Ultraheavy Atomic Dark Matter

Freeze-out through Rearrangement

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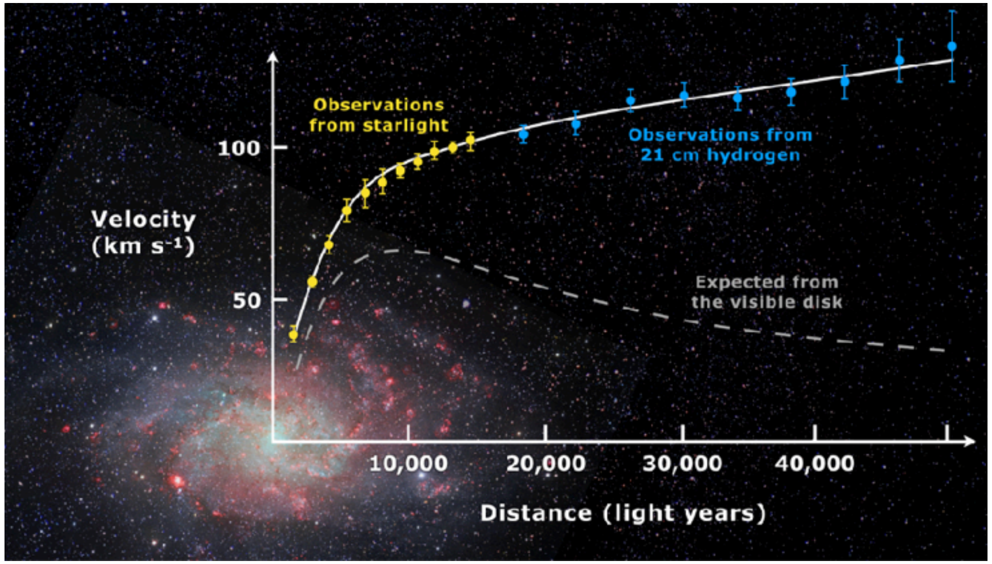
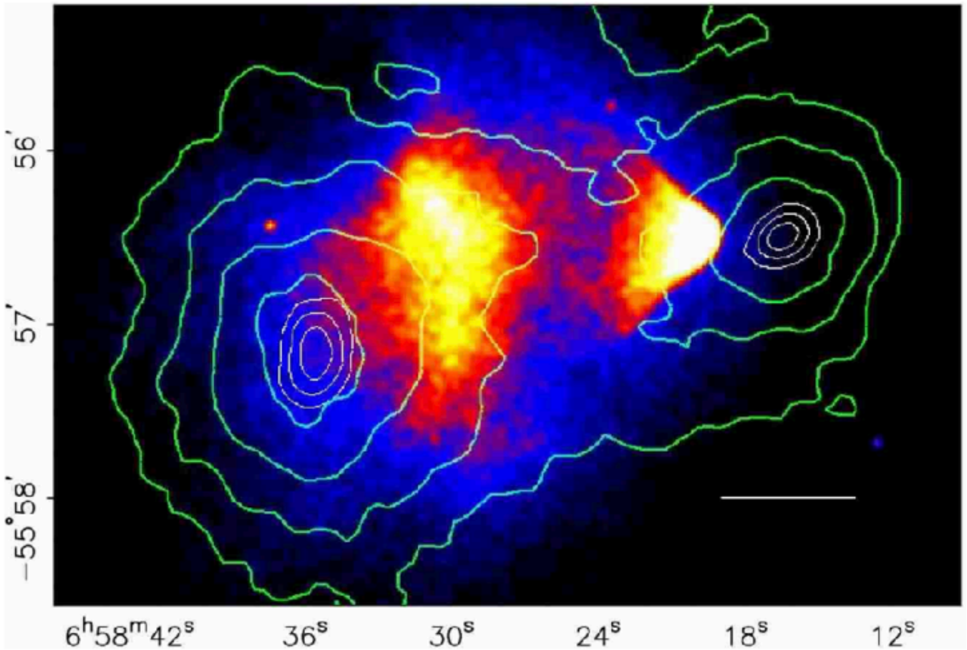
2312.13758 With **Jie Sheng**, **Liang Tan**, and **Chuan-Yang Xing**

Why DM?

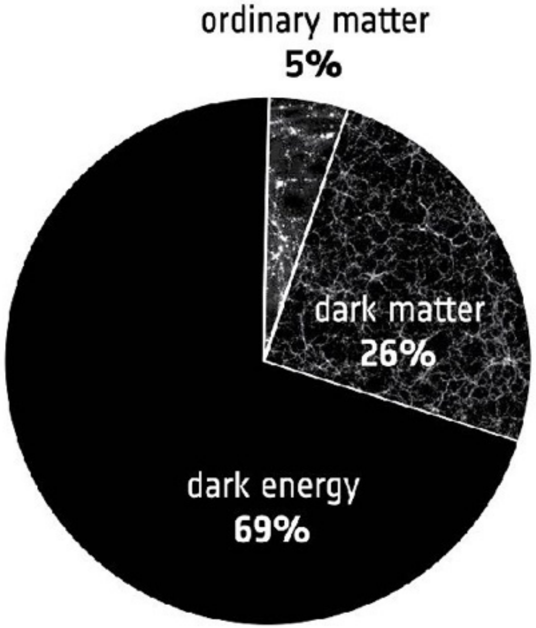


Galaxy rotation curve. Credit: Mario De Leo



Bullet Cluster. From astro-ph/0608407

What is DM?

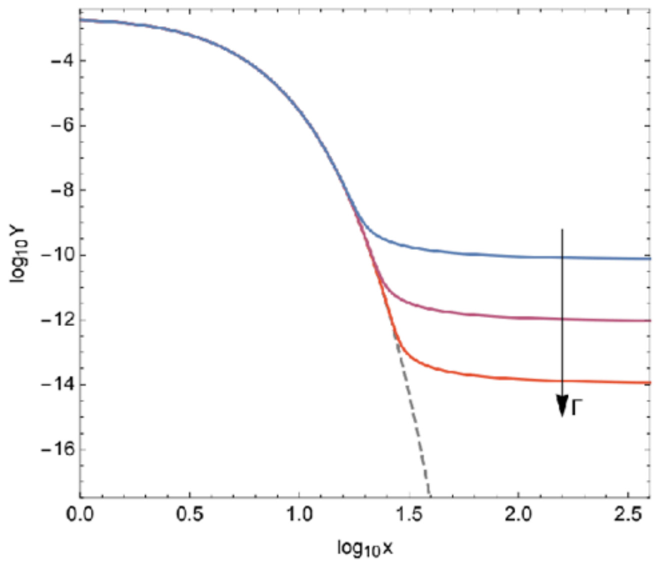


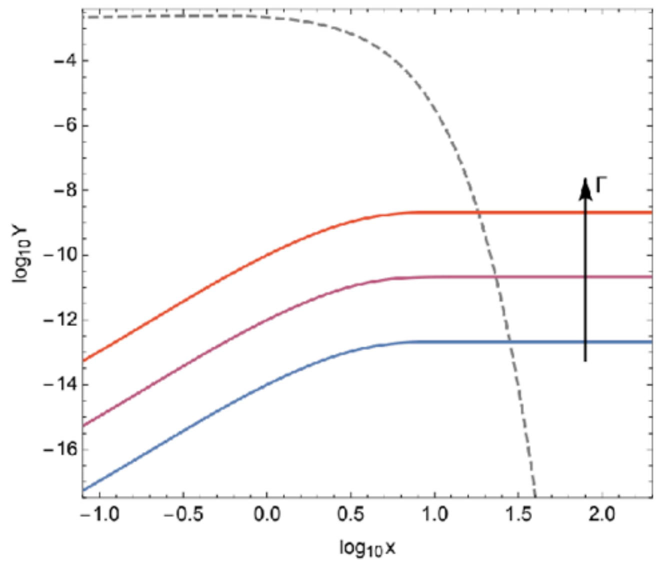
Energy budget of our Universe.
Copyright:ESA. https://sci.esa.int/s/ABdZM5W

- Mass?
- Coupling with baryon?
- Spectrum?
- Elementary or composite?

DM Production

- Thermal Freeze-out.
- Freeze-in.
- Misalignment.
- Decay.
- PBH.

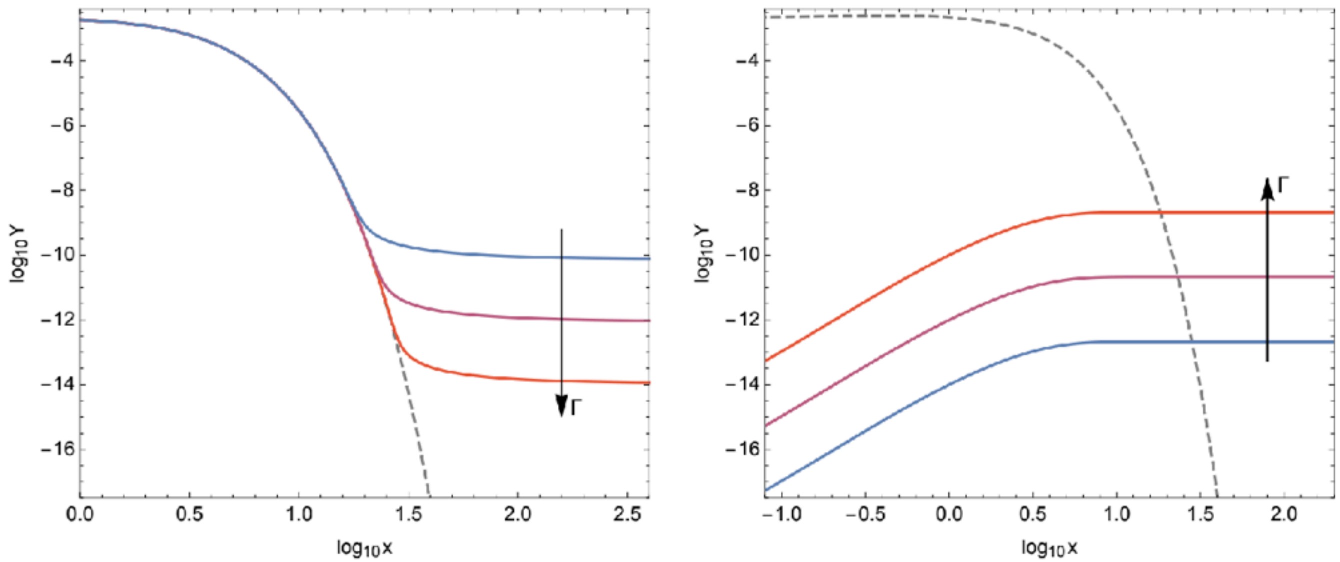




From 1705.01987

DM Production

- Thermal Freeze-out.
  - $T \simeq m_\chi/10$, the DM starts to deviate from thermal equilibrium.
  - Larger Depletion rate Γ indicates smaller freeze out value Y_χ^∞.



From 1705.01987

Unitarity Bound

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Unitarity Limits on the Mass and Radius of Dark-Matter Particles

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Using partial-wave unitarity and the observed density of the Universe, we show that a stable elementary particle which was once in thermal equilibrium cannot have a mass greater than 340 TeV. An extended object which was once in thermal equilibrium cannot have a radius less than 7.5×10^{-7} fm. A lower limit to the relic abundance of such particles is also found.

PACS numbers: 98.80.Cq, 11.80.Et

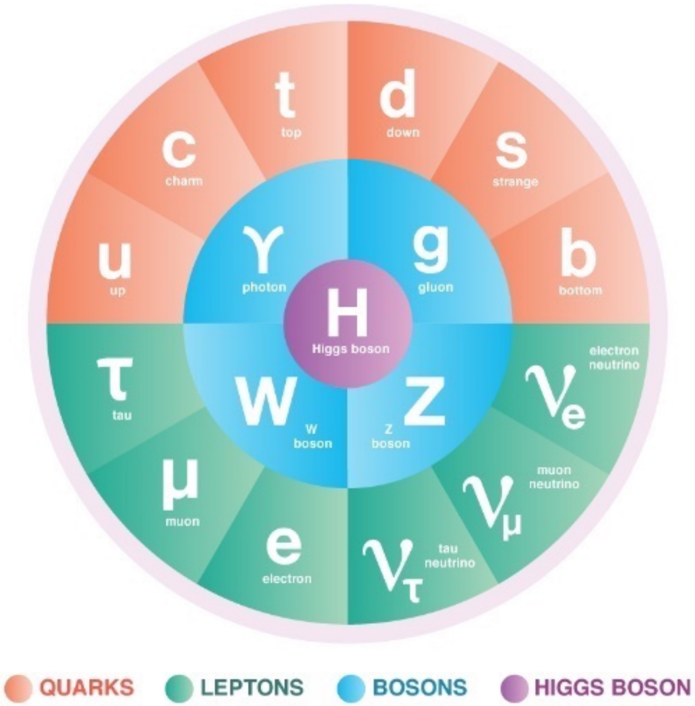
Model-independent !

Thermal freezeout DM Mass should be bounded from above:

$m_\chi \lesssim \mathcal{O}(10^5)$ GeV

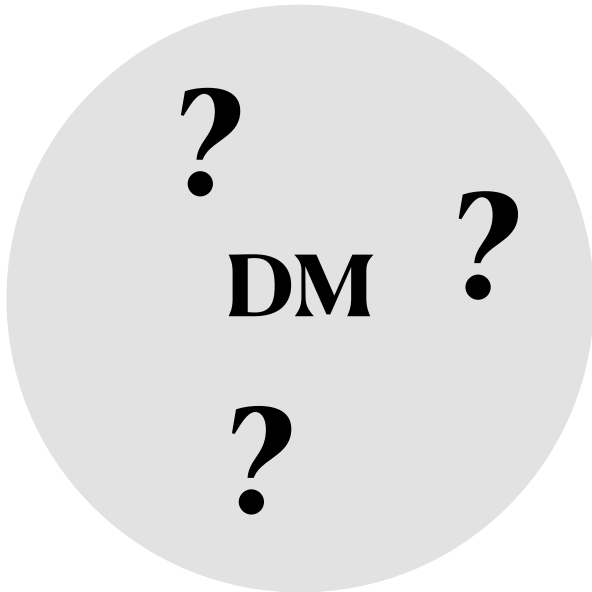
The Unitarity bound could be violated if there is a secondary stage of freeze out.

Atomic DM



Standard Model Spectrum
Artwork by Sandbox Studio, Chicago.

- Higgs Hierarchy
- Strong CP
- SUSY
- ...



The simplest structure:
(symmetric) Dark Atom

The Model $U(1)_X$(SSB)

$$\mathscr{L} \supset \epsilon F'F - \frac{1}{4}F'F' + \frac{1}{2}m_{A'}A'^2$$ Dark photon

$$+\bar{\chi}_p\left(i\gamma\cdot D - m_{\chi_p}\right)\chi_p + \bar{\chi}_e\left(i\gamma\cdot D - m_{\chi_e}\right)\chi_e$$ Dark proton and electron

$$+y_p\phi\bar{\chi}_p\chi_p + y_e\phi\bar{\chi}_e\chi_e + \cdots$$ Dark Higgs

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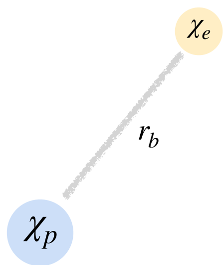
$$\chi_p(+1) + \chi_e(-1) \rightarrow (\chi_p\chi_e)(0)$$

$$\langle\sigma_{\mathrm{AF}}v\rangle \simeq \frac{16\pi}{3\sqrt{3}}\frac{\alpha_D^2}{\mu^2}\left(\frac{E_b}{T_\chi}\right)^{1/2}\ln\left(\frac{E_b}{T_\chi}\right)$$



$$E_b = \frac{1}{2}\alpha_D^2\mu\ , \quad r_b \simeq \frac{1}{\alpha_D\mu}$$

$$m_{\chi_p} \gg m_{\chi_e} \gg m_{A'} \qquad \mu = \frac{m_{\chi_p}m_{\chi_e}}{m_{\chi_p} + m_{\chi e}} \simeq m_{\chi_e}$$

Dark Plasma

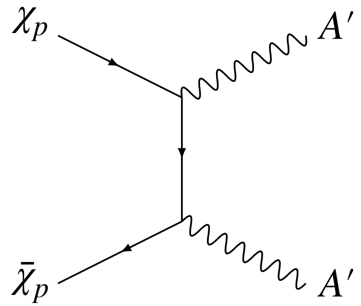
- To protect the BBN, we tune the kinetic mixing $\epsilon < 10^{-12}$,
- And let $T_\chi = T_\gamma \xi$, where $\xi = 0.2$.

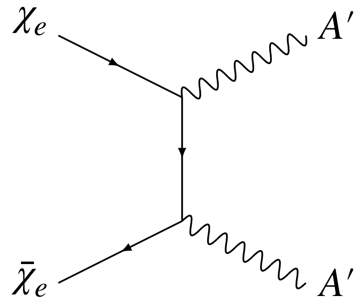
$$\chi_p + \bar{\chi}_p \leftrightarrow 2A'$$

$$\chi_e + \bar{\chi}_e \leftrightarrow 2A'$$

$$\chi_p + \bar{\chi}_p \rightarrow (\chi_p \bar{\chi}_p) \rightarrow 2A'$$

$$\chi_e + \bar{\chi}_e \rightarrow (\chi_e \bar{\chi}_e) \rightarrow 2A'$$



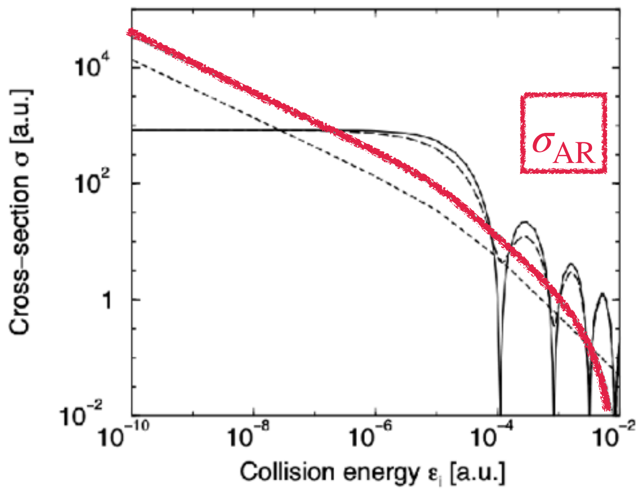


$$\langle \sigma_{\text{anni}}^{p(e)} v \rangle \simeq \frac{\alpha_D^2}{m_{\chi_{p(e)}}^2} \times \mathcal{S} \qquad \mathcal{S} \sim \mathcal{O}(10^2)$$

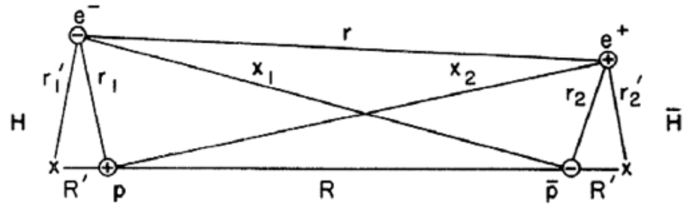
Atoms do not carry net $U(1)$ charge.
They do not annihilate directly.
They rearrange and then annihilate.

Atomic Rearrangement

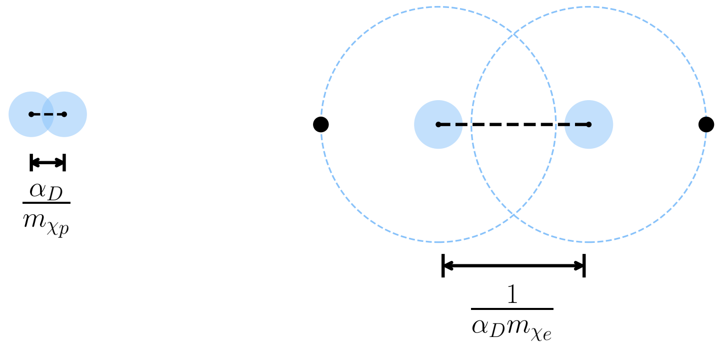
$$
\boxed{\begin{aligned}
&(\chi_p \chi_e) + (\bar{\chi}_p \bar{\chi}_e) \to (\bar{\chi}_p \chi_p) + \chi_e + \bar{\chi}_e \\
&(\chi_p \chi_e) + (\bar{\chi}_p \bar{\chi}_e) \to (\bar{\chi}_p \chi_p) + (\bar{\chi}_e \chi_e)
\end{aligned}}
$$



Phys. Rev. Lett. **84**, 4577



Hydrogen-anti-hydrogen interaction.



Geometric cross section

$$\langle \sigma_{\rm AR} v \rangle \simeq \mathscr{C} \pi r_b^2 \simeq \frac{\mathscr{C}\pi}{\alpha_D^2 m_{\chi_e}^2} \qquad \mathscr{C} \sim \mathcal{O}(1)$$

$$\langle \sigma^p_{\rm anni} v \rangle \ll \langle \sigma_{\rm AR} v \rangle$$

Since $m_{\chi_e} \ll m_{\chi_p}$ and $\langle \sigma^e_{\text{anni}} v \rangle \gg \langle \sigma^p_{\text{anni}} v \rangle$, one generally have more χ_p than χ_e after their freezeout through direct annihilation. One has to produce more χ_e to form $(\chi_p \chi_e)$ and deplete χ_p. Therefore, ϕ is introduced to slowly produce χ_e via

$$\phi \to \chi_e + \bar{\chi}_e.$$

Production

Boltzmann equations for general χ

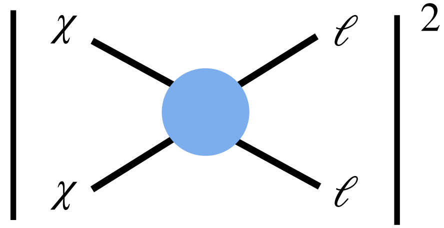
(1) Number density $n(t)$

$$\dot{n}(t) + 3H(t)n(t) = -\langle \sigma_{\chi\chi} v \rangle \left(n(t)^2 - n_{\rm eq}(t)^2 \right)$$

(2) Introduce the yield $Y_\chi = \dfrac{n(t)}{s}$

$$\frac{dY_\chi}{dt} = -s\langle \sigma_{\chi\chi} v \rangle \left(Y_\chi^2 - \left(Y_\chi^{\rm eq} \right)^2 \right)$$

(3) Rescale the cosmic time as $x = \dfrac{m_\chi}{T(t)}$

$\sigma_{\chi\chi} =$ 

$$n_{\rm eq}(t) = \frac{g}{(2\pi)^3} \int d^3p\, f(p)$$

$$\boxed{\frac{dY_\chi}{dx} = -\frac{\lambda_\chi}{x^2} \left(Y_\chi^2 - \left(Y_\chi^{\rm eq} \right)^2 \right)}$$

$$\lambda_\chi = \sqrt{\frac{4\pi g_{*S}^2}{45 g_*}} \langle \sigma_{\chi\chi} v \rangle m_\chi M_P$$

Production

Boltzmann Equations — around $T \sim \mathcal{O}(E_b/10)$

$$\frac{dY_p}{dt} = -\, s\langle\sigma_{\rm AF}v\rangle\left(Y_pY_e - Y_p^{\rm eq}Y_e^{\rm eq}\frac{Y_{\chi_A}}{Y_{\chi_A}^{\rm eq}}\right)$$

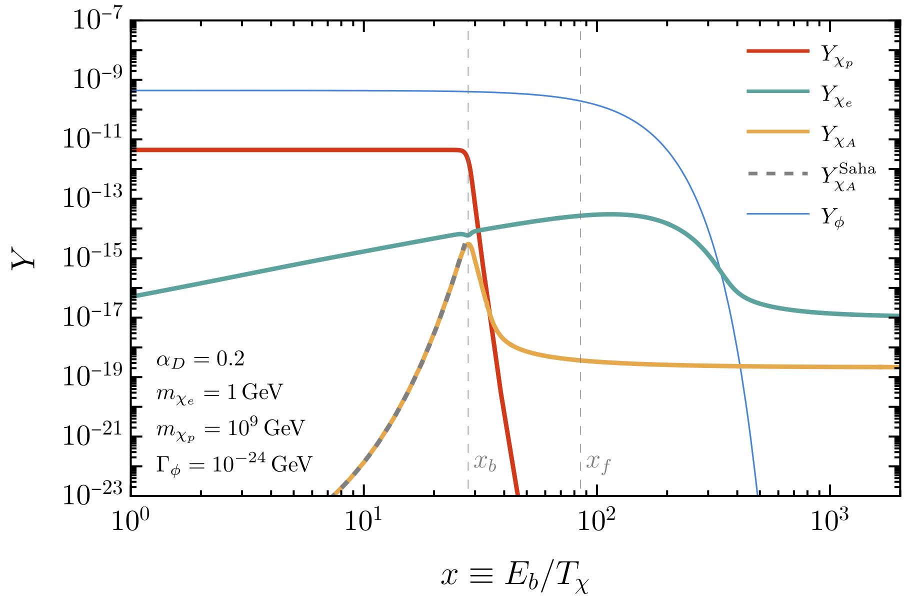
$$\frac{dY_e}{dt} = -\, s\langle\sigma_{\rm anni}^{e}v\rangle\left(Y_e^2 - (Y_e^{\rm eq})^2\right) - s\langle\sigma_{\rm AF}v\rangle\left(Y_pY_e - Y_p^{\rm eq}Y_e^{\rm eq}\frac{Y_{\chi_A}}{Y_{\chi_A}^{\rm eq}}\right) + \langle\Gamma_\phi\rangle Y_\phi + s\langle\sigma_{\rm AR}v\rangle Y_{\chi_A}^2$$

$$\frac{dY_{\chi_A}}{dt} = +\, s\langle\sigma_{\rm AF}v\rangle\left(Y_pY_e - Y_p^{\rm eq}Y_e^{\rm eq}\frac{Y_{\chi_A}}{Y_{\chi_A}^{\rm eq}}\right) - 2s\langle\sigma_{\rm AR}v\rangle Y_{\chi_A}^2$$

Consider $2m_{\chi_p} > m_\phi > 2m_{\chi_e}$, so that only $\phi \to \chi_e + \bar{\chi}_e$ is kinetically allowed.

Production

- (1) χ_p freezeout ($E_b \lesssim T_\chi \lesssim m_{\chi_p}$)
    - χ_p stays constant yield.
    - χ_e slowly freeze-in via $\phi \to \bar{\chi}_e + \chi_e$.
- (2) $(\chi_p\chi_e)$ formation ($T_\chi \sim E_b/30$)
    - $\chi_p + \chi_e \to (\chi_p\chi_e)$
- (3) Rearrangement annihilation ($T_\chi \sim E_b/100$)
    - $(\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + (\bar{\chi}_e\chi_e)$
    - $(\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + \chi_e + \bar{\chi}_e$

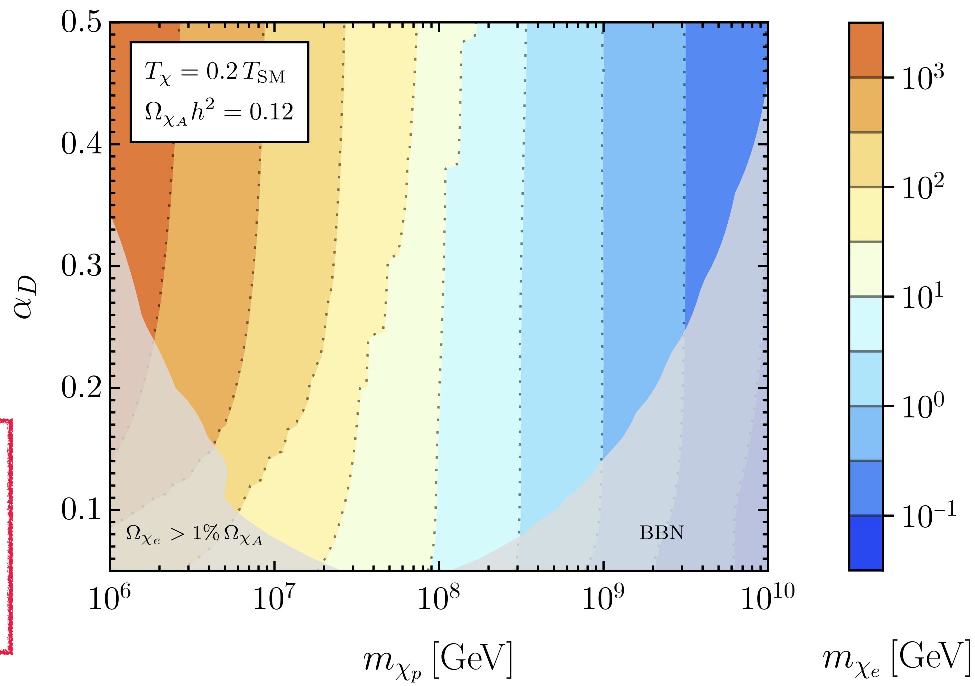


The final DM is mostly made of $\chi_A = (\chi_p \chi_e)$ and $\bar{\chi}_A$, which is symmetric like WIMP.

Parameters

- Choose the initial condition of ϕ as $Y_\phi^0 = 100 \times Y_p^0$ and it decays around $x \sim E_b/100$ by tuning $\{y_p, y_e, m_\phi\}$.
- Free parameters are $\{\alpha_D, m_{\chi_p}, m_{\chi_e}\}$.

$$m_{\chi_A} \approx m_{\chi_p} \in \left(10^6, 10^{10}\right)\ \mathrm{GeV}$$
$$\text{for } \alpha_D \in \left(0.05, 0.5\right)\ \&\ m_{\chi_e} \in \left(10^{-1}, 10^3\right)\ \mathrm{GeV}$$



Naturally much larger than the unitarity bound!

(1) Symmetric Atomic DM could be produced from thermal freeze out,
(2) and it is naturally ultraheavy violating the unitarity bound.

Thank you