Simple Theories of Dark Matter

Clifford Cheung

Berkeley Center for Theoretical Physics, UC Berkeley (Berkeley, CA)
Theoretical Physics Group, Lawrence Berkeley National Laboratory (Berkeley, CA)

M. Baumgart, C.C., J. Ruderman, L. Wang, I. Yavin **(0901.0283)**

C.C., J. Ruderman, L. Wang, I. Yavin **(0902.3246)**

C.C., J. Ruderman, L. Wang, Yavin **(0909.0290)**

outline

- motivations
- a theory of dark matter
- an abelian theory
- a non-abelian theory
- collider phenomenology
- conclusions

motivations

This work is dually motivated by

experiment:

Anomalies from astrophysics.

Unchartered low energy, high luminosity frontier.

theory:

Theoretical prejudice!

a new primary source of e^+e^-?

- **PAMELA:** e^+ rise at 10-100 GeV
- **ATIC:** e^+e^- bump at 300-800 GeV
- **HESS:** e^+e^- rise at 1 TeV
- **FERMI:** e^+e^- rise at 300-1000 GeV
- **WMAP Haze:** synchotron from e^+e^-?

No associated anti-proton excess!

disclaimer!

Possible resolutions are

0) experiments perhaps not be entirely reliable.

1) galactic propagation is not fully understood.

2) new astrophysical sources (pulsars, SNR).

3) dark matter!

Unlike other hypotheses, DM has many implications outside astrophysics.

evidence of non-minimal DM?

- **DAMA:**

  8σ signal conflicts with other experiments.

  $\longrightarrow$ Reconciled by Inelastic DM?

- **INTEGRAL:**

  Spectral line from $e^+e^- \to \gamma\gamma$.

  $\longrightarrow$ Sourced by Exciting DM?

IDM, XDM need mass splittings $\sim$100 keV, 1 MeV.

Tucker-Smith and Weiner **(hep-ph/0101138)**, Finkbeiner and Weiner **(astro-ph/0702587)**

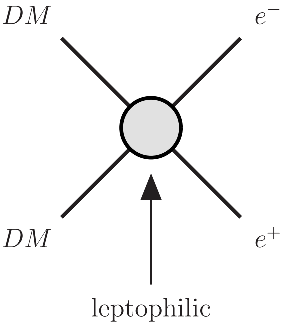
the bottom line(s)

A good theory of DM should have:

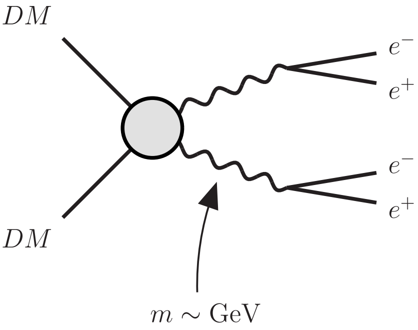
- **more leptons, fewer hadrons**
- **large flux today**
- **possibility for DM substructure**

more leptons, fewer hadrons

dynamics



kinematics



Cholis, Finkbeiner, Goodenough, and Weiner**(0810.5344)**

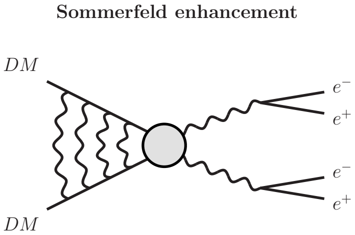
large flux today

decaying DM:

Need dimension 6 GUT decays $\rightarrow \tau \sim 10^{26} s$.

annihilating DM:

$\sigma_{\text{today}} \gg \sigma_{\text{freezout}}$ implies non-thermal production, or Sommerfeld enhancement via a GeV force carrier.

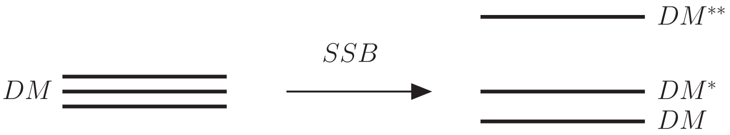


Arvanitaki et. al, **(0904.2789)**, Cholis, Finkbeiner, Goodenough, and Weiner**(0810.5344)**

DM substructure

Why is weak scale DM multiplet degenerate to within 100 keV - 1 MeV?

New gauge or flavor symmetry is broken:

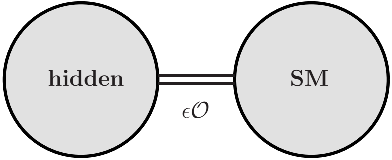


and radiative splittings generated at $\alpha m \sim$ MeV.

Arkani-Hamed, Finkbeiner, Slatyer, and Weiner **(0810.0713)**

a theory of hidden matter

Arbitrary hidden sector:



couples to us via leading marginal couplings

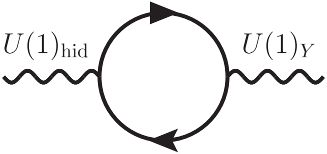
$$\mathcal{O} \;=\; F_{\mu\nu}^{\text{hidden}} B^{\mu\nu}, |\phi_{\text{hidden}}|^2 |h|^2$$

if there is a hidden photon or hidden scalar.

generating ϵ

$\epsilon \sim 10^{-4} - 10^{-3}$ from integrating out heavy fields.

$\epsilon =$



$= \frac{g_{\rm dark} g_Y}{16\pi^2} \log\left(\frac{M}{M'}\right)$

which is generic if $U(1)$'s live in a GUT.

the Holdom effect

At low energies,

$$\begin{aligned}\mathcal{O} &= F_{\mu\nu}^{\text{hidden}} B^{\mu\nu} \\ &= \cos\theta_W F_{\mu\nu}^{\text{hidden}} F^{\mu\nu}\end{aligned}$$

Integrating by parts,

$$F_{\mu\nu}^{\text{hidden}} F^{\mu\nu} \quad \longrightarrow \quad A_{\mu}^{\text{hidden}} J_{\text{EM}}^{\mu}$$

Hidden photons couple to EM charge!

a theory of dark matter

"A theory of DM" is simply a hidden sector with

1) weak scale DM

2) that is charged under $G_{\rm dark} \supset U(1)_{\rm dark}$

3) and $U(1)_{\rm dark}$ is Higgsed at a GeV.

leptons ✓ Sommerfeld ✓ mass splittings ✓

Arkani-Hamed, Finkbeiner, Slatyer, and Weiner **(0810.0713)**

our emphasis

Additions (subtractions) from original framework:

- **GeV scale automatic:**

  Dark Higgsing $\Rightarrow$ dark hierarchy problem.

  With SUSY, GeV$\sim \sqrt{\epsilon g_Y v_{EW}^2}$.

- **extra mileage from abelian G$_{\rm dark}$:**

  Abelian theories easily admit mass splittings.

C.C., J. Ruderman, L. Wang, I. Yavin **(0902.3246)**

an abelian theory

How minimal is the most minimal dark sector?

dark matter: (Φ, Φ^c), $M = 100$ GeV - 1 TeV

dark gauge: $U(1)_{\rm dark}$

dark Higgs: (H, H^c)

All states have unit charge under $U(1)_{\rm dark}$.

origin of scales

With SUSY, the kinetic mixing includes

$$\mathcal{O} \;=\; -\frac{1}{2}\int d^2\theta\, W_{\rm dark} W_Y \supset D_{\rm dark}\langle D_Y\rangle$$

But $\langle D_Y\rangle \neq 0$ due to EWSB

$$\langle D_Y\rangle \;=\; \frac{g_Y}{2}\left(\langle H_u\rangle^2 - \langle H_d\rangle^2\right)$$

So there is a low energy FI term for $U(1)_{\rm dark}$.

dark higgs potential

Integrating out $D_{\rm dark}$ yields

$$V_D \;=\; \frac{g_{\rm dark}^2}{8}\left[(|H|^2 - |H^c|^2 + |\Phi|^2 - |\Phi^c|^2) + v_{\rm dark}^2\right]^2$$

where we have defined

$$v_{\rm dark}^2 \;=\; 2\epsilon\langle D_Y\rangle/g_{\rm dark} \sim (1 \text{ - } 10 \text{ GeV})^2$$

Either gauge breaking or SUSY breaking at a GeV!

the vacuum

SUSY preserving, $U(1)_{\mathrm{dark}}$ breaking minimum at

$$\langle H^c \rangle \; = \; v_{\mathrm{dark}}$$

with all other fields set to zero.

The dark photon gets a mass

$$m^2 \; = \; g_{\mathrm{dark}}^2 v_{\mathrm{dark}}^2 \sim (1\text{-}5 \text{ GeV})^2$$

guaranteeing leptons and Sommerfeld enhancement.

superpotential

Impose a $\mathbb{Z}_2$ on (Φ, Φ^c) for stable DM.

Impose PQ forbidding HH^c.

The leading order superpotential is

$$W = M\Phi\Phi^c + \frac{\lambda}{4M}\Phi^2 H^{c2} + \dots$$

with λ generated by integrating out heavy fields.

mass splittings

DM multiplet is split by dark Higgsing!

In the (Φ, Φ^c) basis

$$\mathcal{M}_{\rm fermion} \; = \; \begin{pmatrix} \frac{\lambda v_{\rm dark}^2}{M} & M \\ M & 0 \end{pmatrix}$$

with mass eigenstates

$$\Phi_\pm \; = \; (\Phi \pm \Phi^c)/\sqrt{2}$$

where Φ_- is stable DM.

realization of idm

Mass eigenvalues are split by

$$M_+ - M_- = \frac{\lambda v_{\rm dark}^2}{M} \sim \frac{\rm GeV^2}{\rm TeV} \sim 0.1\text{ - }1\ {\rm MeV}$$

and gauge interactions are inelastic

$$\mathcal{L}_{\rm fermion\text{-}gauge} \;=\; g_{\rm dark} A^{\mu}_{\rm dark} \left(\bar{\Phi}_+ \bar{\sigma}_\mu \Phi_- + \bar{\Phi}_- \bar{\sigma}_\mu \Phi_+ \right)$$

which is a realization of IDM!

direct detection

Unfortunately, this theory is a bit too predictive!

DM-nucleon scattering cross-section goes as

$$\sigma \sim \frac{\alpha_{\rm dark}\epsilon^2}{m^4} = \frac{1}{16\pi \left\langle D_Y \right\rangle^2}$$

and all dependence on $\alpha_{\rm dark}$ and ϵ has cancelled!

There is an intimate connection between the EW scale and direction detection.

dark higgs spectrum

problem:

H^c is eaten, H is massless.

Dark photons decay to H-inos rather than e^+e^-!

resolution:

Lift H with an NMSSM-like singlet N.

The operator $\kappa NH\langle H^c \rangle$ gives (N, H) a Dirac mass.

Cranking up κ ensures that $2m_{NH} > m$.

minimality vs reality

The simplest model of $U(1)_{\rm dark}$ charged DM yields

- leptons via kinematics
- Sommerfeld enhancement
- small mass splitting

and all the correct mass scales automatically!

But the SM is anything but minimal.

What if DM is less than minimal?

a non-abelian theory

We considered $G_{\mathrm{dark}} = SU(2) \times U(1)$.

Model building issues:

- G_{dark} completely Higgsed at a GeV
- dark gauge boson is lightest state
- appropriate mass splittings (100 keV - 1 MeV) to realize IDM or XDM.
- no leftover custodial symmetries which could impede IDM or XDM.

M. Baumgart, C.C., J. Ruderman, L. Wang, I. Yavin **(0901.0283)**

copying the SM

Simplest non-abelian theory:

$SU(2) \times U(1)$ with n Higgs doublets.

Gauge mass matrix in $(W_1, W_2, W_3, B)_{\mathrm{dark}}$ basis:

$$m^2 = \begin{pmatrix} a & 0 & 0 & b_1 \\ 0 & a & 0 & b_2 \\ 0 & 0 & a & b_3 \\ b_1 & b_2 & b_3 & c \end{pmatrix}$$

Charge is broken.

custodial symmetry

Apply an $SU(2)_L$ transformation

$$\begin{pmatrix} a & 0 & 0 & b_1 \\ 0 & a & 0 & b_2 \\ 0 & 0 & a & b_3 \\ b_1 & b_2 & b_3 & c \end{pmatrix} \overset{SU(2)_L}{\longrightarrow} \begin{pmatrix} a & 0 & 0 & 0 \\ 0 & a & 0 & 0 \\ 0 & 0 & a & \sqrt{b_i^2} \\ 0 & 0 & \sqrt{b_i^2} & c \end{pmatrix}$$

Residual $U(1)_{\mathrm{cust}}$ acts on $W^{\pm}_{\mathrm{dark}}$.

A_{dark} and Z_{dark} mix with photon, but $W^{\pm}_{\mathrm{dark}}$ cannot.

transitions among DM

problem:

DM states have distinct $U(1)_{\rm cust}$ charges, and thus transitions are mediated by $W^{\pm}_{\rm dark}$.

But $W^{\pm}_{\rm dark}$ does not couple to $J_{\rm EM}$!

resolution:

$U(1)_{\rm cust}$ broken at one loop. Or,

$U(1)_{\rm cust}$ broken at tree with triplet Higgses.

higgs galore

Lots of symmetry breaking $\Rightarrow$ lots of Higgses.

SUSY adds complications:

- **symmetry breaking difficult:**

  SUSY highly constrains the potential. For instance, the MSSM cannot break charge.

- **even more Higgses:**

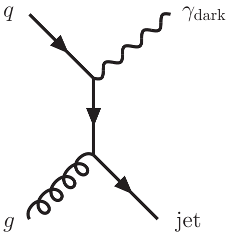
  Anomaly cancellation, scalars complex.

Collider signatures?

collider portals

Dark photon couples to EM current.

Analogous to prompt photon production



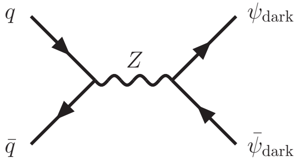
recoiling off a jet.

collider portals

Z couples to dark gauge current

$$\begin{aligned} \mathcal{O} &\supset -\sin\theta_W Z_\mu J^\mu_{\rm dark} \\ J^\mu_{\rm dark} &= g_{\rm dark} \sum \phi^\dagger_{\rm dark} i D^\mu \phi_{\rm dark} + \bar{\psi}_{\rm dark} \gamma^\mu \psi_{\rm dark} \end{aligned}$$

Dark states from rare Z decays!

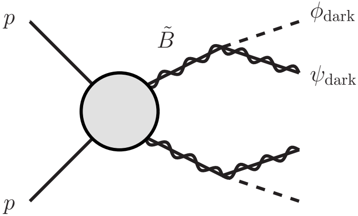


collider portals

MSSM bino couples to dark bino current

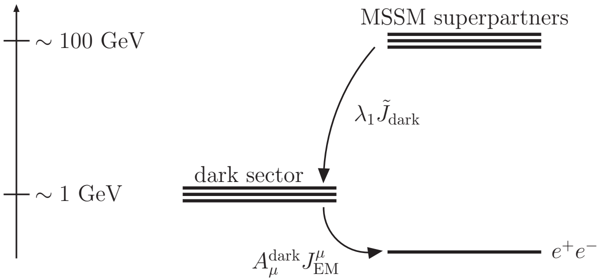
$$\mathcal{O} \supset \lambda_1 \tilde{J}_{\rm dark}$$
$$\tilde{J}_{\rm dark} = g_{\rm dark} \sum \bar{\psi}_{\rm dark}\phi_{\rm dark}$$

Dark state from -ino production!



to, and back

SUSY production cascades into the dark sector

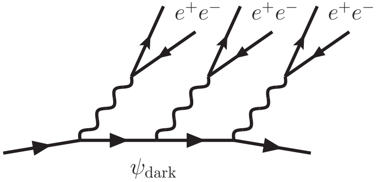


and comes back as collimated "lepton jets".

e^+e^- in every SUSY event!

dark showering

Also, boosted dark states will radiate dark photons

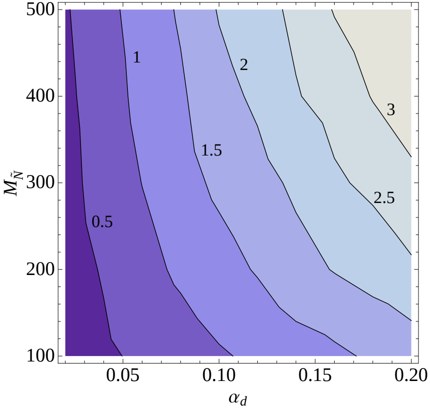


Sudakov estimates number of dark photons as

$$N_{A^\mu_{\mathrm{dark}}} \sim \frac{\alpha_{\mathrm{dark}}}{2\pi} \log\left(\frac{M^2_{\mathrm{EW}}}{M^2_{\mathrm{dark}}}\right)^2$$

dark sudakov

Or, via simulation, we find



conclusions

- SUSY hidden sectors with abelian force carriers generically acquire a $\sim$GeV mass scale.
- Given stable DM, this accommodates leptophilia and Sommerfeld enhancement.
- Additional structure is optionally generated in abelian and non-abelian theories.
- These models are motivated by past *and* future experiments!