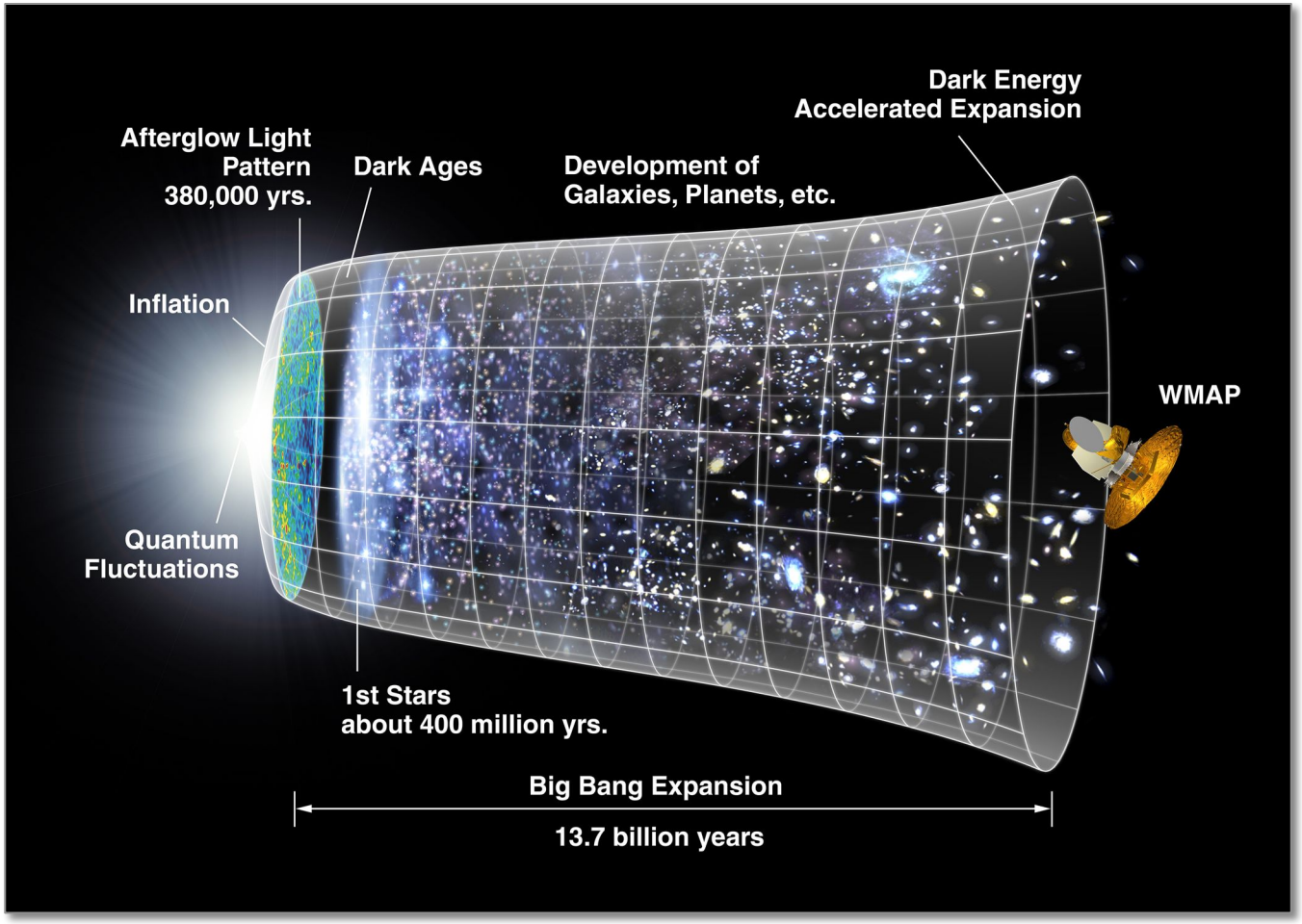
G6010: Physical Cosmology
Overview of Cosmology

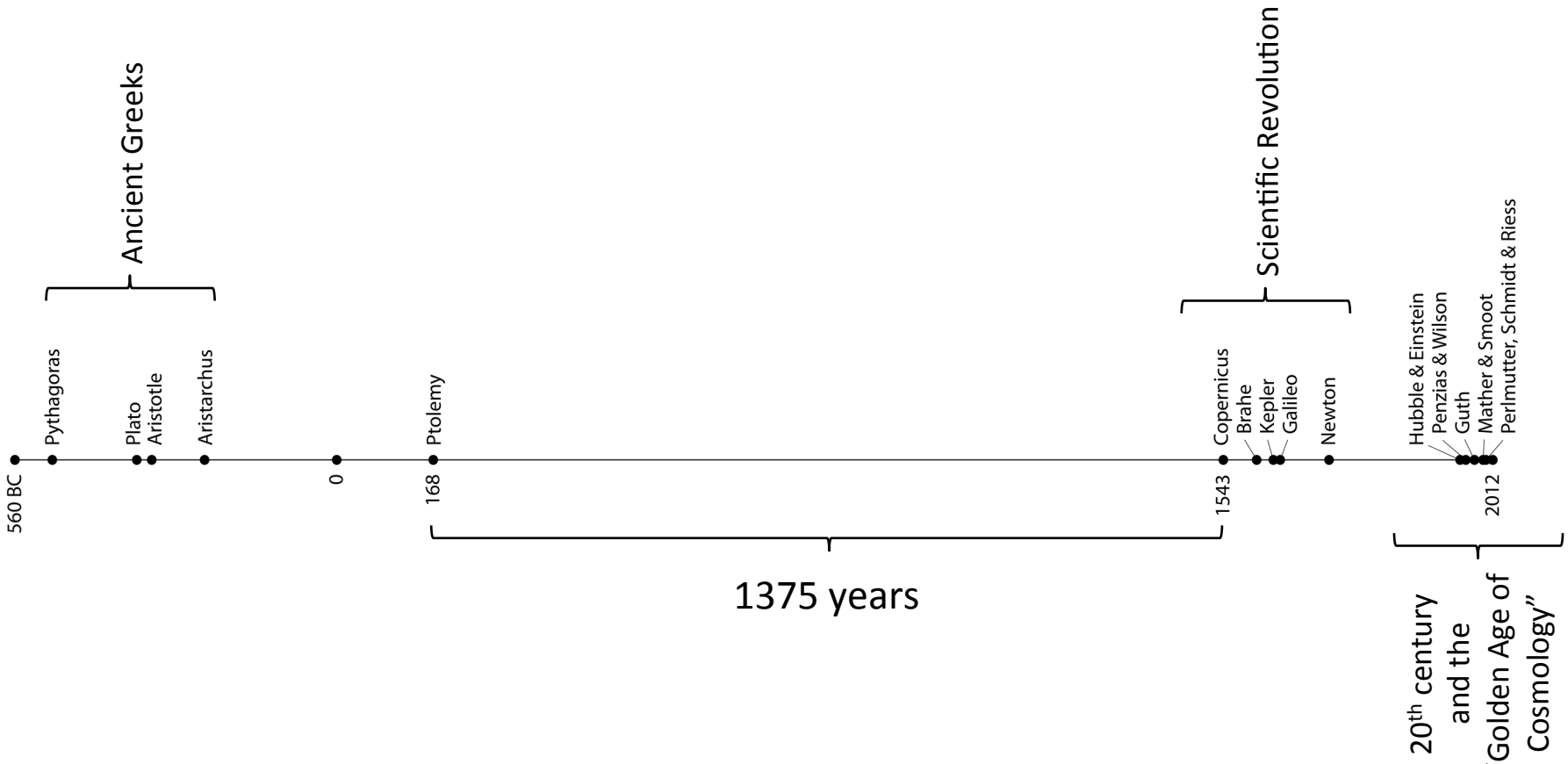
Brad Johnson

September 4th, 2014

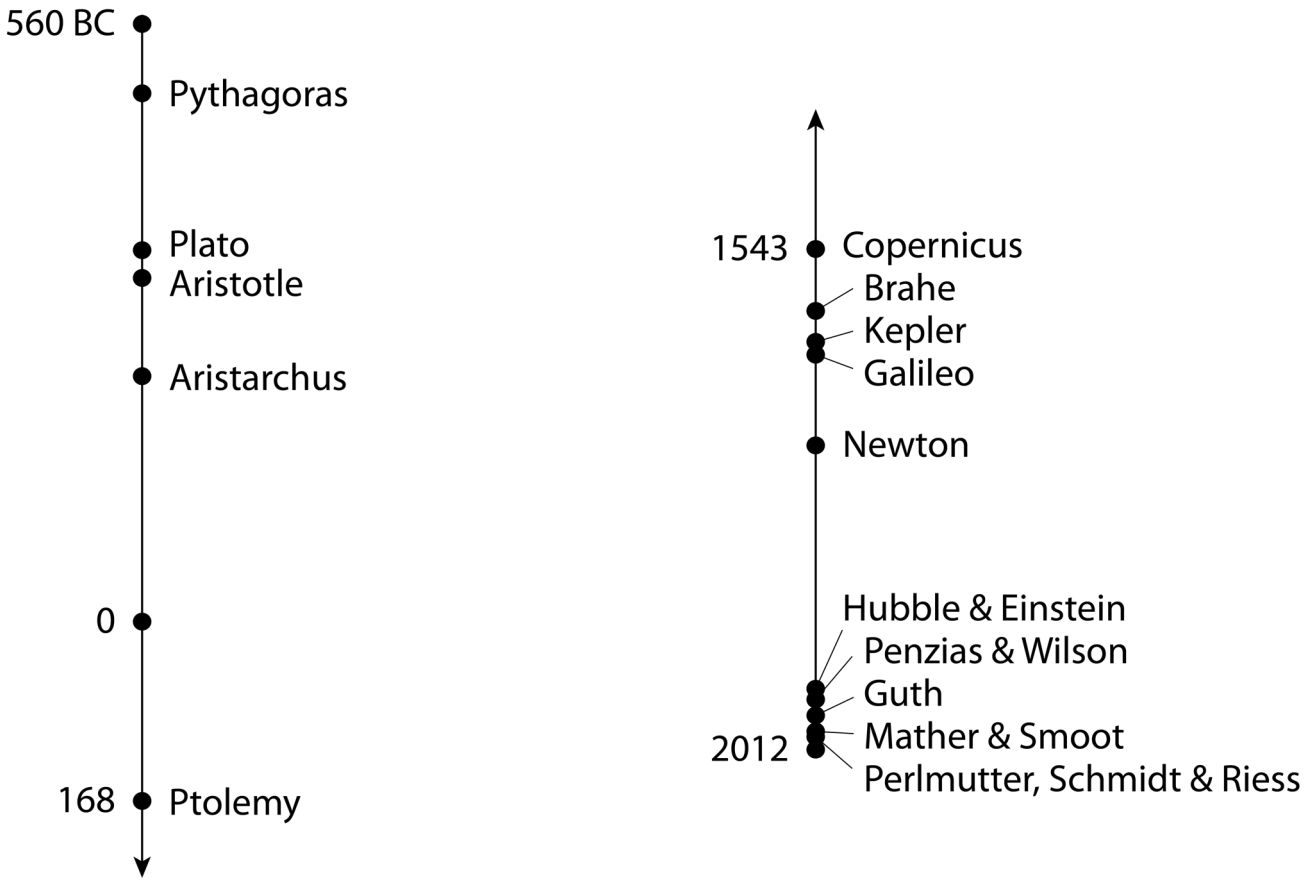
Standard Model of Cosmology



Timeline


Ancient Greeks
Scientific Revolution
Pythagoras
Plato
Aristotle
Aristarchus
Ptolemy
Copernicus
Brahe
Kepler
Galileo
Newton
Hubble & Einstein
Penzias & Wilson
Guth
Mather & Smoot
Perlmutter, Schmidt & Riess
560 BC
0
168
1543
2012
1375 years
20th century and the "Golden Age of Cosmology"

Timeline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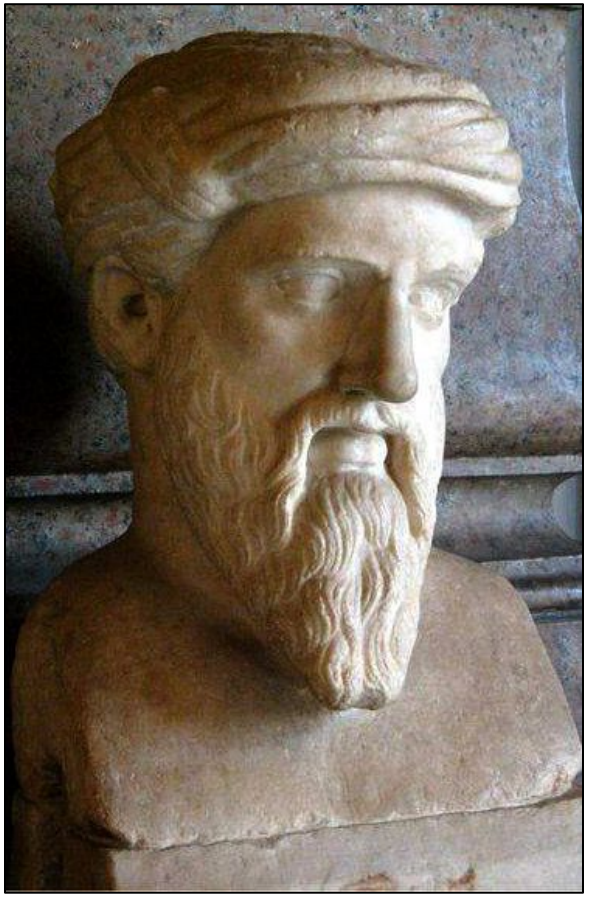
The Ancient Greeks

Geocentric Universe

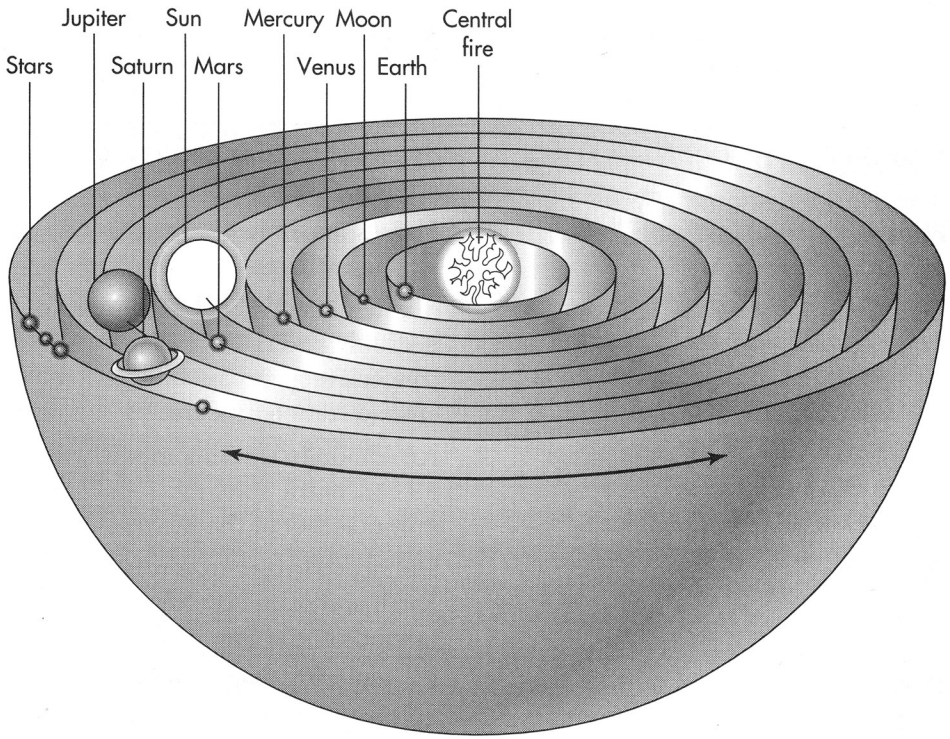
- Pythagoras of Samos was a Greek mathematician and philosopher.
- He thought the Earth was the center of the Universe, and the planets, the Sun and the Moon moved around the Earth.
- Ideas based on concentric spheres.
- No telescopes were available at that time, so his theory couldn't be rigorously tested.

"The State of the Universe. A Primer in Modern Cosmology."
by Pedro Ferreira

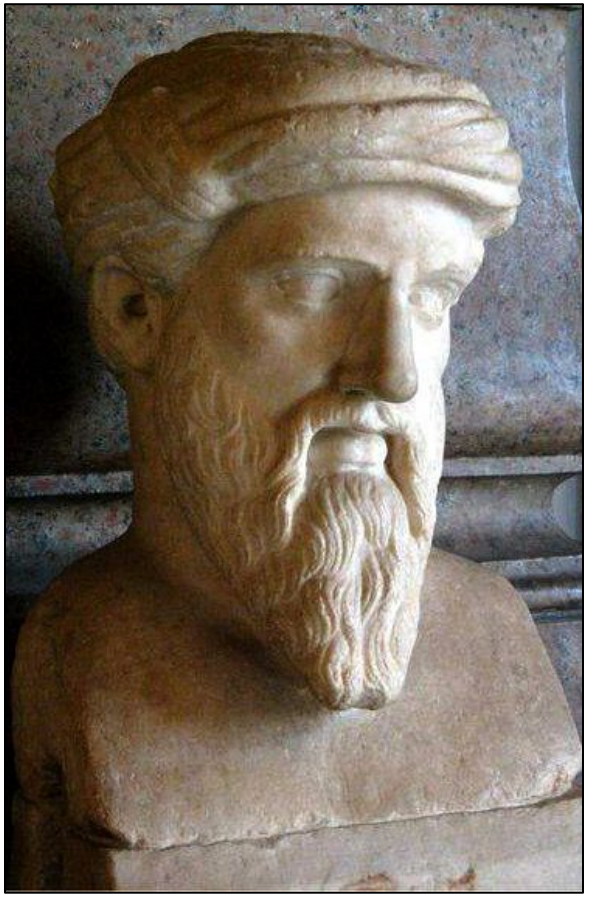


Pythagoras (570 BC – 495 BC)

Geocentric Universe



"The Big Bang."
By Joe Silk



Pythagoras (570 BC – 495 BC)

Geocentric Universe

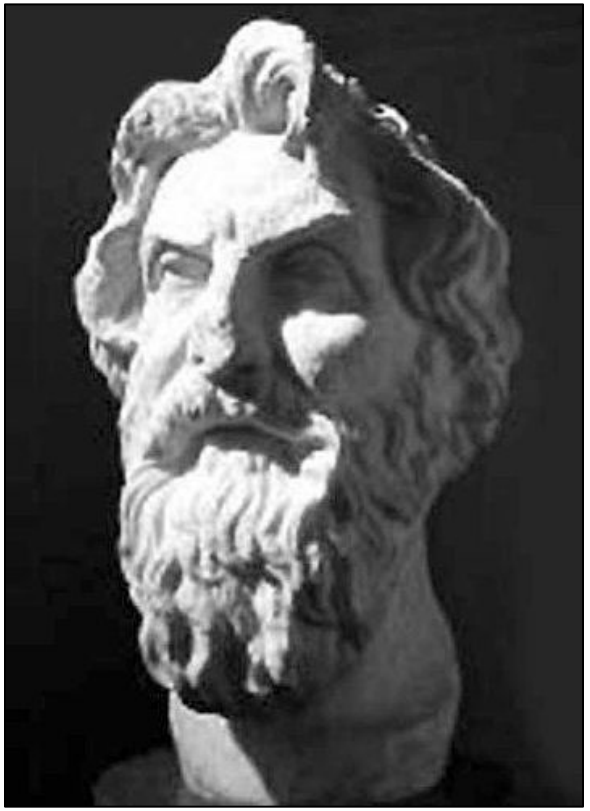
- Plato and Aristotle were Greek philosophers who worked in Athens.
- They supported and advanced Pythagoras' geocentric theory based on concentric spheres.
- Aristotle worked to develop a quantitative model though was only partially successful.

Plato (424 BC – 348 BC)
Aristotle (384 BC – 322 BC)

"The State of the Universe. A Primer in Modern Cosmology."
by Pedro Ferreira

Heliocentric Universe Introduced

- Aristarchus of Samos was an astronomer and mathematician.
- Also born on the island of Samos.
- First know model that places the sun at the center of the universe.
- Ideas not accepted.
- No strong wind observed.
- Stars do not get brighter and dimmer.



Aristarchus (310 BC – 230 BC)

"The State of the Universe. A Primer in Modern Cosmology."
by Pedro Ferreira

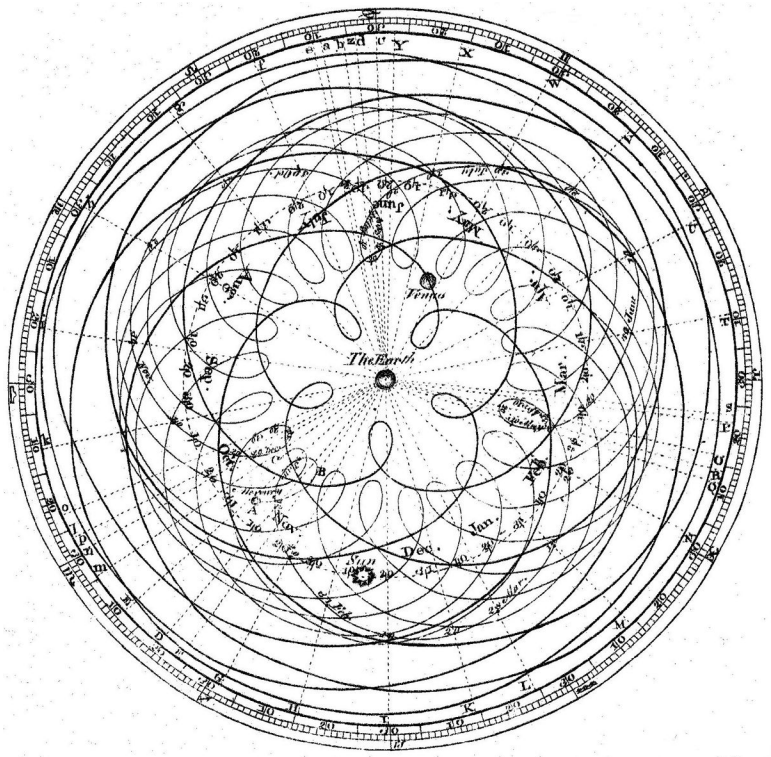
Geocentric Ptolemaic Universe

- Ptolemy was Greek-Roman citizen living in Alexandria, Egypt.
- Author of Almagest – a mathematical and astronomical treatise written in Greek considered to be one of the most influential scientific texts of all time
- Geocentric model of the universe broadly accepted for approximately 1300 years.

Claudius Ptolemy (90 AD – 168 AD)

"The State of the Universe. A Primer in Modern Cosmology."
by Pedro Ferreira

Geocentric Ptolemaic Universe



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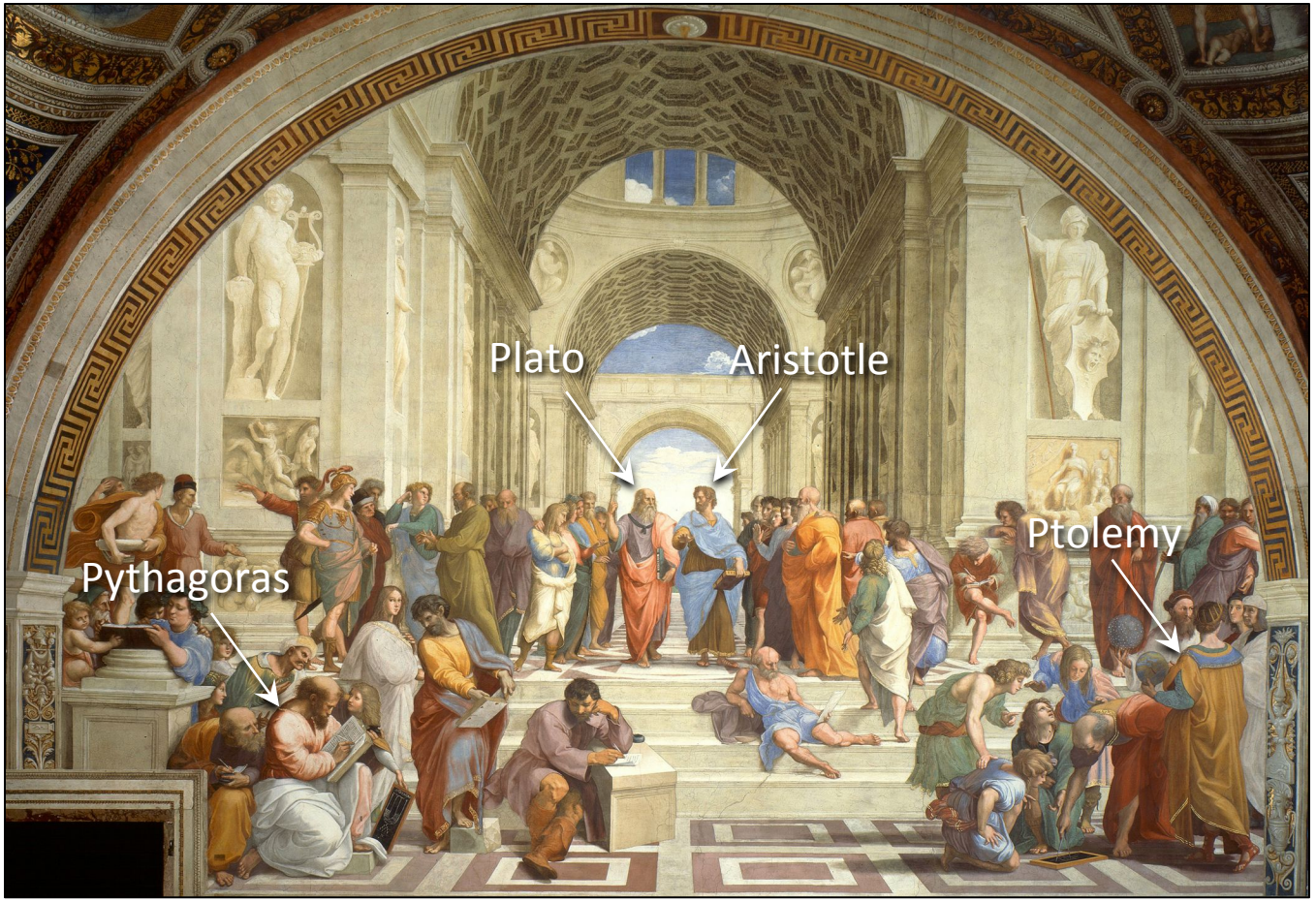
Claudius Ptolemy (90 AD – 168 AD)

School of Athens

fresco in the Apostolic Palace in the Vatican by Raphael (1510-1511)

School of Athens

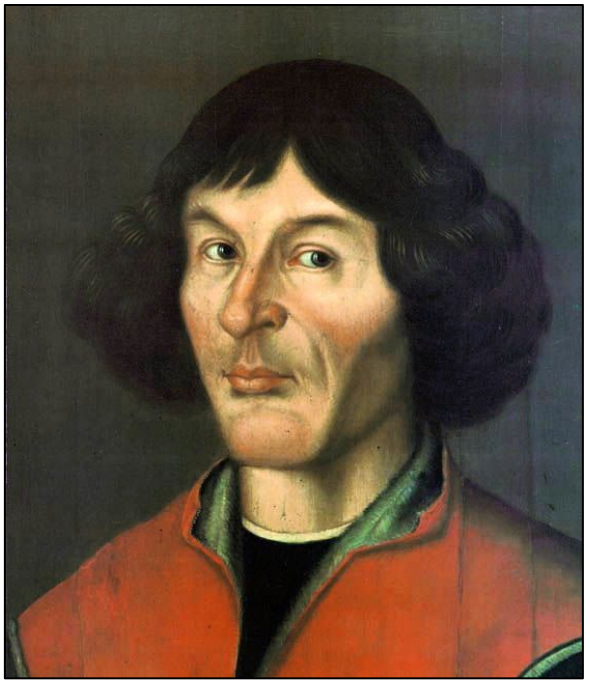


fresco in the Apostolic Palace in the Vatican by Raphael (1510-1511)

The Scientific Revolution

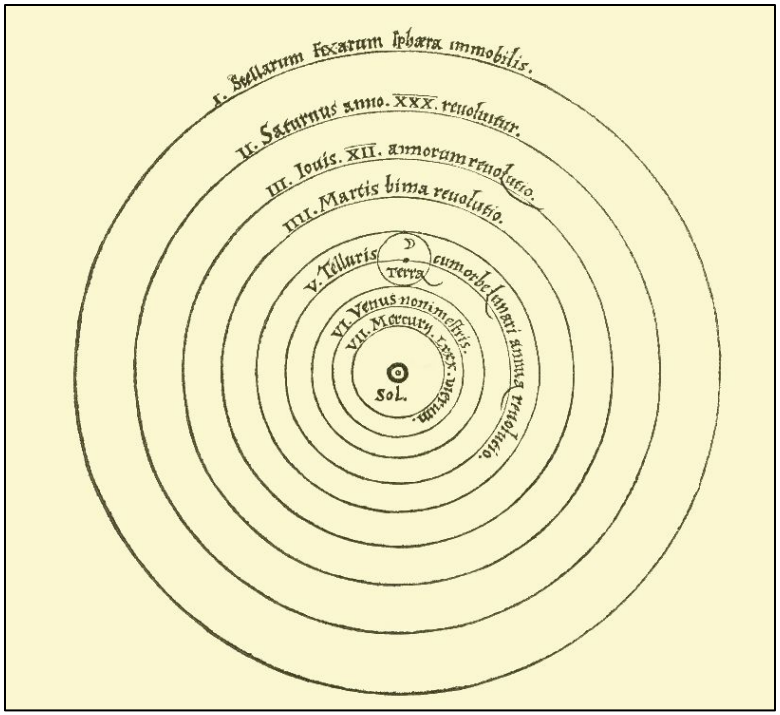
Heliocentric Universe (Revisited)

- Copernicus was an astronomer from the Kingdom of Poland.
- Author of *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*)
- Seminal work on the heliocentric theory.
- Began the scientific revolution.

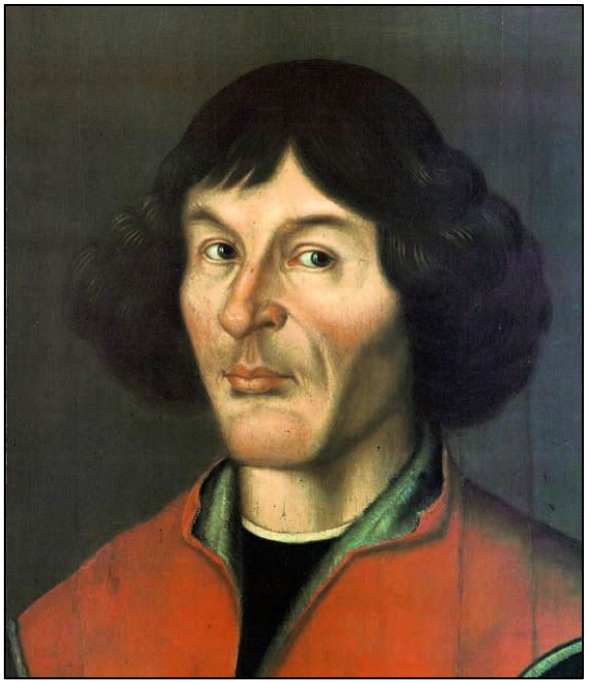


Nicholaus Copernicus (1473-1543)

Heliocentric Universe (Revisited)



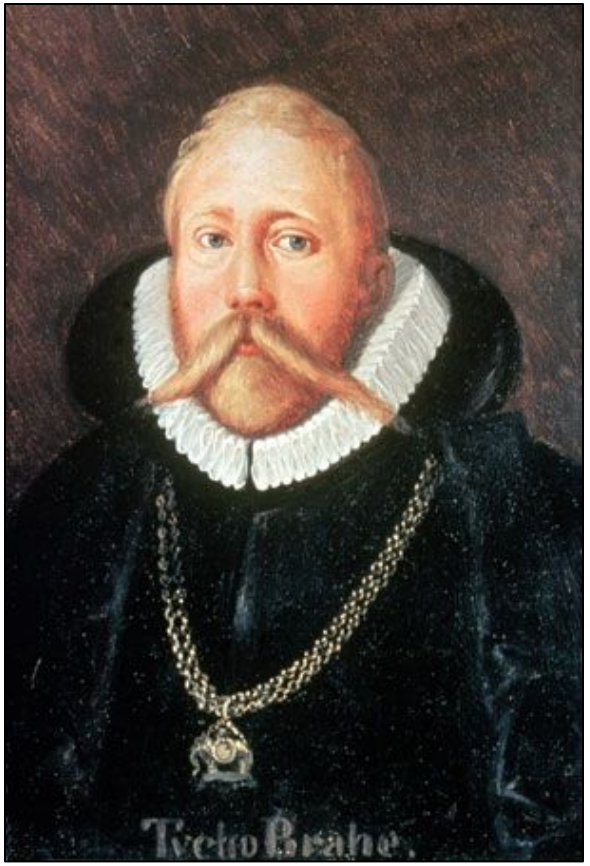
from *De revolutionibus orbium coelestium*



Nicholaus Copernicus (1473-1543)

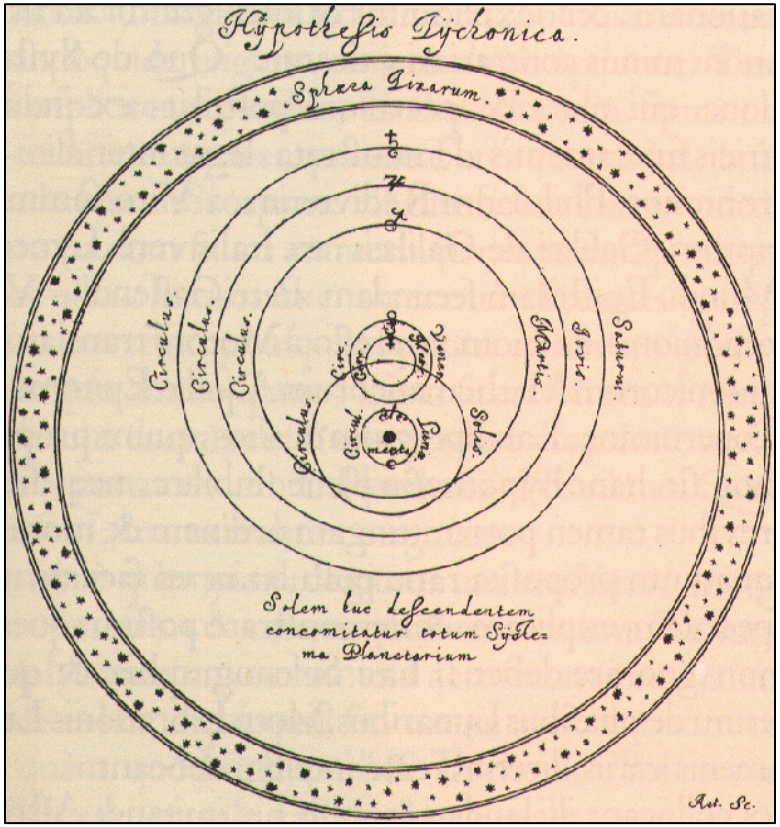
Geo-heliocentric Tychonian Universe

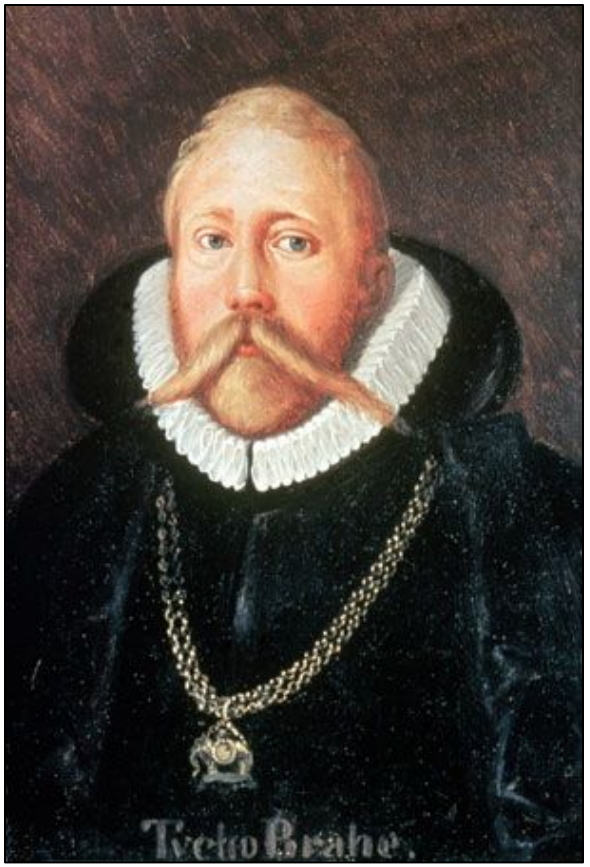
- Tycho Brahe was a Danish nobleman and astronomer.
- Last of the major "naked eye" astronomers, working without a telescope.
- Combined aspects of the Copernican model with the Ptolemaic model.
- Challenged the Aristotelian belief that the celestial realm is unchanging because he observed supernovae.



Tycho Brahe (1546-1601)

Geo-heliocentric Tychonian Universe





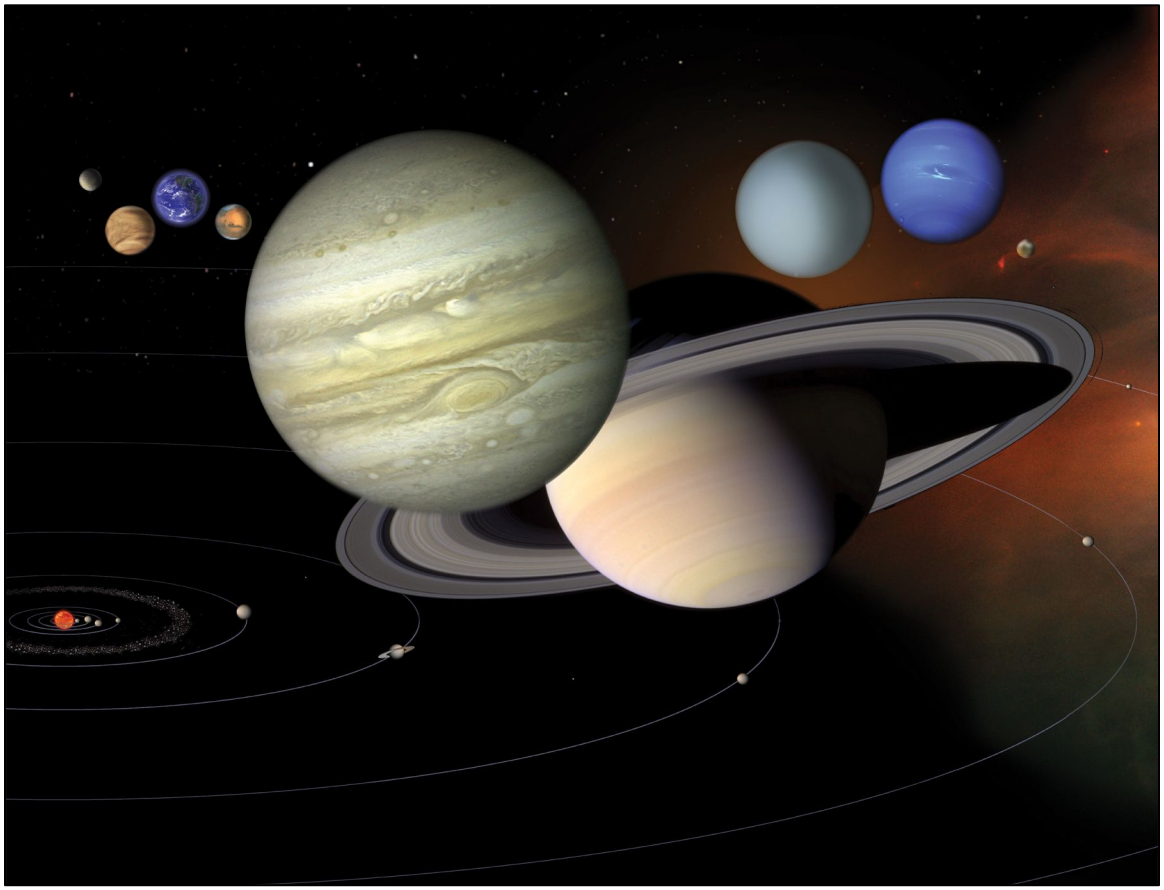
Tycho Brahe (1546-1601)

Johannes Kepler

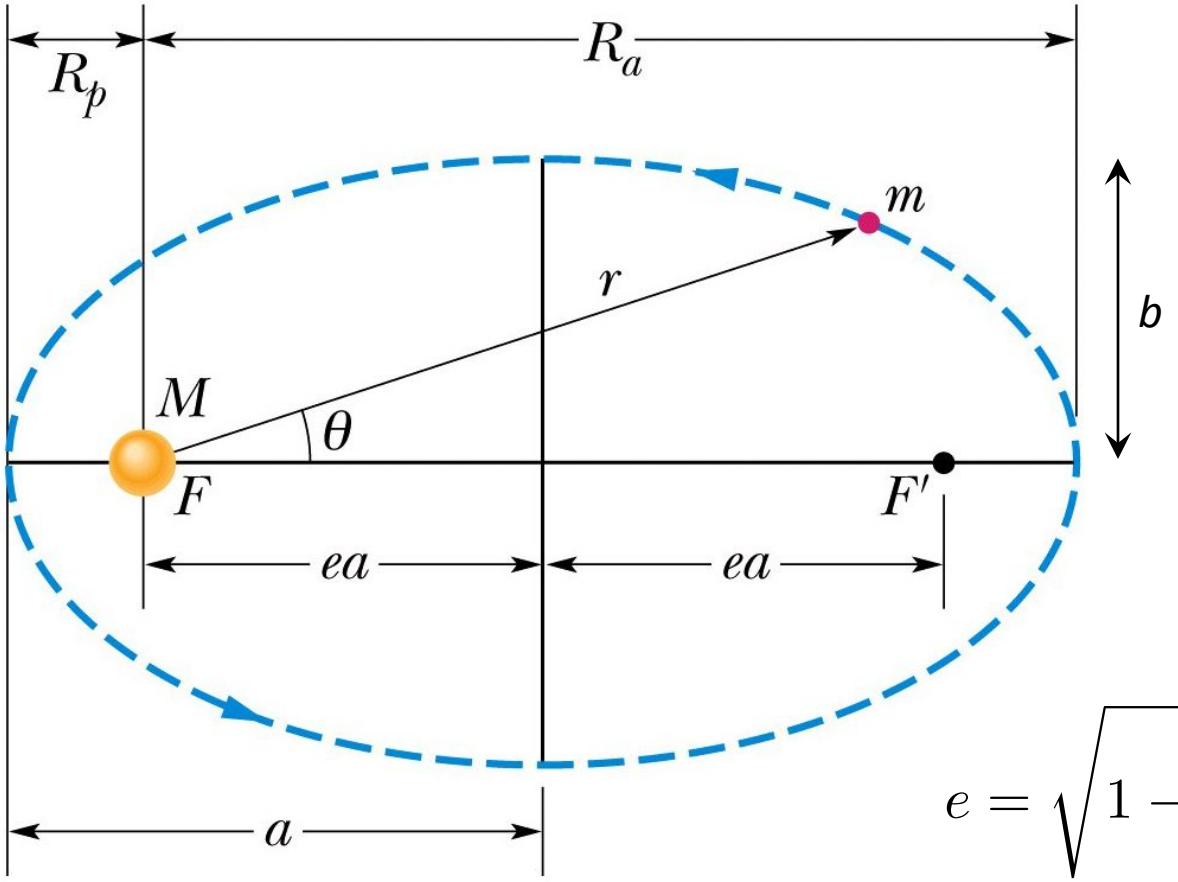
- Kepler was a German mathematician and astronomer.
- Key figure in the 17th century scientific revolution.
- Empirically studied planetary motion.
- Author of *Astronomia nova*, *Harmonices Mundi* and and *Epitome of Copernican Astronomy.*
- The work published in these books served as a foundation for Isaac Newton's theory of universal gravitation.

Johannes Kepler (1571-1630)

Planetary Orbits

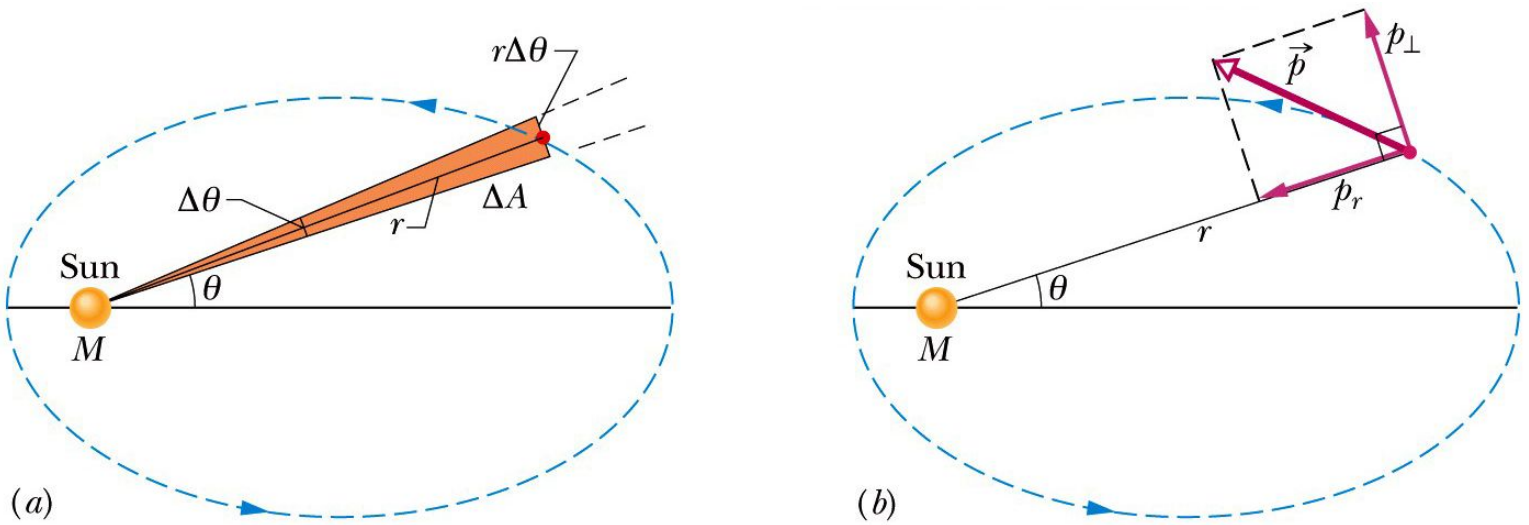


Kepler's Laws



The Law of Orbits: All planets move in elliptical orbits with the Sun at one focus.

Kepler's Laws



The Law of Areas: A line that connects a planet to the Sun sweeps out equal areas in the plane of the planet's orbit in equal time intervals; that is , the rate dA/dt at which it sweeps out area A is constant.

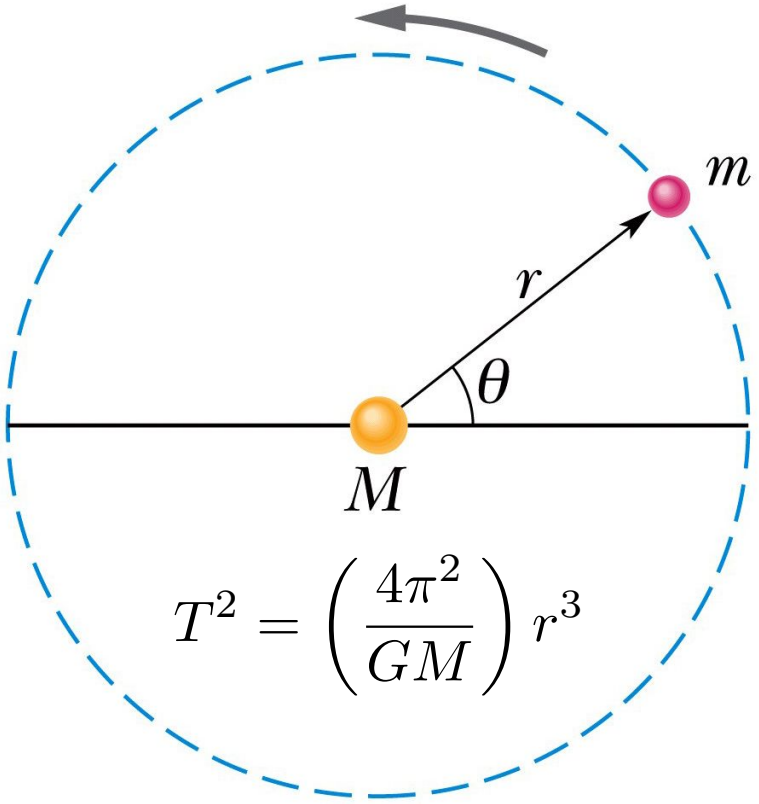
$$\frac{dA}{dt} = \frac{1}{2} r^2 \frac{d\theta}{dt} = \frac{1}{2} r^2 \omega = \frac{L}{2m}$$

Kepler's Laws

Table 13-3

Kepler's Law of Periods for the Solar System

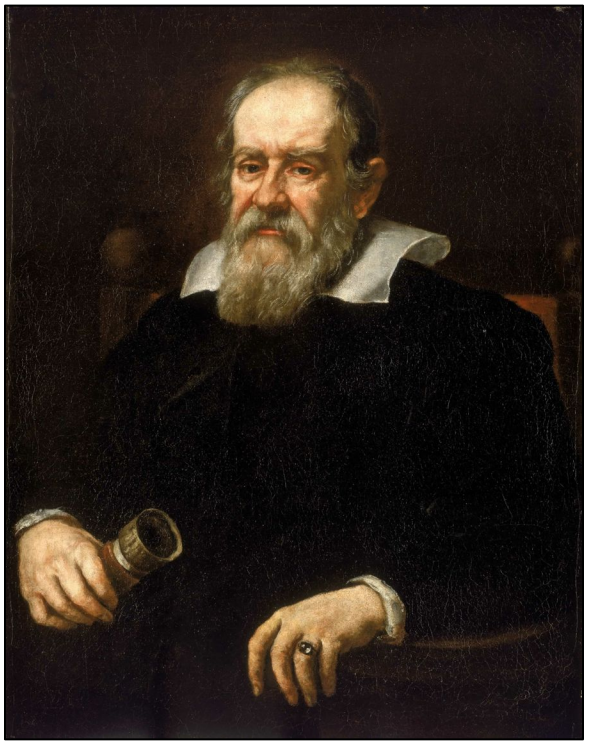
Planet	Semimajor Axis a (10^{10} m)	Period T (y)	T^2/a^3 (10^{-34} y^2/m^3)
Mercury	5.79	0.241	2.99
Venus	10.8	0.615	3.00
Earth	15.0	1.00	2.96
Mars	22.8	1.88	2.98
Jupiter	77.8	11.9	3.01
Saturn	143	29.5	2.98
Uranus	287	84.0	2.98
Neptune	450	165	2.99
Pluto	590	248	2.99



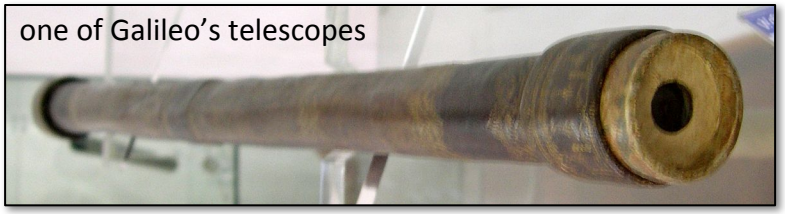
The Law of Periods: The square of the period of any planet is proportional to the cube of the semimajor axis of its orbit.

Invention of the Telescope

- Galileo Galilei was an Italian physicist, mathematician, astronomer, etc.
- Early developer of the telescope and key figure in the scientific revolution.
- Advanced the heliocentric theory.
- Authored the book *Dialogue Concerning the Two Chief World Systems*
- Convicted of heresy and spent the rest of life under house arrest.



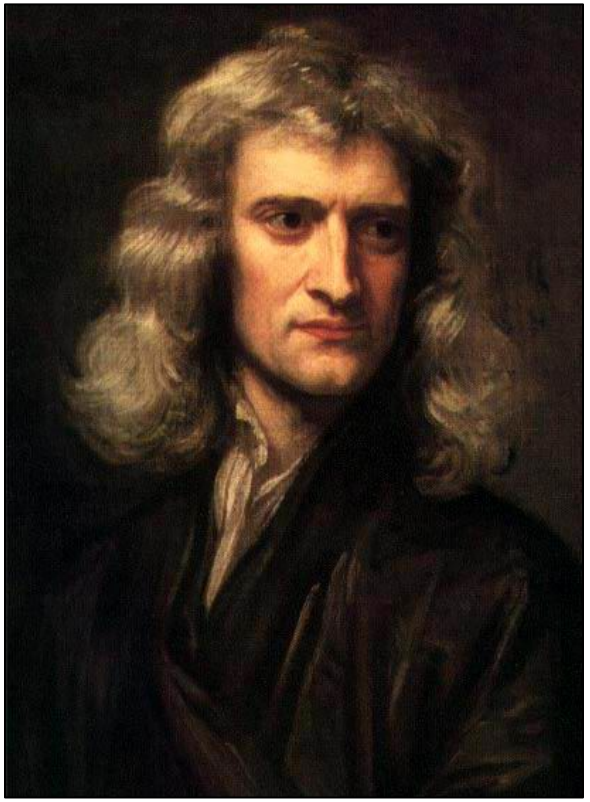
Galileo Galilei (1564-1642)



Newtonian Gravity

- Isaac Newton was an English physicist, mathematician, astronomer, etc.
- Author of *"Principia,"* which described universal gravitation and the three laws of motion.
- Mathematically confirmed Keplers empirically determined laws of planetary motion.

$$F = G\frac{m_1 m_2}{r^2}$$

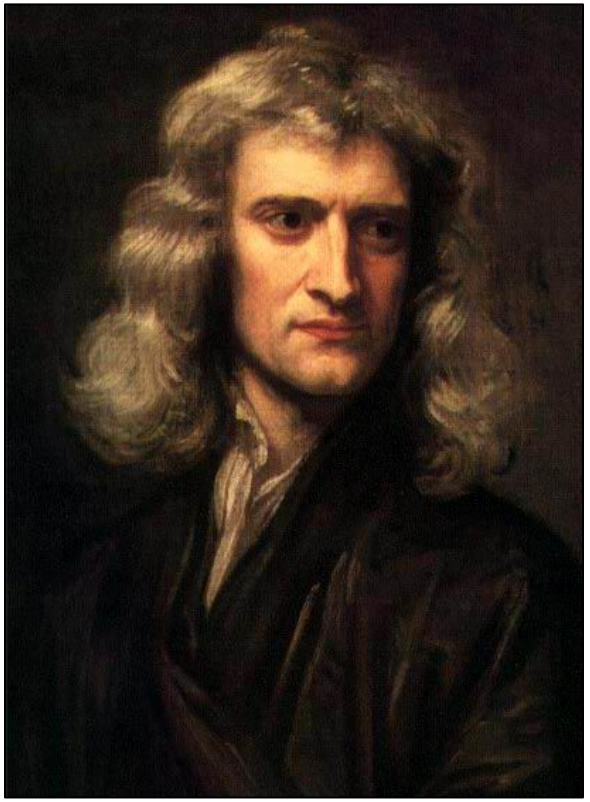


Sir Isaac Newton (1642 – 1727)

Newtonian Gravity

- Hugely successful work though some problems remained ...
- Gravitational force travels faster than light.
- Law of gravitation could not explain the perihelion shift of Mercury.

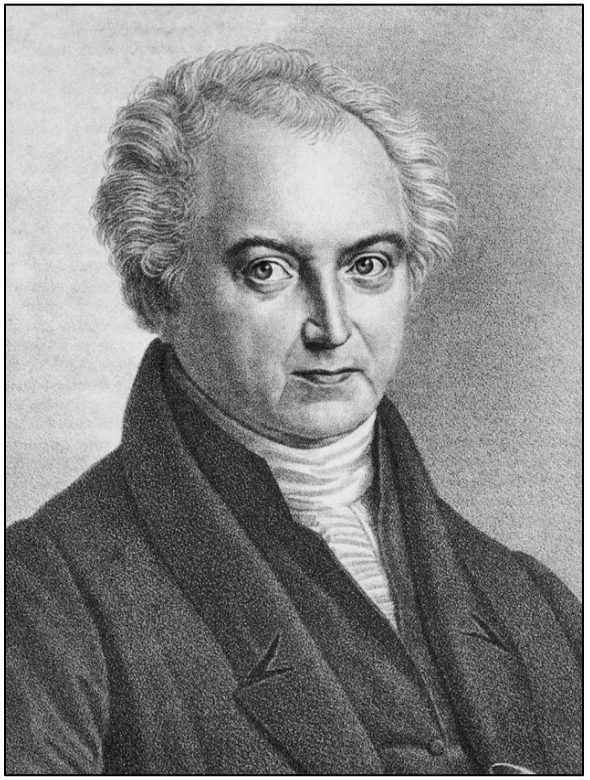
$$F = G\frac{m_1 m_2}{r^2}$$



Sir Isaac Newton (1642 – 1727)

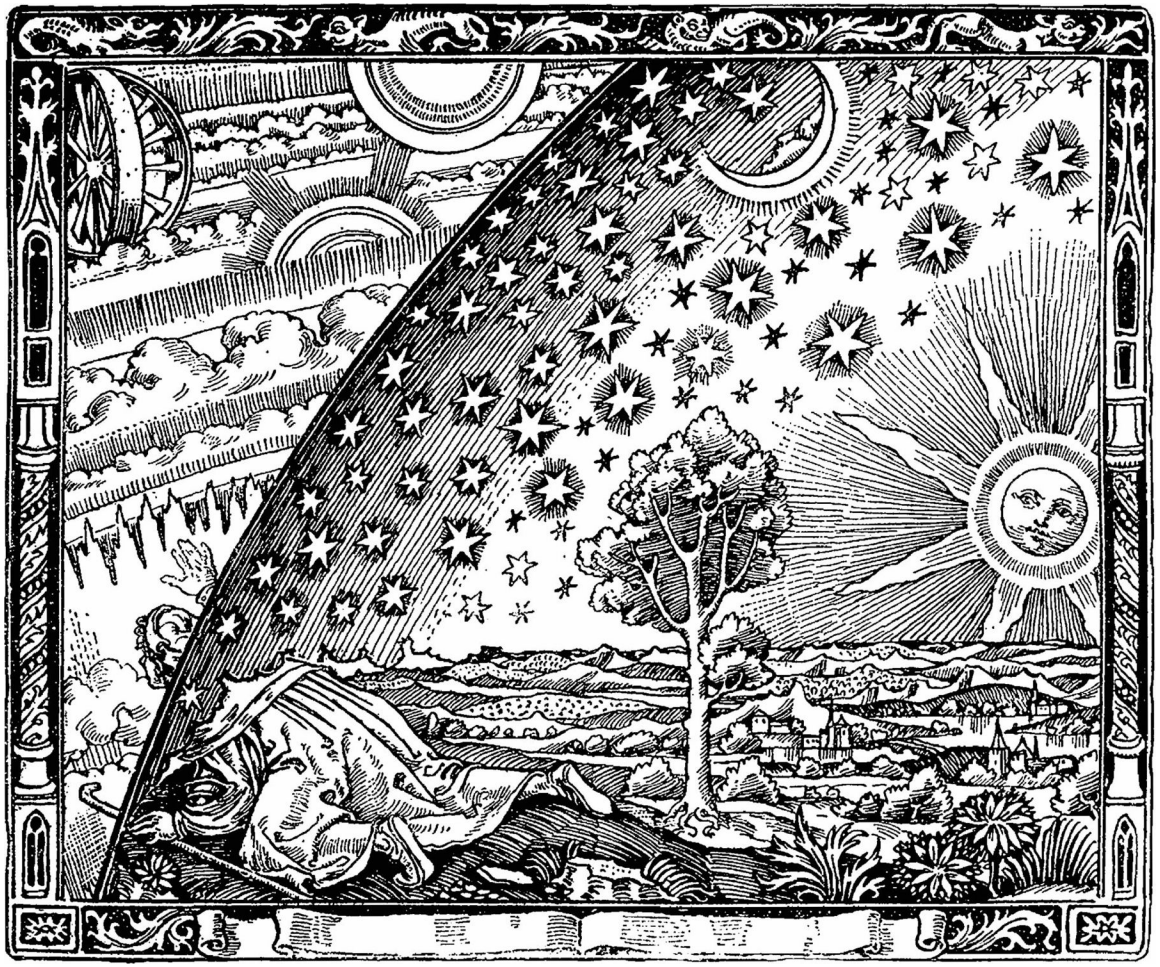
Olber's Paradox

- Heinrich Wilhelm Matthias Olbers was a German physician and astronomer.
- If the Universe is infinite, eternal and static, then the night sky should be filled with starlight – not dark.



Heinrich Olbers (1758 – 1840)

Flat Earth



The Flammarion engraving published in *L'atmosphère: météorologie populaire* in 1888

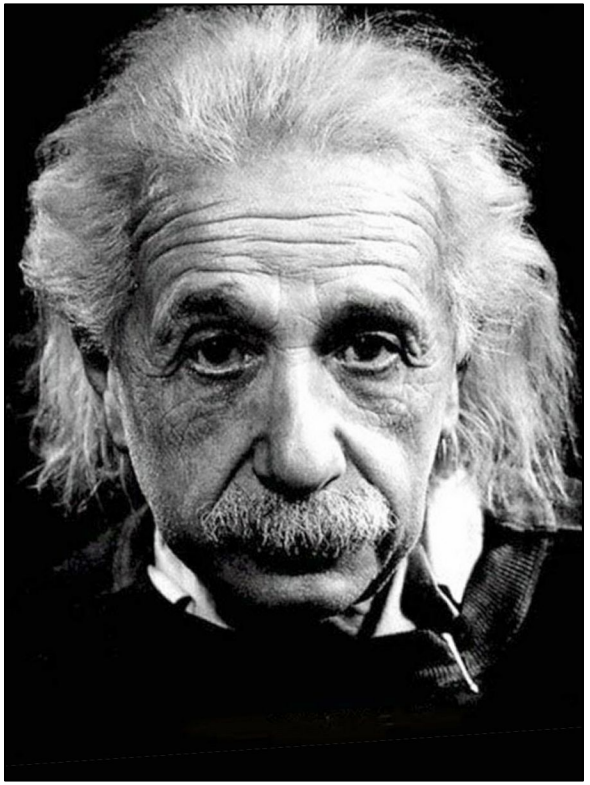
Flat Earth

Copyright in 1893

The 20th Century
and the
"Golden Age of Cosmology"

General Relativity

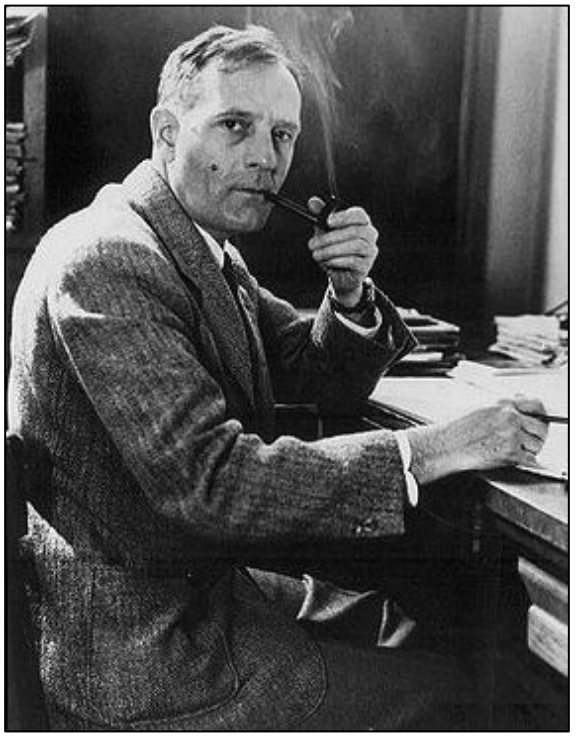
- Albert Einstein was a German-born theoretical physicist.
- Developed General Theory of Relativity
- Nothing travels faster than the speed of light, and gravity can be described as curved spacetime.
- General Relativity solved the perihelion shift of Mercury problem and allowed for the existence of gravitational waves.
- It also allowed for an expanding universe ....



Albert Einstein (1879 – 1955)

The Expanding Universe

- Edwin Hubble was an American astronomer.
- Played a critical role in establishing the field of extragalactic astronomy.
- Credited with discovering galaxies outside our Milky Way galaxy.
- Discovered that these galaxies are moving away from us.



Edwin Hubble (1889-1953)

The Expanding Universe

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

BY EDWIN HUBBLE

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON

Communicated January 17, 1929

Determinations of the motion of the sun with respect to the extra-galactic nebulae have involved a K term of several hundred kilometers which appears to be variable. Explanations of this paradox have been sought in a correlation between apparent radial velocities and distances, but so far the results have not been convincing. The present paper is a re-examination of the question, based on only those nebular distances which are believed to be fairly reliable.

Proceedings of the National Academy of Sciences of the United States of America
Volume 15, Issue 3, pp. 168-173

The Expanding Universe

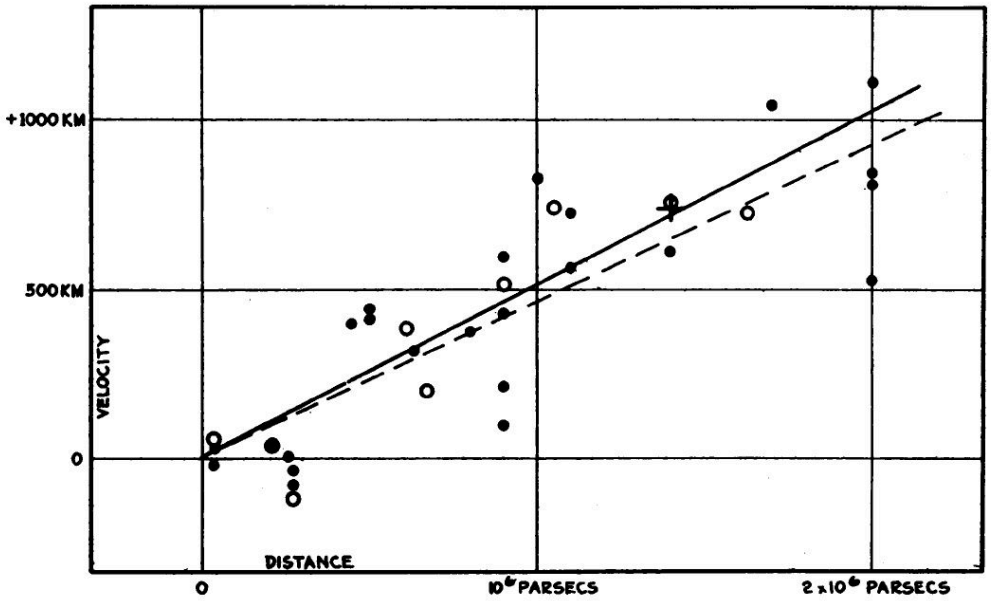


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

Cosmic Microwave Background (CMB)

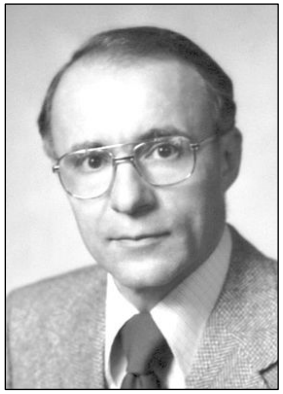
A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

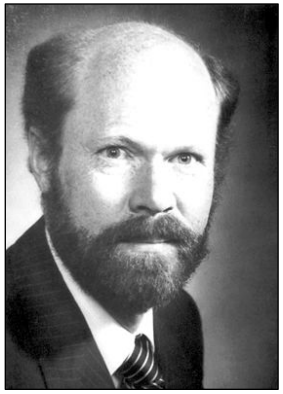
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

A. A. PENZIAS
R. W. WILSON

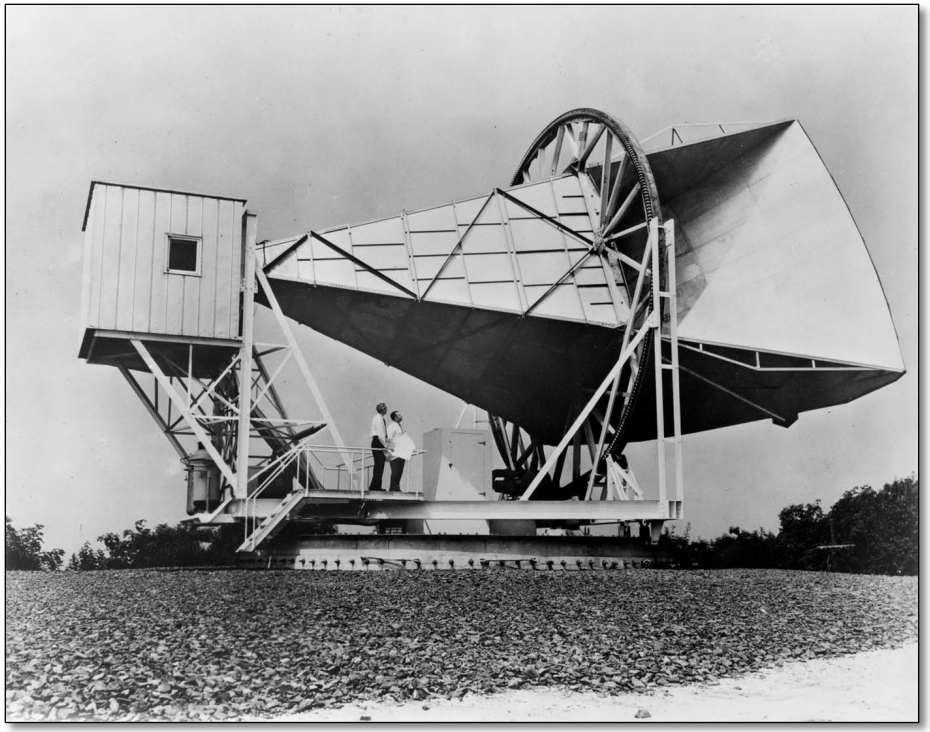
May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

Cosmic Microwave Background (CMB)

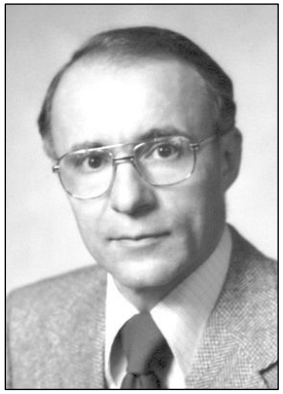

Penzias

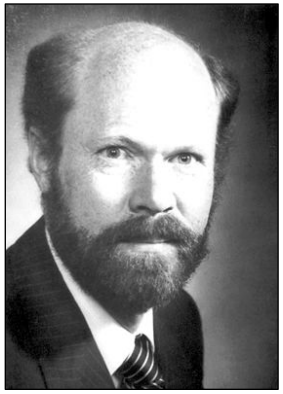

Wilson

The **1978** Nobel Prize in Physics was awarded jointly to Arno Allan Penzias and Robert Woodrow Wilson *"for their discovery of cosmic microwave background radiation."*


20-foot horn reflector antenna at Crawford Hill Laboratory in New Jersey

Cosmic Microwave Background (CMB)


Penzias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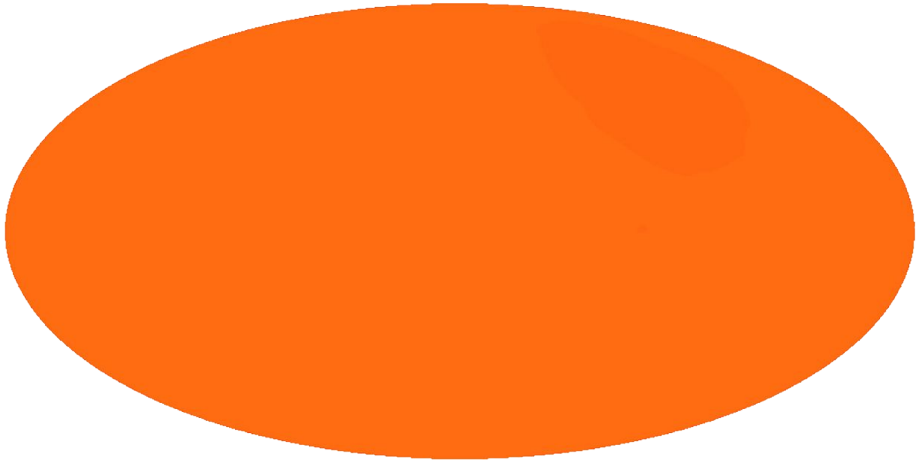


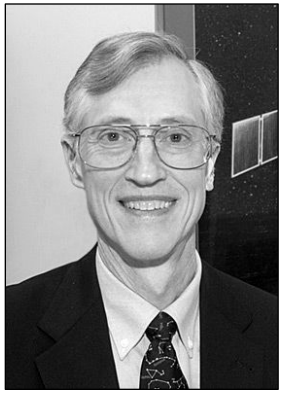
2.7 K CMB monopole

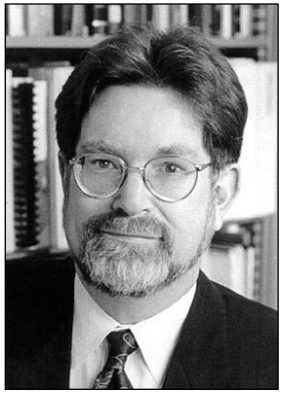
Inflation

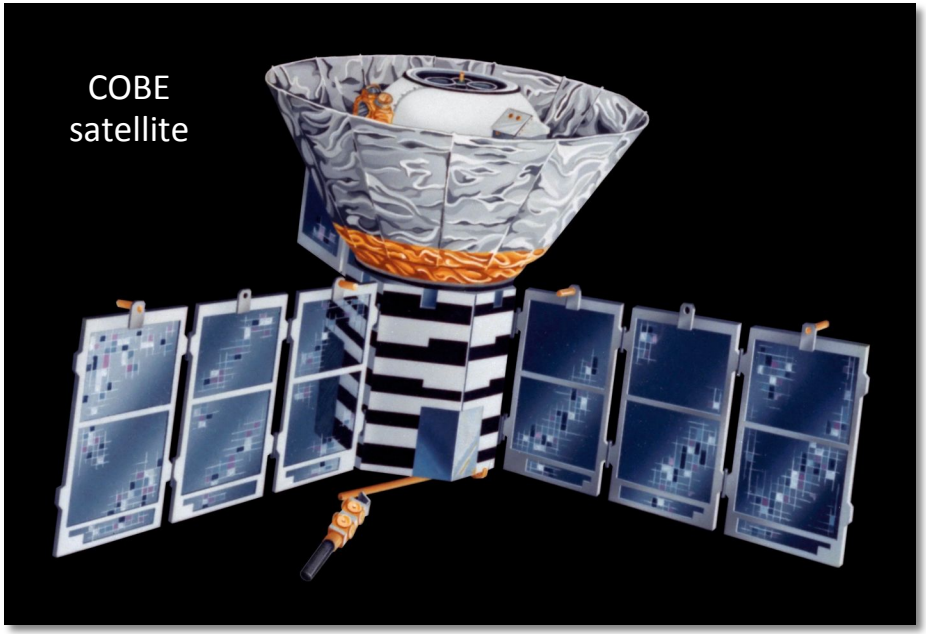
- Alan Guth is an American theoretical physicist and cosmologist.
- Currently a professor at MIT.
- Developed the idea of cosmic inflation in 1979.
- Inflation explains why the Universe appears flat, homogeneous, and isotropic.
- Inflation also explains the origin of the large-scale structure of the cosmos.
- Has yet to be experimentally proven.

Alan Guth (1947-present)

CMB Spectrum & Anisotropy


Mather


Smoot



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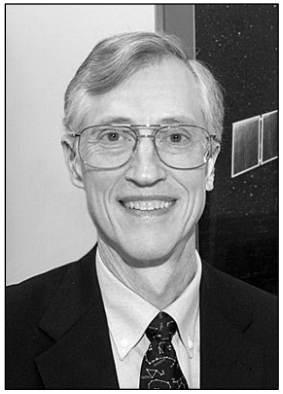
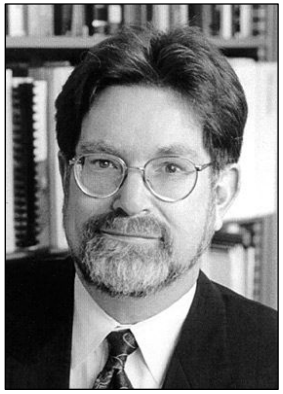
CMB Spectrum & Anisotropy


Mather


Smoot

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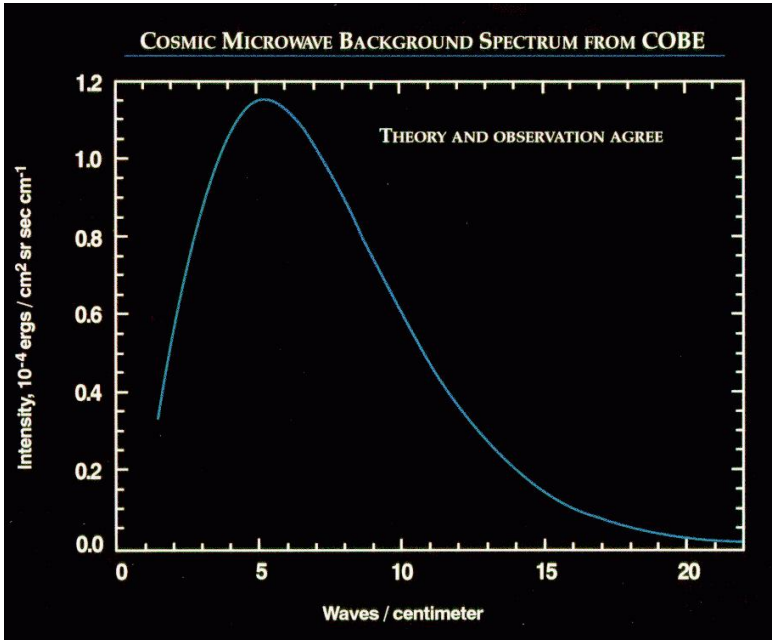
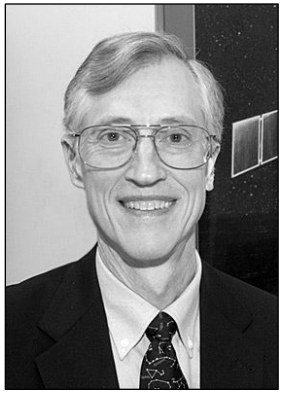
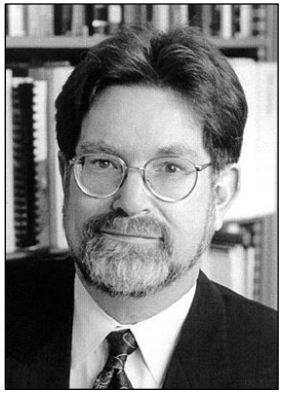


CMB Spectrum & Anisotropy


Mather


Smoot

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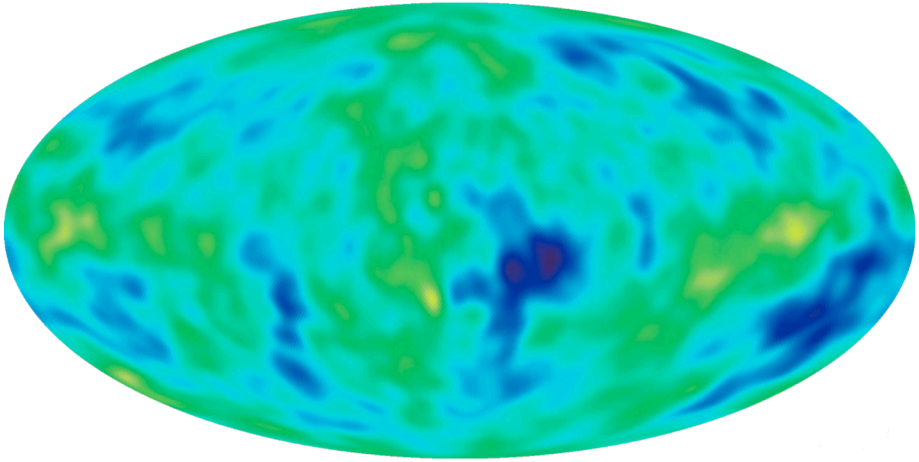
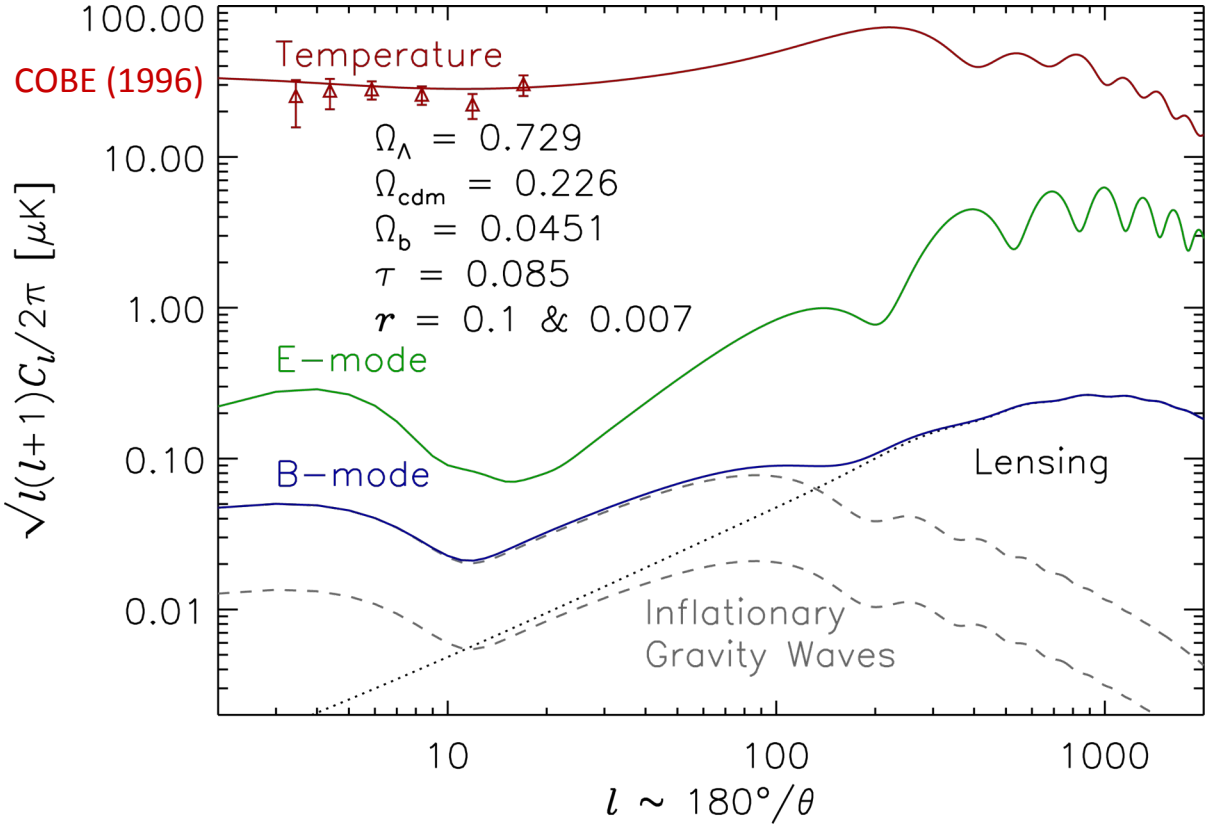


primordial anisotropy
(monopole, dipole, and Galactic signals removed)

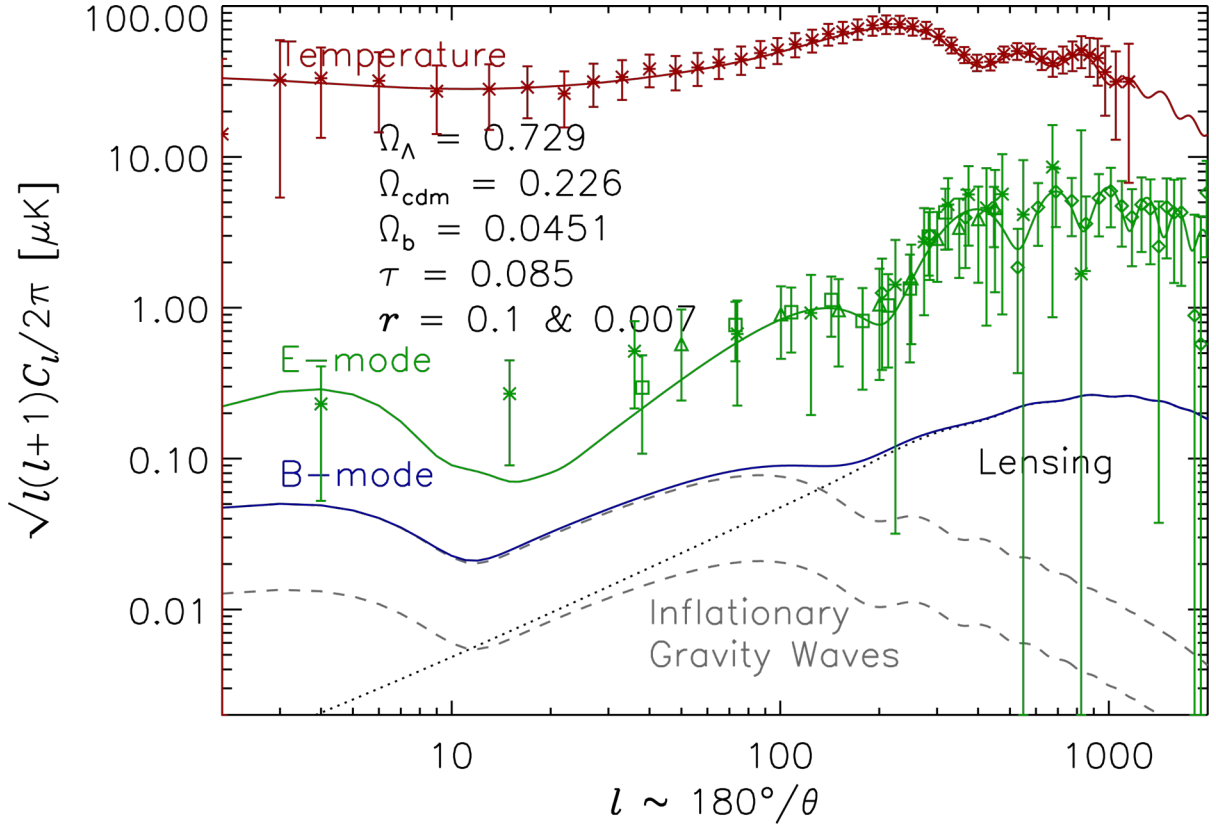
Penzias & Wilson, COBE

monopole
off
the plot



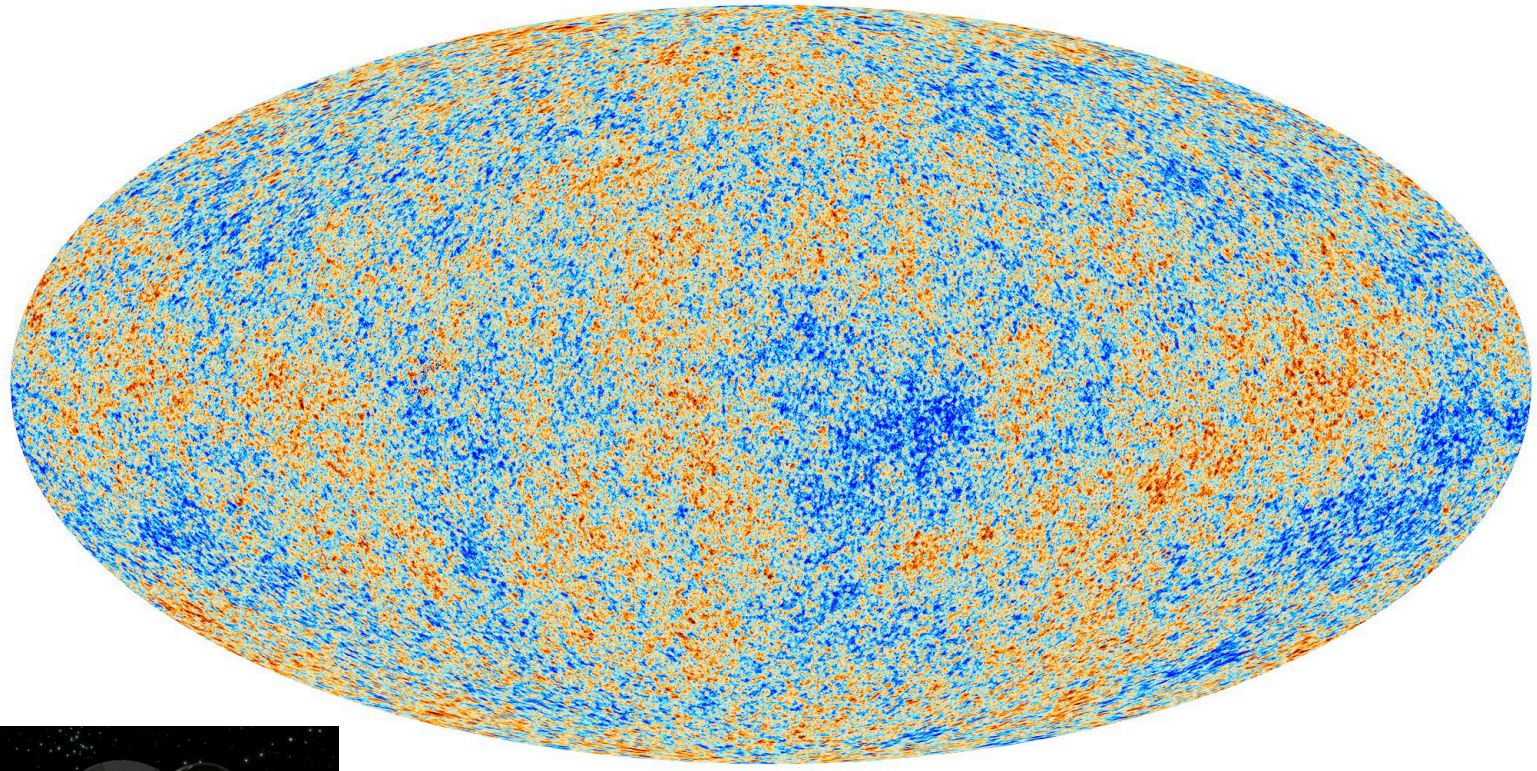
IMPORTANT: the power spectrum is the point of contact between theory and measurements

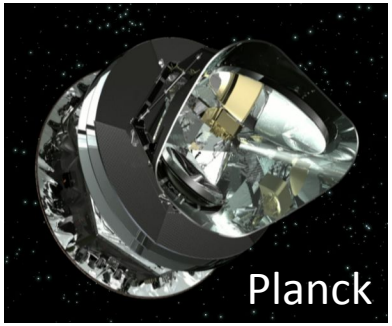
Last Year's State-of-the-Art



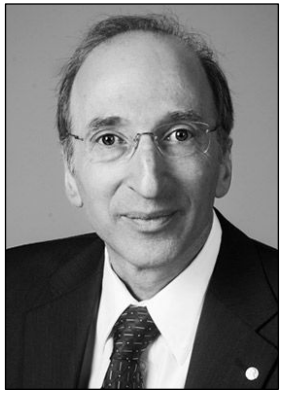
New Picture of the Infant Universe

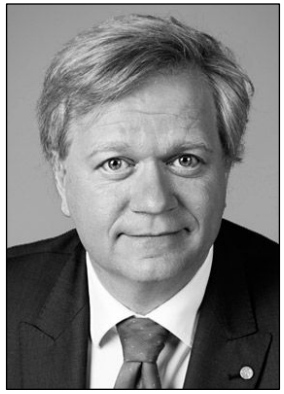
New Image of the Infant Universe





Accelerating Expansion of the Universe

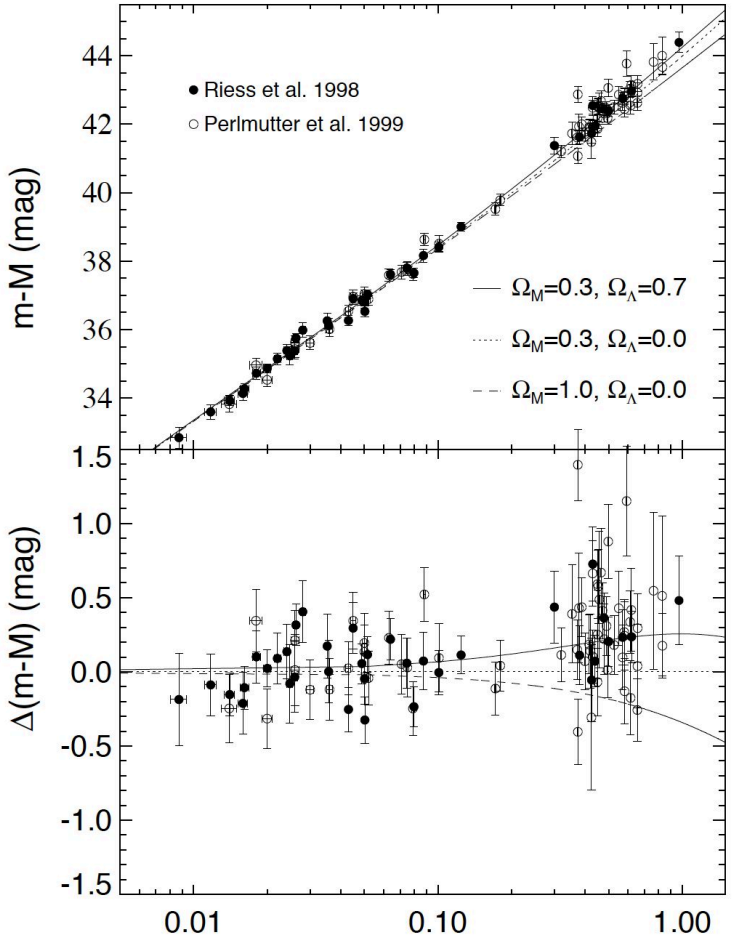

Pearlmutter


Schmidt


Reiss

The Nobel Prize in Physics **2011** was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

Accelerating Expansion of the Universe



Riess et al. (1998). *ApJ*, 116, 1009.

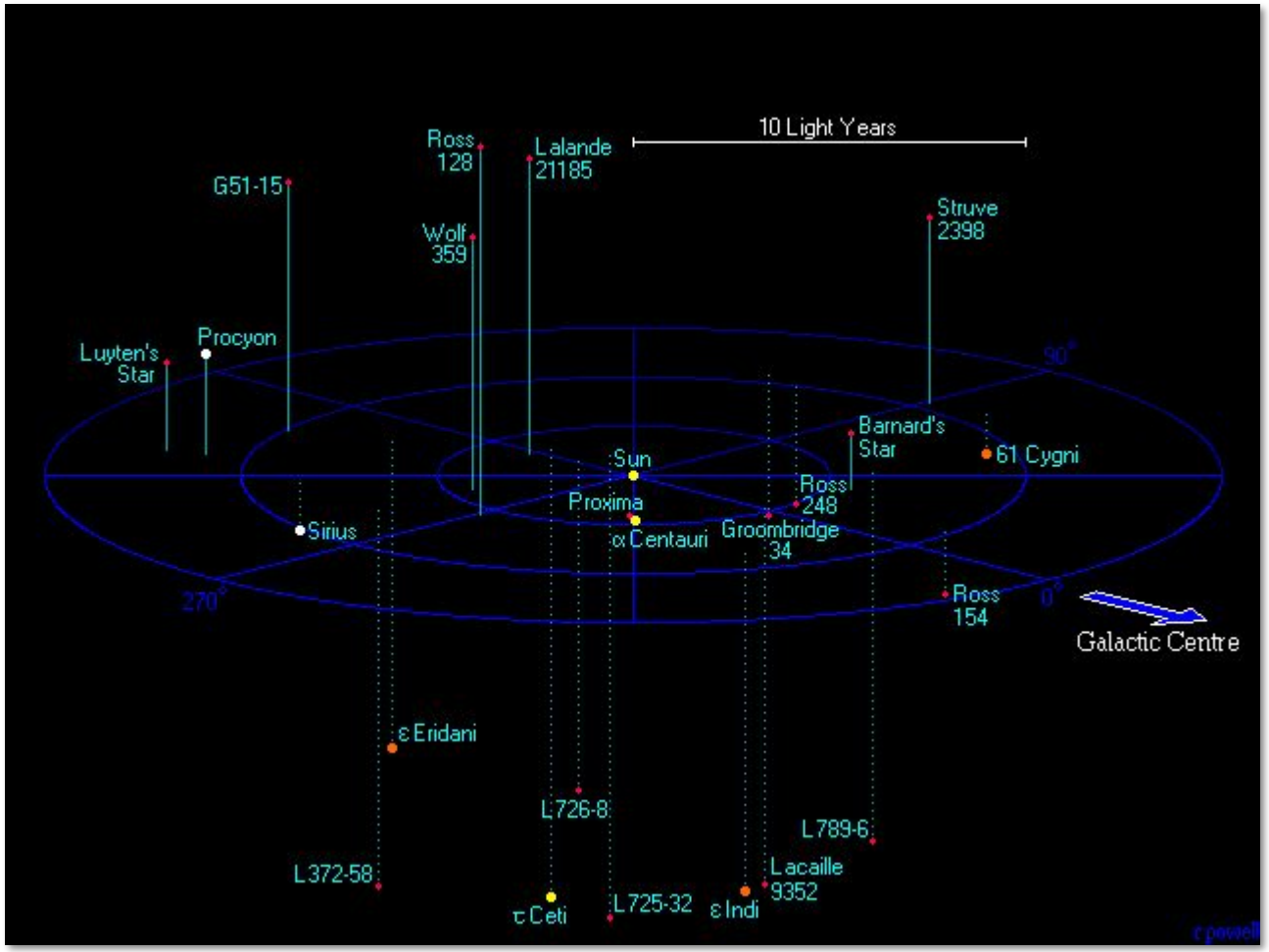
Perlmutter et al. (1999). *ApJ*, 517, 565.

FIG. 1.—Hubble diagrams of SNe Ia from Perlmutter et al. (1999; SCP) and Riess et al. (1998; HZT). Overplotted are three cosmologies: "low" and "high" Ω_M with $\Omega_\Lambda = 0$ and the best fit for a flat cosmology, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$. The bottom panel shows the difference between data and models from the $\Omega_M = 0.3$, $\Omega_\Lambda = 0$ prediction. The average difference between the data and the $\Omega_M = 0.3, \Omega_\Lambda = 0$ prediction is 0.28 mag.

A lot of other measurements happened …

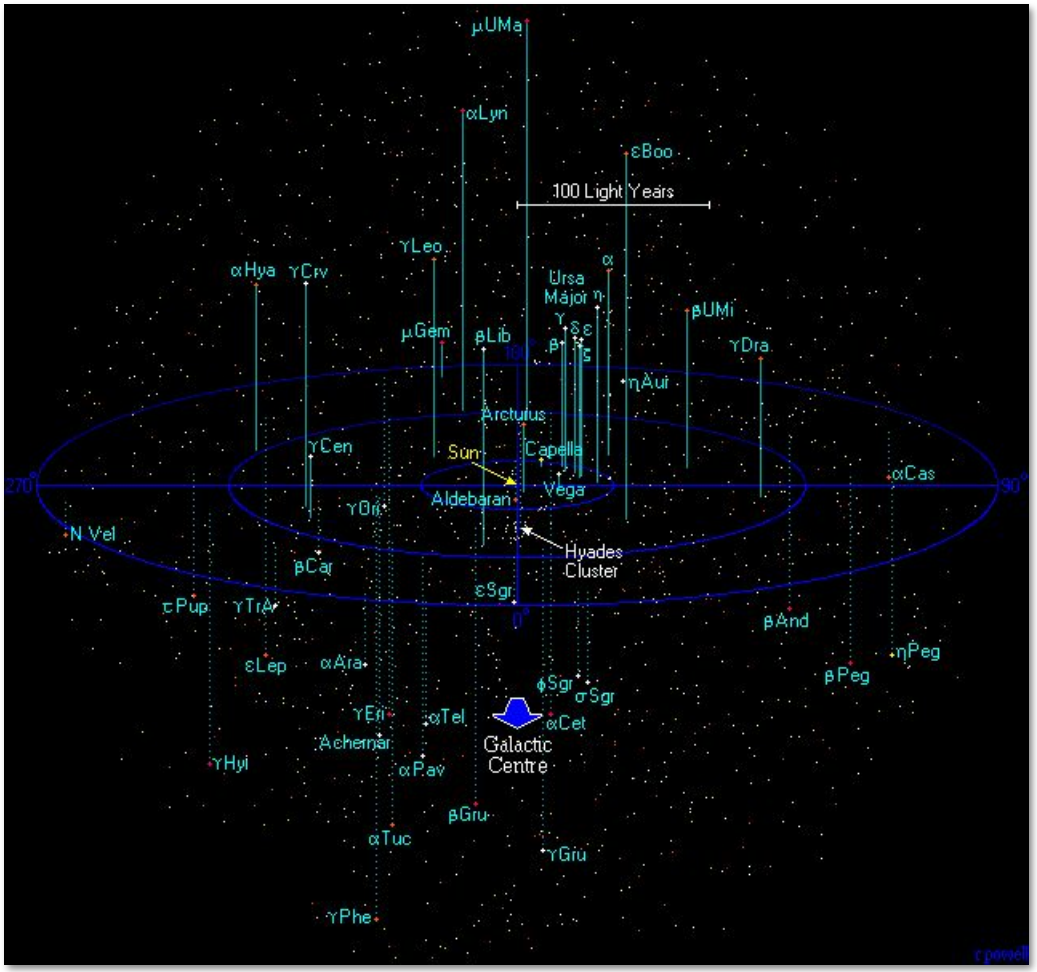
What does the universe look like?

The Nearest Stars



http://www.atlasoftheuniverse.com

The Solar Neighborhood



http://www.atlasoftheuniverse.com

A Tangent: Searching for Exoplanets

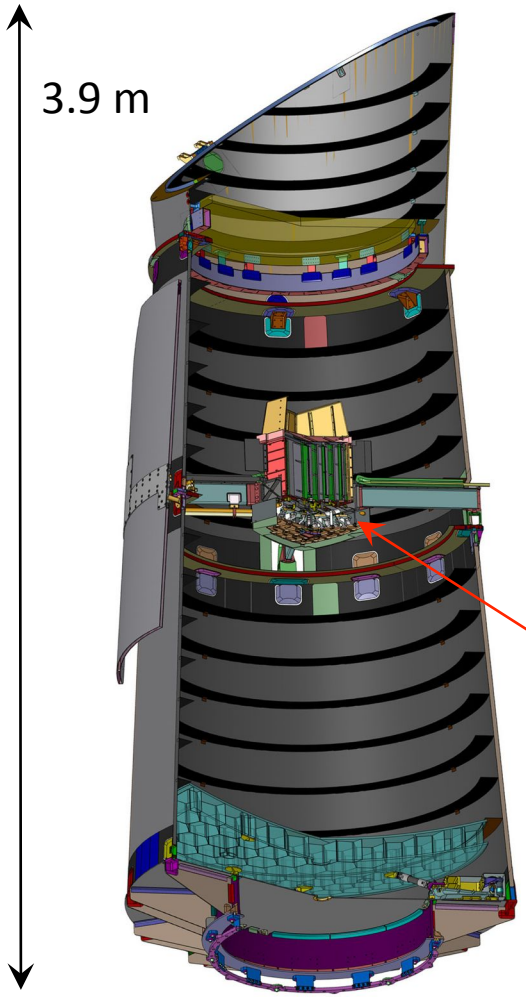
An extrasolar planet, or exoplanet, is a planet outside the Solar System.

A Tangent: Searching for Exoplanets

NASA's Kepler Mission was developed over several decades as a way of answering the question: **How frequent are other Earths** in our galaxy? In particular, what is the frequency of Earth-size planets in the "Habitable Zone" of solar-like stars?

http://kepler.nasa.gov/

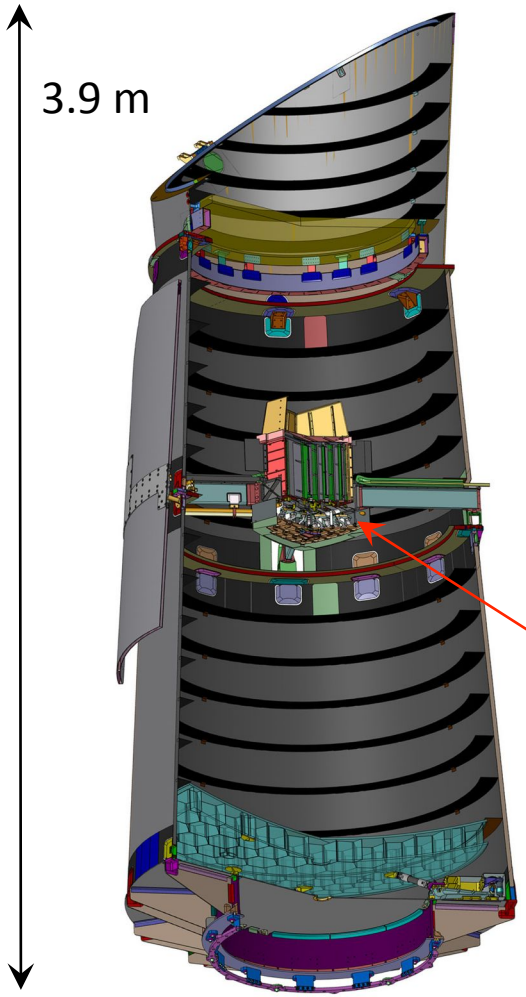
A Tangent: Searching for Exoplanets



- The Kepler photometer is a single purpose instrument.
- Schmidt telescope design with a 0.95-meter aperture and a 105 deg^2 (about 12 degree diameter) field-of-view (FOV).
- It is pointed at and records data from just a single group of stars for the four year duration of the mission.

http://kepler.nasa.gov/

A Tangent: Searching for Exoplanets



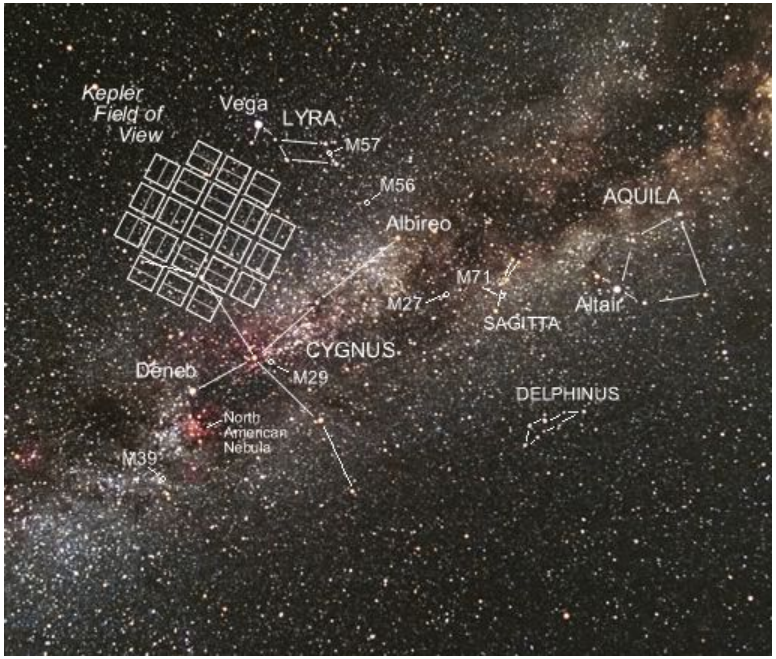
- The photometer composed of array of forty-two 50 x 25 mm CCDs (charge coupled devices), and each CCD has 2200x1024 pixels.
- The CCDs are not used to take pictures. The images are intentionally defocused to 10 arc seconds to improve the photometric precision.

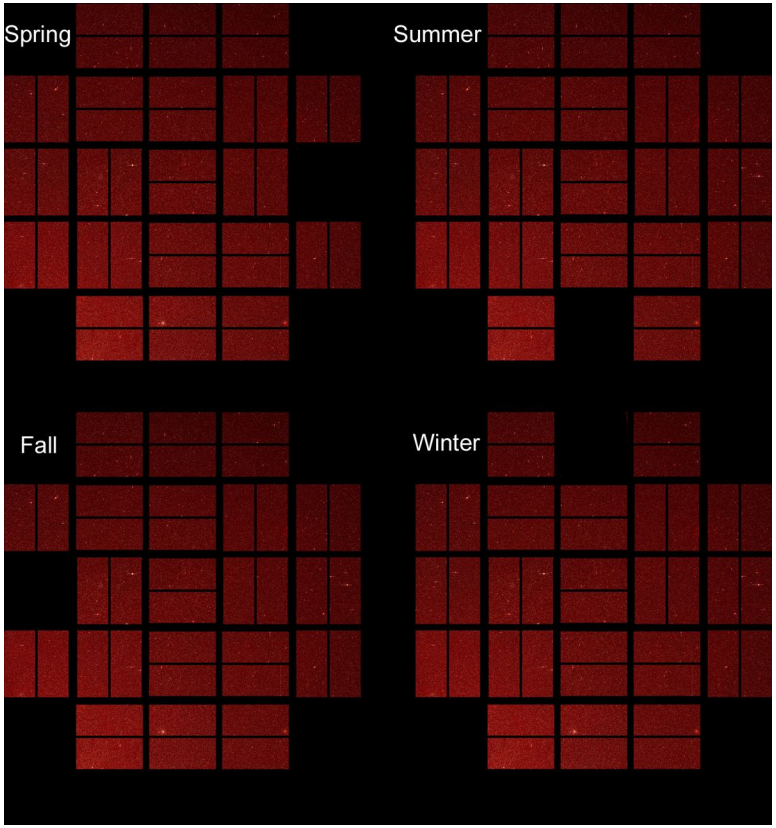
http://kepler.nasa.gov/

A Tangent: Searching for Exoplanets

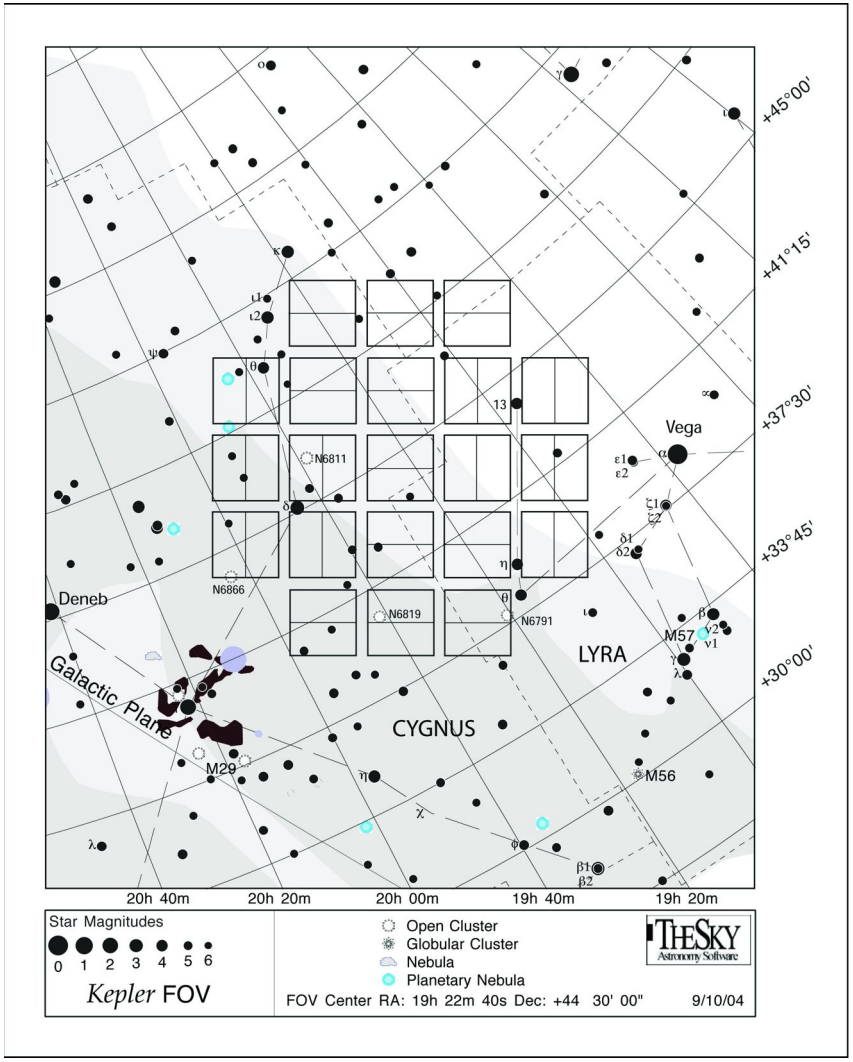
Kepler was launched at night (10:48 PM EST) on 12/29/2009
on a Delta 2 expendable launch vehicle.

The Kepler Field of View

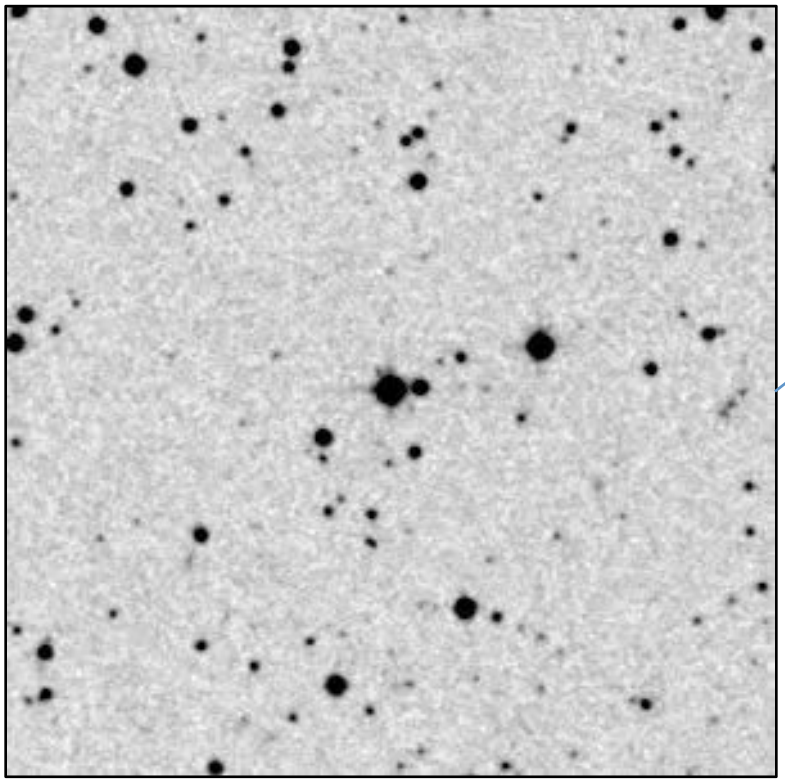




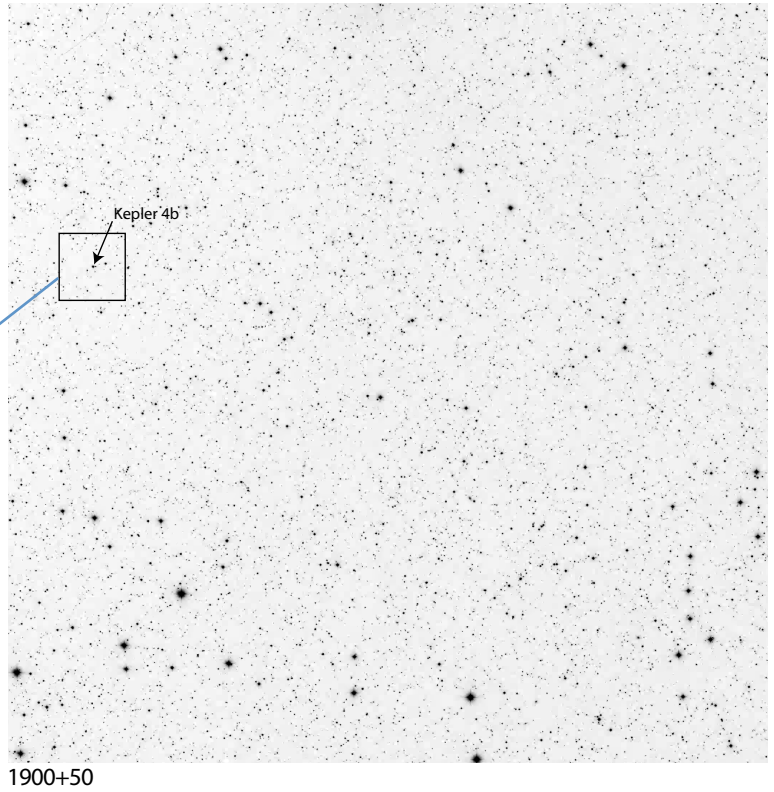
The Kepler Field of View



One Example Discovery: Kepler-4b

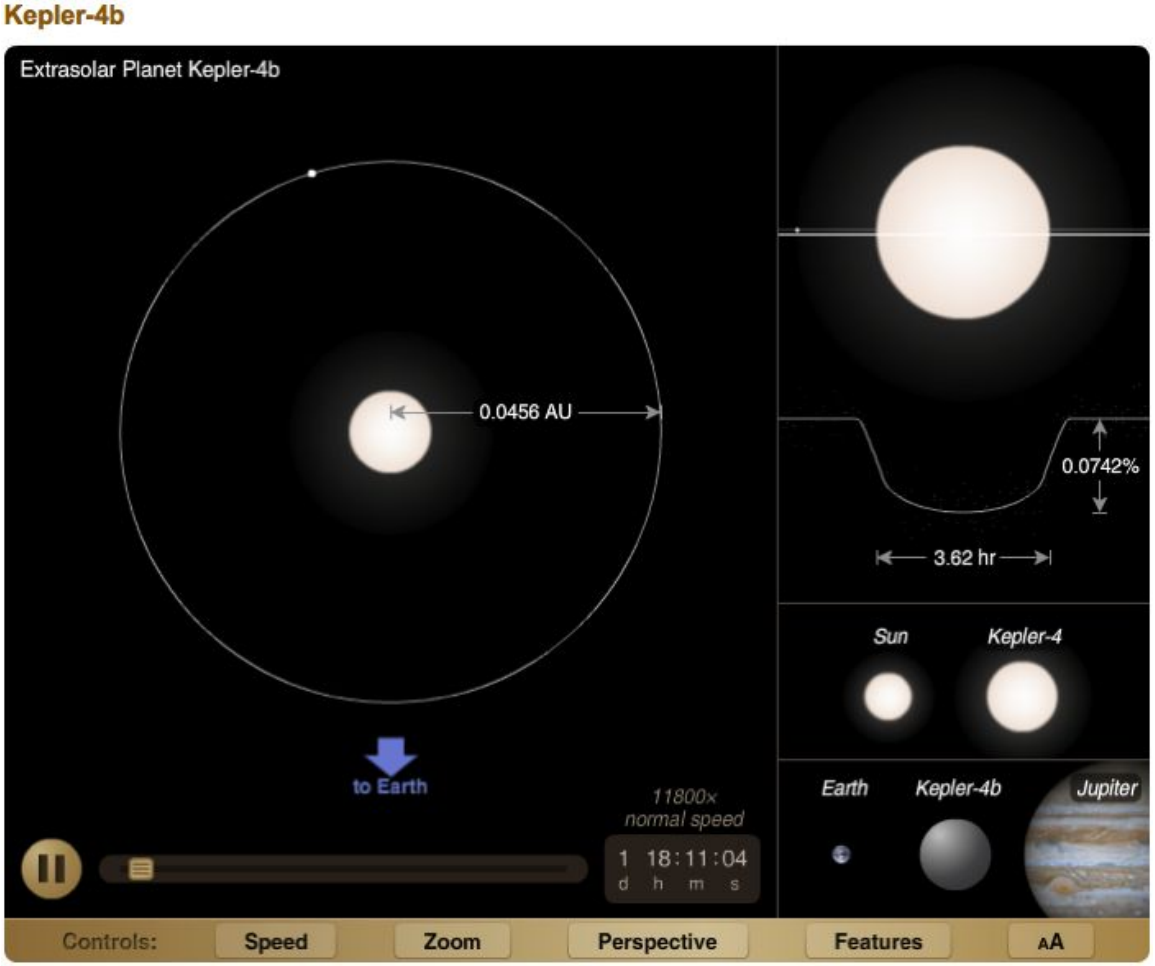


5 arcmin x 5 arcmin

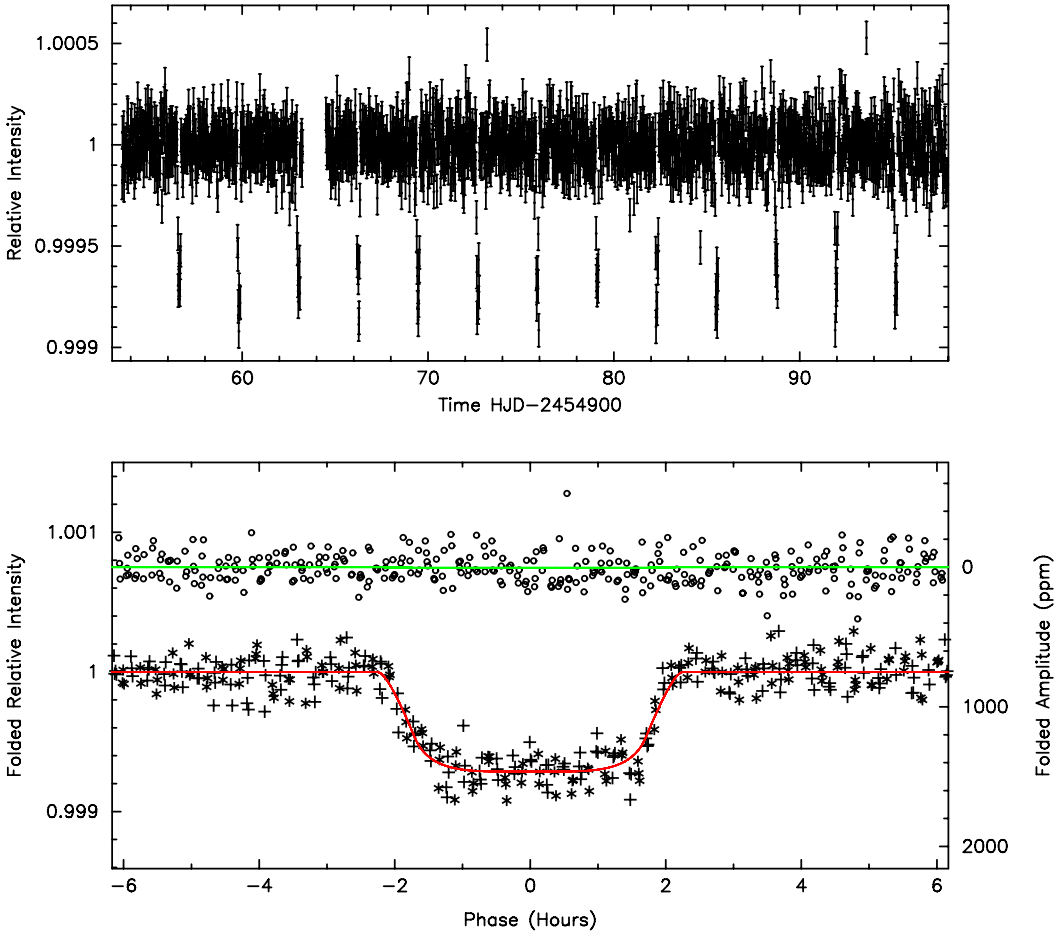


1 deg x 1 deg

One Example Discovery: Kepler-4b

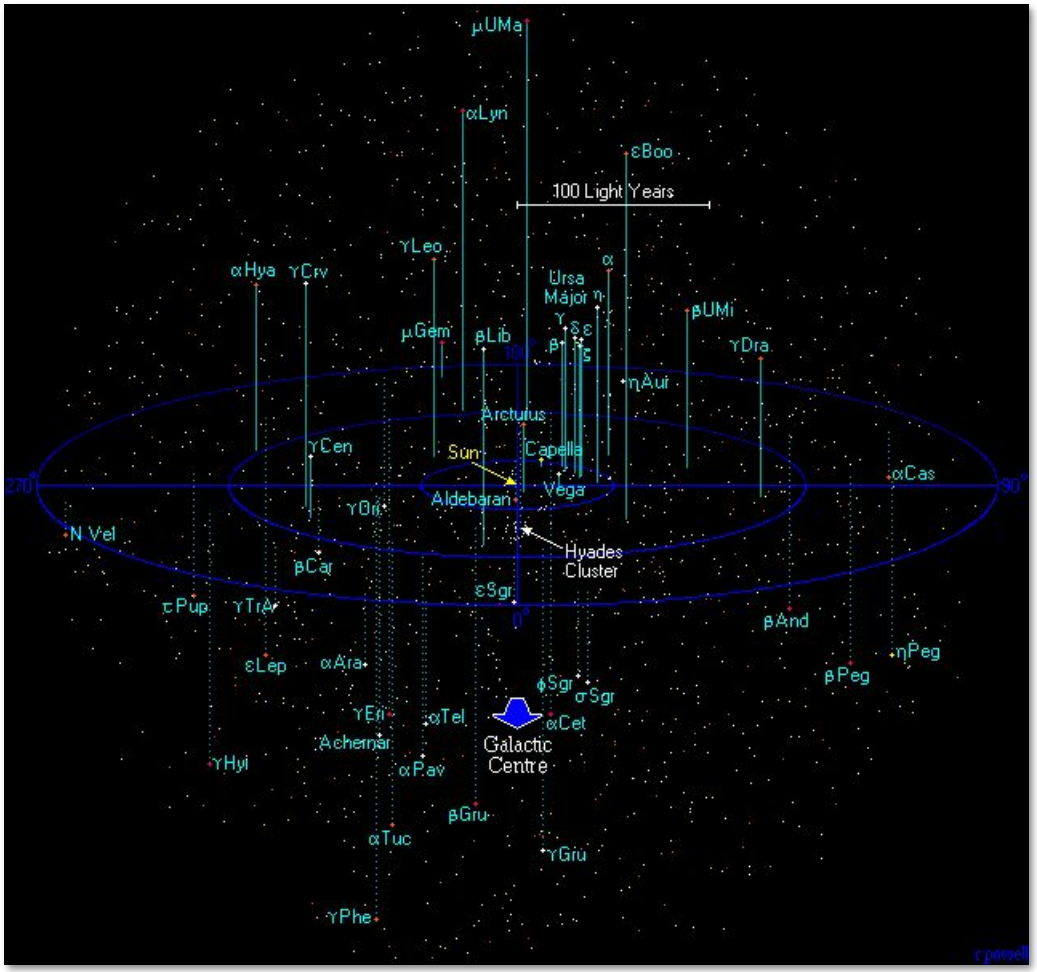


One Example Discovery: Kepler-4b



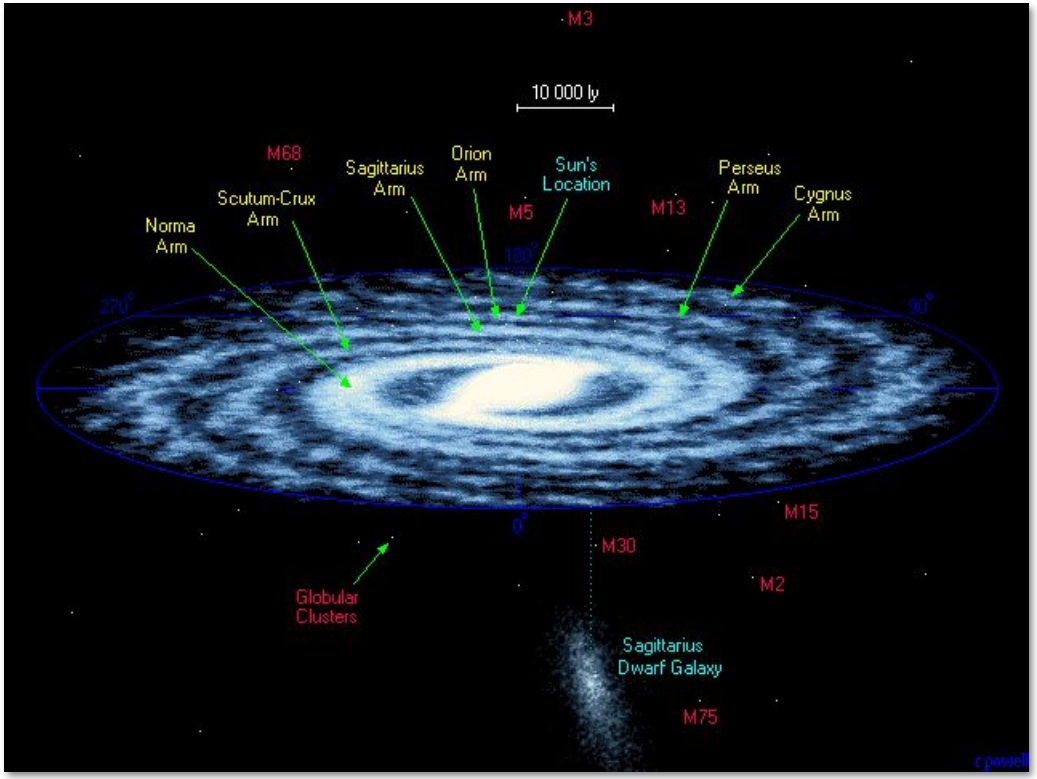
To date, a total of 150 exoplanets have been discovered by Kelper.

The Solar Neighborhood



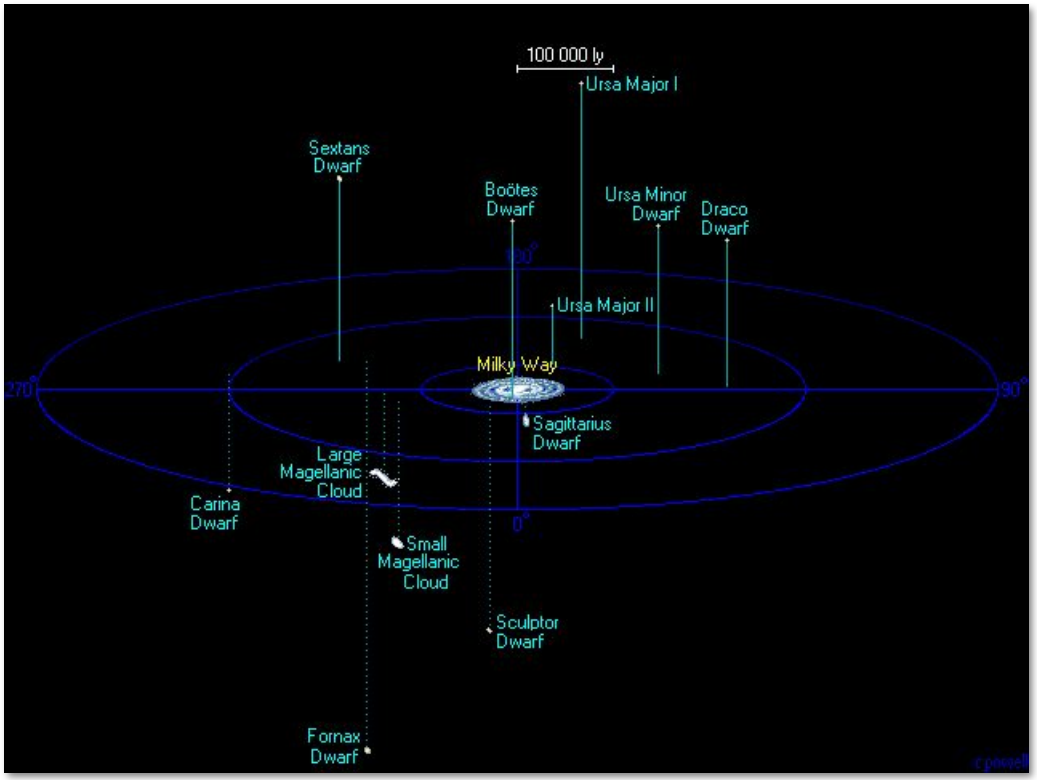
http://www.atlasoftheuniverse.com

The Milky Way Galaxy



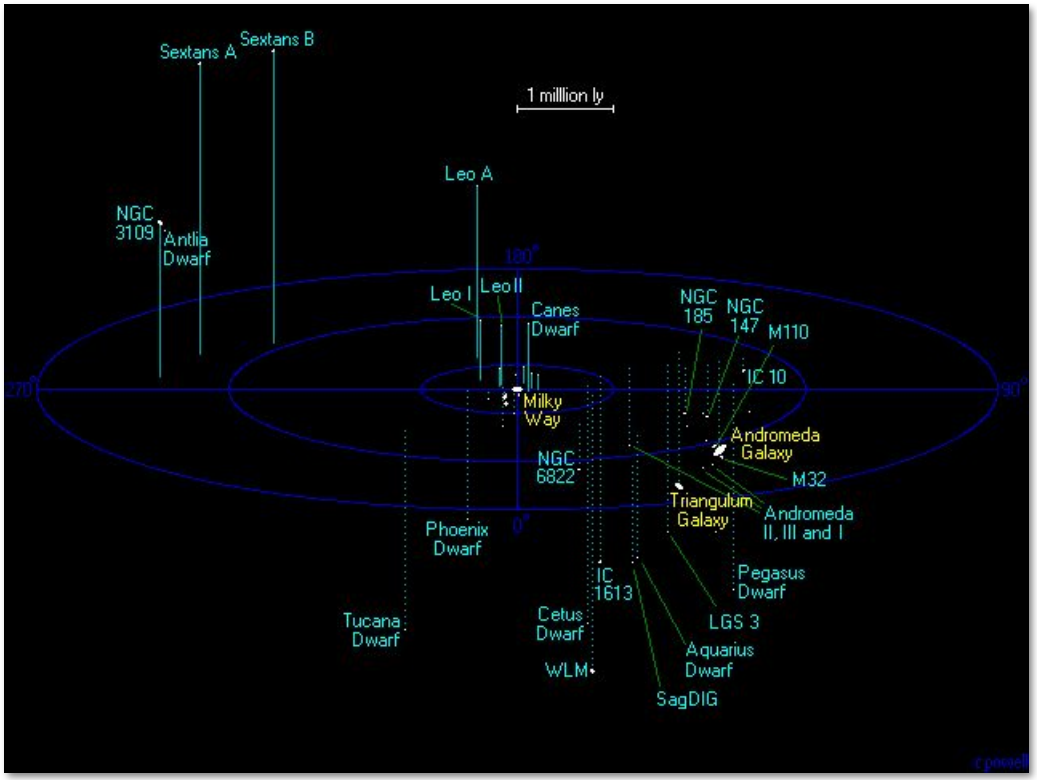
http://www.atlasoftheuniverse.com

The Satellite Galaxies



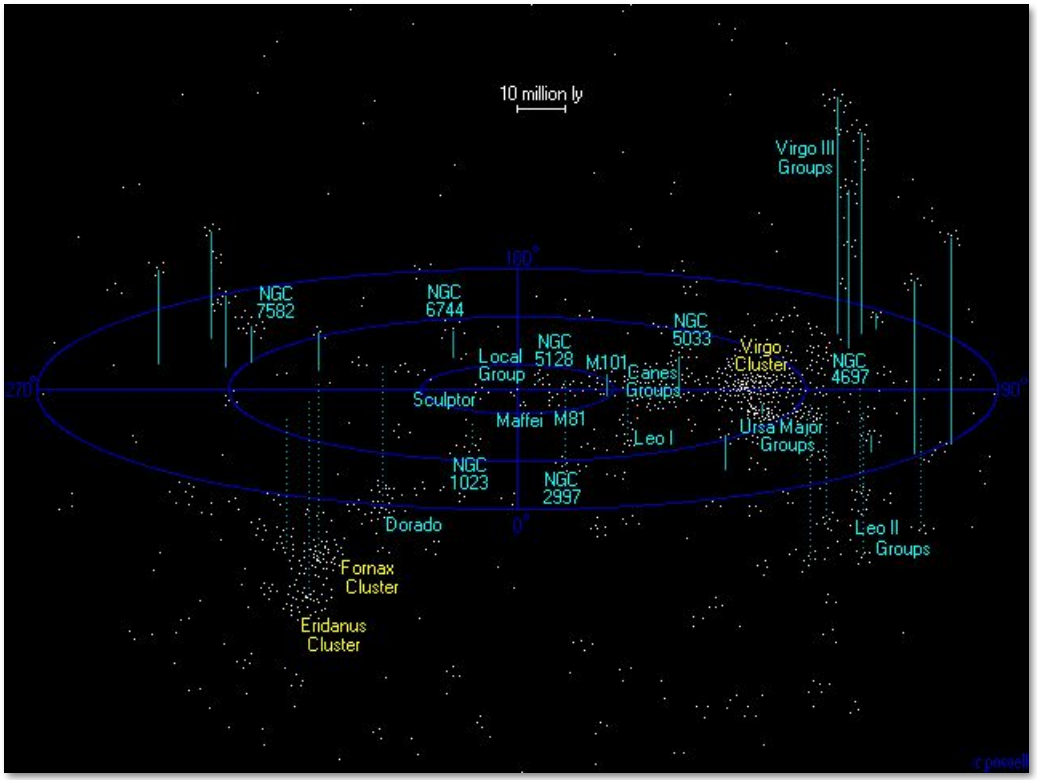
http://www.atlasoftheuniverse.com

The Local Group of Galaxies



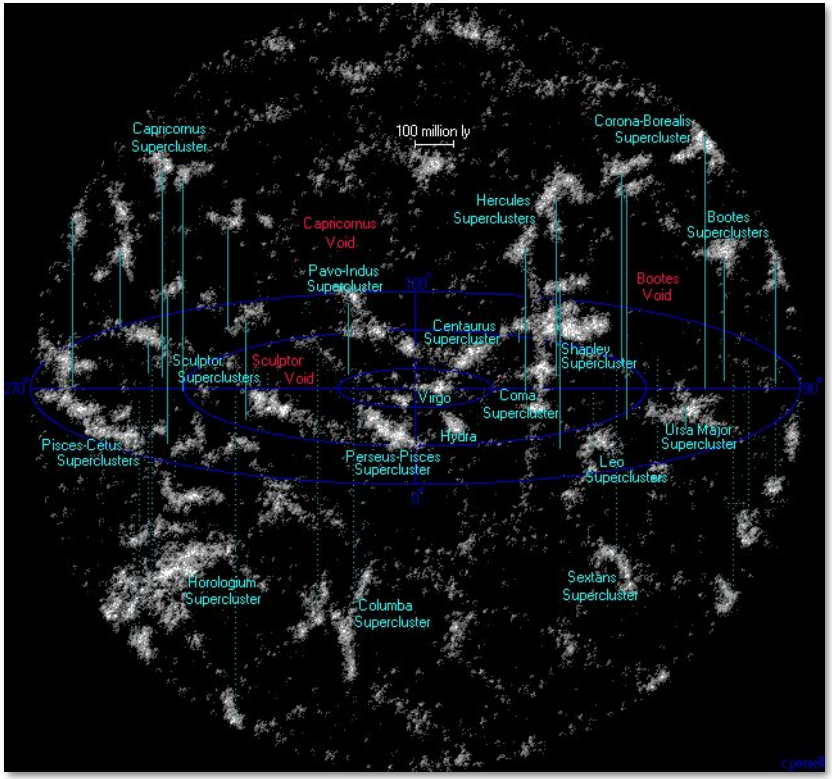
http://www.atlasoftheuniverse.com

The Virgo Supercluster



http://www.atlasoftheuniverse.com

The Neighboring Superclusters



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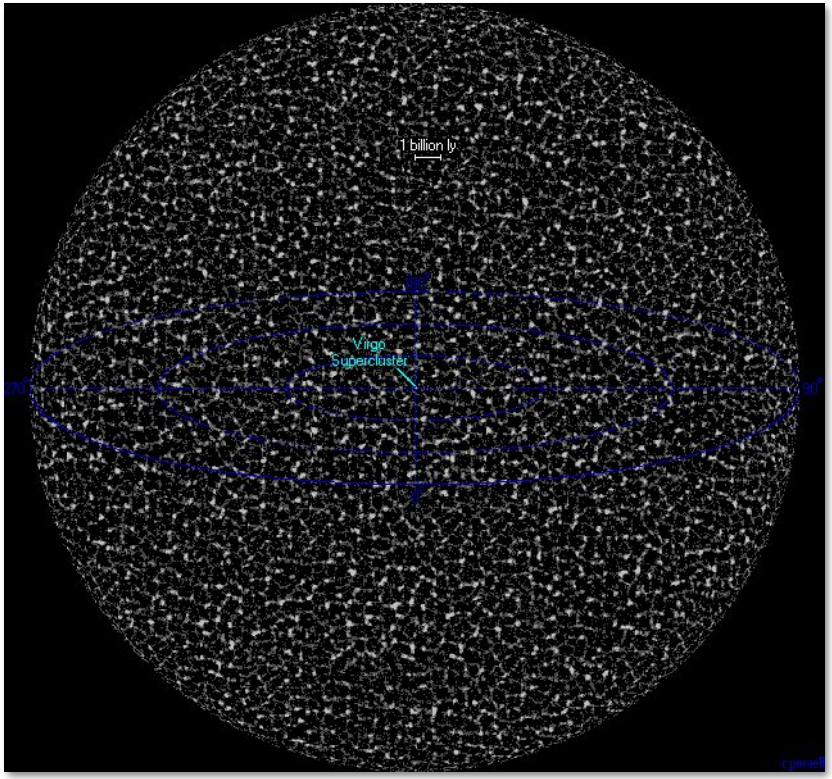
The Visible Universe



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Standard Model of Cosmology