Gravitational Probes of Dark Matter Physics

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The Problem of Dark Matter

- We know dark matter exists.

The Problem of Dark Matter

• ...but where is it?

WIMP-nucleon \( \sigma \) [cm\(^2\)]

\[
\begin{array}{c|c|c|c}
\text{WIMP mass [GeV/c}^2\text{]} & 10^1 & 10^2 & 10^3 \\
\hline
\text{XENON1T (this work)} & 10^{-47} & 10^{-45} & 10^{-44} \\
\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{DM Mass (GeV)} & 10^1 & 10^2 & 10^3 \\
\hline
\text{Fermi LAT 1611.03184} & 10^{-23} & 10^{-21} & 10^{-19} \\
\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{Axion Mass (\text{\mu eV})} & 3.35 & 3.4 & 3.45 \\
\hline
\text{Unvirialized} & 10^{-10} & 10^{-9} & 10^{-8} \\
\text{Virialized} & 10^{-11} & 10^{-10} & 10^{-9} \\
\end{array}
\]

\[
\begin{array}{c|c|c|c}
\text{Frequency (MHz)} & 820 & 830 & 840 \\
\hline
\text{KSVZ} & 10^{-16} & 10^{-15} & 10^{-14} \\
\text{DFSZ} & 10^{-17} & 10^{-16} & 10^{-15} \\
\end{array}
\]
The Problem of Dark Matter

• We have well-motivated ideas about what the particle physics of dark matter could be:
  • Axions! (solve the CP-problem)
  • WIMPs! (solve the Naturalness and Hierarchy problems)
  • sterile neutrinos
• We just haven’t found convincing evidence for any of them.

• The question we theorists want to answer:
  • What is the particle physics of dark matter?
Back to the Basics

• What do we know about dark matter?
  • It exists! (in galaxies today)
  • It existed in the early Universe
  • It doesn’t interact with unsuppressed weak/EM/strong charges
  • It was non-relativistic by $z \sim 3000$
  • If fermionic, its mass is $\gtrsim 100$ eV. If bosonic, $\gtrsim 10^{-22}$ eV
  • It doesn’t interact with itself very much.

• That is it. That’s everything we know for a fact about dark matter.
  • But how do I know any of this?
Every property of dark matter we know of (other than non-observation in the lab) comes from its gravitational interactions.

Dark Matter exists today in galaxies and clusters. Non-relativistic by matter/radiation equality.
Gravity!

- Every property of dark matter we know of (other than non-observation in the lab) comes from its gravitational interactions.

Dark Matter existed in the early Universe.
No unsuppressed E&M interactions
Gravity!

- Every property of dark matter we know of (other than non-observation in the lab) comes from its gravitational interactions.

No unsuppressed strong nuclear interactions

Gravity!

- Every property of dark matter we know of (other than non-observation in the lab) comes from its gravitational interactions.
So What?

- We’re interested in the *particle physics* of dark matter, not the astrophysics.
- How do we extract these things from the distribution and evolution of dark matter?
A Thought Experiment

• Imagine you’re a scientist in the dark sector: you can see dark matter, but not baryons.
• Using the Dark CMB, you discover the existence of some mysterious substance with $\Omega_b \sim 0.05$
• What can you learn about its particle physics?

• Dark scientists would by stymied if they use the classic experimental triad

Credit to Annika Peter (OSU) for idea. Buckley & Peter 1712.06615
A Thought Experiment

• But what if you turn to the astrophysics?
  • The z of matter-radiation equality gives you baryonic light degrees of freedom.
  • Two-point correlation of dark halos gives you Baryon Acoustic Oscillation — baryons are strongly self-interacting
  • A difference between dark matter halos and baryonic galaxies — baryons must be capable of cooling.
A Thought Experiment

- Baryons have some effective 2-to-3 scattering mechanism.
- Reasonable to conclude that the light d.o.f. are responsible
A Thought Experiment

• Scattering rate implied by disk cooling would be too high for a thermal relic: the baryons consist of particles but not antiparticles!

• Other particle physics solutions certainly possible, but if the dark scientists consider a $U(1)$ gauge interaction, they’ll find they need
  • a virialized kinetic energy set by a heavy particle
  • a scattering rate set by a light particle.
  • a fine-structure constant large enough to allow thermal bremsstrahlung, but not too large so that the biggest galaxies can’t reionize.

$$10^{-7/3} \left( \frac{m_H/m_L}{m_p/m_e} \right)^{1/2} \left( \frac{m_L}{m_e} \right) \lesssim \alpha \lesssim 10^{-2} \left( \frac{m_H/m_L}{m_p/m_e} \right)^{1/2}$$
A Thought Experiment

- Can’t guarantee that dark scientists would hit on the right answer.
  - But they can learn that baryons must be multicomponent, strongly interacting, with a complicated cooling history involving relativistic particles.

- So, let’s ask: if we’re studying the dark matter particle physics…
  - …what can astrophysics do for us?
Particle Physics from Astrophysics

• Not a novel idea — we constrain dark matter models with astrophysics all the time.

• Sterile neutrinos:
  • Warm dark matter free-streams out of small structures in the early Universe.

• Self-Interacting Dark Matter:
  • Bullet Cluster, tri-axiality of halos, etc limit $\sigma/m_\chi$
Particle Physics from Astrophysics

• So what’s new?
• On the astrophysics side:
  • New big-data surveys and observatories: SDSS, DES, GAIA, LSST, JWST, WFIRST(?),…
  • New dwarf galaxies, gravitational lensing, stellar kinematics, galaxy surveys, galaxy evolution from high-z to today,…

• On the theoretical physics side:
  • A recognition that WIMPs are not the end-all-be all
  • A need for new data to narrow down the possibilities
The Goal

• Use astrophysical probes of the structure of dark matter to constrain the particle physics of the dark sector.

• Compare to “pure” cold dark matter — gravity-only interactions
  • Predicts a primordial power spectrum of dark matter structure that extends down to arbitrarily small scales.
  • This is perhaps the key prediction of cold dark matter.
Halos

\[ z = 0 \]
\[ M_{\text{vir}} \text{ (central)} : \sim 10^8 - 10^{11} M_\odot \]
\[ M_* \text{ (central)} : \sim 10^2 - 10^9 M_\odot \]
\[ M_* \text{ (total)} : \sim 10^{-4} M_{\text{vir}} \]

(steeply falling at low masses)

\[ v_{\text{vir}} \sim M_{\text{vir}}^{1/3} : 10 - 1000 \text{ km/s} \]
\[ R_{\text{vir}} \sim M_{\text{vir}}^{1/3} : 10 - 100 \text{ kpc} \]
\[ R_* \sim 0.02 R_{\text{vir}} : \sim 0.1 - 1 \text{ kpc} \]
\[ k_{\text{hm}} \sim M_{\text{vir}}^{-1/3} : \sim 4 - 40 \text{ Mpc}^{-1} \]

\[ M_{\text{halo}} = \frac{4\pi}{3} (\Delta \times \rho_c) R_{\text{vir}}^3 \]
Views of Dark Matter

- Particle physicists and astrophysicists speak different languages:
  - Dark matter as a particle physicist problem:
    - What is its mass?
    - Its interactions?
    - How does it fit into some larger model?
Views of Dark Matter

- Particle physicists and astrophysicists speak different languages:
  - Dark matter as an astrophysicist problem:
    - How is it distributed in the Universe?
    - Is our cosmology correct?
    - Are we modeling galaxies correctly?
  - Not always clear how a particle model of dark matter fits into this
A Common Language

- A parameter space that captures important phenomenology for both particle physics and astrophysics.

- Particle Physics parameter: strength of interaction with the Standard Model
  \[ \Lambda^{-1} \equiv \frac{\lambda^2}{4\pi M} \]

- Astrophysics parameter: the mass of a dark matter halo at which a deviation from pure CDM occurs \( M_{\text{halo}} \)
Example: WIMPs

- The canonical dark matter model
- Weak-scale interactions:
  \[ \Lambda^{-1} \sim \frac{g^2}{4\pi M_W} \sim (\text{few}) \times 10^{-5} \text{ GeV}^{-1} \]
- Density perturbations that follow “pure” CDM down to very low scales
- Suppressed by thermal contact with the Standard Model at high temperatures.
  \[ M_{\text{halo}} \sim 10^{-5} - 10^{-2} M_\odot \]

Figure 1. The power spectrum on scales \( k > k_b \) for model A (B). This introduces errors at high\( \Lambda \) times due to the cosmological constant.

Sets \( M_{\text{halo}} \).
Example: Axions

- All phenomenology controlled by a single parameter, $f_a$
  \[
  \Lambda^{-1} \sim \frac{e^2}{4\pi f_a} \sim 10^{-(11-15)} \text{ GeV}^{-1}
  \]
- Or could be axion-like, suppressing interactions even further (ALPs or fuzzy dark matter)
  \[
  m_X \sim 10^{-(21-22)} \text{ eV}
  \]
  \[
  \Lambda^{-1} \sim 10^{-(17-19)} \text{ GeV}^{-1}
  \]
- Halos modified by large wavelengths, possible BECs (caustics? or axion “nuggets”?)
  \[
  M_{\text{halo}} = 10^{-11} M_{\odot} - 10^{11} M_{\odot}
  \]
Example: SIDM
Example: SIDM

- Model-dependent particle physics
- Alters halos in two ways:
  - Primordially: suppressed initial power spectrum, fewer small haloes today with lower central densities.
  - Evolutionarily: scattering today turns the “cusps” of halos into “cores.”
    \[ M_{\text{halo}} \lesssim 10^{11} M_\odot \]
    (phenomenological constraint)
The Crisis at Small Scales

- There are already indications of deviations from pure CDM:
  \[ M_{\text{halo}} \sim 10^{8-11} M_\odot \]
- Missing Satellites
- “Too Big to Fail”
- cusp/core
- Has driven model-building that alter halos at these scales
Lessons from a Crisis

- CDM predictions were derived from dark-matter only simulations
- But baryons can have an important effect on the structure of halos at exactly the scales where the deviations appear.
  - May solve the “Crisis.”
- Take-away: we need to know the predictions of CDM+baryons if we are to use astrophysics to discover particle physics.
Benchmark Scenarios

• What can particle theorists do to help?
  • Understand what the new data sets are going to say about galaxy structures across mass scales
  • Develop robust predictions from dark matter models, in a way that is applicable to astrophysicists.
    • Help analyze the data!

• Provide concrete models for novel non-CDM phenomenology
## Astrophysical Opportunities

<table>
<thead>
<tr>
<th>$M_{\text{halo}}$</th>
<th>Probes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^2 M_{\odot}$</td>
<td>Gravitational nanolensing (time domain)</td>
</tr>
<tr>
<td>$10^3 M_{\odot}$</td>
<td>Milky Way stellar halo perturbations (astrometry)</td>
</tr>
<tr>
<td>$10^8 M_{\odot}$</td>
<td>Dwarf &amp; ultradiffuse galaxy counts as a function of z (wide-field galaxy surveys, targeted surveys)</td>
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<tr>
<td>$10^{11} M_{\odot}$</td>
<td>Stellar kinematics (astrometry, spectroscopy)</td>
</tr>
<tr>
<td>$10^{14} M_{\odot}$</td>
<td>Cluster component offsets (lensing, wide-field surveys)</td>
</tr>
<tr>
<td>$10^{15} M_{\odot}$</td>
<td>Local measurements of $H_0$ (astrometry)</td>
</tr>
</tbody>
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**Invisibles**

- Final frontier
- $10^3 M_{\odot}$
- $10^8 M_{\odot}$

**Visible dwarfs**

- $10^{11} M_{\odot}$

**Galaxies**

- $10^{14} M_{\odot}$

**Clusters**

- $10^{15} M_{\odot}$

**Large scales**

- Local measurements of $H_0$ (astrometry)

- Galaxies
  - Substructure lensing
    - Lyα forest (spectroscopy)
    - Stellar-mass—halo-mass relation w/ cosmological tools on wide-field surveys

- Clusters
  - Cluster mass from wide-field surveys

- Large scales
  - Galaxy survey & CMB measurements of $H_0, \sigma_8, N_{\text{eff}}$

- Invisibles
  - Final frontier
  - $10^3 M_{\odot}$
  - $10^8 M_{\odot}$

### Probes

- Gravitational waves from compact-object DM (multi-messenger)
- Microlensing of compact-object DM (time domain)
- Substructure lensing subhalo mass functions of group & cluster halos (galaxy surveys, ground- and space-based spectroscopy)
Collapsing Dark Matter

- CDM subhalos are expected to be tidally disrupted this close to the Milky Way disk.
  - So astronomers haven’t looked
  - Can we develop a dark matter model which makes denser subhalos that would survive close to a galaxy?
  - Without modifying the bigger halos.
- That is: get small halos to cool and collapse, while keeping the big halos untouched.
A Baryonic Analogy

• We have a model which already does this: baryons
• Baryons in Milky Way-mass galaxies ($M_{\text{halo}} \sim 10^{12} M_\odot$) cool and collapse
• Baryons in galaxy clusters do not.

• Why?
  • Because the virial temperature of clusters is too high.
  • Can’t radiate away the kinetic energy in a dynamical time.
  • Sets a maximum mass for galaxies.
Like Baryons, But Dark

- The simplest example:
  - Two component dark matter: \( m_H > m_L \)
  - Charged under dark electromagnetism (\( \alpha_D \))

- A halo will collapse if the virial kinetic energy \( T_V \propto M_{\text{halo}}^{2/3} \) can be radiated away in the dynamic time.
  - Primarily through collisional excitation of the bound state by free \( L \)

\[
\sqrt{3\pi/32G\rho_{\text{DM}}} > \frac{3}{2} n_{\text{DM}} T_V / \Pi
\]
Like Baryons, But Dark

- For a halo to collapse, it must first exist.
- Dark photon acoustic oscillations in the early Universe will erase small scale-structures.
- We will have to require small $\xi \equiv T_D/T$
Collapsed Halos

- Can dial $m_H, m_L, \alpha_D$ to pick a maximum collapsed $M_{\text{halo}}$
- ~10% of the parent halo will be in collapsed subhalos (per decade of $M_{\text{halo}}$)

- What happens then?
  - Collapses to ~50% of original size, then fragments.
  - The final number and size of the fragments would depend on the microphysics of the dark matter models
Halo Hunting

- One would expect ~2000 compact halos of mass $10^{7-8} M_\odot$ in the Milky Way would be something we know couldn’t exist.
  - As far as I can tell, that isn’t the case.
  - Objects are too diffuse for MACHO searches to apply.

- A useful benchmark for GAIA.
  - Can we find these things?
Astrophysical Opportunities

• Dark matter is new physics.
  • We theorists just need a hint as to what kind of new physics
  • Astrophysicists need to know what to look for.

• Gravity has been the key to dark matter
  • It has a lot more to tell us