Ultra-relativistic freeze-out during reheating: cold dark matter from a hot birth

Stephen E. Henrich

Co-authors: Keith A. Olive, Yann Mambrini, and Mathieu Gross
Based on: arXivs 2511.02117 (*PRL*), 2505.04703 (*PRD*), and 2511.... (forthcoming *JCAP* submission)

University of Minnesota

Department of Physics

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Outline

- Characterize the basic features of UFO and compare to standard (WIMP-like) freeze-out and freeze-in
- UFO during radiation domination (standard hot DM scenario)
- UFO during reheating
- Z' portal UFO DM
- Results and conclusions

Revisiting an old mechanism

(Ultra)relativistic freeze-out (UFO) has been considered since the 1960's-70's
$\Rightarrow$ hot or warm dark matter. **But, reheating changes the story**

Why is UFO worth studying?

- UFO is inevitable in the WIMP-to-FIMP transition for many interactions
- UFOs have distinct properties from both WIMPs and FIMPs

	WIMPs	**FIMPs**	**UFOs**
DM reaches equilibrium?	Yes	No	Yes
Relic density determined by	annihilations	production	production *
Interaction strength	weak	feeble	intermediate
UV vs. IR behavior	No	Yes	Yes
Can be cold DM?	Yes	Yes	Yes

*Annihilations play an important role for UV UFO

Definition: Chemical freeze-out without Boltzmann suppression.

$T_{\mathrm{FO}} \gg m_\chi$ such that the interaction rate $\Gamma = \langle \sigma v \rangle n$ at freeze-out is in the ultra-relativistic regime.

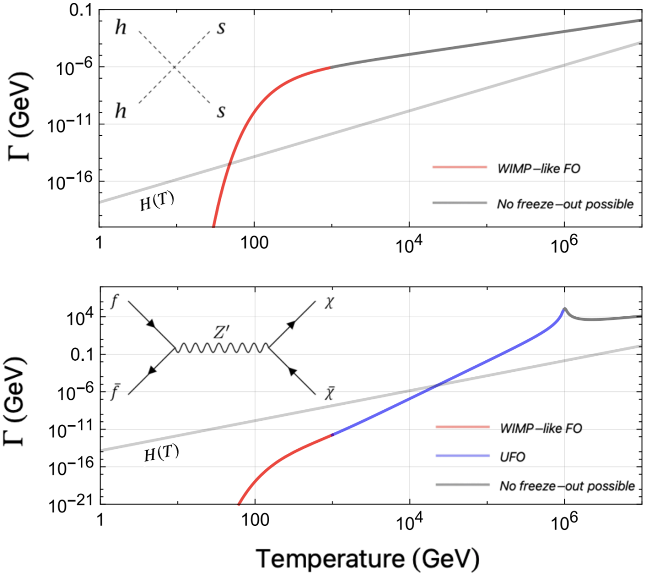
Cross section	**Number density**	**Rate**
$\langle \sigma v \rangle = \beta \frac{T^n}{\Lambda^{n+2}}$	$n_\chi(T) = g_\chi \frac{\zeta(3)}{\pi^2} T^3 \quad \rightarrow$	$\Gamma = \frac{g_\chi \zeta(3) \beta}{\pi^2} \frac{T^{n+3}}{\Lambda^{n+2}}$

β is a numerical factor from thermal averaging
$n = -2$ for a contact interaction between scalars
$n = 2$ for a heavy mediator

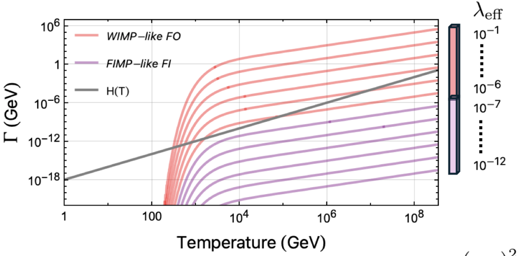
Example: classical neutrino decoupling

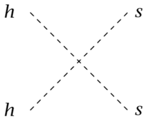
$$\Gamma \sim H \quad \rightarrow \quad G_F^2 T^5 \sim T^2 / M_P \quad \rightarrow \quad T_d \approx 1 \text{ MeV} \gg m_\nu$$

UFO vs. WIMP-like FO



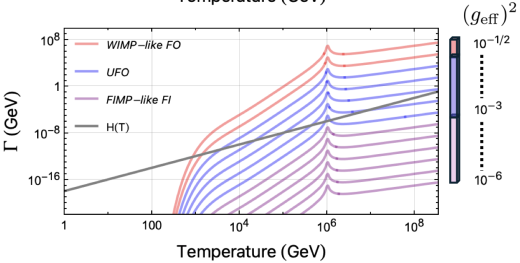
Two distinct WIMP-to-FIMP Transitions

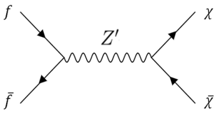




$$\langle \sigma v \rangle \propto \frac{\lambda^2}{T^2}$$

$$\Gamma \propto \lambda^2 T$$





$$\langle \sigma v \rangle \propto \frac{T^2}{\Lambda^4}$$

$$\Gamma \propto \frac{T^5}{\Lambda^4}$$

Conditions required for UFO

Consider a generic BSM interaction and a generic cosmological era with

$$\Gamma_{\text{rel}}(T) \propto T^{\gamma_1} \text{ and } H(T) \propto T^{\gamma_2}$$

We require $\gamma_1 > \gamma_2$ for UFO to be possible. Equivalently,

Master UFO condition:

$$\frac{d \ln \Gamma_{\text{rel}}}{d \ln T} > \frac{d \ln H}{d \ln T}$$

Recall that $\gamma_1 = n + 3$, where in the ultra-relativistic regime $\langle \sigma v \rangle \propto \frac{T^n}{\Lambda^{n+2}}$.

UFO during radiation domination: requires $n > -1$

UFO during reheating: requires $n > \frac{3-k}{k-1}$ ($n > 1$ for quadratic minimum)

Heavy mediator interactions ($n = 2$) automatically satisfy these conditions

UFO during radiation domination

The ultra-relativistic freeze-out temperature can be determined by

$$\Gamma_{\rm rel}(T_{\rm FO}) = H(T_{\rm FO}) \quad \Rightarrow \quad T_{\rm FO} = \Lambda \left(\frac{\Lambda}{M_P}\right)^{\frac{1}{n+1}} \left(\frac{2\pi^2}{g_\chi \zeta(3)}\sqrt{\frac{\alpha}{3}}\right)^{\frac{1}{n+1}} .$$

The relic abundance is independent of $T_{\rm FO}$ and Λ, up to $g_{\rm FO}$.

$$\Omega_\chi h^2 \simeq 0.12 \left[g_\chi \left(\frac{106.75}{g_{\rm FO}}\right)\left(\frac{m_\chi}{170\ {\rm eV}}\right)\right] .$$

Thus, to satisfy $\Omega_\chi h^2 = 0.12$, we require

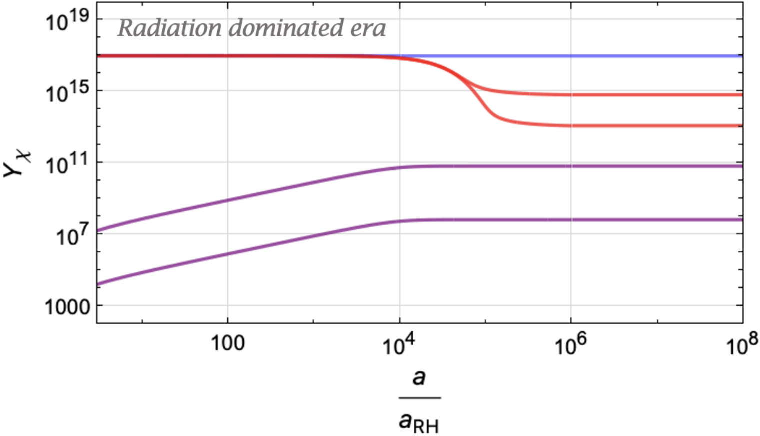
$$11\ {\rm eV} \lesssim m_\chi \lesssim 170\ {\rm eV}$$

However, warmness constraints from the Lyman-α forest require $m_\chi \gtrsim 5$ keV.

Conclusion:

There is no regime in which UFO during radiation domination can satisfy both $\Omega_\chi h^2 = 0.12$ and cold relic DM.

UFO during radiation domination

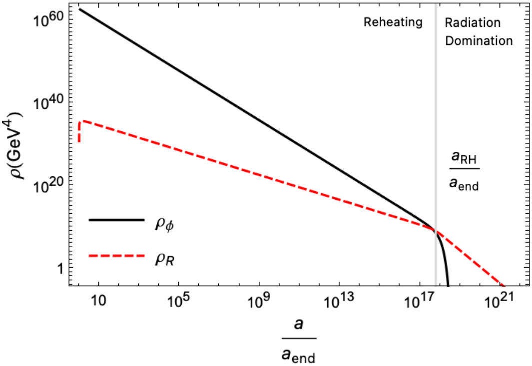


The co-moving DM number (Y_χ) remains essentially unchanged after freeze-out $\Rightarrow$ minimal flexibility in parameter space

Non-instantaneous reheating

At the end of inflation, the inflaton oscillates about the minimum of its potential ($V(\phi) \propto \phi^k$) and transfers energy to the SM radiation bath.

$$\dot{\rho}_\phi + 3H\left(\frac{2k}{k+2}\right)\rho_\phi = -\Gamma_\phi \rho_\phi\,, \quad \dot{\rho}_R + 4H\rho_R = \Gamma_\phi \rho_\phi, \qquad H^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$



Reheating (for $k = 2$):

$$H(T) = \sqrt{\frac{\alpha}{3}}\frac{T^4}{T_\text{RH}^2 M_P}$$

$$T \propto a^{-3/8}$$

$$\rho_R = \alpha T_\text{RH}^4 \left(\frac{a_\text{RH}}{a}\right)^{\frac{3}{2}}$$

UFO during reheating

Solve the Boltzmann equation for n_χ :

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle(n_\chi^2 - n_{\rm eq}^2) \tag{1}$$

After UFO, **SM source particles continue to be produced by inflaton decays**, while n_χ drops relative to its equilibrium density. Thus, it is the *production term* which dominates after UFO $\Rightarrow$

$$\frac{dY_\chi}{da} = \frac{a^2 R_\chi(a)}{H(a)} \tag{2}$$

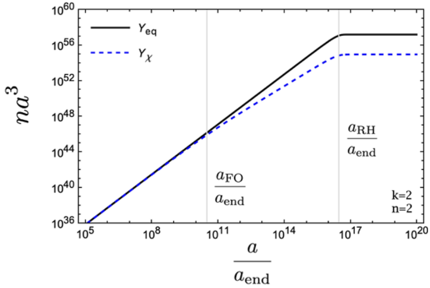
where $Y_\chi = n_\chi a^3$. We can solve this analytically to obtain

$$Y_\chi(a_{\rm RH}) = Y_{\rm FO} + \frac{g_\chi^2 \zeta(3)^2 \beta}{\pi^4}\left(\frac{2k+4}{3n-3nk-6k+30}\right)\times \sqrt{\frac{3}{\alpha}}\frac{T_{\rm RH}^{n+4} M_P}{\Lambda^{n+2}}\left[a_{\rm RH}^3 - a_{\rm FO}^3\left(\frac{a_{\rm FO}}{a_{\rm RH}}\right)^{\frac{3n-3nk+18-12k}{2k+4}}\right]. \tag{3}$$

UV vs. IR UFO

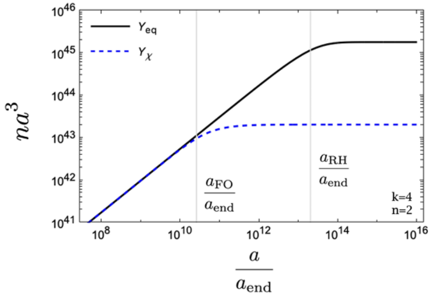
IR UFO

- Out-of-equilibrium production is greatest at low energies
- Y_χ increases after freeze-out
- Naive freeze-in calculation yields correct result



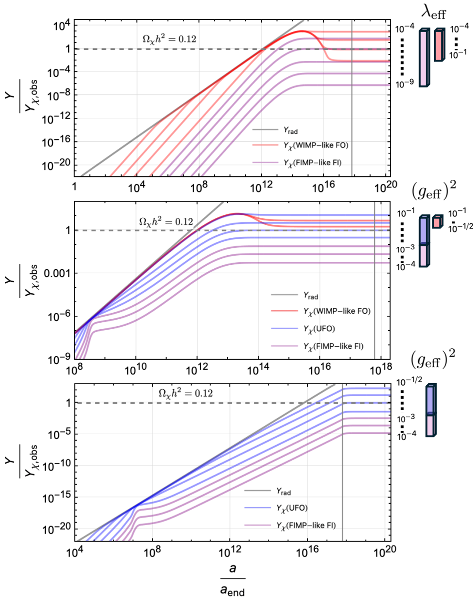
UV UFO

- Out-of-equilibrium production is greatest at high energies
- $Y_\chi \approx$ constant after freeze-out
- Naive freeze-in calculation typically over-estimates by many orders of magnitude



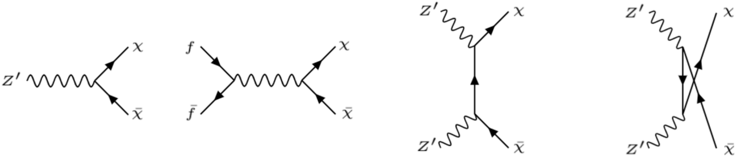
UV if $n \geq \frac{10-2k}{k-1}$, IR if $n < \frac{10-2k}{k-1}$

Two distinct WIMP-to-FIMP Transitions



Heavy Z' portal DM necessarily includes UFO

$$\mathcal{L} \supset \bar{\chi}\gamma^\mu(V_\chi + A_\chi\gamma_5)\chi Z'_\mu + \sum_f \bar{f}\gamma^\mu(V_f + A_f\gamma_5) f Z'_\mu - \frac{1}{2}M_{Z'}^2 Z'^\mu Z'_\mu - m_\chi\bar{\chi}\chi$$

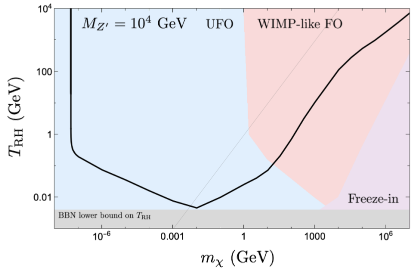


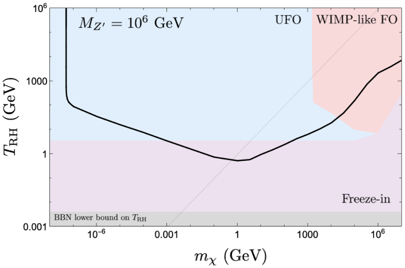
Pure vector or axial vector contributions to $\bar{f}f \to \bar{\chi}\chi$:

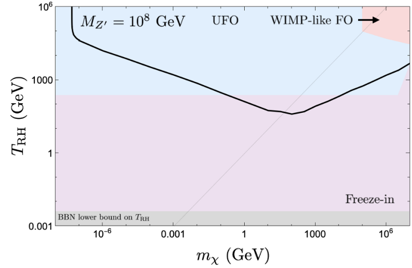
$$|\overline{\mathcal{M}_{\rm vv}}|^2 = \frac{2V_f^2 V_\chi^2}{(s - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}\left[s^2 + 2st + 2(m_\chi^2 + m_f^2 - t)^2\right],$$

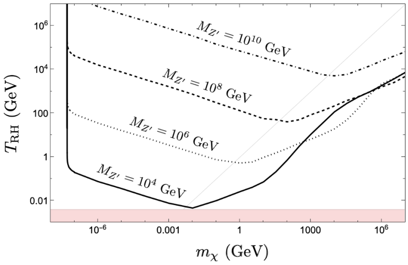
$$|\overline{\mathcal{M}_{\rm aa}}|^2 = \frac{2A_f^2 A_\chi^2}{(s - M_{Z'}^2)^2 + \Gamma_{Z'}^2 M_{Z'}^2}\Bigg[s^2 + 2st + 2(m_\chi^2 + m_f^2 - t)^2 - 4s(m_\chi^2 + m_f^2) + 16 m_f^2 m_\chi^2 - 16\frac{s m_f^2 m_\chi^2}{M_{Z'}^2} + 8\frac{s^2 m_f^2 m_\chi^2}{M_{Z'}^4}\Bigg].$$

$\Omega_\chi h^2 = 0.12$ parameter space for Z' portal DM









Is UFO DM cold though?

Lyman-α forest constraint requires a typical DM velocity at structure formation ($T \approx 1$ eV) $v_\chi < 2 \times 10^{-4}$. Taking $v_\chi = p_\chi / m_\chi$ and $p_\chi \simeq T_{\rm FO}(a_{\rm FO}/a)$, we can redshift the DM momentum

$$p_\chi \simeq T_{\rm FO} \left(\frac{a_{\rm FO}}{a_{\rm RH}} \right) \left(\frac{a_{\rm RH}}{a} \right) \tag{4}$$

so that for $k = 2$

$$p_\chi \simeq T_{\rm FO} \left(\frac{T_{\rm RH}}{T_{\rm FO}} \right)^{\frac{8}{3}} \left(\frac{T}{T_{\rm RH}} \right) \tag{5}$$

and at $T = 1$ eV, we have the constraints

$$m_\chi > 5\ \text{keV} \left(\frac{T_{\rm RH}}{T_{\rm FO}} \right)^{5/3} \quad \text{(for UV UFO)} \qquad m_\chi > 5\ \text{keV} \quad \text{(for IR UFO)}$$

Even sub-eV DM can become cold with UFO during reheating! $\Omega_\chi h^2 = 0.12$ still requires $m_\chi \gtrsim 20$ eV.

Conclusions

- UFO is an unavoidable, intermediate regime between WIMPs and FIMPs for many interactions
- UFO during radiation domination cannot produce cold relic DM with $\Omega_\chi h^2 = 0.12$
- UFO **during reheating** can produce cold relic DM and the correct abundance in large regions of parameter space
  - $10^{-7} \lesssim m_\chi \lesssim 10^6$ GeV
  - $10^{-2} \lesssim T_{\rm RH} \lesssim 10^{15}$ GeV
  - $10^3 \lesssim \Lambda \lesssim 10^{14}$ GeV
- UFO is easily manifest in realistic, well-motivated particle physics models such as Z' portal DM

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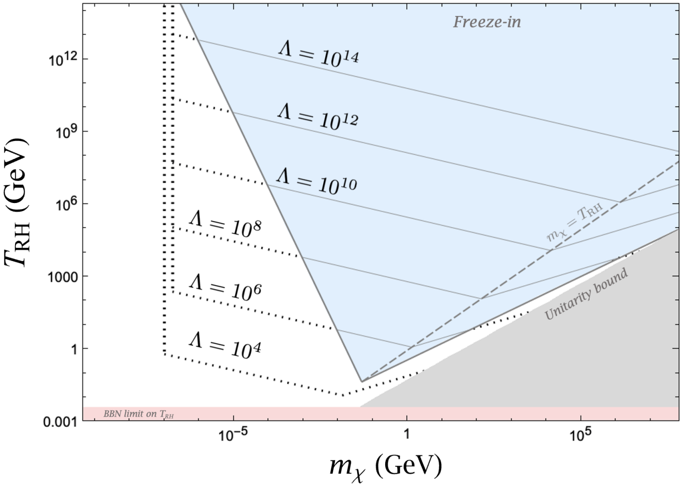
$\Omega_\chi h^2 = 0.12$ parameter space ($k = 2$, $n = 2$)



Parameter space for UFO during reheating

DM mass	Λ	T_{RH}
5 keV	7.1×10^2 – 4.3×10^{13} GeV	4 MeV – 9.7×10^{11} GeV
100 keV	1.5×10^3 – 1.1×10^{11} GeV	4 MeV – 1.2×10^8 GeV
1 MeV	2.7×10^3 – 1.1×10^9 GeV	4 MeV – 1.2×10^5 GeV
100 MeV	7.7×10^2 – 9.6×10^4 GeV	6.5 MeV – 0.10 GeV
1 GeV	3.5×10^3 – 2.8×10^5 GeV	41 MeV – 0.50 GeV
100 GeV	6.9×10^4 – 2.3×10^6 GeV	1.6 – 12 GeV
1 TeV	3.1×10^5 – 6.8×10^6 GeV	10 – 60 GeV
100 TeV	6.2×10^6 – 5.7×10^7 GeV	4.1×10^2 – 1.5×10^3 GeV
1 PeV	2.7×10^7 – 1.6×10^8 GeV	2.6×10^3 – 7.2×10^3 GeV

UFO during radiation domination

The ultra-relativistic freeze-out temperature can be determined by

$$\Gamma_{\rm rel}(T_{\rm FO}) = H(T_{\rm FO}) \quad \Rightarrow \quad \frac{g_\chi \zeta(3)}{\pi^2} \frac{T_{\rm FO}^{n+3}}{\Lambda^{n+2}} = 2\sqrt{\frac{\alpha}{3}} \frac{T_{\rm FO}^2}{M_P} \quad \Rightarrow$$

$$T_{\rm FO} = \Lambda \left(\frac{\Lambda}{M_P}\right)^{\frac{1}{n+1}} \left(\frac{2\pi^2}{g_\chi \zeta(3)} \sqrt{\frac{\alpha}{3}}\right)^{\frac{1}{n+1}} .$$

Number density at freeze-out:

$$n_\chi(T_{\rm FO}) = \frac{g_\chi \zeta(3)}{\pi^2} T_{\rm FO}^3 \Rightarrow n_\chi(T_0) = n_\chi(T_{\rm FO}) \left(\frac{a_{\rm FO}}{a_0}\right)^3 = n_\chi(T_{\rm FO}) \left(\frac{T_0}{T_{\rm FO}}\right)^3 \left(\frac{g_0}{g_{\rm FO}}\right)$$

The relic abundance is given by

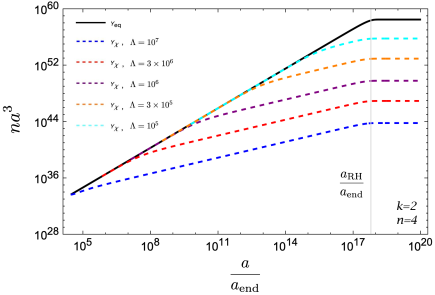
$$\Omega_\chi h^2 \simeq 0.12 \left[g_\chi \left(\frac{106.75}{g_{\rm FO}}\right) \left(\frac{m_\chi}{170~\text{eV}}\right) \right] .$$

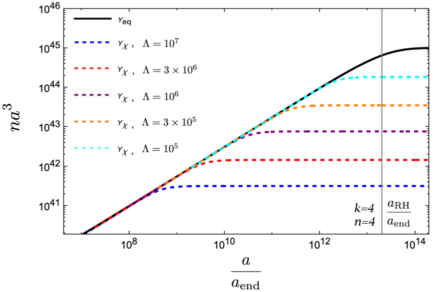
DM Production Rate

$$\frac{dY_\chi}{da} = \frac{a^2 R_\chi(a)}{H(a)} \tag{6}$$

$$R_\chi(T) = \frac{1}{1024\pi^6} \int f(E_1) f(E_2) E_1 \, \mathrm{d}E_1 E_2 \, \mathrm{d}E_2 \, \mathrm{d}\cos\theta_{12} \int |\mathcal{M}|^2 \, \mathrm{d}\Omega_{13}, \tag{7}$$

Λ-dependence





$\Omega_\chi h^2 = 0.12$ parameter space ($k = 4$, $n = 2$)