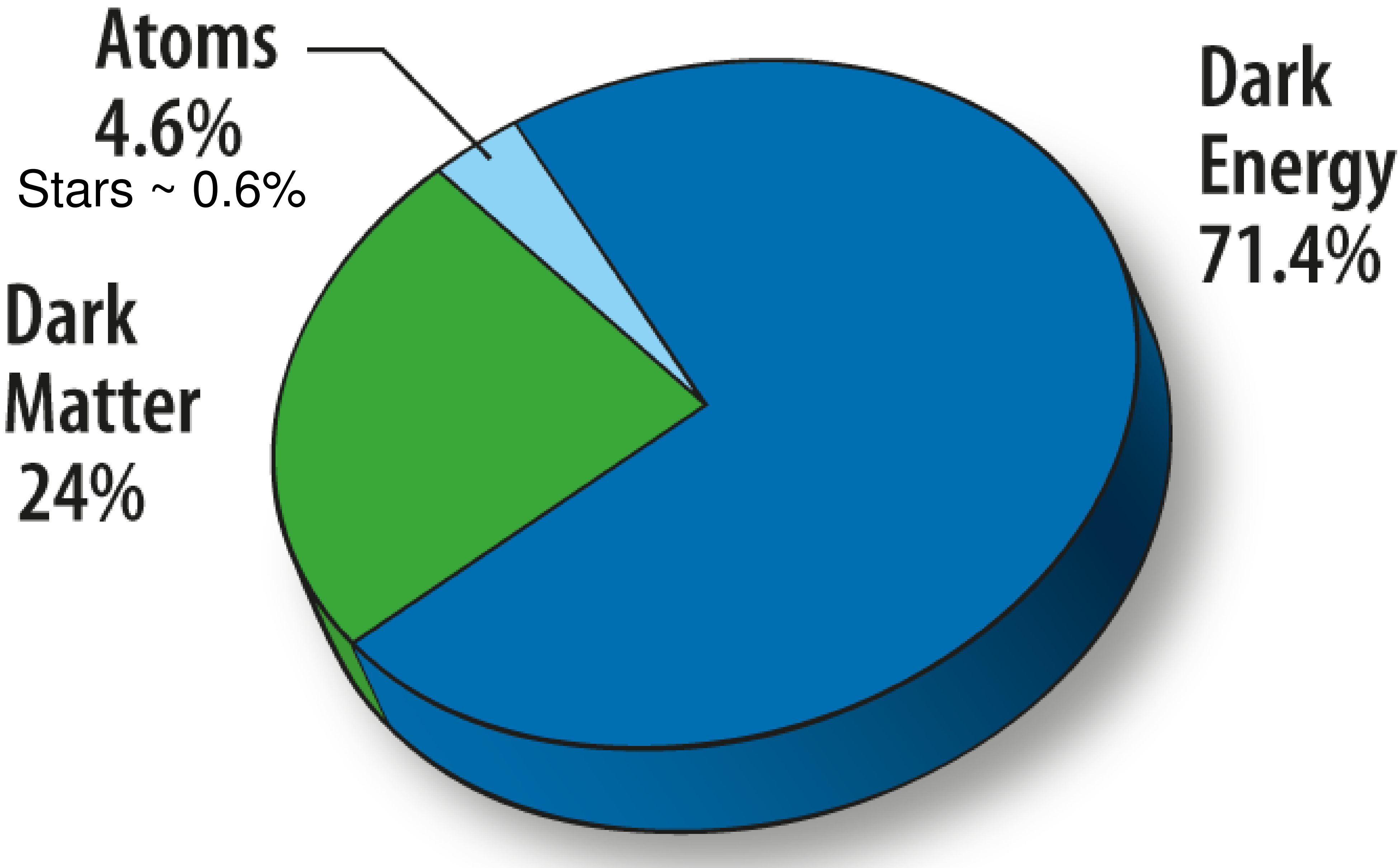
Lectures 1 - 2

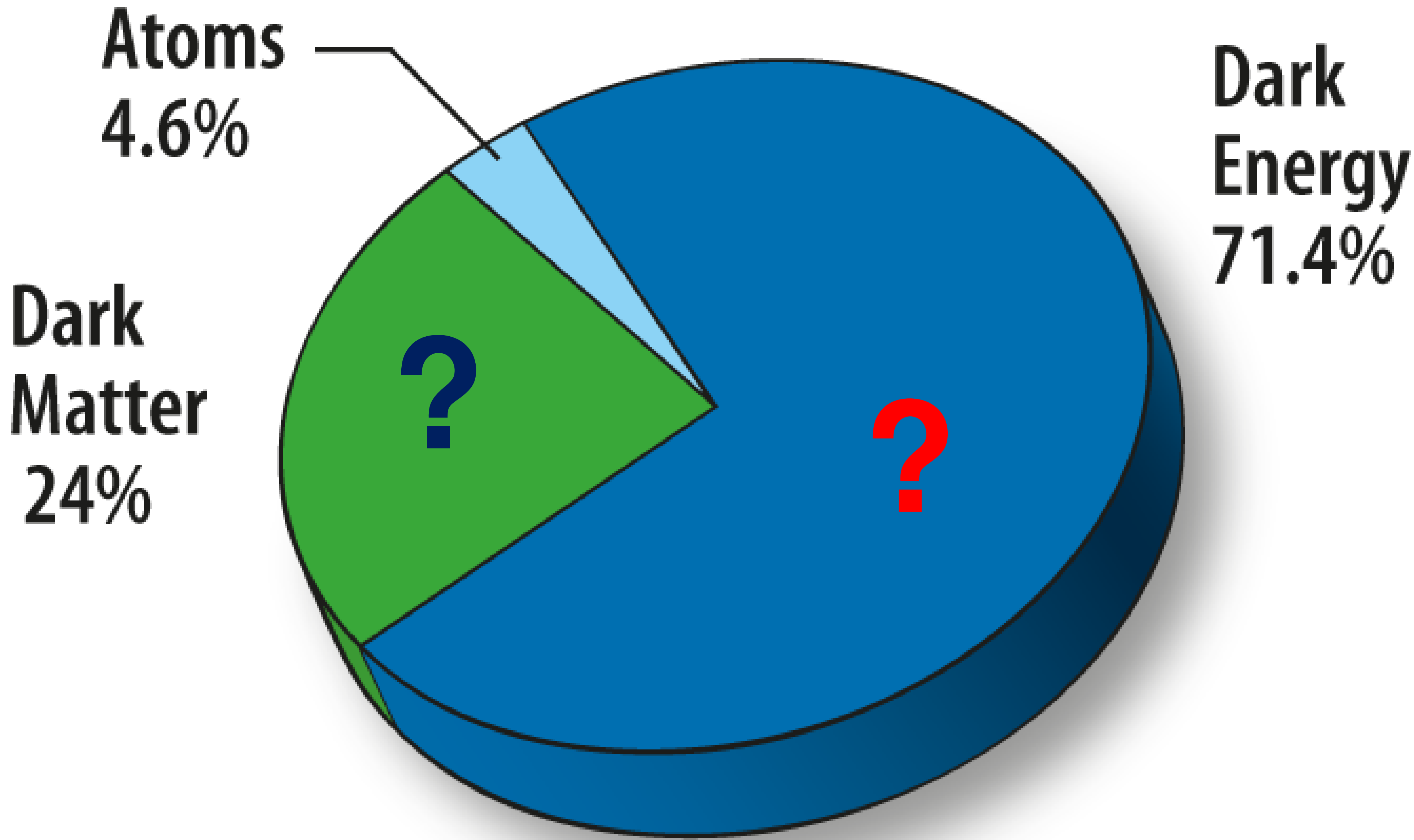
What is the Universe made of?

The puzzle of dark matter.

What is the Universe made of?

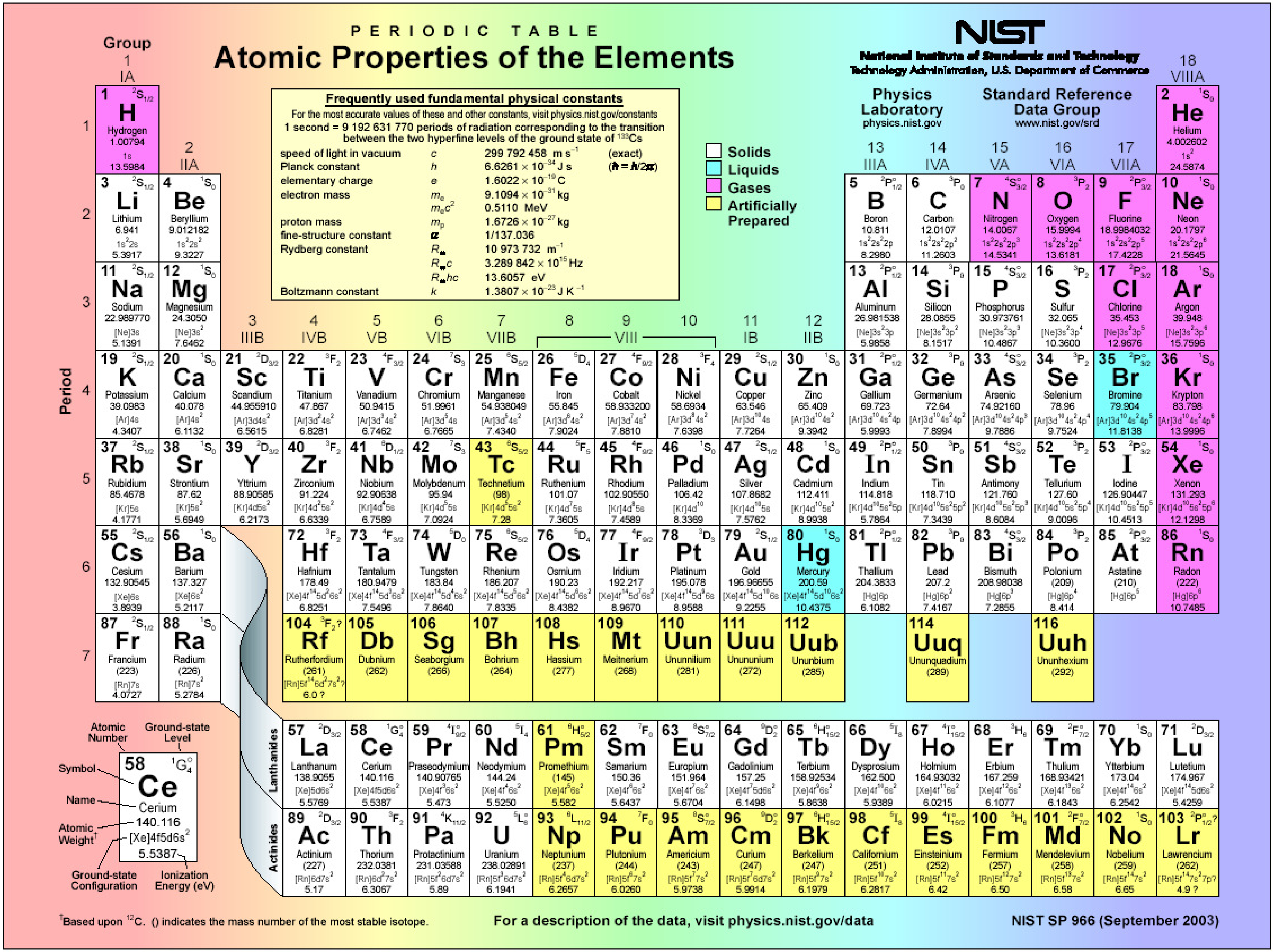


What is the Universe made of?



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

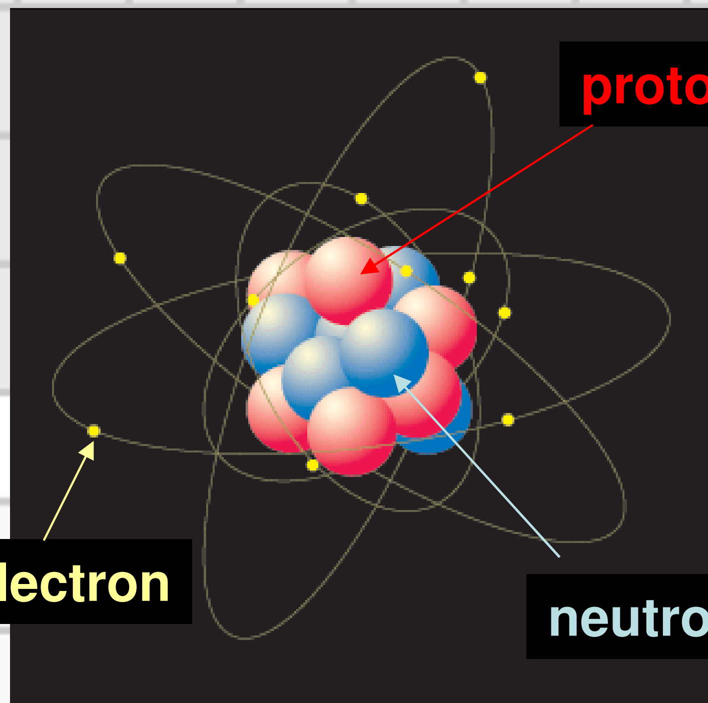
"ORDINARY MATTER":
People, Stars, Molecules, Atoms



Atoms

Atoms are all similarly made of:
- protons and neutrons in the nucleus
- electrons orbiting around

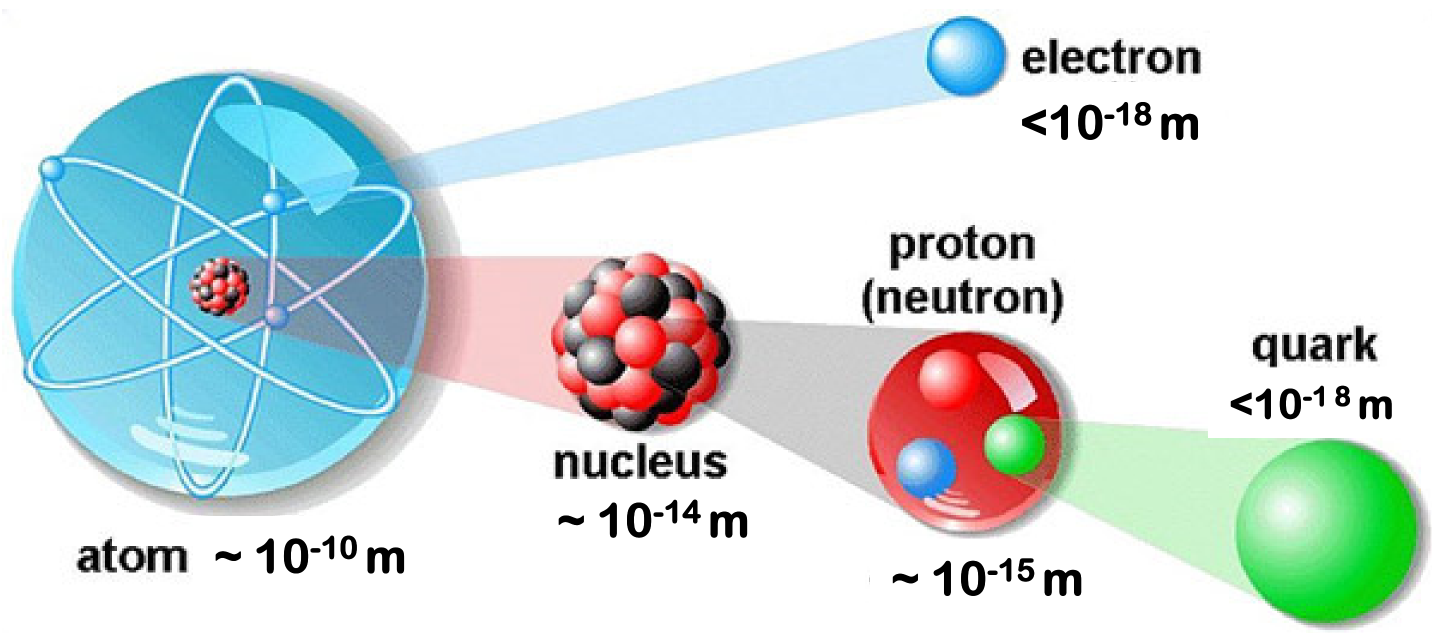
The electron was the first elementary particle to be discovered (JJ Thomson 1897)



Protons, neutrons are made up of quarks

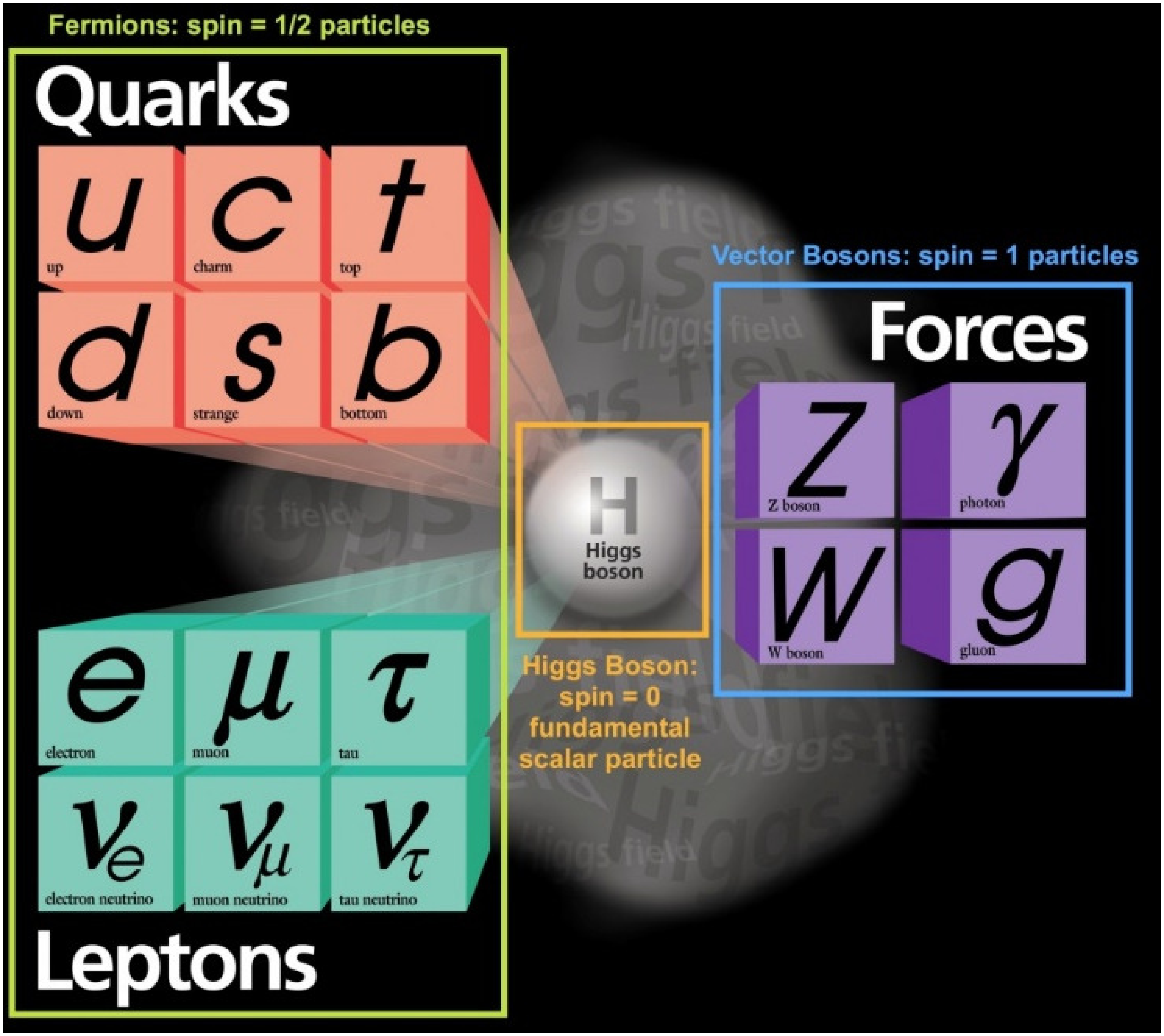
From atoms to elementary particles: electrons and quarks

How small are the smallest constituents of matter?

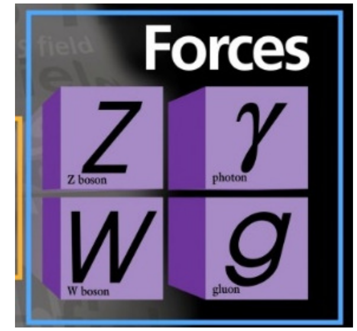


Elementary particles: not consisting from other particles
(to the best of our knowledge)

ORDINARY MATTER:
Standard model of Elementary particles



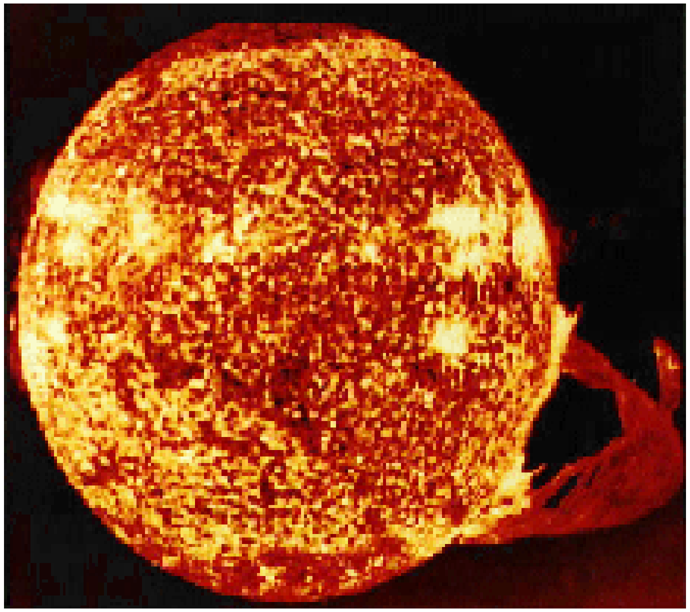
The 4 forces
Fundamental interactions

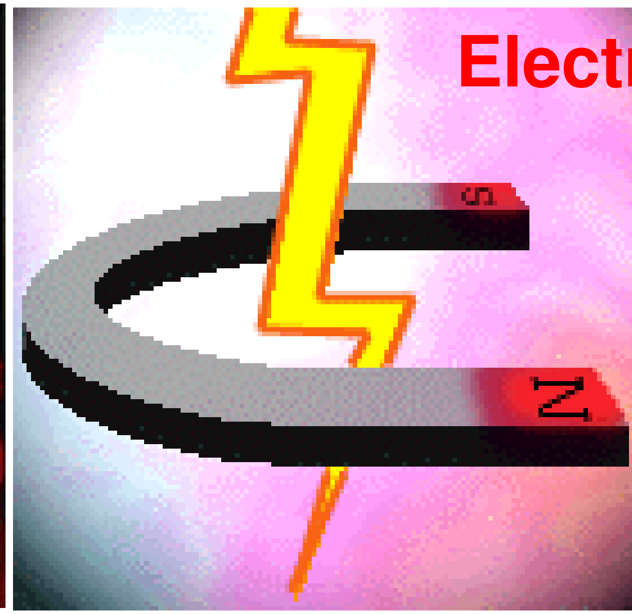


Weak

Beta-decay
pp fusion

weak
charge





Electromagnetic

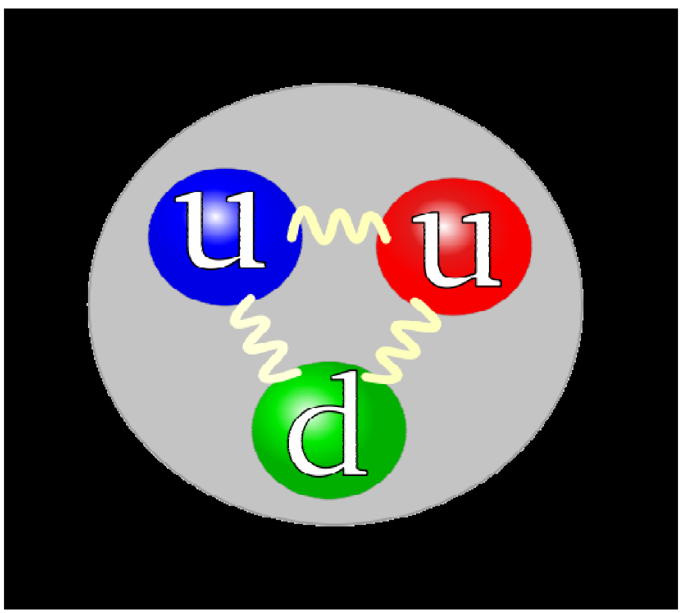
Electricity,
lasers,
magnets …

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

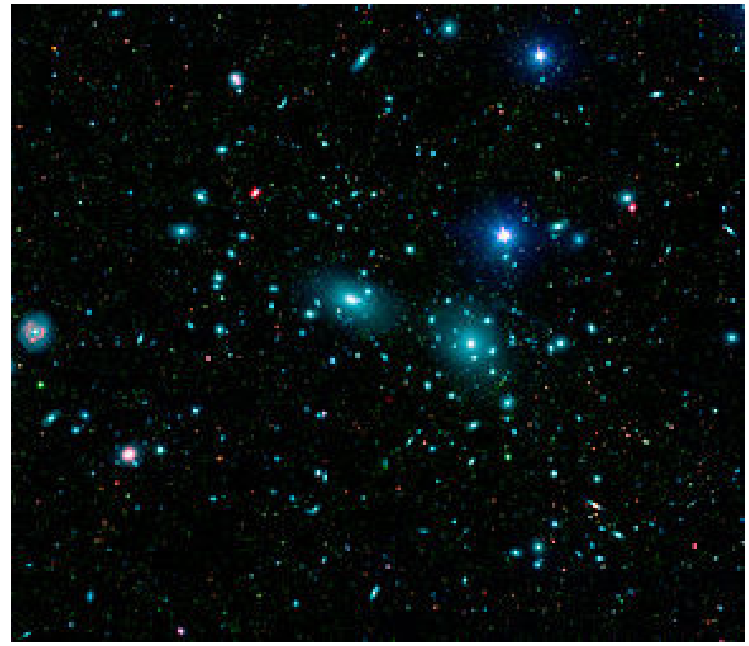
Dark matter:

How do we know that it exists?

Overview of experimental evidence

First evidence for dark matter: 1933

Fritz Zwicky
California Institute of Technology



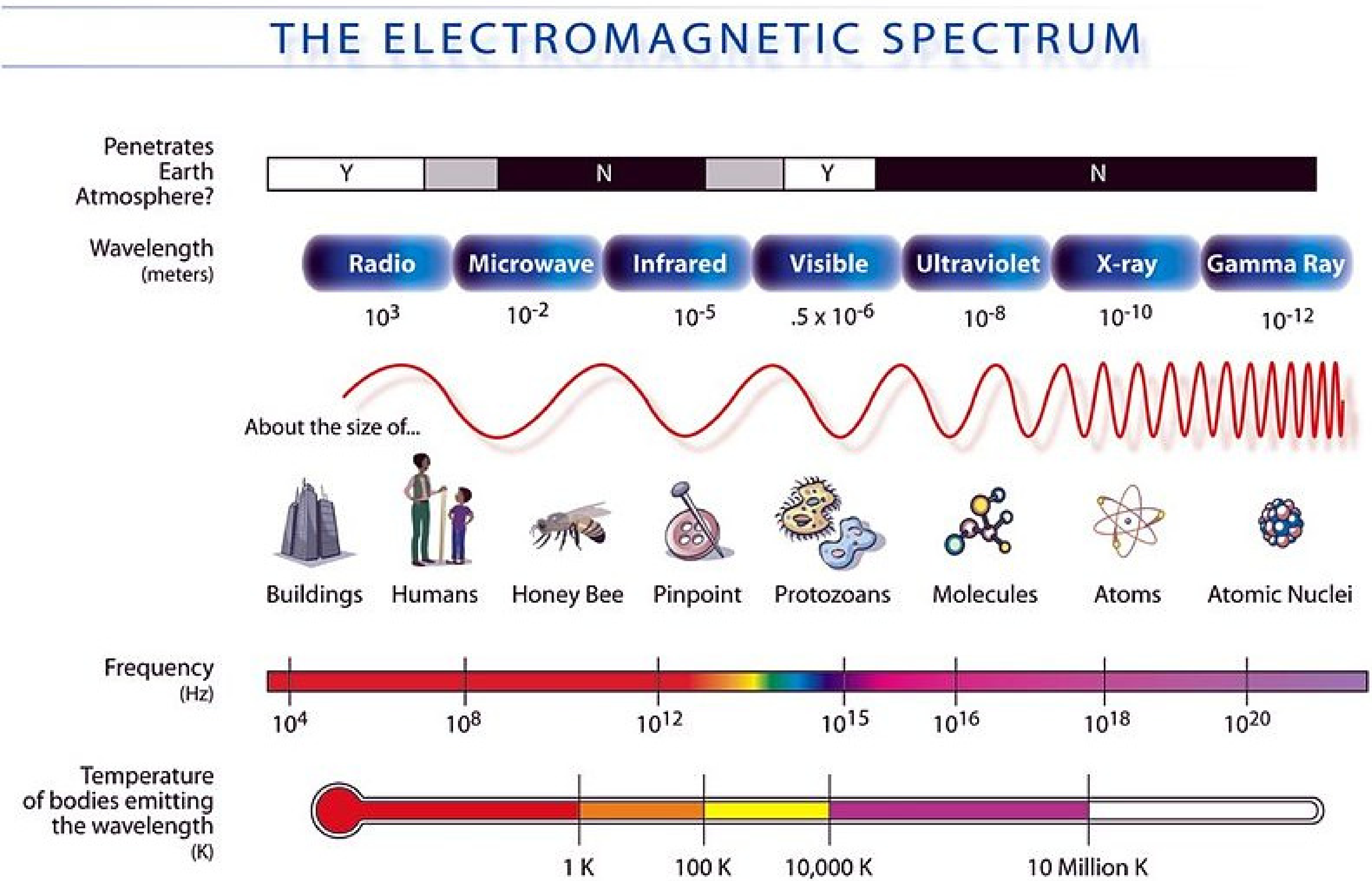
Coma Cluster: 1000 galaxies
321 million light years away

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

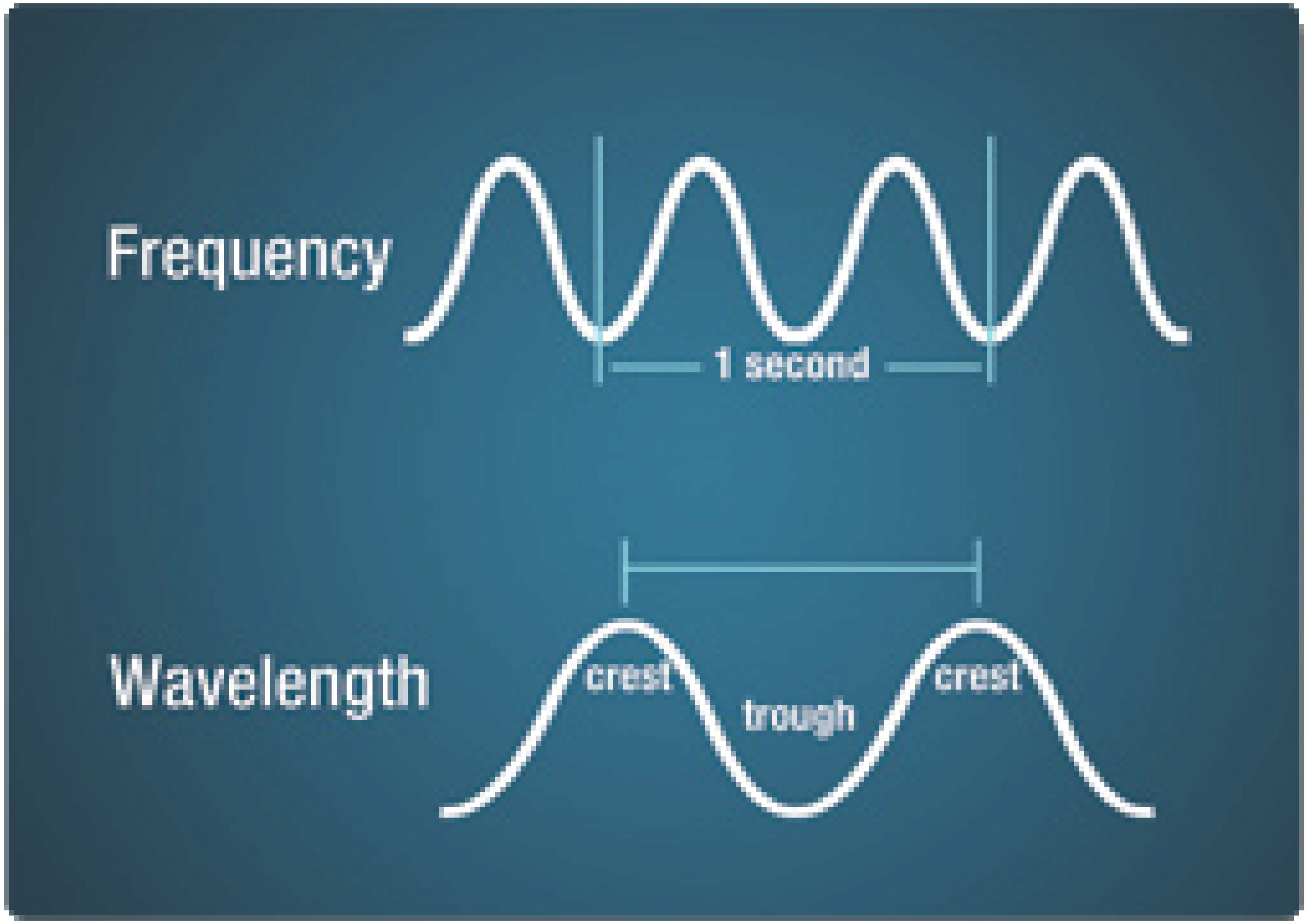
He used the18 inch telescope to make a survey of all the galaxies in the Coma cluster and used measurements of the **Doppler shift of their spectra** to determine their velocities.

A few slides on explanation of:

“Doppler shift of their spectra”



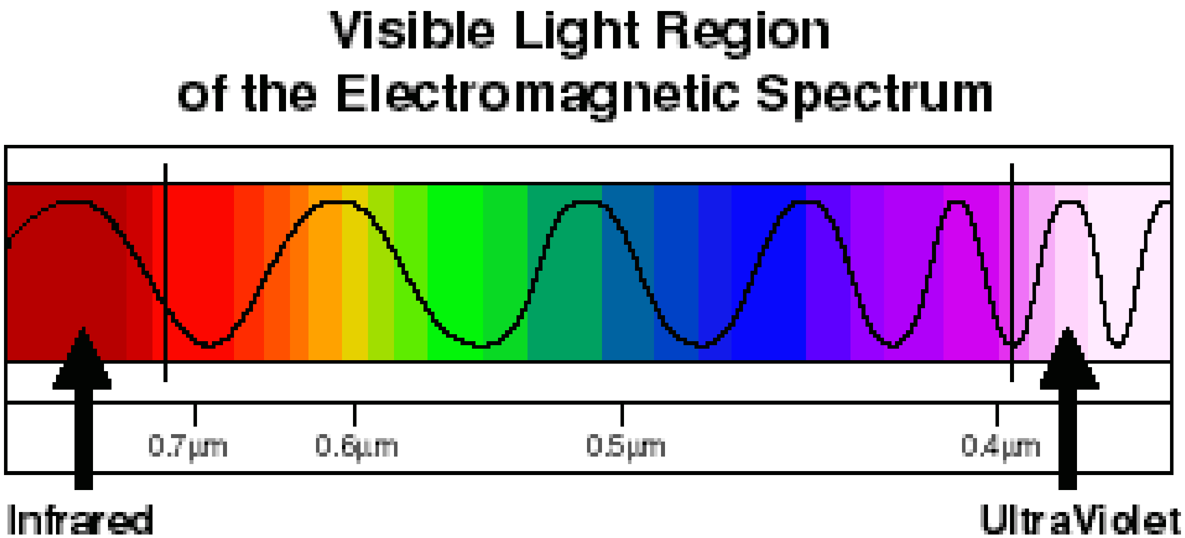
https://commons.wikimedia.org/wiki/File:EM_Spectrum3-new.jpg



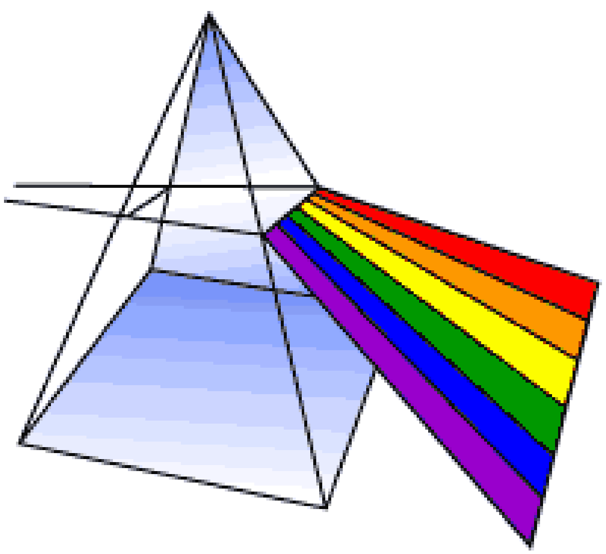
http://missionscience.nasa.gov/ems/

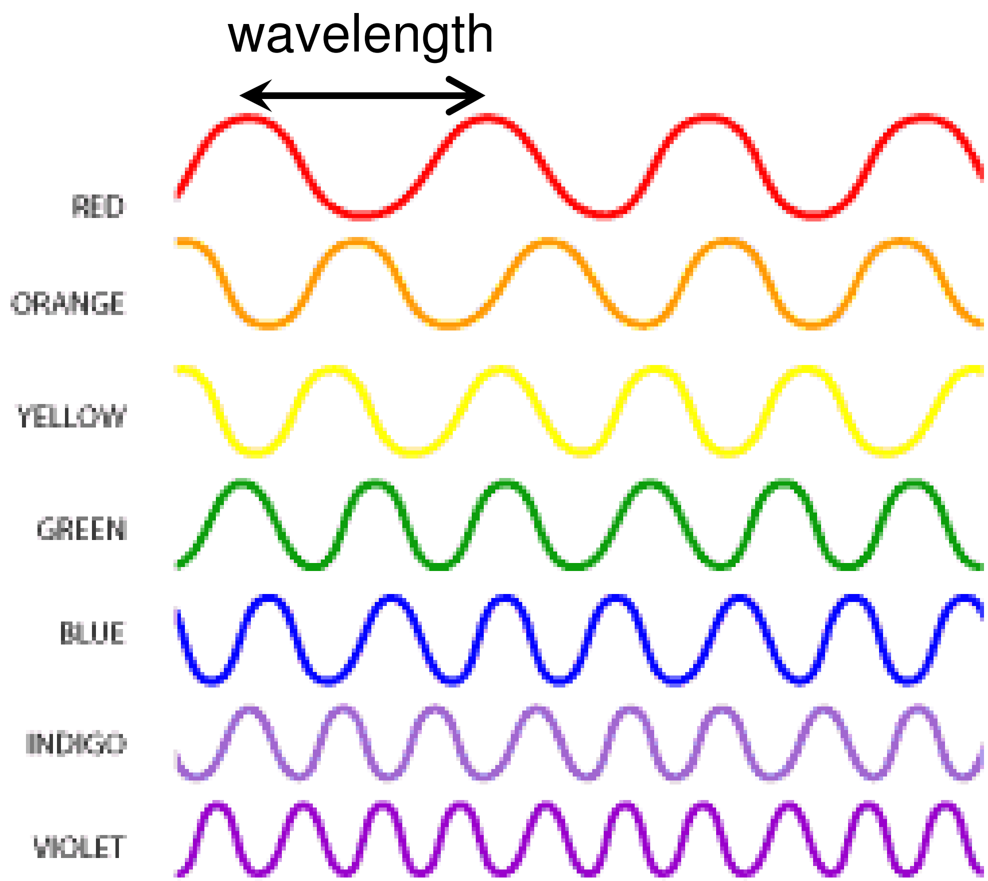
800 nm

$nm=10^{-9}$ m



350 nm



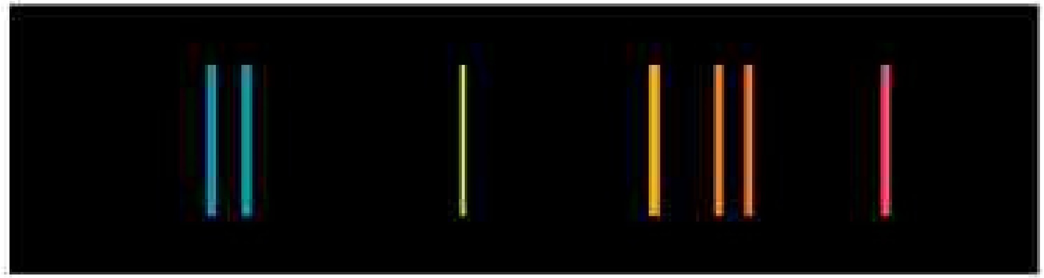


http://science.hq.nasa.gov/kids/imagers/ems/visible.html

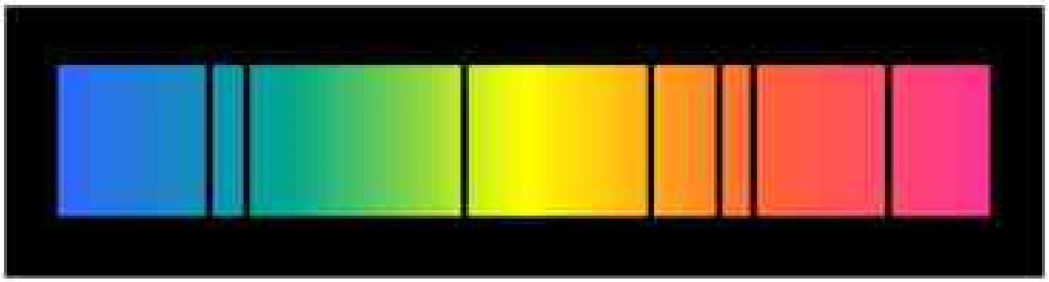
Astronomy and atomic spectral lines

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.



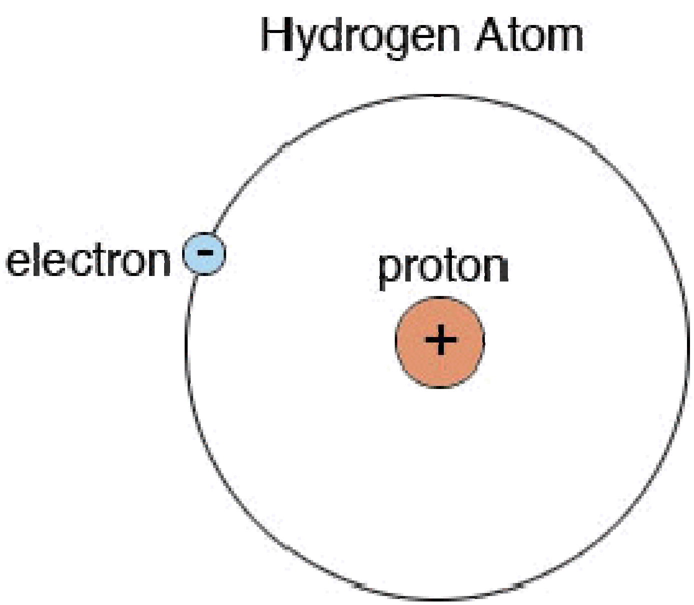
Absorption lines: the result of specific wavelengths being absorbed along the line-of-sight.



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?

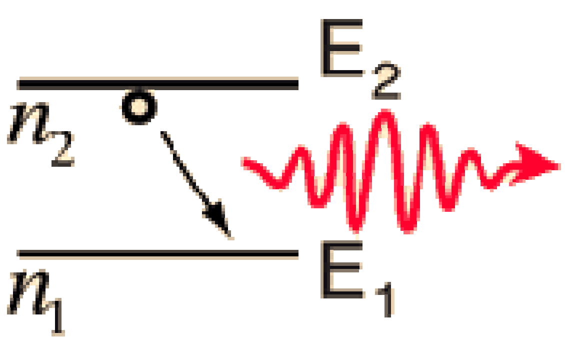


Quantum mechanics:

Election 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.

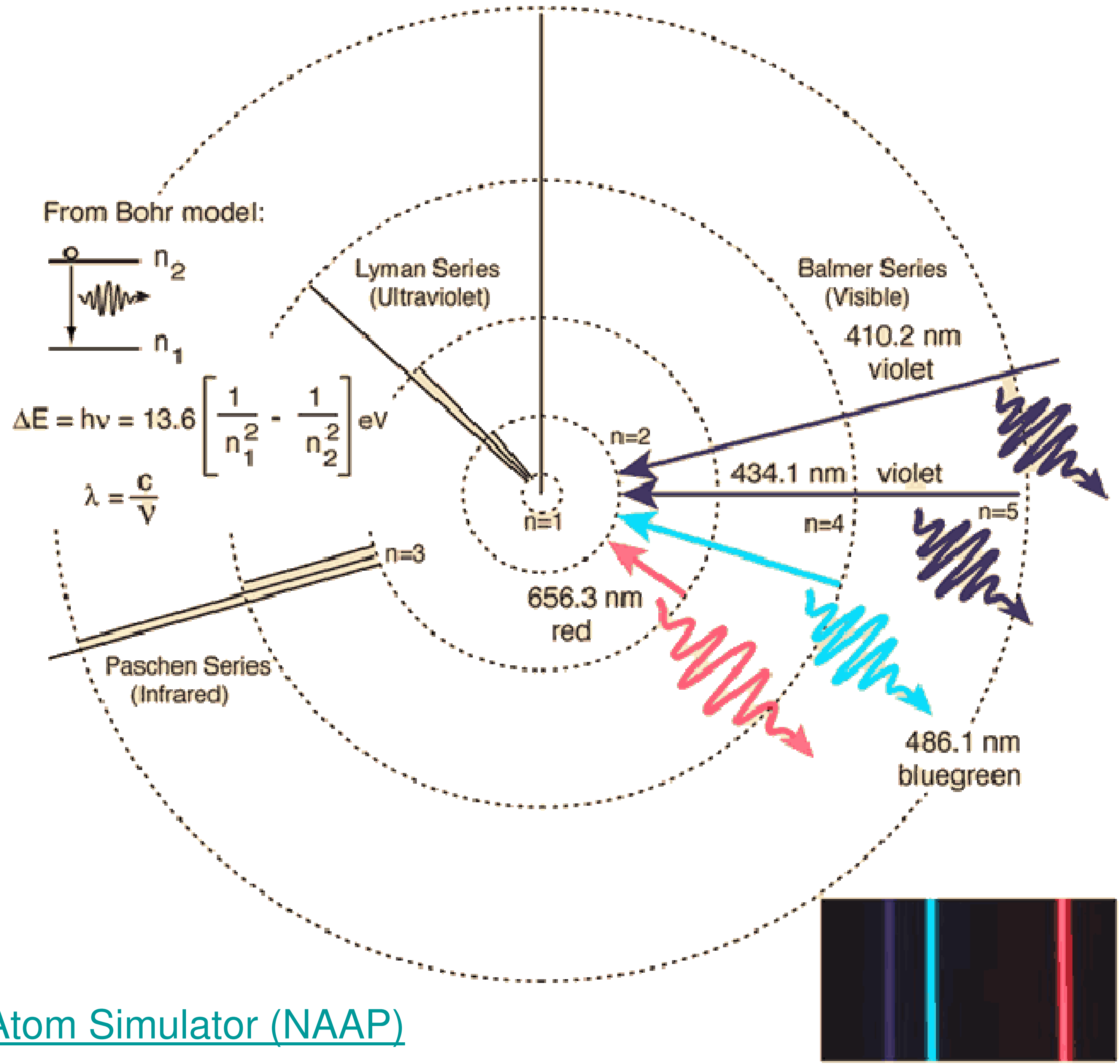
The wavelength of such electromagnetic radiation is determined from the **difference between two energy levels.**



A downward transition involves emission of a photon of energy:

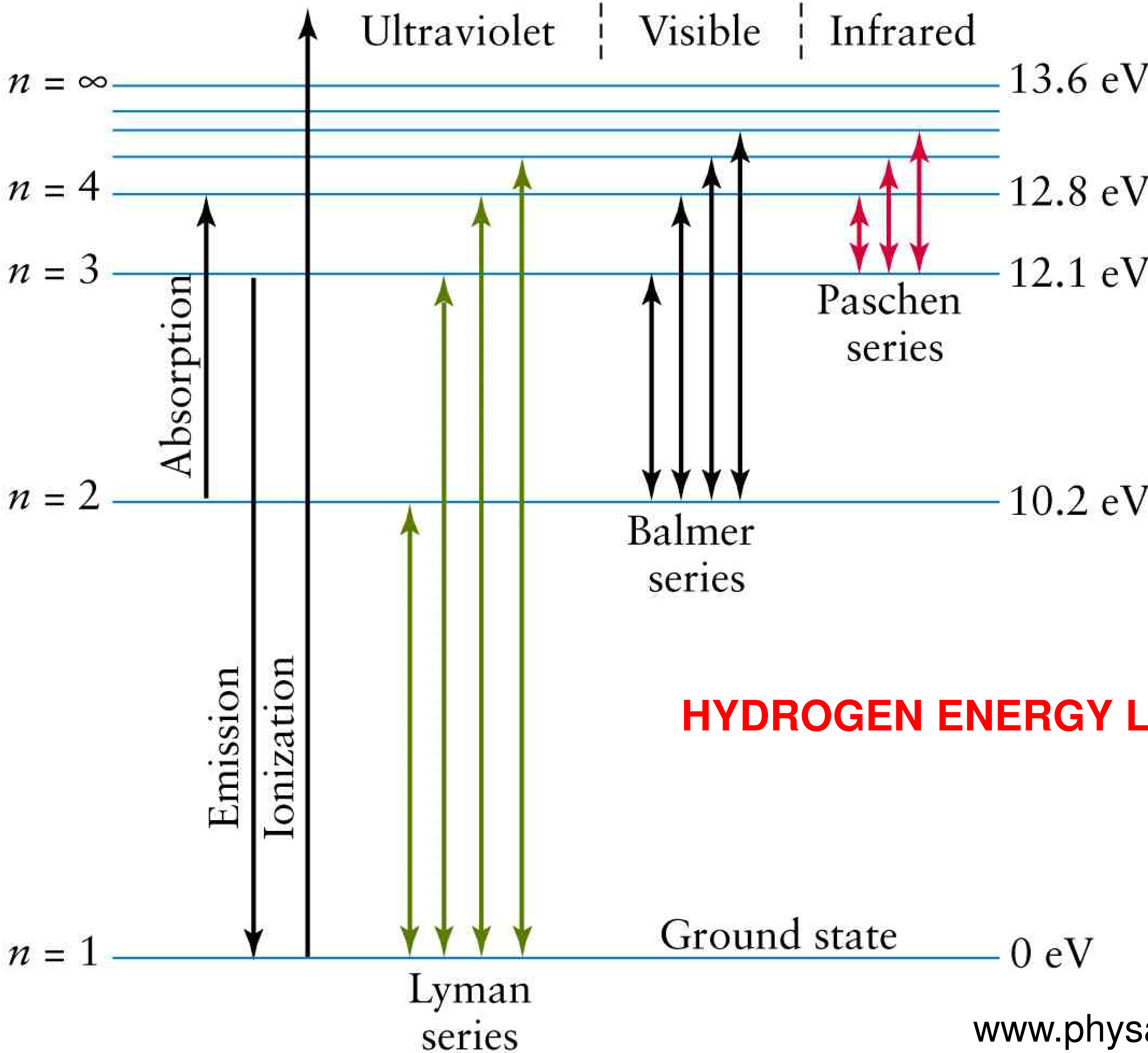
$$E_{photon} = h\nu = E_2 - E_1$$

http://hyperphysics.phy-astr.gsu.edu/hbase/hyde.html



[Hydrogen Atom Simulator (NAAP)]

http://hyperphysics.phy-astr.gsu.edu/hbase/hyde.html

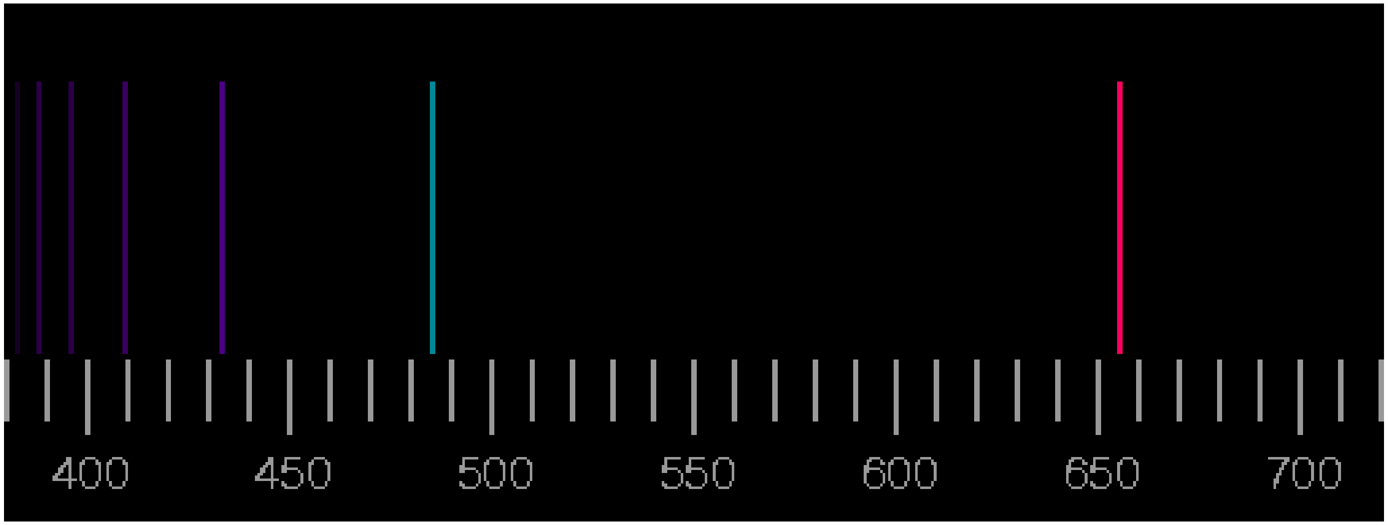


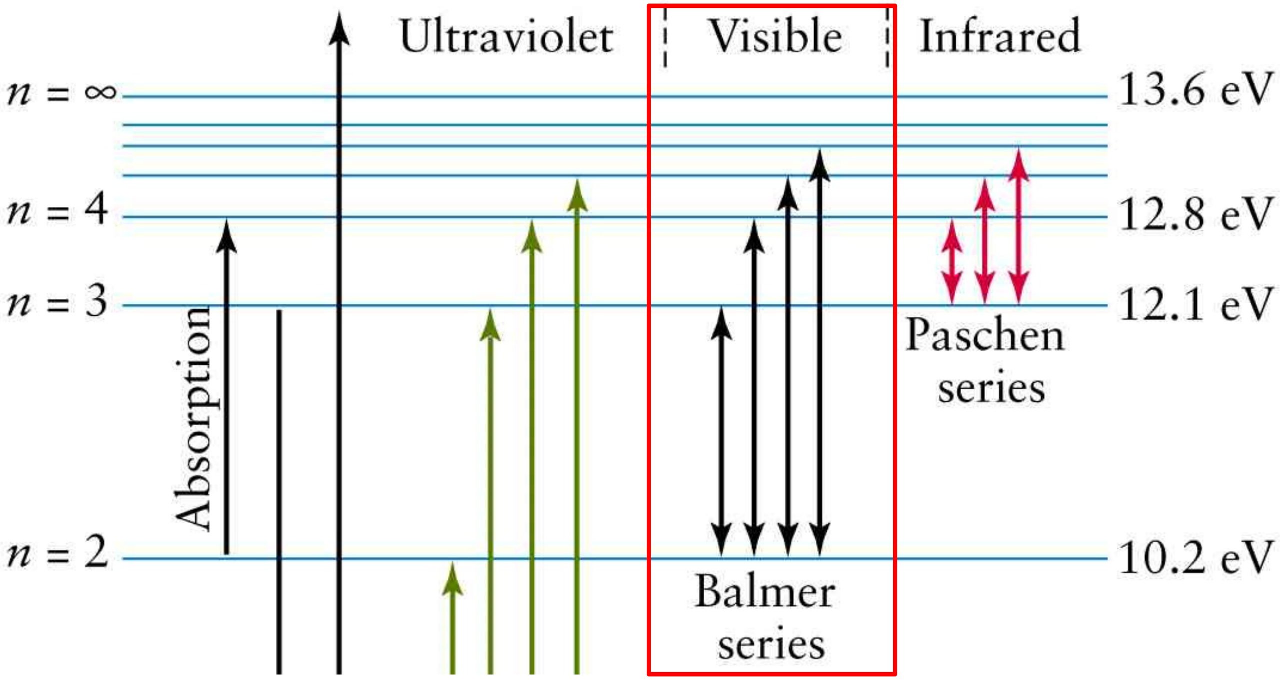
HYDROGEN ENERGY LEVELS

www.physast.uga.edu

Link: http://astro.unl.edu/classaction/animations/light/hydrogenatom.html

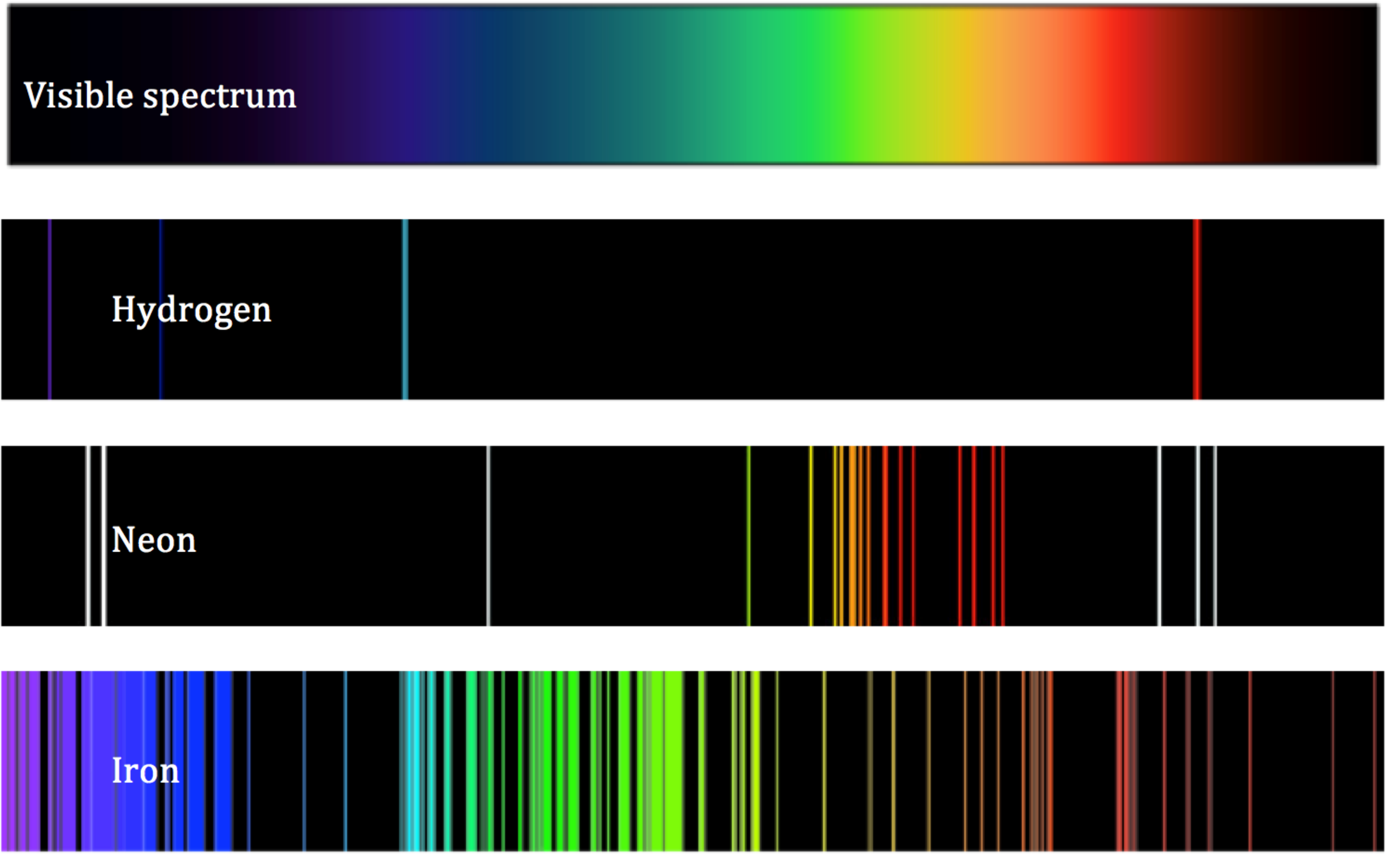
Visible part of the hydrogen spectrum





https://www.itp.uni-hannover.de/~zawischa/ITP/atoms.html

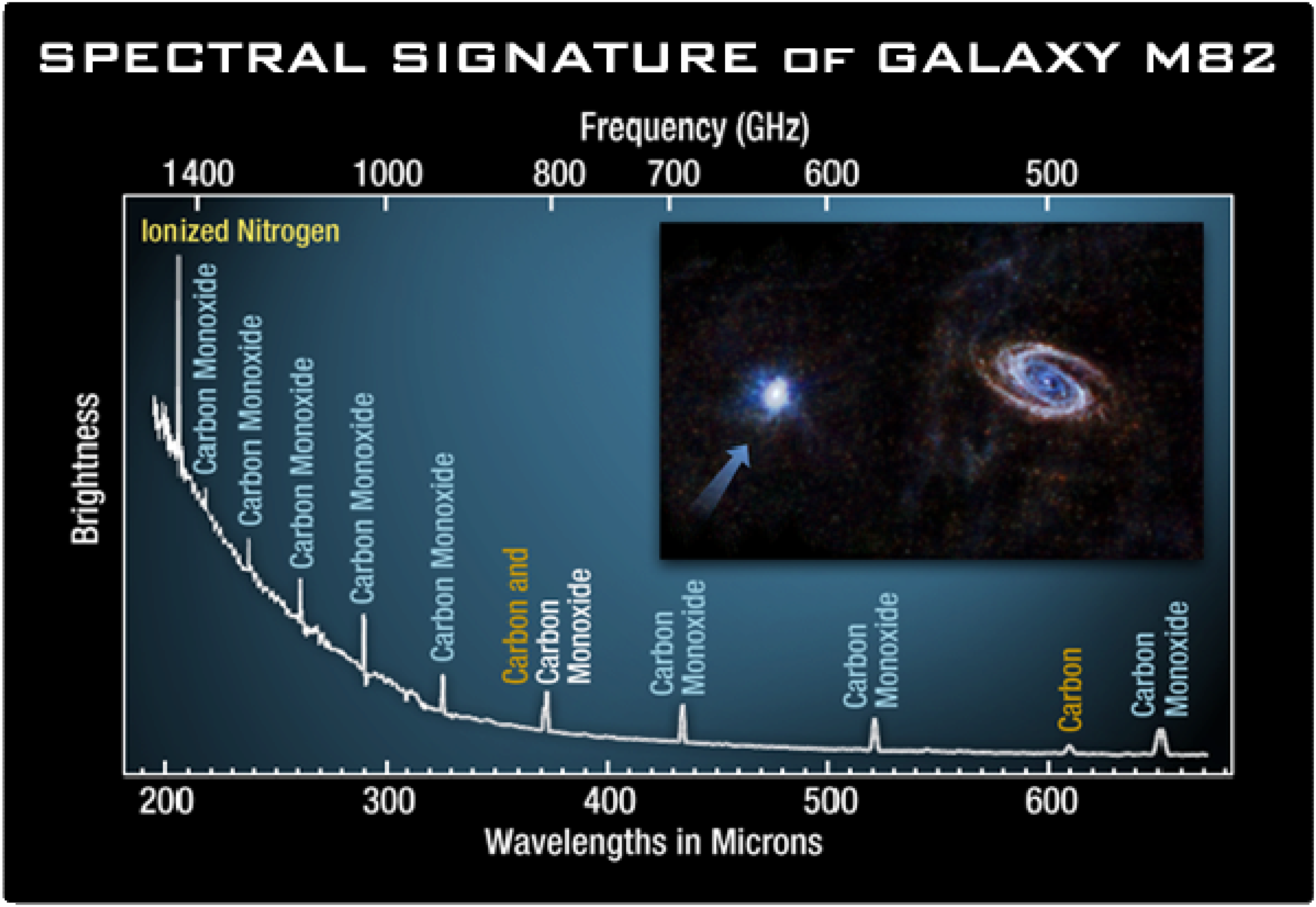
Spectra from different atoms



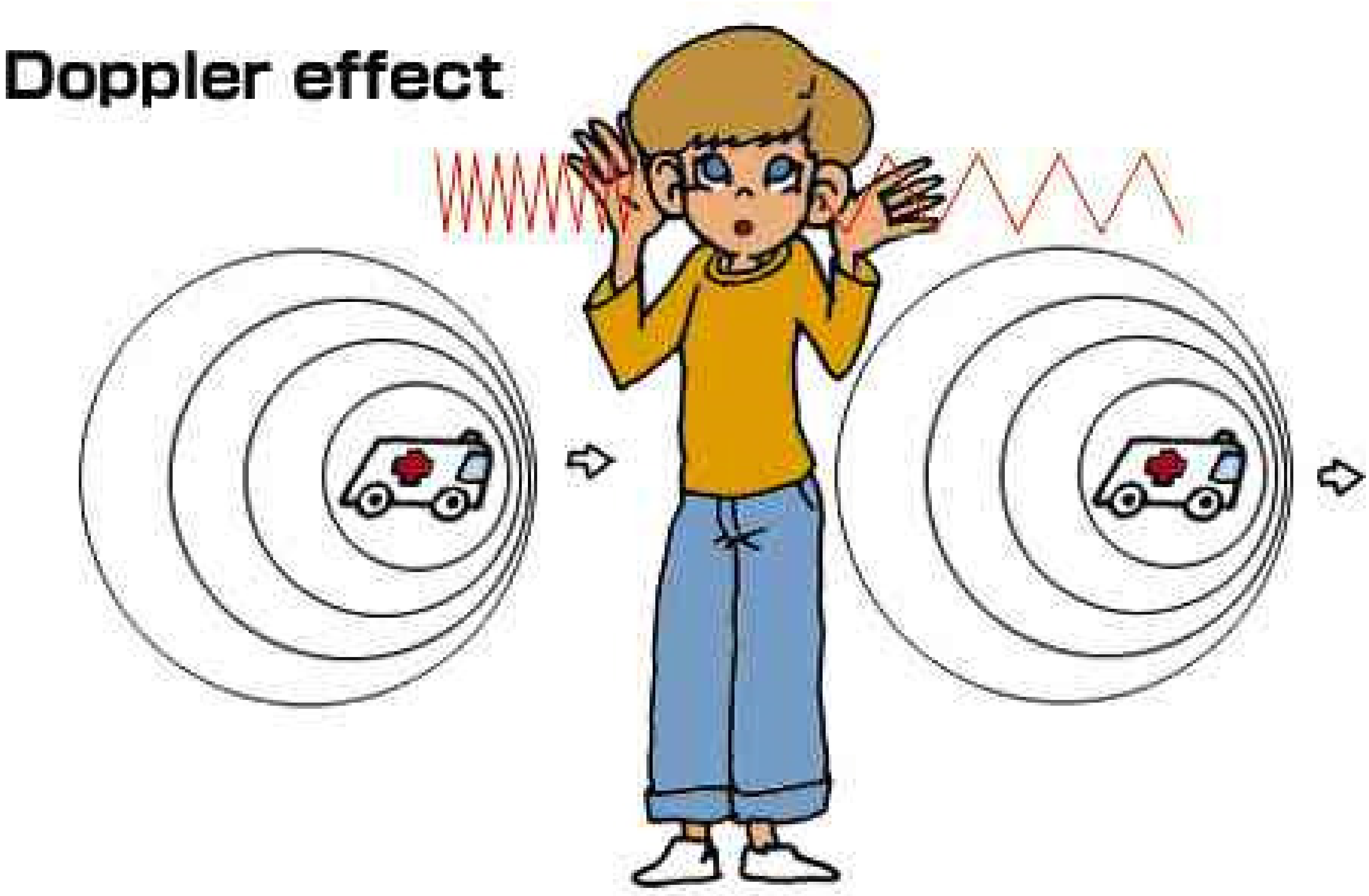
www.visionlearning.com

Link: Electromagnetic Spectrum Module

Link: How spectrographs work
Spectroscopy: Turning Light Into Data
http://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/08.html



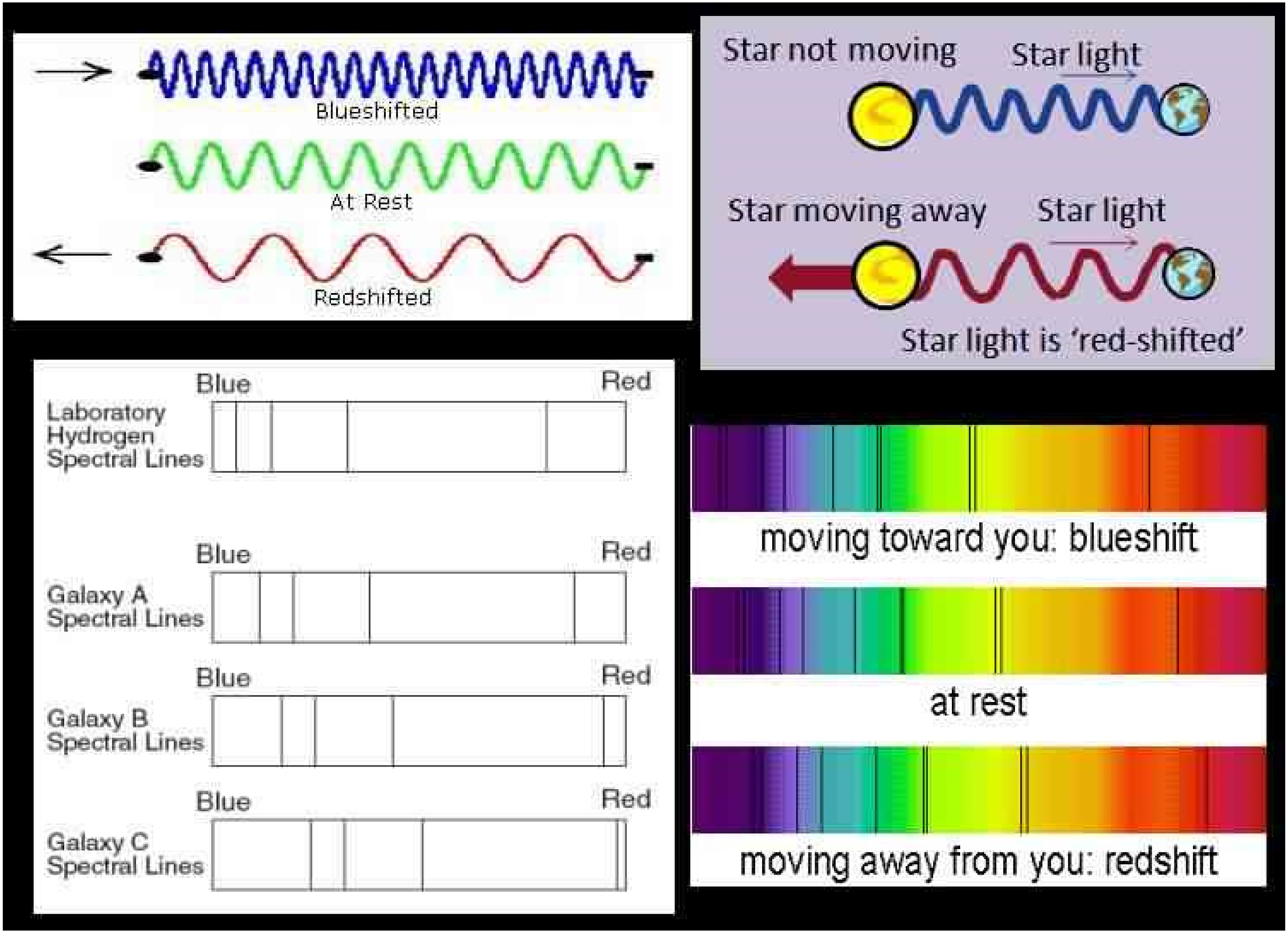
http://missionscience.nasa.gov/ems/03_behaviors.html



Link: Doppler Shift Demonstrator

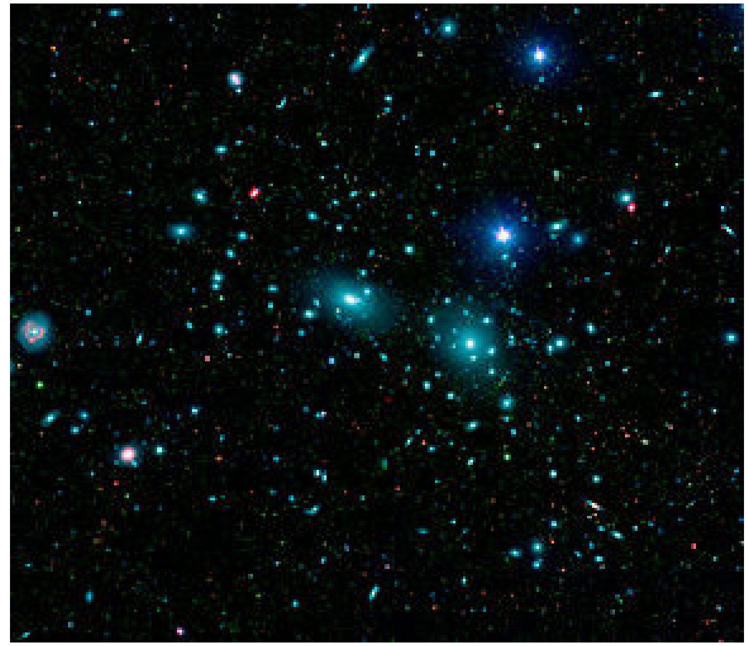
www.redorbit.com

Doppler effect: measure velocities from shift of spectral lines



Back to dark matter

Fritz Zwicky
California Institute of Technology



Coma Cluster: 1000 galaxies
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Dark matter

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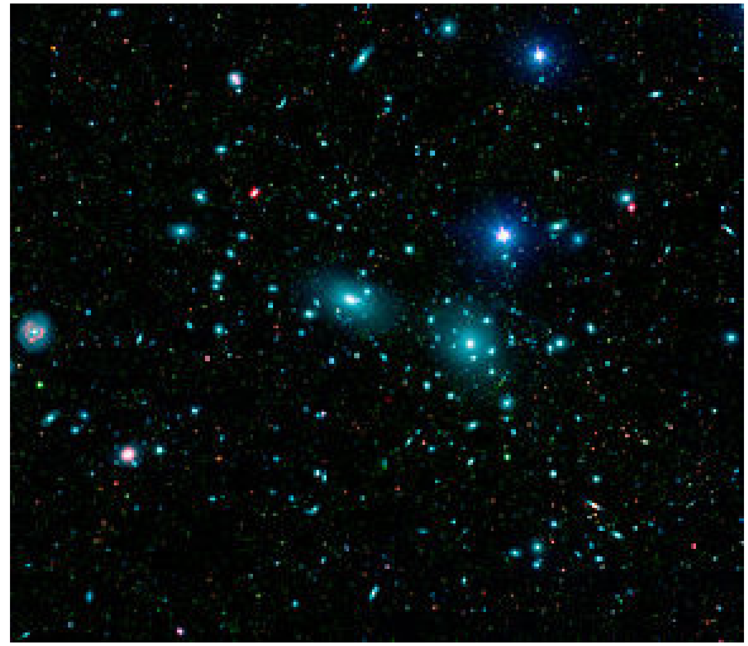
California Institute of Technology

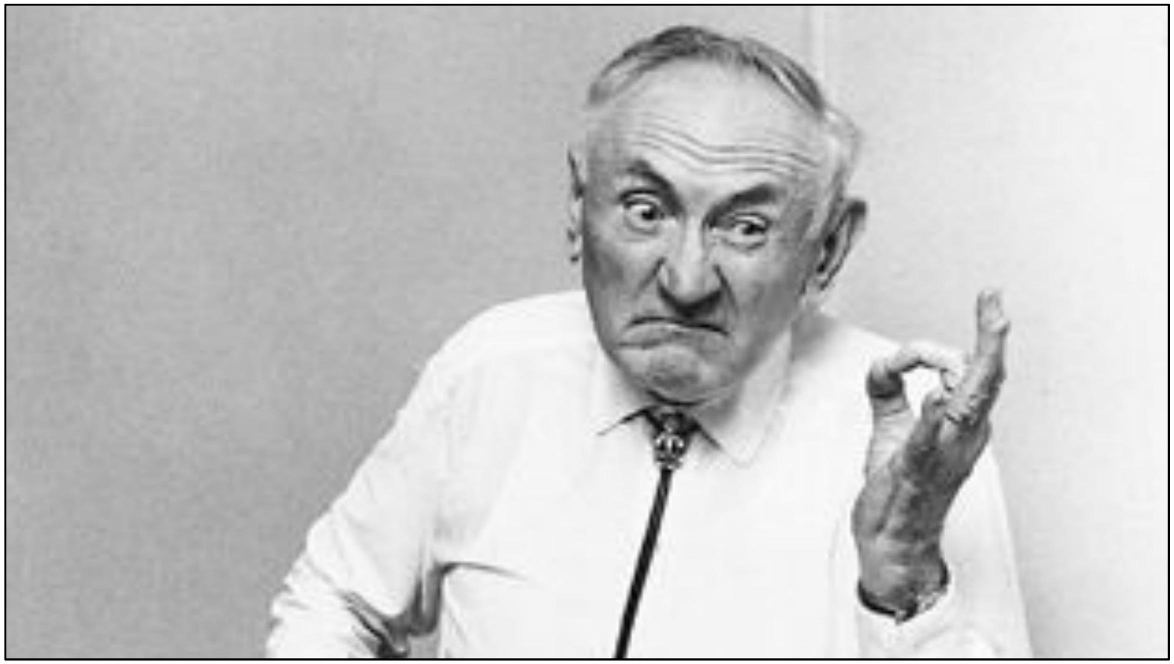


Coma Cluster: 1000 galaxies
321 million light years away

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.

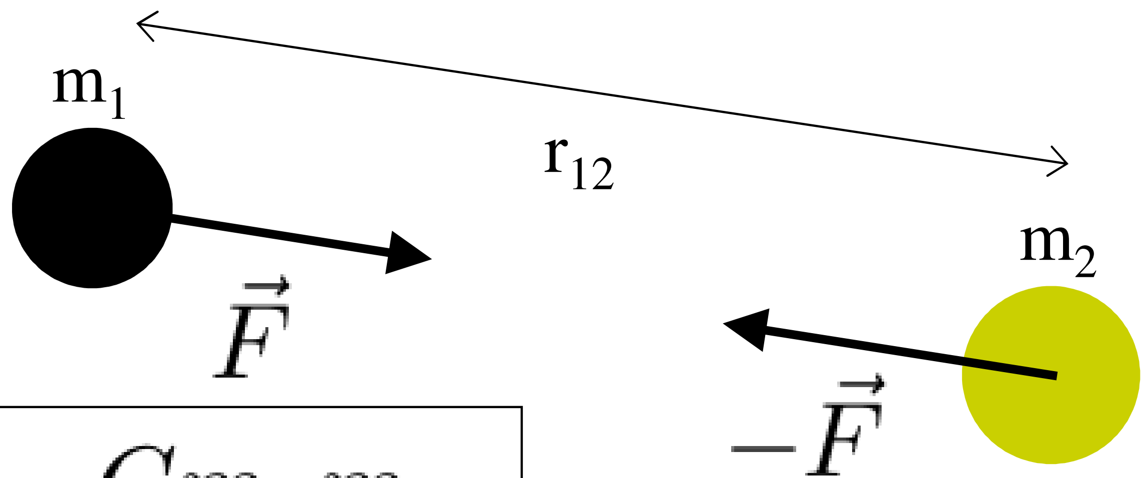
Half a century will pass before any serious considerations of dark matter …



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.



$$\left|\vec{F}\right| = \frac{G m_1 m_2}{r_{12}^2}$$

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.

http://www.hep.shef.ac.uk/cartwright/phy111/ppt/dark_matter_intro.ppt

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

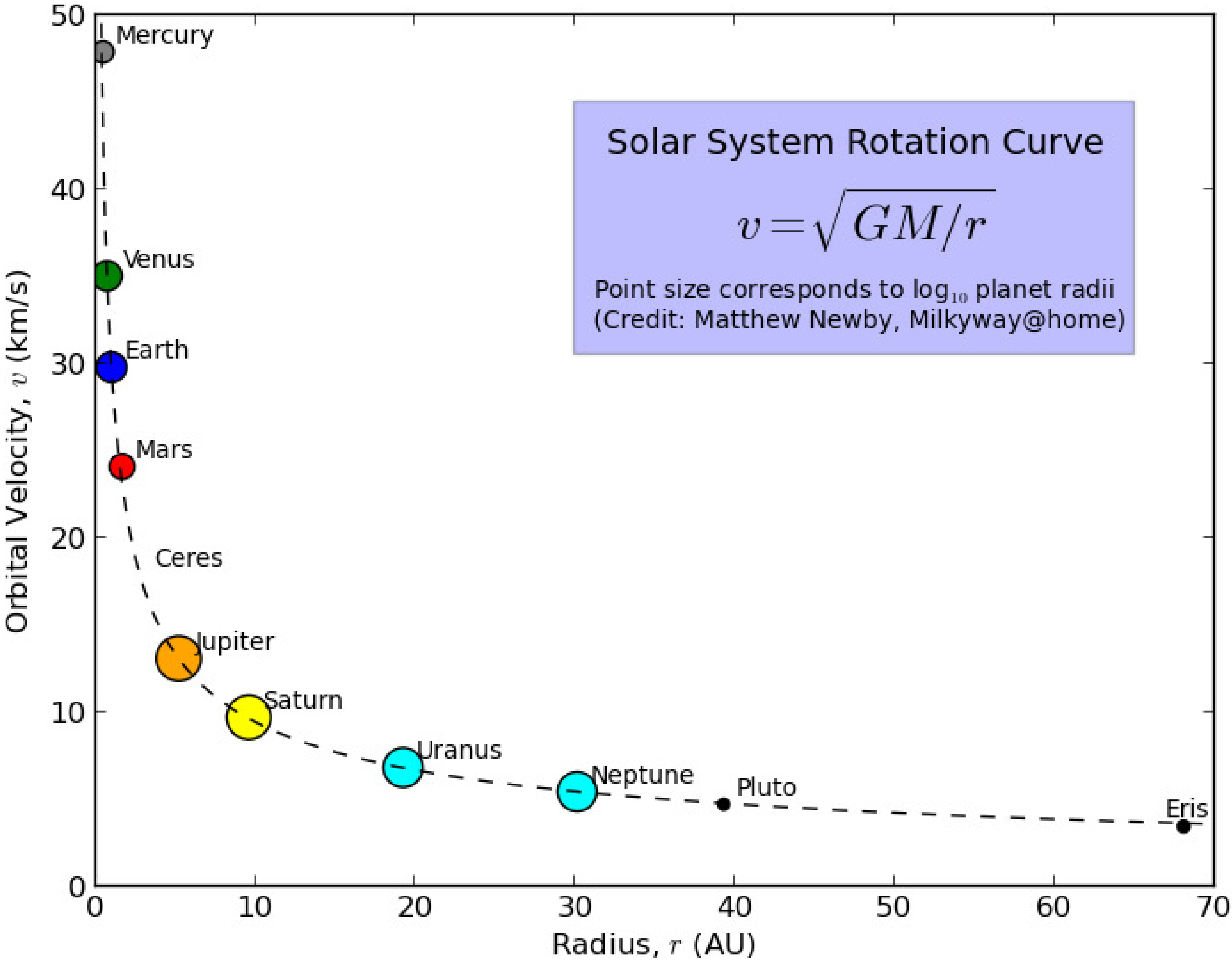
Vera Cooper Rubin at the Lowell Observatory.

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.

https://www.learner.org/courses/physics/unit/text.html?unit=10&secNum=2



milkyway.cs.rpi.edu

Galaxies Rotate

Galaxies are collections of billions of stars.

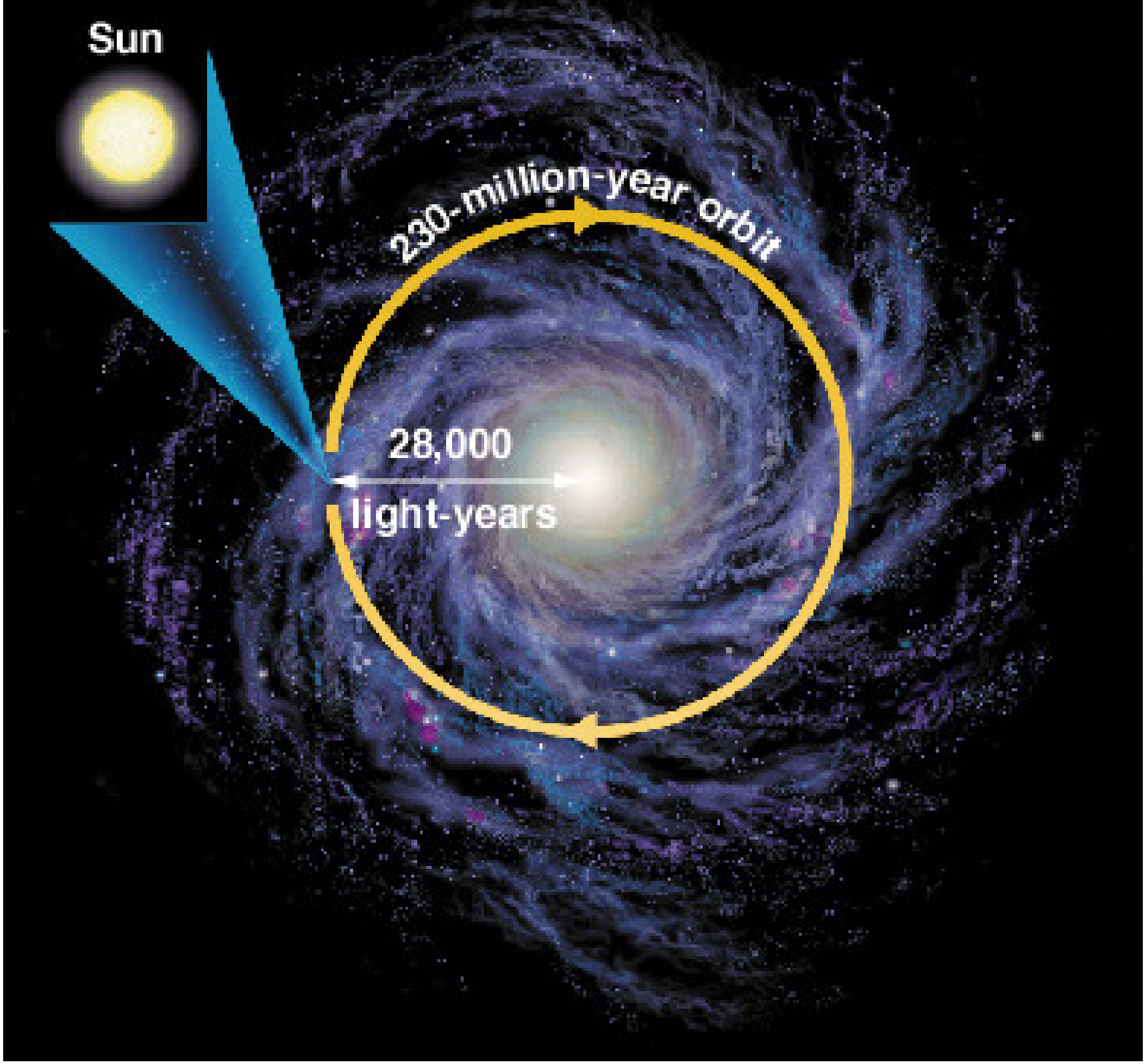
Most of the light from a galaxy comes from its center.

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.

http://www.haystack.mit.edu/edu/pcr/Astrochemistry/3 - MATTER/Dark Matter.ppt

Our galaxy



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

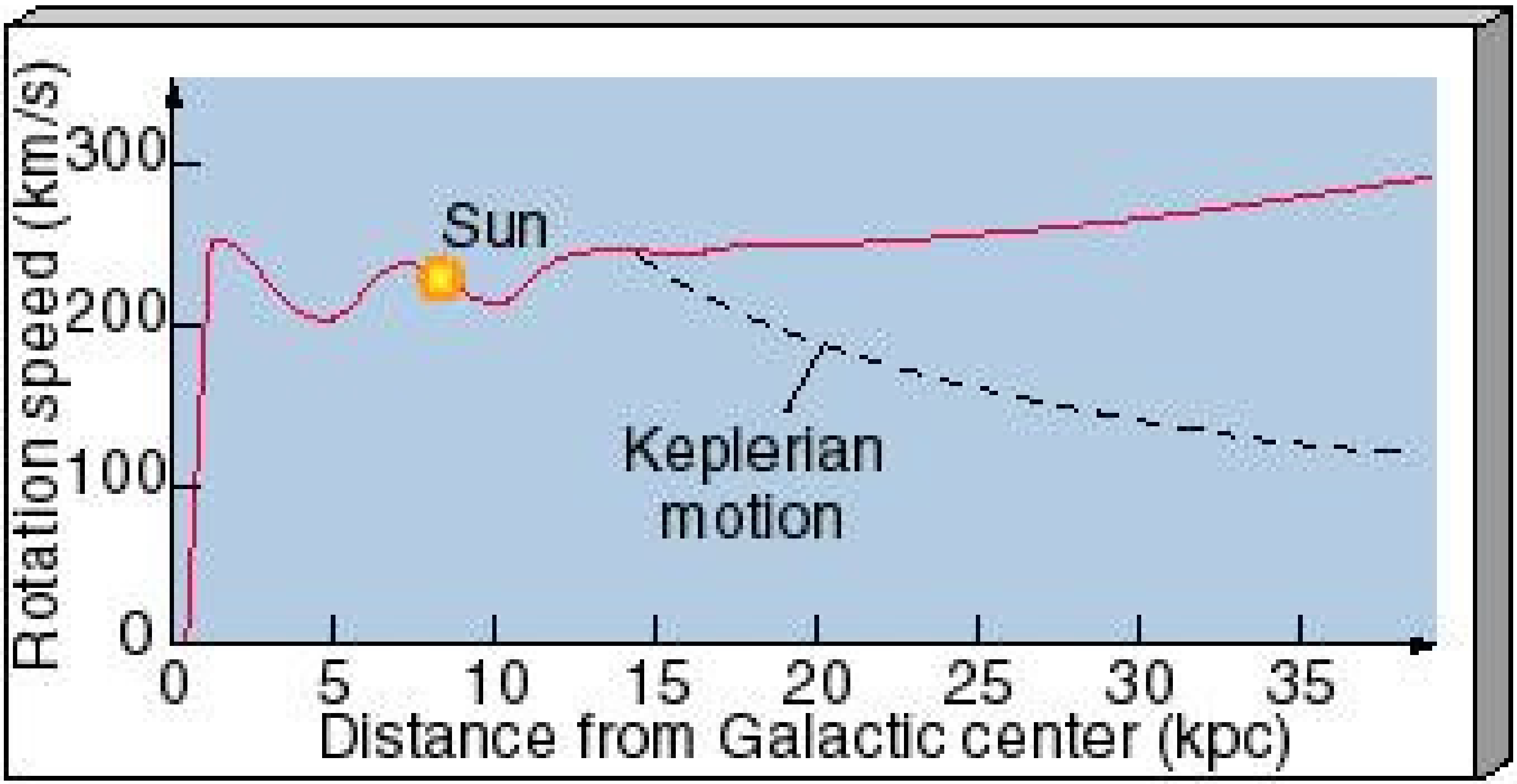
$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

http://www.hep.shef.ac.uk/cartwright/phy111/ppt/dark_matter_intro.ppt

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.



http://www.haystack.mit.edu/edu/pcr/Astrochemistry/3 - MATTER/Dark Matter.ppt

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

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

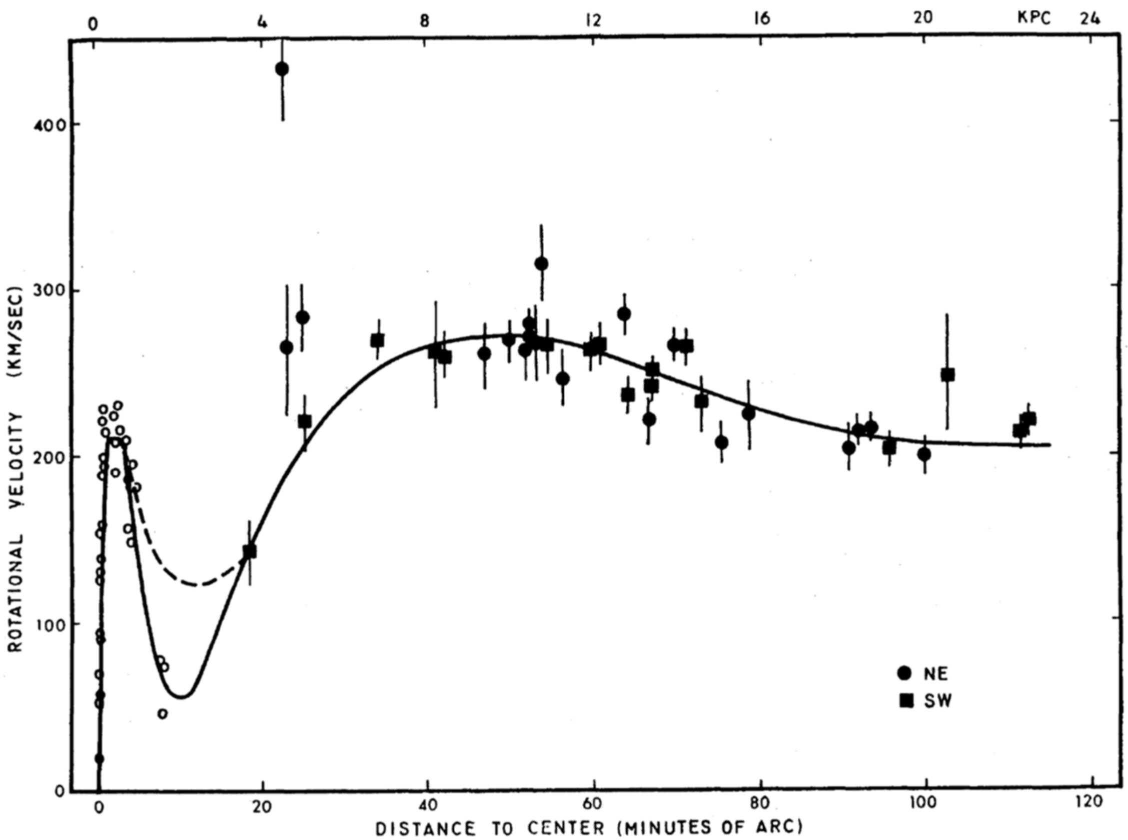
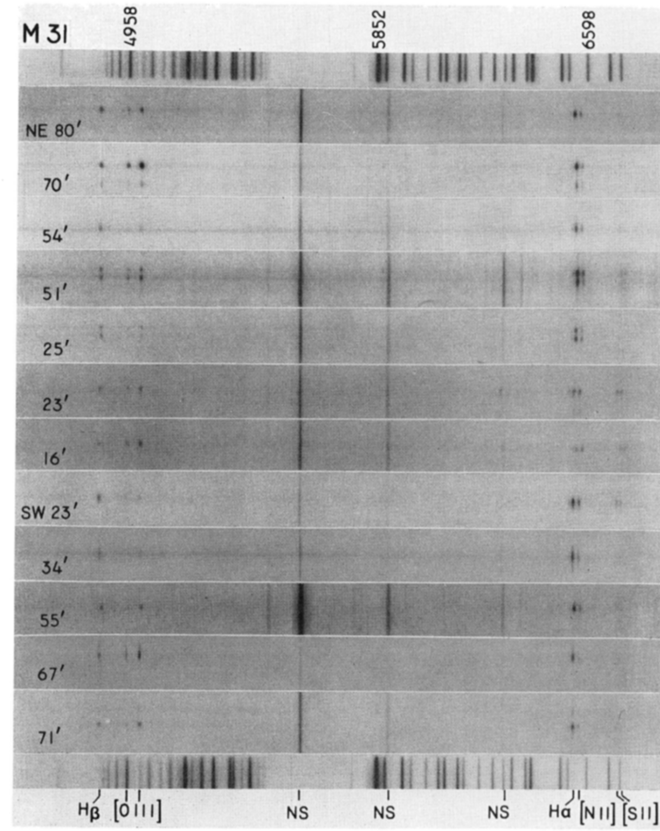
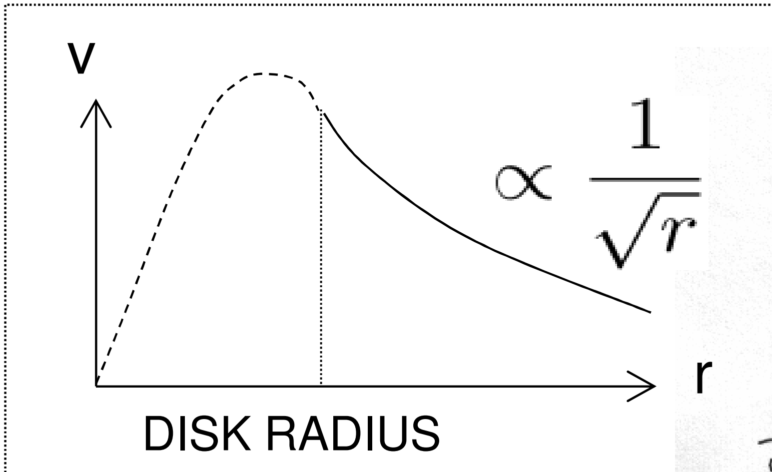


PLATE 2

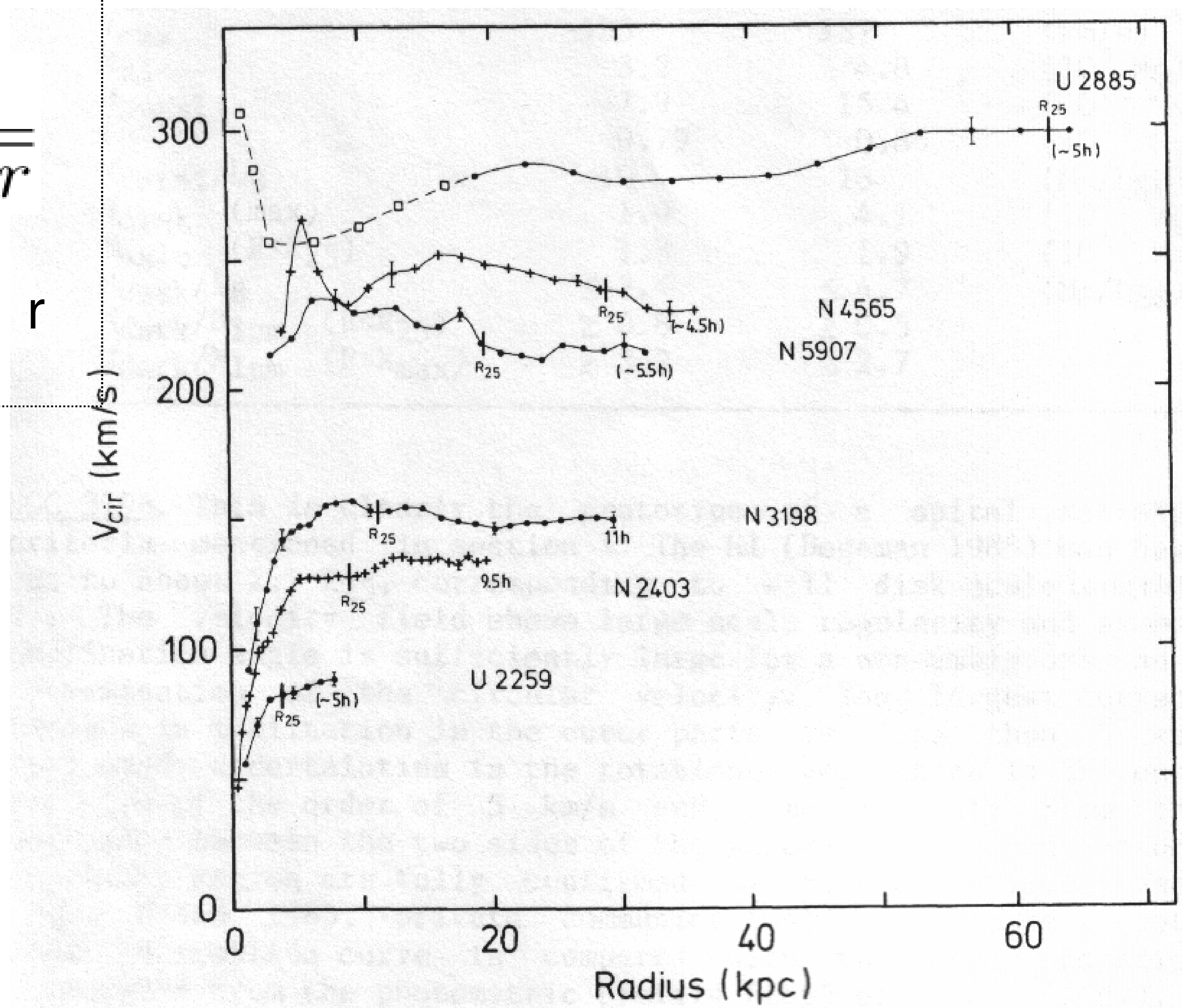


Galactic rotation curves

This is what we expect....

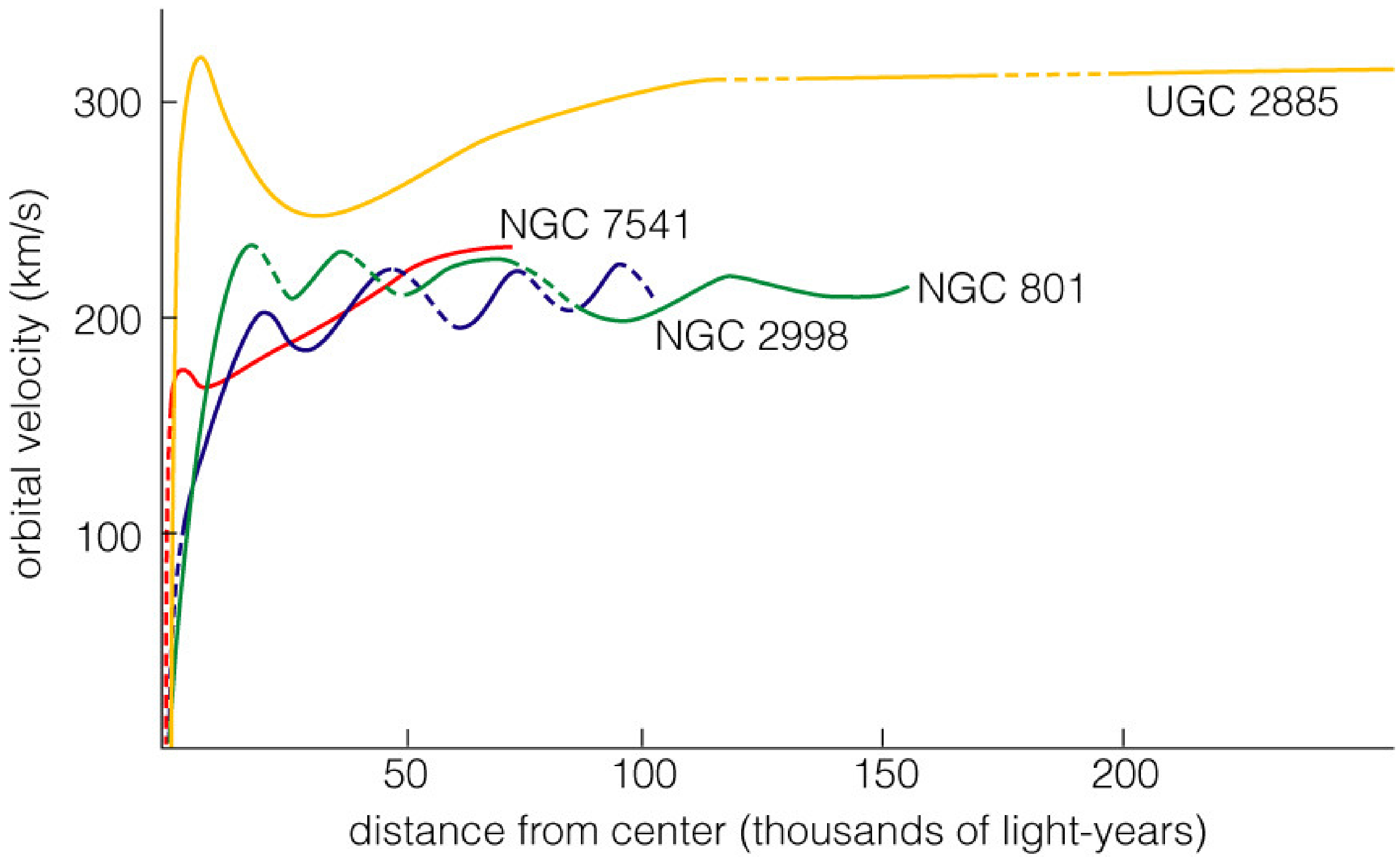


...but here are some typical results



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

http://www.hep.shef.ac.uk/cartwright/phy111/ppt/dark_matter_intro.ppt



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

• **Milky Way Rotational Velocity**

http://www.sjsu.edu/people/monika.kress/courses/sci255/

Possible Interpretations

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

WHAT MATTER?
Faint stars ? Planets ? Rocks ? Gas ? Dust ?
Exotic Particles ?

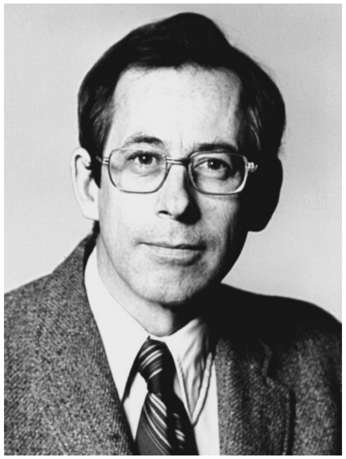
Need about 10 times as much dark matter as visible matter to explain the rotation curve discrepancy !

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

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

http://www.hep.shef.ac.uk/cartwright/phy111/ppt/dark_matter_intro.ppt

1973: Further evidence for dark matter
Problem with galactic simulations



James Peebles

Jeremiah Ostriker

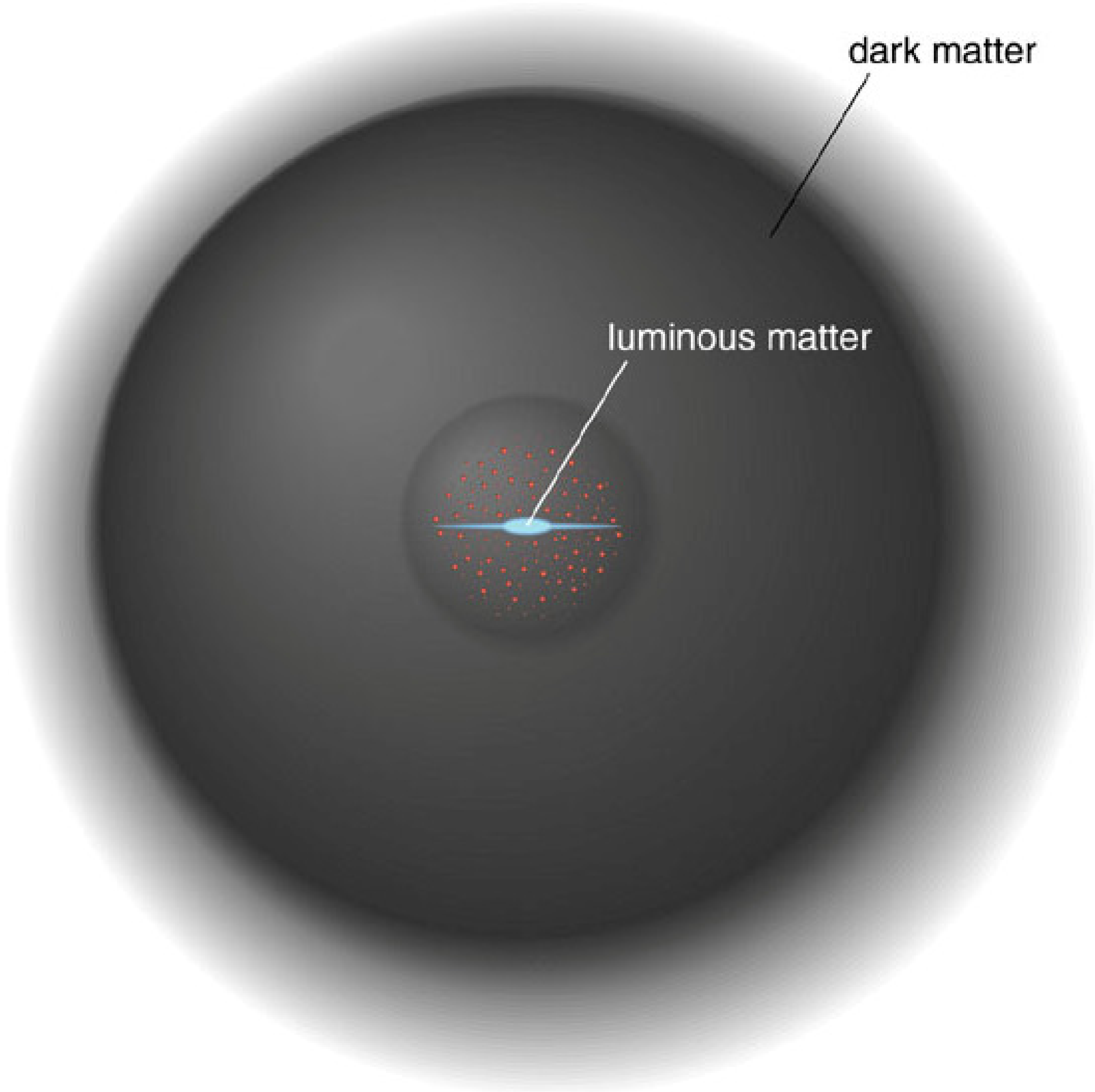
Princeton University

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.

https://www.learner.org/courses/physics/unit/text.html?unit=10&secNum=2



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

http://www.sjsu.edu/people/monika.kress/courses/sci255/

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

http://www.haystack.mit.edu/edu/pcr/Astrochemistry/3 - MATTER/Dark Matter.ppt

The story of gravitational lensing

1704: Isaac Newton published “Opticks”

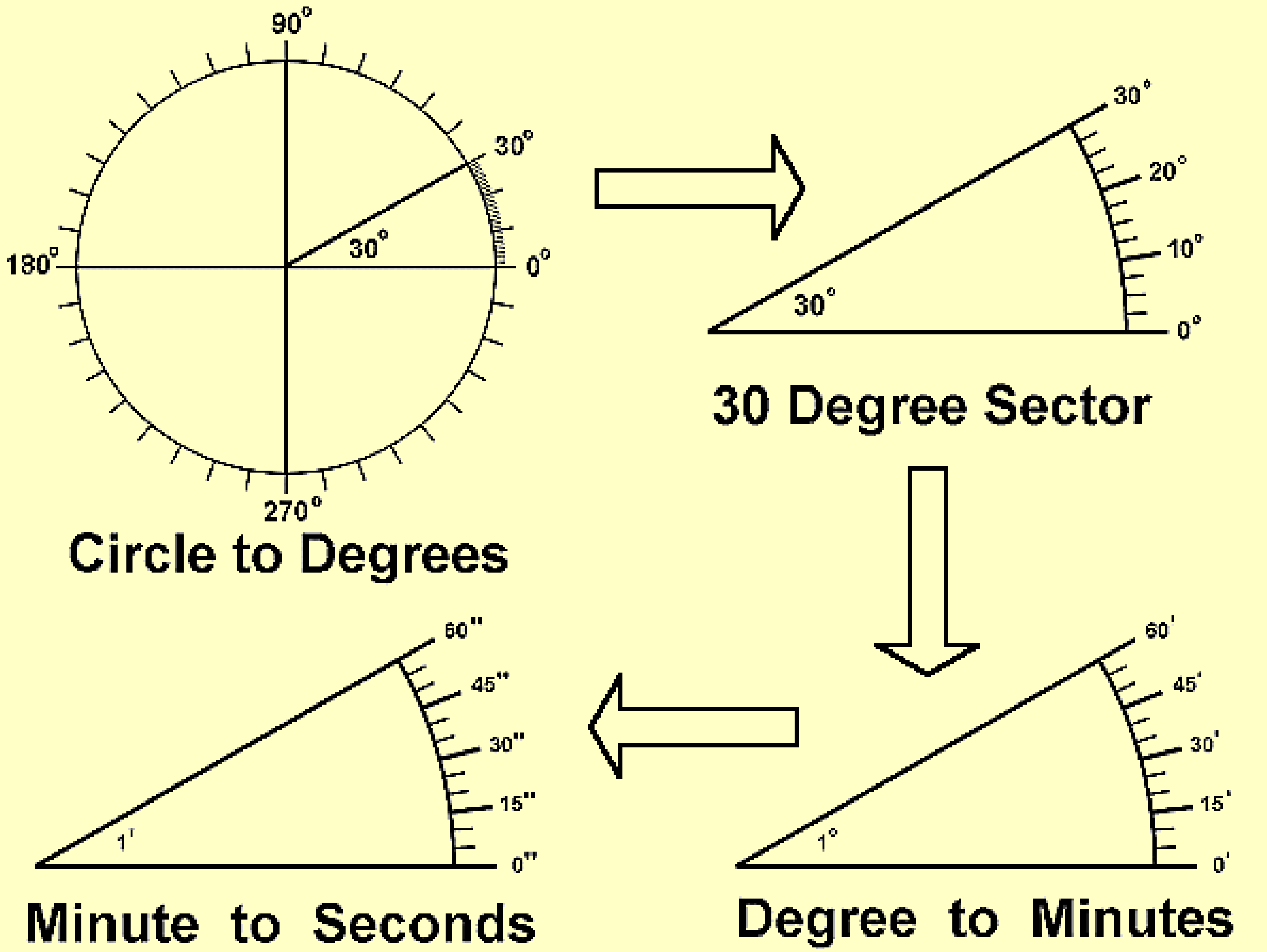
Query:
Do not Bodies act upon Light at a distance and by their action bend its Rays?

Lets rephrase:

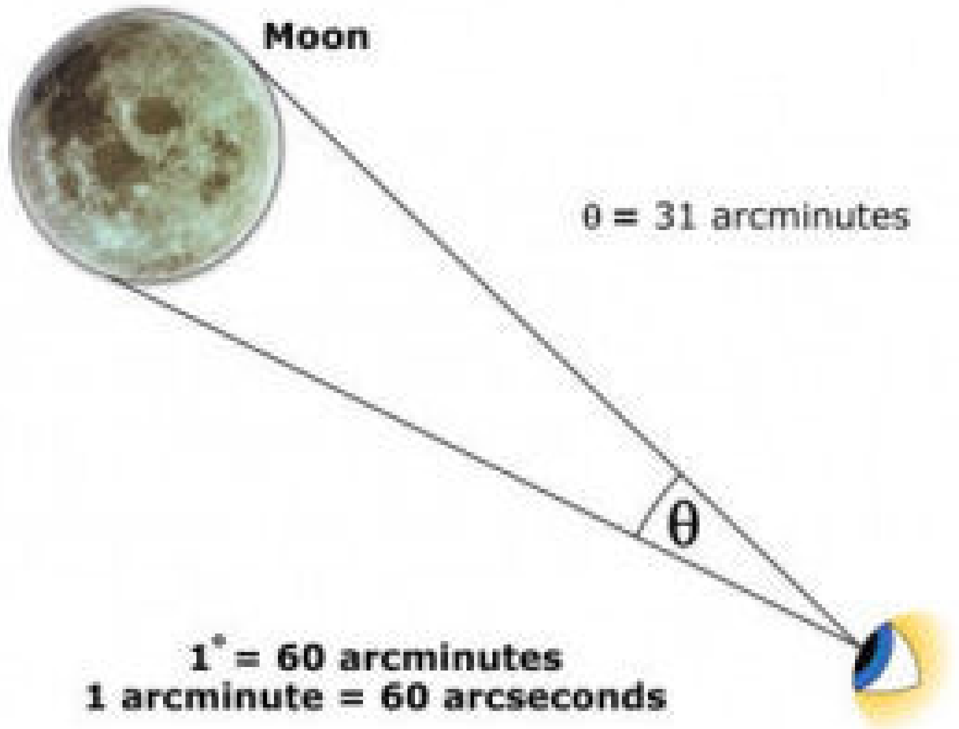
How large is the angle α of bending for the light of distant star passing near the surface of the sun?

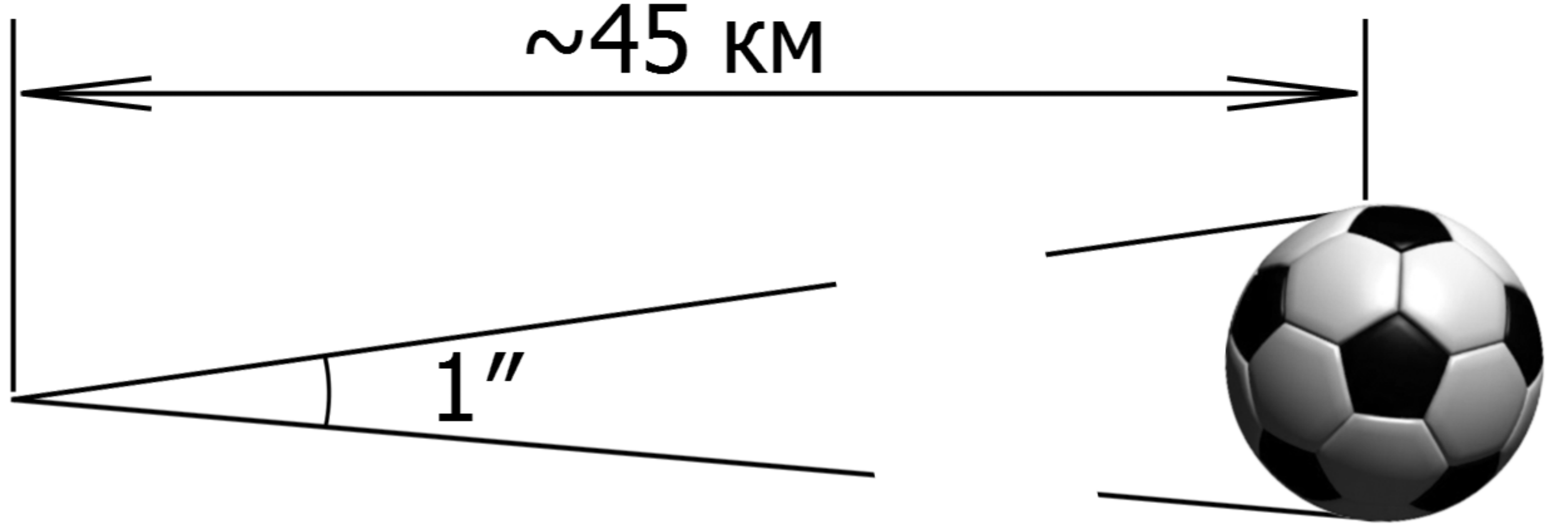
A. 0 (classical physics, light is a wave with no mass)
B. $\alpha = 0.87''$ [**arcsecond**] (classical physics, light consists from particles with mass, angle of deflections depends only on velocity)
C. $\alpha = 1.75''$ (General relativity, no assumptions aabout the nature of light)

The harvest of the century, Siegmund Brandt

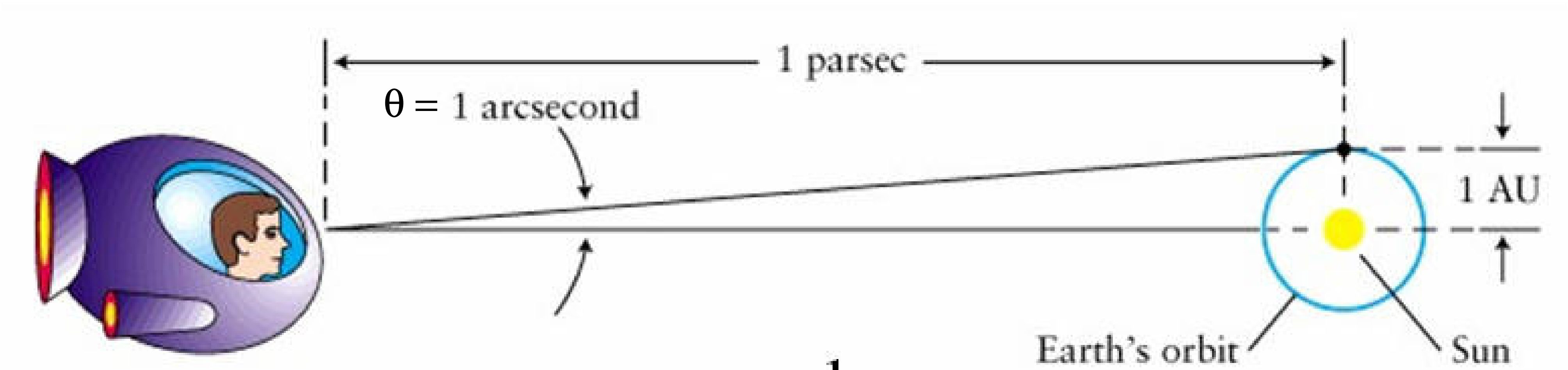


Angle Units Relationships





www.fortworthastro.com



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

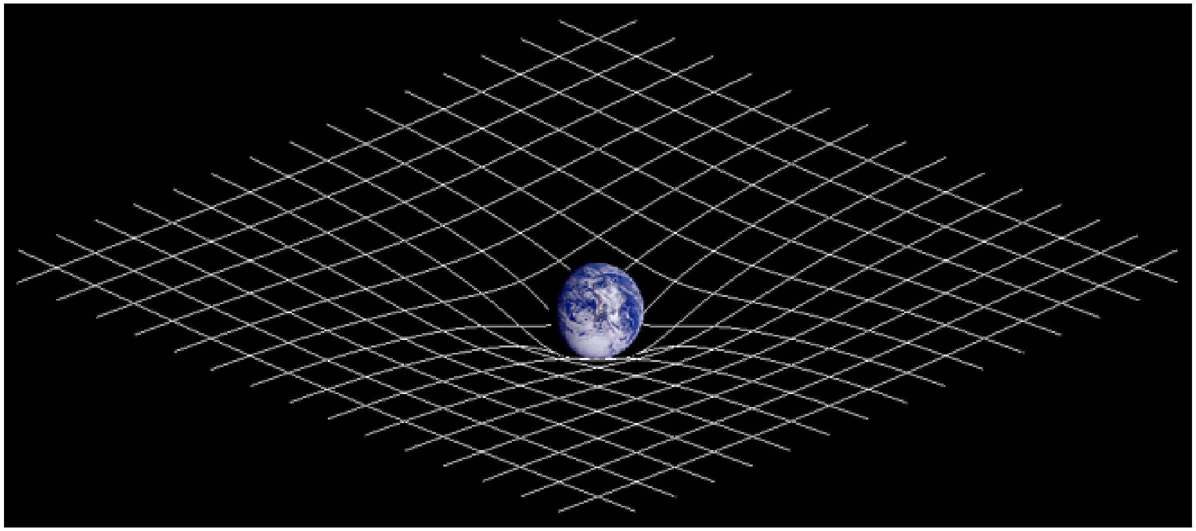
d is in parsecs when ***p*** is in arcseconds

1 parsec = 3.26 light-years

https://people.highline.edu/iglozman/classes/astronotes/astrometry.htm

Key ideas of general relativity

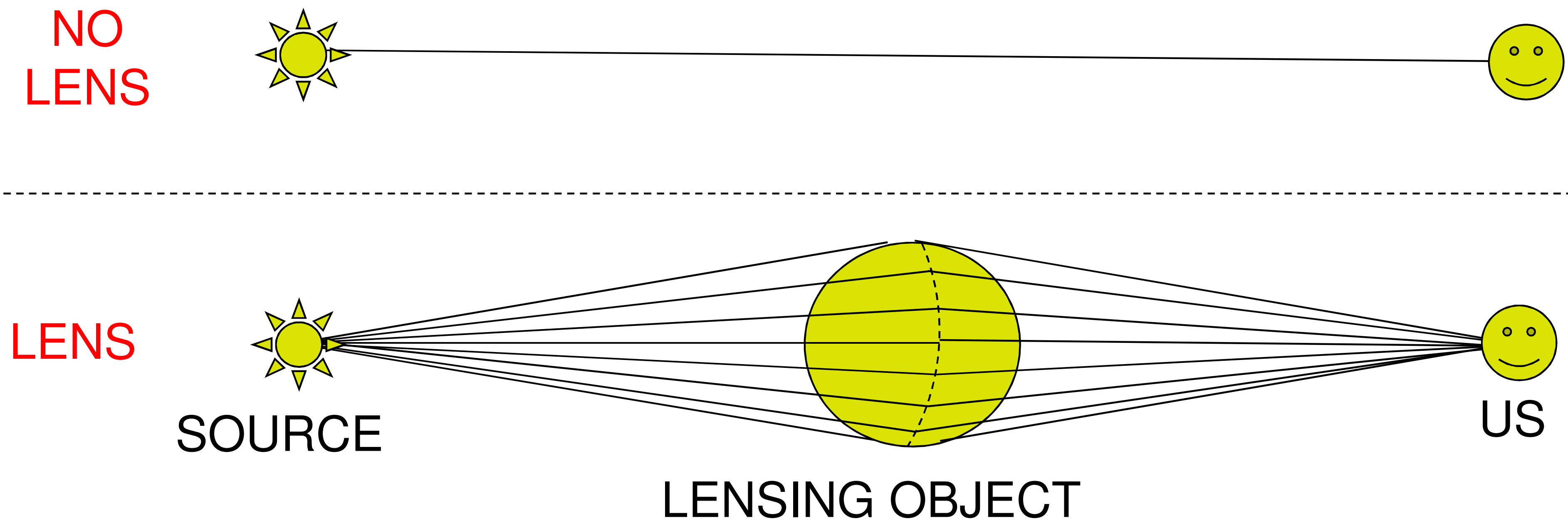
- Mass and energy warp spacetime.
- Objects move around in the wrapped spacetime along the "shortest path".
- The shortest path in a curved space in no longer a straight line.
- Light always moves along this shortest path, and thus light travels through space along curved path.



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



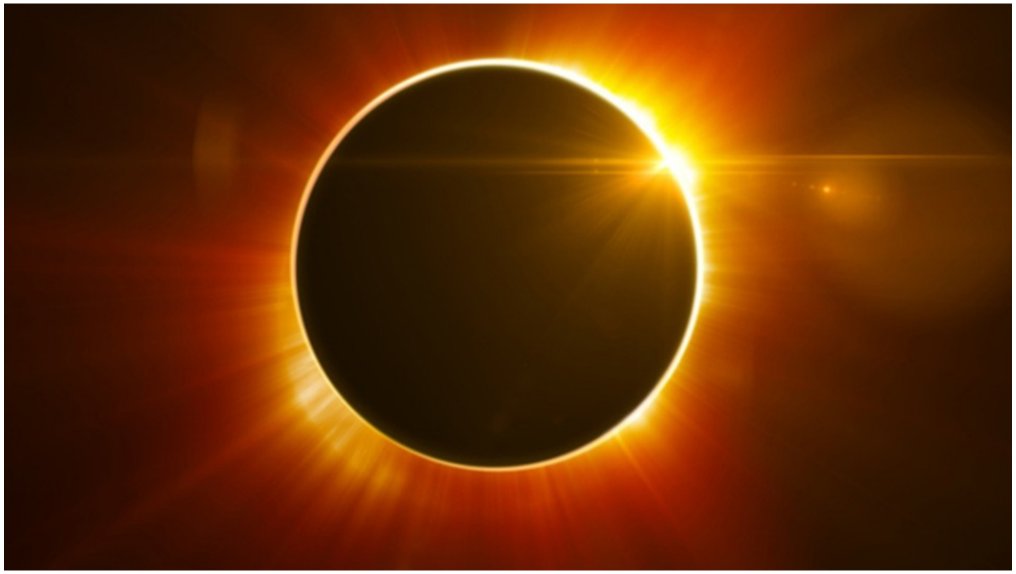
Strong or close lens, expect a ring of light, or a ring of images in the presence of the lens.

When not resolved, expect increased intensity.

http://www.hep.shef.ac.uk/cartwright/phy111/ppt/dark_matter_intro.ppt

Sun, star light, and the general relativity

Erwin Finlay Freundlich



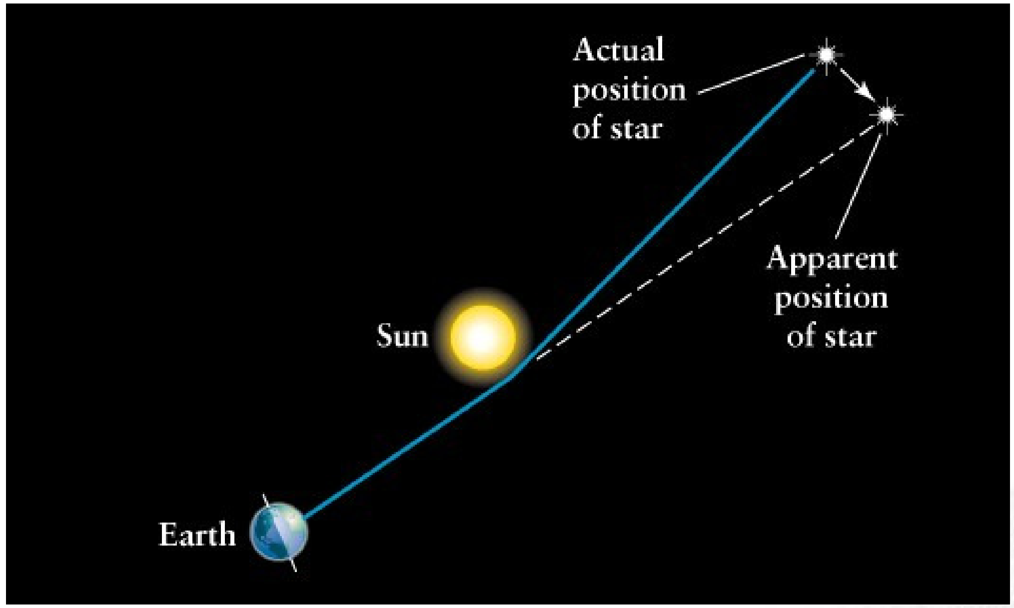
Freundlich was interested in measuring the deflection in a light ray passing close to the sun to test then incomplete Einstein's theory of relativity. The only way to make such measurements at this time was during an eclipse and Freundlich got funding to travel to Crimea in 1914.

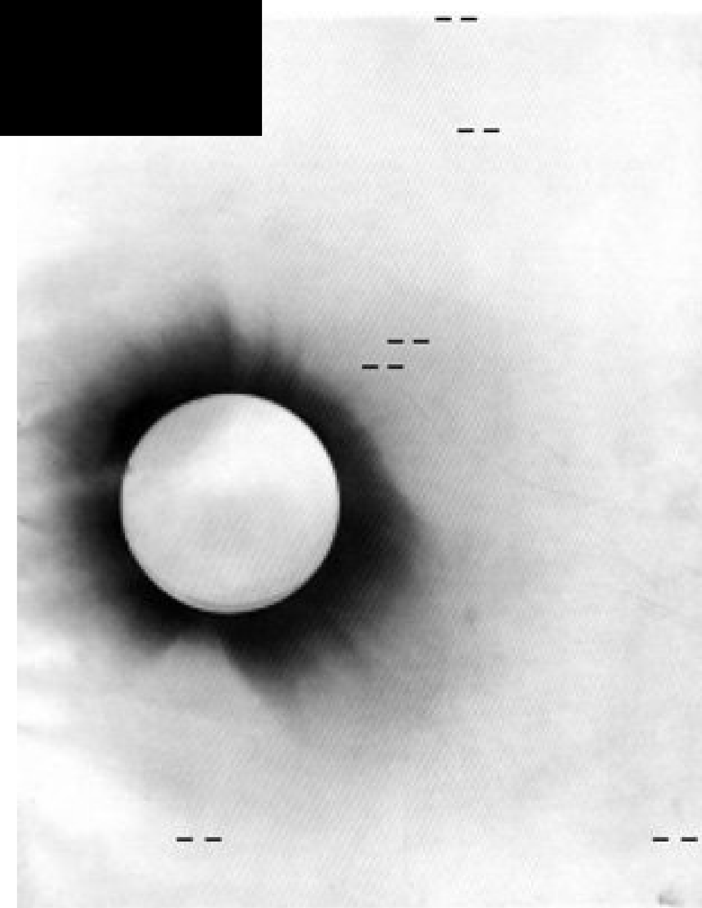
World War I broke out before the time for the eclipse and the expedition was abandoned. Freundlich was interned for a while before being able to return to Berlin.

https://bpsfuelforthought.wordpress.com/2015/03/20/solar-eclipse/

1919 solar eclipse: test of general relativity

Arthur Stanley Eddington



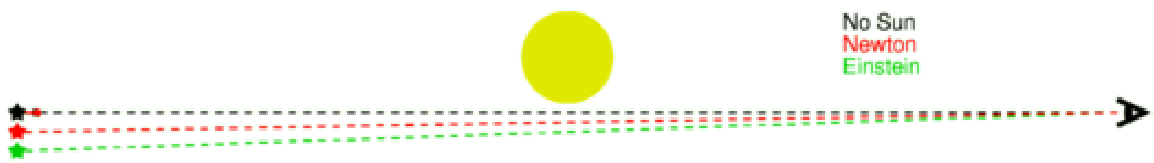


Compare positions of the star near the sun during eclipse with positions of the same stars at other times.

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

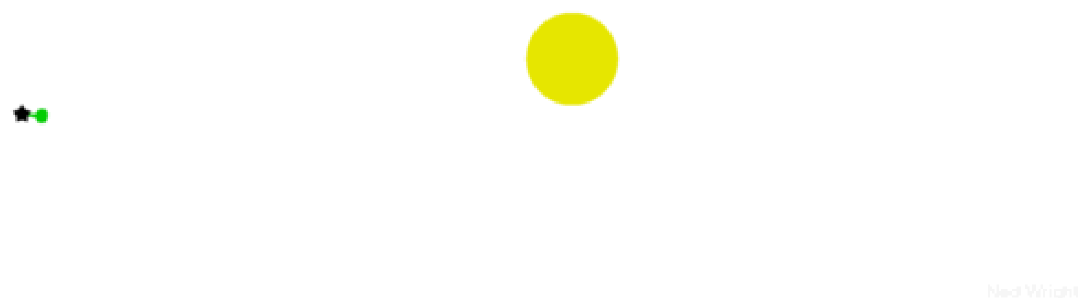
frigg.physastro.mnsu.edu
http://www.esa.int/spaceinimages/Images/2003/06/Negative_photo_of_the_1919_solar_eclipse

Animation by Edward L. Wright



http://www.astro.ucla.edu/~wright/deflection-delay.html

Animation by Edward L. Wright



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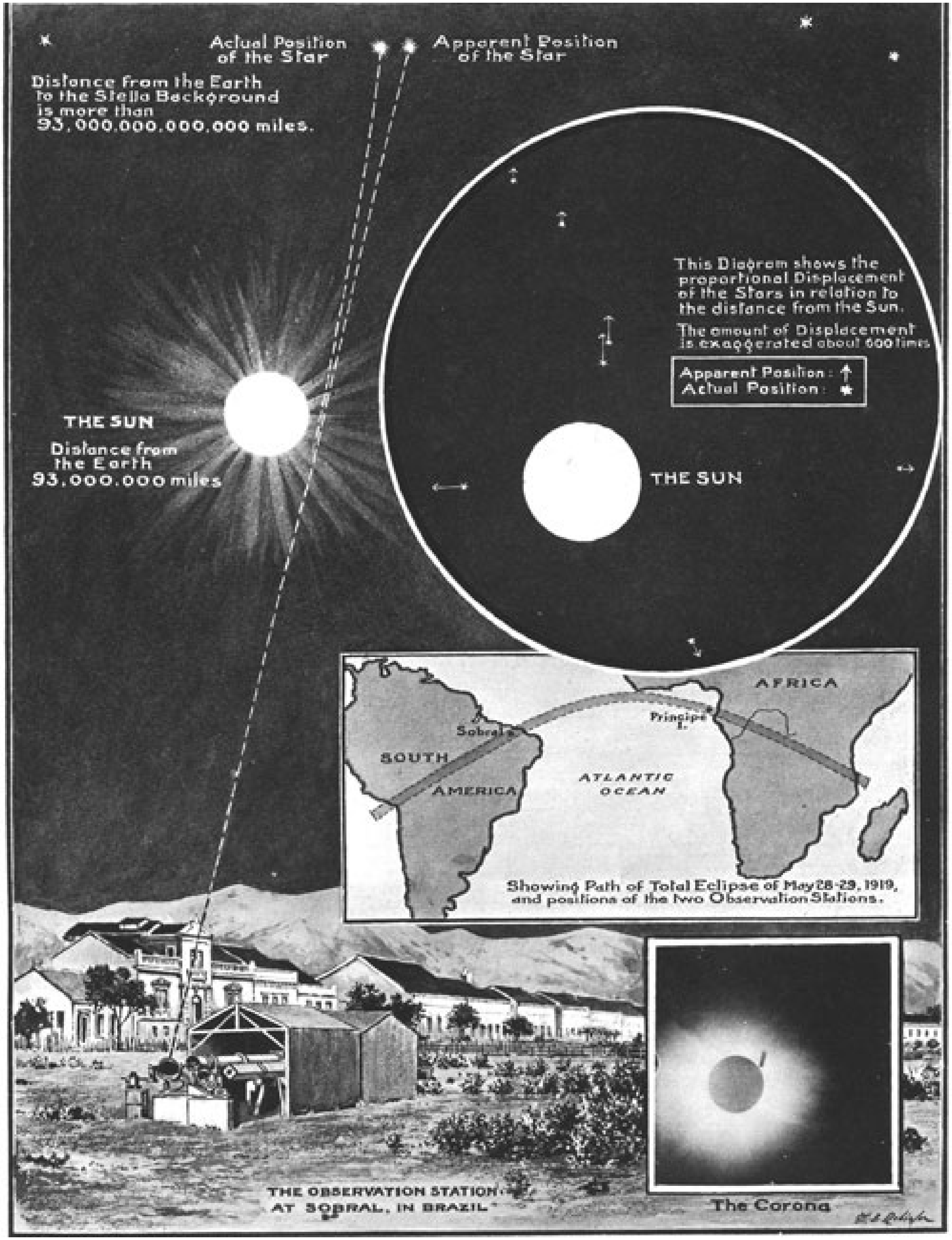
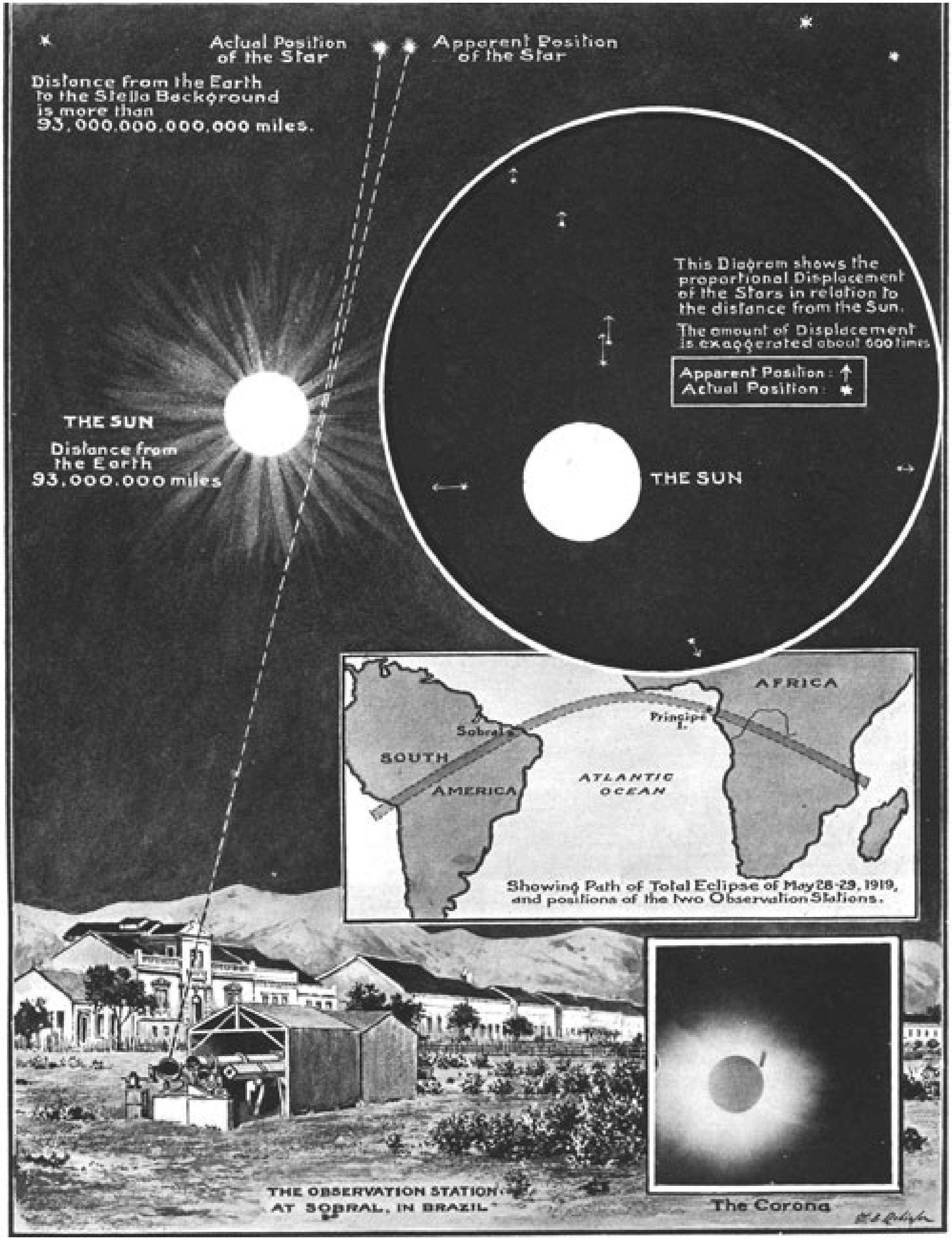


22 November 1919 edition of the Illustrated London News.

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.

NASA/AP Photo, ESA/Hubble & NASA - http://www.spacetelescope.org/images/potw1403a/

1979: Twin quasar – First identified gravitationally lensed object

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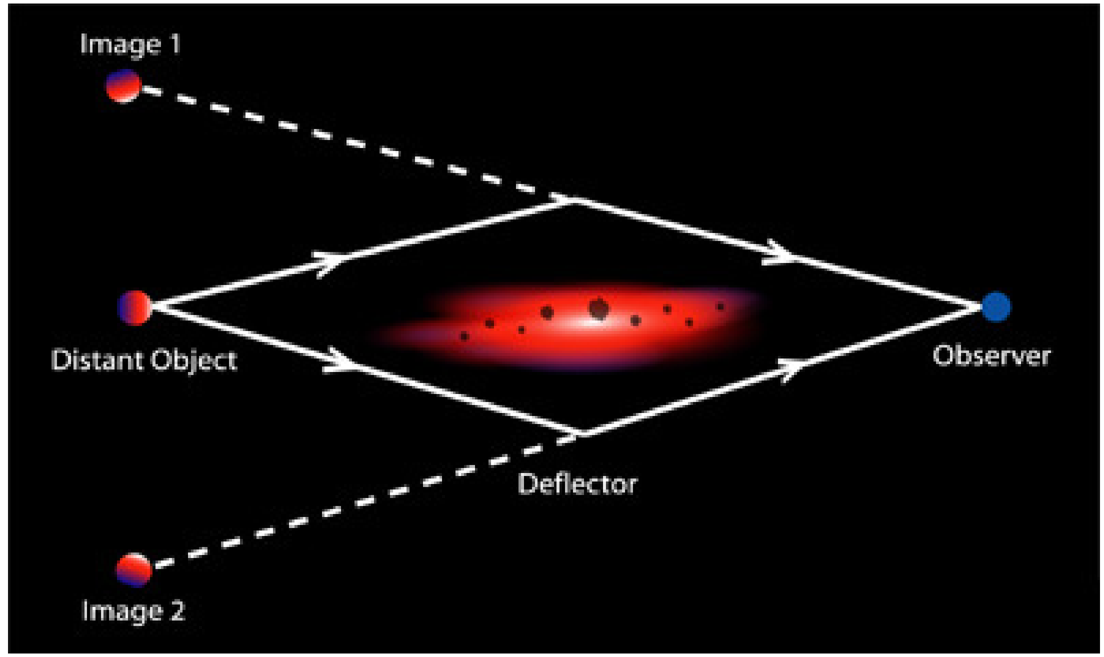
NASA/AP Photo, ESA/Hubble & NASA - http://www.spacetelescope.org/images/potw1403a/

Gravitational Lensing

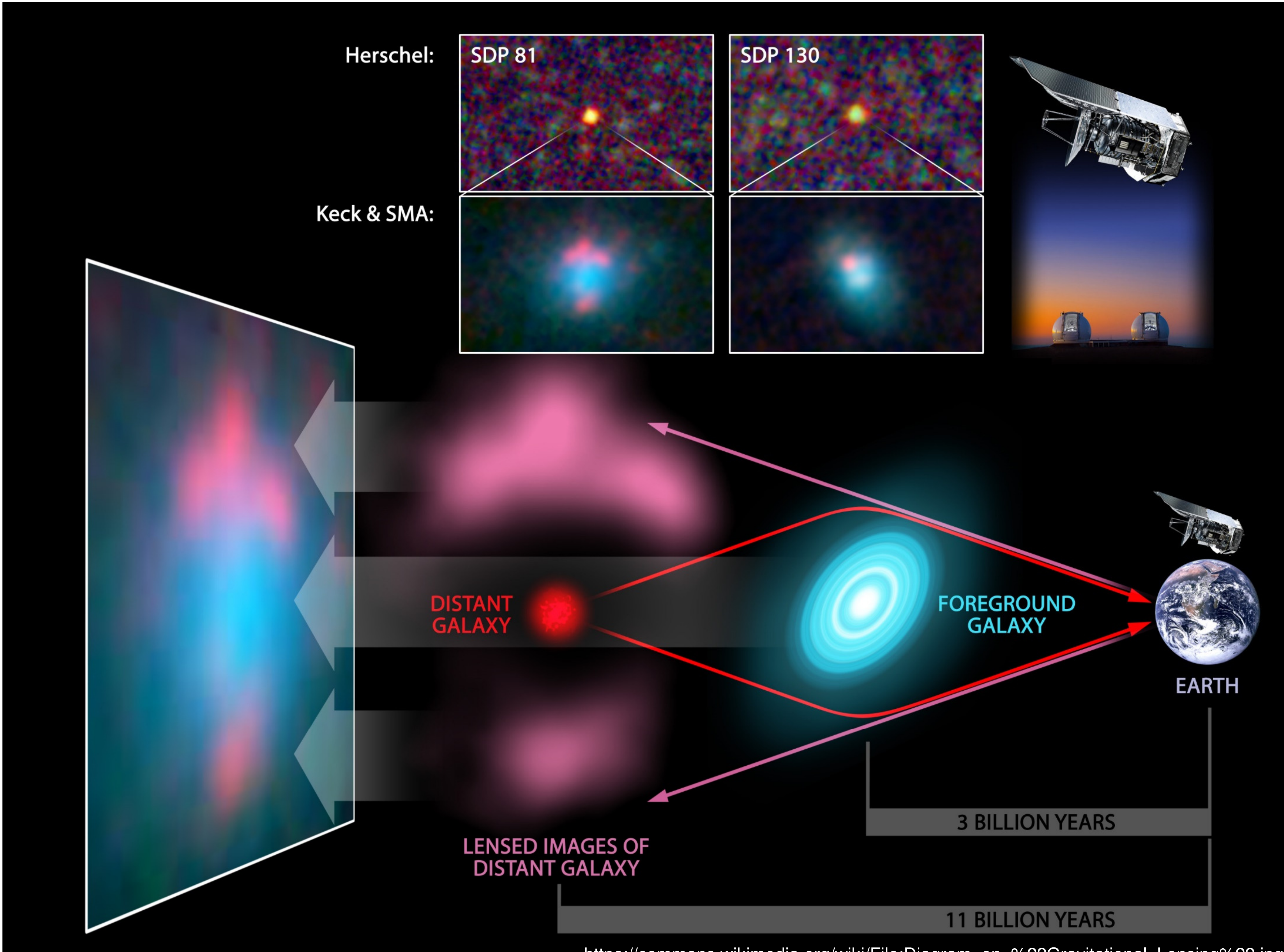
The images of the galaxies were stretched out due to gravity.

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

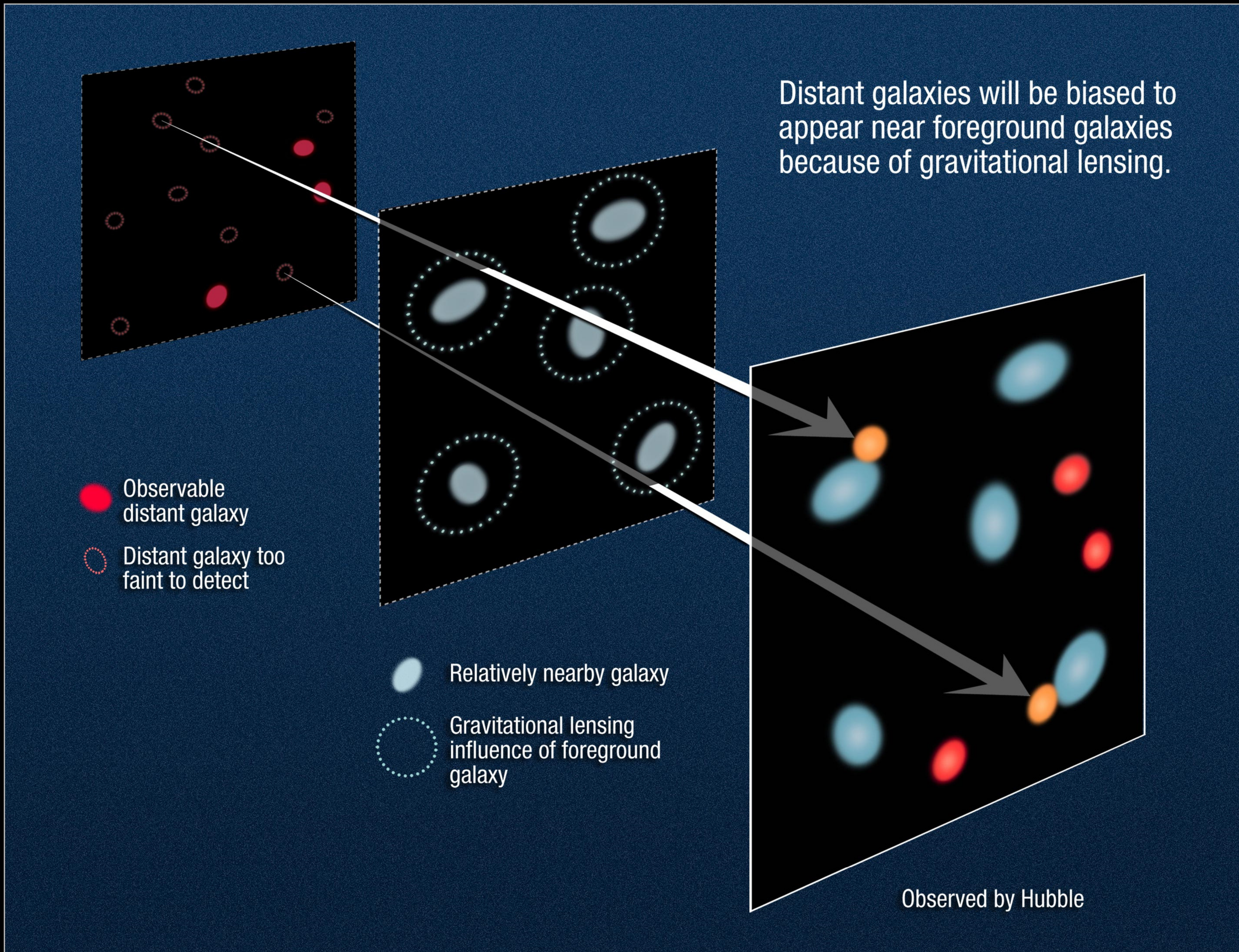


This attraction bent the light and caused the galaxies to look distorted, as if they were being seen through a crooked lens.

http://www.haystack.mit.edu/edu/pcr/Astrochemistry/3 - MATTER/Dark Matter.ppt



https://commons.wikimedia.org/wiki/File:Diagram_on_%22Gravitational_Lensing%22.jpg

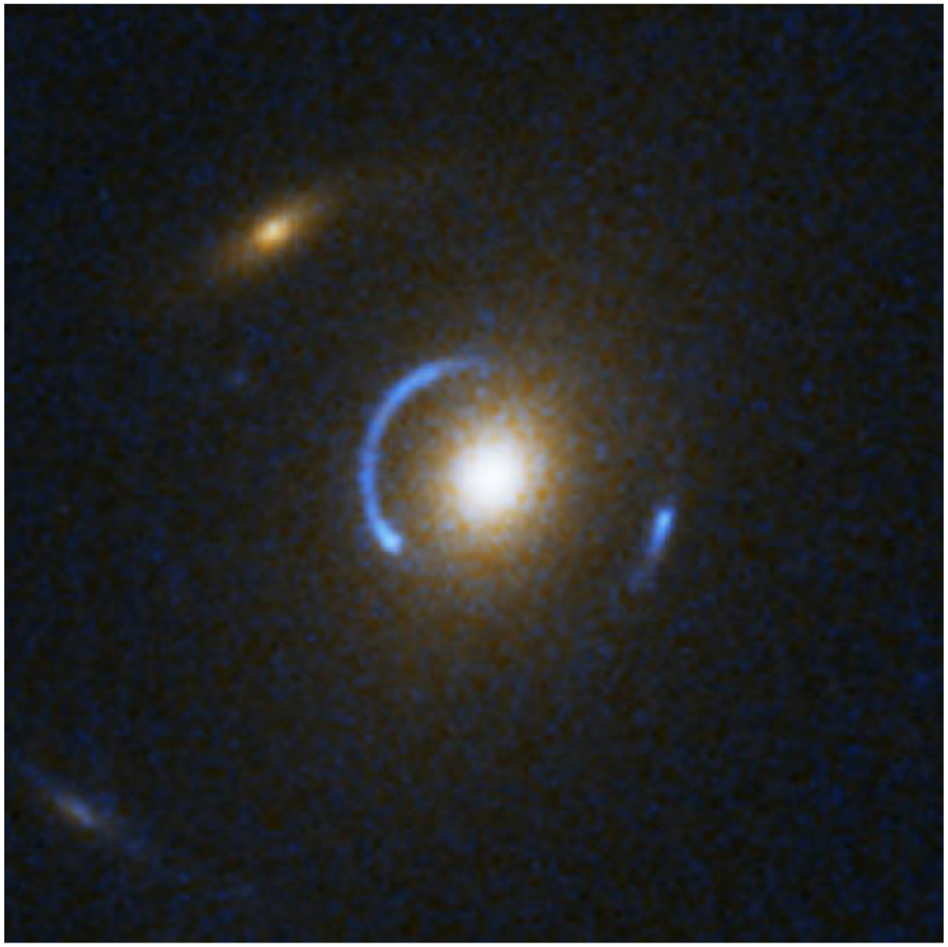


NASA, ESA, and Z. Levay and A. Feild (STScI)

STScI-PRC11-04

Animation links: https://en.wikipedia.org/wiki/Gravitational_lens

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



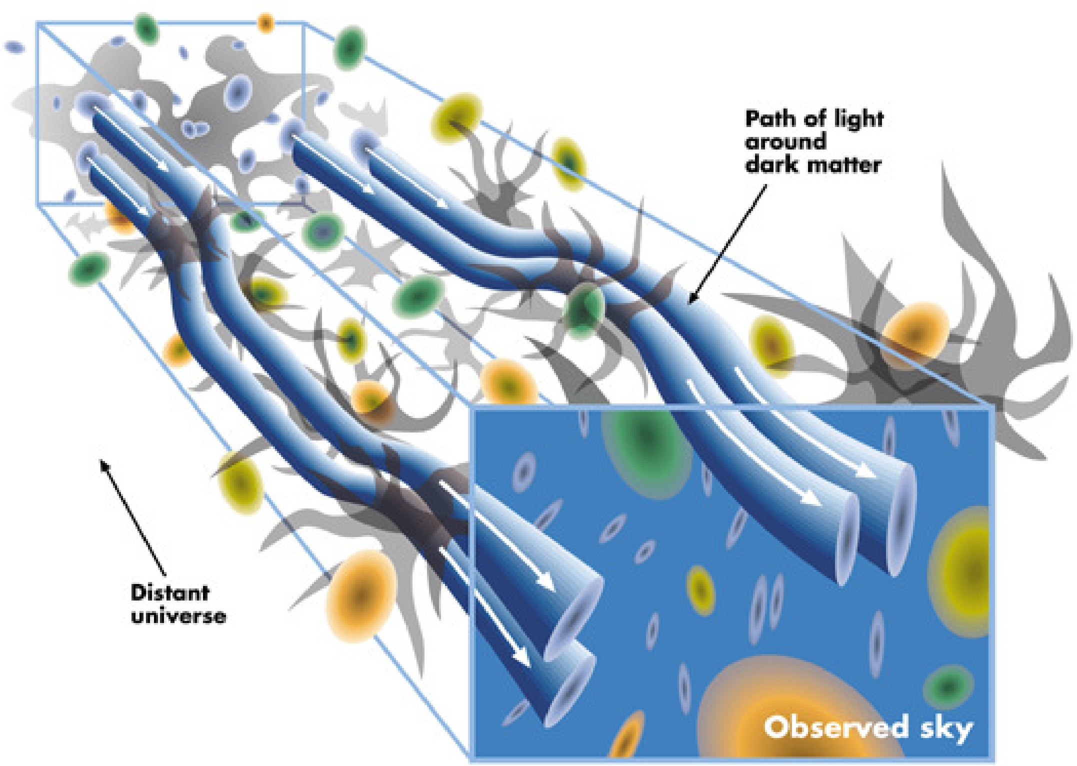
Gravitational lensing by dark matter

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.

https://www.nsf.gov/od/lpa/news/press/00/pr0029.htm

Next: redo Fritz Zwicky measurements with much better instruments.

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

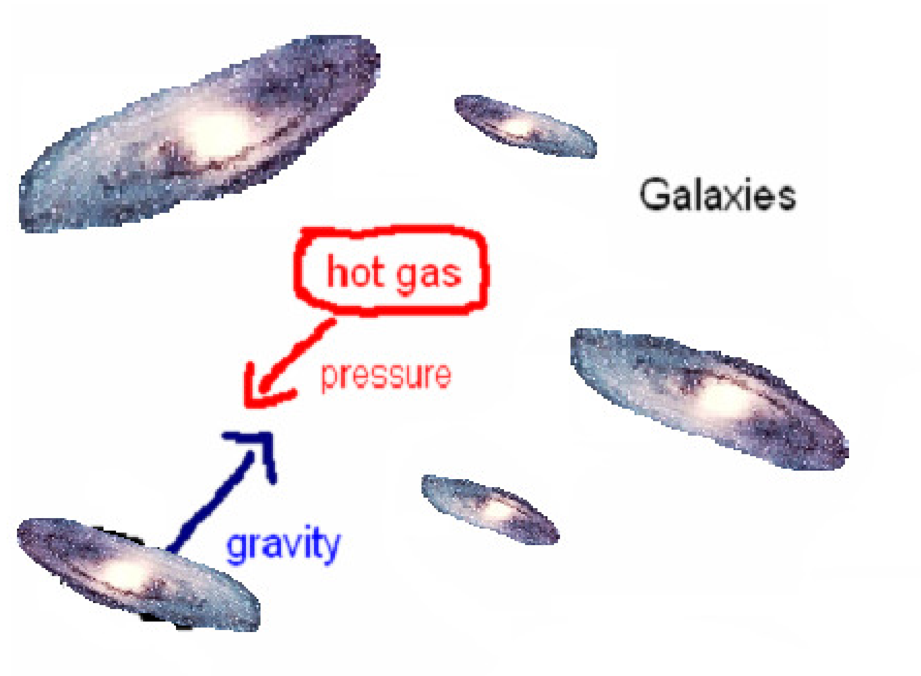
The mass we find from galaxy motions in a cluster is about 50 times larger than the mass in stars!

Note on galaxy cluster compositions

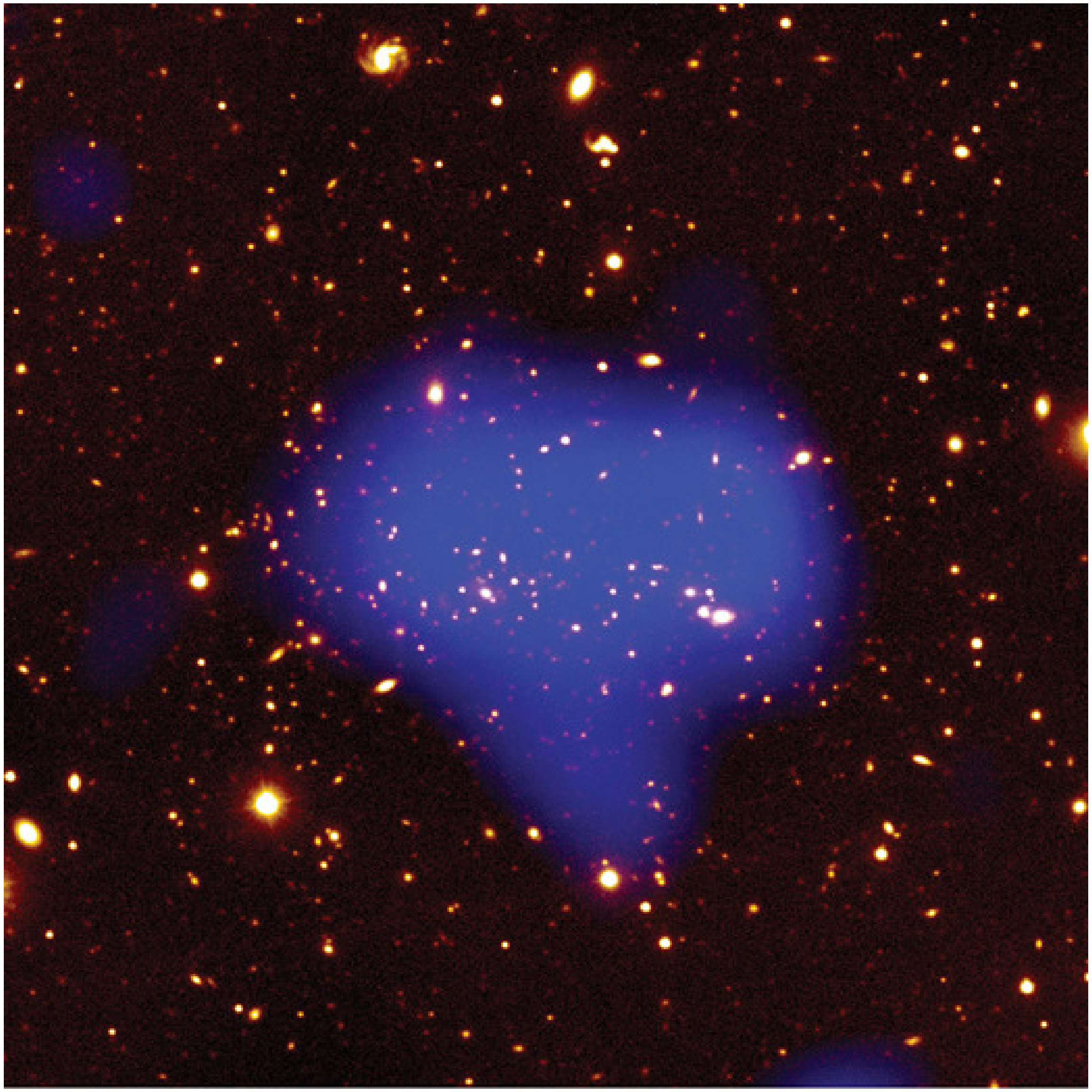
Radio astronomers have found hot gas in the space between galaxies in a cluster. This gas produces a pressure that pushes the galaxies apart.

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?



http://www.haystack.mit.edu/edu/pcr/Astrochemistry/3 - MATTER/Dark Matter.ppt



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

Here's one simple way to mass a galaxy

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

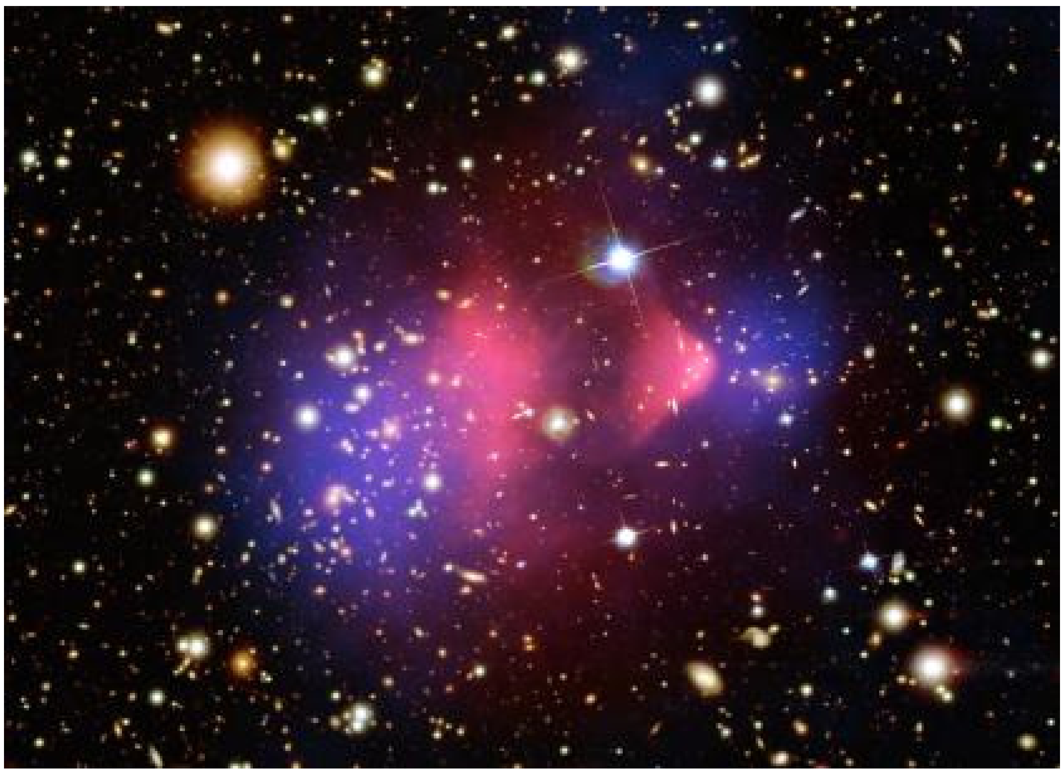
Mass of galaxy = number of stars x average mass of star

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.

http://www.haystack.mit.edu/edu/pcr/Astrochemistry/3 - MATTER/Dark Matter.ppt

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.



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.

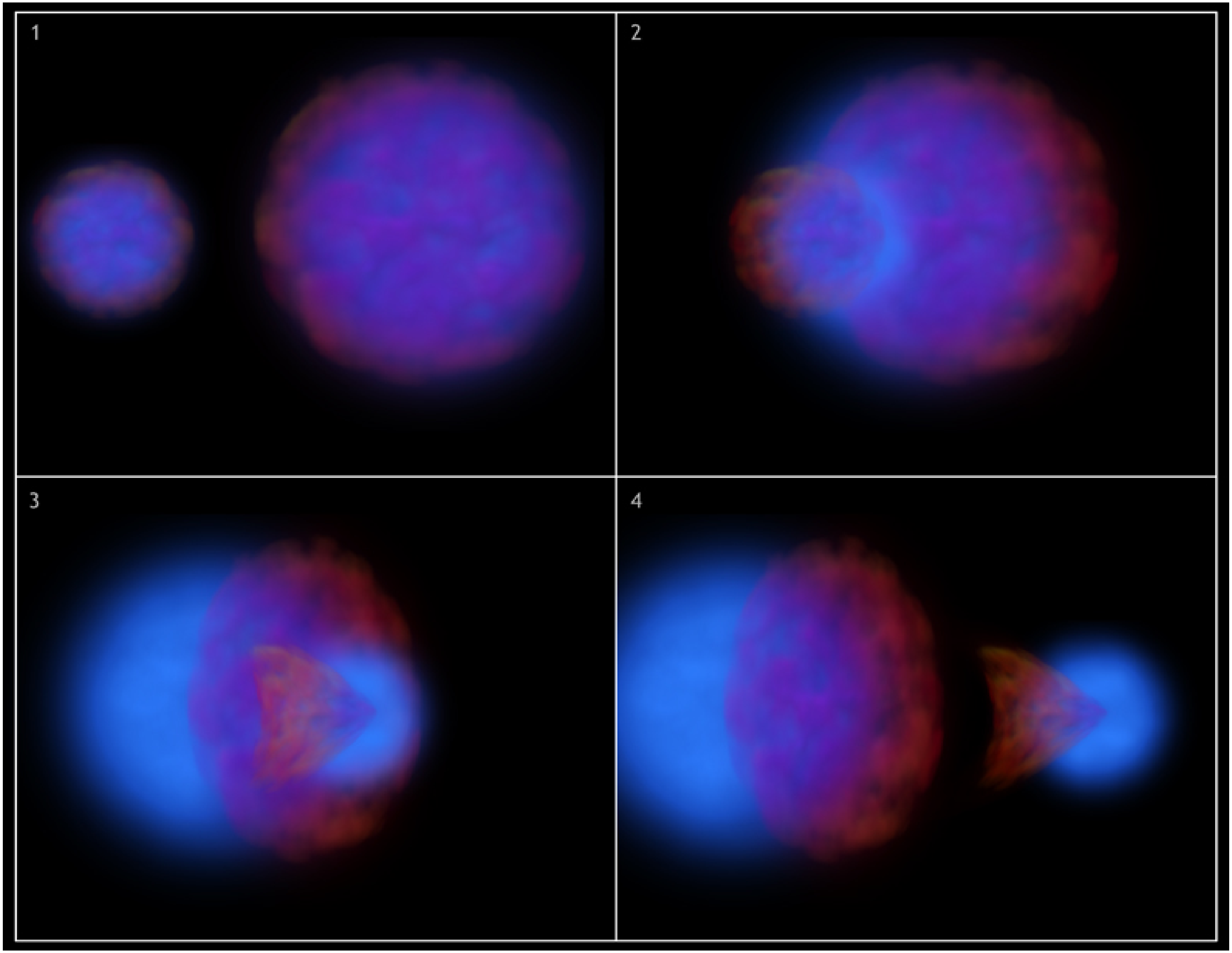
Hot gas detected by Chandra in X-rays is seen as two pink clumps in the image and contains most of the "normal," or baryonic, matter in the two clusters.

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.

http://chandra.harvard.edu/press/06_releases/press_082106.html

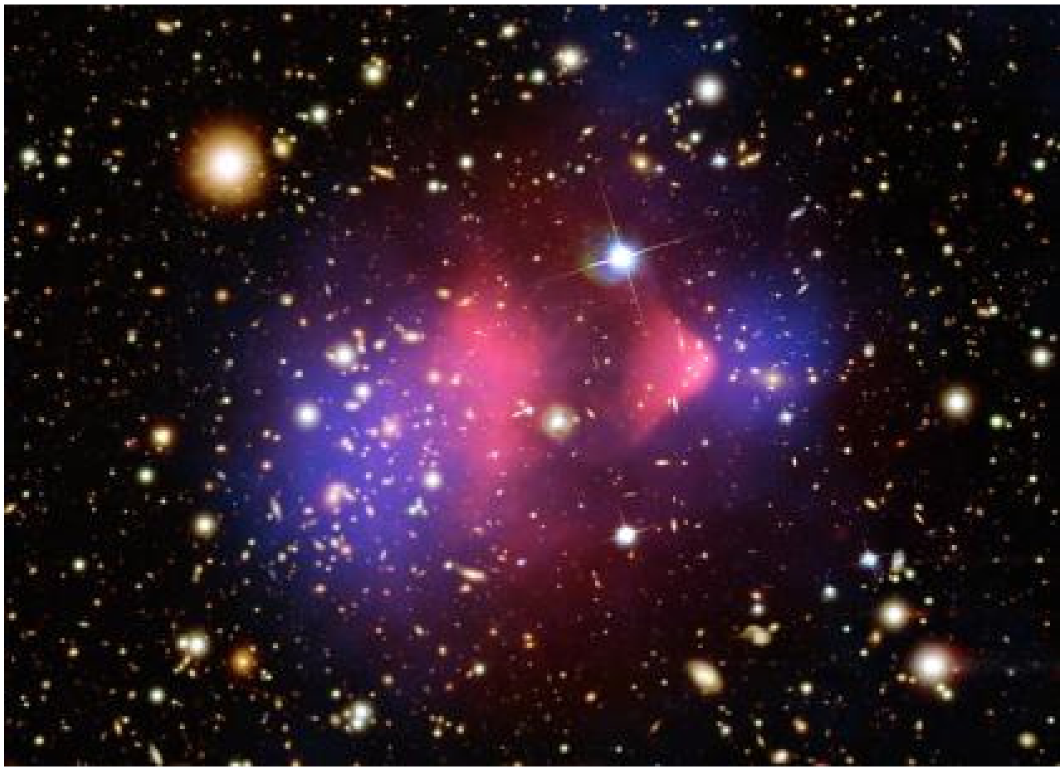
Bullet cluster collisio



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.

http://chandra.harvard.edu/press/06_releases/press_082106.html

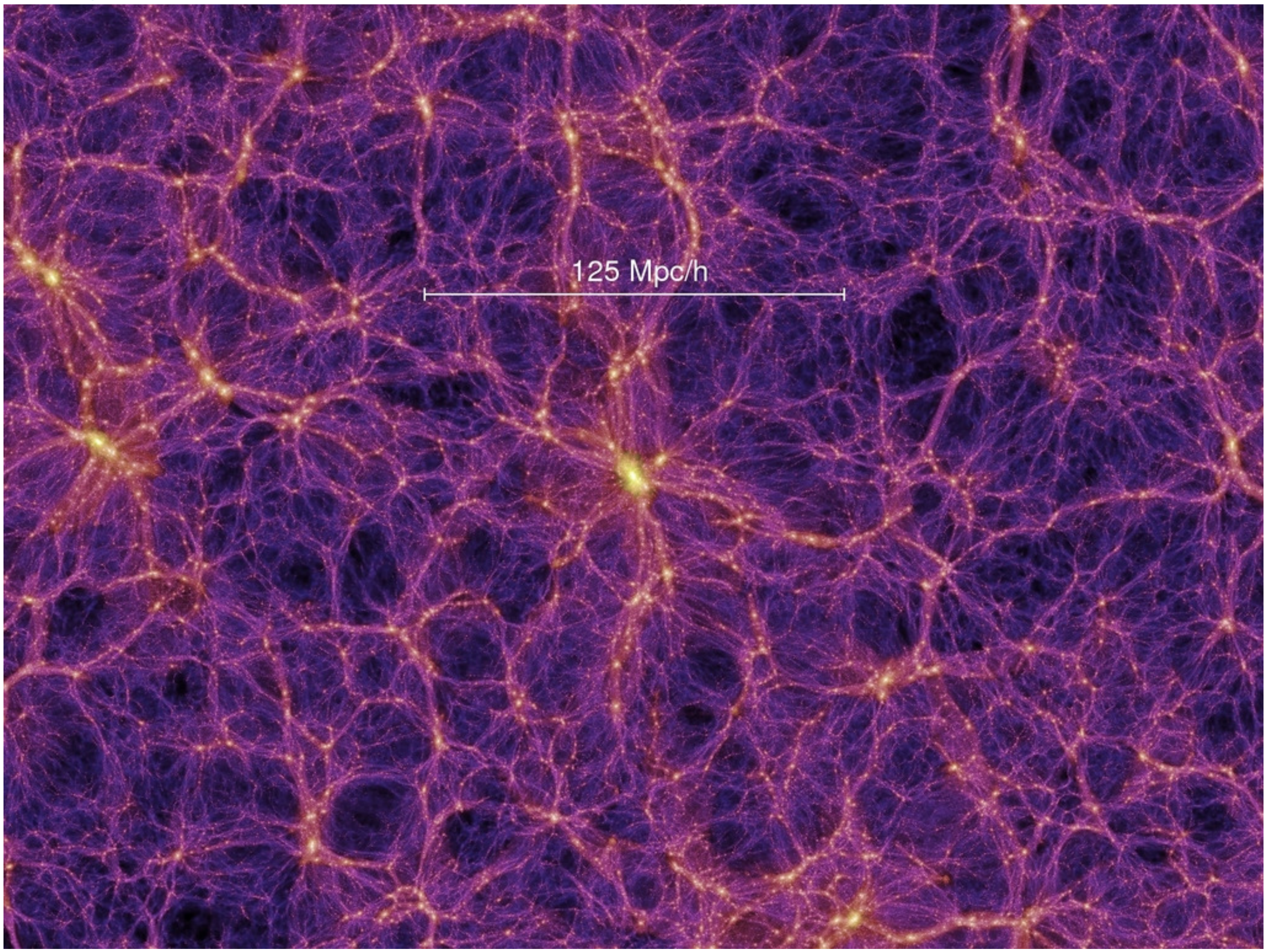
Dark Universe Planetarium Show: Dark Matter

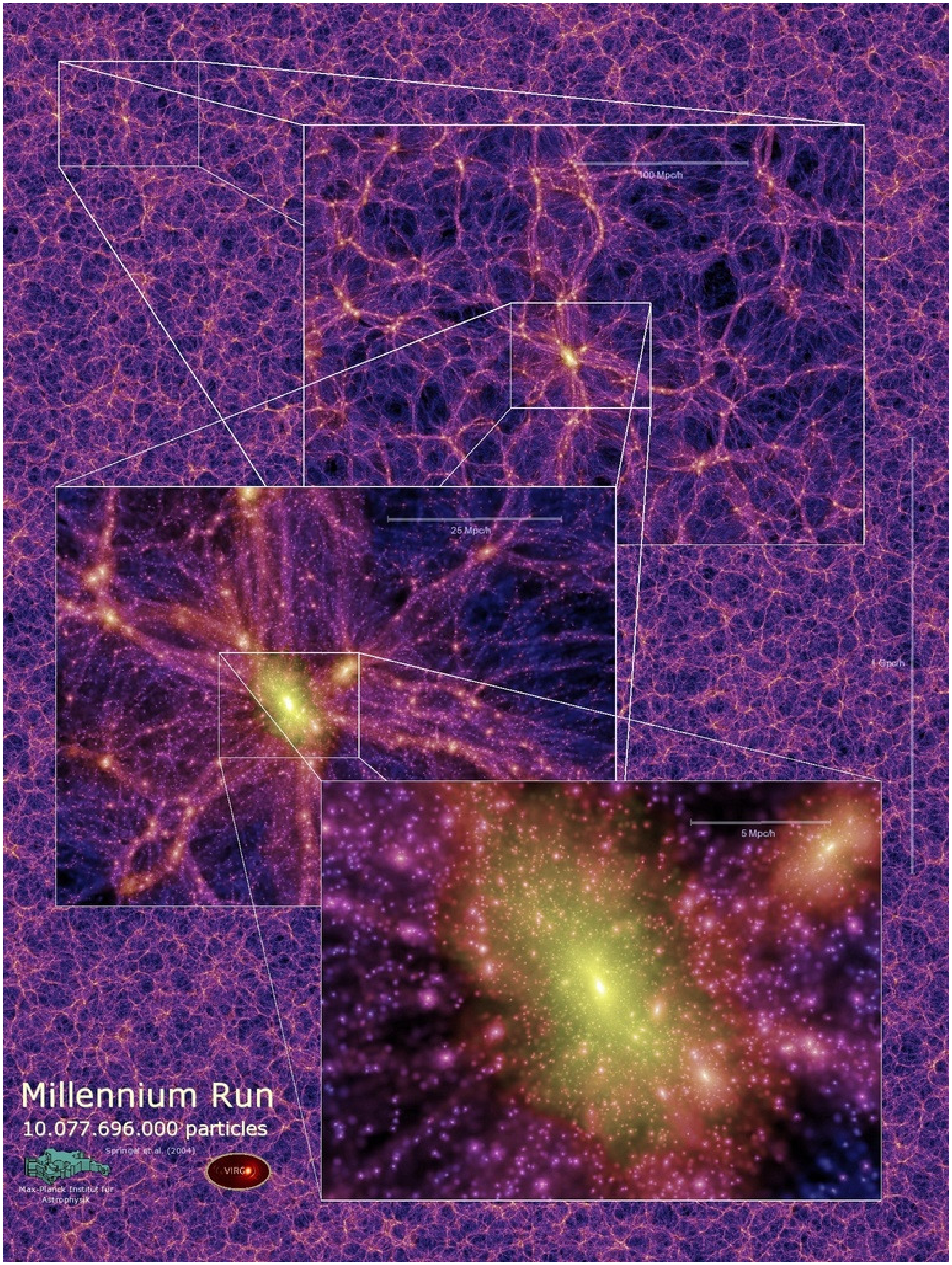
https://www.slac.stanford.edu/~kaehler/homepage/visualizations/dark-matter.html

Millennium Simulation

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

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

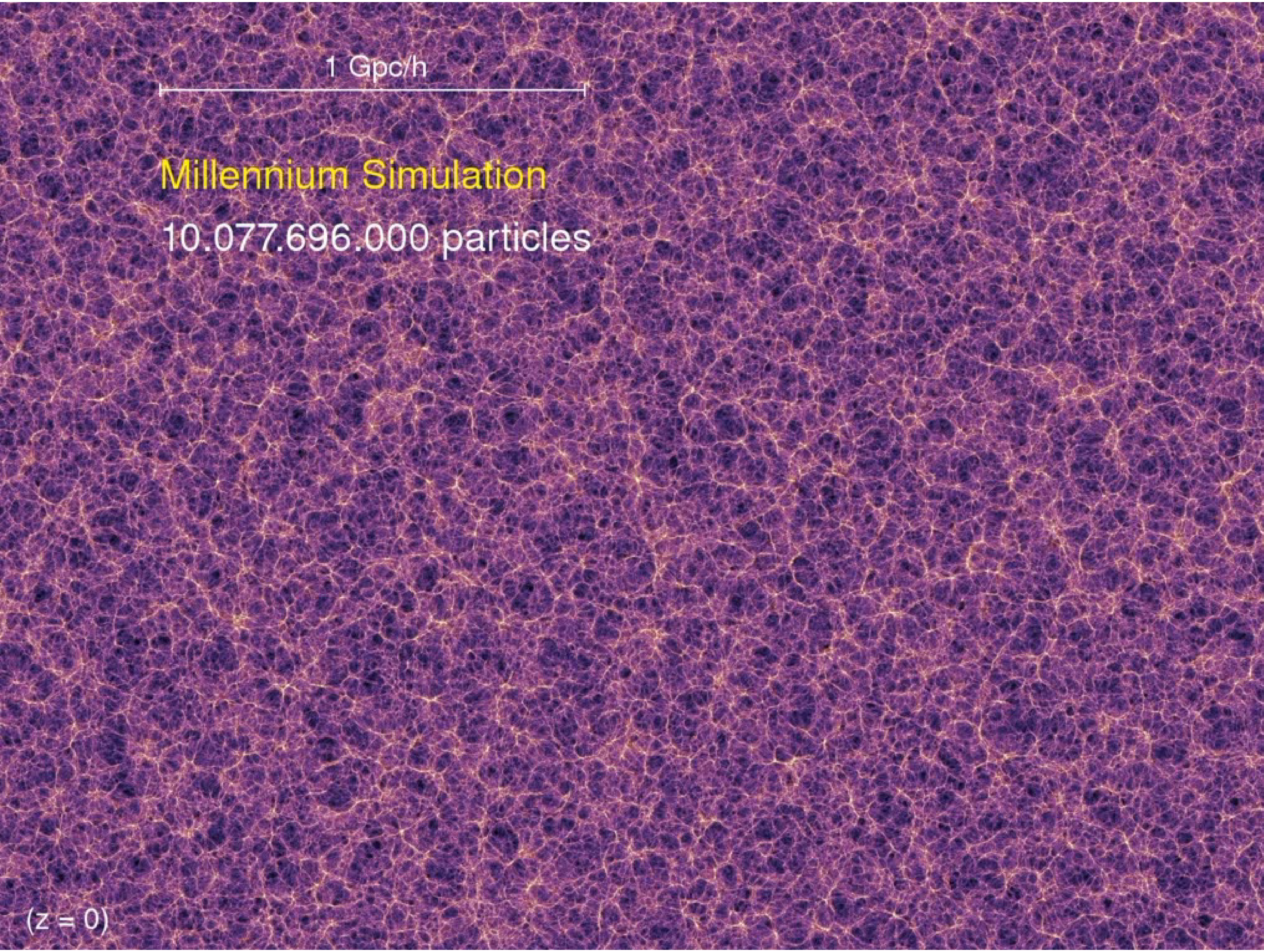




The movie shows the dark matter distribution in the universe at the present time, based on the *Millennium Simulation*, the largest N-body simulation carried out thus far (more than 10^{10}particles).

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.

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


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)