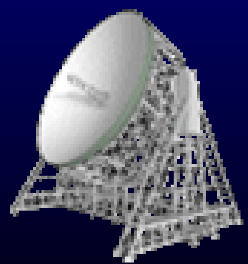
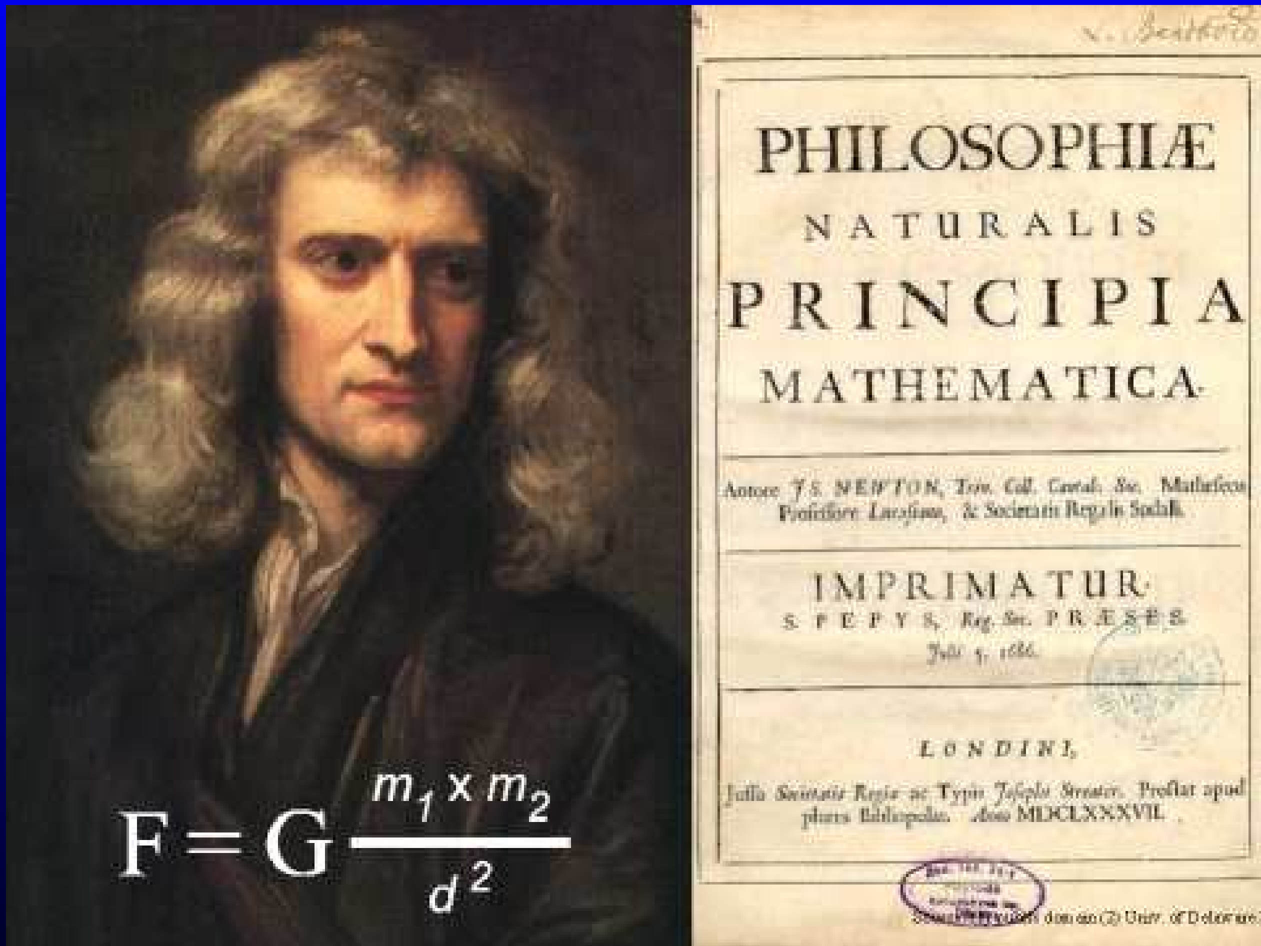
Cosmology

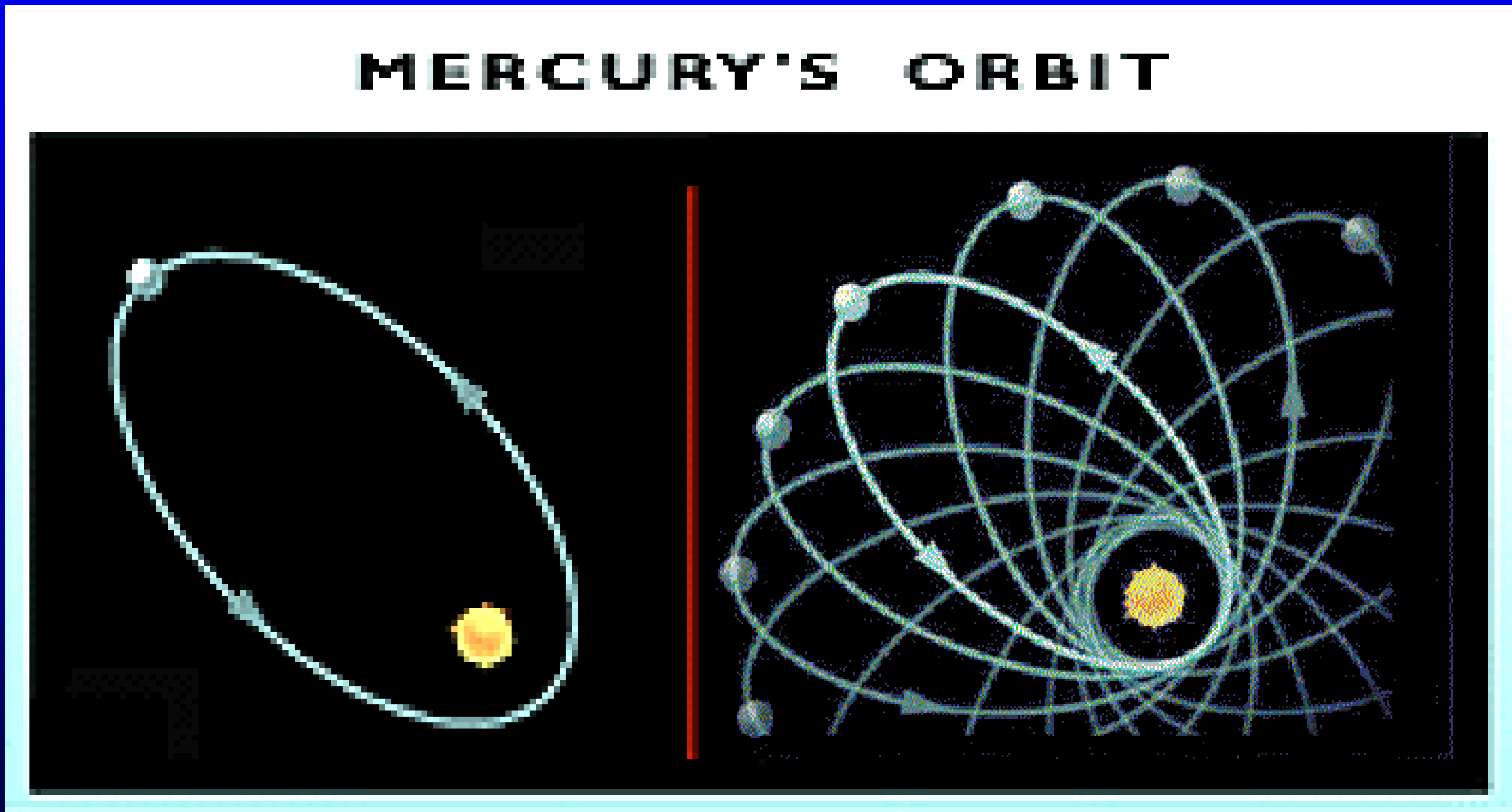
The Origin and Evolution of the Universe



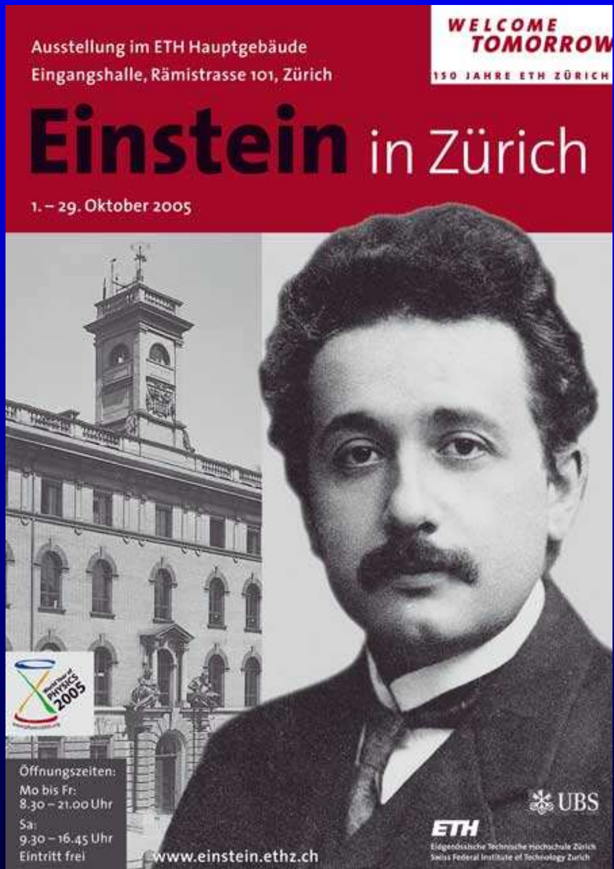
Isaac Newton



A problem - Mercury



Albert Einstein



1905 – Annus Mirablis

- Three outstanding papers:
  - 1) Light is in the form of discrete particles – photons. The Photo-electric Effect. Awarded Nobel Prize for this work in 1921.
  - 2) The cause of Brownian Motion – a demonstration of the random motion of atoms.
  - 3) The Theory of Special Relativity – with a supplementary paper relating energy to mass.

The Special Theory of Relativity

- Light travels through space at a constant speed c = 186,282 miles per second

  = 299,792,458 metres per second.

No material thing or any information can travel through space faster than the speed of light.

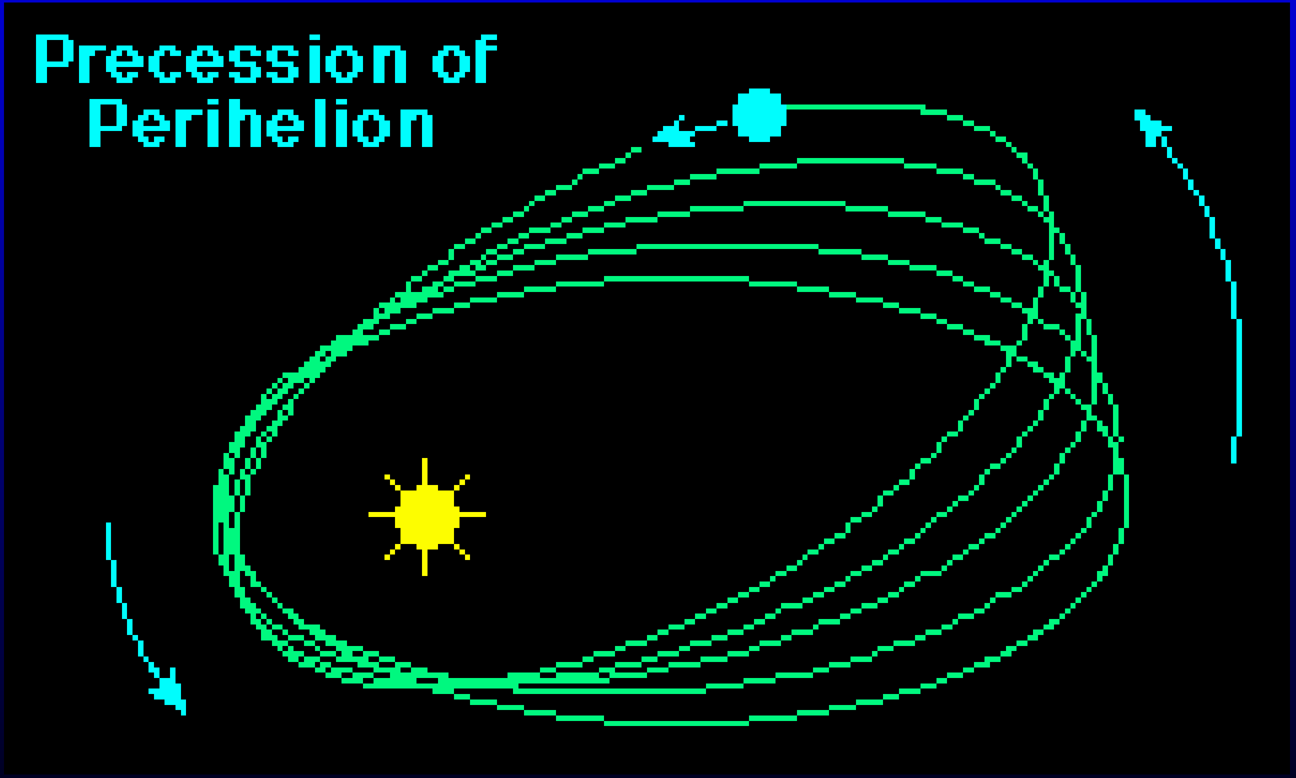
1915 The General Theory of Relativity

- Really a theory of gravity.
- He realised that there was a fundamental problem with Newton’s Theory.
- Let’s consider what would happen in the Sun suddenly disappeared.

His Theory

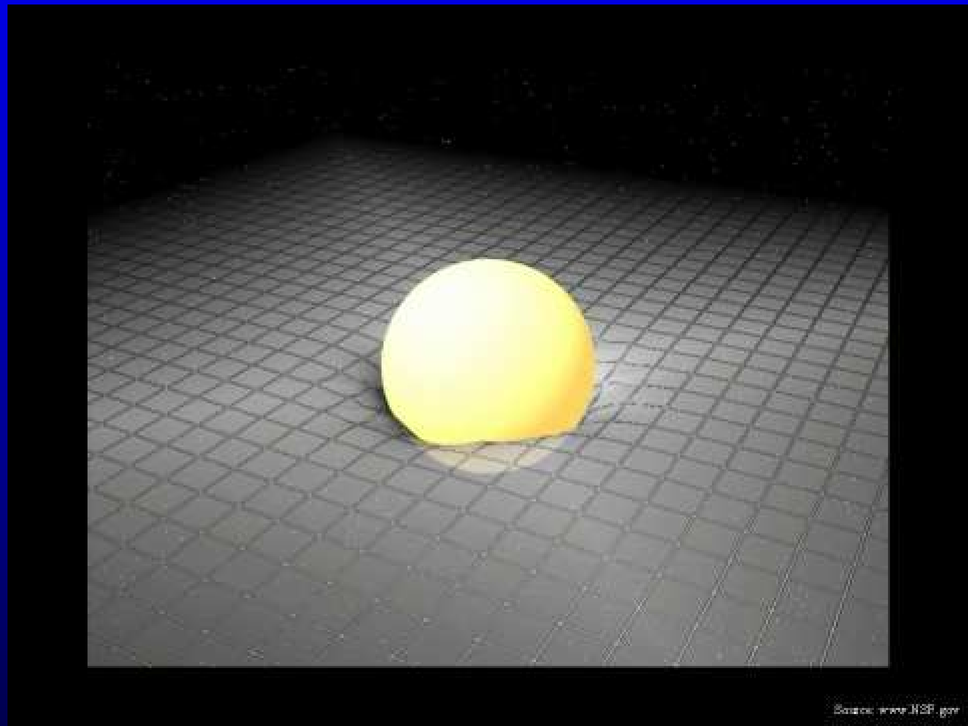
- The effects of a change in mass distribution cannot propagate faster that the speed of light.
- These changes are carried by gravitational waves that travels through space at the speed of light.
- So he predicted the existence of gravitational waves.

Explains the error in the observed precession of the orbit of Mercury

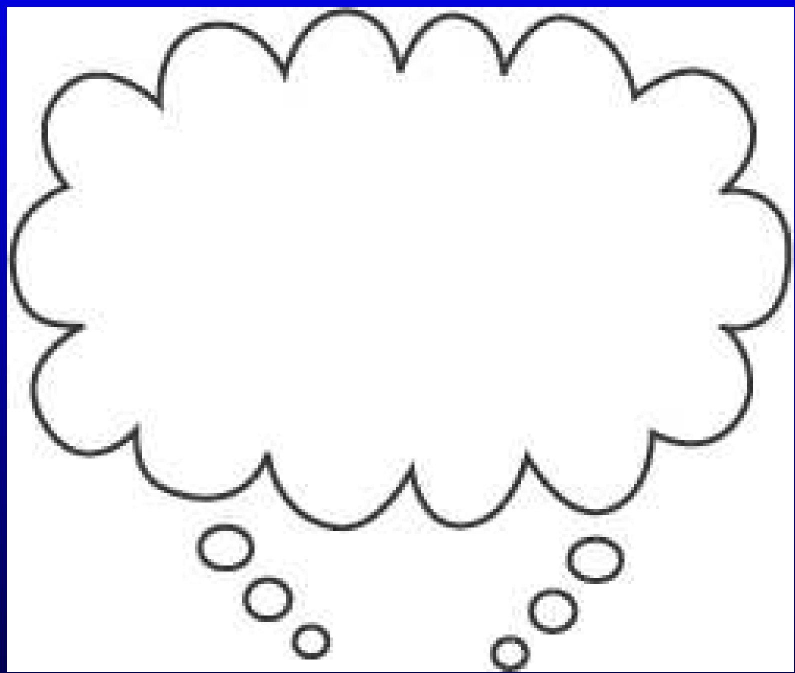


What is gravity?

- Einstein's Theory predicts that a mass will distort the "space-time" around it – giving the surrounding space positive curvature.



A thought Experiment.



General Theory of Relativity

- Einstein wanted to solve his equations for a "Static Universe" – unchanging in size.
- Problem: gravity is attractive so would make the Universe collapse.
- He thus had to include a form of anti-gravity which results from a term in his equation - the Λ term.
- Its effects increase with greater separation.

Einstein’s “greatest blunder”

- BUT such a Universe is unstable.

- Einstein called this model of the Universe the “greatest blunder” of his life.

Edwin Hubble

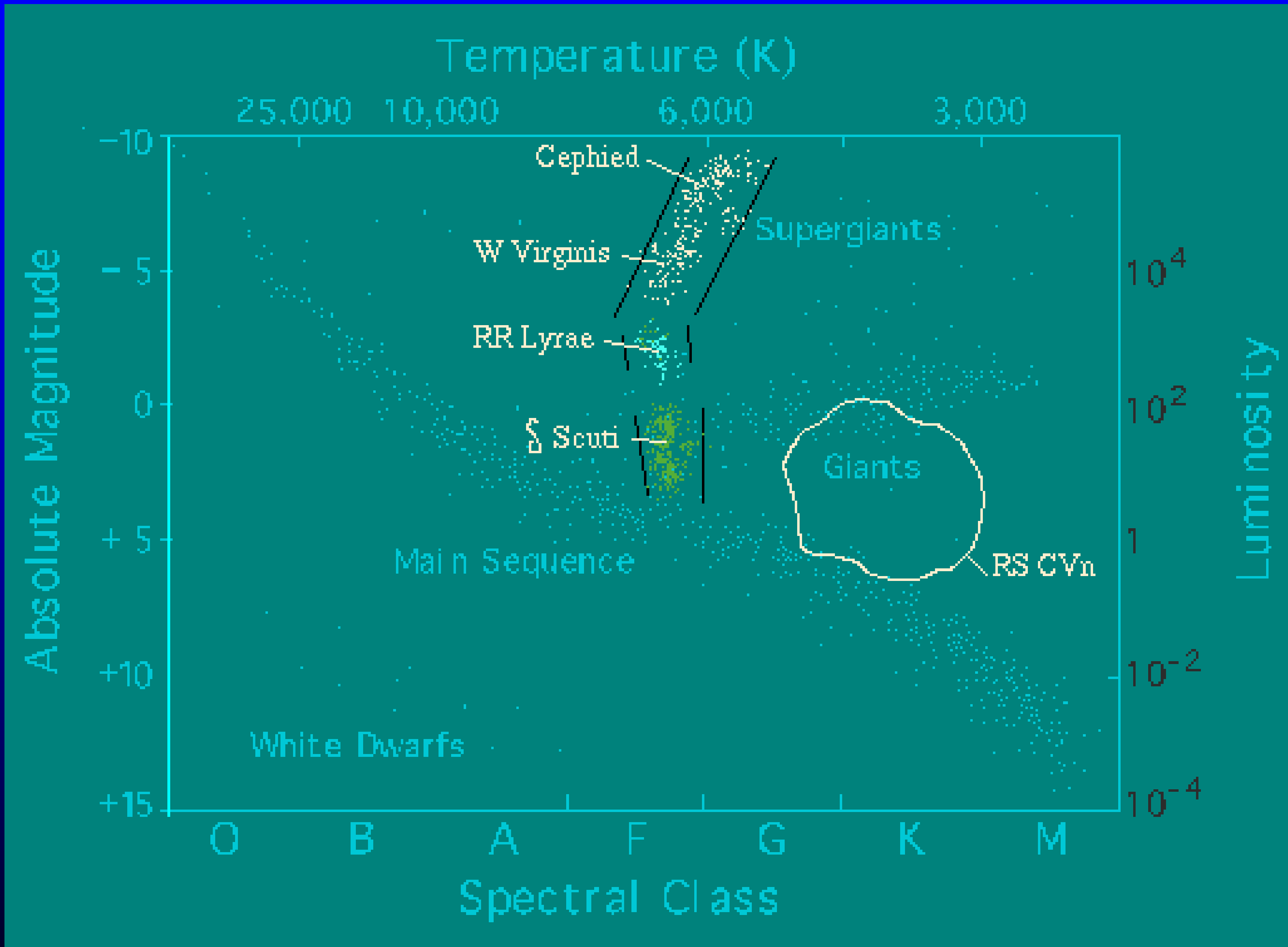
Showed that the Universe was expanding.

HOW?

Delta Cepheus

- Nearly two hundred years ago English astronomer John Goodricke discovered a new type of variable star in the Cepheus constellation called delta Cepheid. The star brightness varies regularly with period 5 days, 8 hours and 48 minutes.
- Delta Cepheid stars are rhythmically breathing in and out, becoming alternately brighter and dimmer in the process.

Where they lie in the HR diagram

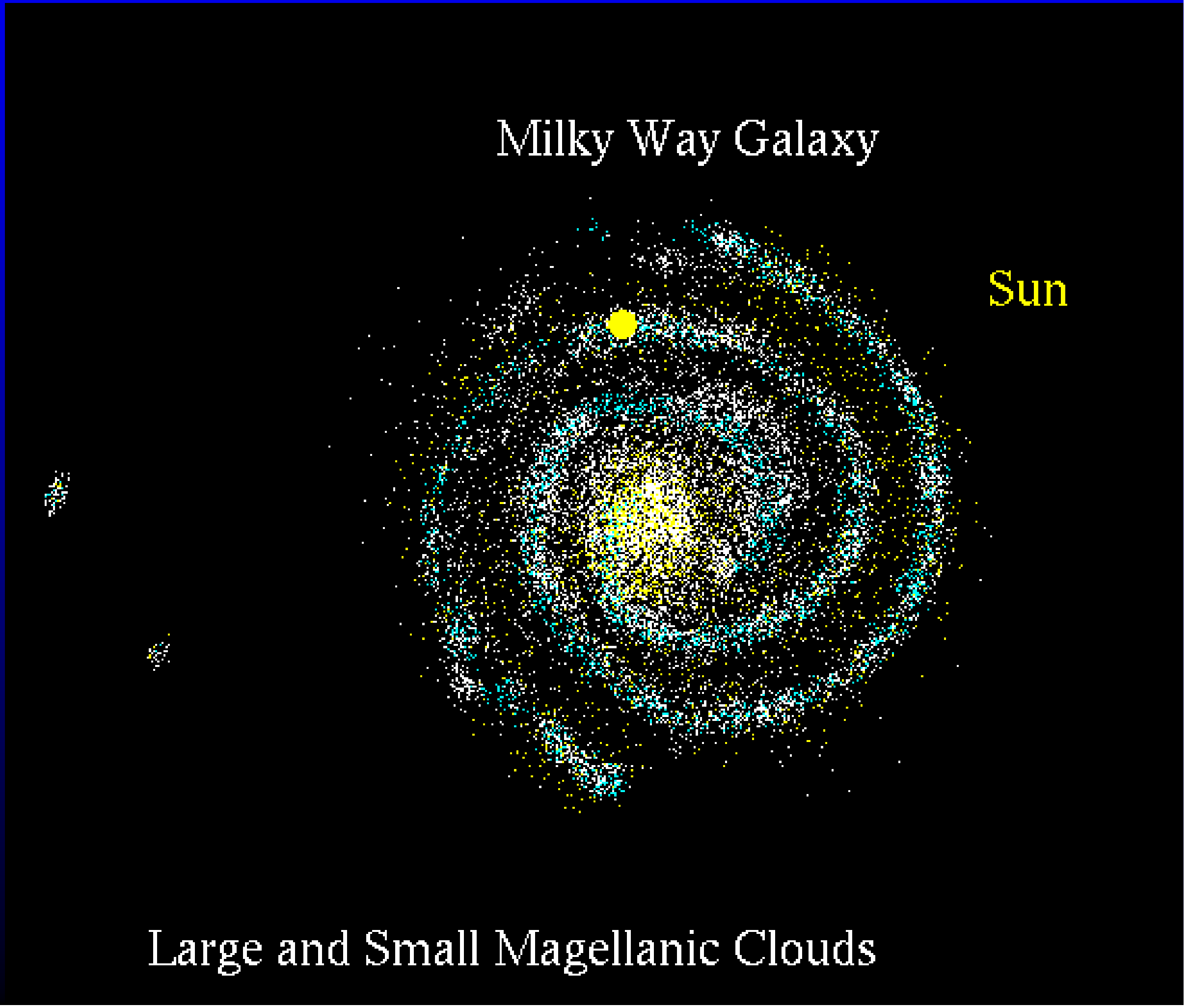


Henrietta Leavitt 1868 - 1921

- Born in Cambridge Mass, she studied Astronomy at Radcliffe College.
- Illness left her very deaf.
- Joined the Harvard Observatory in 1895 – 30 cents per hour. She became head of the stellar photometry dept.
- Discovered 2400 variable stars – half of those then known.
- The most brilliant woman in Harvard!

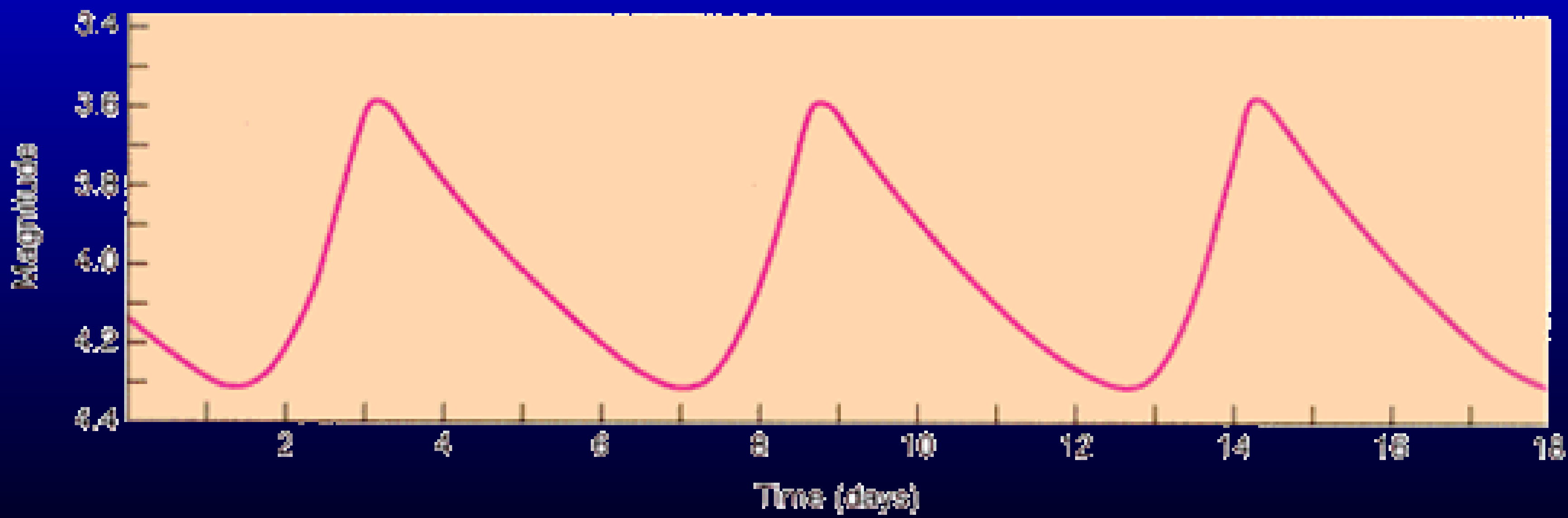
The Magellanic Clouds

- Henrietta Leavitt observed many of these cepheid variable stars in the Small Magellanic Cloud.
- These would all be at essentially the same distance.



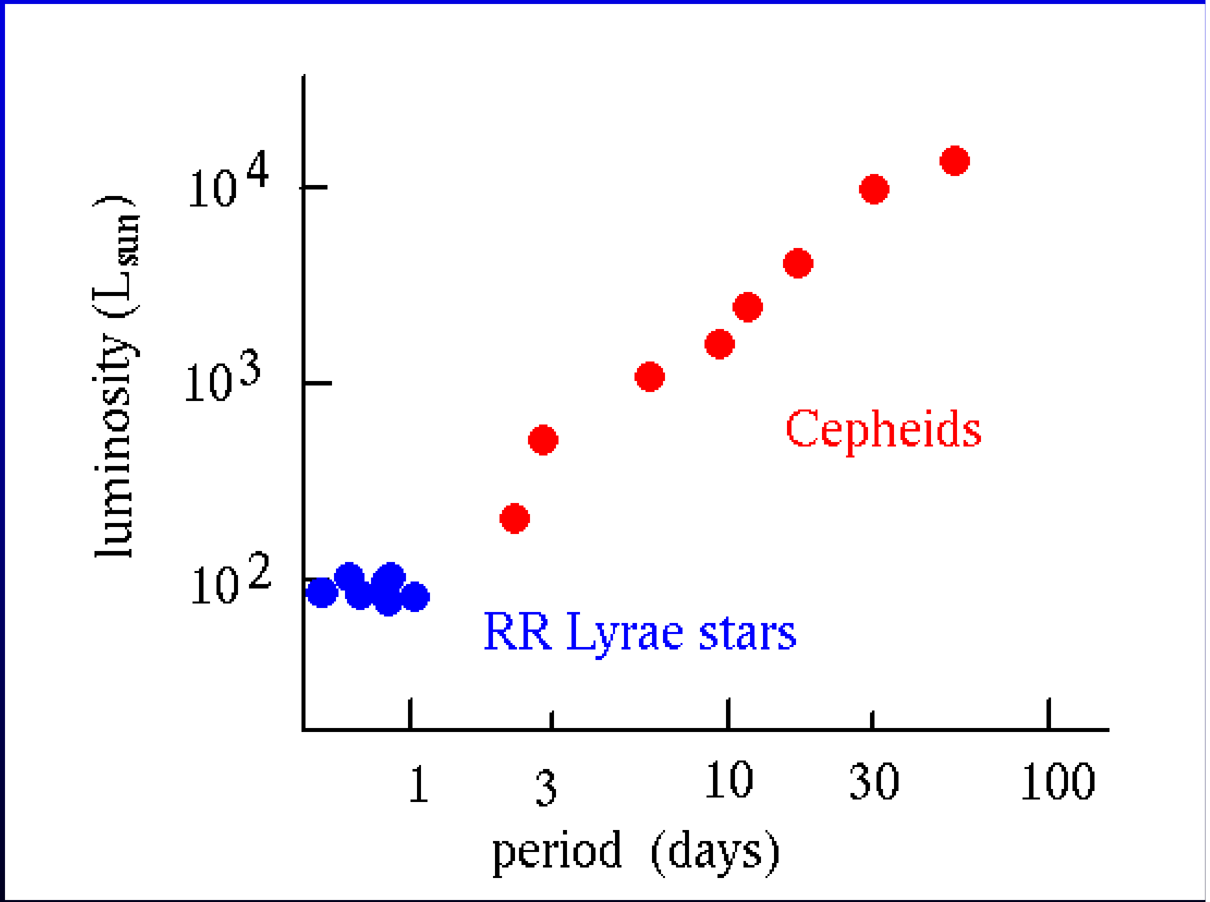
The Cepheid Variables

- Miss Leavitt observed that the Cepheid Variables had a very regular variation in brightness.



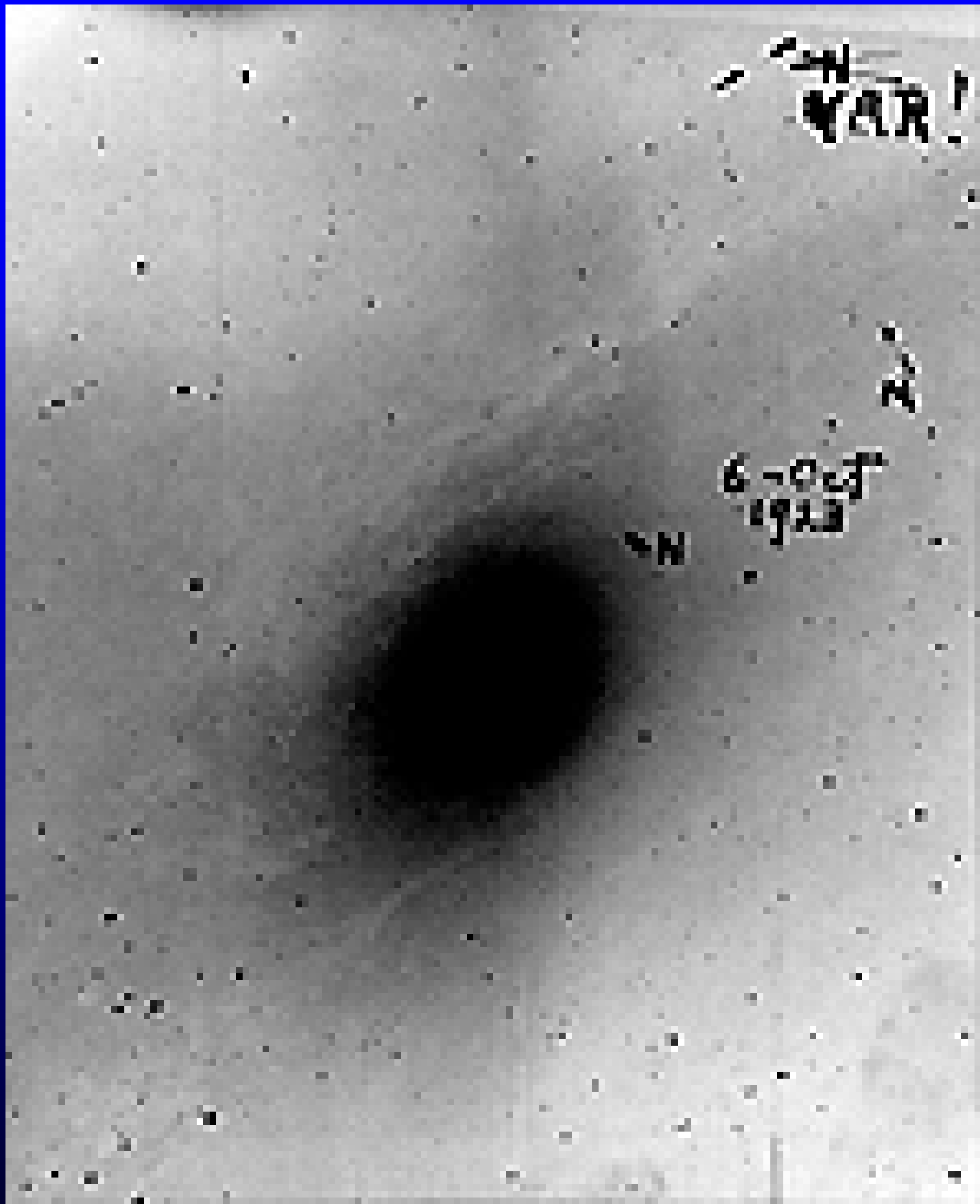
The Period-Luminosity relationship

- She noticed that the period was related to the luminosity.
- The more luminous stars had longer periods.
- This gave a way of measuring distances to any galaxy in which a cepheid variable could be seen.

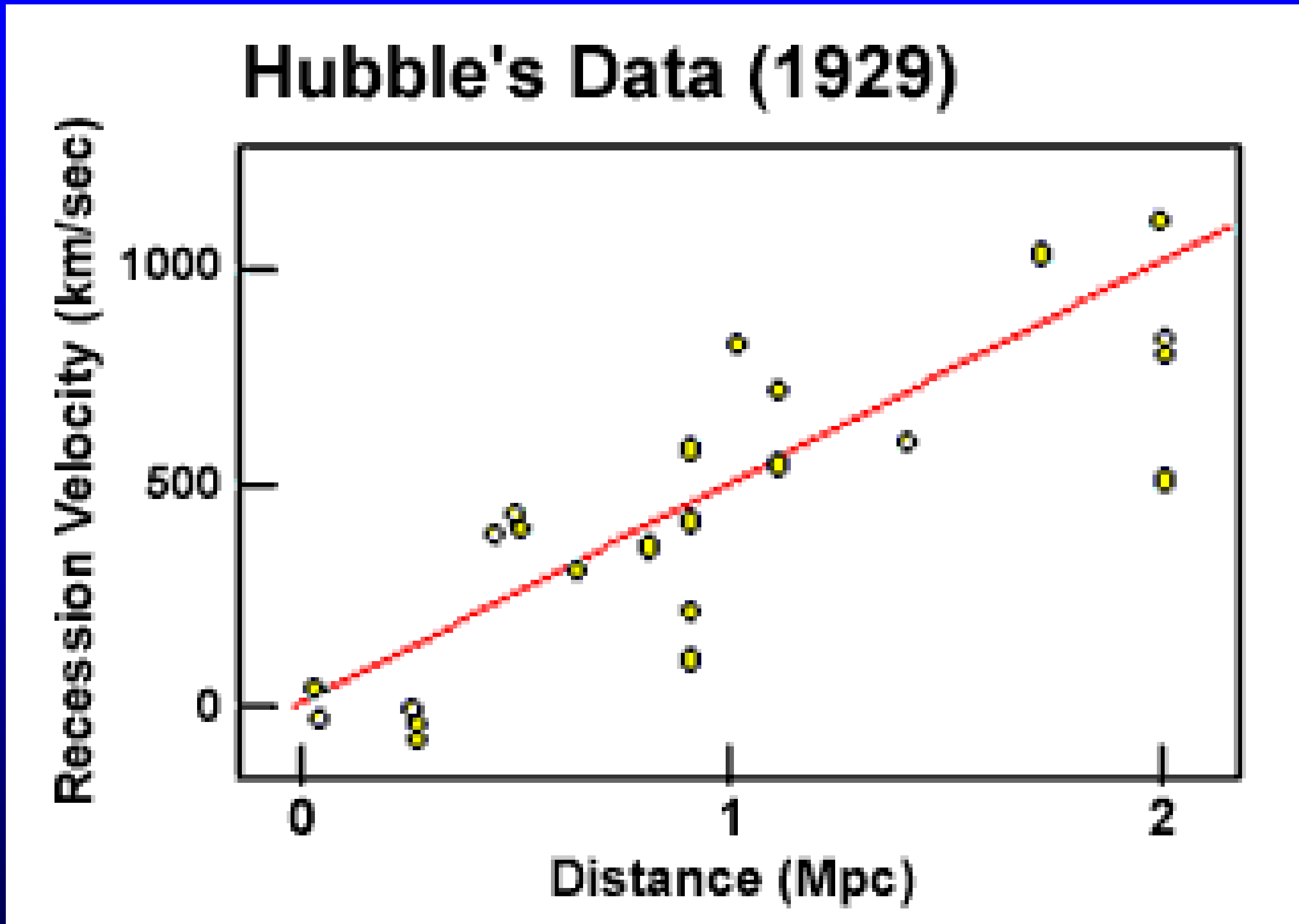


A Cepheid Variable in M31

- A photographic plate taken with the 100 inch Telescope.
- Hubble had discovered a Cepheid Variable.

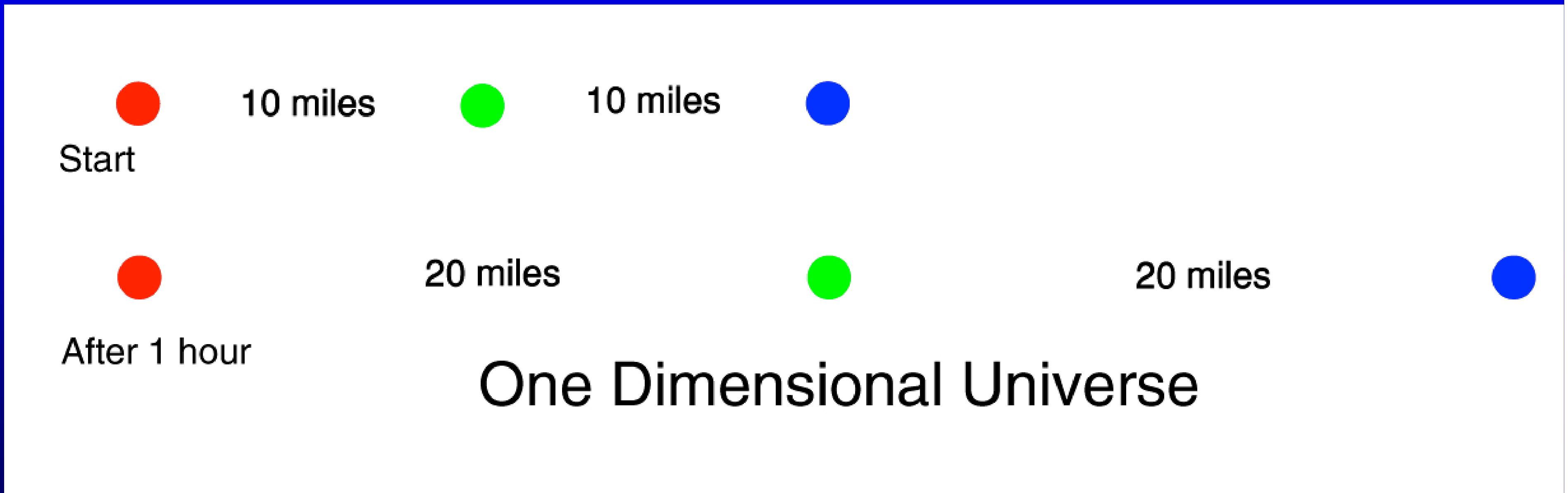


Hubble Diagram



$V = H_0 x R$ where H_0 = Hubble's Constant

An Expanding Universe

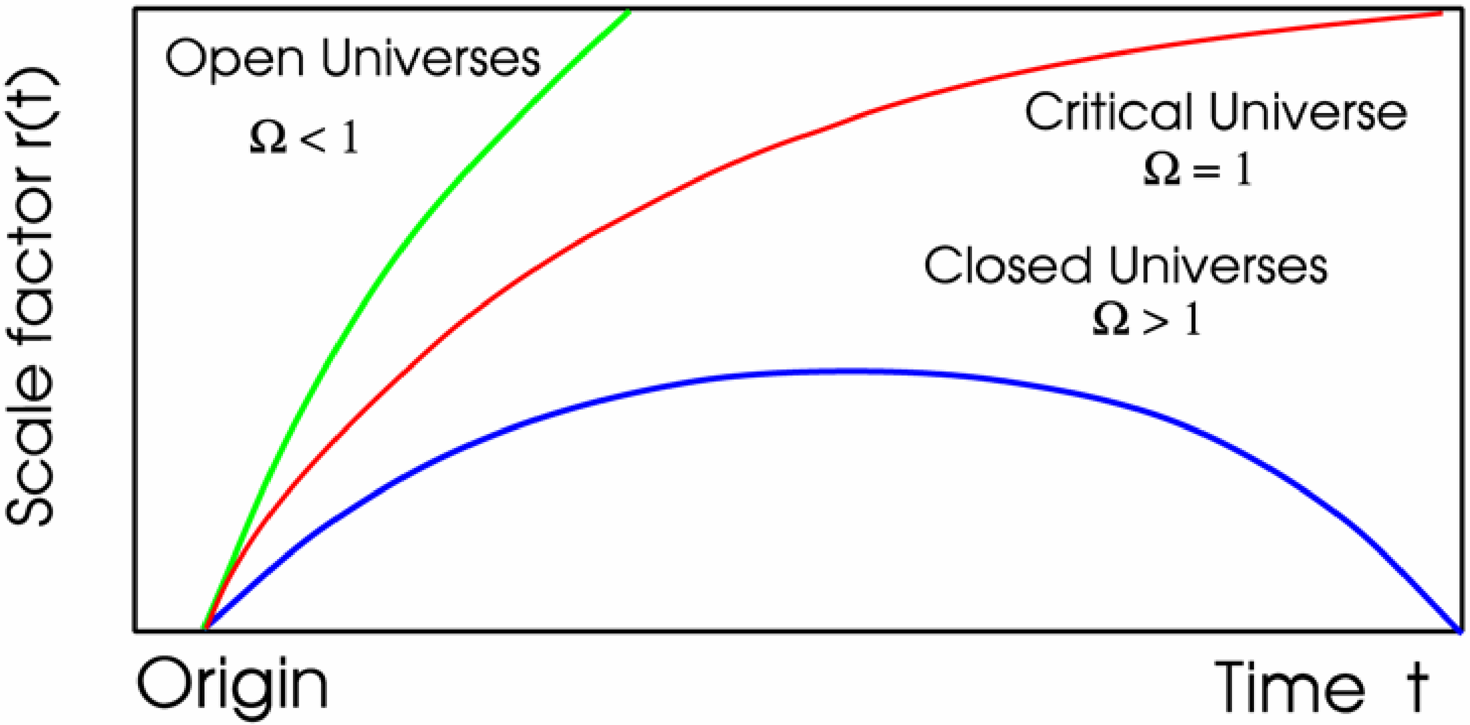


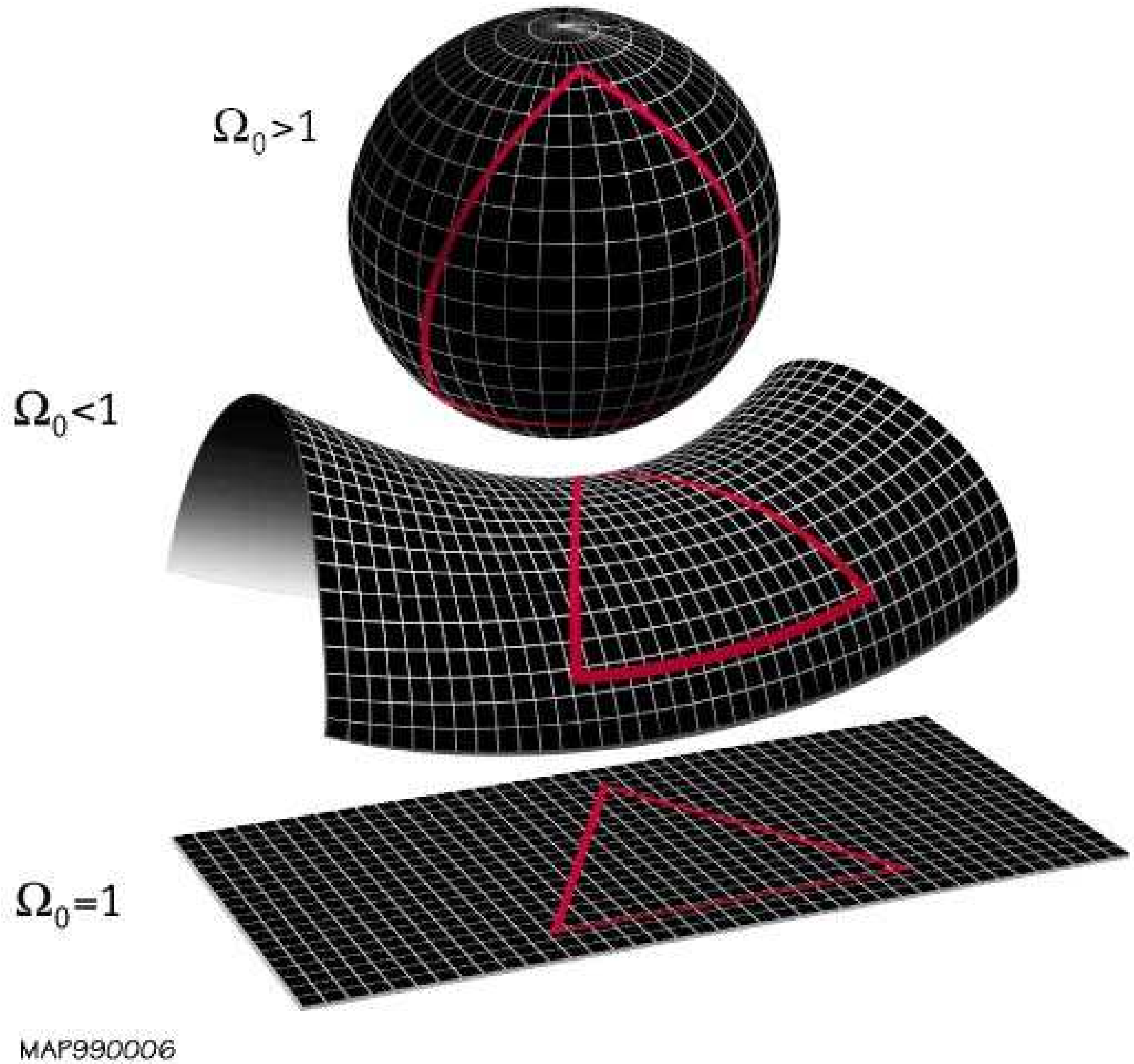
- The fact that the more distant galaxies were receding from us at a speed proportional to their distance implies that we live in an expanding Universe.

The ‘Big Bang’ Models

- A.A. Friedman solved Einstein’s equations to produce an infinite set of models of an expanding universe which have become known as the Big Bang models – a derogatory term given them by Fred Hoyle who opposed them.
- In all, the universes begin in a point singularity.
- The initial high rate of expansion then falls with time due to the mutual gravitation of all the matter in the universe.

Freidman “Big Bang” Models




$\Omega_0 > 1$
$\Omega_0 < 1$
$\Omega_0 = 1$
MAP990006

Open, Critical (Flat) and Closed universes.

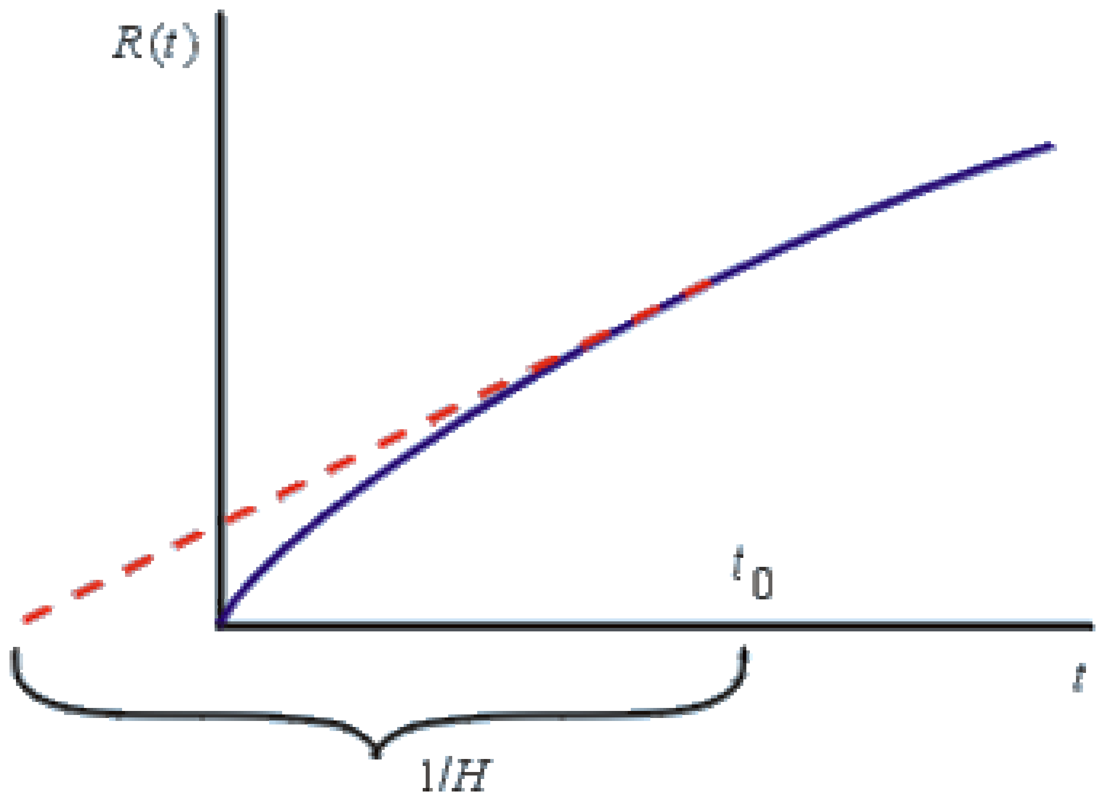
- The Critical or Flat universe is the boundary between the open and closed universes.
- The universe then has a “critical density”
- If the density is greater than this we have closed universes which will eventually collapse to a “Big Crunch”
- The ratio of the actual density to the critical density is called Ω, Omega.

- If Ω is > 1 we have closed universes.
  - Space is positively curved
- If Ω is $= 1$ we have the critical universe.
  - Space is “flat”
- If Ω is < 1 we have open universes.
  - Space is negatively curved.

The Hubble Age

- If we assume a constant rate of expansion, then we can extrapolate back to find when the Universe had no size – its origin.
- The age – called the Hubble Age or the Hubble Time - is then simply $1/H_0$.

From the present slope we can estimate the age of the Universe



Hubble Age

$1/H_0 \;=\; 1\text{ Mpc} \;/\; 500\text{ km/sec}$

$= \;\; 3.26\text{ million light years}/\;500\text{ km} \quad \text{sec}$

$$= \frac{3.26 \times 10^6 \times 365 \times 24 \times 3600 \times 3 \times 10^5}{500}\text{ sec}$$

$$= \frac{3.26 \times 10^6 \times 3 \times 10^5}{500}\text{ years}$$

$= \; 1.96 \times 10^9\text{ years} \;=\sim\; 2\text{ Billion years}$

Actual Age is Less

- In all the Friedman Models the actual age is less than the Hubble Age as the initial expansion was greater.
- In the case of the “Critical” or “Flat” Universe the actual age is 2/3 of the Hubble Age.
- = 2/3 x 2 Billion year

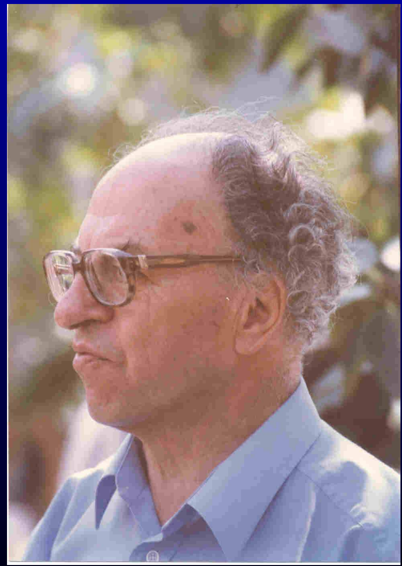
  = ~ 1.3 Billion years

This was a problem!

- Measurements of the age of our Earth – 4.5 billion yrs, and calculations made by Fred Hoyle and others of the lifetimes of stars ~ 8 billion years indicated that the Universe must be older than this.
- Could the Big Bang theories be wrong?

The Steady State Theory

- In 1949, Fred Hoyle, Thomas Gold and Herman Bondi produced a rival theory of cosmology – the Steady State Theory or the Theory of Continuous Creation.



The Cosmological Principle

- All cosmologies adhere to the Cosmological Principle:
  - what one would see on the large scale at a specific time will be the same everywhere in the Universe
- The Steady State Theory changes this to the Perfect Cosmological Principle:
  - what one would see on the large scale will be the same everywhere in the Universe for all time.
- The Universe is unchanging on the large scale.

Continuous Creation

- The Universe is expanding, so galaxies will gradually move apart decreasing the density of galaxies in space.   Bondi, Hoyle and Gold proposed in the space between the galaxies new matter, in the form of Hydrogen, was being created.
- This would eventually form Galaxies so the average density would remain constant.

How can we decide?

- The rate of creation of new matter is too low to observe.
- But problem to explain the amount of Helium in the Universe - BHG assumed that all Helium was formed in supernova explosions. It does not look as though enough Helium could be formed this way.

M1

The Crab Nebula

Another Problem for the Steady State Theory

- The Universe a long way away should look like the Universe nearby as, on the large scale, the Universe should not change with time.
- The discovery of Quasars did not seem to agree with this.

Quasars

- Quasi-Stellar Objects – looking like a star!
- In fact, galaxies with active galactic nuclei
- These were a long way away.
  - 3C273 - 2000 million light years distant
  - 3C48 - 7000 million light years distant
- Remember that we see these as they were in the past.
- There are none close to us.
- This means that, in the past, the Universe was not the same as now.

Compare the density of galaxies now and back in time.

- Take a volume of space surrounding our Galaxy – this is the Universe now.
- Take the same volume of space a long way away - that was the Universe a long time ago.
- Compare the densities.
  - Steady State = the same
  - Big Bang = denser then than now

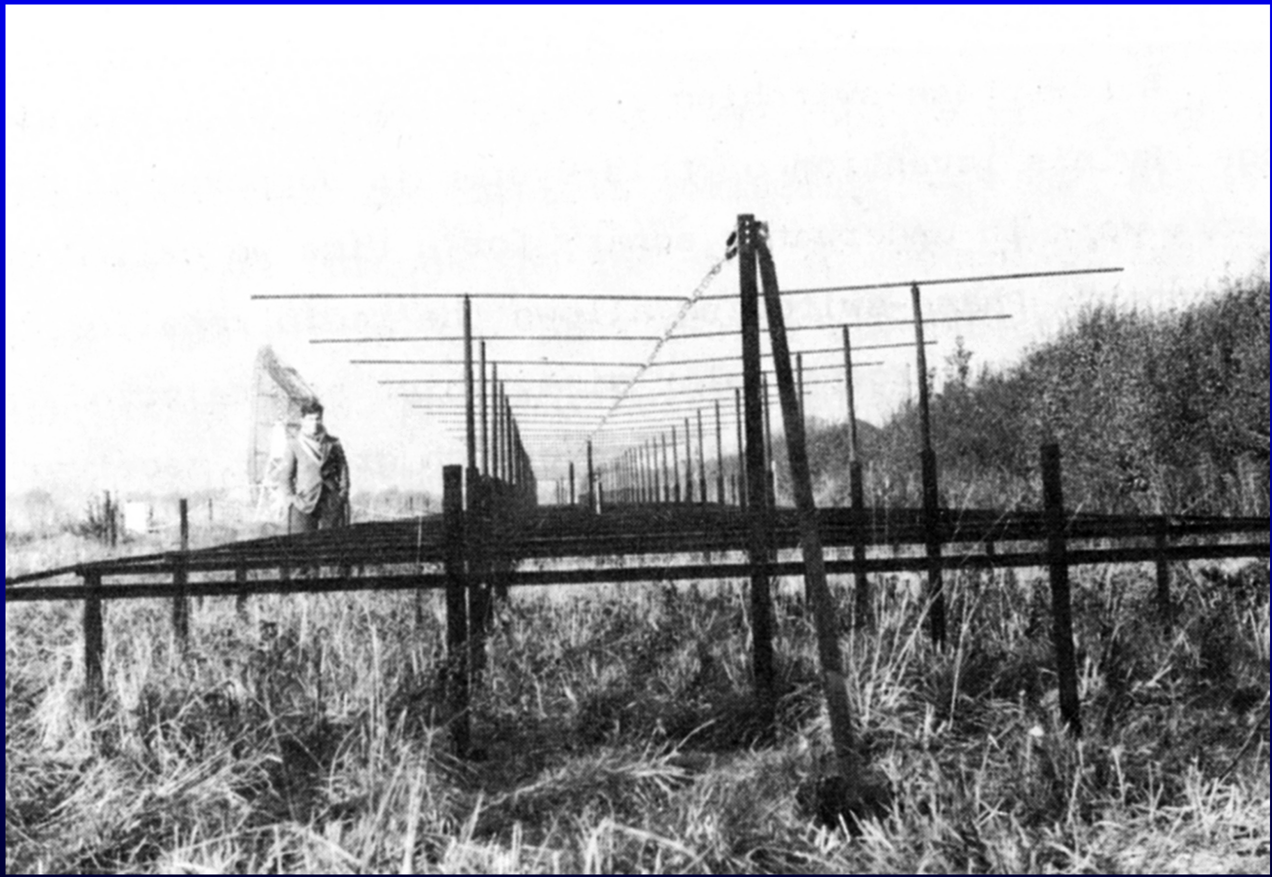
Observing Radio Sources

- Martin Ryle set about observing the density of radio sources nearby and far away.
- Ryle's results showed a great excess of distant sources over nearby ones – Steady State was out!
- His results were initially flawed.
- Enormous rows with Hoyle resulted.

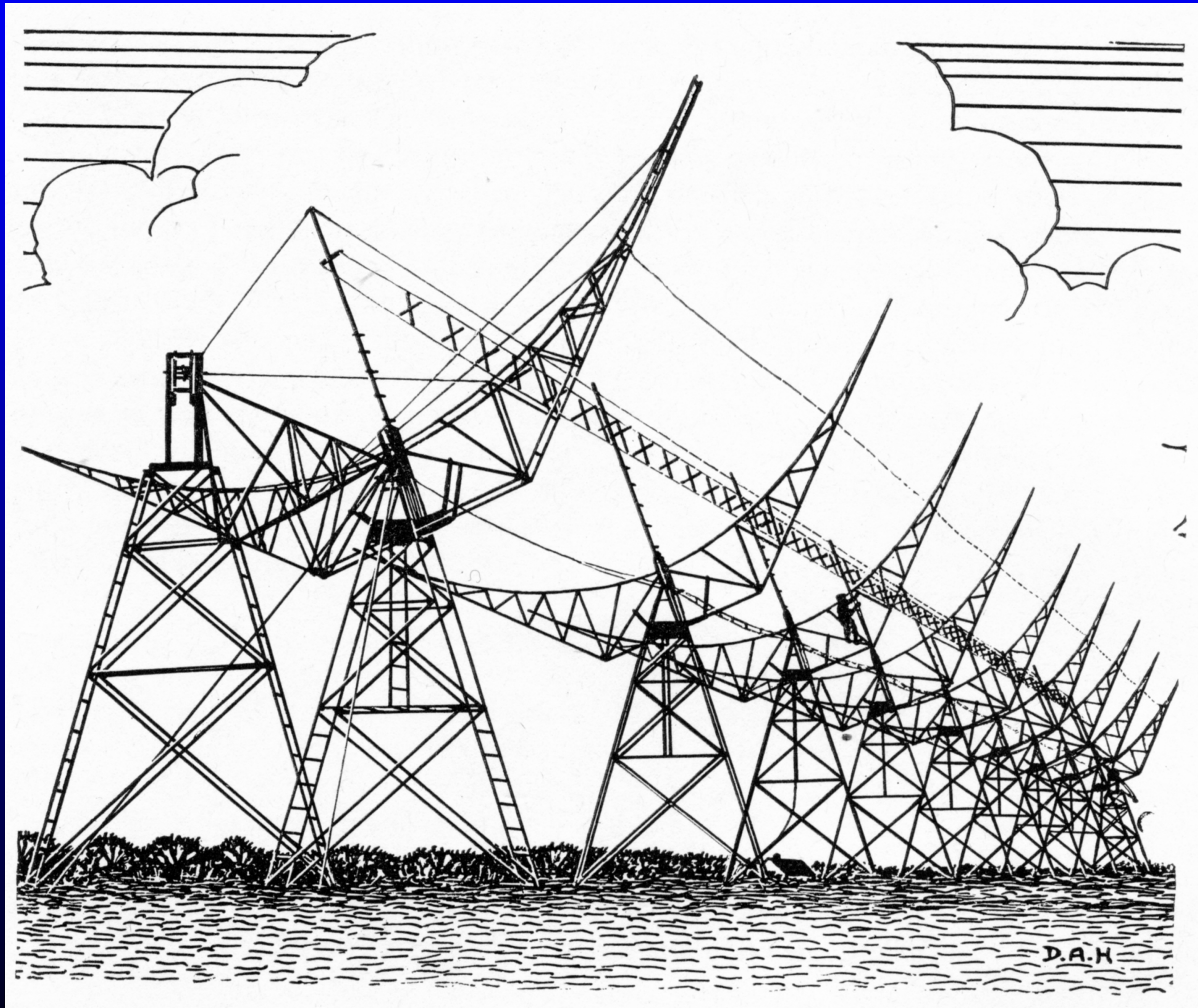
Martin Ryle

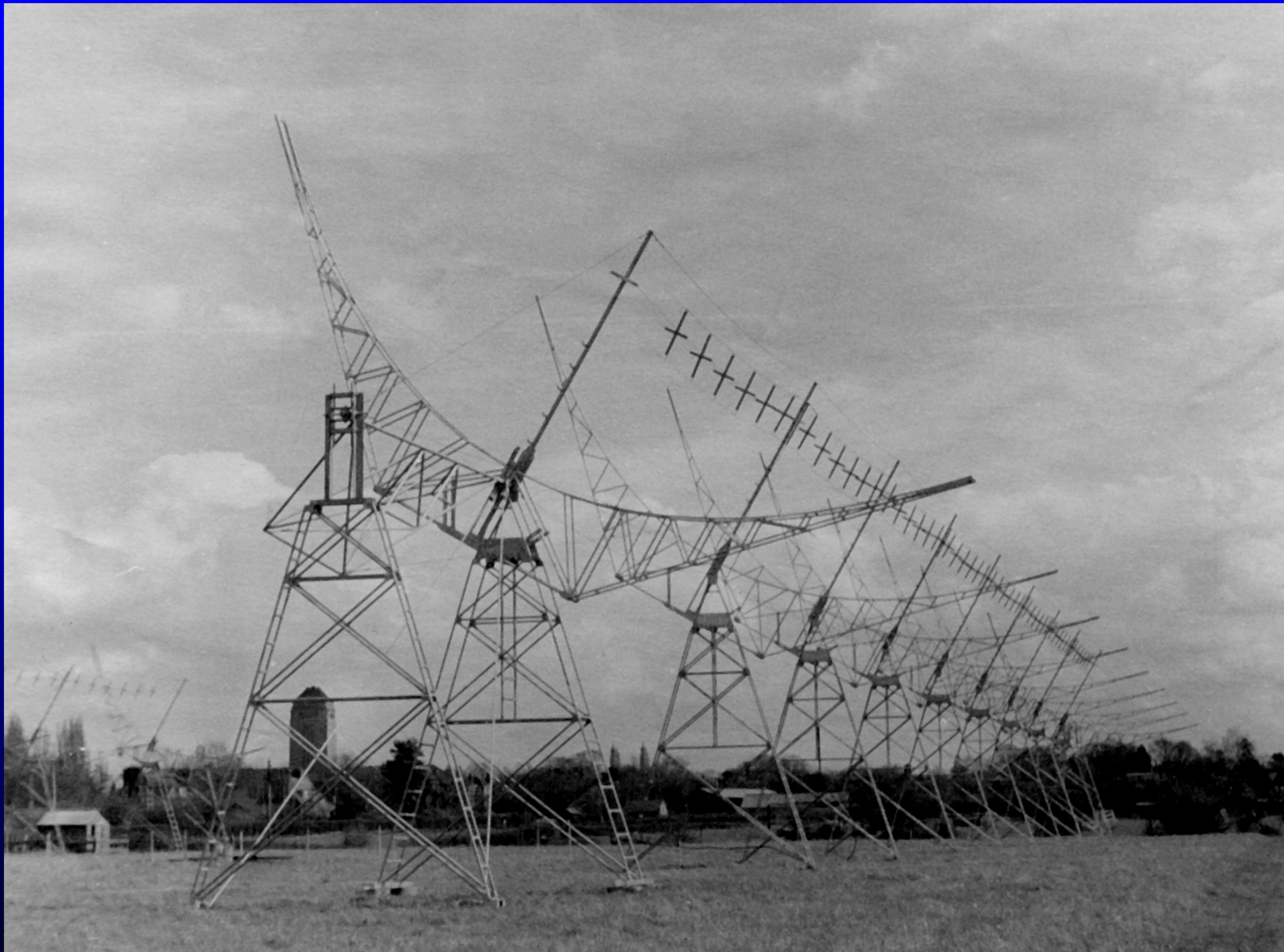
Two Astronomers Royal

81 MHz Interferometer



3C Array



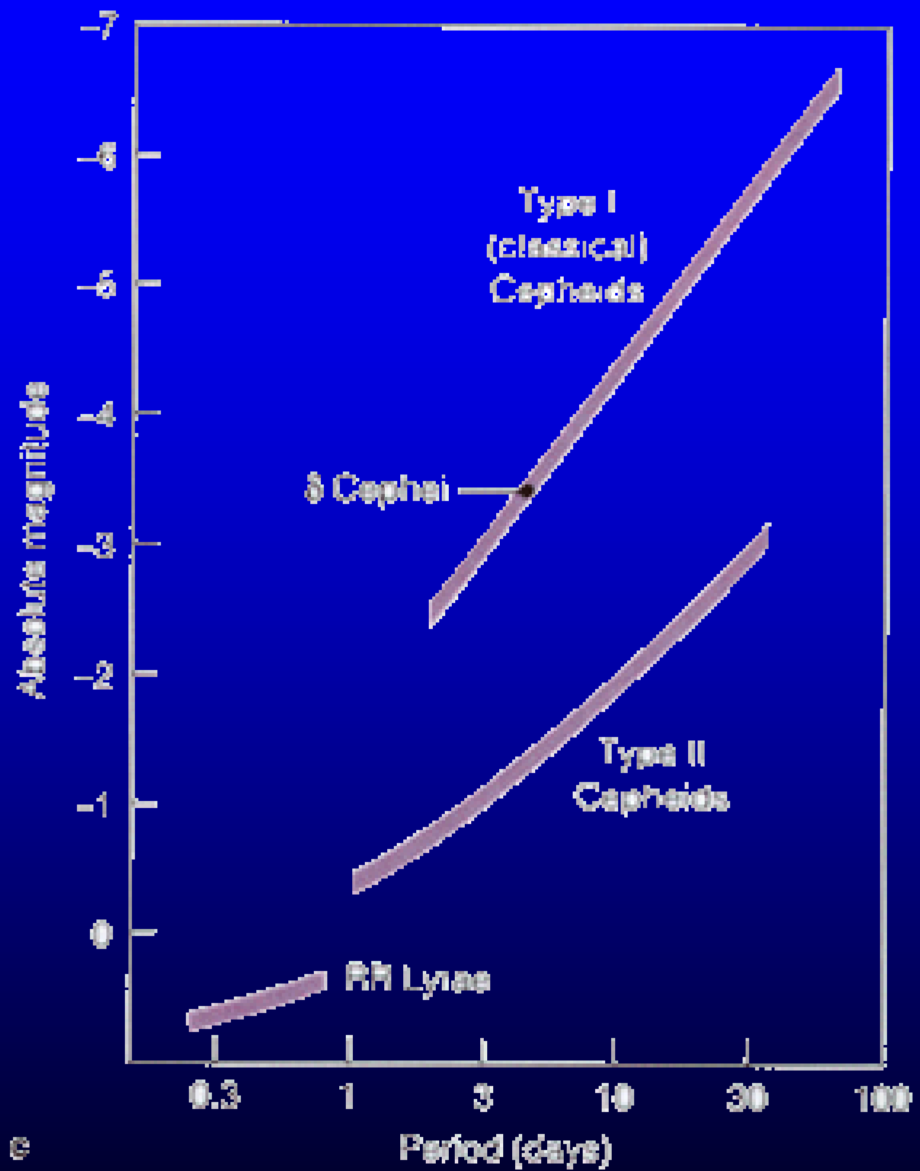


The third set of results

- Finally Ryle got it right.
- The data still showed that radio sources were more densely packed in the early Universe.
- Hoyle was not convinced!
- Finally came the nail in the coffin for the Steady State Theory – we shall look at shortly.
- But what about Hubble's value of the age?

Two Types of Cepheids!

- There were two types of cepheids.
- Those that were observed in the distant galaxies were about 4 times brighter



His original value was wrong

- Over the years the value of the age has gradually been refined.
- The Hubble Space telescope has observed many Cepheid Variables and shown that the value of H is 72 +/- 8.
- Jodrell Bank are also measuring this value using gravitational lenses– latest value is 71+/- 6.
- BUT age (in the Friedmann models) is still only ~10 billion years.
- Ignore for the time being but a problem for the standard big bang theories.

Proof of a "Hot Big Bang"

- George Gamow was the first to point out that if the origin of the Universe had been very hot, there should still be some radiation from that time which should pervade the whole of the Universe.
- We now call this the Cosmic Microwave Background.

The Cosmic Microwave background

- For ~300,000 years the Universe was too hot for atoms to form.
- Matter and radiation were interacting – a plasma.
- So the Universe was opaque – like in a fog or a cloud.

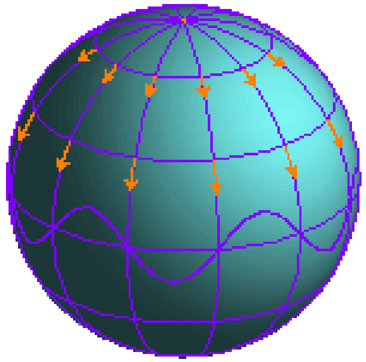
The Cosmic Microwave Background

- Finally it was cool enough for atoms (H and He) to form. (~380,000 years after the origin)
- The Universe then became transparent – so this is as far back in time as we can see.
- Radiation then had the same temperature as matter ~ 3000K.
- It would have had a Black Body Spectrum with the radiation peaking in the visible part of the spectrum.

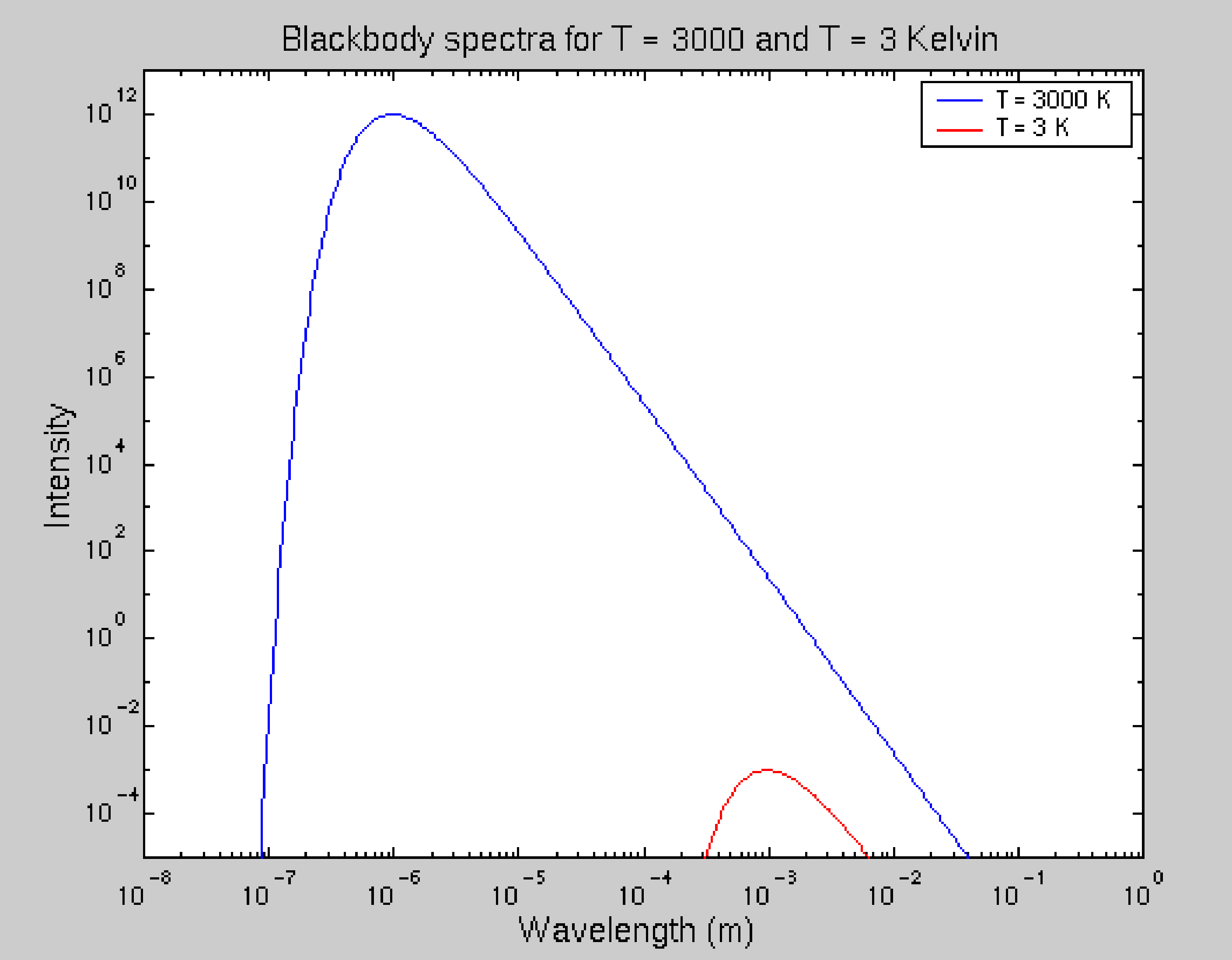
The Cosmic Microwave Background

- Since then, the Universe has expanded by 1000 times.
- As a result, the temperature of this radiation has fallen by the same ratio – so now ~ 3K

Wavelengths expand as the Universe expands



The Cosmic Microwave Background



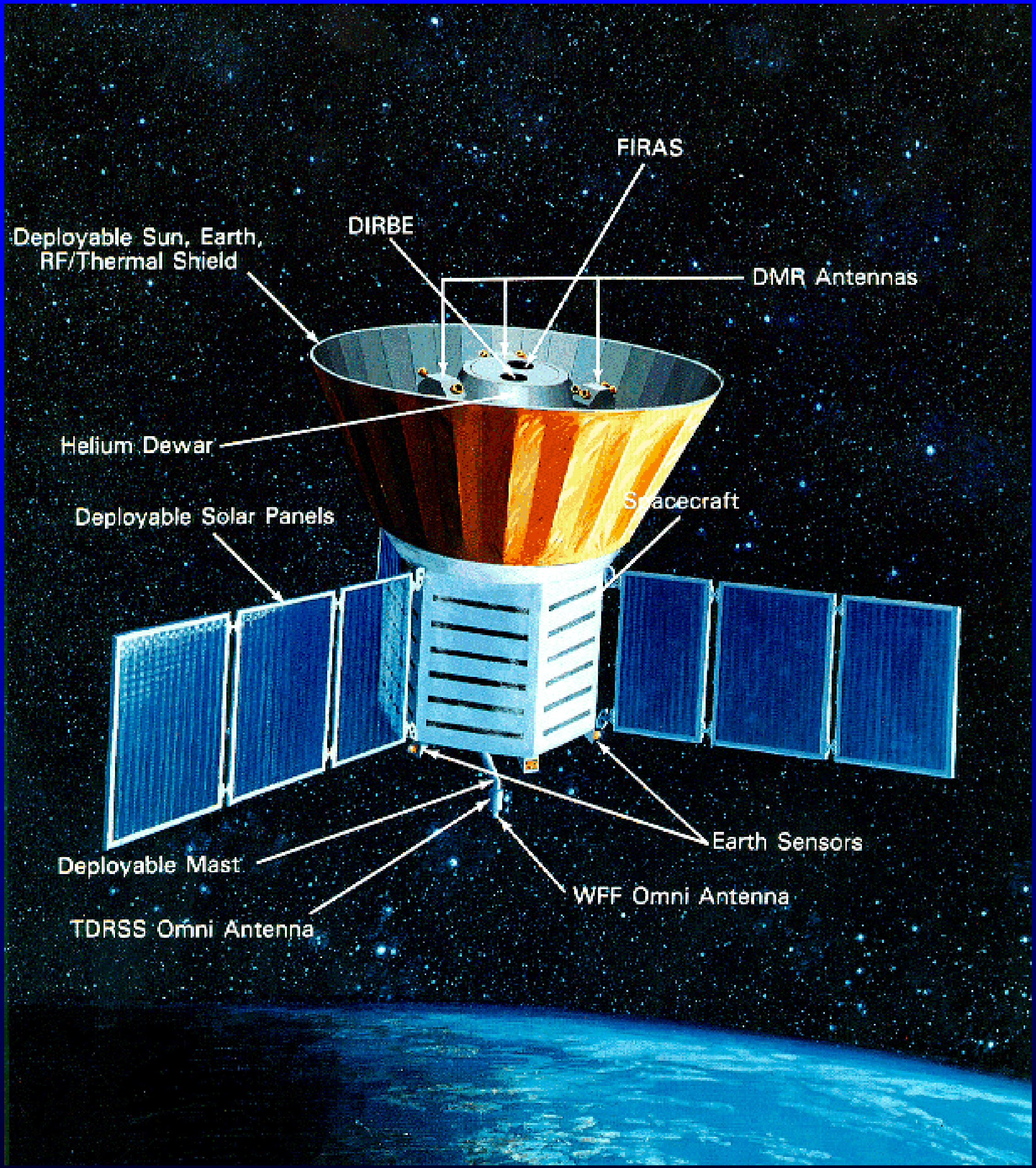
- The CMB now peaks in the far infra-red and very short radio wave part of the spectrum

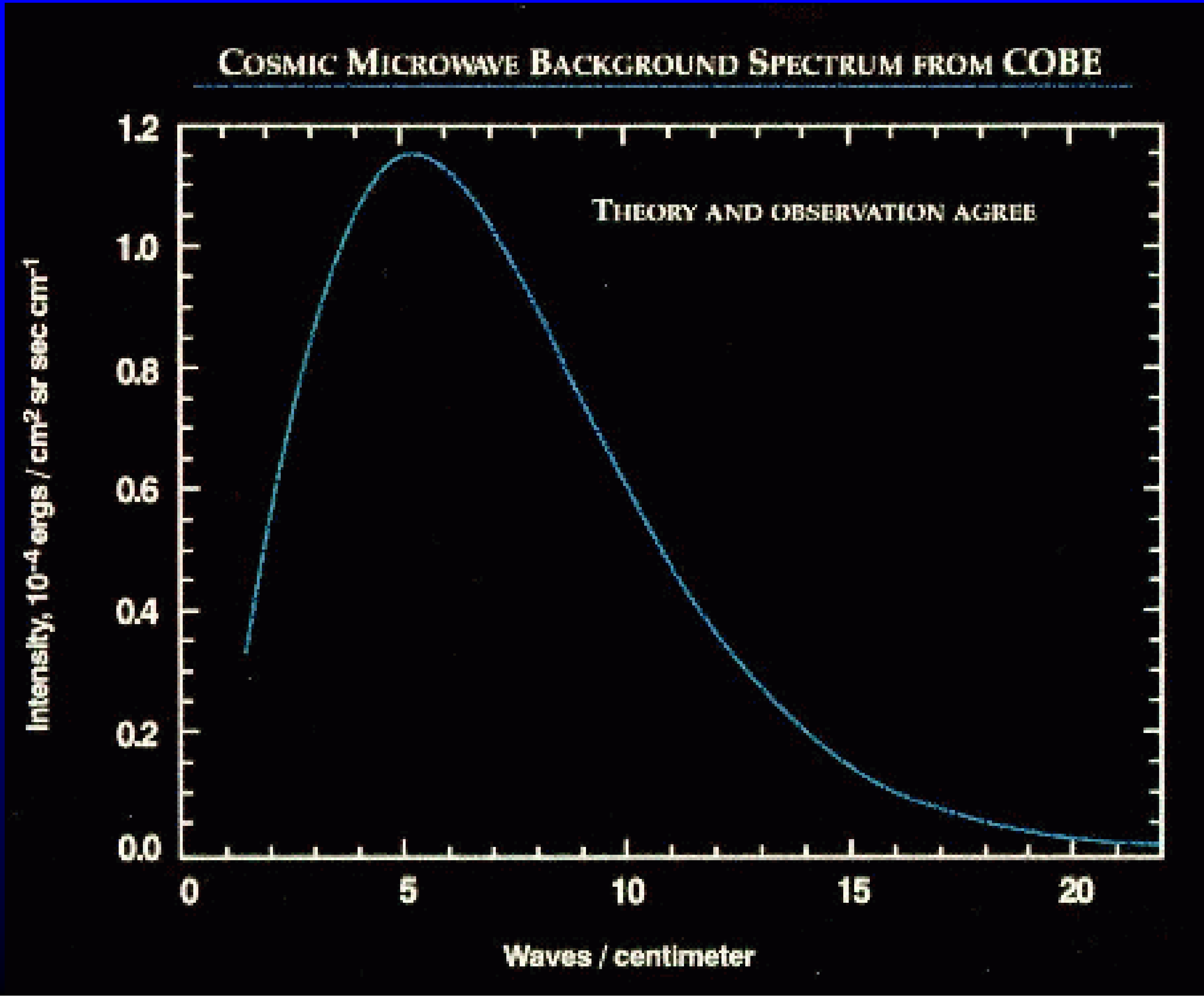
Penzias
and
Wilson

Pigeon Trap

COBE

Far Infrared Absolute Spectro-photometer





COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
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

Discovery of the Cosmic Microwave Background

- Penzias and Wilson discovered the CMB serendipitously in 1965 using an antenna at Holmdale, New Jersey.
- It was shown to have a blackbody curve, which peaks in the far infra-red, by the COBE satellite in 1992.
- There WAS a hot Big Bang.

Why is space so flat?

- As far as it could be measured the curvature of space in our Universe appeared to be very close to zero.

- Why should the Universe be so close to this critical division between the open and closed Universes?

Fine Tuning

- Any curvature that the Universe has close to its origin tends to get enhanced as the Universe ages - a slightly positively curved space become more and more so and vice versa.
- In fact, had not Ω been in the range 0.999999999999999 to 1.000000000000001 one second after its origin the Universe could not be as it is now.
- This is incredibly fine tuning, and there is nothing in the standard Big Bang theory to explain why this should be so.

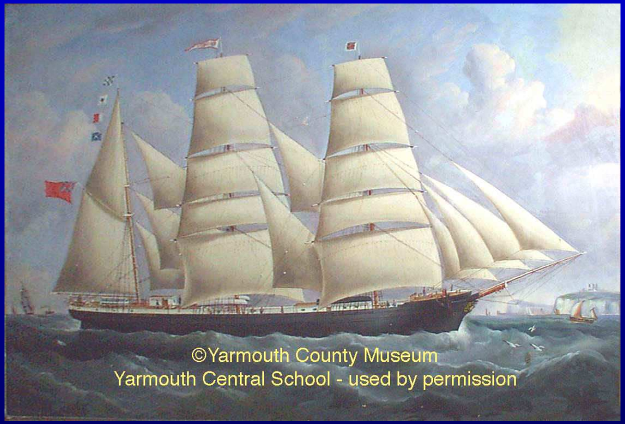
Why is the CMB so uniform?

The Horizon problem

- Radiation has not had time to traverse the whole universe so why is it all at the same temperature?
- We see the CMB is two opposing directions
  - The radiation has taken ~ 14 billion years to reach us from each direction.
  - There has not been time to travel from one side to the other.

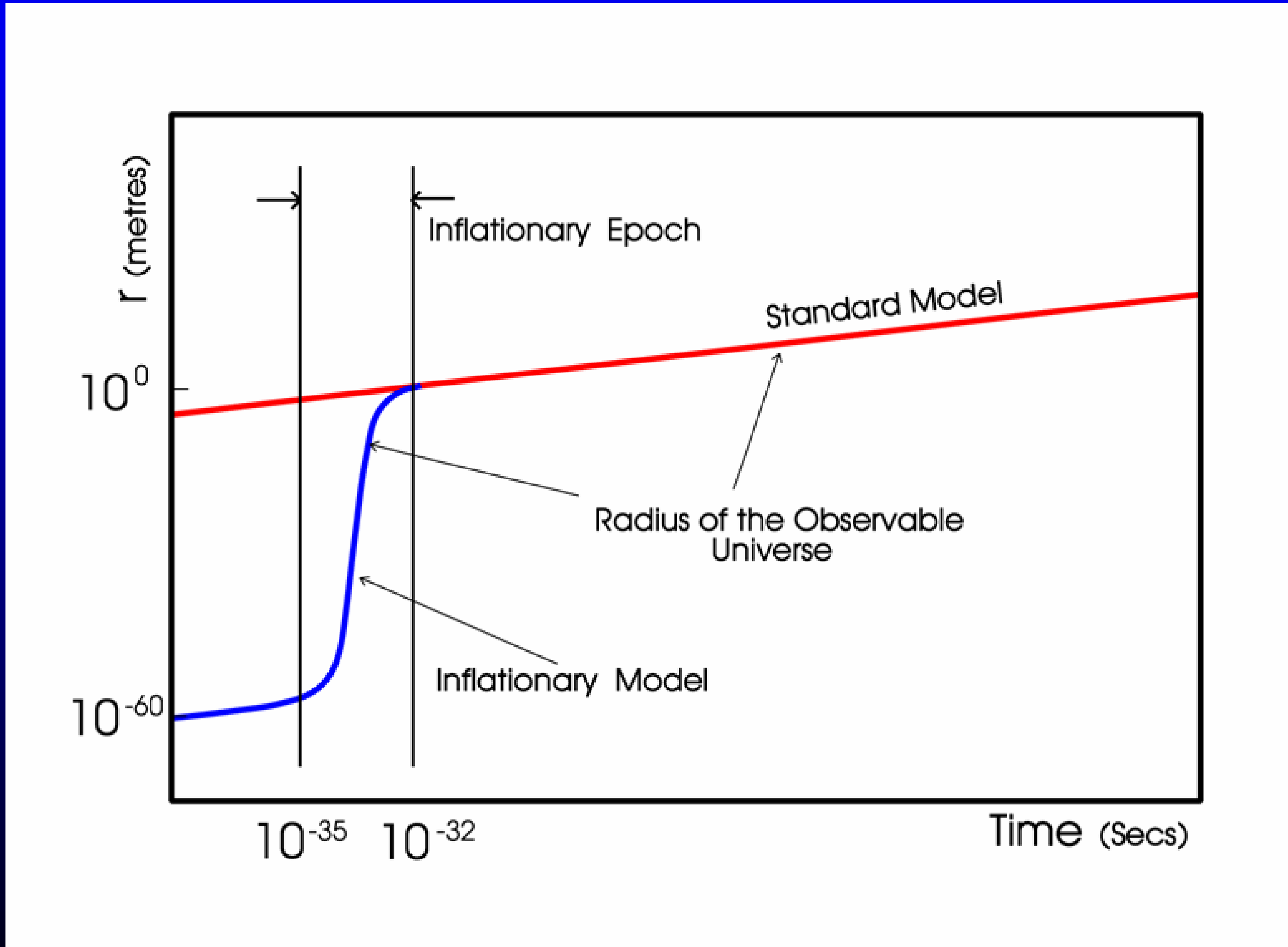
The Horizon Problem

- Another Thought Experiment

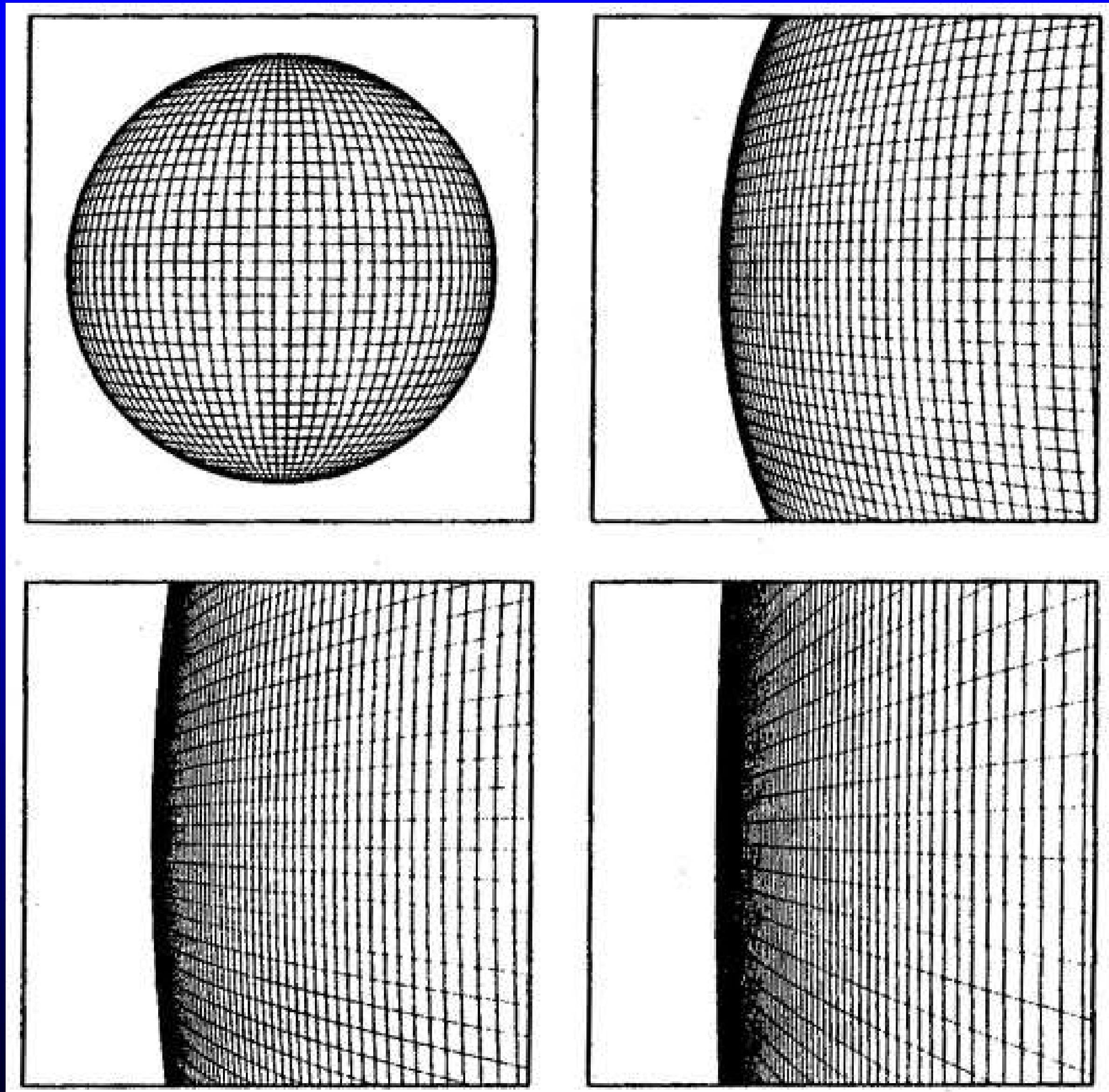


Alan Guth

Alan Guth's Idea: Inflation



Inflation would make space "flat"



- Inflation solves the flatness problem.
- It also solves the horizon problem as ALL of the visible Universe would have been in “causal contact” before the inflationary period hence in thermal equilibrium.

The Big Bang

- The energy created during the inflationary period was 50% Gravitational Potential Energy and 50% Kinetic Energy.
- So net energy is zero!
- Out of the Kinetic energy was created an almost equal number of matter particles and antimatter particles. But with a 1 part in ~ 8 Billion excess of matter particles.

- The antiparticles annihilated the equivalent no of antiparticles producing the photons that make up the Cosmic Microwave Background.
- The normal matter particles left over were mostly Up and Down quarks.
- Up quarks have +2/3 charge.
- Down quarks have -1/3 charge.

- The quarks combined in groups of three
  - Two Up and one Down give a proton with +1 charge. (+2/3 + +2/3 + -1/3 = 3/3 = 1)
  - Two Down and one Up give a neutron with 0 charge. (-1/3 + - 1/3 + +2/3 = 0)

Initially there are an almost equal numbers of Protons and Neutrons.

- But free neutrons decay into protons and electrons with a half life of ~ 16 minutes.
- So in the first few minutes the number of neutrons reduced and the number of protons increased.
- Only those neutrons which combined with protons to from helium nuclei (2 protons, 2 neutrons) survived.

- The Universe thus began with 75% Hydrogen nuclei (Protons) and 25% Helium Nuclei (Alpha Particles) along with one electron for each Proton.
- It was so hot that the radiation prevented any atoms forming.
- Only after 380,000 years did the Universe cool sufficiently to allow atoms to form.

Where is all the mass/energy required to make space flat?

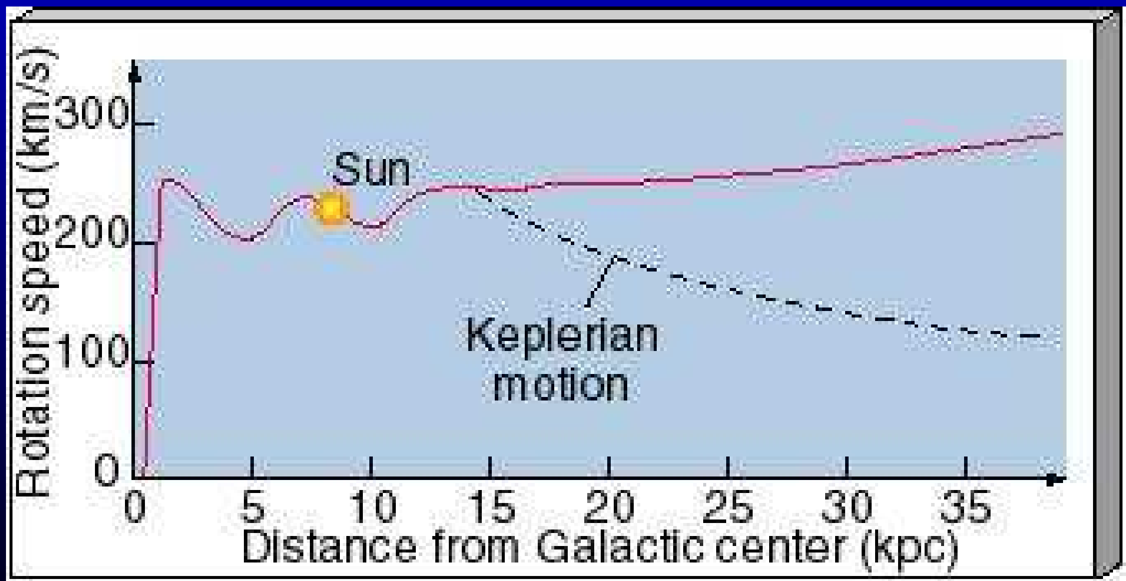
- If, as inflation predicts, and observations seemed to require, space is “flat” we know what the density of matter and energy in the Universe must be.

- The “normal” matter that we can see along with some we cannot see (black holes etc) only make up about 4 - 5% of that required.

- Dark Matter can help solve this problem.

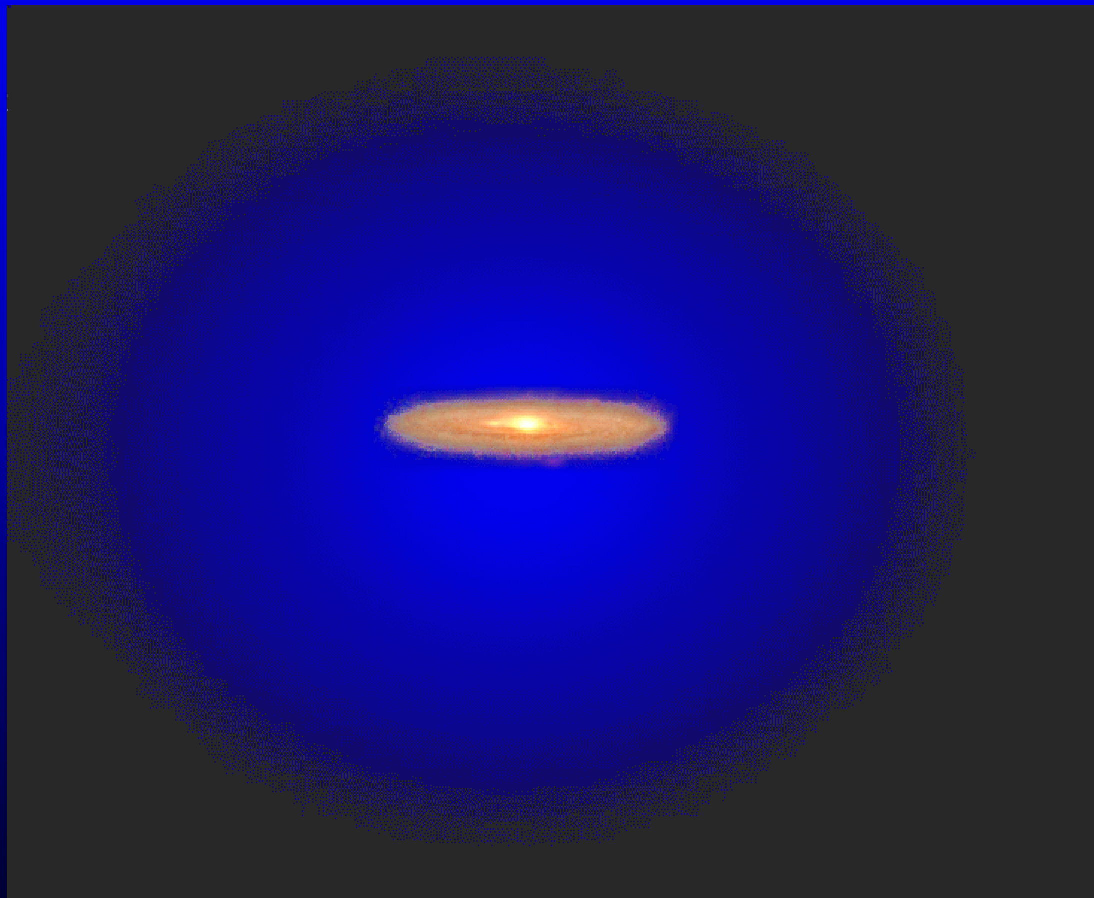
Evidence for Dark Matter

- Radio and Optical Astronomers have shown that the Galaxies must be embedded is a halo of unseen matter to account for the speed at which stars and gas rotate around the galactic nuclei.



Evidence for Dark Matter

- Spiral Galaxies cannot be stable unless they are embedded in a halo of matter



But there was still a problem!

- Of the mass energy required to make space flat we believe that:
  - ~4% is in the form of normal matter.
  - ~26% is in the form of dark matter.
- But that only makes up ~ 30% of the total
  - What can make up the rest?

A solution to the missing mass/energy problem?

- Normal and Dark matter appear to only make up about 30% of the mass/energy required to make space flat.
- So what makes up the remaining70%?
- DARK ENERGY?!
- Do we have any evidence for it? …Yes.

Observations of Distant Type Ia Supernovae

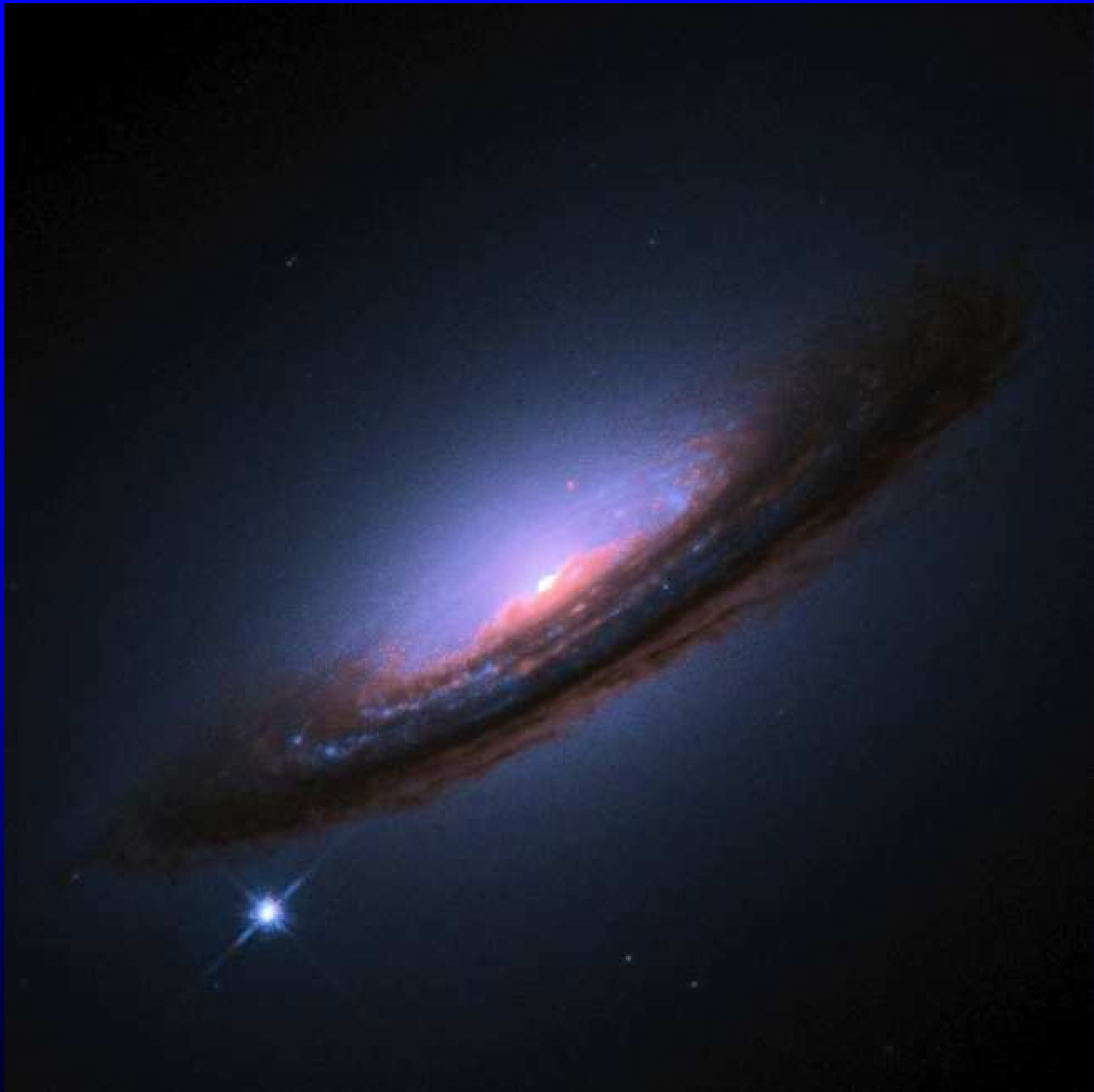
Type Ia Supernova

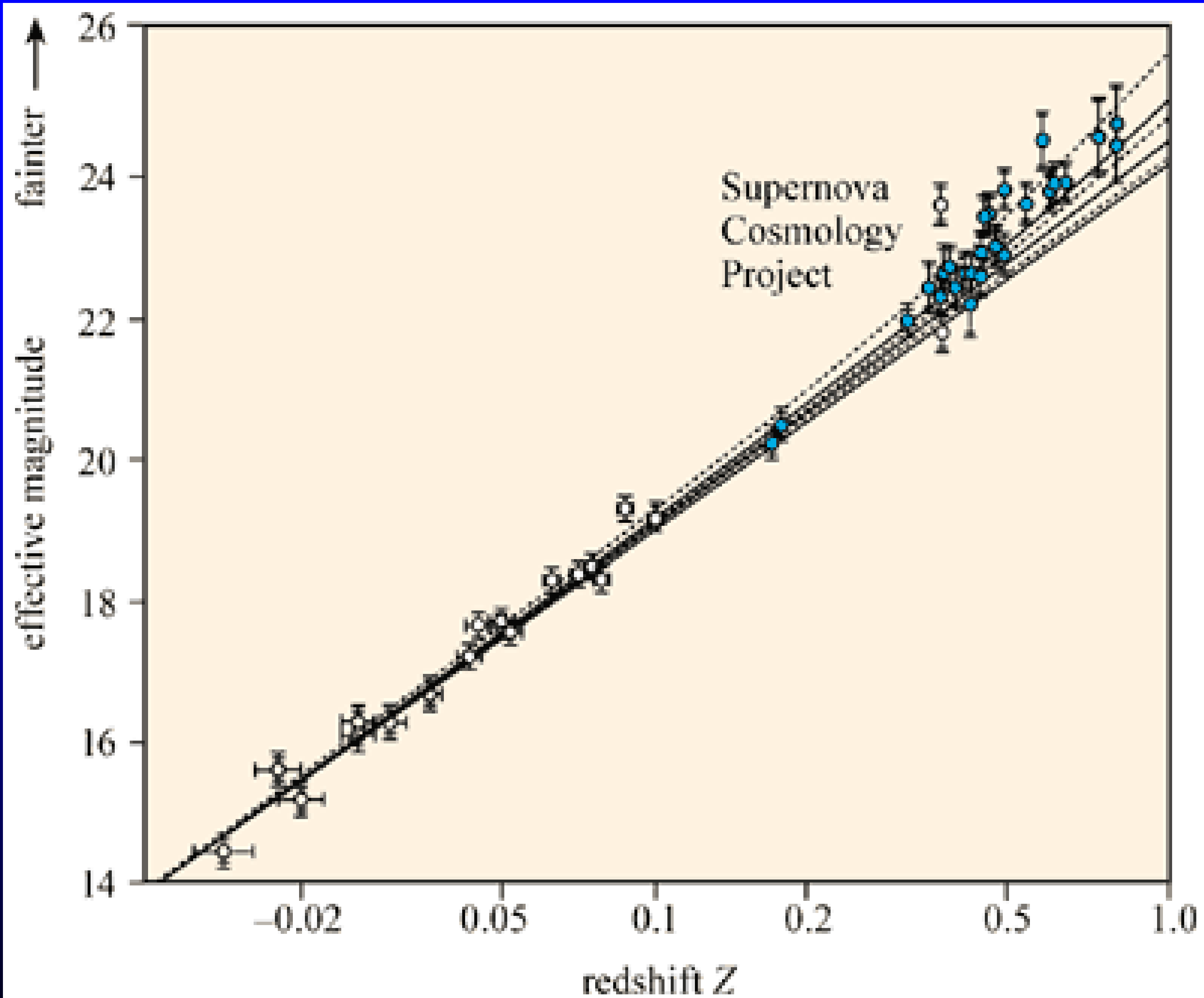
As very bright we can see at very great distances.

We believe that they all have the same peak brightness.

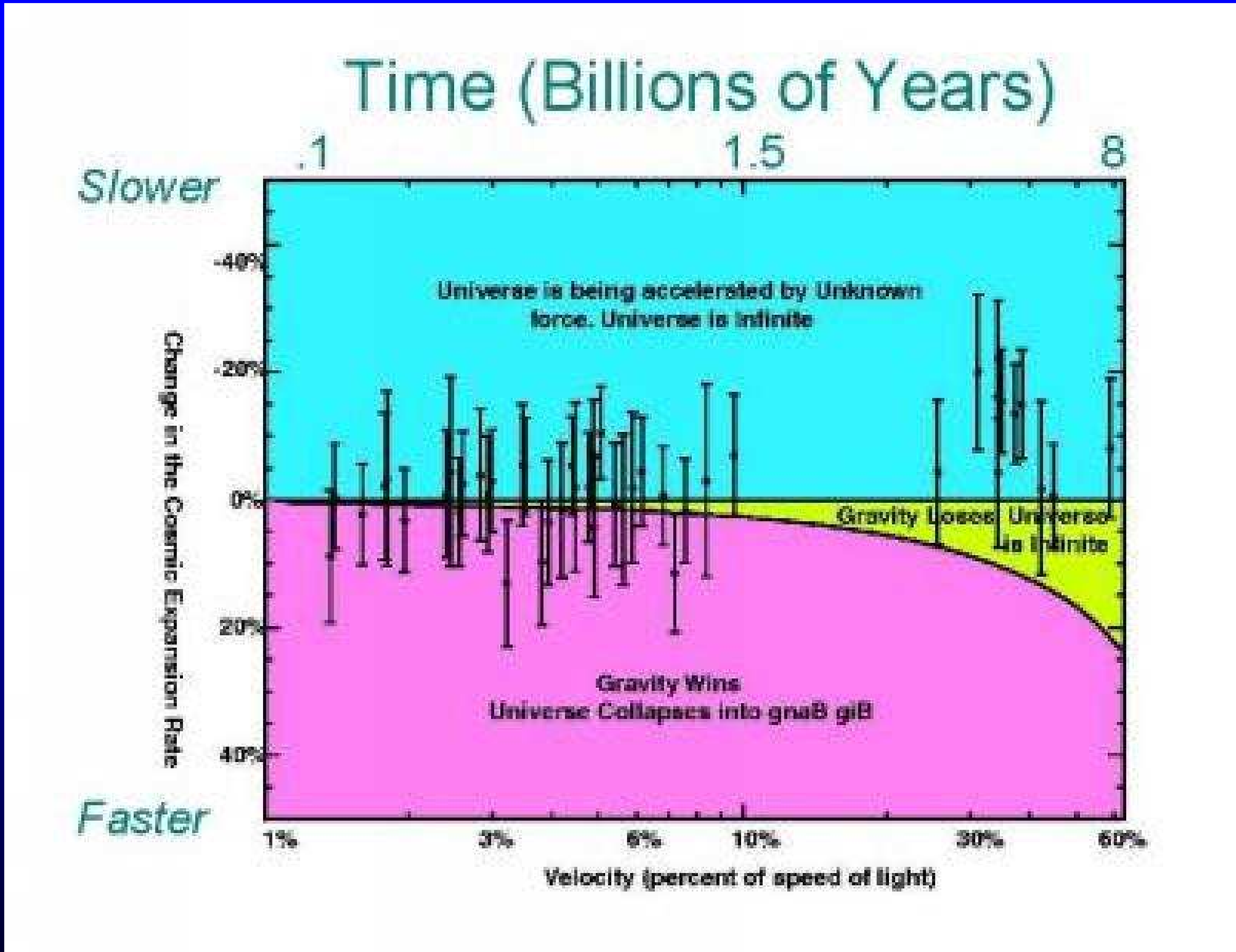
So we can use as "standard candles".

These enable astronomers to extend the Hubble Plot out to far greater distances





fainter
effective magnitude
26
24
22
20
18
16
14
Supernova
Cosmology
Project
-0.02
0.05
0.1
0.2
0.5
1.0
redshift Z



Time (Billions of Years)
.1
1.5
8
Slower
Faster
Change in the Cosmic Expansion Rate
-40%
-20%
0%
20%
40%
Universe is being accelerated by Unknown
force. Universe is infinite
Gravity Loses: Universe
is infinite
Gravity Wins
Universe Collapses into gnaB giB
1%
3%
6%
10%
30%
60%
Velocity (percent of speed of light)

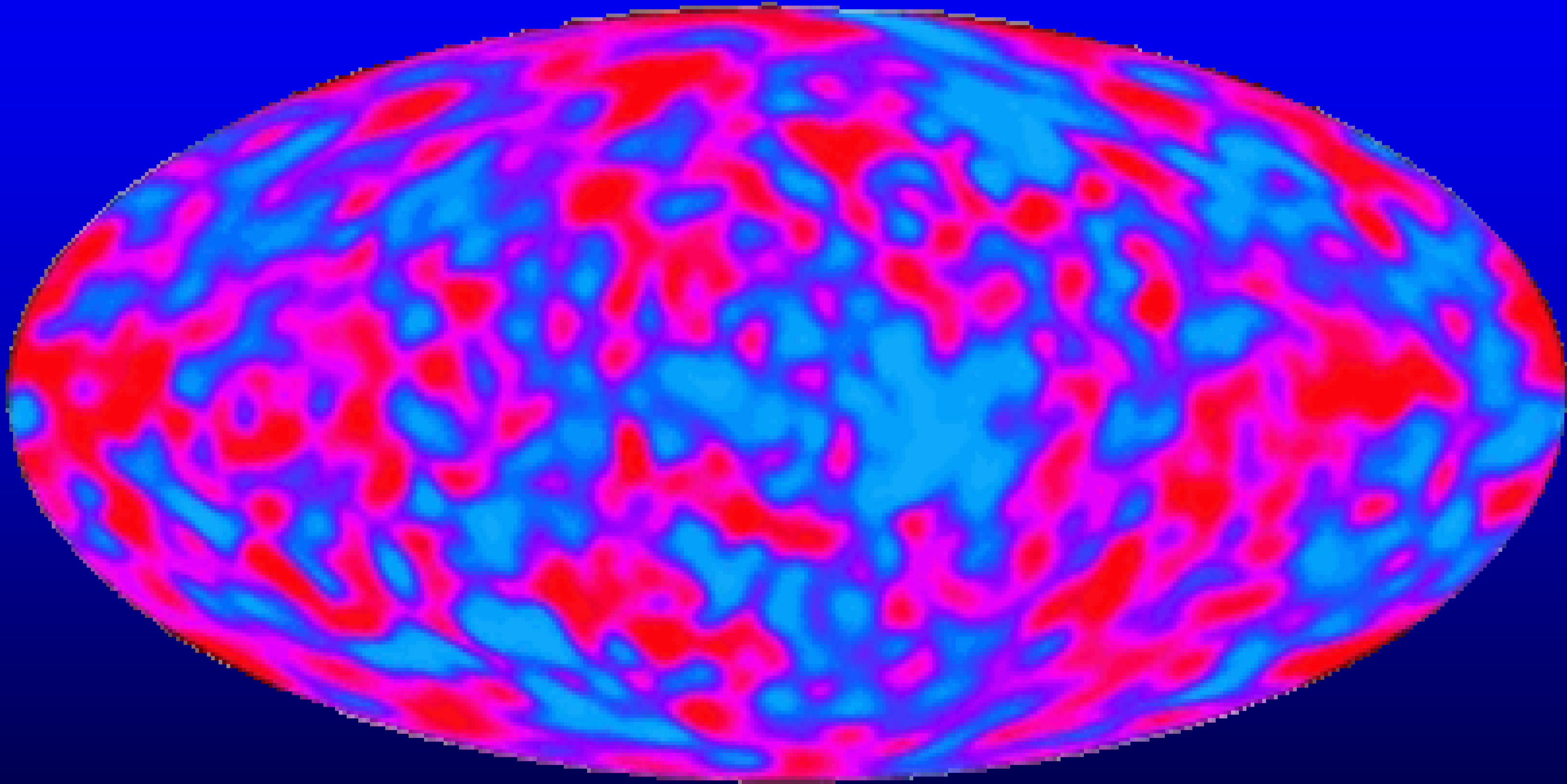
An Accelerating Universe?

- In contrast to the standard Big Bang Models - all of which have a rate of expansion that is reducing with time – these observations indicate that the rate of expansion is now increasing.
- Could this be the Λ term in Einstein's equations making itself felt?
- Radio Observations of the CMB can help.

Fluctuations in the CMB

- The density variations (largely of dark matter) in the Universe 300,000 years after its origin would have affected the observed temperature of the Cosmic Microwave background - producing fluctuations of up to ~150 microKelvin.
- The COBE spacecraft first showed that these fluctuations existed.

COBE MAP

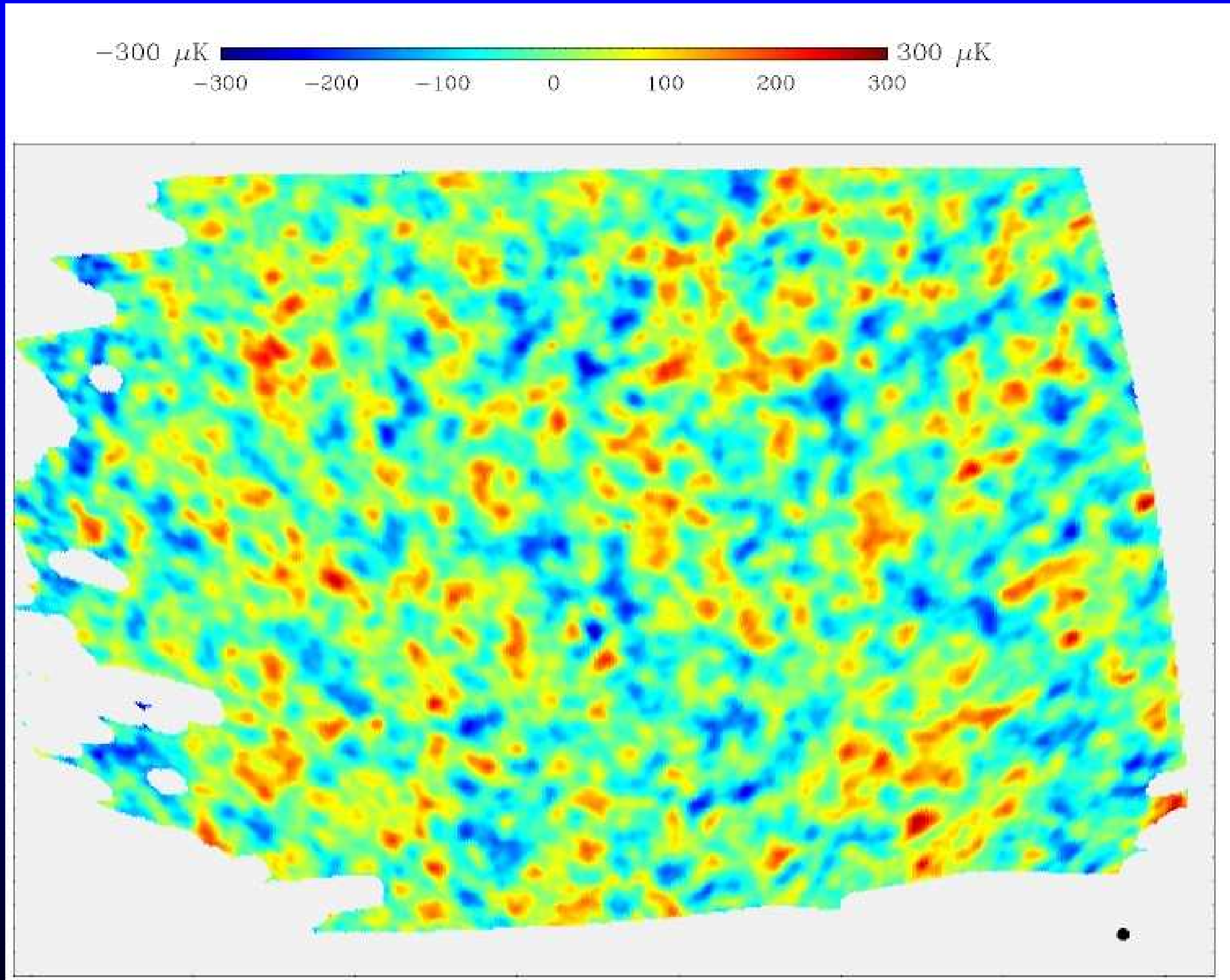


- This was NOT a map of the fluctuations.

Observations of the CMB

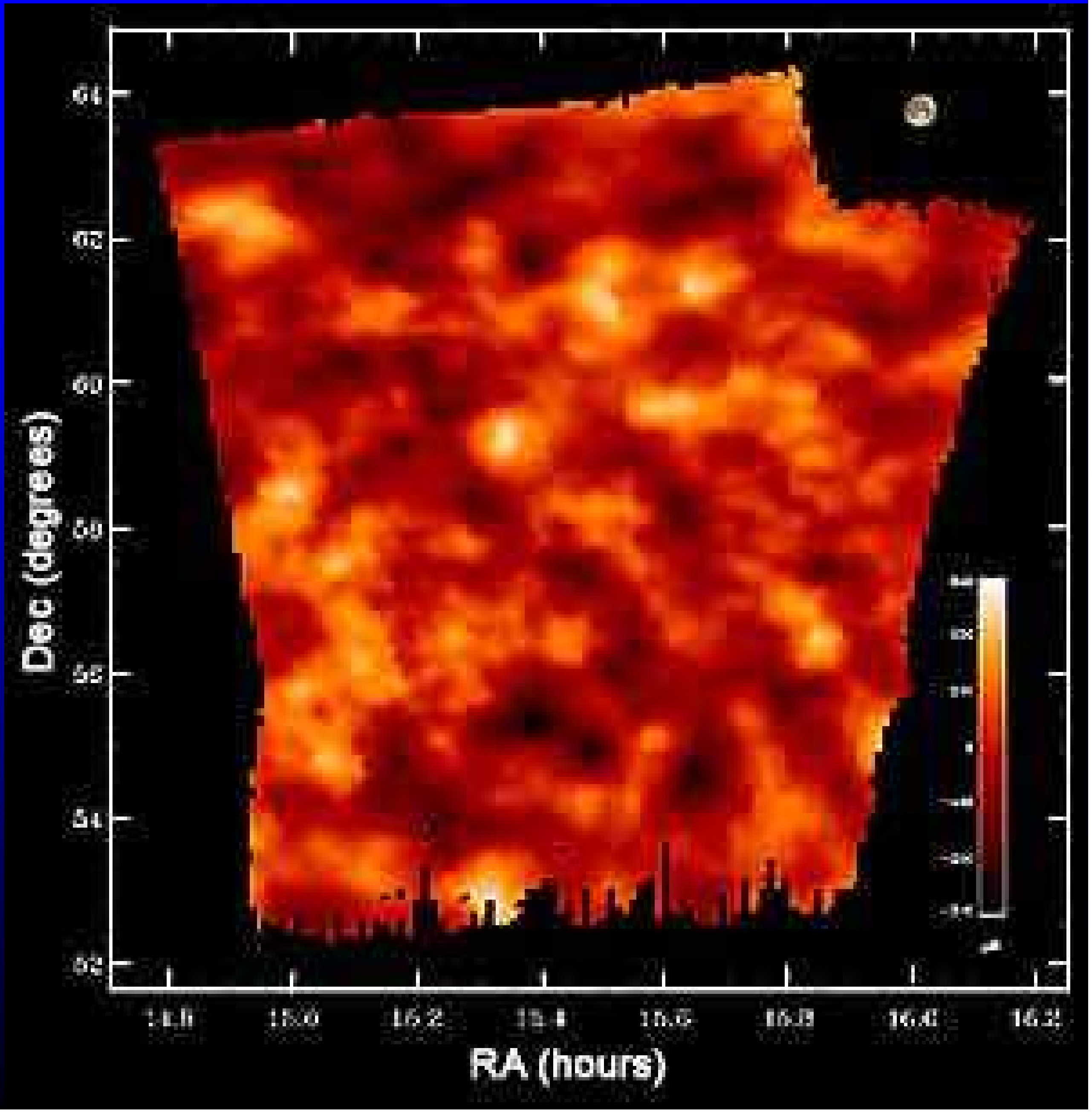
- Boomerang

Boomerang Map of the CMB Fluctuations



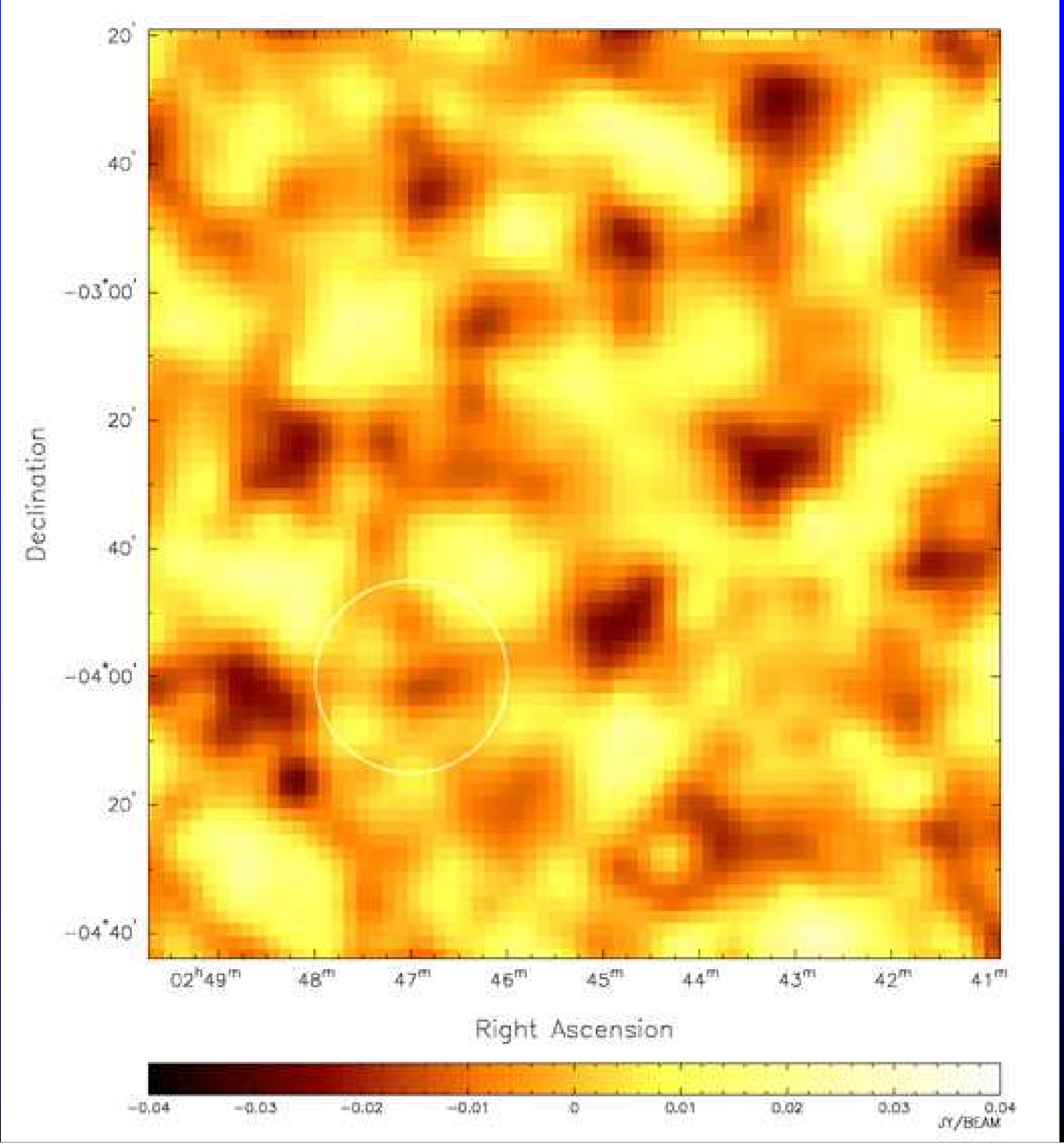
Maxima

Maxima Map



CBI

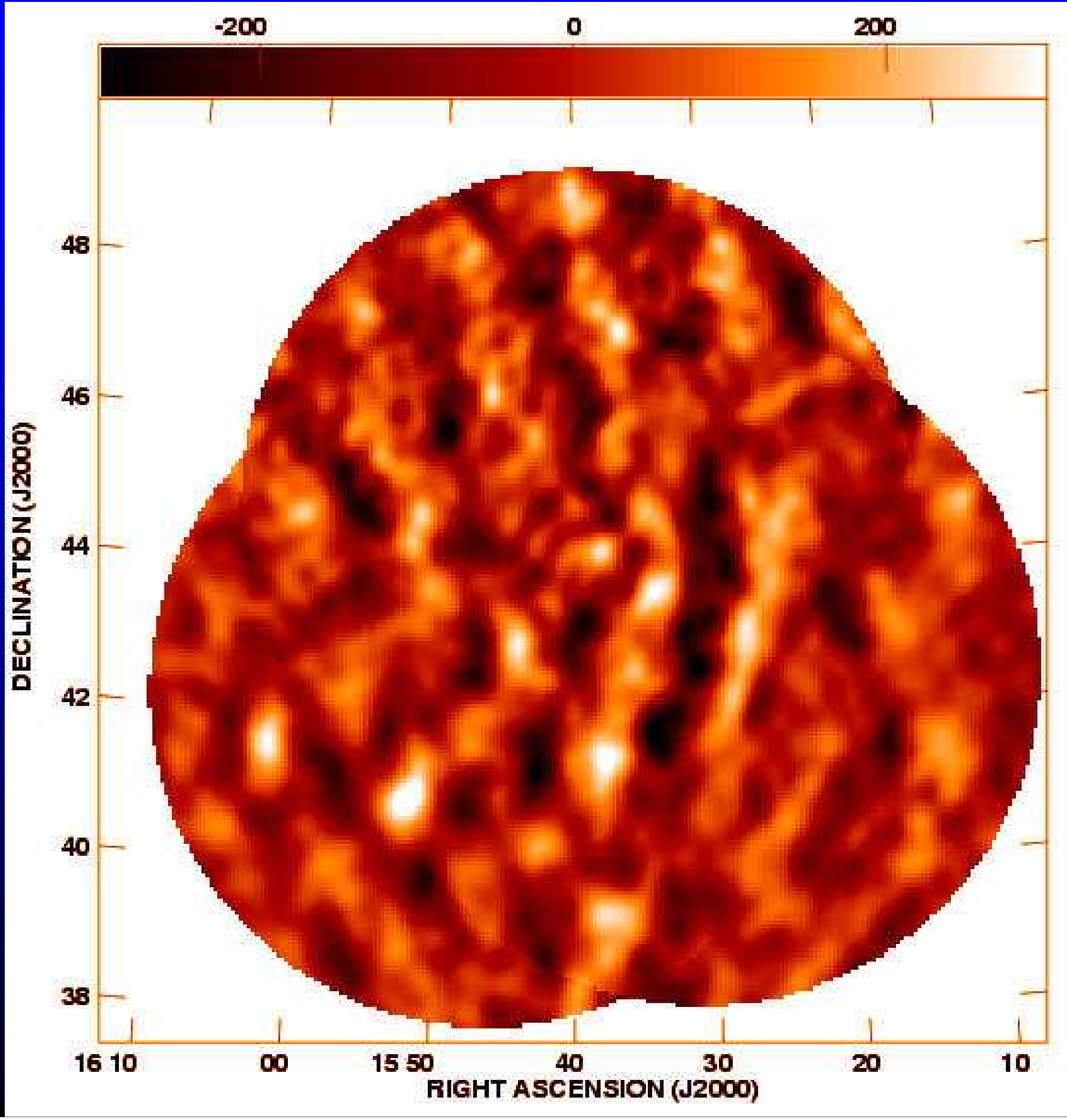
CBI Map



Declination
Right Ascension
20'
40'
−03°00'
20'
40'
−04°00'
20'
−04°40'
02h49m
48m
47m
46m
45m
44m
43m
42m
41m
−0.04
−0.03
−0.02
−0.01
0
0.01
0.02
0.03
0.04
JY/BEAM

VSA on Mount Teide

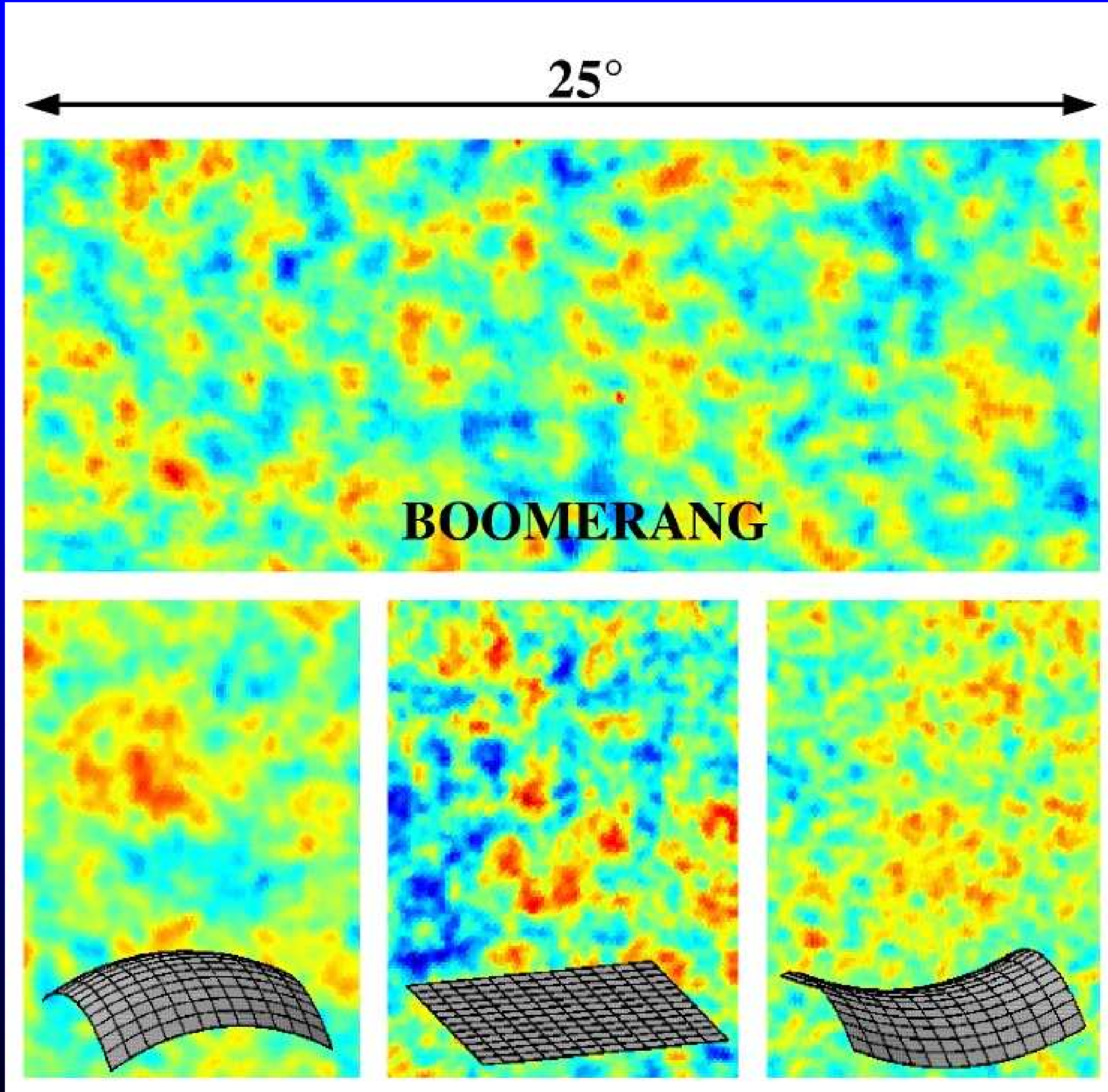
VSA Map



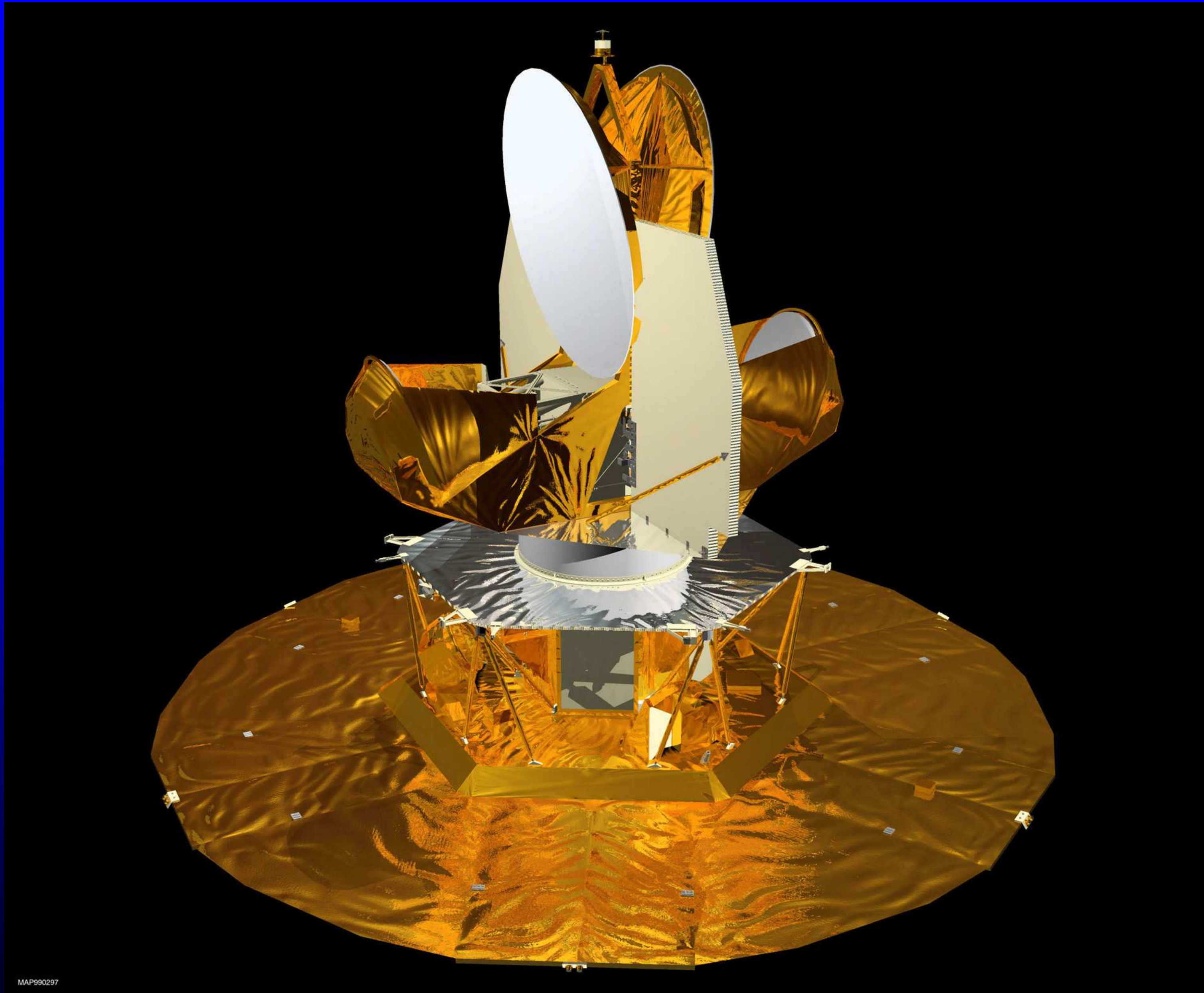
-200
0
200
48
46
44
42
40
38
DECLINATION (J2000)
16 10
00
15 50
40
30
20
10
RIGHT ASCENSION (J2000)

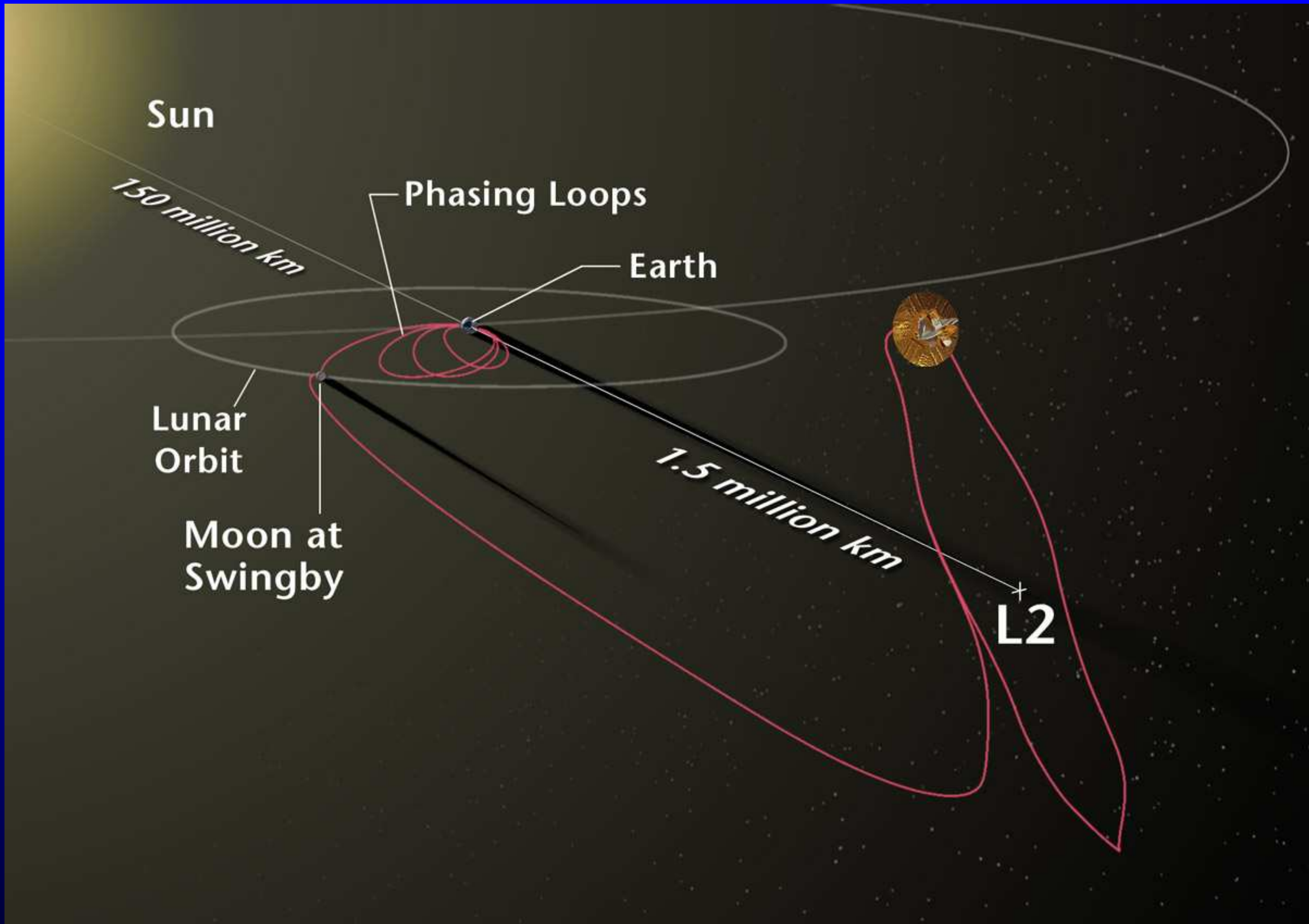
First Important result.

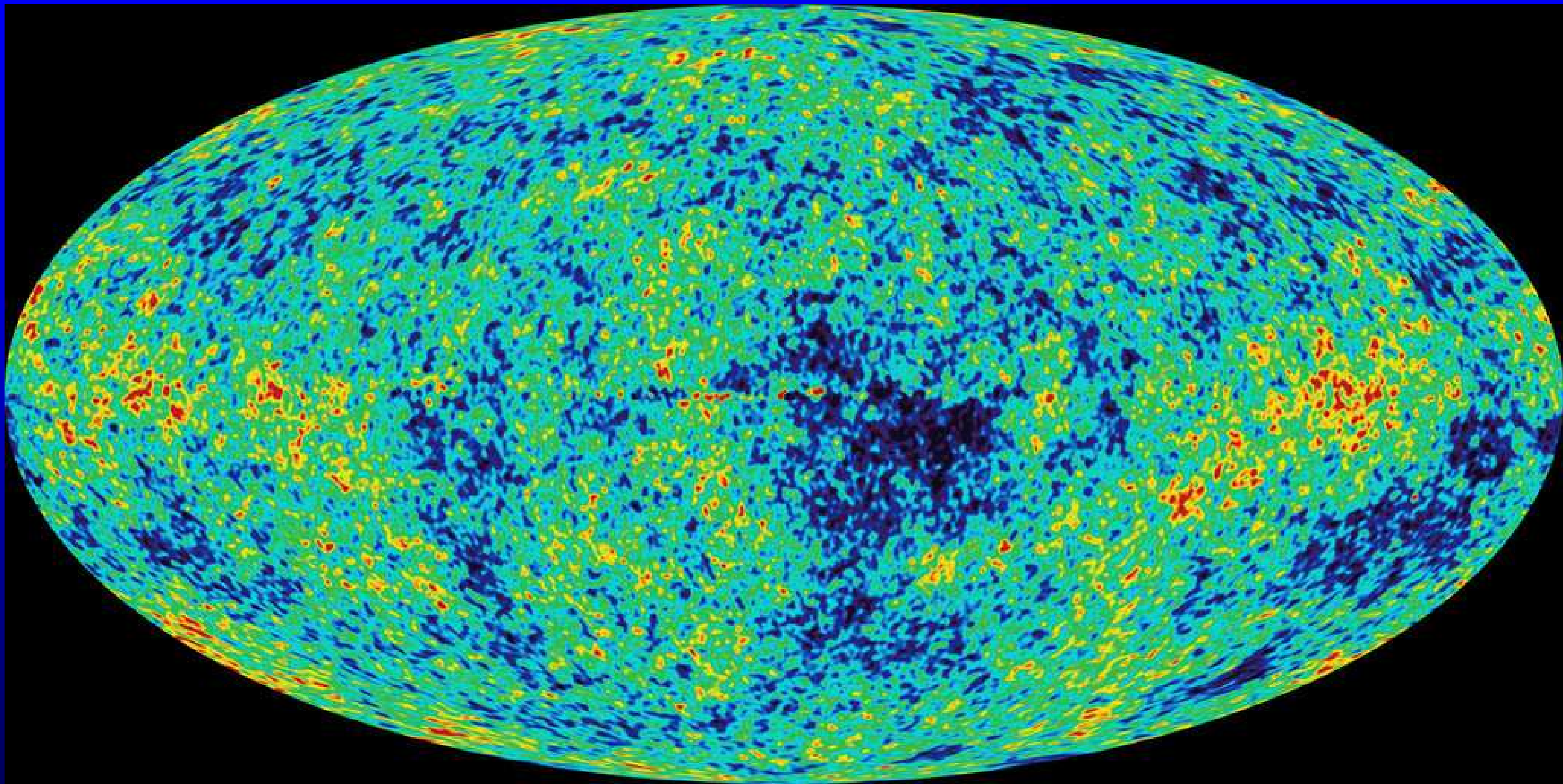
Space is "flat" as predicted by "Inflation"

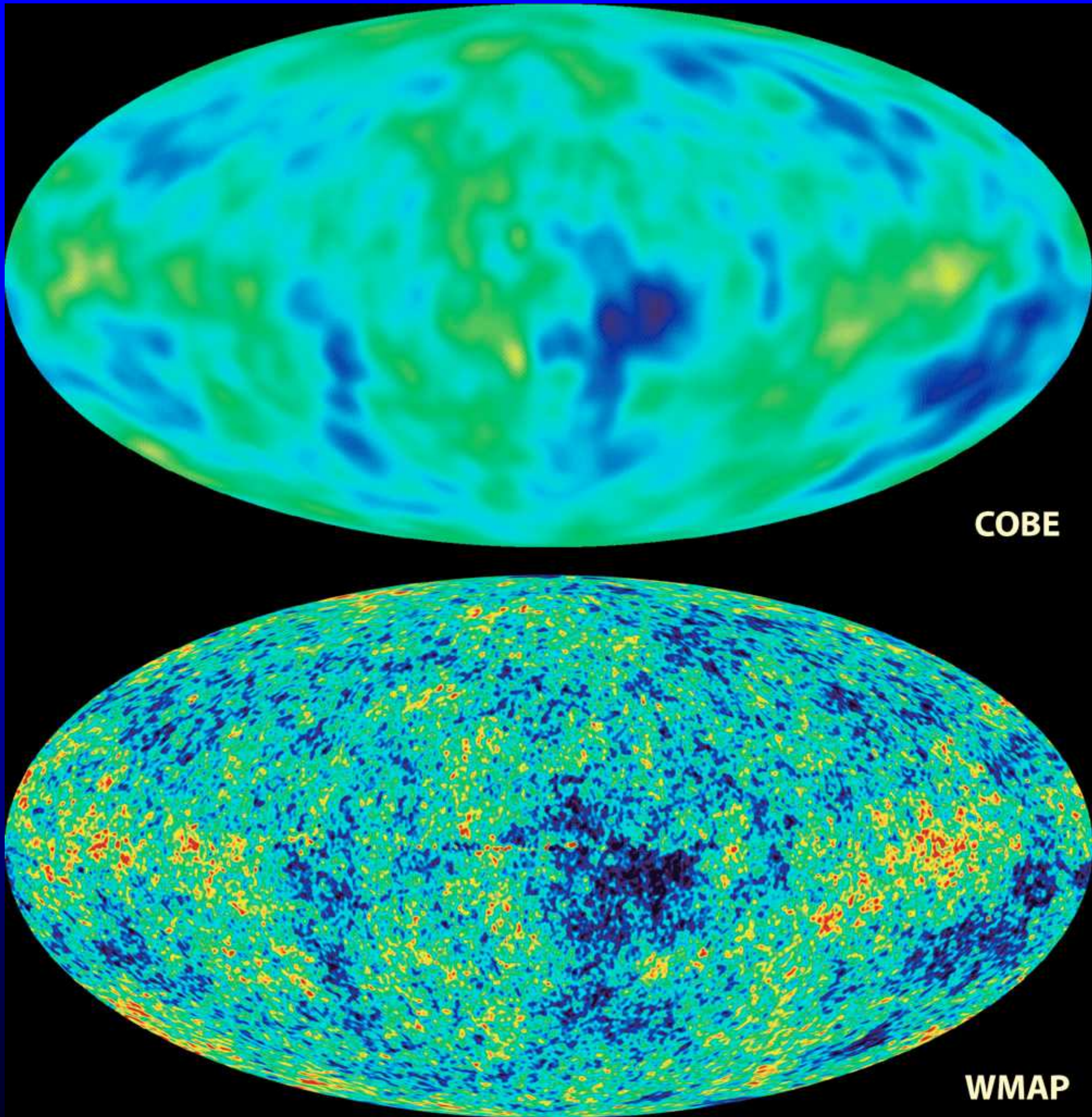


WMAP

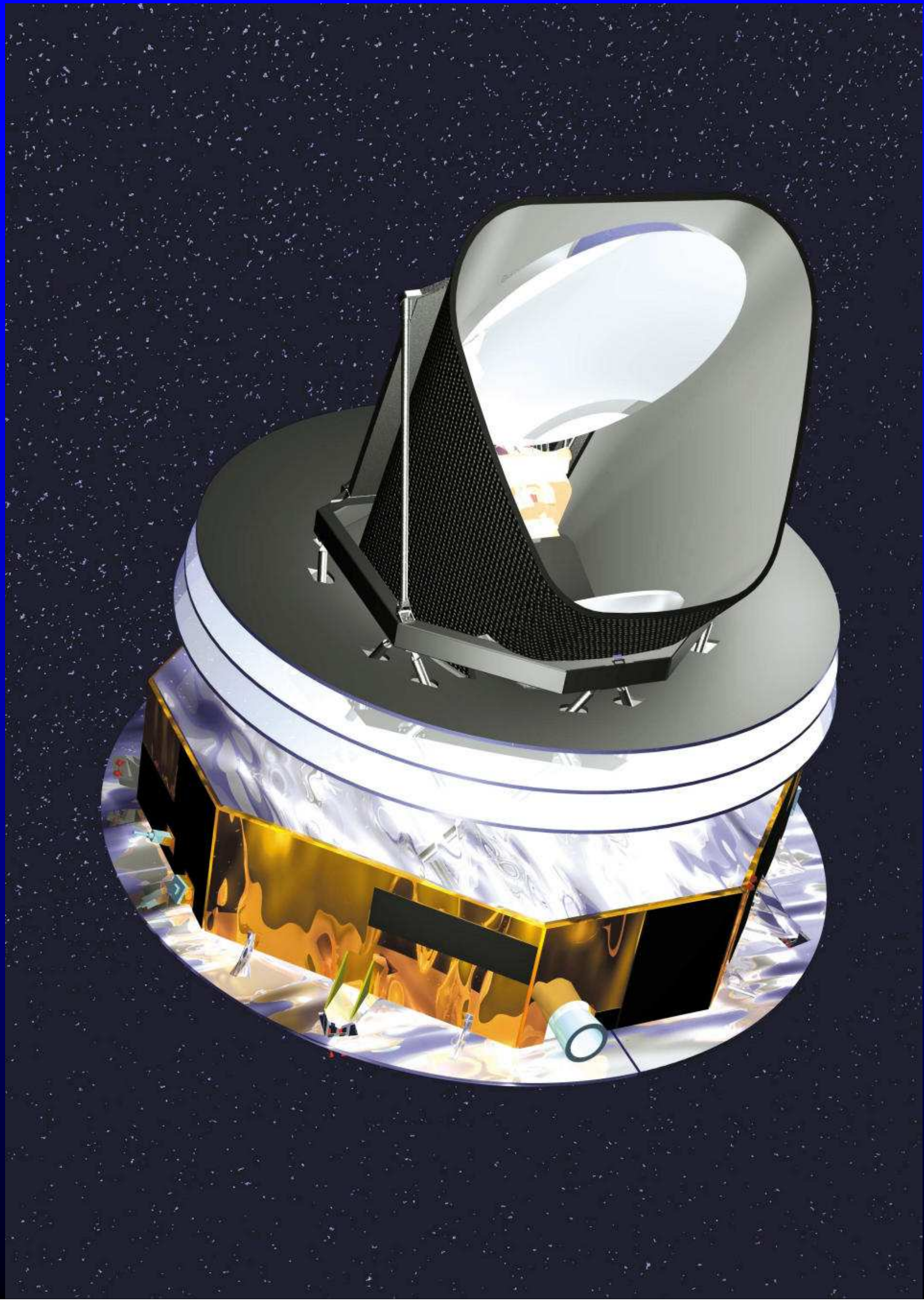



Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2




COBE
WMAP

The Planck Spacecraft



A standard model of the Universe

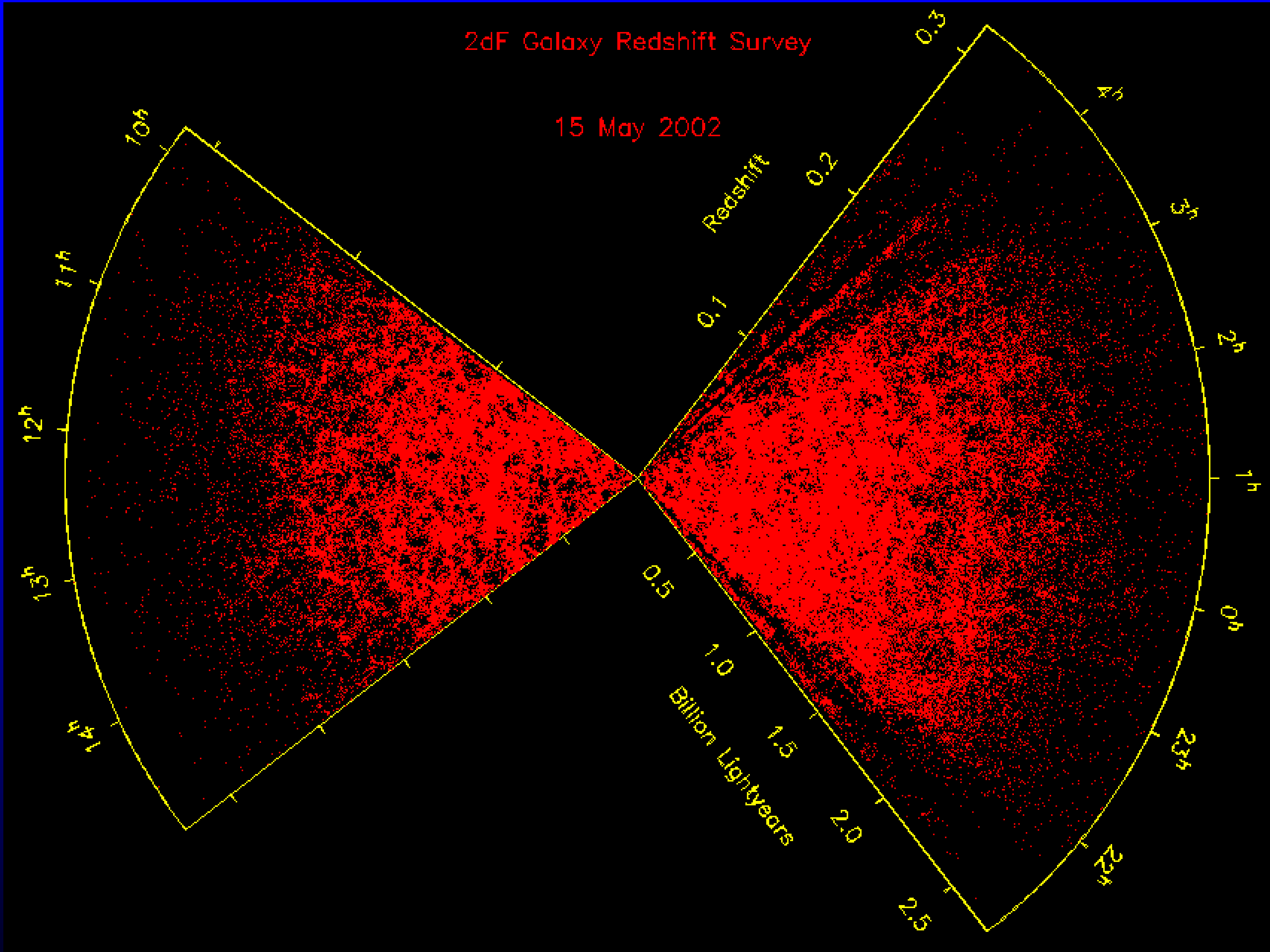
- We can combine the data from the CMB observations with:

  1) Latest values of Hubble's Constant from:

  – Gravitational Lenses (70+/-6)km/sec/Mpc

  – HST Key Project (72+/- 8)km/sec/Mpc

  2) Galaxy Distribution Maps (which also measure the "clumpyness of matter")


2dF Galaxy Redshift Survey
15 May 2002
Redshift
0.1
0.2
0.3
0.5
1.0
1.5
2.0
2.5
Billion Lightyears
10h
11h
12h
13h
14h
4h
3h
2h
1h
0h
23h
22h

A standard model of the Universe

- We can combine the data from the CMB observations with:

3) Type Ia Supernovae results

4) Nucleoynthesis (the relative percentages of light elements produced in the Big Bang)

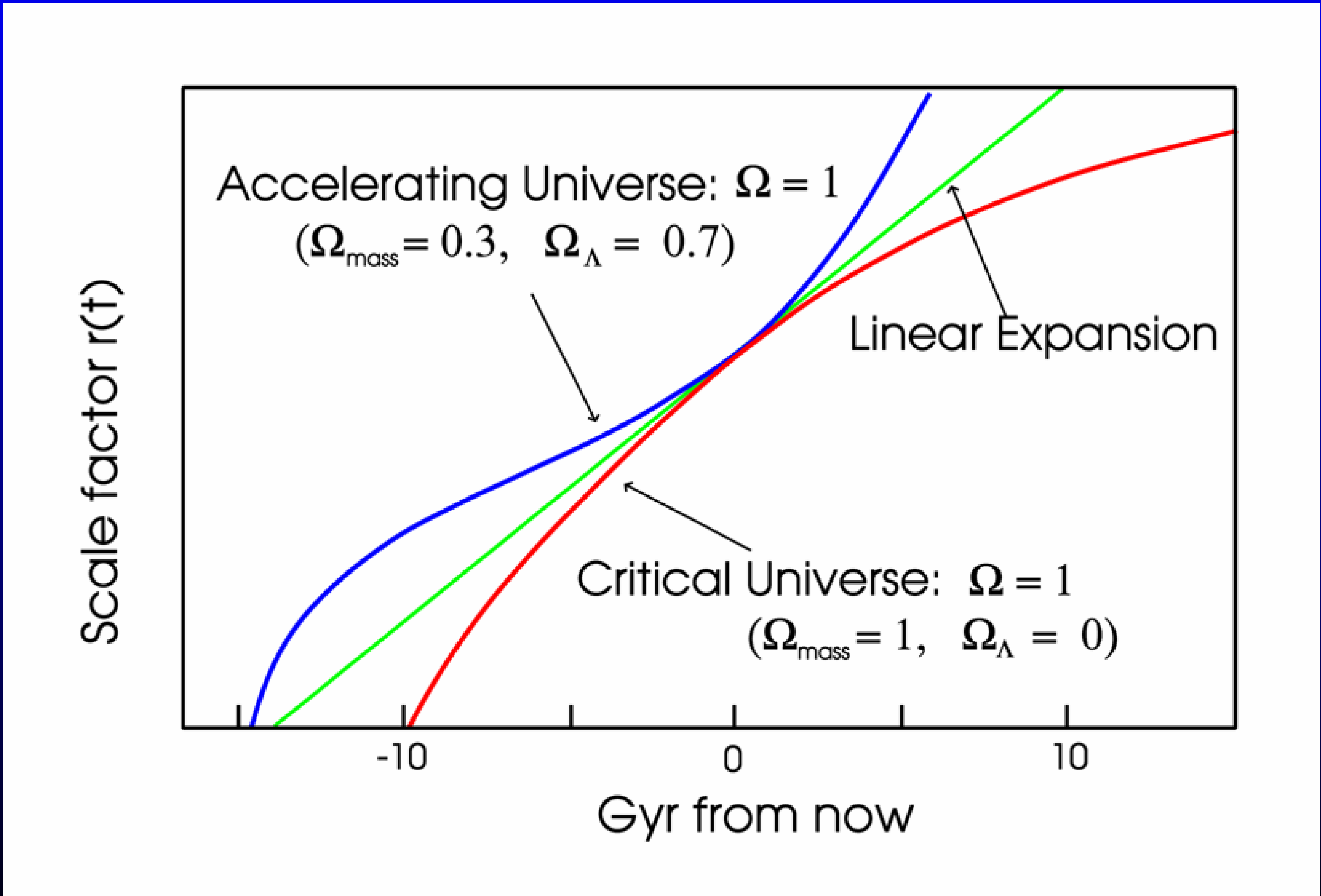
All give a consistent model

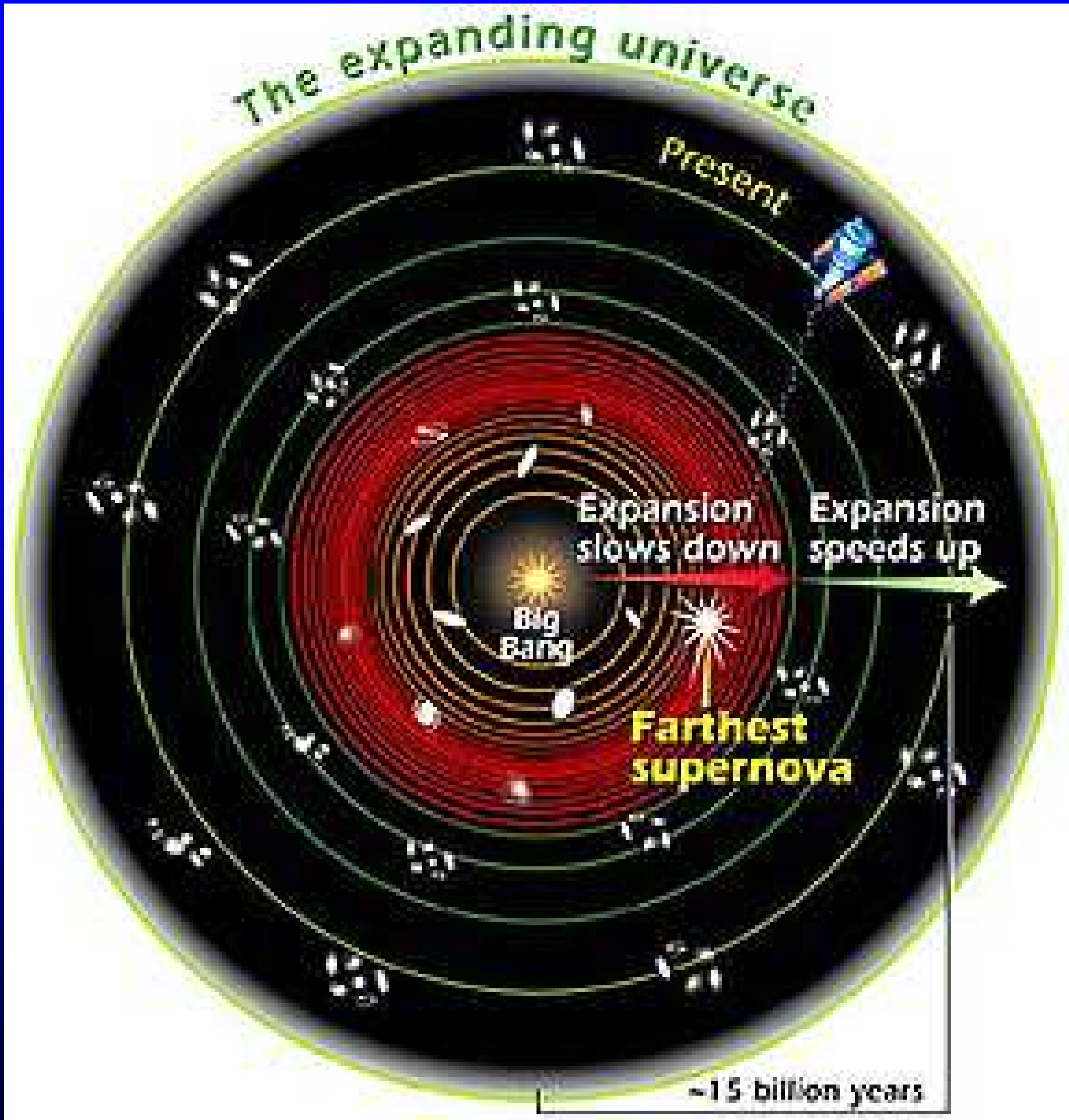
- ~4-5 % Normal Matter
- ~25-26% Dark Matter
- ~70% Dark Energy

- Age of Universe: ~ 13.6 Billion Years

- The pressure produced by the Dark Energy is now making the expansion of the Universe accelerate.

The size of the Universe over time.





The expanding universe
Present
Expansion slows down
Expansion speeds up
Big Bang
Farthest supernova
~15 billion years

The Far Future

- As the clusters of Galaxies move further apart, carried ever faster by the expansion of the space between them, there will be less and less for astronomers to see.

- Isn’t it a good thing that we are living now!