Freeze-in of light Dark Matter

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SUSY Conference, Melbourne, 4th July, 2016

Outline

Sterile neutrino dark matter

- DM comprises $\sim 25\%$ of the Universe's energy density; weakly interacts with SM particles
- DM could be linked to other open questions in particle physics
- **keV sterile neutrino** from a generic seesaw mechanism is a popular candidate
- Dodelson-Widrow mechanism ruled out (Boyarsky et al. '09): $m_N \leq 4$ keV (x-ray) & $m_N \geq 8$ keV (Ly-α)
- Scalar decay a very interesting WDM alternative

Structure Formation

- Dark matter (DM) momentum distribution crucial for accretion
- Characterised by **free-streaming horizon**, $\lambda_{FS} = \int_{t_i}^{t_0} \frac{\langle v(t) \rangle}{a(t)} dt$
- "Hot": $\lambda_{FS} \geq 0.1$ Mpc, e.g. standard model neutrinos
  $\rightarrow$ Predicts top down formation; we observe bottom up formation
- "Cold": $\lambda_{FS} \lesssim 0.01$ Mpc, e.g. WIMPs
  $\rightarrow$ Challenged by the **missing satellites problem**
- "Warm": $0.01 \text{ Mpc} \lesssim \lambda_{FS} \leq 0.1$ Mpc

The complex scalar ϕ

- Real scalar models provide viable WDM (Shaposhnikov & Tkachev '06; Petraki & Kusenko '08; Merle et al. '13; Adulpravitchai & Schmidt '14 etc.):
- Typically have discrete symmetry breaking $\Rightarrow$ **domain walls**
- Therefore introduce a complex scalar with $U(1)$ symmetry
- Interplay between heavy ϕ_1 and **pseudo-Goldstone boson** ϕ_2
- ϕ_2 potentially a DM candidate

The Lagrangian

- Add complex scalar singlet ϕ and singlet sterile neutrino N to SM
- Lagrangian for full theory:

$$\mathcal{L} = \mathcal{L}_{SM} + i\overline{N}\partial\!\!\!/ N - y_i \left(H\overline{L_i}N + h.c.\right) - \frac{\mathbf{f}}{2}\left(\phi\overline{N^C}N + h.c.\right)$$
$$+ \partial_\mu\phi\partial^\mu\phi - V(H,\phi)$$

- Higgs potential given by:

$$V(H,\phi) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2 + \mu_\phi^2\phi^\dagger\phi + \boldsymbol{\lambda_\phi}(\phi^\dagger\phi)^2 + \boldsymbol{\kappa}\phi^\dagger\phi H^\dagger H$$

Symmetries

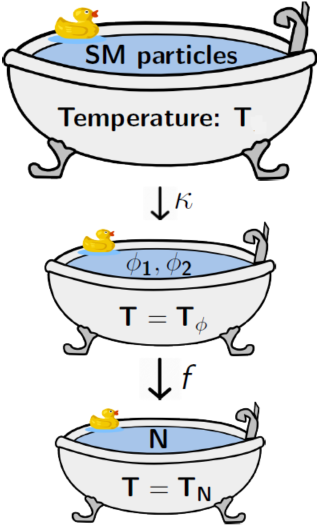
- Lagrangian for full theory:

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{N}\partial\!\!\!/ N - y\left(H\bar{L}N + h.c.\right) - \frac{\mathbf{f}}{2}\left(\phi\bar{N^C}N + h.c.\right) - V(H,\phi)$$

- N has Majorana mass term
- ϕ set as: $\phi = v_\phi + \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$
- $U(1)_X$ is **anomalous**, so ϕ_2 is a pGB
- Thermal corrections to ϕ_2 mass: $m^2_{\phi_2}(T) = m^2_{\phi_2} + \frac{\lambda_\phi}{12}T^2$

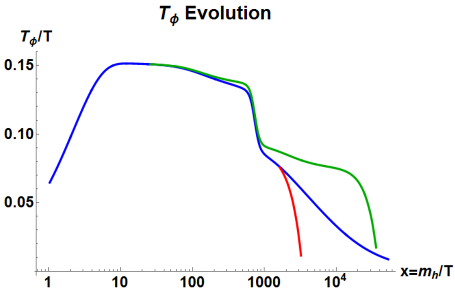
	SU(2)	$U(1)_Y$	$U(1)_L$	$U(1)_X$
L_i	2	$-\frac{1}{2}$	1	0
N	1	0	0	1
ϕ	1	0	0	-2

Schematic of model



Thermal bath of ϕ

- Production of ϕ mainly through $h \to \phi_i \phi_i$, $hh \to \phi_1$
- $\frac{\Gamma(\phi_1 \to NN)}{\Gamma(\phi_1 \to \phi_2 \phi_2)} \sim \frac{m_N^2}{m_{\phi_1}^2} \ll 1$
  $\Rightarrow \phi_1$ decays **only** to ϕ_2, then $\phi_2 \to NN$ produces N
- Evolution of $g_*^{\rho,S}$ important (Wantz and Shellard '11)



Green: smaller λ_ϕ

Red: larger m_{ϕ_2}

Thermal bath of ϕ

- Boltzmann Equation for T_ϕ:

$$\int \frac{d^3 p_\phi}{(2\pi)^3} E_\phi \frac{df_{\phi_2}}{dt} = \frac{1}{2} \int \frac{d^3 p_\phi}{(2\pi)^3} E_\phi \left(\hat{C}^+ - \hat{C}^- \right)$$

- Solution for $z = \frac{T_\phi}{T}$ is broken into three sections:

$$z_1 \propto \frac{\sqrt{\kappa}(g_*^S)^{1/3}}{\sqrt{|m_h^2 - m_{\phi_1}^2|}} \text{ early on}$$

$$z_2 \propto \frac{m_{\phi_1}^2 (g_*^S)^{1/3}}{C_1 m_{\phi_1}^2 + C_2 \lambda_\phi^2 m_N^2 x} \text{ for most time}$$

$$z_3 \propto (g_*^S)^{1/3} \left(C_3 - \frac{\lambda_\phi m_{\phi_2}^2 m_N^2 x^3}{m_{\phi_1}^2} \right) \text{ when } T_\phi \lesssim m_{\phi_2}$$

Free-streaming horizon

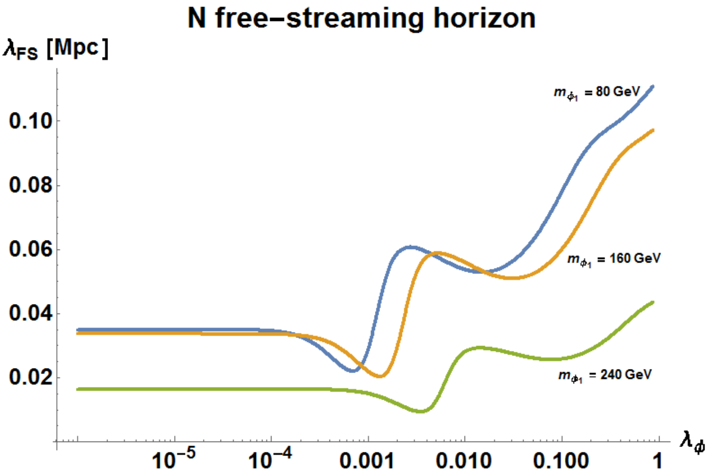
- Assume $\langle v \rangle \approx 1$ early, then $\langle v \rangle = \frac{\langle p \rangle}{m_N}$ for $t > t_{N,nr}$
- Find $\langle p \rangle = \frac{\langle P \rangle}{n}$ from the Boltzmann Equation

$$\frac{df_N}{dt} = \hat{C}[\phi_2 \to NN]$$

- Find when N becomes **non-relativistic**: $T_{N,nr} \propto m_N$
- Divide up timeline (Adulpravitchai & Schmidt '14):

$$\lambda_{FS} = \int_{t_{in}}^{t_{nr}} \frac{1}{a(t)} dt + \int_{t_{nr}}^{t_{eq}} \frac{\langle v(t) \rangle}{a(t)} dt + \int_{t_{eq}}^{t_0} \frac{\langle v(t) \rangle}{a(t)} dt$$

Free-streaming horizon results



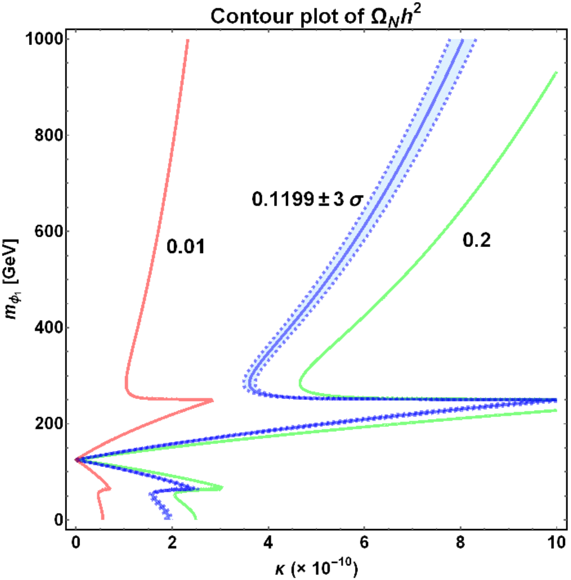
Dark matter density

- $\Omega_{DM} = \frac{m_N Y_N S h^2}{\rho_c} = 0.1199 \pm 0.0027$ (Planck collaboration, Ade et al. '15)

- Simple counting argument: $Y_N \approx 4Y_{\phi_1} + 2Y_{\phi_2}$, as ϕ_2 remnants are typically small

- This gives $Y_N \propto \frac{\kappa^2}{(m_h^2 - m_{\phi_1}^2)^2} G(m_{\phi_1}, \lambda_\phi)$, where $G(m_{\phi_1}, \lambda_\phi)$ is dependent on which processes are **kinematically allowed**

Dark matter density



Conclusions

- N is a viable WDM candidate for $\kappa \sim 10^{-10}$ and $10^{-6} \lesssim \lambda_\phi \lesssim 1$
- ϕ_2 also a WDM candidate, need $\sim 0.1 - 1$ MeV scale sterile neutrino and $m_{\phi_2} \lesssim 1$ keV
- x-ray lines best possibility for direct or indirect evidence

Matrix elements

For the $h-\phi$ sector we have:

$$|\mathcal{M}(h\to\phi_1\phi_1)|^2 = \frac{2\kappa^2 v^2(m_h^2+2m_{\phi_1}^2)^2}{(m_h^2-m_{\phi_1}^2)^2} \qquad |\mathcal{M}(h\to\phi_2\phi_2)|^2 = \frac{2\kappa^2 v^2 m_h^4}{(m_h^2-m_{\phi_1}^2)^2}$$

$$|\mathcal{M}(hh\to\phi_1)|^2 = \frac{2\kappa^2 v_\phi^2(2m_h^2+m_{\phi_1}^2)^2}{(m_h^2-m_{\phi_1}^2)^2} \qquad |\mathcal{M}(\phi_1\to\phi_2\phi_2)|^2 = \frac{m_{\phi_1}^4}{2v_\phi^2}$$

The squared matrix elements for $\phi_i \to NN$ summed (not averaged) over the final state spins is given by:

$$|\mathcal{M}(\phi_{1,2}\to NN)|^2 = 2\left(f^2 k\cdot k'^2 \mp f^2 m_N^2\right)$$
$$\Rightarrow |\mathcal{M}(\phi_1\to NN)|^2 = f^2(s^2-4m_N^2) \text{ and}$$
$$|\mathcal{M}(\phi_2\to NN)|^2 = f^2 s,$$

where s is the Mandelstam variable $s=(k+k')^2$.