Dark Matter Searches: Hunting for Missing Mass

Noah Kurinsky
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Outline

• Motivation: Why do we think dark matter must exist?

• Theory: What could dark matter be?

• Method: How do we look for new particles?

• Results: What are the constraints on dark matter mass and interactions?

• Path Forward: What’s next?
Before other galaxies are shown to exist, Kapteyn (1922) presents his model for the galaxy, and suggests we’re missing mass somewhere.

In 1929, Edwin Hubble provides evidence for an expanding universe, and the first compelling evidence that the ‘nebulae’ catalogued over the previous centuries are in fact galaxies; the idea of a galaxy as a building block of a larger universe start to solidify.

In 1933, Fritz Zwicky uses observations of Coma cluster’s kinematics to infer a large amount of missing mass, the first person to show quantitatively that systems outside our galaxy seem to defy gravitational predictions based on visible mass.
Zwicky’s argument uses the virial theorem (which relates kinetic and potential energy in rotationally supported systems) to infer mass as a function of radius from orbital velocities.

- Zwicky’s initial measurement is low statistics, high error.

Rubin and Ford (1970-1980) measure rotation curves for many galaxies, showing that the curves are flat well beyond visible matter.

Non-optical studies, mapping hot gas (x-rays) and cold gas (radio waves) come later; at this point, matter distributions are questioned, MOND theories abound.
Galaxy Rotation Curves: A Problem

![Galaxy Rotation Curve Diagram](image)

- Observations from starlight
- Observations from 21 cm hydrogen
- Expected from visible disk
Building the Rotation Curve Case

• We find that all remote galaxies seem to have dark matter halos, and smaller galaxies have a larger halo contribution to total mass.

• We also find that galaxy clusters have halos as well; halos seem to form large structures.

• The rotation curve in the milky way is mapped, and components broken down; at right are a large sample of stars with accurate distance and rotational velocity measurements.
Mass Inferred from Strong Gravitational Lensing

• Both Newtonian and Relativistic gravity predict “lensing” that is the bending of light about concentrations of mass
  • The relativistic prediction is larger, but we need not rely on GR for this effect

• The rings shown here are called “Einstein rings”, and the curvature and distance (from redshift) can be used to infer the mass of the cluster

• Observations in multiple electromagnetic regimes can be used to infer the luminous mass, and thus estimate the amount and distribution of dark matter

Cluster Structure: Halos and Subhalos

- The blue in this image is the inferred DM halo, the red is the luminous mass.
- Red dominates the center.
- Blue dominates the outer reaches and extends far beyond the bulk of the luminous matter.
- Blue is not clumpy; this is important for inferring the properties of the DM!

http://apod.nasa.gov/apod/ap030814.html
Mapping Mass in Cluster Collisions: Lensing

http://chandra.harvard.edu/photo/2015/dark/
Mapping Mass in Cluster Collisions: Xray (hot gas)

http://chandra.harvard.edu/photo/2015/dark/
Cosmic Microwave Background Anisotropies

- Dark matter must have existed very early in the universe, and should thus impact the CMB and structure formation.

- If we model the “clumpiness” of the CMB, which traces structure shortly after the big bang, we can determine the amount of “baryons” and total mass, thus inferring the dark matter content of the universe.
Cosmic Microwave Background Anisotropies

[Graphs showing power spectrum vs. multipole moment]
The Case for Dark Matter

- Dark matter is necessary to explain observed motion of galaxies and galaxy clusters.

- It must be real matter; galaxy collisions imply a separate type of matter, dominating the mass, that does not interact during collisions (makes MOND very unattractive).

- It must exist primordially, produced somehow after the big bang, and incredibly early; cannot be primarily late-stage stellar objects.

- Must be kinematically “cold” to form the structures we infer from lensing and clustering maps.

- Seems to outweigh normal matter by 5 to 1; the stuff you are made of is just along for the ride.
What Could Dark Matter Be?

- When missing mass was first posited, a bevy of explanations were suggested
  - Black holes, neutron stars or other “MACHOs” (Massive Compact Halo Objects) - ruled out by lensing surveys
  - Neutrinos - too kinematically hot, and given latest mass estimates, interaction rate too high to produce trends seen in collisions
  - New particles - prevailing hypothesis

- What sorts of new particles is the question
  - Sterile neutrino - neutrino with different interaction
  - WIMPS - weakly interacting massive particles
    - originally referred to weak force, now weak in general
  - Axions - ultralight particles, suggested to solve CP-violation in the standard model
  - Lightest “Supersymmetric” particle

- Many theories abound; we have a lot of free parameter space
Thermal Relic Abundance

- A key handle on the properties of dark matter comes from the fact that it must ‘freeze out’ very early in the universe.

- As the velocity or cross-section increase, the annihilation rate increases, until it stops at a critical number density:
  \[ \Gamma = n \sigma v \rightarrow n \propto \frac{1}{\sigma v} \]

- This also can be converted to a line in mass versus cross section and velocity:
  \[ n = \frac{\rho}{m_\chi} \rightarrow m_\chi \sim \left( \frac{\rho \Gamma_A}{v} \right) \sigma_A \]
The measured relic abundance from Planck is \( \sim 0.26 \), and we find that the predicted relic abundance is given by the relation

\[
\Omega_M \propto \frac{m^2}{g^4}
\]

Much excitement in recent years came from two developments:

- WIMPs with mass in the 10 MeV - 10 TeV range shown to produce roughly the correct thermic relic abundance
- DAMA and CoGent announced possible WIMP detections near the sweet-spot

The natural parameter space which initially caused the excitement has been ruled out, but much of the space remains allowed, if not slightly less “miraculous”

- The WIMPless miracle may also allow for dark matter with these properties in a supersymmetric framework (http://arxiv.org/pdf/0803.4196v3.pdf)
Thermal Relic Abundance: Lighter Dark Matter

Phil Schuster, “Dark Matter at Accelerators Primer”, Dark Sectors 2016, SLAC
Precise Thermal Relic Density Lines

The Thermal Origin Target
(for vector portal)

Invariant & important targets!

Phil Schuster, “Dark Matter at Accelerators Primer”, Dark Sectors 2016, SLAC
Possible Creation Scenarios, Particle Types

- **Scalar**
- **Fermion**

- **Thermal Elastic**
- **Thermal Inelastic**

+ additional scenarios not discussed...

Phil Schuster, “Dark Matter at Accelerators Primer”, Dark Sectors 2016, SLAC
Dark Matter “Effective Field Theory”

• With so many possibilities for what dark matter could be, we need a way to search for it in a theory-agnostic way.

• An “Effective Field Theory” collapses all of the specifics into the most minimal set of interactions.

• The diagram at right assumes some force with a mediator much larger than the dark matter, and we start to list the possible types of particle DM could be, and what the shape of the cross-section curve would be with mass.

Figure adapted from Ref. 1 (ATLAS Collaboration)
Effective Field Theory Operators

Nuclear Scattering

\[ O_1 = 1_x 1_N \]
\[ O_2 = i \bar S_N \cdot \left[ \frac{\vec q}{m_N} \times \vec \tau^\perp \right] \]
\[ O_3 = \bar S_x \cdot \left[ \frac{\vec q}{m_N} \cdot \vec \tau^\perp \right] \]
\[ O_4 = \bar S_x \cdot \bar S_N \]
\[ O_5 = i \bar S_x \cdot \left[ \frac{\vec q}{m_N} \times \vec \tau^\perp \right] \]
\[ O_6 = \left( \frac{\vec q}{m_N} \cdot \vec \tau^\perp \right) \left( \bar S_N \cdot \vec \tau^\perp \right) \]
\[ O_7 = \bar S_N \cdot \vec \tau^\perp \]
\[ O_8 = \bar S_x \cdot \vec \tau^\perp \]
\[ O_9 = i \bar S_x \cdot \left[ \bar S_N \times \vec q \right] \]
\[ O_{10} = i \bar S_x \cdot \left[ \frac{\vec q}{m_N} \right] \]
\[ O_{11} = i \bar S_x \cdot \left[ \frac{\vec q}{m_N} \right] \]
\[ O_{12} = \bar S_x \cdot \left[ \bar S_N \times \vec \tau^\perp \right] \]
\[ O_{13} = i \left[ \bar S_x \cdot \vec \tau^\perp \right] \left( \frac{\vec q}{m_N} \cdot \vec \tau^\perp \right) \]
\[ O_{14} = i \left[ \bar S_x \cdot \frac{\vec q}{m_N} \right] \left( \bar S_N \cdot \vec \tau^\perp \right) \]
\[ O_{15} = - \left[ \bar S_x \cdot \frac{\vec q}{m_N} \right] \left( \bar S_N \times \vec \tau^\perp \right) \cdot \frac{\vec q}{m_N} \]

Production/Annihilation

<table>
<thead>
<tr>
<th>Name</th>
<th>Initial state</th>
<th>Type</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>qq</td>
<td>scalar</td>
<td>$\frac{m_q}{M^3} \chi^\dagger \chi q q$</td>
</tr>
<tr>
<td>C5</td>
<td>gg</td>
<td>scalar</td>
<td>$\frac{1}{4M^2} \chi^\dagger \chi \alpha_a (G_{\mu\nu}^a)^2$</td>
</tr>
<tr>
<td>D1</td>
<td>qq</td>
<td>scalar</td>
<td>$\frac{m_q}{M^3} \chi \bar \chi q q$</td>
</tr>
<tr>
<td>D5</td>
<td>qq</td>
<td>vector</td>
<td>$\frac{1}{M^2} \chi \gamma^\mu \chi \bar \chi \gamma^\mu q$</td>
</tr>
<tr>
<td>D8</td>
<td>qq</td>
<td>axial-vector</td>
<td>$\frac{1}{M^2} \chi \gamma^\mu \gamma^5 \chi \bar \chi \gamma^\mu \gamma^5 q$</td>
</tr>
<tr>
<td>D9</td>
<td>qq</td>
<td>tensor</td>
<td>$\frac{1}{M^2} \chi \sigma^{\mu\nu} \chi \bar \chi \sigma^{\mu\nu} q$</td>
</tr>
<tr>
<td>D11</td>
<td>gg</td>
<td>scalar</td>
<td>$\frac{1}{4M^3} \chi \chi \alpha_a (G_{\mu\nu}^a)^2$</td>
</tr>
</tbody>
</table>

Table from Ref. 1 (ATLAS Collaboration 2014)

K. Schneck et. al. 2015
Converting Theory to Experiment

- By measuring the interaction rate for this process abstractly, we can sum over relevant operators to learn about new physics

- The same terms contribute to all directions in this diagram; there are three methods that can look for DM in complementary ways!
  - Indirect detection looks for gamma rays or other abnormal astrophysical signatures indicative of DM annihilation
  - Colliders smash high energy SM particles together, and we can look to see if DM was produced
  - Direct detection methods use the background dark matter density to try to observe elastic scattering of DM on nuclei

- If one experiment sees a hint, we should be able to check with a complementary experiment; in the meantime, they tend to probe different regimes
Indirect Detection

• Idea is to look at areas of high dark matter density for annihilation lines, which would be sharply concentrated in energy about twice the DM mass energy

• The only places with high enough statistics are astrophysical sources; the complication being that they are not simple systems

• Searches occur both in distance galaxies and at our galactic center

• Indirect searches would give a really good idea of the DM mass through the energy resolution, but the density and velocities are less well known, so the cross section is much harder to compute
Indirect Detection: Signatures

WIMP Dark Matter Particles
$E_{CM} \sim 100$GeV

$\chi$ WIMP

$W^-/Z/q$

Gamma-rays

$\gamma$

$\pi^0$

$\nu_\mu$

$\nu_\mu\nu_e$

$\pi^+$

$\mu^+$

$\mu^-$

$\nu_\mu$

$\nu_e$

$e^+$

$e^-$

Neutrinos

$+ a few p/\bar{p}, d/\bar{d}$

Anti-matter
Example: Fermi Galactic Center Searches

Uncovering a gamma-ray excess at the galactic center

Unprocessed map of 1.0 to 3.16 GeV gamma rays

Known sources removed

https://www.nasa.gov/content/goddard/fermi-data-tantalize-with-new-clues-to-dark-matter
Example: Fermi Galactic Center Searches

Uncovering a gamma-ray excess at the galactic center

Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3.5 keV line

Tesla Jeltema* and Stefano Profumo†
*Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA
†Department of Physics University of California, Santa Cruz, CA 95064, USA

11 August 2014

https://arxiv.org/abs/1408.1699v1

Unprocessed map of 1.0 to 3.16 GeV gamma rays

Known sources removed

https://www.nasa.gov/content/goddard/fermi-data-tantalize-with-new-clues-to-dark-matter
Collider Detection

- Particle colliders slam billions of protons together millions of times per second, looking for a single “hard” scatter per “bunch crossing”

- Any quark or gluon operators can be looked at at the LHC
  - No spin dependence can be measured due to the number of protons being used at a time, and quark-antiquark operators are suppressed

- Any “final state” needs to have a visible particle in it; we add “initial state radiation” to our diagrams, and look for final states without standard model backgrounds

Figure from Andrew Beddall, TR-ATLAS Gaziantep Grid Workshop, June 19-21 2008
Collider Detection: ATLAS & CMS

- An interaction will occur in the center of the detector, and the products are flung outward radially

- Different particles are identified by the signatures they leave in various layers of the detector
  - Neutrons land in the HCal
  - Protons land in the HCal, but are seen in the ECal
  - Neutrinos are invisible
  - Muons pass through all layers
  - Photons are seen by the CCDs and ECal

- A big concern when looking for new physics is the mis-identification of particles, or missing particles entirely
Example: Using Jets

- A common “channel” to search in is the “monojet” channel; events are selected with have one concentrated spot with a particle shower created by a quark or gluon.

- This channel is nice because it lacks significant standard model backgrounds; the only true background is the neutrino production by Zs.

- As noted, sometimes particles are missed; missing a muon would make this W event also look like a dark matter event.

- We look for dark matter by trying to find an excess of events above the expected backgrounds.
Direct Detection

• Finally, we can wait for dark matter to recoil off nuclei in detectors on earth, and measure the recoil energy spectrum and rate to determine mass and cross-section

• This is very hard! Cutting edge experiments would probably see 10s of events per year

• Backgrounds include radioactivity and cosmic rays; things like lead, copper, and concrete are too radioactive and would ruin the experiment
  • Semiconductor experiments have to content with radioisotopes created in detectors for the short time they sit at the surface
  • Liquid Xenon detectors have to constantly remove radioactive isotopes and contaminants from a huge detector volume

• The signal is also tiny; the highest statistics come below 1keV in recoil energy! We have to cool our detectors to cold (often sub-Kelvin) temperatures and use hyper-sensitive electronics to read the signals with enough noise removed
Energy Deposits from Nuclear Recoils

[Graphs showing energy deposits from nuclear recoils for different WIMP masses.]
SuperCDMS (Cryogenic Semiconductors)

- Nuclear recoil produces charge carriers and phonons in a detector
  - Normal detectors measure the energy in charge and phonons, and can determine whether an event came from an electron or nucleon
  - Low-mass detectors amplify the signal by forcing the charge at high speed through the crystal, generating “luke phonons” as charge carriers exceed the sound speed

- Phonons are absorbed into superconducting aluminum, which is read-out by a superconducting transition-edge sensor, and then a SQUID measures the resulting current
  - Energy resolution is ~300 meV; these are super sensitive devices!
SuperCDMS SNOLAB (Cryogenic Semiconductors)
LUX/ZEPLIN (LZ) (Liquid Xenon)

- Nuclear recoil produces charge carriers and light in the detector
  - S1 and S2 signals combined for position measurement and to isolate nuclear recoils
- Light and charge both measured using photomultiplier tubes
- Huge mass; LZ plans to operate ~7 tons of liquid xenon, using the outer ton just as a shield to collect residual radiation
LUX/ZEPLIN (LZ) (Liquid Xenon)
Direct Detection Limits and Reach
Collider Limits in Indirect Detection Space
Collider Limits in Indirect Detection Space

ATLAS

$95\%$ CL \hspace{1cm} $\sqrt{s}=8\text{ TeV}, 20.3\text{ fb}^{-1}$

- $2 \times$ (Fermi-LAT dSphs ($\chi\chi_{\text{Majorana}}$) $\rightarrow$ $u\bar{u}$, 4 years)
- $2 \times$ (HESS 2011 ($\chi\chi_{\text{Majorana}}$) $\rightarrow q\bar{q}$, Einasto profile)
- $2 \times$ (HESS 2011 ($\chi\chi_{\text{Majorana}}$) $\rightarrow q\bar{q}$, NFW profile)

- D5: $\chi\gamma^5\chi\gamma^5 q \rightarrow (\chi\chi)$
- D8: $\chi\gamma^5\chi\gamma^5 q \rightarrow (\chi\chi)$

$\langle \sigma v \rangle_{\chi \rightarrow q\bar{q}}$ [cm$^3$/s]

$10^{-18}$

$10^{-19}$

$10^{-20}$

$10^{-21}$

$10^{-22}$

$10^{-23}$

$10^{-24}$

$10^{-25}$

$10^{-26}$

$10^{-27}$

$10^{-28}$

$10^{-29}$

$10^{-30}$

$10^{-31}$

$10^1$ $10^2$ $10^3$

WIMP mass $m_\chi$ [GeV]
Conclusions and Path Forward

- Dark matter is well motivated Astrophysically, and we can easily find ways of incorporating it into existing physics, but we have few clues so far which theories might be correct

- All search modes are useful for narrowing the DM parameter space

- The Collider search still has plenty of parameter space to explore IF larger colliders, or ppbar colliders, are built
  - No limits are final; there is no total rate measurement, only limits on certain operators

- The indirect space will be greatly helped by higher resolution imaging in all bands
  - It is very hard to demonstrate that a given signal is really dark matter

- The direct space is looking exciting in the near future, but if we don’t find anything we need to move to lower mass and/or directional detection
  - The background is complicated; already there have been many detection claims that were erroneous, or were not replicated

- When someone does find dark matter, the next challenge will be showing that what was found really is dark matter, and the community is struggling now how to define what that test would be; complementarity would help the case greatly; then, how do we pick a model that fits?

- Stay SASSy, SLAC