Atomic Dark Matter

Keith Rehermann

W/ DE Kaplan, C Wells, & G Krnjaic
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THEME: AtDM Implies Interesting Physics on Many Scales

Theoretical Particle

Experimental Particle

Theoretical Astro

Observable Astro

ATOMIC DARK MATTER
This Diagram Will Guide Talk
Let’s Talk About Well Known Data

DARK MATTER

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ATOMIC DARK MATTER
Galactic Rotation Curves Suggest Missing Mass Density

- Rotational Velocity Curves Suggest a Dark Matter Halo in which the Luminous Matter is embedded
Gravitational Lensing Observations Suggest Miss Mass Density

- Light From Distance Sources is Deflected too much given Mass Estimates From Luminous Density
Bullet Cluster: Luminous and Non-Luminous Matter Have Different Interactions

- **UV Imaging** and **Gravitational Lensing** Show Mis-Match between **Mass Centers** and **Luminous Material** in Cluster-Cluster Collision
Clustering Observations Suggest Extra Source of Gravitational Potential

- Structure on scales from Galaxies to Cluster of Galaxies Suggest Are not well described by SM physics
Sprinkle In Some Theory

ATOMIC DARK MATTER

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CMB & SN Ia Data Measure Energy Density Fractions

[Image of CMB data] + [Image of supernova] + [Image of scientist]

→

73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.
The General Theory of Relativity of 1915 changed the way we view the Universe overnight. However, it took Einstein 10 years to perfect it, something like 3650 days and 3650 nights.
Standard Model of Cosmology is $\Lambda$CDM
Data Constrain Particle Physics

$\rightarrow$ DM Electrically Neutral

$\rightarrow$ Small Self-Interaction Cross Section

$\rightarrow <\sigma v>_{\text{ann}} \approx 10^{-26}\text{cm}^2$  -OR- Non-Thermal
Astrophysics of Atomic Dark Matter

Atomic Dark Matter

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Atomic Dark Matter is Simple

\[ L_{\text{dark}} = \overline{\Psi}_p (\not{D} + m_p) \Psi_p + \overline{\Psi}_e (\not{D} + m_e) \Psi_e \]

\[ \not{D} = i\partial + gQA \quad Q_{\Psi_p, \Psi_e} = +1, -1 \]

- For now, asymmetry is assumed.
Can Atomic Dark Matter Be “Cold”?  

\[ V(r) = \frac{-1}{r} - \frac{C}{r^4} - \frac{A}{r^6} \]

<table>
<thead>
<tr>
<th>V(r)</th>
<th>( \frac{d\sigma}{d\Omega} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(-1/r)</td>
<td>( \frac{1}{E_{cm}^2 \sin^4 \theta/2} )</td>
</tr>
<tr>
<td>(-C/r^4)</td>
<td>( (\kappa a_0)^2 )</td>
</tr>
<tr>
<td>(-A/r^6)</td>
<td>( (\kappa' a_0)^2 )</td>
</tr>
</tbody>
</table>

- charge-charge
- charge-induced dipole
- induced dipole-induced dipole

ADM → Astro → Data + Theory
Can Atomic Dark Matter Be “Cold”? 

\[ V(r) = \frac{-1}{r} - \frac{C}{r^4} - \frac{A}{r^6} \]

- charge-charge
- charge-induced dipole
- induced dipole-induced dipole

\[ \frac{d\sigma}{d\Omega} \rightarrow \text{cnst: reminiscent of s-wave scattering} \]

\begin{align*}
\text{V}(r) & \quad \frac{d\sigma}{d\Omega} \\
- \frac{1}{r} & \quad \frac{1}{E_{cm}^2 \sin^4 \theta/2} \\
- \frac{C}{r^4} & \quad (\kappa \ a_0)^2 \\
- \frac{A}{r^6} & \quad (\kappa' \ a_0)^2
\end{align*}
Residual Ionization is Key to Cosmological Dynamics

\[ X_e \equiv \frac{n_e}{n_e + n_H} \]

Effective Interaction of DM

Structure Formation

Direct Detection

Self-Scattering Bounds

“Re”combination is Analogous to SM

\[ e + p \leftrightarrow H + \gamma \]

Recombination governed by Boltzmann

\[
\frac{dX_e}{dx} = C \frac{1}{Hx} \left[ (1 - X_e)\beta - X_e^2 n_{DM} \langle \sigma v \rangle \right]
\]

Atomic disintegration  Atom production

Dodelson ‘03
Spitzer ‘78
Ma & Bertschinger
astro-ph/9506072
Efficient Atom Production

Lines of constant Xe
Bullet Cluster Constrains
Xe and Bohr Radius
Bullet Cluster Constrains Xe and Bohr Radius
Bullet Cluster Constrains Xe and Bohr Radius
Cartoon of Bullet Cluster

\[ \Xi_s \equiv \int_0^R \rho(z) \, dz \]

Surface Density

\[ \Xi_p \]

\[ \Xi_e \]

\[ \Xi_H \]

Markevitch et al
astro-ph/0309303

Scattering Depth

\[ \tau_{ij} = \Xi_T \frac{f_i}{\sum_k f_k m_k} \sigma_{ij} f_j \]
• Observations Imply ~ 30% of Original Mass is Scattered out of Bullet Cluster
• Assume All Ions are Scattered out of BC
• Constrains Scattering Depth, and thus the cross section and fractional composition of the Cluster

\[
\left( \frac{0.1}{\alpha_D} \right)^2 \left( \frac{1 \text{ GeV}}{\mu_H} \right)^2 \left( \frac{100 \text{ GeV}}{m_H} \right) \lesssim (20-200) \frac{0.2-X_e}{1-X_e^2}
\]

22

ADM → Astro → Data + Theory
Allowed Space

\[ M_p = 100 \]

\[ M_p = 300 \]

Log_{10} M_e (GeV) \quad Log_{10} \sigma (\text{GeV})

---

BC constraint

\[ \frac{\sigma}{M_p + M_e} \quad (\text{cm}^2/\text{g}) \]
Non-Standard CDM & Observable Properties

Decoupling when photons stop transferring energy to atoms

\[ \Gamma(T_{\text{dec}}) = H(T_{\text{dec}}) \]

\[ \gamma + e, p \rightarrow \gamma + e, p \ \& \ e, p + H \rightarrow e, p + H \]

\[ T_{\text{dec}, (p,e)H} \approx 0.1 \left( \frac{1}{X_e} \right)^{2/3} \alpha_D^{4/3} \left( \frac{m_{(e,p)}}{1 \text{ GeV}} \right)^{4/3} \left( \frac{m_{(p,e)}}{1 \text{ GeV}} \right) \text{keV} \]

\[ M_{\text{strc}} > \frac{4\pi}{3} \left( \frac{\pi}{k_{\text{damped}}} \right)^3 \Omega_{DM} \rho_{\text{crit}} \]

\[ M_{\text{ADM}}^{\text{strc}} > 10^5 \left( \frac{T}{10 \text{ keV}} \right)^{-3} M_\odot \]

\[ M_{\text{CDM}}^{\text{strc}} > 10^{-4} \left( \frac{T}{10 \text{ MeV}} \right)^{-3} M_\odot \]

Atomic DM can suppress power on small scales

Loeb & Zaldarriaga astro-ph/0504112
Green et al. astro-ph/0509621
Decoupling Dynamics May Have Implications for ‘Missing Satellites’

About an order of magnitude too few satellites
A Word Concerning Halos

- Different Interaction Potentials for Atoms and Ions Can Effect the Radial Profiles
- Implications for Direct and Indirect Detection

Non-Interacting Profiles

Interacting Profiles
Galactic Cartoon
Density Distributions

- Atoms Behave like CDM - NFW Profile

- BUT Ion Scattering Maintains Kinetic Equilibrium

- Ion Phase Space Distribution Governed by Boltzmann Stats - Isothermal Profile

\[
\begin{align*}
    n_{\pm}(r) & \sim N(X_e) \int v^2 d v f_{\pm}(v,r) \\
    \rightarrow N(X_e) \int v^2 d v e^{-\frac{(KE(v)-PE(r))/T}{}} \\
    &= C(X_e) e^{-\frac{U(r)}{T}}
\end{align*}
\]
Local Ion Density is Suppressed

 Ionized Mass Density

\[ n_\pm(r) \sim C(X_e) e^{-\frac{U(r)}{T}} \]

Independent of \( X_e \)

\[ X_e(r_\odot) \sim 10^{-2} X_e^{\text{global}} \quad (X_e^{\text{global}} \lesssim 0.1) \]

Catena & Ullio Milky Way Model 0907.0018

Log of Neutral and Ionized DM
Atomic Dark Matter

Astro Summary

• Atomic Dark Matter has very different microscopic properties than typical CDM
  • Significant Parameter Space Consistent with Observations
  • May have Interesting Implications for Small Scale Structure
    • Late decoupling > Missing Satellites?
  • Multicomponent (Atoms and Ions) halo, likely with very different radial profiles
• Explicit example that DM can have dynamics far more complicated than standard CDM
Now Review Standard WIMP Phenomenology
Direct Detection

[Henderson! I believe I'm onto something]

DARK MATTER RESEARCH UNIT

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Direct Detection

- DM Scatters off Nucleus, Depositing Electronic and Vibrational Energy
Expect Time Dependent Scattering

- Mean velocity of DM wrt Earth varies sinusoidally throughout the year
- Mean Lab Frame Energy oscillates as Earth orbits
DAMA Sees The Predicted Time Variation

- Counts per Day per Kilogram per keV
- Exactly in phase with Earth’s orbit
BUT it’s Not a WIMP

- Best fit WIMP is Ruled out by 2-3 orders of magnitude
it's Not a WIMP

- Best fit WIMP is Ruled out by 2-3 orders of magnitude
DAMA Spectrum Inconsistent with Elastic scattering

Approximate Elastic Scattering Shape

Possible Inelastic Shape
DAMA Spectrum Inconsistent with Elastic scattering

Approximate Elastic Scattering Shape

Possible Inelastic Shape

Tucker-Smith & Weiner: hep-ph/0101138
Chang et al. arxiv:0807.2250
Cui et al. arxiv:0901.0557
Atomic Dark Matter

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Atoms Have Many Energy States - Could Transitions Explain DAMA?

- Requires State Change
- Corresponding Velocity Threshold for Reaction
  \[ v_t = \sqrt{2\delta/\mu_N} \]
- Threshold depends on Target Mass (through reduced Mass)

Scattering excites Atom
Coupling Dark Atoms to SM

Want DM to Flip Spin When Interacting with SM

\[ \delta E = E_{hf} = \frac{2}{3} g_e g_p \alpha_D^4 \mu_H \frac{m_e}{m_p} \]
Introducing a DM-spin Dependent Force

Introduce New Axial GB

$M_A \sim 1 - 10 \text{ MeV}$

Along with Kinetic Mixing
$|\mathcal{M}|^2 \sim \left( \frac{g_5 e e c_w}{q^2 + M_X^2} \right)^2 \left| C(S_e \cdot \vec{p}_i, m_i) F_{ei}(q^2, M_H) + D(S_p \cdot \vec{p}_i, m_i) \right|^2 |F_n|^2$
Coupling Dark Atoms to SM

Want DM to Flip Spin When Interacting with SM

\[
\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{Dark\ Gauge}
\]

\[
\mathcal{L}_{DM} = \bar{\Psi}_p (i \partial - g_5 \gamma_5 \lambda + g A + m_p) \Psi_p +
\]

\[
\bar{\Psi}_e (i \partial + g_5 \gamma_5 \lambda - g A + m_e) \Psi_e - \frac{\epsilon s_w}{m_Z^2} J_{Z\mu} J_D^\mu
\]

\[
\mathcal{L}_{Dark\ Gauge} = -\frac{1}{4} A_{\mu\nu}^2 - \frac{1}{4} X^2_{\mu\nu} -
\]

\[
\epsilon c_w J_{EM}^\mu + \epsilon s_w \left( \frac{M_X}{m_Z} \right)^2 J_Z^\mu X + \frac{M_X^2}{2} X^2
\]

\[
J_D^\mu = -g_5 \bar{\Psi}_p \gamma^\mu \gamma_5 \Psi_p + g_5 \bar{\Psi}_e \gamma^\mu \gamma_5 \Psi_e
\]

Axial Vector Coupling Reduces To Spin-Spin Coupling in NR limit

Kinetic Mixing Between Broken Axial U(1) and U(1)_Y lead to Scattering Between SM and DM

Wacker et al arXiv:0901.0557
Holdom '86
ADM Can Fit DAMA

Modulated DAMA Spectrum

<table>
<thead>
<tr>
<th></th>
<th>Green</th>
<th>Red</th>
<th>Black</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_p$ (GeV)</td>
<td>70</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>$m_e$ (GeV)</td>
<td>1.7</td>
<td>1.7</td>
<td>2.1</td>
</tr>
<tr>
<td>$f_{eff}$ (GeV)</td>
<td>67</td>
<td>92</td>
<td>103</td>
</tr>
</tbody>
</table>

$$f_{eff}^4 = \frac{M_X^4}{2g_5 \epsilon c_w}$$

$X_e \ll 1 \Rightarrow$ Very Small Ion Scattering Dir. Det. Rate
Bounds From Other DD Observations

\[ \sigma_n = 1 \times 10^{-40} \text{ cm}^2 \]

\[ \sigma_n = 5 \times 10^{-40} \text{ cm}^2 \]

XENON10 911.4438
Kinetic Mixing and Allowed Parameter Space

Integrate out $\psi_H \rightarrow \mathcal{L} \ni \epsilon F_{\mu\nu} y F_D^{\mu\nu}$

Redefine $A_\mu \rightarrow A_\mu - \epsilon A_\mu$

Induce coupling of SM current to $A_\mu$

$\mathcal{L}_{\text{mix}} = -\epsilon J_{\mu}^{\text{SM}} A_\mu$

$\epsilon < (10^{-2} - 10^{-3})$ Ok for Interesting DAMA Region
Let’s Put ADM into Focus

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• Embed $U(1)_D$ to $SU(2)_D$ to avoid Landau pole below $M_{pl}$

• Introduce Higgsing Field $\chi$

• Introduce Scalars to generate Asymmetry

<table>
<thead>
<tr>
<th></th>
<th>$SU(2)_D$</th>
<th>$U(1)_A$</th>
<th>$Z_2$</th>
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<tbody>
<tr>
<td>$E$</td>
<td>$\Box$</td>
<td>$-1$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$E^c$</td>
<td>$\Box$</td>
<td>$-2$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$\varphi_e$</td>
<td>$\Box$</td>
<td>$1$</td>
<td>$-1$</td>
</tr>
<tr>
<td>$P$</td>
<td>$\Box$</td>
<td>$1$</td>
<td>$1$</td>
</tr>
<tr>
<td>$P^c$</td>
<td>$\Box$</td>
<td>$2$</td>
<td>$1$</td>
</tr>
<tr>
<td>$\varphi_P$</td>
<td>$\Box$</td>
<td>$-1$</td>
<td>$1$</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Adj</td>
<td>$3$</td>
<td>$1$</td>
</tr>
</tbody>
</table>
Generating the Asymmetry

\[
\mathcal{L} = -\frac{1}{2} M_n n_i^2 - y^{ij} n_i \ell_j h + \lambda^i n_i E \varphi_e + \lambda^i_n n_i P \varphi_P + y_e \chi E E^c + y_p \chi^\dagger P P^c + \text{h.c.}
\]

\[
\begin{array}{c}
\text{SM} \\
\downarrow \\
E, P
\end{array}
\]

\[
\begin{array}{c}
\int \\
\text{Dark}
\end{array}
\]

<table>
<thead>
<tr>
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<th>(SU(2)_D)</th>
<th>(U(1)_A)</th>
<th>(\mathbb{Z}_2)</th>
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<td>3</td>
<td>1</td>
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Falkowski et al 1101.4936
Luty PRD '91
Generating the Asymmetry

\[ \mathcal{L} = \frac{1}{2} M_n n_i^2 + y^{ij} n_i \ell_j h + \lambda^i_n \varphi_e + \lambda^i_p \varphi_p + y_e \varphi_e \varphi_e^c + y_p \varphi_p \varphi_p^c + \text{h.c.} \]

See-Saw Neutrino Masses

<table>
<thead>
<tr>
<th>Field</th>
<th>( SU(2)_D )</th>
<th>( U(1)_A )</th>
<th>( Z_2 )</th>
</tr>
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<tbody>
<tr>
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<td>1</td>
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<td>2</td>
<td>1</td>
</tr>
<tr>
<td>( \varphi_p )</td>
<td>□</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>( \chi )</td>
<td>Adj</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Falkowski et al 1101.4936
Luty PRD '91
See-Saw Leptogenesis

\[ \frac{T}{M_N} \sim 1 \]

\[ T \frac{M_N}{N} \ll 1 \]
Light Dark Atoms?

- Asym Mechanism Naturally gives $M_{DM} \approx 10$ GeV
- Parameter Space available for $L \approx 10$ GeV Dark Atoms
- Exploring connection with DAMA and CoGENT
- Region will potentially interesting Structure formation

$$T_{dec, (p,e)H} \simeq 0.1 \left( \frac{1}{X_e} \right)^{2/3} \alpha_D^{4/3} \left( \frac{m_{e,p}}{1 \text{ GeV}} \right)^{4/3} \left( \frac{m_{p,e}}{1 \text{ GeV}} \right) \text{ keV}$$
ADM Conclusions

- ADM is Cosmologically Viable
- Interesting and Varying Dynamics, Largely Governed by Xe
- May Have Observable Consequences on Galactic and Sub-Galactic Scales
- Explicit Example of Allowed Variability in “CDM”
- Can be “Modular” relative to Astro Considerations
- Explicit Example Offers Possible Explanation of DAMA Data
- Possible Multi-Channel Signal, Ion-SM and Atom-SM Scattering, Depending on Xe