Warning: Most figures are not my own, found on internet
Talk Goals

• Give you a brief intro to dark matter
• Pieces of Evidence
• Example dark matter candidate, weakly interacting massive particle (WIMP)
• Experimental approaches to find dark matter
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Weighing Galaxies by Rotation Curves

Centripetal Acceleration

\[ G_N \frac{M(r)}{r^2} = \frac{v(r)^2}{r} \]

Milky Way
Observations pioneered by Vera Rubin

New dark stuff

\[ v(r) \sim \text{constant} \]

\[ \rho_{\text{dark}}(r) \sim 1/r^2 \]

Only luminous stuff

\[ v(r) \propto 1/\sqrt{r} \]

Hint that we are surrounded in a dark matter halo
Weighing space by gravitational lensing

General Relativity predicts that light will be bent by gravity.

Thus, galaxies can be lensed, allowing mass distribution to be inferred.

hubblesite.org
Bullet Cluster - Collision of Two Galaxy Clusters

Pink - Distribution of Hot Gas in Clusters (majority of visible mass)
Blue - Mass distribution from Gravitational Lensing

Interpretation: Dark Matter has passed through without interactions
Evidence on size of Universe
Cosmic microwave background

Planck Satellite Map of Cosmic Microwave Background Temperature Anisotropy

Power Spectrum (essentially Spherical Harmonic amplitudes) has distinctive peaks

Size of peaks consistent with dark matter
Dark matter is a consistent theory passing several different checks

However, only dark matter’s gravitational interactions have been confirmed

Next step is to understand its fundamental particle nature (if any)
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Early Universe was a hot plasma (soup)

Particles that we now produce in colliders were in great abundance

E.g. Muons

\[ \mu^- + \bar{\nu}_\mu \leftrightarrow e^- + \bar{\nu}_e \]

were produced by scattering processes when temperature was high enough so they were energetically favorable
Assumption: dark matter was in thermal equilibrium in the early universe
Thermal equilibrium set by Dark Matter annihilation into Standard Model particles

\[ \chi + \chi \leftrightarrow SM + SM \]

As universe expands, it cools to temperature where dark matter is no longer energetically favorable.

Rate of this process determines how much dark matter remains in the universe, this prediction then leads to estimate of signals to detect dark matter.
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Three Approaches

• Indirect Detection - Cosmic Rays
• Direct Detection - Dark Matter scattering on Target Nuclei
• Colliders - Production of Dark Matter at Colliders
Indirect Detection

Through this process, dark matter could be annihilating into distinctive Standard Model particles

E.g. antiparticles such as antielectrons, antiprotons

Energetic gamma rays or neutrinos
Antielectrons (aka positrons)

Satellite experiments looking for antielectrons

Positron Fraction = \( \frac{N_{e^+}}{N_{e^-} + N_{e^+}} \)

Rising fraction is consistent with dark matter, but also pulsars

Stay tuned...
Photons

Evidence for a gamma ray line in Fermi satellite’s data

If confirmed, would tell us mass of dark matter

Unfortunately, could be an instrumental effect

Weniger analysis of Fermi data
Direct Detection: DM-nuclei scattering

Turning the process on its side, we could have scattering off nuclei though interactions with quarks
Backgrounds for Direct Detection Experiments

Pb shielding to reduce EM backgrounds from radioactivity

Polyethylene contains hydrogen needed to moderate neutrons from radioactivity

Depth is necessary to reduce flux of fast neutrons from cosmic ray interactions (although active veto may partially substitute for depth)

Schematic of an experiment

Can probe dark matter in the Milky Way, by looking for interactions with target nuclei

Events are rare, so need to go underground and shield against backgrounds
Direct Detection Technologies

Several sophisticated ways to measure tiny, tiny recoil energies and be sure that it wasn’t some background process

Example experiments: CDMS, XENON, DAMA

Dark matter in galaxy is nonrelativistic, \( v \sim 10^{-3} \, c \)
Leads to nuclear recoils of \( O(10) \) keV
Before

Lab Frame

ımı x m

\( \mu \equiv \frac{m_x m}{m_x + m} \)

COM Frame

ımı x m

After

ımı x m

\( E_R = \frac{1}{2} m |\vec{v}_f|^2 = \frac{1}{2} m \left( \frac{\mu}{m} \right)^2 [(1 - \cos \theta)^2 + (\sin \theta)^2] \)

\[ = \frac{\mu^2}{m} v^2 (1 - \cos \theta) \]

For electrons, \( \mu \sim m \sim .5 \text{ MeV} \), so \( E_R \sim .5 \text{ eV} \)

For protons \( E_R \sim \text{keV} \)
Direct detection anomalies keep cropping up

Example: CDMS saw 2 events in latest release (blue contours)

Ruled out by XENON expts (green lines)

Possibilities:

i) One or more expts are wrong

ii) Dark matter interpretation is incorrect
An upcoming frontier

Burgess et.al.

Next Generation of Direct Detection Sensitivity

Dark Matter Interacting with Higgs

Figure 4: The predictions for the elastic cross section, \( \sigma_{\text{el}} \), as a function of \( m_S \), which follows from the \( \lambda \)(\( m_S \)) dependence dictated by the cosmological abundance. Also shown is the exclusion limit from the CDMS-Soudan experiment [6].

Falsify than are more complicated models, with much of the parameter space covered by the next generation of experiments [4]. Most importantly, the projected sensitivities of the CDMS-Soudan and Genius experiments will completely over the range \( m_S \lesssim 50 \text{ GeV} \), for values of the Higgs mass between 110 and 140 GeV. As we show in the next section, this range of masses and coupling constants has important implications for the Higgs searches at colliders.

On the other hand, there exists the possibility of completely "hiding" the dark matter by choosing \( 0.4 < m_h < \sim m_S \leq 0.5 \).

In this case annihilation at freeze-out is very efficient, requiring small \( \lambda \)'s which lead to elastic cross sections suppressed to the level of \( 10^{-48} \text{ cm}^2 \). These levels so of sensitivity are not likely to be achieved in the foreseeable future.

Our model of a singlet real scalar predicts a smaller signal for underground detectors than does a model where the dark matter consists of \( N \) singlet scalars (including the model considered in ref. [10], for which \( N = 2 \)). This is because every individual species must be \( 1/N \) of the total dark matter abundance, \( \Omega_i = \Omega_{\text{tot}}/N \). This requires a larger annihilation rate at freeze-out for every species, and so an enhancement...
Colliders

Produce dark matter particles at Large Hadron Collider
Study and infer their properties
After two year LHC shutdown we will get more data

Missing Energy Events ala Supersymmetry
Conclusion

• Dark matter evidence is strong, but we still have to solve the puzzle of what it actually is

• Depending on the dark matter theory, there are ongoing tests to confirm or refute it

• The next decade should be extremely exciting for dark matter physics
For more, I highly recommend “Dark Matters” on PhD Comics