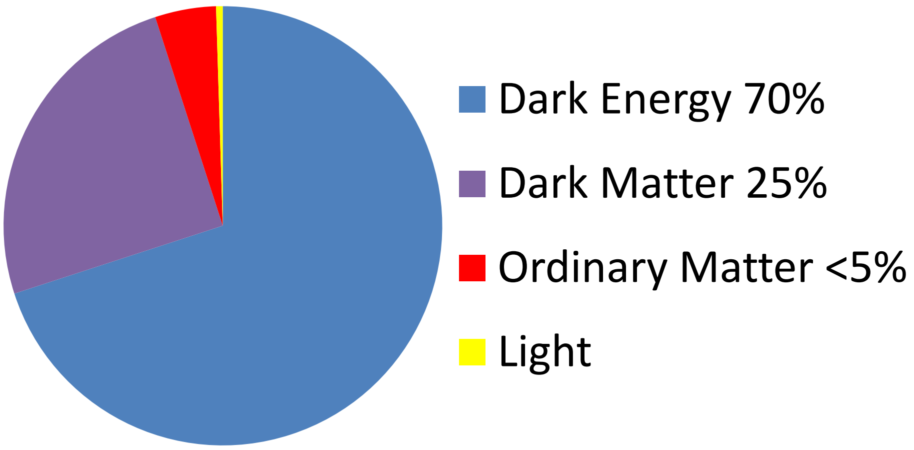
Lucía Fonseca de la Bella.
Mathematical and Physical Sciences School,
Physics and Astronomy Department, University of Sussex

THE ACCELERATING EXPANSION OF THE UNIVERSE

Contents

1. What is Cosmology?

- NASA definition:“the scientific study of the large scale properties of the Universe as a whole”.
- Cosmology study the Universe as a “fluid” where galaxies are point-like particles (large scales).
- At the present, the Universe is formed by a 70% of an exotic component called Dark Energy, a 25% of invisible matter called Dark Matter, <5% of ordinary matter (planets, stars, living beings …) and the rest is light.

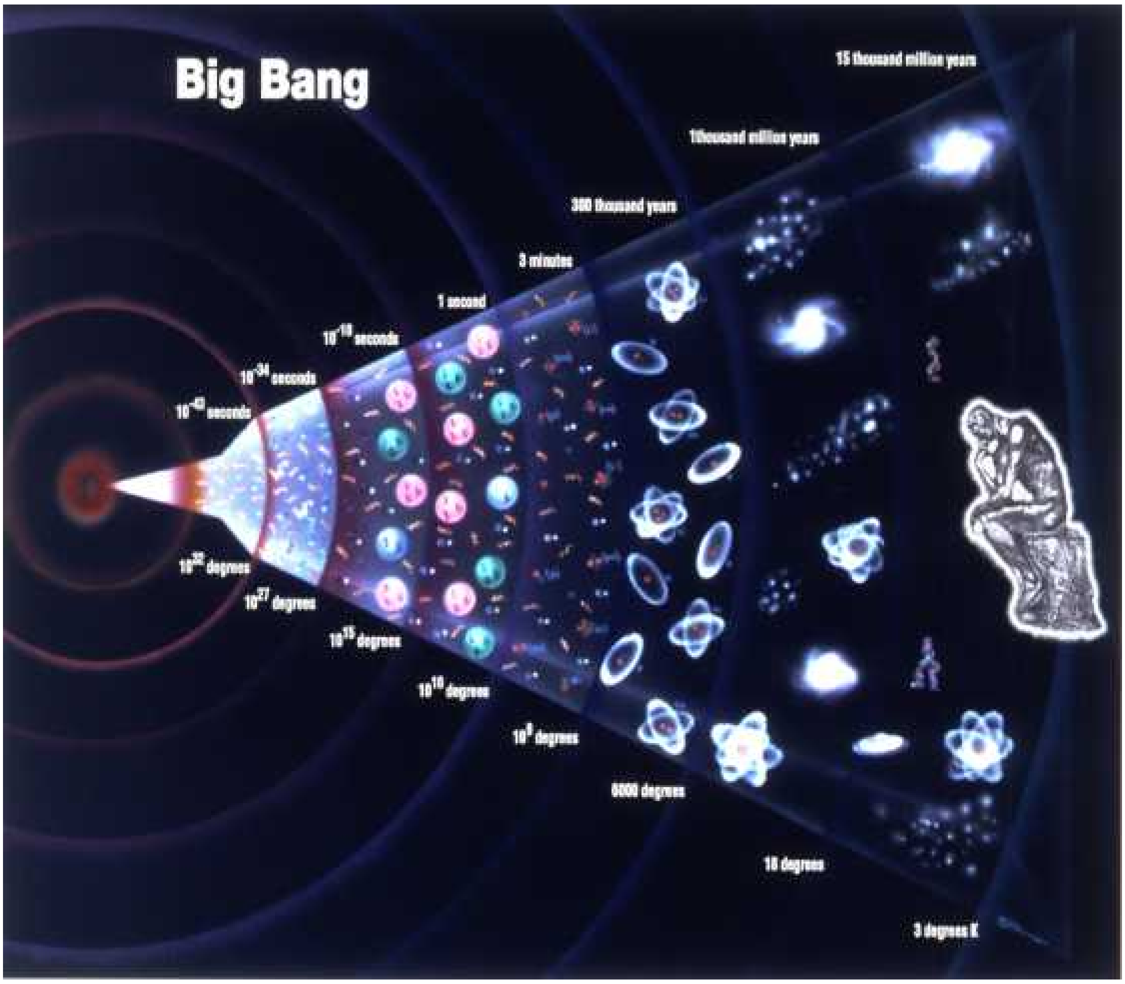


2. The History of the Universe.

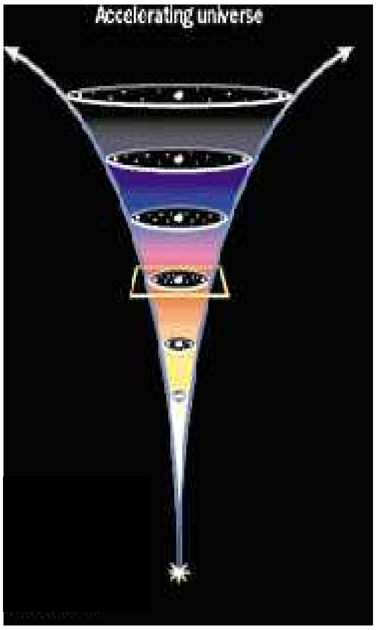
- Big Bang: big explosion, origin of our Universe.
- Very Early Universe: the Universe is very hot and must be described by Quantum Theory. Fundamental particles have very strong interactions.
- Inflation: very fast expansion of the Universe.
- Light is released: **CMB** is the cosmic microwave background radiation, fundamental to observational cosmology because it is the oldest light in the Universe we can see.
- Galaxy formation: stars are formed and they cluster in galaxies.

- Accelerating expansion: nowadays the Universe enters in a new accelerating phase due to Dark Energy or "Cosmological Constant" component. The age of the Universe: ~13.8 billion years.
- The end (several options):
    1. Big Rip: the expansion would keep being accelerated, increasing without limit, therefore everything will be diluted and torn apart.
    2. Big Crunch: it would be possible that the expansion of the Universe would reverse and the Universe would contract towards a hot, dense state.
    3. Big Freeze: the Universe will expands and cool down, therefore it will go dark. This is the most likely scenario.

The Universe cools down as it expands.



3. The Universe today.



- General Relativity of Einstein with a Cosmological Constant or Dark Energy component is the simplest theory which describes the expanding Universe.
- Distances are modified by the so-called scale factor, $a(t)$, which varies with time:

$$d(t) = a(t)\, x$$

x is the distance between two point-like galaxies in case the Universe does not expand.

We do not feel the expansion because it is important at very large scales (much larger than galaxy size).

An important concept is the *Hubble parameter, H(t),* which measures the ratio of the expansion

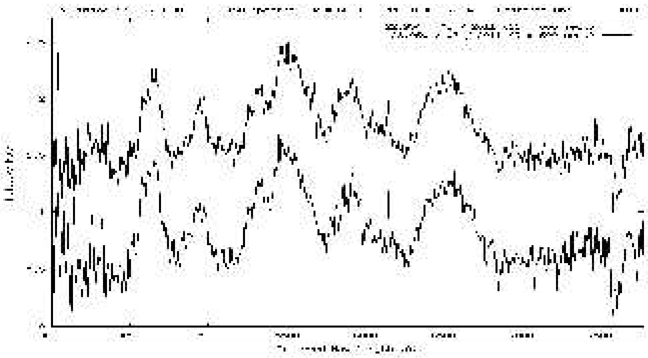
$$H(t) = \frac{\dot{a}}{a}$$

Theory predicts accelerating expansion today.

4. Observations.

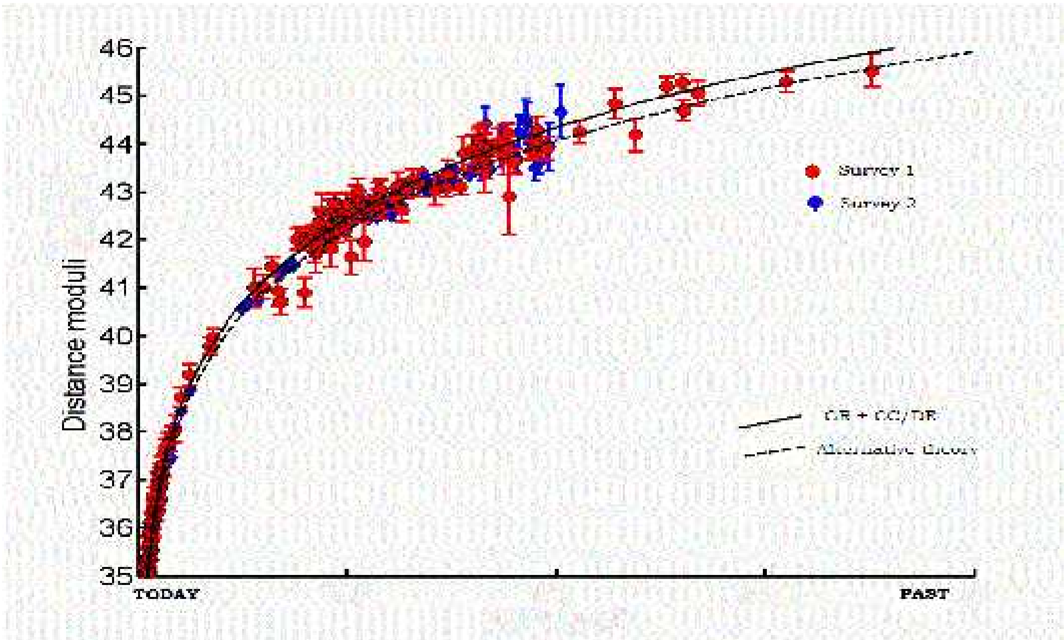
- Many stars die with a big explosion called Supernovae. It briefly outshines an entire galaxy, radiating as much energy as the Sun or any ordinary star is expected to emit over its entire life span, before fading from view over several weeks or months.
- Supernovae are very bright, therefore distances are easily measured. For that purpose, it is needed a supernovae spectrograph. The figure below represents a supernovae spectrograph and the graphic of the brightness along the time.
- **Distance modulus:** is the mathematical expression which relates the magnitude (bright) of an object with its distance.

« $= 5\log d - 5$



5. Data and theory predictions.

- We can use the observational data obtained from the supernovae brightness in order to check theoretical predictions or if a theory is good enough to describe the Universe.
- General Relativity of Einstein with a Cosmological Constant or Dark Energy component fits data points very well. Therefore, it is able to describe the current accelerating expansion of the Universe very good.
- Although the previous description is quite good, there exist many more theories which compete with General Relativity such that: Quintessence, scalar-tensor theories, etc



This plot represents the distance modulus points from two different supernovae surveys and two different competing theories (solid and dashed line). Both theories are good but we need to distinguish among them, then further analysis are needed.

6. Open questions…

- What is the physical interpretation of Cosmological Constant or Dark Energy?
- Why it cannot be observed?
- Are we misinterpreting observational data?
- Is there a better theory without this exotic component?
- …and much more.

At the end of the day you should know…

1. Cosmology treats the Universe as a fluid where galaxies are particles.
2. Ordinary matter today is less than 5% of the total content of the Universe.
3. The Universe has gone through different epochs and it cools down as it expands.
4. Theories as General Relativity +Cosmological Constant/ Dark Energy predicts accelerating expansion of the Universe nowadays.
5. Theories can be falsified by using supernovae datasets.

Main references in order of difficulty:
** S. Hawking, "A brief History of time", Batam Press edition, London UK (1988).

** A.Liddle, "An introduction to modern cosmology", Chichester, UK: Wiley (1998).
** V.Mukhanov, "Physical foundations of cosmology",Cambridge, UK: Univ. Pr. (2005).