Particles in the Early Universe

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Saturday Morning Physics, October 16, 2010
Using Little Stuff to Explain Big Stuff

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Can we explain this?
Or this?
Or this?
Or this?

OMG, is fulla starz.
The Really Big Question

- Can we explain the Universe using the physics we know?

  What is its large scale structure?

  How did it evolve over time?

- Really Ambitious!

  “Physics we know” comes from experiments on Earth.

  Will it still work over much larger astronomical distances?
Looking Around, from Near to Far
There are lots of stars out there.

(Ours is the sun.)
Galaxies

- Stars bunch together into galaxies.

(Ours is the Milky Way.)
Galaxy Clusters

- Galaxies bunch together into galaxy clusters.

*(Ours is the local cluster.)*
Even Bigger Distances – Cosmology

- Astronomy over bigger distances is called cosmology. (Not to be confused with cosmetology.)

- Three Main Observations:
  1. Everything is the same (on average) everywhere.
  2. Distant galaxies are moving away from us.
  3. Outer space isn’t empty – it has a faint amount of light.

- We can use these facts, together with particle physics, to reconstruct the history of the Universe!
Important Observation #1

- The universe is the same in all directions, on average:
Important Observation #2

- All the stuff out there is moving away from us:

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“Hubble Expansion”
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Important Observation #3

• Empty “space” is not quite empty. Outer space is filled a very faint glow of light.

• This Cosmic Microwave Background (CMB) has a temperature of $T \simeq 2.73 \, K$.
  (Room temperature is about 293 $K$, freezing is 273 $K$.)

• It is extremely uniform: $\Delta T / T \simeq 1/10000$. These variations contain a lot of information.
• Cosmic Microwave Background (CMB).
• Temperature Fluctuations
What Gravity has to Say About This

• Gravity is this only force that matters over astronomical and cosmological length scales.

• Equations for Gravity ↔ General Relativity [Einstein 1915]

• Look for gravity solutions that have:
  
  – spacetime that is the same everywhere (≡ “homogeneous and isotropic”)
  
  – contains a smooth density of matter and energy (e.g. background CMB light, dust, stars, galaxies, . . .)
• Result: spacetime is expanding.

• This is precisely what we see – Hubble Expansion.
The Big Bang [Alpher, Bethe, Gamow ’1947]

- Remember all that $T = 2.73 K$ CMB light? As the universe expands it cools off.

- Going back in time, the universe must have been much hotter in the past.

- $T \to \infty$ as $t \to 0$!

Big Bang!
Looking Inside,
Elementary Particles
Elementary Particles at High Temperatures

- The early Universe was very very hot.

- At high temperatures, matter gets ripped apart into its basic building blocks.
• Temperature corresponds to the average particle energy:

\[ T \sim E_{\text{avg}} \]

• Relativity tells us that

\[ E = mc^2 \]

• Particles can be created spontaneously when \( T > 2mc^2 \)!
# Elementary Particles

## Fermions

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## Bosons

| $\gamma$ | $g$ | $W^+$ | $Z^0$ | $h$ |
In Stuffed Toy Form
Four Fundamental Forces

1. Gravity – mediated by the graviton.
   Very weak, always attractive, infinite range.

2. Electromagnetism – mediated by the photon.
   Medium strength, attractive or repulsive, infinite range.

   Strong, holds nuclei together, binds quarks into nucleons.

4. Weak – mediated by the $W^\pm$ and $Z^0$ vector bosons.
   Weak, leads to radioactive nuclear decays.
e.g. Electromagnetic Scattering of Two Electrons

\[ e -\gamma - e \]
Cosmology:
Storytelling about our Universe
In the Beginning . . .

...we don’t really know. (42?)

- Elementary particles and forces have been tested only up to energies near 200 GeV.

- Start with a soup of elementary particles at $T \sim 100$ GeV.
Aside: we measure energy in units of eV = electronvolts.

1 eV = energy of an electron through a 1 Volt potential

1 MeV = $10^6$ eV = 1 million electronvolts

1 GeV = $10^9$ eV = 1 billion electronvolts

Room Temperature $\sim 300 \text{ K} \sim \frac{1}{40} \text{ eV}$
Hot Soup: $t \sim 10^{-10}$ s

- Start with a hot soup of elementary particles at $T \sim 100$ GeV.
  - free quarks and gluons
  - electrons and photons
  - muons, taus, neutrinos
  - $W^\pm$, $Z^0$, Higgs, . . .

- The soup cools as the Universe expands.
  Unstable particles disappear when $T$ falls below $mc^2$.
  \[(\text{Rate of Production}) < (\text{Rate of Decay})\]
Protons and Neutrons: $t \sim 10^{-6}\ s$

- Protons and neutrons form when $T$ falls below 1 GeV.

Proton = $p = u + u + d$

Neutron = $n = u + d + d$

- Why? Binding Strength $\sim m_p \sim m_n \sim 1$ GeV.

$T > 1$ GeV: plasma collisions rip nucleons apart

$T < 1$ GeV: plasma collisions don't have enough energy
Light Nuclei: \( t \approx 1 \text{s} - 1 \text{min} \)

- At \( T > 1 \text{MeV} \) \((t < 1 \text{s})\) we have:

\[
p + e^- \leftrightarrow n + \nu_e, \quad (m_n - m_p = 1.2 \text{MeV})
\]

- For \( T < 1 \text{MeV} \) the reverse reaction is more likely.

The reaction “turns off” when \( T \approx 0.3 \text{MeV} \) with

\[
\frac{N_n}{N_p} \approx \frac{1}{7}.
\]
- At $T < 0.1\,\text{MeV}$, some light nuclei start to form:

  $$p + n \rightarrow D + \gamma$$

  $$p + D \rightarrow ^3\text{He} + \gamma$$

  $$n + ^3\text{He} \rightarrow ^4\text{He} + \gamma$$

  ...

- We can predict element abundances from particle physics!
• Calculations agree well with observations:

• Only light ($A \lesssim 7$) nuclei are produced this way due to small temperatures and densities.
Atoms: $t \sim 10^{10}\,s \sim 1000\,yr$

- Hydrogen atom:

  Binding Strength $= 13.6\,eV$

  $\Rightarrow$ for $T > 13.6\,eV$ we only have ions and free electrons.

- For $T < 13.6\,eV$, electrons and nuclei bind into atoms:

  $$p + e^- \rightarrow H + \gamma$$

- Nearly all free charges are bound by $T \sim 0.3\,eV$ ($t \sim 10^{12}\,s$).
With no free charges, photons nothing to scatter with.

⇒ light travels unimpeded

⇒ universe becomes transparent

These photons are what we see today as the $T \simeq 2.73 \, K$ cosmic microwave background (CMB) light.

Surface of Last Scattering
The Cosmic Microwave Background (CMB)

- The CMB is a snapshot of the universe at recombination.
- It is almost completely uniform: $\Delta T/T \approx 10^{-4}$
Structure Formation: $t > 10^{10} \text{ s} \simeq 1000\text{ yrs}$

- CMB spots represent local density variations.

- These grow with time, and eventually become unstable to gravitational collapse at $t \simeq 10^{10} \text{ s}$.

- Gravity pulls matter together into clumps of dust that eventually become galaxies, stars, planets, ...
Star Formation: \( t > 10^{15} \text{s} \approx 100 \text{ million yrs} \)

- Clumps of dust get pulled together by gravity at \( t \approx 10^{15} \text{s} \). As they condense, they heat up.

- Thermal pressure eventually balances out gravity when \( T_{dust} \approx 10^8 \text{ K} \approx 0.01 \text{ MeV} \), hot enough to ignite nuclear fusion and make a star!

- Stars evolve over their lifetime to make heavier elements. We can predict their abundances as well!
• $t_{\text{today}} \approx 13.7 \text{ billion yrs}$
The Dark Side
Missing Matter: CMB

- Variations in the Cosmic Microwave Background (CMB) temperature contain a lot of information.
• Cosmic Microwave Background (CMB).
• The heights and locations of the peaks depend on the amount of matter in the Universe.

• (Total Matter) \( \approx 5 \times \) (Visible Matter)

Where’s the missing matter!?
Missing Matter: Gravitational Lensing

- Gravitational Lensing: light is bent by gravity.
  \[(\text{Amount of Bending}) \sim (\text{Amount of Matter})\]

- Much more matter than is visible!
Missing Matter: Galaxies

- We need hidden matter to explain the structure of galaxies.
Dark Matter

- Missing cosmological matter is called Dark Matter (DM).

- None of the known particles can be the DM.

- A DM particle needs to be heavy, stable, and neutral.

DM Hunting:
- Create DM in particle colliders (LHC).
- Look for DM scattering off sensitive detectors.
- Search for DM effects in the galaxy.
DM can be created in energetic particle collisions.

*e.g.* CERN LHC: proton–proton with $E = 14000$ GeV.
• DM leaves no trace in particle detectors.

No trace is still a signal: missing momentum.
Summary

• Science Works . . .
  Physics on the Earth seems to work in the Cosmos!

• Cosmology = Storytelling
  – Start with a hot plasma of elementary particles
  – Expand and cool
  – Form nucleons, nuclei, atoms, stars, galaxies, . . .

• But what is the Dark Matter?
Extra Slides: Stars
$H$ Burning: Main Sequence Stars

- $H$ burning is the first process to take place:
  
  \[ p + p \rightarrow D + e^+ + \nu_e \]
  
  \[ p + D \rightarrow ^3_2\text{He} + \gamma \]
  
  \[ ^3_2\text{He} + ^3_2\text{He} \rightarrow ^4_2\text{He} + p + p \]

- Net result: \( 6p \rightarrow ^4_2\text{He} + 2p \). (Other processes too.)

- Energy released by $H$ burning provides thermal pressure that supports the start from gravitational collapse.

- Star supported only by $H$ burning = "main sequence". The sun is a familiar example of this.
He Burning and Beyond: Giants

- When $H$ is used up:  
  - gravity compresses the core more  
  - the core heats up  
  - $He$ burning starts

- $He$ burning: $\frac{4}{2}He + \frac{4}{2}He + \frac{4}{2}He \rightarrow \frac{1}{6}C$, $\frac{4}{2}He + \frac{12}{6}C \rightarrow \frac{16}{8}O$

- When $\frac{4}{2}He$ is used up, $C$ and $O$ burning kicks in.

- (Red) Giant Star
• $^{20}_{10}Ne$, $^{24}_{11}Na$, $^{24}_{12}Mg$ burning next.

• $^{28}_{14}Si$ burning next

• This chain stops when the core becomes $^{56}_{28}Fe$.

$^{56}_{28}Fe$ is the lowest energy nuclear state.

⇒ no more energy can be obtained from nuclear fusion
• So what next?

• Big stars with $M \gtrsim 10 M_\odot$ blow up – supernova!

• Smaller stars might never get to the $^{56}_{26}Fe$ core stage.

• White dwarf = star supported by electron degeneracy.
Supernova!

- Big stars with a $^{56}_{28}Fe$ core can no longer support themselves against gravity.

- The core collapses creating a huge pressure. Pure neutron matter then becomes energetically favourable.

\[ p \rightarrow n + e^+ + \nu_e \]

- Neutron degeneracy pressure stops the core collapse.

- The core “bounces” sending off a shock wave and that blows away the outer layers of the star.

→ Supernova!!!
- Heavy elements are produced in the outgoing neutron-rich shock wave via the *r*-process.

- These drift off, and are incorporated into new stars.