The dark side of the Universe

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P1X Frontiers of Physics Lectures, October 2007

A long time ago,

in a galaxy far, far away…

Aims of these two lectures

We are going to explore our current understanding of cosmology, the branch of astrophysics that seeks to describe properties of the Universe as a whole – its origin, evolution and eventual fate.

More specifically, we will:

- describe the **Hot Big Bang** theory for the origin of the Universe;
- learn why (almost all) cosmologists believe the matter in the Universe is **exotic dark matter**;
- learn why (almost all) cosmologists believe that the expansion of the Universe is **accelerating**, driven by mysterious **dark energy**;
- highlight some of the future telescopes and space missions that might shed further light on the dark side of the Universe.

Lecture 1

Lecture 2

Our approach in these lectures….

- Lecture slides, movies and animations available on Moodle after each lecture - **no need to scribble frantically!**

(Remember, you will see the exam question in advance)

- Focus is on the **Big Picture**:
  - physical concepts behind modern cosmology;
  - how these relate to the physics covered in your degree;
  - key questions tackled by current, and future, research projects

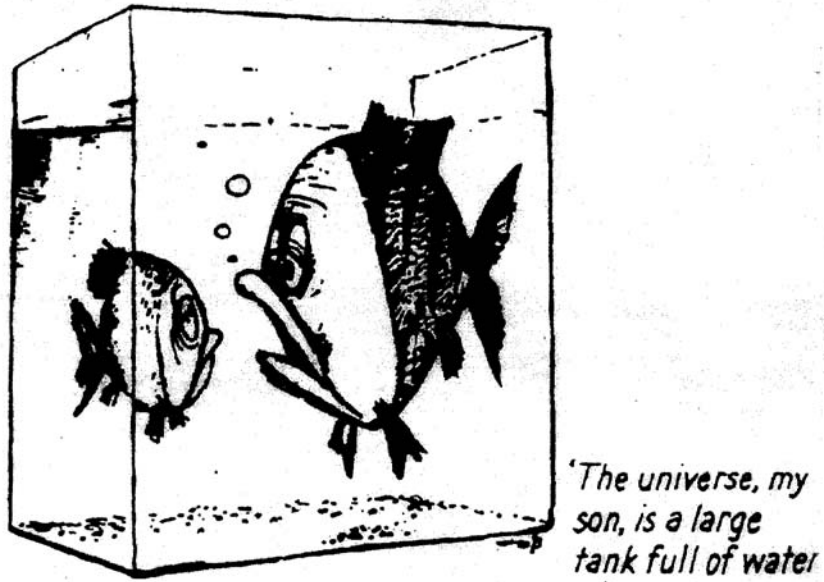
Not many equations, but lots of ideas!

The exam question will ask you to describe and explain things, not just plug some numbers into a formula.

1. The Hot Big Bang theory

Since the dawn of civilisation we have proposed cosmological theories.

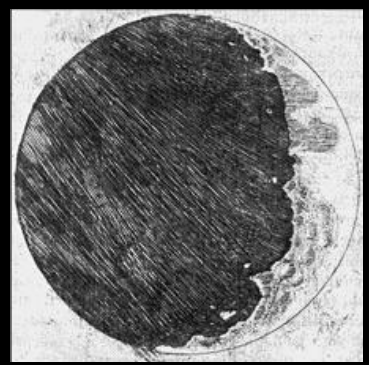
These have improved as more and better data became available to us.

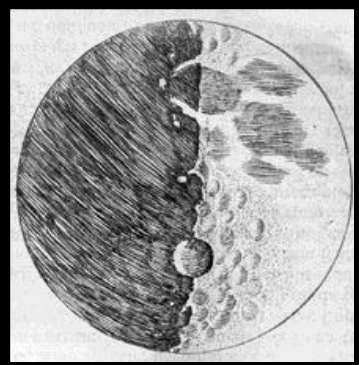


(e.g. early 17th century: use of the **telescope** showed that the Earth is not the centre of the Universe; revealed the true nature of the **Milky Way**).

Galileo Galilei:
1564 – 1642 AD


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
unicuique, præsertim vero
PHILOSOPHIS, necnon ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
QVATVOR PLANETIS
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M. DC. X.





Galileo Galilei:
1564 – 1642 AD

"I have observed the nature and the material of the Milky Way. With the aid of the telescope this has been scrutinized so directly and with such ocular certainty that all the disputes which have vexed philosophers through so many ages have been resolved, and we are at last freed from wordy debates about it.

The galaxy is, in fact, nothing but a collection of innumerable stars grouped together in clusters. Upon whatever part of it the telescope is directed, a vast crowd of stars is immediately presented to view. Many of them are rather large and quite bright, while the number of smaller ones is quite beyond calculation."

from The Starry Messenger (1610)

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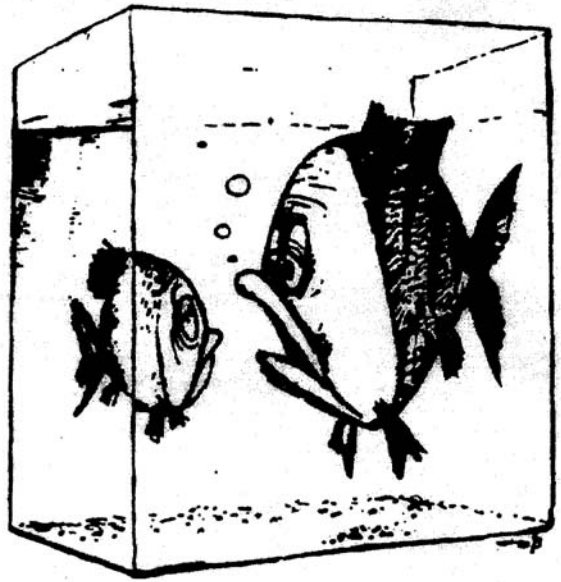
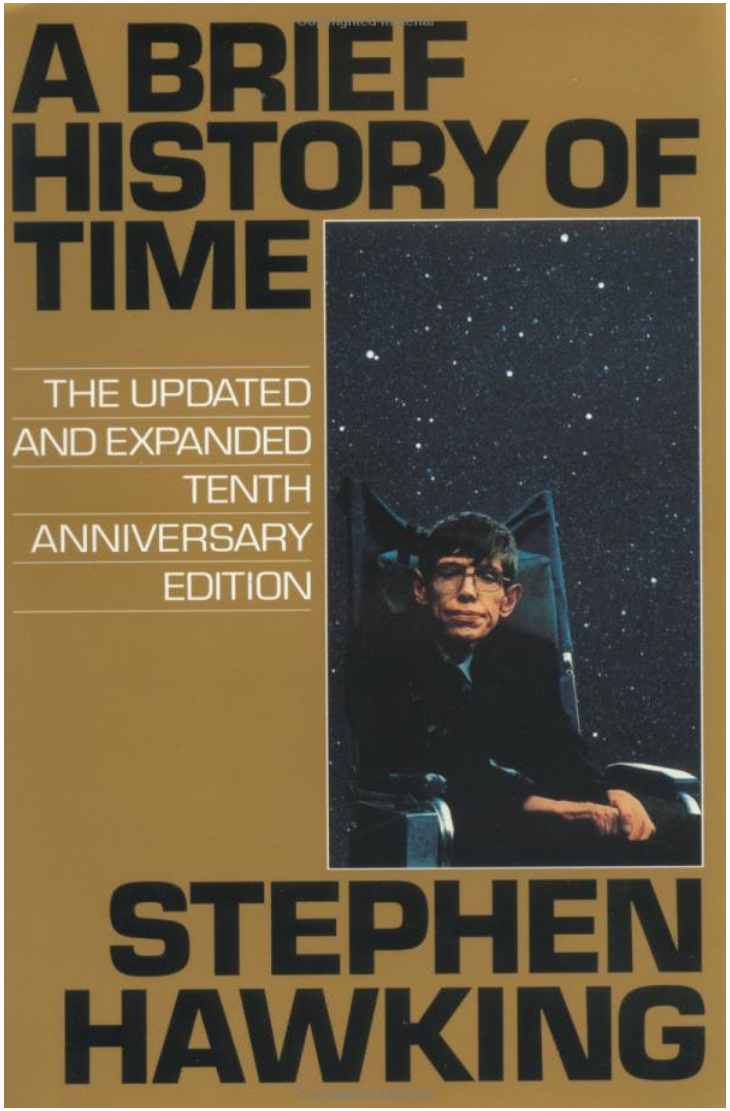


(e.g. early 17th century: use of the **telescope** showed that the Earth is not the centre of the Universe; revealed the true nature of the **Milky Way**).

Some cosmological theories are obviously ridiculous!...

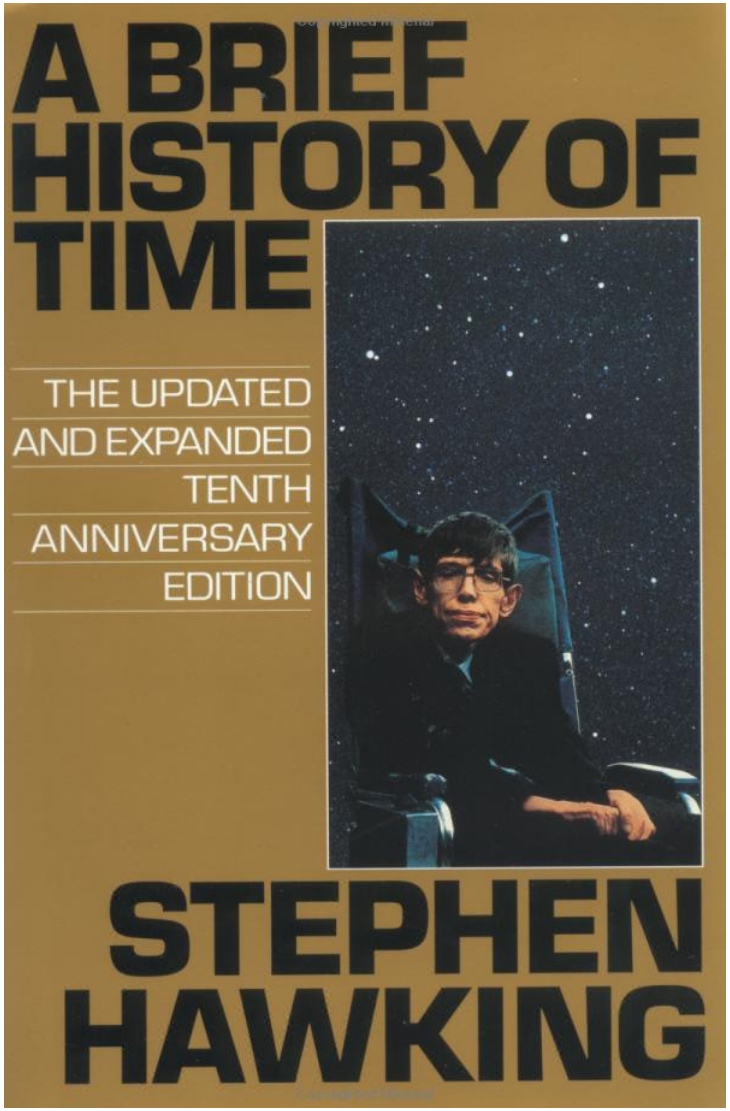


CHAPTER 1

OUR PICTURE OF THE UNIVERSE

…A little old lady at the back of the room got up and said: “What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise.” The scientist gave a superior smile before replying “What is the tortoise standing on?”

“You’re very clever young man, very clever,” said the old lady. **“But it’s turtles all the way down!”**


A BRIEF HISTORY OF TIME
THE UPDATED AND EXPANDED TENTH ANNIVERSARY EDITION
STEPHEN HAWKING


it's turtles all the way down

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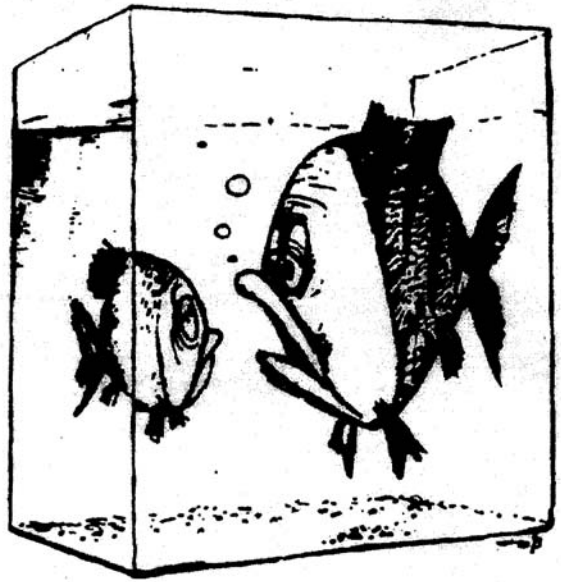


(e.g. early 17th century: use of the **telescope** showed that the Earth is not the centre of the Universe; revealed the true nature of the **Milky Way**).

Some cosmological theories are obviously ridiculous!...

However, to the non-scientist, the **Hot Big Bang theory** might look equally implausible.

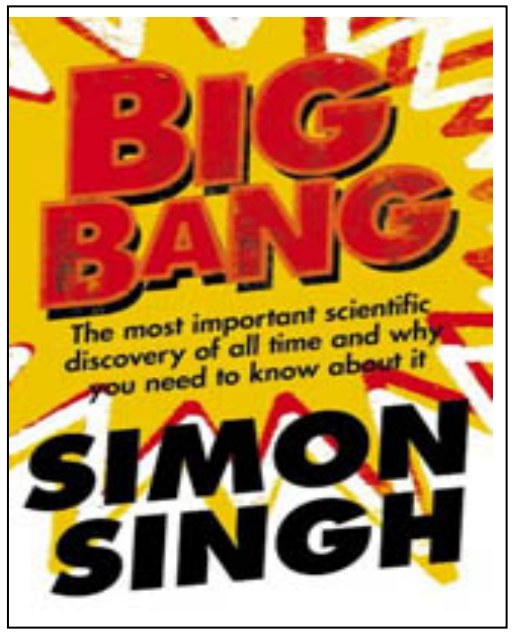
What is the HBB theory, and why do we believe it?

1. The Hot Big Bang theory

According to the Hot Big Bang theory, the Universe began at a finite time in the past, as an incredibly hot and dense **'fireball'** which has been expanding, and cooling, ever since.

Evidence for the Big Bang

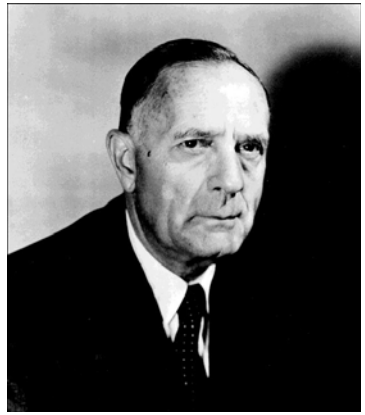
1. Expansion of the Universe
2. Evolution of the Universe
3. The cosmic microwave background radiation (CMBR)
4. Abundances of the lightest chemical elements



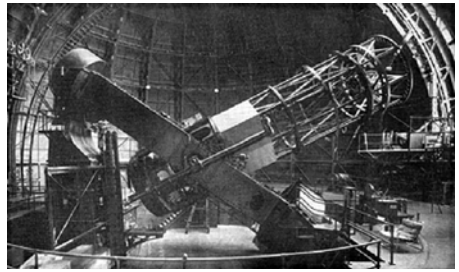
For a non-technical, and very clear overview of the early development of the Big Bang theory, you might like to read the excellent book by the science writer Simon Singh.

1.1 The Expanding Universe

In the 1920s Edwin Hubble solved a long-standing puzzle: the nature of the **Spiral Nebulae**.



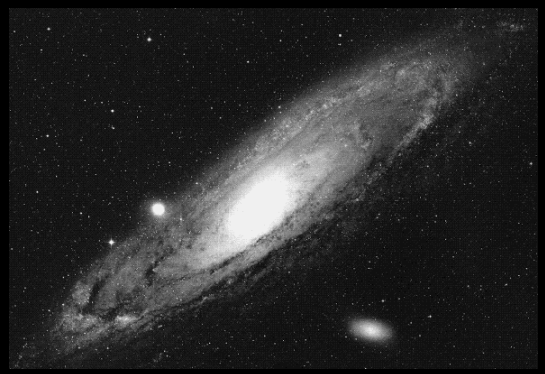
Edwin Hubble

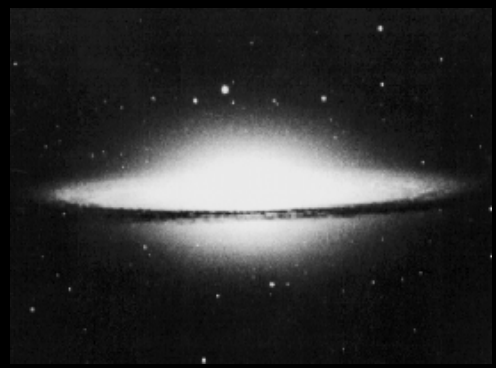


100 inch Lick Telescope on Mount Wilson, near Los Angeles, used by Hubble to measure galaxy distances

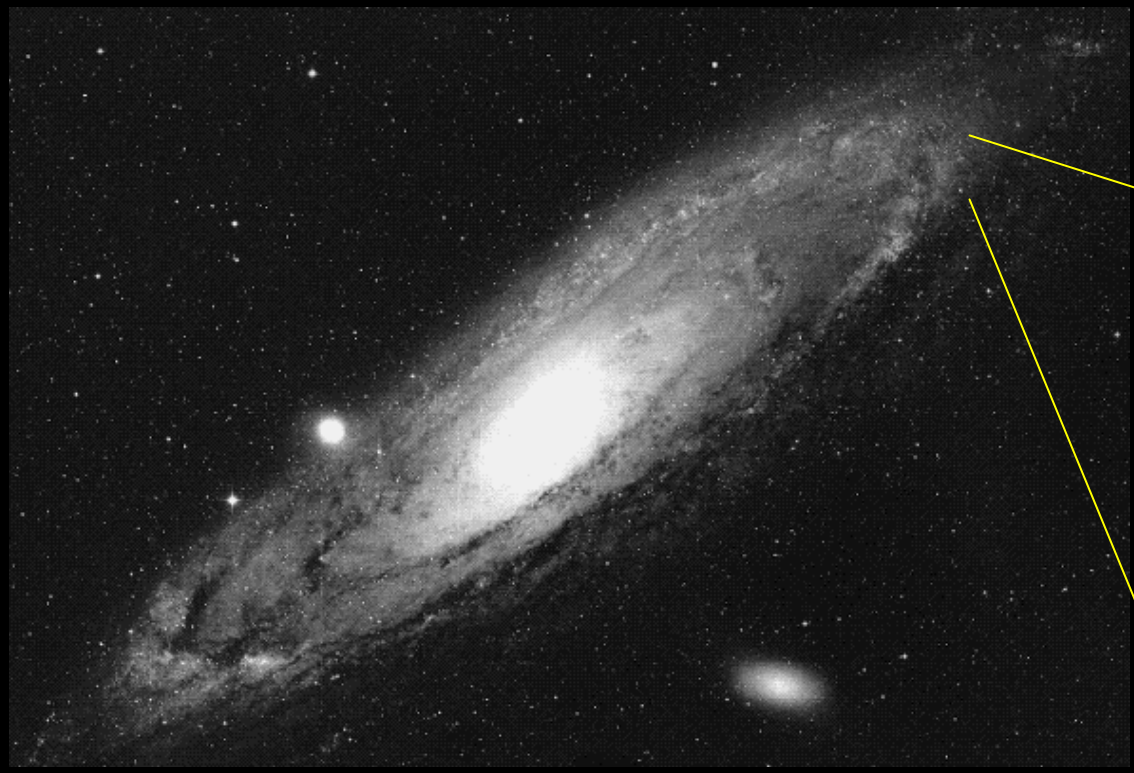
Early 20th Century

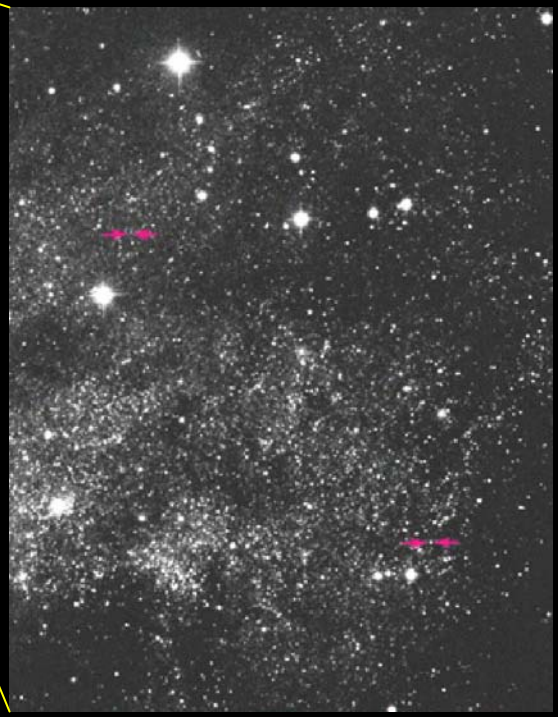
The nature of the nebulae?…

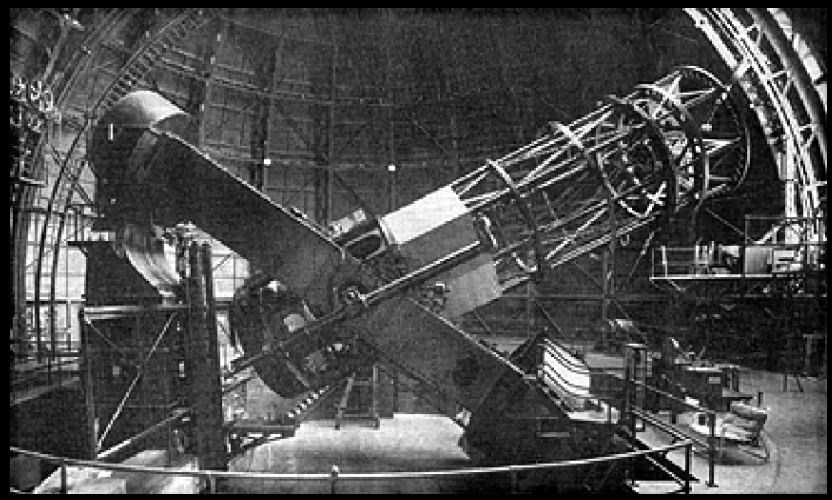




Gas clouds within the Milky Way,
or Island Universes?….







1922: Hubble finds **Cepheids** in the Great Nebula in Andromeda

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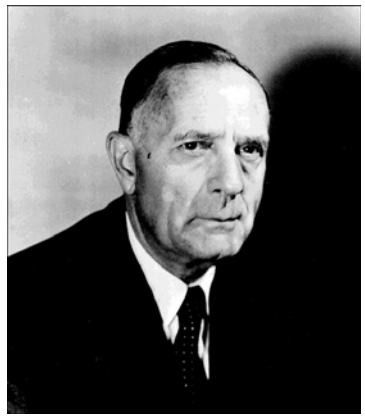
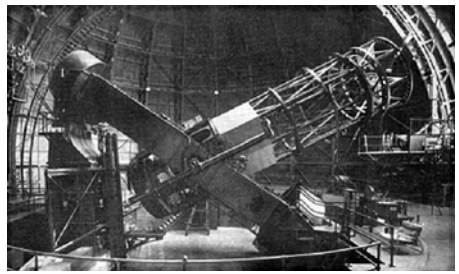


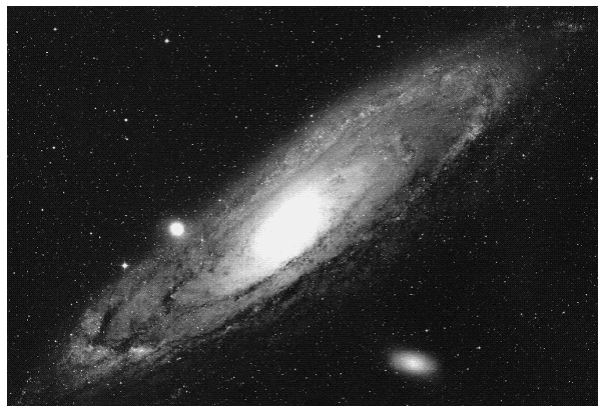
Edwin Hubble



100 inch Lick Telescope on Mount Wilson, near Los Angeles, used by Hubble to measure galaxy distances

These were not gas clouds *within* the Milky Way, but separate galaxies lying well *beyond* it.

Even the nearest, the **Andromeda Galaxy** was about **2 million light years** distant.

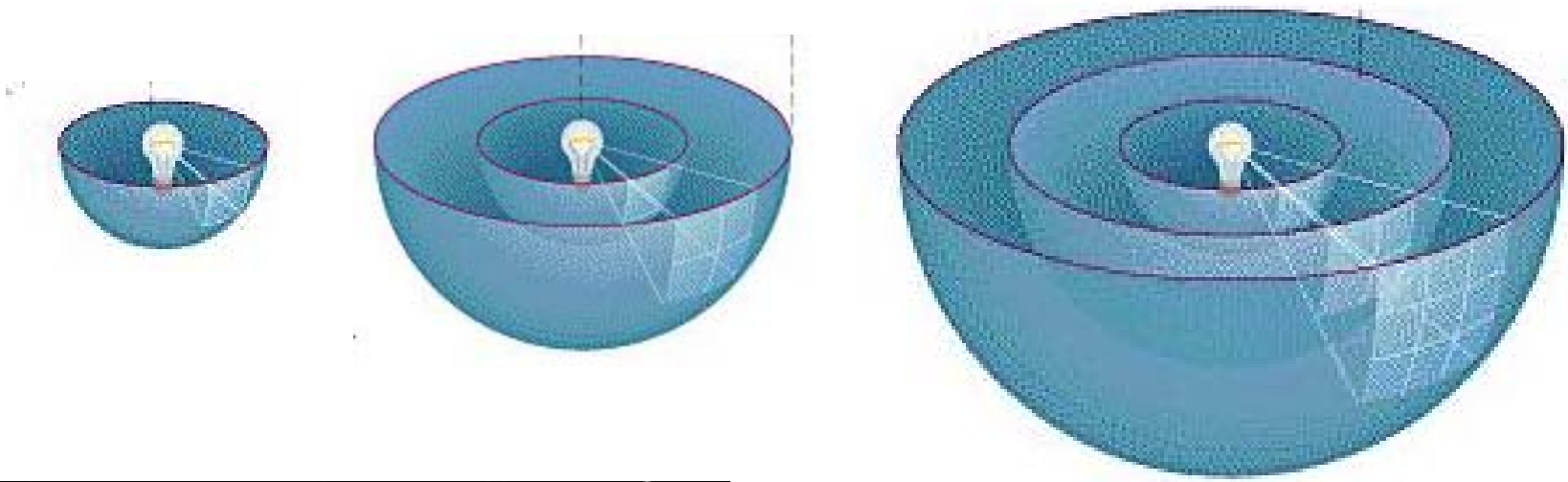


The Great Spiral Galaxy in Andromeda, which we now know lies at a distance of more than 2 million light years

Hubble measured distances using **standard candles**: stars whose **intrinsic** brightness could be worked out independently.

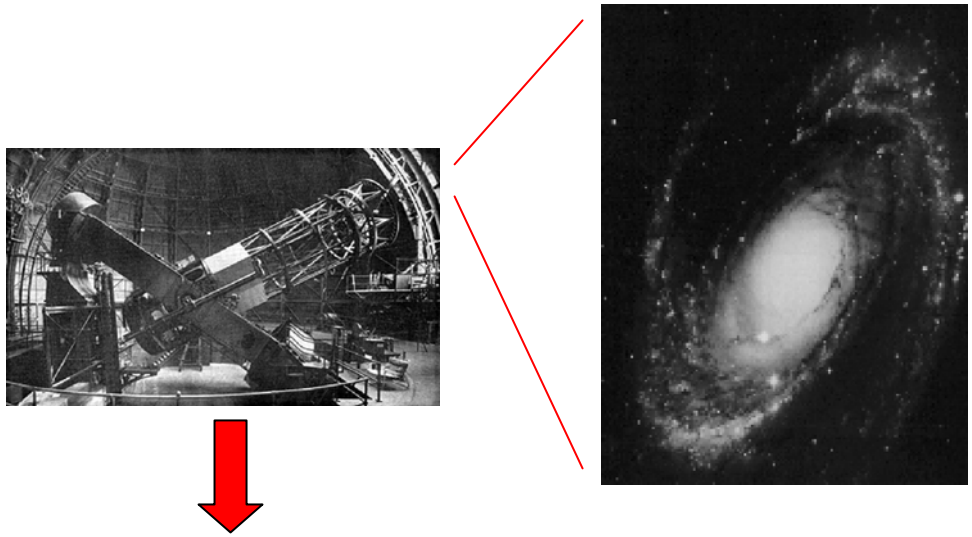
Comparing with their ***apparent*** brightness told Hubble their distance.

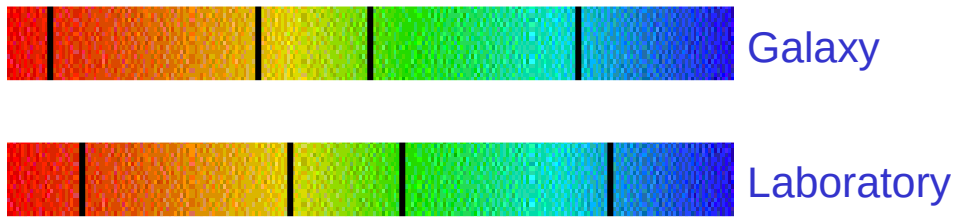
Hubble's method was based on the **inverse-square law**: the apparent brightness, or **flux**, of a radiation source falls off as the square of its distance from us.



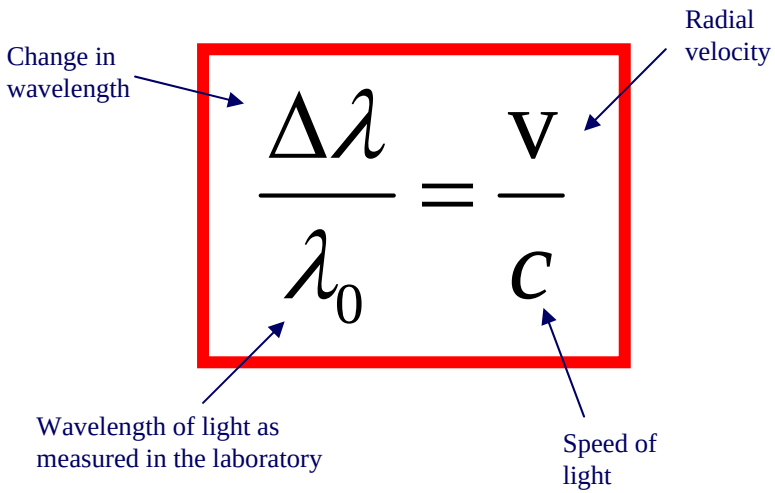
So a 10W light bulb, seen from a distance of e.g. 1m, will have the same apparent brightness as a 1000W light bulb seen from a distance of 10m.

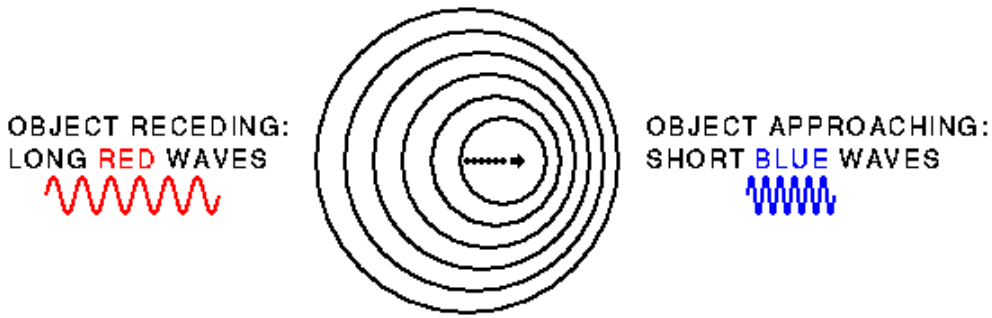
Hubble also measured **spectra** of dozens of galaxies. He found that, for almost all galaxies, their spectral lines were **redshifted**, indicating they were *moving away* from us.



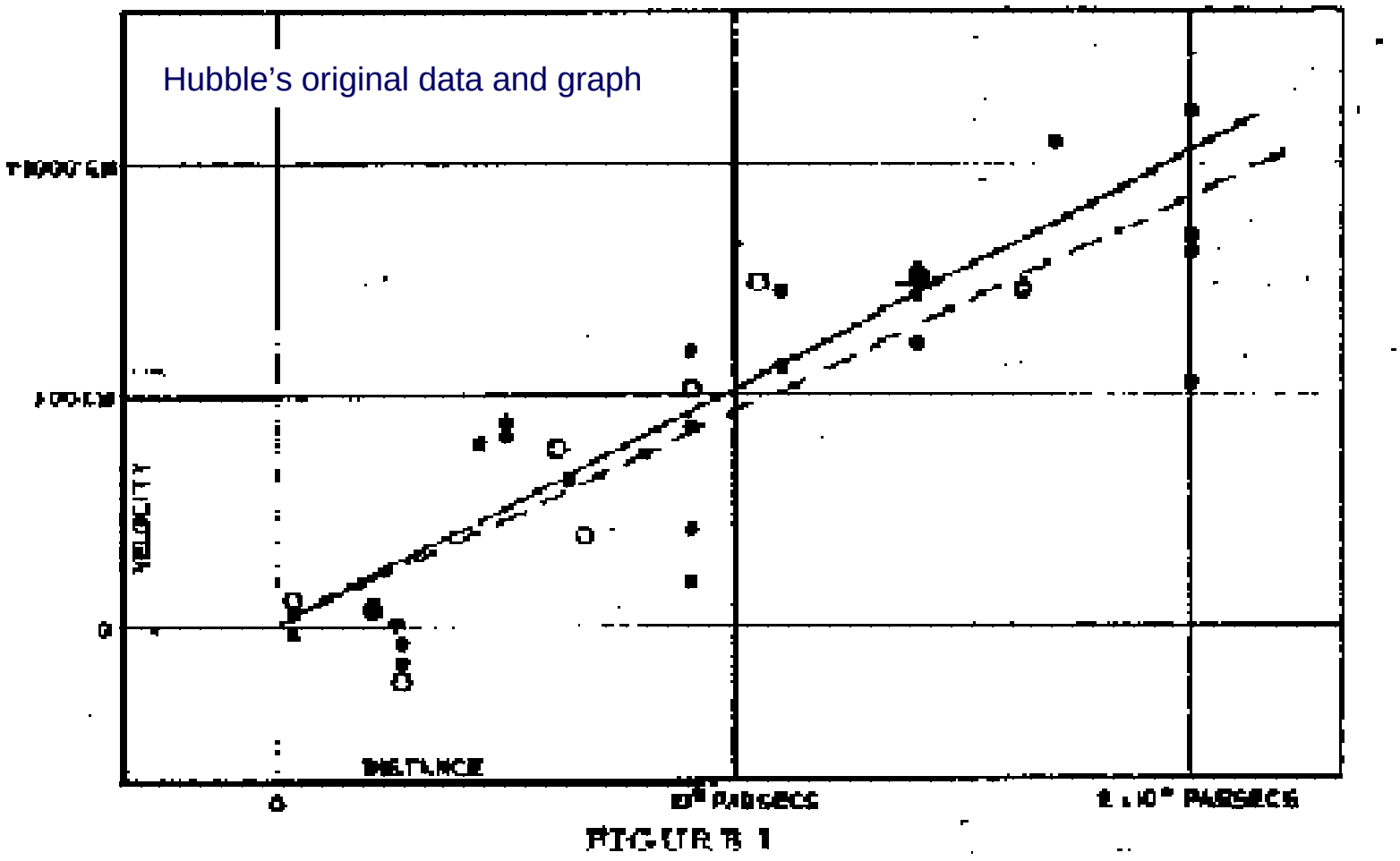


Radial velocities followed from the *Doppler formula*, in its simple form:





Hubble then found that a galaxy's recession velocity was proportional to its distance – a result known today as **Hubble's law**.



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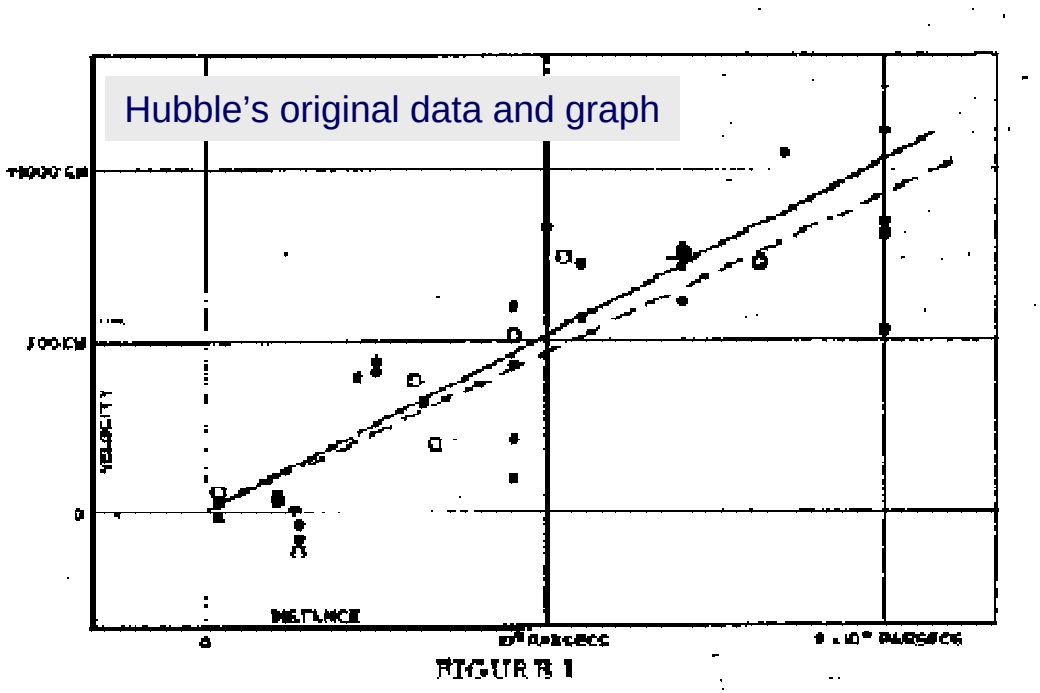


in equation form…

$$v_{\text{rec}} = H_0 d$$

v_{rec} : kms^{-1}

H_0 : Hubble's constant

d : Mpc

H_0 is hard to measure accurately.

(Hubble himself got it wildly wrong!)

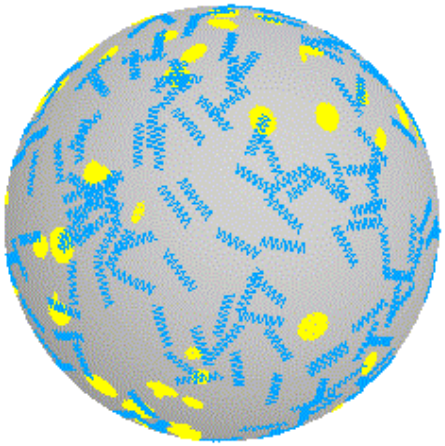
Distance usually measured in **Megaparsecs**, where

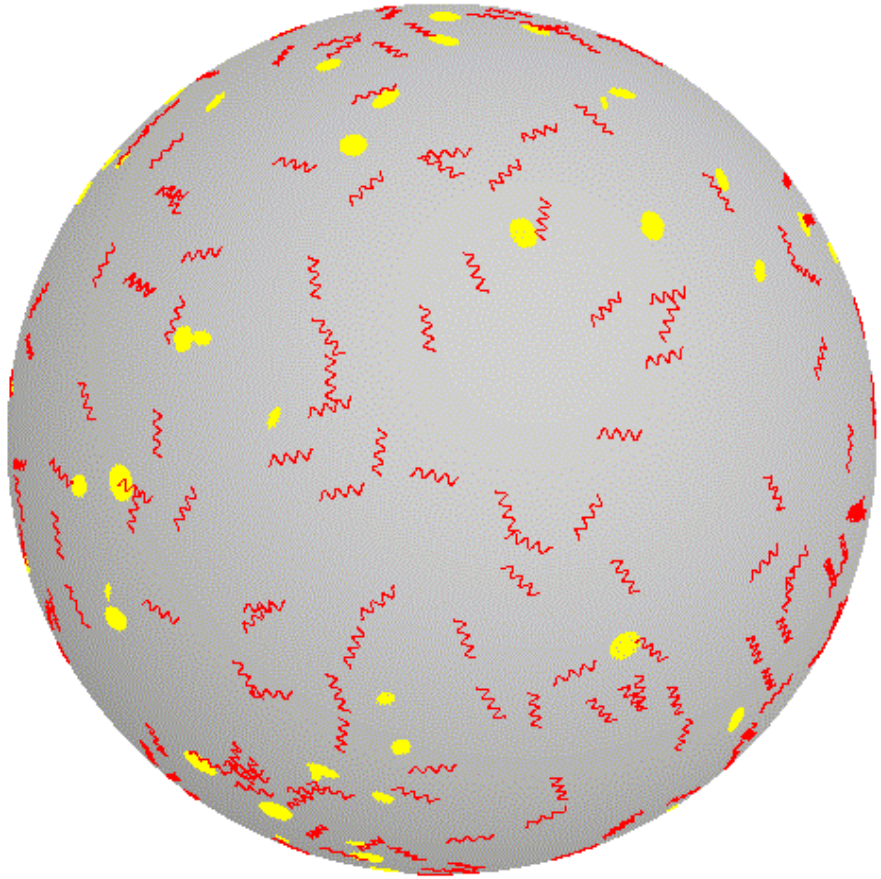
$$1\,\text{Mpc} = 10^6\,\text{pc} = 3.086\times10^{22}\,\text{m}$$

i.e. $1\,\text{pc} \approx 3.26\,\text{light years}$

What does Hubble's law mean?....

We interpret Hubble's law not as evidence that galaxies are moving away from us *through* space. It is space *itself* between the galaxies which is expanding, like the surface of a balloon.

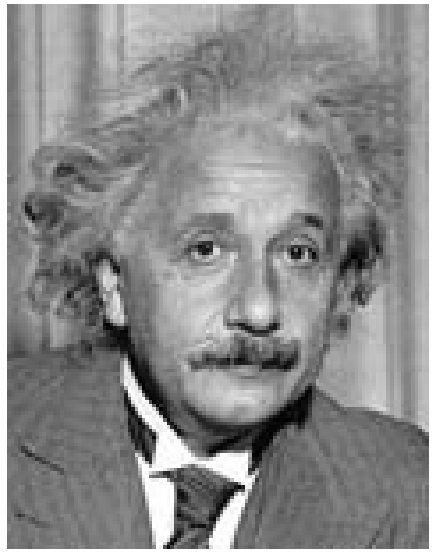




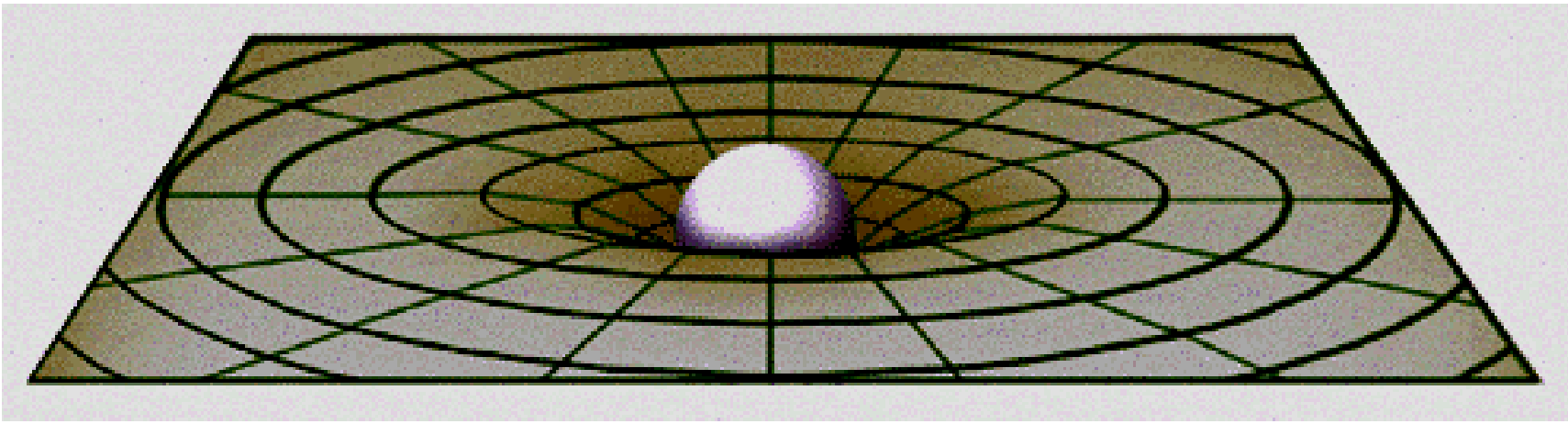
Light emitted by the galaxies is **redshifted**, its wavelength stretched by the expansion.

There is nothing special about our view of the Universe; an observer in *any* galaxy will see other galaxies moving away according to Hubble's law.

An expanding universe is consistent with Einstein's **General Theory of Relativity**, which describes gravity as the curvature of spacetime.



"Matter tells spacetime how to curve, and spacetime tells matter how to move"



(When Einstein published GR, in the decade before Hubble's discovery, he 'fudged' his theory to give a ***static*** *universe – see lecture 2)*

1.2 The Evolving Universe

The speed of light is **finite**, so looking out into the Universe means looking back in time, seeing the Universe as it was in the distant past.

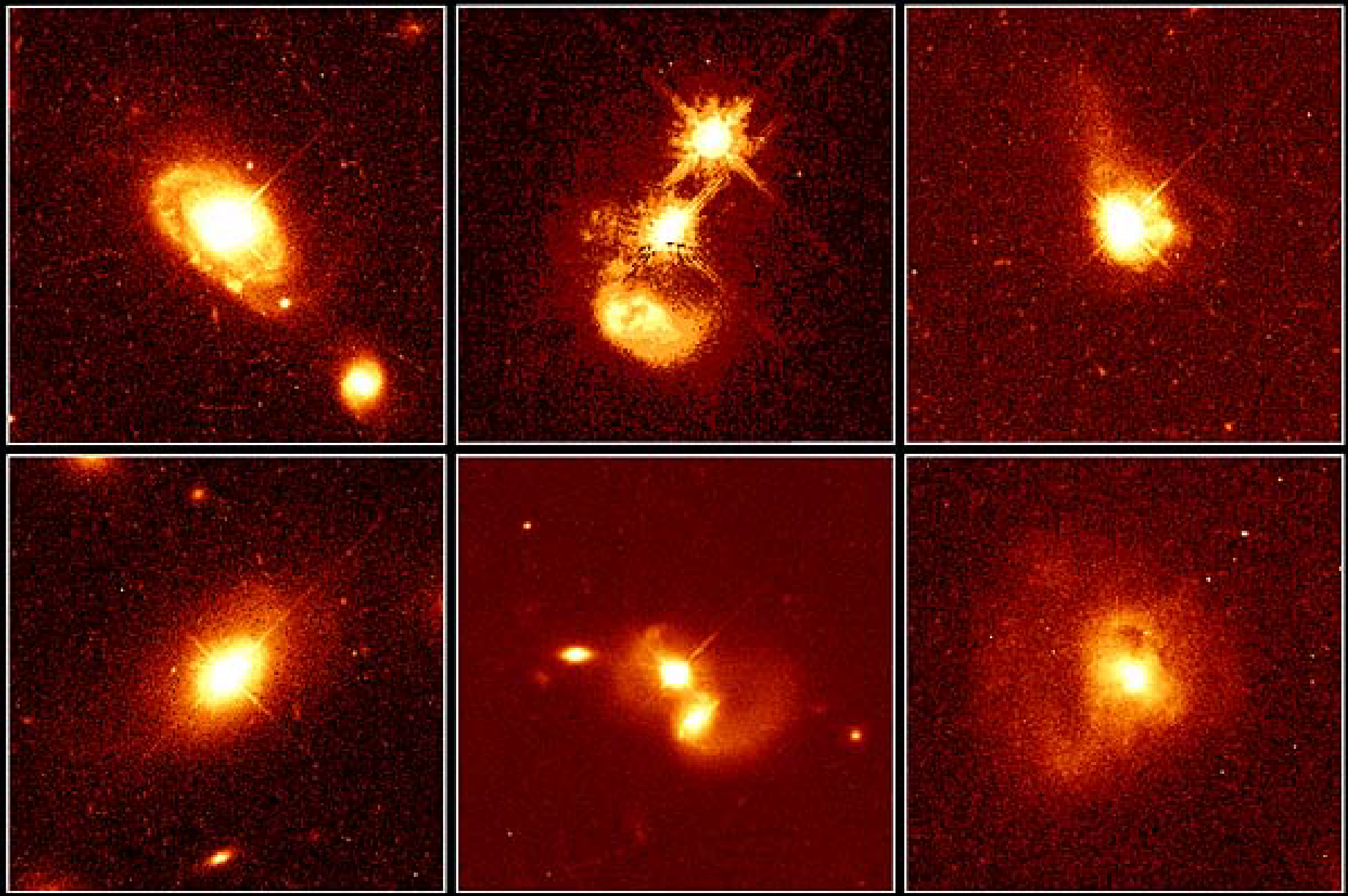
*(We often refer to this as seeing the Universe at high **redshift**, since the further light has travelled the more it will be redshifted by the expansion of the Universe since the light was emitted)*

We see many examples of how the high redshift Universe looked very different, e.g.

- presence of **quasars** and **active galaxies**
- existence of **spiral galaxies** in clusters

And, at even higher redshift, long before there *were* any galaxies…

- the **C**osmic **M**icrowave **B**ackground **R**adiation

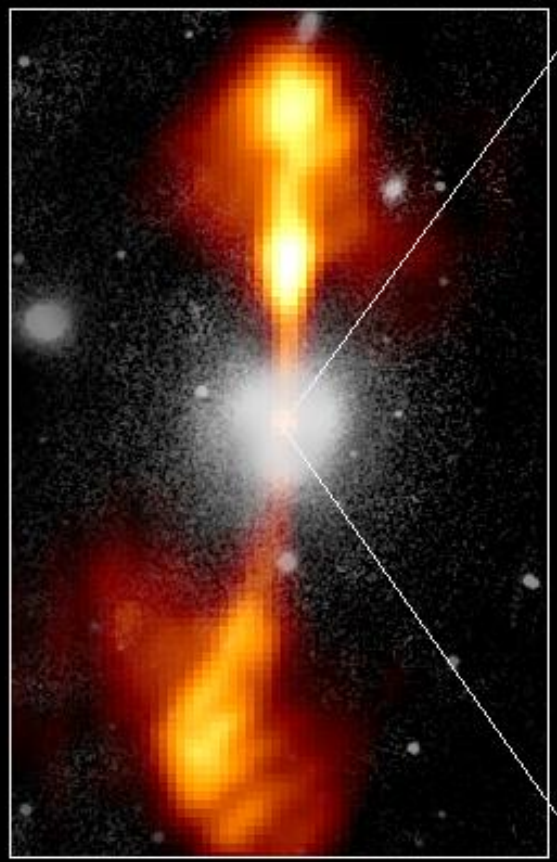


Core of Galaxy NGC 4261

Hubble Space Telescope

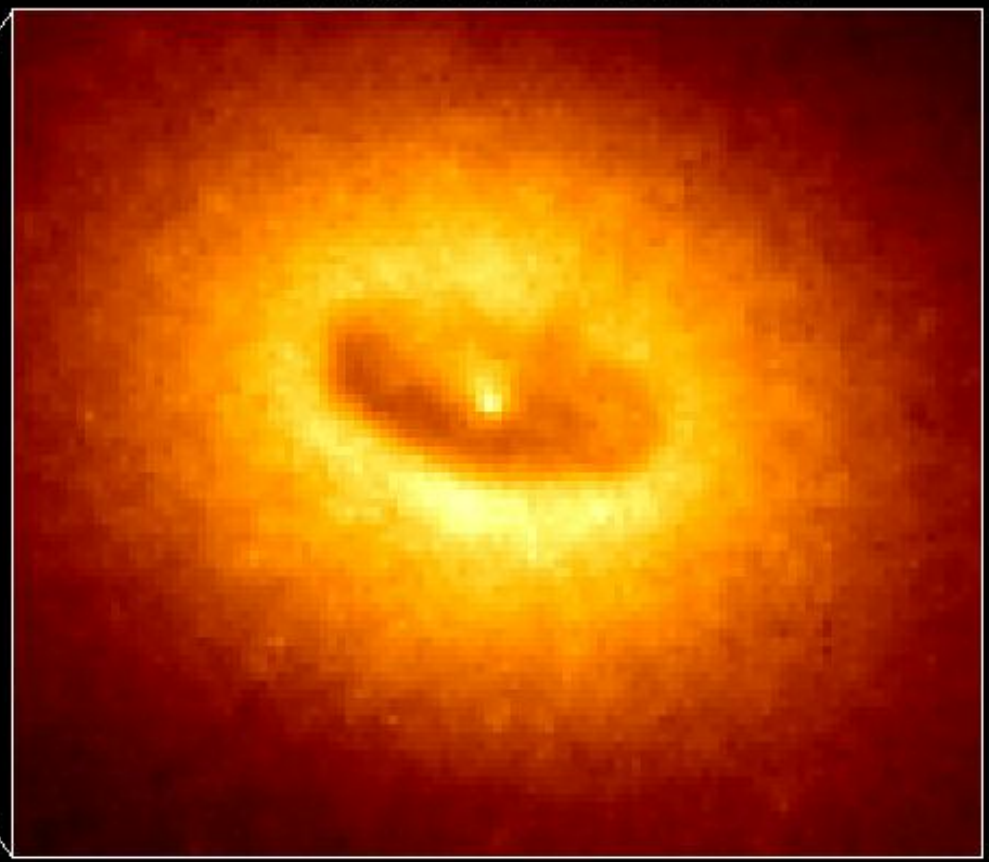
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image

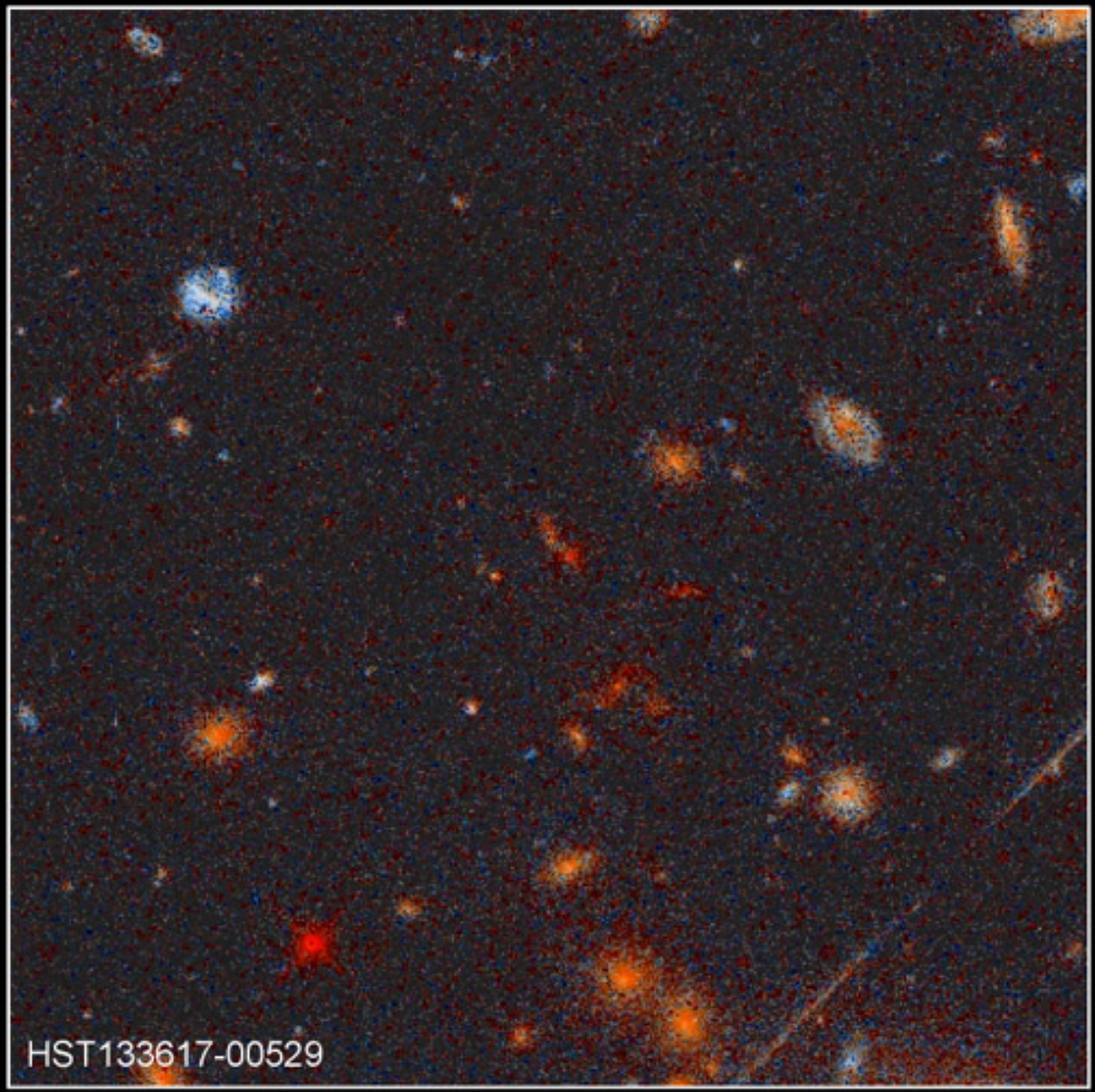


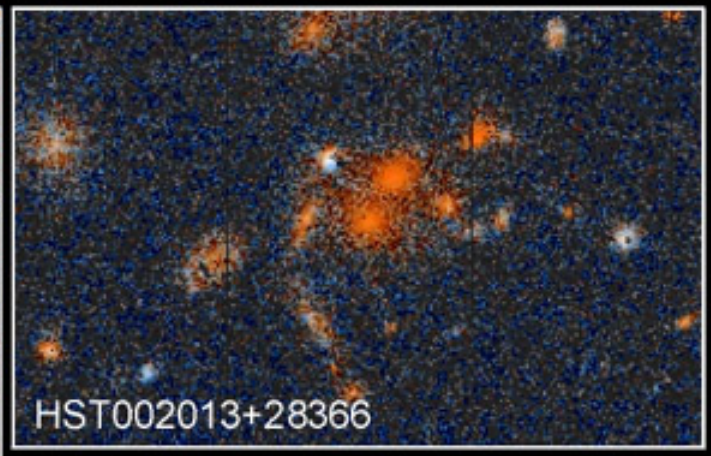
380 Arc Seconds
88,000 LIGHT-YEARS

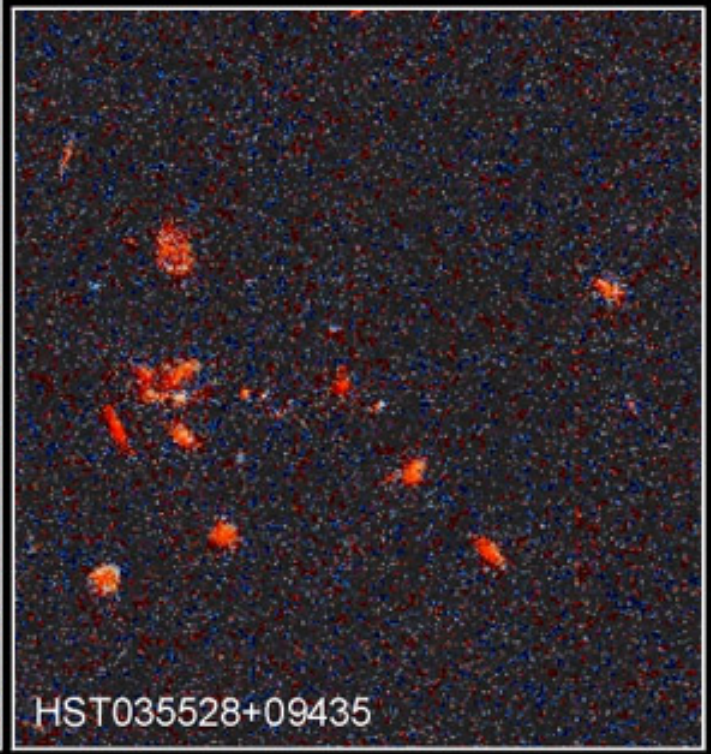
HST Image of a Gas and Dust Disk



1.7 Arc Seconds
400 LIGHT-YEARS







Distant Galaxy Clusters **HST • WFPC2**

PRC98-27 • ST ScI OPO

E. J. Ostrander, K. U. Ratnatunga, R. E. Griffiths (Carnegie Mellon University) and NASA

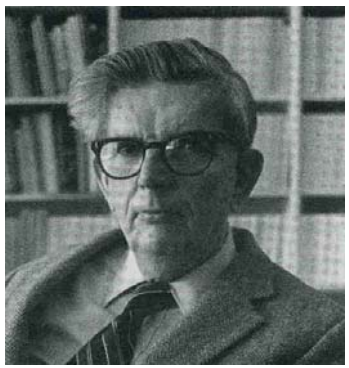
1.3 The Cosmic Microwave Background Radiation

The CMBR is relic radiation from the Big Bang itself, which has been cooling ever since.

First predicted in the late 1940s by George Gamow (with Alpher and Bethe).

Then in more detail, by Gamow, Dicke and Peebles, in the 1950s and early 1960s.

George Gamow



Robert Dicke

Jim Peebles

They predicted that the relic radiation would be **black body** in form *(see P1X Thermal Physics)* emitted when the Universe was much younger and hotter.

We should 'see' relic radiation emitted when $T_{\text{Universe}} \sim 3000\text{K}$

Why $T_{\text{Universe}} \sim 3000\text{K}$?

- At hotter temperatures the Universe (mainly hydrogen gas) was **fully ionised**, containing a dense 'fog' of free electrons which are very good at scattering light.

- *Only* when the Universe cooled to $T_{\text{Universe}} \sim 3000\text{K}$ did neutral hydrogen form.

We call this the epoch of recombination

- Much less scattering of light after that. Photons could 'free stream' through the Universe (cooling as it expands).

- We see these photons, now cooled to about 3K: black body curve peaks in the **microwave** part of the E-M spectrum.

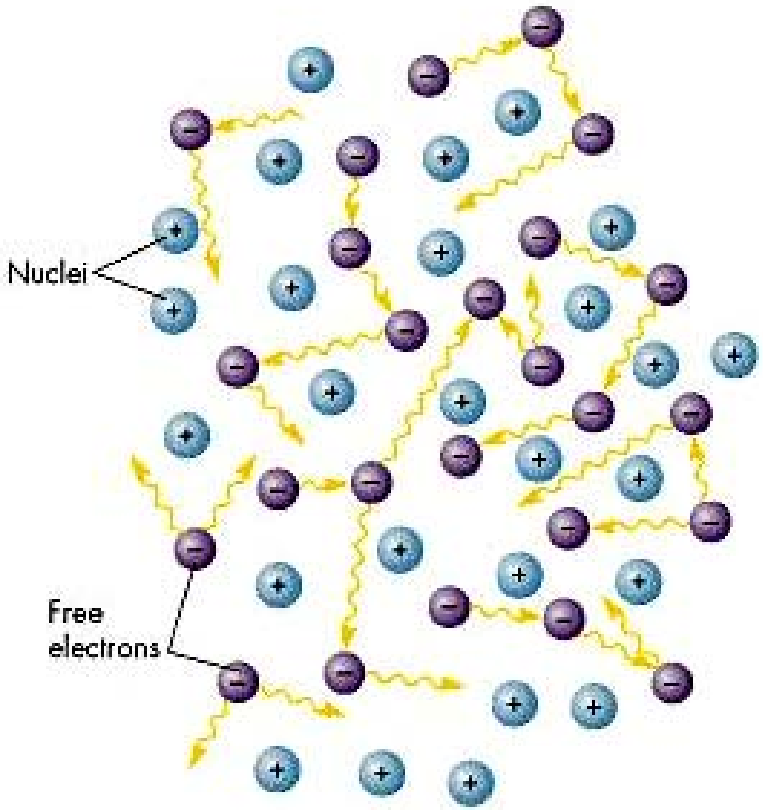
*Hence C**M**BR*

We see the background radiation as far back as the epoch of recombination, but no further – like observing a bank of fog.

We say the CMBR is emitted at the ***surface of last scattering***

Before

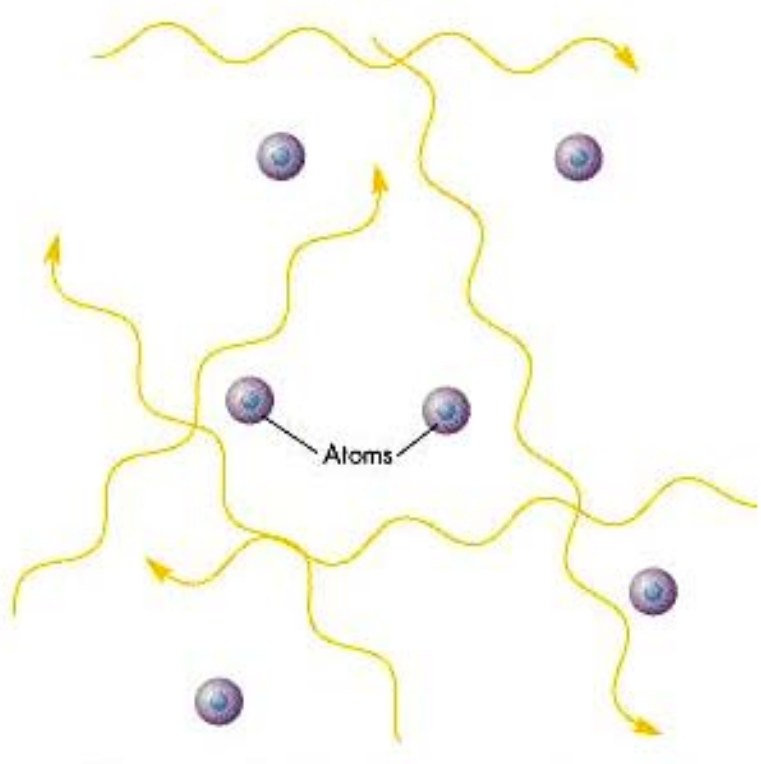
$T_{\text{Universe}} > 3000\text{K}$



Photons continually scattered, absorbed and re-emitted by fog of free electrons.

After

$T_{\text{Universe}} < 3000\text{K}$

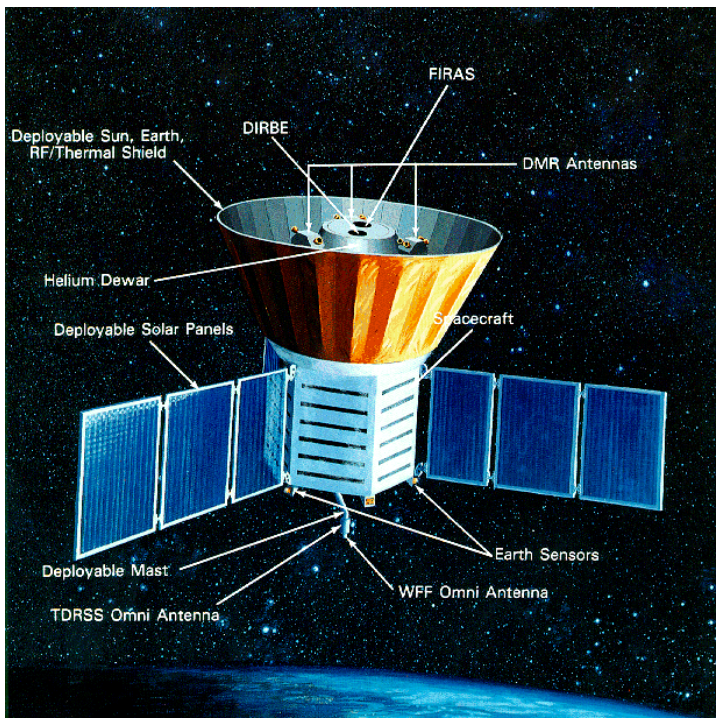


No more free electrons. Photons now able to travel freely through the Universe: the fog has cleared!

The CMBR was discovered by accident in 1965 by Penzias and Wilson, two radio engineers working for Bell Laboratories.

Much of the radiation is absorbed by the Earth's atmosphere….

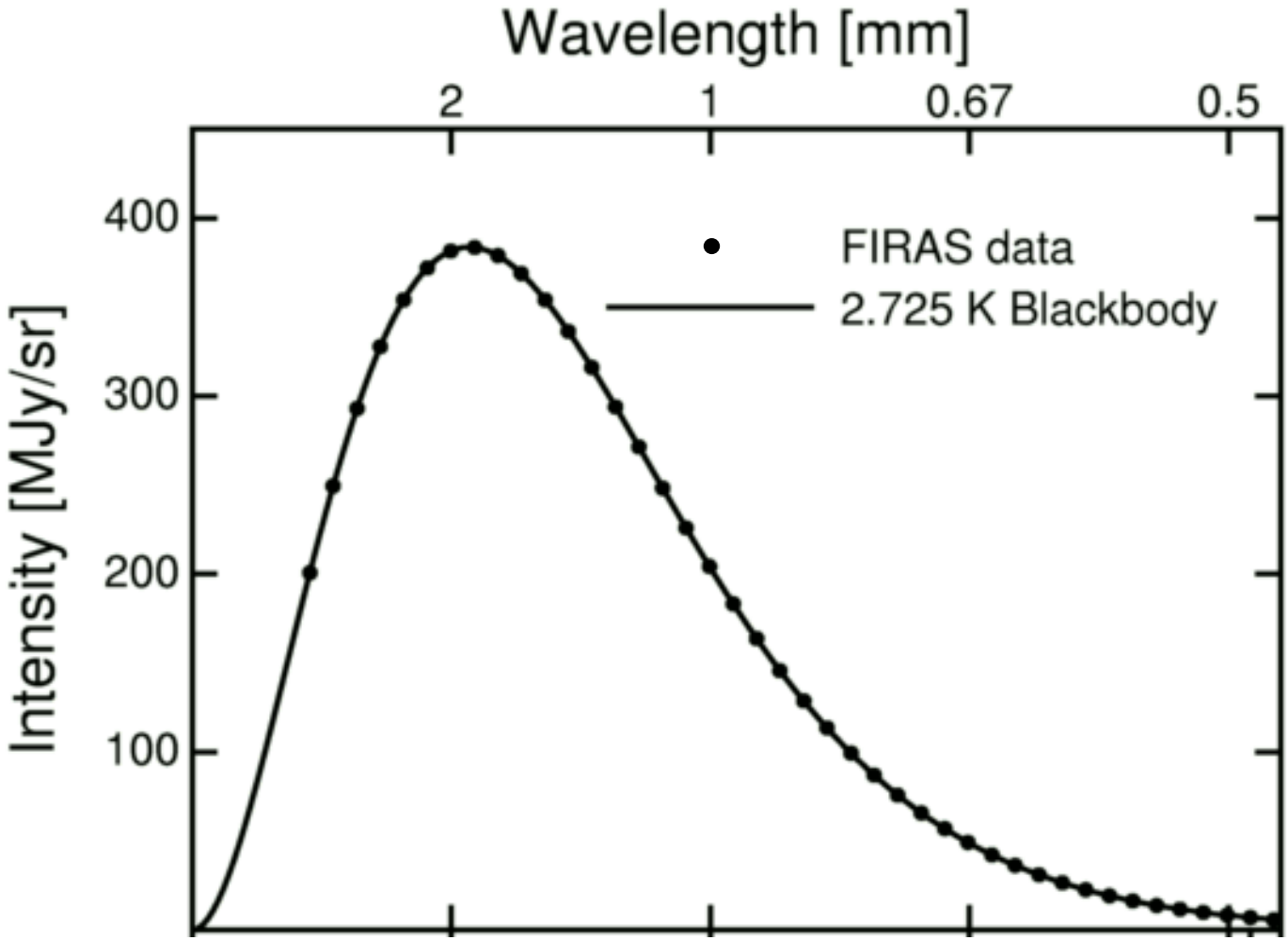
Arno Penzias and Robert Wilson



….but in 1989 the CoBE satellite was launched, to observe the CMBR from space.

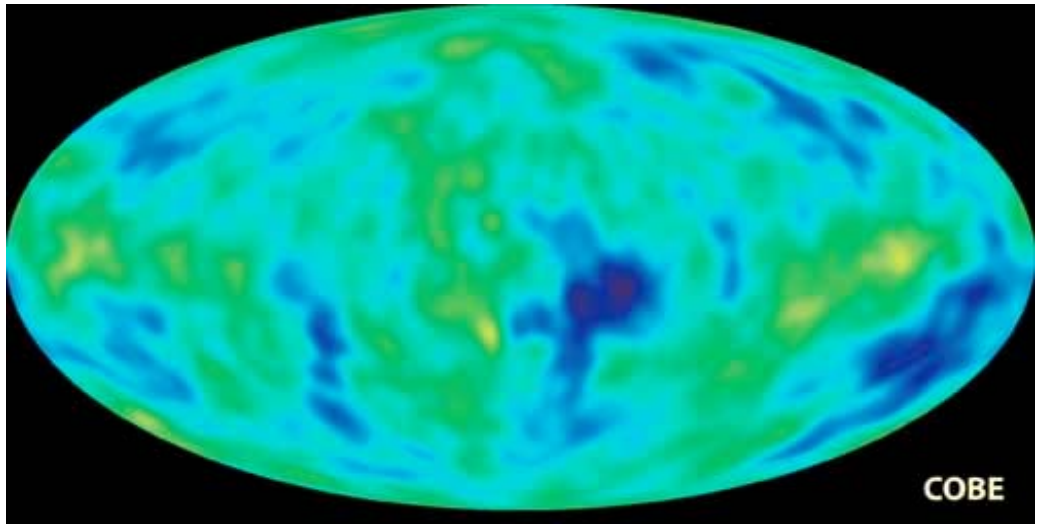
CoBE could detect the radiation over a much wider range of wavelengths..

CoBE confirmed that the CMBR was an almost perfect source of black body radiation….



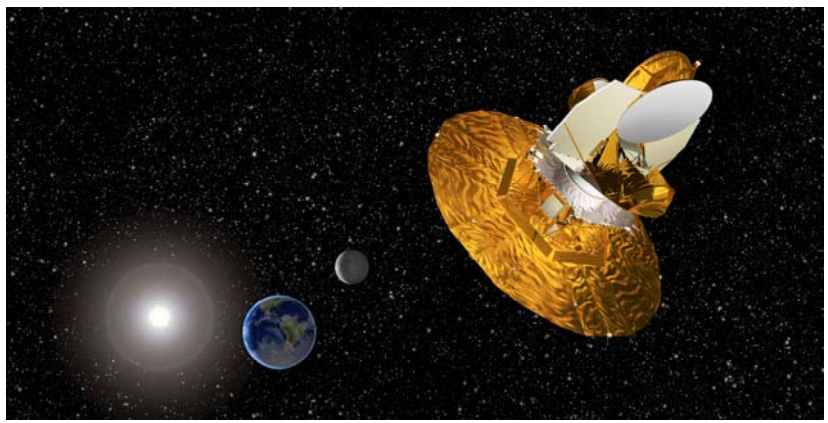
….CoBE also detected tiny variations in T_{CMBR} with direction, at the level of a few $\times 10^{-5}\,\mathrm{K}$.

These ‘ripples’ in the CMBR are very important. They are believed to be the ‘seeds’ of the clustered distribution of galaxies we see around us in the Universe today.

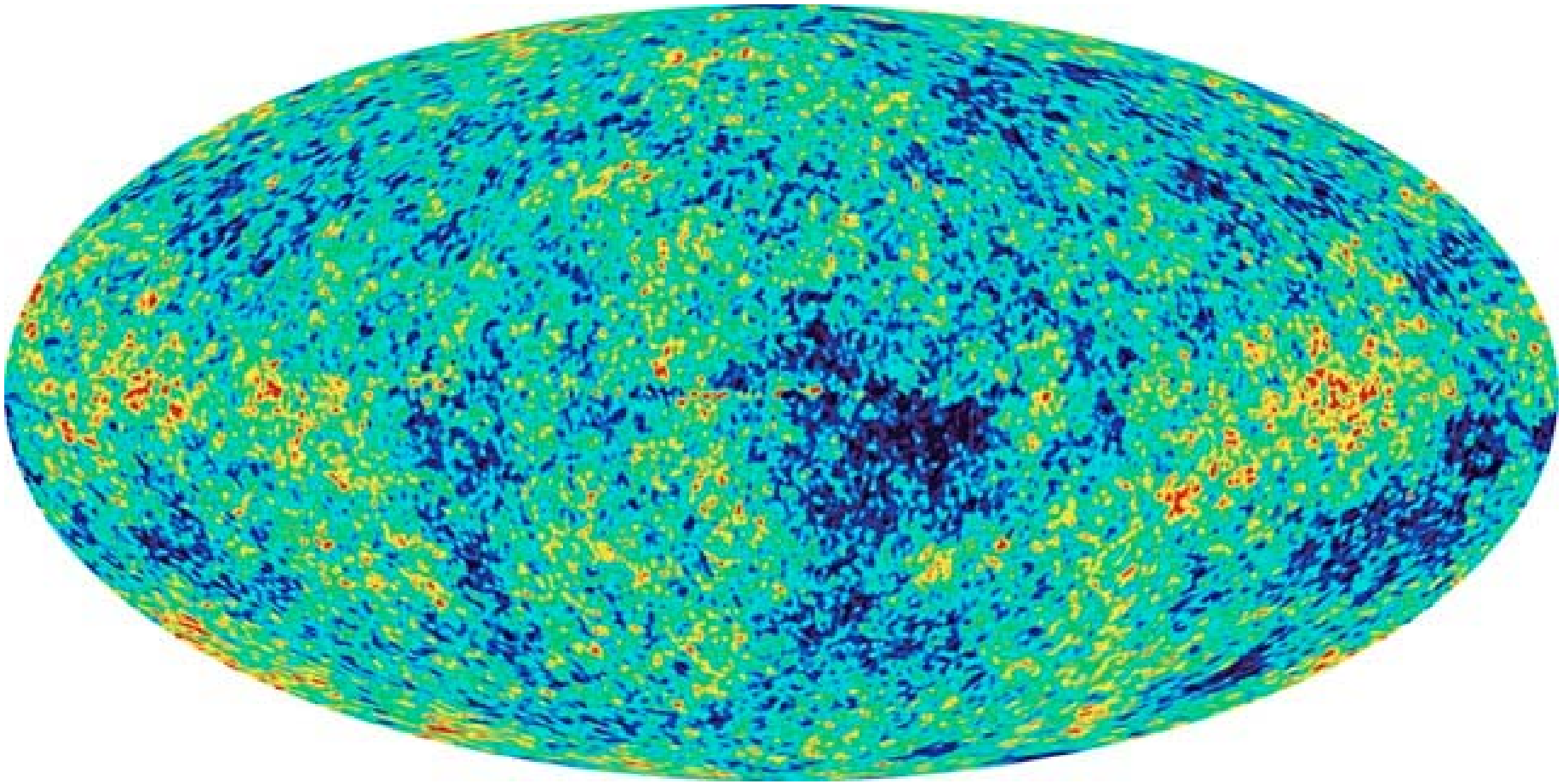


Map of CMBR temperature across the sky, showing variations from the average temperature ($T = 2.725\ \mathrm{K}$) of a few hundred thousandths of a degree

More recently (since 2003) these ripples have been mapped, with much greater precision and angular detail, by the Wilkinson Microwave Anisotropy Probe, or **WMAP** (see also Lecture 2).



WMAP map of temperature across the sky



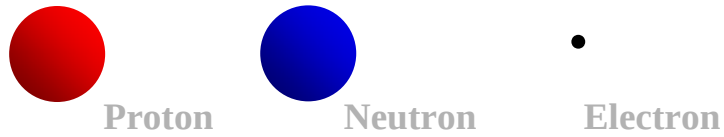
1.4 Abundances of the Lightest Elements

According to the Hot Big Bang theory, in the first few minutes after the Big Bang the lightest chemical elements were made.

As the universe expanded, it first became cool enough for protons and neutrons, and then for stable nuclei, to form.

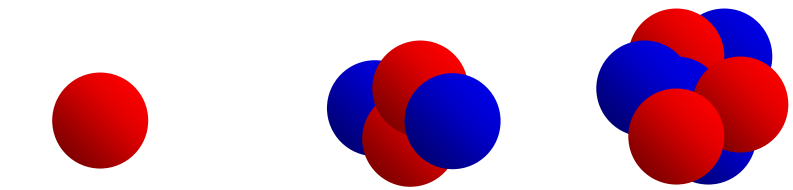
These included isotopes of hydrogen + helium and lithium.

We can predict precisely how much of each element should be produced, as a function of time.

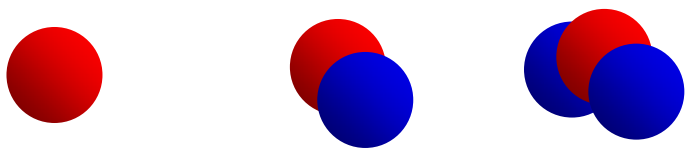


Relative Masses 1 : 1 : 0.0006

Relative Charge +1 : 0 : -1



^{1}H ^{4}He ^{7}Li

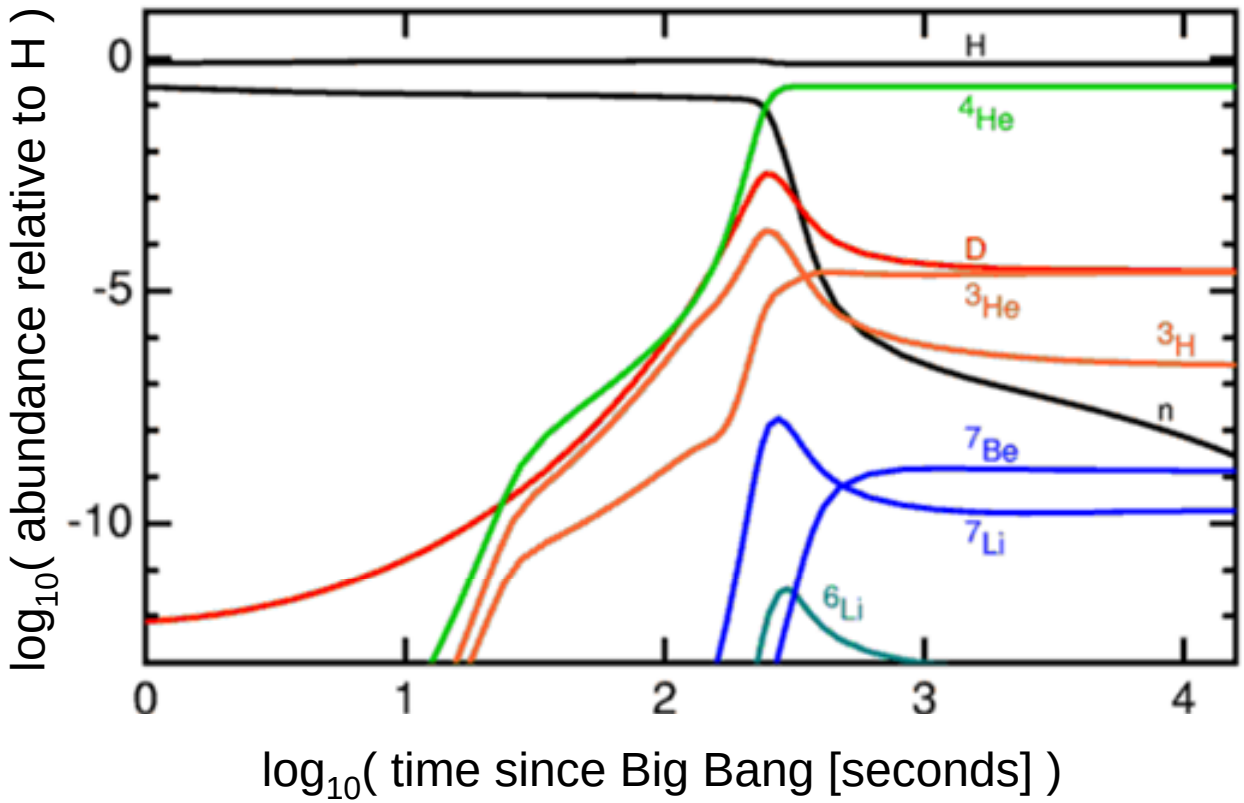


^{1}H ^{2}H ^{3}H

1.4 Abundances of the Lightest Elements

From about 20 mins after the Big Bang, the abundances remain constant:

Universe too cool for any more ‘cooking’ of elements + not enough high-energy photons to ‘blast’ apart the elements already formed.



Remarkably, the predicted element abundances match what we observe extremely well – **a major success of the Big Bang theory.**

(but to make them match gives us important clues about dark matter; see later!)

These 4 ‘pillars’ make the Hot Big Bang theory very successful:

- **explains the expansion and evolution of the Universe;**
- **explains the CMBR: the ‘smoking gun’;**
- **successfully predicts the light element abundances.**

But the theory doesn’t tell us:

➢ what ‘caused’ the Big Bang?...

NewScientist

'Heretical' cosmologist does away with the big bang

10 September 2007
NewScientist.com news service
Zeeya Merali

"I am a heretic," Cristiano Germani announced to an audience of cosmologists last month. Few would disagree, as he is proposing a radical alternative to standard cosmology: a universe with no big bang creation moment, and no rapid inflation. Rather than a big bang, he suggests a slingshot.

In the early 1980s, Alan Guth at the Massachusetts Institute of Technology proposed that our universe underwent inflation - a period of rapid expansion in the first 10^{-34} seconds after the big bang. Germani, a cosmologist at the International School of Advanced Studies in Trieste, Italy, says that inflation is beautiful and successful, yet he insists that we need to replace it.

"We don't have any fundamental physical explanation for how or why it occurred," he says. "Yet cosmologists today accept it as though it is a religion."

Controversies concern what happened in first 10^{-34} seconds.

These 4 ‘pillars’ make the Hot Big Bang theory very successful:

- **explains the expansion and evolution of the Universe;**
- **explains the CMBR: the ‘smoking gun’;**
- **successfully predicts the light element abundances.**

But the theory doesn’t tell us:

- what ‘caused’ the Big Bang?...
- what the Universe is made of?
  how fast it is expanding?
  will it expand forever?...

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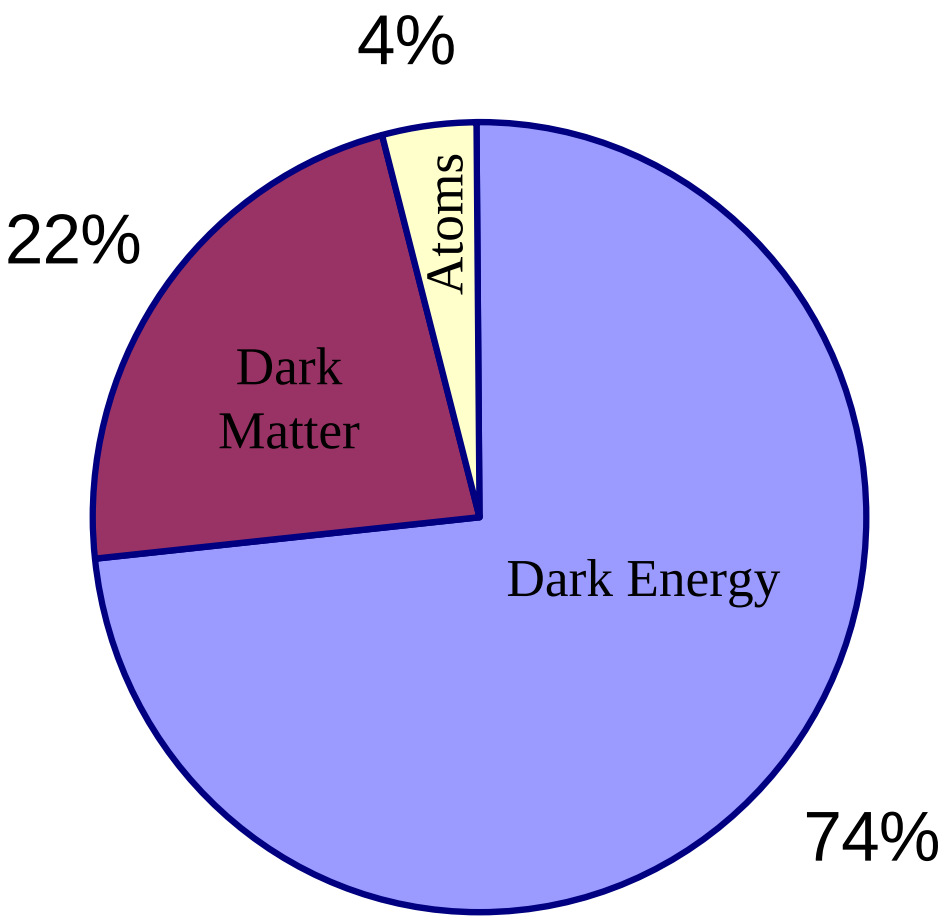
We need to make observations to answer these questions

State of the Universe – Oct 2007



More than 95% of matter and energy in the Universe exists in a mysterious, unknown form…

This picture is known as the **Concordance Model**