The WIMPless Miracle and the DAMA Puzzle

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Relic Density

- matter in early universe in thermal equilibrium
- matter decouples because of the expansion of the universe
  - when particles can’t find each other to interact, they decouple from equilibrium
- matter is non-relativistic at decoupling
- Boltzmann equation
  \[
  \frac{d\eta}{dt} + 3H\eta = -\langle \sigma_{\text{ann}} v \rangle (\eta^2 - \eta_{\text{eq}}^2)
  \]
- \( x \sim 20 \), \( \rho \propto T^3 \left( M_p \langle \sigma v \rangle \right)^{-1} \)

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Y. Zeldovich (1965)
E. Kolb, M. Turner (1990)
WIMP miracle

- knowing $\sigma$, we can figure out relic density
- to get observed DM density need $\sigma \sim 1 \text{ pb}$
- stable matter with coupling and mass of the electroweak theory would have about right relic density for dark matter
  - WIMP miracle
- best theoretical idea for dark matter
- guide for most theory models and experimental searches
- but is this miracle really so miraculous?
A New Dark Matter Scenario

• common feature of beyond-the-Standard-Model physics
  – hidden gauge symmetries, particles

• arise in most theory frameworks
  – supersymmetry, string theory, GUTs, etc.

• possible dark matter candidates?
  – can get left over symmetries which stabilize particles
  – if stable, they contribute to dark matter
    • could be either good, or bad

• what are the dark matter implications for this scenario?
Setup

- the standard “low-energy SUSY” setup
  - one sector breaks supersymmetry
  - an energy scale is generated in Standard Model sector by gauge-mediation from the SUSY-breaking sector
  - this sets the mass of the W, Z, Higgs, etc.
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- we add to this extra gauge sectors, which behave in a qualitatively similar way
  - symmetry stabilizes particle at SUSY-breaking scale
Motivation

• hidden gauge sectors (several) arise typically in string theory and beyond-the-standard-model

• gauge-mediation provides an elegant solution to flavor-problem

• in string models like intersecting brane models, naturally have many sectors and lots of bifundamental matter
  – gauge mediators
  – extra sectors can leave global or discrete symmetries behind

• but even aside from these motivations, this is an interesting, reasonable and simple scenario
The Energy Scale

- gauge interactions determine energy scale in a known way
- \( F, M_{\text{mess}} \) set by dynamics of supersymmetry-breaking
  - same for all sectors
- in each sector, ratio of coupling to mass is approximately fixed
  - same ratio determines annihilation cross-section
    - determines relic density
      (Scherrer, Turner; Kolb, Turner)
    - if WIMP miracle gets it right, so does every other sector

\[
\begin{align*}
 m_{\text{scalar}}^2 &= \frac{g^4 N_{\text{mess}}}{(4\pi)^4} \left( \frac{F}{m_{\text{mess}}} \right)^2 \\
 \frac{g_h^4}{m_h^2} &\propto \left( \frac{m_{\text{mess}}}{F} \right)^2 = \text{const.} \\
 \Omega &\propto \frac{1}{\langle \sigma v \rangle} \propto \left( \frac{g_h^4}{m_h^2} \right)^{-1} \propto \left( \frac{F}{m_{\text{mess}}} \right)^2
\end{align*}
\]
we find in this scenario, a generic charged stable particle should have the right density (order of magnitude) to be dark matter

maybe this is really a WIMPlless miracle … any gauge sector with any coupling would have worked

in fact, it should have worked for the MSSM in gauge-mediation
  – two stable particles → the LSP and the electron
  – first accident → electron Yukawa coupling is extremely (perhaps unnaturally) small
    • mass much lighter than “natural” scale ($m_{\text{top}}$)
    • if electron mass were $\sim m_{\text{top}}$, would have the right relic density
  – second accident → in gauge mediation, the LSP is not gauge charged

but in any other sector, a discrete symmetry can stabilize a hidden sector gauge charged particle
  – in the right ball-park for dark matter
  – distinct from gravity mediated result, where WIMPs really needed
Upshot

• a new well-motivated scenario for dark matter

• natural dark matter candidates with approximately correct mass density

• unlike “WIMP miracle” scenario, here dark matter candidate can have a range of masses and couplings

• opens up the window for observational tests, beyond standard WIMP range

• implications for cosmology, direct and indirect detection
  – such as the DAMA puzzle....
Detection Overview

- **direct detection**
  - DM scatters of nucleus in earth-based detector, and the recoil is measured
  - DAMA, CDMS, XENON10, CoGeNT, LUX, etc.

- **indirect detection**
  - DM annihilates to SM final states, which shower off $\gamma$, $\nu$, $e^+e^-$
  - GLAST, PAMELA, ANTARES, Super-K, etc.

- **LHC**

Dan Hooper
SUSY '07

NASA website
Detection Scenarios

- if no connection between SM and hidden sector...
  - no direct, indirect or collider signature
  - only gravitational

- but could have connectors between those sectors
  - either exotics charged under both SM and hidden sector
  - or hidden sector DM charged also under SM

- focus on the latter
  - more natural in IBM models, where hidden sector only gets SM coupling at loop level
  - more interesting signals
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Yukawa coupling

$W = \lambda X Y_L f_L + \lambda X Y_R f_R + m Y_L Y_R$

- $f$ is a SM multiplet
- $Y_{L,R}$ are 4th generation-like connector particles

- allows both annihilation to and scattering from SM particle $f$

- new signatures at small mass
  - direct detection signal
  - number density larger
    - strong indirect detection possibilities
    - signal $\propto (\# \text{ density})^2$

dark matter annihilation

dark matter-nucleon scattering
DAMA/LIBRA result

- NaI direct detection experiment
- large mass / large signal / large background
- uses annual modulation of signal to separate from background
- when earth and solar motion add, DM flux is maximized
  - larger signal
  - peaked ~ June 2
  - 8.2 $\sigma$ effect

DAMA/LIBRA Collaboration arXiv:0804.2741
Issues

- is the experimental result really a DM signal?
- why do other experiments not see it?
- what theory model could generate a signal in that region of parameter space?
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  – don’t address this….
• why do other experiments not see it?
  – low recoil energy
  – particle physics uncertainties
  – channeling effect, etc.
  – astrophysics uncertainties
• dark matter streams, etc. (Gelmini, Gondolo)
• what theory model could generate a signal in that region of parameter space?

![Graph showing the relationship between mass and cross-section for dark matter models.](image-url)
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  – we address this with WIMPless dark matter
How can DAMA be consistent with other experiments?

- dark matter mass estimates depend on kinematics of non-relativistic scattering
- recoil energy threshold for experiment gives you a cutoff on mass sensitivity
- channeling effect
  - crystalline scintillators
  - some recoiling nuclei lose no energy to phonons, only to electrons
- dark matter streams
  - changes halo velocity as seen at earth
- more complicated (CPW, FS, SGGF)
WIMPIless Model

- we now have a dark matter model which seems to naturally give us the right relic density, but at a variety of mass scales
  - no theory prediction now for the mass scale

- let’s treat the DAMA/LIBRA signal as an experimental hint for where the DM mass scale is

- can a consistent WIMPIless model to fit this experimental hint?

- want $m_X \sim 2-10$ GeV, $g \sim 0.1$
- $\sigma_{SM} \sim 10^{-38-41}$ cm$^2 \propto \lambda^4/m_\gamma^2$
- scaling gives us hints for indirect and collider searches
Scattering from $b$-quarks

- assume WIMPless DM couples to 3$^{\text{rd}}$ generation quarks
  - coupling to other generations can be Cabibbo-suppressed

- this gives a coupling to gluons in nucleus via loop of $b$-quarks
  - coupling via $t$-quarks suppressed by $m_{\text{top}}$

- can compute coupling via conformal anomaly (Shifman, Vainshtein, Zakharov)

\[
\sigma_{SI} = \frac{\lambda^4}{4\pi} \frac{m_N^2}{(m_N + m_X)^2} \frac{[ZB_b^p + (A - Z)B_b^n]^2}{A^2(m_X - m_Y)^2}
\]

\[
\propto \frac{\lambda^4}{m_Y^2}
\]

\[
B_{b}^{p,n} \sim \frac{2}{27} \frac{m_p f_g^{p,n}}{m_b}
\]

\[
f_g^{p,n} \sim 0.8
\]

\[
m_Y \sim 400 \text{ GeV}
\]

\[
\lambda \sim 0.5
\]
Gamma ray signal

- **b-quarks** shower off gamma rays which can be probed at GLAST
- pick a point consistent with DAMA/LIBRA signal
  - $m_Y \sim 400 \text{ GeV}$, $m_X \sim 6 \text{ GeV}$
  - $\langle \sigma_{\text{SM}} \nu \rangle \sim 7 \text{ pb}$
    - little large, but close enough (Feng, Tu, Yu)
- assume $\rho \propto 1 / r^{0.8}$
- spectrum peaks at $m_X/25$ (Baltz, Taylor, Wai)
  - internal brem. (peak near $m_X$) suppressed by high mass final state
- tough signal, but not impossible

\[
\sigma_{\text{SM}} \nu = \frac{\lambda^4}{4\pi} \left( \frac{m_Y^2}{m_Y^2 + m_X^2} \right)^2 \sqrt{1 - \frac{m_b^2}{m_X^2}} \propto \frac{\lambda^4}{m_Y^2}
\]
Collider signature

- collider searches for 4\textsuperscript{th} generation quarks
  - constrained by direct limits from Tevatron
  - precision electroweak constraints from LEP

- would require $m_\gamma > \sim 260$ GeV

- but exotic quarks in the mass range 300-500 GeV are possible and can be detected at LHC (Kribs, Plehn, Spannowsky, Tait)
  - consistency check for WIMPIless model of DAMA/LIBRA signal

- exotics usually require higher mass Higgs for consistency with precision EW
  - interesting correlation with Higgs searches
Corroborating at Super-K
(see also Hooper, Petriello, Zurek, Kamionkowski; Savage, Gelmini, Gondolo, Freese)

• need another experiment to figure out what DAMA is seeing
  • direct detection experiment
    – need low threshold
    – if DAMA result comes from earth-specific physics, won’t know
  • indirect detection experiment
    – model-dependent relation to DAMA
• Super-Kamiokande
  – model-independent, but very different from direct detection tests
  – low threshold
How Super-K can set limits….

- sun/earth capture DM by elastic scattering
  - absorb energy
- capture yields higher density
  - higher DM annihilation rate
  - $\nu$s get out
- if sun is in equilibrium, annihilation rate = capture rate
  - capture rate $\propto \sigma_{DM\text{-nucleon}}$
- if Super-K can bound $XX \rightarrow \nu\nu$ flux, can then bound $\sigma_{DM\text{-nucleon}}$
- Super-K sensitive to low $E_\nu$
  - good for DAMA
  - model-independent (largely)

Desai, et al., hep-ex/0404025
Super-K bounds….

- $\nu_\mu$ convert to $\mu$ in/near detector, and $\mu$ detected at Super-K
- if data matches atmospheric $\nu$ background
  - statistical uncertainty bounds $\nu$ flux contribution from $XX \rightarrow \nu\nu$
- old bound from throughgoing $\mu$
  - pass all the way through detector
- $>18\text{GeV}$ limit $\rightarrow >90\%$ of $\mu$ are TG
- for 5-10GeV range, mostly fully-contained events
  - $\mu$ form in detector and stop there

projected Super-K bounds using fully-contained events and 3000 live days, plus WIMPless and neutralino (Bottino, et al) predictions
Conclusion

• new theoretical window for dark matter
  – can address dark matter at low mass

• possible explanation for results of DAMA/LIBRA

• interesting corroborative checks at LHC, and possibly at GLAST

• possible to corroborate WIMPless (and other) models for DAMA/LIBRA very soon at Super-Kamiokande

Mahalo…!