RECENT DEVELOPMENTS IN DARK MATTER AND IMPLICATIONS FOR COLLIDERS

Fermilab Wine & Cheese
19 June 2009

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EVIDENCE FOR DARK MATTER

• There is now overwhelming evidence that normal (standard model) matter is not all the matter in the Universe:

  Dark Matter: 23% ± 4%
  Dark Energy: 73% ± 4%
  Normal Matter: 4% ± 0.4%
  Neutrinos: 0.2% ($\Sigma m_\nu/0.1eV$)

• To date, all evidence is from dark matter’s gravitational effects. We would like to detect it in other ways to learn more about it.
A PRECEDENT

- In 1821 Alexis Bouvard found anomalies in the observed path of Uranus and suggested they could be caused by dark matter.

- In 1845-46 Urbain Le Verrier determined the expected properties of the dark matter and how to find it. With this guidance, Johann Gottfried Galle discovered dark matter in 1846.

- Le Verrier wanted to call it “Le Verrier,” but it is now known as Neptune, the farthest known planet (1846-1930, 1979-99, 2006-present).
DARK MATTER CANDIDATES

- There are many
- Masses and interaction strengths span many, many orders of magnitude
- Here focus on candidates with mass around $m_{\text{weak}} \sim 100$ GeV

HEPAP/AAAC DMSAG Subpanel (2007)
THE WIMP MIRACLE

(1) Assume a new (heavy) particle $\chi$ is initially in thermal equilibrium:

$$\chi \chi \leftrightarrow f \bar{f}$$

(2) Universe cools:

$$\chi \chi \rightarrow f \bar{f}$$

(3) $\chi$s “freeze out”:

$$\chi \chi \uparrow \rightarrow f \bar{f}$$

Zeldovich et al. (1960s)
THE WIMP MIRACLE

• The resulting relic density is

\[ \Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4} \]

\[ \begin{array}{c}
X \\
\hline
X
\end{array} \quad \begin{array}{c}
f \\
\hline
\bar{f}
\end{array} \]

• For a WIMP, \( m_X \sim 100 \text{ GeV} \) and \( g_X \sim 0.6 \) \( \Rightarrow \Omega_X \sim 0.1 \)

• Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter
RELIC DENSITY CONSTRAINTS

$\Omega_{DM} = 23\% \pm 4\%$ stringently constrains new physics models

Cosmology excludes many possibilities, favors certain regions with distinctive collider signatures
WIMP DETECTION

Correct relic density \(\rightarrow\) “lower bound” on DM-SM interactions

Efficient annihilation now (Indirect detection)

Efficient scattering now (Direct detection)

Efficient production now (Particle colliders)
DIRECT DETECTION

• WIMP properties
  – $v \sim 10^{-3}$ c
  – Kinetic energy $\sim 100$ keV
  – Local density $\sim 1$ / liter

• Detected by nuclear recoil in underground detectors; two leading methods

• Background-free detection
  – Spin-independent scattering is typically the most promising
  – Theory and experiment compared in the $(m_X, \sigma_{\text{proton}})$ plane
  – Expt: CDMS, XENON, …
  – Theory: SUSY region – WHAT ARE WE TO MAKE OF THIS?

[Graph showing cross-section vs. WIMP mass with data points and lines representing experimental and theoretical results.]

CDMS: 2004+2005 (reanalysis) +2008 Ge
XENON10 2007 (Net 136 kg-d)
SuperCDMS (Projected) 25Kg (7-ST@Snolab)
LUX 300 Kg LXe Projection (Jul 2007)
Baltz and Gondolo 2003
Baltz and Gondolo, 2004, Markov Chain Monte Carlos
DARK MATTER VS. FLAVOR PROBLEM

• Squark and slepton masses receive many contributions

• The gravitino mass $m_{\tilde{G}}$ characterizes the size of gravitational effects, which generically violate flavor and CP

• For $\sim 100$ GeV sfermions, these violate low energy constraints (badly)
  – Flavor: Kaon mixing, $\mu \rightarrow e \gamma$
  – Flavor and CP: $\varepsilon_K$
  – CP: neutron EDM, electron EDM

\[
m_{\tilde{q}}^2 = \begin{pmatrix}
\sim m_G^2 & \sim m_G^2 & \sim m_G^2 \\
\sim m_G^2 & \sim m_G^2 & \sim m_G^2 \\
\sim m_G^2 & \sim m_G^2 & \sim m_G^2 
\end{pmatrix}
\]
THE SIGNIFICANCE OF $10^{-44}$ CM$^2$

- Some possible solutions
  - Set flavor violation to 0 by hand
  - Make sleptons and squarks heavy (few TeV or more)
- The last eliminates many annihilation diagrams, collapses predictions
- Summary: The flavor problem $\Rightarrow \sigma_{SI} \sim 10^{-44}$ cm$^2$
  (focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,...)
DIRECT DETECTION

Annual modulation: Collision rate should change as Earth’s velocity adds constructively/destructively with the Sun’s.

Drukier, Freese, Spergel (1986)

DAMA: $8\sigma$ signal with $T \sim 1$ year, max $\sim$ June 2

2-6 keV

DAMA/NaI (0.29 ton\(\times\)yr) (target mass = 87.3 kg)

DAMA/LIBRA (0.53 ton\(\times\)yr) (target mass = 232.8 kg)
CHANNELING

• DAMA’s result is puzzling, in part because the favored region was considered excluded by others

• This may be ameliorated by
  – Astrophysics
  – Channeling: in crystalline detectors, efficiency for nuclear recoil energy $\rightarrow$ electron energy depends on direction

Gondolo, Gelmini (2005)

• Channeling reduces threshold, shifts allowed region to
  – Rather low WIMP masses (~GeV)
  – Very high $\sigma_{SI}$ (~$10^{-39}$ cm$^2$)
DAMA AND SUPER-K

• Ways forward
  – Examine channeling
  – Other low threshold direct detection experiments

• Super-K indirect detection
  – DM captured in the Sun
  – Annihilates to neutrinos
  – Neutrinos seen at Super-K

• Comparing apples to oranges? No! The Sun is full, so $\sigma_{SI} \rightarrow$ capture rate $\rightarrow$ annihilation rate
  • Current bound: through-going events, extends to $m_X = 18$ GeV
  • Ongoing analysis: fully contained events, sensitive to $m_X \sim 5$ GeV?

Hooper, Petriello, Zurek, Kamionkowski (2008); Feng, Kumar, Learned, Strigari (2008)
INDIRECT DETECTION

Dark Matter annihilates in _________ to the halo _________

_________ a place

positrons _________, which are detected by _________
some particles PAMELA/ATIC/Fermi…

an experiment
PAMELA AND ATIC 2008

Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)
ARE THESE DARK MATTER?

- Must fit spectrum, not violate other constraints (photons, anti-protons, ...)
- Neutralinos in supersymmetry
  - $\chi\chi \rightarrow e^+e^-$ suppressed by angular momentum conservation
  - $\chi\chi \rightarrow WW \rightarrow e^+$ gives softer spectrum, also accompanied by large anti-proton flux
- Kaluza-Klein dark matter in UED
  - $B^1B^1 \rightarrow e^+e^-$ unsuppressed, hard spectrum
  - $B^1$ couples to hypercharge, $B(e^+e^-) = 20\%$
  - $B^1$ mass $\sim 600$-$1000$ GeV to get right $\Omega$
- BUT: flux is a factor of $100$-$1000$ too big for a thermal relic; requires enhancement
  - astrophysics (very unlikely)
  - particle physics
FERMI AND HESS 2009

- Fermi and HESS do not confirm ATIC: no feature, consistent with background with modified spectral index

- Pulsars can explain PAMELA
  
  Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)
  Yuksel, Kistler, Stanev (2008)
  Profumo (2008); Fermi (2009)
BEYOND WIMPS

• The anomalies (DAMA, PAMELA, …) are not easily explained by canonical WIMPs

• Start over: What do we really know about dark matter?
  – All solid evidence is gravitational
  – Also solid evidence against strong and EM interactions

• A reasonable 1st guess: dark matter has no SM gauge interactions, i.e., it is hidden
  
  Kobsarev, Okun, Pomeranchuk (1966); many others

• What one seemingly loses
  • Connections to central problems of particle physics
  • The WIMP miracle
  • Signals
CONNECTIONS TO CENTRAL PROBLEMS IN PARTICLE PHYSICS

• We want hidden sectors

• Consider SUSY
  – Connected to the gauge hierarchy problem
  – new sectors are already required to break SUSY

• Hidden sectors appear generically, each has its own
  – particle content
  – mass scale $m_X$
  – Interactions, gauge couplings $g_X$
• What can we say about hidden sectors in SUSY?

• Generically, nothing. But the flavor problem motivates models in which squark and slepton masses are determined by gauge couplings (and so flavor blind):

\[ m_X \sim g_X^2 \]

(Gauge mediation, anomaly-mediation, …)

• This leaves the relic density invariant!
The thermal relic density constrains only one combination of $g_X$ and $m_X$

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

These models map out the remaining degree of freedom; candidates have a range of masses and couplings, but always the right relic density

The flavor problem becomes a virtue

Naturally accommodates multi-component DM, all with relevant $\Omega$
HOW LARGE CAN HIDDEN SECTORS BE?

• Hidden sectors contribute to expansion rate

• BBN: $N_\nu = 3.24 \pm 1.2$, excludes an identical copy of the MSSM  
  Cyburt et al. (2004)

• But this is sensitive to temperature differences; even a factor of 2 makes a hidden MSSM viable

\[ g^h_{\text{heavy}} (T^h_{\text{BBN}}) \left( \frac{T^h_{\text{BBN}}}{T_{\text{BBN}}} \right)^4 - \frac{7}{8} \cdot 2 \cdot (N_{\text{eff}} - 3) \leq 2.52 \text{ (95\% CL)} \]
• Hidden DM has no SM gauge interactions, but may interact through non-gauge couplings

• For example, introduce connectors Y with both MSSM and hidden charge

• Y particles mediate both annihilation to and scattering off SM particles
EXAMPLE

• Assume WIMPless DM X is a scalar, add fermion connectors Y, interacting through

\[ \mathcal{L} = \lambda_f X \bar{Y}_L f_L + \lambda_f X \bar{Y}_R f_R \]

For f=b, Y’s are b’, t’ with hidden charge  
Kribs, Plehn, Spannowsky, Tait (2007)

• Explains DAMA easily
  – \( \lambda_b \sim 0.3-1 \)
  – \( m_X \sim 5 \text{ GeV} \) (WIMPless miracle)
  – \( m_Y \sim 400 \text{ GeV} \) (large \( \sigma_{SI} \))

• Any such DAMA explanation \( \rightarrow \) exotic b’, t’ at Tevatron, LHC
**HIDDEN CHARGED DM**

How is dark matter stabilized? Conventional answer is by a parity conservation, but there are no such SM examples.

<table>
<thead>
<tr>
<th>MSSM</th>
<th>Hidden, flavor-free MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_W ) sparticles, ( W, Z, t )</td>
<td>( m_\chi ) sparticles, ( W, Z, q, l, \tilde{\tau} ) (or ( \tau ))</td>
</tr>
<tr>
<td>~GeV ( q, l )</td>
<td></td>
</tr>
<tr>
<td>0 ( p, e, \gamma, \nu, \tilde{G} )</td>
<td>0 ( g, \gamma, \nu, \tilde{G} )</td>
</tr>
</tbody>
</table>

- If the hidden sector is a flavor-free MSSM, natural DM candidate is any hidden charged particle, stabilized by exact \( U(1)_{EM} \) symmetry, just like the SM electron.
HIDDEN CHARGED DM

Feng, Kaplinghat, Tu, Yu (2009)

DM with hidden charge requires a re-thinking of the standard cold DM picture:

• Bound states form (and annihilate) in the early Universe \rightarrow relic density

• Sommerfeld enhanced annihilation \rightarrow decays in protohalo

• Compton scattering \( X \gamma^h \rightarrow X \gamma^h \) delays kinetic decoupling \rightarrow small scale structure

• Rutherford scattering \( XX \rightarrow XX \): self-interacting, collisional dark matter
BOUNDS ON COLLISIONAL DM

- Hidden charged particles exchange energy through Rutherford scattering
- Constraints on collisions
  - Bullet cluster
  - Non-spherical halos $\rightarrow$ DM can’t be too collisional
- Consistent with WIMPless miracle for $1 \text{ GeV} < m_{DM} < 10 \text{ TeV}$
- Interesting astrophysics
- Many interesting, related ideas
  
  Pospelov, Ritz (2007); Hooper, Zurek (2008)
  Ackerman, Buckley, Carroll, Kamionkowski (2008)

Kamionkowski, Profumo (2008), …
CONCLUSIONS

• Rapid experimental progress
  – Direct detection
  – Indirect detection
  – Colliders (LHC)

• Proliferation of new classes of candidates with widely varying properties and implications for particle physics and astrophysics

• In the next few years, many DM models will be stringently tested; we will either see something or be forced to rethink some of our most cherished prejudices