RECENT DEVELOPMENTS
IN DARK MATTER:
THEORY PERSPECTIVE

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TOPICS

• PAMELA, FERMI, … ↔ BOOSTED WIMPS

• CDMS, XENON, … ↔ WIMPS

• DAMA, COGENT, … ↔ LIGHT WIMPS

For more, see “Dark Matter Candidates from Particle Physics and Methods of Detection,” 1003.0904, Annual Reviews of Astronomy and Astrophysics
• Assume a new (heavy) particle $X$ is initially in thermal equilibrium

• Its relic density is

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

• $m_X \sim 100$ GeV, $g_X \sim 0.6 \Rightarrow \Omega_X \sim 0.1$

• Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter
WIMP STABILITY

- Simple solution: impose a discrete parity, so all interactions require pairs of new particles. This also makes the lightest new particle stable.

  Cheng, Low (2003); Wudka (2003)

- This is a general argument for a stable weak-scale particle

- In specific contexts, this may be augmented by additional arguments. E.g., in SUSY, proton decay → R-parity.
WIMP DETECTION

Correct relic density $\rightarrow$ Lower bound on DM-SM interaction

Efficient annihilation now
(Indirect detection)

Efficient scattering now
(Direct detection)

Efficient production now
(Particle colliders)
INDIRECT DETECTION

Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

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ARE THESE DARK MATTER?

• Astrophysics can explain PAMELA
  
  Zhang, Cheng (2001)
  Hooper, Blasi, Serpico (2008)
  Yuksel, Kistler, Stanev (2008)
  Profumo (2008); Fermi (2009)

• For dark matter, there is both good and bad news

• Good: the WIMP miracle motivates excesses at ~100 GeV – TeV

• Bad: the WIMP miracle also tells us that the annihilation cross section should be a factor of 100-1000 too small to explain these excesses. Need enhancement from
  – astrophysics (very unlikely)
  – particle physics
If dark matter X is coupled to a hidden force carrier $\phi$, it can then annihilate through $XX \rightarrow \phi \phi$

At freezeout: $v \sim 0.3$, only 1st diagram is significant, $\sigma = \sigma^{th}$

Now: $v \sim 10^{-3}$, all diagrams significant, $\sigma = S\sigma^{th}$, $S \sim \pi \alpha_X/v$, boosted at low velocities

If $m_X \sim 2$ TeV, $S \sim 1000$, seemingly can explain excesses, get around WIMP miracle predictions

SOMMERFELD ENHANCEMENT

SOMMERFELD (1931)
Hisano, Matsumoto, Nojiri (2002)

Cirelli, Kadastik, Raidal, Strumia (2008)
CONSTRAINTS ON SOMMERFELD ENHANCEMENTS

Feng, Kaplinghat, Yu (2009)

• Unfortunately, large $S$ requires large $\alpha_X$, but strongly-interacting DM does not have the correct relic density

• More quantitatively: for $m_X = 2$ TeV, $S \sim 1000 \sim \pi \alpha_X / v$,

  $v \sim 10^{-3} \rightarrow \alpha_X \sim 1 \rightarrow \Omega_X \sim 0.001$

• Alternatively, requiring $\Omega_X \sim 0.25$, what is the maximal $S$?

• Complete treatment requires including
  – Resonant Sommerfeld enhancement
  – Impact of Sommerfeld enhancement on freeze out
FREEZE OUT WITH SOMMERFELD ENHANCEMENT

- Sommerfeld enhancement $\rightarrow$ many interesting issues
  
  Dent, Dutta, Scherrer (2009)
  Zavala, Vogelsberger, White (2009)

- To maximize $S$, turn knobs in the most optimistic direction
  
  - Assume $XX \rightarrow \phi\phi$ is the only annihilation channel
  - Delay kinetic decoupling as much as possible
  - Stop annihilations when the velocity distribution becomes non-thermal
PAMELA, Fermi fits: Bergstrom, Edsjo, Zaharias (2009)

$m_\phi = 0.25$ GeV

$T_{kd} = T_{kd}^e$
WAYS OUT

• Best fit region excluded by an order of magnitude

• Astrophysical uncertainties
  • Local density, small scale structure
  • Cosmic ray propagation, proton contamination in PAMELA,…

• Particle physics
  • More complicated Sommerfeld models (smaller boosts required, but generically tighter bounds)
  • Resonant annihilation
    Feldman, Liu, Nath (2008); Ibe, Murayama, Yanagida (2008); Gou, Wu (2009)
  • Non-thermal DM production (e.g., Winos)
    Grajek et al. (2008); Feldman, Kane, Lu, Nelson (2010); Cotta et al. (2010)
  • DM from decays
    Arvanitaki, Dimopoulos, Dubovsky, Graham, Harnik, Rajendran (2008)
DIRECT DETECTION

- The big picture
- Strongly-interacting window now closed

Mack, Beacom, Bertone (2007)

Albuquerque, de los Heros (2010)
DIRECT DETECTION

Aprile et al. (2010)
THE SIGNIFICANCE OF $10^{-44}$ CM$^2$

- New weak scale particles generically create many problems
- For example: K-$\bar{K}$ mixing

Three possible solutions
  - Alignment: $\theta$ small
  - Degeneracy (e.g. gauge mediation): typically not compatible with neutralino DM, because neutralinos decay to gravitinos
  - Decoupling: $m > \text{few TeV}$
THE SIGNIFICANCE OF $10^{-44} \text{ cm}^2$

- Consider decoupling

- Remaining diagram depends on 3 parameters: $M_1$, $M_2$, $\mu$ ($\tan \beta$)

- Impose gaugino mass unification, $\Omega h^2 = 0.11$

- One parameter left: $m_\chi$

- Predictions collapse to a line
STATUS OF SUSY

$10^{-43} \text{ cm}^2$

$10^{-44} \text{ cm}^2$

No DM

DM
LIGHT WIMPS

- ~10 GeV DM may explain DAMA

- This region is now tentatively supported by CoGeNT (2010), disfavored by XENON100 (2010)

- Conventional WIMPs?
  - Low masses: unusual, but not so difficult (e.g., neutralinos w/o gaugino mass unification)
  - High cross sections: very difficult (chirality flip implies large suppression)

Dreiner et al. (2009)

Bottino et al. (2006)

Kuflik, Pierce, Zurek (2010)
LIGHT WIMP MODELS

• Mirror matter

• Asymmetric DM: relate DM number asymmetry to baryon number asymmetry, so $m_X / m_p \sim \rho_X / \rho_p \sim 5$

• WIMPless DM

• Other candidates, related issues

Foot (2008)

Talk of An

Talks of Kumar, Badin, Yeghiyan, Fan, Sessolo

Talks of Ibe, McCaskey, Ralston
• Thermal relics in a hidden sector with mass $m_X$ and gauge coupling $g_X$

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

• This decouples the WIMP miracle from WIMPs

Feng, Kumar (2008); Feng, Tu, Yu (2008)
THE WIMPLESS MIRACLE

• Can this be arranged? Consider GMSB

\[ m \sim \frac{g^2}{16\pi^2} \frac{F}{M} \]

\[ m_X \sim \frac{g_X^2}{16\pi^2} \frac{F}{M} \]

Superpartner masses \( \sim \) gauge couplings squared

• Cosmology

\[ \frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M} \]

\( \Omega \) depends only on the SUSY Breaking sector:

\[ \Omega_X \sim \Omega_{\text{WIMP}} \sim \Omega_{\text{DM}} \]

• This is generic in SUSY (AMSB, gMSB, no-scale SUGRA,…): is this what the flavor problem is telling us?
WIMPLESS SIGNALS

- Hidden DM may interact with normal matter through non-gauge interactions

![Diagram showing interactions between MSSM, Connector, SUSY Breaking, and Hidden X with y and q]
WIMPLESS DIRECT DETECTION

- The DAMA/CoGeNT region is easy to reach with WIMPless DM

- E.g., assume WIMPless DM X is a scalar, Y is a fermion, interact with b quarks through
  \[ \lambda_b ( X Y_L b_L + X Y_R b_R ) + m_Y Y_L Y_R \]

- Naturally correct mass, cross section
  - \( m_X \sim 5 - 10 \text{ GeV} \) (WIMPless miracle)
  - Large \( \sigma_{SI} \) for \( \lambda_b \sim 0.3 - 1 \) (flip chirality on heavy Y propagator)
FUTURE PROSPECTS

• More direct detection, of course, but also

• **SuperK, IceCube**
  
  Hooper, Petriello, Zurek, Kamionkowski (2009)
  Feng, Kumar, Strigari, Learned (2009)
  Kumar, Learned, Smith (2009)
  Barger, Kumar, Marfatia, Sessolo (2010)

• **Light DM in Upsilon decays**
  
  McKeen (2008)
  Yeghiyan (2009)
  Badin, Petrov (2010)

• **Tevatron and LHC can find connector particles: colored, similar to 4th generation quarks**
EXOTIC 4TH QUARKS AT LHC

Direct searches, perturbativity \( \rightarrow 300 \text{ GeV} < m_Y < 600 \text{ GeV} \)

The entire region can be excluded by 10 TeV LHC with 300 \( \text{pb}^{-1} \) (~7 TeV LHC with 1 \( \text{fb}^{-1} \)); significant discovery prospects

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CONCLUSIONS

• DM searches are progressing rapidly on all fronts
  – Direct detection
  – Indirect detection
  – LHC

• Proliferation of DM candidates, but many are tied to the weak scale

• In the next few years, these DM models will be stringently tested