Beyond the WIMP – Alternative dark matter candidates

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Outline

- WIMPs and the thermal production mechanism
- Generalized WIMPs
- Other candidates / production mechanisms
  - freeze-in
  - misalignment mechanism
  - asymmetric dark matter
- Summary and open questions
Standard WIMPs: basic properties

- Weak interactions

- Non-relativistic at chemical decoupling

- Present cosmological density via freeze-out mechanism

- $\mathcal{O}(1) \text{ GeV} \leq m_\chi \leq \mathcal{O}(100) \text{ TeV}$
  - lower bound: $\Omega_{WIMP} \leq 1$
    Lee and Weinberg, 1985
  - upper bound: $\Omega_{WIMP} \leq 1$ and partial wave unitarity
    Griest and Kamionkowski, 1989
Boltzmann equation for WIMP number density:

$$\frac{dn_\chi}{dt} + 3H n_\chi = -\langle \sigma_{\text{ann}} v \rangle \left( n_\chi^2 - n_{\chi \text{eq}}^2 \right)$$

RHS accounts for number changing reactions:
$$\chi + \chi \iff \text{SM} + \text{SM}$$

Steigman, Dasgupta and Beacom, 1204.3622
Neutralino

- MSSM field content:

<table>
<thead>
<tr>
<th>spin 0</th>
<th>spin 1/2</th>
<th>spin 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\tilde{u}_L \quad \tilde{d}_L)$</td>
<td>$(u_L \quad d_L)$</td>
<td>$(3, 2, \frac{1}{6})$</td>
</tr>
<tr>
<td>$\tilde{u}_R$</td>
<td>$u_R^\dagger$</td>
<td>$(\bar{3}, 1, -\frac{2}{3})$</td>
</tr>
<tr>
<td>$\tilde{d}_R$</td>
<td>$d_R^\dagger$</td>
<td>$(\bar{3}, 1, \frac{1}{3})$</td>
</tr>
<tr>
<td>$(\tilde{\nu} \quad \tilde{e}_L)$</td>
<td>$(\nu \quad e_L)$</td>
<td>$(1, 2, -\frac{1}{2})$</td>
</tr>
<tr>
<td>$\tilde{e}_R^\ast$</td>
<td>$e_R^\dagger$</td>
<td>$(1, 1, 1)$</td>
</tr>
<tr>
<td>$(H_u^+ \quad H_0^u)$</td>
<td>$(H_u^+ \quad H_0^u)$</td>
<td>$(1, 2, +\frac{1}{2})$</td>
</tr>
<tr>
<td>$(H_d^0 \quad \tilde{H}_d^-)$</td>
<td>$(\tilde{H}_d^0 \quad \tilde{H}_d^-)$</td>
<td>$(1, 2, -\frac{1}{2})$</td>
</tr>
</tbody>
</table>

- Neutralino mass matrix:

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} \psi^T M_{\tilde{\chi}^0} \psi + \text{h.c.}$$

$$M_{\tilde{\chi}^0} = \begin{pmatrix}
M_1 & 0 & -g' v_d / \sqrt{2} & g' v_u / \sqrt{2} \\
0 & M_2 & g v_d / \sqrt{2} & -g v_u / \sqrt{2} \\
-g' v_d / \sqrt{2} & g v_d / \sqrt{2} & 0 & -\mu \\
g' v_u / \sqrt{2} & -g v_u / \sqrt{2} & -\mu & 0
\end{pmatrix}$$
Prospects for neutralino dark matter detection

Arrenberg et al., Snowmass 2013 CF4 Working Group Report, 1310.8621

- **Open question**: How much is the fate of WIMP dark matter related to the one of SUSY?
Generalized WIMPs

- Canonical WIMPs only couple to nucleon and nucleon spin densities, i.e. SI and SD interactions
- Canonical WIMPs are collision-less after kinetic decoupling
- Two alternatives:
  - generalized WIMP-nucleon interactions
  - self-interacting WIMPs
Example: Non relativistic effective field theory of dark matter-nucleon interactions (NREFT)

Fan et al., 1008.1591; Fitzpatrick et al., 1203.3542

NREFT is based upon two assumptions:
- there is a separation of scales: \( |q|/m_V \ll 1 \), where \( m_V \) is the mediator mass
- dark matter is non-relativistic: \( v/c \ll 1 \)

It follows that the Hamiltonian for dark matter-nucleon interactions is

\[
\hat{H}(r) = \sum_{\tau=0,1} \sum_k c_k^\tau \hat{O}_k(r) t^\tau
\]

\( \hat{O}_k(r) \) are Galilean invariant operators; \( t^0 = \mathbb{1}_{\text{isospin}} \), \( t^1 = \tau_3 \)
Generalized WIMP-nucleon interactions

- Inspection of the operators $\hat{O}_k(r)$ shows that at linear order in the transverse relative velocity $\hat{v}^\perp$, they only depend on 5 nucleon charges and currents:

  \[
  1_N \quad \hat{S}_N \quad \hat{v}^\perp \quad \hat{v}^\perp \cdot \hat{S}_N \quad \hat{v}^\perp \times \hat{S}_N
  \]

- This structure leads to 8 independent nuclear response functions (if nuclear ground states are CP eigenstates)

- For example: $\hat{O}_1(r) = 1_N 1_X \delta^3(r)$ and $\hat{O}_4(r) = \hat{S}_N \cdot \hat{S}_X \delta^3(r)$ are the SI and SD interactions, respectively
Generalized WIMP-nucleon interactions

Kavanagh, Catena and Kouvaris, 1611.05453
Catena, Ibarra and Wild, 1602.04074

DM with non-zero spin

\[ Q_{\text{Na}} = 0.3, \; Q_1 = 0.09 \]

Only DD

\[ \text{DD + Super-K} \] 
\[ (\tau^+\tau^-/W^+W^-) \]

\[ N_{\text{max}} \]

\[ m_\chi \text{ [GeV]} \]

\[ \gamma = \cos^{-1}(\hat{v}_\chi \cdot \hat{r}_\text{det}) \]

\[ N_{\text{pert}}/N_{\text{free}} \]

\[ O_1, O_8, O_{12} \]

Atten. only
Atten.+Defl.
Self-interacting WIMPs

- Example: Thermal WIMP with self-interactions mediated by a light vector messenger

\[ \mathcal{L}_{\text{int}} = -g_\chi \bar{\chi} \gamma^\mu V_\mu \chi - g_\nu \bar{\nu} \gamma^\mu V_\mu \nu \]

Van den Aarssen, Bringmann and Pfrommer, 1205.5809
Bringmann et al., 1612.00845

- The main motivation for this model is to clarify three problematic aspects of ΛCDM Cosmology:
  - cusp vs. core
  - too big to fail
  - missing satellites

- The three aspects are explained via neutrino-induced late kinetic decoupling of dark matter
The small scale “problems” of $\Lambda$CDM mainly rest on the outcome of dark matter only N-body simulations.

In principle, ordinary astrophysics can reconcile theory and observations (Read, Agertz, and Collins, 1508.04143), but a general consensus has not been reached.

E.g., energy injection via supernovae explosion is expected to play a key role in this context.

Open question: Canonical WIMPs are collision-less and cold. Is this the framework currently favored by Cosmology?
A critical view on the thermal production mechanism

- CMB is a thermal relic
- Cosmological neutrinos are a thermal relic
- Present cosmological baryon density determined by: 1) the initial baryon-antibaryon asymmetry; 2) the freeze-out of weak interactions; 3) BBN
- Dark energy??

Open question: Is the thermal production mechanism guiding or misleading us?
Freeze-in mechanism

It applies to Feebly Interacting Massive Particles (FIMPs), X, of negligible initial abundance

Hall et al., 0911.1120
Consider for example the interaction $\lambda XB_1 B_2$, where $B_1$ and $B_2$ are thermal bath particles.

If $m_{B_1} > m_{B_2} + m_X$, $n_X$ obeys the equation

$$\frac{dn_X}{dt} + 3Hn_X = \frac{g_{B_1} m_{B_1}^2 \Gamma_{B_1}}{2\pi} TK_1(m_{B_1}/T)$$

An approximate solution is

$$\Omega_X h^2 \simeq \frac{1.09 \times 10^{27} g_{B_1}}{g^s \sqrt{g^\rho}} \frac{m_X \Gamma_{B_1}}{m_{B_1}^2}$$

Since $\Gamma_{B_1} \propto \lambda^2 m_{B_1}$, $\Omega_X h^2 \simeq 0.1$ implies $\lambda \sim 10^{-13} (m_{B_1}/m_X)^{1/2}$
Freeze-in mechanism

- Notice that $\lambda \sim v / M_*$, where $M_* \sim 10^{15}$ GeV
- This suggests various implementations of the freeze-in mechanism. For example:
  - Moduli with weak scale supersymmetry
  - Dirac neutrino masses within weak scale supersymmetry
  - FIMPs from kinetic mixing
  - Very heavy FIMPs and extra dimensions
    Hall et al., 0911.1120

- FIMPs typically have an unstable partner called “Lightest Observable Sector Particle” (LOSP) with weak scale interactions
- Key experimental signature: production and decay of LOSPs at the LHC $\implies$ displaced vertices
Asymmetric dark matter

Kaplan, Luty and Zurek, 0901.4117

- Freeze-out and -in mechanisms naturally explain the observed order of magnitude of the dark matter relic abundance, but not why this is close to the baryon abundance.

- Asymmetric dark matter: the dark matter density arises from a dark matter particle-antiparticle asymmetry related to the \((B - L)\) asymmetry leading to baryogenesis.

- This mechanism predicts \(n_{DM} \sim n_B\), and therefore \(\Omega_{DM} \sim (m_{DM}/m_B)\Omega_B\).
Asymmetric dark matter

- ADM may modify energy transport in the Sun, changing local neutrino production
  Lopes and Silk, 1209.3631

- The formation of stable compact dark matter objects is predicted
  Kouvaris and Nielsen, 1507.00959

- Direct, indirect and LHC signals possible, but model dependent and non specific do ADM
Asymmetric dark matter

Maximum mass of dark stars (Chandrasekhar limit) for self-interacting ADM

Kouvaris and Nielsen, 1507.00959
Misalignment mechanism

- It is relevant for dark matter candidates that can be described by a classical scalar field $\theta$
- This is a good approximation in the limit of large occupation number for the $\theta$ quanta
- In this case, the cosmological evolution of $\theta$ determines the present density of its quanta
- If $V(\theta) = m_a^2(T) f_a^2 (1 - \cos \theta)$, then
  \[ \ddot{\theta}_0 + 3H \dot{\theta}_0 + m_a^2 \theta_0 = 0 \]
  where $\theta_0$ is the zero mode of $\theta$
- The solution is
  \[ \Omega_{\theta_0} h^2 \sim 0.1 \left( \frac{f_a}{10^{12} \text{GeV}} \right)^\frac{7}{6} \theta_*^2 \]
  where $\theta_*$ is the initial “misalignment”
Popular examples of dark matter candidates produced via misalignment mechanism are:

- Axions
- Axion-like particles (ALPs)
- Wave (or Fuzzy) dark matter

Axions \((a = f_a \theta)\) couple to ordinary matter as follows:

\[
\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu}
\]

\[
\mathcal{L}_{a\bar{f}f} = -i \frac{C_f m_f}{f_a} a \bar{f} \gamma_5 f
\]
Axion searches at ADMX via inverse Primakoff effect

Stern et al., 1612.08296
There is a window for PBHs to be DM if the BH mass is in the range $20 M_\odot \lesssim M \lesssim 100 M_\odot$. Lower masses are excluded by microlensing surveys. Higher masses would disrupt wide binaries.

if DM consists of $\sim 30 M_\odot$ BHs, then the rate for mergers of such PBHs falls within the merger rate inferred from LIGO.

Microlensing and dynamical constraints exclude all the dark matter being in PBHs, when for PBHs mass function produced by inflation models are considered.
Summary and open questions

- Is the thermal production mechanism guiding or misleading us?
- How much is the fate of WIMP dark matter related to the one of SUSY?
- Canonical WIMPs are cold and collision-less. Is this the framework currently favored by Cosmology?
- If dark matter will not be detected in the next 5-10 years, is WIMP dark matter ruled out? If so, what is the next priority?