Introduction to Cosmology

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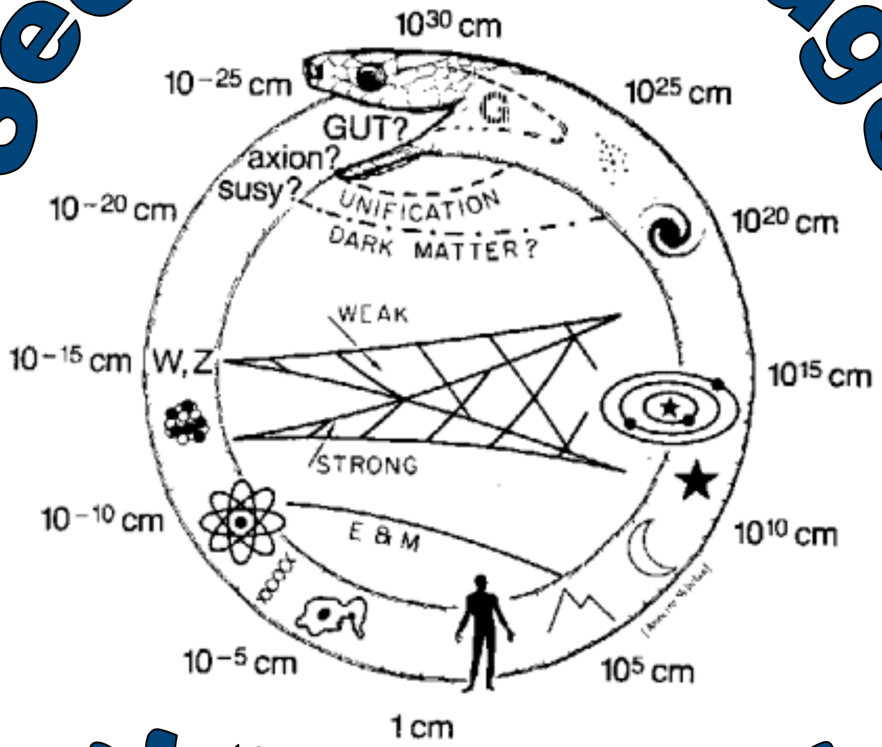
CERN Summer training Programme, 22-28 July 2008

- **Seeing the edge of the Universe:** From speculation to science
- **Constructing the Universe:** Relativistic world models
- **The history of the Universe:** Decoupling of the relic radiation and nucleosynthesis of the light elements
- **The content of the Universe:** Dark matter & dark energy
- **Making sense of the Universe:** Fundamental physics & cosmology

http://www-thphys.physics.ox.ac.uk/user/SubirSarkar/cernlectures.html

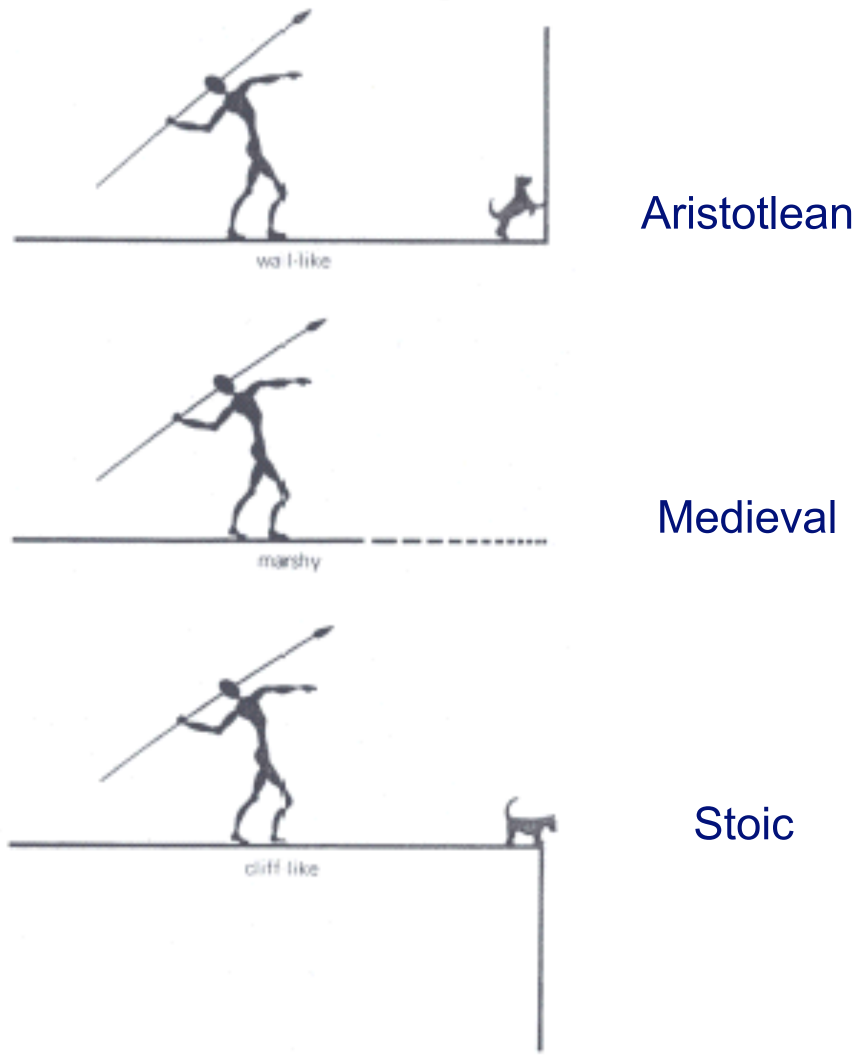
Lecture 1

Seeing the edge of the universe



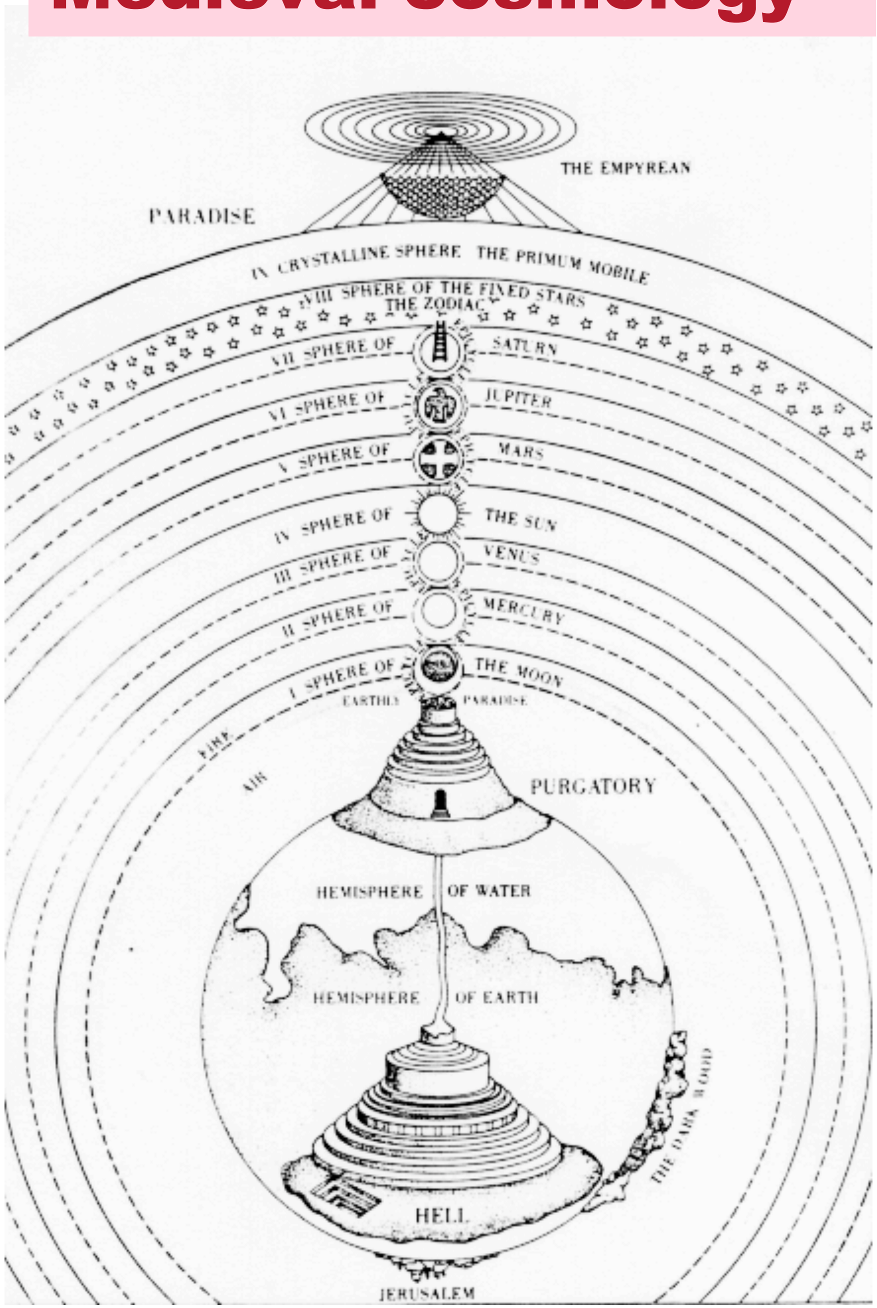
from speculation to science

Is there an edge to the universe …
What happens when a spear is thrown across it?



Archytas of Tarentum (5th Century BC)

Medieval cosmology



"The Divine Comedy", Dante Aligheri (1321)

The belief was that space is finite with an *edge*

Immanuel Kant's 'Antimony of space': *Space has to be finite in extent and homogeneous in composition, and to obey the laws of Euclidean geometry*

… but all three assumptions cannot be true at once!

The infinite universe

Thomas Digges (1576)

"I could be bounded in a nutshell and count myself a king of infinite space"
***"Hamlet"*, William Shakespeare (1601)**

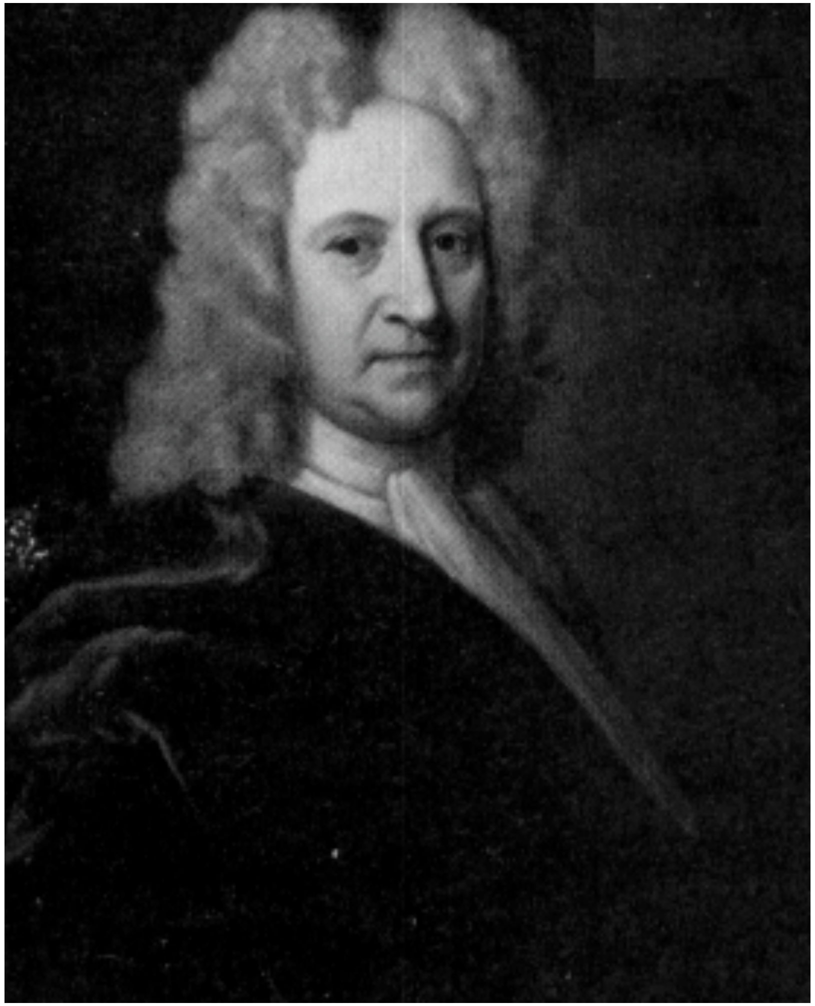
"If this is true and if they are suns having the same nature as our Sun, why do these suns not collectively outshine our Sun in brilliance?

… you do not hesitate to declare that there are over 10,000 stars. The more there are and the more crowded they are, the stronger becomes my argument against the infinity of the universe.

This world of ours does not belong to an undifferentiated swarm of countless others ... Otherwise the whole celestial vault would be as luminous as the Sun!"

"Conversations with the Starry Messenger"

Johannes Kepler (1601)

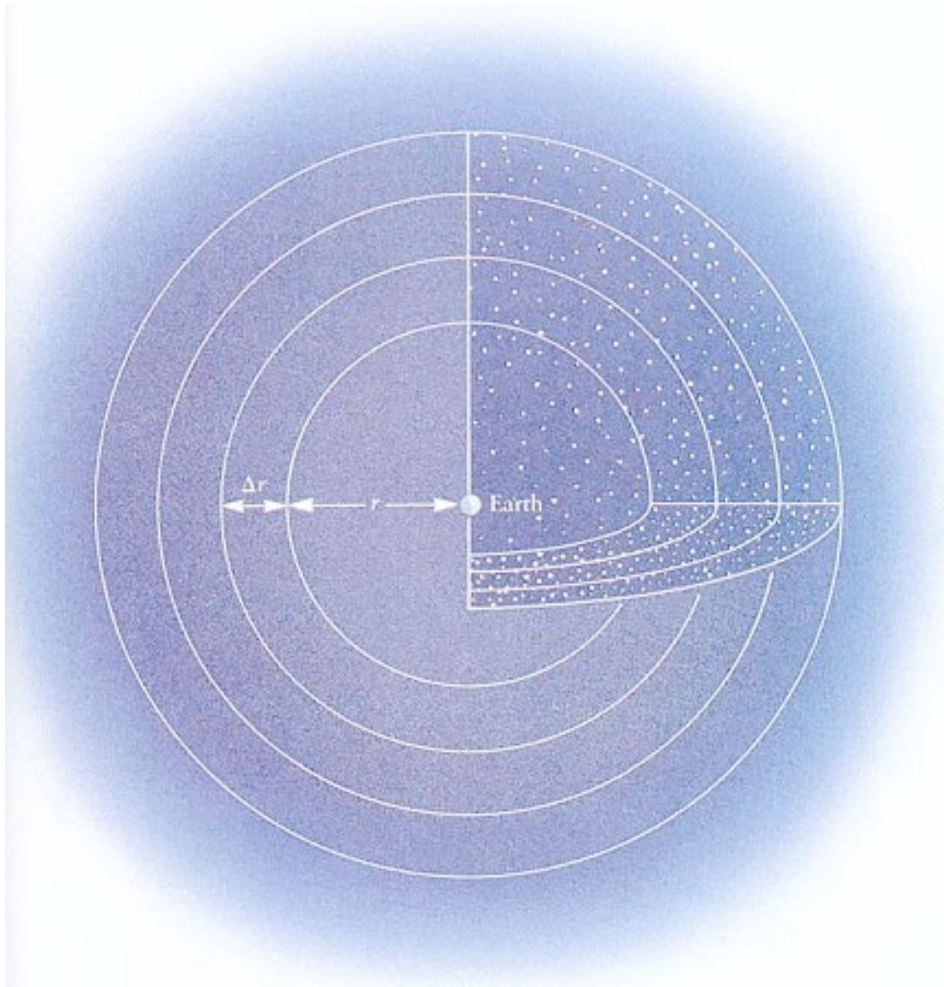


"… the more remote stars and those far short of the remotest vanish even in the nicest telescopes, by reason of their extreme minuteness; so that tho' it were true, that some such stars are in such a place, yet their Beams, aided by any help yet known, are not sufficient to move our sense; after the same manner as a small Telescopical fixt star is by no means perceivable to the naked eye"

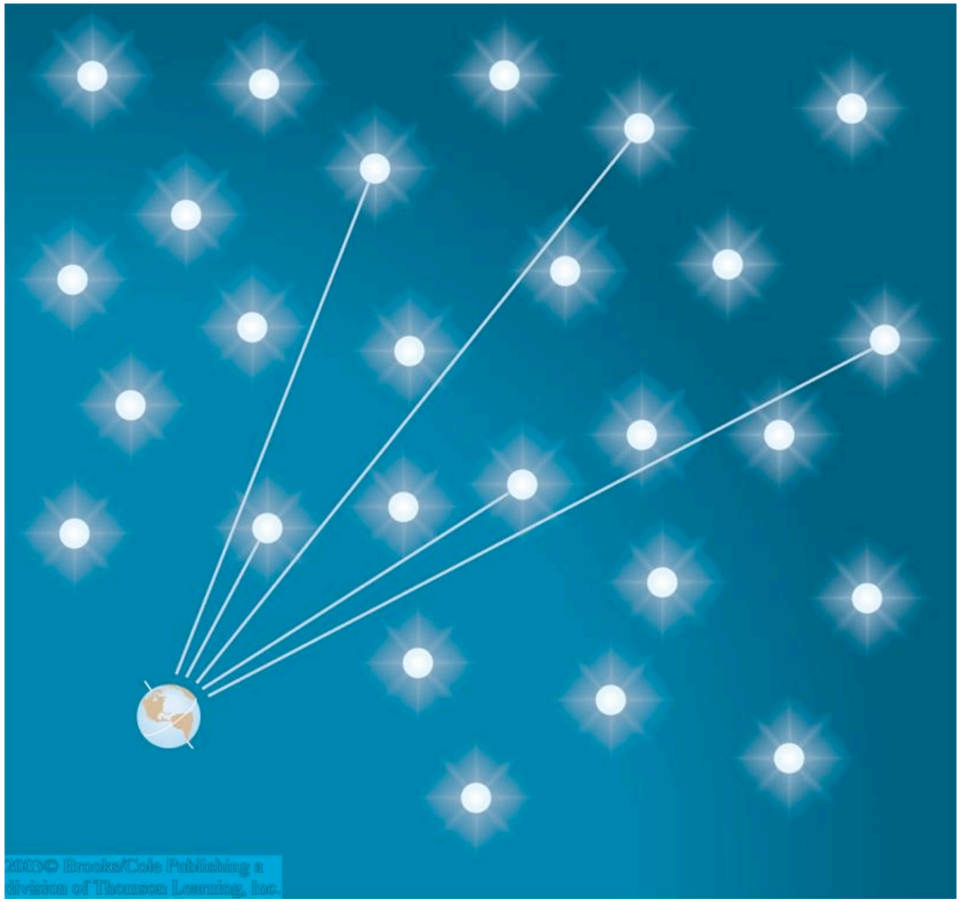
Edmund Halley (1720)

Clearly he had not appreciated his friend Isaac Newton's newly invented calculus - distant stars do shrink in size ($\propto 1/r^2$) but their number grows ($\propto r^2$) to compensate!

$$
\begin{aligned}
B_{\text{shell}} = B_{\text{star}} \times \text{Number of stars in shell} \\
= \frac{L_{\text{star}}}{4\pi r^2} \times 4\pi r^2 \Delta r \times N \\
= L_{\text{star}} \Delta r N
\end{aligned}
$$



So each shell of stars is *equally* bright …
thus adding up all the shells from zero to infinity would yield an infinitely bright sky!



However the distant stars are obscured by foreground ones, so the expectation would be *a sky totally covered by stars*

i.e. 10^{10} times brighter than reality!

Why is the sky dark at night?

… later named "Olbers' Paradox"

"The enormous difference which we find between this conclusion and actual experience shows either that the sphere of the fixed stars is not infinite but that it is actually much smaller than the finite extent I have supposed for it, or that the power of light diminishes in greater proportion than the inverse square of the distances …

This latter supposition is plausible enough, it requires only that the heavens are filled with some fluid capable of intercepting light, however slightly …"

Jean-Phillipe Loys de Cheseaux (1744)

But **Lord Kelvin** showed (later) that this would not solve the problem … the fluid would ultimately heat up and reradiate the light it absorbed

How far do we have to look to see the 'wall of stars'?

A star of radius R at distance r covers the fraction $\pi R^2/4\pi r^2$ of the sky. Multiplying by the number of stars in the shell between r and $r + \mathrm{d}r$ we see that a fraction $\pi R^2 n \mathrm{d}r$ is luminous. Thus the entire sky would be covered with stars at a distance ℓ such that $\int_0^\ell \pi R^2 n \mathrm{d}r = 4\pi$, i.e.

$$\ell = \frac{1}{\pi R^2 n} . \tag{1}$$

The integrated flux from these stars (of average luminosity L) would be

$$B = \int_0^\ell n L \mathrm{d}r = \frac{L}{\pi R^2} , \tag{2}$$

Note that ℓ is also the typical distance a photon travels before encountering another star. Since the encounters are random and occur at a rate ℓ^{-1} per unit distance, the probability that the distance to the first collision is r is

$$P(r) = \frac{1}{\ell} \exp\left(-\frac{r}{l}\right) . \tag{3}$$

Considering the photons emitted in a spherical shell of thickness $\mathrm{d}r$ and integrating upto a distance $r_\star$, the likelihood that a photon emitted towards the observer will arrive there is

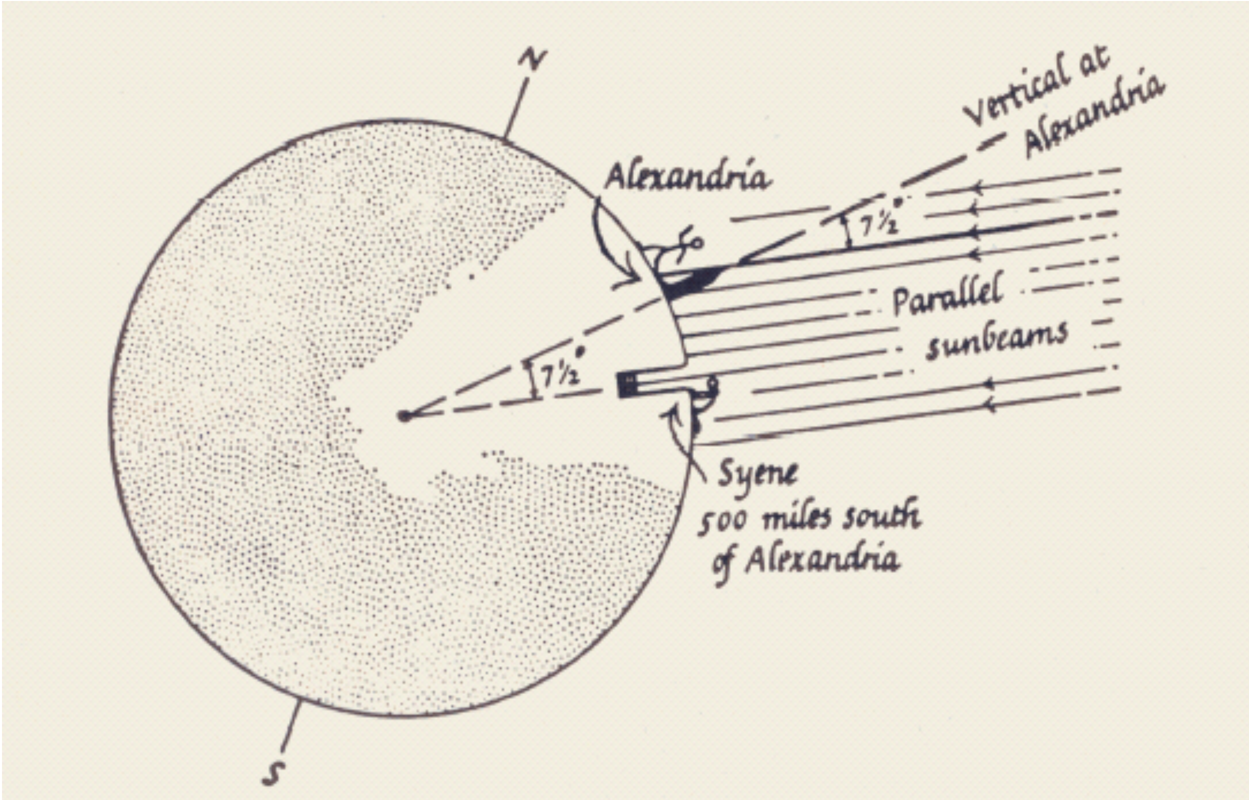
$$f(r_\star) = \int_0^{r_\star} \frac{1}{\ell} \exp\left(-\frac{r}{l}\right) \mathrm{d}r = 1 - \exp\left(-\frac{r_\star}{\ell}\right) . \tag{4}$$

This fraction approaches unity only if the universe is spatially much bigger than ℓ.

… to calculate l we need to know how big stars are and how far apart they are

Measuring the universe: Step 1- the size of the Earth

Eratosthenes (235 BC)



At noon on mid-summers day (22 June), the Sun is vertically overhead at Aswan
… but at Alexandria (~800 km due North) it casts a shadow, being 7.5^0 to the vertical

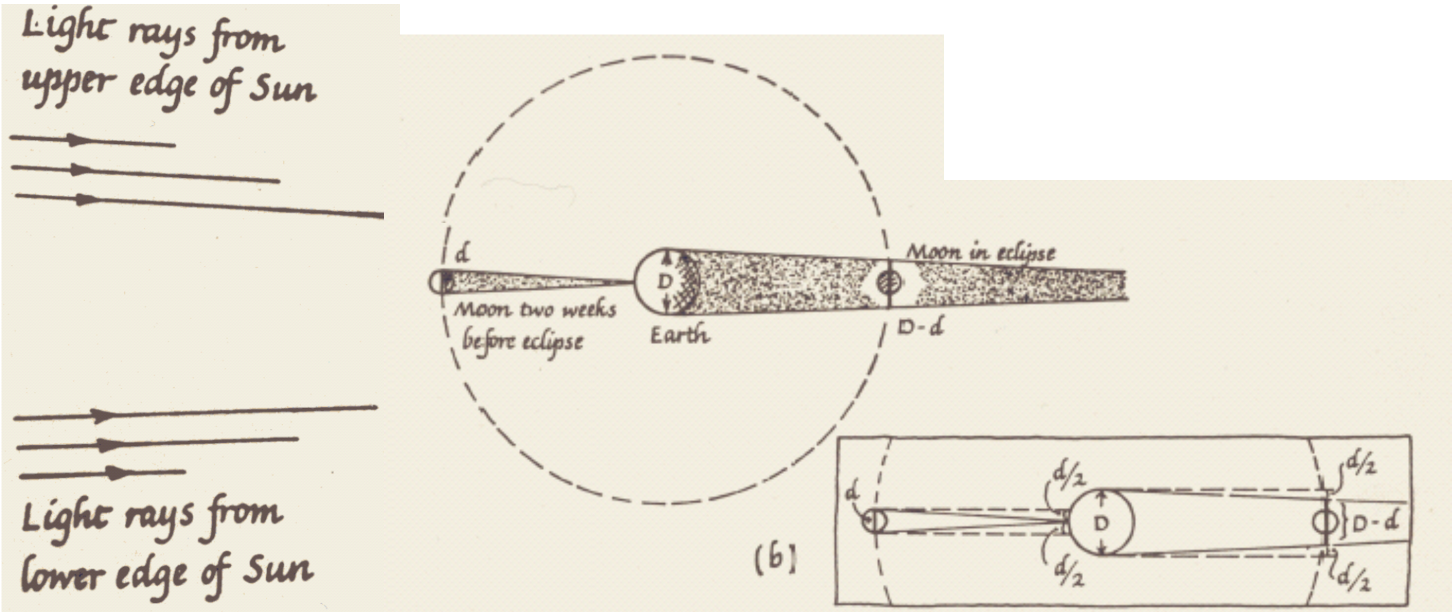
→ if 7.5^0 corresponds to 800 km (5000 "stadia"), then 360^0 corresponds to ~40000 km
i.e. Earth's radius is ~6000 km (knowing the value of $\pi \approx 3.1$)

Measuring the universe: Step 2 - the distance to the Moon

Aristarchus (230 BC)

The Moon subtends ~0.5^0 on the sky so its distance must be ~110 times its diameter →
(hold a coin at arm's length to cover the Moon – measure its distance and diameter)

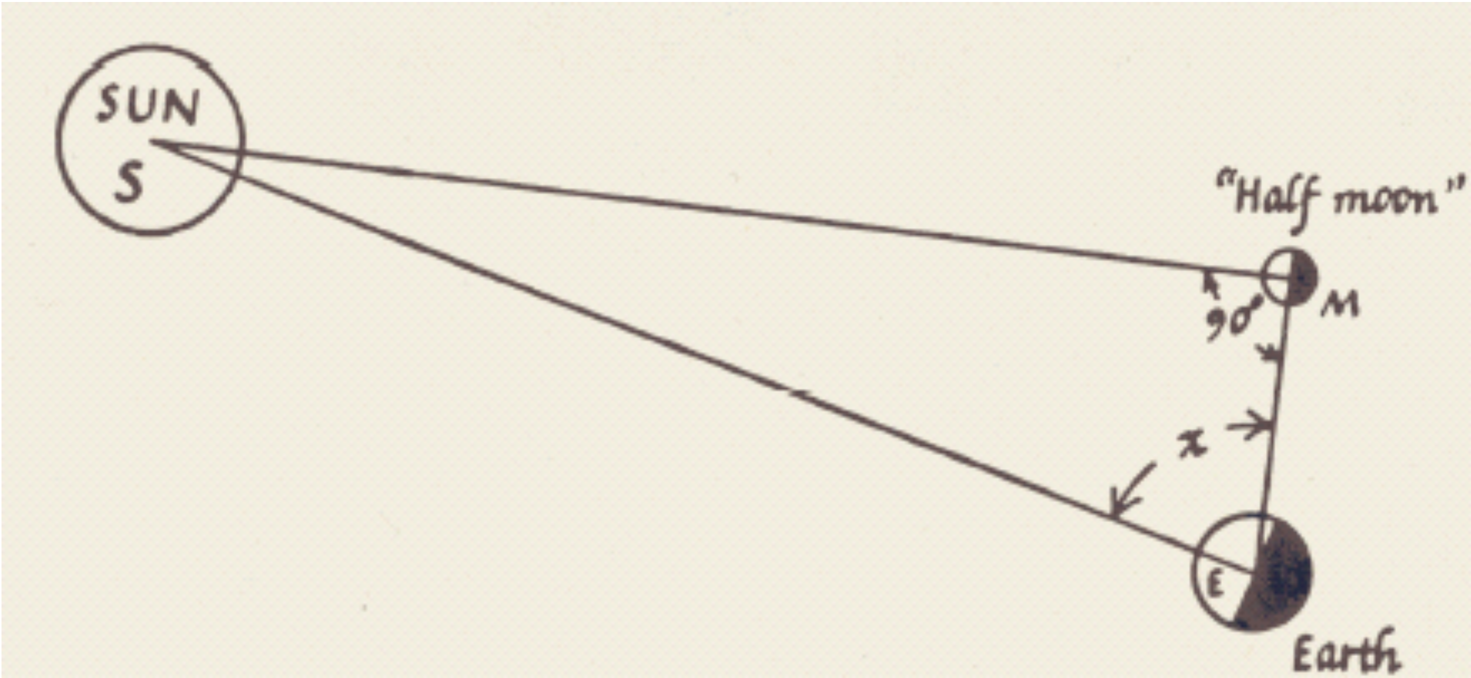
The absolute value can be obtained by careful observation of lunar eclipses …



By triangulation: Earth's diameter – Moon's diameter = 2.7 x Moon's diameter
⇒ **Moon's distance = 110 x Moon's diameter = 30 x Earth's diameter ≈ 400,000 km**

Measuring the universe: Step 3 - the distance to the Sun

Aristarchus (230 BC)



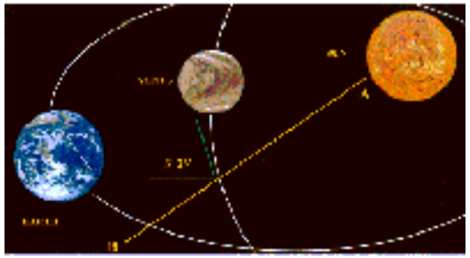
When the Moon is exactly half-full, light from the Sun must be falling on it exactly at right angles → so measure the angle S-E-M

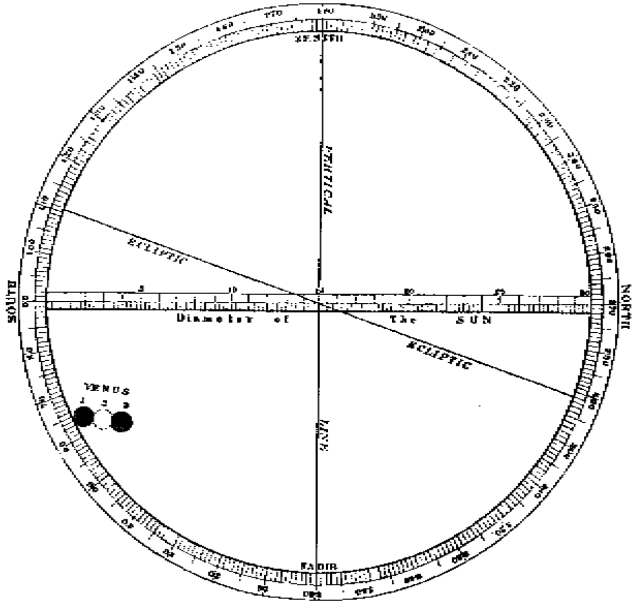
Aristarchus' guess was 87^0 so he deduced that the Sun is 20 times further than the Moon … in fact this angle is $89^0 50'$ so the Sun is actually 400 times further than the Moon

The advent of precision astronomy
(“big science”)

Tycho Brahe (1582) and his great quadrant at Uraniborg
… could measure angles as small as $30''$

An attempt to measure the distance to the Sun was first made by **Jeremiah Horrocks** during the "Transit of Venus" 24th Nov 1639



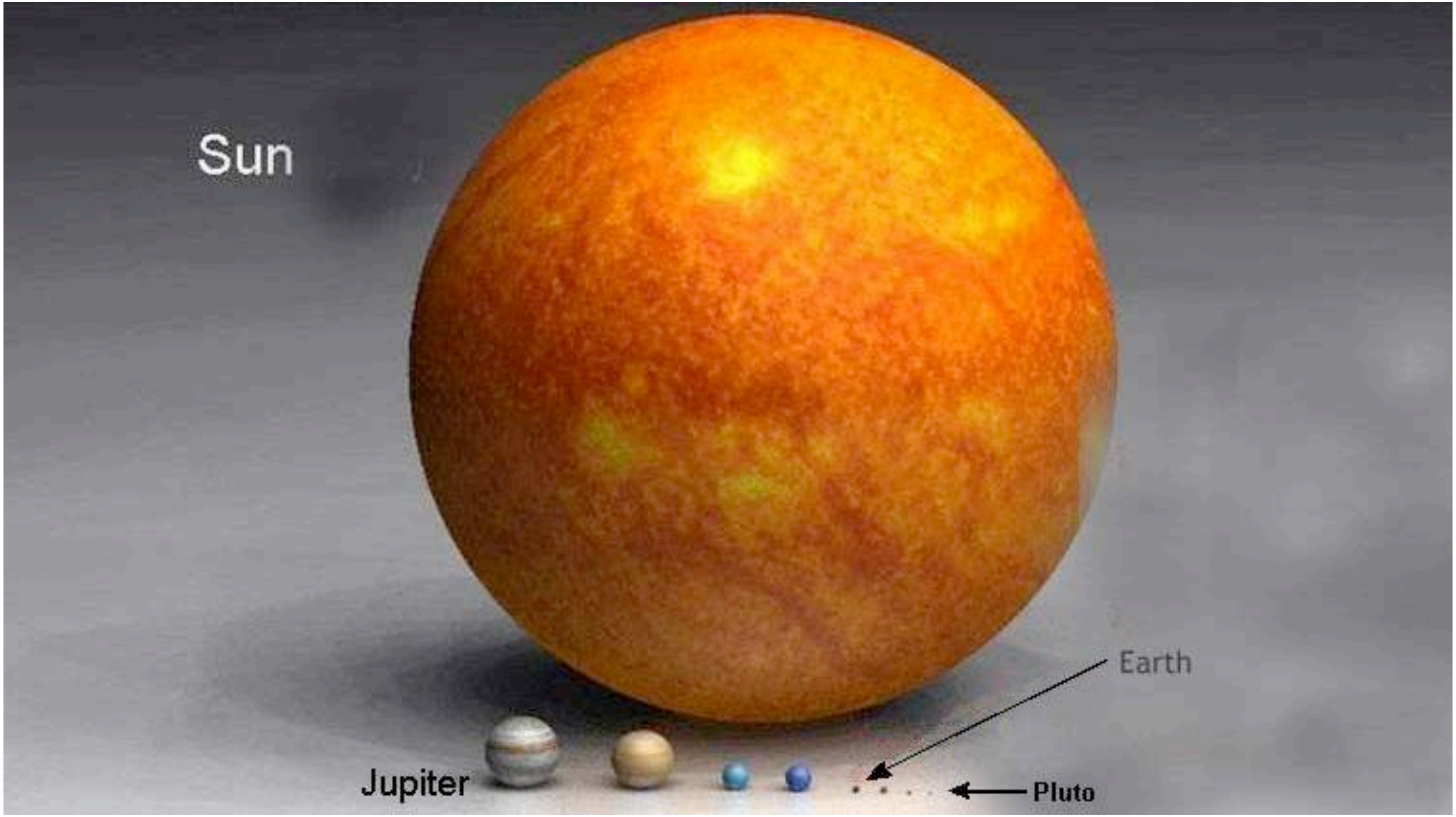


The Sun's disc is ~33 times bigger than Venus but Venus is ~3.4 times closer than the Sun* hence the Sun is 112 times bigger than Venus

Assuming Venus is the same size as the Earth (fortuitously true!)
the Sun's distance ≈ 110 x 112 x Earth's diameter ~ 150 million km

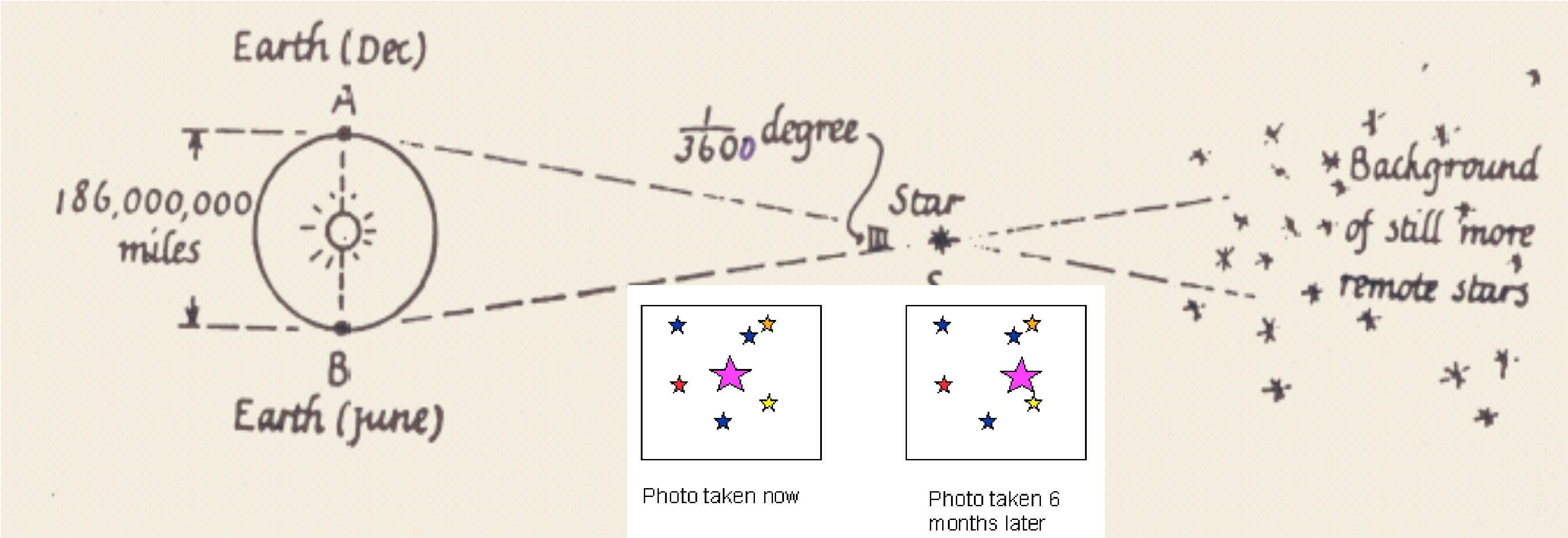
**The maximum angle between Venus and the Sun is 45^0 so the distance ratio (Sun-Venus)/(Sun-Earth) ≈ $1/\sqrt{2}$ assuming Earth and Venus move on circular orbits*

The Sun also subtends ~0.5^0 on the sky, so its diameter is 1/110 times the Sun-Earth distance, i.e. ~1.5 million km



It is convenient to measure such huge scales in terms of the light travel time e.g. the Sun is ~5 light-seconds across and ~8.5 light-minutes away

Measuring the universe: **Step 4 - the distance to the stars**



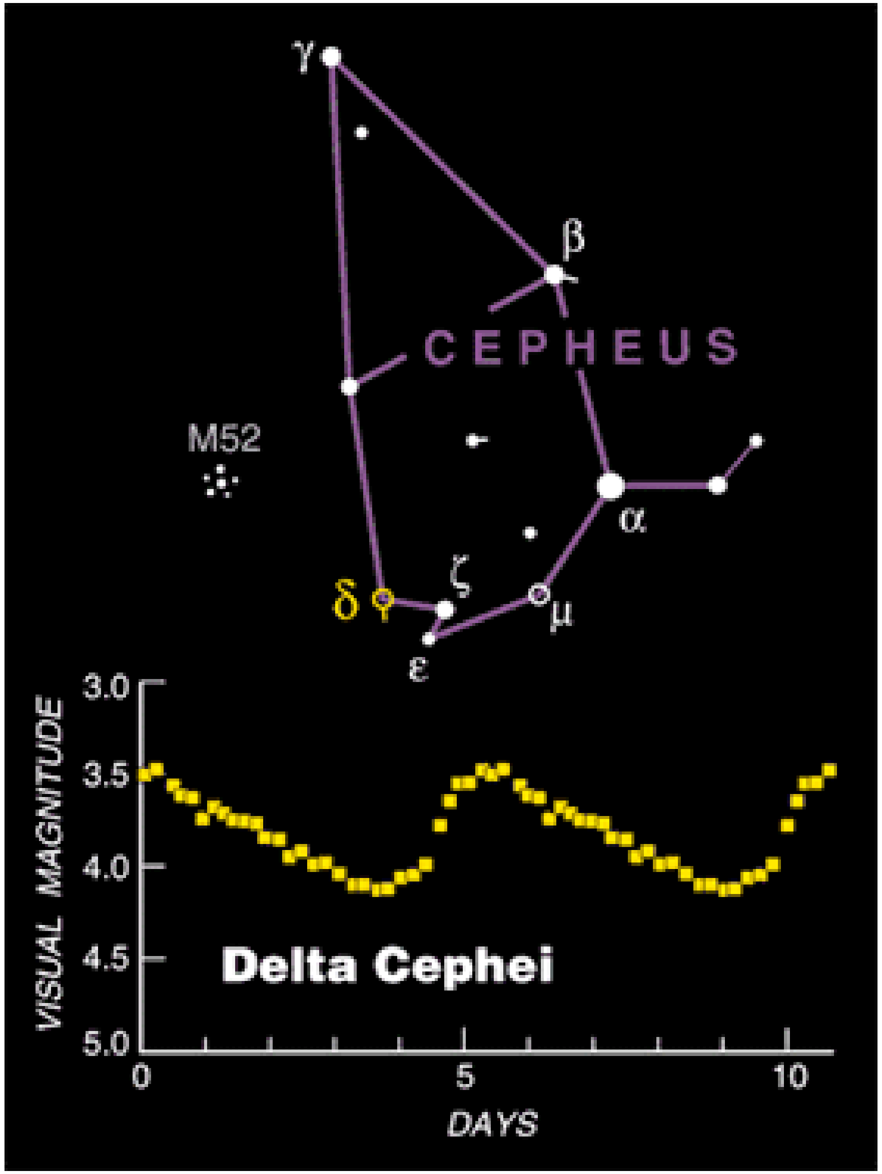
Diameter of the Earth's orbit is ~1000 light-seconds. so if the 'parallax' of a star is 1", then its distance is 1 parsec ⇒ ~3.3 light-years

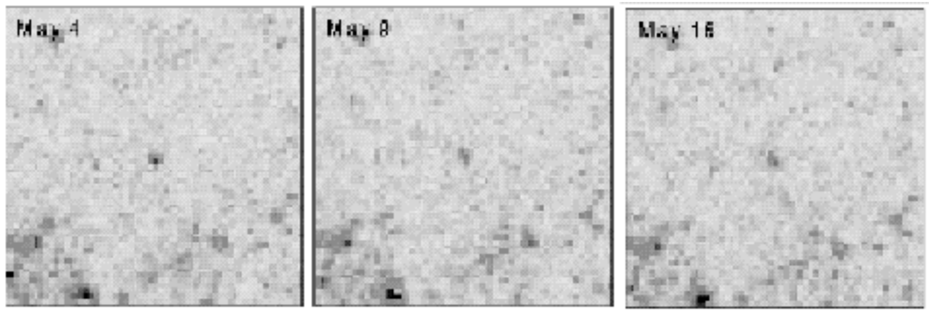
First measured in 1838 by **Wilhelm Bessel** for *61 Cygni* (0.3")

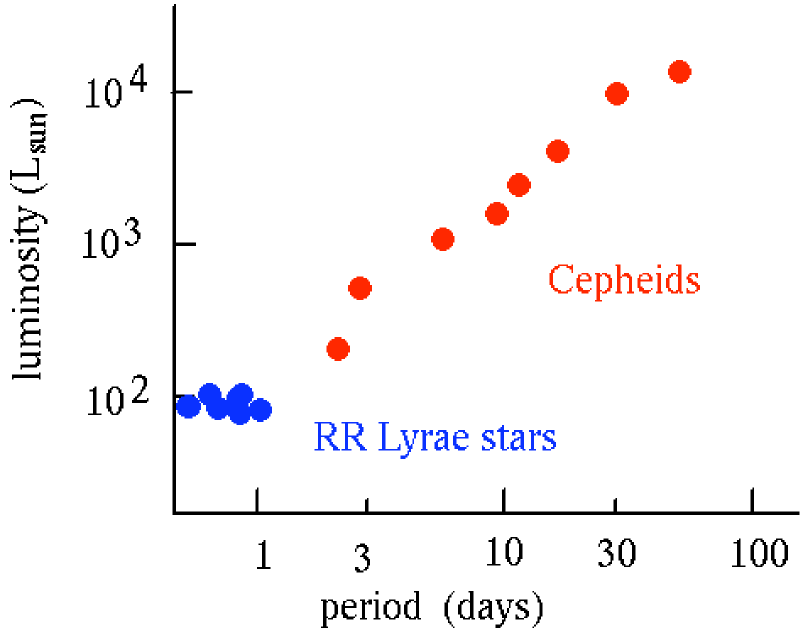
Modern satellites (*Hipparcus)* can measure angles down to ~0.001"
… future missions (*Gaia,* launch 2010*)* will measure down to ~0.0001"

→ to measure longer distances other methods had to be developed:
The Cosmic Distance Ladder

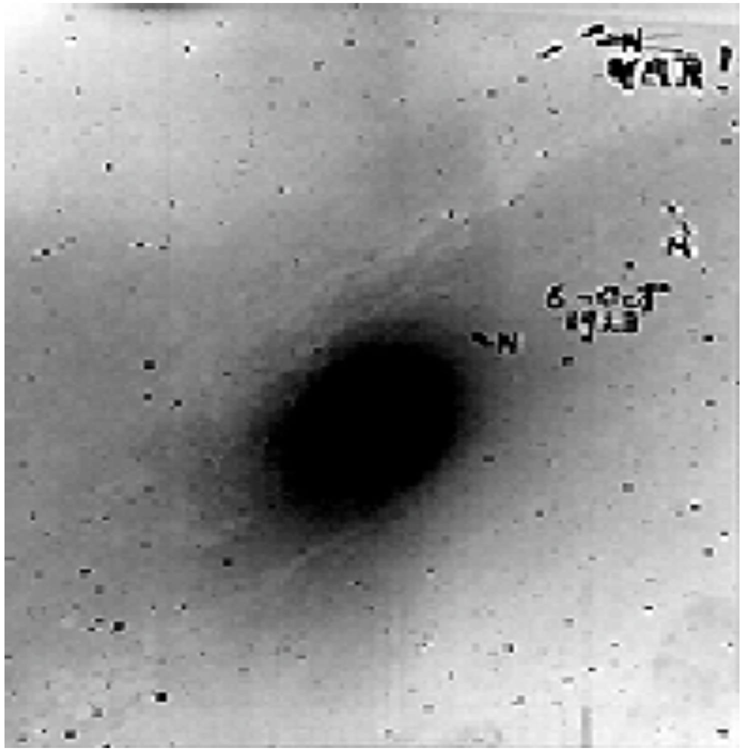
To measure astronomical distances we need **“standard candles”** – sources whose *absolute* luminosity is correlated with some other observable … e.g. pulsation period in the case of **Cepheid variable stars**





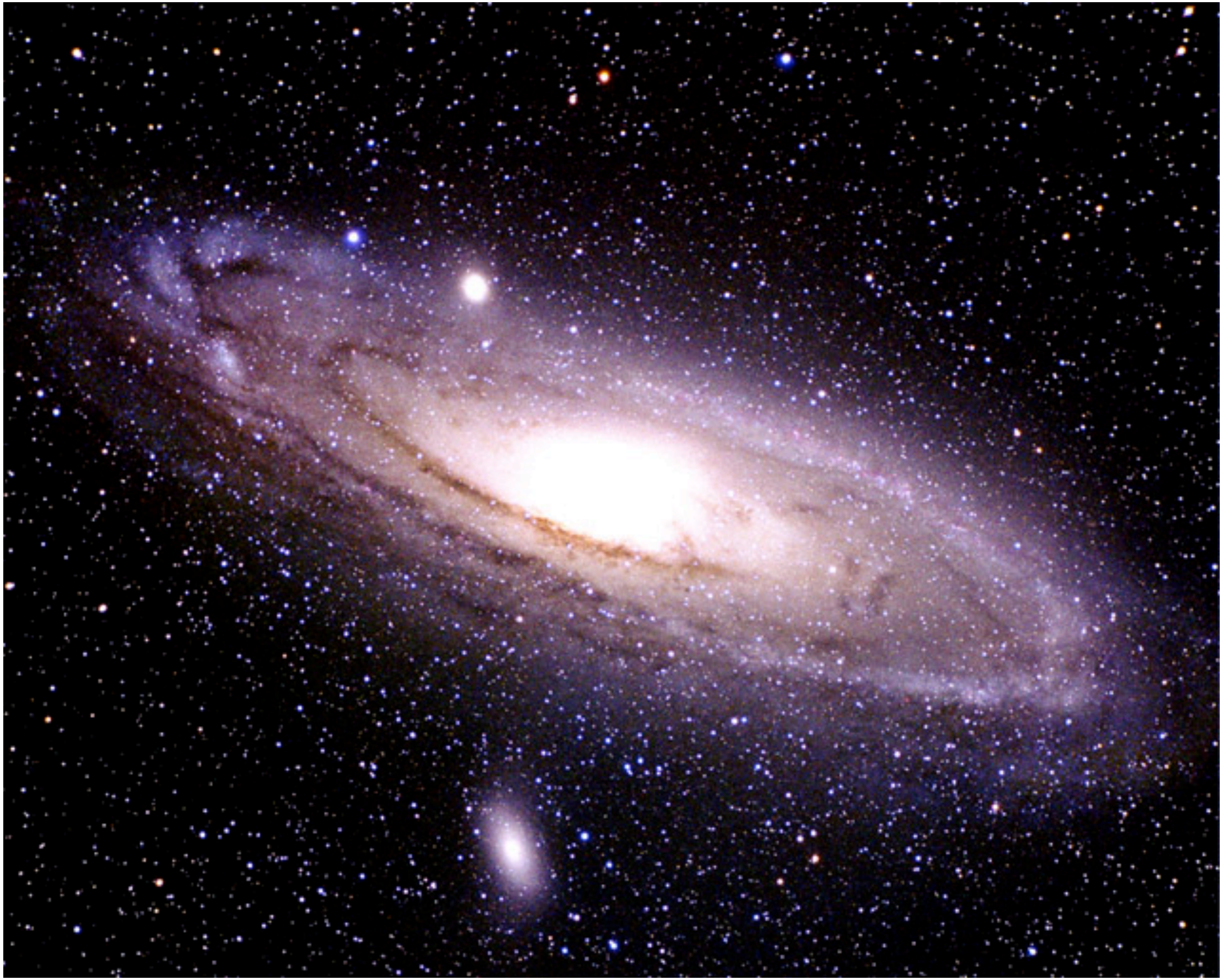


Edwin Hubble (1923) used the 100 inch Mt. Wilson telescope to determine the distance to the Andromeda Nebula



While searching for "novae" (stars which suddenly increase in brightness) he found a Cepheid variable, which had been shown by **Henrietta Leavitt** (1912) to be a type of star which can be used as a distance indicator

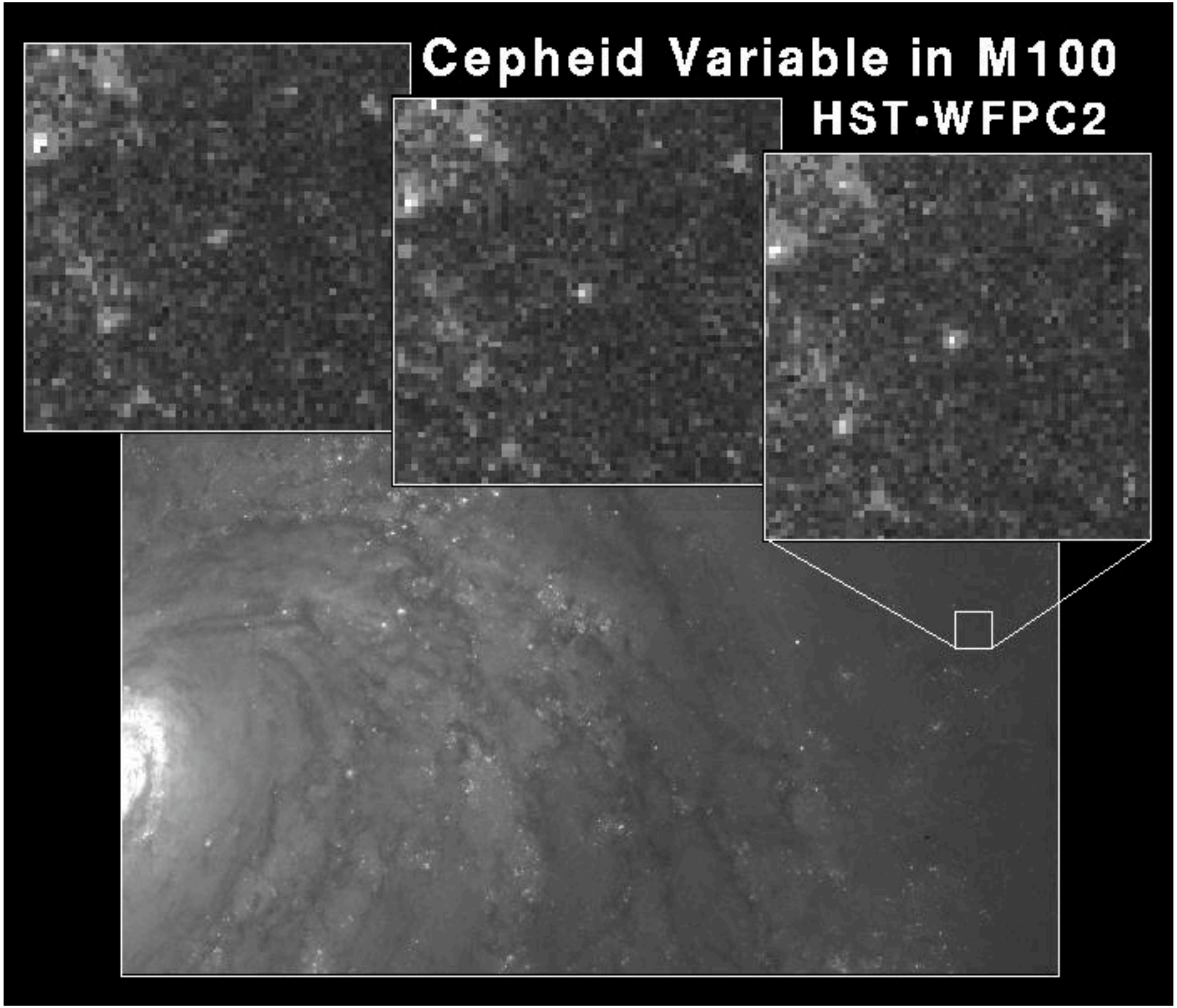
Hubble discovered that Andromeda is not just a cloud of stars and gas in the Milky Way, but a large galaxy similar to our own at a very substantial distance … **the universe became a *lot* bigger!**



In fact Andromeda (M31) is 2.2 million light-years away from us

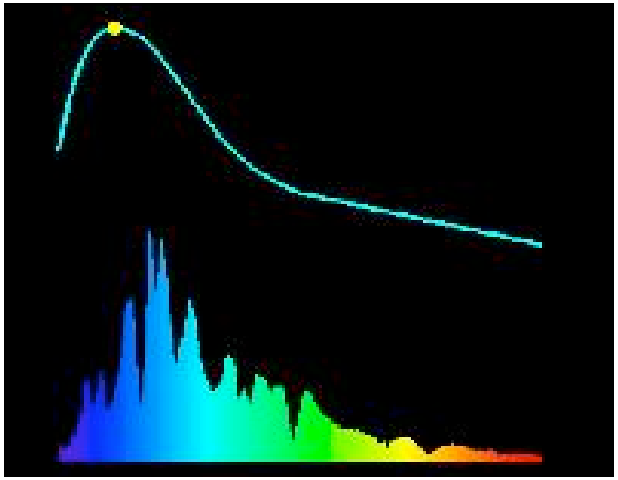
The Hubble Space Telescope

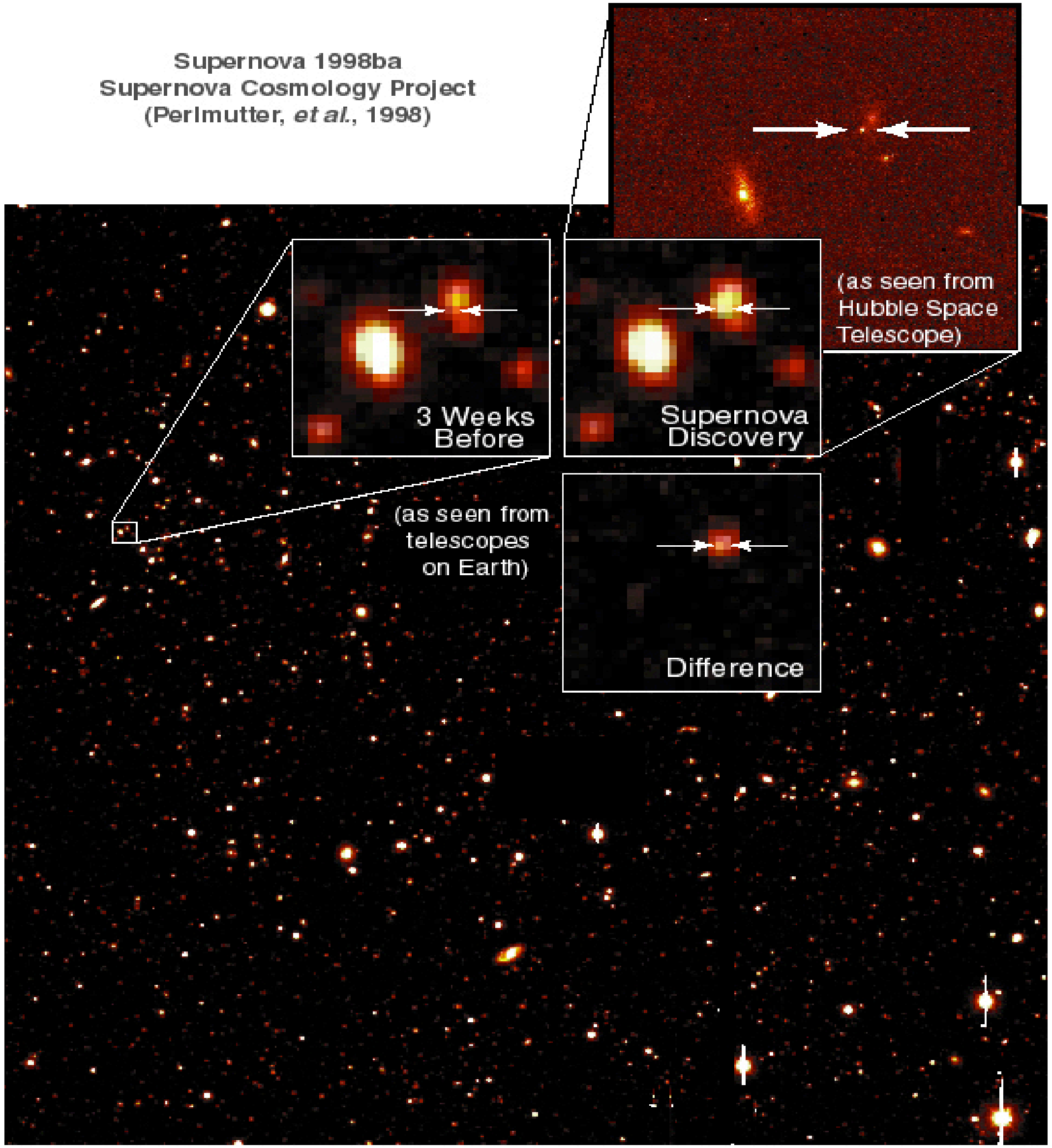
… can resolve Cepheids in galaxies much further away



M100 is one of the galaxies in the Virgo cluster
... which is 54 million light-years away

Cepheids can be used to 'calibrate' other sources such as supernovae – exploding stars which are bright enough to be seen *much* further away





… using supernovae we can now measure distances of *billions* of light-years

So how far must we look to see the 'wall of stars'?

$$\text{Lookout limit} = 1/\pi R^2 n$$

R : radius of star
n : # stars per unit volume

→ for stars of typical size ~5 light-seconds,

separated on average by ~1000 light-years,

we will have to look out for ~10^{24} light-years

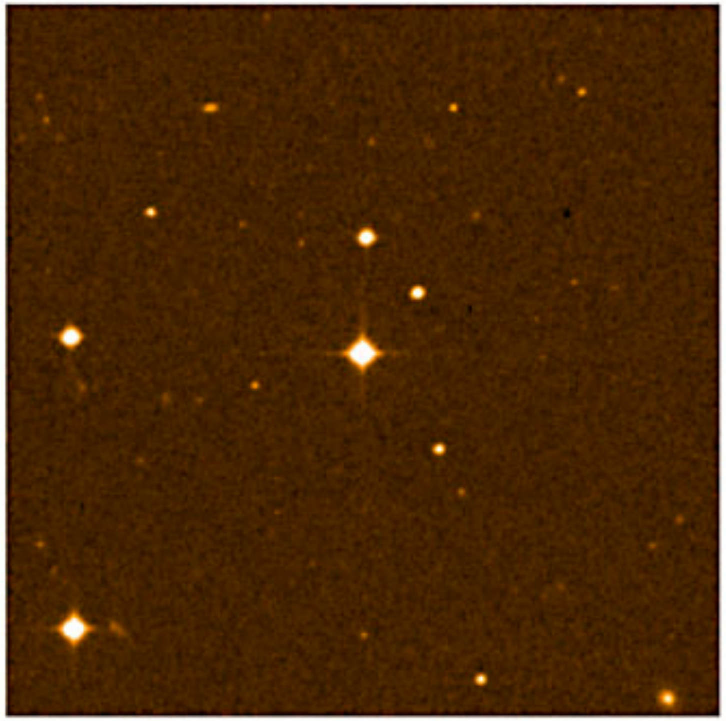
i.e. to get to us the light would have had to set out

1,000,000,000,000,000,000,000,000 years ago!

But have the stars been around for that long?

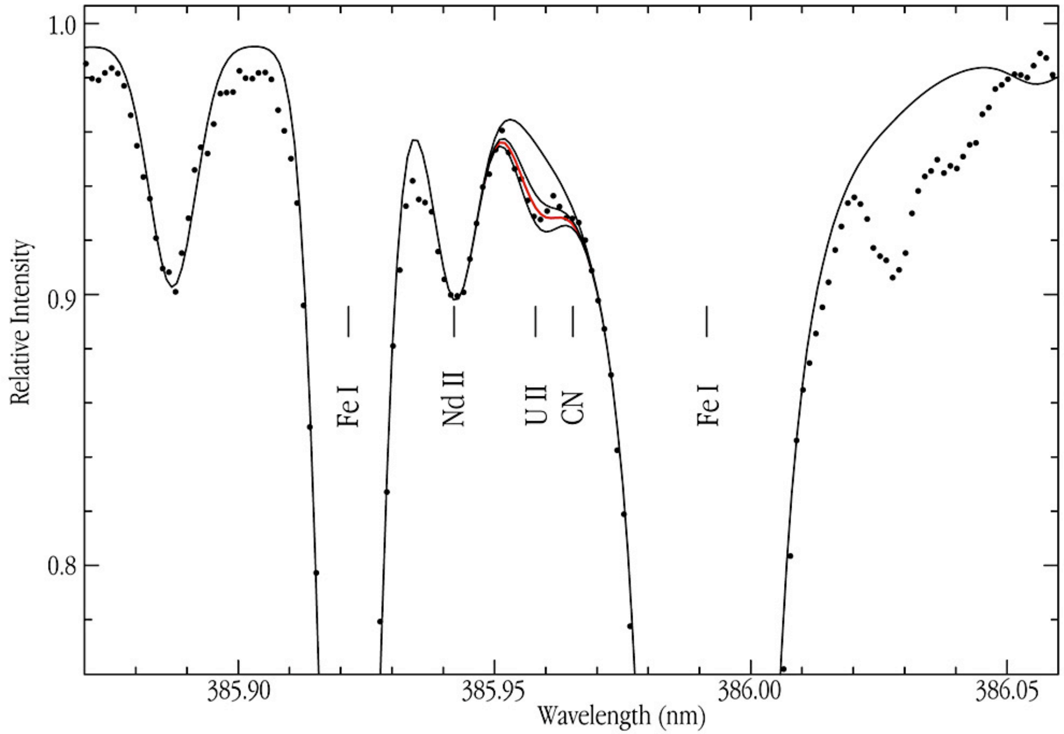
Earth is only 4.6 x 10^9 yr old (from radioactive dating of uranium)
… can similarly date stars from uranium lines in their spectra

Cosmic chronometry with the Very Large Telescope (ESO Chile)



The Old Star CS 31082-001
(UK Schmidt Telescope)

ESO PR Photo 05a/00 (7 February 2001) ©European Southern Observatory



Uranium Line in the Spectrum of the Old Star CS 31082-001
(VLT KUEYEN + UVES)

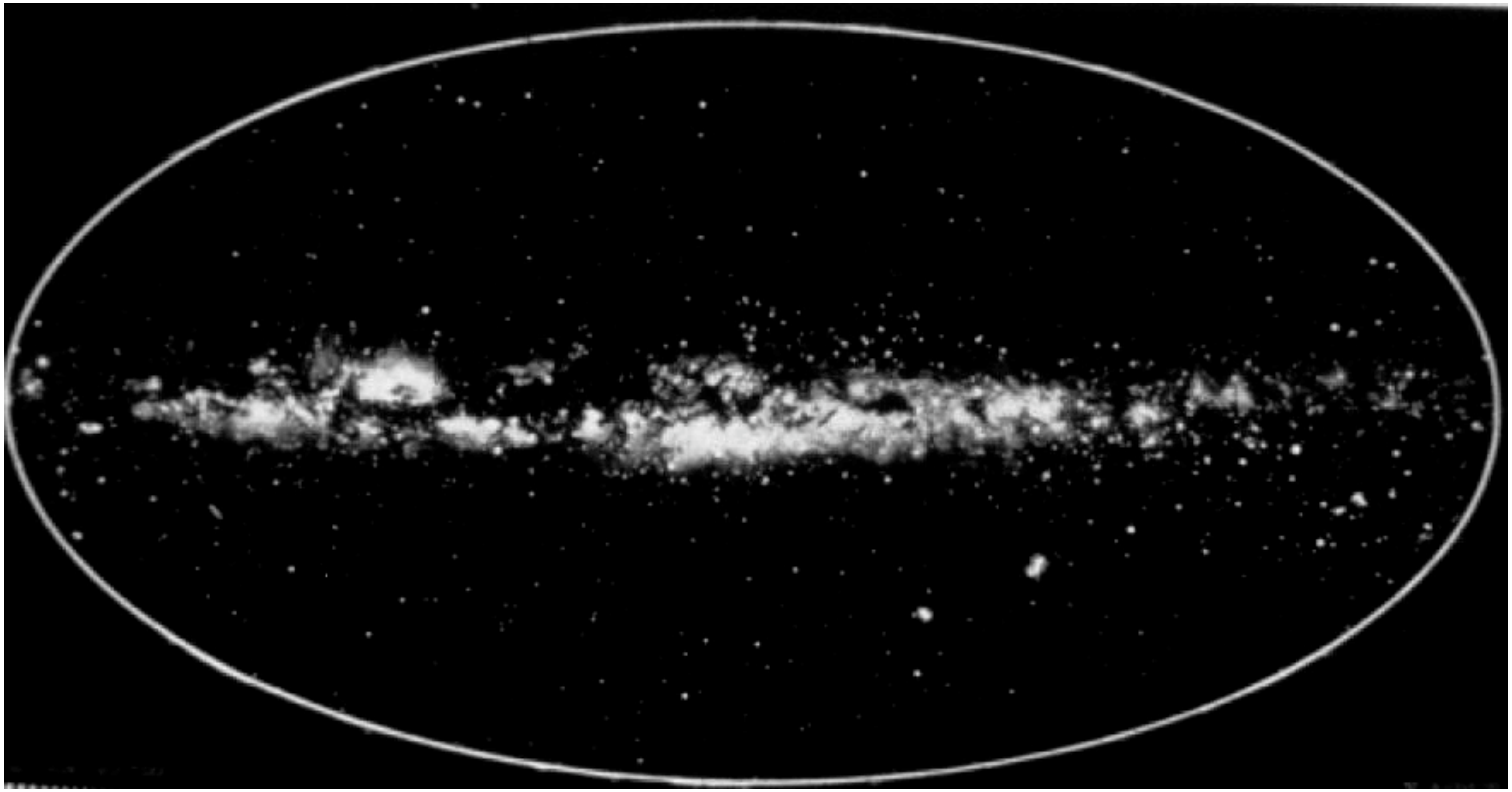
ESO PR Photo 05b/01 (7 February 2001) ©European Southern Observatory

"… The synthetic spectrum was computed for the adopted abundances of the stable elements and for 4 different values of the abundance of uranium in the atmosphere of the star. The best fit is the middle (red) line, representing an uranium abundance of approximately 6% of the Solar value …"

→ this implies an age of "only" 12.5 x 10^9 years

there are not enough stars in the universe we can see to cover the sky

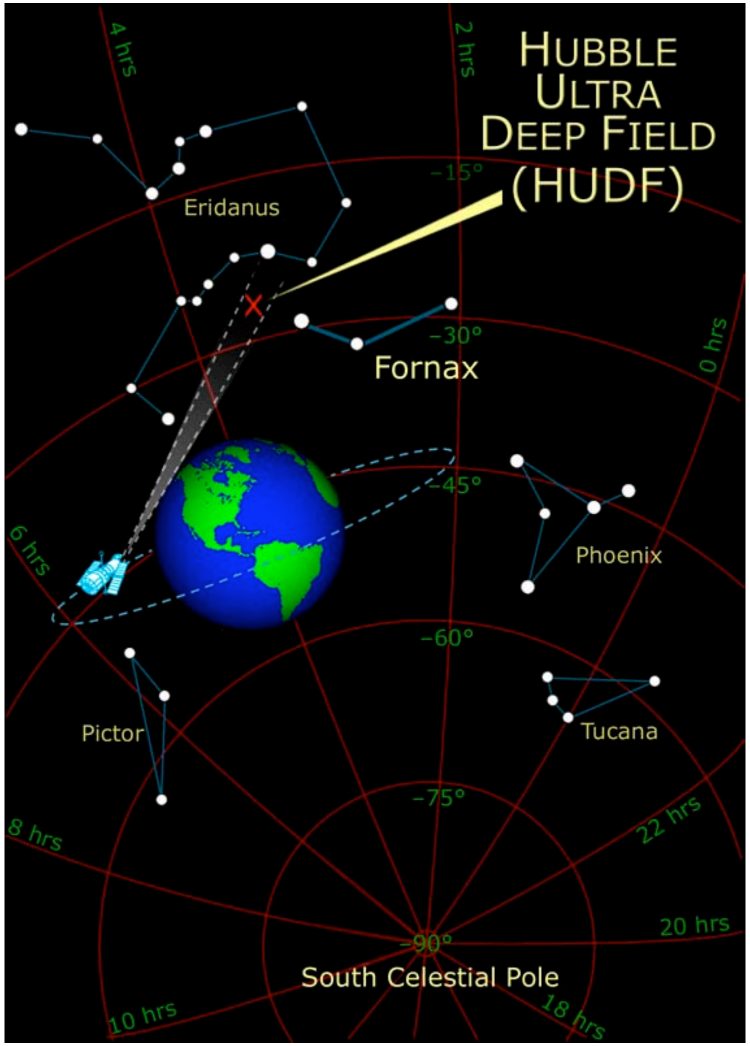
… this is why the sky is dark at night



"Were the succession of stars endless, then the background of the sky would present us an uniform luminosity, like that displayed by the Galaxy – since there would be absolutely no point in all that background, at which there would not exist a star. The only mode therefore in which under such a state of affairs we could comprehend the vistas which our telescopes find in innumerable directions, would be by supposing the distance of the invisible background to be so immense that no ray from it has yet been able to reach us at all"

***'Eureka'*, Edgar Allan Poe (1848)**

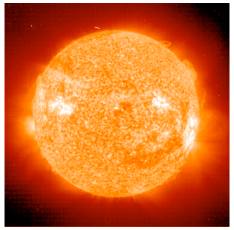
Our deepest view of the universe through a telescope



There are several thousand galaxies in this tiny patch of sky $\Rightarrow$ ~10^{11} galaxies over the whole sky

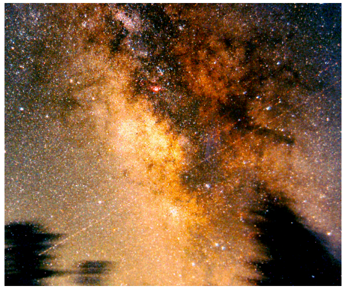
We are seeing *out* of the ‘forest’ of galaxies – what lies beyond?

Looking far away is the same as looking back into our past ...



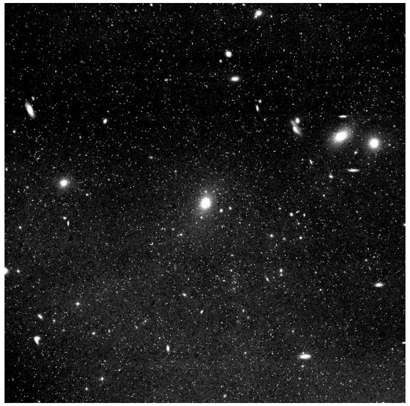
We see the
Sun as it was
8 minutes ago

We see the nearest
star Proxima Centauri,
as it was 4 years ago



We see the Galactic
centre as it was
30,000 years ago

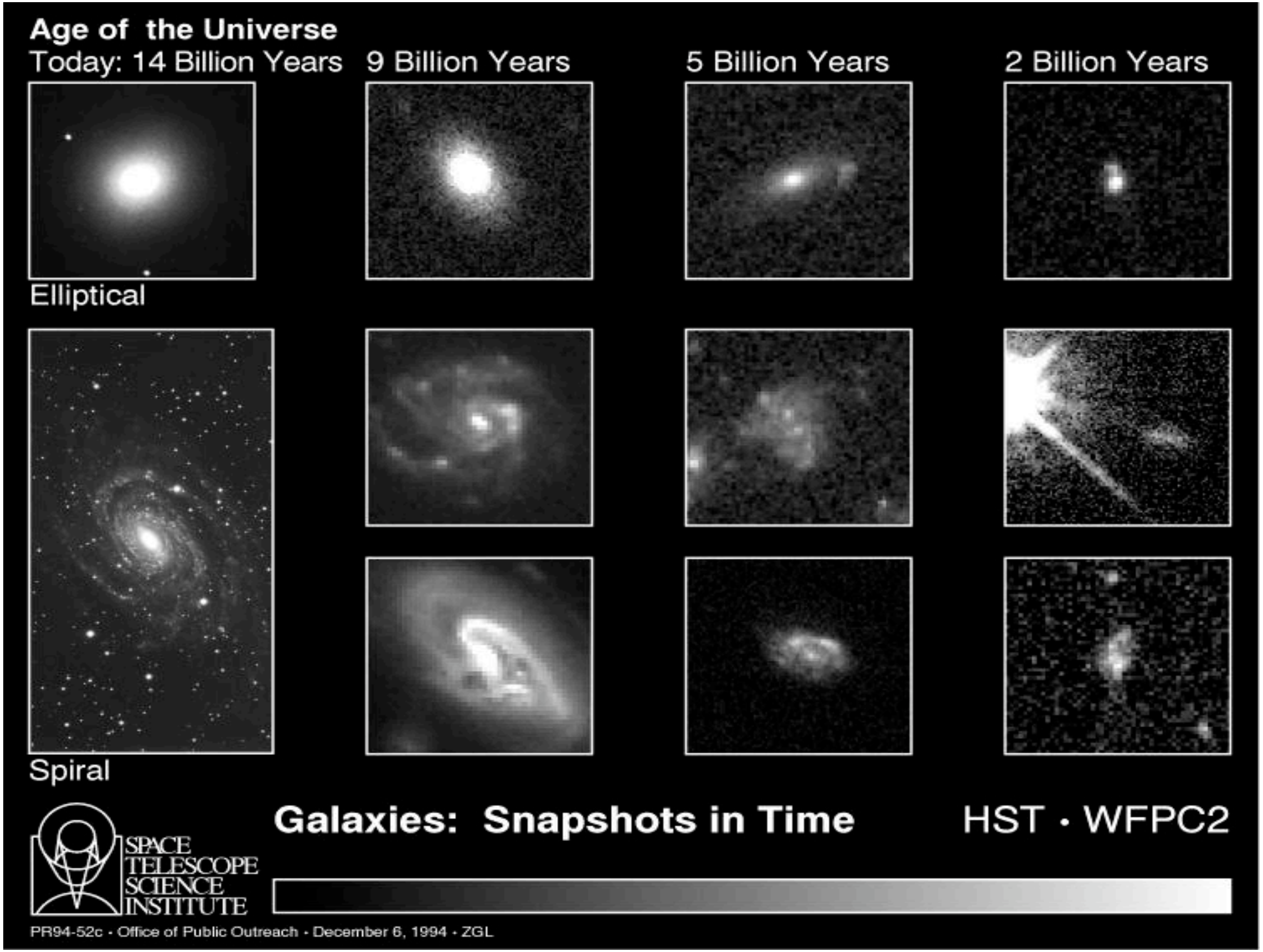
We see our nearest galaxy
Andromeda as it was
2 million years ago



We see the Virgo
cluster as it was
50 million years ago

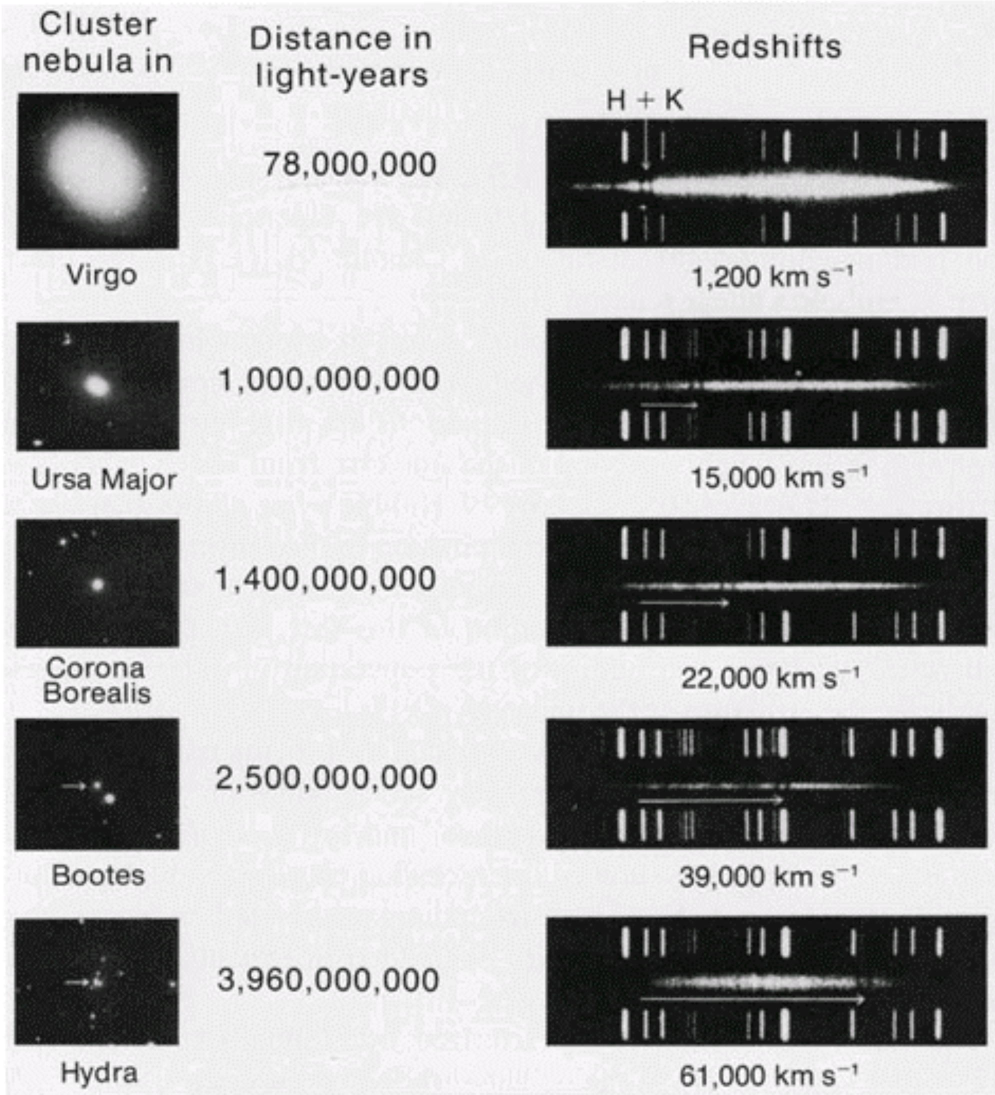
We see galaxies in the
Hubble Ultra Deep Field
as they were upto
12 billion years ago

We are looking right back to the time when the *first* galaxies were forming …



But there is something odd about the spectra of distant galaxies

… they are all shifted towards the *red* end of the spectrum

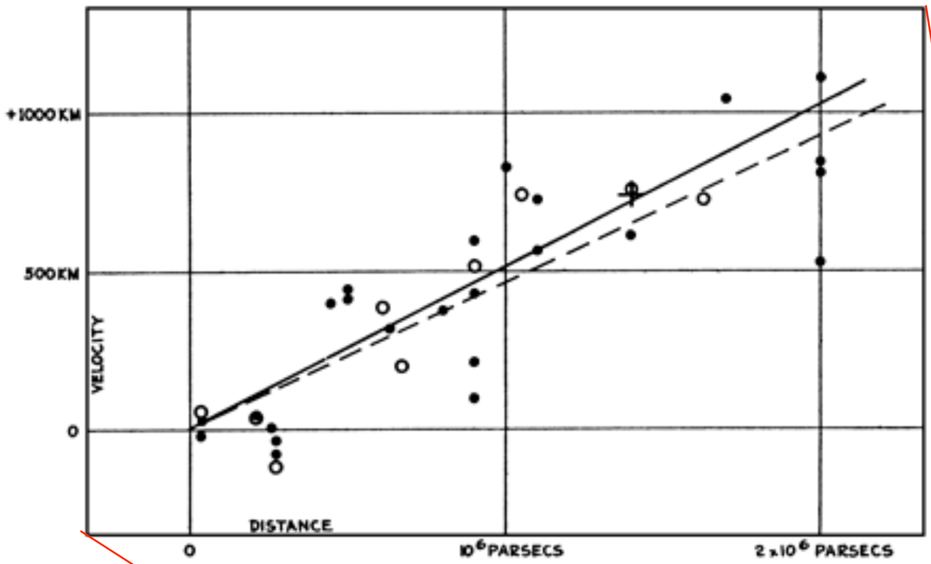


$$\text{Red Shift: } z = \frac{\lambda_{\text{emitted}} - \lambda_{\text{observed}}}{\lambda_{\text{emitted}}} \simeq v/c, \text{ for } z \ll 1$$

Hubble discovered that the *further* a galaxy is the *faster* it seems to be moving away from us

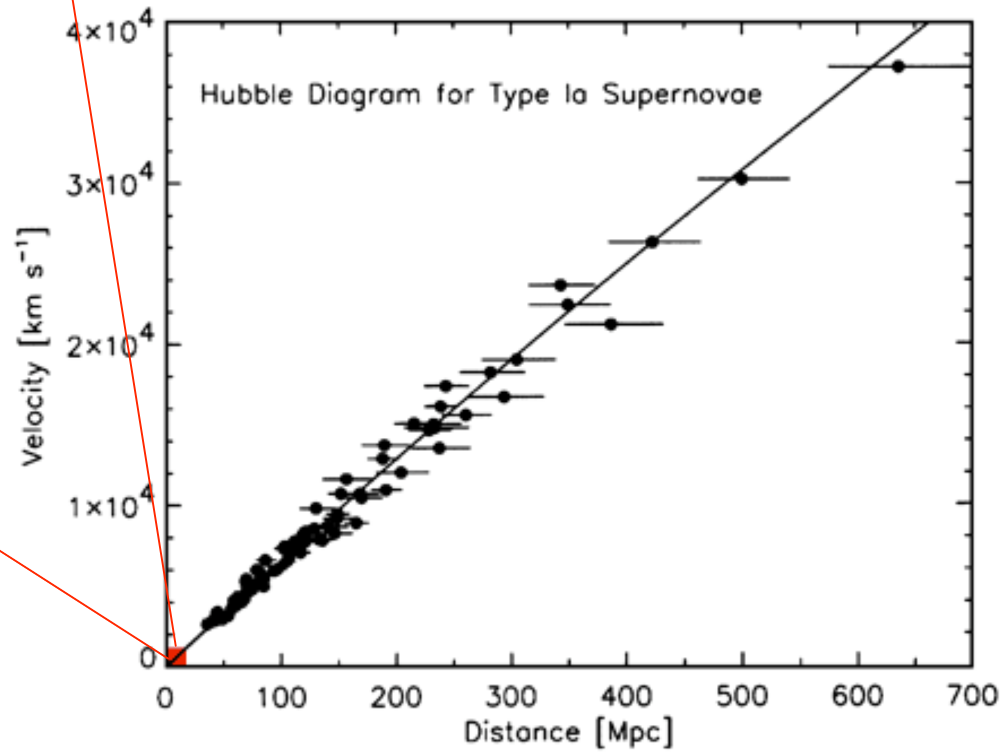
"Every time I see Edwin Hubble, he's moving rapidly away from me!"

The expansion of the universe

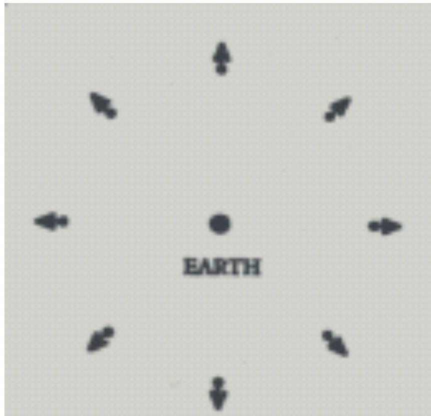


Hubble's data (1929)

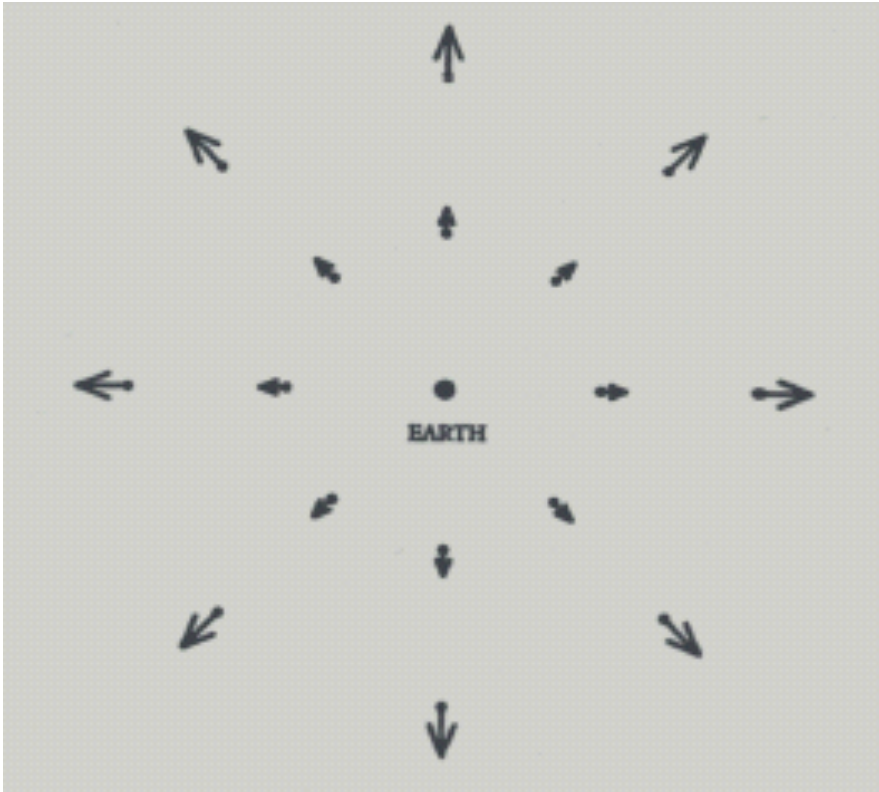
Modern data using supernovae (2002)



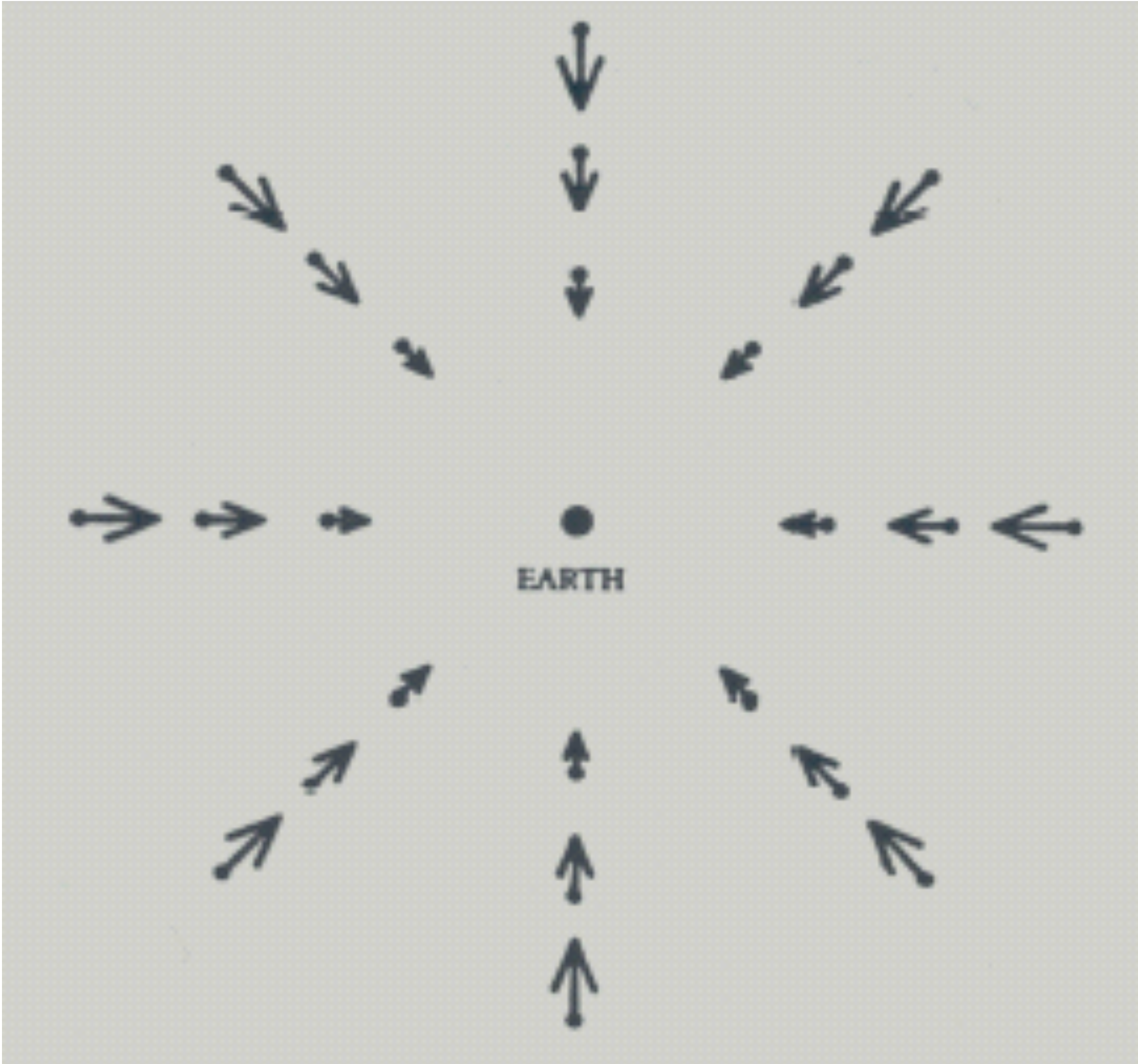
Galaxies equidistant from us, all moving away at the same speed



Galaxies twice as far, are moving away twice as fast

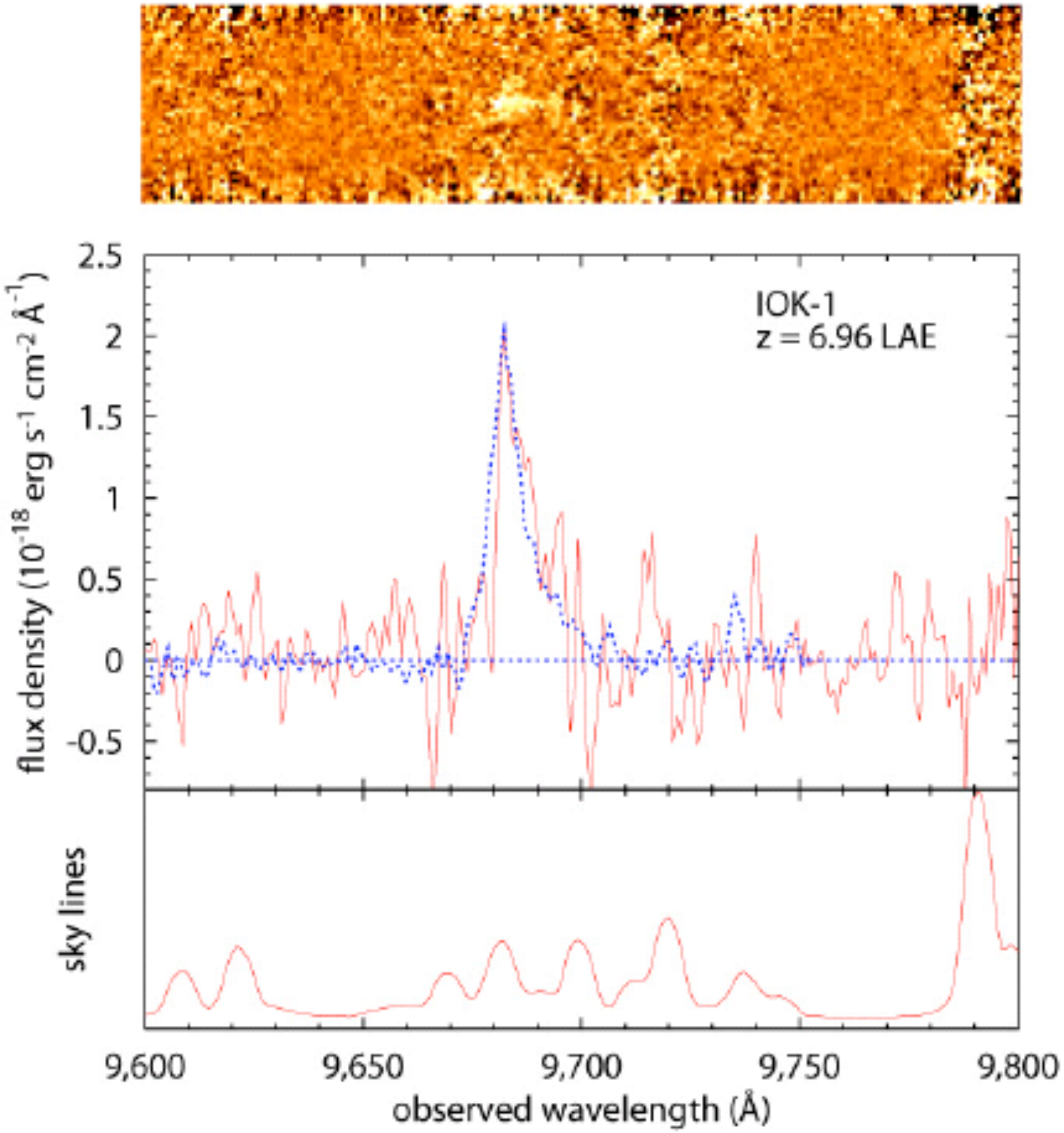


So going back in time, *all* galaxies will come together at the *same* instant at $\sim 1/H_0 \approx 14 \times 10^9$ yr (given the present expansion rate: $H_0 \approx 70$ km/s/Mpc)



i.e. the entire universe originated in a 'Big Bang' about 14 billion years ago
… but this was the birth of space-time, *not* an explosion in space!

The redshift *cannot* be a Doppler shift because there are galaxies with $z > 1$ …
their recession speed *cannot* be just *cz*!



This is one of the most distant galaxies known (having a measured spectrum) at $z \sim 7$

To get around this problem some texts suggest using the Special Relativistic formula:

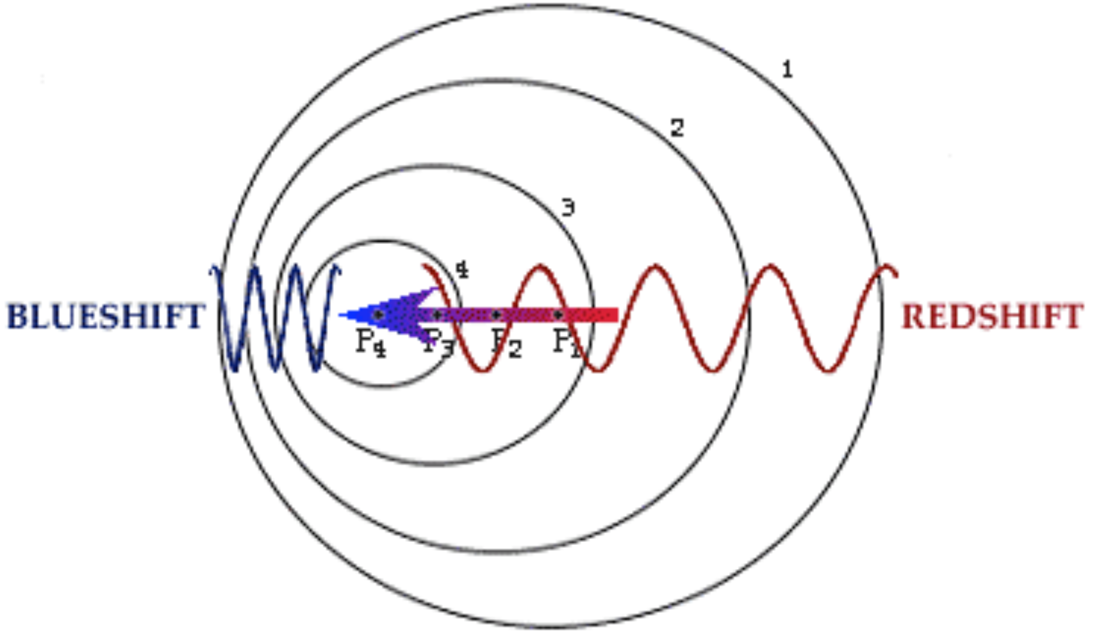
$$z = \frac{1 + v/c}{\sqrt{1 - v^2/c^2}} - 1$$

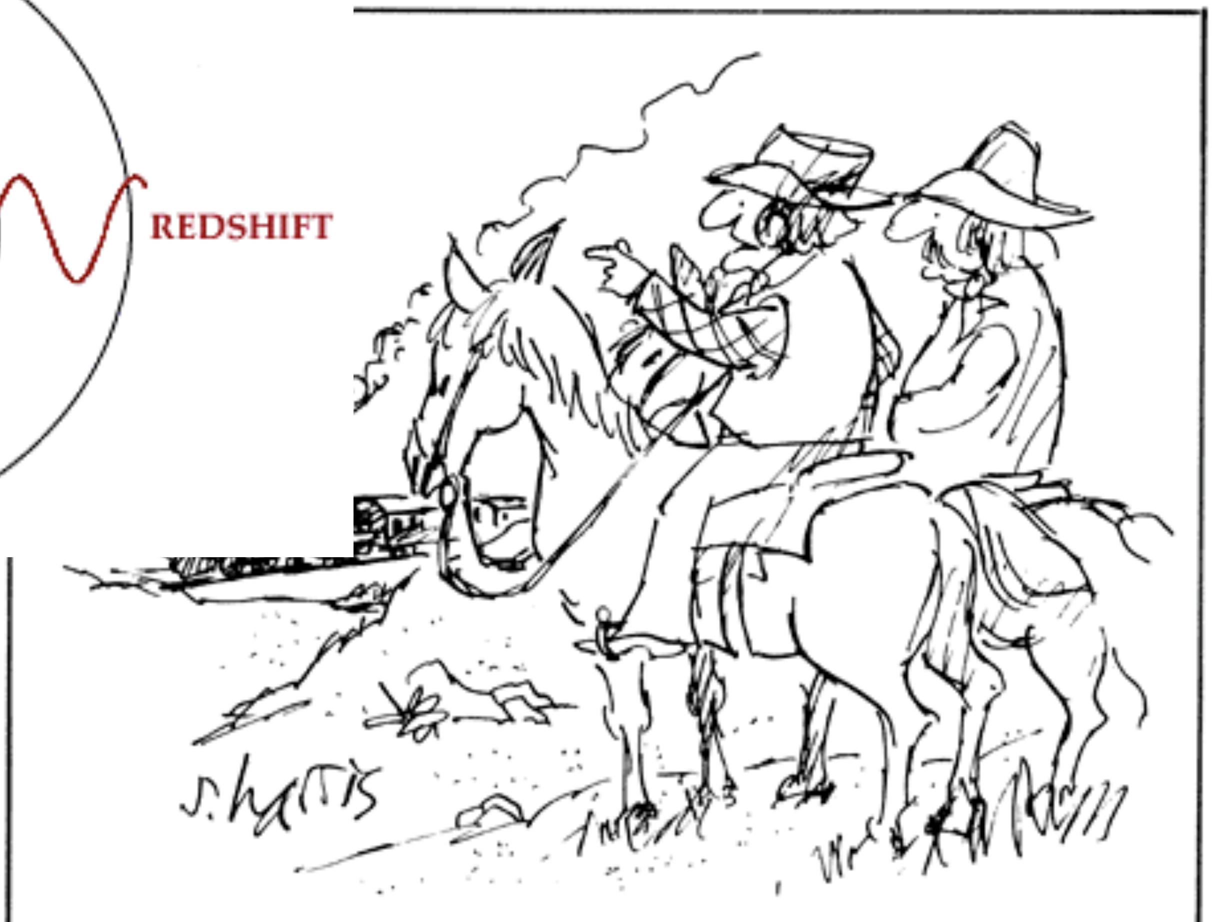
… But then *all* galaxies at high *z* would have the *same* speed ~0.999999… times c

so their distribution *cannot* be homogeneous any longer
➔ this would violate the Copernican Principle!

The redshift of distant galaxies should *not* be interpreted as a **Doppler effect**

… **it is not a concept appropriate to *curved* space-time**

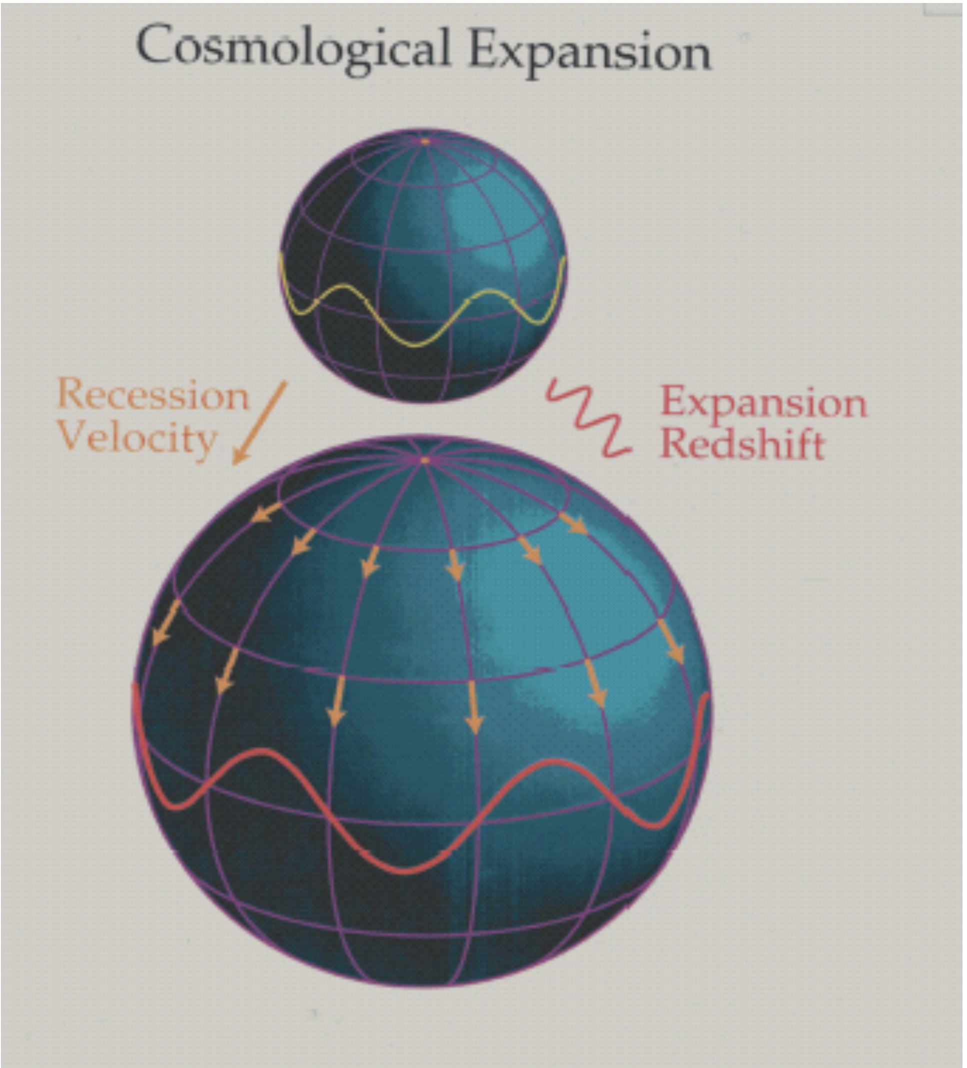




"I love hearing that lonesome wail of the train whistle as the magnitude of the frequency of the wave changes due to the Doppler effect."

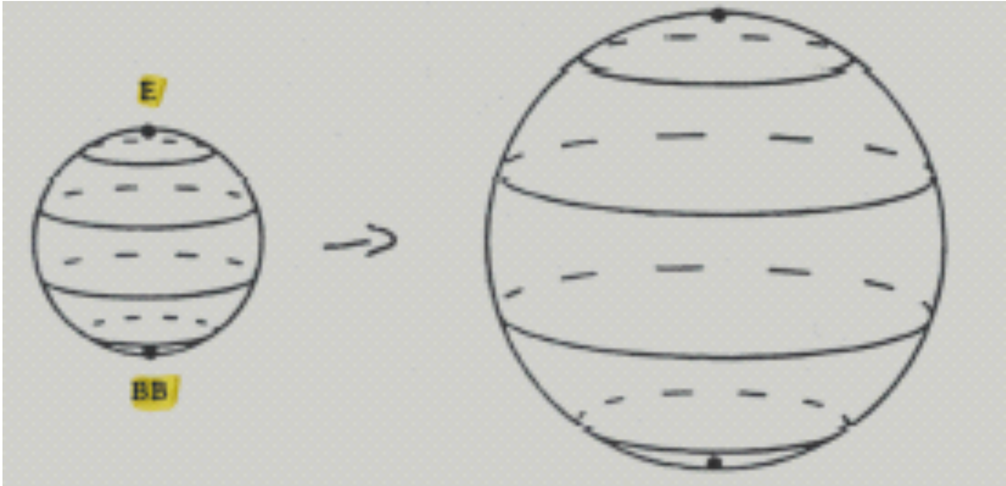
The redshift occurs because the wavelength of light is increased by the *stretching* of space-time

$$\frac{\lambda_{\mathrm{observed}}}{\lambda_{\mathrm{emitted}}} \equiv 1 + z = \frac{a_{\mathrm{observed}}}{a_{\mathrm{emitted}}}$$

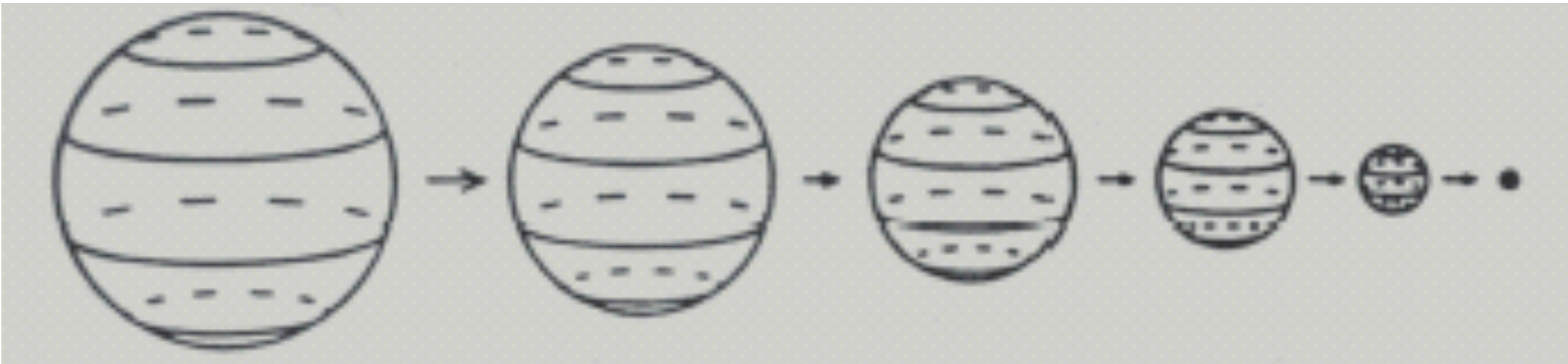


This analogy also illustrates that the expansion has no 'centre'

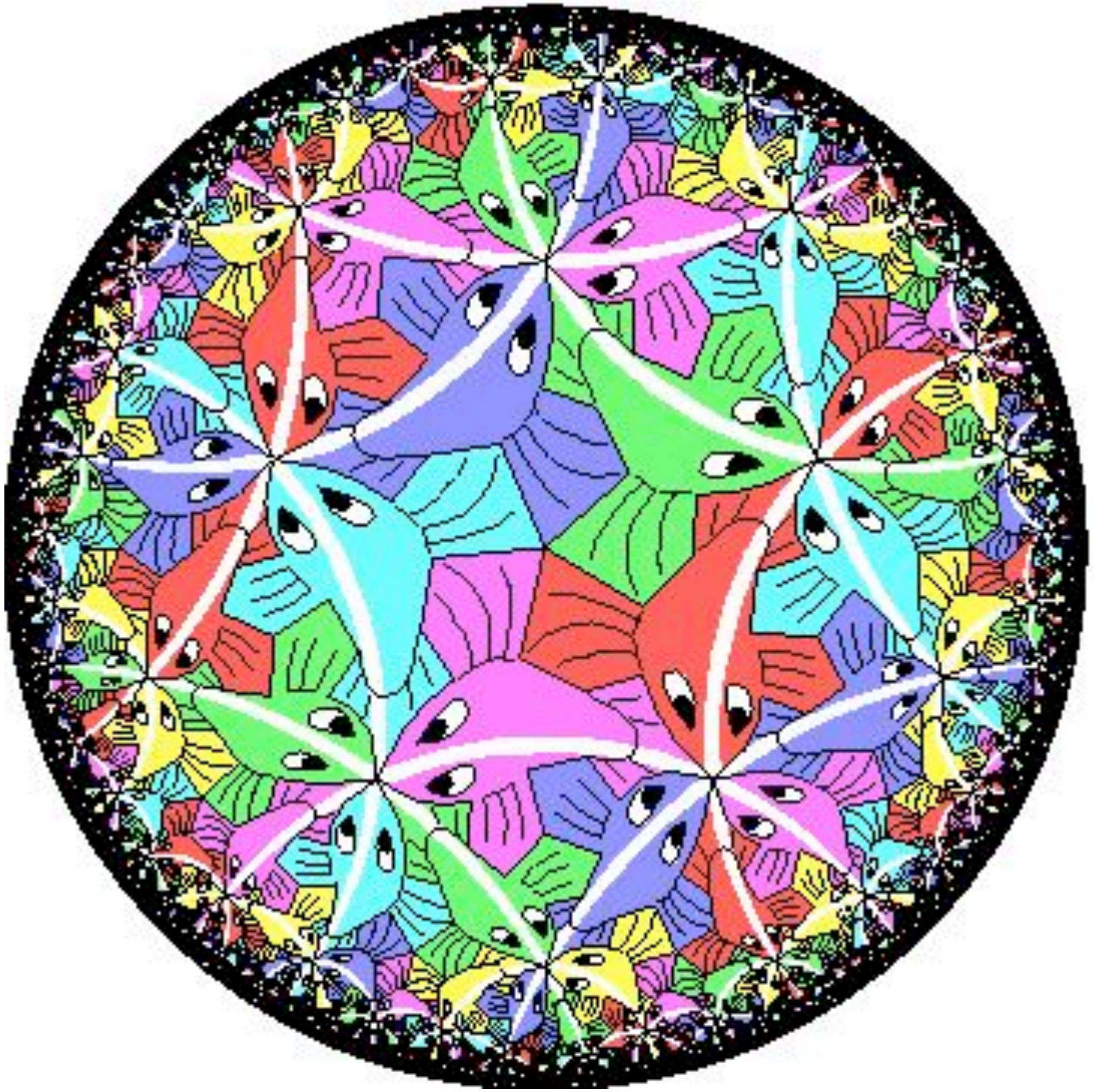
The Big Bang is the *antipodal* point of an expanding hypersphere



… going back in time we are all subsumed in the initial singularity wherein *all* of space-time and matter seem to have been created

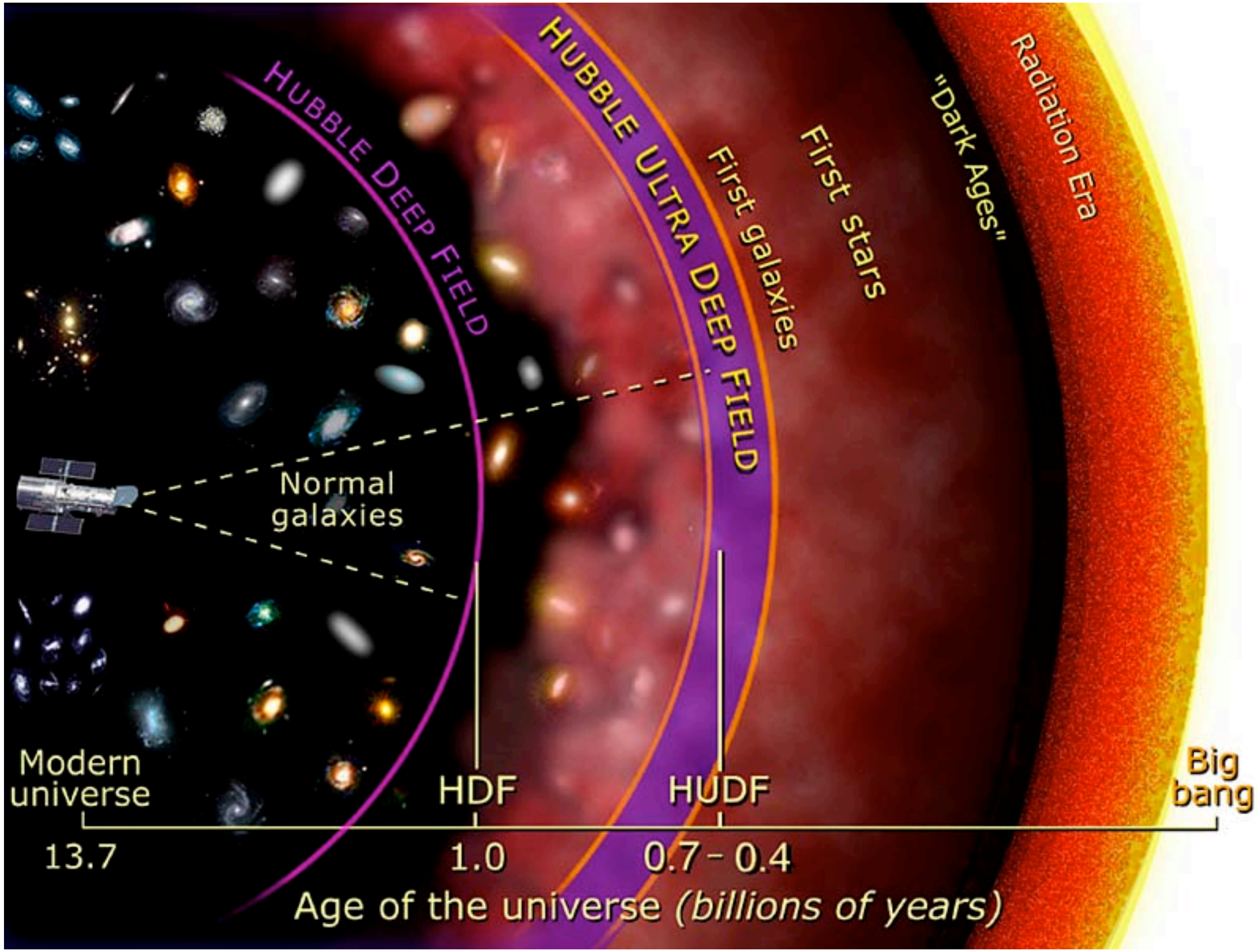


Matter curves space-time (Einstein's 'General Theory of Relativity') so when we look out at the universe we see ...



'Circle Limit III', M.C. Escher (1959)

When the universe was younger, it was smaller therefore hotter ...



So if we can look back far enough in time, we should see a hot, dense 'fireball' covering the sky

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

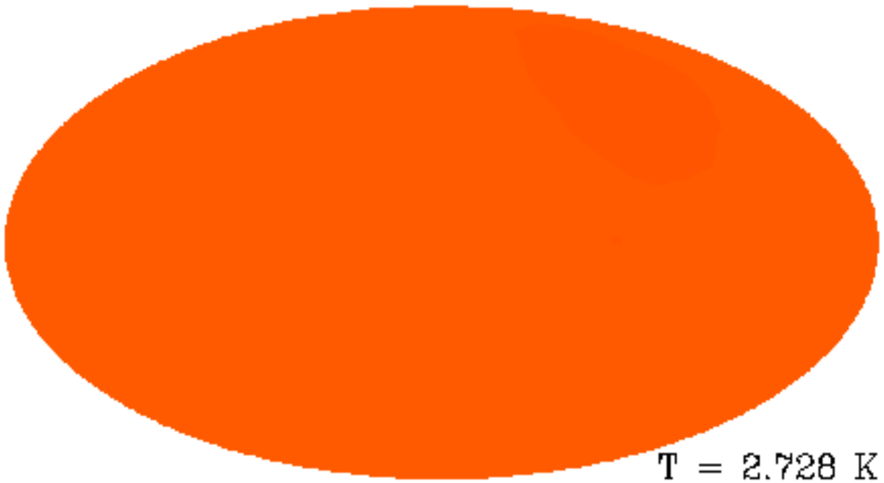
Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our 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

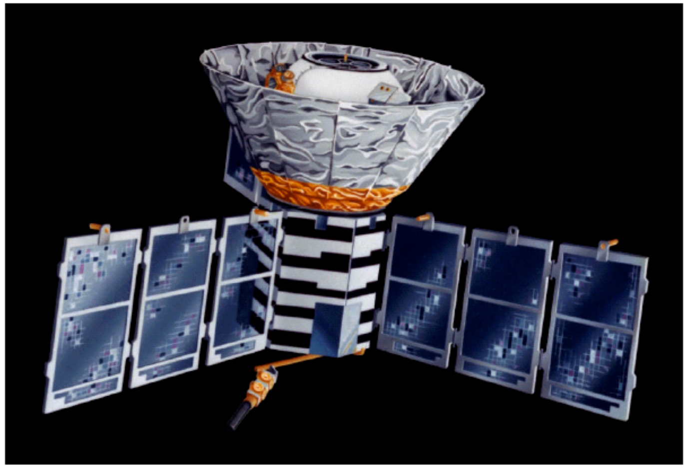
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

Nobel Prize (1978)



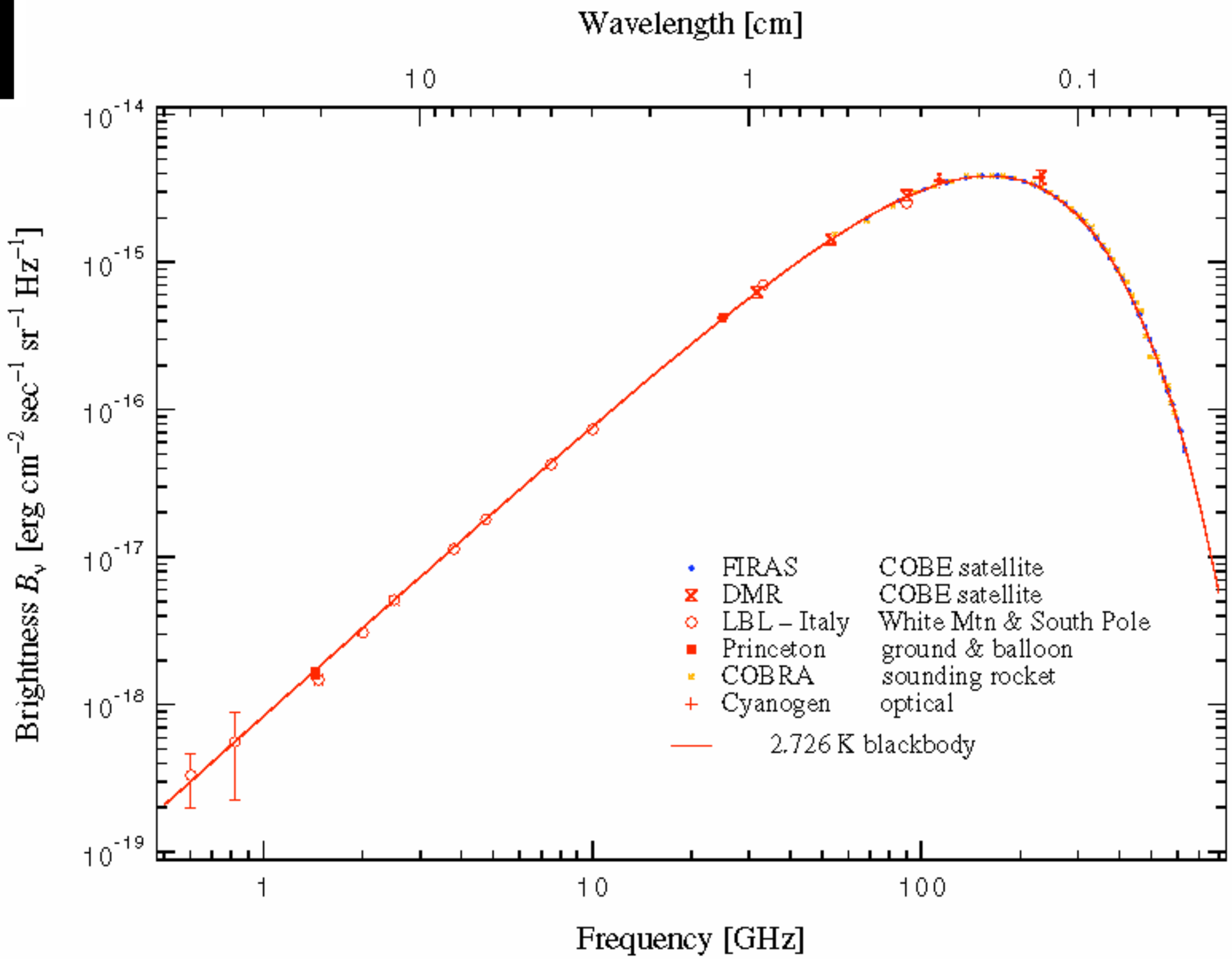
Finally we have found the ‘bright sky’ we were looking for … but this primordial light from the hot plasma of the early universe (about 400,000 years after the Big Bang) has been redshifted to *microwave* frequencies …

The *Cosmic Background Explorer* (1992)

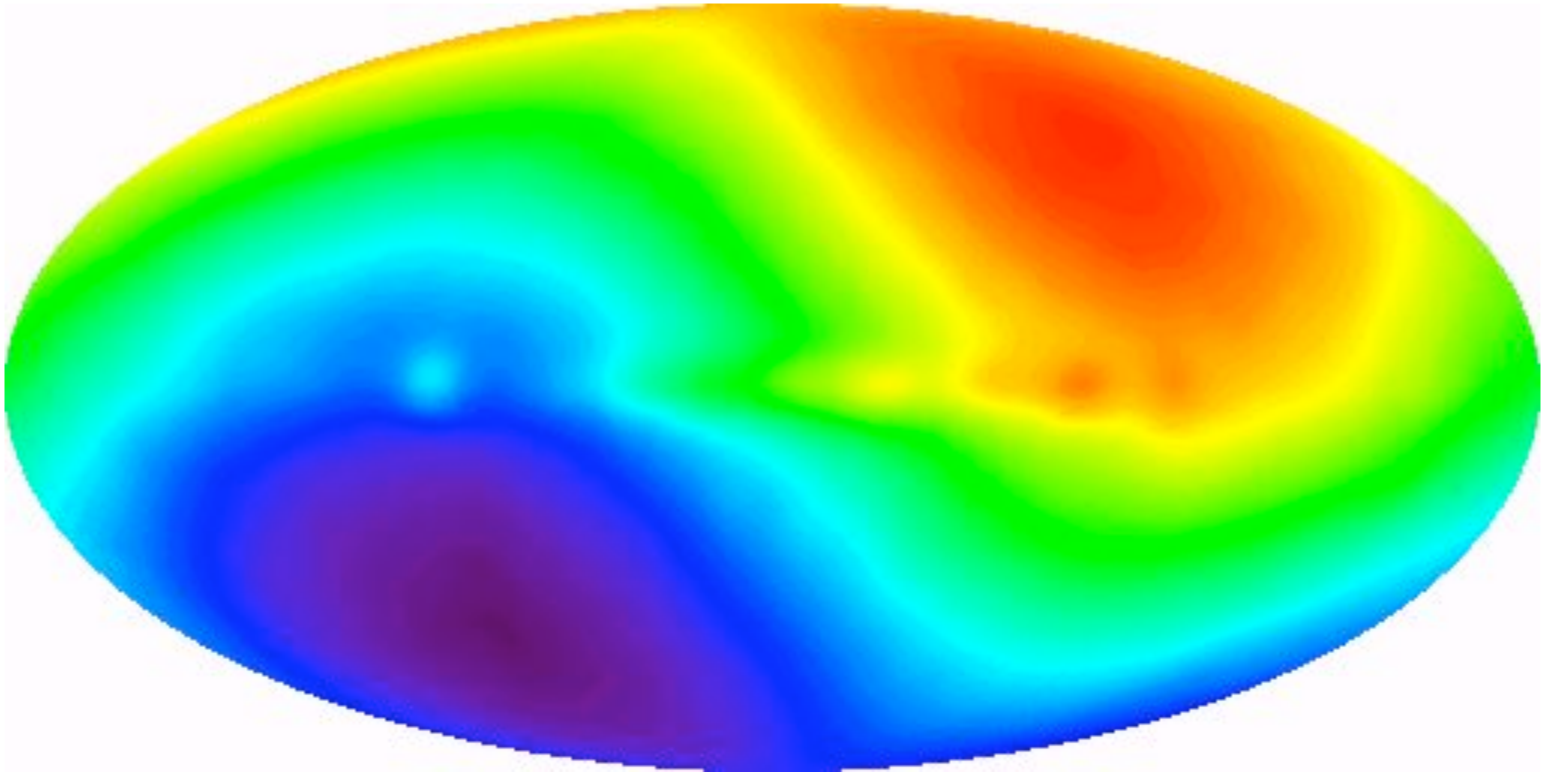


… measured the spectrum of this relic radiation to be as *perfect* a blackbody as the calibrating source!
(John Mather, Nobel Prize 2007)

This *requires* the radiation to have originated from a hot and dense state … and *rules out* the steady-state theory (wherein it is created by the thermalisation of starlight by dust)



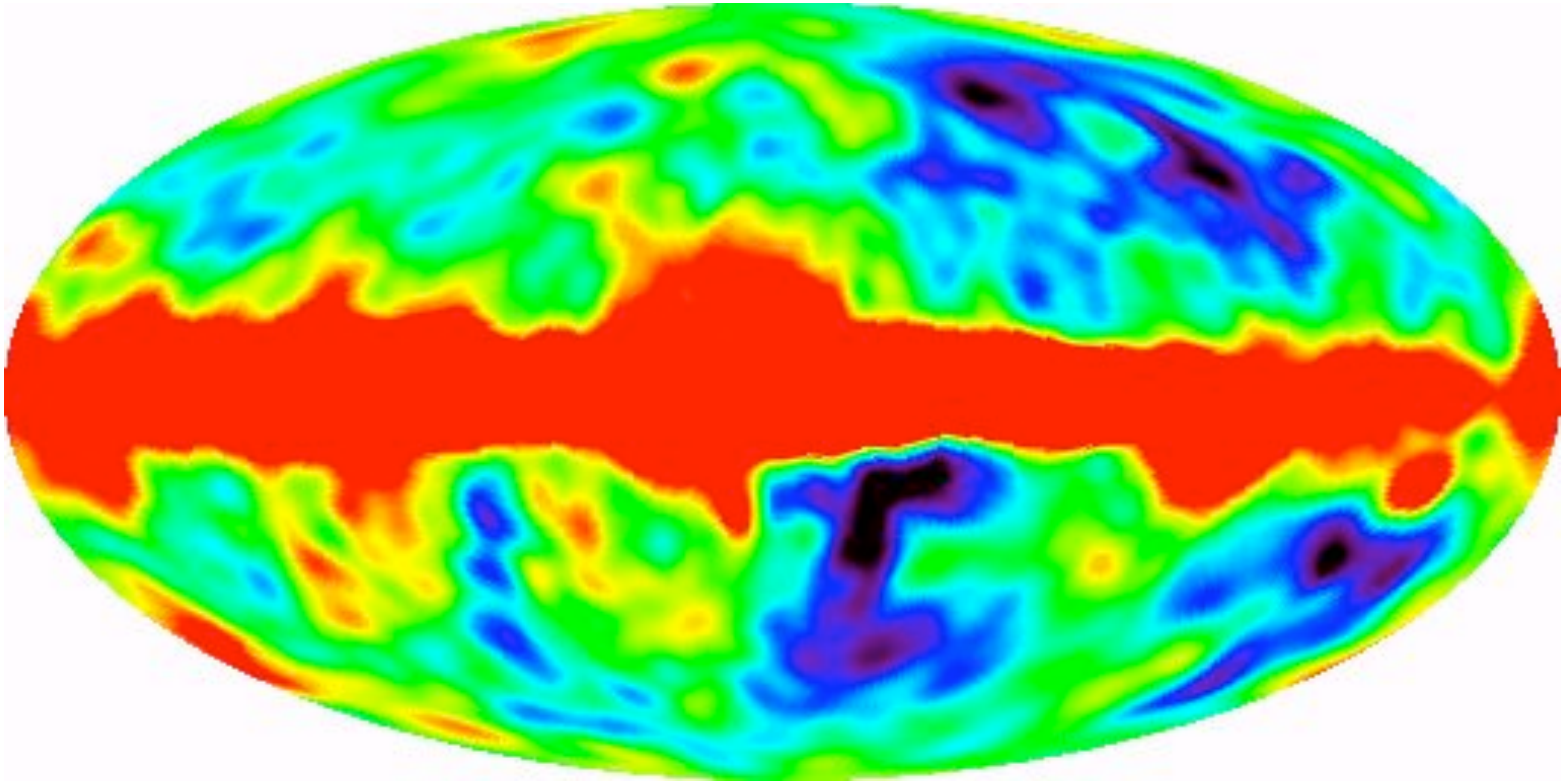
But on closer inspection, the radiation is not quite uniform ...



Dipole anisotropy with $\delta T/T \sim 10^{-3}$

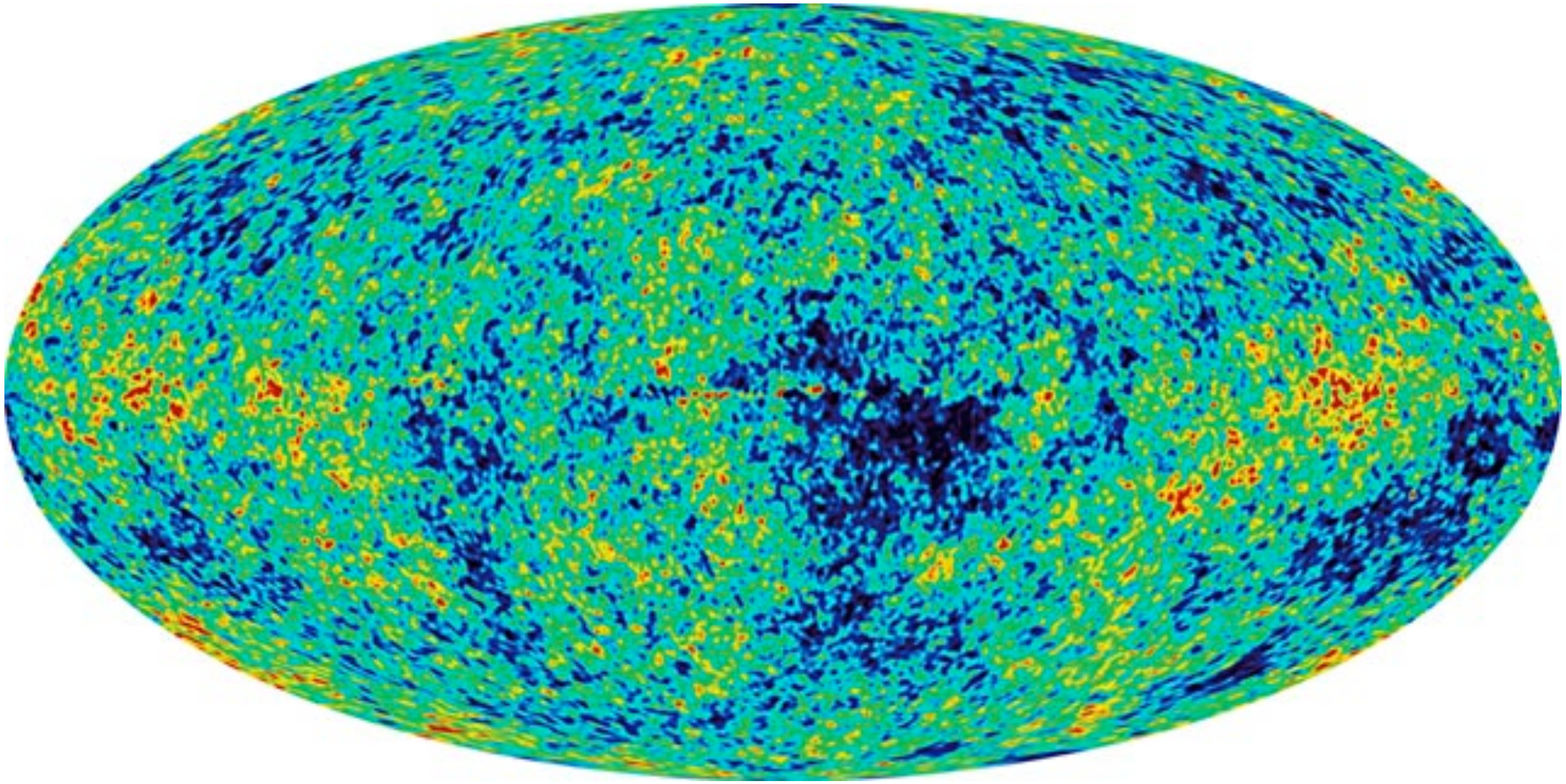
due to our motion at ~370 km/s wrt the CMB rest frame
(there is however nothing *special* about this frame)

COBE also detected the expected tiny temperature fluctuations due to primordial density inhomogeneities (which are *required* to seed the formation of structure) (George Smoot, Nobel prize 2007)



$\delta T/T \sim 2 \times 10^{-5}$

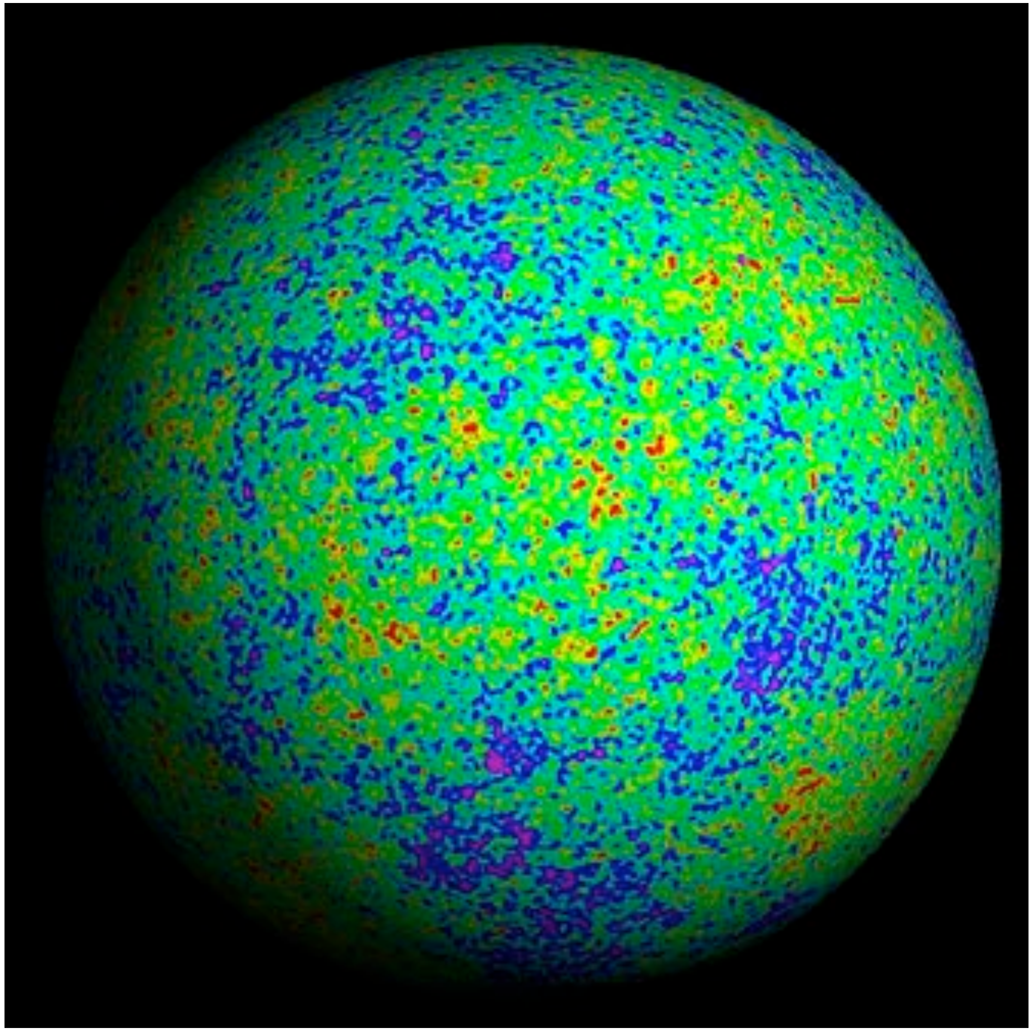
Wilkinson Microwave Anisotropy Probe (2003-)



The hot/cold patches are believed to be due to **quantum fluctuations** generated during inflation, when the universe was *smaller* than a nucleus

… these excited sound waves in the plasma filling the early universe and provided the 'seeds' for the formation of galaxies

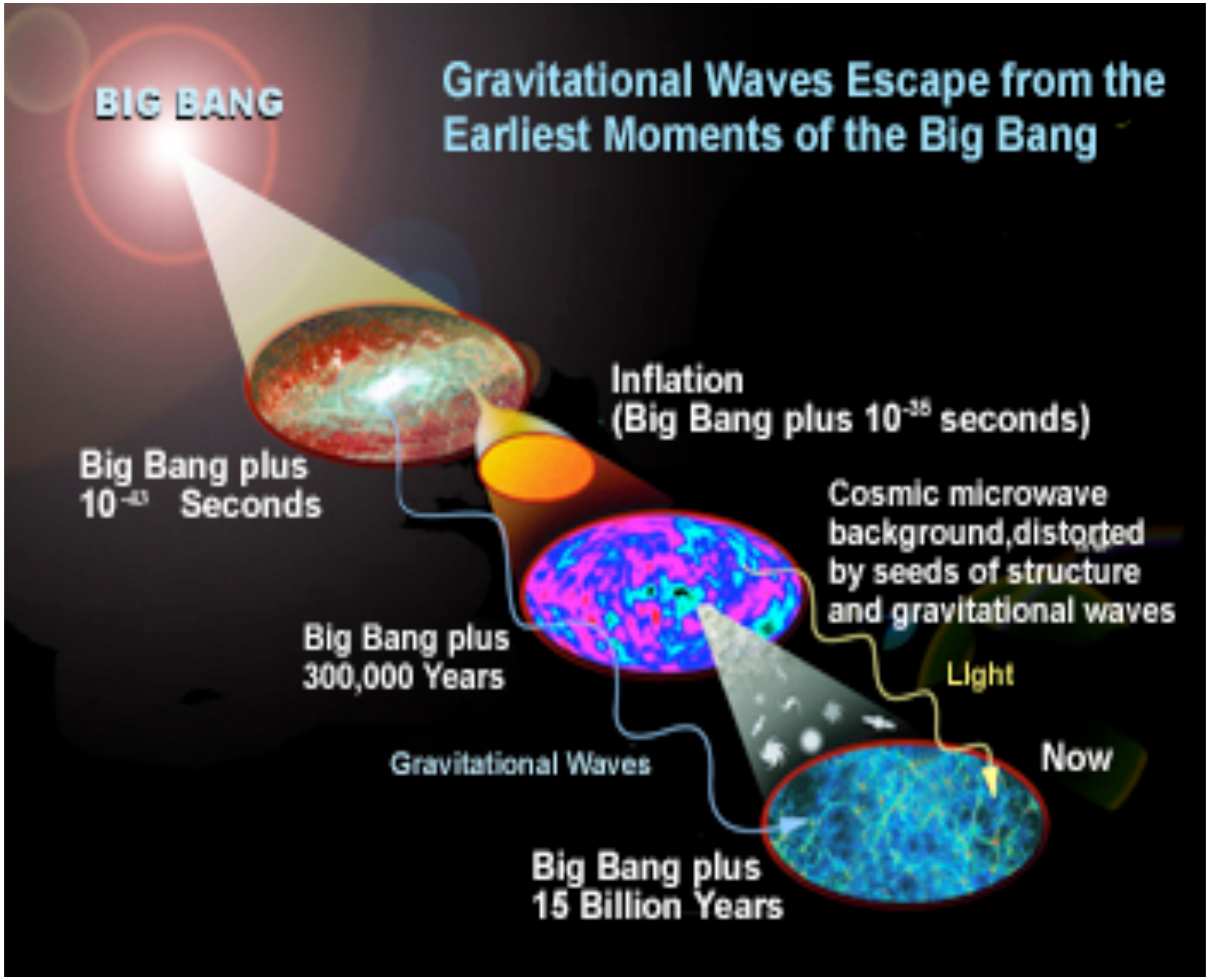
This is the edge of the *visible* universe ...

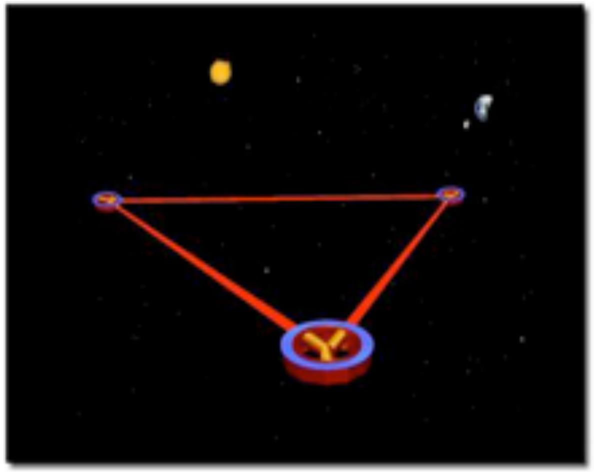


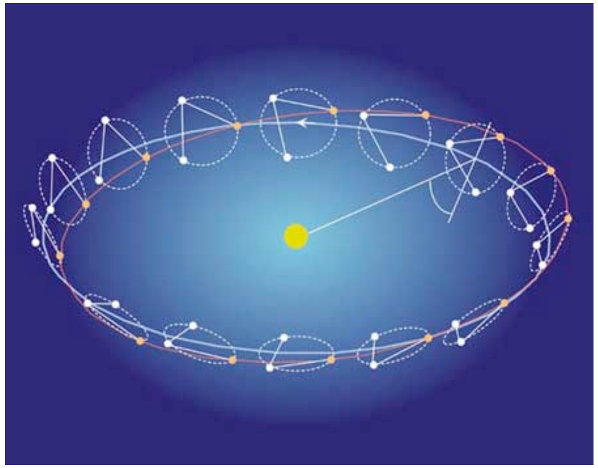
"Our entire observable universe is inside this sphere of radius 13.3 billion light-years, with us at the center. Space continues outside the sphere, but this opaque glowing wall of hydrogen plasma hides it from our view. This censorship is frustrating, since if we could see merely 380000 light-years beyond it, we would behold the beginning of the universe"

Max Tegmark (2003)

One day we may indeed look back to the *very* beginning







… perhaps with the Laser Interferometer Space Array (*LISA*) which aims to detect gravitational waves from the Big Bang itself

"Ill tell you what's beyond the observable universe -- lots and lots of <u>un</u>observable universe."