Relativistic Cosmology
When the Universe Rang:
Harmonics in the Early Universe

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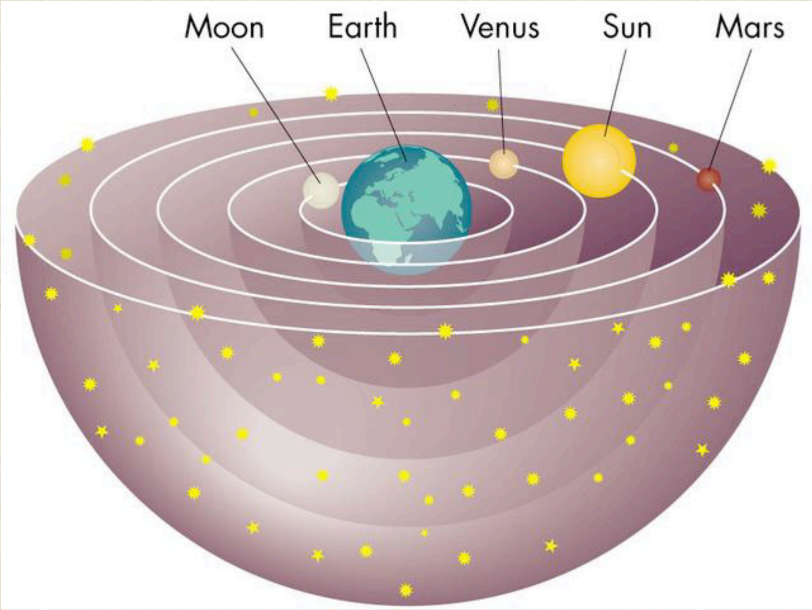
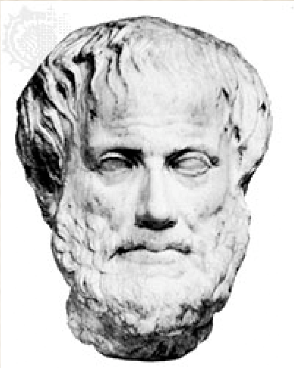
The rise of models

- Perhaps the most important idea developed by the ancient Greeks was creating models of nature.
- Starts with school of Pythagorus - Nature can be described by numbers and not the capricious whims of the gods. E.g. music, stringed instruments, …
- Certainly other cultures were scratching their heads and trying to explain what they observed, but the idea and implementation of models in a mathematical and logical form really catches on with ancient Greeks.

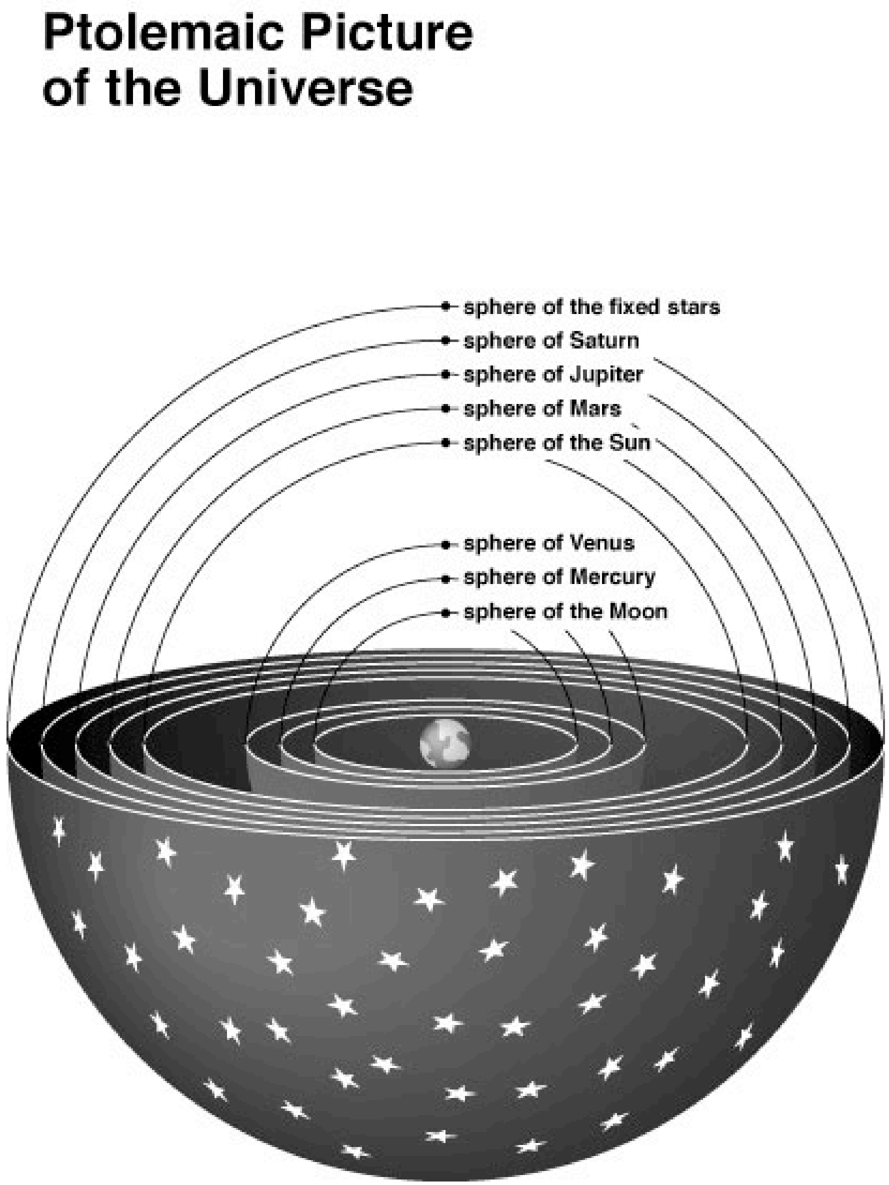
Pythagorus 550 BC

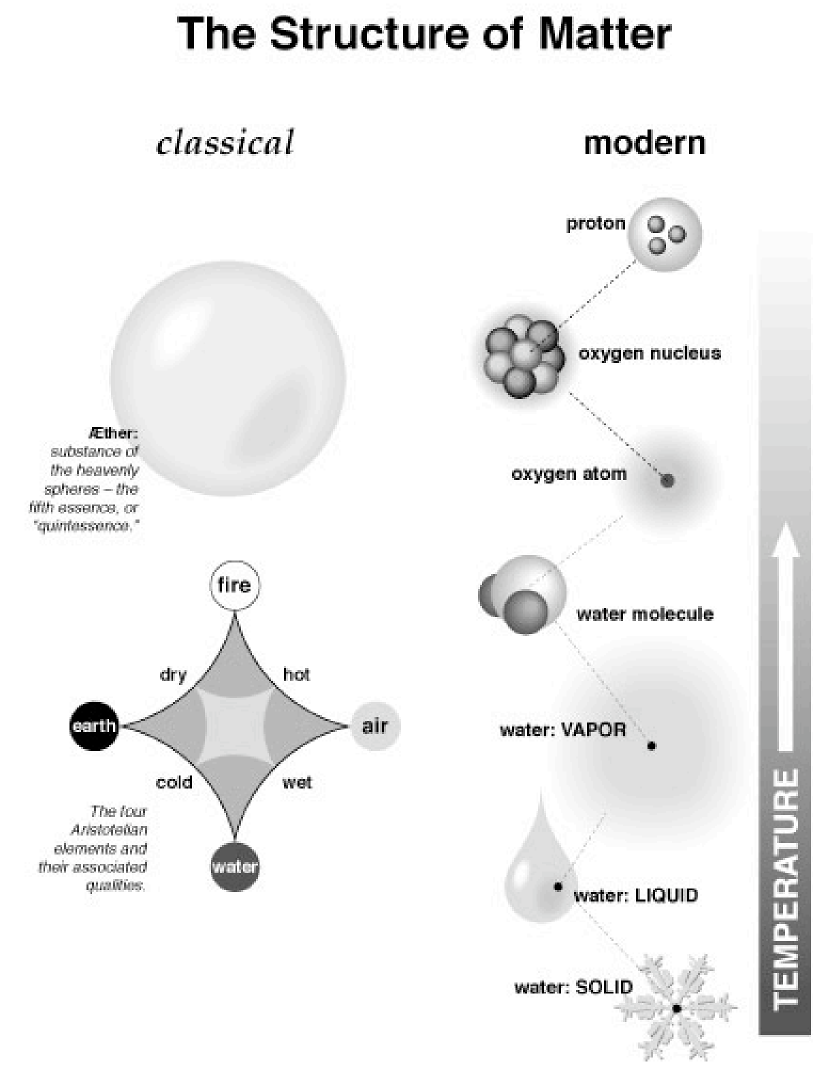




Aristotle 350 BC

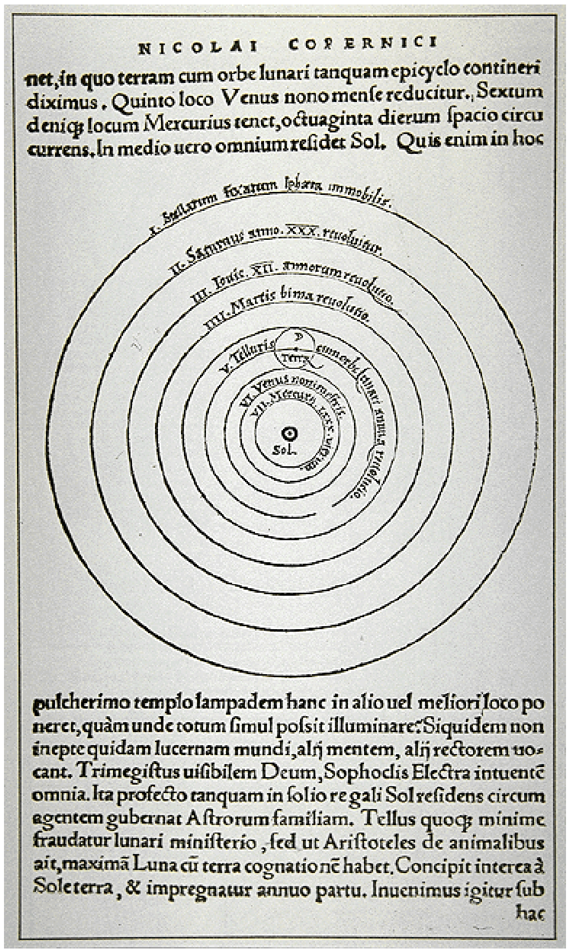
Road to modern Science Thought





Nicholas Copernicus

- On his deathbed in 1543, Copernicus saw the first printed copy of his book "De Revolutionibus Orbium Caelestrium" or "Concerning the Revolutions of the Heavenly Spheres".



NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denicp locum Mercurius tenet, octuaginta dierum spacio circu currens. In medio uero omnium residet Sol. Quis enim in hoc

I. Stellarum fixarum sphæra immobilis.
II. Saturnus anno. XXX. reuoluitur.
III. Iouis. XII. annorum reuolutio.
IIII. Martis bima reuolutio.
V. Telluris cum orbe lunari annua reuolutio.
VI. Venus nono mense.
VII. Mercurii. LXXX. dierum.
Terra
Sol.

pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentē omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quocp minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

- In addition to its aesthetics, the Sun-centered system allowed him to discover the difference between sidereal synodic periods, and obtain distances to the planets.

- His model didn't predict the planetary positions much better than Ptolemy's geocentric model because he held to the ancient Greek belief that the heavenly bodies must follow perfect circles.

Tycho Brahe

- Lack of quality data made it hard to improve either geo- or helio-centric systems.
- In 1566 a brash Danish nobleman, Tycho Brahe, set out to correct this problem.
- Funded by King Rudolf, he built the biggest metal instruments in the world for his own observatory on a private island and reached 1 arc minute accuracy.

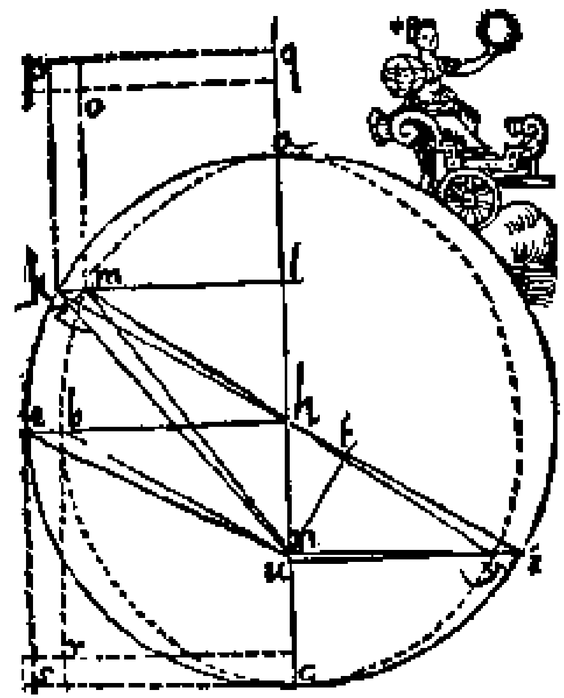
Tycho Brahe

- Tycho's data remain the most accurate naked-eye observations ever made.

Johannes Kepler

- Tycho bequeathed all his data to his assistant Johannes Kepler, begging him to make some sense of his observations so “that I may not have lived in vain”.

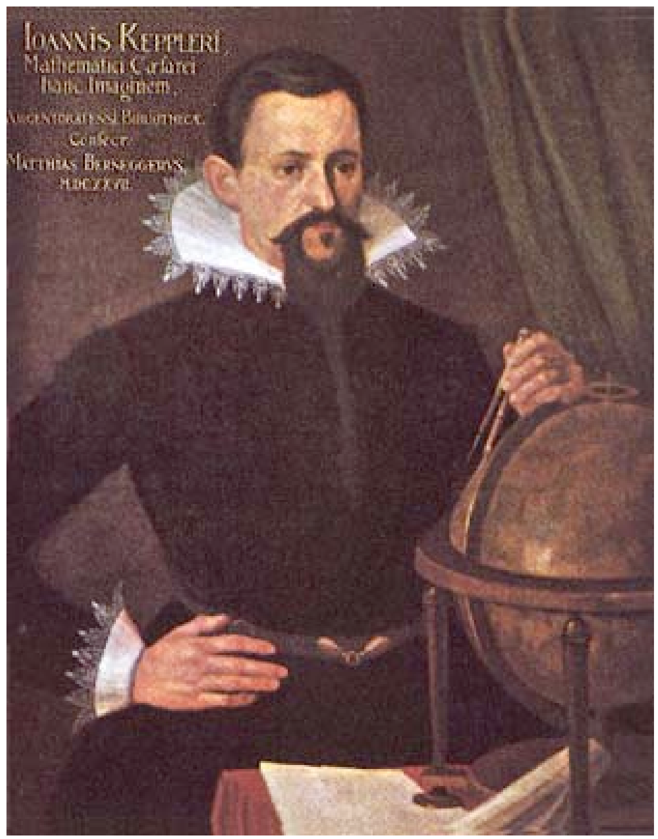
- Kepler worked very hard to find an orbit for Mars, which posed the greatest difficulty in matching the data to a circular orbit.



Johannes Kepler

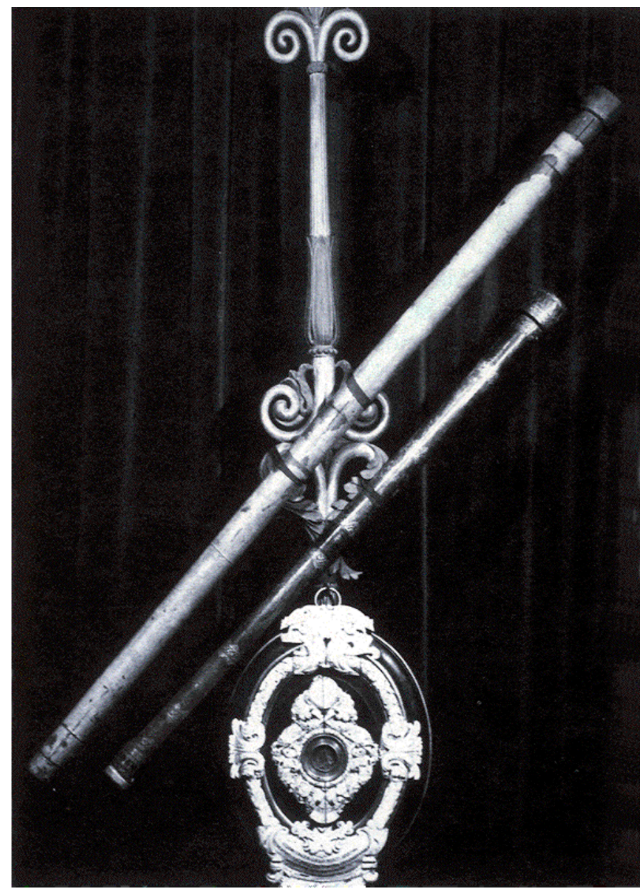
- Kepler found a circular orbit that matched Tycho's data to 2 arc minutes, but in two cases found the error to be about 8 arc minutes.

- "If I had believed that we could ignore these 8 arc minutes, I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those 8 arc minutes pointed to a complete reformation in astronomy".



Galileo Galilei

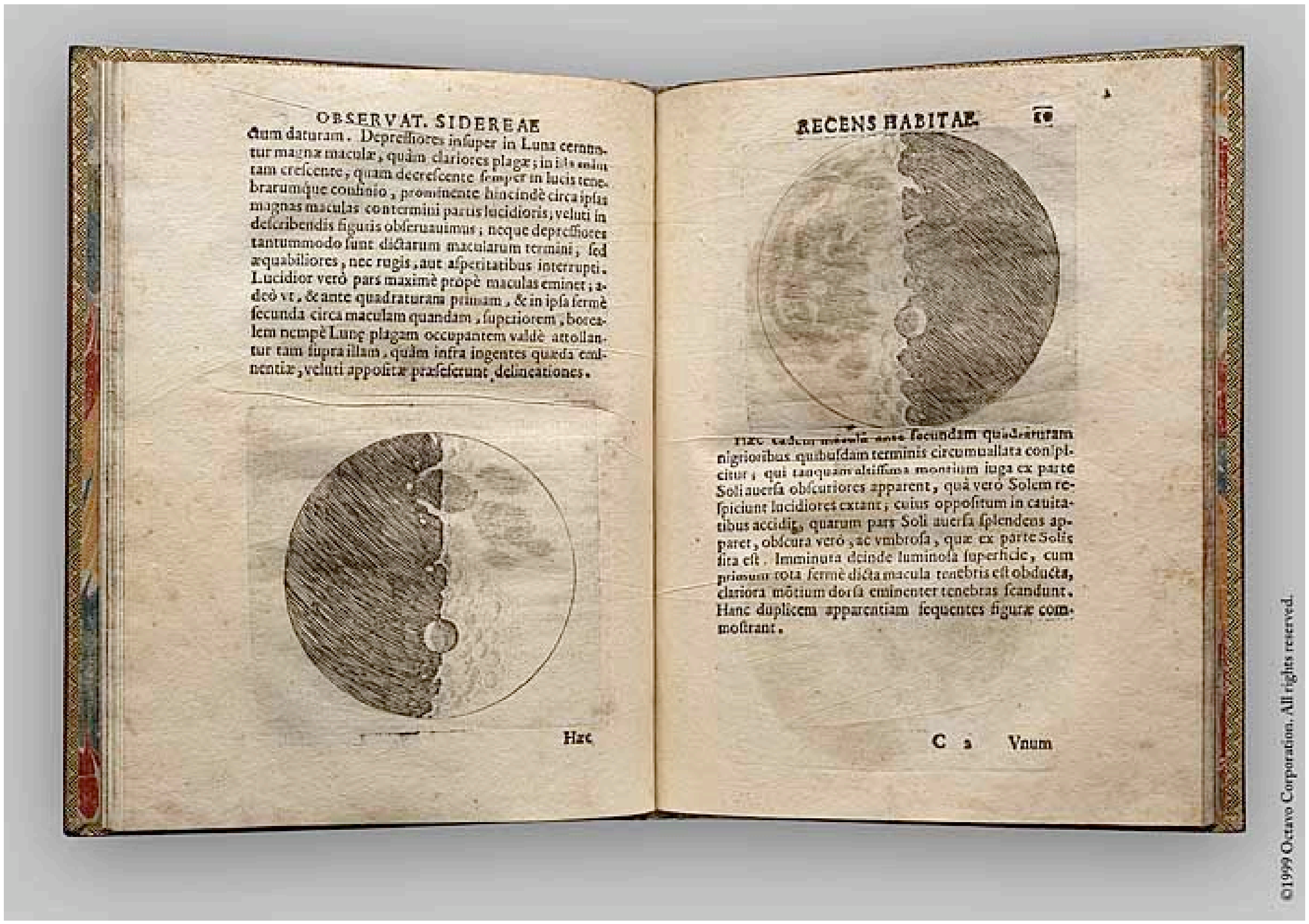
- A contemporary and correspondent with Kepler, Galileo created an enormous sensation when he built one of the first telescopes in 1609 and published his discoveries in 1610 in "Sidereus Nuncius" or "Starry Messenger". What did he observe?



Galileo Galilei

1. Sunspots on the Sun and mountains on the Moon.

   This showed the heavenly bodies were not "perfect", suggesting that elliptical orbits was not so objectionable.



Galileo Galilei

2. The Moons of Jupiter: Io, Europa, Ganymede, & Callisto.

This showed there was other centers of motion.
Suggesting the Moon could orbit Earth and not be "left behind"

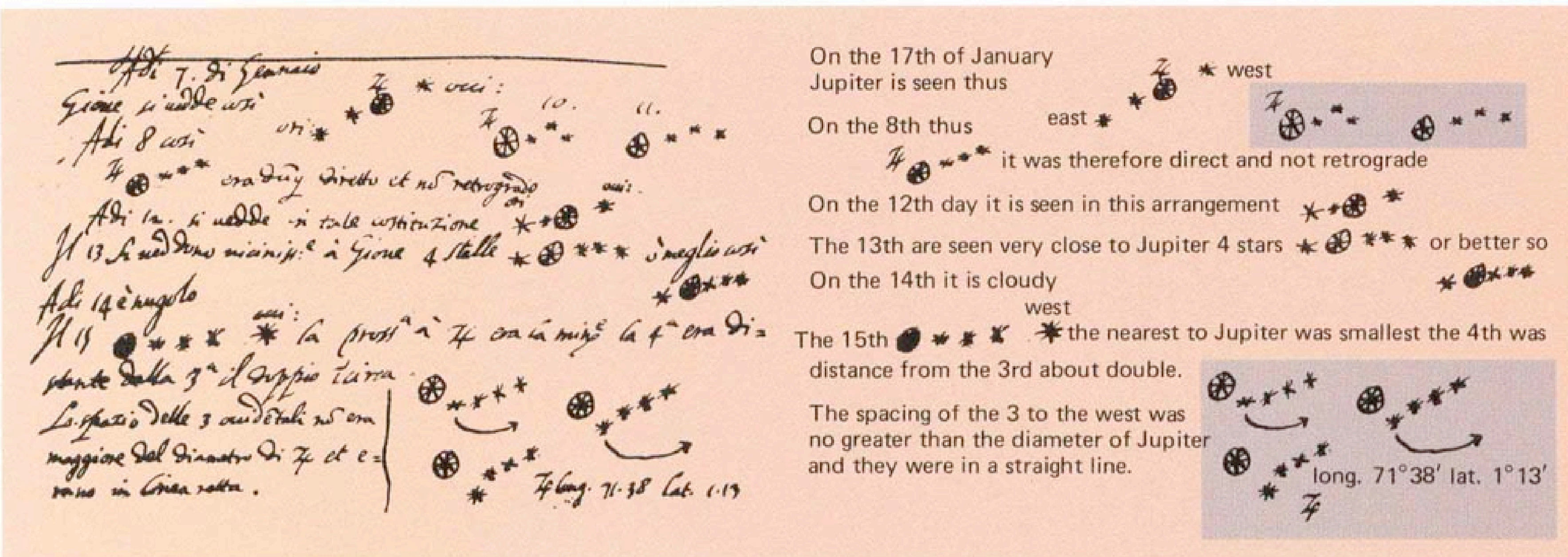
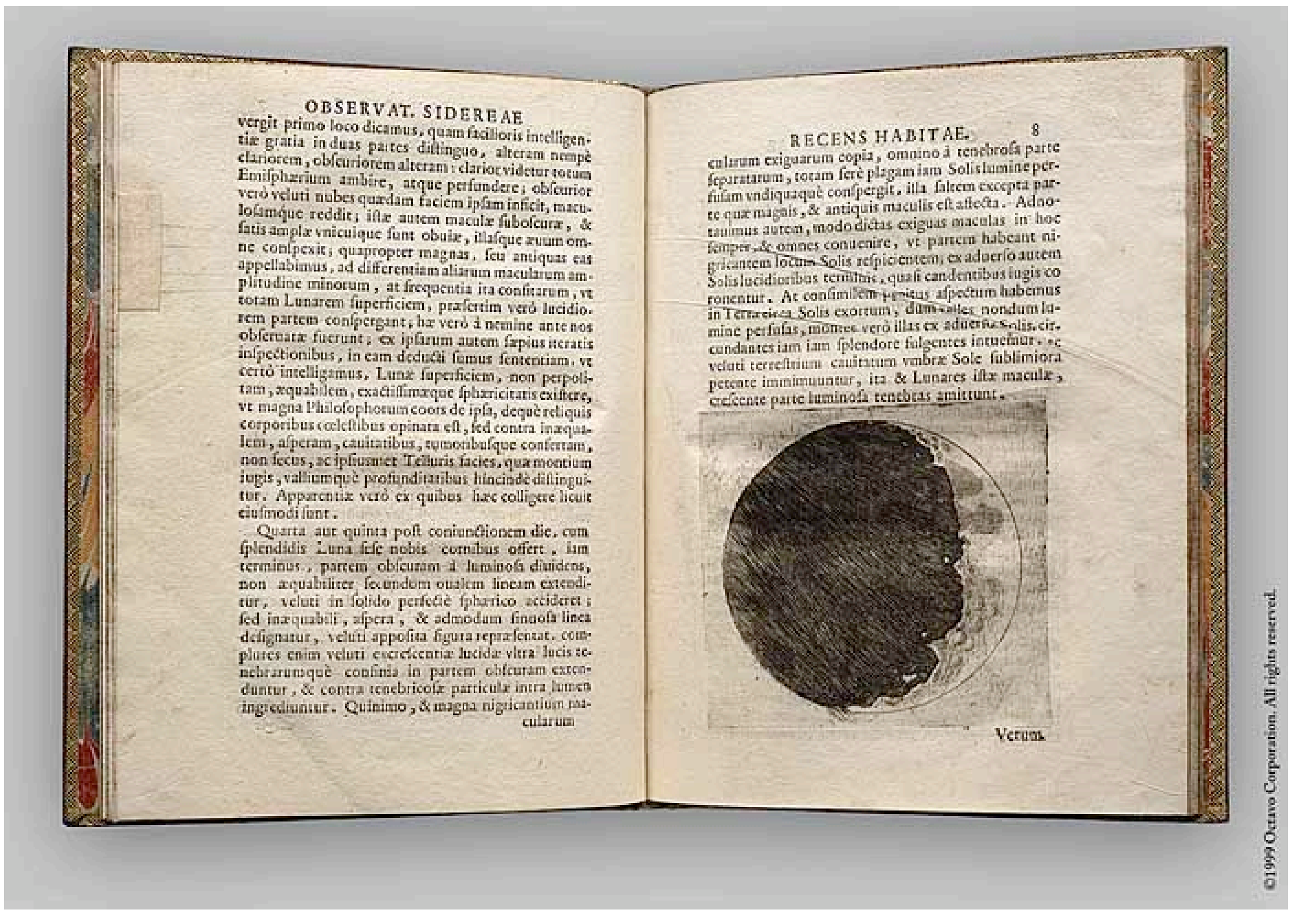


Figure 3–14 A translation (*right*) of Galileo's original notes (*left*) summarizing his first observations of Jupiter's moons in January 1610. The shaded areas were probably added later. It had not yet occurred to Galileo that the objects were moons in revolution around Jupiter.

Galileo Galilei

3. Observed all the phases of Venus.

This is IMPOSSIBLE in a *geocentric* cosmology, and can only happen if Venus orbits the Sun. This observation killed the Ptolemaic system.



OBSERVAT. SIDEREAE

vergit primo loco dicamus, quam facilioris intelligentiæ gratia in duas partes distinguo, alteram nempè clariorem, obscuriorem alteram: clarior videtur totum Emisphærium ambire, atque perfundere; obscurior verò veluti nubes quædam faciem ipsam inficit, maculosámque reddit; istæ autem maculæ subobscuræ, & satis amplæ vnicuique sunt obuiæ, illasque æuum omne conspexit; quapropter magnas, seu antiquas eas appellabimus, ad differentiam aliarum macularum amplitudine minorum, at frequentia ita consitarum, vt totam Lunarem superficiem, præsertim verò lucidiorem partem conspergant; hæ verò à nemine ante nos obseruatæ fuerunt; ex ipsarum autem sæpius iteratis inspectionibus, in eam deducti sumus sententiam, vt certò intelligamus, Lunæ superficiem, non perpolitam, æquabilem, exactissimæque sphæricitatis existere, vt magna Philosophorum coors de ipsa, deque reliquis corporibus cœlestibus opinata est, sed contra inæqualem, asperam, cauitatibus, tumoribusque confertam, non secus, ac ipsiusmet Telluris facies, quæ montium iugis, valliumquè profunditatibus hincindè distinguitur. Apparentiæ verò ex quibus hæc colligere licuit eiusmodi sunt.

Quarta aut quinta post coniunctionem die, cum splendidis Luna sese nobis cornibus offert, iam terminus, partem obscuram à luminosa diuidens, non æquabiliter secundum ouale lineam extenditur, veluti in solido perfectè sphærico accideret; sed inæquabili, aspera, & admodum sinuosa linea designatur, veluti apposita figura repræsentat. complures enim veluti excrescentiæ lucidæ vltra lucis tenebrarumquè confinia in partem obscuram extenduntur, & contra tenebricosæ particulæ intra lumen ingrediuntur. Quinimo, & magna nigricantium ma-

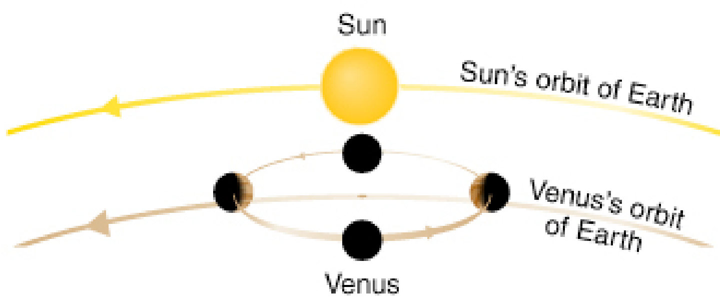
cularum

RECENS HABITAE. 8

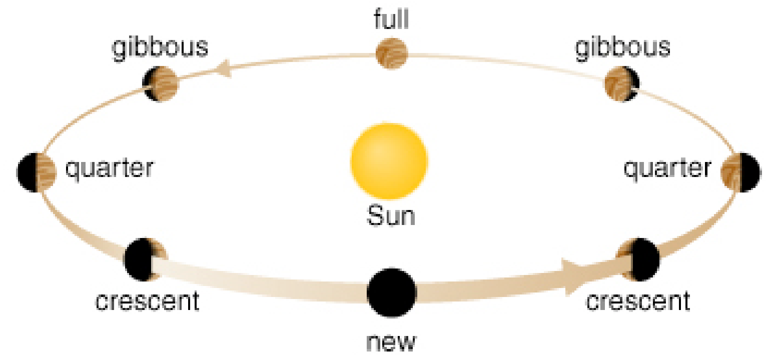
cularum exiguarum copia, omnino à tenebrosa parte separatarum, totam ferè plagam iam Solis lumine perfusam vndiquaquè conspergit, illa saltem excepta parte quæ magnis, & antiquis maculis est affecta. Adnotauimus autem, modo dictas exiguas maculas in hoc semper, & omnes conuenire, vt partem habeant nigricantem locum Solis respicientem, ex aduerso autem Solis lucidioribus terminis, quasi candentibus iugis coronentur. At consimilem penitus aspectum habemus in Terra circa Solis exortum, dum valles nondum lumine perfusas, montes verò illas ex aduerso Solis circundantes iam iam splendore fulgentes intuemur: ac veluti terrestrium cauitatum vmbræ Sole sublimiora petente imminuuntur, ita & Lunares istæ maculæ, crescente parte luminosa tenebras amittunt.

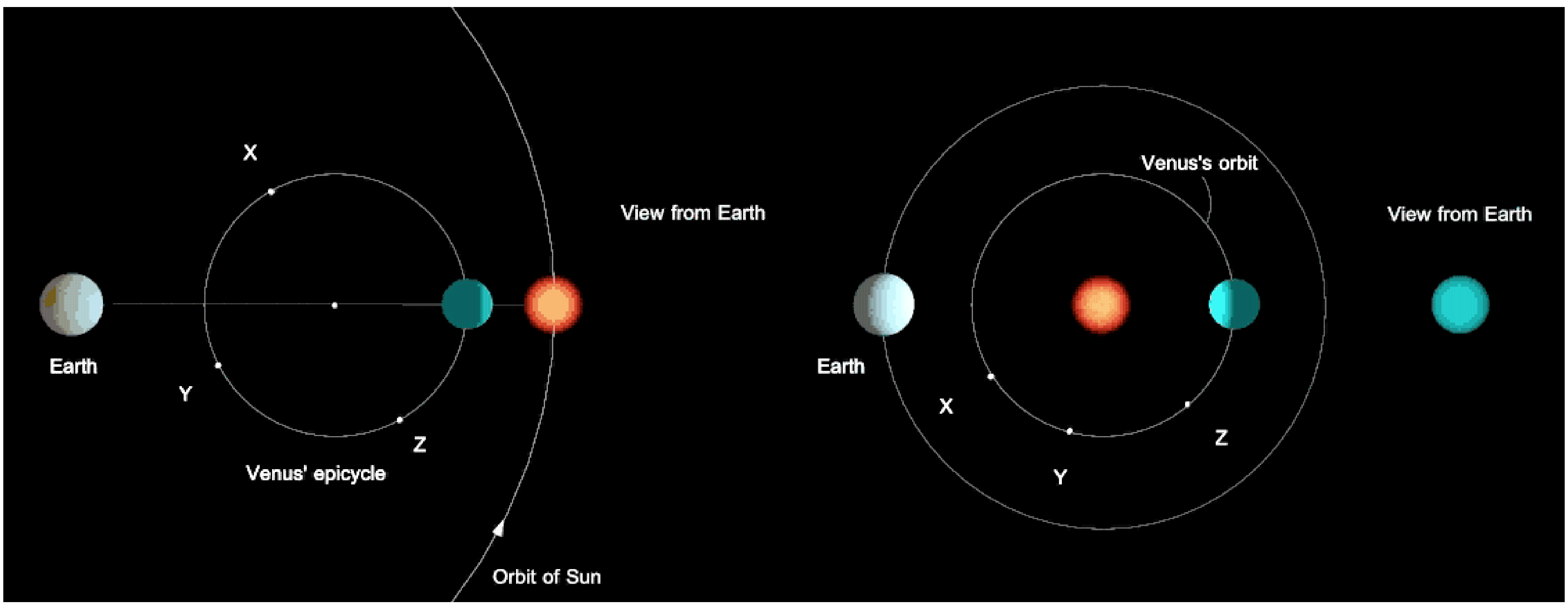
The Phases of Venus

Geocentric Cosmology



Heliocentric Cosmology



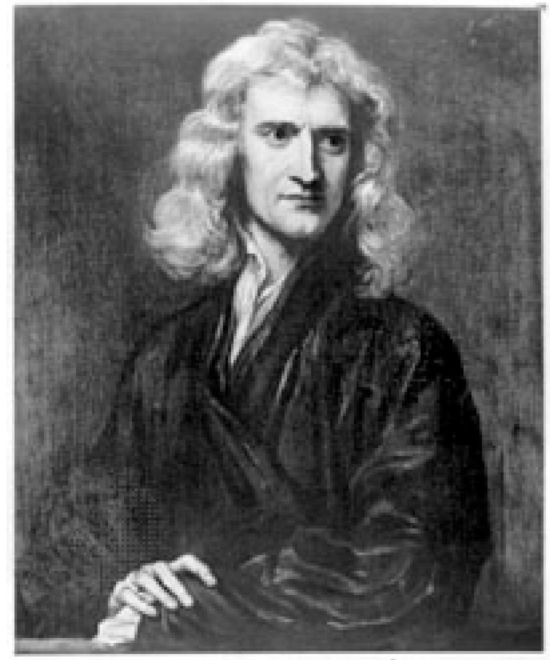


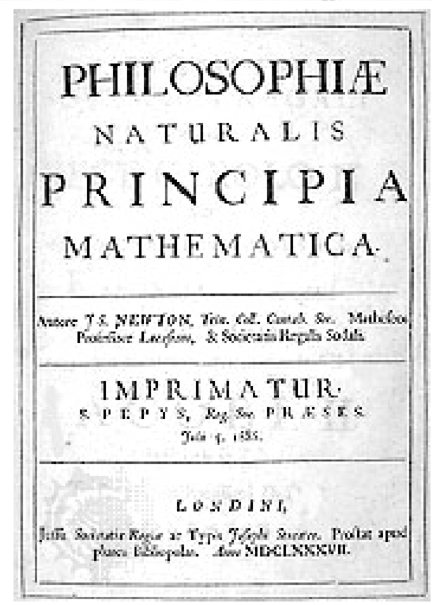
Galileo Galilei

- "Dialogue concerning the two chief world-systems", published in Florence in 1632 in Italian, was Galileo's scientific and literary masterpiece.
- In it he discusses the relative merits of the Ptolemaic and Copernican systems by means of three interlocutors:
  - Filippo Salviati (a committed Florentine Copernican),
  - Giovanfrancesco Sagredo (an open-minded Venetian, initially neutral)
  - Aristotelian Simplicio (a defender of the Ptolemaic theory).

Isaac Newton

- With the heliocentric model firmly established, the outstanding problem was why Kepler’s laws worked.
- Kepler speculated his laws might be explained by magnetism, and idea shared by Galileo.
- In 1687, Isaac Newton published “Philosophiae Naturalis Principia Mathematica”, or “Mathematical Principles of Natural Philosophy”, where he postulates three laws of motion and the existence of a force he called gravity.
- It was a universal law of gravitation affecting everything in the Universe - including the moon and beyond.
- Kepler’s laws were a consequence of Newton’s three laws of motion and the law of universal gravitation.





PHILOSOPHIÆ

NATURALIS

PRINCIPIA

MATHEMATICA.

IMPRIMATUR.

S. PEPYS, Reg. Soc. PRÆSES.

LONDINI,

Anno MDCLXXXVII.

Newtonian Cosmology

- Very limited - space and time are fixed
- Only components of Universe were Stars
- Everyone knew Universe was static
  - the sky was unchanging: “fixed stars”
- Stationary stars array unstable against gravitation
- An infinite array of uniformly distributed stars
  - Equal gravitational pull in all directions
  - Only solution (Newton and Rev. Bently)
- Unstable against the slightest perturbation

Relativistic Cosmology

- Rich Possibilities - space and time major actors
- Curvature of Space implies Scale
- The scale is dynamic driven by gravity
  - General Relativity implies that the Universe must be expanding or contracting
- Everyone knew Universe was static
  - the sky was unchanging: “fixed stars”
- Einstein introduces Cosmological Constant
  - Effect of repulsive force increasing with distance
  - Arranged to just counter attraction of gravity
- Unstable against the slightest perturbation
- Einstein: “My greatest Blunder” but hangs about

Quantum Gravity/Cosmology

- Extremely Rich - very many options
- Complex topologies - handles, wormholes, …
- Extra Dimensions
  - String or M Theory in 10 or 11 dimensions
  - Large extra dimensions
    - E.g. we live on the brane and gravity goes into the bulk
- “Everyone knows” the Big Bang is right
  - The Universe is expanding and evolving
  - Lots of experimental evidence
- No Observation requires more than Relativity
- Interestingly the Universe stretches imagination

He burned his house down
for the fire insurance
and spent the proceeds on a telescope.

Robert Frost

The Star-Splitter

Edwin Hubble (1889-1953)

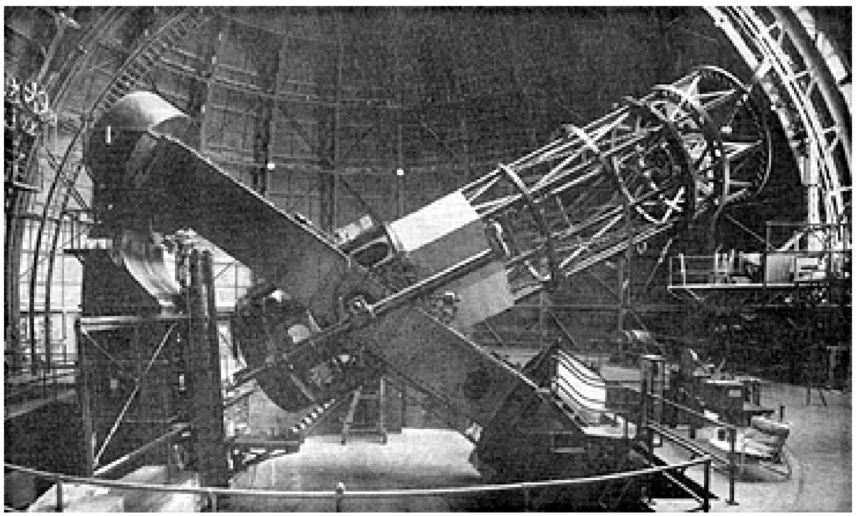
Four major accomplishments in extragalactic astronomy

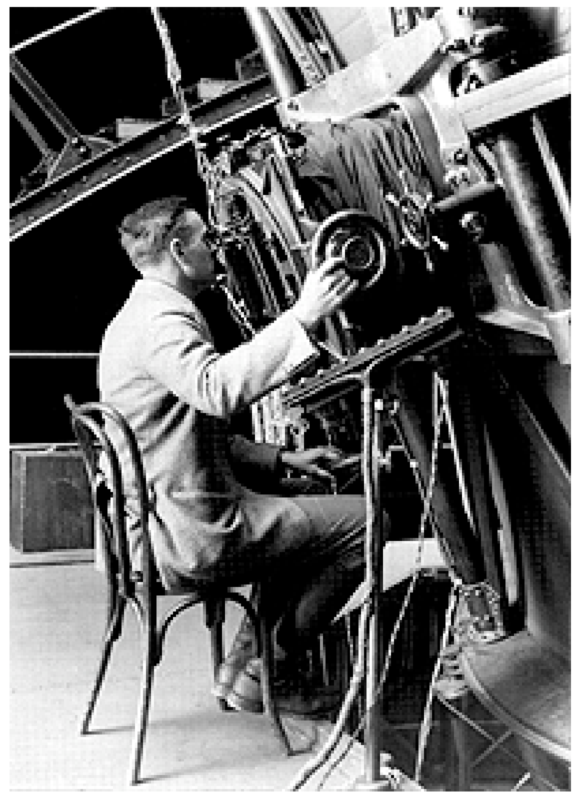
- The establishment of the Hubble classification scheme of galaxies
- The convincing proof that galaxies are island "universes"
- The distribution of galaxies in space
- The discovery that the universe is expanding

The discovery of galaxies

- His distance measurements with Cepheids proved that Andromeda sat far beyond the Milky Way, demonstrating that it is a separate galaxy.

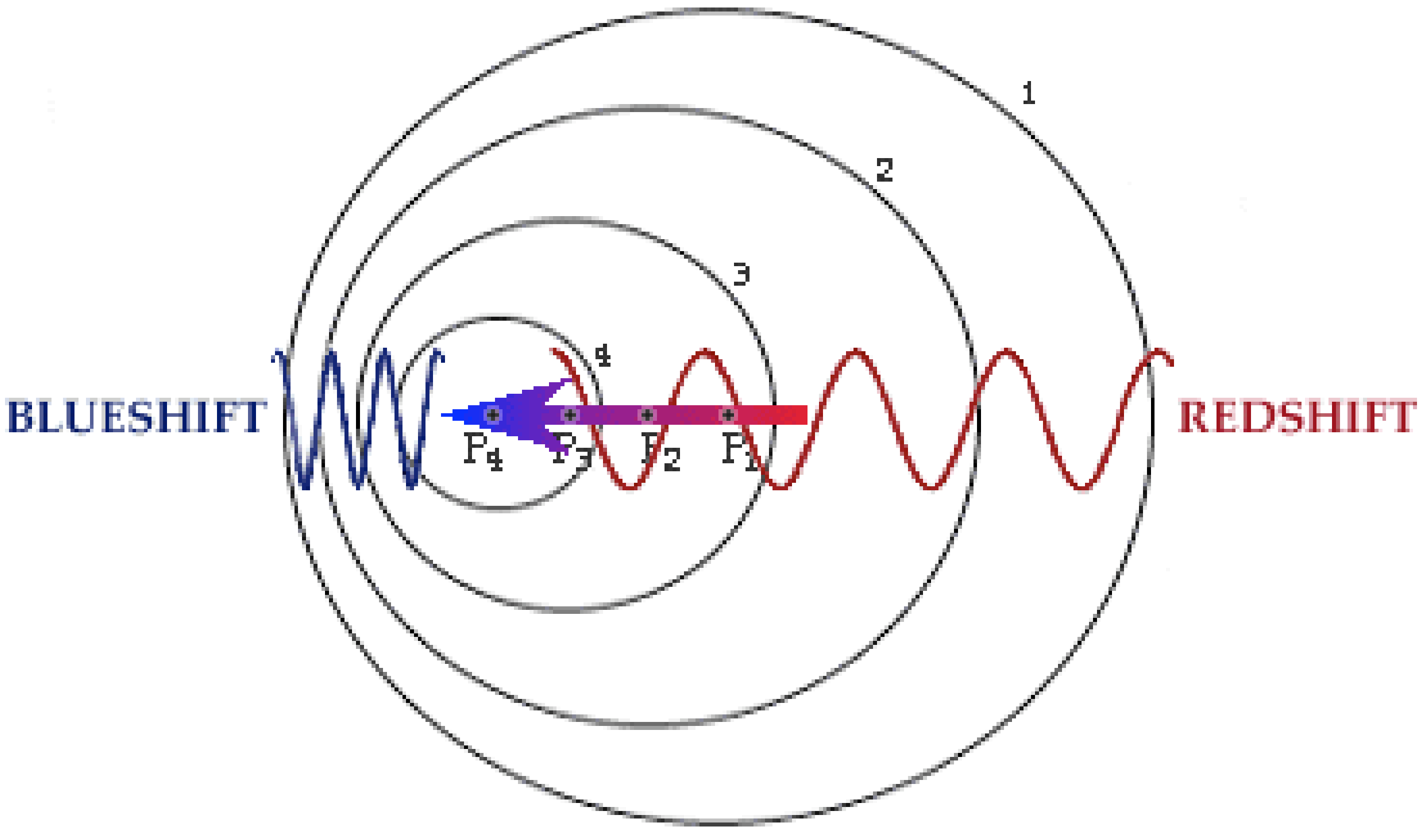
- This single stroke changed our view of the universe. Rather than inhabiting a universe that ended with the Milky Way, we suddenly knew that we live in just one among billions of galaxies.





The 100 inch Hooker telescope, and Hubble at the controls.

Doppler effect



Doppler effect

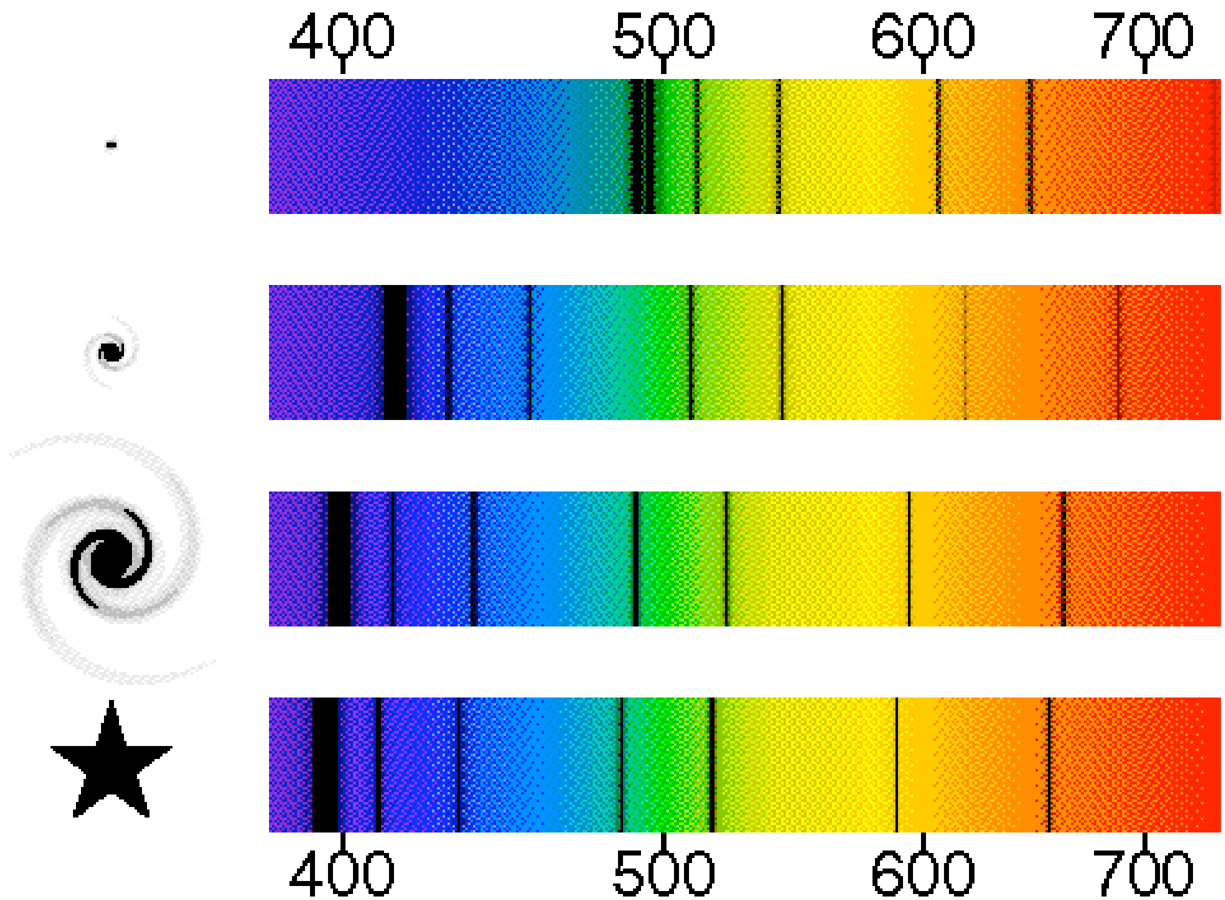
redshift:

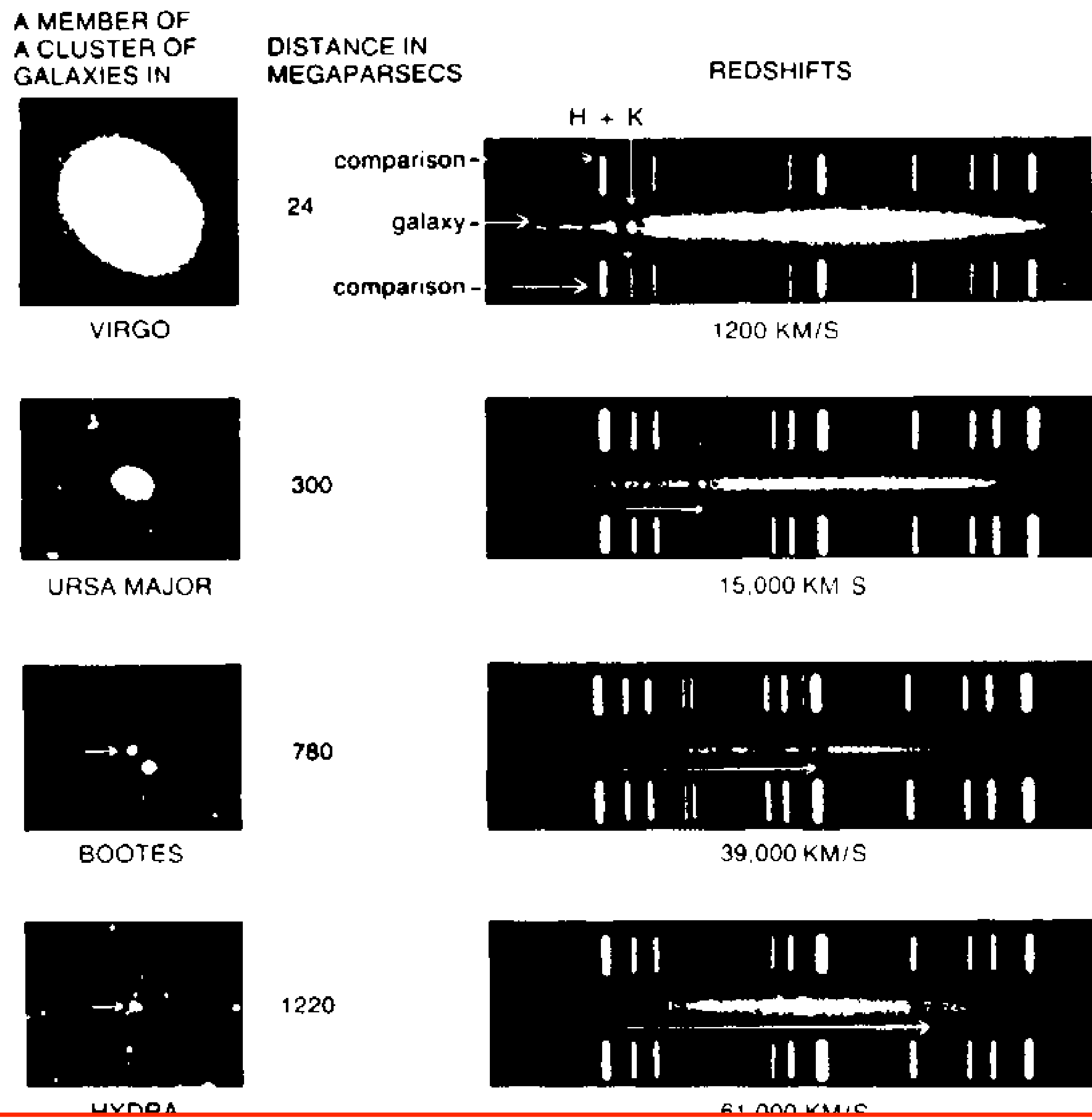
$$1 + z = \sqrt{\frac{1 + v/c}{1 - v/c}}$$

z=0: not moving

z=2: v=0.8c

z= : v=c




A MEMBER OF
A CLUSTER OF
GALAXIES IN
DISTANCE IN
MEGAPARSECS
REDSHIFTS
H + K
comparison
galaxy
comparison
24
VIRGO
1200 KM/S
300
URSA MAJOR
15,000 KM S
780
BOOTES
39,000 KM/S
1220

The redshift-distance relation

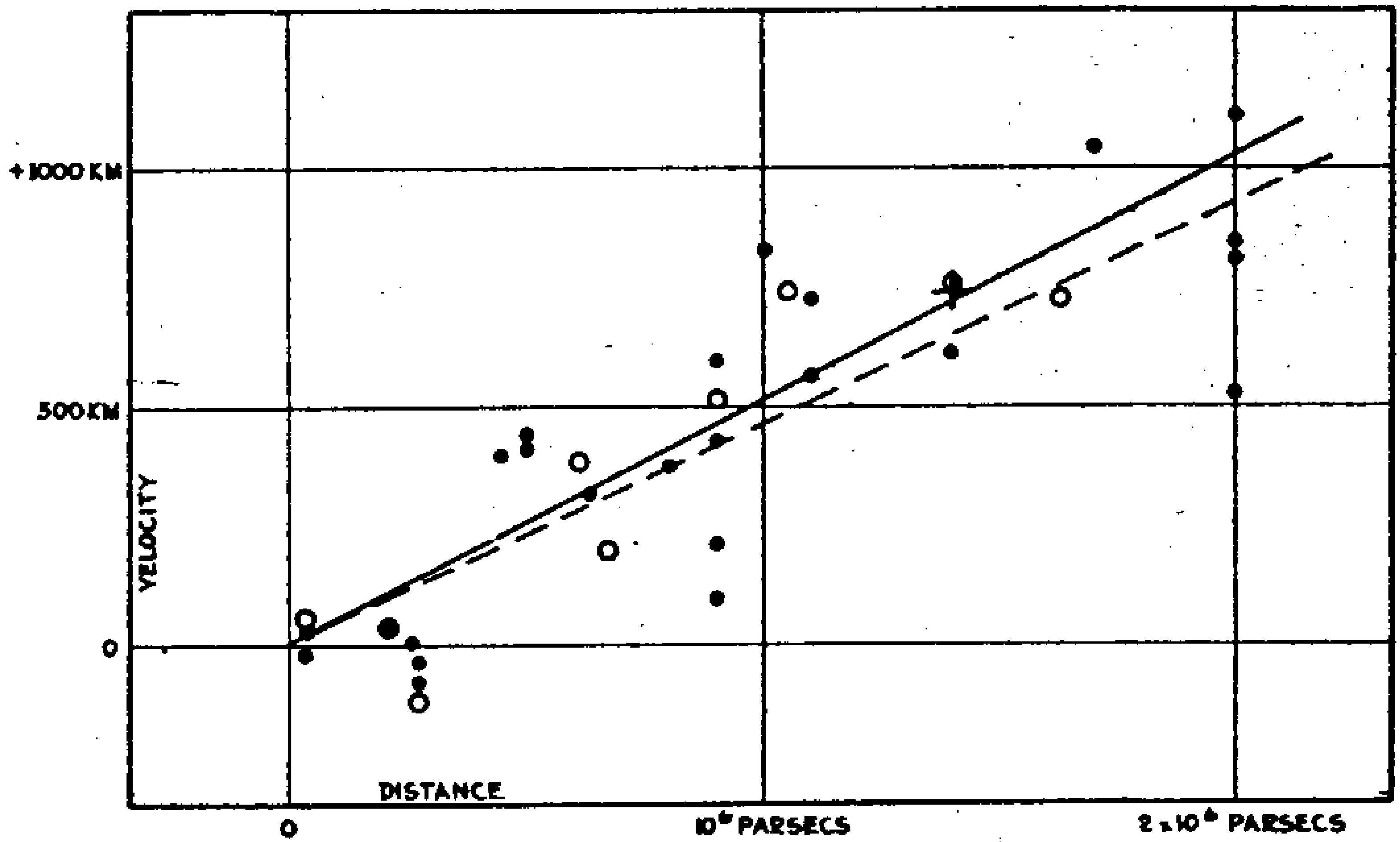
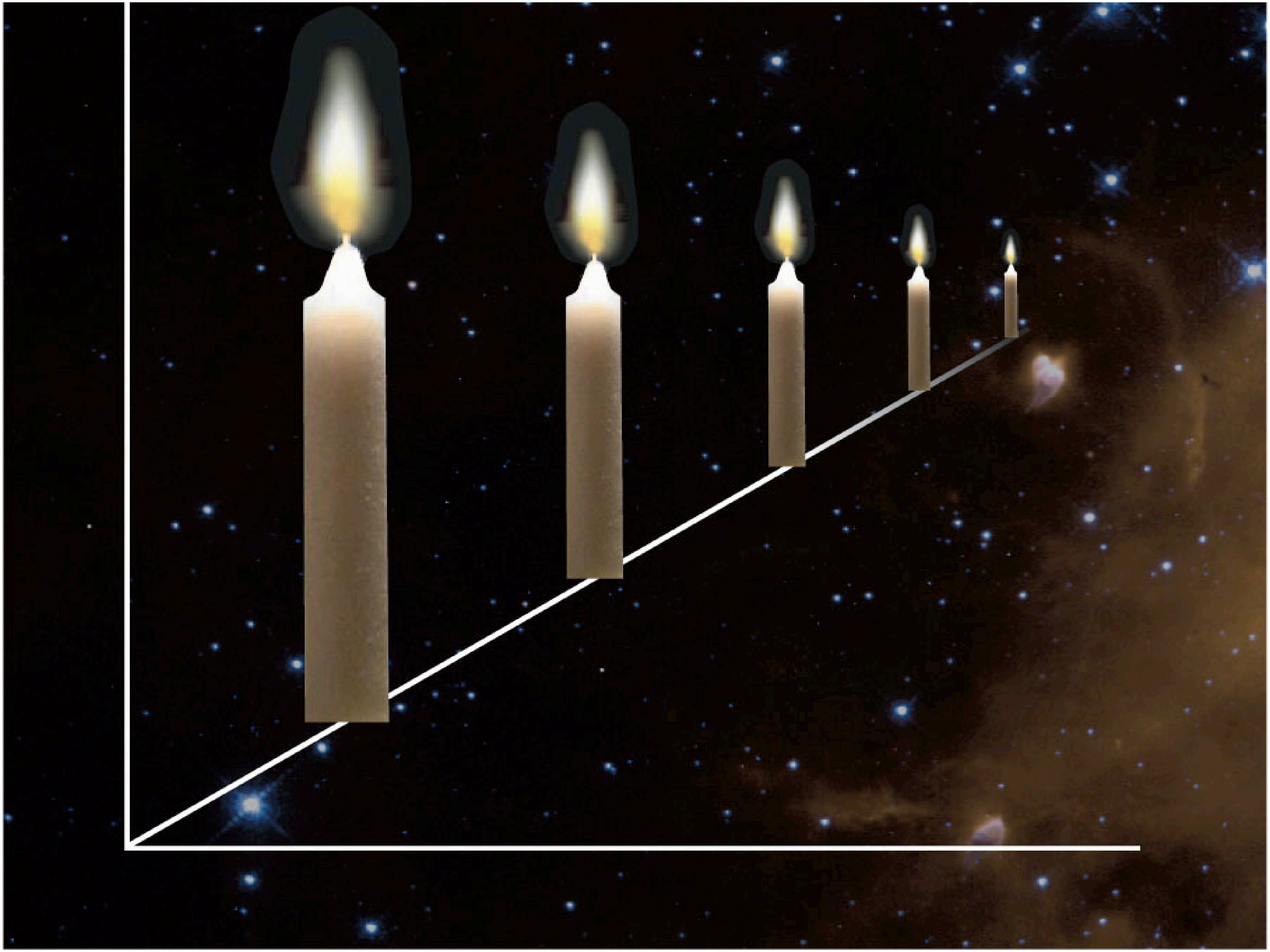
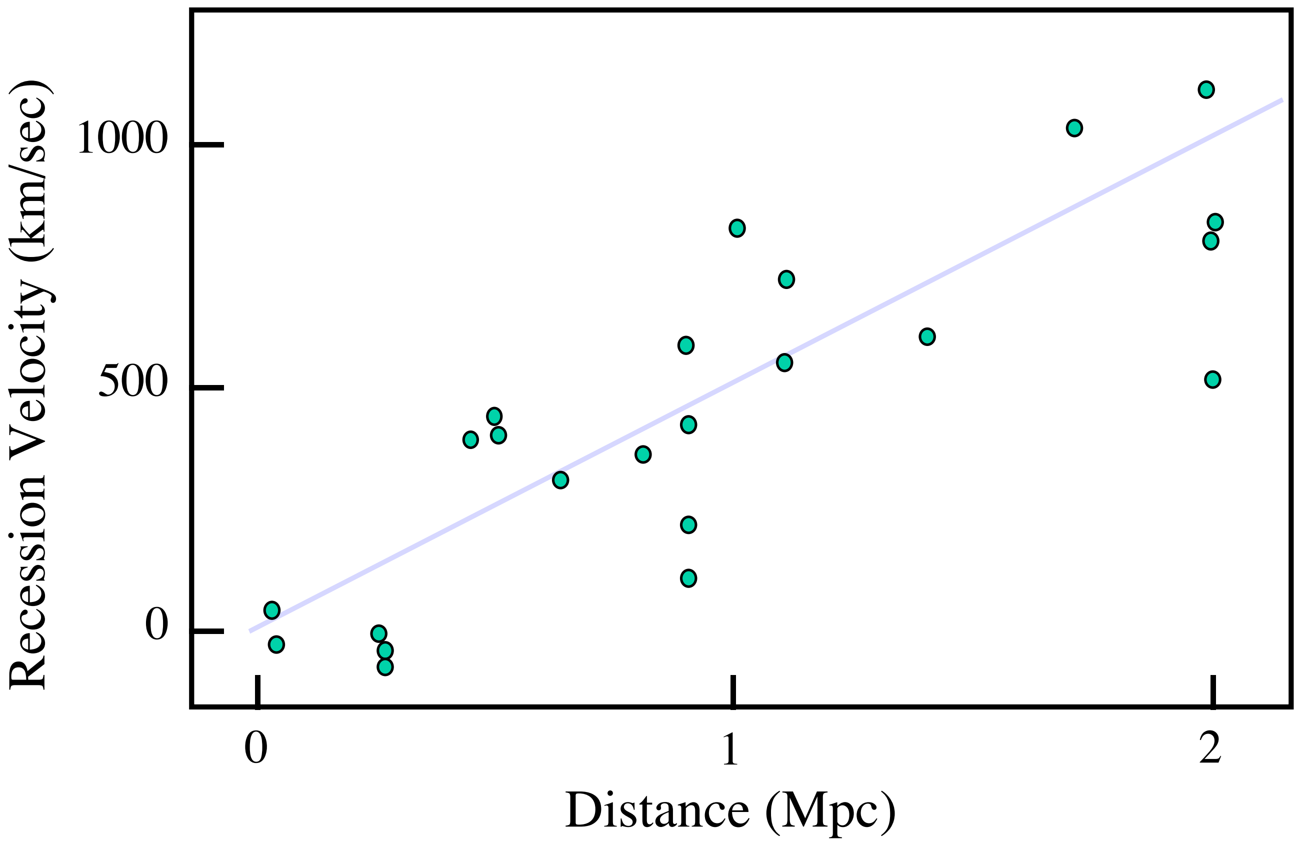


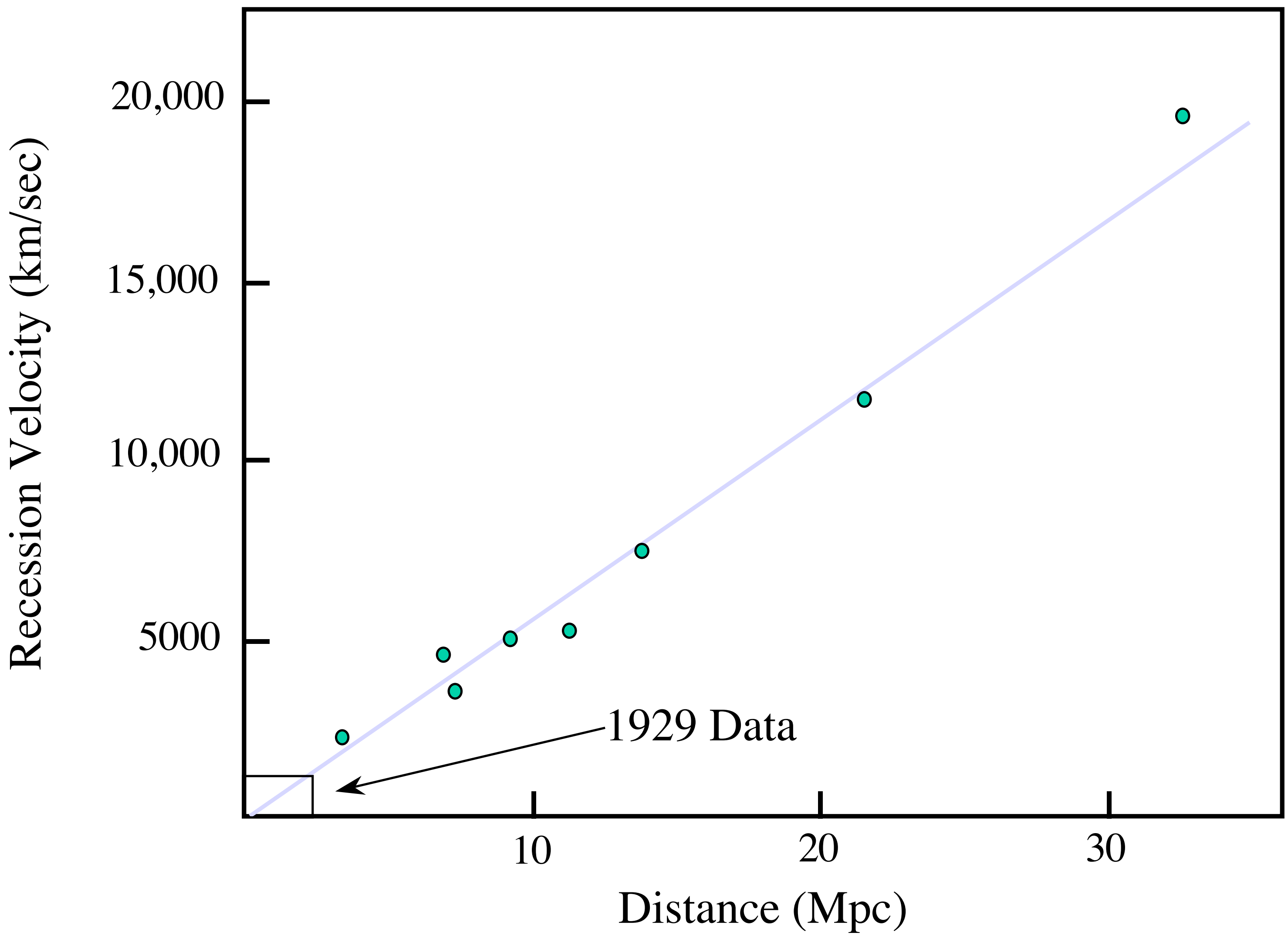
FIGURE 1



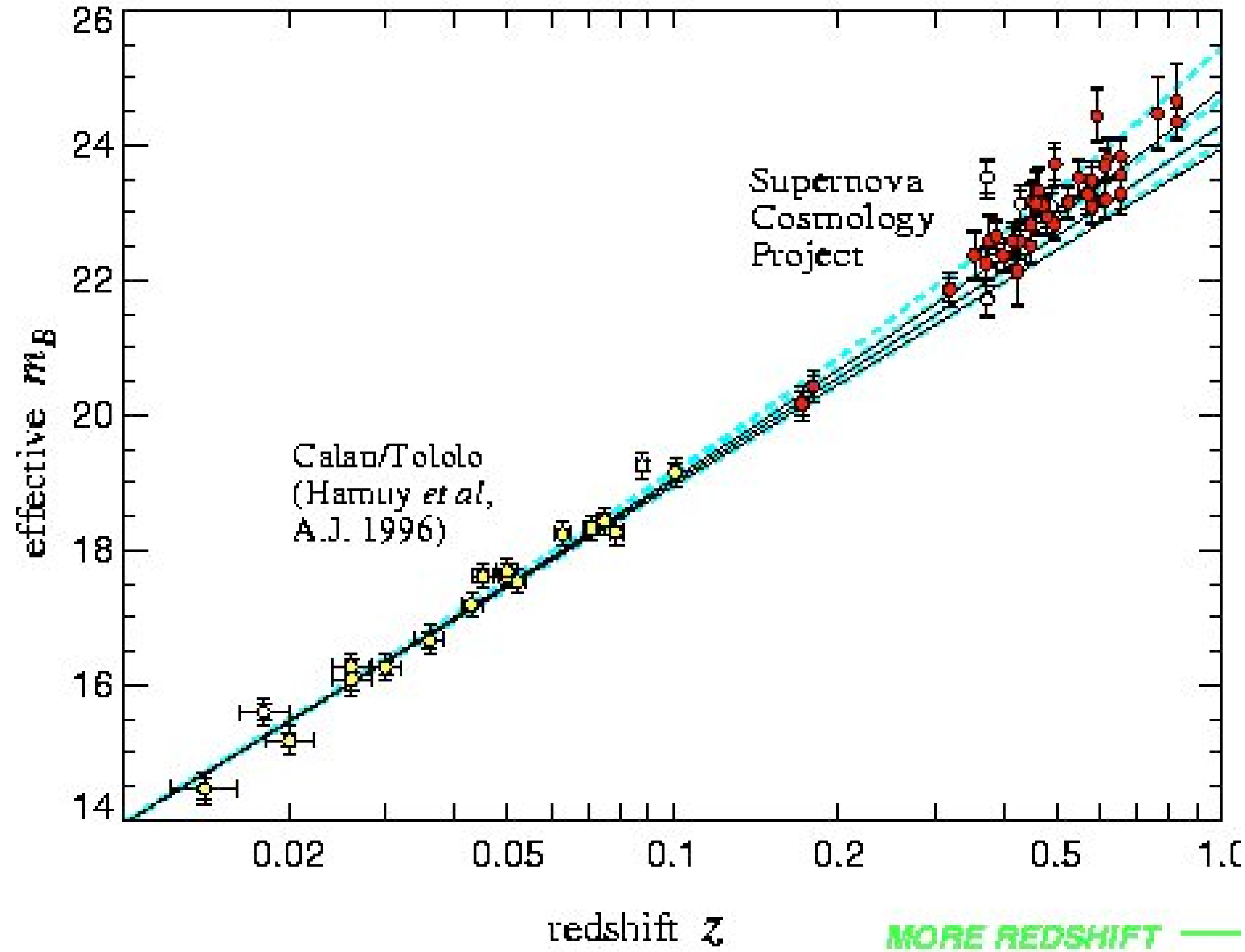
Hubble's Data (1929)

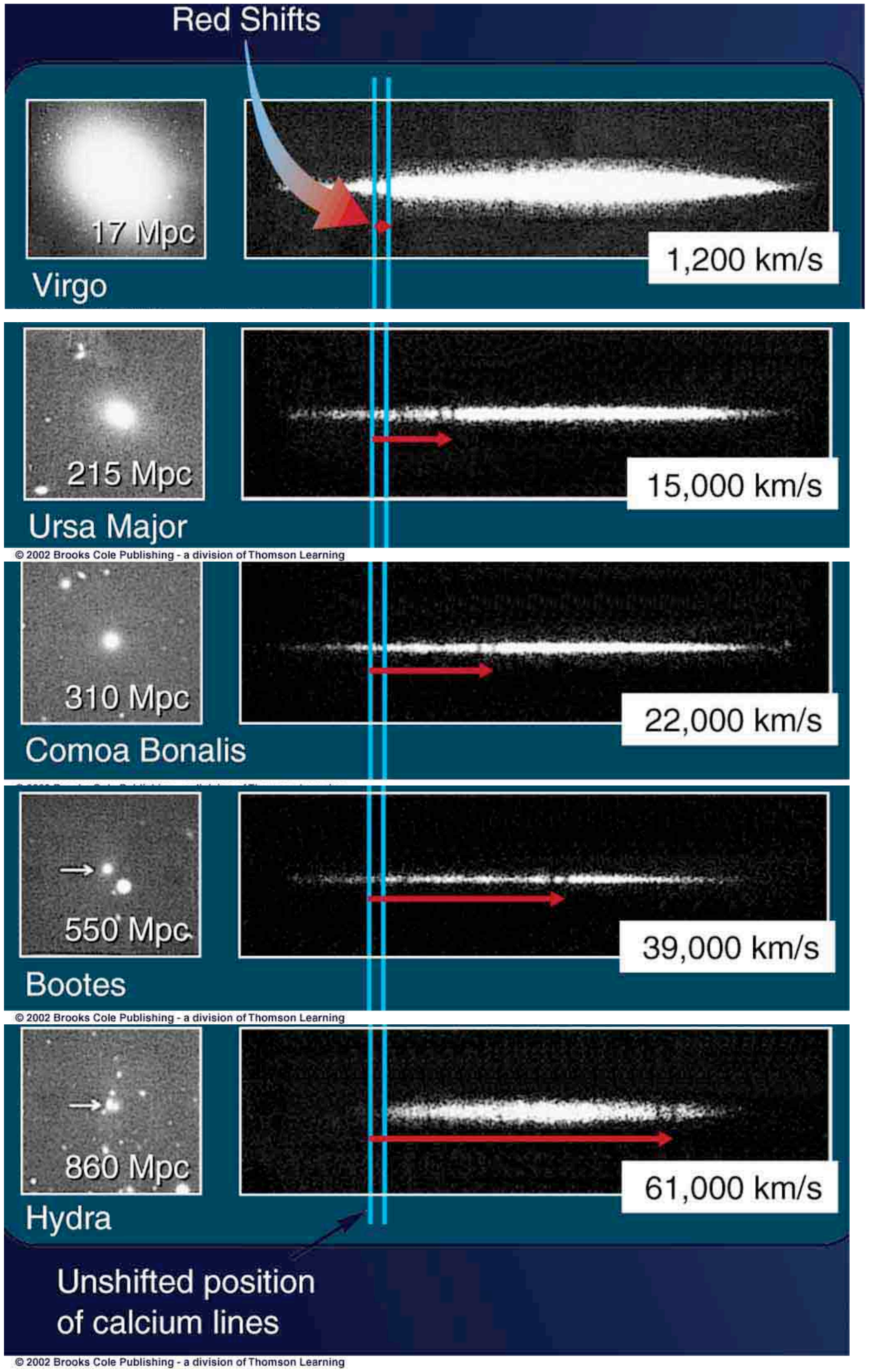


Hubble & Humason (1931)

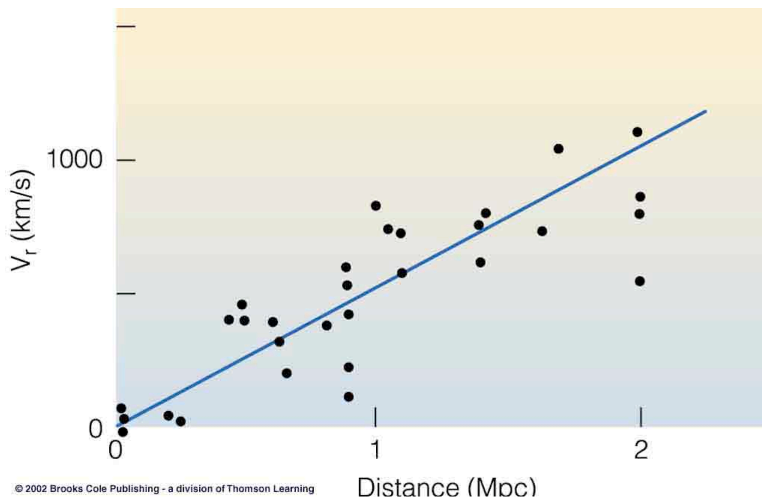


The redshift-distance relation





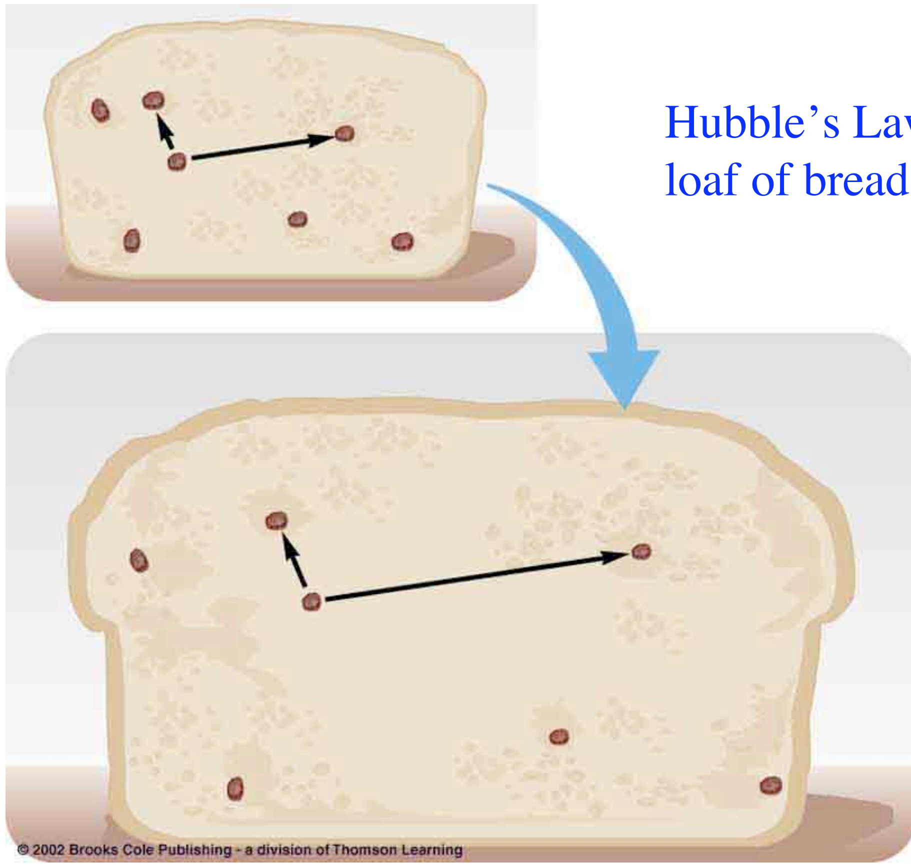
Hubble's Law Revisited
(it's interpretation)



Hubble's Law means that
the universe is expanding.

Think of space as made up of sugar cubed sized chunks. Each chunk is growing with time and all matter is being carried along.

The Raisin Bread Analogy

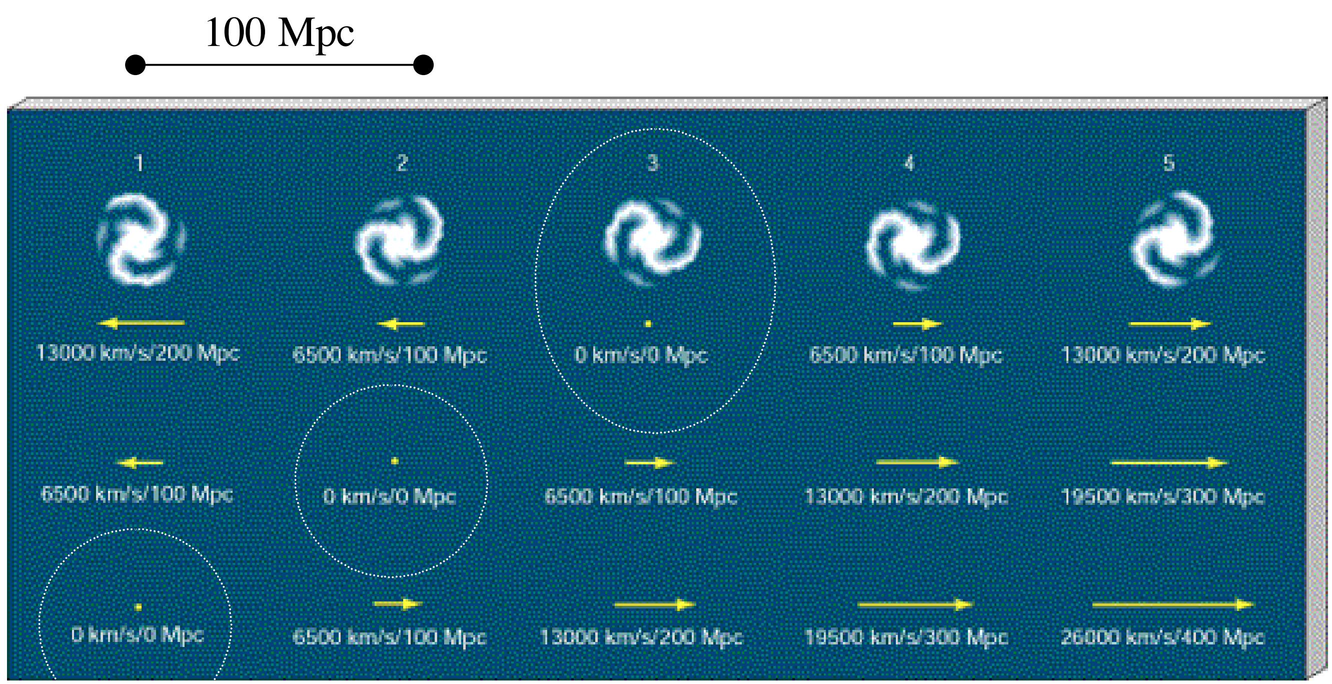


Hubble's Law in a loaf of bread!

Every grain of bread is expanding and the raisins are going along for the ride.

The further apart two raisins, the more grains between them, the faster they are "carried" away from one another. Its an additive effect by summing up all grains between the raisins.

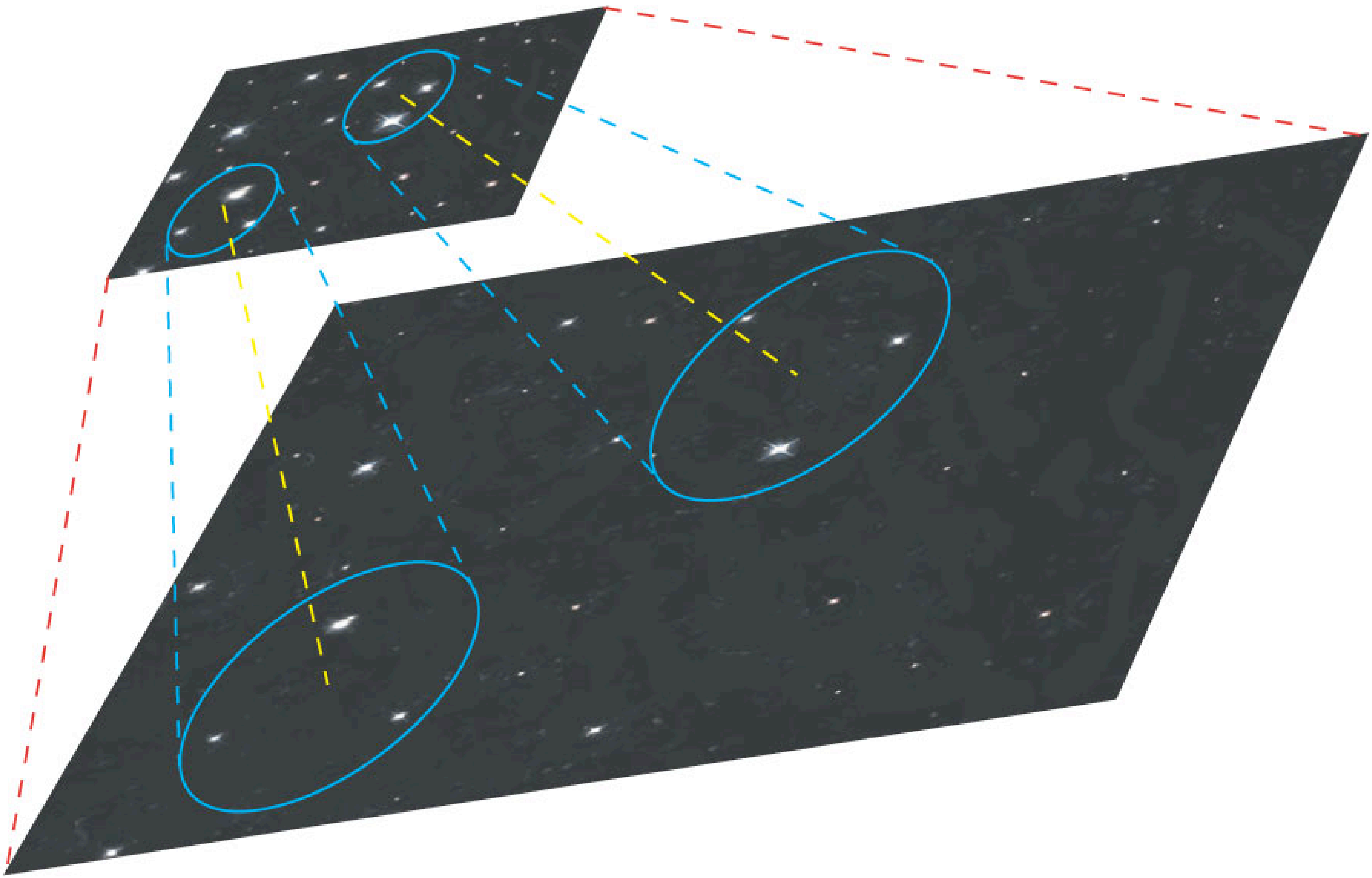
Galaxy Raisins

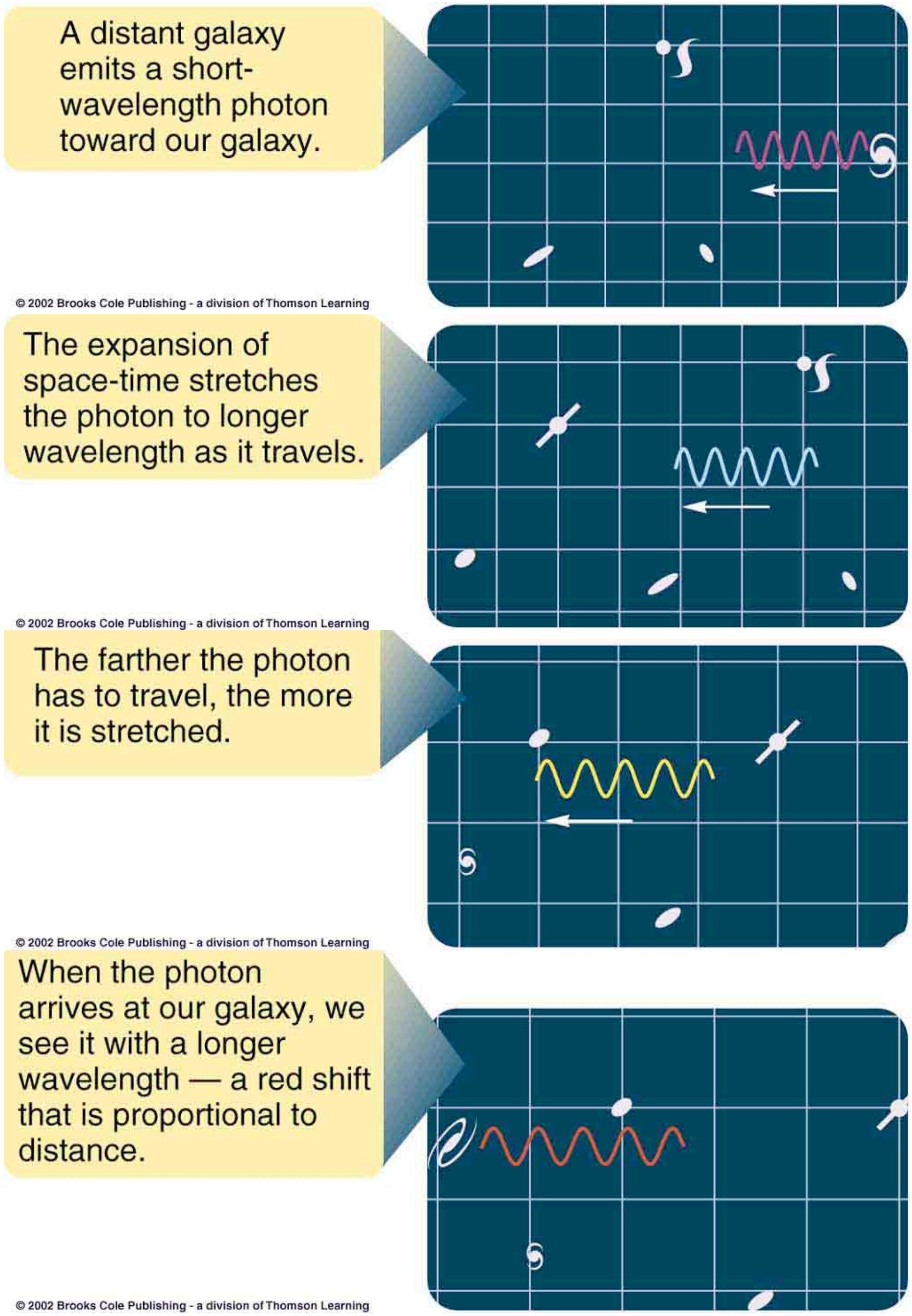


No matter which galaxy you are on, all other galaxies are moving away.

The further away the galaxy, the faster the galaxy is moving away from you!

All points equivalent





The photon has a well defined wavelength of "3" (peak to peak) on imaginary grid of space.

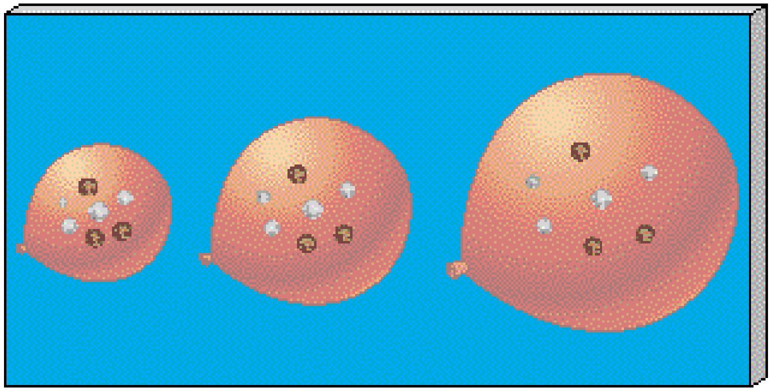
That wavelength does not change relative to the imaginary grid. It always is "3" from peak to peak.

As the grid size stretches, because the area of space inside each grid is expanding, the photon also stretches.

The color changes. A photon that was very blue when it was emitted eons ago, would now be very red!

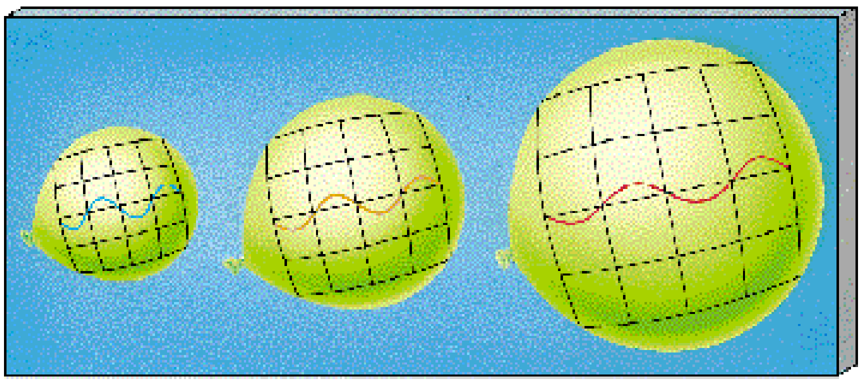
Since the speed of light is constant, the distance the photon traveled is directly related to its travel time.

The Balloon Analogy



Objects on the surface are carried along as each location on the balloon stretches

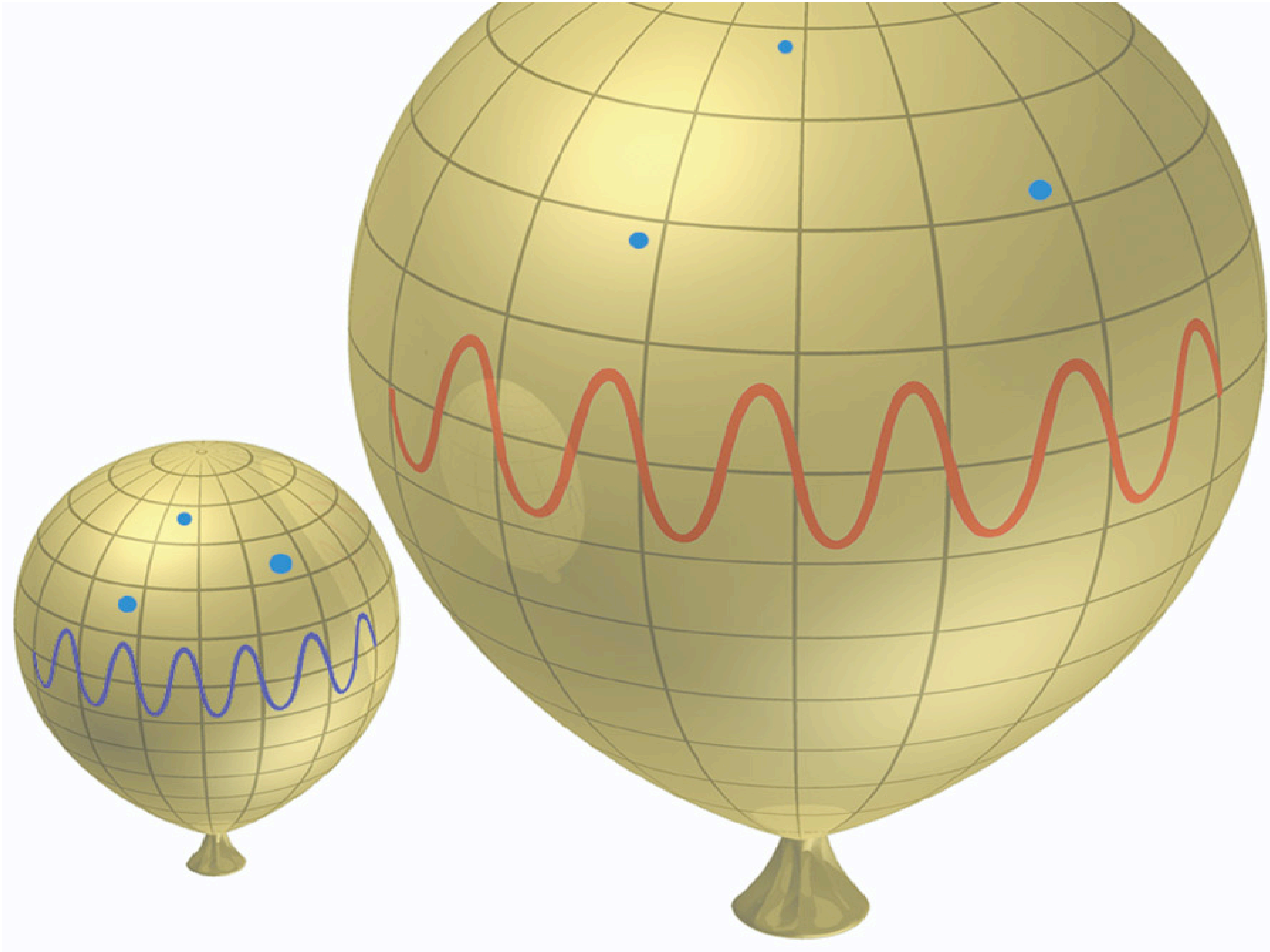
Hubble's Law on a big fat balloon!



Photons are stretched as well. Since the color is defined by wavelength, the color changes! Photons get "redder".

Cosmological Redshift.

This stretching of the wavelength causes a reddening of the light. This is a redshift (just like the Doppler redshift), but it is not due to the motion of the object, but to the stretching of the photon.

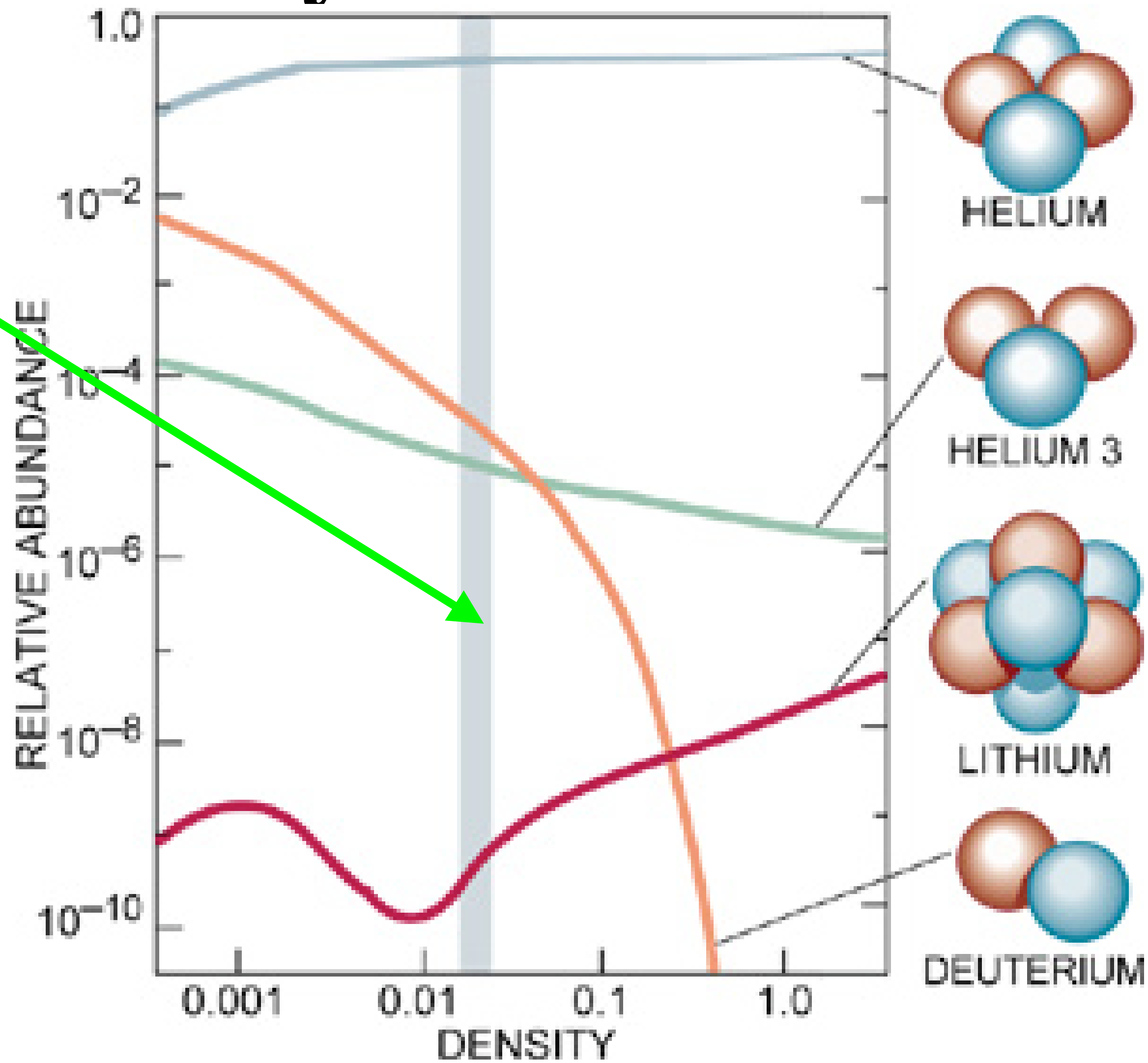


George Gamov (1904-1968)

- If the universe is expanding, then there has been a big bang
- Therefore, the early universe must have been very dense and hot
- Optimum environment to breed the elements by nuclear fusion (Alpher, Bethe & Gamow, 1948)
  - success: predicted that helium abundance is 25%
  - failure: could not reproduce elements more massive than lithium and beryllium (□ formed in stars)

Primordial nucleosynthesis

Consistent with
abundance
of H, He and Li



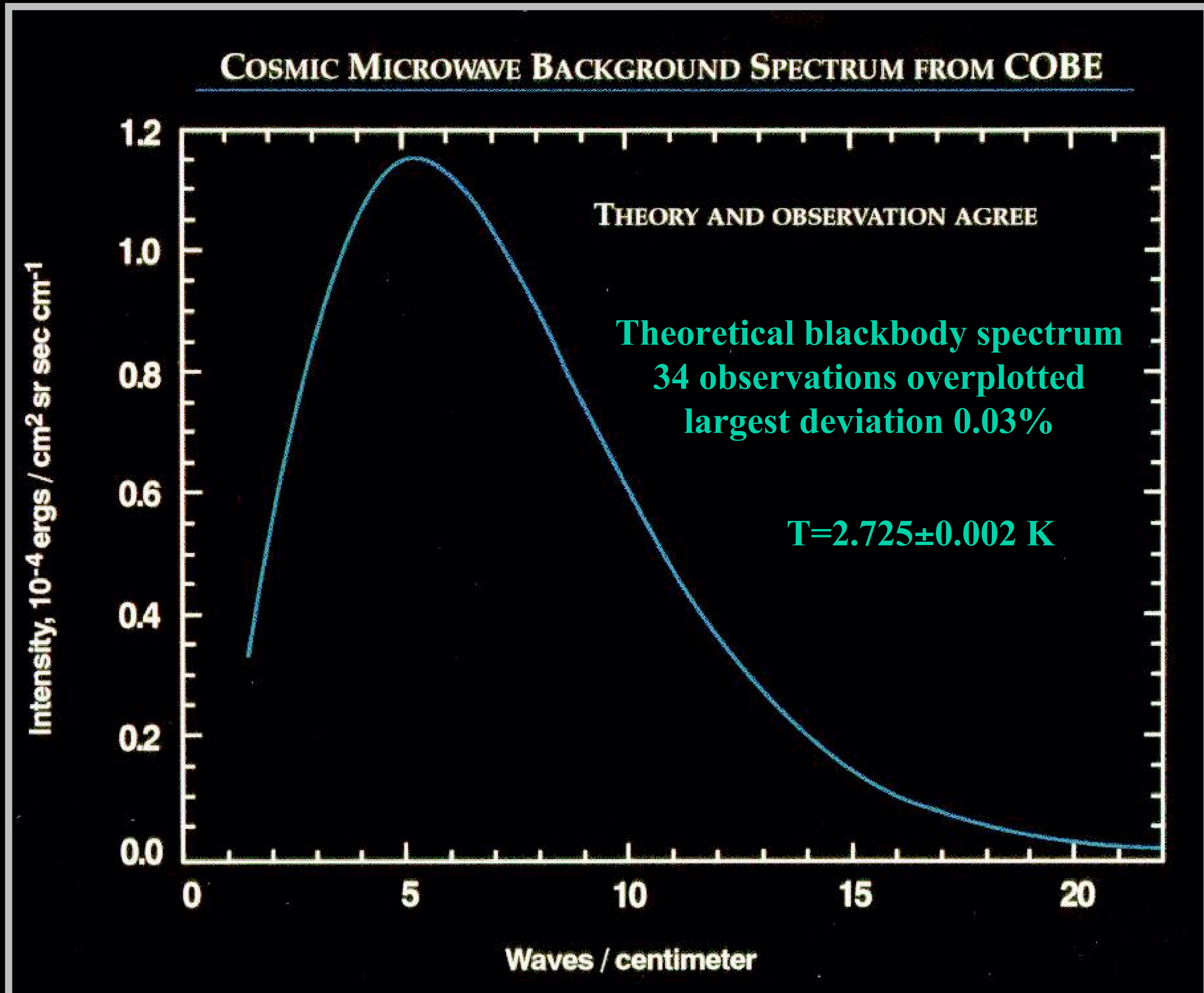
Result:

- abundance of H,He and Li is consistent
- but: □$_b$ ~0.04

Penzias and Wilson 1965

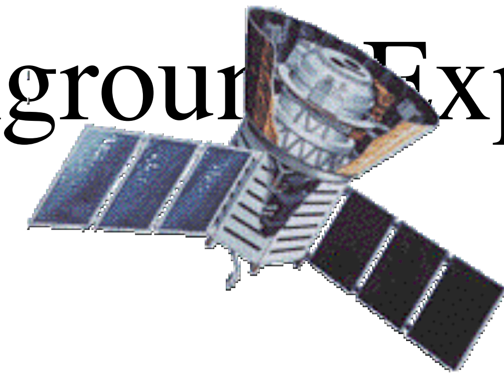
- Working at Bell labs
- Used a horn antenna to measure radio emission of the sky, expected to be mostly from the Galaxy.
- They found some extra noise coming into the receiver, but couldn’t explain it
   discovery of the Big Bang relic radiation
  - Cosmic Microwave Background (CMB)
- Most significant cosmological observation since Hubble
- Awarded Nobel prize for physics in 1978

The COBE satellite being assembled at Vandenberg AFB

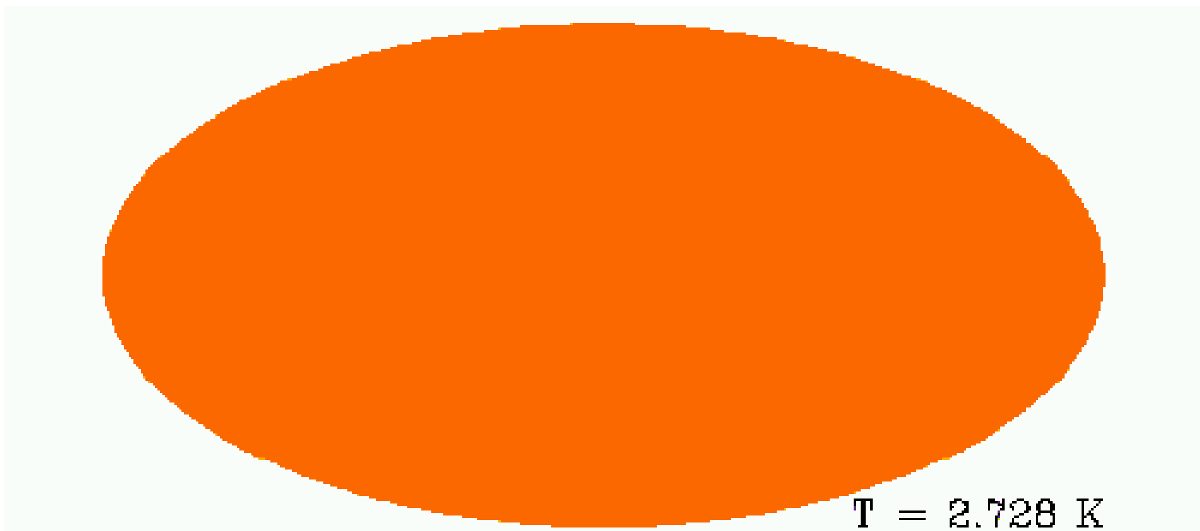


COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Theoretical blackbody spectrum
34 observations overplotted
largest deviation 0.03%
T=2.725±0.002 K
Intensity, 10^-4 ergs / cm^2 sr sec cm^-1
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

The COsmic microwave Background Explorer

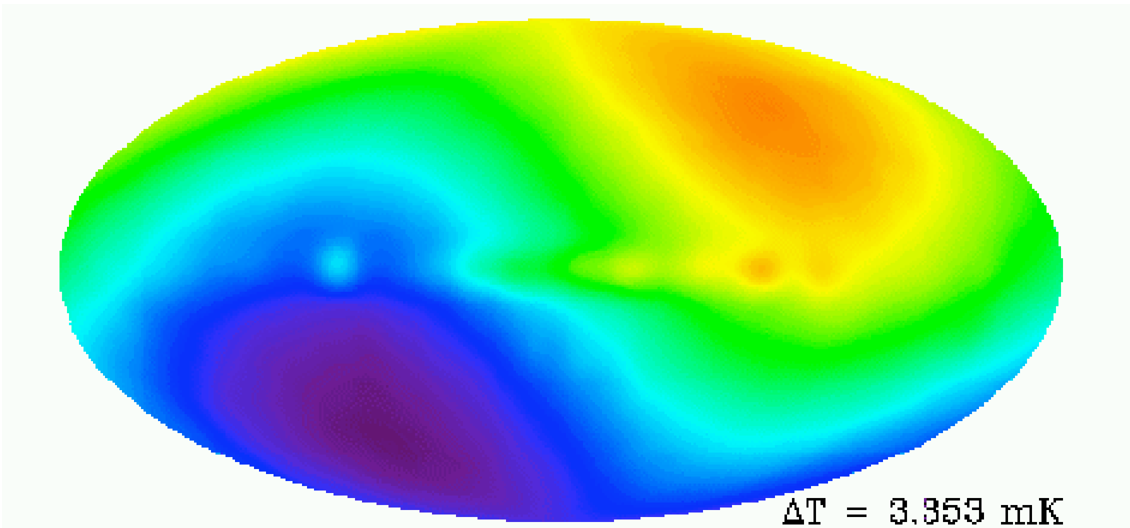


COBE satellite, launched 1991



COBE All-sky image looks *completely* uniform; 2.7 degrees above absolute zero.
The Universe has expanded 1000 times since this light began its journey in the 3000°K plasma.

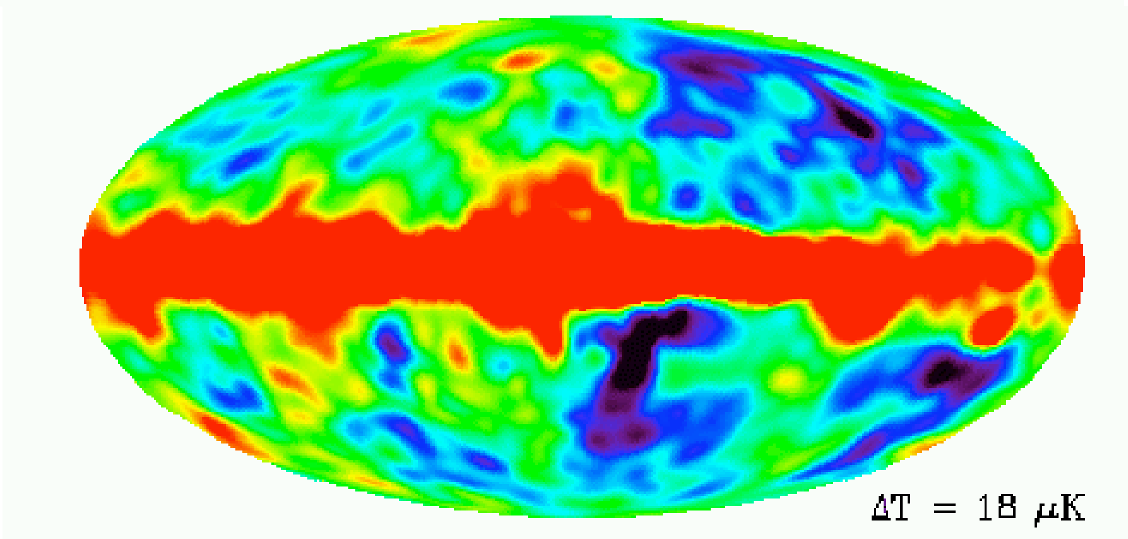
Processed COBE Data reveals structure in CMB



Subtracting off 2.728°K shows *dipole*, indicating motion

Moving towards□ blue, away from□ red (Doppler shift) at a speed of 611 km/s

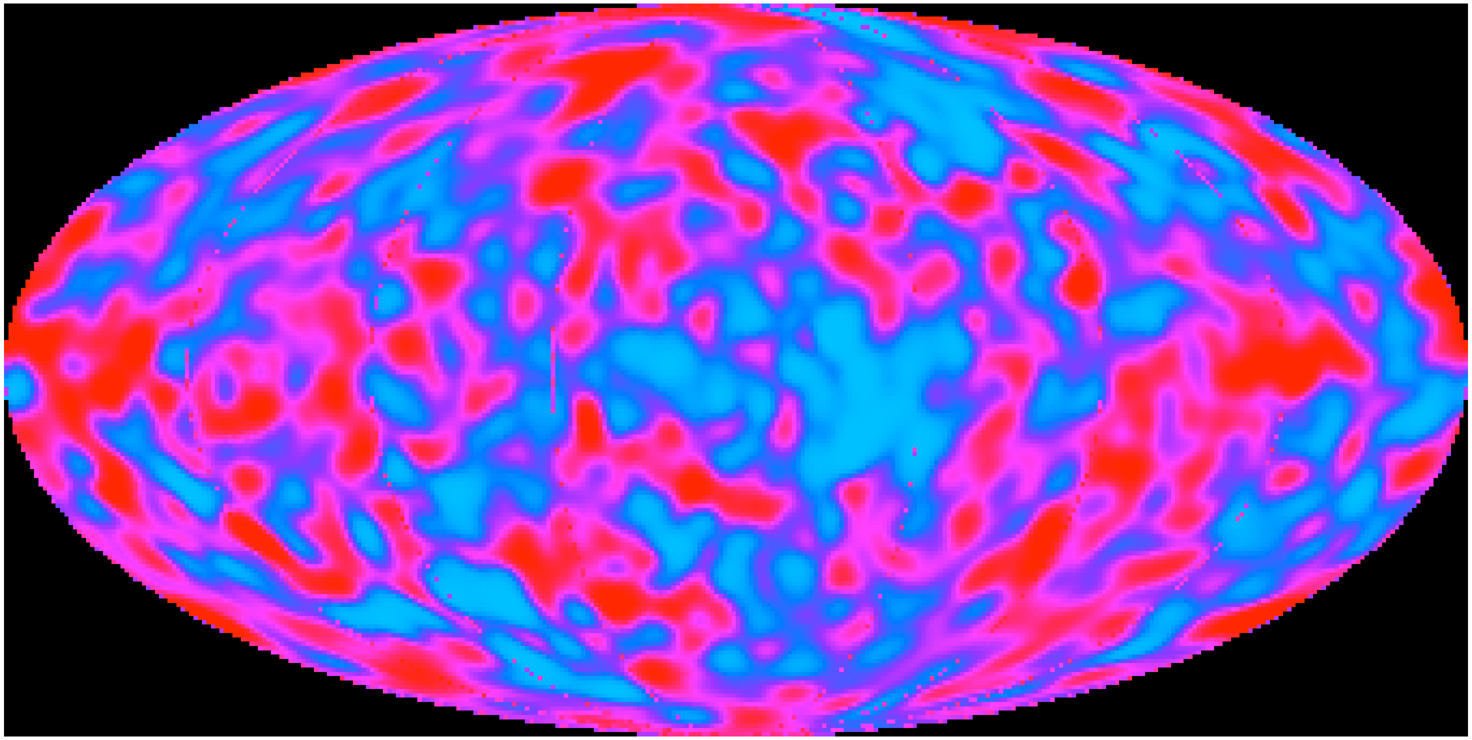
Dipole amplitude is one part per thousand of 2.7°K.



Subtracting dipole map, the Milky Way Galaxy stands out, plus variations at 18 □K.

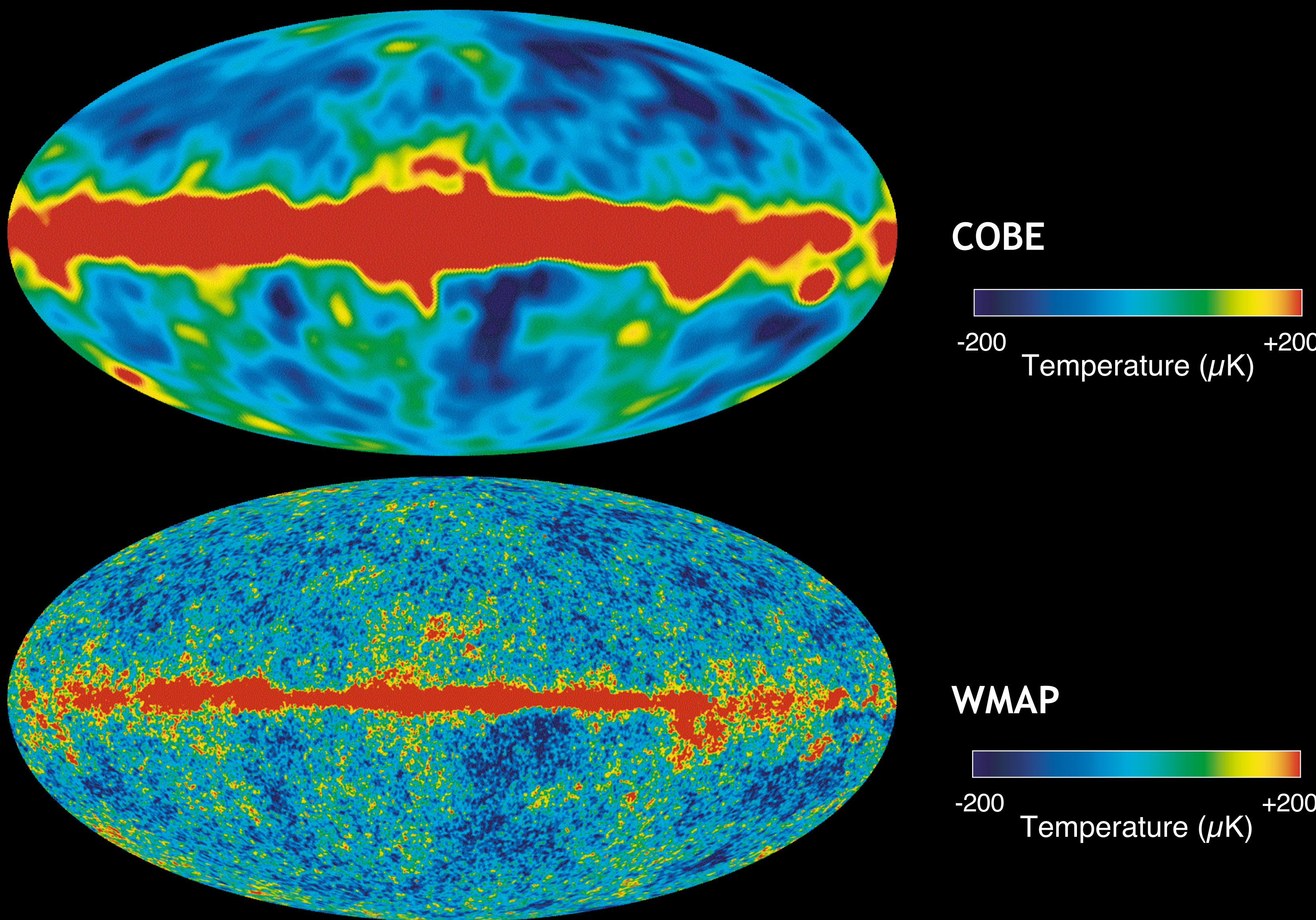
Galaxy light can be removed because it has different spectrum than CMB (COBE had multi-color vision).

COBE's Great Finding: Anisotropy in the CMB

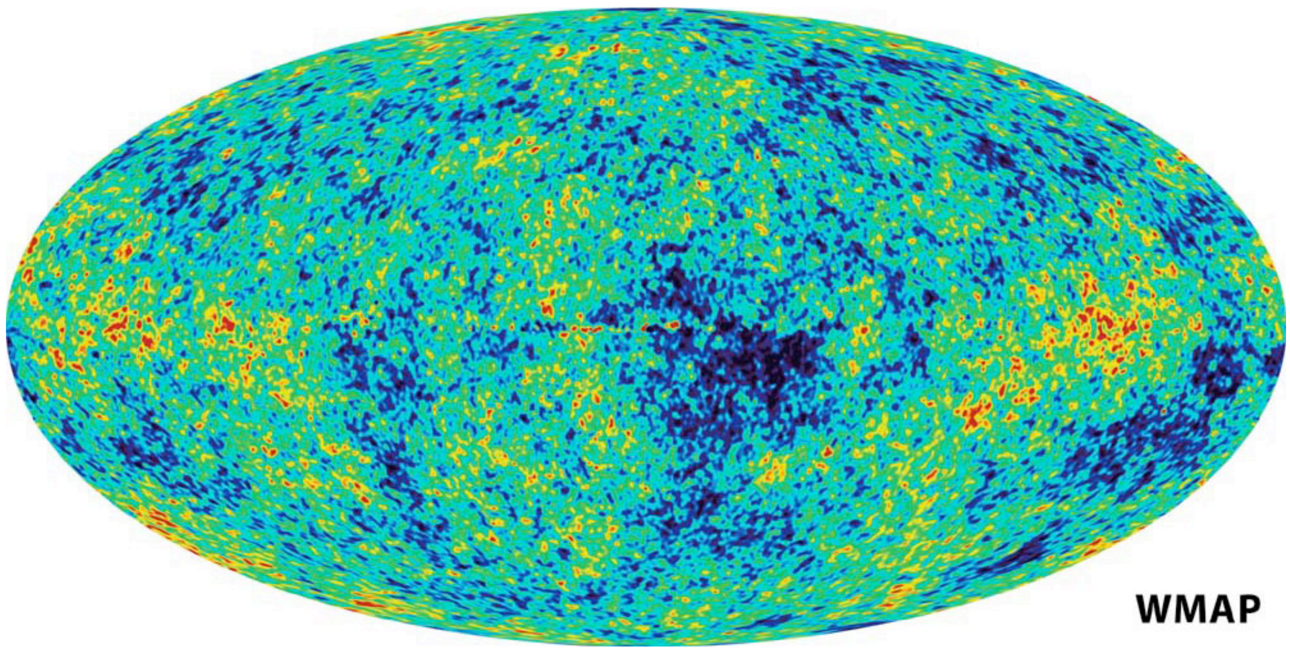


Red means cooler, blue means warmer, but only by tens of micro-Kelvins. COBE's vision was limited to 7 degree resolution, but we see structure at this scale, representing density variations in the recombining plasma when atoms first formed. These density variations reveal the seeds of galaxy formation. **This is as far back as we see--the wall to our vision.**

COBE-WMAP Comparison

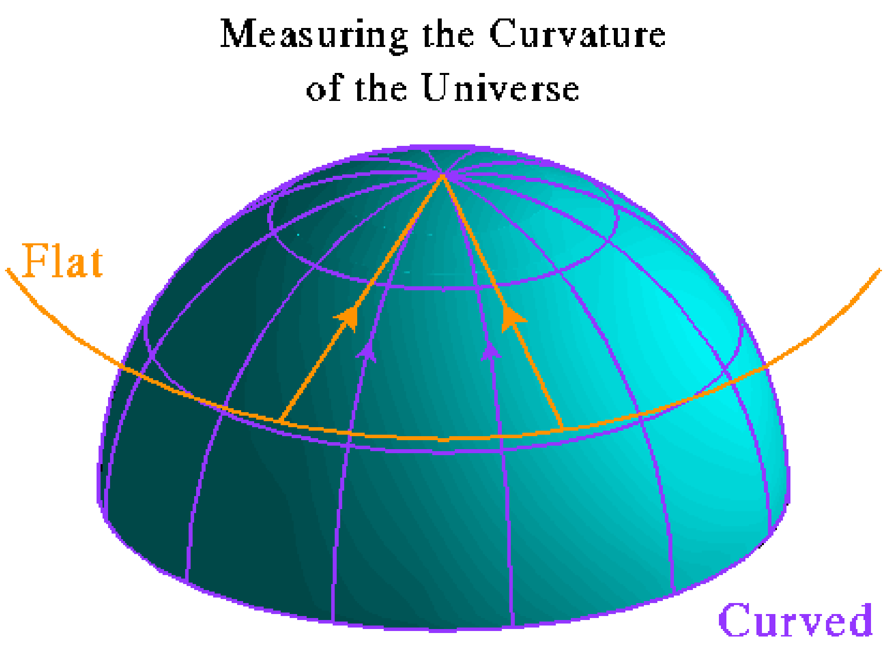


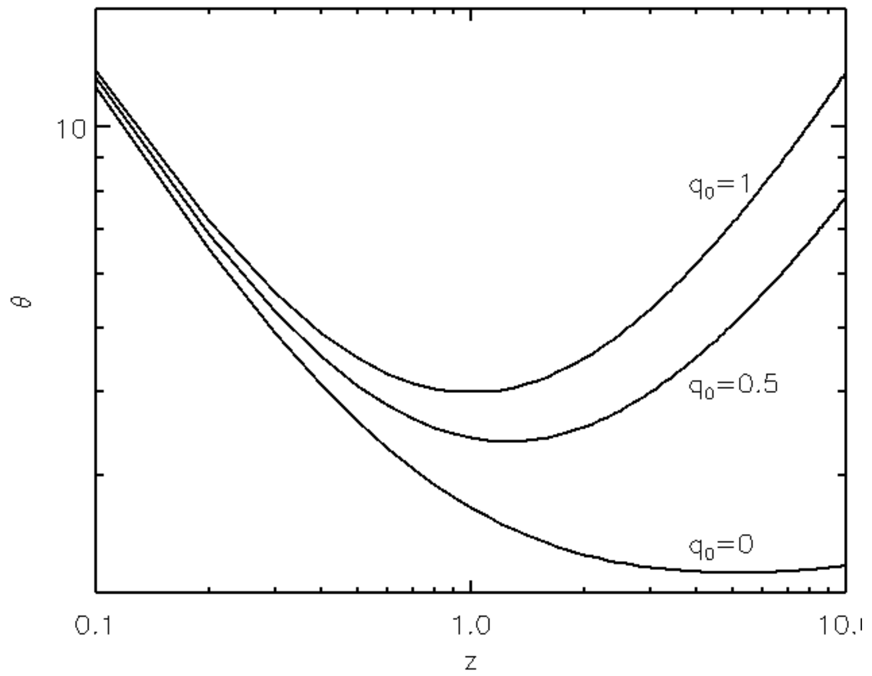
The Cosmic Microwave Background Radiation From COBE (1994) to WMAP (2003)



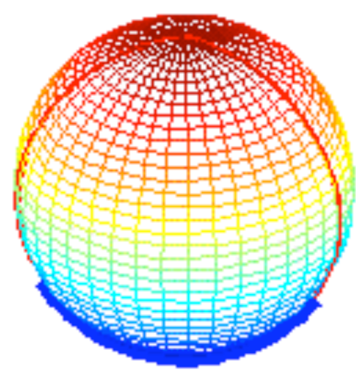
How can we measure the geometry of the universe

- We need a yard stick at great distance
- For different curvatures, a yard stick of given length appears under different angles

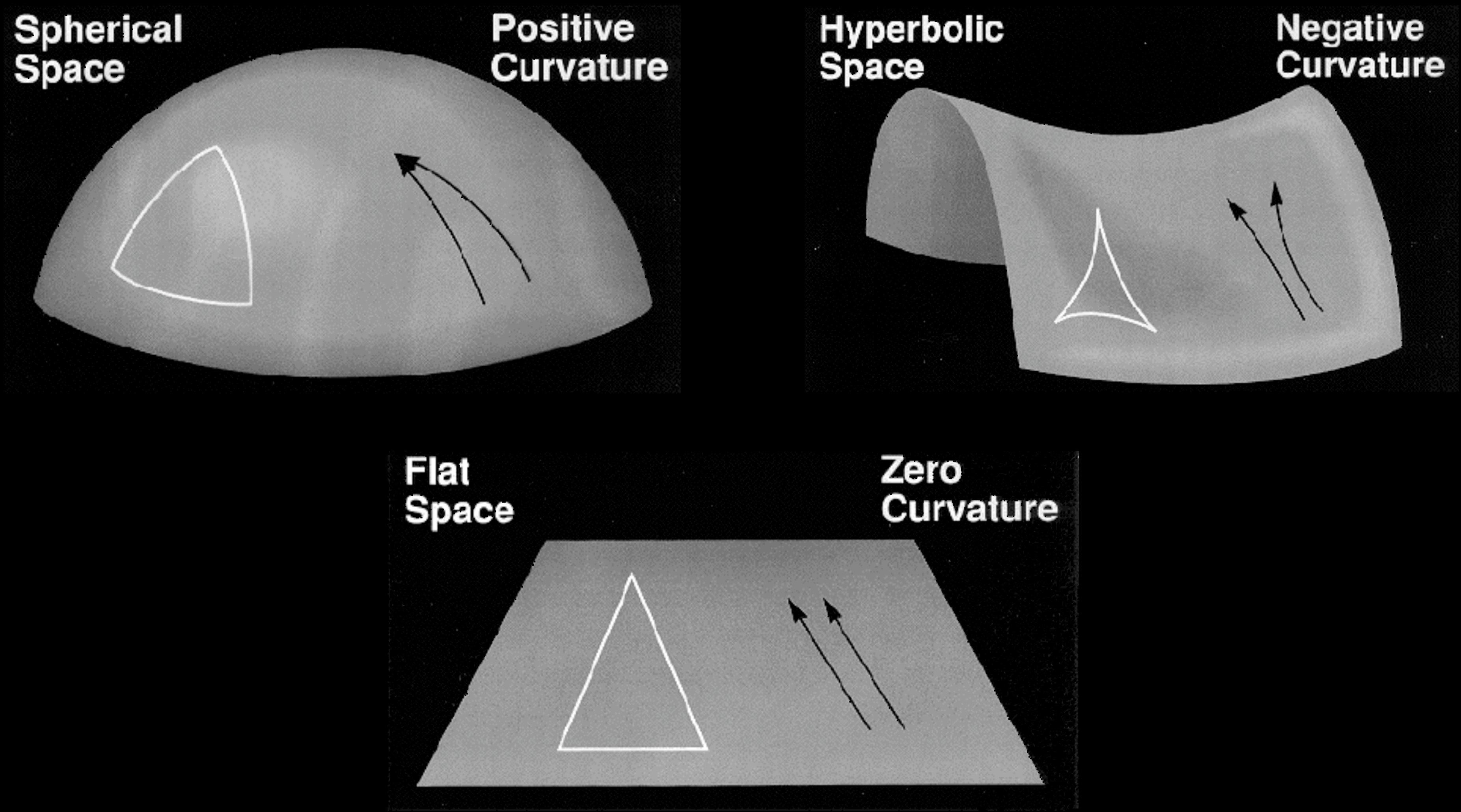




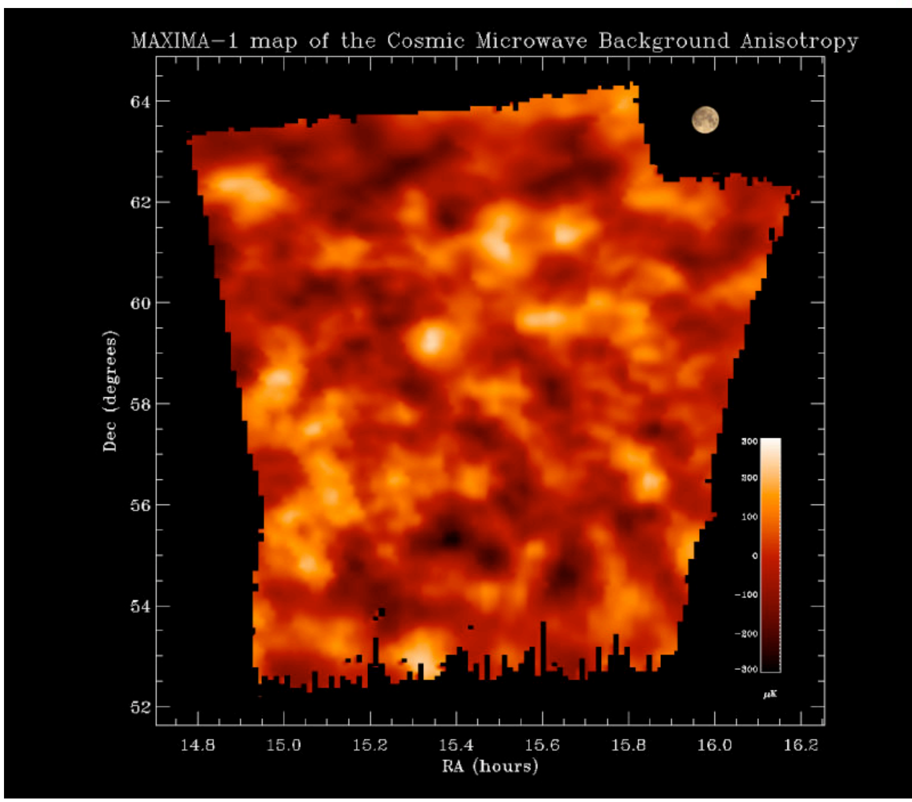
Scale Size and angle of vision

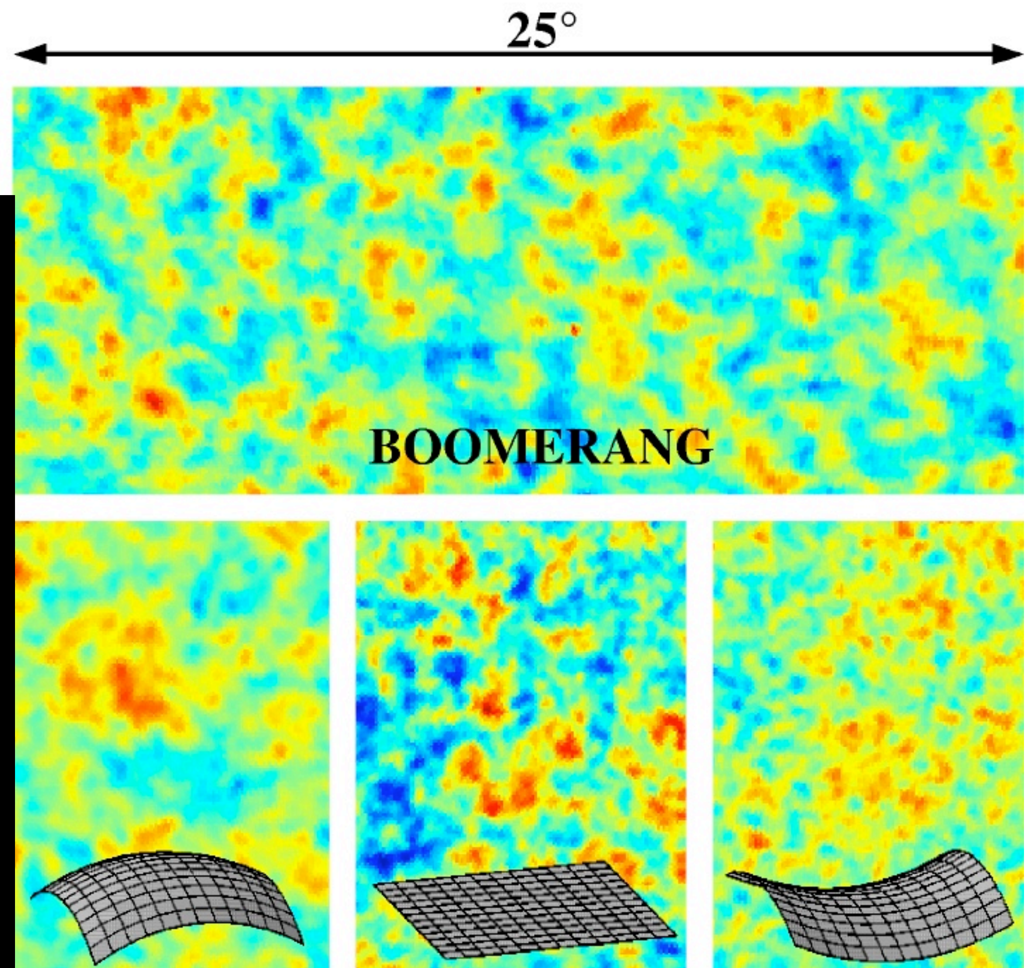


2-D Examples of Curved Spaces

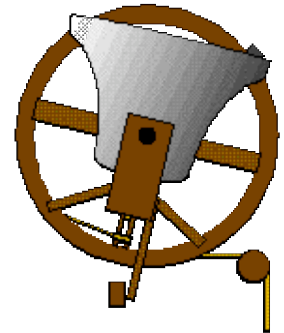


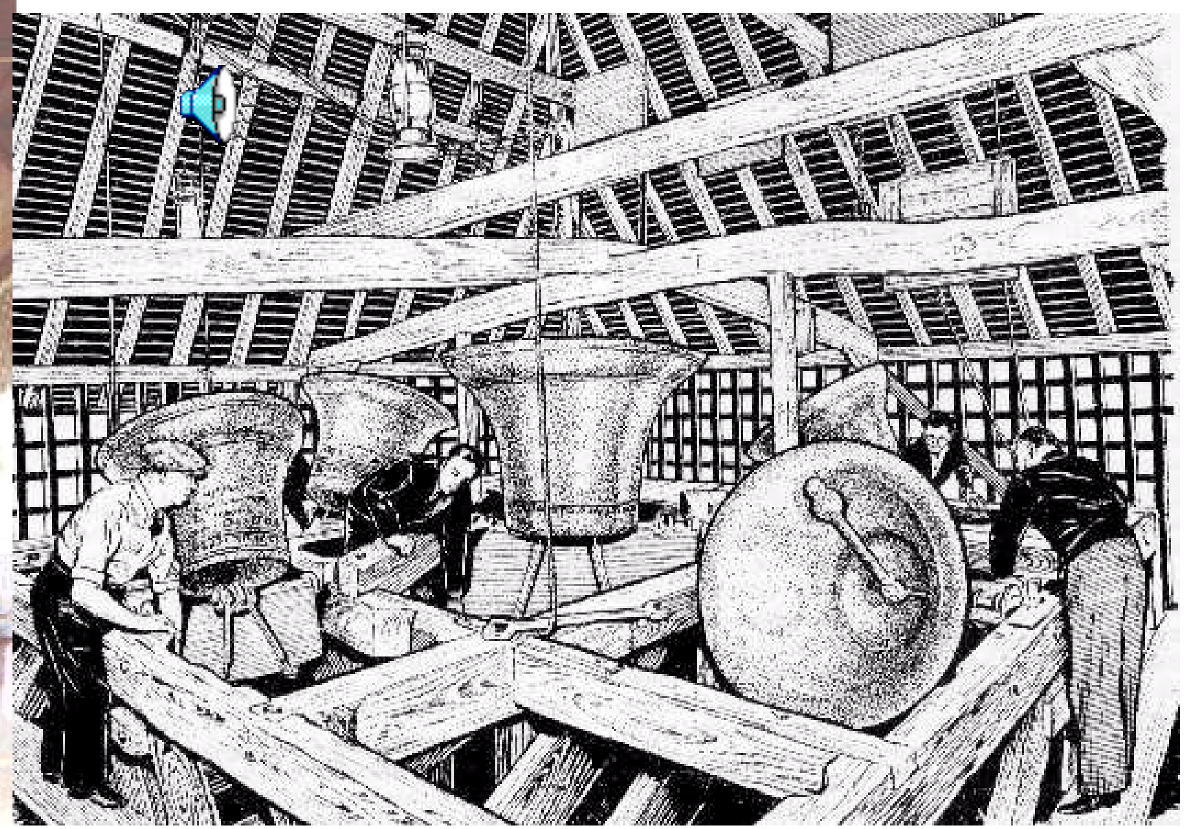
Measuring the Curvature of the Universe Using the CMB



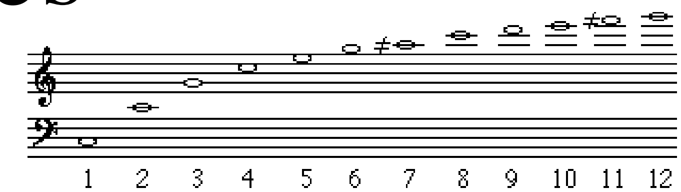


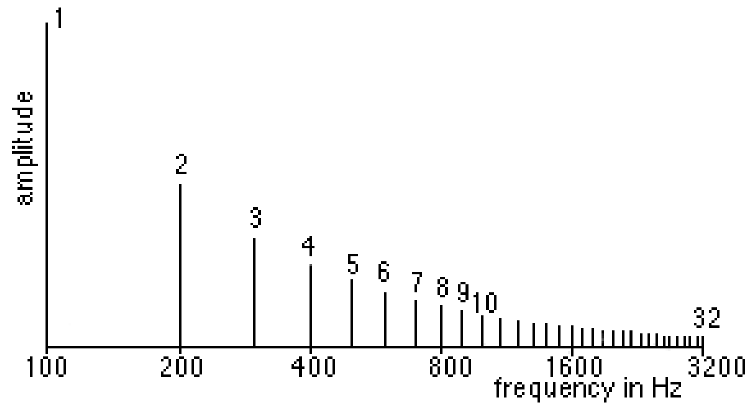
Harmonics of bells and Universe tell us their properties

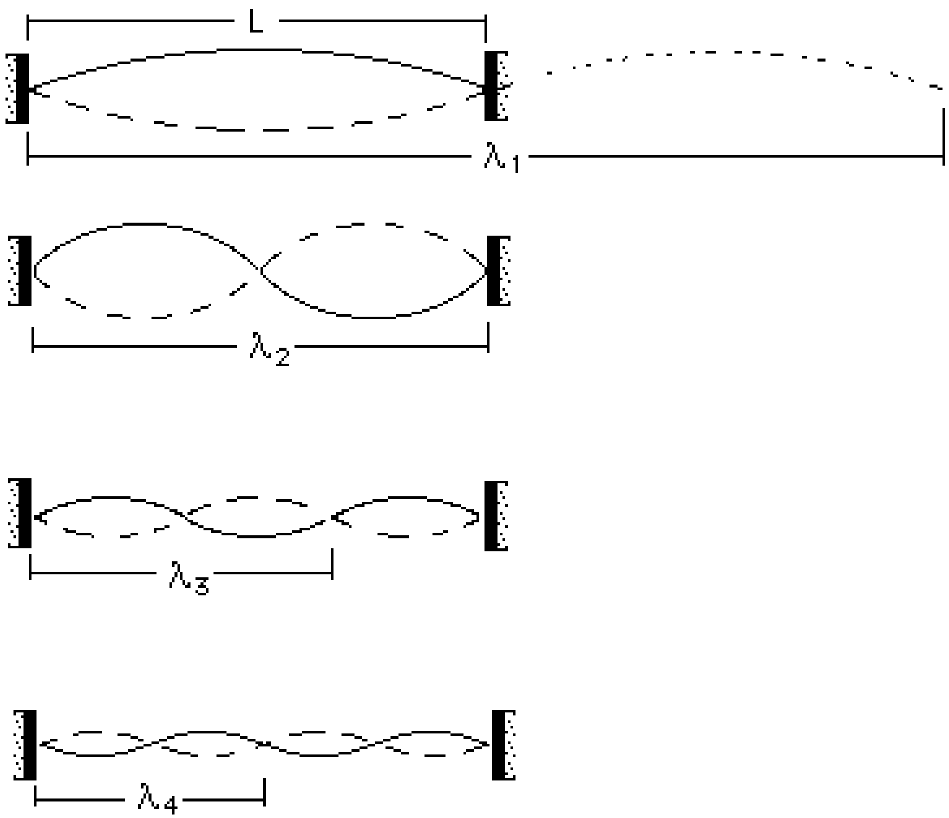


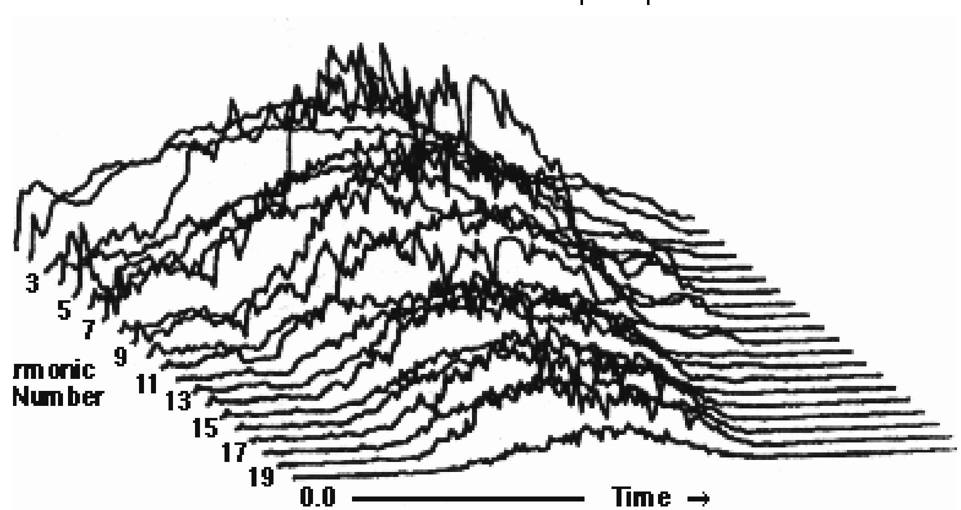


Acoustic Waves

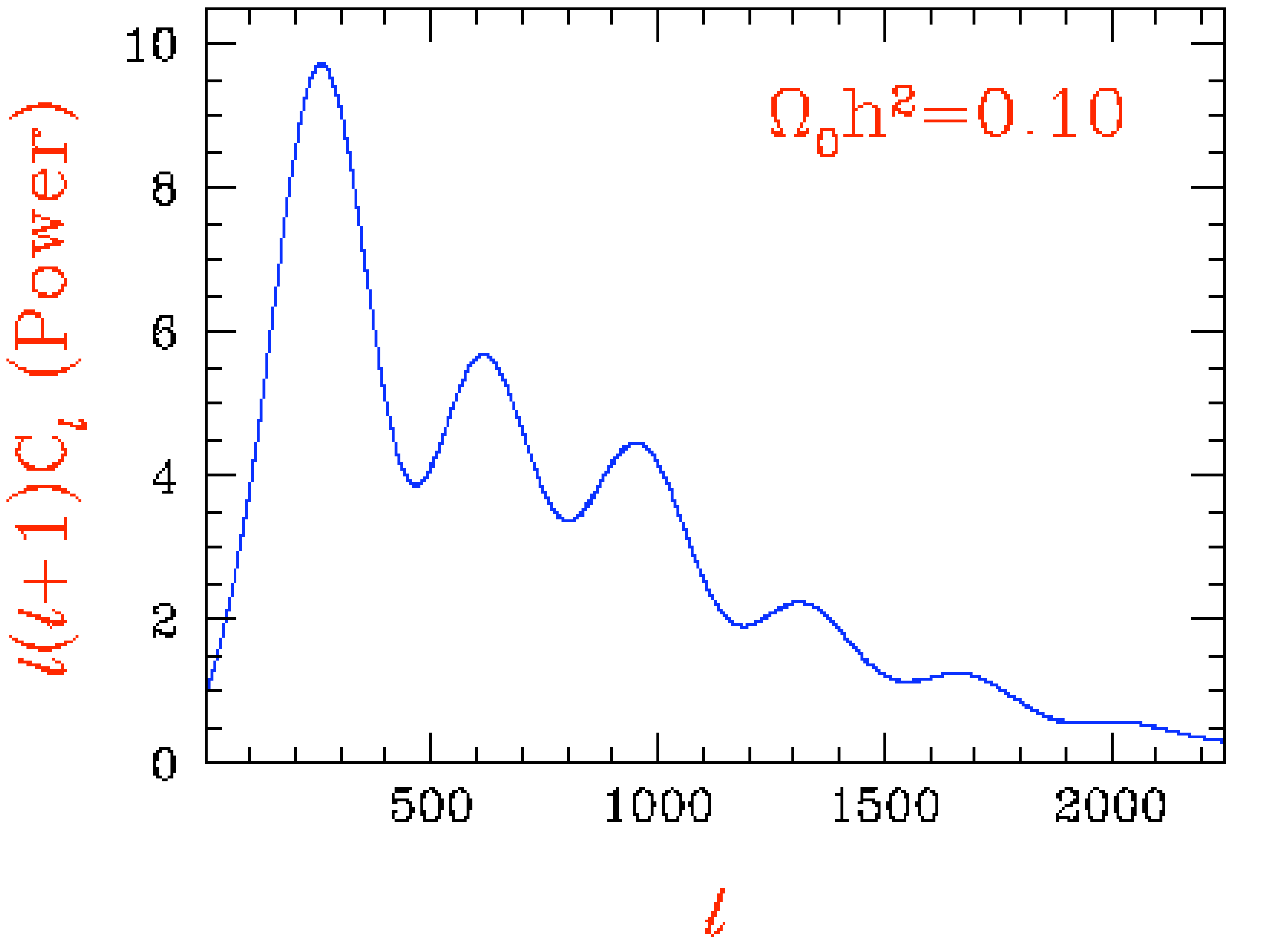








First 20 harmonics of trumpet tone

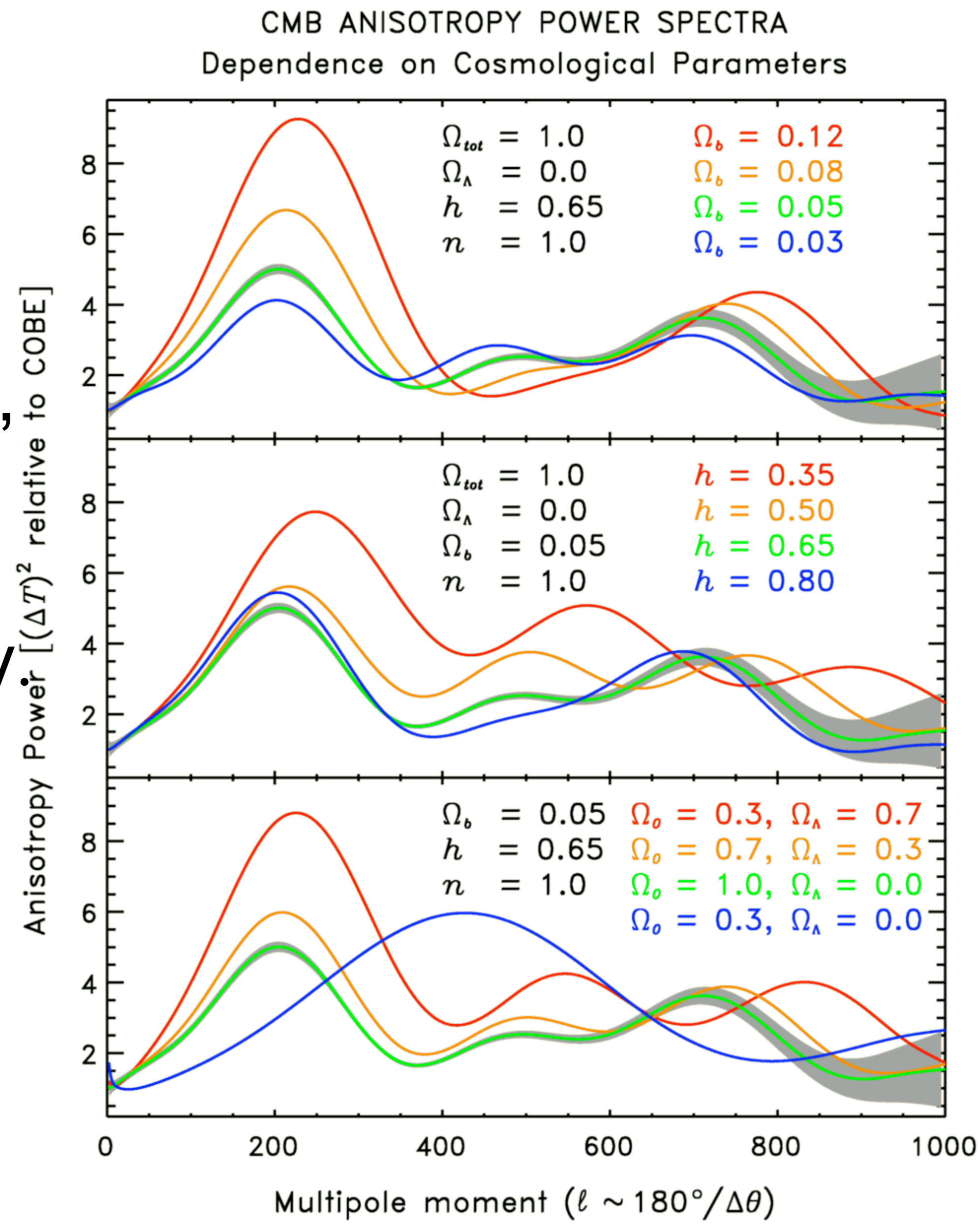


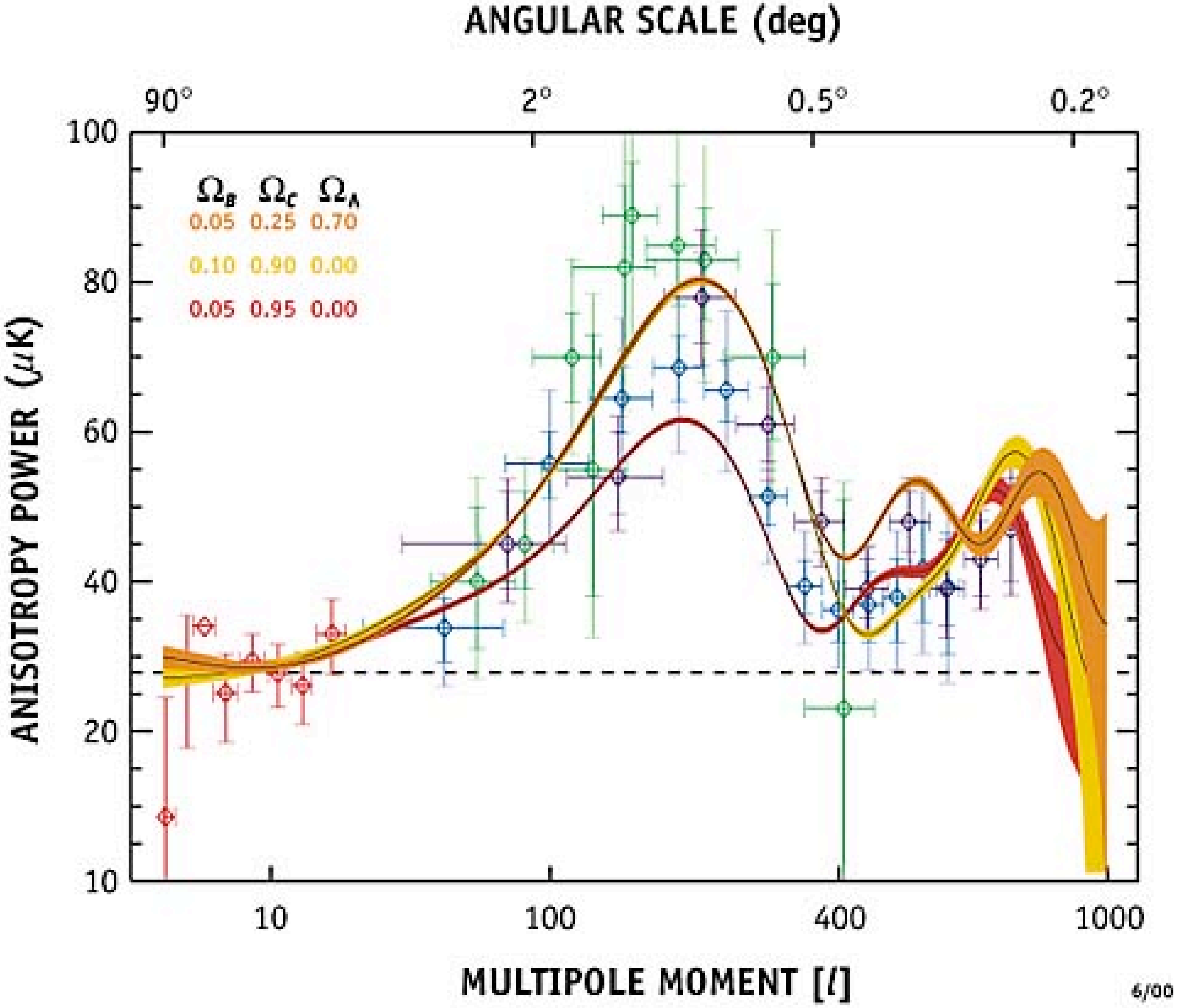
$\Omega_0 h^2 = 0.10$
$l(l+1)C_l$ (Power)
l
0
2
4
6
8
10
500
1000
1500
2000

Many cosmological parameters to measure

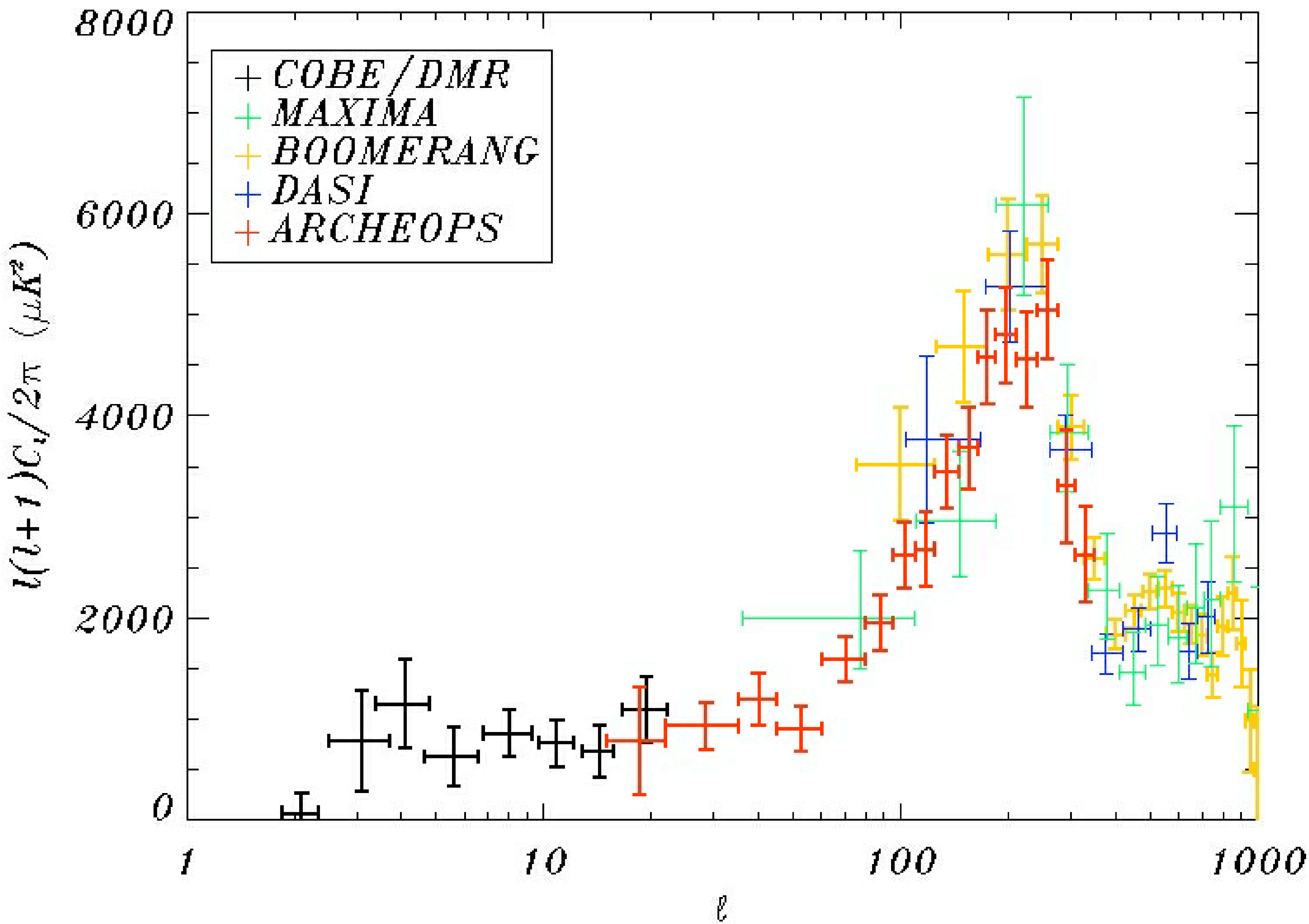
Careful measurements of the power versus angular scales can determine:

the Hubble expansion rate,
the matter density,
the baryon density, and
the vacuum energy density.

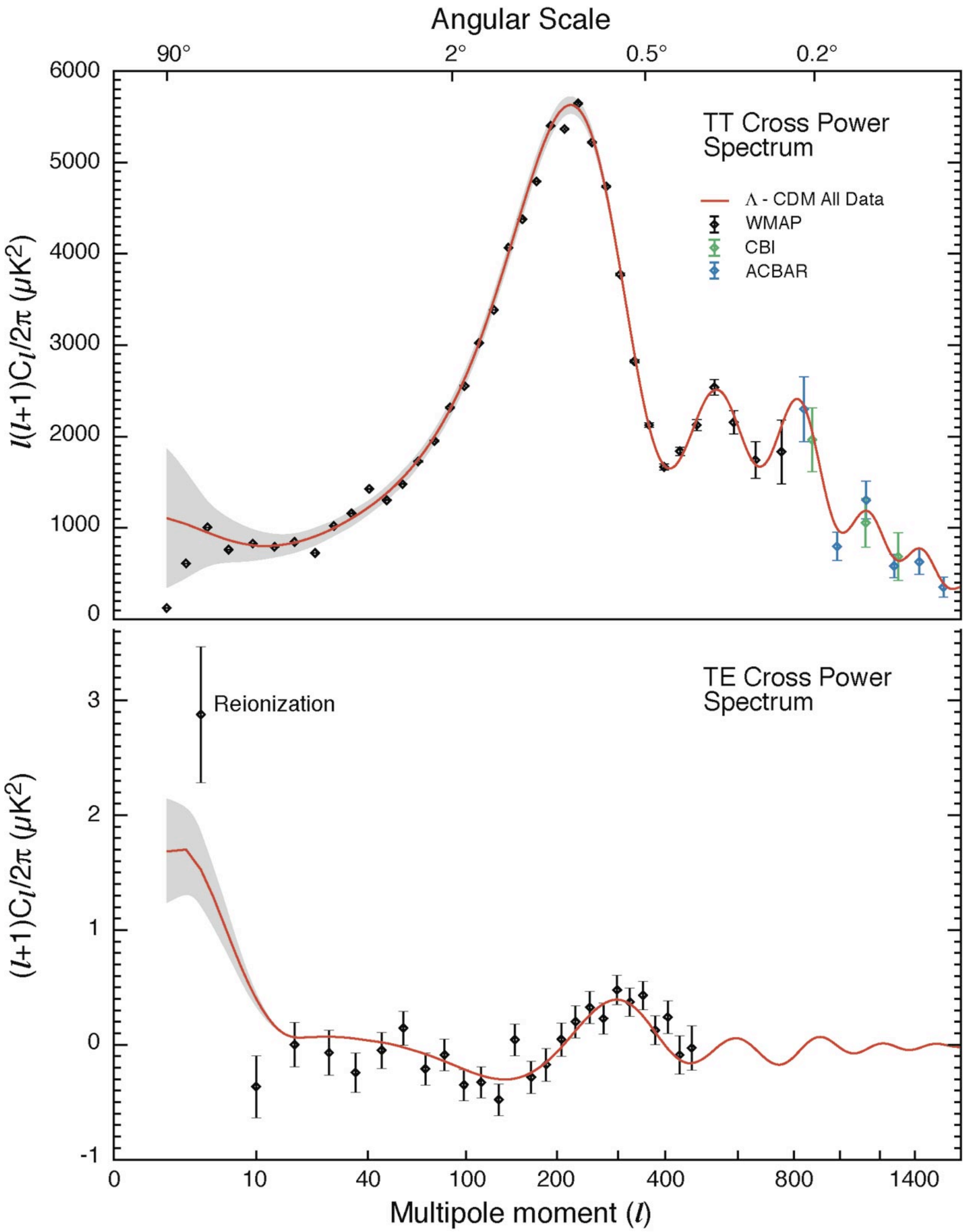



ANGULAR SCALE (deg)
90°
2°
0.5°
0.2°
100
80
60
40
20
10
ANISOTROPY POWER (μK)
Ω_B Ω_C Ω_Λ
0.05 0.25 0.70
0.10 0.90 0.00
0.05 0.95 0.00
10
100
400
1000
MULTIPOLE MOMENT [l]
6/00


MAP
990346



8000
6000
4000
2000
0
1
10
100
1000
ℓ
$l(l+1)C_l/2\pi$ (μK^2)
COBE/DMR
MAXIMA
BOOMERANG
DASI
ARCHEOPS

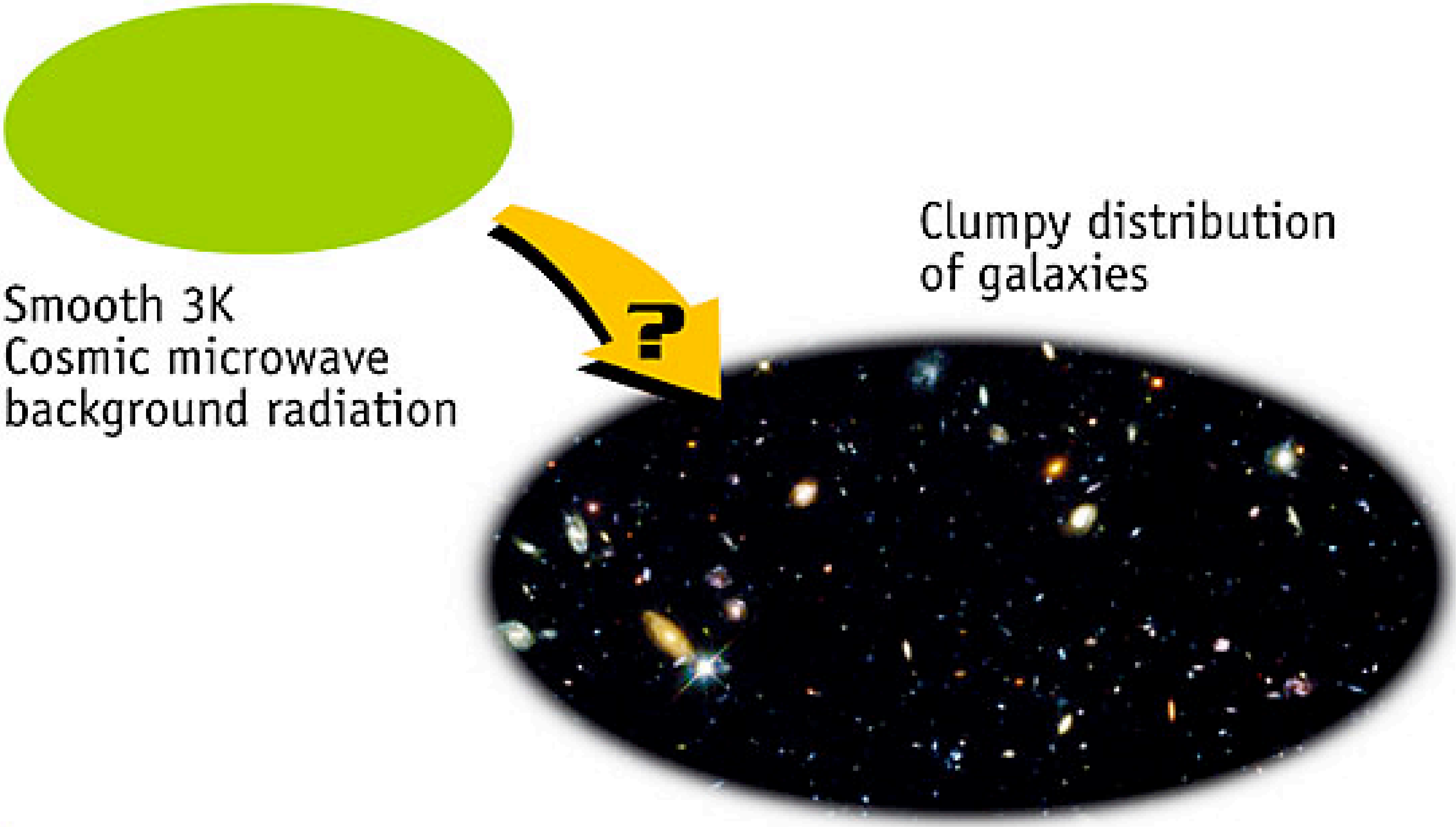


The Sonogram in Numbers: Angular Power Spectrum

Top: Temperature fluctuations vs. angular scale

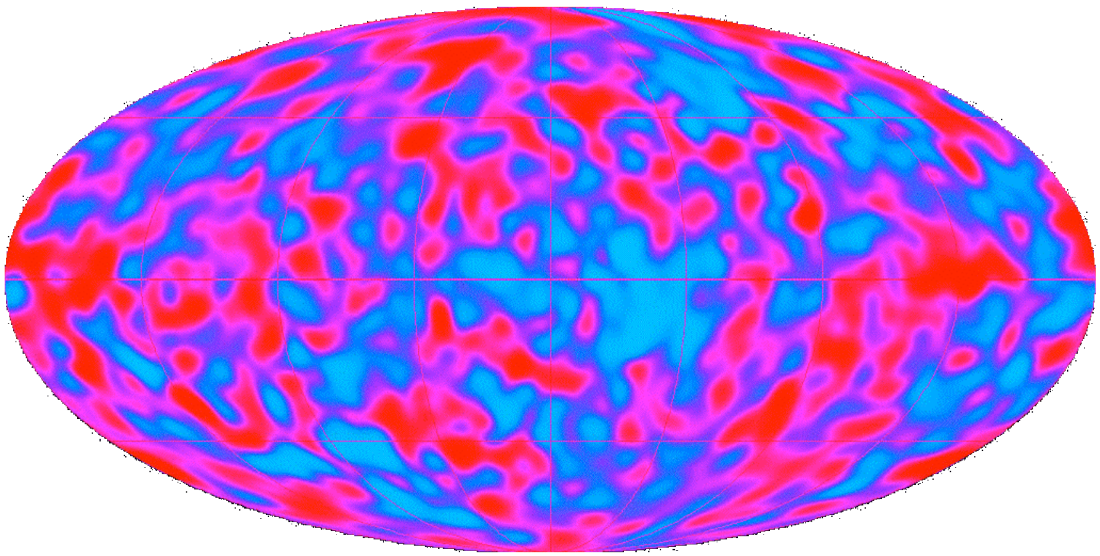
Bottom: Cross-correlation of temperature and linear polarization vs. angular scale

STRUCTURE PROBLEM



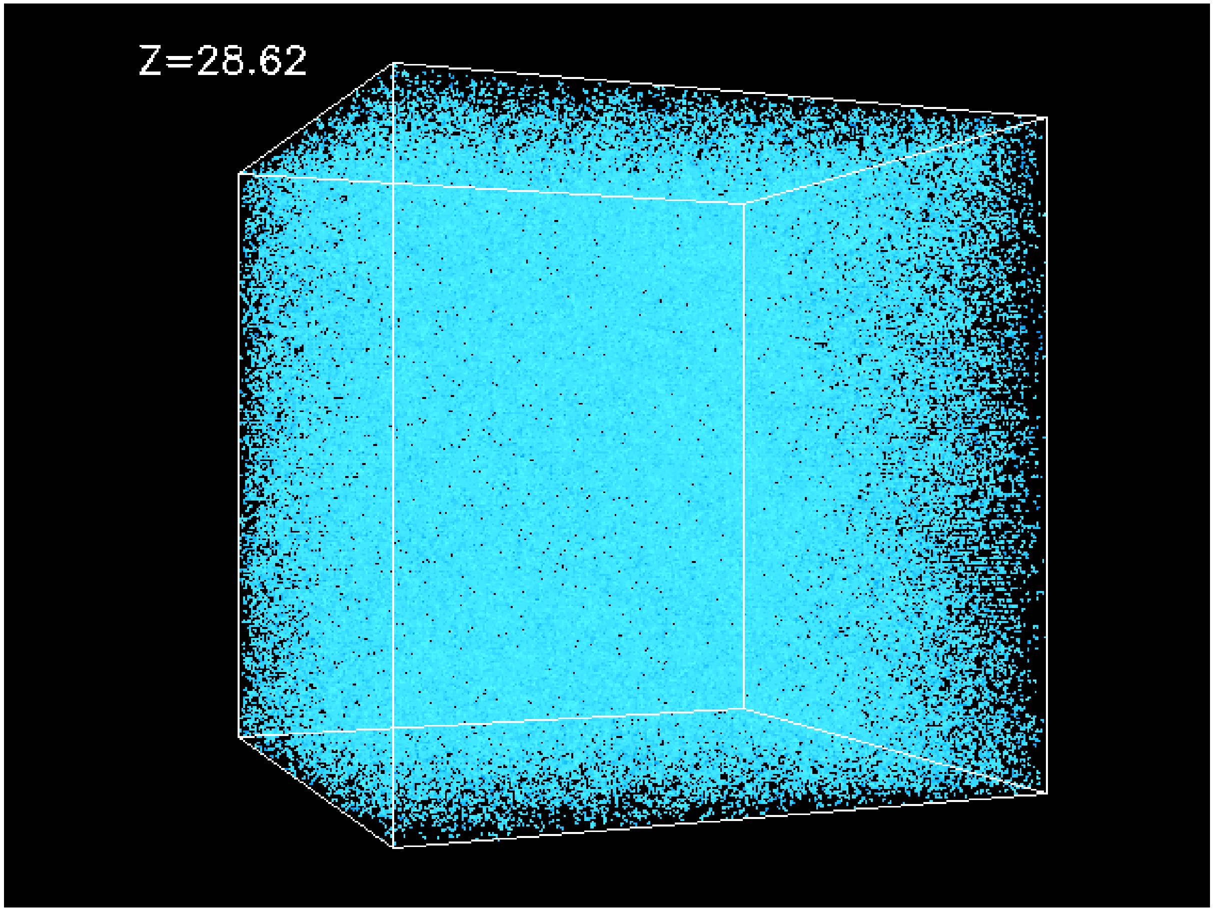
Origin of structure

- These variations in temperature indicate that the density of the early universe was slightly different from place to place - the seeds of structure were indeed present when the microwave background was released.



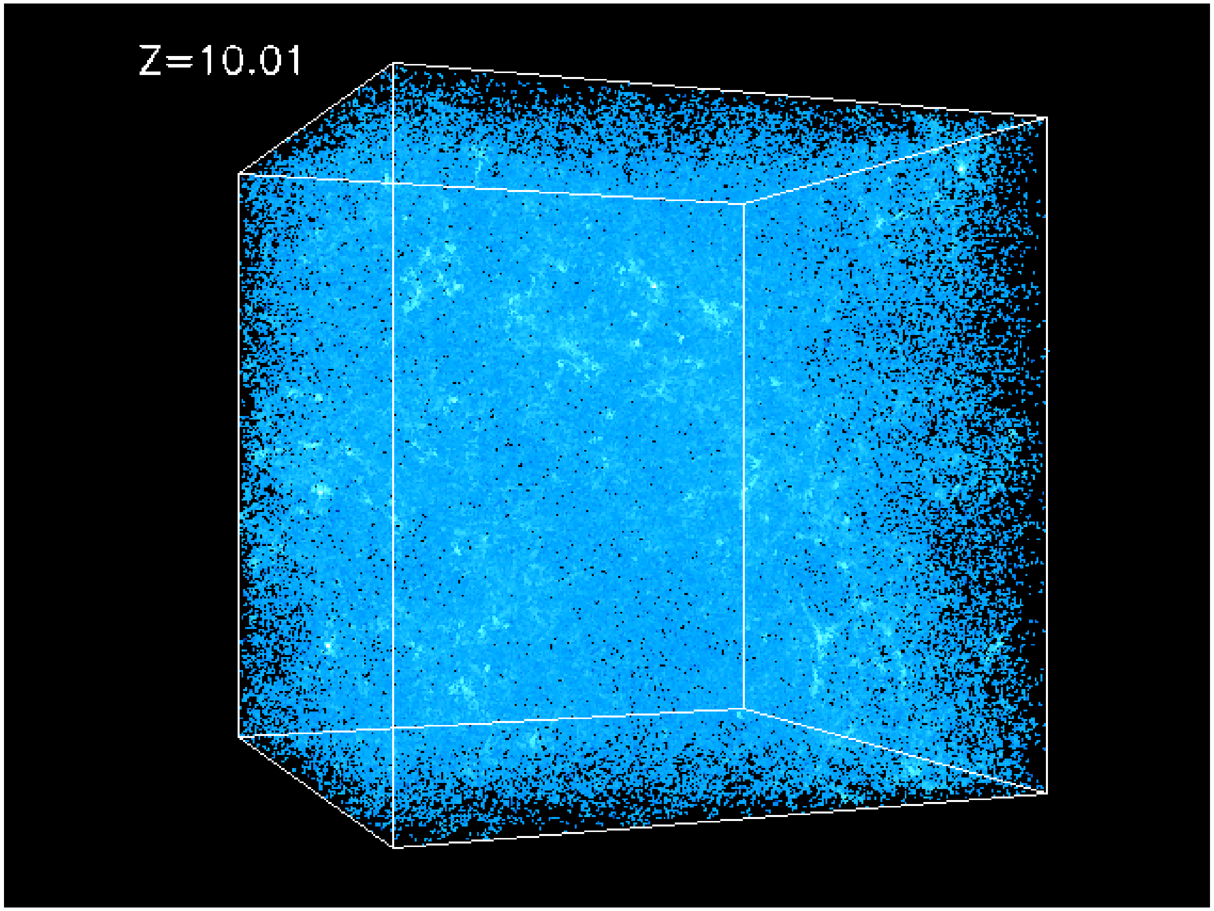
- Galaxies form in the cooler, denser, blue, seed regions.
  Voids form from in hotter, less dense, red, regions.

Galaxy formation



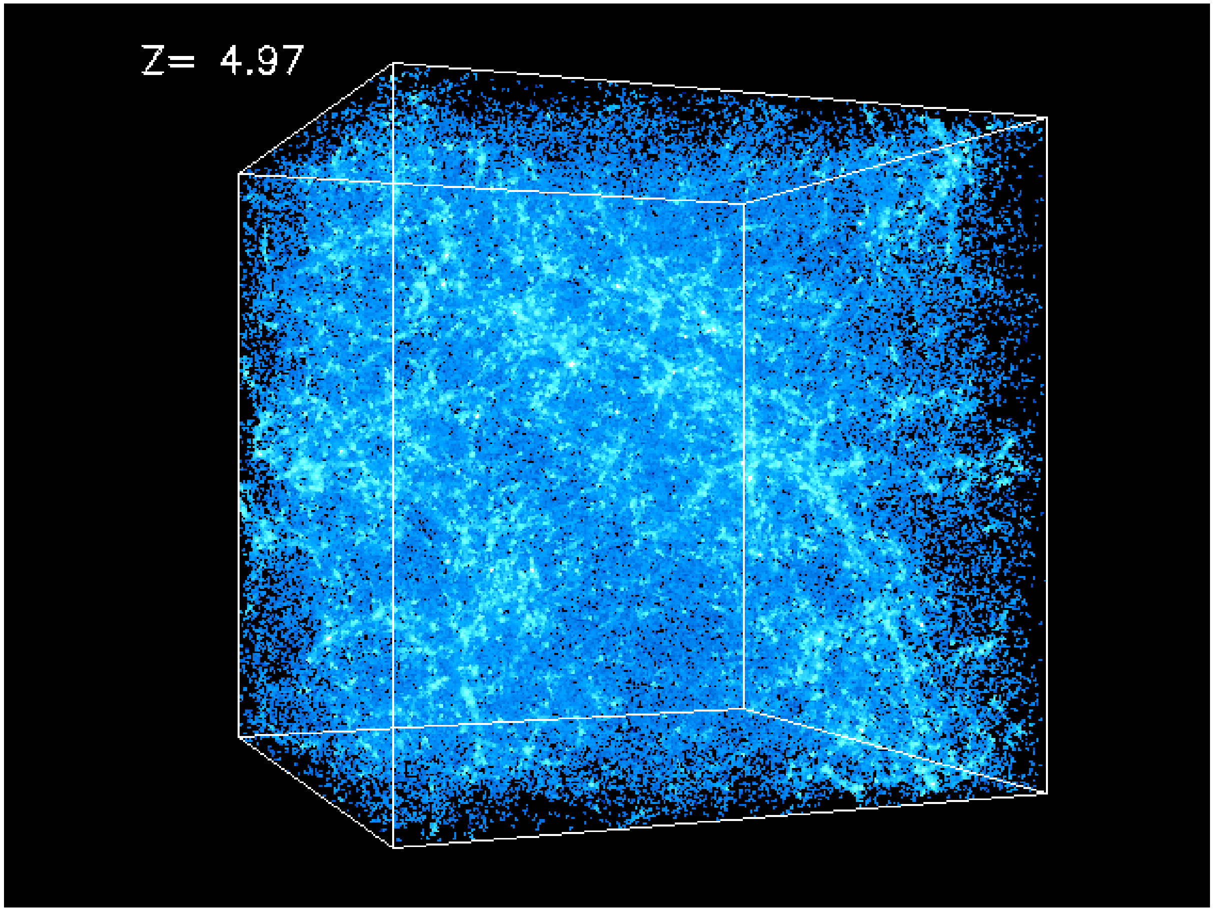
- A box of gas that is uniform to 1 part in 100,000 (the same magnitude as found in the COBE data). We'll let this universe in a box evolve over time.

Galaxy formation

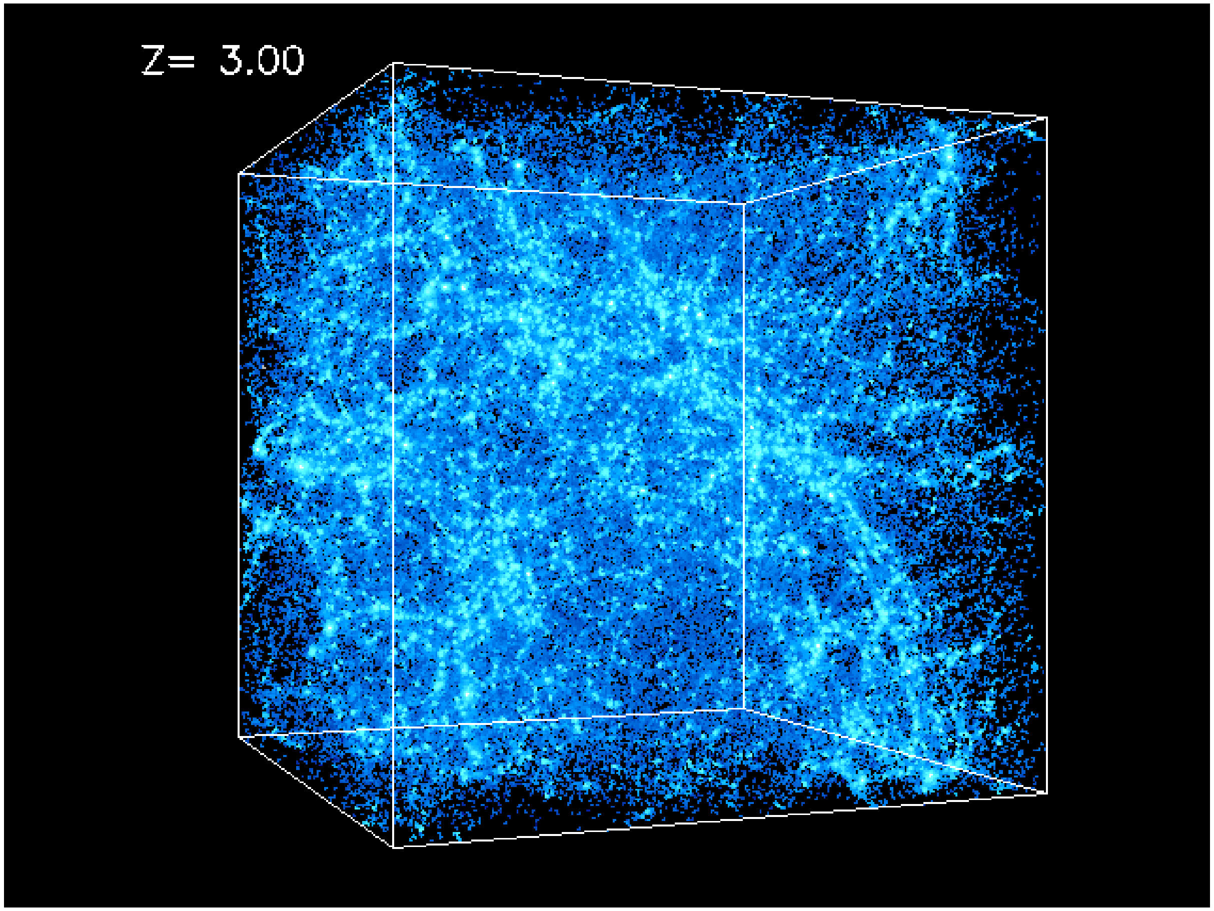


- Gravity starts making the slightly over-dense regions, a little more dense …

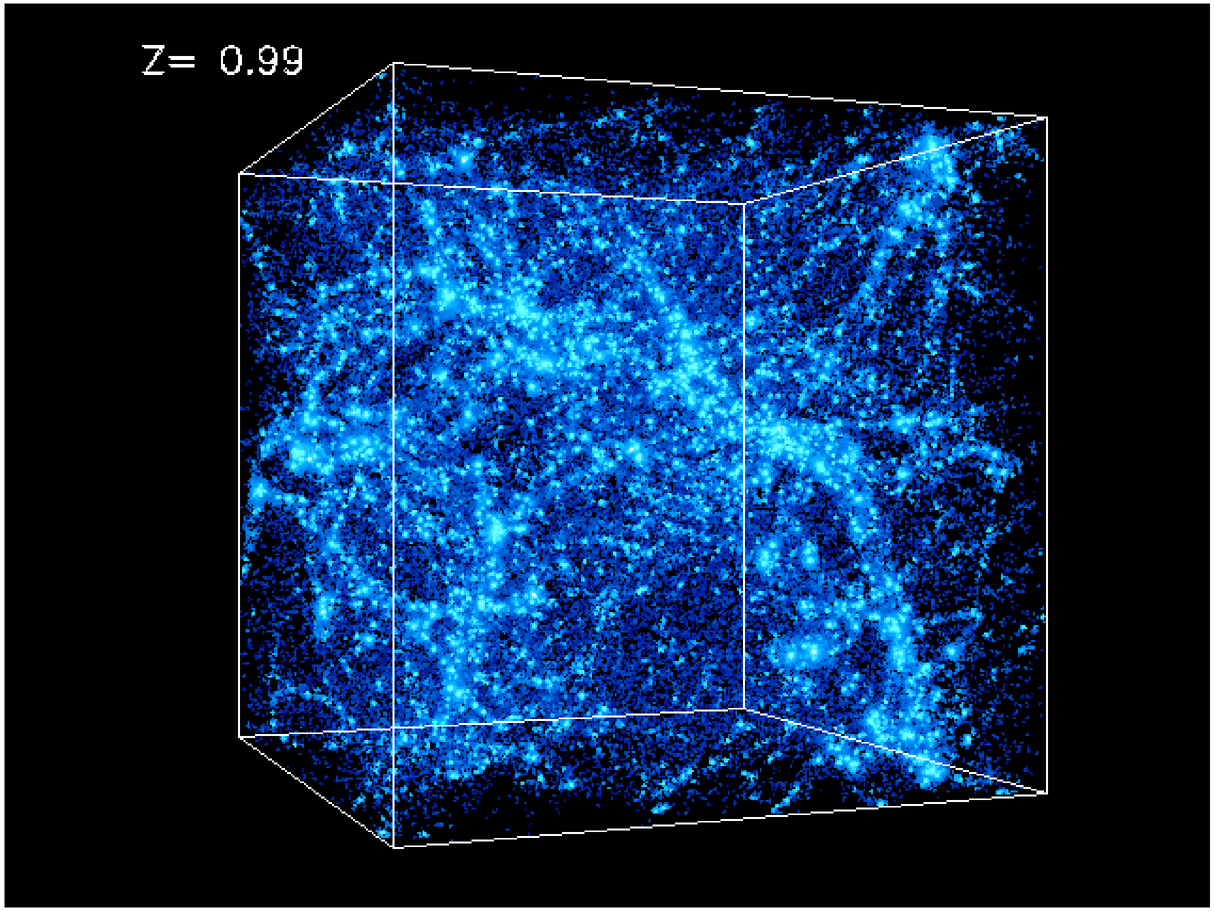
Galaxy formation



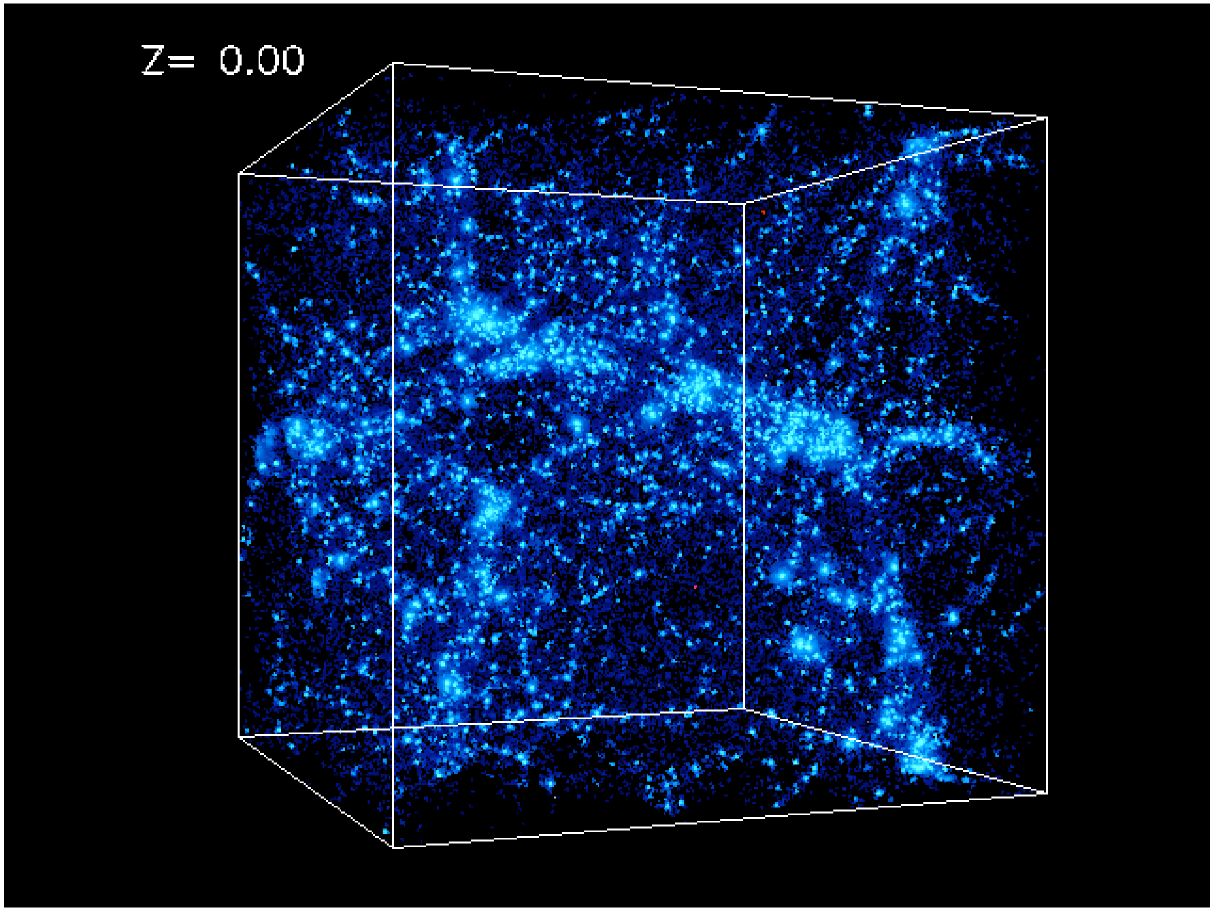
Galaxy formation



Galaxy formation

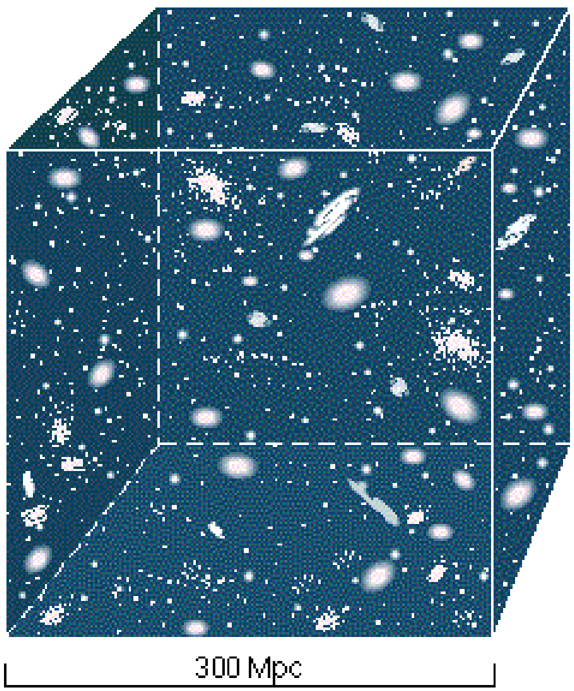


Galaxy formation



- Those 1 part in 100,000 deviations from perfect uniformity allow gravity to form galaxies in the large, lacey, filamentary structures that we see today.

Cosmological Assumptions



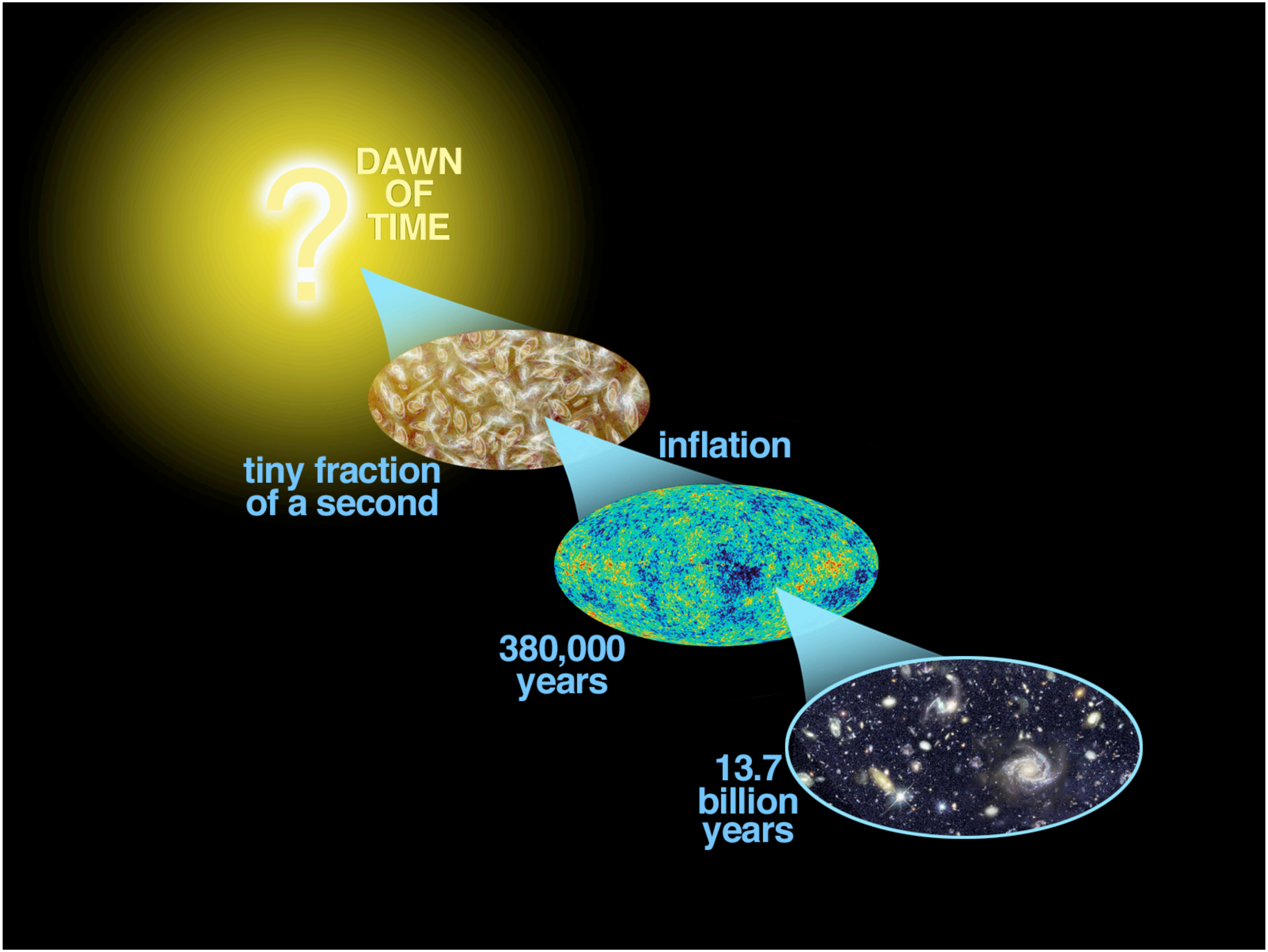
Here is a typical chunk of universe at the current cosmological epoch. It is assumed that all chunks of this size will look and behave the same.

1. Homogeneity
   Matter is distributed evenly throughout the universe on the largest scales (~ 300 Mpc).

2. Isotropy
   The universe looks the same no matter where you are. Again, this is on the largest scales.

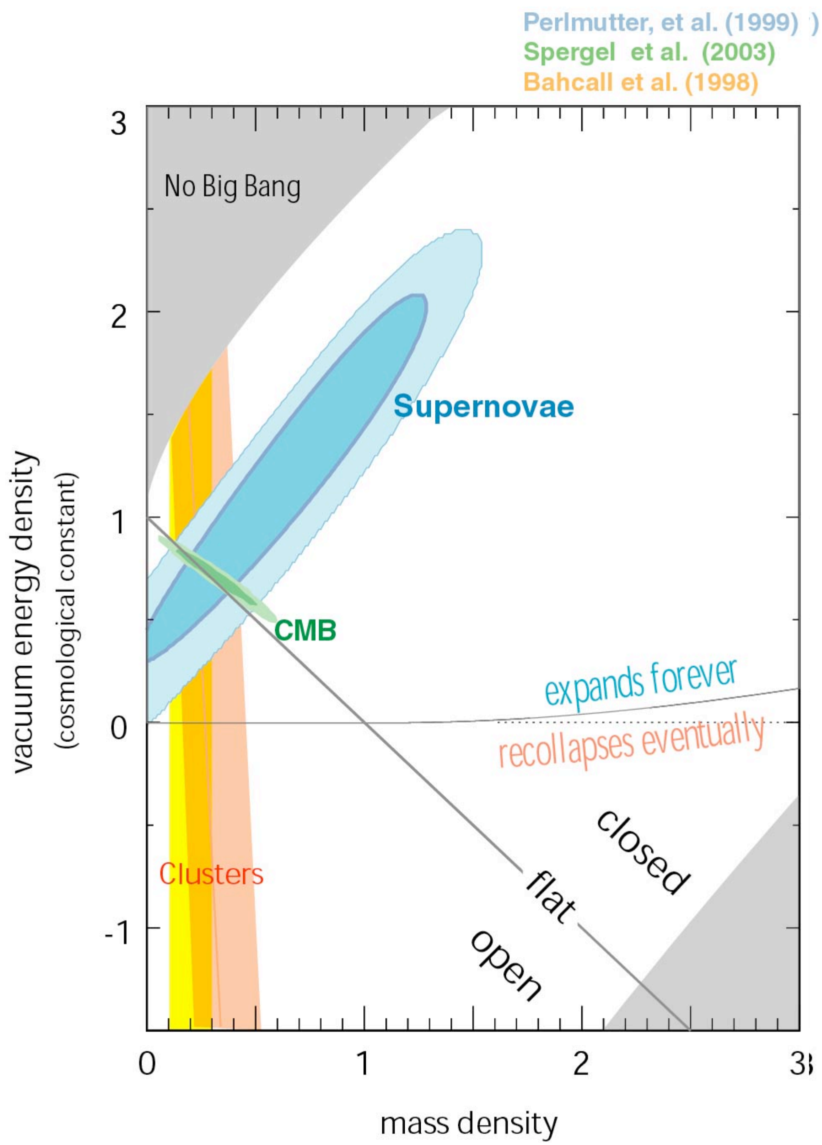
3. Universality
   The laws of physics as measured on Earth are everywhere the same. This also implies that these laws do not change with time.

4. Cosmological Principle
   A result of accepting both the homogeneity and (especially) the isotropy of the universe. This principle states that any observer in a any galaxy will see the same features of the universe. Since the universe changes with time, this principle applies only for observers living during the same cosmic epoch.



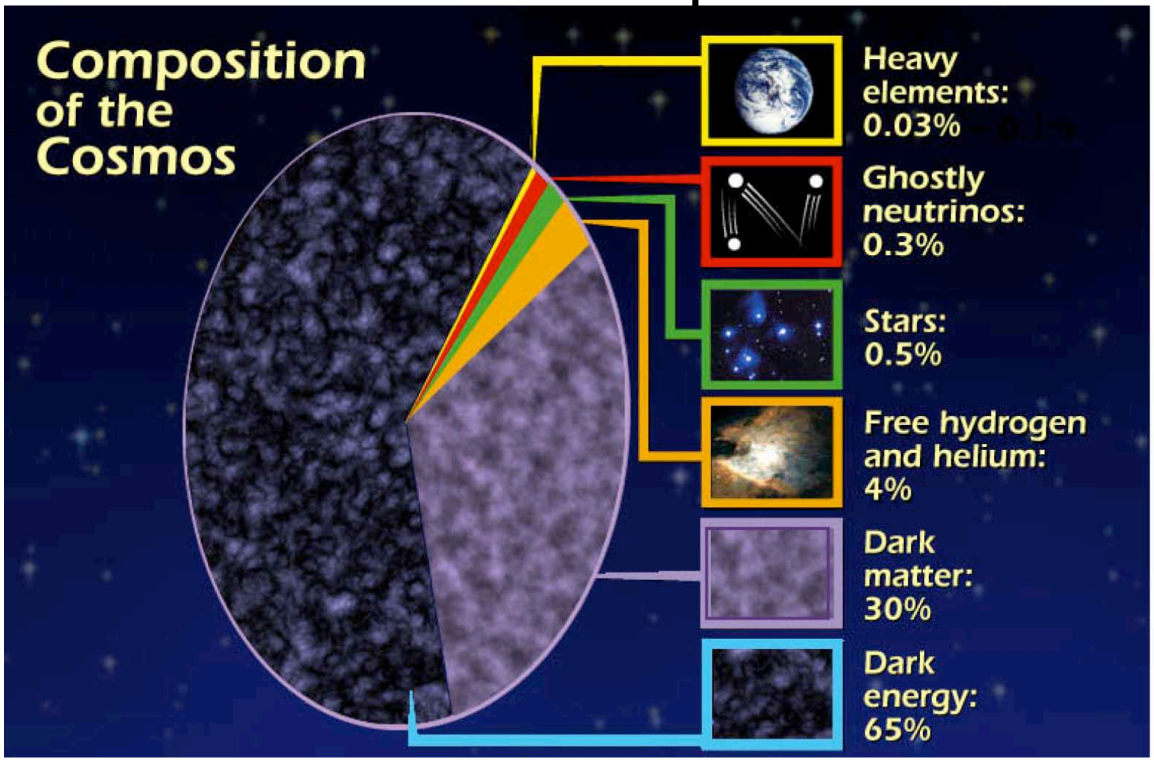
DAWN
OF
TIME
inflation
tiny fraction
of a second
380,000
years
13.7
billion
years

Cosmic Concordance

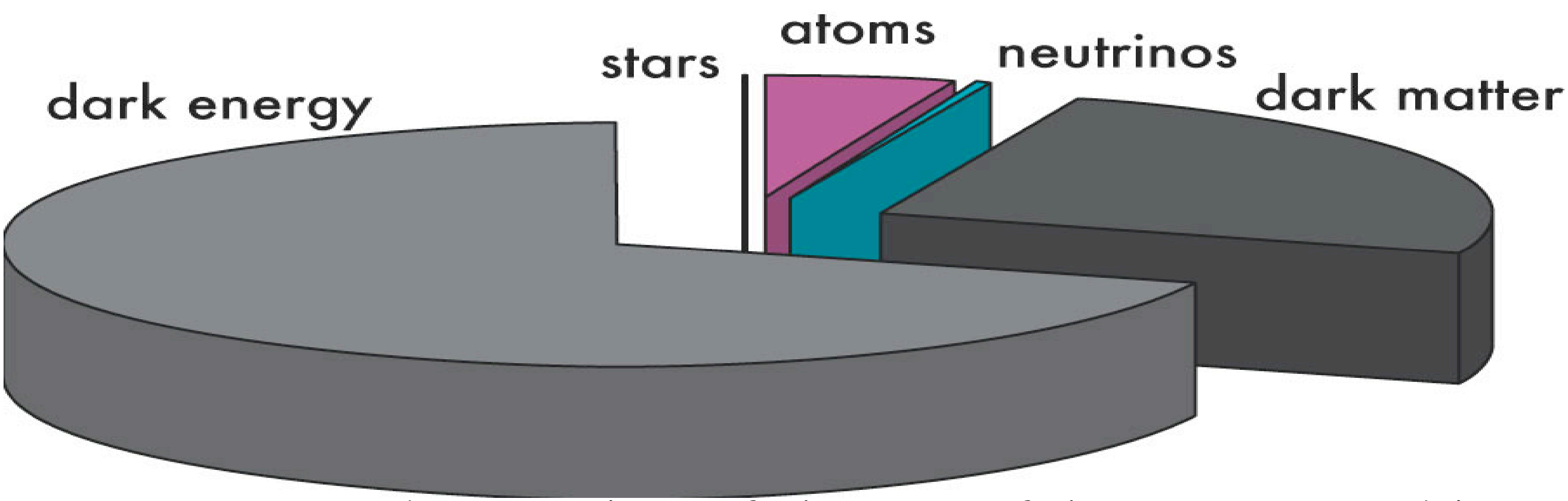


- *Supernovae alone*
  - □ **Accelerating expansion**
  - □ **□ > 0**
- *CMB alone*
  - □ **Flat universe**
  - □ **□ > 0**
- *Any two of SN, CMB, LSS*
  - □ **Dark energy ~70%**

Composition of the Cosmos



This diagram shows the ingredients that make up the universe. Astronomers now realize that the universe's main ingredient is "dark energy," a mysterious form of energy that exists between galaxies. The next largest constituent is dark matter, which is an unknown form of matter. The rest of the universe consists of ordinary matter. Most of it is locked up in stars and clouds of gas. A tiny fraction of this matter is composed of heavier elements, the stuff of which humans and planets are made.



- We do not yet know of what most of the universe is made!

Summary Conclusions

- It is very exciting times!
- We have a model of cosmology, that can be well tested and vetted by observations.
- That model gives us a description of the creation and development of the Universe.
- We can predict the Universe statistically to good accuracy.
- This is a tremendous intellectual achievement.