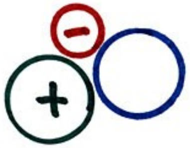
ORDINARY MATTER

Protons: ⊕ Neutrons: ○

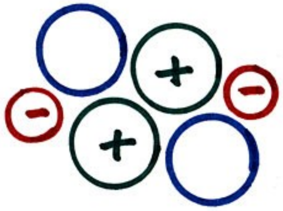
Electrons: ⊖

Hydrogen

Deuterium



Helium



- We can estimate the total amount of all matter. (From its gravitational effects.)
- We can estimate the amount of ordinary matter. (From its effect on cosmological nucleosynthesis.)

It turns out that there is much less ordinary matter than all matter. We don't see what is missing, so we call it dark matter.

TOTAL MASS DENSITY

One way to measure the total cosmic mass density, is to look at clusters of galaxies, like the Coma Cluster.
(F. Zwicky, 1937)

From the motion of hot gases in a clusters of galaxies, we can infer the strength of its gravitational field, and from that infer the total mass of the cluster. The mass of galaxy clusters per amount of light emitted is about 260 times the mass per luminosity of the sun. That is, if the mass of a cluster were entirely in stars just like the sun, its luminosity would be 260 times greater.

From the measured mass per luminosity (assumed to be typical of the whole universe) and the measured luminosity of very large volumes of the universe, the density of all matter is found to be roughly

$$0.000000000000000000000000000002 \text{ g/cc}$$

or more compactly, about

$$2 \times 10^{-30} \text{ g/cc}$$

(1 g/cc $=$ density of water)

Could this be ordinary matter?

COSMOLOGICAL NUCLEOSYNTHESIS

The expansion of the universe has cooled the radiation it contains. During the first three minutes, it was too hot for atoms or even atomic nuclei to hold together. The ordinary matter of the universe consisted of free protons, neutrons, and electrons. Then at the end of the first three minutes the temperature of the universe dropped to a billion degrees, and nuclear reactions started.

$$p + n \rightarrow D + \text{radiation}$$

$$D + D \rightarrow He^3 + n$$

$$D + He^3 \rightarrow He^4 + p$$

Some deuterium was left over as an unburned ash. The greater the density of ordinary matter at a temperature of a billion degrees, the less deuterium was left over. From the observed ratio of present D and H atoms, we can infer the abundance of ordinary matter when the temperature was a billion degrees. From the temperature of the radiation still filling the universe now ($T = 2.725$ degrees Centigrade above absolute zero) we know how much the universe has expanded since its temperature was a billion degrees. So we can infer the average cosmic density (mass per volume) of ordinary matter now.

From the observed deuterium abundance, we infer that the average cosmic density of ordinary matter now is

$$0.000000000000000000000000000000402 \text{ g/cc}$$

or more compactly

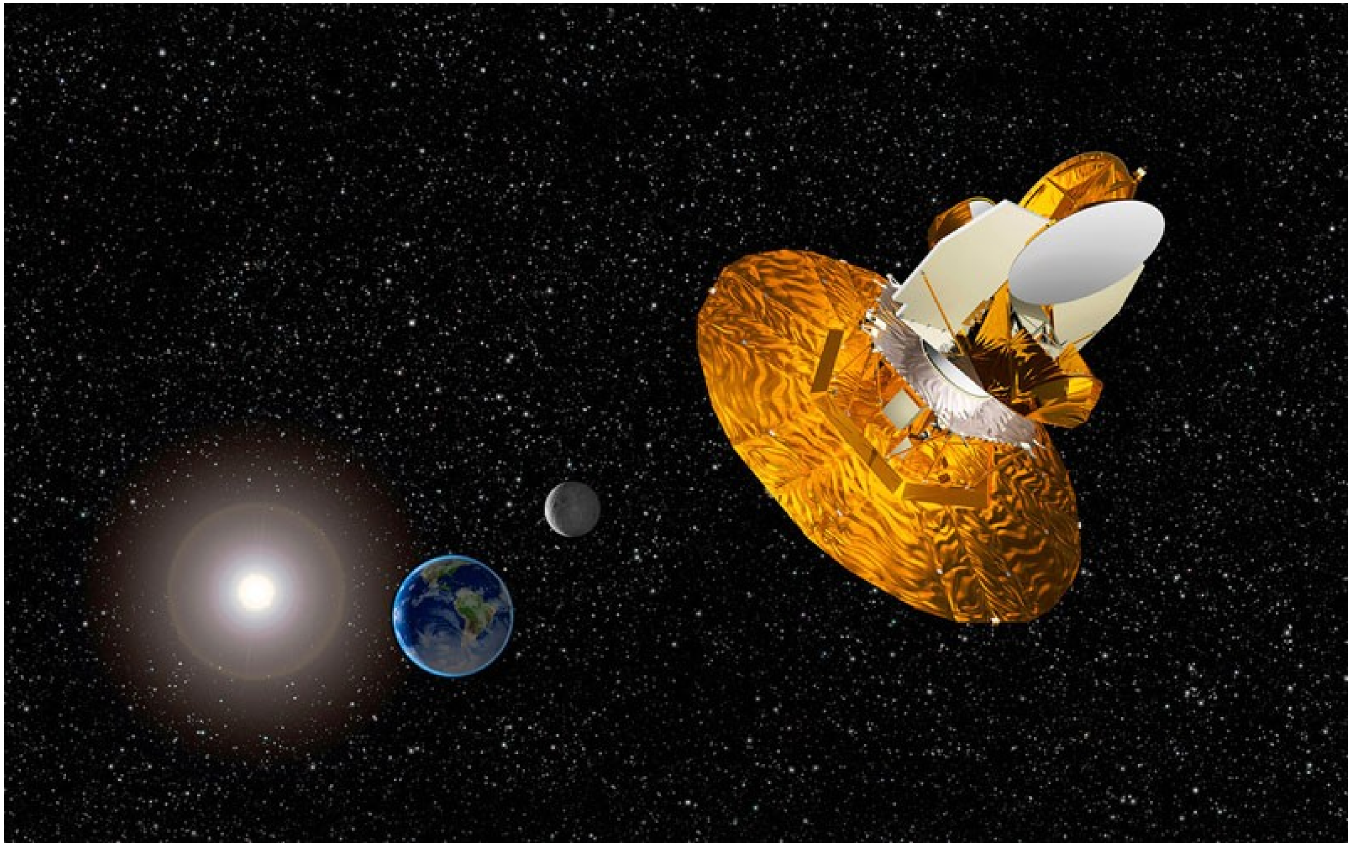
$$4.02 \times 10^{-31} \text{ g/cc}$$

This ordinary matter is mostly hydrogen and helium interstellar and intergalactic gas. Stars make up only about 12% of the ordinary matter. Elements heavier than helium in stars and gas make up only about 1/2 % of ordinary matter.

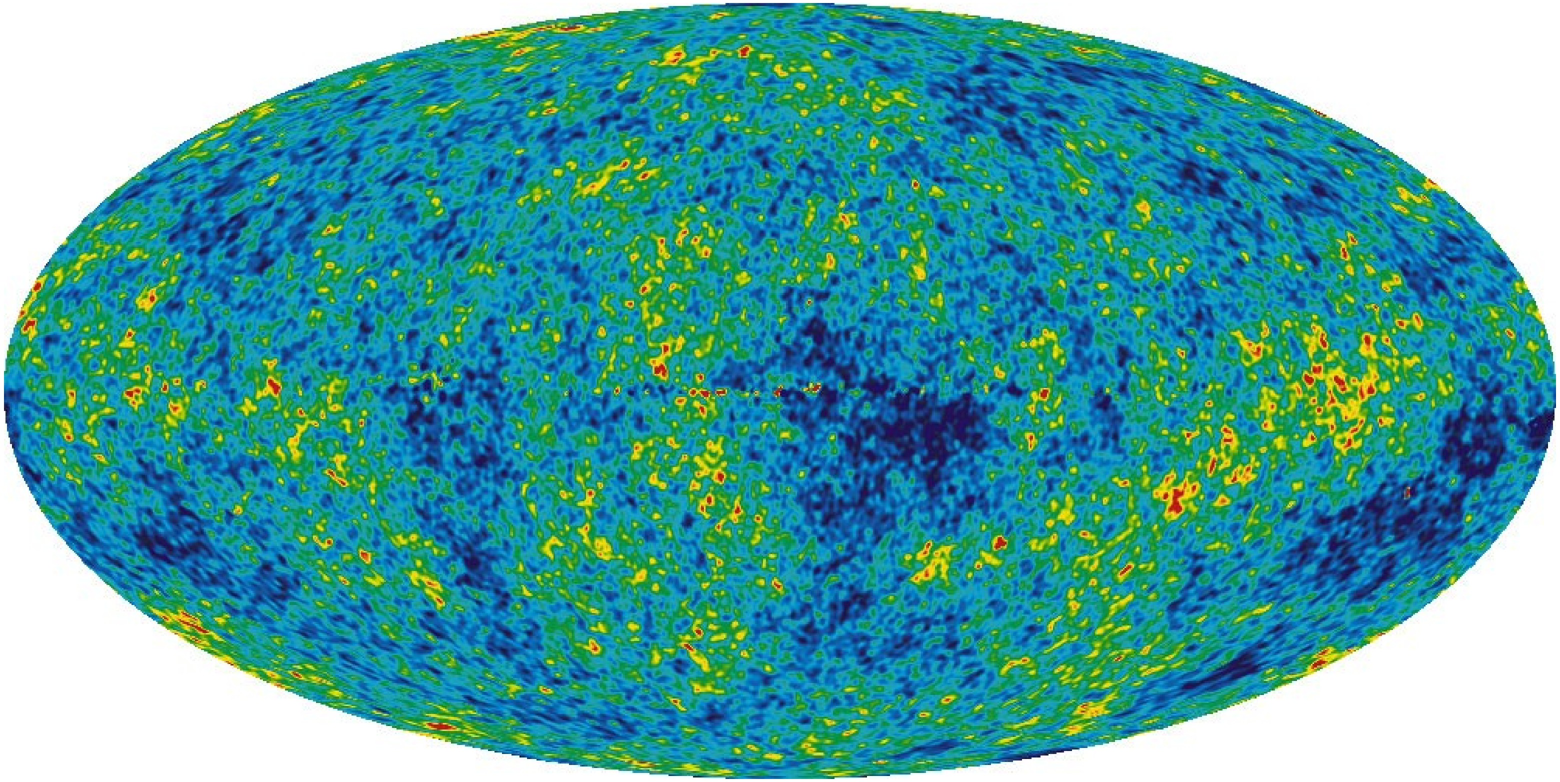
Even with an uncertain estimate of the density of all matter, it is clearly much greater than the density of ordinary matter.

$$\frac{\text{all matter}}{\text{ordinary matter}} \simeq \frac{2 \times 10^{-30}}{4 \times 10^{-31}} = 5$$

We get much more precise results by studying fluctuations in radiation left over from the first four hundred thousand years, known as the Cosmic Microwave Background. These fluctuations have been studied over the past five years by the Wilkinson Microwave Anisotropy Probe.



We see a pattern of slightly more intense and slightly less intense spots in the microwave radiation, arising from random sound waves when at the time when the expansion of the universe first made it transparent to radiation. This pattern depends on both the densities of ordinary matter and of all matter.



Results from the Cosmic Microwave Background

Ordinary matter density:

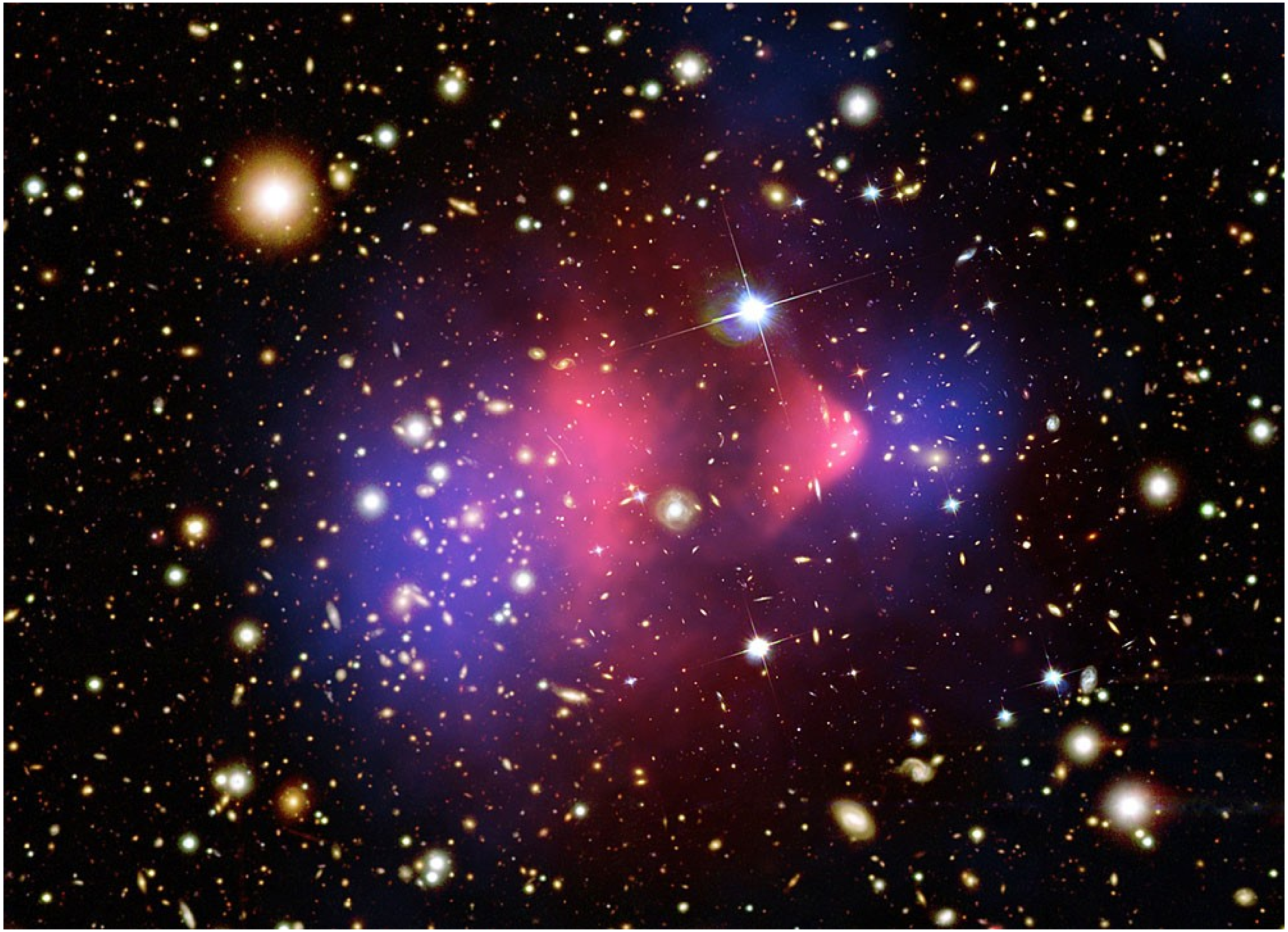
$$4.26 \times 10^{-31}\ \text{g/cc}$$

Total matter density: 24.6×10^{-31} g/cc

$$\frac{\text{total matter}}{\text{ordinary matter}} = \frac{24.6}{4.26} = 5.77$$

Direct evidence of dark matter:

The "Bullet Cluster" of Galaxies



Weakly Interacting Massive Particles

Perhaps dark matter consists of particles left over from the early universe.

- They must be weakly interacting (no electric charge) or we would see them.
- They must be stable, or they would have disappeared by now.
- But they better annihilate in pairs, or there would be too many now.

They stop annihilating when the expansion of the universe makes their density so low that they no longer collide with each other. (B. Lee & SW, 1977)

The annihilation rate experienced by any one dark matter particle is proportional to the number per volume of the dark matter particles with which it can collide. From the observed abundance of dark matter, we can calculate the ratio of the annihilation rate to the number per volume. For a reasonable guess about the forces between dark matter particles, we find from this that the dark matter have mass

$$\frac{\text{dark matter particle mass}}{\text{proton mass}} \approx 10 \text{ to } 100$$

Known Elementary Particles

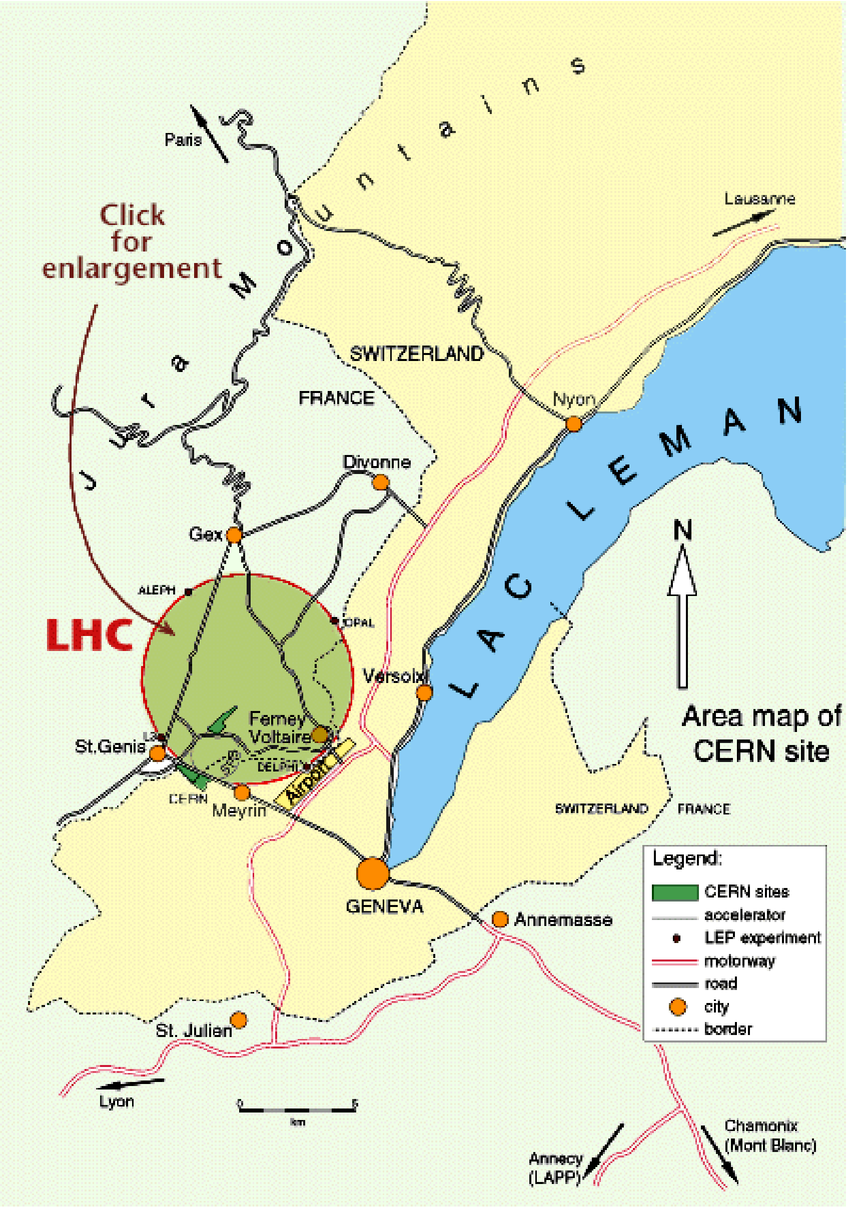
Spin =	1	1/2	0
	photons		
	$W^{\pm}, Z^0$		
		electrons	
		neutrinos	
		quarks	
			Higgs

Supersymmetry

Spin =	1	1/2	0
	photons	photinos	
	$W^{\pm}, Z^0$	winos, zinos	
		electrons	selectrons
		neutrinos	sneutrinos
		quarks	squarks
		Higgsinos	Higgs

Discovering WIMPs

- Discover annihilation products from dark matter in galaxy, sun, etc.
  Pamela, ATIC, GLAST, HESS
- Observe dark matter particles from space hitting atomic nuclei in laboratories on Earth
  DAMA, CRESSE, EDELWEISS, UK, CDMS, WARP
- Create dark matter particles at accelerators
  LHC


Click for enlargement
LHC
Area map of CERN site
Paris
Lausanne
Jura Mountains
SWITZERLAND
FRANCE
Nyon
LAC LEMAN
N
Divonne
Gex
ALEPH
OPAL
Versoix
Ferney Voltaire
St.Genis
L3
SPS
DELPHI
Airport
CERN
Meyrin
GENEVA
Annemasse
SWITZERLAND
FRANCE
St. Julien
Lyon
0
5
km
Annecy (LAPP)
Chamonix (Mont Blanc)
Legend:
CERN sites
accelerator
LEP experiment
motorway
road
city
border