The Birth of Non-Baryonic Matter

- Death of Baryonic Dark Matter
- BBNS
- CMBR
- Neutrinos as Dark Matter
Notes

Gas and Dust..
What could the dark matter be?

**Ordinary Matter**

- Gas or Dust?
- Small, faint stars (or near-stars)?
  - white dwarfs
  - red dwarfs
  - brown dwarfs
  - Jupiters
- Black Holes?

**Exotic Particles**

- Neutrinos (ν)
- Weakly Interacting Massive Particles (‘WIMPs’)
- Other exotics

Other arguments against baryonic Dark Matter...
Baryons form the Big Bang
Big Bang Nucleosynthesis (BBNS)

BBNS is the process by which the light elements get produced in the early Universe - H, D, He, Li

What is of interest for dark matter is the Baryon Number Density (the number of Baryons per unit volume) - can BBNS be used to predict it? or rather the value of $\Omega_B$

For instance how does it compare with our measurements of $\Omega_0$ e.g. if $\Omega_B = 1$ then we know that all the matter in the Universe is made of Baryons.
What is a Baryon?

Extra Note

What is a Baryon?

Baryons are made from three quarks

Hadrons

Mesons (unstable) are made from quark-antiquark pairs

For reasons not well understood, hadrons only comes in colorless composites
Early History of the Baryonic Universe

Extra Note

t=10^{-6} \text{ s}, T \sim 10^{13} \text{K} \quad \text{Quarks bind to form protons & neutrons}

t=1-3 \text{ s}, T \sim 10^{10} \text{K} \quad \text{BIG BANG NUCLEOSYNTHESIS - Protons and neutrons bind to form light nuclei, up to Lithium}

t=10^{13} \text{ s}, T \sim 10^{4} \text{K} \quad \text{Atoms form from nuclei and electrons. Universe becomes sufficiently low that it is transparent to the cosmic background radiation (more in a later lecture)}

(Light elements form stars, heavier elements created in stars.)

t=3 \times 10^{16} \text{ s}, T \sim 10 \text{K}, \quad \text{Formation of the Milky Way}

t=4 \times 10^{17} \text{ s}, T \sim 3 \text{K}, \quad \text{seconds NOW}

For a more detailed picture of this, see Kolb and Turner, *The Early Universe*, Addison Wesley 1990, Figure 3.7
But concentrations of $^7\text{Li}$ and $^3\text{He}$ both low, so low rate.
Binding energies per nucleon - 2.2, 2.2, 2.8, 7.1, 5.6 MeV for Deuterium, Tritium, $^3\text{He}$, $^4\text{He}$, $^7\text{Li}$, respectively.
Because there are many photons per baryon, nucleosynthesis starts around $t \approx 1$ minutes (the famous “first three minutes”):

- $\tau_{1/2} = 10.6$ min
- $\eta = 3 \times 10^{-10}$
- $N_\nu = 3$
Big Bang Nucleosynthesis (BBNS)

The relative abundances is very sensitive to Baryon Density. e.g. if we increase B then at a given temperature there is a greater density of neutrons and protons. Hence, the reaction $n + P \rightarrow ^2H + \gamma$ becomes important at a higher temperature (or if you like, at an earlier time i.e. it overtakes the competing reverse reaction at a higher temperature) (remember the temperature is dropping).

At this earlier time, e.g. high temperature, there will be more neutrons about because there has been less time since the neutrino reactions above stopped for neutron decay to occur.

This also means the reactions ending in $^4\text{He}$ are more efficient because there are more neutrons.
Big Bang Nucleosynthesis (BBNS)

Thus the effect of slightly more baryons is dramatic we get:

(i) more $^4\text{He}$,
(ii) very much less $^2\text{H}$ and $^3\text{He}$,
(iii) complex effect on the very small amount of Li produced

So we can plot this abundance of light elements against Baryon number. We can do this in terms of the baryon density NOW because we know how the universe expands (obviously the density will be less now than it was).

Two key factors which influence the reactions and result:

(i) the Baryon Number Density $B$ or the number of baryons per unit volume $n_B$ at some temperature $T$ in the early universe
(ii) the Ratio of Neutrons to Protons $n_n/n_p$ which is about 1:5.
Initial Conditions for Synthesis of Light Nuclei

The ratio of the neutron to proton abundances in the universe at the onset of nucleosynthesis.

Neutrons and Protons are in THERMAL EQUILIBRIUM in the early universe, due to exchange of neutrinos.

\[ \frac{N_n}{N_p} = e^{-\frac{(m_n-m_p)c^2}{k_B T}} = 0.2 \]

If we were confident of the particle physics in the early universe then it would be possible to fully predict both B and p-n ratio

Instead work out what the effect is on the various abundances of changing the baryon number and ratio and compare this with observation of the abundances
Nucleosynthesis simulations predict the abundances of light elements (D, He, Li) as a function of the baryon density.

The relative abundances of the light nuclides predicted for different values of the present day baryon fraction. \( \Omega_b \) is 1 if ordinary matter (rocks) dominate today's universe.

**Vertical Axis:**
abundances of light isotopes relative to Hydrogen at the end of nucleosynthesis

**Horizontal Axis:**
present day baryon fraction, derived from ratio of baryon to photon number densities at end of nucleosynthesis

\(^4\text{He} + \, ^3\text{H} \) production dominates

\(\text{D} + \text{D} + ^3\text{H} \) production dominates
Abundances vs. $\Omega_B$ Measurements

Extra Note

It turns out that measurements of $^4\text{He}$ and $^2\text{H}$ give us the strictest bounds on $\Omega_B$.

i) $^4\text{He}$ abundance

This is quite difficult to measure because as you now know the abundances in the ISM, for instance, include elements that clearly could not have been produced in the big bang. i.e. they have come from reprocessing in stars. But we can say that the outcome of this reprocessing is to produce more He and more heavy elements than would be in the primeval soup. It is very difficult to remove $^4\text{He}$. Also we can measure the ratio of He to heavy elements in different clouds and space and extrapolate back to zero heavy elements. This gives $^4\text{He}$ abundance: $Y = 0.23 \pm 0.02$

ii) $^2\text{H}$ abundance

This can be measured by Lyman series absorption lines in the uv spectra of bright stars. This gives a typical mean interstellar value of $X(^2\text{H}) = 2 \times 10^{-5}$

iii) $^7\text{Li}$ and $^3\text{He}$

Observations of this tend to rule out the very minimum of the plateau.
Big Bang Nucleosynthesis (BBNS)

\[ \Omega_b h^2 = 1 \quad : \text{all matter baryonic} \]
\[ \Omega_b h^2 = 0 \quad : \text{no baryonic matter} \]

The measured values (circles) line up to suggest a value of

\[ \Omega_b \sim 0.04 \]

Measurements complicated by astrophysical production mechanisms, but primordial D abundance now give

\[ \Omega_b = 0.040 \pm 0.004. \]

Data consistent with about 4% of the matter density of the universe being baryonic.
Notes

Explain how BBNS rules out baryons as dark matter...
Consider Hydrogen. How do you measure the Hydrogen abundance in our universe? Using the LYMAN ALPHA FOREST

Distant quasars emit the lyman-alpha line of H strongly. But the line of sight between us and quasars at high redshifts is dotted with hydrogen clouds at lower redshifts. These clouds absorb light at shorter wavelengths from that same line. How much absorption depends on the abundance of hydrogen in the cloud.
(BBNS) Lyman alpha emission and absorption at low and high redshifts

The lyman alpha emission from the quasar at high redshift is clearly visible at around 1200 angstroms. Notice that the plotted quantity is. The observed wavelength on Earth will be different for the two redshifts. The narrow absorption lines for lyman alpha in intervening clouds are at shorter wavelength, so lower redshift, as expected.
Baryons and the CMBR
Amazing new data in last 10 years

Cosmic Microwave Background

**COBE (1989-1993)**
Angular resolution: 7°
Temperature sensitivity: $10^{-5}$

**WMAP (2001-present)**
Angular resolution: 15'
Temperature sensitivity: $3 \times 10^{-6}$

**Big Result:** Universe is “flat” and the expansion of the universe is accelerating
“Power spectrum” (size) of Temperature fluctuations is sensitive to different matter/energy components. We can tell the density and rate of expansion in the early universe. The exact mixture of material in the early Universe (baryons, neutrinos, dark matter), cosmological parameters ($H_0$, vacuum energy) and initial perturbation spectrum, control the position and amplitude of these peaks and troughs.
Baryons and the CMBR

The "angular spectrum" of the fluctuations in the WMAP full-sky map. This shows the relative brightness of the "spots" in the map vs. the size of the spots. The shape of this curve contain a wealth of information about the history the universe.


## WMAP Results

### Selected results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubble constant</td>
<td>$H_0 = 0.72 \pm 0.05 \text{ km s}^{-1} \text{ Mpc}^{-1}$</td>
</tr>
<tr>
<td>Matter abundance</td>
<td>$\Omega = \Omega_M = 0.29 \pm 0.07$</td>
</tr>
<tr>
<td>Baryon abundance</td>
<td>$\Omega_B = 0.047 \pm 0.006$</td>
</tr>
<tr>
<td>Age of universe</td>
<td>$t_0 = 13.4 \pm 0.3 \text{ GYr}$</td>
</tr>
<tr>
<td>Age of microwave background</td>
<td>$t_D = 372 \pm 14 \text{ kYr}$</td>
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- Normal Matter (Baryons)
  - Account for only a small % of the matter in the universe
- What ever Dark Matter is, **most of it ISN’T Baryonic!**

See Excellent Web site:

http://map.gsfc.nasa.gov/index.html
Notes
Explain how CMBR observations rule out baryons as dark matter...
Contribution to $\Omega$

- **Theoretical Expectation**
  - Large Scale Structure
  - Clusters of Galaxies
  - Galaxy: All Mass
  - Nucleosynthesis
  - Baryon Limits

- **Solar Neighbourhood**: $\Omega = \frac{\rho}{\rho_{\text{crit}}}$
Can Neutrinos be Dark Matter?

So a purely Baryonic Universe is at odds with the evidence:

1. Not much evidence for Dark Baryons (MACHOs etc...)
2. Baryon fraction from BBNS way too small
3. CMBR and other observations suggest structure formation via gravitational instability does not work with Baryons alone

Could Dark Matter be non-Baryonic particles?

The only particle known to exist in large numbers is the neutrino, so if they have a small mass then they could be the dark matter.

In order to understand if they could represent the dark matter we need to calculate their cosmic abundance as a function of their assumed mass.
Cosmic neutrino mass density as a function of neutrino mass. The hatched band indicates the range for $\Omega h^2$ which the dominant particle dark matter component must provide.
Can Neutrinos be Dark Matter?

Worked Example

(1) Neutrino mass upper limit

in the hot big-bang cosmology one expects about as many cosmic "black-body neutrinos" as there are microwave photons.

\[ \rho_v = \frac{3}{11} n_\gamma \sum m_v \]

sum extends over the masses of all sequential neutrino flavours

present-day density in microwave background photons

from earlier

\[ \Omega_v = \frac{\rho_v}{\rho_c} \]

\[ \rho_c = 3H_o^2/8\pi G \]

taking \( h \) to be between 0.6-0.7 we get (for all three families)

\[ \Omega_0 h^2 \approx \sum \frac{m_v}{100eV} \]

\[ \Omega_0 h^2 \leq 0.4 \quad m_v \leq 40eV \]
Can Neutrinos be Dark Matter?

Worked Example

(1) Neutrino mass lower limit

It is also interesting to ask for a lower limit on \(h^2\) which the dominant dark-matter component must obey.

Allowing for a significant baryon fraction indicates that particle dark matter (PDM) should obey \(\Omega_\nu > 0.2\)

Taking \(h > 0.5\) as a lower limit for the expansion rate implies

\[
0.05 \leq \Omega_\nu h^2 \leq 0.4
\]

So a reasonable range where this dark matter candidate could be all of the nonbaryonic dark matter, therefore neutrinos with mass

\[
4eV \leq m_\nu \leq 40eV
\]

could represent all of the dark matter
Can Neutrinos be Dark Matter?

Extra Note

There is a second solution at large masses. If the mass significantly exceeds the cosmic temperature at a given epoch, the neutrino density is suppressed by a Boltzmann factor

\[ e^{-m_v/T} \]

The weak interaction rates in the early universe become slow relative to the overall expansion when the temperature falls below about 1MeV. For masses exceeding this weak freeze-out temperature the Boltzmann suppression occurs while the neutrinos are still in thermal equilibrium, reducing the relic density accordingly. A detailed calculation of the relic density requires an approximate solution of the Boltzmann collision equation.
Energy Density and Neutrinos

Worked Example

The amount of energy in radiation in today's universe can be estimated with the **Stefan-Boltzmann Law**, considering that the universe is filled with blackbody radiation at 2.7 K. The energy density in this equilibrium radiation is given by:

\[ u = \frac{4}{c} \sigma T^4 = \frac{4 \times 5.7 \times 10^{-8} \text{Wm}^{-2}\text{K}^{-4} x (2.7 \text{K})^4}{3 \times 10^8 \text{m/s}} \]

\[ u = 4.0 \times 10^{-14} \text{ J/m}^3 = 0.25 \text{ MeV/m}^3 \]

You should know this equation

From this work out the number density of gammas you expect in the Universe

ANS: given in lecture ... use

\[ n_\gamma = \frac{u(T)}{kT} \]
work out the number density of gammas you expect in the Universe

\[ u(T) = \text{const} \times T^4 \]

\[ n_\gamma = \frac{u(T)}{kT} \]

Know these useful equations

What is the number density of neutrinos?
Death of Neutrino Dark Matter

(1) The new neutrino experiments
the latest experiments looking for neutrino oscillations suggest that $\sum m_\nu < \sim 1$ eV.

(2) Large scale structure with neutrinos
N-body simulations show that neutrinos tend to smooth out small scale structure

simulations with Cold Dark Matter

simulations with Neutrino Hot Dark Matter

more next lecture
A Brief Review

The observed motions of stars and clusters due to the force of gravity on other known massive bodies are inconsistent with the predictions of the currently accepted laws of gravitation.

Low luminosity stars? NO - not enough microlensing events from MACHO, OGLE, etc

Anything made out of protons and neutrons? - NO -
abundances of the light elements give estimate of the baryon fraction and it’s not high enough.

Neutrinos? - NO - too light and too relativistic at the time of formation of galaxies and clusters.

That is all there is in terms of stable particles in standard model particle physics.