New Models of Dark Matter

Kathryn M. Zurek
University of Michigan
What do we know about DM?

- Its density
- It is cold
- It is weakly interacting with ordinary matter
- It has weak interactions with itself

Bullet cluster: \[ \frac{\sigma}{m} \gtrsim \frac{1}{\text{GeV}^3} \]
Established Paradigm of DM

- Weakly Interacting Massive Particle (WIMP) and the thermal freeze-out paradigm
- Magic thermal cross-section
- Same cross-section sets relic abundance and size of indirect detection signals

\[ \sigma v \approx \frac{g^4}{1 \text{ TeV}^2} \approx 3 \times 10^{-26} \text{ cm}^3/\text{s} \]

\[ \Omega h^2 \approx 2 \times 10^{-10} \text{GeV}^{-2} \frac{\langle \sigma v \rangle}{(\sigma v)} \]

\[ \Omega h^2 = 0.114 \pm 0.003 \]
SUSY WIMP paradigm

- Further specialization of weak-scale WIMP paradigm
- Sets direct and indirect detection signal expectations, Collider experiment expectations
What do we know about DM?

- Its density correct relic abundance
- It is cold kinetically decouples above 1GeV
- It is weakly interacting with ordinary matter eliminates sneutrino
- It has weak interactions with itself charge neutral particles in MSSM have weak interactions
Actual requirements on DM much weaker

- Its density: Why are the DM and baryon densities so close to each other?
- It is cold: can kinetically decouple well below 1 GeV, as long as before 1 keV
- It is weakly interacting with ordinary matter: will happen with any state connecting through TeV mediator
- It has weak interactions with itself: no dark massless forces with $O(1)$ gauge couplings
Looking beyond SUSY neutralinos

... and UED, little Higgs, etc ... WIMPs

Dark matter is single, stable, weakly interacting massive particle, with density set by thermal freeze-out

Two classes of models that have recently gained traction because of data
Looking Beyond SUSY Neutralino

- Models with gauged dark forces, and a dark Higgs sector
- Solutions to the Baryon-DM coincidence problem
The Data

Forcing us to look beyond an MSSM SUSY neutralino

Fermi and PAMELA


Conley, Cotta, Gainer, Hewett, Rizzo

Don’t obtain hard enough spectrum from neutralino
The Data

Forcing us to look beyond a MSSM SUSY neutralino

DAMA and CoGeNT

Hooper, Collar, Hall, McKinsey

Don’t obtain large enough cross-section from neutralino

Pierce, Kuflik, KZ
The Data

Forcing us to look beyond a MSSM SUSY neutralino

- PAMELA and Fermi
- DAMA and CoGeNT

Dark Gauged Forces

- Don’t obtain hard enough spectrum from neutralino

Asymmetric Dark Matter

- Don’t obtain large enough cross-section from neutralino
Baryon-DM coincidence

In standard picture, DM abundance set by thermal freeze-out

\[ \Gamma_{\text{ann}} \lesssim H \]

What if instead set by baryon density?

Experimentally, \[ \Omega_{DM} \approx 5\Omega_b \]

Find mechanism \[ n_{DM} \approx n_b \]

\[ m_{DM} \sim 5 \text{ GeV} \]
DM–baryon coincidence

- First models used EW sphalerons to transfer the asymmetry
  - S. Barr (1992) and D. B. Kaplan (1993)
  - Kribs, Roy, Terning, KZ (2009)

DM carries EW quantum numbers

\[ L_4 = \begin{pmatrix} \ell_4 \\ \nu_4 \end{pmatrix} \]

Visible sector

- These models no longer work because a) DM cannot be \( > 45 \text{ GeV} \) b) coupling to the Z rules them out
Weak scale DM and the coincidence

The DM can be heavier if operators relating DM and baryon densities decouple *after* DM becomes non-relativistic.

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

\[ \rho_{DM} = m_{DM} (n_X - n_{\bar{X}}) \]

Partial DM asymmetry wash-out

Used in techni-baryon DM models

DM mass from source other than EWSB

Chivukula, Barr, Farhi (1992)
Gudnason, Kouvaris, Sannino (2006)
Two mass windows

\[
\frac{\rho_{DM}}{\rho_{matter}}
\]

\[T_{EWPT}\]
Asymmetric Dark Matter

Asymmetric Dark Matter

Cosmological history:

Asymmetric Dark Matter

Cosmological history:

1. Transfer lepton or baryon asymmetry to DM through higher dimension operator

Cosmological history:

1. Transfer lepton or baryon asymmetry to DM through higher dimension operator

2. Have asymmetry transferring operator decouple before DM becomes non-relativistic (otherwise DM asymmetry washes out)
Asymmetric Dark Matter

Cosmological history:

1. Transfer lepton or baryon asymmetry to DM through higher dimension operator

2. Have asymmetry transferring operator decouple before DM becomes non-relativistic (otherwise DM asymmetry washes out)

3. Annihilate away symmetric abundance

Asymmetric Dark Matter

An example of Asymmetric Dark Matter

DM carries lepton number $L = 1/2$

$$W = \frac{\bar{X}^2 LH}{M}$$

Operator transfers lepton asymmetry to DM

$$2(n_X - n_{\bar{X}}) \approx n_L - n_{\bar{L}}$$

$$m_X \approx 2.4 \text{ GeV} \frac{\Omega_X}{\Omega_b} \approx 11 \text{ GeV}$$

Operator goes out of equilibrium
Asymmetric Dark Matter

An example of Asymmetric Dark Matter

DM carries lepton number $L=1/2$

$$W = \frac{\dot{X}^2 LH}{M}$$

- Prevents wash-out of asymmetry
- Symmetric abundance annihilated away
Many Examples of ADM

Integrate out heavy state
Effective operators:

\[ W = \frac{\bar{X}^2 LH}{M} \]
\[ W = \frac{\bar{X}^2 udd}{M^2} \]
\[ \mathcal{L} = \frac{\bar{X}^2 LHLH}{M^4} \]

Standard Model

Dark sterile state, fundamental or composite
Many Examples of ADM

Integrate out heavy state
Effective operators:

\[ W = \frac{\bar{X}^2 L \bar{H}}{M} \]
\[ W = \frac{\bar{X}^2 u d d}{M^2} \]
\[ \mathcal{L} = \frac{\bar{X}^2 L H \bar{L} H}{M^4} \]

Standard Model
Visible

Dark sterile state,
fundamental or composite
Hidden
Annihilating Symmetric Abundance

- The asymmetry is very small relative to the symmetric part: \( n_X - n_{\bar{X}} \approx 10^{-10}(n_X + n_{\bar{X}}) \)
- Remove via annihilation through heavy states because \( n_b / n_\gamma \approx 10^{-10} \)
- Or, add new light states
- The new states could be part of mechanism for DM mass generation

\[
\ell \quad H' \quad \bar{\ell} \\
\begin{array}{c}
X \\
\bar{X}
\end{array}
\]

\[
m_{H'}/y \lesssim 200 \text{ GeV}
\]

\[
\bar{X} X \rightarrow aa
\]

\[
e^{ia/f} m_X \bar{X} X
\]
ADM: Gateway to a Hidden World

Visible

Higher dimension operator

Hidden

Could be complex!

Multiple resonances

Dark forces and dark Higgs mechanism
Looking Beyond SUSY

Neutralino

- Models with gauged dark forces, and a dark Higgs sector
- Solutions to the Baryon-DM coincidence problem
Dark Forces in Dark Sectors

- Dark Forces in the Dark Sector are not new
- An example: MeV Dark Matter

\[
g' = 1 \quad g = 10^{-6}
\]

\[
m_{DM} = 1 \text{ MeV} \quad m_U = 1 \text{ MeV}
\]

511 keV line observed by integral toward galactic center
A recent example of dark forces

Arkani-Hamed, Finkbeiner, Slatyer, Weiner  
Pospelov and Ritz

- PAMELA and Fermi positron excesses
- How to obtain annihilation to *leptons*?

Requires light hidden gauge boson, light hidden Higgses
How does SUSY enter?

It can stabilize the Higgses in the hidden sector, even when they are much lighter than the weak scale!

An example: MeV Dark Matter

\[ g' = 1 \quad g = 10^{-6} \]

Weak coupling to SUSY breaking

\[ m_D \sim g g' m_{SUSY} \]

Small hidden SUSY masses!

\[ m_{DM} = 1 \text{ MeV} \quad m_U = 1 \text{ MeV} \]
Little Gauge Mediation

- Two loop graphs
- Introduce negative $m^2$ for D, break dark gauge group
- MeV example:
  \[ m_D^2 = \frac{-g^2 g'^2}{128 \pi^4} m_f^2 \log \left( \frac{\Lambda_{UV}^2}{m_f^2} \right) \]
  \[ \simeq -5 \text{ MeV}^2 \left( \frac{g g'}{3 \times 10^{-6}} \right)^2 \]
- How to obtain small couplings?
Kinetic Mixing

Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Pospelov and Ritz
Cheung, Ruderman, Wang, Yavin

A mechanism for naturally generating GeV scale

\[ m_D^2 = - \frac{g^2 g'^2 \chi^2}{128 \pi^4} m_f^2 \log \left( \frac{\Lambda_{UV}^2}{m_f^2} \right) \]

\[ \approx -5 \text{ GeV}^2 \left( \frac{gg' \chi}{3 \times 10^{-3}} \right)^2 \]

\[ m_D^2 \sim g' \chi v^2 \cos 2\beta \]
Asymmetric Dark Matter, recap

- Use this mechanism both to generate the DM mass scale and to provide an efficient annihilation mechanism for symmetric abundance
- ADM is charged under dark gauge group
Outlook

- Not seeking to over-emphasize the specifics of any single model.
- However, as data arrives, we may continue to be pushed to look at New Models of DM
- The SUSY neutralino is a well motivated DM candidate ...
- BUT there is a broad world of models
Outlook

- Considered specifically
  
  **Asymmetric Dark Matter**
  
  **GeV Hidden Sectors**
  
- Found both classes of models have qualitatively different cosmology than SUSY neutralinos

- There is a broad world of DM models to explore!