The Cosmos

Planets & Life

PHYS 214

Dr Rob Thacker

Dept of Physics (308A)

thacker@astro.queensu.ca

Please start all class related emails with "214:"

Today's Lecture

- Cosmology continued…
  - The Early Universe to Galaxies

Assignment 1 will be on the web tonight

Due in two weeks time

Origin of Galaxies

- The formation of galaxies is intimately tied to the earlier history of the Universe
- Thus, to fully understand galaxy formation, we must look at even earlier epochs of the Universe
- In fact, we must go almost all the way back to just after the Big Bang to discover the first processes that contribute to the formation of galaxies

Galaxy formation in a nutshell

- Gravity is the driving force behind galaxy formation
- Any region of space that contains enough matter (is at a high enough *density*) to overcome the expansion of the Universe will begin "gravitational collapse" and start to form a galaxy
  - Two competing effects: cosmic expansion versus the gravitational attraction of the matter
  - Any region that has enough density to contract is called *overdense* relative to the average density of the Universe
- The distribution of these regions is very variable
  - There will be small regions that are overdense and large ones

Movie of gravitational collapse

But how do these overdense regions arise? What is the *perturbation* that causes them?

The Planck Epoch

- Before $t=10^{-43}$ s after the Big Bang the Universe was governed by a single force "Superforce"
  - All the forces of Nature (Gravity, Electromagnetism, Weak Nuclear Force, Strong Nuclear Force) were merged into this Superforce
- Temperature is above 10^{32} K
- This epoch is not open to scientific investigation as we don't have the theory we need
  - Could be string (or now "m-") theory
  - Could be something else

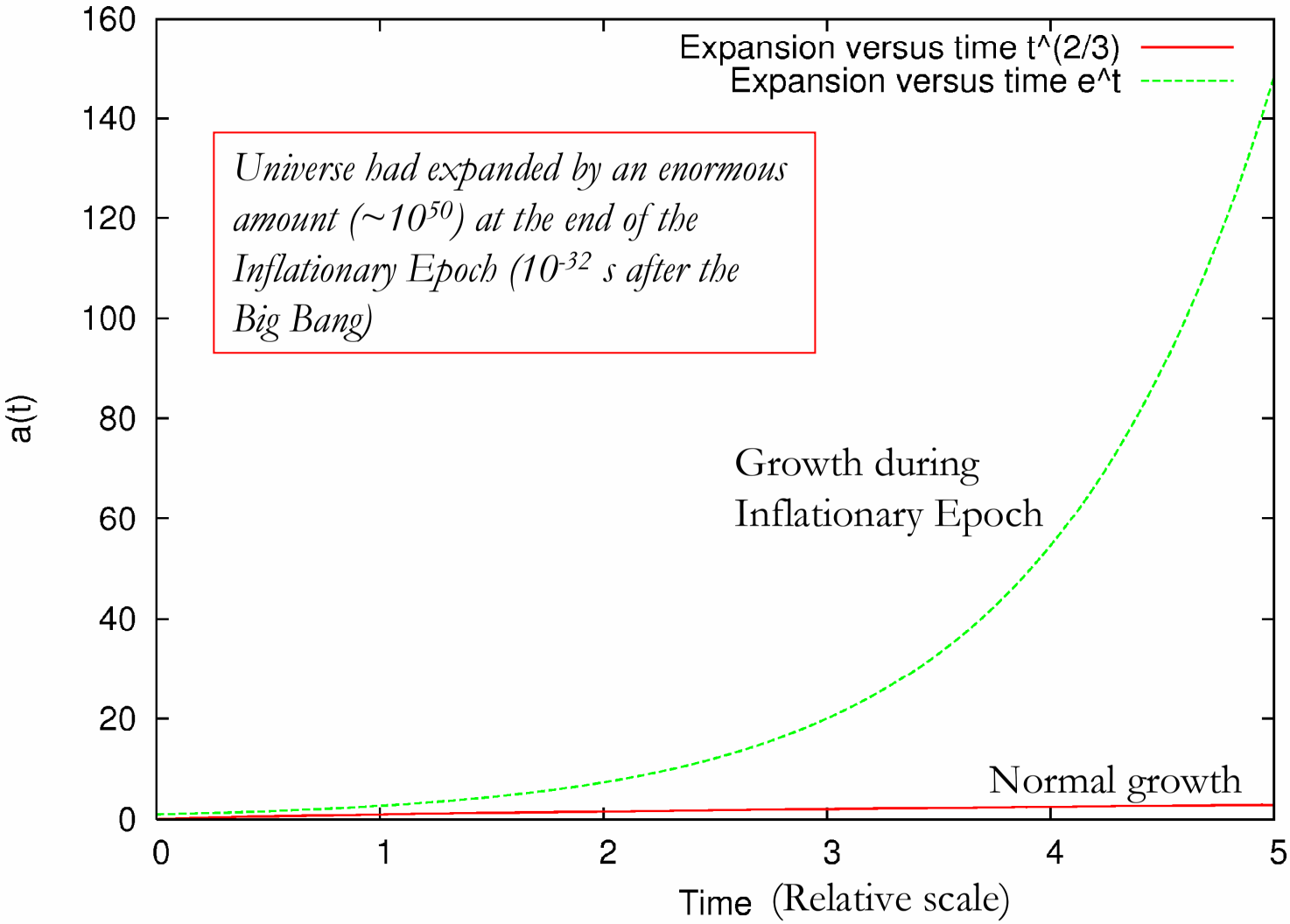
The Epoch of Grand Unification

- Once gravity separates from the Superforce we are left with Gravity + the three other forces unified into a Grand Unified Theory
  - So two forces now
- Time is now just after 10^{-43} s
- Temperature is around 10^{32} K
- Universe is now full of various "GUT" particles

Inflation (Alan Guth, 1982)

- It is now widely believed that 10^{-35} s after the Big Bang the Universe went through a period of *accelerated expansion*
  - The Universe suddenly "inflated" in size
  - Universe temperature was about 10^{27} K
- We measure the amount of expansion in terms of the relative scale of the Universe at one epoch to another
  - A simple function the *scale factor, a(t),* gives the relative size versus time
- Normally the amount of expansion versus time, *t,* is $a(t) \propto t^{2/3}$
- During inflation, the amount of expansion is proportional to $a(t) \propto e^{t}$

Growth of the scale factor during Inflationary Epoch



But what caused this expansion?

- Around 10^{-35} s after the Big Bang the Strong Nuclear force separates out of the Grand Unified Theory
  - So now have Gravity, Strong Force, but Weak Force and electromagnetism are combined in the Electroweak force
- It is believed this separation leads to the creation of a very unusual energy state for the vacuum a "*false vacuum*"
  - This energy state essentially means *space repels itself*
- Once the Universe has a reached a certain point though this field "turns off" and the expansion rate slows down enormously
  - Exactly how this happens is still the subject of much research

What happens to average density of space?

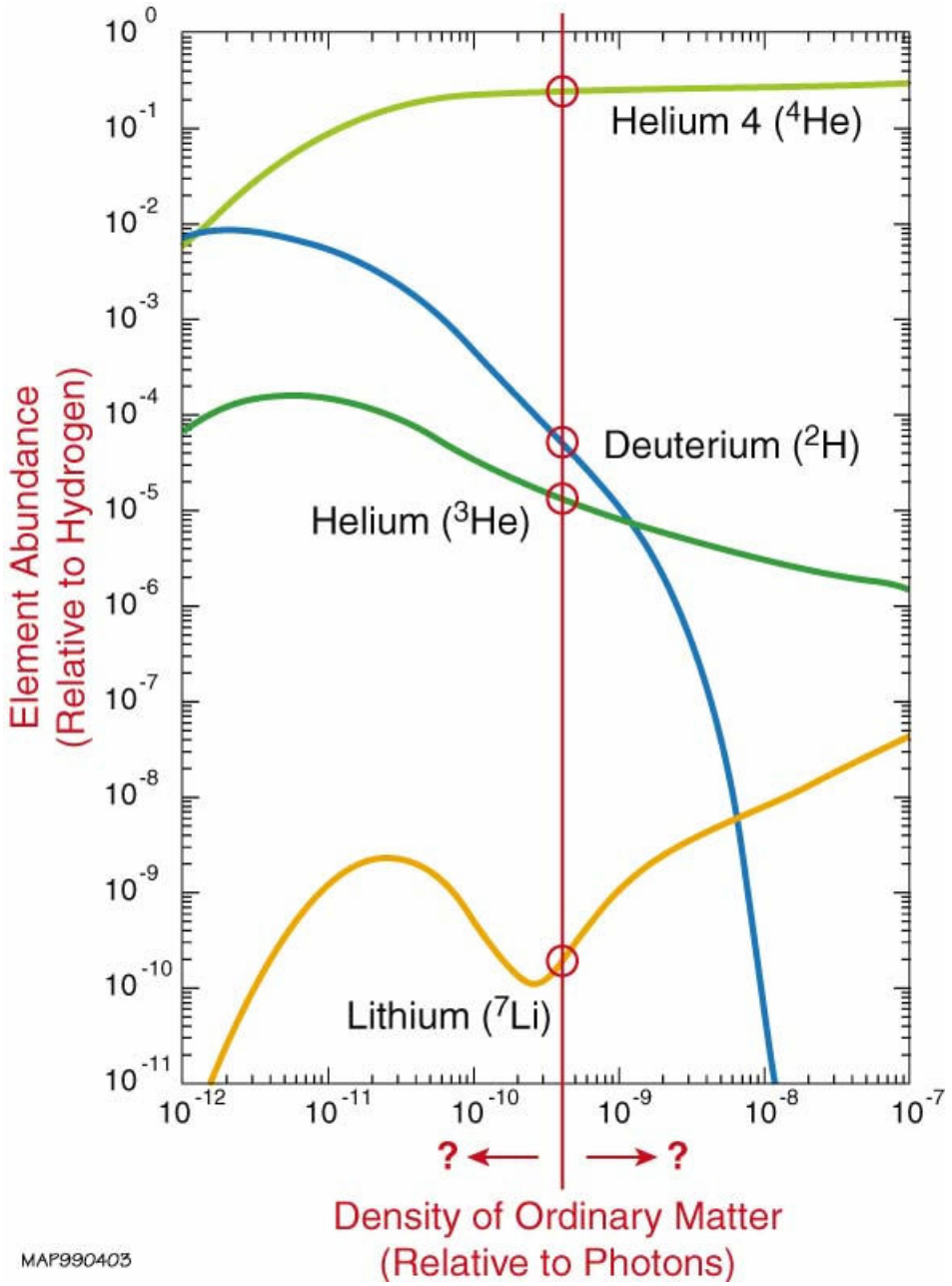
- Things are really very very smooth early on
- As inflation begins the energy of the universe is dominated by the quantum field that makes up the "false vacuum"
- Due to quantum effects this field will be minutely different from one place to another
- There will be different energies in one place to another
- So there will be very small, but predictable, differences in density from one place to another
- *These differences in density will be the seeds of galaxy formation later on*

At 10^{-12} seconds…

- The Electroweak force splits into the weak nuclear force and electromagnetism
- Temperature is now 10^{15} K
- Still too hot to create atoms as protons and neutrons have not been formed
- At 10^{-6} s, 10^{13} K protons and neutrons are formed
- After 3 minutes, 10^{9} K, neutrons and protons combine to form nuclei of atoms - *nucleosynthesis*

Big Bang Nucleosynthesis

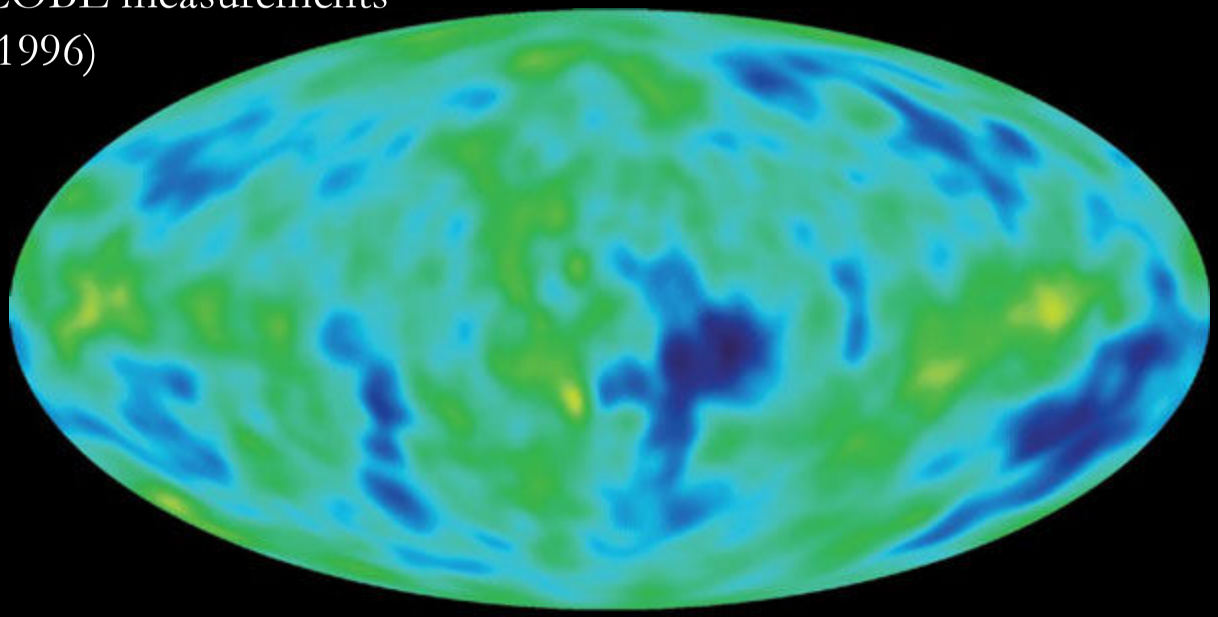
- This is a triumph of modern nuclear theory
- We can calculate - with exquisite precision - the primordial levels of Hydrogen, Helium, Lithium (very little of anything else created)
  - One **He** for ten **H**
- This composition (predicted by nuclear theory) is in excellent agreement with the levels *observed in the oldest stars*



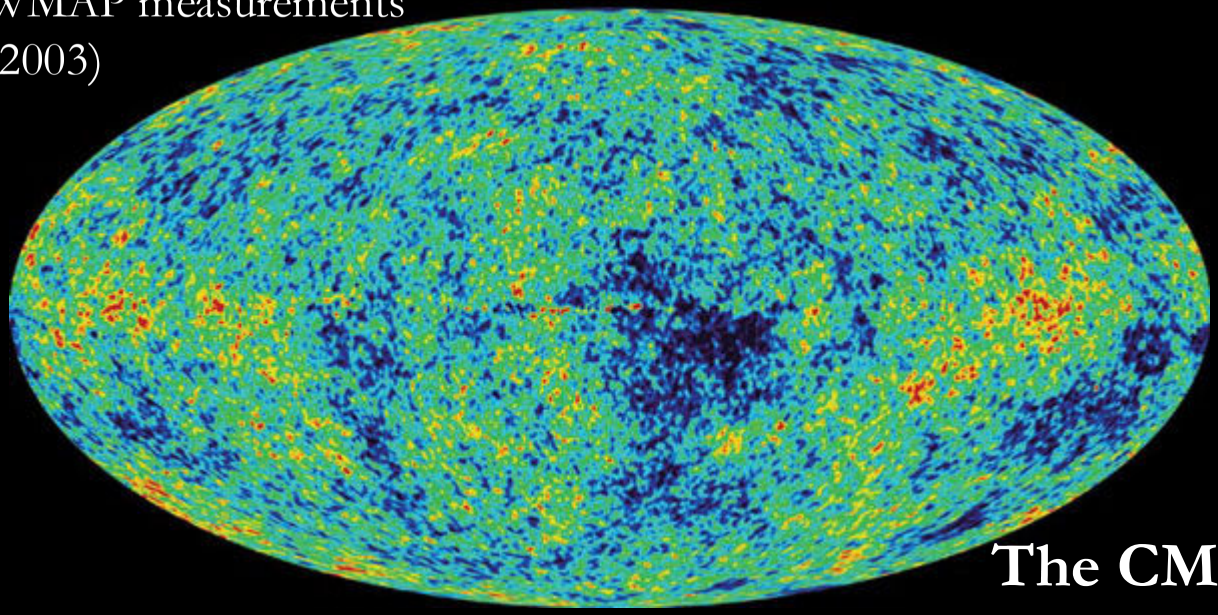
Formation of atoms & the Cosmic Microwave Background

- Even though the nuclei are formed, before about 300,000 years after the Big Bang it is still too hot (above 3000 K) for electrons to join with nuclei and form neutral atoms
- Up to this point we have a plasma of mostly protons and electrons
  - Remember there is $1/10^{th}$ as many **He** nuclei
- When the electrons and protons combine to form **H** a photon of light is released
- We detect these photons of light today as the *Cosmic Microwave Background*
  - An echo of the Big Bang

COBE measurements
(1996)



WMAP measurements
(2003)

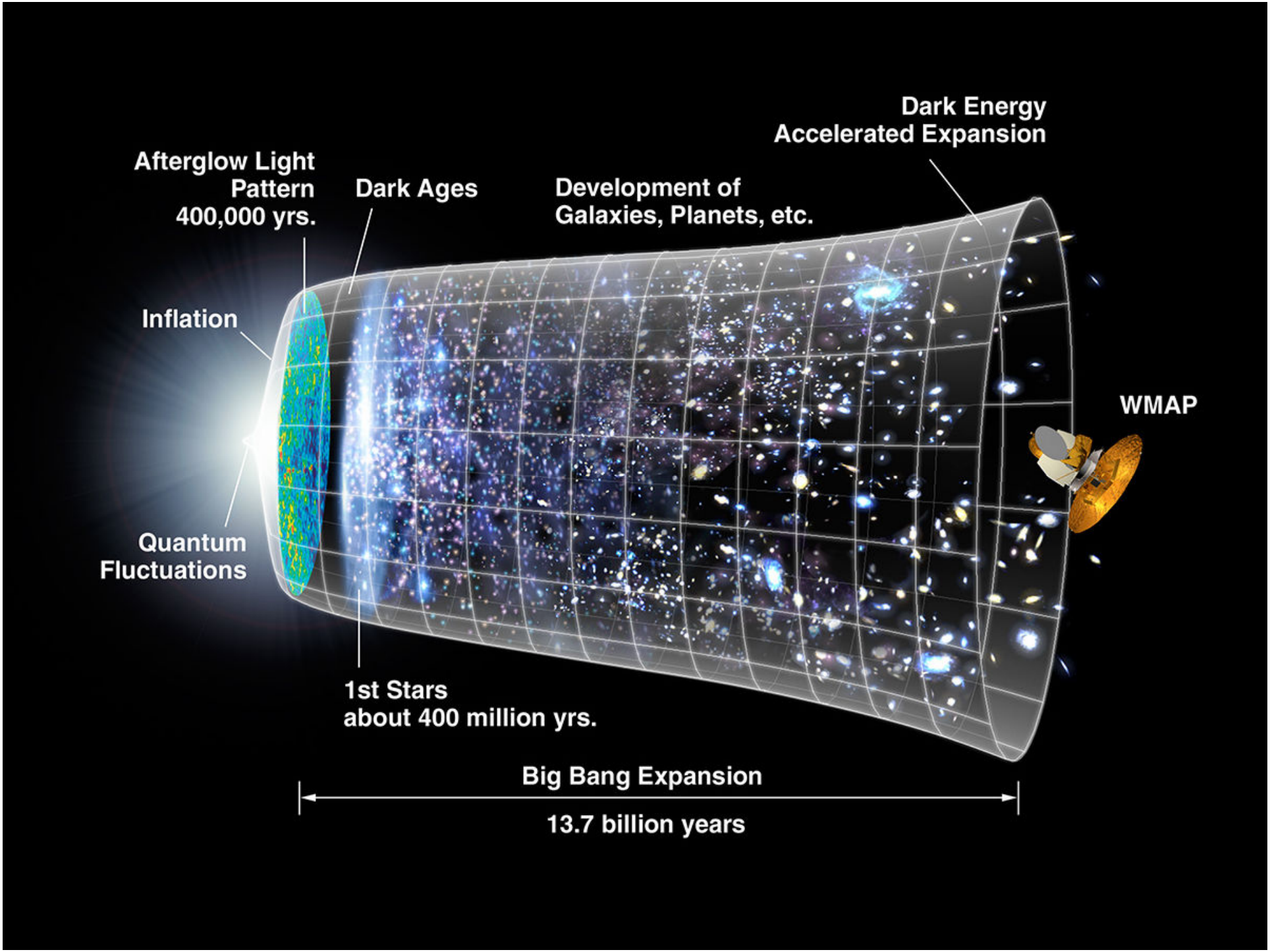


- We can associate a temperature with the photons arriving from the Microwave background
- For each direction on the sky we can then make a map of those temperature fluctuations
- The temperature turns out to be $T=2.735\pm0.060$ K
- Less dense regions appear hotter, more dense regions appear cooler

The CMB is still smooth to one part in 10^5!

Cosmological Evolution from the CMB onwards

- We're now in the realm of star & galaxy formation
- Initially the universe is filled with neutral Hydrogen which can absorb photons of light above a certain frequency (the cosmic "Dark Ages")
  - This frequency corresponds to the ionization potential of H = 2.2×10^{-18} J, via the photon energy equation E=hf
- The formation of the first stars will be just before the first galaxies
- Which will then merge to form larger galaxies….


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

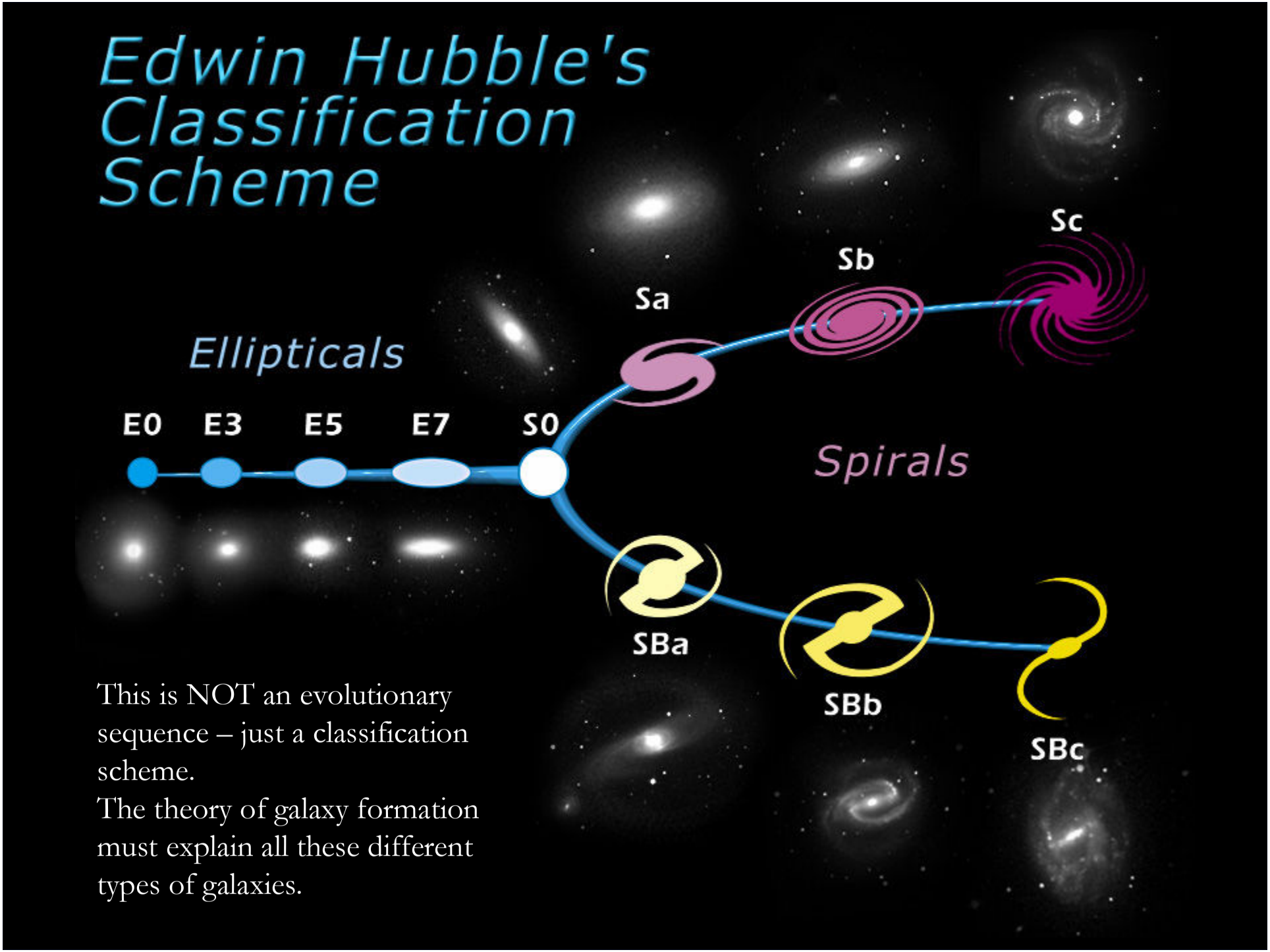
Summary of evidence for the Big Bang

- **Hubble flow**: **recession** of the galaxies, and **expansion** of the universe
- The existence and nature of the **Cosmic Microwave Background**
- The **abundances** of Helium, Lithium, Boron, Beryllium
- Age of **universe** and **oldest stars** agree

Hubble's deepest view of the Universe

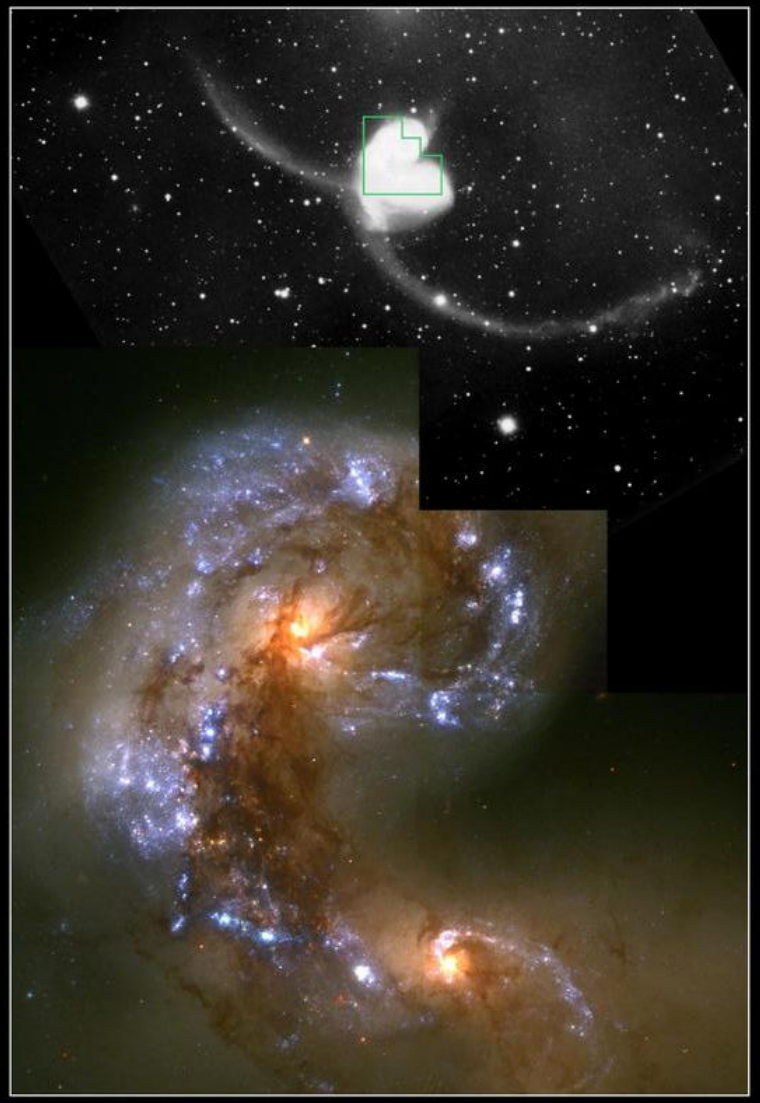
Formation of Galaxies

- Because dark matter is the dominant matter component of the Universe it "drives" the galaxy formation process
- Visible matter in galaxies (*i.e.* stars) will always be embedded within the larger dark matter "halo"
- Mapping dark matter is extremely hard since it does not emit electromagnetic radiation
  - We can only infer it's presence


Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc
This is NOT an evolutionary sequence – just a classification scheme.
The theory of galaxy formation must explain all these different types of galaxies.

Hierarchical Formation of Galaxies

- The first movie of galaxy formation I showed clearly demonstrates how important galaxy mergers are
- There were many more mergers in the past than now
- Nonetheless, we can still see these mergers today

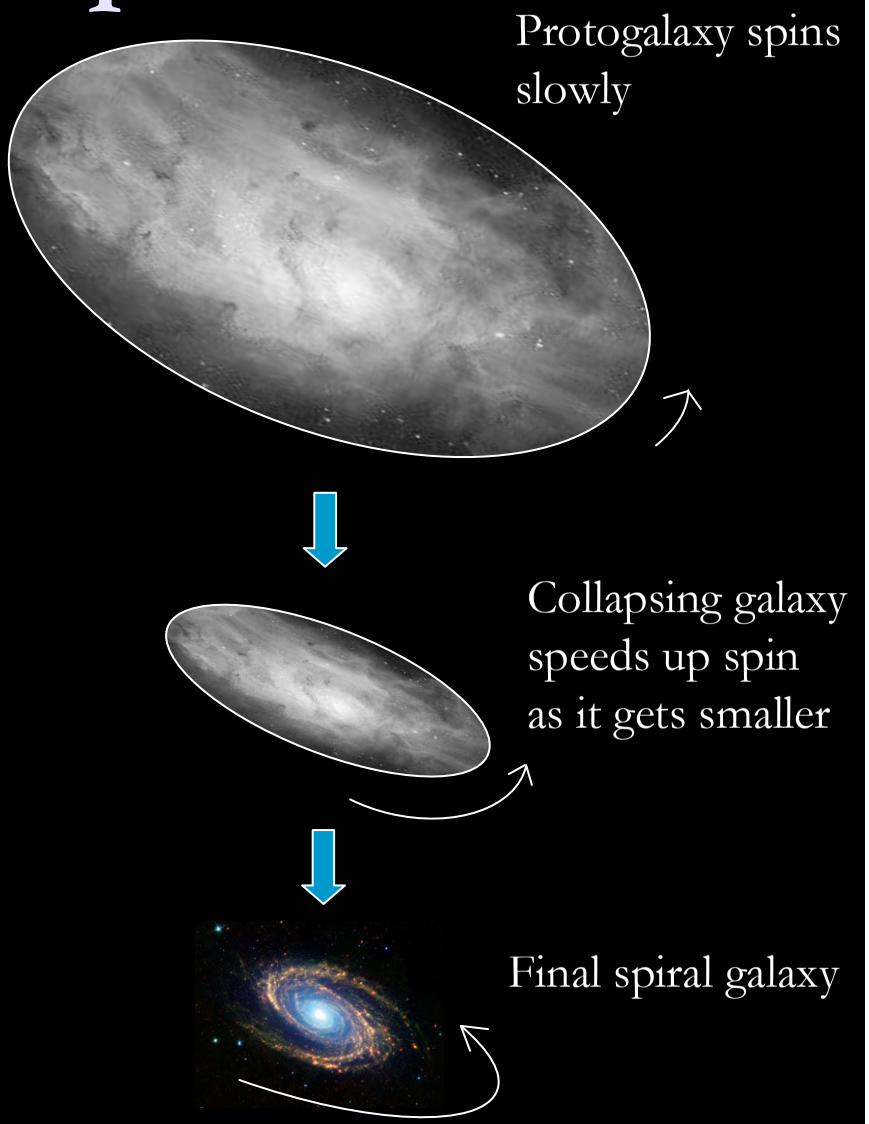


Origin of spin

- Galaxies spin partly because they collapse in an asymmetric fashion
- Material around them then exerts an unequal pull on the material as it falls in
- This (really small) amount of rotation is amplified greatly as the radius of the collapsing material reduces
- This is due to conservation of angular momentum

$$\vec{L} = \vec{r} \times m\vec{v}$$

  - Recall a skater spins faster as they pull their arms in



Food for thought: the fundamental constants of nature

- There are many (unexplained) constants used in the equations for the physical forces
  - *e.g.* G, Newtons gravitational constant, or the unit of charge on the electron, e
- If any of these values were changed - by even a small amount - stars would not form
- Since the formation of stars is a precursor to the formation of life, ***is the Universe in fact tuned to form life?***

Summary of lecture 5

- There are 4 strong pieces of supporting evidence for the Big Bang
  - Big Bang Nucleosynthesis
  - Expansion of the Universe
  - Age of the oldest stars versus estimated age of the Universe
  - The Cosmic Microwave Background
- The origin of galaxies dates back to some of the earliest moments after the Big Bang
- Minute quantum fluctuations in the density of space are eventually amplified to form galaxies
- Galaxies form through the merger of smaller systems to form larger ones

Next lecture

- Questions of fine tuning & life: The Cosmological Anthropic Principle(s)