Dark Matter in the Cosmos and in the Lab

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May, 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.

T. A. Rector and B. A. Wolpa - NOAO/AURA/NSF
Our story begins in 1933, when Fritz Zwicky, measured the mass of the Coma cluster of galaxies.

Fritz Zwicky

O. Lopez-Cruz and I. K. Sheldon - Kitt Peak
from the observed motion of galaxies within a cluster:

use the virial theorem to 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>
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<tbody>
<tr>
<td>17</td>
<td>200</td>
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<tr>
<td>20</td>
<td>30-200</td>
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<tr>
<td>44</td>
<td>890</td>
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<td>50-100</td>
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<td>50-100</td>
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<td>100</td>
<td>900</td>
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<tr>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>118 (one cluster)</td>
<td>&lt; 1000</td>
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<tr>
<td>(total)</td>
<td>1000</td>
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Look at other galaxies. From the Doppler shifts of outlying stars, measure the ‘rotation curve’ $v(r)$.

According to Kepler’s law, we expect

$$T^2 \sim R^3 \quad \text{or} \quad v \sim 1/\sqrt{R}$$

if the mass of the galaxy is concentrated in the region where stars are visible.
but for the outlying stars in galaxies, one finds:

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 reconstructed 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 amplified from the primordial spectrum of fluctuations as matter falls into local gravitational potentials.

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

The sound waves are created. The reverberations measure the dissipation of the cosmic plasma.
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 rebounds, we measure a very small dissipation. This implies that only 20% of the matter is atoms; 80% is non-interacting.

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

\[
\begin{align*}
\Omega_b &= \frac{\rho_b}{\rho_c} = 4.2\% \\
\Omega_d &= \frac{\rho_d}{\rho_c} = 20\% \\
\Omega_\Lambda &= \frac{\rho_\Lambda}{\rho_c} = 76\%
\end{align*}
\]

Atoms

Dark matter

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 smaller than galaxies like the Milky Way. Large galaxies should thus contain many layers of substructure.

Some of this is obvious to the eye. But smaller components have been stripped of matter; these are more difficult to detect.
The Large and Small Magellanic Clouds
Dark matter structure of a model galaxy, from simulations of Taylor and Babul

visualization of $\Phi_\gamma \sim \int dz \rho^2$ by Baltz.
This analysis raises many fascinating questions:

Can we see that dark matter in the disk of the galaxy is clumpy rather than smooth?

Is there a dark matter cusp at the center of the galaxy?

Cold dark matter predicts many more dwarf companions of our galaxy. Where did they go? Could some be completely dark?
To analyze these questions, we need to learn how to see dark matter. To understand how to do this, we must answer:

What kind of particle is dark matter made of?
We need a particle that is stable, neutral, heavy, and very weakly interacting. Bahcall called 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: Compare

the rate for the WIMP density to be changed by interactions:

\[ \sigma n \sim A \sqrt{\frac{T^3}{m}} e^{-m/T} \quad \text{with} \quad A \sim 10^{-4} \]

for electroweak interactions

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

\[ H \sim \frac{T^2}{m_{Pl}} \quad \text{with} \quad m_{Pl} = 10^{19} \text{ GeV} \]

so \( H \) is smaller for almost any value of \( A \).
the universe expands and cools …
until today ...
By integrating the Boltzmann equation for the WIMP density through this era of ‘freeze-out’, it is possible to work out how much WIMP matter 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

\[ \langle \sigma v \rangle = 1 \text{ pb} = \frac{\pi \alpha^2}{8m^2} \text{ for } m = 100 \text{ GeV} \]

This points to the length scale of weak interactions.
As an elementary particle theorist, this strikes me as an amazing conclusion.

Our precision knowledge of the weak interactions tells us that the correct model of weak interactions is a gauge theory with spontaneous symmetry breaking. The mechanism of symmetry breaking requires new physics at the 100 GeV mass scale. It is tantalizing that dark matter could be a manifestation of this new physics.
In fact, almost all explicit models of symmetry-breaking mechanisms for the electroweak interactions contain heavy neutral particles with only weak interactions.

These particles are \textit{stable} if the new particles in the model carry a \textit{conserved discrete symmetry}. Usually, such a discrete symmetry is required for other reasons, e.g., to prevent rapid proton decay.

One such model is supersymmetry - the idea that all bosons and fermions in Nature have partners with the opposite statistics. In supersymmetry, the \textit{fermionic photon} is a plausible candidate for the particle of dark matter.

In the past few years, many new models based on extra space dimensions have been studied. All have candidates for WIMP dark matter.
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 tens of 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
The current bounds on the WIMP-nucleon cross section approach

\[ 10^{-7} \text{ pb} = 100 \text{ zeptobarn} \]

for some range of masses. Supersymmetry models can give this value, but more commonly this cross section is

\[ 1 - 10 \text{ zeptobarn} \]

or even below.

Larger solid-state devices and large liquid argon/xenon detectors could reach the 1 zb level.
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
simulated high-energy event in ATLAS
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.
It is complex to evaluate the Standard Model backgrounds. Nevertheless, these events are highly characteristic for large jet activity and large missing energy.
However, it is not sufficient to observe these events. We need to use them to make precision measurements of the properties of dark matter particles.

It is not so obvious that this can be done:

We do not know the momenta of the quarks or gluons that initiate the reaction.

We do not observe the (two) outgoing dark matter particles.

Still, it is possible to work from the observed final-state particles.
A feature of many supersymmetry spectra is the decay chain

\[ \tilde{q} \rightarrow q \rightarrow N_2 \rightarrow N_1 \rightarrow l^+l^- \]

The lepton momenta are measured completely, and we can construct their spectrum of invariant masses. If

\[ m(N_2) - m(N_1) < m_Z \]

this spectrum terminates at

\[ m(l^+l^-)_{\text{max}} = m(N_2) - m(N_1) \]

Here is a worked example that makes use of this effect.
Kitano-Nomura
Now try to combine a quark with the lepton pair. Find the two hardest jets of particles observed in the event, and try to combine one with the lepton pair.

Some useful variables are:

$$\min_{1,2}\{m(\ell\ell j)\}$$

$$M^2 = \min_{p_T^1 + p_T^2 = p_T} \max\{m^2_T(p_1 \phi_1), m^2_T(p_2 \phi_2)\}$$

Lester and Summers
$M_{llq}$ [GeV]
$m_{N_1} = 169 \pm 17$ GeV \quad m_{\tilde{q}} = 486 \pm 11$ GeV

Kitano-Nomura
With these and other tricks, one can determine masses at the level of

10% or below for WIMP, squark, gluino masses

1% for mass differences in l+l- cascades
These seems promising, but the study of dark matter raises more difficult problems:

We need to evaluate the cross sections for WIMP annihilation, and for WIMP scattering from matter, from high-energy physics data. It is not possible to make beams of WIMPs, so these cross section must be obtained indirectly.

In most models, the values of these cross sections are very sensitive to the detailed properties of the WIMP.

An ambitious strategy -- but the only one available -- is to obtain a broad quantitative description of the underlying physics model.
We could obtain an even higher level of precision by building a different type of particle accelerator.

By colliding $e^+e^-$ instead of pp, we eliminate major difficulties of the LHC environment:

- electrons are elementary particles, so the initial momenta are known
- the Standard Model annihilation cross sections are small and can be computed precisely, so backgrounds are small and controlled
- the CM energy can be adjusted, so we can concentrate on the lightest superparticles with the simplest decay processes

The unobservability of the WIMP is still a problem.
A major new e+e- collider is now under design.

the International Linear Collider (ILC)

The design CM energy is 500 GeV, with the potential for upgrade to 1000 GeV.

The ILC will be a global project. The design team is drawn from laboratories in the US, Europe, and Japan.

Argonne, Brookhaven, Cornell, DESY, Fermilab, Frascati, KEK, Novosibirsk, Orsay, and SLAC are among the labs with major involvement in this project.
the International Linear Collider (ILC)
To understand how we could go from LHC and ILC results to the determination of dark matter cross sections, Baltz, Battaglia, Wizansky and I worked through the determination of model parameters in some specific models of supersymmetric dark matter.

Here are the results for one of our model points (LCC2).

A typical supersymmetry event at the ILC looks like this:
$e^+e^- \rightarrow \tilde{C}_1^+ \tilde{C}_1^-$

$\rightarrow e^+ \nu \tilde{N}_1 \quad q \bar{q} \tilde{N}_1^0$
precision determination of mass differences from the dilepton spectrum:

\[ m(\tilde{N}_2) - m(\tilde{N}_1) = 58.7^{+0.2}_{-0.1} \text{ GeV} \]

\[ m(\tilde{N}_3) - m(\tilde{N}_1) = 82.0^{+0.4}_{-0.1} \text{ GeV} \]

The detailed shape of the distribution is predicted by supersymmetry.

J. Alexander, et al.
For this model, the spectrum constraints from the LHC alone give multiple solutions with different WIMP properties.
The ILC-500 cross section measurements resolve the ambiguity.
from the parameter determination, we obtain a microscopic prediction of the cosmic dark matter density
Here is the microscopic prediction of the neutralino annihilation cross section at threshold.
By using this cross section, we can turn measurements of gamma ray fluxes into estimates of the dark matter density in space:

\[ J = \int d\rho^2 \]

- galactic center
- LCC2
- sub-halo clump
Here is the microscopic prediction of the direct detection cross section dominated by exchange of the Higgs boson.
In this model, the 25kg Super-CDMS should see 67 events. Using this number (with its statistical error) and the cross section just determined, we can directly evaluate the flux of dark matter impinging on the CDMS detector. Here is the likelihood distribution:
In this and the other examples,

The LHC and the ILC give precision data on the spectrum of new particles that is in its own right important information about the fundamental interactions.

In addition, these data constrain the WIMP properties so that astrophysicists can use these to determine the distribution of WIMPs in the galaxy.

In the next 5 - 10 years I expect major developments both in elementary particle physics and in the astrophysics of dark matter.

Be there!