In Search of Dark Matter:
Theoretical Models and Their Experimental Signatures

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Overwhelming Evidence for Dark Matter
Evidence for DM
Overwhelming

All evidence points toward

- BBN (baryons)
- CMB (curvature)
- LSS (matter)
- Supernovae (DE)
- Galaxy curves (matter)
New Physics

Dynamical Selection?

New Dynamics in Particles, Definitely BSM
What Do We Know About the Dark Matter?

Afshordi, McDonald, Spergel

[Diagram showing various stages of the universe's development, including BBN, CMB, and MACHO searches + Lyα, with references to radius of the visible universe, age of the universe, and various models of the Big Bang, inflation, quark soup, big freeze out, parting company, first galaxies, and modern universe.]

BBN (baryons)  CMB (curvature)  Supernovae (DE)  LSS (matter)  Galaxy curves (matter)
What Do We Know About the Dark Matter?

- BBN (baryons)
- CMB (curvature)
- Supernovae (DE)
- LSS (matter)
- Galaxy curves (matter)

CMB
LSS
LSS+Bullet Cluster
Not Modified Gravity
What Do We Know About the Dark Matter?

BBN (baryons)  CMB (curvature)  Supernovae (DE)  LSS (matter)  Galaxy curves (matter)

Halo Shapes  Weakly Self-interacting  Direct Probes  Weakly Interacting with Us

FIG. 1: Allowed regions in ($m_X, \alpha_X$) plane, where $m_X$ is the mass of the dark matter charged under the unbroken hidden sector U(1)$_{EM}$ with fine-structure constant $\alpha_X$. Contours for fixed dark matter cosmological relic density consistent with WMA Pre results, $\Omega_X h^2 = 0.1$, are shown for $(\tan \theta h W, \xi_{RH}) = (\sqrt{3}/5, 0.8), (\sqrt{3}/5, 0.1), (10, 0.1)$ (dashed), from top to bottom, as indicated. The shaded regions are disfavored by constraints from the Bullet Cluster observations on self-interactions (dark red) and the observed ellipticity of galactic dark matter halos (light yellow). The Bullet Cluster and ellipticity constraints are derived in Secs. VIII and VII, respectively. Of the parameter space of these models are excluded because the predicted minimum mass halo is in conflict with observations.

In this section, we analyze the kinetic decoupling of hidden charged dark matter. One notable difference between the WIMP and hidden charged dark matter is that the charged dark matter interacts not only through weak interactions, but also through EM interactions. For the case of $\tilde{\tau}_h$ dark matter, this implies that the dark matter remains in kinetic contact not only through the weak process $\tilde{\tau}_h \nu_h \leftrightarrow \tilde{\tau}_h \nu_h$, but also through the Compton scattering process $\tilde{\tau}_h \gamma_h \leftrightarrow \tilde{\tau}_h \gamma_h$. As we will see, at low temperatures, the thermally-average cross section is suppressed by $T_h^2/m_X^2$, but this suppression is absent for Compton scattering, creating a large, qualitative difference between this case and the canonical WIMP scenario. Note also that, in principle, in the case of charged dark matter, bound state formation also impacts kinetic decoupling. As we will see in Sec. V, however, very few staus actually bind, and so this effect is not significant and may be neglected in our analysis.

We follow Refs. [54, 55] to determine the temperature of kinetic decoupling for the dark matter particle. In the hidden sector, the Boltzmann equation governing the evolution of the dark matter particle's phase space distribution is

$$\frac{df}{dt} = \Gamma(T_h)(T_h m_X \Delta \vec{p} + \vec{p} \cdot \nabla \vec{p} + 3) f(\vec{p})$$

(6)
How Dark is Dark Matter?

Consider All Epochs!

McDermott, Yu, KZ '10
How Dark is Dark Matter?

- Which probe is the most constraining?

\[
\frac{d\sigma}{d\Omega} \propto \frac{1}{v^4}!
\]

Figure 1: Constraints from various sources, from top to bottom: (i) Scattering in the bullet cluster and NGC720, (ii) DM as a charged thermal relic, and (iii) DM virial processes, and (iv) recombination epoch.

The thermally averaged momentum transfer per unit time is
\[
\frac{d\langle \delta p^2 \rangle}{dt} = \sum b = e,p n_b \int d^3v_B d^3v_X f(v_B) f(v_X) d\Omega^* d\sigma_{Xb} d\Omega^* v_{rel} \delta p^2_X ,
\]

(11)

where \(d\sigma_{Xb}/d\Omega^*\) is given by Eq. (2), \(n_b\) is the number density of the baryon, and \(\delta p^2_X\) is the momentum transfer after one collision:
\[
\delta p^2_X = 2\mu_b^2 v^2_{rel} (1 - \cos \theta^*).
\]

(12)

Note that this quantity is reference frame independent. The thermally averaged momentum squared of the DM particle in its comoving frame is
\[
\langle p^2_X \rangle = \int d^3v_X f(v_X)(m_X v_X)^2 = \frac{3}{2} m_X^2 v_0^2 = 3 m_X T
\]

(13)

for a DM particle in a thermal Maxwell distribution. To evaluate the thermal average for \(v_{rel}^2\), we derive a general formula. For a given function of \(g(v_{rel})\), we have
\[
\int d^3v_a d^3v_b f(v_a) f(v_b) g(v_{rel}) = \int dv_{rel} v_{rel}^2 \frac{4}{\sqrt{\pi}} \frac{1}{(v_{rel}^2 a + v_{rel}^2 b)^{3/2}} e^{-v_{rel}^2 v_0^2 b + v_{rel}^2 v_0^2 a} g(v_{rel}),
\]

(14)
Neutrinos and the Weak Interactions

\[ M_{pl} \sim 10^{19} \text{ GeV} \]

Gravitational Interactions

\[ M_{p} \sim 1 \text{ GeV} \]

Weak Interactions
\[ M_{wk} \sim 100 \text{ GeV} \]

Neutrinos

Inaccessibility

Energy

Standard Model

Tuesday, October 2, 12
Super-Weakly Interacting

- Gravitational Coherence
- Helps us learn about aggregate properties of dark matter
- Particle properties much harder
Particle Physics Provides Some Ideas

- Fundamental premise: DM has interactions other than gravitational

Sub-weak Interactions

$M_p \sim 1 \text{ GeV}$

Standard Model

Weak Interactions

Dark Matter

?
Particle Physics Provides Some Ideas

- Particle Physics Zoo!

Sub-weak Interactions
Dark Matter Resides Here!
Weakly Interacting Massive Particles (WIMPs)

\[ M_p \sim 1 \text{ GeV} \]

Tuesday, October 2, 12
Sub-Weakly Interacting Massive Particles

Weak interactions
Z boson

Standard Model

Dark Matter

\( \sigma_n \sim 10^{-39} \text{ cm}^2 \)
Sub-Weakly Interacting Massive Particles

This result excludes a large fraction of previously unexplained spin-independent elastic WIMP-nucleon cross-section. This limit is consistent with the absence of a signal above background and is also shown as the thick blue line together with the blue area favored by XENON100 (2011) and a density of gray. 

The impact of uncertainties in the energy scale as indicated in the figure. 

Uncertainties in the energy scale as well as uncertainties in the acceptance as indicated in the figure. Uncertainties in the energy scale as well as the kaon area are also shown. 

The sensitivity is the expected limit in the new XENON100 results. The new result challenges the interpretation of the DZ 

We gratefully acknowledge support from the Volkswagen Foundation, FCT, SNF, DFG, and the Weizmann Institute of Science. 

We are grateful to LNGS for hosting and supporting XENON. 

Portions of this run are indicated at XENON100 and XENON100 (2010) as well as channeling. 

The energy resolution is negligible at low keV. 

The sensitivity is the expected limit in the new XENON100 results. The new result challenges the interpretation of the DZ 

We gratefully acknowledge support from the Volkswagen Foundation, FCT, SNF, DFG, and the Weizmann Institute of Science.
Sub-Weakly Interacting Massive Particles

$\chi^{(')}$

$\sigma_n \sim 10^{-45-46} \text{ cm}^2$

$\chi$

$N$

Higgs boson

$M_p \sim 1 \text{ GeV}$

Standard Model

Dark Matter

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• “Generic” WIMP also doesn’t give correct relic density

from a talk by H. Baer

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Theories of Dark Matter

- **Axions**
  - Solve Strong CP
  - Correct density of high scale axions via selection

- **WIMPs**
  - Naturally obtain correct density via freeze-out
  - Connected to weak scale

- **Chemical Potential Dark Matter**
  - Naturally obtain correct density via chemical potential
  - Connected to weak scale
Chemical Potential Dark Matter
**Baryon and DM Number Related?**

- Standard picture: freeze-out of annihilation; baryon and DM number unrelated
- Accidental, or dynamically related?

Experimentally, Mechanism

\[
\Omega_{DM} \approx 5\Omega_b \\
n_{DM} \approx n_b \\
m_{DM} \approx 5m_p
\]

Nussinov, Hall, Gelmini, Barr, Chivukula, Farhi, D.B. Kaplan
DM Mass Scales

- DM can be heavier if DM number violating operators decouple late

\[ n_X - n_{\bar{X}} \sim (n_b - n_{\bar{b}}) e^{-m_{DM}/T_d} \]

- Extra Boltzmann suppression
Technibaryon and Quirky dark matter

- Use sphalerons to transfer asymmetry
- First used in the context of technicolor, by Barr, Chivukula, Farhi; D. B. Kaplan
- Sphalerons mix SM fields carrying $B,L$ with technifermions
Technicolor and Technibaryons

Technifermions transform under SM

Technibaryon is gauge singlet (scalar or fermion)

TB number is accidental global symmetry, completely analogous to baryon number.

- LEP, precision EW and Technicolor
- Self-interacting Dark Matter constraints
- Struggle to obtain correct relic density
A SIMPLE PRESCRIPTION: 
ASYMMETRIC DM

• Avoids the pitfalls of models which have their asymmetry related to the baryon asymmetry via standard model quantum numbers

• Essential idea is to use higher dimension operators to transfer the asymmetry between sectors
Asymmetric DM

Integrate out heavy state
Effective operators:

\[ X u^c d^c d^c \]

\[ M_p \sim 1 \text{ GeV} \]

Standard Model

Inaccessibility

Dark Matter
(Hidden Valley)

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**Asymmetric DM**

\[ O_{B-L}O_X \]

Energy

\[ O_{B-L} = LH_u, LLE^c, QLD^c, U^c D^c D^c \]

\[ O_X = X, X^2 \]

\[ M_p \sim 1 \text{ GeV} \]

Standard Model

Dark Matter

Inaccessibility
Asymmetric Dark Matter
Robust alternative: annihilate to light states!

\[ n_{DM} \sim T^3 \rightarrow 10^{-10} T^3 \]

\[ \Delta W = \lambda_X S X \bar{X} + \lambda_H S H_u H_d + \frac{\kappa}{3} S^3. \]

\[ \Delta \mathcal{L}_{\text{eff}} = m_X \bar{X} X e^{ia/s} + \text{h.c.}, \]
Dark Forces and DM Self-Interactions

- Dark Forces Natural for ADM
- Structure problems and dark forces
- Very big scattering cross-sections!

\[ \sigma / m_X \sim 0.1 \text{ cm}^2 / \text{g} \approx 0.2 \times 10^{-24} \text{ cm}^2 / \text{GeV} \]

\[ \sigma_T \approx 5 \times 10^{-23} \text{ cm}^2 \left( \frac{\alpha_X}{0.01} \right)^2 \left( \frac{m_X}{10 \text{ GeV}} \right)^2 \left( \frac{10 \text{ MeV}}{m_{\phi}} \right)^4 \]
Is CDM and Halo Structure a Problem?

- Halo substructure: satellite galaxies and sub-halos -- more satellites found
- Halo cores and central densities
- Feedback?  
  Governato et al ‘10
- In dwarves hard to understand how so little stellar feedback could blow out so much material: $M_* \sim 10^6 M_\odot$ blows out $5 \times 10^7 M_\odot$
  
Bolyan-Kolchin et al ‘11

“Too Big to Fail”
Scattering Not Generically Constant

- Quantum  $\sigma \sim \frac{m_X^2}{(m_X^2 v^2 + m_\phi^2)^2}$
- Classical  $\sigma \sim \frac{\pi \ln \beta}{m_\phi^2}$
- Resonant -- Born approx breaks down
  \[ \beta = 2\alpha_X m_\phi / m_X v^2 \]
- Many modes contribute -- fairly intensive
Resonant Dark Forces and Structure

- Verify classical result numerically and presence of Sommerfeld-like effect for scattering
Resonant Dark Forces and Structure

- Verify classical result numerically and presence of Sommerfeld-like effect for scattering
Astrophysical Implications

- DM does not annihilate
- It can accumulate in the center of stars
- Notable case: neutron stars
- Elastically scatter, come to rest in core
- High density!
ADM, Black Hole and Neutron Stars

• Scalar case can lead to BH formation
• DM continues to accumulate until there are enough that they self-gravitate
• OR, they first form Bose-Einstein condensate and then self-gravitate
• Once they self-gravitate, they can collapse to form a BH!
Figure 2. Regions (colored) excluded by the nearby pulsars J0437-4715 (left) and J2124-3358 (right). The shaded, diagonal and square cross-hatched, and black regions are as in Fig. 1.

With the formation of a BEC it is also sensitive to the mass range \( m_X \sim 100 \mathrm{MeV} \). The captured scalar ADM cannot form a BEC in the pulsar J1124-3358. This is because it has a relatively high central temperature, and the formation of a BEC requires a DM-nucleon cross section larger than the saturation cross section \( \sigma_{\text{max}} \).

Since the bound is sensitive to the DM density, we also consider neutron stars in regions with high \( \rho_X \) (cm\(^{-3}\)). This type of environment and observations of Pulsar Bkpljglp place it in the globular cluster M15 with an age of \( t \sim 10^8 \text{ years} \). Since it is far away from us, its surface temperature is unknown, and we are not able to calculate its central temperature. In our analysis, we take \( T \sim 10^6 \text{ K} \) as a reasonable approximation due to its advanced age. We take \( \rho_X \sim 10^3 \text{ GeV/cm}^3 \) for the DM density and \( \bar{v} \) for the DM velocity.

Motivated by simulations, we take \( \sigma_X \sim 10^{-48} \text{ cm}^2 \) and all captured DM particles collapse before a BEC forms.

VII. CONCLUSIONS

We have studied the consequences of scalar ADM accumulation in neutron stars. Neutron stars have high density and are ideal objects for capturing DM at high rates. Since ADM does not selfannihilate, a high mass of DM can accrete in the neutron star and, lacking Fermi degeneracy pressure, rapidly selfgravitate and exceed the Chandrasekhar limit.
New Avenues for Baryogenesis

Need Baryon violation and CP violation beyond what is currently observed in experiments
Generating an Asymmetry

• Original ADM scenario assumed an asymmetry was generated and then transferred

• Higher dimension operators make a natural playing field for Affleck-Dine Cogenesis = simultaneous generation of asymmetries

Cheung, KZ ‘11
**Cogenesis -- Natural for ADM!**

\[ \mathcal{O}_{B-L} = LH_u, LLE^c, QLD^c, U^c D c D^c, \]

\[ \mathcal{O}_X = X, X^2 \]

\[ \mathcal{O}_{B-L} \mathcal{O}_X \]

- Affleck-Dine works by utilizing flat directions with non-zero \( <B-L> \)
- Note there is a symmetry \( U(1)_{B-L+X} \)
  which generates \(-n_{B-L} = n_X \neq 0\).
- At low temperature, symmetry breaks when \( \mathcal{O}_{B-L} \mathcal{O}_X \) decouples, separately freezing in the asymmetries

\[ U(1)_{B-L+X} \rightarrow U(1)_{B-L} \times U(1)_X \]

Cheung, KZ '11
Cogeneration in the Early Universe

- To see how it works, map to simple mechanical analog: pseudo-particle in 2-dimensions
  \[ \phi = \frac{1}{\sqrt{2}} r_\phi e^{i \theta_\phi} \]
  \[ n_\phi = j^0 = i(\phi \phi^\dagger - \phi^\dagger \phi) = r_\phi^2 \theta_\phi \]
- B-L and X asymmetry: torque on mechanical analog
Cogenesi in the Early Universe

- Two ingredients for successful Affleck-Dine Cogenesis
  - Stabilization: non-zero B-L and X vevs
  - Torque: non-zero angular momentum

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2. Torque

- The torque is exerted when $fm = gH$

$$V_{\text{soft}} \supset (fm + gH) \frac{O_{B-L} O_X}{M^{d-4}}$$

- Claim is that $-n_{B-L} = n_X \neq 0$.

- Easily seen from Lagrangian

$$\mathcal{L} = \frac{1}{2}(r_{B-L}^2 \dot{\theta}_{B-L}^2 + r_X^2 \dot{\theta}_X^2) - V(\theta_{B-L} - \theta_X)$$

Note $\theta_\pm$ conserved!

$$\theta_\pm = \theta_{B-L} \pm \theta_X$$
2. Torque

- Calculable asymmetry, using impulse approximation

\[
\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}_-} = \frac{d}{dt} (n_{B-L} - n_X) = -\frac{\partial V}{\partial \theta_-}
\]

Impulse approximation; evaluate at:

\[
V_{\text{soft}} \supset (f m + g H) \frac{\mathcal{O}_{B-L} \mathcal{O}_X}{M^{d-4}} \quad \text{and} \quad H \sim f m/g.
\]

\[
-n_{B-L} = n_X \sim \frac{\arcsin(f/g)}{g} \frac{\mathcal{O}_{B-L} \mathcal{O}_X}{M^{d-4}}
\]
Oscillating ADM

- Asymmetry may be erased
- Any violation of DM number can lead to dark-anti-dark oscillations
- Like $\nu$ oscillations
- Become important when mass exceeds Hubble expansion

\[ \eta_{\text{DM}} = \frac{Y_X - Y_{\bar{X}}}{\Omega_{\text{DM}}} \]

Cohen, KZ ’09
Falkowski, Rudermann, Volansky ’10
Buckley, Profumo ’11
Cirelli, Panci, Servant, Zaharijas ’11
Tulin, Yu, KZ, ’12
Numerical Results

- Vector interactions
- Quantum Zeno prevents oscillation
- Scattering causes de-coherence and washout
- Washout when oscillations commence
Numerical Results

- Scalar interactions
- Oscillations turn on
- Depletion continues as soon as oscillations commence
Why is it Important to Think About New Models?

Lamp post problem: Experimental results have forced us to look outside the lamp post
1. Direct Detection

CRESST 2011

DAMA
CoGeNT
CRESST
All complicated by uncertainties …

• ... of the experimental kind

• How do you calibrate energy?
\[ O_N = A^\mu \bar{N}(p) (F_1(q)(p+p')_\mu + (F_1(q) + F_2(q))2i\Sigma_{\mu\nu}q^\nu) N(p'). \]

\[ O_a = \bar{\chi}\gamma^\mu\gamma_5\chi A_\mu \]
\[ O_d = \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}/\Lambda \]

\[ \sigma_a = \frac{\mu_N^2}{4\pi(q^2 + M^2)^2} \left( \left( 4v^2 - q^2 \frac{(m_N + m_\chi)^2}{m_N^2m_\chi^2} \right) F_1^2 + \left( F_1 + F_2 \right)^2q^2 \frac{2}{m_N^2} \right), \]
\[ \sigma_d = \frac{4\mu_N^2q^2}{\pi\Lambda^2(q^2 + M^2)^2} \left( \left( 4v^2 - q^2 \left( \frac{1}{m_N^2} + \frac{2}{m_Nm_\chi} \right) \right) F_1^2 + \left( F_1 + F_2 \right)^2q^2 \frac{2}{m_N^2} \right) \]
DM in a Data Rich Discovery Era

- Meaning of experimental results still unclear -- as not uncommonly the case in a discovery era!
- Neutralino from MSSM not viable
- Consider range of theoretically motivated theories
- Is 7-10 GeV mass window suggestive of something else?

Kuflik, Pierce, KZ '10
2. Search Via Annihilations

- How do we get photons from DM annihilation?

1. Direct
2. Final State Radiation
3. Inverse Compton
2. Search Via Annihilations

- Missions in space
- 1. Fermi - photons
  - Many anomalies!
  - DM or astrophysical source?
A Line was Supposed to be a Smoking Gun ...

- Slightly off galactic center
- A broken power law?
- Detector systematic?
A Line was Supposed to be a Smoking Gun ...

- *Large* rate
- Why no continuum photons?
- Continuum should dominate by \( \frac{R_{SM}}{R_{\gamma\gamma}} \sim (\pi/\alpha)^2 \approx 10^5 \)
- Need special models
Some way to:

- suppress continuum photons
- obtain the observed abundance of DM
**Three Exceptions**

- Can suppress continuum today with p-wave cross-section $\langle \sigma v \rangle \sim v^2$
- Annihilation still too large for relic; need additional mechanism $v \sim 0.3$

1. Coannihilation  
2. Forbidden Channels
Three Exceptions

- Can suppress continuum today with p-wave cross-section $\langle \sigma v \rangle \sim v^2$
- Annihilation still too large for relic; need additional mechanism $v \sim 0.3$

3. Asymmetric Dark Matter

(4.) Degenerate States
2. Forbidden Channels
The Road Ahead

- Direct Detection experiments will continue to probe Higgs mediated scattering
- Higgs pole largely covered within 5 - 10 years

\[ \sigma_n \sim 10^{-45} - 10^{-46} \text{ cm}^2 \]
The Road Ahead

- LHC will continue looking for physics Beyond the Standard Model at the weak scale
- Evidence for Higgs; further accumulate this year
- Be patient! Current energy 8 TeV; Ramp-up to 14 TeV after 1-2 year shutdown
The Road Ahead

- PAMELA / Fermi and cosmic ray positrons
- Fermi photons
- Data rich! Many experiments collecting data
SUMMARY

• Dark Matter has not shown itself yet, but we continue to probe from all sides!

Astro Objects
AMS
CDMS
COUPP
CoGeNT
Cresst
DM ICE
Fermi
Icecube
KIMS
LHC
LUX
PAMELA
Panda-X
XENON
....