Spontaneous freeze-out of dark matter from an early thermal phase transition

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■ In the scenarios of cold Dark Matter (DM) production, the WIMP has a constant mass

■ But all masses in the Standard Model (SM) arise by Higgs Mechanism

$\Longrightarrow$ More natural to **assume an Higgs-like mechanism to generate DM mass**

■ **Consequences :**

- **The DM-Mass vary in time**
- To account for the DM relic abundance, **the cross-section DM-SM can be 1 or 2 orders of magnitude larger**

Working principle

■ **Dark sector includes :**

• **A dark matter fermion ψ (Dirac, Majorana,...) that will yield the relic density**

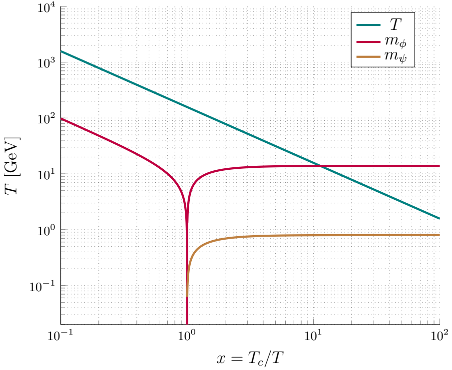
• **A scalar ϕ that will not participate to the relic density**

• **ψ has a Yukawa mass $y\phi$**

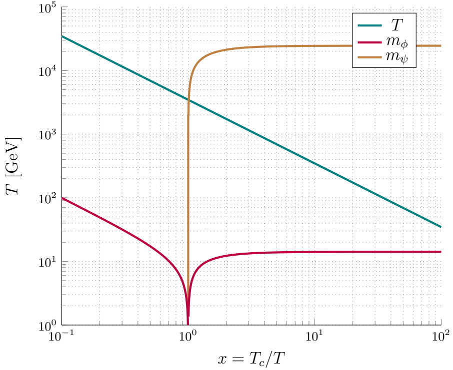
■ At some early epoch (after inflation) they are in **thermal equilibrium with the SM**

■ Compute the quantum effective potential of ϕ at finite temperature

$$
\begin{aligned}
T > T_c: \quad & \langle\phi\rangle = 0 & \Longrightarrow \quad & m_\psi = 0 \\
T < T_c: \quad & \langle\phi\rangle \neq 0 \quad \text{depends on } T & \Longrightarrow \quad & m_\psi = y\langle\phi\rangle
\end{aligned}
$$



$\Longrightarrow$ Constant-Mass Freeze-out



$\Longrightarrow$ Spontaneous Freeze-out (SFO)

E.g., for $y = 10^{-2}$, $\mu = 10$ GeV and $\lambda = 10^3 y^2 = 0.1$ or $\lambda = 10^{-2} y^4 = 10^{-10}$

Expectations

■ **For given mass m_ψ^0 and yield Y_ψ^0 today what are the differences between SFO and constant mass FO ?**

At freeze-out $m_\psi^{\rm SFO} < m_\psi^0 = m_\psi^{\rm standard\ FO}$

$\Longrightarrow$ $T^{\rm SFO} < T^{\rm standard\ FO}$

$\Longrightarrow$ Interactions with the SM must be stronger, to maintain ψ in thermal equilibrium up to this lower $T^{\rm SFO}$

$$\sigma^{\rm SFO} > \sigma^{\rm standard\ FO}$$

Since σ increases with m_ψ, **this is even more the case today**

Related works and ideas

■ The idea of temperature-dependent mass has already been used for different purposes

- VAMPs (interaction DM-DE) [Aderson, Carroll, '97] [Rosenfeld, '05] [Rosenfeld, Franca, '04]
- Flip-Flop Vev mechanisms [Baker, Breitbach, Kopp, Mittnacht, '18] [Baker, Mittnacht, '18]
- Forbidden Freeze-In [Darmé, Hryczuk, Karamitros, Roszkowski, '19]
- Super-Cool DM [Hambye, Strumia, Teresi, '18]
- Superheavy WIMPS [Hui, Stewart, '95]
- ...

Simplest model

At tree level

$$\mathcal{L}_{\text{tree}} = i\bar{\psi}\not{\partial}\psi + \frac{1}{2}(\partial\phi)^2 - y\phi\bar{\psi}\psi - \mathcal{V}_{\text{tree}}(\phi) + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{int}}$$

$$\mathcal{V}_{\text{tree}}(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4!}\phi^4 \qquad \mathbb{Z}_2 \text{ symmetric}$$

- $\mathcal{L}_{\text{SM}}$ is the SM Lagrangian
- $\mathcal{L}_{\text{int}}$ couples ψ and ϕ to the SM

■ **We add to $\mathcal{V}_{\text{tree}}$ the 1-loop free energy + Coleman-Weinberg effective potential of ϕ and ψ**

- Taking 2 derivatives of $\mathcal{V}_{\text{tree}} \implies m_0^2 = -\mu^2 + \frac{\lambda}{2}\phi^2 \,, \qquad m_\psi = y\phi$

$$\mathcal{F}(T,\phi) = -\frac{\pi^2}{90}T^4 + \frac{T^2}{24}m_0^2 - \frac{T}{12\pi}\left(m_0^2\right)^{\frac{3}{2}} - \frac{m_0^4}{64\pi^2}\log\left(\frac{m_0^2}{16\alpha T^2}\right) + \mathcal{O}\left(\frac{m_0^6}{T^2}\right)$$

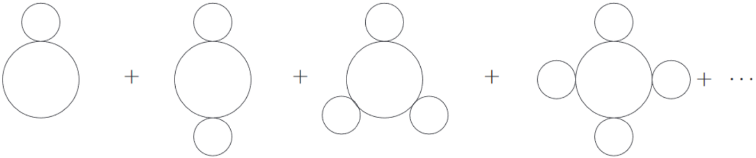
$$- n_F\left[\frac{7\pi^2}{720}T^4 - \frac{T^2}{48}m_\psi^2 - \frac{m_\psi^4}{64\pi^2}\log\left(\frac{m_\psi^2}{\alpha T^2}\right) + \mathcal{O}\left(\frac{m_\psi^6}{T^2}\right)\right]$$

$$\mathcal{V}_{\text{CW}}(\phi) = \frac{m_0^4}{64\pi^2}\left[\log\left(\frac{m_0^2}{Q^2}\right) - \frac{3}{2}\right] - n_F\frac{m_\psi^4}{64\pi^2}\left[\log\left(\frac{m_\psi^2}{Q^2}\right) - \frac{3}{2}\right]$$

where $\alpha = \pi^2 \exp(3/2 - 2\gamma_E)$

- **At high T,** the (thermal mass)^2 of ϕ is positive $\implies \langle\phi\rangle = 0$
- $\implies \mathbb{Z}_2$ symmetry is restored : Thermal loops dominate the tree level contribution : **Perturbation theory breaks down**

■ The high T quantum corrections are dominated by the **"ring diagrams", with arbitrary number of loops** [Dolan, Jackiw, '74] [Carrington, '92][Delaunay, Grojean, Wells, '07][Martin, '14][Elias-Miró, Espinosa, Konstandin, '14]...



$$\Longrightarrow \quad \text{Add} \quad \mathcal{V}^{\text{th}}_{\text{ring}}(T,\phi) = \frac{T}{12\pi}\left[\left(m_0(\phi)^2\right)^{\frac{3}{2}} - \left(m_0(\phi)^2 + \Pi_\phi(T)\right)^{\frac{3}{2}}\right]$$

where the mass shift Π_ϕ is the dominant thermal correction to m_0^2 arising from $\mathcal{F}$

$$\Pi_\phi(T) = \frac{T^2}{24}(\lambda + n_F y^2)$$

■ **The thermal effective potential becomes**

$$\mathcal{V}_{\rm eff}^{\rm th}(x,\phi) = \mathcal{V}_0(x) - \frac{\mu_{\rm eff}(x)^2}{2}\phi^2 + \frac{\lambda_{\rm eff}(x)}{4!}\phi^4 \,,$$

where $x \equiv \frac{T_c}{T}$, $\qquad Q = \pi e^{-\gamma_{\rm E}} T_c$

$$T_c = \frac{2\sqrt{6}\,\mu}{\sqrt{\lambda + n_F y^2}} \sqrt{\frac{1 - \frac{\sqrt{6}}{8\pi}\,\xi + \frac{\log 2}{8\pi^2}\,\lambda}{1 - \frac{\sqrt{6}}{4\pi}\,\xi}} \,, \qquad \xi \equiv \frac{\lambda}{\sqrt{\lambda + n_F y^2}}$$

$$\mu_{\rm eff}(x)^2 = \mu^2 \left[\left(1 - \frac{\sqrt{6}}{8\pi}\,\xi + \frac{\log 2}{8\pi^2}\,\lambda\right)\left(1 - \frac{1}{x^2}\right) - \frac{\lambda}{16\pi^2}\log x\right],$$

$$\lambda_{\rm eff}(x) = \lambda\left(1 - \frac{3\sqrt{6}}{8\pi}\,\xi + \frac{3\log 2}{8\pi^2}\,\lambda\right) + \frac{3}{16\pi^2}\left(4 n_F y^4 - \lambda^2\right)\log x \,.$$

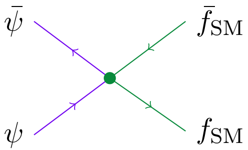
$$\Longrightarrow \qquad x < 1 \ : \ \langle\phi\rangle = 0 \,, \qquad x > 1 \ : \ \langle\phi\rangle = \mu_{\rm eff}(T)\sqrt{\frac{6}{\lambda_{\rm eff}(T)}}$$

Freeze-out

■ What we said is valid until ψ or ϕ freezes out

■ **Assumption :**

• **ψ is maintained in thermal equilibrium with the SM by contact interactions**



$$n_\psi \langle \sigma_{\mathrm{SM}\leftrightarrow\psi\bar{\psi}}\, v\rangle > H$$

• **ϕ remains in thermal equilibrium even after freeze-out of ψ, thanks to interactions with the SM (see below)**

■ We have a "Spontaneous Freeze-Out" when $T_c \gtrsim T_{\rm FO}$

Define $\quad x_{\rm FO} \equiv \dfrac{T_c}{T_{\rm FO}} \quad$ and $\quad \kappa = \dfrac{m_\psi(x_{\rm FO})}{T_{\rm FO}} = \mathcal{O}(20\text{–}30)$ in practice

$$\lambda \gg n_F y^2 \quad \Longrightarrow \quad x_{\rm FO} \simeq \mathcal{O}\left(\frac{2\kappa}{y}\right) \gg \kappa\,,$$

$$\lambda \ll n_F y^2 \quad \Longrightarrow \quad 1 < x_{\rm FO} \simeq \left[1 + \kappa^2\left(\frac{4\lambda}{n_F y^4} + \frac{3}{\pi^2}\log x_{\rm FO}\right)\right]^{1/2}$$

$$\lesssim \kappa \quad \text{when} \quad \frac{4\lambda}{n_F y^4} < 1 : \text{"Spontaneous FO"}$$

■ The regime $1 \lesssim x_{\rm FO} \ll \kappa$ is excluded because we need the effective potentiel at $T = 0$ to admit a minimum $\langle\phi\rangle > 0$, which imposes

$$\frac{4\lambda}{n_F y^4} > \frac{3}{2\pi^2}\left(\log\frac{2}{3} + 2\gamma_{\rm E}\right) \simeq 0.12$$

■ **Spontaneous FO** $\Longleftrightarrow$ $\boldsymbol{x_{\rm FO} \simeq \kappa}$ $\Longleftrightarrow$ $\boldsymbol{0.12 < \dfrac{4\lambda}{n_F y^4} < 1}$

Numerical simulations

■ **Specify interactions**

$\mathcal{O}_V = G_V\, \bar{\psi}\gamma_\mu\psi\bar{f}\gamma^\mu f$ or $\mathcal{O}_S = G_S\, \bar{\psi}\psi\bar{f}f$, where f is a SM fermion

■ Thermally averaged cross section

$$\langle\sigma v\rangle_V \simeq \frac{G_V^2}{2\pi}\Big(1 + \frac{x^{-1}T_c}{m_\psi(x)}\Big)\, m_\psi^2(x) \qquad s\text{-wave}$$

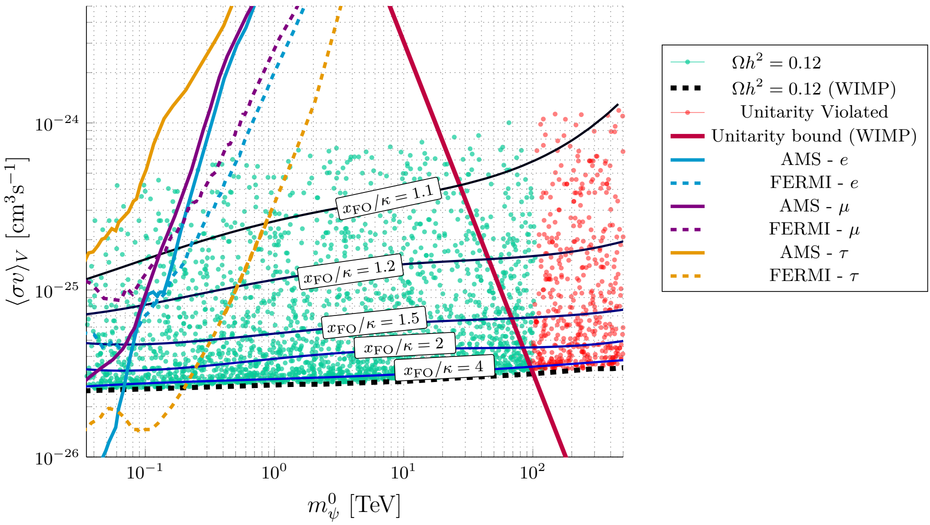
$$\langle\sigma v\rangle_S \simeq \frac{3G_S^2}{8\pi}\, x^{-1}T_c m_\psi(x) \qquad p\text{-wave}$$

■ **Solve Boltzmann equation**

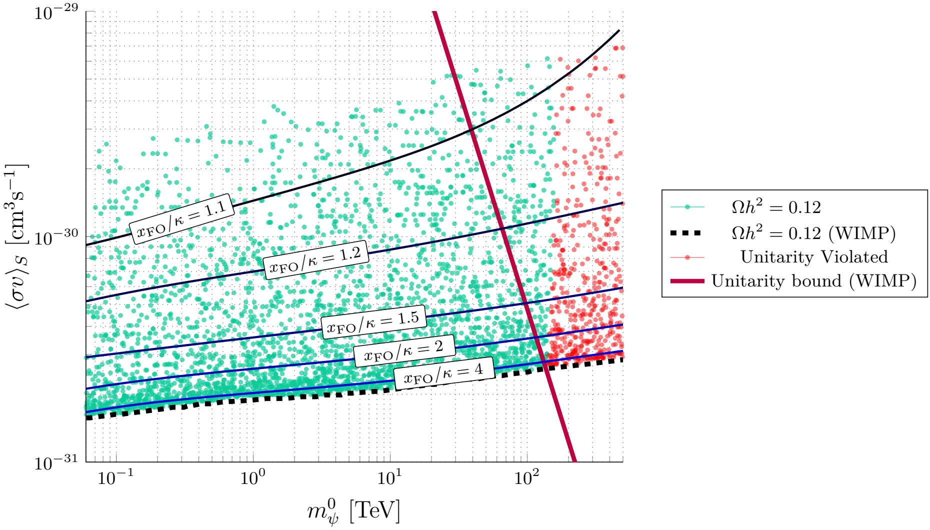
$$\frac{\mathrm{d}Y_\psi}{\mathrm{d}x} = \frac{\langle\sigma v\rangle s}{xH}(Y_{\psi,\mathrm{eq}}^2 - Y_\psi^2)\ , \qquad Y_\psi = \frac{n_\psi}{s}$$

Scan over the parameter space μ, λ, y, $G_{V,S}$ such that the correct relic density is obtained

■ For $\mathcal{O}_V$ (s-wave) : Cross section as fonction of mass, today



■ For $\mathcal{O}_S$ (p-wave)



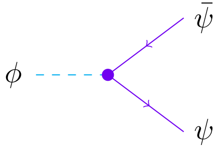
■ **Increase of DM mass**

$$x_{\rm FO} \simeq 1.1 \qquad \Longrightarrow \qquad m_\psi^0 \simeq 2 m_\psi(x_{\rm FO})$$

Thermalization of ϕ

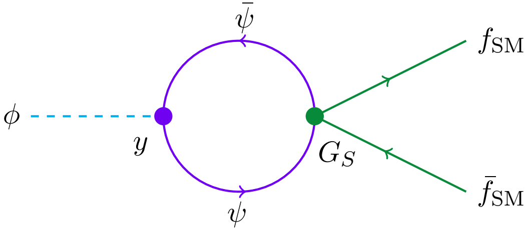
■ **We have assumed ϕ is in thermal equilibrium with the SM**

- Before phase transition, ψ is massless $\Longrightarrow$ inverse decay



- After phase transition, it is model-dependent:

E.g.



or coupling to the Higgs

■ **The decay of ϕ**

$\Longrightarrow$ **Increases the damping of the oscillations of ϕ in the well of its thermal effective potential**

$\Longrightarrow$ **helps $\langle\phi\rangle$ to track the T-dependent minimum**

■ **Without decay, when $T <$ mass of ϕ, the energy stored in the oscillations of ϕ contributes as the energy density of massive matter**

$\Longrightarrow$ **overclose the universe** [Preskill, Wise, Wilczek, '83] [Abbott, Sikivie, '83] [Dine, Fischler, '83] [Coughlan, Fischler, Kolb, Raby, Ross, '83] [Ellis, Nanopoulos, Quiros, '86]

Conclusion

■ **Masses in the dark sector might be generated by the spontaneous breaking of some global or gauge symmetry**

- At high T, the symmetry is restored

- At $T = T_c$, the 2nd order phase transition triggers the Spontaneous Freeze Out of the dark matter, provided its mass has not reached its constant value yet

■ **The cross section necessary to generate the correct DM relic abundance is larger than in the constant mass WIMP scenario**

■ **Unitarity bounds of the WIMP cross section is overshot**