IMPLICATIONS OF RECENT DATA FOR THEORIES OF DARK MATTER

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Strings at the LHC and in the Early Universe
KITP Santa Barbara
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TOPICS

• PAMELA, FERMI, … ↔ BOOSTED WIMPS

• CDMS, XENON, … ↔ WIMPS

• DAMA, COGENT, … ↔ LIGHT WIMPS

• TEVATRON, LHC ↔ SUPERWIMPS
  LIGHT GRAVITINOS

For more, see “Dark Matter Candidates from Particle Physics and Methods of Detection,” 1003.0904, Annual Reviews of Astronomy and Astrophysics
THE WIMP MIRACLE

• 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

• The WIMP miracle assumes a stable new particle. Why should this be?

• LEP and SLC confirmed the standard model, stringently constrained effects of new particles

• Problem: Gauge hierarchy \(\rightarrow\) new particles \(\sim 100\) GeV
  - LEP/SLC \(\rightarrow\) 4-fermi interaction mass scale \(> 3\) TeV
  - (even considering only flavor-, CP-, B-, and L-conserving effects)
LEP’S COSMOLOGICAL LEGACY

- 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 → stable LSP.
EXAMPLES

Supersymmetry
- R-parity
- Neutralino DM
  - Fayet, Farrar (1974)
  - Goldberg (1983)
  - Ellis et al. (1984)

Universal Extra Dimensions
- KK-parity
  - Appelquist, Cheng, Dobrescu (2000)
- Kaluza-Klein DM
  - Servant, Tait (2002)
  - Cheng, Feng, Matchev (2002)

Branes
- Brane-parity
- Branons DM
  - Cembranos, Dobado, Maroto (2003)
...
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)


Fermi (2009)
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
      - Winos
      - Resonances
      - DM from Decays
      - Sommerfeld enhancements
SOMMERFELD ENHANCEMENT

• 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

  \[
  \text{Sommerfeld (1931)} \\
  \text{Hisano, Matsumoto, Nojiri (2002)}
  \]

• If $S \sim 1000 \frac{m_X}{2 \text{ TeV}}$, seemingly can explain excesses, get around WIMP miracle predictions

  \[
  \text{Cirelli, Kadastik, Raidal, Strumia (2008)} \\
  \text{Arkani-Hamed, Finkbeiner, Slatyer, Weiner (2008)}
  \]
CONSERVATIVE ON
SOMMERFELD ENHANCEMENTS

Feng, Kaplinghat, Yu (2009, 2010)

• 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,

  \[ S \sim \frac{\pi \alpha_X}{v} \sim 1000, \quad v \sim 10^{-3} \rightarrow \alpha_X \sim 1 \rightarrow \Omega_X \sim 0.001 \]

• 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
  – Maximize S by pushing all parameters in the most optimistic direction
FREEZE OUT AND MELT IN

\[
\frac{1}{Y(x_s)} = \frac{1}{Y(x_f)} + \sqrt{\frac{\pi}{45}} m_{\text{p1}} m_{\chi} \int_{x_f}^{x_{\text{kd}}} \frac{(g_{ss}/\sqrt{g_s}) \langle \sigma_{\text{an}} v_{\text{rel}} \rangle}{x^2} dx + \sqrt{\frac{\pi}{45}} m_{\text{p1}} m_{\chi} \int_{x_{\text{kd}}}^{x_s} \frac{(g_{ss}/\sqrt{g_s}) \langle \sigma_{\text{an}} v_{\text{rel}} \rangle}{x^2} dx,
\]

\[
\frac{m_{\chi}}{500 \text{ GeV}} \quad \alpha_{\chi} = 0.0119 \quad m_{\phi} = 0.904 \text{ GeV} \quad T_{kd} = T_{\phi}
\]

\[
\Omega_{\chi} h^2 = 0.048 \quad (T_s = T_{\text{nt}}) \quad \Omega_{\chi} h^2 = 0.00063 \quad (T_s = 1 \text{ eV})
\]

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CONSTRAINTS ON SOMMERFELD ENHANCEMENTS

- Best fit region [Bergstrom et al. (2009)] excluded by over an order of magnitude

- Astrophysical uncertainties
  - Local density
  - Small scale structure
  - Cosmic ray propagation

- More complicated models
  - Smaller boosts required
  - Tighter bounds
DIRECT DETECTION

- Direct detection searches for nuclear recoil in underground detectors
- Spin-independent scattering is typically the most promising
- Theory and experiment compared in the \((m_X, \sigma_p)\) plane
  - Expts: CDMS, XENON, …
  - Theory: Shaded region is the predictions for SUSY neutralino DM – what does this mean?
NEW PHYSICS FLAVOR PROBLEM

- New weak scale particles generically create many problems
- One of many possible examples: K-K mixing

\[ \theta \]

\[ \tilde{d}, \tilde{s}, \tilde{b} \]

\[ \tilde{g} \]

\[ \tilde{d}, \tilde{s}, \tilde{b} \]

- Three possible solutions
  - Alignment: $\theta$ small
  - Degeneracy: squark $\Delta m << m$: typically not compatible with DM, because the gravitino mass is $\sim \Delta m$, so this would imply that neutralinos decay to gravitinos
  - Decoupling: $m >$ few TeV
THE SIGNIFICANCE OF $10^{-44}$ CM$^2$

- Decoupling is the strategy taken in many theories
  - focus point SUSY, inverted hierarchy models, more minimal SUSY, 2-1 models, split SUSY,…

- This eliminates many annihilation diagrams, collapses predictions

- Universal prediction:

\[ \sigma_p \sim 10^{-44} \text{ cm}^2 \]

Stay tuned!
DIRECT DETECTION: DAMA

- **Annual modulation expected**
  - Drukier, Freese, Spergel (1986)

- **DAMA: 8.9σ signal with**
  - $T \sim 1$ year, max $\sim$ June 2

![Graph showing residuals and time (day) for DAMA/NaI and DAMA/LIBRA experiments.](image)
CHANNELING

• DAMA’s results have been puzzling, in part because the allowed region is excluded by other experiments.

• This may be ameliorated by astrophysics and channeling: in crystalline detectors, efficiency for nuclei recoil energy → electron energy depends on direction.

• Channeling reduces threshold, shifts allowed region to lower masses. Consistency restored?

Gondolo, Gelmini (2005)
LIGHT WIMPS

- Channeling may open up a new ~10 GeV region that is marginally acceptable
- This region is now tentatively supported by CoGeNT, disfavored by XENON100
- Low masses and high cross sections are hard to obtain with conventional WIMPs: for example, for neutralinos, chirality flip implies large suppression
HIDDEN SECTORS

• Can we obtain something like the WIMP miracle, but with hidden DM? Need some structure.

• Consider standard GMSB with one or more hidden sectors

• Each hidden sector has its own gauge groups and couplings
THE WIMPLESS MIRACLE

Feng, Kumar (2008)

- Particle Physics

\[ \langle S \rangle = M + \theta^2 F \]
\[ W = \lambda \tilde{\Phi} S \Phi + \lambda_X \tilde{\Phi}_X S \Phi_X \]

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

- 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:

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

Any hidden particle with mass \(~m_X\) will have the right thermal relic density (for any \(m_X\))

Superpartner masses, interaction strengths depend on gauge couplings
• The thermal relic density constrains only one combination of $g_X$ and $m_X$. These models map out the remaining degree of freedom; candidates have a range of masses and couplings, but always the right relic density.

• This decouples the WIMP miracle from WIMPs (is this what the flavor problem is really trying to tell us?)
WIMPLESS SIGNALS

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

\[ X \rightarrow Y \rightarrow Q \]

\[ X \rightarrow q \]

\[ SUSY \]

\[ \text{Breaking} \]

\[ \text{MSSM} \]

\[ \text{Connector} \]

\[ Y \]

\[ \text{Hidden} \]

\[ X \]
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
  \[ \lambda_b \left( X Y_L b_L + X Y_R b_R \right) + m_Y Y_L Y_R \]

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

• SuperK can probe this region

Hooper, Petriello, Zurek, Kamionkowski (2009)
Feng, Kumar, Strigari, Learned (2009)
Kumar, Learned, Smith (2009)

• Tevatron and LHC can find connector particles: colored, similar to 4\textsuperscript{th} generation quarks

• EW precision studies, direct searches, perturbativity $\Rightarrow$
  $300 \text{ GeV} < m_Y < 600 \text{ GeV}$
EXOTIC 4\textsuperscript{TH} QUARKS AT LHC

- Entire $m_X \sim 10$ GeV region can be excluded by 10 TeV LHC with 300 pb\textsuperscript{-1} ($\sim$7 TeV LHC with 1 fb\textsuperscript{-1})

- Significant discovery prospects with early LHC data

Alwall, Feng, Kumar, Su (2010)
Consider supersymmetry (similar story in UED). There is a gravitino, mass ~ 100 GeV, couplings ~ $M_W/M_{Pl} \sim 10^{-16}$

- $\tilde{G}$ not LSP

- Assumption of most of literature

- $\tilde{G}$ LSP

- Completely different cosmology and particle physics
SUPERWIMP RELICS

- Consider $\tilde{G}$ LSPs: WIMPs freeze out as usual, but then decay to $\tilde{G}$ after $M_{\text{Pl}}^2/M_W^3 \sim$ seconds to months
COSMOLOGY OF LATE DECAYS

Late decays impact light element abundances

- Lots of complicated nucleoparticlecosmochemistry
- BBN typically excludes very large lifetimes
- BBN excludes \( \chi \to Z \tilde{G} \), but \( \tilde{I} \to I \tilde{G} \) ok

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LATE DECAYS AND $^7$Li/$^6$Li

- $^7$Li does not agree with standard BBN prediction
  - Too low by factor of 3, ~5σ at face value
  - May be solved by convection in stars, but then why so uniform?

- $^6$Li may also not agree
  - Too high

- Late decays can fix both
- For mSUGRA, fixing both, and requiring $\Omega_\tilde{G} = 0.1 \rightarrow$ heavy sleptons > TeV
MODEL FRAMEWORKS

- mSUGRA’s famous 4+1 parameters: $m_0^2, M_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
- Excluded regions: LEP limits, Stau LSP
- But this is incomplete: Missing $m_G$, assumes $m_0^2 > 0$
THE COMPLETE MSUGRA

- Extend the mSUGRA parameters to
  \[ m_0^2, M_{1/2}, A_0, \tan \beta, \text{sign}(\mu), \text{and } m_{3/2} \]

- If LSP = gravitino, then no reason to exclude stau (N)LSP region

- Also include small or negative
  \[ m_0 \equiv \text{sign}(m_0^2) \sqrt{|m_0^2|} \]

- This includes no-scale/gaugino-mediated models with \( m_0 = 0 \)

- Much of the new parameter space is viable with a slepton NLSP and a gravitino LSP
CURRENT BOUNDS

- Current Bounds
  - LEP: slepton mass > 97.5 GeV, chargino > 102.5 GeV
  - CDF Run I: slepton cross section < 1 pb
  - CDF Run II: top squark mass > 249 GeV
– D0 Run II: chargino mass > 200 GeV

– D0 Run II: slepton cross section < 0.1 pb
  – assumes only Drell-Yan pair production (no cascades)
  – require 2 slow, isolated “muons”
  – about a factor of 5 from unexplored mass territory
LHC DISCOVERY POTENTIAL

- Look for Drell-Yan slepton pair production

- Require events with 2 central, isolated "muons" with
  - $p > 100$ GeV
  - $p_T > 20$ GeV

- Finally assume TOF detector resolution of 1 ns, require both muons to have TOF delays $> 3$ ns

<table>
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<th>Model</th>
<th>Total cross-section</th>
<th>After Drell-Yan cuts</th>
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<td>Model A</td>
<td>18pb</td>
<td>9pb</td>
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<tr>
<td>Model B</td>
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<td>28fb</td>
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<td>$\gamma^* / Z \rightarrow \mu \mu$</td>
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<td>360mb</td>
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<td>Z+jet</td>
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<td>$t\bar{t}$</td>
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<tr>
<td>WW,WZ,ZZ</td>
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<th>3ns</th>
<th>4ns</th>
<th>5ns</th>
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<tbody>
<tr>
<td>Drell-Yan; background</td>
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<td>1.35pb</td>
<td>3.3fb</td>
<td>0.2ab</td>
<td>$&lt; 0.1$ab</td>
<td>$&lt; 0.1$ab</td>
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<tr>
<td>Drell-Yan; Model A</td>
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<td>5.2pb</td>
<td>2.9pb</td>
<td>1.8pb</td>
<td>1.1 pb</td>
<td>750fb</td>
</tr>
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</table>
• Require $5\sigma$ signal with $S > 10$ events for discovery

• Model A is “best case scenario”
• Lesson: Very early on, the LHC will probe new territory
CHARGED PARTICLE TRAPPING

- SuperWIMP DM $\rightarrow$ metastable particles, may be charged, far more spectacular than missing $E_T$ (1st year LHC discovery)

- Can collect these particles and study their decays

- Several ideas
  - Catch sleptons in a 1m thick water tank (up to 1000/year)  
  Feng, Smith (2004)
  
  - Catch sleptons in LHC detectors  
  
  - Dig sleptons out of detector hall walls  
  De Roeck et al. (2005)
LIGHT GRAVITINO DM

• The original SUSY DM scenario
  – Universe cools from high temperature
  – Gravitinos decouple while relativistic, $\Omega_\tilde{G} h^2 \approx \frac{m_\tilde{G}}{800 \text{ eV}}$
  – Favored mass range: keV gravitinos

  Pagels, Primack (1982)

• This minimal scenario is now excluded
  – $\Omega_\tilde{G} h^2 < 0.1 \rightarrow m_\tilde{G} < 80 \text{ eV}$
  – Gravitinos not too hot $\rightarrow m_\tilde{G} > \text{few keV}$
  – keV gravitinos are now the most disfavored

  Viel, Lesgourgues, Haehnelt, Matarrese, Riotto (2005)
  Seljak, Makarov, McDonald, Trac (2006)

• Two ways out
  – $\Lambda$WDM: $m_\tilde{G} > \text{few keV}$. Gravitinos are all the DM, but thermal density is diluted by low reheating temperature, late entropy production, …
  – $\Lambda$WCDM: $m_\tilde{G} < 16 \text{ eV}$. Gravitinos are only part of the DM, mixed warm-cold scenario
CURRENT BOUNDS

• Remarkably, this lifetime difference is observable at colliders!

\[ c\tau_{\text{NLSP}} \approx 50 \text{ cm} \left( \frac{200 \text{ GeV}}{m_{\text{NLSP}}} \right)^5 \left( \frac{m_{\tilde{G}}}{\text{keV}} \right)^2 \]

• \( m_{\tilde{G}} > \text{few keV} \): Delayed photon signatures

• \( m_{\tilde{G}} < 16 \text{ eV} \): Prompt photon signatures
LIGHT GRAVITINOS AT THE LHC

Lee, Feng, Kamionkowski (2010)
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