Changes in Dark Matter Properties After Freeze-Out

Timothy Cohen
with David Morrissey and Aaron Pierce
arXiv:0808.3994

University of Michigan

PHENO Symposium
May 11, 2009

Outline

- Textbook dark matter (DM) analysis assumes a weakly interacting massive particle (WIMP).
- The thermal cross section required to generate $\Omega_{\rm DM}\, h^2 = 0.106$ is $\langle \sigma_a\, v \rangle \approx 3 \times 10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$.
- Recent results from satalite experiments have led many to believe that $\langle \sigma_a\, v \rangle$ is $\mathcal{O}(100)$ times larger today then it was at freeze-out.
- This has inspired many models to explain DM utilizing non-thermal production or the Sommerfeld enhancement.
- We will provide a novel dynamical mechanism to explain how the freeze-out annihilation cross section may be different from the one relevant today.

- Our approach is to change the DM mass and/or couplings after it freezes out.
- Then at $T \approx 0$ we observe the (altered) mass and couplings.
- Assuming a thermal history, we use these measurements to calculate the relic density $(\Omega_{\mathrm{DM}}\, h^2)_{particle}$.
- This calculation will not match the astrophysical value $(\Omega_{\mathrm{DM}}\, h^2)_{astro} = 0.106$ even though the relic abundance was **ACTUALLY** produced thermally.

Our cosmological time-line:

T (GeV)	Event
$\gg$ a few	End of inflation/Reheating
$T_{fo} \approx m_{DM}/20$	Dark matter freeze out
$T_{\rm PT} = ?$	Phase transition $\Rightarrow$ properties of DM change
$T_{\rm BBN} \sim 10^{-3}$	BBN
$T \sim 10^{-13}$	Measure dark matter properties

Outline

Introduce a phase transition (PT) “module”

- A Standard Model singlet scalar field P
- N_Q families of “massless” fermions Q and $\overline{Q}$
- A coupling $\mathcal{L} \ni \lambda_{PQ}\, P\, \overline{Q}\, Q$

Introduce a phase transition (PT) "module"

- A Standard Model singlet scalar field P
- N_Q families of "massless" fermions Q and $\overline{Q}$
- A coupling $\mathcal{L} \ni \lambda_{PQ}\, P\, \overline{Q}\, Q$

This implies a temperature-dependent potential for P of the form

- $V_P(T) = -\frac{1}{2}\left(|m_P|^2 - \frac{N_Q}{6}\,\lambda_{PQ}^2\, T^2\right) P^2 + \frac{1}{4!}\lambda\, P^4$

which has the following properties

- $T_{\mathrm{PT}} = \sqrt{\frac{6\,|m_P|^2}{N_Q\,\lambda_{PQ}^2}}$
- $v_P(T > T_{\mathrm{PT}}) = 0$
- $v_P(T = 0) = \sqrt{\frac{6|m_P|^2}{\lambda}}$

- Due to the strong trapping of the P field at the origin the PT will be 1^{st} order
- This will lead to a brief period of thermal inflation with an associated reheat temperature (T_{RH})

- Due to the strong trapping of the P field at the origin the PT will be 1^{st} order
- This will lead to a brief period of thermal inflation with an associated reheat temperature (T_{RH})
- This effect will dilute the DM abundance by a factor

$$D = \left(\frac{g_*^{\mathrm{PT}}}{g_*^{\mathrm{RH}}} \frac{T_{\mathrm{PT}}^3}{T_{\mathrm{RH}}^3} \right)$$

- such that

$$(\Omega_{\mathrm{DM}}\, h^2)_{astro} = D \times \left(\frac{m_{\mathrm{DM}}^{v_P \neq 0}}{m_{\mathrm{DM}}^{v_P = 0}} \right) \times \Omega_{\mathrm{DM}}^{v_P = 0} h^2$$

Outline

1. Introduction
2. A Late-time Phase Transition
3. A Toy Dark Matter Sector
4. Phenomenology of a Late-time Phase Transition
5. Conclusions and Future Work

- Many possible DM sectors would work with the PT module
- The is an example of a “level-changing” model
- Introduce a vector-like pair of $SU(2)_L$ doublet fermions (ψ_L, $\psi_{\bar{L}}$) (similar to the MSSM Higgsinos)
- Introduce a gauge singlet fermion (ψ_s)
- Introduce DM parity as a symmetry of the Lagrangian

- The Lagrangian is given by (H is the SM Higgs)

$$\mathcal{L} \ni \mu\,\psi_L\psi_{\bar{L}} + \lambda_1\, H\,\psi_L\,\psi_s + \lambda_2\, H^*\,\psi_{\bar{L}}\,\psi_s + \,(\mu_s + \lambda_s\, P)\,\psi_s\,\psi_s$$

- which leads to the mass matrix in the basis $(\psi_L,\, \psi_{\bar{L}},\, \psi_s)$

$$\mathcal{M}^0 = \begin{pmatrix} 0 & \mu & -\lambda_1\,\frac{v_H}{\sqrt{2}} \\ \mu & 0 & \lambda_2\,\frac{v_H}{\sqrt{2}} \\ -\lambda_1\,\frac{v_H}{\sqrt{2}} & \lambda_2\,\frac{v_H}{\sqrt{2}} & 2\,(\mu_s + \lambda_s\,v_P) \end{pmatrix}$$

where $v_H = 246$ GeV

In the limit that $\mu < 2\,\mu_s$

- At high temperature ($T > T_{\rm PT}$) the DM is approximately an equal admixture of ψ_L and $\psi_{\bar{L}}$
- To good approximation (including co-annihilations with the "charginos")

$$\Omega_{\rm DM}^{v_P=0}\,h^2 = 0.1\left(\frac{m_{\rm DM}}{1\,\rm TeV}\right)^2,$$

In the limit that $\mu < 2\,\mu_s$

- At high temperature ($T > T_{\rm PT}$) the DM is approximately an equal admixture of ψ_L and $\psi_{\bar{L}}$
- To good approximation (including co-annihilations with the "charginos")

$$\Omega_{\rm DM}^{v_P=0}\, h^2 = 0.1 \left(\frac{m_{\rm DM}}{1\,{\rm TeV}}\right)^2 ,$$

- While at low temperature ($T < T_{\rm PT}$) the DM is mostly ψ_s (for $\lambda_s < 0$)
- Its annihilation rate (into Q's) is dominated by s-channel P exchange
- To good approximation

$$(\Omega_{\rm DM}\, h^2)_{particle} = \frac{0.02}{N_Q\,(\lambda_{PQ}\,\lambda_s)^2} \left(\frac{m_{\rm DM}}{1\,{\rm TeV}}\right)^2 ,$$

- With this toy model it is relatively easy to realize

$$(\Omega_{\rm DM}\, h^2)_{particle} \gg (\Omega_{\rm DM}\, h^2)_{astro}$$

- Please see arXiv:0808.3994 for specific parameters
- If one would like to obtain

$$(\Omega_{\rm DM}\, h^2)_{particle} \ll (\Omega_{\rm DM}\, h^2)_{astro}$$

  one must increase $\langle \sigma_a\, v \rangle$ after freeze-out which leads to the additional complication of "recoupling" (please see the paper for more details)

Outline

- In order to realize this mechanism one needs the hierarchy

$$T_{\rm PT} < T_{fo}$$

and

$$\lambda_{P-{\rm DM}}\, v_P \sim m_{\rm DM} \sim 20 \times T_{fo}$$

- Satisfying both conditions implies $v_P > |m_P|$
- This requires $|m_P| = \mathcal{O}({\rm GeV})$ and $\lambda \ll 1$
- This results in a light scalar field with allowed couplings to the Higgs boson (via the "Higgs Portal")

- Therefore the phenomenology of P is a generic prediction of this type of model
- Its mass can range from tens of GeV to a fraction of an MeV

- Therefore the phenomenology of P is a generic prediction of this type of model
- Its mass can range from tens of GeV to a fraction of an MeV

Depending on the mass of P it is constrained by

- Rare meson decays ($m_P \sim$ GeV)
- $Z^0 \to Z^0 + P$ at LEP ($m_P \sim 10$ GeV)
- Astrophysical processes (similar to the axion) ($m_P \sim$ MeV)

and could be discovered in

- Rare meson decays ($m_P \sim$ GeV)
- Rare Higgs decays ($m_P \sim$ GeV)
- Light scalar searches at the LHC

Outline

Conclusions

- We have shown how to obtain "thermal" dark matter even if a thermal freeze-out calculation based on observation yields a relic abundance that does not match the astrophysical observation
- This mechanism introduces a late-time phase transition with $(T_{\mathrm{PT}} < T_{fo})$ which couples to the DM sector thereby changing its properties
- We investigated the phenomenology of our phase transition module

Conclusions

- We have shown how to obtain "thermal" dark matter even if a thermal freeze-out calculation based on observation yields a relic abundance that does not match the astrophysical observation
- This mechanism introduces a late-time phase transition with $(T_{\mathrm{PT}} < T_{fo})$ which couples to the DM sector thereby changing its properties
- We investigated the phenomenology of our phase transition module

Future Work

- Use this mechanism to explain the PAMELA anomaly
- Build a toy model where all ingredients are observable in the near future
- Embed in a supersymmetric framework

THANK YOU

Are there any questions?