Dark Matter through the Axion Portal

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arXiv:0810.5397

with Yasunori Nomura

Recent progress with Jeremy Mardon and Daniel Stolarski
New source of galactic electrons/positrons!

Astrophysical source?
SNR/Pulsars are $e^+e^-$ machines

[Blasi, Hall, Hooper, Kistler, Pohl, Profumo, Serpico, Stanev, Yuksel, ...]

Dark matter decay?
$\tau \sim 10^{26}$ sec $\sim (M_{\text{GUT}})^4$/TeV$^5$

[Arvanitaki, Bi, Chen, Dimopoulos, Dubovsky, Graham, Hamaguchi, Harnik, Hisano, Ibarra, Ishiwata, Kawasaki, Kohri, Liu, Matsumoto, Moroi, Nakayama, Nardi, Nojiri, Pospelov, Rajendran, Sannino, Shirai, Strumia, Takahashi, Torii, Tran, Trott, Yanagida, Yin, Yuan, Zhang, Zhu, ...]

Dark matter annihilation?
$\langle \sigma v \rangle \sim 10^3 \times$ WIMP thermal freezeout


Paradigm shift in astrophysics?
in dark matter physics?
DM Annihilation Interpretation?

What is connection?

Physics of EWSB

Physics of Dark Matter

Mass is 10x larger than standard SUSY neutralino!

Annihilation rate is 1000x larger than thermal freezeout!

Lepton-rich annihilation!

There are certainly DM models that can explain PAMELA/ATIC

Are there models as compelling as the standard SUSY neutralino?
The Axion Portal

Novel connection between EWSB and DM!

\[ W = W_{\text{Yukawa}} + \chi S H_u H_d + \kappa S^3 + \xi S \Psi \Psi^c \]

Independent motivation: PQ limit of NMSSM (has light “axion”)  
Common origin for Higgsino and DM mass!
Simple construction to explain PAMELA/ATIC as DM annihilation

Novel collider signatures!

Rare \( \Upsilon \) decays to \( \gamma \mu^+ \mu^- \) at BaBar/Belle  
Modified Higgs physics at Tevatron/LHC  
Muon-rich SUSY cascade decays (no, not CDF anomaly)

As well as interesting constraints from LEP, direct detection, gamma ray and neutrino telescopes, ...
The Axion Portal

Outline

Introducing the Axion Portal

Connecting DM and EWSB

Galactic Signals and Constraints
Introducing the Axion Portal
DM and Spontaneous Symmetry Breaking

Connecting DM and EWSB

Galactic Signals and Constraints
Basic Setup

Goal: Heavy dark matter with enhanced halo annihilation and large annihilation rate to leptons

Model: Fermion mass from spontaneous symmetry breaking

\[ \mathcal{L} = -\xi S \bar{\psi} \psi^c \]

\[ S = \left( f_a + \frac{s}{\sqrt{2}} \right) \exp \left[ \frac{i}{\sqrt{2}} \frac{a}{f_a} \right] \]

\[ m_{\text{DM}} = \xi f_a \]

Scalar \( s \): enhanced halo annihilation
(non-perturbative effects for \( m_s \ll f_a \))

“Axion” \( a \): annihilation to leptons
(\( S h_u h_d \) coupling make \( a \) like a heavy DFSZ axion)

\[ m_{\text{DM}}, f_a \quad \sim \quad \text{TeV} \]

\[ m_s \quad \sim \quad 1-10 \text{ GeV} \]
(hierarchy problem?)

\[ m_a \quad \gtrsim \quad 2m_\ell \]
Thermal Relic Abundance

\[ \langle \sigma v \rangle \sim \mathcal{O}(v^2) \]

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\[ \langle \sigma v \rangle \sim \mathcal{O}(v^0) \]

\[ \langle \sigma v \rangle = \frac{m_{DM}^2}{128\pi f_a^4} + \mathcal{O}(v^2) \]

\[ \simeq 3 \times 10^{-26} \text{cm}^3/\text{sec} \]

\[ \mathcal{L} = -\xi S \psi \psi^c \]

\[ S = \left( f_a + \frac{s}{\sqrt{2}} \right) \exp \left[ \frac{i}{\sqrt{2}} \frac{a}{f_a} \right] \]

(micrOMEGAs result)

\[ L = -\xi S \psi \psi^c \]

(standard WIMP thermal relic)
Halo Annihilation

Scalar \( s \) mediates attractive force between DM
Non-perturbative annihilation enhancements at \( v_{\text{halo}} \sim 10^{-3} \)

Dominant \( s \) Decay

\[
\mathcal{L} = \frac{1}{\sqrt{2} f_a} s (\partial_{\mu} a)^2
\]

Axion Portal to SM

\[
\Gamma_{a \rightarrow \ell \ell} = \frac{c_{\ell}^2 m_a m_\ell}{16\pi f_a^2}
\]

Sommerfeld effect or WIMPonium formation

\[
B \simeq \frac{\alpha_\xi}{m_s} \frac{m_{\text{DM}}}{v_{\text{halo}}^2} \to \frac{\alpha_\xi}{m_{\text{DM}}} \frac{m_s}{v_{\text{halo}}^2}
\]

(Need to explain why \( s \) is so light)

\[
v_{\text{halo}} < \alpha_\xi < v_{\text{freezeout}}
\]

(For enhancement today and not at freezeout)

[Hisano, Matsumoto, Nojiri, Saito; Cirelli, Kadastik, Raidal, Strumia; Arkani-Hamed, Finkbeiner, Slatyer, Weiner; March-Russell, Hooper, West; Pospelov, Ritz; ...]
Low Energy Axion Constraints

Axion \( a \) is *not* the QCD axion, since we take axion mass as a free parameter. For PQ charges, like a heavy DFSZ axion.

\((S h_u h_d \text{ coupling gives standard model fields } U(1)_{PQ} \text{ charges})\)

\[2m_e \quad 2m_{\mu} \quad m_{\rho} + m_{\pi} \quad 2m_{\tau} \quad 2m_b\]

\[m_K - m_{\pi} \quad 360 \text{ MeV} < m_a < 800 \text{ MeV}\]

\[\text{Br}(\Upsilon \to a\gamma) \sim 3 \times 10^{-6} \sin^4 \beta \left(\frac{\text{TeV}}{f_a}\right)^2\]

**CLEO:** < few \( 10^{-6} \) from 20M \( \Upsilon(1S) \)

**Belle:** \( \sim 50\text{M} \Upsilon(3S) \) on tape!

**BaBar:** \( \sim 110\text{M} \Upsilon(3S) \) & \( \sim 50\text{M} \Upsilon(2S) \) on tape!
The Axion Portal

DM mass from SSB

$$\mathcal{L} = -\xi S \psi \psi^c$$

$$S = \left( f_a + \frac{s}{\sqrt{2}} \right) \exp \left[ \frac{i}{\sqrt{2}} \frac{a}{f_a} \right]$$

Annihilation in halo...

...and at freezeout

s: enhanced halo annihilation

a: annihilation to leptons

(U(1)$_{\text{PQ}}$: 360 MeV < $m_a$ < 800 MeV, Rare $\Upsilon$ Decays)

$\Upsilon(nS)$

$$m_{\text{DM}}, f_a \sim \text{TeV}$$

$$m_s \sim 1-10 \text{ GeV}$$

$$m_a \gtrsim 2m_\ell$$
Introducing the Axion Portal

Connecting DM and EWSB
A Supersymmetric Axion Portal

Galactic Signals and Constraints
Adding Supersymmetry

Focus on a heavy Peccei-Quinn axion

\[ \mathcal{L} = -A_\lambda S h_u h_d - \xi S \psi \psi^c \]

SUSY extension:

\[ W = \lambda S H_u H_d + \kappa S^3 + \xi S \Psi \Psi^c \]

PQ-symmetric NMSSM
(Solves \(\mu\) problem with spontaneous \(U(1)_{\text{PQ}}\) violation)

[Susy Axion Portal: Just add DM]

[Ciafaloni, Pomarol; Hall, Watari]
[Nomura, JT]

Higgsino and DM masses have common origin!
(Assuming DM is a thermal relic, no free parameters beyond PQ-SUSY!)

For light scalar \(s\), need small \(\lambda\) and small SUSY breaking for \(\Psi/\Psi^c\).

Axion \(a\) mass from explicit \(U(1)_{\text{PQ}}\) violation (\(\kappa\) term, say).
PQ Limit of NMSSM (with DM)

4 free parameters! Assuming DM thermal relic, same as PQ-SUSY

\[ W = \lambda S H_u H_d + \xi S \Psi \Psi^c \]

\[ \mathcal{L}_{\text{soft}} = -\lambda A_\lambda S h_u h_d + m_1^2|h_u|^2 + m_2^2|h_d|^2 \]

\[ \{ m_{\text{DM}}, \mu_H, \tan \beta, m_a \} \]

All else derived from thermal relic or EWSB

\[ \mu_H = \lambda f_a \quad m_{\text{DM}} = \xi f_a \quad \tan \beta = \tan \beta(m_1^2, m_2^2, A_\lambda) \]

\[ A_\lambda = \frac{2\mu_H}{\sin 2\beta} \quad v_{\text{EW}} = v_{\text{EW}}(m_1^2, m_2^2, A_\lambda) \]

Spectrum controlled by two \( O(10^{-1}) \) parameters

\[ \lambda \equiv \frac{\mu_H}{f_a} \quad \epsilon \equiv \frac{v_{\text{EW}}}{f_a} \]

\[ m_{\text{DM}}, f_a \quad \text{TeV} \]

\[ v_{\text{EW}} \quad \epsilon f_a \quad 100 \text{ GeV} \]

\[ \mu_H \quad \lambda f_a \quad 10 \text{ GeV} \]

\[ m_s \quad \lambda \epsilon f_a \quad 1 \text{ GeV} \]

\[ m_{\tilde{s}} \quad \lambda \epsilon^2 f_a \quad 1 \text{ GeV} \]

\[ m_a \]
Three states below $Z$: $s, a, \tilde{s}$. Mixing angles with Higgs fields $O(\varepsilon)$, and LEP bounds safe on direct production for $f_a$ at TeV or higher. Chargino bound also satisfied.

Must ensure that $\tilde{s}$ does not overclose the universe. Assume $\tilde{s}$ decays to 1-10 eV gravitino, and it is cosmologically ok. Actual DM stabilized by additional $Z_2$.

Scalar $s$ can give a large DM-nucleon force. Mild fine-tuning necessary to get Sommerfeld enhancement without contradicting CDMS/XENON bounds.

To have light scalar $s$, scalar/fermion DM must be nearly degenerate. Coannihilation shifts preferred values of $m_{DM}/f_a$. 

\[
m_{DM}, f_a \quad \text{TeV}
\]

\[
v_{EW} \quad \epsilon f_a \quad 100 \text{ GeV}
\]

\[
\mu_H \quad \lambda f_a \quad 100 \text{ GeV}
\]

\[
m_Z \quad 91 \text{ GeV}
\]

\[
m_s \quad \lambda \epsilon f_a \quad 10 \text{ GeV}
\]

\[
m_{\tilde{s}} \quad \lambda \epsilon^2 f_a \quad 1 \text{ GeV}
\]

\[
m_a \quad 1-10 \text{ eV}
\]

\[
m_{\text{gravitino}} \quad 1-10 \text{ eV}
\]
Collider Phenomenology

Higgs decays to muons via axion portal

(Also, $h_0 \rightarrow 2s \rightarrow 4a \rightarrow 8\mu$

Since we are in small $\lambda$ limit, not expected to be dominant mode.

$$\frac{\Br(h_0 \rightarrow aa)}{\Br(h_0 \rightarrow b\bar{b})} \sim \frac{\lambda^4}{\lambda_b^2}$$

Extended SUSY Cascades with s/a Fields

Would-be lightest neutralino decays to $\tilde{s}$.

$\tilde{s}$ is typically stable on collider time scales, and gives “massless” missing energy.

Lots of muons from a decays.

Lots of muons from $s \rightarrow aa$ decays.

Because of mixing, $\chi_0$ can decay to Higgs or Z, too.
A SUSY Axion Portal

Extend PQ-SUSY with DM

\[ W = \lambda S H_u H_d + \xi S \Psi \Psi^c \]

Same number of free parameters
\[ \{ m_{DM}, \mu_H, \tan \beta, m_a \} \]

Muon-rich Collider Signals

+ standard SUSY final states

\[ m_{DM}, f_a \]
\[ v_{EW} \]
\[ \mu_H \]
\[ \lambda f_a \]
\[ m_s \]
\[ \lambda \epsilon f_a \]
\[ m_{\tilde{s}} \]
\[ \lambda \epsilon^2 f_a \]
\[ m_a \]
A Revised TeV-Scale Paradigm

Introducing the Axion Portal

Connecting DM and EWSB

Galactic Signals and Constraints

From Positrons to Gamma Rays
Axion portal is in broader class of cascade annihilation models

Generic Axion Portal is like a One-and-a-Half Step Cascade

\((\Psi\Psi \rightarrow sa, s \rightarrow aa, a \rightarrow \ell\ell)\)

For muon decays, electron spectrum looks as if two extra steps

\(U(1)_{PQ}\) Axion Portal is effectively a Three-and-a-Half Step Cascade

\((\Psi\Psi \rightarrow sa, s \rightarrow aa, a \rightarrow \mu\mu, \mu \rightarrow e\nu\nu)\)
From Injection to Earth

Folded with Galactic Propagation

[Moskalenko, Strong; Baltz, Edsjo; Delahaye, Lineros, Donato, Fornengo, Salati; ...]

Electrons diffuse in (turbulent) galactic magnetic fields (~μG)...

...and lose energy from inverse Compton scattering, synchrotron.

$$K \sim \frac{(100 \text{ pc})^2}{\text{Myr}}$$

$$\frac{dE}{dt} \sim \frac{E^2}{\text{TeV Myr}}$$

Hard electrons/positrons come from “local” region (< kpc, compare galactic center at 8 kpc)
Any of these cascades give reasonable fit to PAMELA/ATIC
(Approximate HESS electron spectrum also shown)
Gamma Rays from FSR

Cascade annihilation give softer photons & fewer photons

Photon Spectrum in Collinear Limit:
\[
\frac{dN_\gamma}{dx} \sim \frac{\alpha_{\text{EM}}}{\pi} \frac{1}{x} \log \frac{Q}{m_\mu}
\]

Direct: \( Q = m_{\text{DM}} \)

Cascades: \( Q = m_{\text{portal}} \) & Softer

Cascade annihilation weaken FSR gamma ray bounds!

(Inverse Compton scattering affects these bounds, but dependent on galactic starlight maps.)
Under Investigation...

Neutrinos from Galactic Center in Muon Cascades

Muon-type neutrinos hit rock, create upward-going muon flux. Important constraints from Super-K

[see also Liu, Yin, Zhu; Hisano, Kawasaki, Kohri, Nakayama; ...]

For TeV neutrinos, standard assumptions about neutrino-nucleon scattering cross section and muon energy loss start to break down.

Direct Detection Constraints

Scalar $s$: Couples to strange quark through mixing with down-type Higgs. Mediates spin-independent DM-nucleon force. CDMS/XENON bounds very sensitive to $m_{DM}$, $m_s$, and mixing angle.

Axion $a$: Only contributes spin-dependent DM-nucleon force, but not at zero velocity. What are the bounds? How does one properly calculate this? (violates micrOMEGAs assumptions)
WMAP Haze vs. 408 MHz Radio?

A question for the experts

**WMAP Haze:** apparent excess of synchrotron emissions from galactic center (23-61 GHz).

[Finkbeiner; Hooper, Dobler, Finkbeiner]

In light of PAMELA/ATIC, DM annihilation uniquely positioned to explain haze

[Zhang, Bi, Liu, Liu, Yin, Qiang Yuan, Zhu; ...]

Recent claims that DM annihilation gives too much synchrotron at 408 MHz

[Bertone, Cirelli, Strumia, Taoso; Bergstrom, Bertone, Bringmann, Edsjo, Taoso; see also Borriello, Cuoco, Miele]

But 408 MHz sky map used to extract Haze!

**Q:** Is WMAP Haze from DM annihilation consistent with 408 MHz observations?
The Axion Portal

Straightforward idea...
\[ \mathcal{L} = -\xi S \psi \psi^c \quad \langle S \rangle = f_a \]
...that (re)connects DM and EWSB
\[ W = \lambda S H_u H_d + \xi S \Psi \Psi^c \]

Is this the right explanation for PAMELA/ATIC?

Enhanced halo annihilation...

...with copious lepton production

Muon-Rich Collider Signals

PRELIMINARY