Dark Matter Models

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OUTLINE

INTRODUCTION

‣ Research Interests
‣ Important Experiments

DARK MATTER - EXPLAINING PAMELA AND ATIC

‣ Some models to explain data
‣ Freeze out
‣ Sommerfeld effect

SUMMARY
Research Interests

- BSM model building
- Supersymmetry
- Higgs Physics
- Neutrino Physics
- Flavour Physics
- Extra Dimensions
- Early Universe Cosmology
  - Baryogenesis/Leptogenesis
  - BBN
  - Dark Matter
Dark Matter

Dark matter

- At the LHC
- Astrophysics Experiments

Evidence for Dark matter:
- Cosmological Scales: CMB power spectrum...WMAP
  \[ \Omega_{h^2}^{dm} = 0.1143 \pm 0.0034 \]
- Galactic Scales: Rotation Curves, expect velocity of stars \( v(r) \propto 1/\sqrt{r} \) but measure flat rotation curves
- Galaxy Cluster Scales: Bullet cluster, other cluster dynamics

\[ \text{Graph of rotation curves} \]
**Important Experiments**

**Current Data:**
- **PAMELA** \( (e^\pm, p^\pm) \)
- **ATIC** \( (e^\pm, p^\pm) \)
- **Hess** \( (\gamma) \)
- + many more
- **CDMS**
- **Zeplin**
- **DAMA**
- + many more

**Future Data:**
- **FERMI/GLAST** \( (\gamma) \)
- **Icecube** \( (\nu) \)
- **LHC?...**

**Indirect Detection**

**Direct Detection**
Galactic Cosmic Rays (GCRs)

GCRs ⇒ high-energy particles flowing into our solar system from far away in the Galaxy.

Composition:
- Protons ~ 90%
- Helium ~ 9%
- Electrons ~ 1%
- + Other heavier nuclei

Origins:
- Probably accelerated in the blast waves of supernova remnants (SNRs)
- Particles/Nuclei bouncing back and forth in magnetic field of the remnants
- Some gain enough energy to escape into Galaxy and become GCRs
Some GCRs observed with energies above max possible energies produced by SNRs

**Observed range** \(1 - 1,000,000 \text{ GeV/n}\)

**Compared to** \(E_{\text{max}}^{\text{SNR}} \sim 10,000 \text{ GeV/n}\)

**Origins?**
- Sources outside the Galaxy
- Quasars/Pulsars
- Gamma ray bursts
- Exotic new physics:
  - E.G. Dark Matter...

**Some cosmic rays are observed above expected rates...**
Payload for Antimatter Matter Exploration and Light nuclei Astrophysics

- S1, S2, S3; double layers, x-y
- Plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF > 3 ns)
- Lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

- Permanent magnet, 0.43 T
- 21.5 cm² sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR
  ~800 GV (6 plane) ~500 GV (5 plane)

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm² sr

- 36 $^3\text{He}$ counters
- $^3\text{He}(n,p)T$; $E_p = 780$ keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

~470 Kg / ~360 W

Trigger, ToF, dE/dx

Sign of charge, rigidity, dE/dx

Electron energy, dE/dx, lepton-hadron separation

Neutron detector

~1.3 m
PAMELA
Payload for Antimatter Matter Exploration and Light nuclei Astrophysics

- Satellite experiment launched in 2006
- Primary goal: measure antimatter component of cosmic rays.
- Able to identify positively and negatively charged particles
- Measure spectra of antiprotons and positrons
PAMELA Results:

Anti-Proton fraction

**PAMELA Results: Positron Fraction**

Advanced Thin Ionization Calorimeter

- Balloon experiment collecting data in 2000, 2003 and 2007

- Cannot distinguish between $e^{-}$ and $e^{+}$

- Measures total electronic flux ($e^{-} + e^{+}$) in energy range 20-2400 GeV

- Also detects protons and heavier nuclei

Striking Results...
ATIC RESULTS


Expected energy dependence of background excess corresponds to 70 out of 210 total

AMS (green stars)
HEAT (open black triangles)
Emulsion chambers (black open diamonds)
BETS (open blue circles)
PPB-BETS (blue crosses)

AMS and HEAT are satellite experiments
BETS and PPB-BETS are balloon experiments
Explaining the rise...

- Nearby astrophysical objects e.g. **Pulsars**

  See e.g.  
  Büsching et al. arXiv:0804.0220  
  Hooper et al. arXiv:0810.1527  
  Profumo arXiv:0812.4457

Seems possible to explain PAMELA and ATIC with **Pulsars**

- Dark Matter

  Many refs for dark matter, see e.g. Ref list in  
  Profumo arXiv:0812.4457

  - **Decays** \( \tau \sim 10^{26} \text{s} \)
  
  - **Annihilations**
Decaying Dark Matter

Lifetime $\Rightarrow \tau \sim 10^{26}\ s$

Decays have restricted branching fractions:

$$B_{HAD} < 0.1$$

- Candidates:
  - Gravitino
  - “Hidden sector” particle
  - Composite particles
  - Maybe others...

Several ideas along these lines in literature
Annihilating dark matter

1) Annihilations rates must be large to account for large PAMELA and ATIC signals need boosts
   ✴ A problem for standard thermal dark matter

2) Annihilations must not produce too many hadrons
   ✴ Annihilation products usually include both hadrons and lepton

3) Annihilations must not produce too many photons
   ✴ Strong limits exist on photon signals
   ✴ Photons produced at wide range of frequencies for charged decay products
1) **Annihilations rates must be large-problem for standard thermal dark matter**

Particle in thermal eq. present abundance:

\[ n_{eq} \sim (m/T)^{3/2}e^{-m/T} \]

However, if species freezes out i.e. \( \Gamma < H \)

at temp \( T \) such that \( m/T \sim 25 \)

\[ \Omega_{dm}h^2 \sim \mathcal{O}(10^{-27} - 10^{-28}) \frac{\sigma v}{\langle \sigma v \rangle} \text{GeV}^{-2} \]

**Kolb & Turner, `90**

\[ \Rightarrow \text{Can have significant relic abundance today} \]

**Using Boltzmann equations we get**
\[ \Omega_{dm} h^2 \sim \mathcal{O}(10^{-27} - 10^{-28}) \frac{GeV^{-2}}{\langle \sigma v \rangle} \]

**But we know that**

\[ \Omega_{dm} h^2 = 0.1143 \pm 0.0034 \]

\[ \Rightarrow \langle \sigma v \rangle = (10^{-26} - 10^{-27}) GeV^{-2} \]

**This is weak scale interaction with weak scale mass particle**

\[ \Rightarrow \text{WIMP} \]

**This fixes} \langle \sigma v \rangle \]

\[ \Rightarrow \text{sets the size of annihilations of DM particles as a function of DM velocity} \]

**!! A way out !!** \[ \text{Change how} \langle \sigma v \rangle \text{depends on velocity} \]
**The Sommerfeld Effect**

Normally \( \sigma v = a + bv^2 \)

- Heavy DM moving at small (relative) velocity
- Exchange of scalar (or vector) state

Enhancement in annihilation cross section

\[ \Rightarrow \sigma v \propto \frac{1}{v_r} \]

(Sommerfeld; Hisano et al, Strumia et al...)

Corresponds to summation of diagrams

Only significant for s-wave

(A M barrier)

March-Russell, West, Cumberbatch, Hooper.
The Sommerfeld Effect

- Calculation formed in terms on non-rel two body QM problem with a potential

- Equivalent to distorted Born-wave approximation common in nuclear physics.

- Including the effect (to a good approximation)

\[ \sigma = R \sigma_{tree}^{l=0} \]

- Full calculation of \( R \) can be involved

- For a Yukawa potential \( R \) cannot be solved analytically

- Can be enhancement or suppression for vector exchange
Calculating $R$

- Introduce the following term $\frac{\lambda}{2} n \psi_{dm} \psi_{dm}$

- Scalar $n$ states can be the “rungs on the ladder”

- The Schrödinger equation for two DM particle state $\psi \sim \psi_{dm} \psi_{dm}$

\[
- \frac{1}{m_{dm}} \frac{d^2 \psi}{dr^2} + V \psi = K \psi
\]

\[
V = -\frac{\lambda^2}{8\pi r} e^{-m_n} \quad K = m_{dm} v^2
\]

- Enhancement factor

\[
R = \left| \frac{\psi(0)}{\psi(\infty)} \right|^2
\]

- Outgoing B.C

\[
\frac{\psi'(\infty)}{\psi(\infty)} = im_{dm} v
\]
Coulomb Limit

**Analytic form for R in limit** \( \epsilon \equiv \frac{m_n}{m_{dm}} = 0 \)

\[
R = \frac{y}{1 - e^{-y}} \quad y = \frac{\lambda^2}{4v}
\]

**Small \( v \) limit**

\[
R \approx \frac{\lambda^2}{4v}
\]

What about \( \epsilon \neq 0 \)?
Enhancement for $\epsilon \neq 0$

Contours in $R$

$\epsilon \equiv m_n/m_{dm}$

$\alpha = \lambda^2/8\pi$

**Need**

$\alpha/\epsilon > 1$

$\alpha/\beta > 1$

**Freeze out**

$\beta \sim 0.2$

$\Rightarrow \lambda \sim 2$

$\Rightarrow \uparrow_{FO}$

**Indirect detection**

$\beta \sim 10^{-3} - 10^{-5}$

$\Rightarrow \uparrow_{ID}$
3D Version

March-Russell, West.
1) **Annihilations rates must be large** - **Alternatives**

- **Could consider** non-thermal dark matter
  - Late decaying particles
  - Another interesting idea later

- **Over densities** - **No. annihilation** $\propto \rho_{dm}^2$
  - Regions of high density
  - Near Black Holes?
  - Naturally occurring clumps?
2) Annihilations must not produce too many hadrons

- **Leptophilic models**
  - Need to introduce extra quantum numbers
  - Dark matter only talks to leptons due to symmetries

- **Kinematic tricks and extra symmetries**

  ![Diagram](Diagram.png)

  - Particle $\phi$ can generate Sommerfeld enhancement
  - Can introduce two dark matter states and have inelastic scattering
  - Possible to reconcile DAMA with other direct detection experiments

Fox, Poppitz, arXiv:0811.0399

(Arkani-Hamed et al...)
3) **Annihilations must not produce too many photons**

- **All annihilations with charged states can produce photons**
  
  - **Boosting annihilation rates into** \( e^\pm \) **means we produce more photons**
  
  - **Measurements of Cosmic diffuse background radiation tightly constrain scenarios**
**Summary**

- PAMELA and ATIC inspired a lot of model building
- Maybe explained by astrophysics
- If DM is the answer, need large boosts to annihilation cross sections
- Several ways to generate boost factors but all have restrictions and constraints
- PAMELA and ATIC data have inspired a lot of unusual and compelling new ideas - many more to come...

🌟 Exciting times ahead