Thermal History of the Universe

- Present: 13.7 billion years after the Big Bang
- Key events:
  - 10^-32 sec: End of inflation
  - 100 sec: Formation of D & HE
  - 1 month: COBE Spectrum Fixed
  - 56,000 yrs: Radiation = Matter Energy
  - 379,000 yrs: CMB Last Scattering
  - 209 x 10^6 yrs: Reionization

Fermilab's Primordial Soup
Too Much Helium

Our Sun is about 28% helium by mass.
George Gamow and Ralph Alpher
Some of the reaction sequences that led to the formation of helium in the early universe. Compare this figure with Figure 16.28, which depicts the proton-proton chain in the Sun.
Some More Details of the Nuclear Reactions in the Early Universe

Figure 4.2  Nucleosynthesis of the light elements.

\[ n + p \rightarrow ^2H + ^2H \]

\[ ^n + ^3He + n \rightarrow ^4He \]

\[ ^3He + ^4He + n \rightarrow ^7Be + e^- \]

\[ ^4He + ^3H \rightarrow ^7Li \]

\[ ^2H + ^3H \rightarrow ^7Li \]
One Reason Why Physicists Are Good at Calculating Nuclear Reactions
Primordial Nucleosynthesis
Measuring Cosmic Deuterium

Figure 1. QSO 1937-1009: See text for more details
Top: Lick spectrum (FWHM = 4 Å)
Middle and Bottom: Keck-HIRES spectrum of the Lyα region (left) and C II region (right) at z = 3.5722
The Life of Our Universe Before One Second

![Graph showing the life of our universe before one second.](Image)

**Fig. 12.9** Great moments in the history of the universe. Important events and epochs are shown along a line indicating radiation temperature versus time.
At Very Early Times Our Universe Was Filled With a Plasma of Quarks, Anti-Quarks, and Gluons.

**Diagram:**
- **Quarks:** $u$, $d$, $s$, $c$, $t$, $b$
- **Antiquarks:** $\bar{u}$, $\bar{d}$, $\bar{s}$, $\bar{c}$, $\bar{t}$, $\bar{b}$
- **Nucleon:** $u\bar{u}d\bar{d}$
- **Neutron:** $\bar{u}u\bar{d}d$

**Timeline:**
- **1910:** Atom
- **1980:** Quarks
- **Future?**

**Scales:**
- **Centimetres:** $10^{-8}$
- **Time:** $10^{-3}$
Attempts to Make Quark-Gluon Plasmas on Long Island
The Very Early Universe Contained Both Matter and Antimatter, in Nearly Equal Amounts

Carl Anderson

Paul Dirac

Source: NSF/phy.ve
Baryogenesis: Somehow the Matter Slightly “Won” Over the Antimatter

Matter Particles: 10,000,000,001
Antimatter Particles: 10,000,000,000
Andrei Sakharov’s Conditions for Baryogenesis