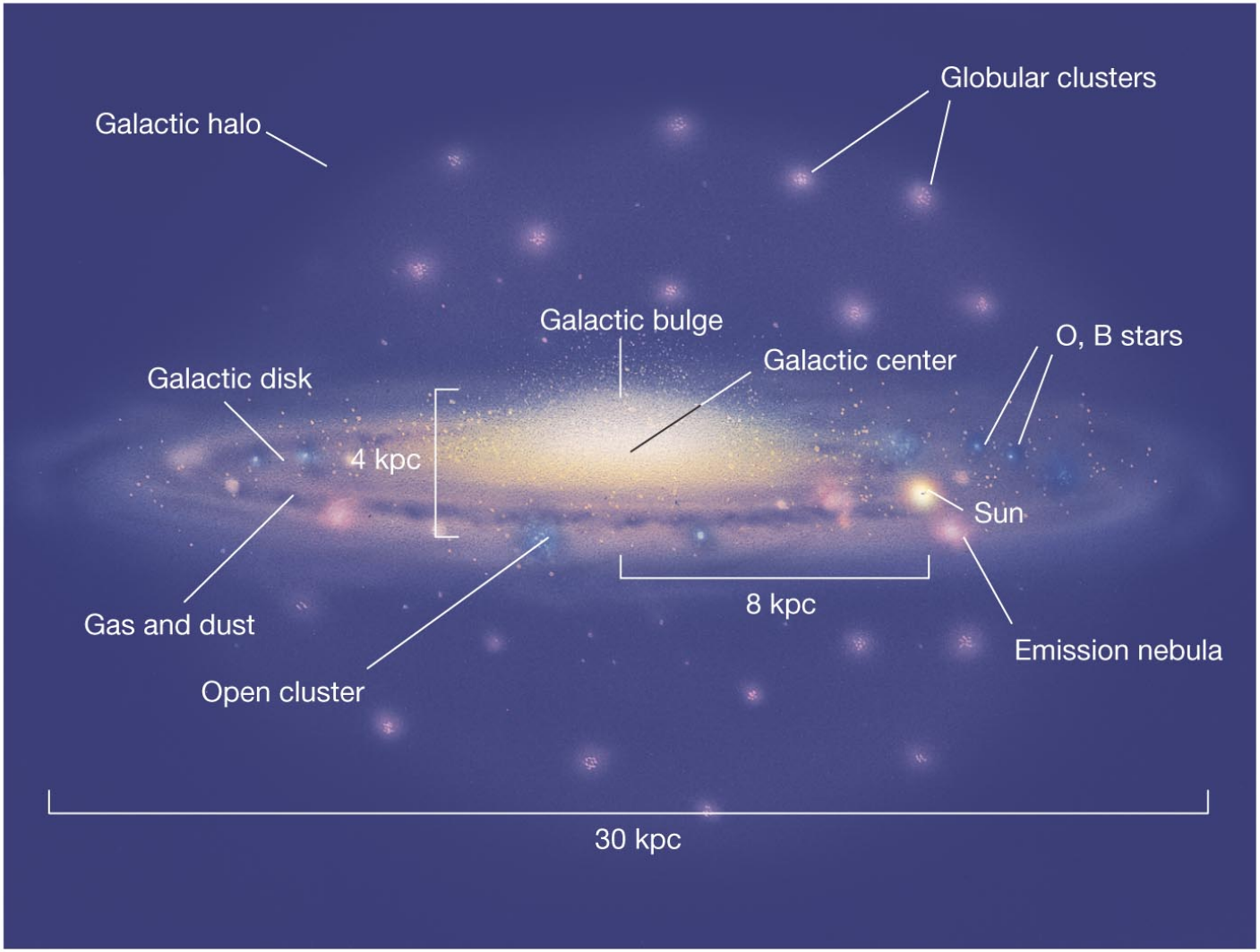
From Lecture 11

Milky Way Structure II



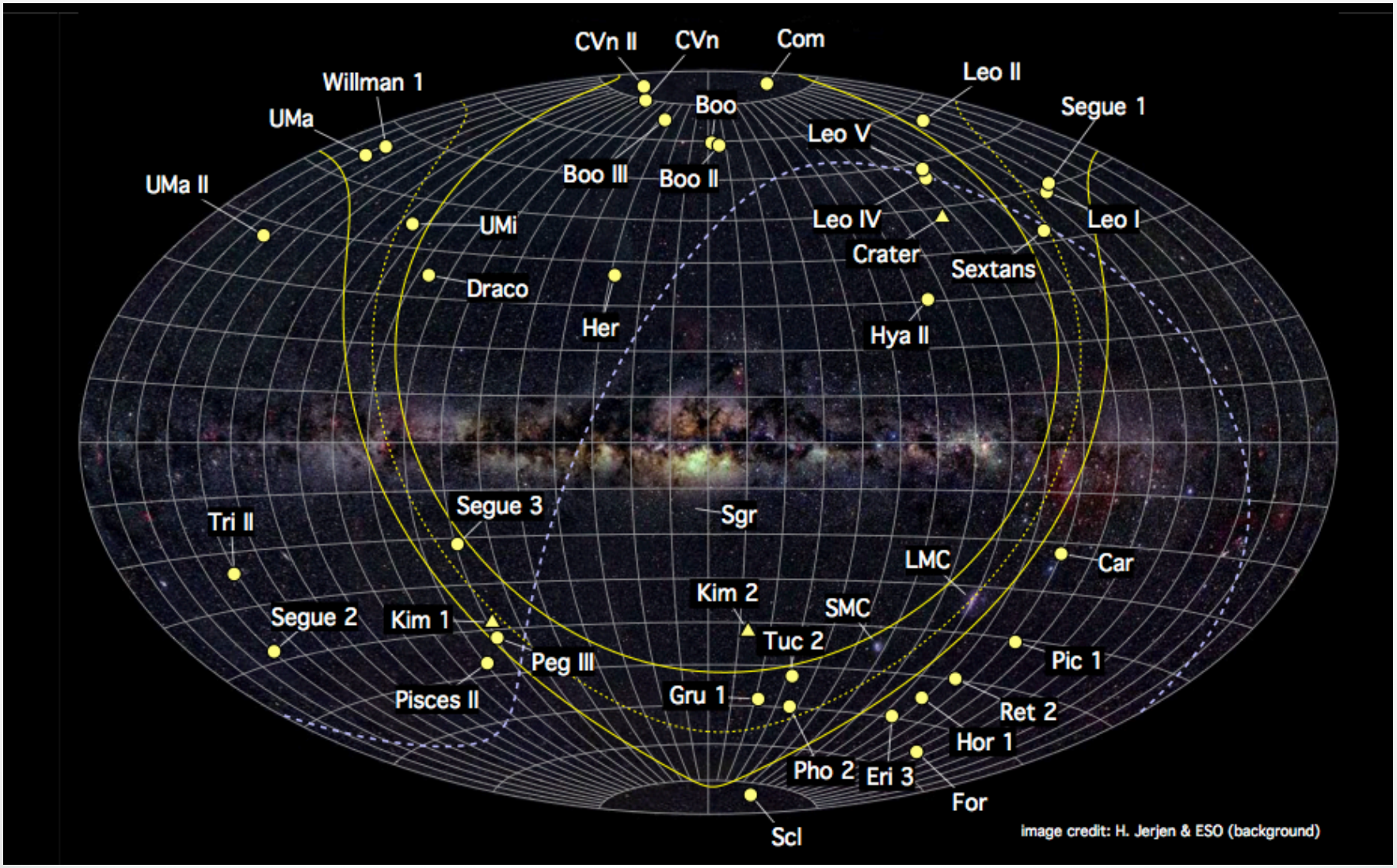

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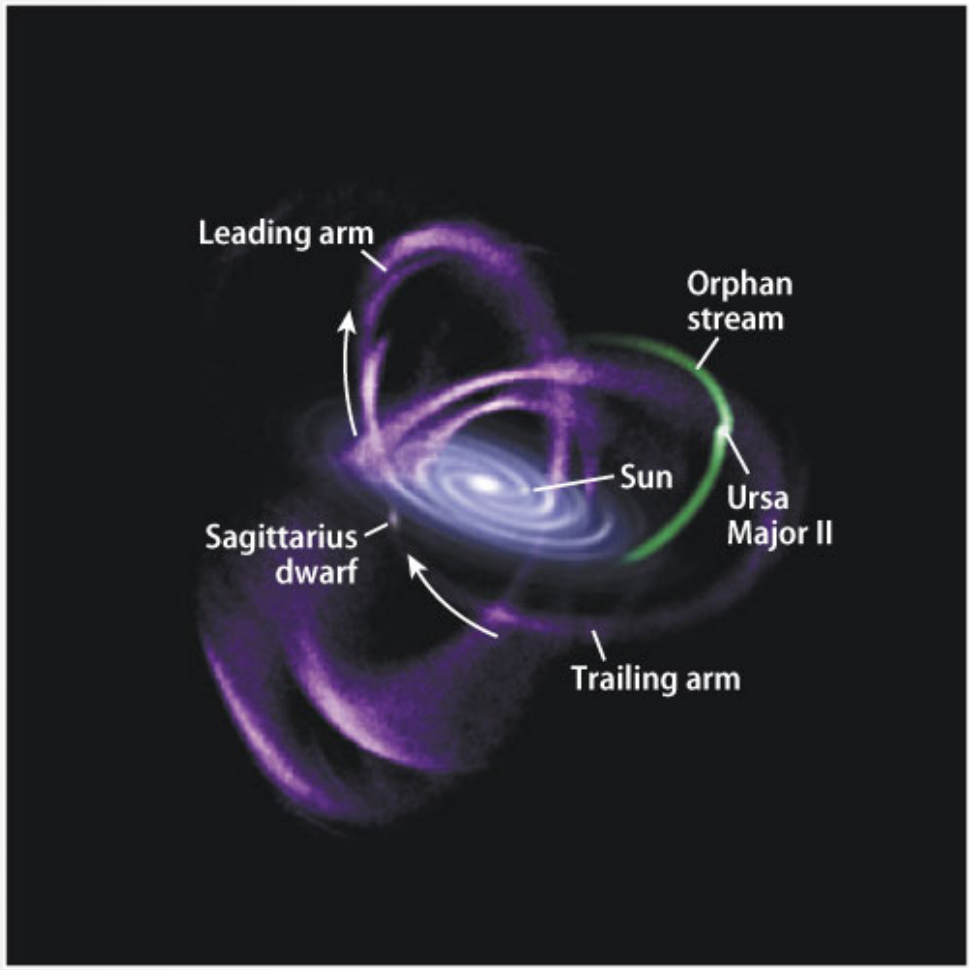
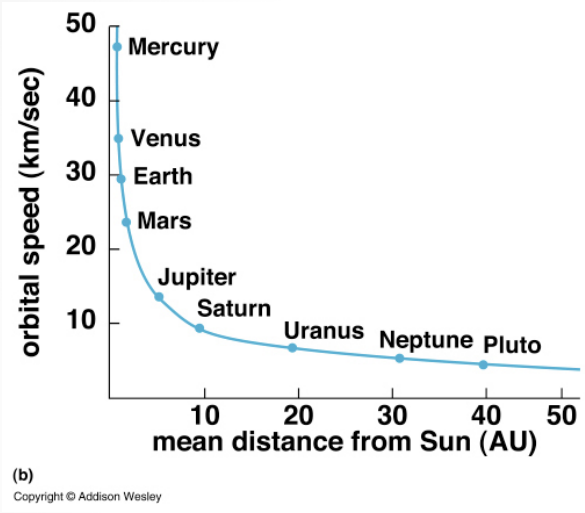
image credit: H. Jerjen & ESO (background)

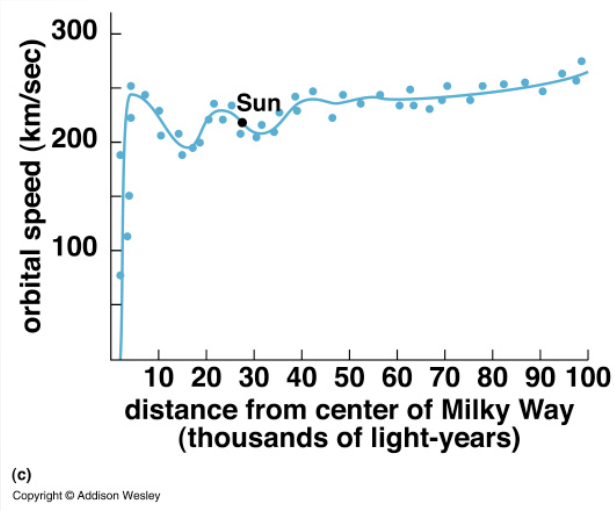
Tidal Streams



- The tidal streams can be very long lived and trace out the orbit of the shredded dwarf/cluster
- We can learn much about the gravitational potential of the Milky Way Galaxy by the behavior of the tidal streams.

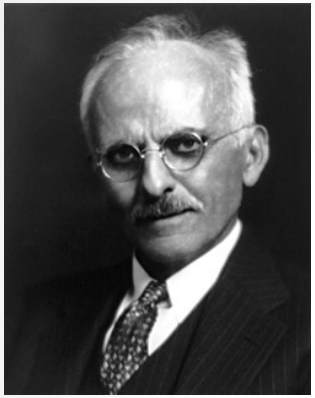
Dark Matter in the Local group





- The orbit speed of the planets follow "Kepler's" Laws for a system with strongly centralized mass
- The orbit speed vs radius plot for the Galaxy was recognized to be very different starting 40 years ago

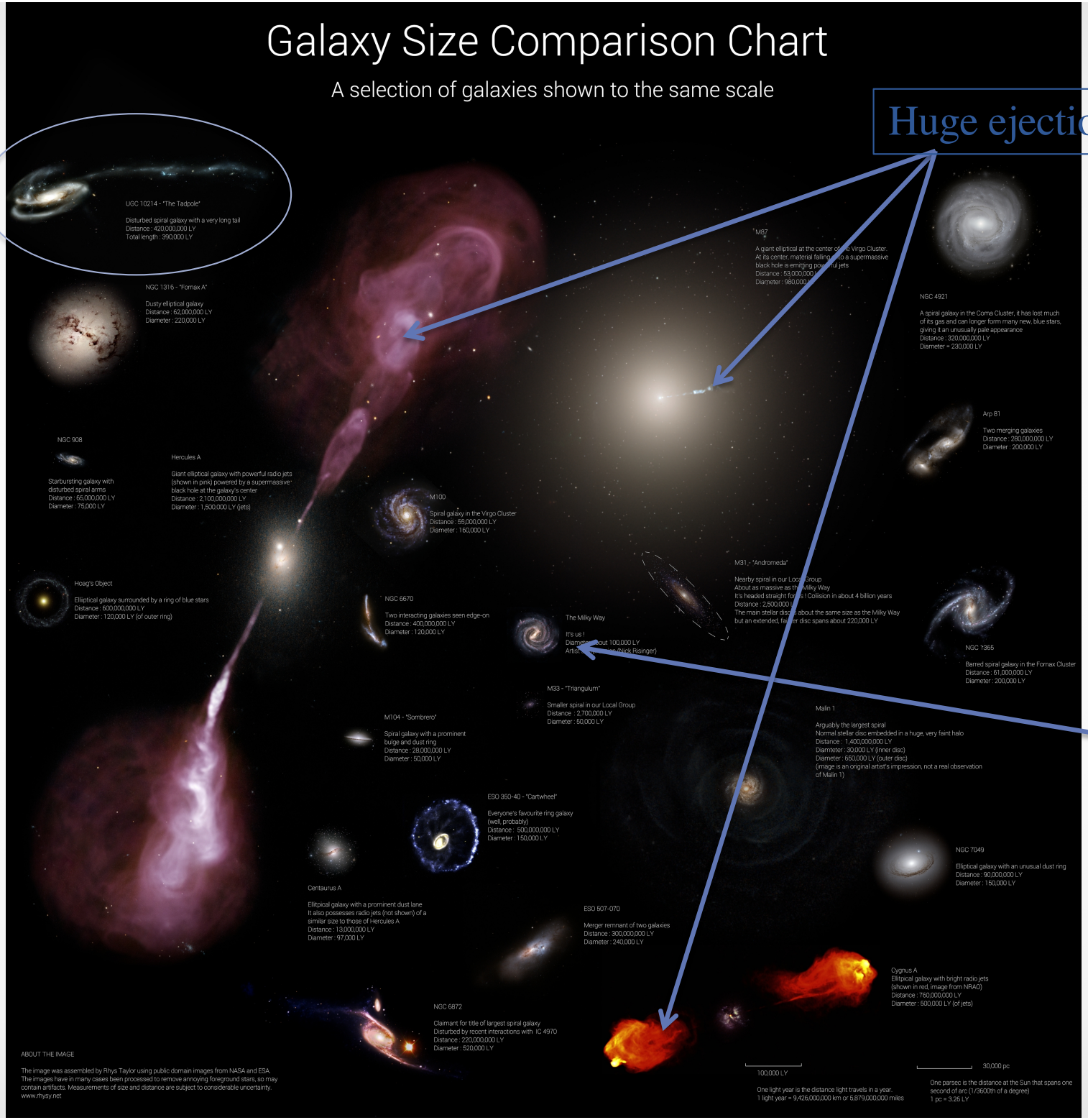
The Great Debate 1920



Herber Curtis

Harlow Shapley

- The question of whether the Galaxy was the entire Universe or just one of millions of "island universes" was the subject of a famous debate in 1920
- Issues were about the distance scale, novae, supernovae and bad data


Galaxy Size Comparison Chart
A selection of galaxies shown to the same scale
Huge ejections of gas
Milky Way Galaxy
UGC 10214 - "The Tadpole"
Disturbed spiral galaxy with a very long tail
Distance : 420,000,000 LY
Total length : 390,000 LY
NGC 1316 - "Fornax A"
Dusty elliptical galaxy
Distance : 62,000,000 LY
Diameter : 220,000 LY
M87
A giant elliptical at the center of the Virgo Cluster.
At its center, material falling into a supermassive
black hole is emitting powerful jets
Distance : 53,000,000 LY
Diameter : 980,000 LY
NGC 4921
A spiral galaxy in the Coma Cluster, it has lost much
of its gas and can longer form many new, blue stars,
giving it an unusually pale appearance
Distance : 320,000,000 LY
Diameter = 230,000 LY
Arp 81
Two merging galaxies
Distance : 280,000,000 LY
Diameter : 200,000 LY
NGC 908
Starbursting galaxy with
disturbed spiral arms
Distance : 65,000,000 LY
Diameter : 75,000 LY
Hercules A
Giant elliptical galaxy with powerful radio jets
(shown in pink) powered by a supermassive
black hole at the galaxy's center
Distance : 2,100,000,000 LY
Diameter : 1,500,000 LY (jets)
M100
Spiral galaxy in the Virgo Cluster
Distance : 55,000,000 LY
Diameter : 160,000 LY
Hoag's Object
Elliptical galaxy surrounded by a ring of blue stars
Distance : 600,000,000 LY
Diameter : 120,000 LY (of outer ring)
NGC 6670
Two interacting galaxies seen edge-on
Distance : 400,000,000 LY
Diameter : 120,000 LY
The Milky Way
It's us !
Diameter : about 100,000 LY
Artist : (Nick Risinger)
M31 - "Andromeda"
Nearby spiral in our Local Group
About as massive as the Milky Way
It's headed straight for us ! Collision in about 4 billion years
Distance : 2,500,000 LY
The main stellar disc is about the same size as the Milky Way
but an extended, fainter disc spans about 220,000 LY
NGC 1365
Barred spiral galaxy in the Fornax Cluster
Distance : 61,000,000 LY
Diameter : 200,000 LY
M33 - "Triangulum"
Smaller spiral in our Local Group
Distance : 2,700,000 LY
Diameter : 50,000 LY
M104 - "Sombrero"
Spiral galaxy with a prominent
bulge and dust ring
Distance : 28,000,000 LY
Diameter : 50,000 LY
Malin 1
Arguably the largest spiral
Normal stellar disc embedded in a huge, very faint halo
Distance : 1,400,000,000 LY
Diameter : 30,000 LY (inner disc)
Diameter : 650,000 LY (outer disc)
(image is an original artist's impression, not a real observation
of Malin 1)
ESO 350-40 - "Cartwheel"
Everyone's favourite ring galaxy
(well, probably)
Distance : 500,000,000 LY
Diameter : 150,000 LY
NGC 7049
Elliptical galaxy with an unusual dust ring
Distance : 90,000,000 LY
Diameter : 150,000 LY
Centaurus A
Elliptical galaxy with a prominent dust lane
It also possesses radio jets (not shown) of a
similar size to those of Hercules A
Distance : 13,000,000 LY
Diameter : 97,000 LY
ESO 507-070
Merger remnant of two galaxies
Distance : 300,000,000 LY
Diameter : 240,000 LY
Cygnus A
Elliptical galaxy with bright radio jets
(shown in red, image from NRAO)
Distance : 760,000,000 LY
Diameter : 500,000 LY (of jets)
NGC 6872
Claimant for title of largest spiral galaxy
Disturbed by recent interactions with IC 4970
Distance : 220,000,000 LY
Diameter : 520,000 LY
ABOUT THE IMAGE
The image was assembled by Rhys Taylor using public domain images from NASA and ESA.
The images have in many cases been processed to remove annoying foreground stars, so may
contain artifacts. Measurements of size and distance are subject to considerable uncertainty.
www.rhysy.net
100,000 LY
One light year is the distance light travels in a year.
1 light year = 9,426,000,000 km or 5,879,000,000 miles
30,000 pc
One parsec is the distance at the Sun that spans one
second of arc (1/3600th of a degree)
1 pc = 3.26 LY

QSO and AGN

- There are now more than 200,000 QSOs known out to 12 billion light years
- Widely accepted model is that they are supermassive black holes at the centers of galaxies in an "active phase" of mass accretion
- Lower luminosity, more nearby systems have also been identified and are labeled "Active Galactic Nuclei"

Iclicker

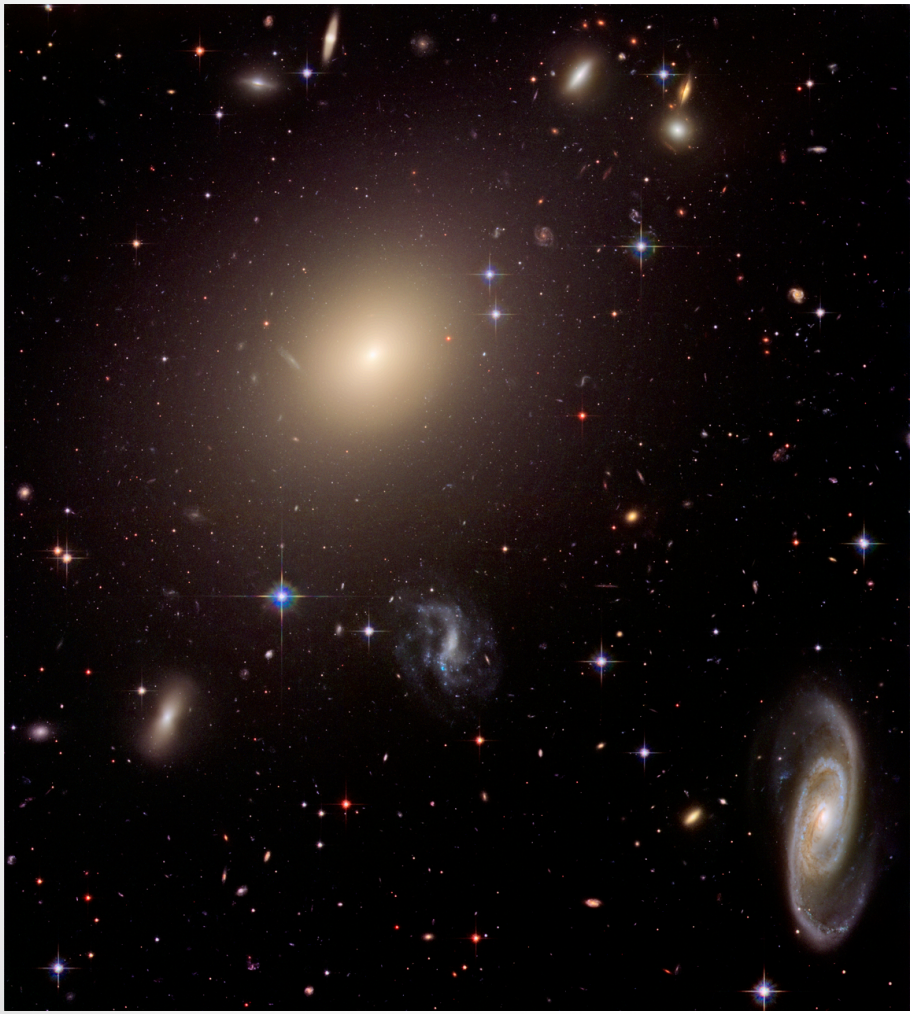
Which of the following best describes why we think there many be a dominant dark matter component in the Galaxy?

A. Dwarf galaxy companions have been discovered that are in the process of being tidally shredded
B. The 4×10^6 M_{sun} black hole in the center of the Galaxy dominates the gravity and dynamics of the Galaxy
C. The spiral density waves in the disk of the Galaxy are excited by dark matter particles
D. The rotation speed of stars in the outer parts of the Galaxy are much too high to be explained only by the stars and gas seen by their light emission

New material: The Expansion of the Universe

- Doppler shift
- Galaxy velocities
- The Extra-galactic distance scale

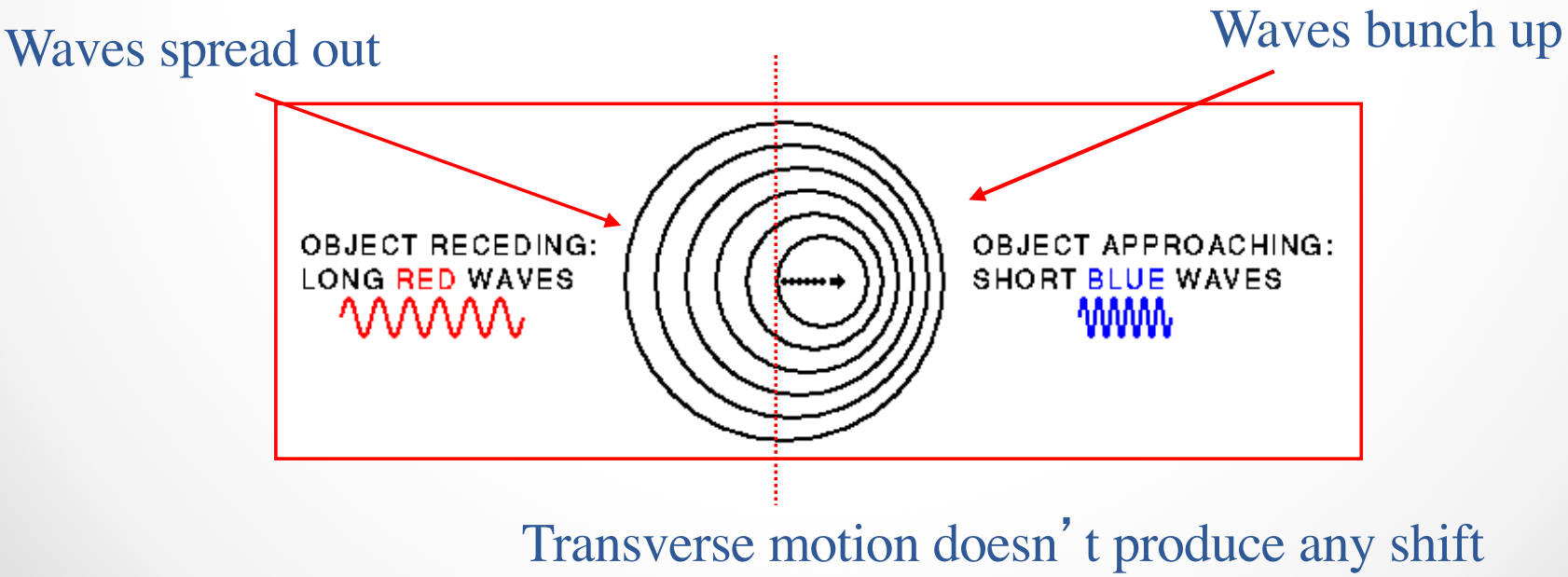
1925



- The Universe was vast and contained many (at least 100's of thousands) galaxies of different types
- Telescopes had grown in size (60" and 100" at Mt Wilson) and it became feasible to get *spectra* of galaxies

The Doppler Shift

- If a light source is moving toward or away from an observer (or visa versa) the *speed* of the light doesn't change, but the frequency/wavelength does.



- The change in wavelength due to a relative radial motion is called the *Doppler Shift*.

$$\frac{\lambda_0 - \lambda_v}{\lambda_0} = \frac{v}{c}$$

λ_0= `rest' wavelength

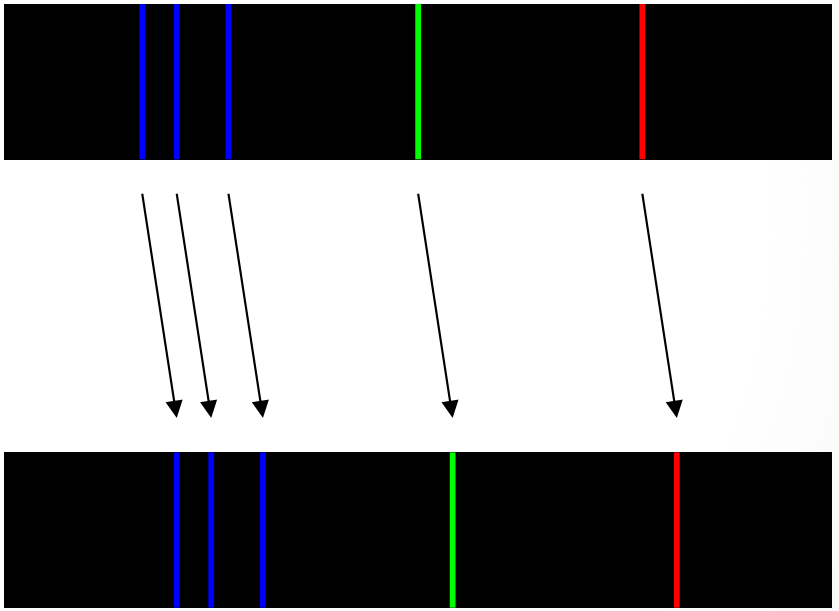
λ_v= wavelength at speed `v'

v = speed toward or away from observer

c = speed light

Doppler Movie

Hydrogen Balmer series



Doppler Shift Example

- You are busy talking on your cell phone and drive through a red light. You claim that because you were approaching the traffic light, it was Doppler shifted and looked green. How fast would you have to have been going?

$$\frac{\lambda_0 - \lambda_v}{\lambda_0} = \frac{v}{c}$$

$$\frac{\lambda_0 - \lambda_v}{\lambda_0} \times c = v$$

$$\left(\frac{600nm - 500nm}{600nm}\right) \times \left(3 \times 10^5 \text{km/sec}\right) = v = 50{,}000 \text{km/sec}$$

$$= 110{,}000{,}000 \text{miles/hr}$$

600nm = rest wavelength of red light
500nm = wavelength of green light
$3x10^5$ km/sec = speed of light
V > speed limit

Motions of Galaxies

- 1912 Vesto Slipher at Lowell Observatory made the first Doppler shift measurement of what turned out to be an extra-galactic "spiral nebula"
- Made possible by a new "fast" camera and speed gain of a factor of 30
- Andromeda (M31) was approaching the Galaxy at 300 km/sec

The Observatory

LOWELL OBSERVATORY

BULLETIN No. 58

VOL. II No. 8

THE RADIAL VELOCITY OF THE ANDROMEDA NEBULA

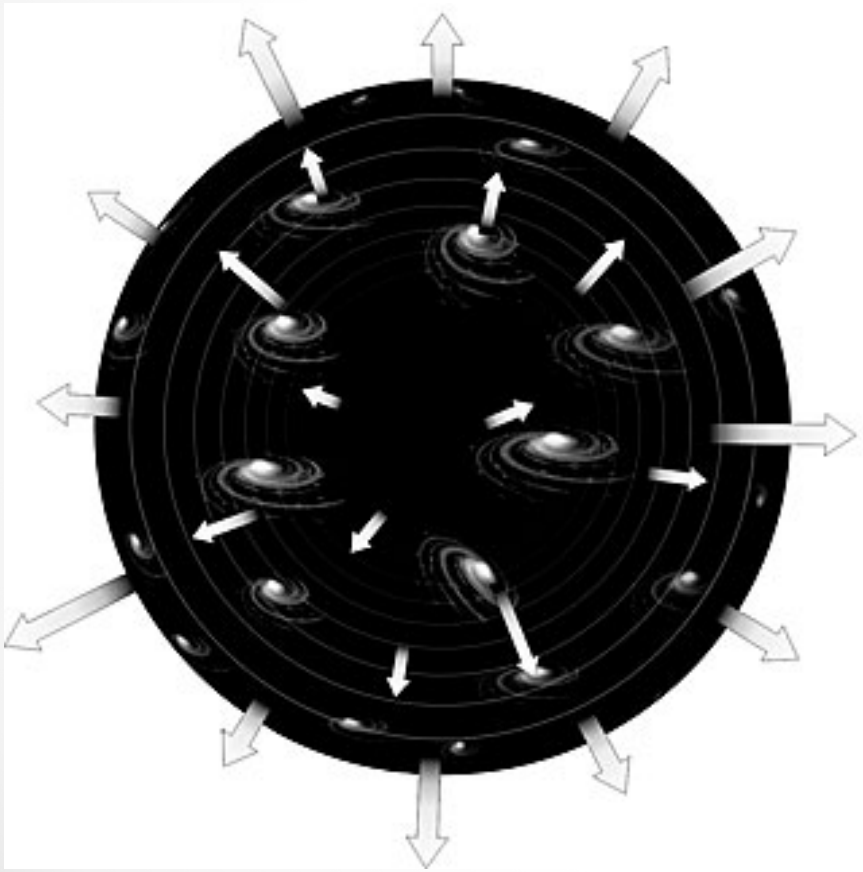
Keeler, by his splendid researches on the nebulæ, showed, among other things, that the nebulæ are generally spiral in form, and that such nebulæ exist in far vaster numbers than had been supposed. These facts seem to suggest that the spiral nebula is one of the important products of the forces of nature. The spectra of these objects, it was recognized, should convey valuable information, and they have been studied, photographically, first by Huggins and Scheiner, and recently more extensively by Fath and Wolf; but no attempt has to my knowledge been made to determine their radial velocity, although the value of such observations has doubtless occurred to many investigators.

The one obstacle in the way of the success of this undertaking is the faintness of these nebulæ. The extreme feebleness of their dispersed light is difficult to realize by

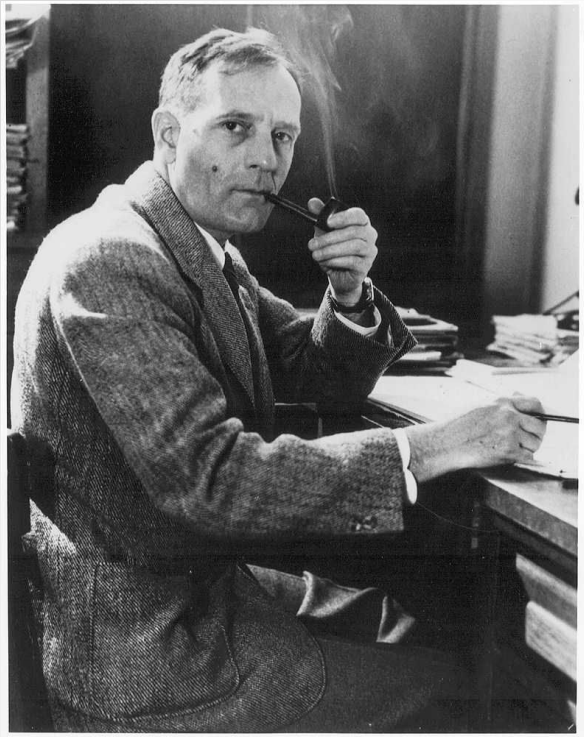
ters. When making this exposure the brightness of the nebula on the slit-plate compared with that of the clusters indicated that one night's exposure should suffice for the single-prism, and suggested that, by extending the exposure through several nights, one could employ the battery of three dense flint prisms whose dispersion would make it possible to observe the velocity of the nebula. The success of the plate bore out this suggestion. Indeed, upon subsequent examination of this plate it was seen that the nebular lines were perceptibly displaced with reference to the comparison lines. The next plate secured showed the same displacement. Still other single-prism plates were obtained during the autumn and early winter, but the observing program with the 24-inch telescope did not allow an opportunity to carry out the original plan to make the longer exposure spectrogram with the prism-train.

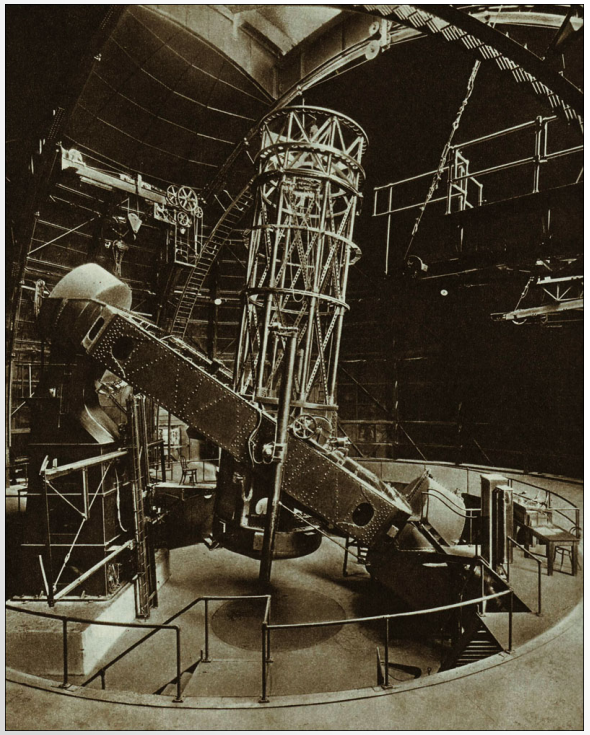
The magnitude of this velocity, which is the greatest hitherto observed, raises the question whether the velocity-like displacement might not be due to some other cause, but I believe we have at the present no other interpretation for it. Hence we may conclude that the Andromeda Nebula is approaching the solar system with a velocity of about 300 kilometers per second.

Slipher 1912-1917



- Slipher continued to obtain spectra of extra-galactic nebulae:
  - 22 of 25 had red-shifted spectra (indicating the galaxies were moving away)
  - Found larger and larger velocities. Record became 2000 km/sec recession speed

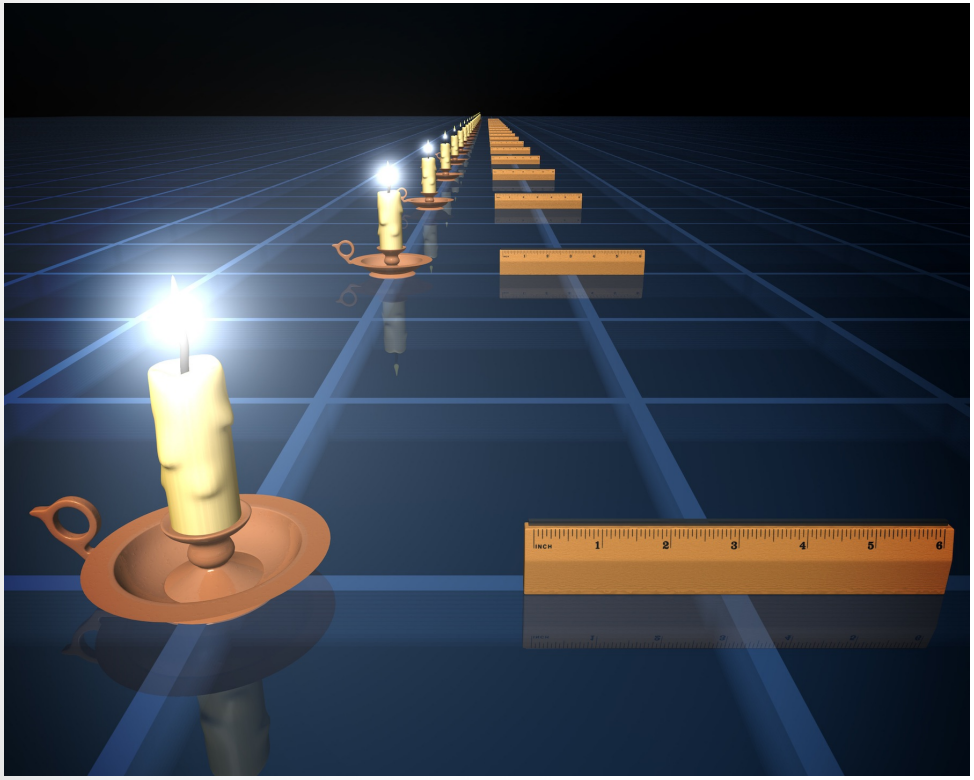




Humason and Hubble

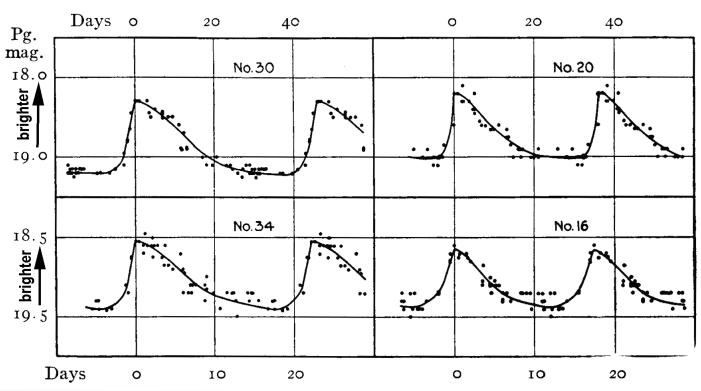
- Spectral observations of galaxies were pursued by Milton Humason and Edwin Hubble, using the largest telescope in the world, the 100-inch reflector at Mt Wilson
- Measured additional redshifts and estimated *distances* to galaxies

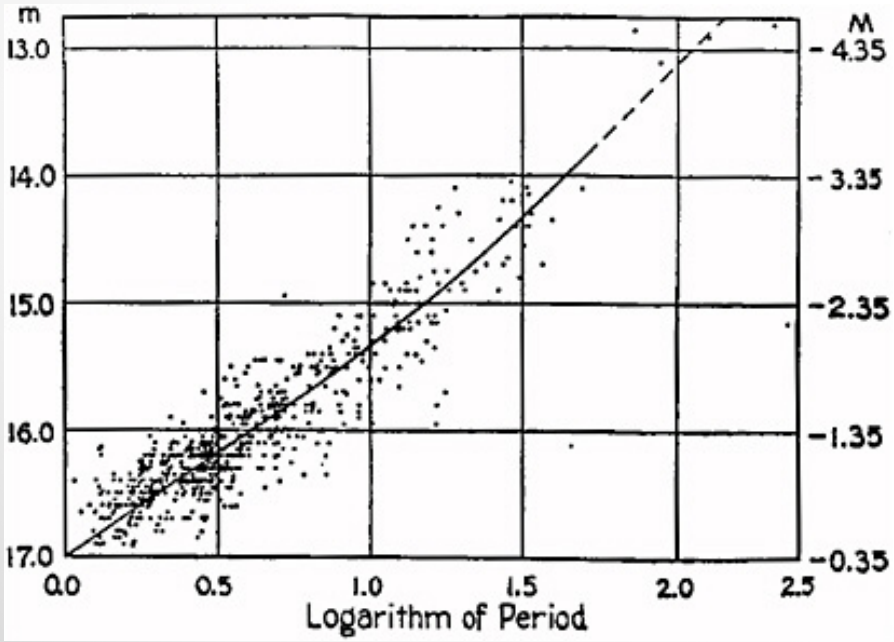
Extra-Galactic Distance Scale



- Beyond where trigonometric parallax can be used to to measure distances you need to have "Standard Candles"
- If there is a type of object with a known *intrinsic luminosity* its distance can be estimated based on its *apparent brightness* using the inverse square law for dimming

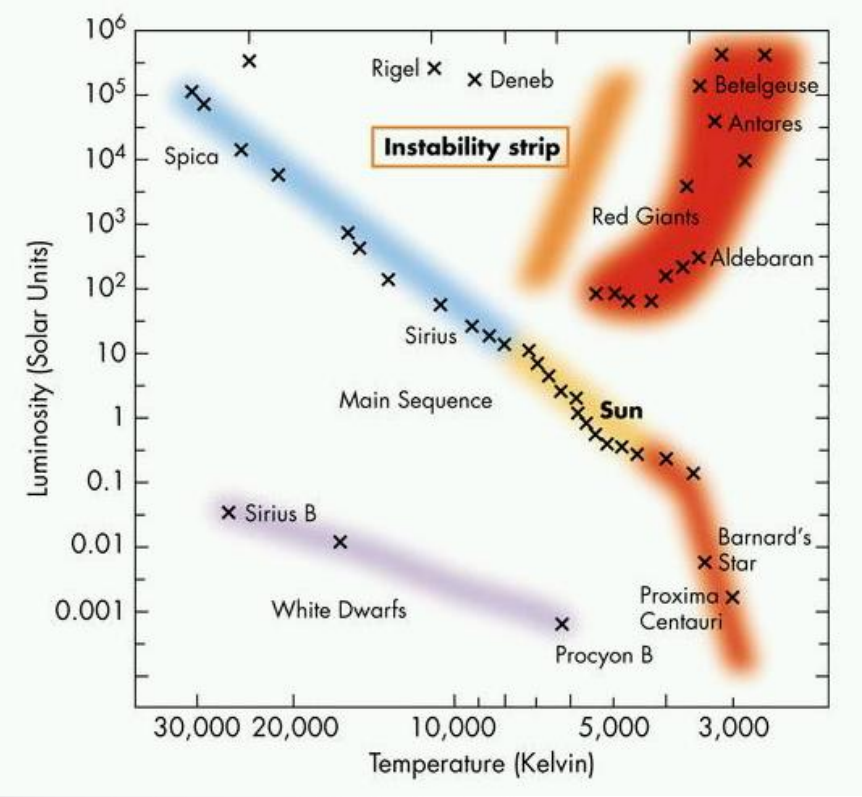
Cepheid Variables



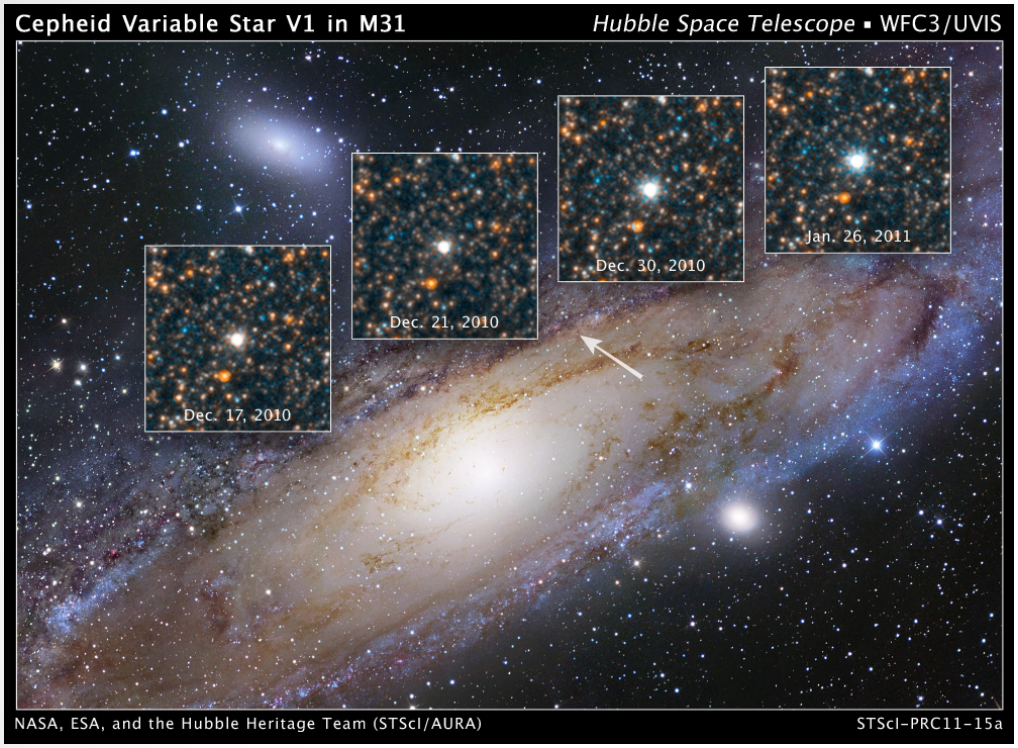


- 1908 Henrieta Swope at Harvard College published a paper noting that for a particular type of star called a Cepheid Variable the period of variability was related to the maximum brightness of the stars

Cepheid Variables

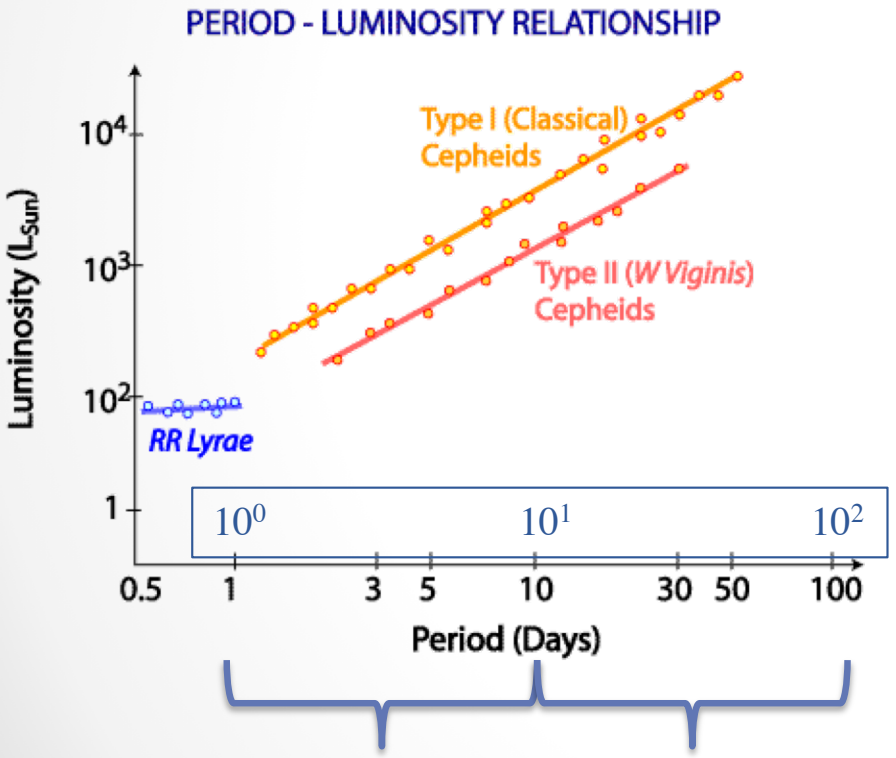


- The Period-Luminosity relation for Cepheids was a key to establishing the extra-galactic distance scale
  - Bright stars
  - Periods of variability are easy to measure
  - Once the calibration of the luminosity was established have a standard candle
- Polaris (the North Star) is a Cepheid



- Take many images of a galaxy
- Identify variable stars and determine period
- Compare to calibration to get intrinsic luminosity of Cepheid
- Apparent brightness compared with intrinsic luminosity gives distance

Distances to Cepheids



- The plot on the left is a "log-log" plot with equal distances on the axes separated by a factor of 10
- Physics approach is:

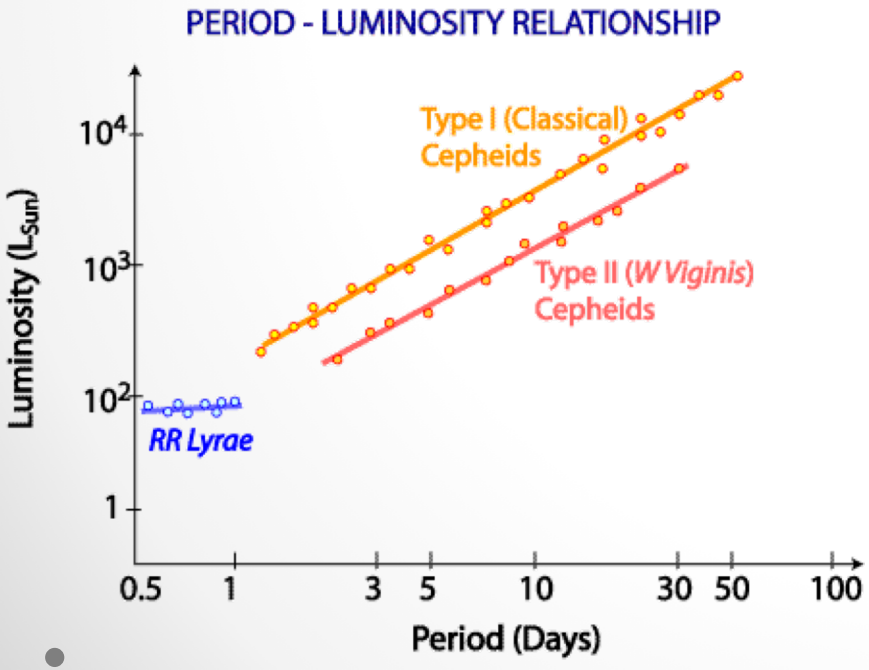
$$f = I = (L)/(4\pi d^2)$$

where, f=I is flux, or intensity or apparent brightness, L is intrinsic luminosity or radiant energy and d is the distance to the source

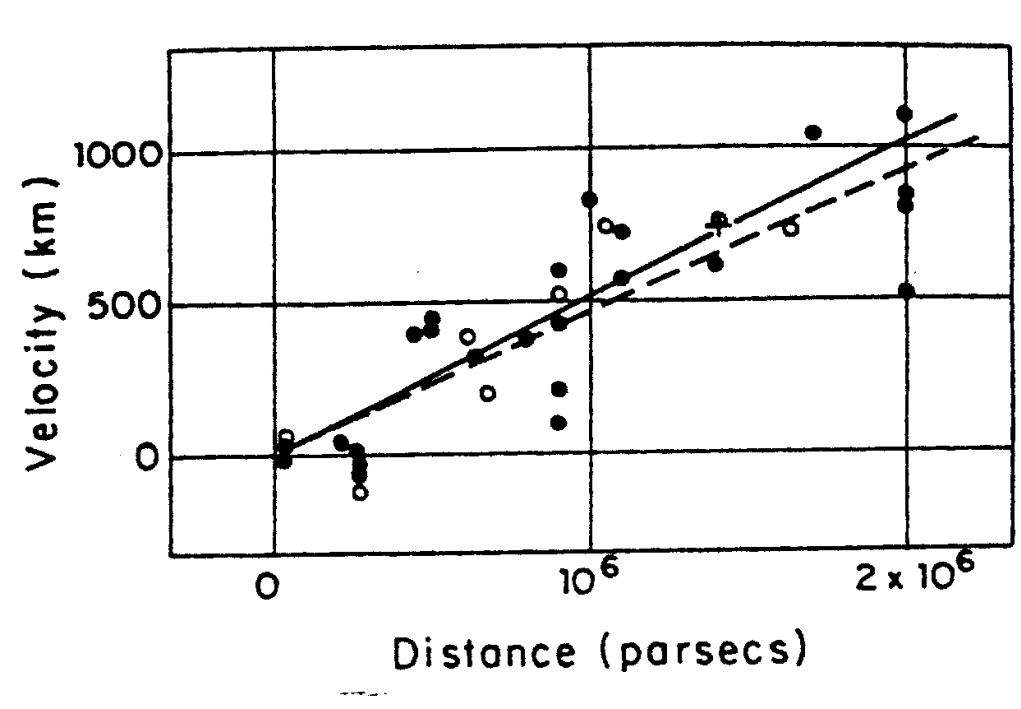
Distances to Cepheids

(1) $$f = \frac{L}{4\pi d^2}$$

(2) $$d = \sqrt{\frac{L}{4\pi f}}$$



1. Measure period of Cepheid in distant galaxy and apparent brightness or "flux" (*f*)
2. Read luminosity off P-L relation and convert to physical units
3. Use formula (2) to get the distance to the galaxy

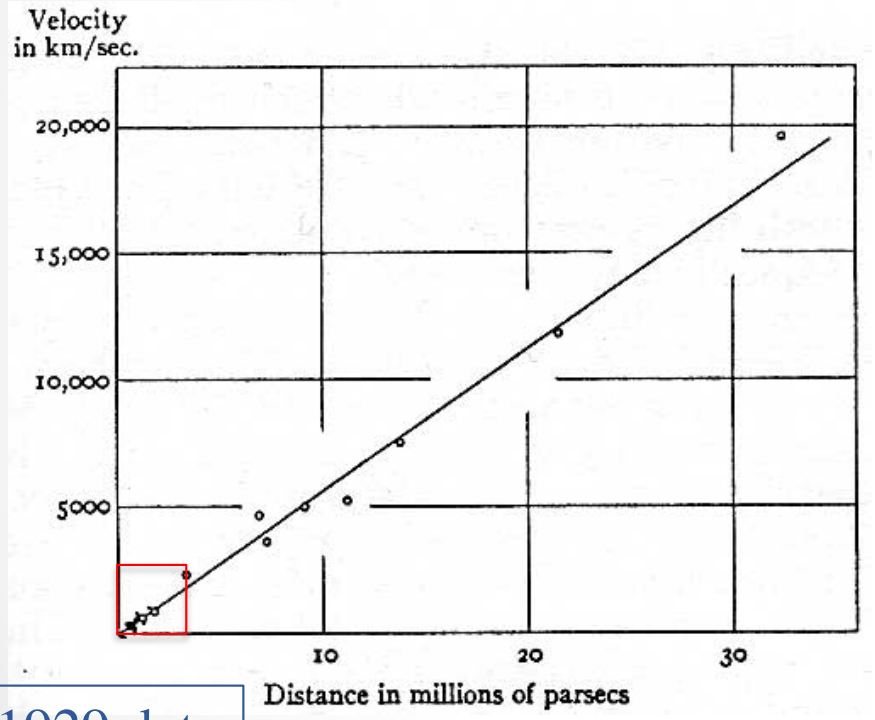


"The results establish a roughly linear relation between velocities and distance among nebulae."

—Edwin Hubble, 1929

- Armed with Cepheid distances and radial velocities, Hubble made a plot of velocity vs distance for galaxies
- He made this plot in 1929 with the remarkable result that the more distant a galaxy, the larger its velocity *away* from the Earth

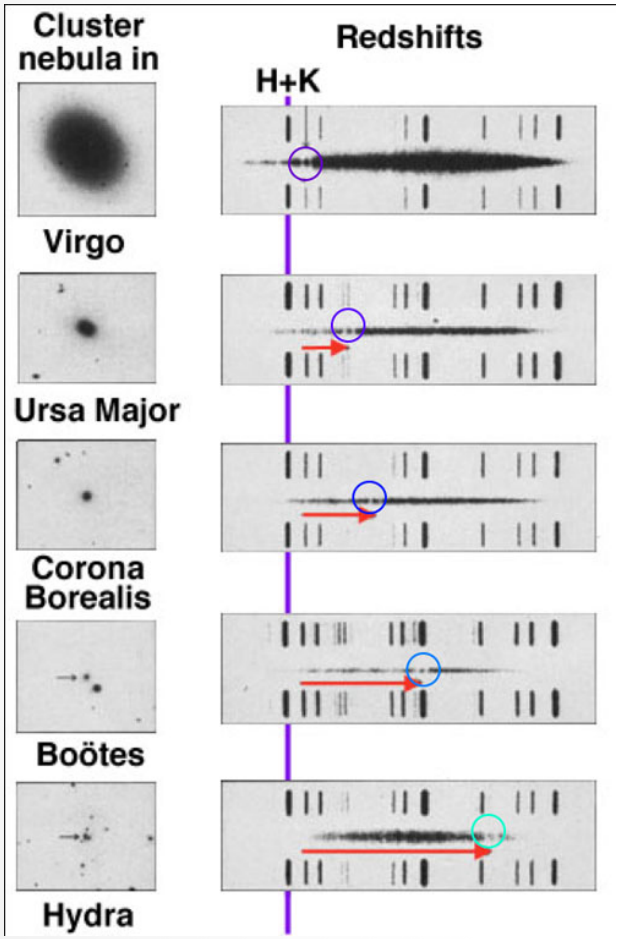
Expanding Universe



1929 data

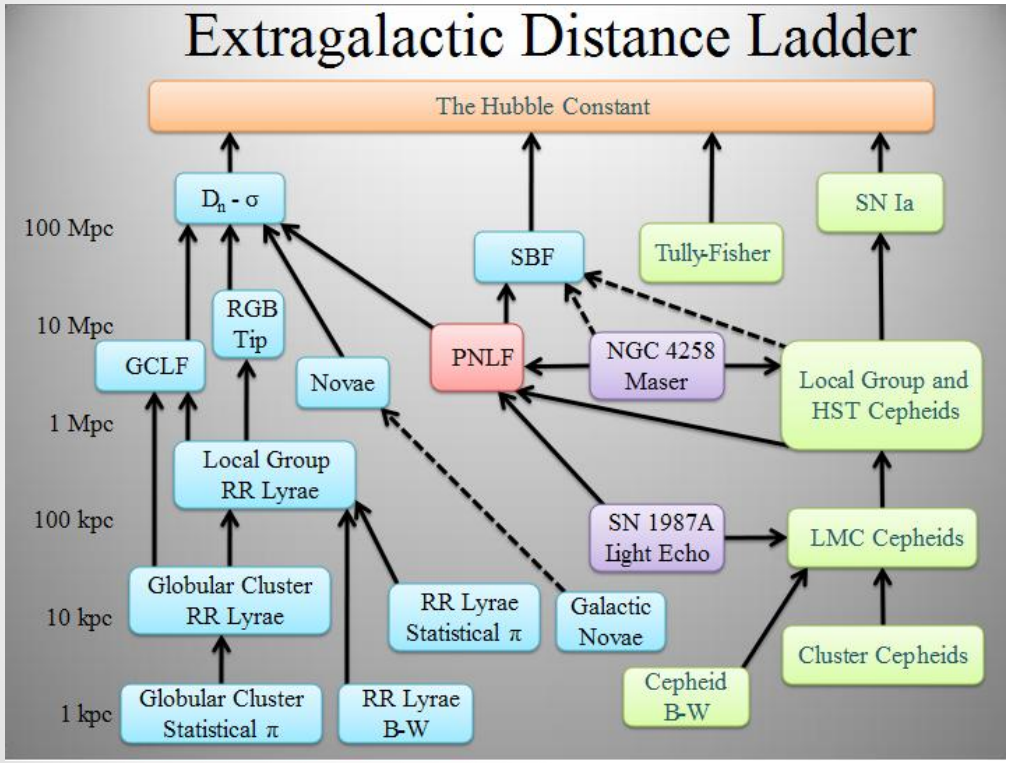
In 1931, Hubble and Humason published a second paper on the distances and velocities of galaxies using additional distance indicators calibrated by the Cepheid work

Expanding Universe



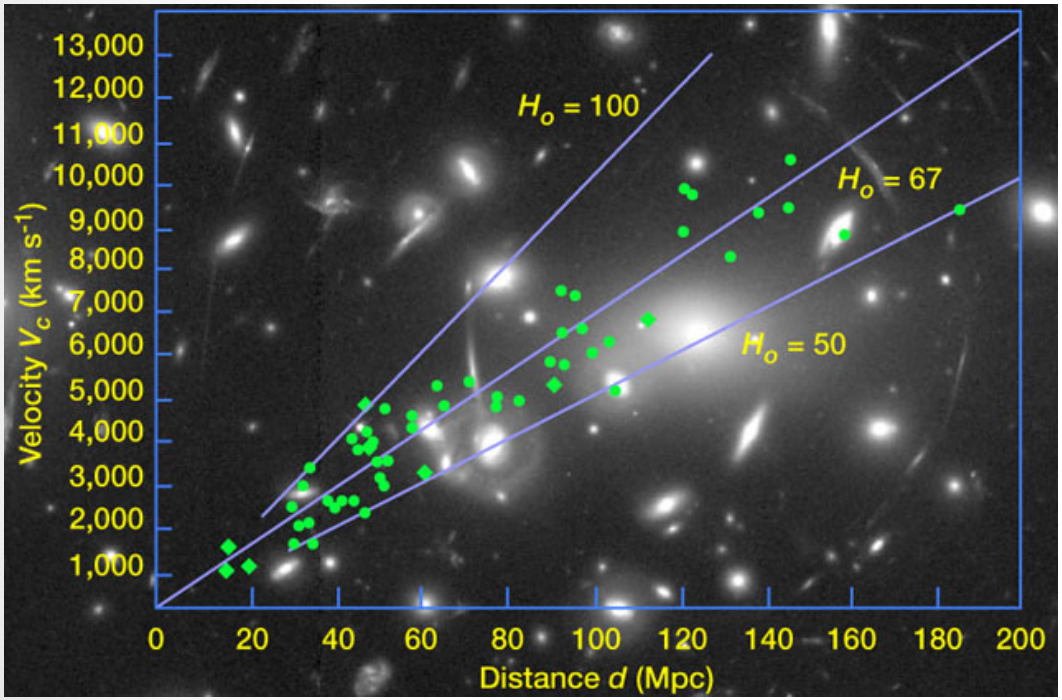
- The recession velocities were based on red-shifted spectral lines
- The shift in spectral lines to longer wavelengths were generally accepted to be because the galaxies were moving away from Earth (Doppler shift)

Side Story:Extra-galactic Distances



- The story of the development of the extra-galactic distance scale is long and interesting and still not completely settled
- Will return to this later, in general, most are part of a bootstrap process

Expansion of the Universe

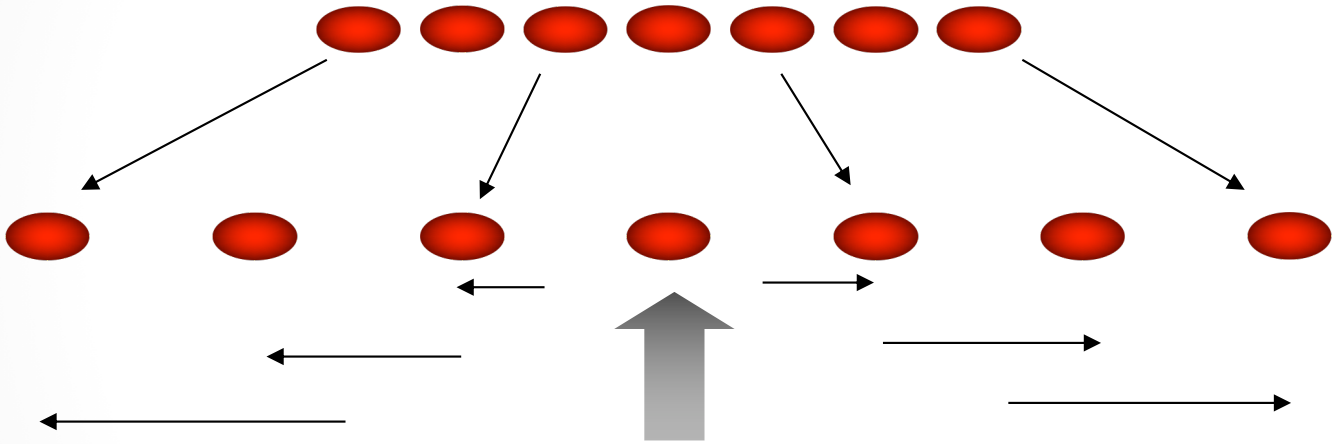


- Expansion of galaxies away from the Milky Way Galaxy was soon verified by other observers
- Expansion rate was named the Hubble Constant, H_0
- H_0=slope of best-fit line through a plot of velocity vs distance. Units are km s^{-1} Mpc^{-1}

The Expanding Universe

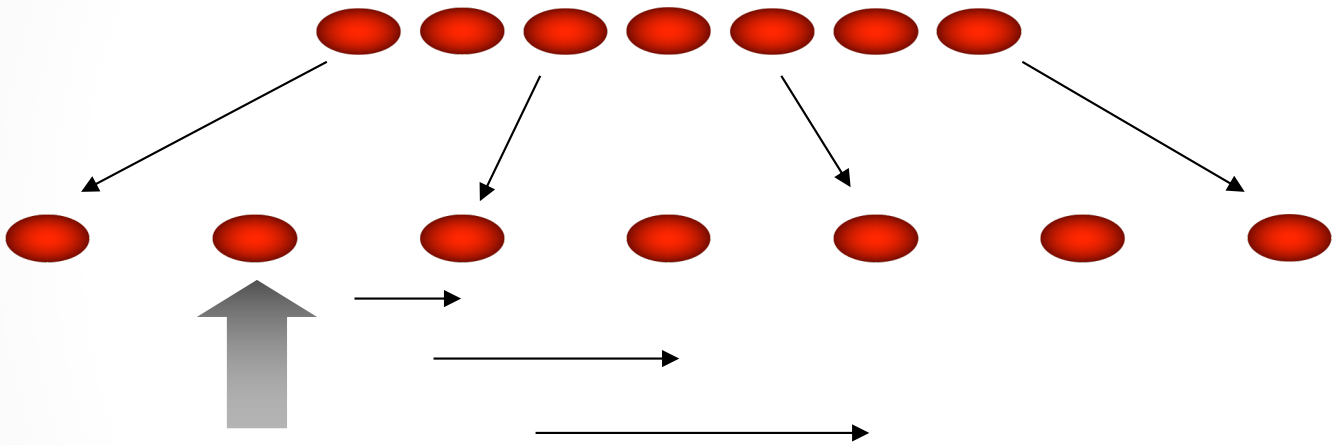
- Although the most naïve interpretation of all galaxies expanding away is we are at the center of the Universe, linear relation between expansion speed and distance is what would be expected from a *uniformly expanding* Universe
  - More distant objects naturally move faster in uniformly expanding medium
- Observers at every galaxy look out and see the other galaxies rushing away.

The Expanding Universe



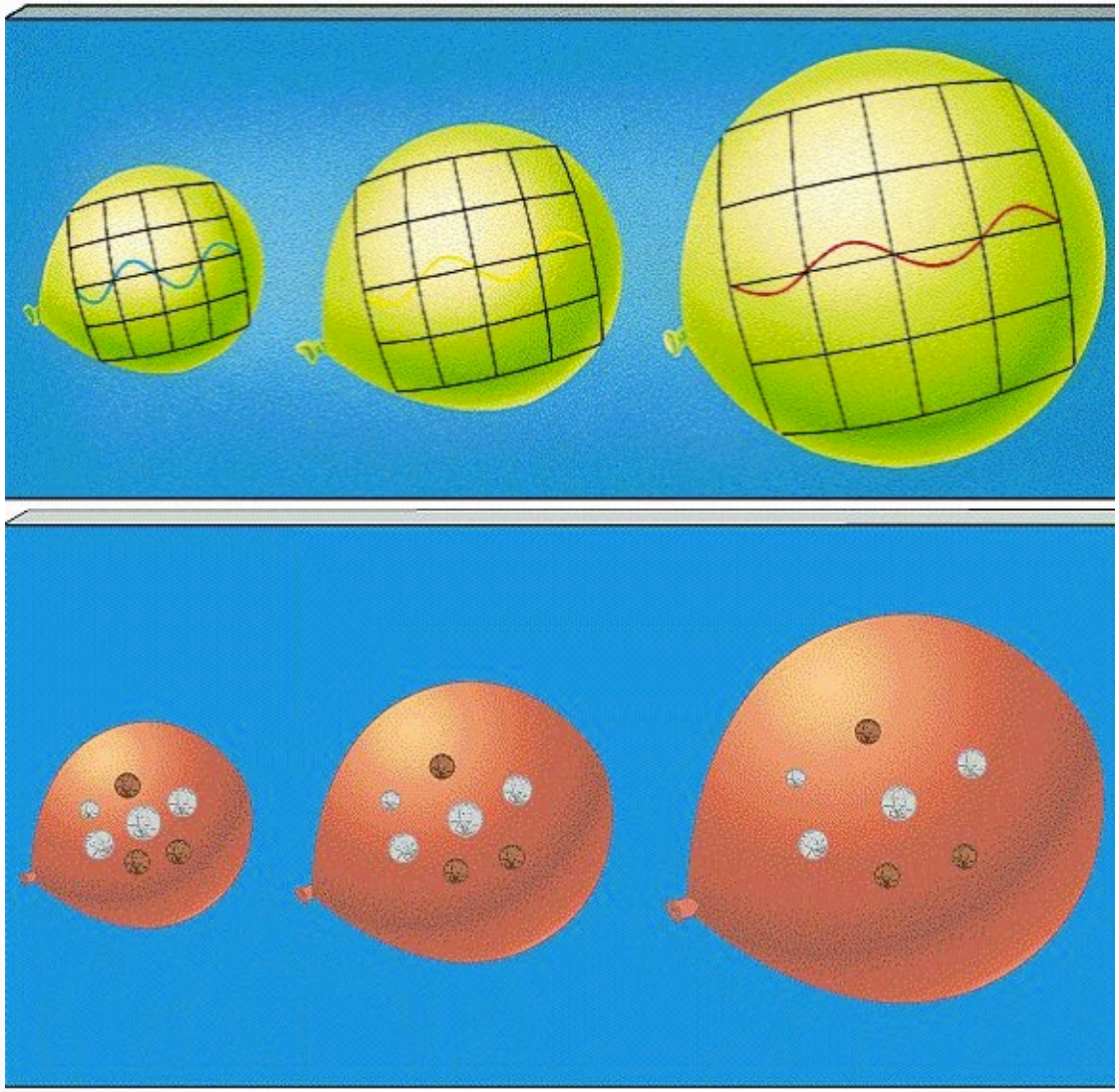
These people measure their nearest neighbors to have moved one unit, the next galaxies to have moved 2 units…

The Expanding Universe

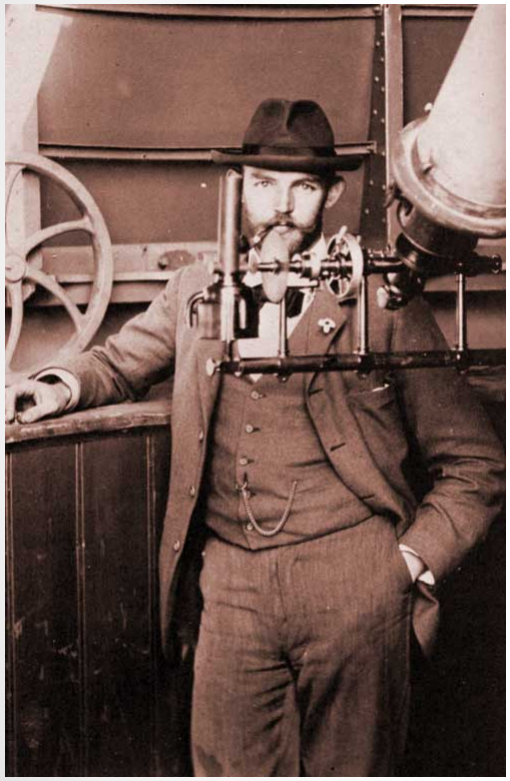


These people measure their nearest neighbors to have moved one unit, the next galaxies to have moved 2 units…

Expanding Universe



Expanding Universe



Willem de Sitter

Alexander Friedmann

- At least two theorist had published solutions to Einstein's General Relativity equations that predicted an expanding Universe
- Alexander Friedmann (Russian) and Willem de Sitter (Dutch) published papers that were widely ignored

Georges Lemaitre

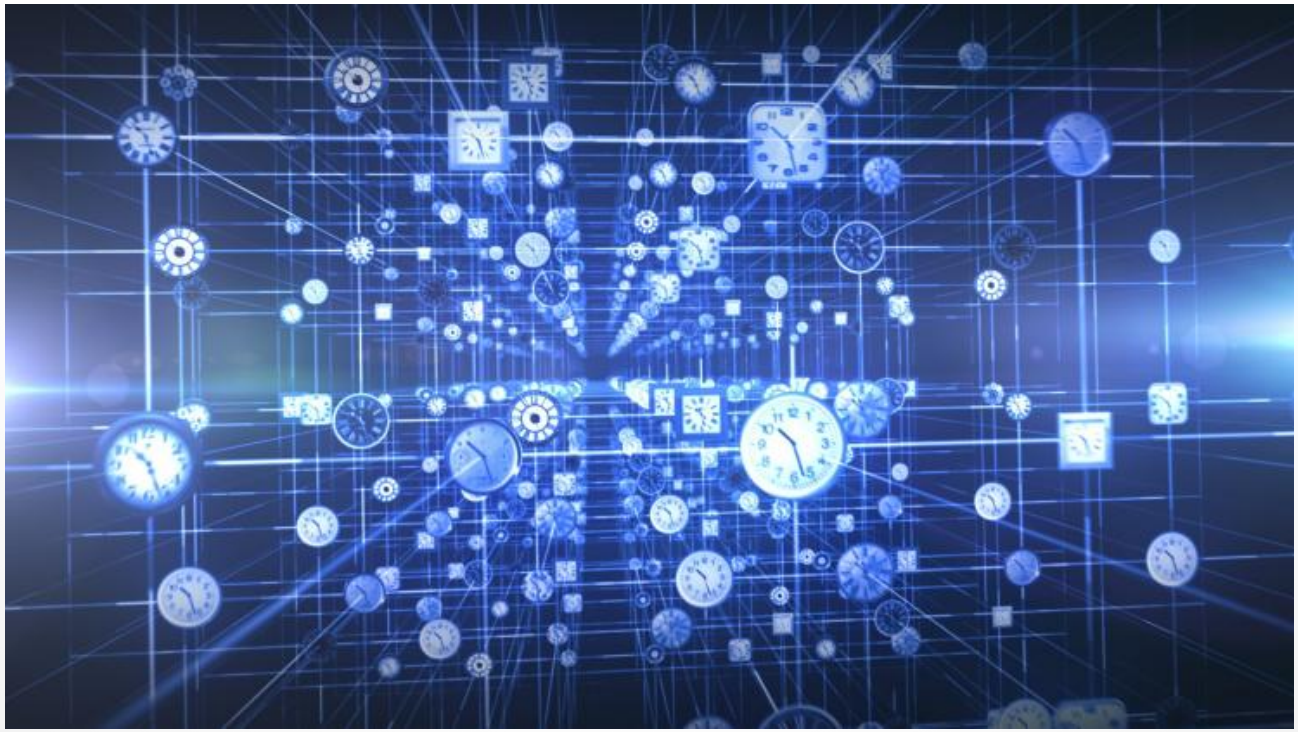
Belgian Catholic priest G. Lemaitre had worked at solutions to Einstein's GR equations applied to the Universe along with Slipher's recession velocities and proposed that *the Universe was expanding* in 1927

What does "Expanding" mean exactly?

- Strictly speaking, the expansion is an increase in the distance between two points in space on large (cosmological) scales
- Can be thought of as an expansion of spacetime available in the Universe
- Photons are stretched by the scale factor
- On smaller distance scales local spacetime distortions do to matter dominate
- Definitely not the matter in the Universe exploding into pre-existing space

Expanding Universe

- If the Universe is expanding, it immediately invites some thought experiments about the future and the past
- First, imagine running the movie of the Universe backward: Universe was smaller, denser and hotter

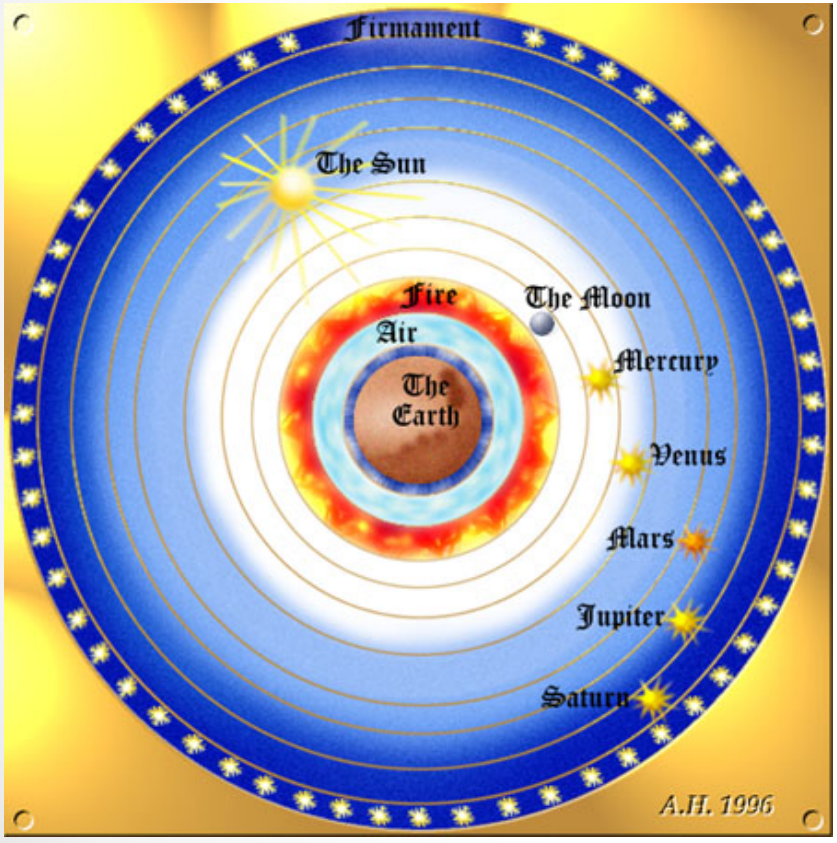


Big Bang

As physicists and astronomers considered the Universe at earlier and earlier times it challenged our knowledge of physics in the 1930s and 1940s, but did put in place a number of very specific predictions of observations that could prove or disprove the Big Bang model for the formation and evolution of the Universe

Cosmology through time and around the world

Sidetrip



- Cosmology: Origin and fate of the Universe
  - Physical Cosmology
  - Mythology/religious cosmology
- Physical cosmology had its start with the early observations of the sky that were used to attempt to understand the motions of the Earth and other planets in the solar system against the "fixed stars". For most of human existence, physical and religious cosmologies were mixed together

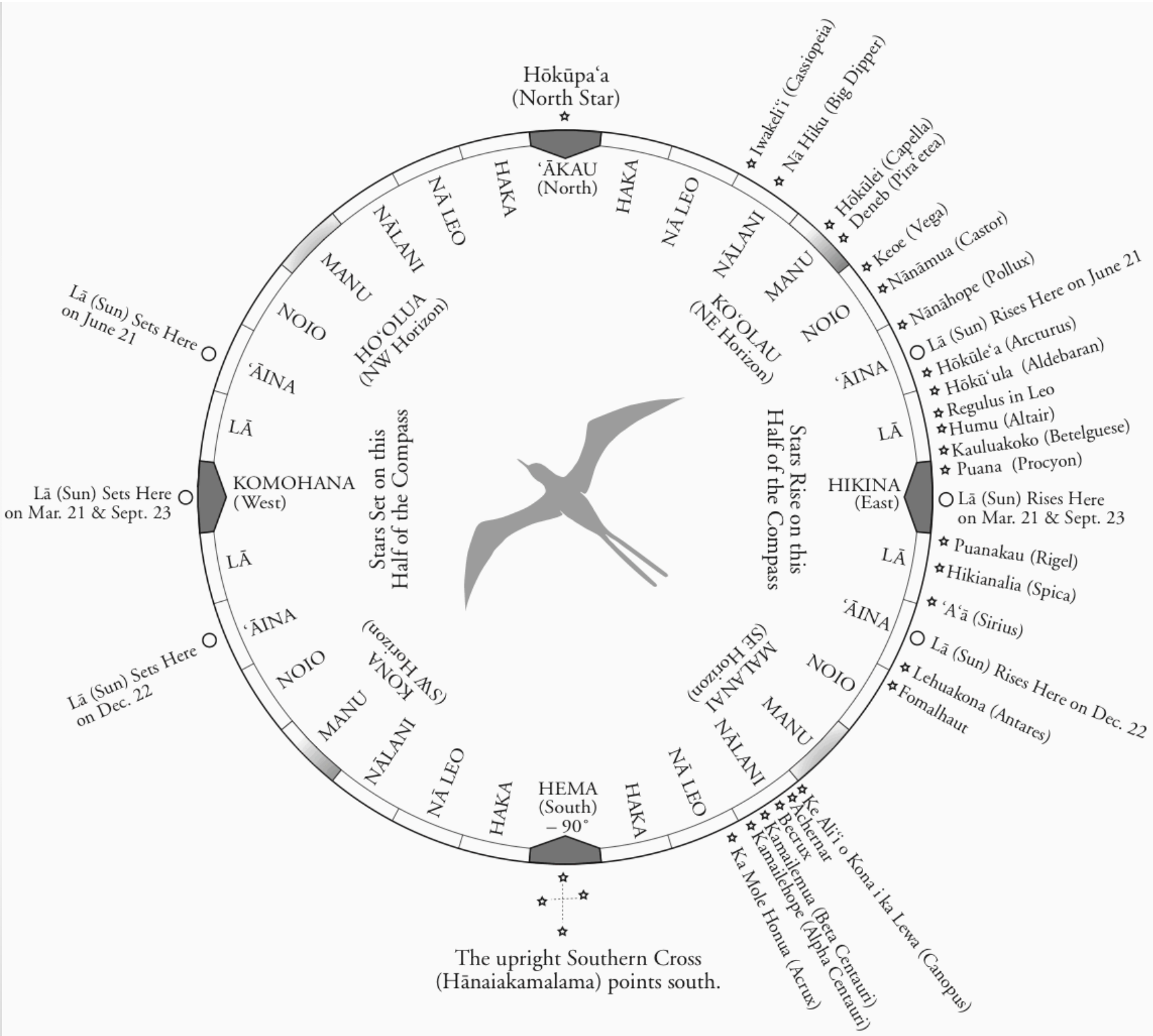
Early Cosmology

- All religions and cultures have origin myths and cosmologys
- The physical cosmology of today grew out of the marriage of science, various religious cosmologies and the practical arts of time tracking by observing the sky

- There are many examples that demonstrate people everywhere and for 1000's of years have understood the basic motion of the Sun and other celestial objects
- The models that the vast majority adopted for the Universe had the Earth at the center

Celestial Navigation

- Another example of the practical use of the motions of celestial objects was navigation
- Mixed with religious practice and beliefs

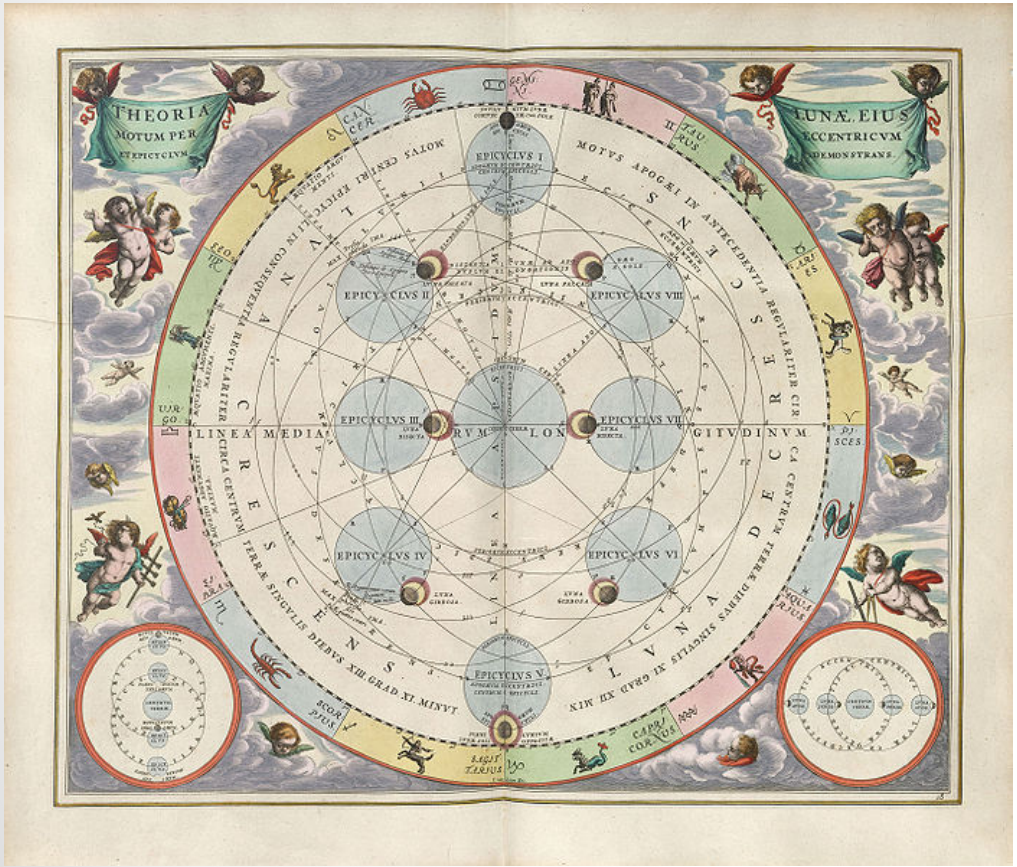

Hōkūpaʻa
(North Star)
ʻĀKAU
(North)
HAKA
NĀ LEO
NĀLANI
MANU
NOIO
ʻĀINA
LĀ
HIKINA
(East)
LĀ
ʻĀINA
NOIO
MANU
NĀLANI
NĀ LEO
HAKA
HEMA
(South)
– 90°
HAKA
NĀ LEO
NĀLANI
MANU
NOIO
ʻĀINA
LĀ
KOMOHANA
(West)
LĀ
ʻĀINA
NOIO
MANU
NĀLANI
NĀ LEO
HAKA
Stars Set on this
Half of the Compass
Stars Rise on this
Half of the Compass
HOʻOLUA
(NW Horizon)
KOʻOLAU
(NE Horizon)
KONA
(SW Horizon)
MALAMA
(SE Horizon)
Iwakeliʻi (Cassiopeia)
Nā Hiku (Big Dipper)
Hōkūlei (Capella)
Deneb (Piraʻetea)
Keoe (Vega)
Nānāmua (Castor)
Nānāhope (Pollux)
Lā (Sun) Rises Here on June 21
Hōkūleʻa (Arcturus)
Hōkūʻula (Aldebaran)
Regulus in Leo
Humu (Altair)
Kauluakoko (Betelguese)
Puana (Procyon)
Lā (Sun) Rises Here
on Mar. 21 & Sept. 23
Puanakau (Rigel)
Hikianalia (Spica)
ʻAʻā (Sirius)
Lā (Sun) Rises Here on Dec. 22
Lehuakona (Antares)
Fomalhaut
Keʻaliʻi o Kona i ka Lewa (Canopus)
Achernar
Becrux
Kamailemua (Beta Centauri)
Kamailehope (Alpha Centauri)
Ka Mole Honua (Acrux)
Lā (Sun) Sets Here
on June 21
Lā (Sun) Sets Here
on Mar. 21 & Sept. 23
Lā (Sun) Sets Here
on Dec. 22
The upright Southern Cross
(Hānaiakamalama) points south.

Earth-Centered Cosmology

Mars motion at opposition

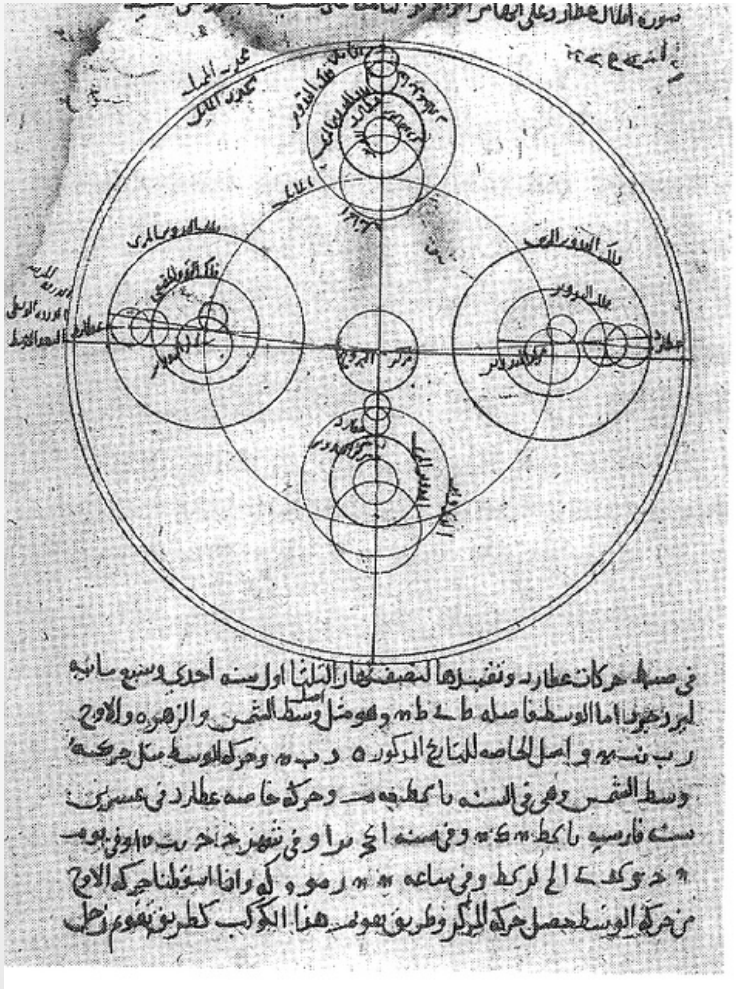
- A complication of putting the Earth at the center of the Universe was the "retrograde motion" of the planets
- Against the stars, planets "wanderers" occasionally reverse direction in the sky

Earth-Centered Cosmology



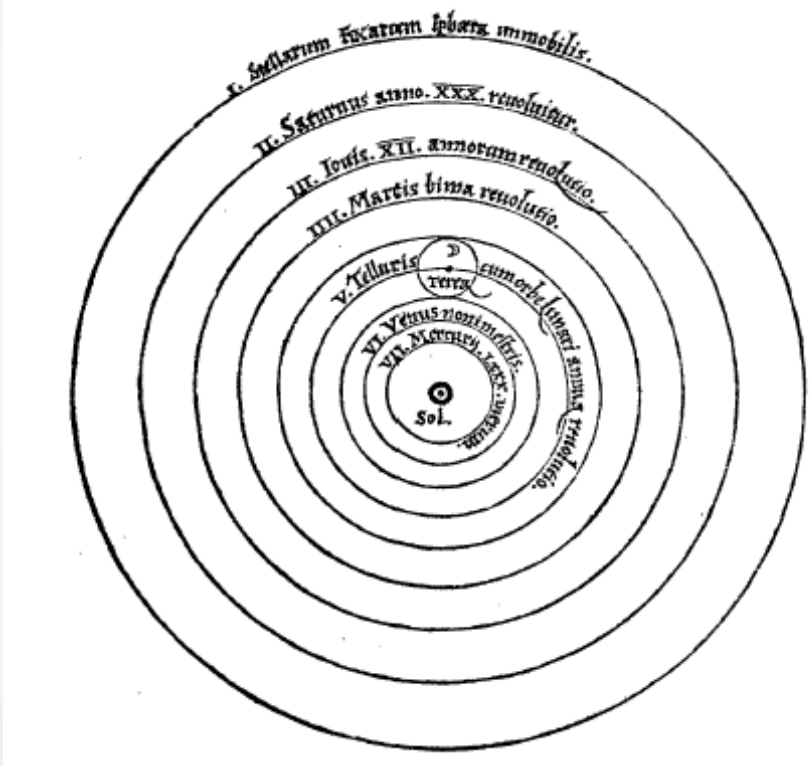
- The Earth-centered solution required "epicycles"
- In addition to orbiting around the Earth, the planets executed secondary circular motions

Earth-centered Cosmology

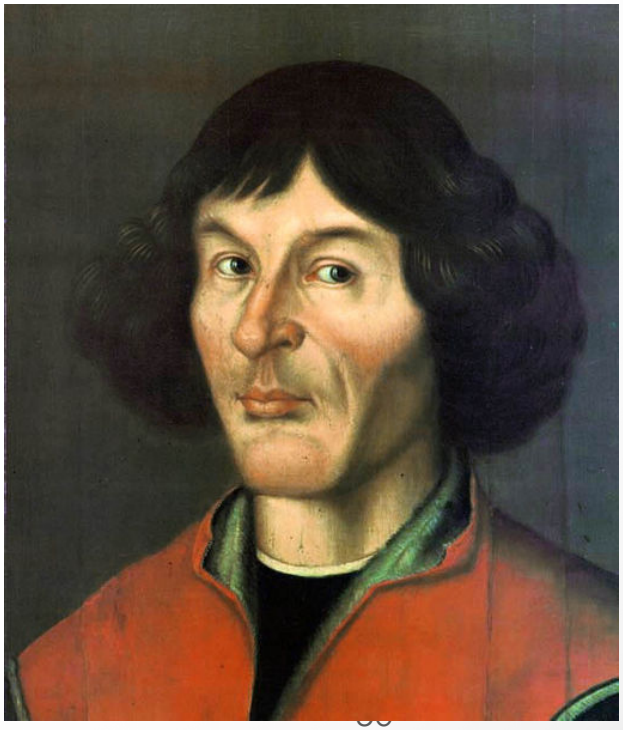


- The same circles within circles solution was adopted by many different cultures
- As observations developed longer and longer baselines, the number of epicycles grew

Heliocentric Models



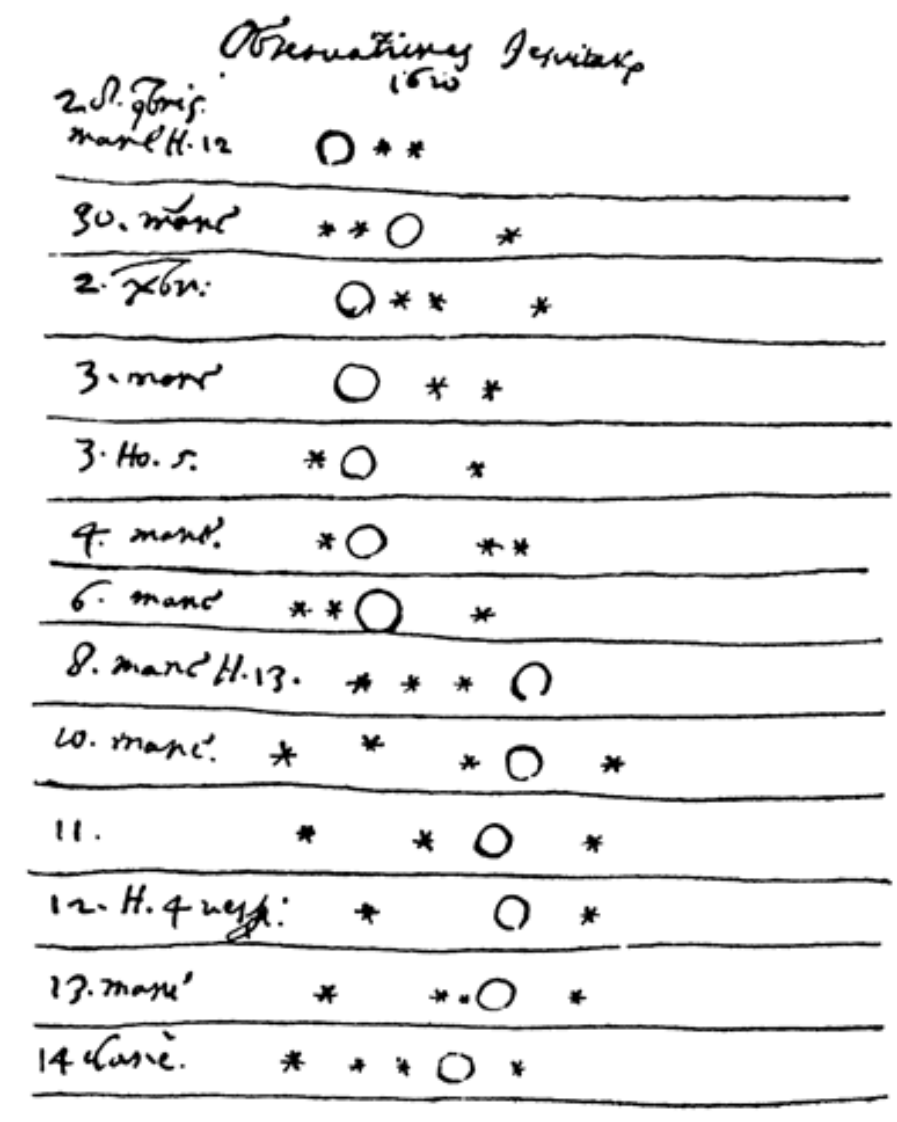
Copernicus is credited with the first defense of a model for the Universe that was centered on the Sun



Galileo

- 1609 Galileo built a 1″ diameter refracting telescope with 3x magnification and made observations of celestial objects
- Could see with higher resolution and could see fainter objects

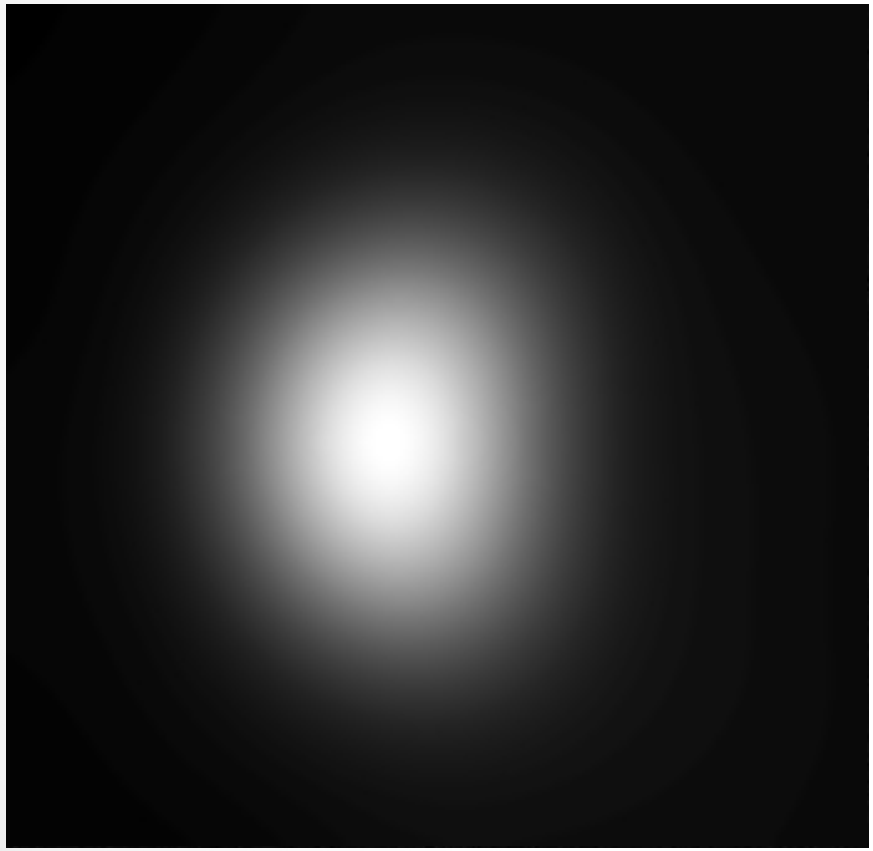
Galileo's Observations



- Observed four faint objects that over time were shown to orbit Jupiter
- Evidence for objects that orbited something other than the Earth

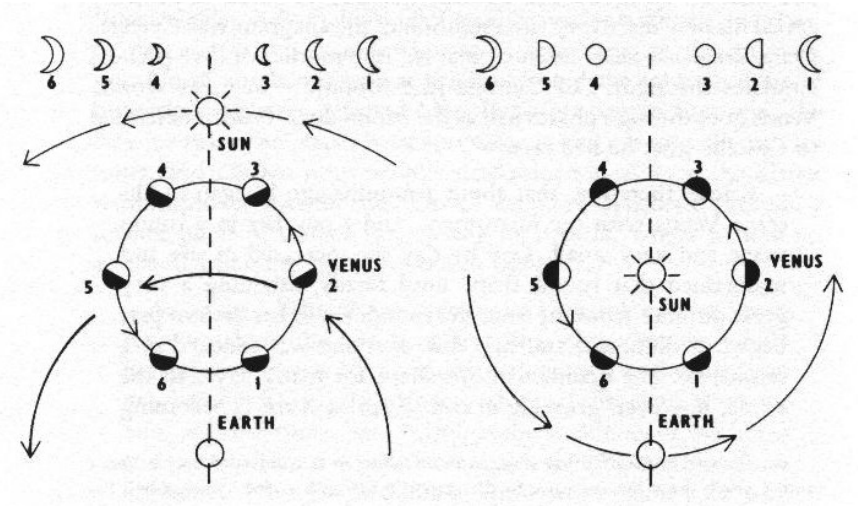
- Galileo observed imperfections on the surface of the moon and the Sun
- Perhaps most importantly, with the improved spatial resolution of his telescopes, Galileo observed that Venus showed different phases

Galileo and Venus



The key observation that demonstrated at least one object in the Solar System orbited the Sun was observing Venus go through different phases

Galileo and Venus



Post Galileo Universe

- After some battles with the Church, the heliocentric model for the Solar System became widely accepted. Work by Kepler and Newton established a physics basis for the motions of objects in the Solar System
- Next major steps forward: General Relativity and the recognition of the universe beyond the Solar System then beyond the Galaxy we have already discussed

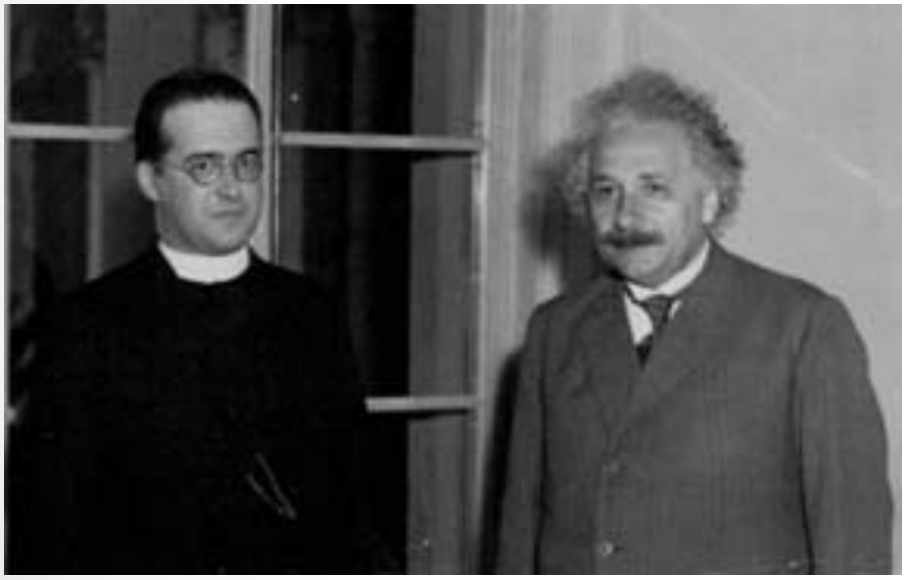
Side Trip II

- Early 1900s were revolutionary for physics and our understanding of the physical Universe
  - Einstein's Theory of General Relativity reshaped our understanding of the nature of the Universe
  - Quantum physics was born and revolutionized our understanding of the microscopic underpinning of the Universe
  - We got our first handle on the size and contents of the Universe

End of Material for Q3

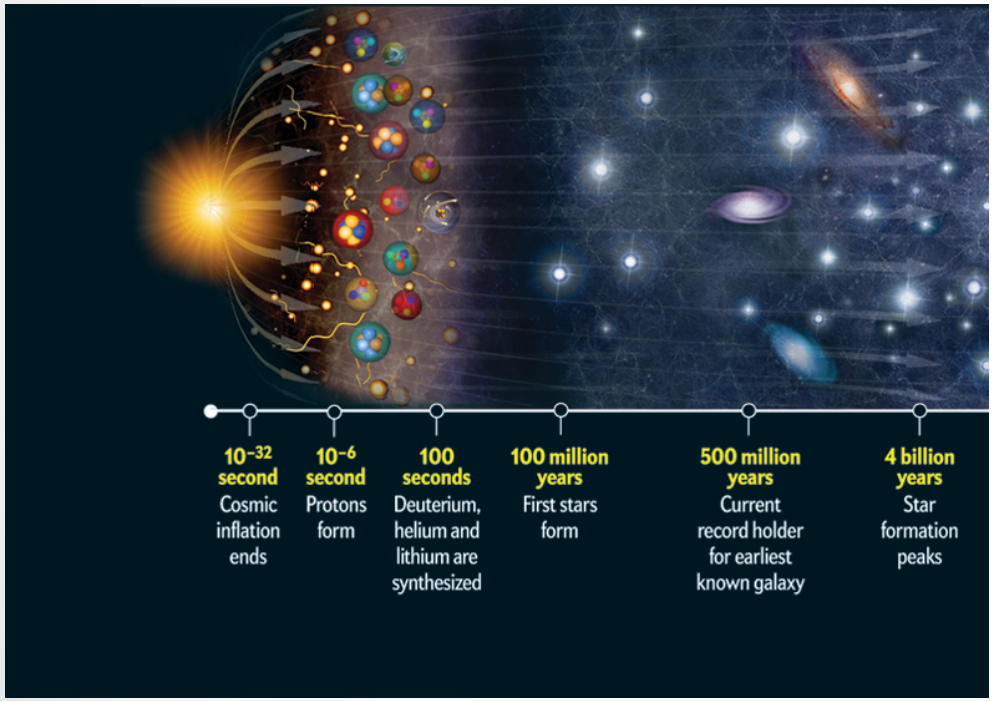
- Make sure you know the answers to all the Q3 homework questions
- Topics:
  - Close Binary Star evolution (Novae and SN I)
  - Special and General relativity
  - Escape velocity and Black Holes
  - Components of the Milky Way Galaxy
  - The zoo of galaxies
  - Doppler shift and the expansion of the Universe

Expanding Universe Implications



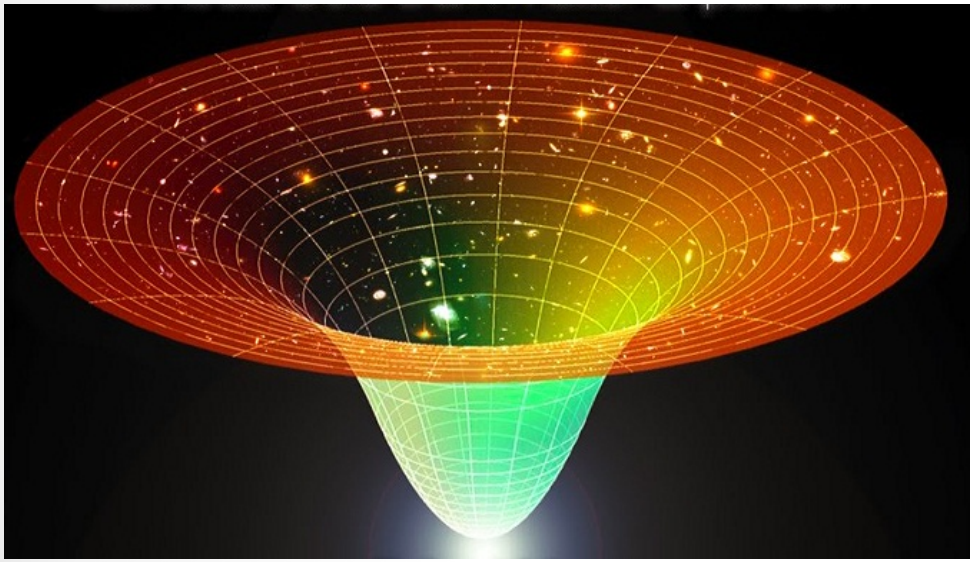
Back to Lemaitre. 1931 he published a paper that suggested the Universe was once contained in a single point, the "primeval atom"

The Big Bang thought experiment

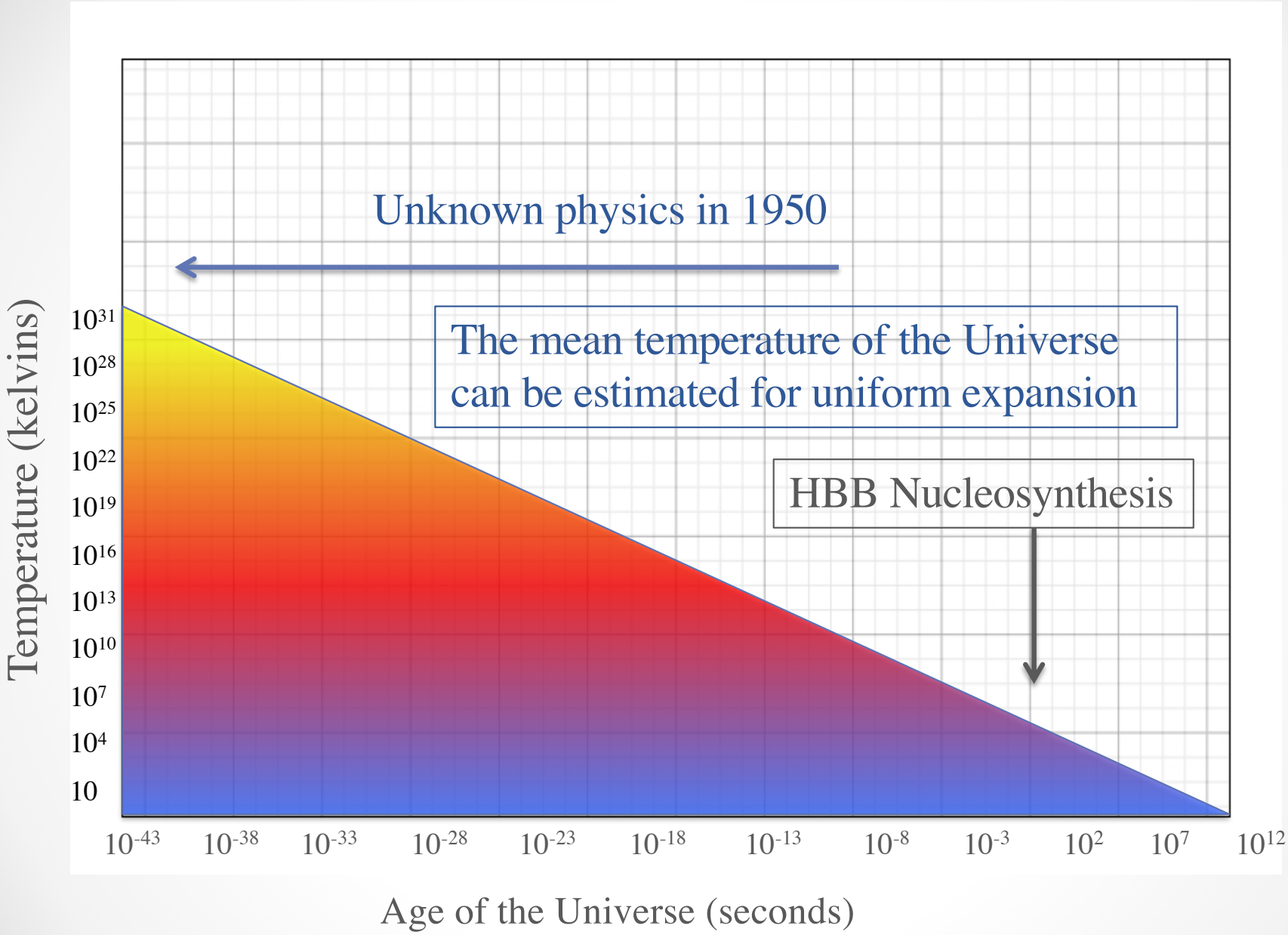


Lemaitre in 1927 discussed the concept of a Universe that started as an extremely dense and hot point and expanded, cooled and evolved into the Universe we live in today

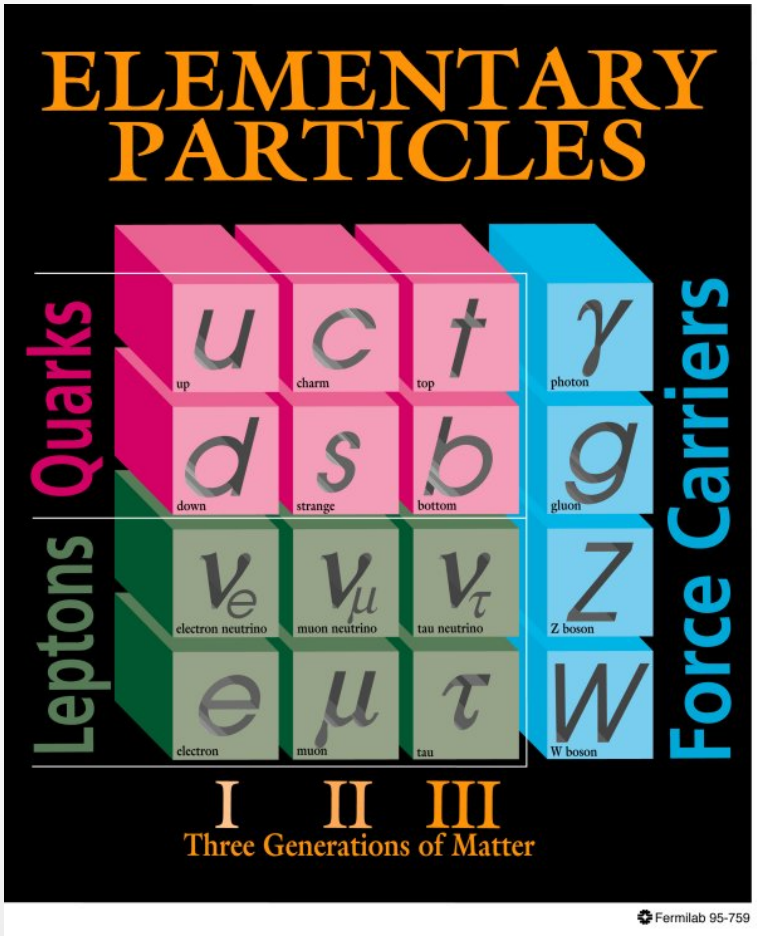
Starting at the Beginning



- Run the Universe timeline backward
- Density and temperature go up, apply physics as we know it
- Will follow the path this unfolded historically

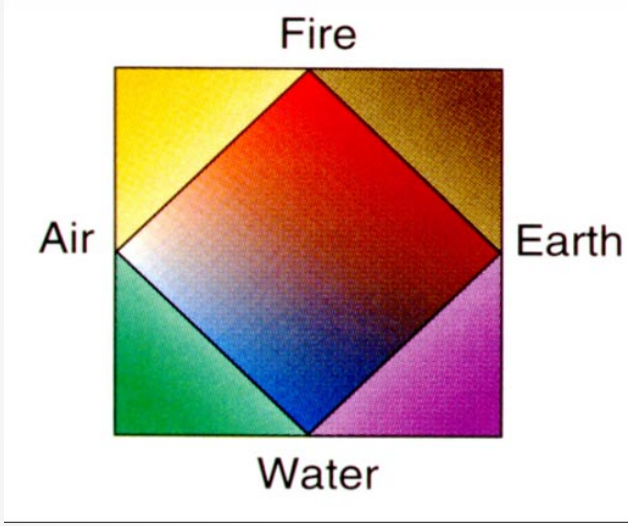

Unknown physics in 1950
The mean temperature of the Universe can be estimated for uniform expansion
HBB Nucleosynthesis
Temperature (kelvins)
10^{31}
10^{28}
10^{25}
10^{22}
10^{19}
10^{16}
10^{13}
10^{10}
10^{7}
10^{4}
10
10^{-43} 10^{-38} 10^{-33} 10^{-28} 10^{-23} 10^{-18} 10^{-13} 10^{-8} 10^{-3} 10^{2} 10^{7} 10^{12}
Age of the Universe (seconds)

Background: Fundamental Particles



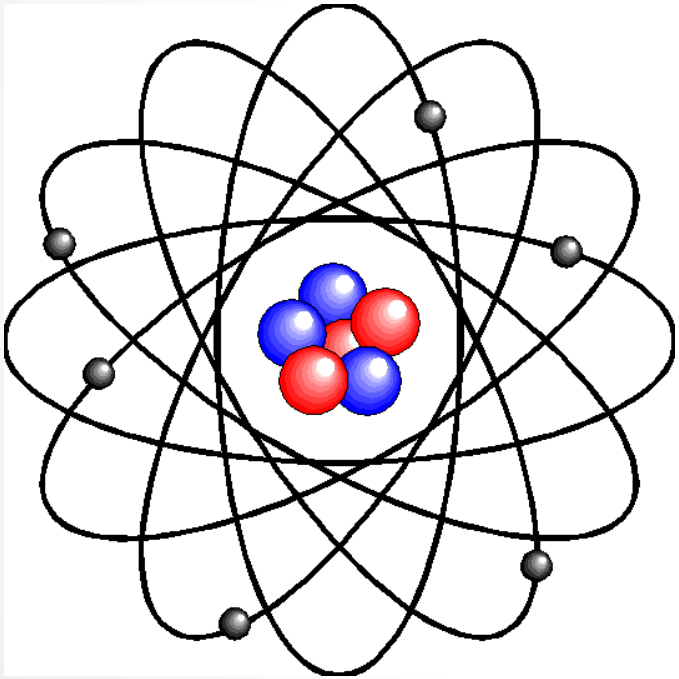
- Identifying the fundamental building blocks of the Universe is a long-time activity of humans
- Like the history of cosmology, there are striking similarities in history and cultures

Earth, Wind, Fire, Water



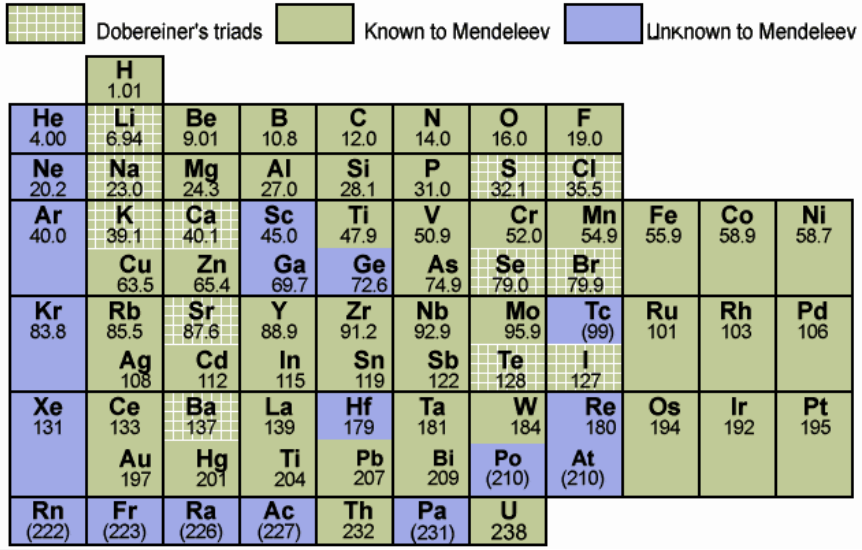
- Greeks: EWFW
- Hindu: Earth, air, fire, water, void (nothing)
- China: Earth, wood, metal, fire, water
- Japan: EWFW, spirit
- Buddhism: EWFW

Atoms



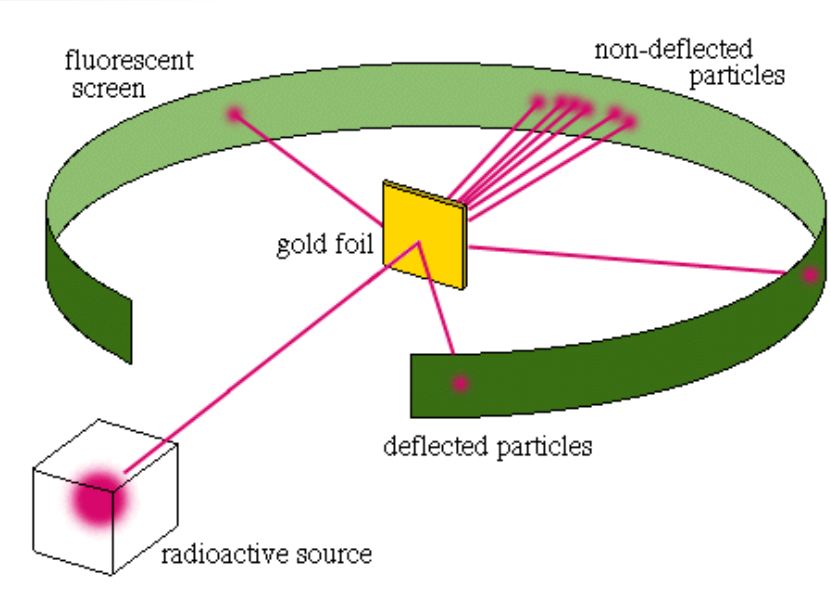
Democritus (greek philosopher and contemporary of Aristotle) considered what would happen if you took matter, divided it in two, then again and again and again, eventually you would have an "atom" that could not be divided further: atomos "not to be cut"

Atoms II: inferences from chemistry



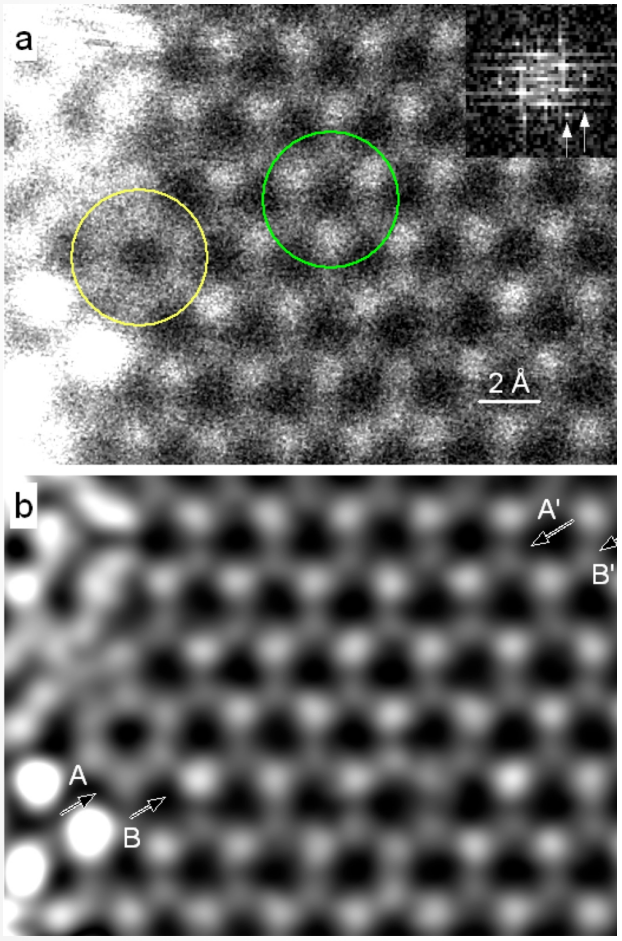
- 1830 John Dalton identified elements with particular types of atom and compounds as combinations of elements
- 1869 Mendeleev proposed the periodic table
- 1897 Thomson discovered electrons and it was realized that atoms were not fundamental but could be further divided

Rutherford and the modern theory



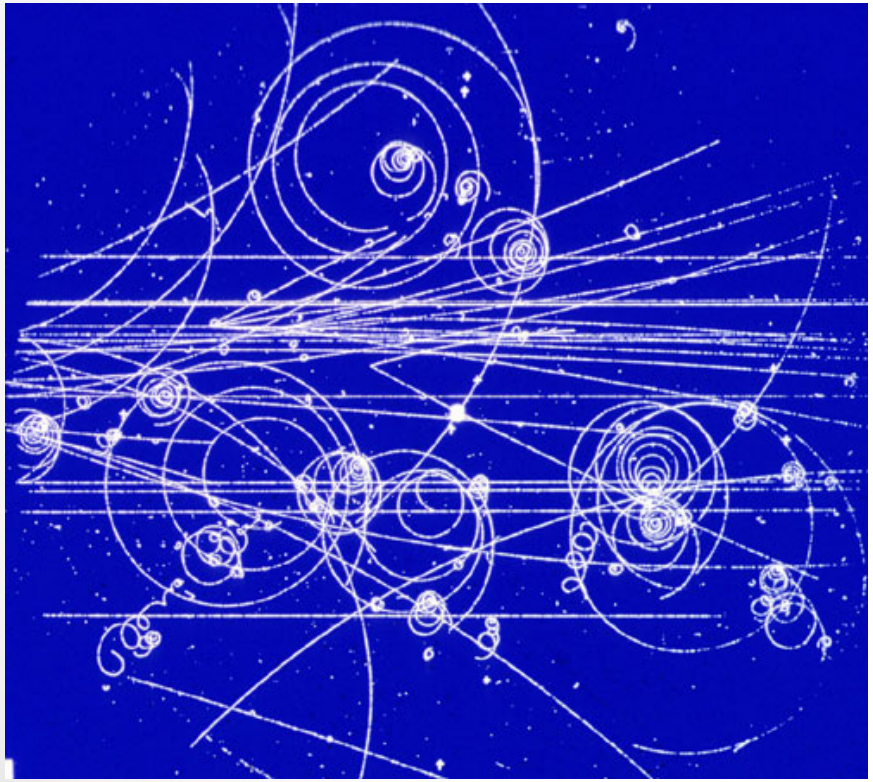
- 1911 Rutherford inferred that atoms hard a strongly centralized mass distribution: he discovered the nucleus
- This is all experimentally difficult because of the tiny size of atoms
  - 10^{-10} meters in diameter
  - Human hair is 10^{6} atoms across
  - Water drop contains ~10^{21} atoms of oxygen

Quantum Physics

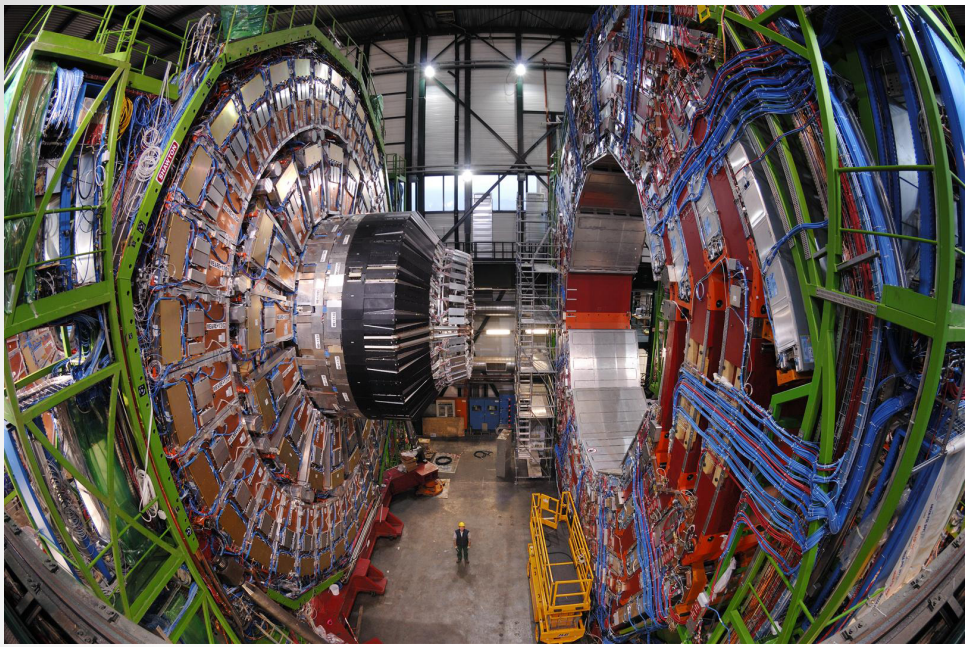


- From 1911 – 1935 our knowledge of the structure of atoms and matter was the subject of intense study "quantum mechanics"
- Fundamental building blocks of everything were thought to be electrons, protons and neutrons

Three Quarks for Muster Mark



- Cosmic ray studies and particle accelerators had been demonstrating a whole slew of unexpected massive particles coming out of energetic collisions
- Particle physics theorists proposed all could be explained by three (then four) truly fundamental particles that got names "quarks" (1964)



- Modern accelerators are incredible machines
- Large Hadron Collider accelerates protons to 0.9999991c
- Super-cooled, vacuum of space
- 10,000 scientists, 100 countries
- 14 x 10^{12} eV (TeV)collisions
- 80,000 computers on private internet
- $6.5B (US)

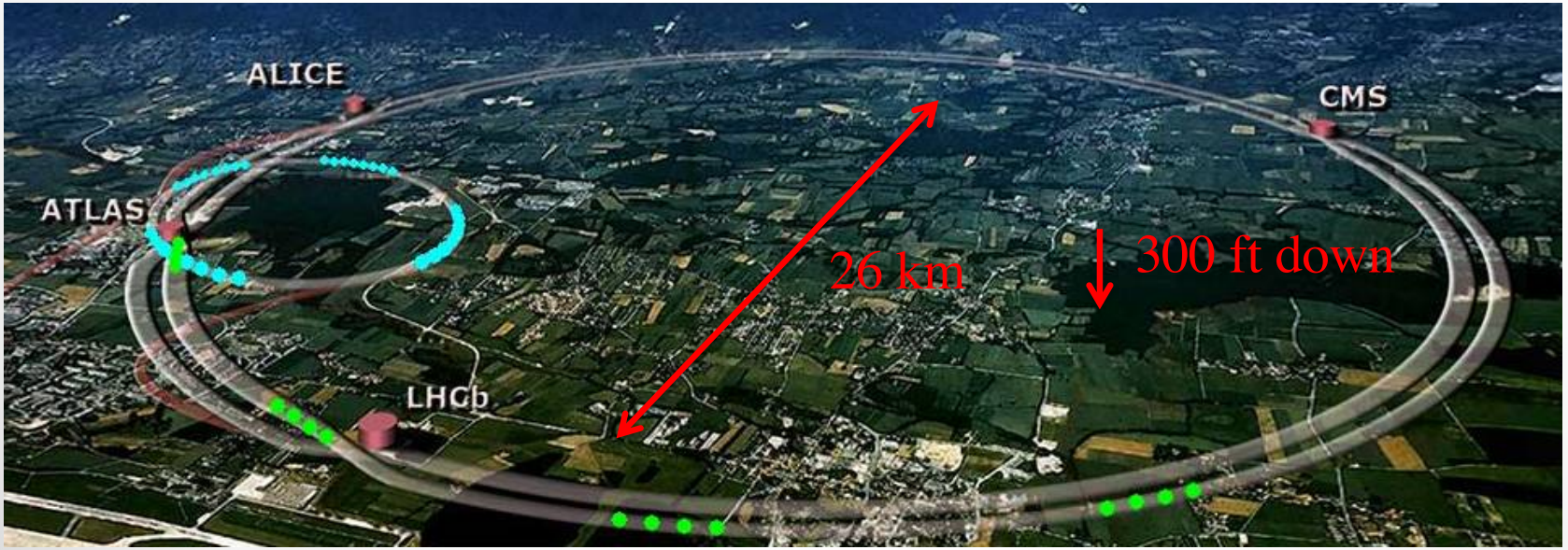
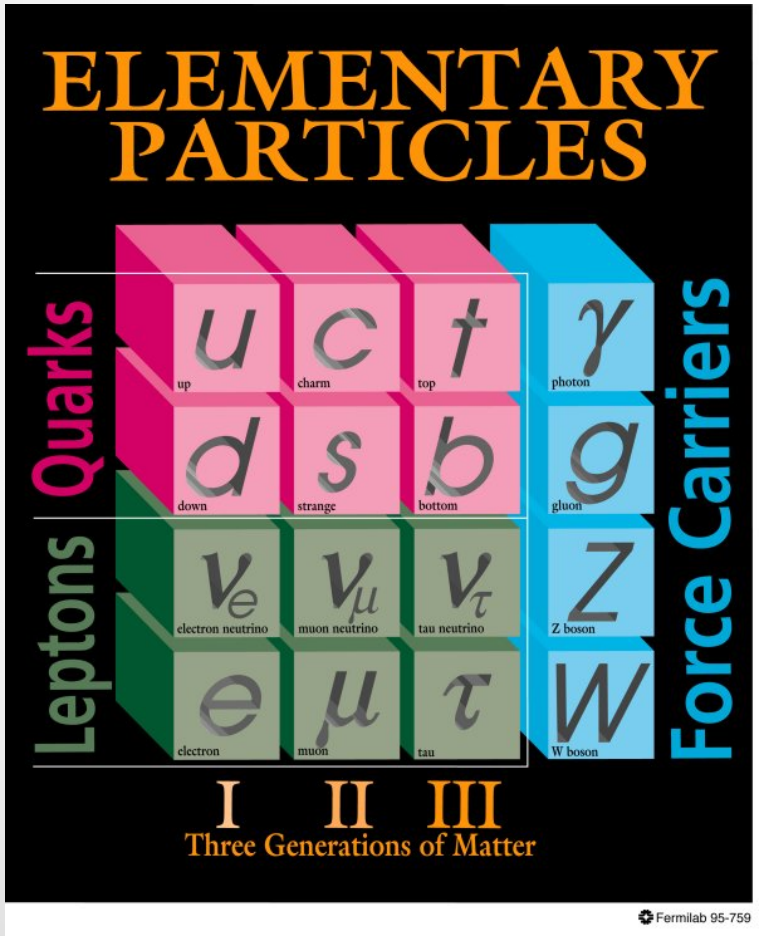
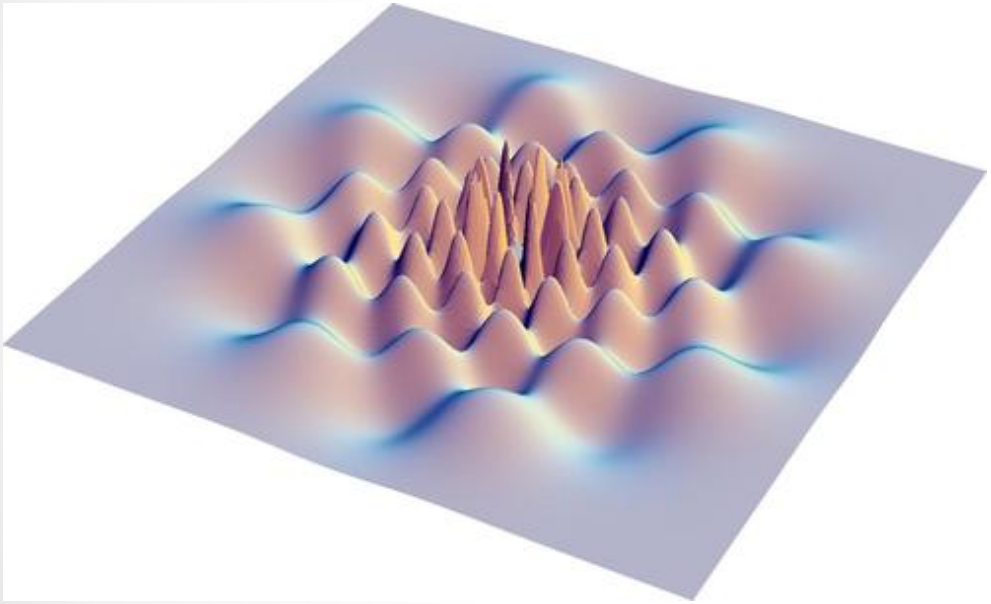


Table of Fundamental Building Blocks



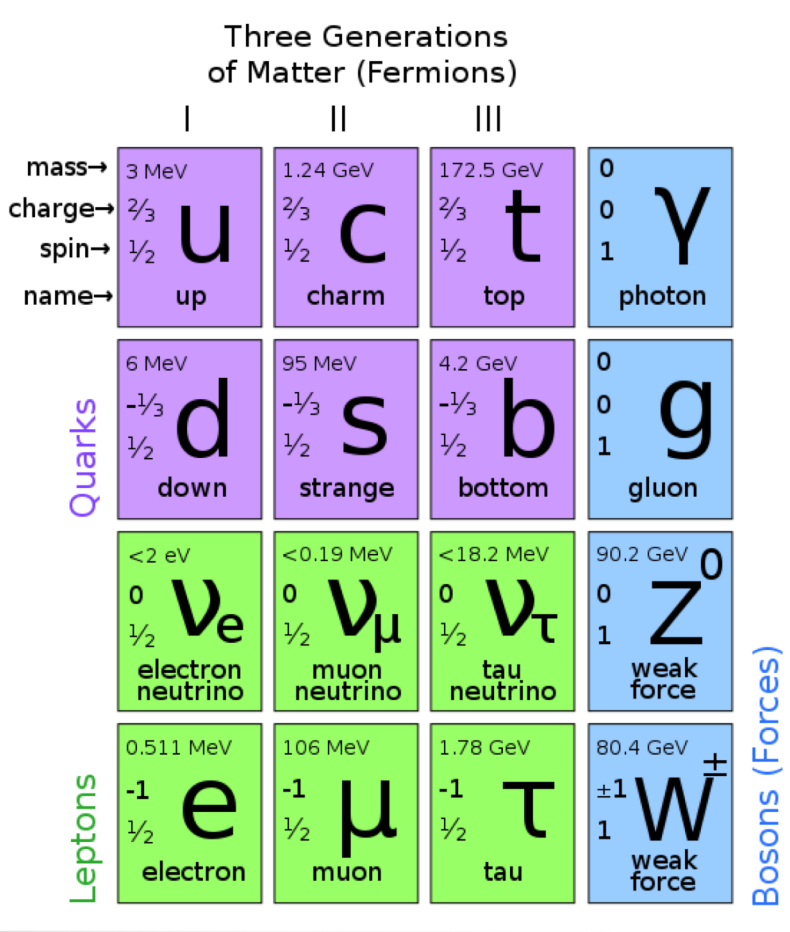
- Fermions: fundamental particles.
  - Leptons
  - Quarks
- Hadrons: combinations of Fermions (i.e. proton, neutron)
- Bosons: particles that exchange forces

Leptons



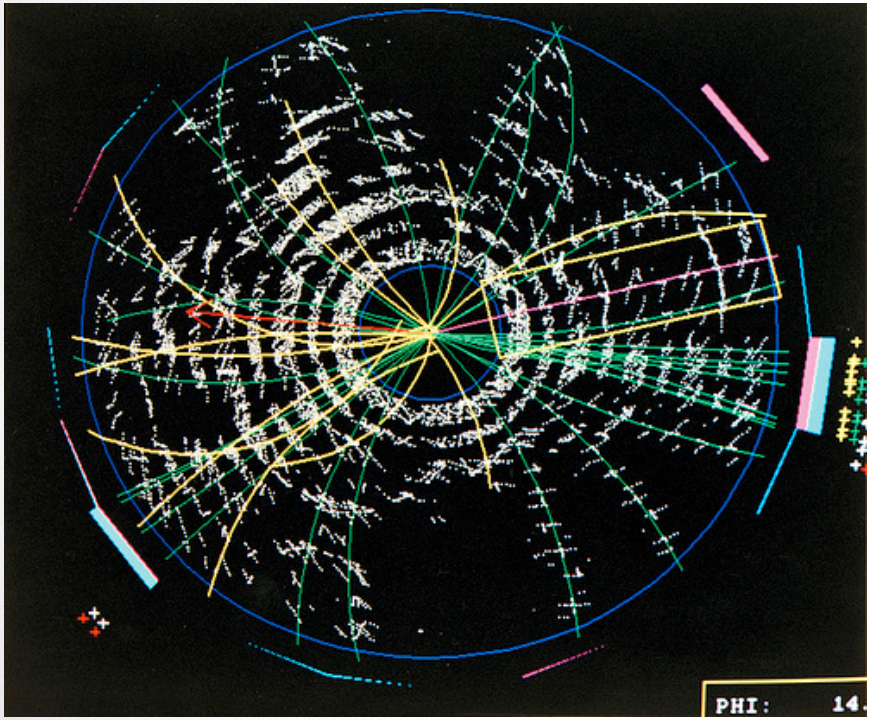
- Near massless, no structure, unknown, but very, very small size
  - Electron, electron neutrino
  - Muon, muon neutrino
  - Tau, Tau neutrino
  - Anti-matter partners

Fermions: Quarks



- Proton: 2u + 1d quarks (uud)
  - Charge: [(2 x 2/3) + (-1/3)]=+1
  - Held together by 3 Gluons
  - Mass=1.672×10^{-27}kg=938.3Mev/c^2
- Neutron: 1u + 2d quarks (udd)
  - Charge: [2/3 + 2 x (-1/3)]=0
  - Held together by 3 Gluons
  - Mass=1.675×10^{-27}kg=939.6Mev/c^2
  - "free" neutrons are unstable and decay via βdecay to become protons with a half-life of 15 minutes

Why do we believe this?



- All this is part of the "Standard Model" for particle physics
- Model calculations (very complex) get made for the production of particles at different energies and the last 40 years of accelerator experiments have shown the models to be remarkably accurate

Back to 1950's: Hot Big Bang Nucleosynthesis

- George Gamov was a nuclear physicist political refugee from Russia who looked in detail at the early times in an expanding Universe run backward
- Made the first predictions of the era of nucleosynthesis and got a big surprise