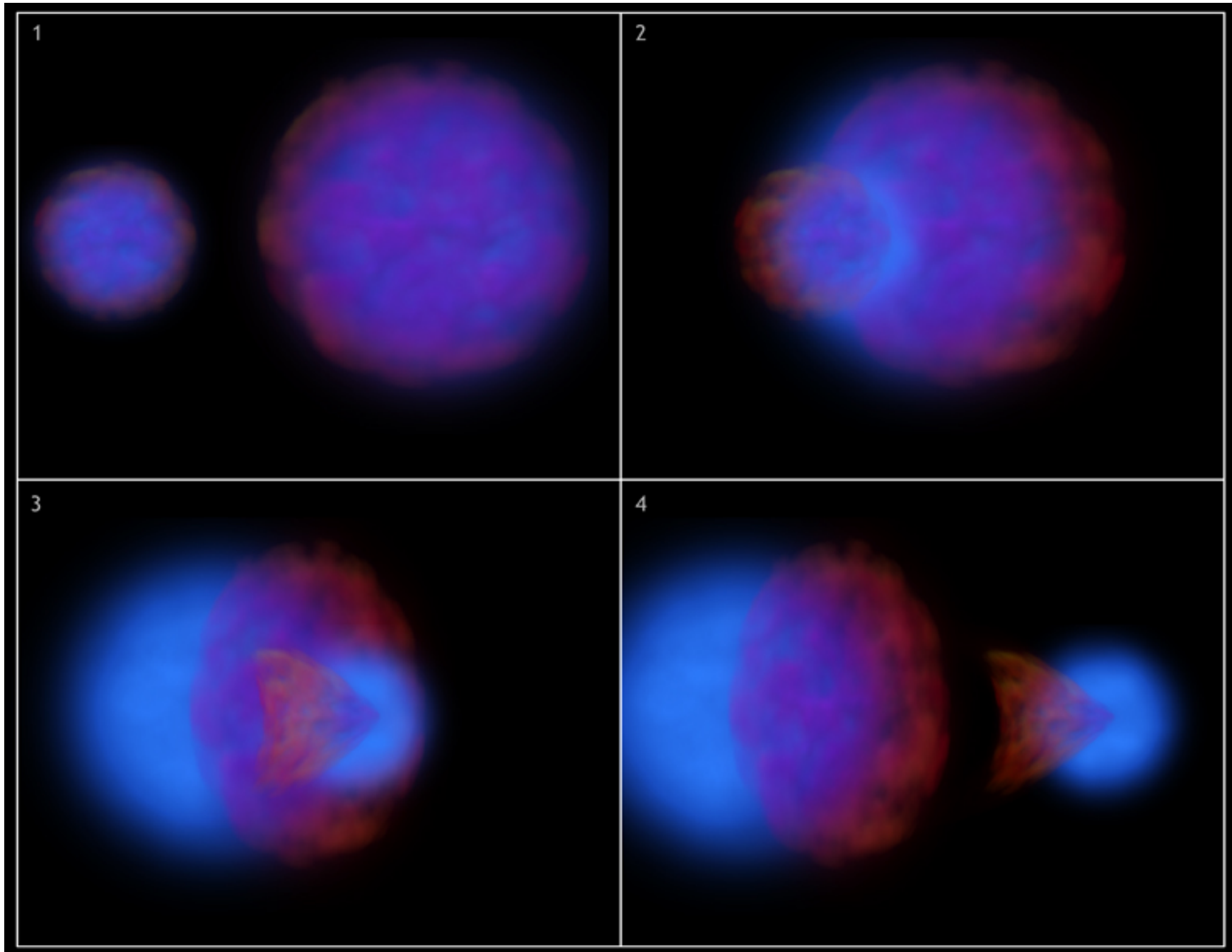
Hot gas detected by Chandra in X-rays is seen as two pink clumps in the image and contains most of the "normal," or baryonic, matter in the two clusters.

The blue areas in this image show where astronomers find most of the mass in the clusters using the effect of gravitational lensing.

Most of the matter in the clusters (blue) is clearly separate from the normal matter (pink), giving direct evidence that nearly all of the matter in the clusters is dark.

Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Bullet cluster collision



Pink clumps: "normal matter"

Blue clumps: dark matter

2006: Bullet cluster

The **hot gas in each cluster was slowed by a drag force**, similar to air resistance, during the collision. In contrast, the **dark matter was not slowed by the impact** because it does not interact directly with itself or the gas except through gravity.



Therefore, during the collision the dark matter clumps from the two clusters moved ahead of the hot gas, producing the separation of the dark and normal matter seen in the image. If hot gas was the most massive component in the clusters, as proposed by alternative theories of gravity, such an effect would not be seen. Instead, this result shows that dark matter is required.

Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

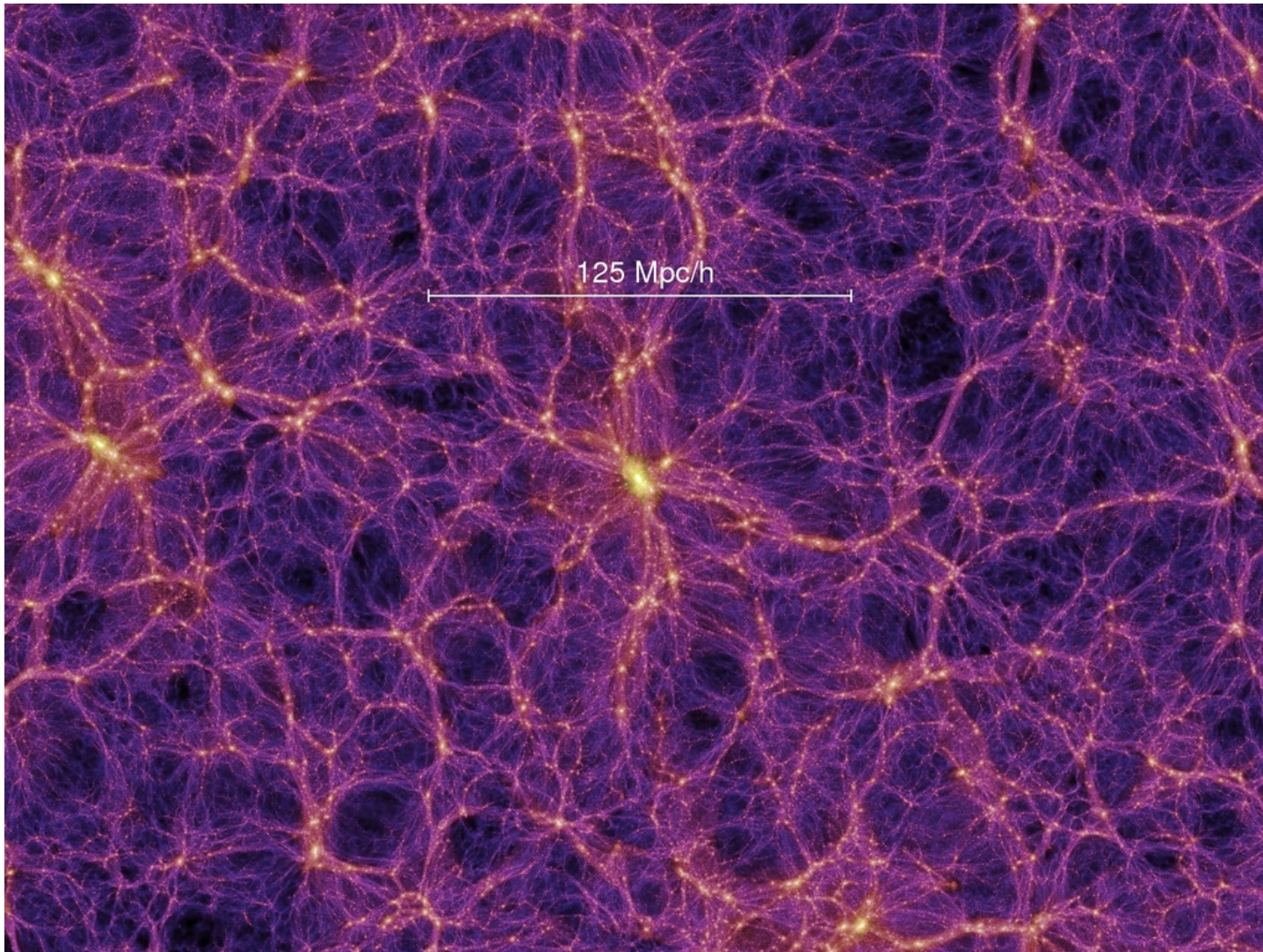
Dark Universe Planetarium Show: Dark Matter

<https://www.slac.stanford.edu/~kaehler/homepage/visualizations/dark-matter.html>

Millennium Simulation

<http://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/>

<https://www.youtube.com/watch?v=Y9yQOb94yI0>



The movie shows the dark matter distribution in the universe at the present time, based on the *Millennium Simulation*, the largest N-body simulation carried out thus far (more than 10^{10} particles).

By zooming in on a massive cluster of galaxies, the movie highlights the morphology of the structure on different scales, and the large dynamic range of the simulation (10^5 per dimension in 3D). The zoom extends from scales of several Gpc down to resolved substructures as small as ~ 10 kpc.

Millennium Run
10,077,696,000 particles



Credit: Springel et al. (2005), the Max-Planck-Institute for Astrophysics

A visualization of the Millennium Simulation, showing a complex, interconnected network of dark purple and blue filaments and nodes, representing the large-scale structure of the universe. The filaments form a dense, web-like pattern, with nodes representing galaxy clusters and individual galaxies. The overall appearance is that of a vast, interconnected cosmic web.

1 Gpc/h

Millennium Simulation

10.077.696.000 particles

($z = 0$)