Lecture 4

Cosmic Inflation: Making Universe(s) from Nothing!

Introduction

How was the Universe created ??

Two remarkable facts:

1) The Universe is staggeringly abundant..... (>10^{10} galaxies...)
   where did all that stuff come from?
   was it somehow crammed into the initial singularity?
   was it created "ex nihilio"?

2) All this stuff is expanding (Hubble flow)
   how did it gain this motion?
   don't dense things tend to collapse?

Inflation answers both these questions, brilliantly.

The Standard Hot Big Bang Theory

The Standard Hot Big Bang Theory (pre-1980) had no launching mechanism.

The beginning was simply assumed, by extrapolating the current expansion of the Universe backwards in time.

If the Universe contains just matter and radiation, then Einstein's theory of gravity demands:
   a moment of infinite density and temperature
   expanding infinitely fast, then rapidly decelerating.
But there was no explanation of how this situation arose.

Solution: We now think a different kind of substance dominated at very early times – a special kind of "dense vacuum" – with extraordinary consequences

1. The Observable Universe: How much stuff?

Total content of Visible Universe

Just how much "stuff" is in the visible Universe (i.e. out to our 14 billion light year visible horizon)?

There are six components:

Atomic Matter	4%
Dark Matter	23%
Light	0.0050%
Neutrinos	0.0034%
Dark Energy	73%

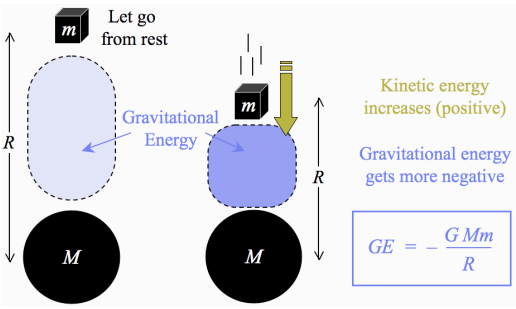
Positive Mass/Energy
Average density: 5.8 m_H/m^3

Total = Volume x Density
= $^4/_3\,\pi\,R^3$ x 5.8
= 10^{53} kg (10^{10} galaxies)

Gravitational Energy !

Negative Energy !

Why is gravitational energy negative?



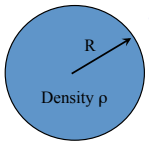
Total mass/energy in the visible Universe

Simple Newtonian Analysis

Mass in Visible Universe

$M_{VU} = {}^{4}/_{3}\,\pi\,R^3 \times \rho$

$M_{VU} \approx 10^{53}$ kg



Gravitational Energy in Visible Universe

$E_{VU} \approx -\dfrac{G\,M_{VU}^2}{R}$

$E_{VU} \approx -10^{70}$ Joules

$\approx -10^{53}$ kg × c^2

Matter + Gravity = Zero !

The Universe sums to nothing!

This is remarkable result
(a more sophisticated analysis using GR gives the same result)

Perhaps the Universe came from nothing!

We need a mechanism to split nothing into
equal amounts of positive mass/energy
and negative gravity

Inflation does exactly this.

But first, let's take a slight detour, to explore dark energy....

2. Dark Energy's mysterious behavior

Dark Energy's Mysterious Behavior

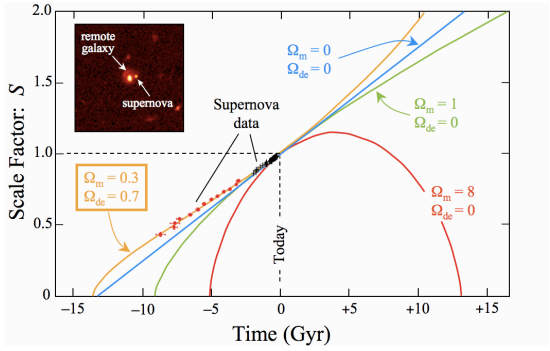
For decades, it was thought that the Universe's expansion would be slowing down (decelerating).

In 1998 two teams made the surprising discovery that the Universe's expansion is speeding up (accelerating)!!

This showed the presence of a new cosmic component with the following property:
it's density does not dilute with cosmic expansion

It is called "dark energy" (though it's nature is not understood)
One possibility is that space itself "weighs something."

Evidence for Cosmic Acceleration

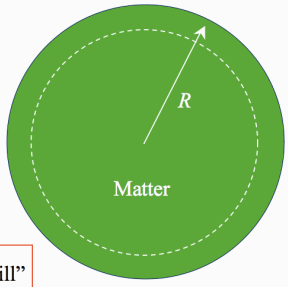


Matter Spheres Fall Inwards

M_{sphere} doesn't change

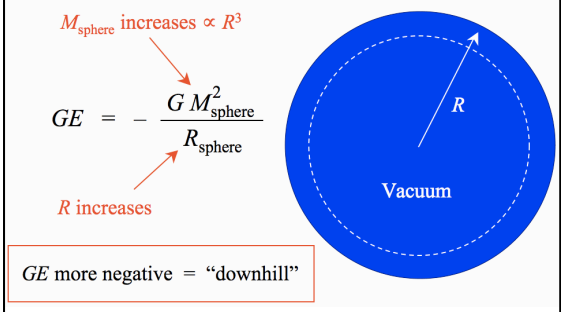
$GE = -\dfrac{G\,M_{sphere}^2}{R_{sphere}}$

R increases



GE more positive = "uphill"

Vacuum Spheres Fall Outwards



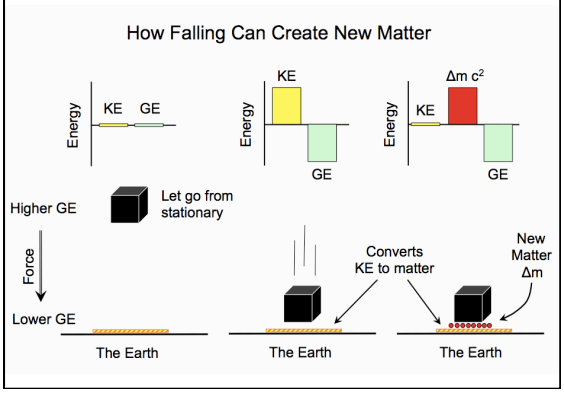
Dark Energy's Mysterious Behavior

Where does the energy come from to make the new shell of vacuum?

It comes from the gravitational energy released as the sphere falls outwards:– Gravity creates the very space into which the Universe is expanding!

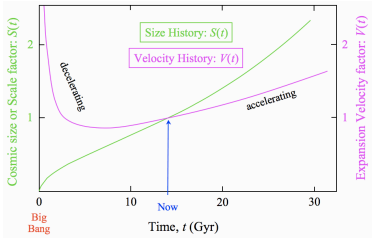
This is an energy conserving process:
one can make arbitrary amounts of vacuum, along with an equal amount of negative gravitational energy

How Falling Can Create New Matter



Dynamics of Vacuum Expansion

The outfalling proceeds in an exponential manner.



The time for the size to double depends on the density, ρ, of the vacuum: $t_{dbl} \approx 1 / \sqrt{G\rho}$ (G = Newton's gravitational constant).

In today's Universe, $\rho_{de} \approx 4.2\ m_H/m^3$ giving $t_{dbl} \approx 10$ Gyr

3. Inflation: Cosmic Creation and Launching

Return to Inflation

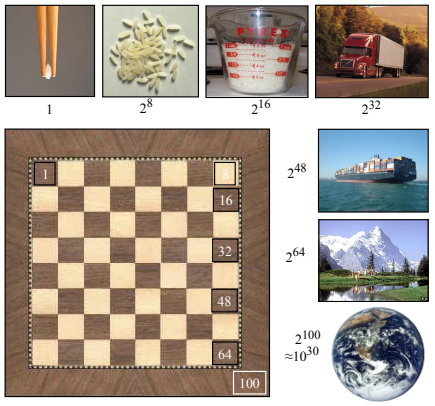
In 1980, Alan Guth suggested a similar mechanism might occur in the early (pre-nanosecond) Universe.


Alan Guth
b. 1947

In this case, the vacuum density was very high (e.g. 10^{26} tons/cm^3). This gives a very rapid outfall: e.g. $t_{dbl} \approx 1 / \sqrt{G\rho} \approx 1$ picosecond (illustrative example).

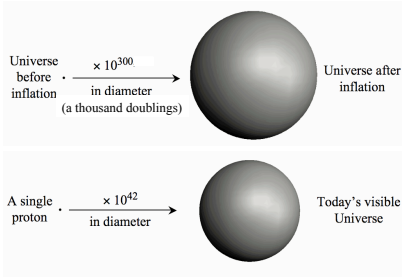
In a nanosecond we have 1000 doubling times, so a tiny region of dense vacuum can create an immense region of dense vacuum that is in a state of rapid expansion.

If this dense vacuum then "decays" into matter/radiation then we have both created and launched the Standard Hot Big Bang expanding Universe!



Exponential expansion is incredibly powerful

E.g a thousand doubling times



What makes the dense vacuum?

This is not well understood, though there are several possibilities.

All particles have quantum fields – "knowledge" of the particle.

A subset of these, called scalar fields, can have finite energy in certain circumstances – e.g. in the unusual conditions of the early universe.

These fields act like a vacuum energy.

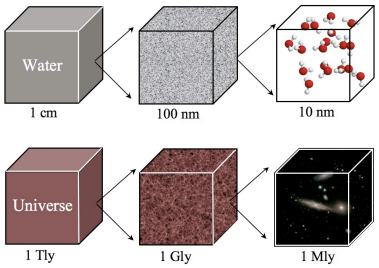
The one responsible for inflation is called the "inflaton field".

We'll return to how a patch of inflaton field might arise in a moment.

4. Inflation makes cosmic structures.

The structure problem

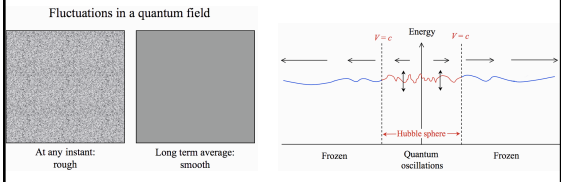
In the standard big bang, there is no mechanism to cause slight roughness that grows to form stars, galaxies, and the galaxy web.



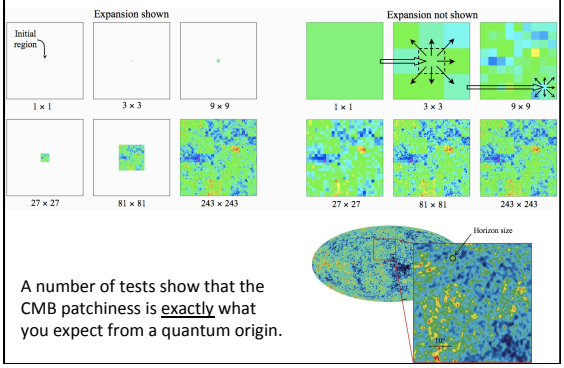
Inflation solves the structure problem brilliantly

The quantum nature of the inflaton field makes its energy fluctuate slightly.

Exponential (accelerating) expansion turns those quantum fluctuations into real fluctuations, which then grow over time.



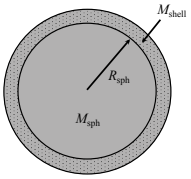
Inflation's fluctations appear "directly" on the CMB



A number of tests show that the CMB patchiness is exactly what you expect from a quantum origin.

5. Inflation needs an initial seed.

A seed is needed to start inflation



gravitational energy released > greater than > new energy in shell

$$\frac{G \times M_{sph} \times M_{shell}}{R_{sph}} > M_{shell} \times c^2$$

$$\frac{G \times M_{sph}}{R_{sph}} > c^2$$

$$\frac{G \times M_{sph}}{c^2} > R_{sph}$$

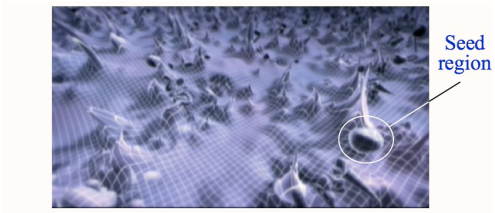
This is in fact the "black hole" condition. If the sphere contained normal matter or radiation it would collapse to become a black hole.

However, if the sphere contains vacuum (whose density is fixed), inflation occurs.

E.g. for GUT inflation, $\rho \sim 10^{73}$ tons/cm^3, R~10^{-11} fm, M~100 gm

How do such seeds arise?

Not well known: possibly via quantum fluctuations



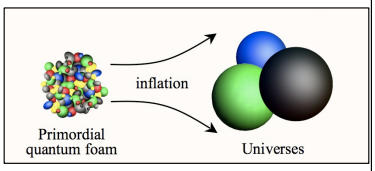
If true, then the Universe may have had no explicit cause: It just happened!

6. Inflation can make many universes!

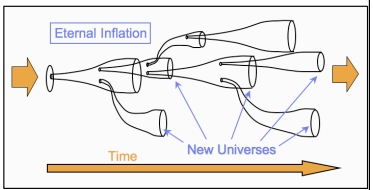
Much more speculative

Inflation can create multiple universes!

Chaotic Inflation: Multiple seeds can make a multiverse



Eternal Inflation: High quantum fluctutions keep inflating



May solve the "fine tuning problem"

The laws of physics seem "fine tuned" for life:

change them, even a bit, and the universe becomes sterile

e.g. atoms are unstable; stars can't form; universe collapses.

There are several possible solutions to this "problem"

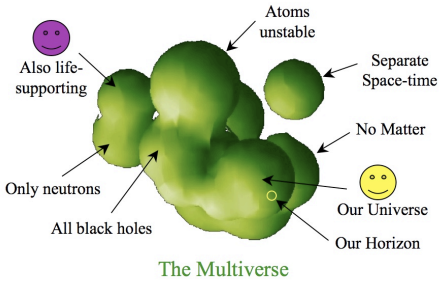
1) final understanding of the laws show they can be only this way

2) divine figure chose these laws with intention for life

3) we're here, so the have to be fertile laws.

4) there is, in fact, a multiverse, and we're in a rare place where the laws are fertile.

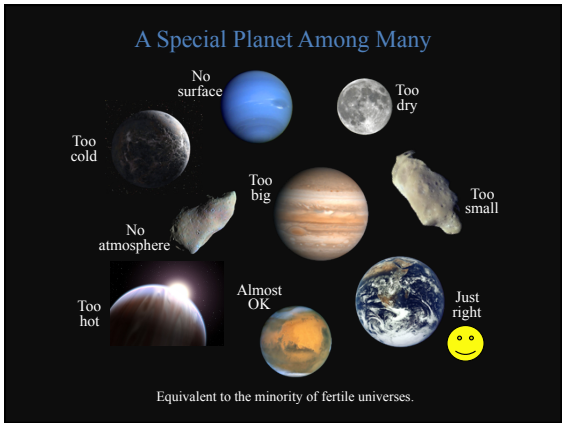
Each universe may have different laws of physics



The Multiverse

Only a few universes have "fertile" laws of physics.
We (obviously) live in one of those….

A Special Planet Among Many



Equivalent to the minority of fertile universes.

Summary

The standard hot big bang lacks a launching mechanism – no "bang!"

First clue: the total energy of the Universe is zero!

Second clue: vacuum (dark) energy "falls outwards" and creates new vacuum in an energy conserving process.

1980: Guth suggests "inflation" as similar process with denser vacuum

Inflation solves: flatness, horizon, and structure problems of the standard big bang theory.

Several qualities of cosmic roughness match those of inflation

Inflation needs a tiny seed to start, but once going can create many universes – perhaps with different laws of physics.

The Universe is Amazingly Abundant