Lecture 21
History of the Universe
News

Presentations

Apr. 14: Life of Galileo, Controlled fusion
Apr. 19: Nuclear power, Search for ET life
Apr. 21: Music, Nuclear terrorism
2 per day 20 min+discussion/Q&A
Presentations will be evaluated by the audience

Come see me if you need help or guidance on topics, and getting material
Your life... starting at the beginning

In the beginning there was...

- **Space-time foam**
  - Not empty space
  - Quantum fluctuations can produce a Universe!

- **$10^{-43}$ s: “Plank time”** Quantum limit of General Relativity
  - The shortest time we can know anything about in Physics
  - We don't know anything before this time

- **$10^{-37}$ s: Inflation starts**
  - Universe is $10^{30}$ times smaller than the size of an atom
  - Space is filled with an unstable “inflaton” field
  - Tremendous repulsive pressure
  - Exponential expansion
Inflation transforms the Universe

- The Universe expanded a factor $10^{40}$ to $10^{100}$ during inflation
- The universe went from a size $\sim 10^{-40}$ cm to the size of a marble
  - The Universe ended up much bigger (1 cm) than the observable universe then (at the time: $d = tc = (10^{-35}s) (3 \times 10^8$ m/s) $\sim 3 \times 10^{-27}$ m)

- What was curved, now is flat
  - Space is flat
  - Two parallel photons remain parallel
  - Sum of angles in triangle=180°

- What was small, now is big
  - Quantum fluctuations become large density/energy fluctuations
  - Act as seeds for large scale structure formation: matter would condense in these fluctuations producing the super-clusters of galaxies and the filaments and voids that we observe today
Early in the history of the Universe, it wasn't possible to distinguish between the forces.

We still haven't proved the unification of Electroweak + Strong, much less the unification with gravity...
Timeline continued

10^{-35} s: **End of Inflation**
- Inflaton field is unstable, it “decays” ending inflation
- Energy driving inflation is dumped into matter and radiation in early Universe, forming a hot, dense, “primordial soup”

10^{-35} s – 10^{-5} s: **“Quark Gluon Plasma”**
- At this point the universe is the size of a marble, and composed of subatomic particles: quarks, electrons, Z, W, gluons, photons at very high Temperature (~10^{27} K)
- The Big Bang description takes over: Universe will keep expanding, but this time at “normal” rate ~80 km/s/Mpc

10^{-5} s: **Bounded hadrons**
- Quarks bound into baryons (protons, neutrons) and mesons

10^{-4} s: **Matter-antimatter asymmetry**
- The Universe has cooled to 1 trillion K: still too hot for nuclear fusion to occur, photons destroy any nuclei that forms
- Protons and anti-protons annihilate, leaving 1 extra proton per billion
- Photons are since then the most abundant particle: 10^9 photons for every baryon
Light elements form

3 minutes: “Big Bang nucleosynthesis”

- It is cool enough (1 billion K) for light nuclei form: Deuterium, He, Li, Be
- No heavier elements than Be could form
- The abundance of H and He is set by the Temperature and density of normal matter between 3 and 30 minutes after the Big Bang
- Abundance: H ~ 75%, He ~ 25%

- Photons are too energetic to allow neutral atoms to form
- Everything is ionized (electrons are not bound into atoms)
- Light cannot travel through ionized gas
- The Universe is opaque: its blackbody radiation trapped
Neutral atoms form

400,000 years: Neutral atoms form

- Cooled to 3,000 K: Hydrogen atoms can form
- Universe becomes transparent, the 3,000K blackbody radiation travels freely
- We see that radiation today, greatly redshifted to 3 K blackbody: Cosmic Microwave Background (→next page)
- It is the farthest thing we can see

CMB discovered in 1964
- “Almost” perfect blackbody radiation at 2.725 K
- Isotropic: the same wherever you look in the sky
- But not perfectly homogeneous: otherwise no galaxies!
- Tiny fluctuations in temperature
Before/After recombination

Before: Ionized = opaque

After: Neutral = transparent
The CMB map: anisotropies in T

Map of the gravitational potential of Earth in the surface: red=high (~9.83 m/s²), blue=low (~9.76 m/s²)

All-sky map in galactic coordinates (map of sky unrolled), with visible light
The Milky Way is seen along the horizontal axis
The same idea applies below, but now in Infrared

COBE map of the anisotropies in the CMB
Temperature: Red areas are 30 μK hotter than average, and the blue areas are 30 μK colder than average

Remember: 1 μK = 10⁻⁶ K
Average CMB temperature = 2.725 K = -454 °F
Timeline continued

400 million years: First stars
- Probably much more massive than today's stars

1 billion years: Galaxies
- Quasars have formed: very active galactic cores, around a super massive black hole
- Globular clusters form in initial collapse that results in formation of galaxies

9 billion years: Solar System
- Large clouds of gas, from previous stars plus interstellar medium inside the Milky Way

13.7 billion years: Now
- Us, pondering about the universe
- The expansion is accelerating
Use supernovae to measure distances to galaxies: they shine with known brightness, so they are seen dimmer the further away they are.

Two groups discovered in the 1990's that supernovae were brighter than the distance (determined by the Hubble law) would suggest.

Together with CMB data, confirms that the Universe is now accelerating.
Supernovae as standard candles

The progenitor of a Type Ia supernova

Two normal stars are in a binary pair.

The more massive star becomes a giant...

...which spills gas onto the secondary star, causing it to expand and become engulfed.

The secondary, lighter star and the core of the giant star spiral inward within a common envelope.

The common envelope is ejected, while the separation between the core and the secondary star decreases.

The remaining core of the giant collapses and becomes a white dwarf.

The aging companion star starts swelling, spilling gas onto the white dwarf.

The white dwarf's mass increases until it reaches a critical mass and explodes...

...causing the companion star to be ejected away.
Blue region:
The expansion of the universe slowed down for a long time and then, with dark energy, sped up.

Gold region:
The expansion of the universe always slowed down after the first fraction of a second.
Size of fluctuations $\rightarrow$ geometry

Angular Size of fluctuations/structure in CMB is sensitive to the geometry of the universe

Measure:
- $\theta_f$ if space is flat
- $\theta_o$ if space is open
- $\theta_c$ if space is closed

Wiggles in the Cosmic Background represent density fluctuations in the early universe

Higher density regions attract matter (especially dark matter) which makes the density higher, which attracts more matter

Clumps of dark matter grew to form the structures we see
A consistent picture

- 13.7 Billion Years Old
- Flat (Euclidean) Spatial Geometry
- Critical Mass + Energy Density
- Expansion Accelerating

Us: ~5%
- Dark matter ~25%
- Dark energy ~70%

95% of the universe is unknown!
Dark Energy

- If the universe is flat, then 70% of the mass/energy is not in the form of normal matter, dark matter, or photons. Then what is it?
- Dark energy provides a pressure to space increasing the rate of expansion, counteracting gravity
- The net effect is like a negative gravity

Analogy:

- See box accelerating down sidewalk
  - We **know** there is a force + source of energy
  - We have ideas, but we don't know for sure the nature of the force/energy:
    - property of space (a constant that doesn’t change as space expands)
    - A field/fluid/energy that dilutes as space expands
    - Einstein equations need modification
Dark energy connections

- We know from particle physics and quantum physics that the energy density of the vacuum is NOT zero.
- We can try to calculate the vacuum energy density by adding the zero-point energies of all quantum oscillators that make up fields (see lecture 18):
  \[ \Omega_{\text{vac}} = 10^{122} \text{ (simplest calculation)} \]
  \[ \Omega_{\text{vac}} = 10^{55} \text{ (improved calculation with supersymmetry)} \]

  In reality, we measure:
  \[ \Omega_{\text{vac}} = 0.70 \]
  (we expected \( \Omega_{\text{vac}} = 0 \) before 1998!)

This embarrassing inconsistency is probably THE biggest issue today in Physics.

- Einstein could not find static solutions to his equations of General Relativity.
- All solutions described a Universe either expanding or contracting.
- He added a term corresponding to the energy of the vacuum, to counteract gravity and make the Universe static.
- His biggest blunder!
- But right after all!
Here be Dragons

A History of the Universe

Inflation, Grand Unification... "The beginning?"

Electroweak Unification
Protons/Neutrons Form
Elements Form, Cosmic Neutrinos

Matter Domination
Universe Becomes Transparent
Cosmic Microwave Background

First Stars and Quasars
End of Galaxy Cluster Formation

You Are Here

Here be Dragons

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You Are Here
History of acceleration

Today

Years in the Past       t         Years from Today

Low-mass Universe

High-mass Universe

Critical Mass Universe

Accelerating Universe

Size
Size Today

1.0
0.5

Today

Years in the Past ↔ t ↔ Years from Today
Spherical harmonic decomposition

\[ l = 2 \]

\[ l = 4 \]

\[ l = 8 \]

\[ l = 16 \]