Terrestrial Planets

Week 3

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Earth and Planetary Sciences
FD Adams 131C

Scaling the Universe

We have learned that materials in the Solar System condensed as long ago as **4.567×10^9** years ago.

We know that our Solar System comprises elements that must have been formed in earlier phases of solar evolution. How have we actually measured the age, and hence size, of our universe?

Scaling the Universe

We require a methodology for determining distance scales of the universe.

We shall see how distance scales relate to the age of the universe.

We shall bootstrap a scaling method for measuring distances that reach to the edge of the "***observable***" Universe.

Scaling the Universe

But first, let’s look to a brief history of astronomical measurement.

Our current understanding of the universe is importantly dependent upon our models and our understanding of the scales inherent in those models.

Astronomy is an old science in that astronomical models were already being introduced at the dawn of recorded civilization.

A brief history of Astronomical Science

The ancient ***Sumerians*** (before 3000 BCE) studied the heavens.

The ***Sumerian Animal Round*** is the first known astronomical "***instrument***" – their ***Signs of the Zodiac***

Babylon: ***En Hedu'anna*** (circa 2354 BCE), high priestess of the Moon Goddess is, perhaps, the first known name in all of Astronomical science. She is also regarded as the first poet!

A brief history of Astronomical Science

The ancient ***Druids*** of Britain, the ***Inca*** of Peru, the ***Mayans*** of Central America, the ***Aztecs*** of Mexico and all the peoples of the Middle East looked to the sky for order and predictability... ***Stonehenge***

The ancient ***Babylonians*** were keen observers of the stars and planets.

The ***Phoenicians***, the Greeks, the ***Indians***, the ***Chinese***, the ***Persians***, the ***Mesopotamians*** ... navigation (the astrological signs)

The ***Polynesians*** almost surely navigated by the stars, Sun, Moon and planets as they sailed the Pacific Ocean a thousand years ago.

What did the ancients know?

By 2000 years BC, the Babylonians already had obtained an accurate measurement of the length of the year.

Anaximander (611-546BC) and the Ionians, developed a primitive cosmology which attempted to describe a universe as consequent to the basic element, water.

Pythagoras (570-500BC) discovered that the planet Earth was a sphere and that the heavenly bodies moved in circular paths, though as ***Plato*** (428-347BC), followed in believing about the central Earth.

What did the ancients know?

Anaxagoras (500-428BC) already knew that the Moon's light was reflected from the Sun. He had a "correct" explanation for both Lunar and Solar Eclipses.

Eudoxus (408-356BC) developed a mathematical-geometrical cosmology based upon a nesting of celestial spheres.

Aristotle (384-322BC) obtained proof that the Earth was a sphere and described a more complex basic chemistry based on ***earth, air, fire and water***. The chemistry of the universe exterior to Earth was made of a fifth element: the ***aether***.

What did the ancients know?

One may argue that the advent of ***Christianity*** and its fundamentalist adherence to the ancient writings of Biblical myth retarded the development of astronomy and of our understanding of nature for the next 1500 years.

Christianity adopted the elaborate epi-cyclic theory of ***Ptolemy***, (CE 100-200) with an Earth-centred (geocentric) universe, the ***Amalgest***.

The pre-Christian-era knowledge of the Solar System was preserved in the cultures of the Middle East; it was, there, refined, especially in the area of mathematics, and improved upon by the Persians and Arabs.

A Renaissance in Astronomy

Two thousand years ago, we knew that the Earth was round. We knew its size. We had measured the relative sizes of and distances to the Moon and the Sun. We had discovered the simplicity of the ***heliocentric reference frame***. Five hundred years ago, we rediscovered this knowledge.

A Renaissance in Astronomy

Copernicus (1473-1543): The great Polish thinker, ***Niklas Koppernigk*** precipitated the scientific renaissance in astronomy with the publication of a manuscript called ***Commentariolis***. He recovered the Aristarchian **heliocentric** viewpoint. The Sun becomes the reference point in the Solar System.

A Renaissance in Astronomy

Tycho Brahe (1546-1601), a Danish astronomer made the important measurements of planetary positions through years.

Still, at his death in 1601, he had not embraced the Copernican heliocentric model even though his data allowed for the first accurate relative scalings of distances in the Solar System

A Renaissance in Astronomy

Johannes Kepler (1571-1630), Brahe's student assistant, used his precise measurements to discover ***Kepler's laws of planetary orbital motion*** which he published in 1609 in a book **The New Astronomy: Commentaries on the Motions of Mars**. We know the paths of the planetary motions.

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A Renaissance in Astronomy

A century after Copernicus, ***Galileo*** (1564-1642) provided supporting evidence of his and Kepler's work. The intolerant Christian church repudiated this challenging science, sentencing Galileo to house arrest for the last decade of his life. The Lutheran Christian Reformation in Northern Europe saved Kepler from a similar fate.

The work of these great scientists allow us to scale the solar system. Later in the course, we shall learn more of the detail of Kepler's Laws and of **Newtonian Mechanics** which explains them.

Distance to Stars and Galaxies

We know that a light at distance looks dimmer than one that is close to us. What is the rule for brightness versus distance:

$$I = \frac{L}{d^2}$$

where I is the intensity of light that we see, d is the distance to the light source and L is the luminosity of the source itself.

So if we know how bright the light "looks" (***apparent magnitude***) and we know how bright the source "is" (***luminosity*** or ***absolute magnitude****), we can calculate how far away the light is:

$$d = \sqrt{L/I}$$

$*M_{abs} = 4.83 - 2.5\ log_{10}\,(L/L_o)$

The Brightness of Stars

Hipparchus of Nicaea (190-120BCE) was a Greek astronomer, geographer, and mathematician.

He is credited as the founder of trigonometry and with the discovery of the precession of the equinoxes. One of his greatest accomplishments was to measure the distance from Earth to the Moon!

He also gave us the ***Magnitude Scale*** by which we measure the brightness of stars. His magnitude scale separated stars into classes according to how bright they appeared in the night sky. His scale offered 7 classes: magnitudes 0 (brightest) to 6 (dimmest). It is a subjective scale.

Now we know that approximately, each increase of number class by ***1 unit*** represents a "***dimming***" of brightness ***by a factor of 2.5***

Magnitudes

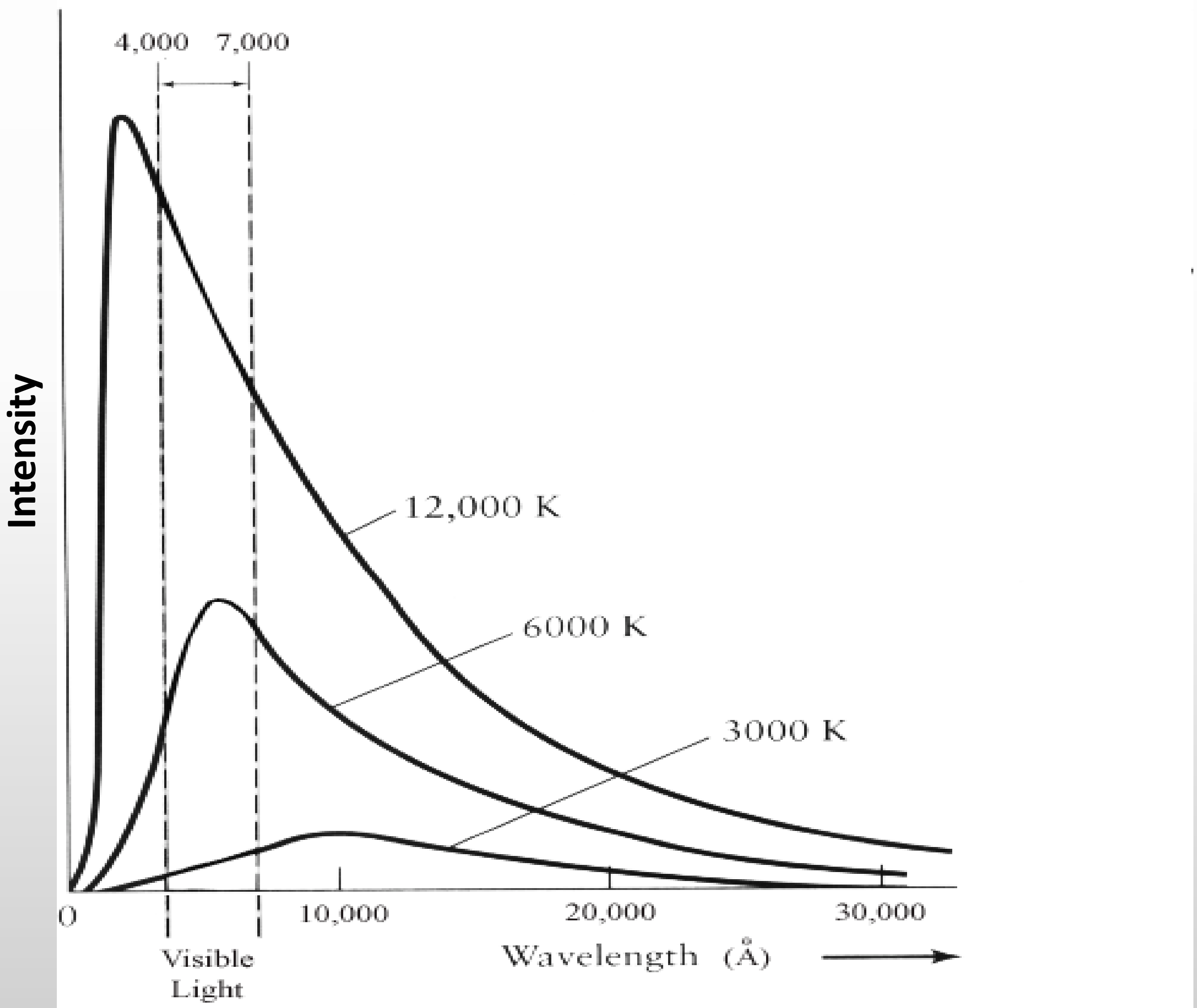
The visual apparent magnitude scale

Magnitude	Vision condition	Example
-26.8		the Sun
-12.6		the full Moon
-6		crescent Moon
-4	naked eye at sunset	planet Venus
-2	naked eye in dusk	planet Jupiter
-1	naked eye in dusk	Sirius (the brightest star)
0	naked eye at dark	Vega (a bright blue star)
+1	naked eye/dark night	planet Saturn
+2	naked eye/dark night	stars of Big Dipper
+6	naked eye/darkest night	the faintest stars we can see
+25	largest telescopes	the photographic limit

Colours of stars and luminosity

Stellar luminosities "correlate" with the colour of the light emitted by a star. The distribution or spectrum of colours or wavelengths of light emitted by a star relates to the temperature of its surface

Colours of stars and luminosity



Spectral type – colour of stars

Astronomers classify stars according to ***Spectral Type*** (colour).

Spectral Type	Temperature	Characteristics
O	30,000 - 60,000 K	Blue stars
B	10,000 - 30,000 K	Blue-white stars
A	7,500 - 10,000 K	White stars
F	6,000 - 7,500 K	Yellow-white stars
G	5,000 - 6,000 K	Yellow stars (like the Sun)
K	3,500 - 5,000K	Yellow-orange stars
M	< 3,500 K	Red stars
L	~ 2,000 K	Too cool for fusion?
T	550 – 1300K	Methane Dwarfs

Spectral type – colour of stars

Oh Be A Fine Girl, Kiss Me Like That!

… song by **Diane Nalini**, the lyrics

Distance to Stars and Galaxies

For stars, if we know how far away they are and we know how bright they look (**apparent magnitude**), we know how bright they are… their intrinsic brightness or ***luminosity***. We measure this in terms of **absolute magnitude**.

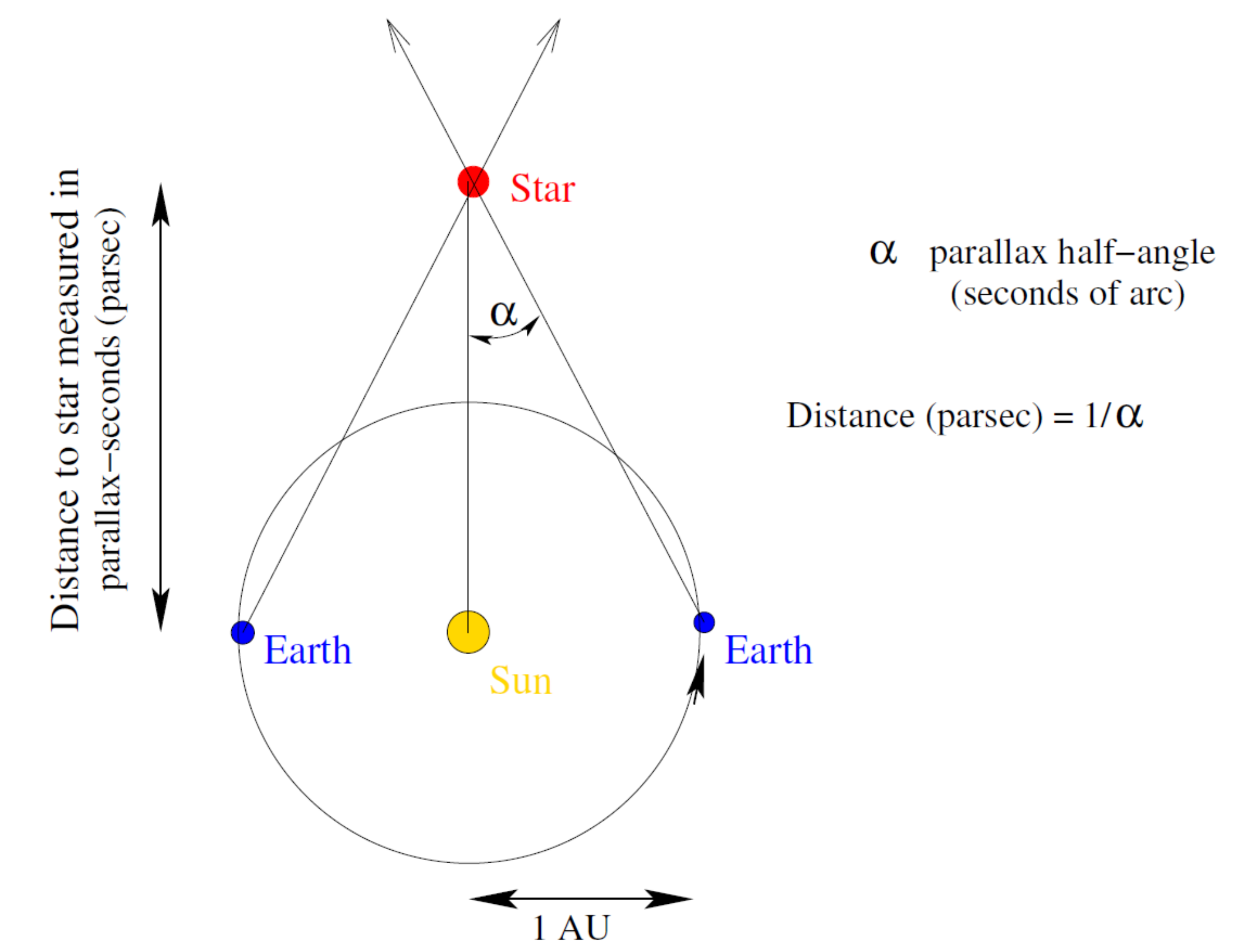
Rather than measuring the inherent luminosity, astronomers describe the intrinsic brightness of a star as the **apparent magnitude** a star would show ***if it were at a distance of exactly 10 parsecs***; this defines the absolute magnitude.

Parallax triangulation

Recently, with high precision astronomical measurement using the Hipparcos satellite's dual telescopes, we have determined the distance to most stars with distances of less than about 300 pc (~ 1000 light years) with an accuracy of 10%...

More recently, and with even greater accuracy, ESA's Gaia satellite has taken on the mapping of the positions of one billion stars in our Milky Way galaxy along with a determination of their apparent brightness.

Parallax triangulation



The 10 nearest Stars

Star	App. Mag.	Abs. Mag.	Distance (pC)	Spectral type
Sun (Sol)	-26.8	+4.83	0.00000485	G2
Proxima Cent.	+11.5	+15.5	1.29	M5
α Centauri A	+0.01	+4.4	1.29	G2
α Centauri B	+1.5	+5.8	1.29	K5
Barnard's star	+9.5	+13.2	1.81	M5
Wolf 359	+13.5	+16.8	2.33	M6
Lalande 21185	+7.5	+10.4	2.48	M2
Luyten 726-8A	+12.5	+15.4	2.52	M5
Sirius A	-1.47	+1.4	2.67	A1
Sirius B	+7.2	+11.5	2.67	A0 (dwarf)

The 10 brightest Stars

Star	App. Mag.	Abs. Mag.	Distance (pC)	Spectral type
Sun (Sol)	-26.8	+4.83	0.00000485	G2
Sirius A	-1.47	+1.4	2.67	A1
Canopus	-0.72	-3.1	30.1	F0
Arcturus	-0.06	-0.3	11.0	K2
α Centauri A	+0.01	+4.4	1.29	G2
Vega	+0.04	+0.5	7.36	A0
Capella	+0.05	-0.6	13.8	G8
Rigel	+0.14	-7.1	276	B8
Procyon	+0.37	+2.7	3.50	F5
Betelgeuse	+0.41	-5.6	159	M2 (giant)

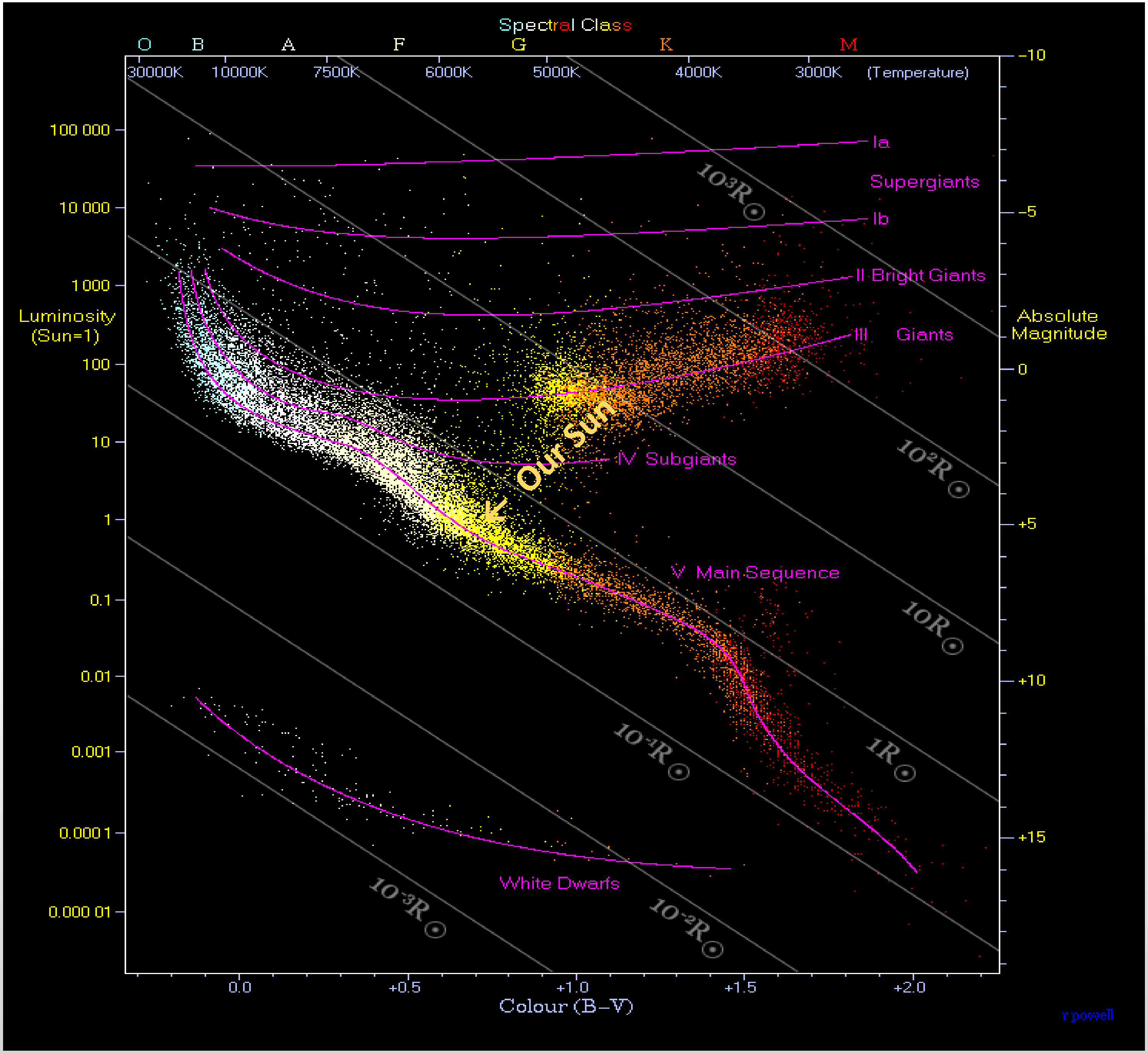
Hertzsprung-Russell Diagram

Knowing the apparent magnitude of a star and its distance, we can easily determine its absolute magnitude or "***luminosity***".

If, then, we place each star into a plot of its luminosity vs. its ***colour temperature*** or "***spectral type***", we obtain the famous ***Hertzsprung-Russell Diagram***.

We can use this to calculate the distance to stars beyond the reach of our parallax triangulation.

The **Hipparchos satellite** has measured the distance to more than 20 000 stars. Let's plot them: brightness vs. colour class. The **Gaïa mission** is now obtaining even more precise H-R diagrams.



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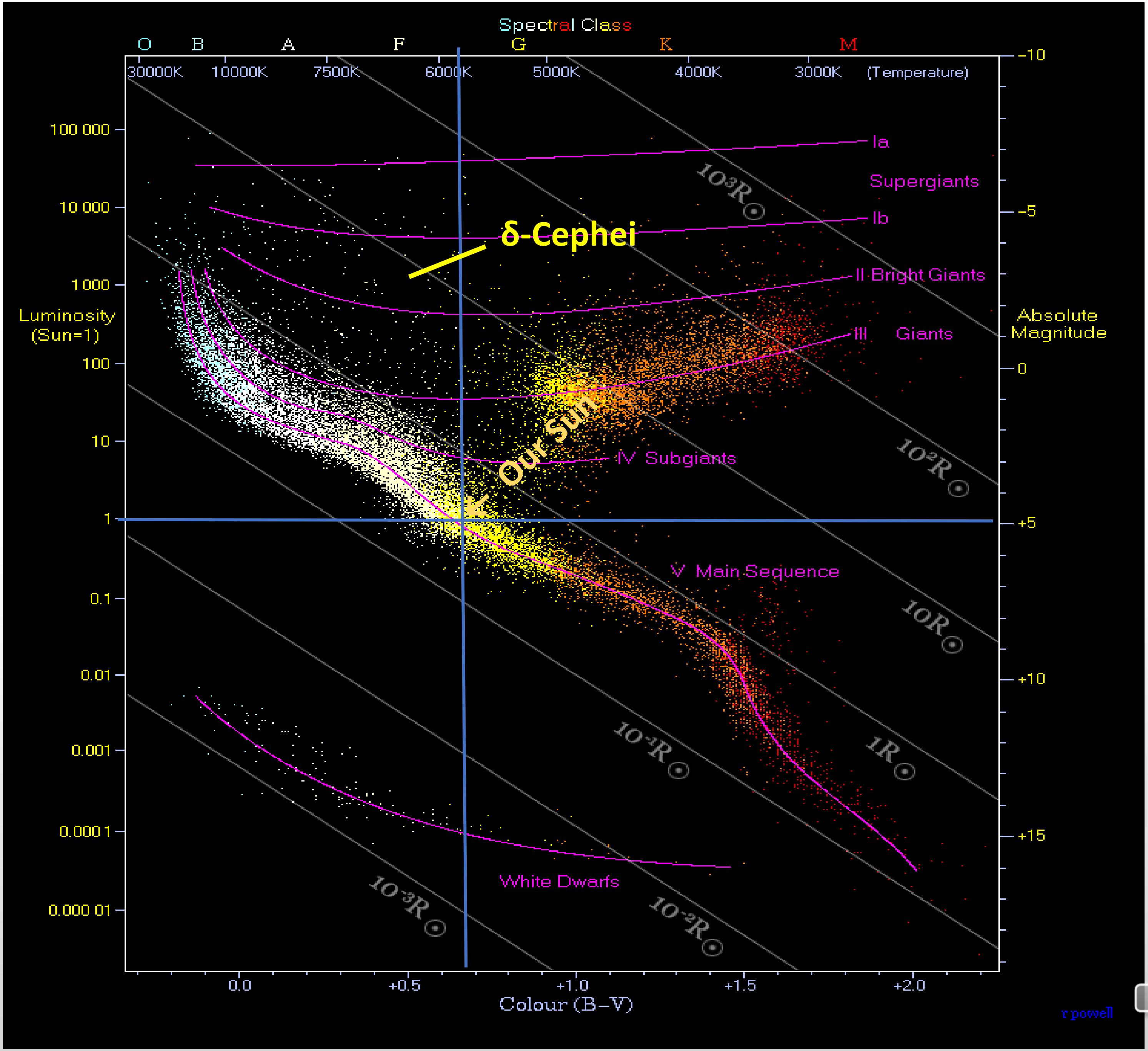

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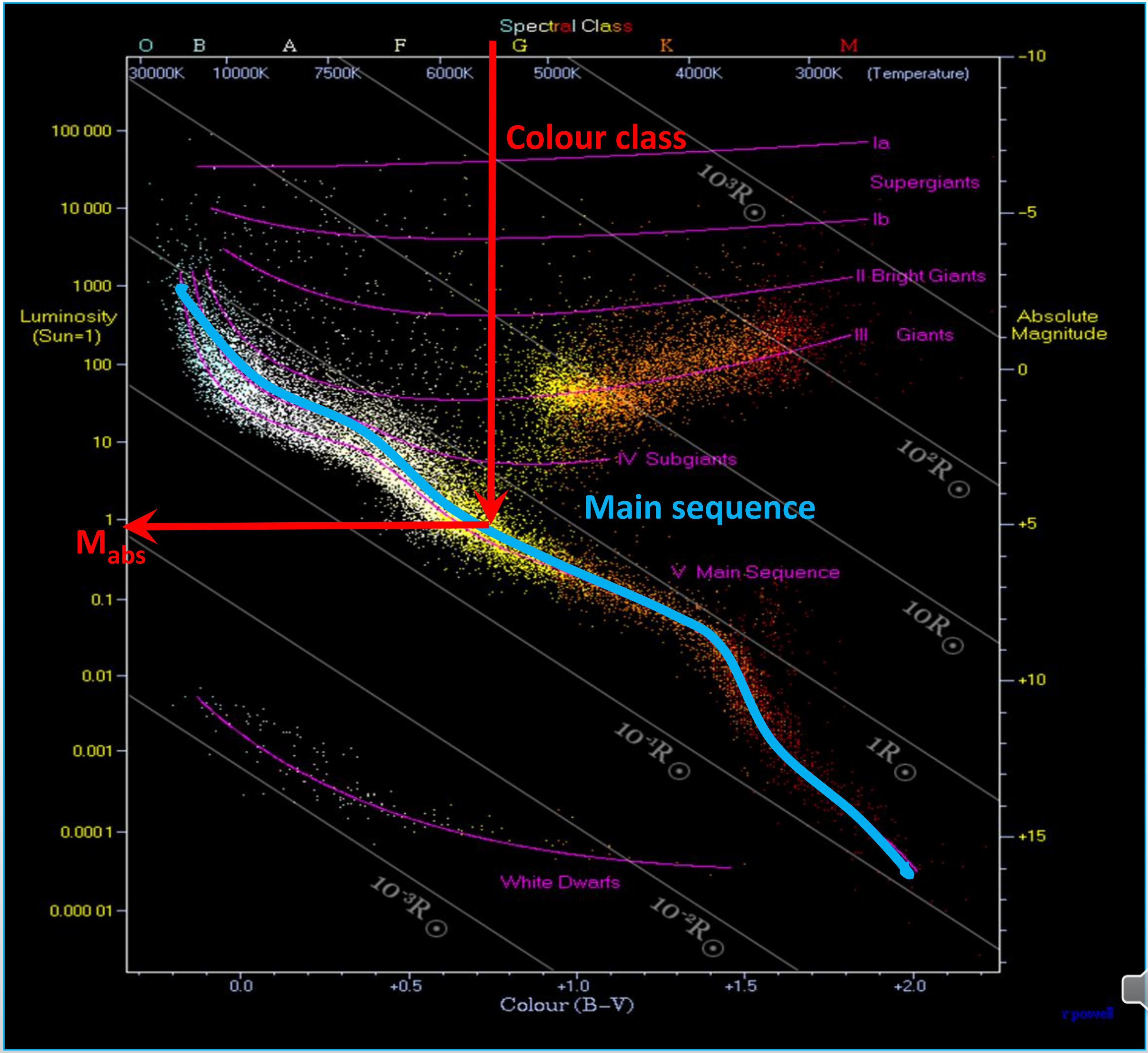


Spectral Class
O B A F G K M
30000K 10000K 7500K 6000K 5000K 4000K 3000K (Temperature)
Colour class
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
Main sequence
V Main Sequence
White Dwarfs
Luminosity (Sun=1)
100 000
10 000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.000 01
M abs
Absolute Magnitude
-10
-5
0
+5
+10
+15
0.0 +0.5 +1.0 +1.5 +2.0
Colour (B–V)
rpowell

Distance by H-R plot

Having correlated the star's luminosity or **absolute magnitude*** with its **Spectral Type** using the **H-R** diagram we determine a star's distance knowing that light intensity decreases proportional to the square of distance, we obtain:

$$\boldsymbol{d = 10^{\left(\frac{Mapp - Mabs + 5}{5}\right)}} \text{ parsecs.}$$

* $\boldsymbol{M_{abs} = 4.83 - 2.5\, log_{10}\left(L/L_o\right)}$

Beyond our Milky Way

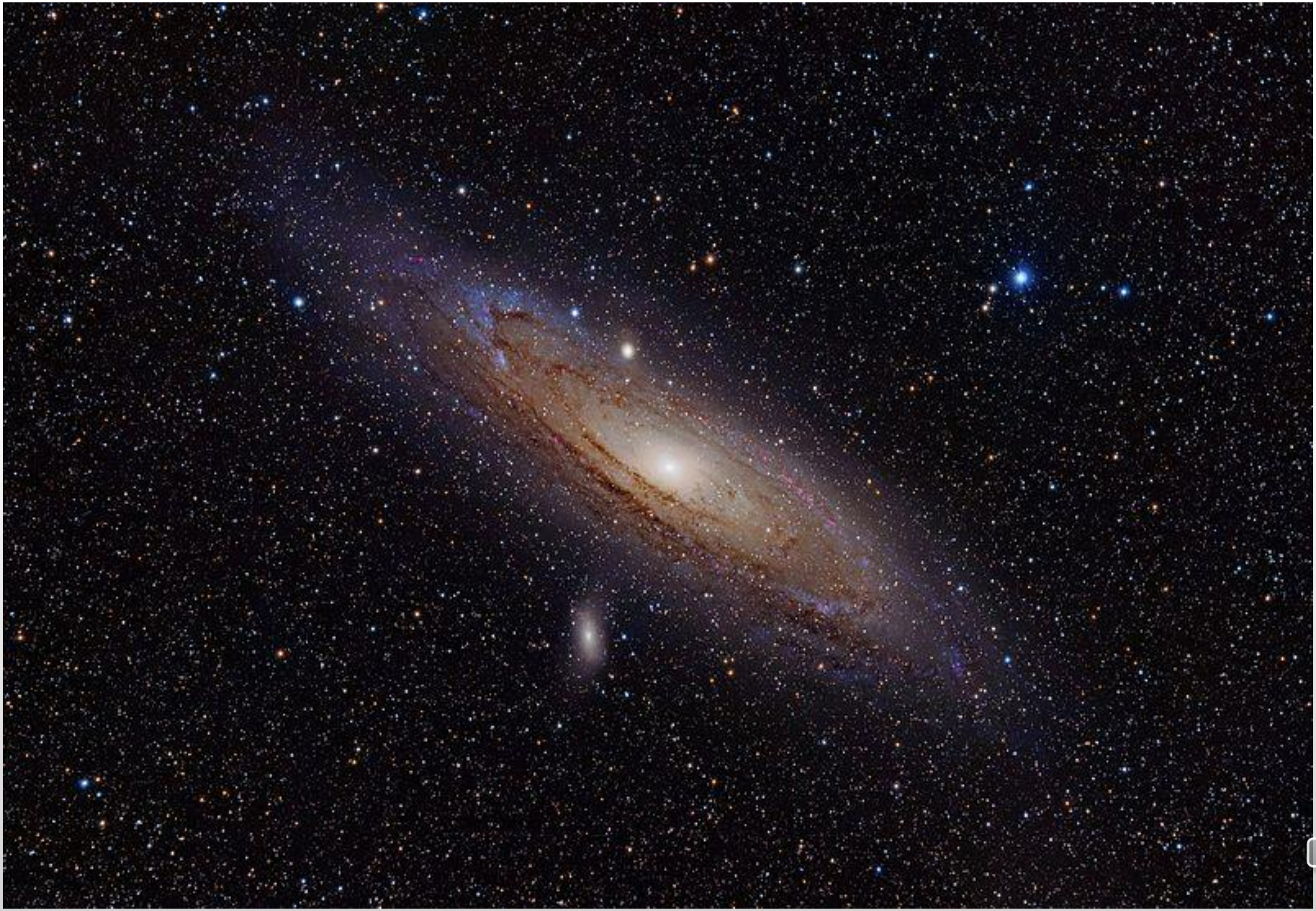
Our large ***Milky Way*** galaxy has two small satellite galaxies which seem to be gravitationally bound to us – the ***Large*** and ***Small Magellanic Clouds***. These are visible from the southern hemisphere.

We can resolve individual stars in these small satellite galaxies and so determine their distances to be **46 000 pC** and **64 000 pC** from the Sun. respectively.

Beyond this distance, to measure the distance to other galaxies in our local group, we employ the **Cepheid variables**.

Beyond our Milky Way

Beyond our Milky Way



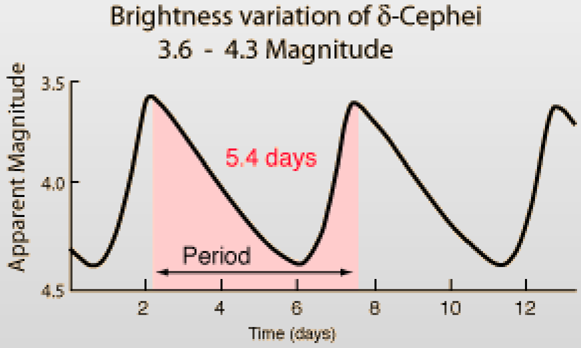
Beyond our Milky Way

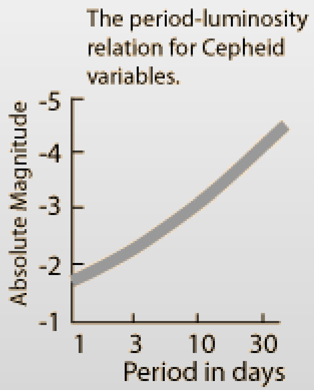
European Southern Observatory, Paranal Chile

Cepheids take us to Galaxies

Henriette Leavitt working with **Edwin Hubble** in the 1920s recognized that a variable type of star called a Cepheid variable, changed brightness periodically and the periodicity was closely related to how bright the star was.

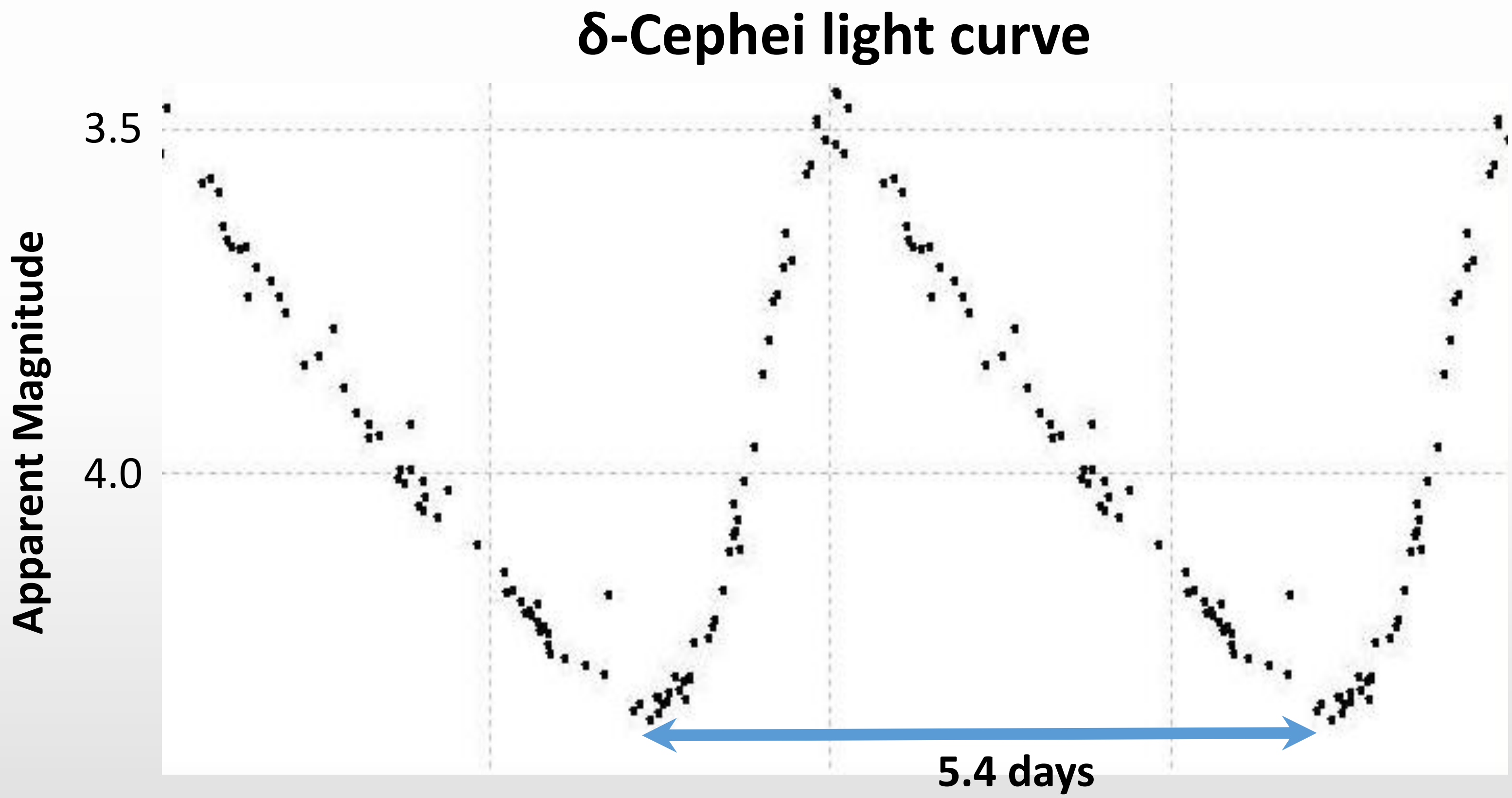
Cepheids are very bright stars (low absolute magnitude) and bright enough to be seen in our local group of galaxies.





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

Cepheids take us to Galaxies



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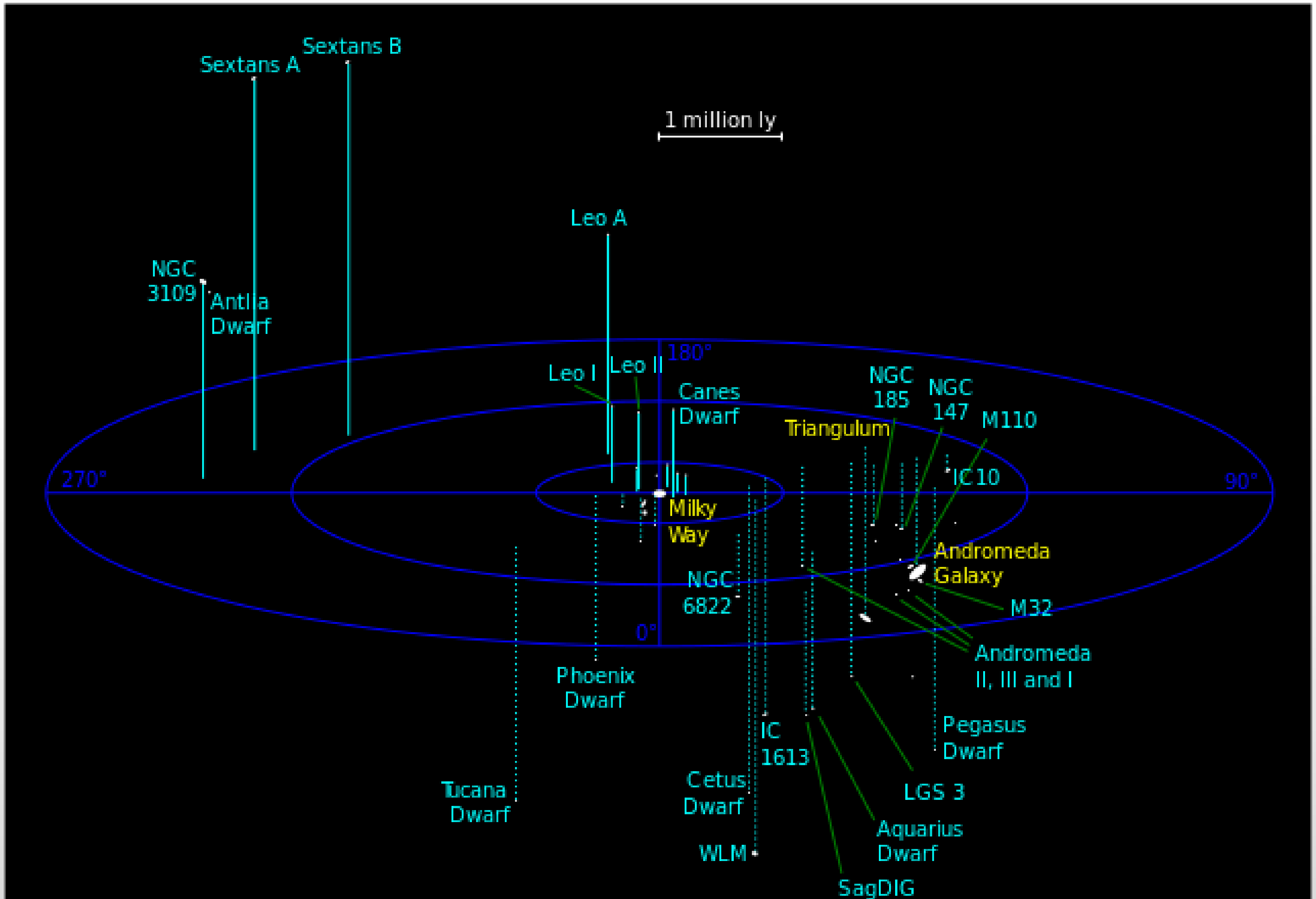
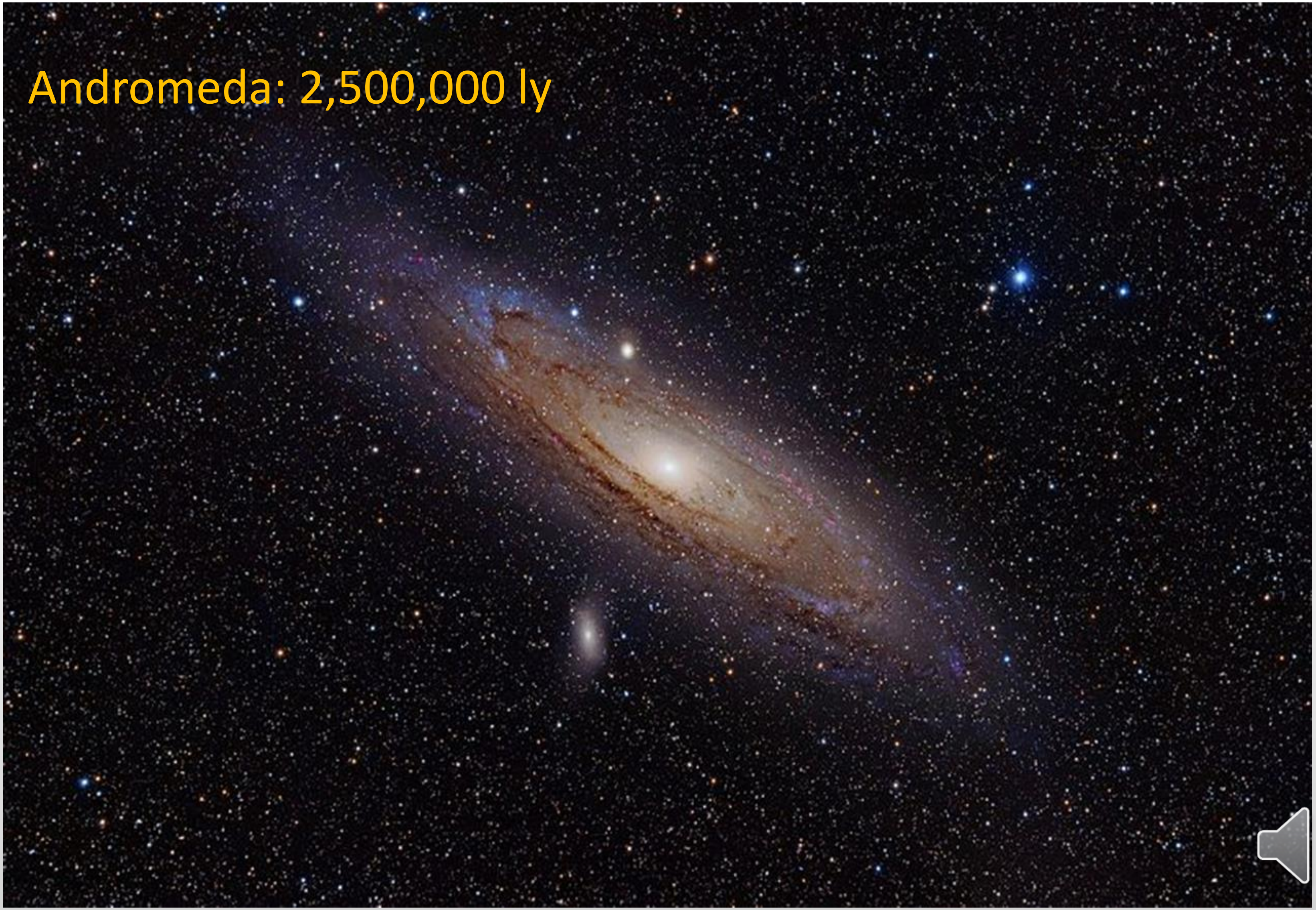
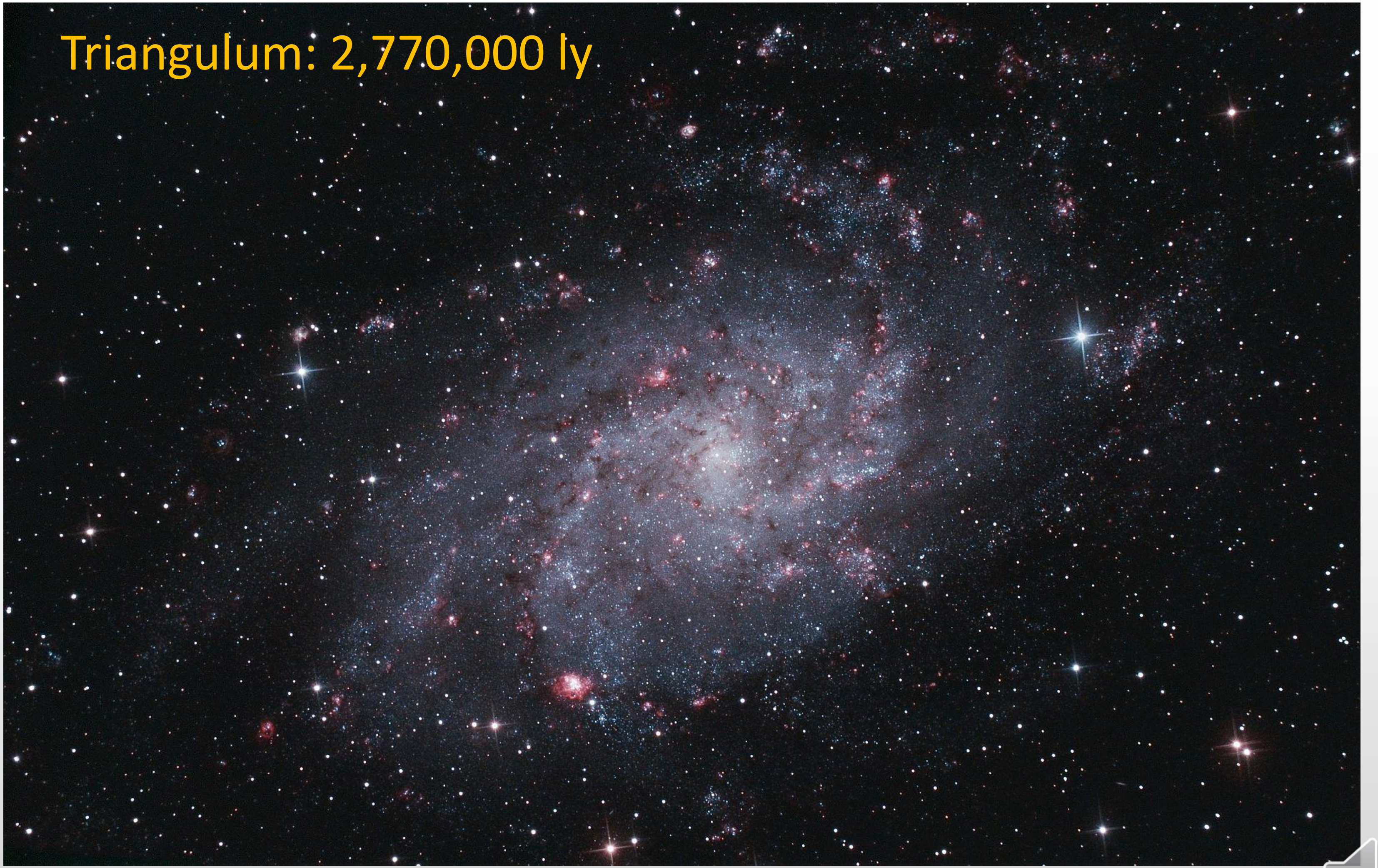
Our Local Group of Galaxies



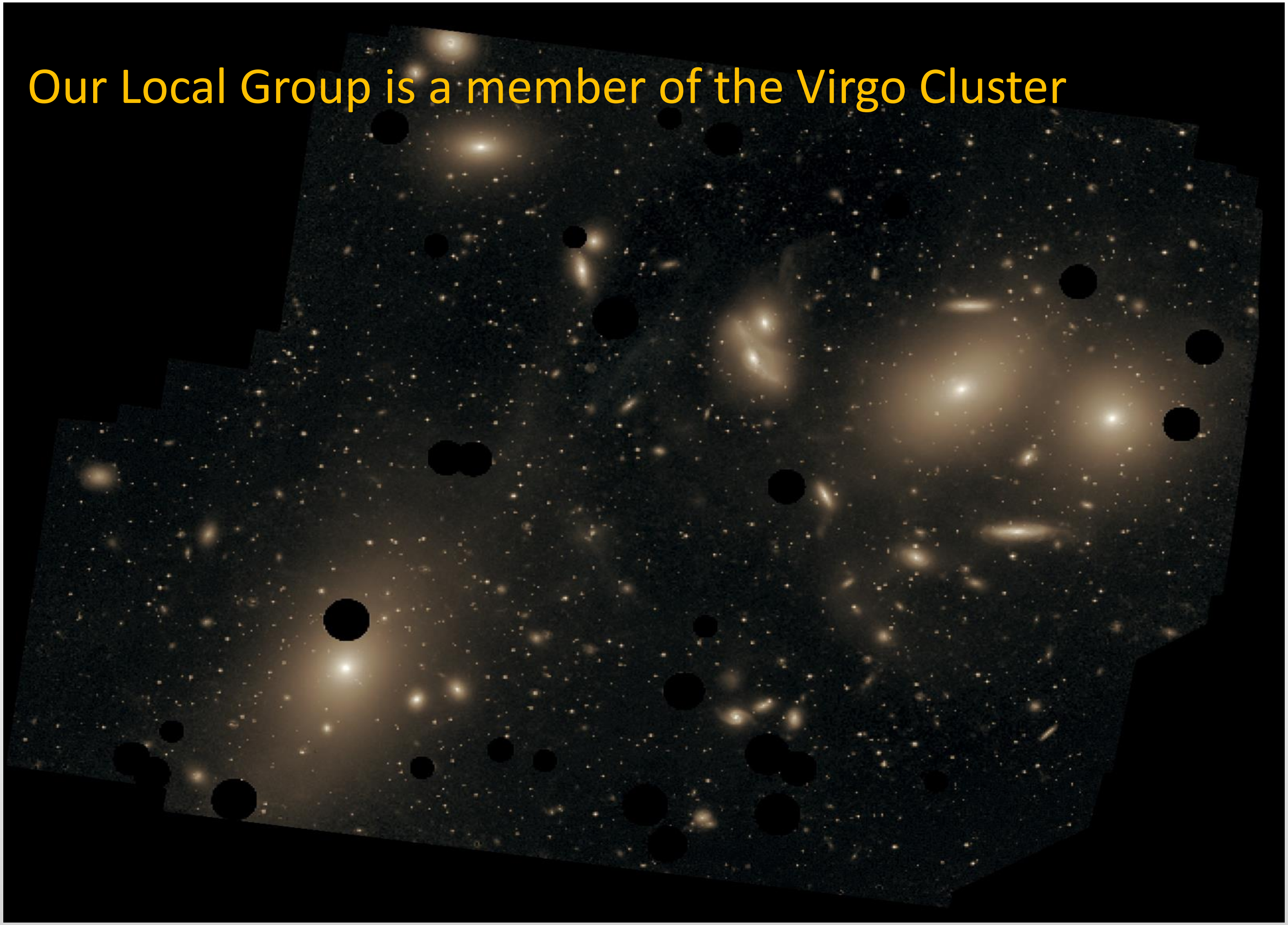
In our Local group



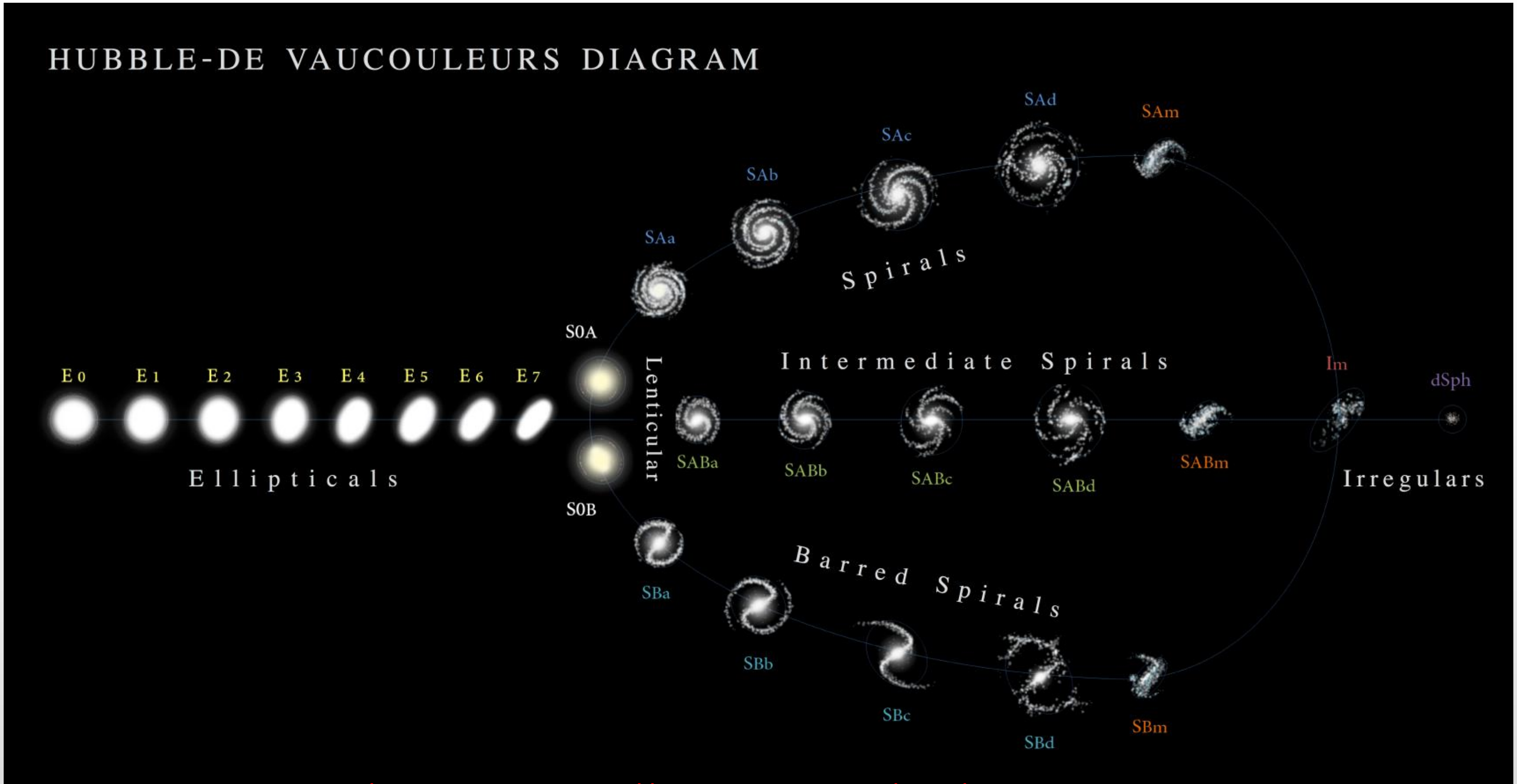
In our Local group



In our Local group



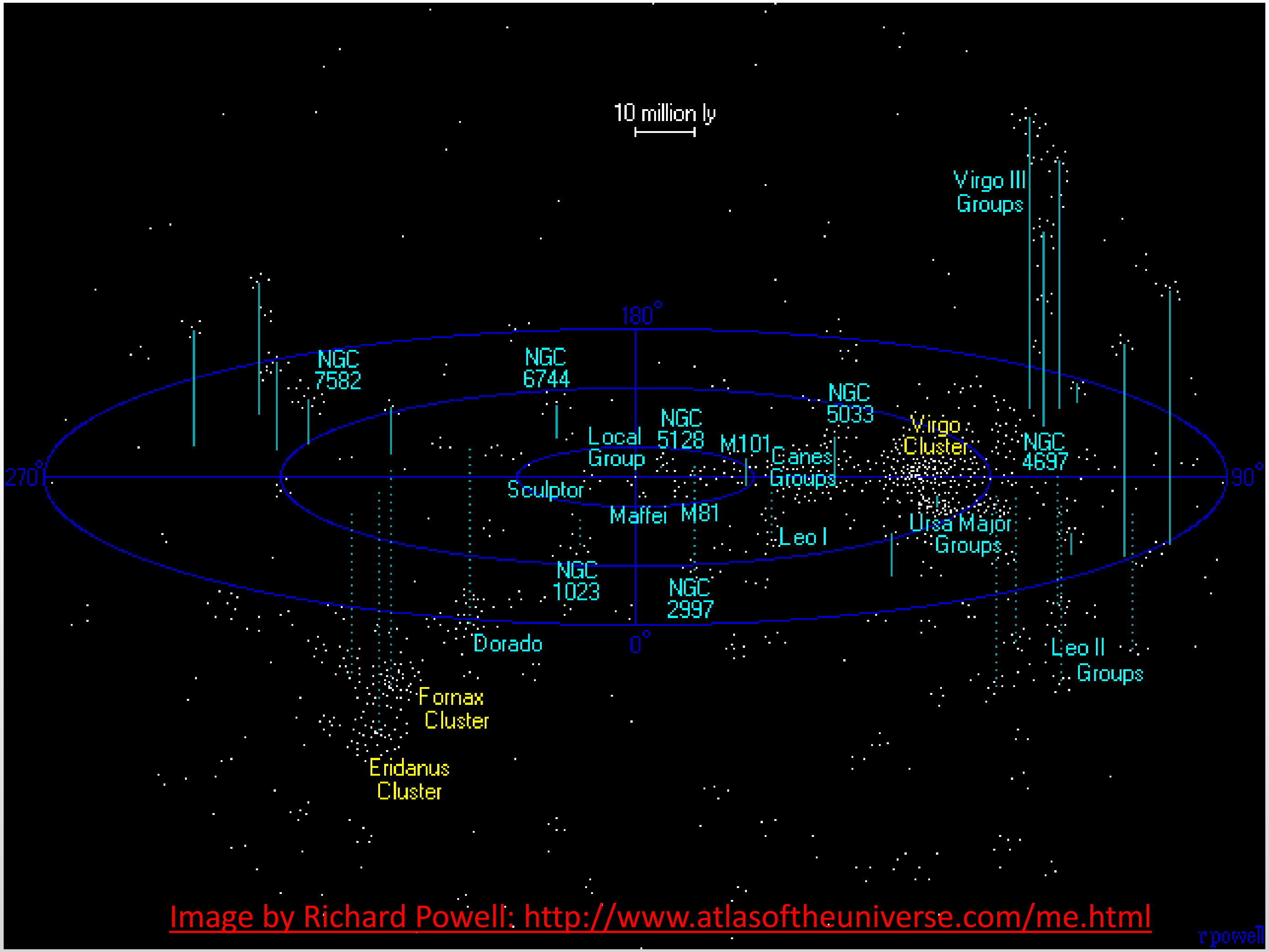
Virgo Cluster and beyond



Antonio Ciccolella / M. De Leo https://en.wikipedia.org/wiki/File:Hubble-aucouleurs.png

Our Milky Way: http://news.nationalgeographic.com/content/dam/news/rights-exempt/nat-geo-staff-graphics-illustrations/2016/02/eso1606a.ngsversion.1456410119606.jpg?01

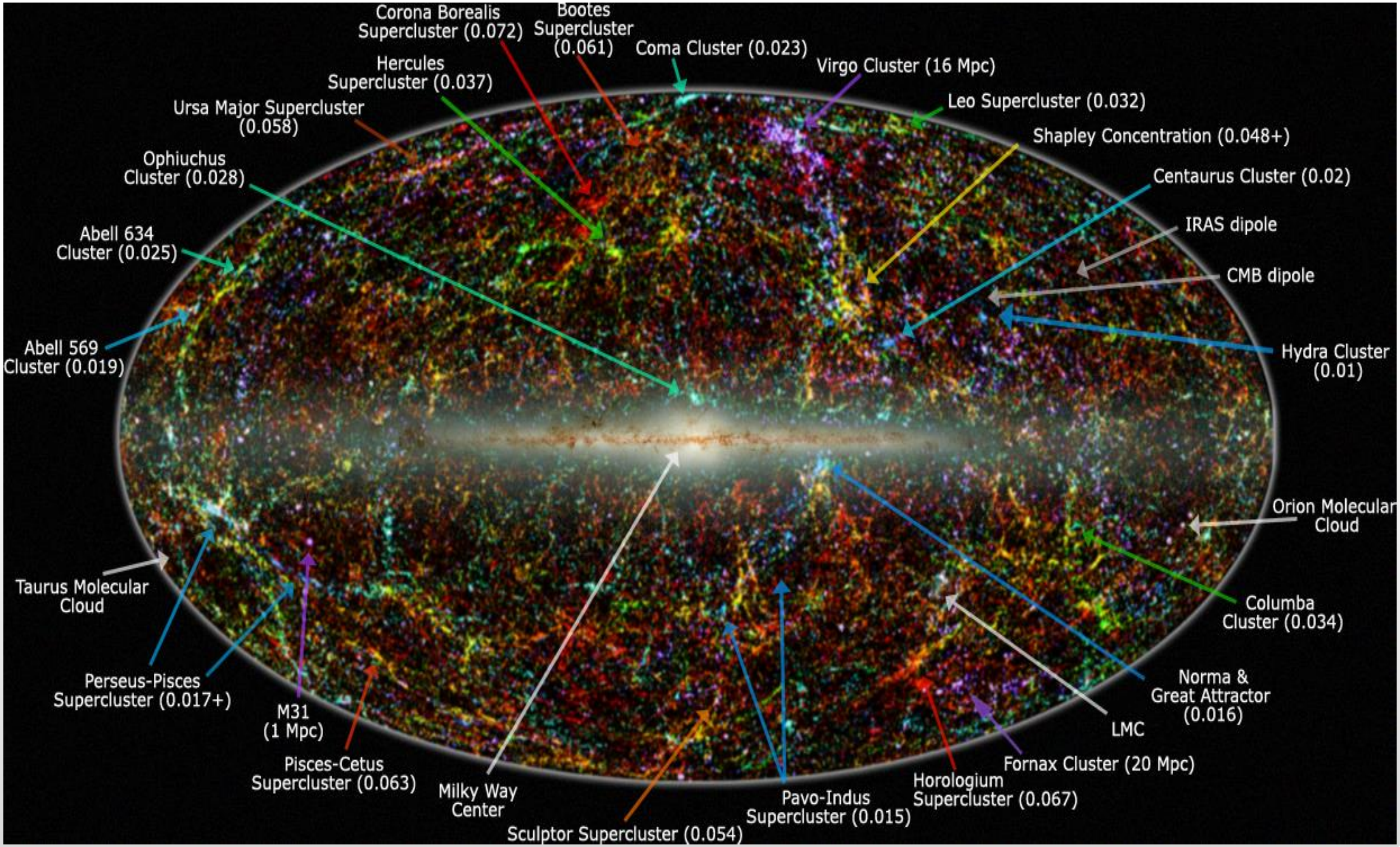
Virgo cluster and beyond



[Image by Richard Powell: http://www.atlasoftheuniverse.com/me.html](http://www.atlasoftheuniverse.com/me.html)

http://www.atlasoftheuniverse.com/12lys.html

Supercluster of clusters



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Supercluster of clusters

Redshift measures recessional velocity

Light emitted by a source that recedes from us is received with "***redder***" color than its emission. The wavelength $\boldsymbol{\lambda}$ of the light is lengthened by $\boldsymbol{\Delta\lambda}$.

We define the reddening by the "***Redshift***" ratio:

$$\boldsymbol{Z = \Delta\lambda/\lambda}$$

The redshift ratio is proportional to the velocity of recession from us, the observer.

The numbers in parentheses show the redshift of each group. All groups (except for 2) are receding from our Local Group!

Cosmological vs. Doppler Redshift

Redshift measures recessional velocity… but what is the reason for the recession?

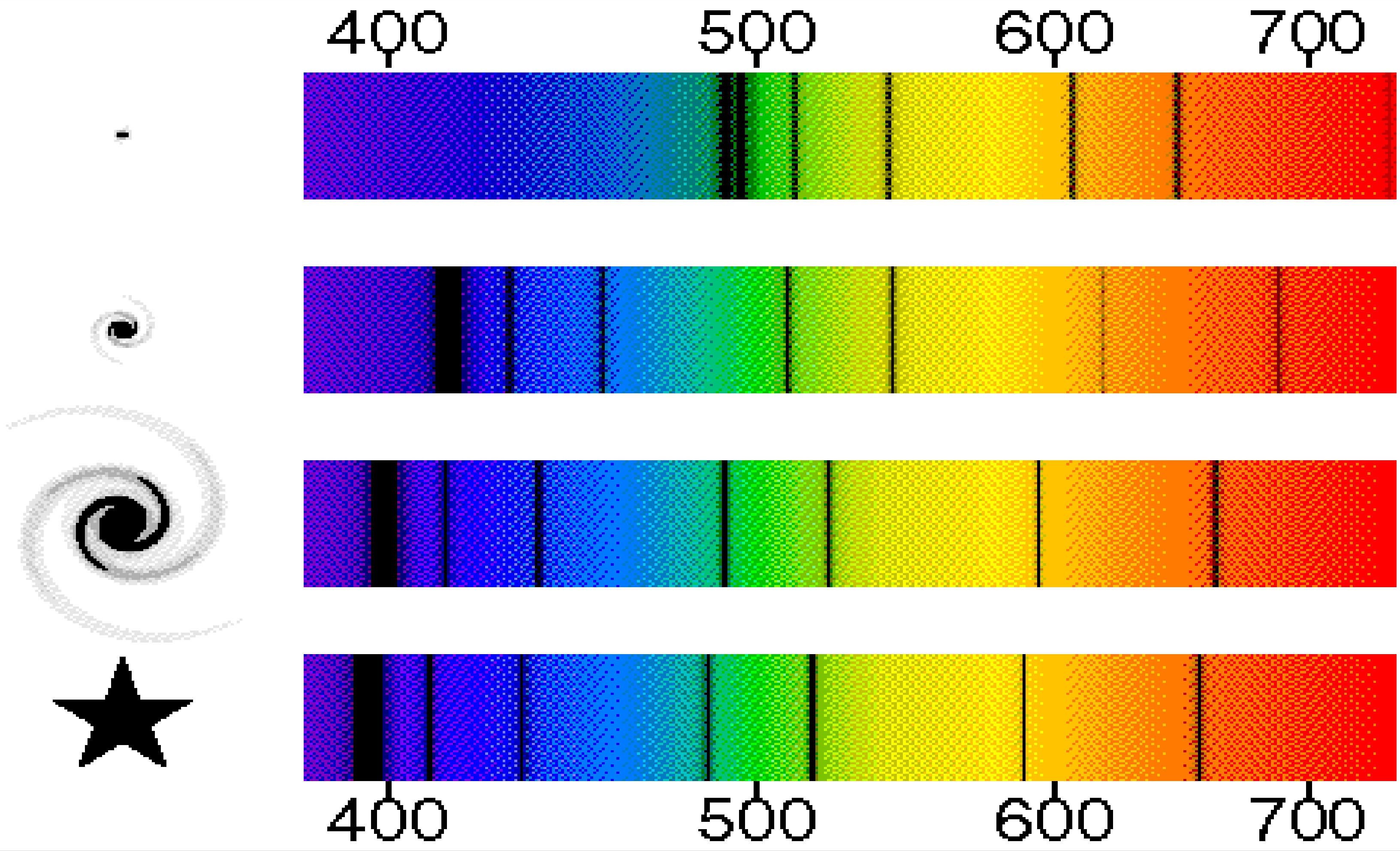
Our Big Bang cosmology describes an ***expansion of space***. Anything "stuck" in that space that is distant from us is seen to be moving away: ***Cosmological Redshift:***

$$\boldsymbol{v = cZ}$$

Within expanding space, anything that is moving with velocity relative to local space also contributes to colour variation: ***Doppler Shift*** (relativistic redshift):

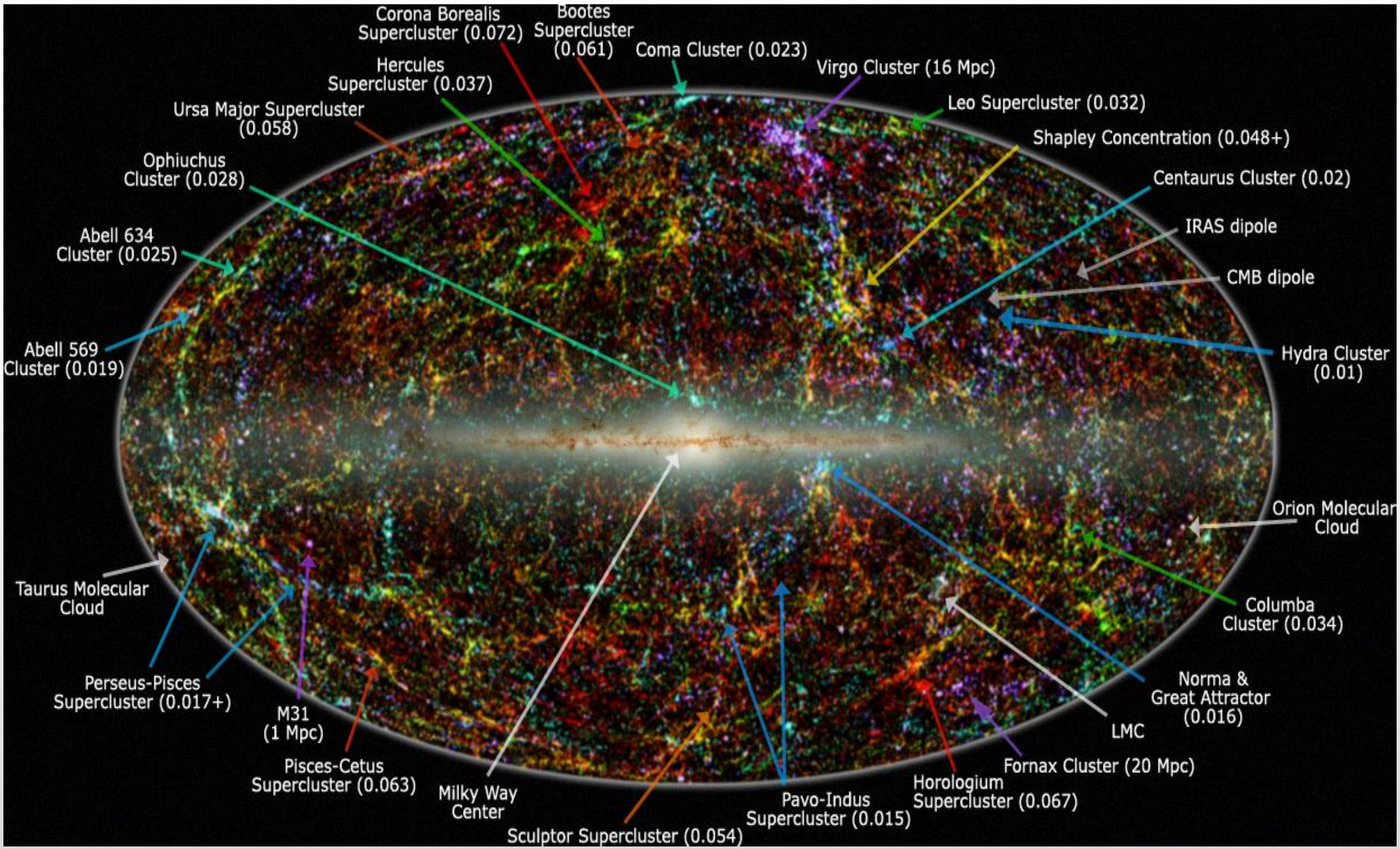
$$\boldsymbol{v = c\,[(Z+1)^2 - 1]/[(Z+1)^2 + 1]}$$

Cosmological vs. Doppler Redshift



http://www.astro.ucla.edu/%7Ewright/doppler.htm

Supercluster of clusters



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Hubble, redshift and age

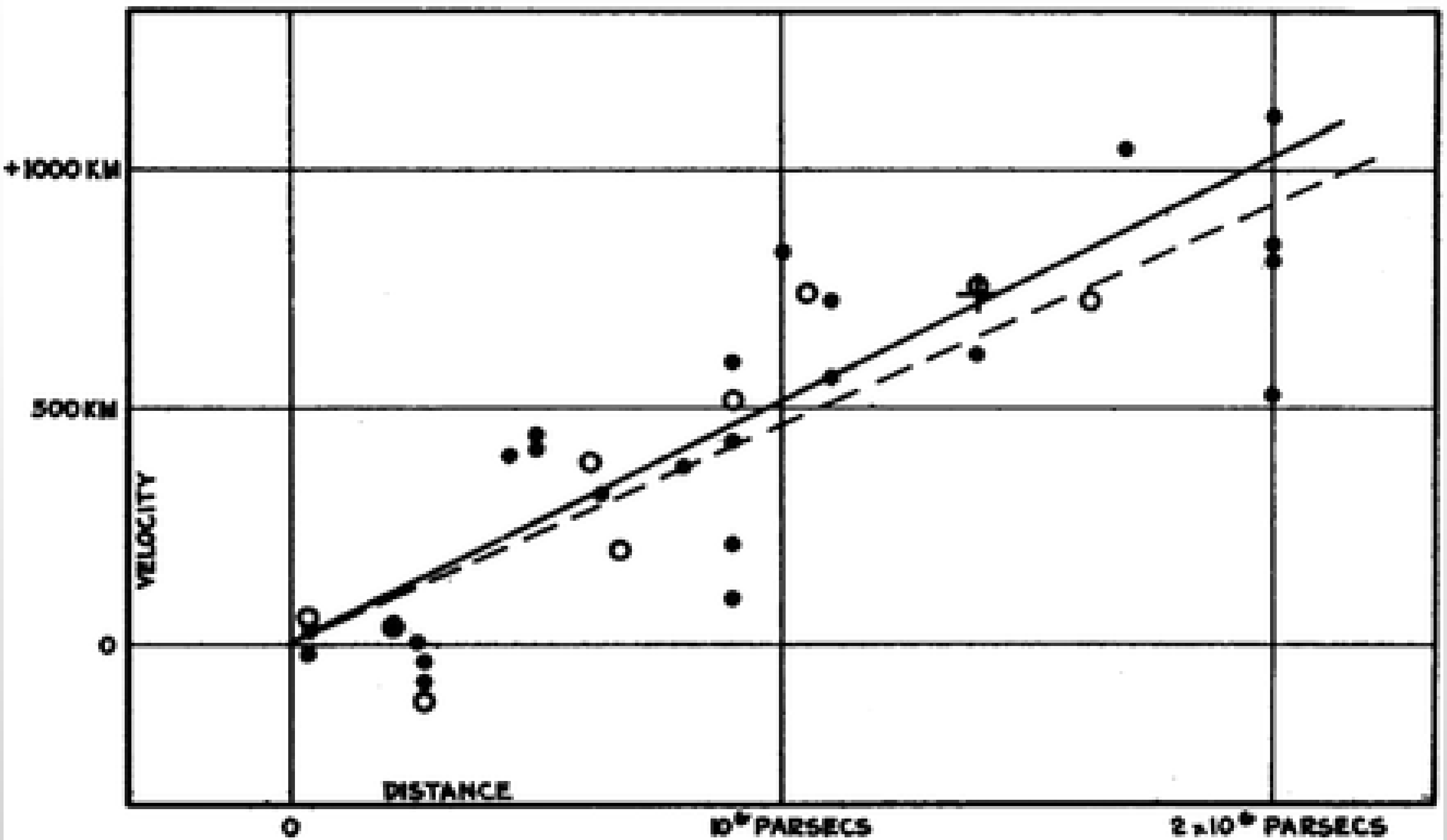
In the 1910s, astronomers (***Vesto Slipher***) had already noticed that known spectral lines such as the lines of sodium vapour absorption lines in the light emanating from the distant nebular clouds (later to be known to be Galaxies) tended to be more shifted towards the red end of the spectrum as they appeared smaller in the field of vision.

Edwin Hubble used the luminosity-period relationship of Cepheid variable stars that he and ***Henriette Leavitt*** had discovered to measure distances to many galaxies.

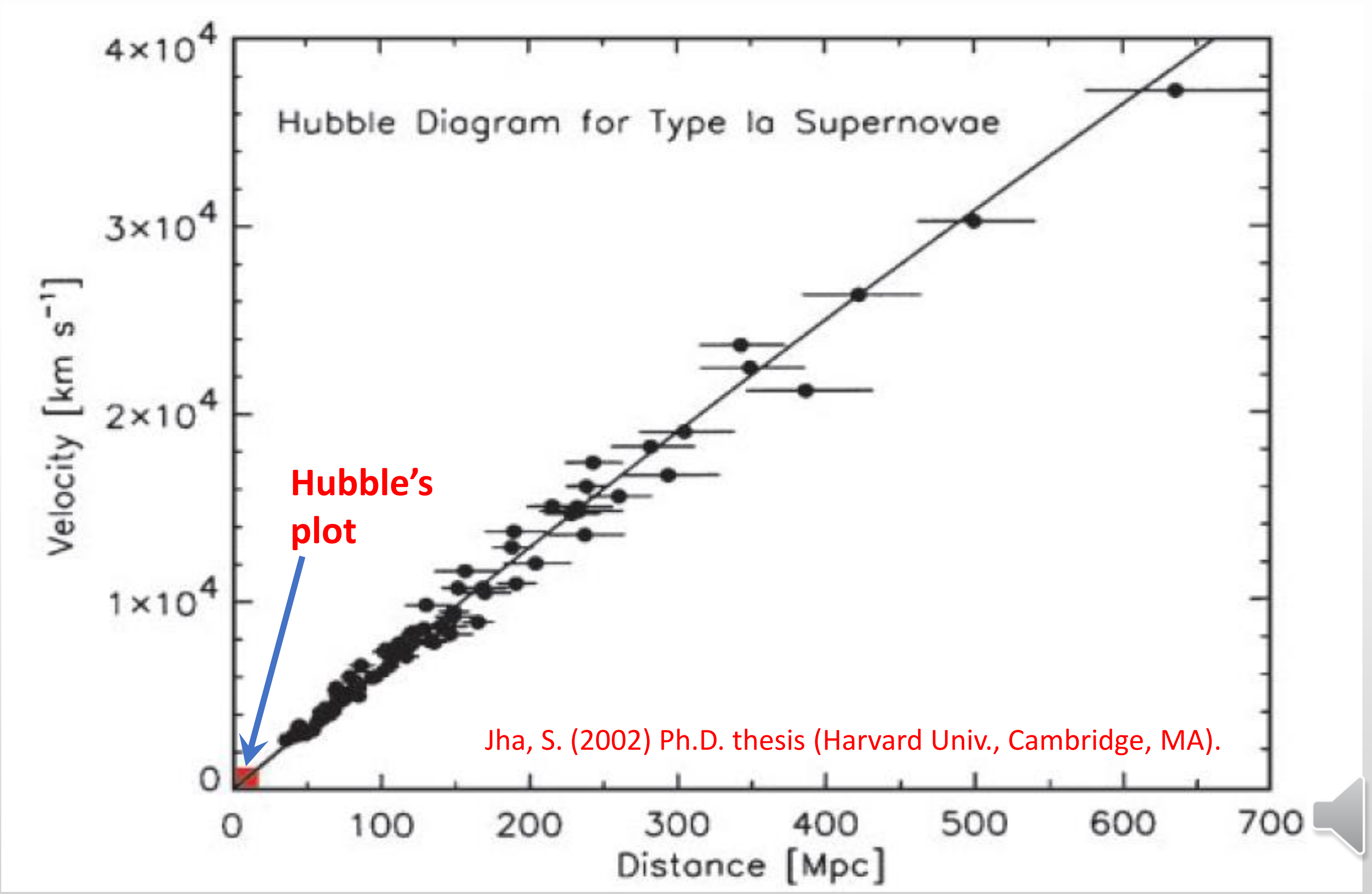
He compared the redshift of their spectra to their distances and found a nearly linear relationship recognizing that they were moving away from us.

Hubble, redshift and age

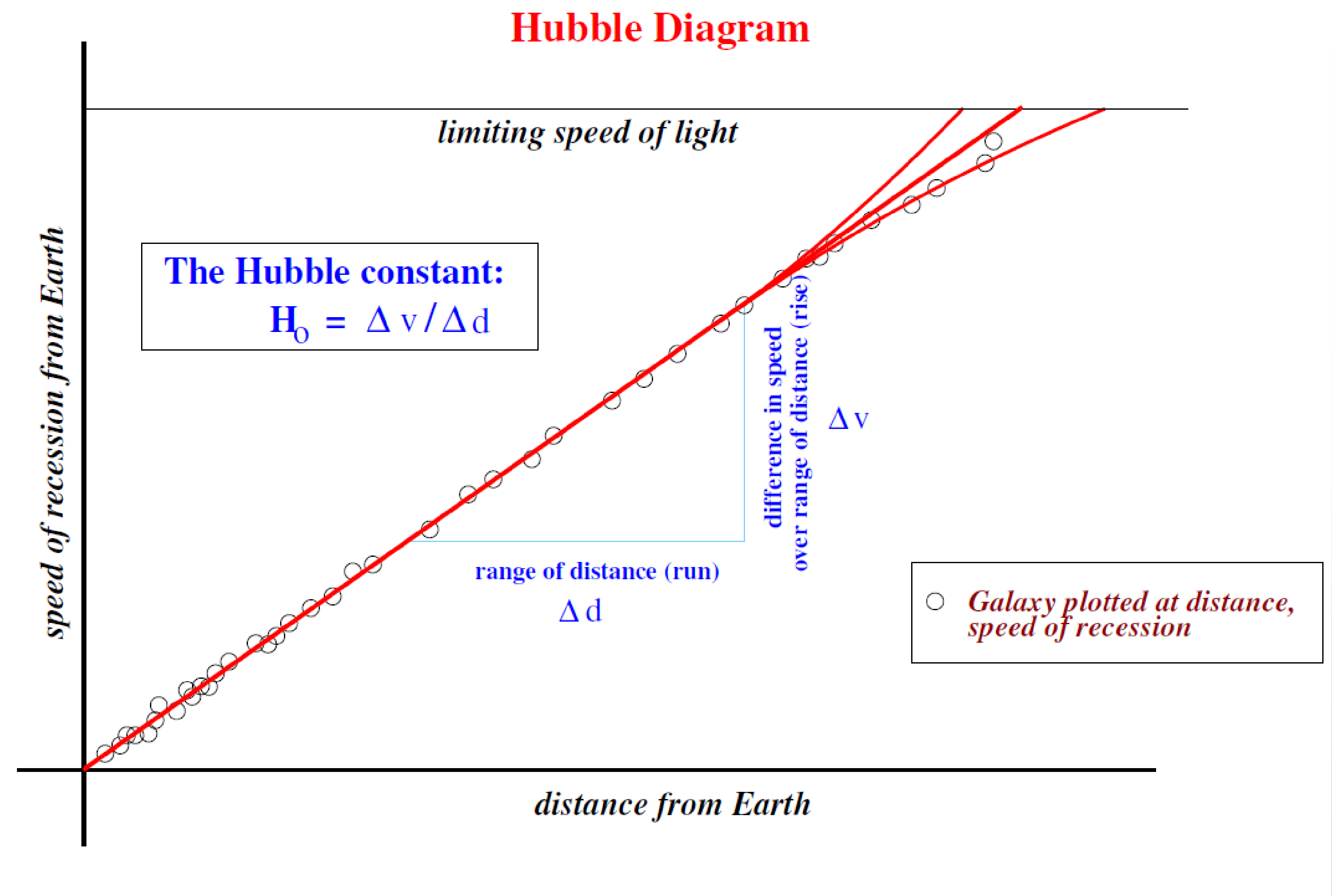
Velocity-Distance Relation among Extra-Galactic Nebulae.



Hubble, redshift and age



The Hubble Constant H_o



The Hubble Constant H_o

Determination of the current and recent value (that is, near the origin of diagram) of the slope gives us a Hubble constant of

H_o = 73.5 ± 1.4 km· s^{-1}/Mpc.

This constant has units of 1/time, its inverse units of time. That time is taken to be the ***"age"*** of the Universe:

12.717 ± 0.064 billion years.

Best fitting all astronomical observations to the ***Λ CDM Concordance model*** gives us a Hubble constant of

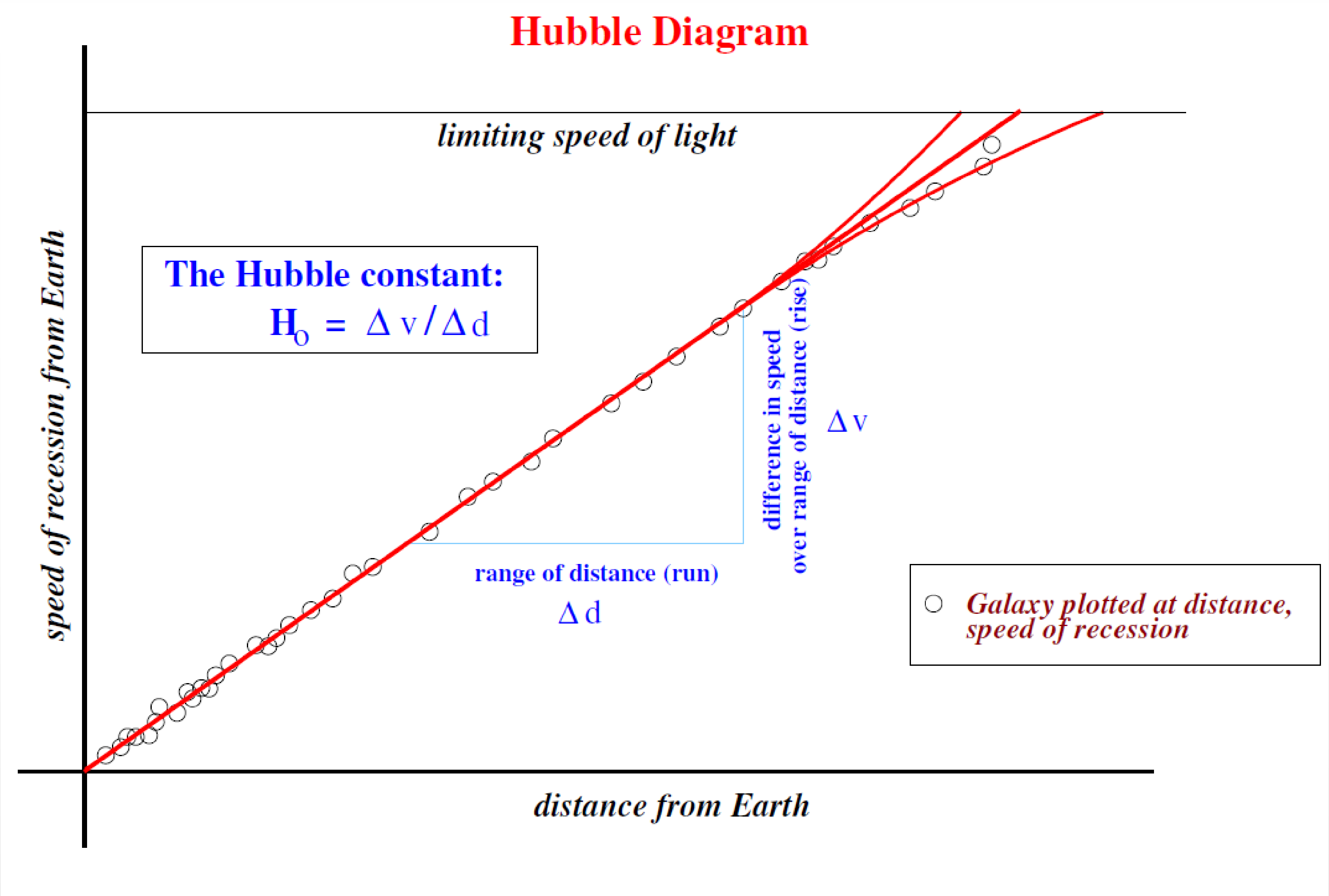
67.74 ± 0.46 km· s^{-1}/Mpc,

and the ***"age"*** of the Universe:

13.799 ± 0.021 billion years.

This accords with a **"radius"** (how far we can see from our perspective) of the "**Observable Universe"** of **4200 Mpc**.

The Hubble Constant H_o



The Hubble Constant H_o

You might recognize that the line that best fits the recession of galaxies is not a straight line – it curves. In the early region (farthest from us) of the Universe, expansion seems to have been slower that it is recently. This gives us two views of the expansion rate and hence the time since the beginning of observable expansion. Our current models of the Universe recognize an accelerated rate of expansion.

This leads us to offer different "age" of the Universe depending upon where we weight the data. The ***Λ CDM Concordance model*** weights early, from the ***CMB*** and evolves to the present (age ~13.798 billion years). Another community of astrophysicists weights late and locally (age ~12.717 billion years).

The Hubble constant: a mystery that keeps getting bigger

Our Milky Way

http://news.nationalgeographic.com/content/dam/news/rights-exempt/nat-geo-staff-graphics-illustrations/2016/02/eso1606a.ngsversion.1456410119606.jpg?01

Our Milky Way

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