Dark Matter: What is it? Where is it? Can we make it in the lab?

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Leigh Page Prize Lectures - 1 April, 2006
As we look out into the universe, we see stars, galaxies, clusters.

It seems that we can see just where the mass is, and how much there is.

But, in fact, it is just the opposite.
Our story begins in 1933, when Fritz Zwicky measured the mass of the Coma cluster of galaxies.
from the observed motion of galaxies within a cluster:

deduce the gravitational forces, and thus the gravitating mass:

The analysis required 400 times more mass than the total mass of the stars in the galaxies.
We now know that much of this mass takes the form of hot gas radiating X-rays:

but still only 10-20% of the mass is accounted for.
Many pieces of evidence corroborate this result.

For example, look at the gravitational potential of our galaxy.
Mass of the Milky Way, determined from the orbital velocities of globular clusters

<table>
<thead>
<tr>
<th>distance (kpc)</th>
<th>result (billion solar masses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>200</td>
</tr>
<tr>
<td>20</td>
<td>30-200</td>
</tr>
<tr>
<td>44</td>
<td>890</td>
</tr>
<tr>
<td>50-100</td>
<td>500</td>
</tr>
<tr>
<td>50-100</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>900</td>
</tr>
<tr>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>118 (one cluster)</td>
<td>&lt; 1000</td>
</tr>
<tr>
<td>(total)</td>
<td>1000</td>
</tr>
</tbody>
</table>

V. Trimble review
Look at other galaxies. From the Doppler shifts of outlying stars, measure the ‘rotation curve’ $v(r)$.
according to Kepler’s laws of planetary motion,

\[ T^2 \sim R^3 \quad \nu \sim \frac{1}{\sqrt{R}} \]

<table>
<thead>
<tr>
<th>Planet</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>46 km/sec</td>
</tr>
<tr>
<td>Venus</td>
<td>35 km/sec</td>
</tr>
<tr>
<td>Earth</td>
<td>30 km/sec</td>
</tr>
<tr>
<td>Mars</td>
<td>24 km/sec</td>
</tr>
<tr>
<td>Jupiter</td>
<td>13 km/sec</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.6 km/sec</td>
</tr>
<tr>
<td>Uranus</td>
<td>6.8 km/sec</td>
</tr>
<tr>
<td>Neptune</td>
<td>5.5 km/sec</td>
</tr>
<tr>
<td>Pluto</td>
<td>4.4 km/sec</td>
</tr>
</tbody>
</table>
Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio $M/L$ greater than 100.

Rubin, Thonnard, Ford

“Such a velocity implies that 94% of the mass is located beyond the optical image; this mass has a ratio $M/L$ greater than 100.”
Here are the 'rotation curves' of 25 more galaxies.
A large concentration of mass such as a cluster of galaxies will bend light, as a ‘gravitational lens’.

If there is a bright galaxy or a quasar behind a cluster, the bending measures the mass of the cluster.

Zwicky actually suggested this technique in 1937.
W. N. Colley, E. Turner, J. A. Tyson -- Hubble Space Telescope
the bullet cluster (1E0657-56) provides an interesting example. Here is the Hubble Space Telescope Image:
Here is the mass distribution from gravitational lensing.
The atomic matter is mainly in hot gas, emitting X-rays. The Chandra satellite measures this component (red).

The gravitating mass is elsewhere (blue).
Finally, it is possible to measure the truly primorial density of matter.

Very early in the history of the universe, it was so hot that all hydrogen was ionized.

The light emitted when the ionized atoms capture electrons is now visible as a ‘microwave background radiation’ at 2.7 K.
Here is a temperature map of the microwave background

WMAP Science Team
Wilkinson Microwave Anisotropy Probe

a double microwave receiver, located at the Lagrange point L2
subtract the Earth’s motion and galactic sources
blow up the residual differences by a factor 100,000
The visible peaks and valleys are sound waves from the gravitational clumping of matter.

These regions were of size 100,000 light-year when created; this expands to 100 M light-yr today.
Angular Scale

TT Cross Power Spectrum

- CDM All Data
- WMAP
- CBI
- ACBAR

$\ell(\ell+1)C_\ell /2$ (µK²)

Multipole moment ($\ell$)

WMAP Science Team
From the first peak position, we learn that the universe is flat when viewed in the large. So the total energy density in the universe is Einstein’s closure density $\rho_c$.

From the rebound, we measure the equation of state of the primordial plasma. The small dissipation implies that only 20% of the matter is atoms; 80% is non-interacting.

In all, the energy of the universe is distributed as:

$$\Omega_b = \frac{\rho_b}{\rho_c} = 4.2\% \quad \text{atoms}$$

$$\Omega_d = \frac{\rho_d}{\rho_c} = 20.\% \quad \text{dark matter}$$

$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c} = 76\% \quad \text{dark energy}$$

WMAP 2006
Until very recently, the energy content of the universe was dominated by cold dark matter.

This leads to a simple and beautiful picture of structure formation in the universe.
cosmological simulations: M. S. Warran et al. (Los Alamos NL)
The final structures are proto-galaxies.

Many of these assemble to a galaxy, others remain as dwarf companions.
The Large and Small Magellanic Clouds
Cold dark matter should be clumpy and cuspy, with a large cusp at the center of the galaxy. Is it there?

Cold dark matter predicts many more dwarf companions of our galaxy. Where did they go?

Possibly, some of these are galaxy-sized objects made purely of cold dark matter. How could we detect them?
To analyze this question, we have to ask,

What kind of particle is dark matter made of?
We need a particle that is stable, neutral, heavy, and very weakly interaction. Bahcall called it this a

**Weakly Interacting Massive Particle (WIMP)**

I will add the property:

**WIMPs can be created and annihilated in pairs.**

If so, WIMPs were created when the universe was very hot.
In the hot era just after the Big Bang, WIMPs were in thermal equilibrium:

rate for the WIMP density to be changed by interactions:

\[ \sigma n \sim A \sqrt{\frac{T^3}{m}} e^{-m/T} \]

with \( A \sim 10^{-4} \) for weak interactions

rate for the WIMP density to be changed by the expansion of the universe:

\[ H \sim \frac{T^2}{m_{Pl}} \]

with \( m_{Pl} \sim 10^{19} m_p \); so H is smaller for almost any A.
the universe expands and cools ...
until today ...
It is possible to work out a precise formula describing how much WIMP material is left over:

\[ \Omega_W = \frac{s_0}{\rho_c} \left( \frac{45}{\pi g_*} \right)^{1/2} \frac{x_f}{m_{Pl}} \frac{1}{\langle \sigma v \rangle} \]

We know the parameters. Put in the numbers:

The cross section for WIMP annihilation is

\[ \langle \sigma v \rangle = (10^{-18} \text{ cm})^2 = (10^{-5} \text{ fm})^2 \]

This points to the length scale of weak interactions.
If dark matter is an elementary particle, we can search for it using methods from elementary particle physics.

For example, dark matter annihilation is still going on at some rate. Can we find the signals of this process?

\[ N + N \rightarrow W \cdots \rightarrow \pi^0 \cdots \rightarrow \gamma \cdots \]

Gamma rays from space!
the Gamma ray Large Aperture Space Telescope
gamma ray tracker and calorimeter of GLAST
EGRET gamma spectrum vs. “conventional model”
Strong, Moskalenko, and Reimer
We can also look for dark matter particles hitting the earth.

One dark matter particle at a time hits one nucleus, bounces off, and departs.

The energy deposited is \( \text{keV} \), but once a month, say, in a macroscopic amount of material.

So, we had better look in a very quiet place.
Soudan mine, northern Minnesota
cryostat of the CDMS detector
A ZIP detector (100 g Si) from the CDMS experiment

Blas Cabrera
performance of a ZIP detector: electrons vs phonons

Ba-133: gamma rays

Cf-252: neutrons

CDMS
calibration with Cf-252

real data
Finally, if it is possible for WIMPs to annihilate in pairs, they can also be produced in pairs. We only have to collect enough energy in one place.

Hopefully, this is within the capability of the world’s highest energy particle accelerators.
the Geneva region

with the CERN Large Hadron Collider
Overall view of the LHC experiments.
the ATLAS experiment
arrival of a superconducting muon toroid at CERN

Paula Collins, CERN
A WIMP produced at the LHC would penetrate the detector and escape, leaving no trace.

But, there is plenty of other activity in the events that produce WIMPs.

The rates are expected to be large -- $10^5$ events/ year.

So we have the opportunity to shed light on dark matter from high-energy particle physics.
How exactly?

This is the subject of the next two lectures.