Ultraheavy Atomic Dark Matter

Freeze-out through Rearrangement

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

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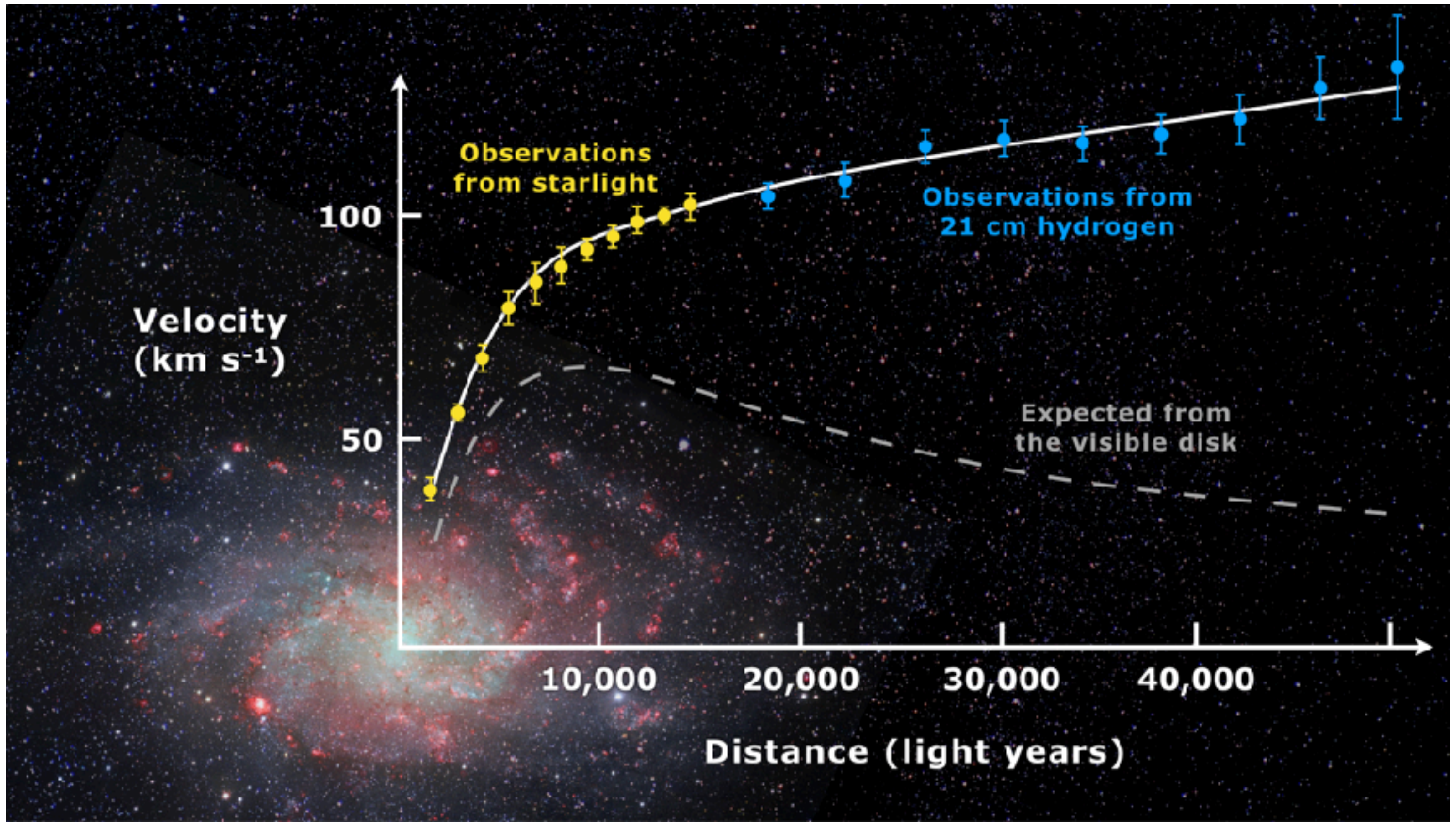
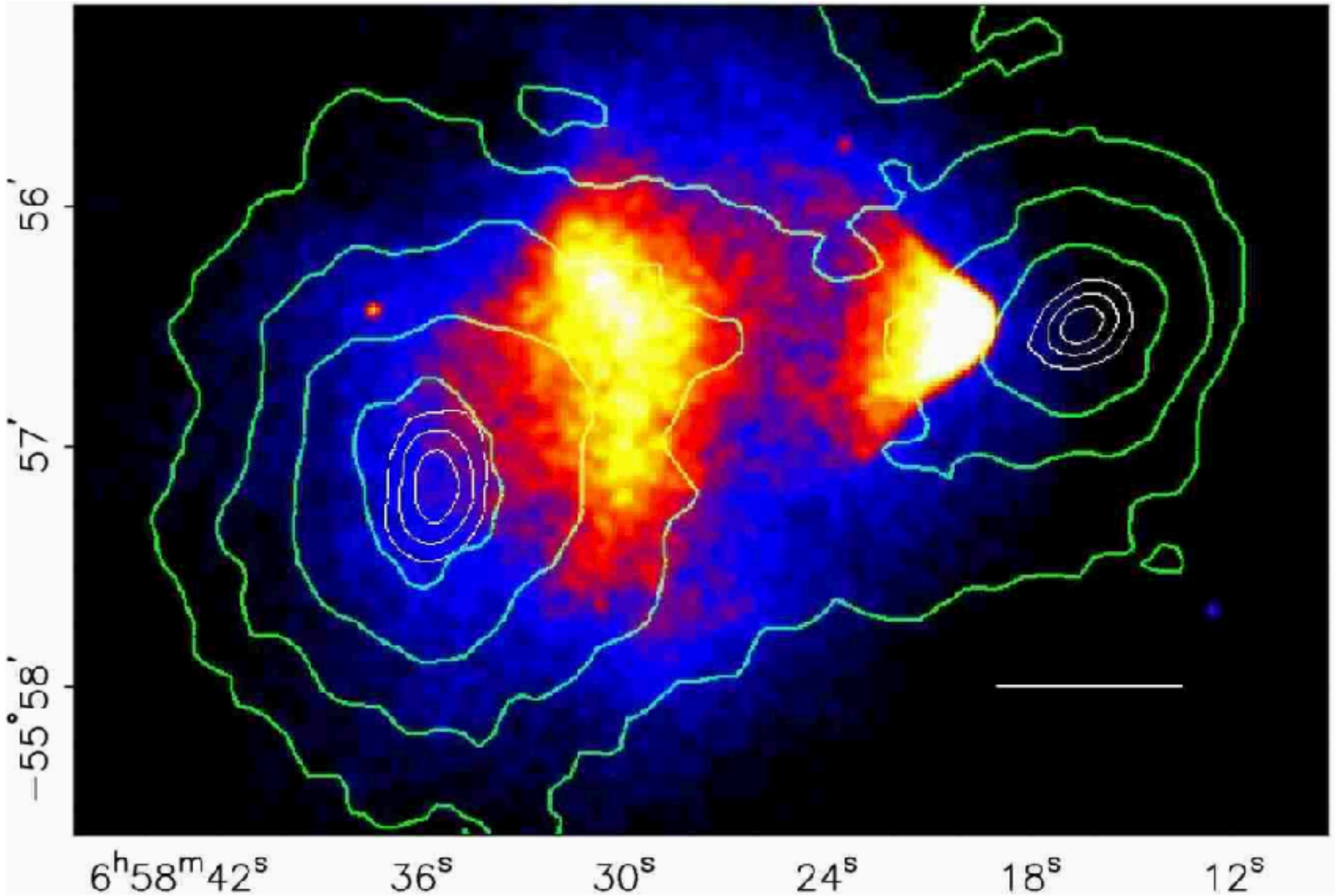
Why DM?

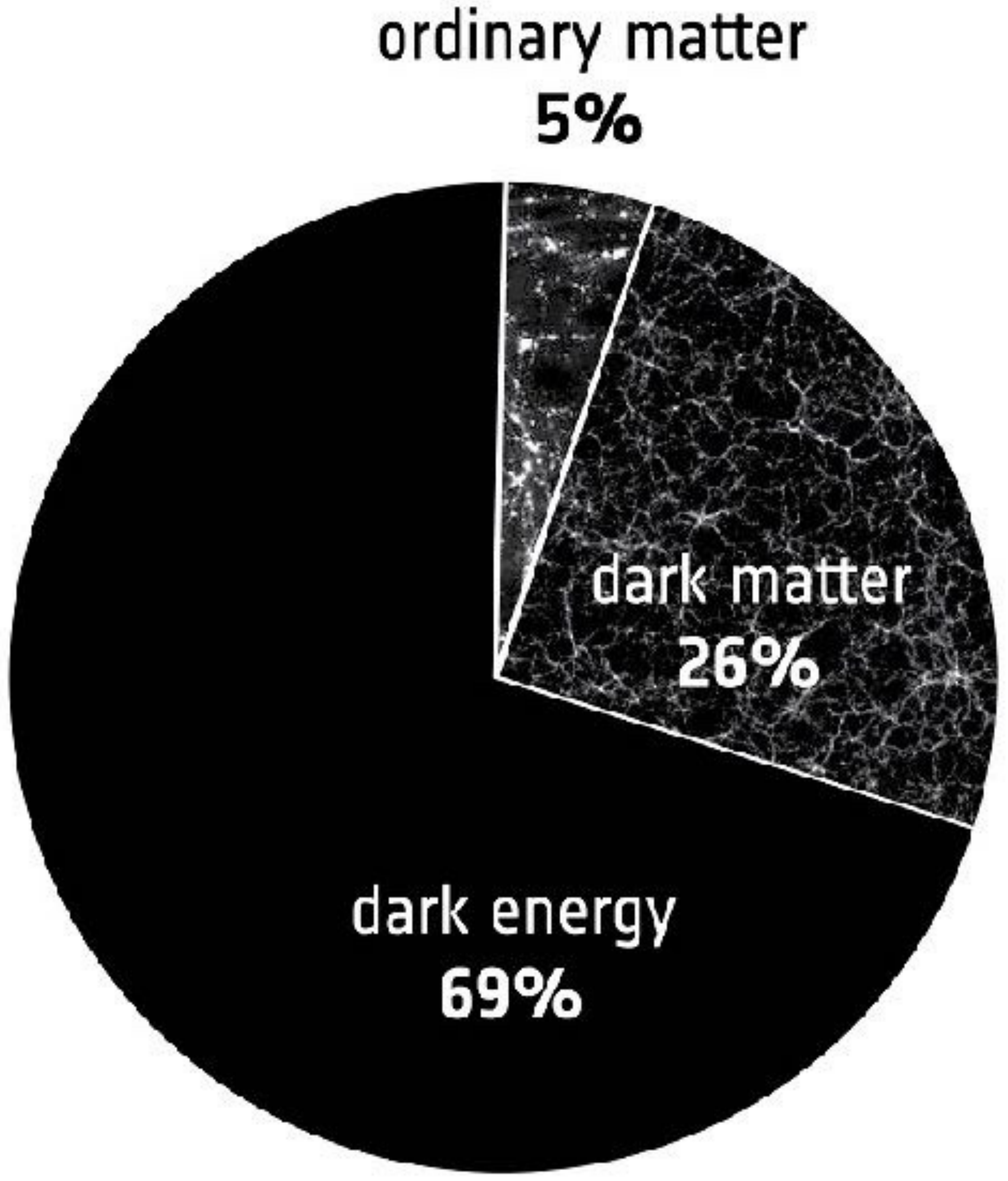


Galaxy rotation curve. Credit: Mario De Leo



Bullet Cluster. From astro-ph/0608407

What is DM?



Energy budget of our Universe.
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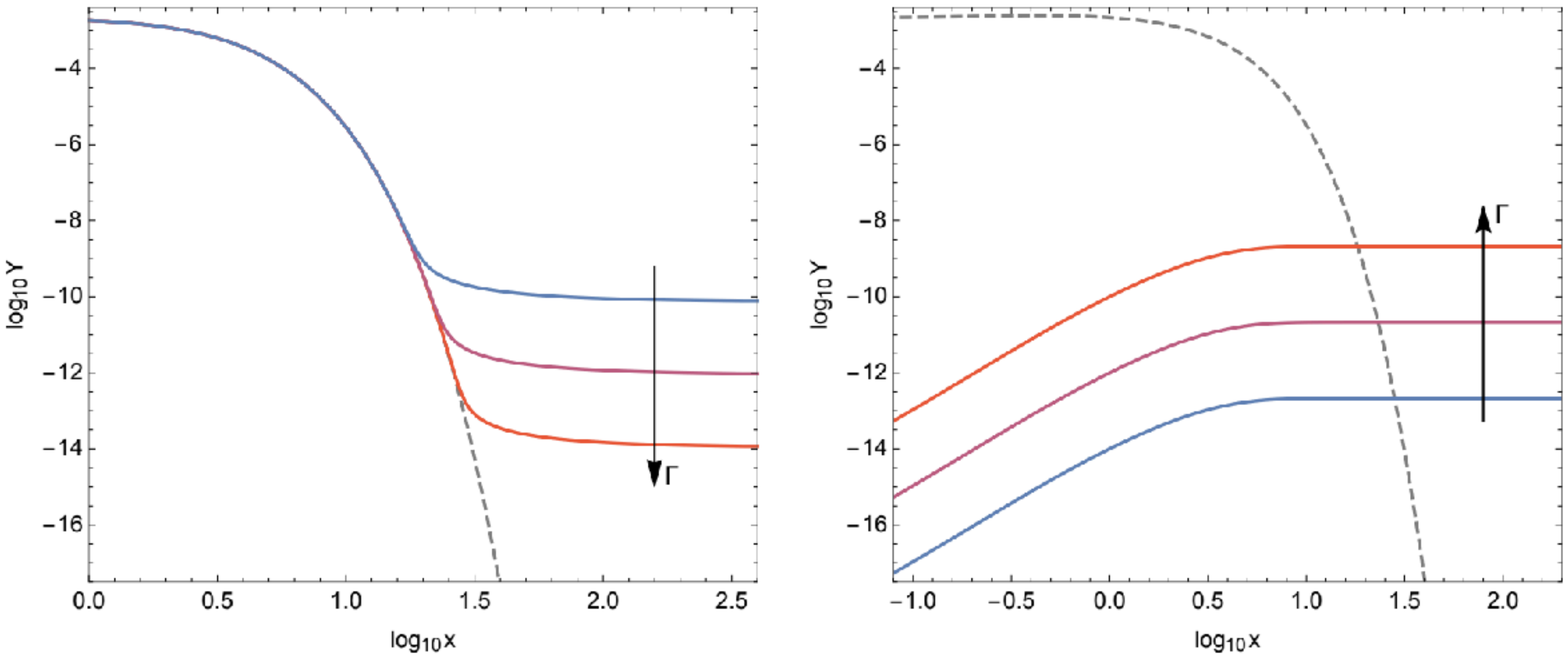
- Mass?
- Coupling with baryon?
- Spectrum?
- Elementary or composite?

DM Production

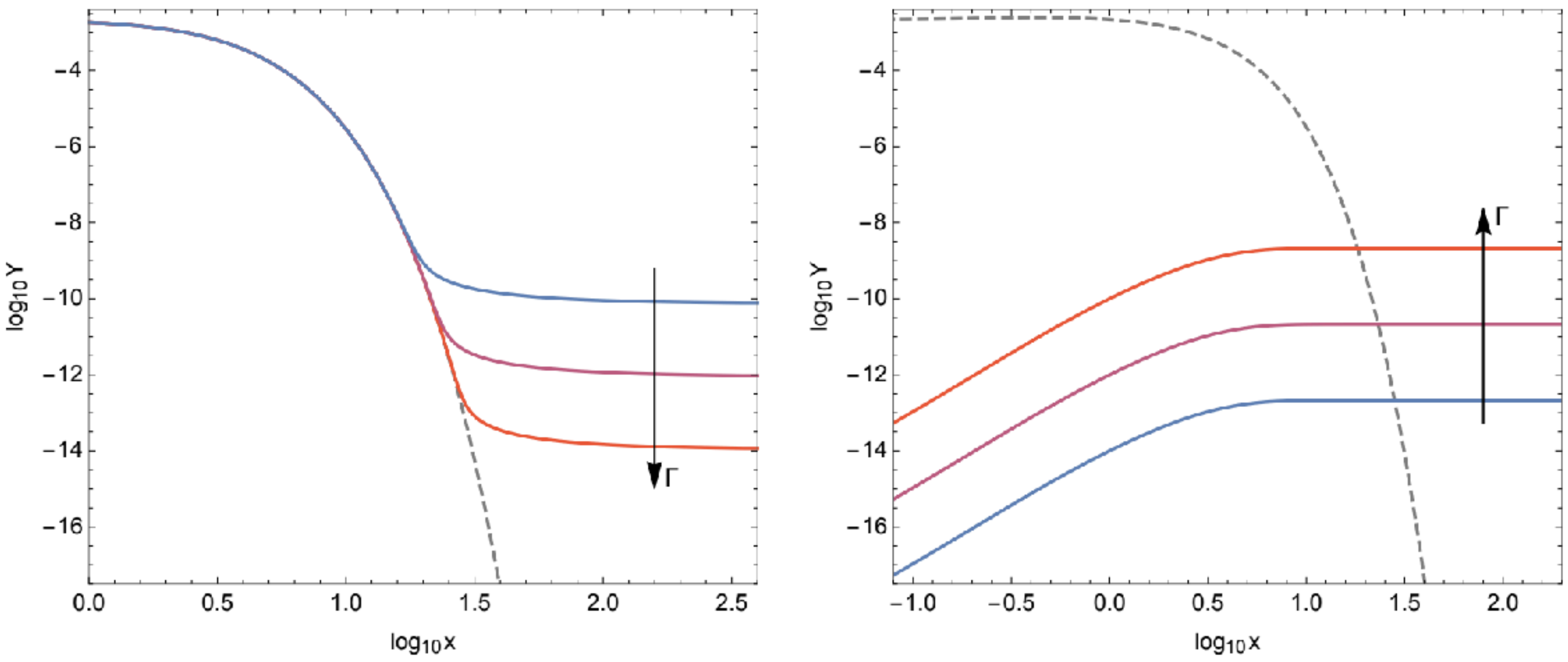
- Thermal Freeze-out.
- Freeze-in.
- Misalignment.
- Decay.
- PBH.



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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(Received 5 October 1989)

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

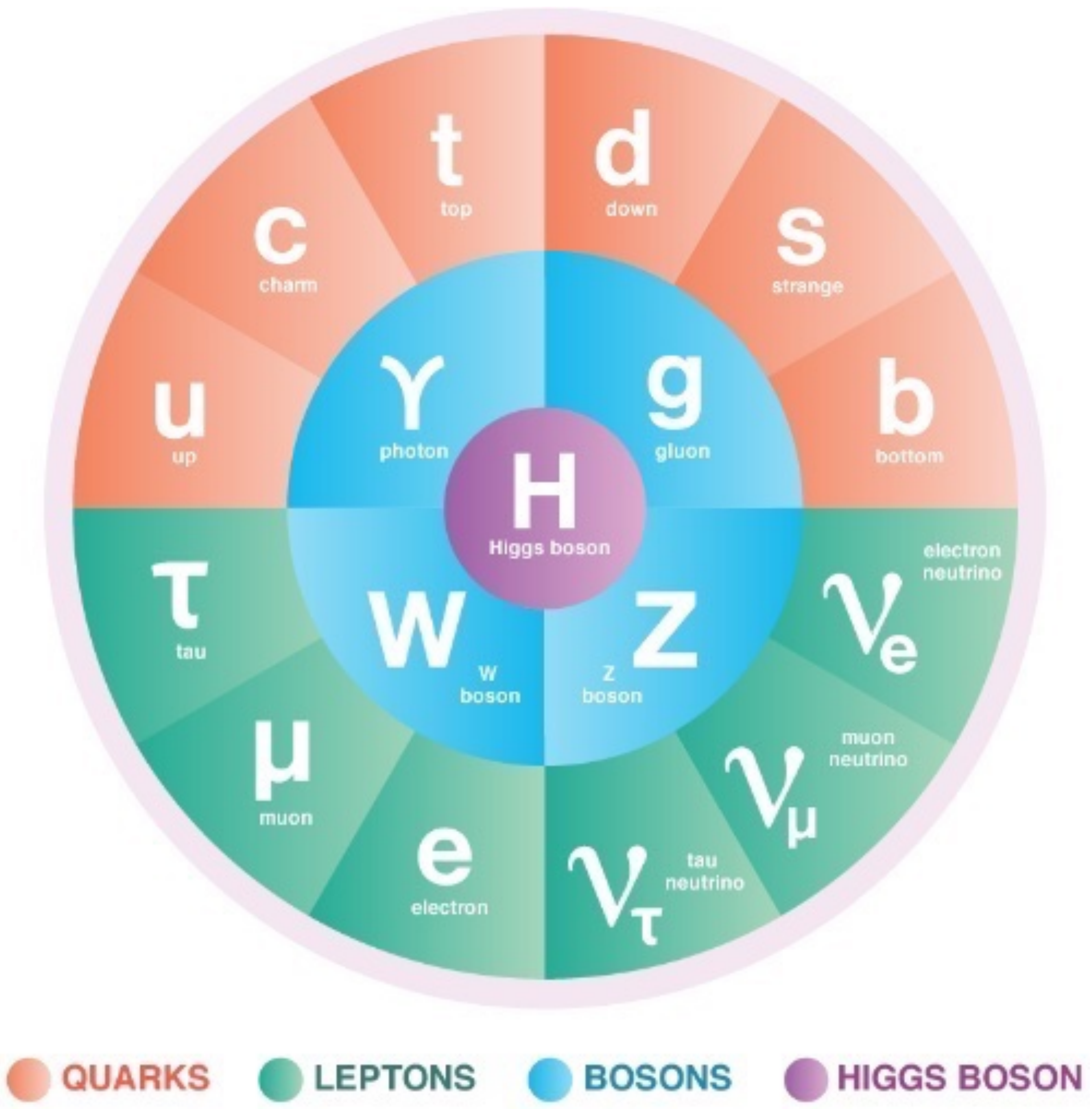
Model-independent

Thermal freezeout DM Mass should be bounded from above:

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

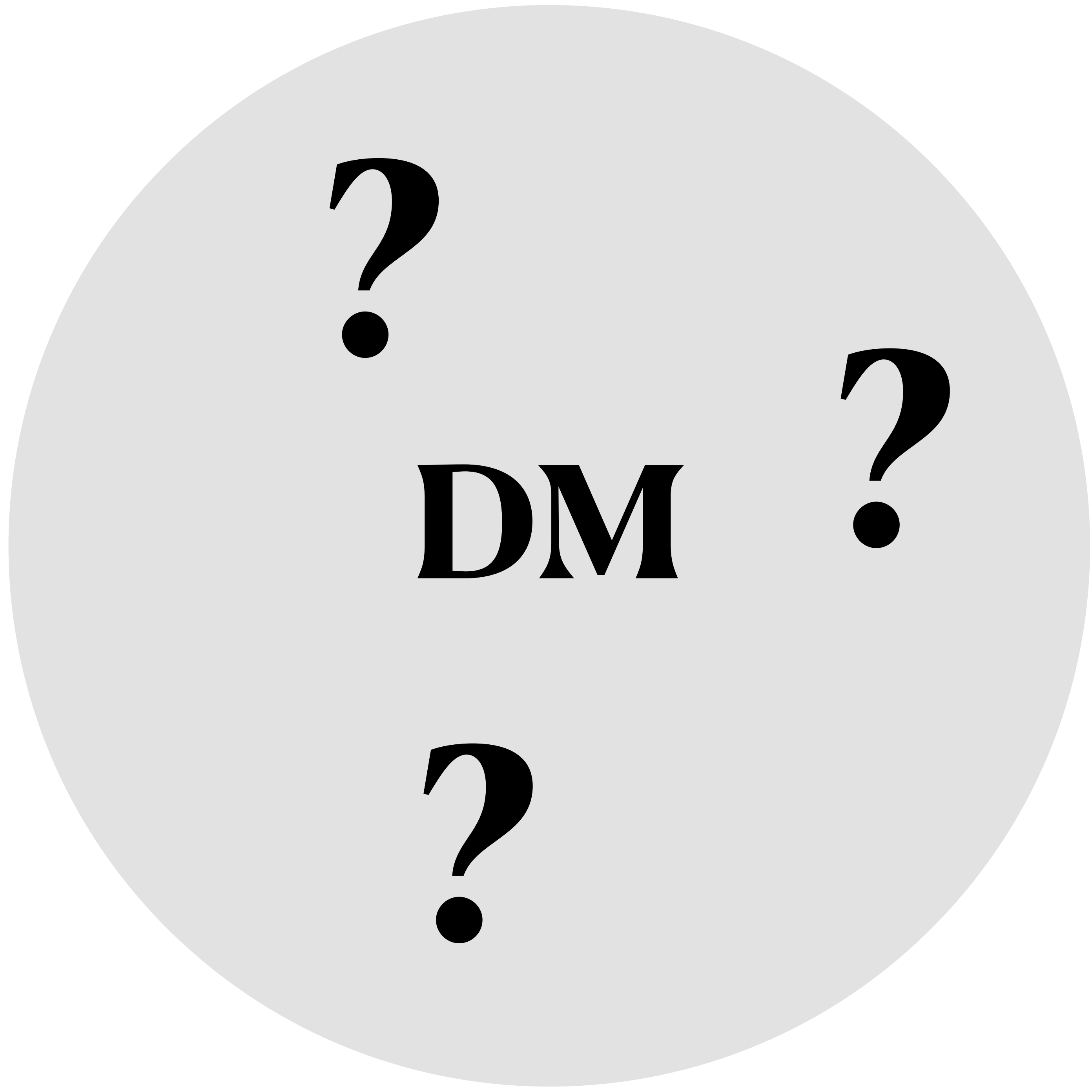
The Unitarity bound could be violated if there is a secondary stage of freeze out.

Atomic DM



Standard Model Spectrum
Artwork by Sandbox Studio, Chicago.

- Higgs Hierarchy
- Strong CP
- SUSY
- …



The simplest structure:
(symmetric) Dark Atom

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Atomic dark matter

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Journal of Cosmology and Astroparticle Physics
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Dark atoms: $\boxed{\text{asymmetry}}$ and direct detection

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Usual atomic DM is asymmetric.

Just like the SM.

Could it be symmetric?

We present a symmetric Dark Atom model that naturally violates the unitarity bound.

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

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

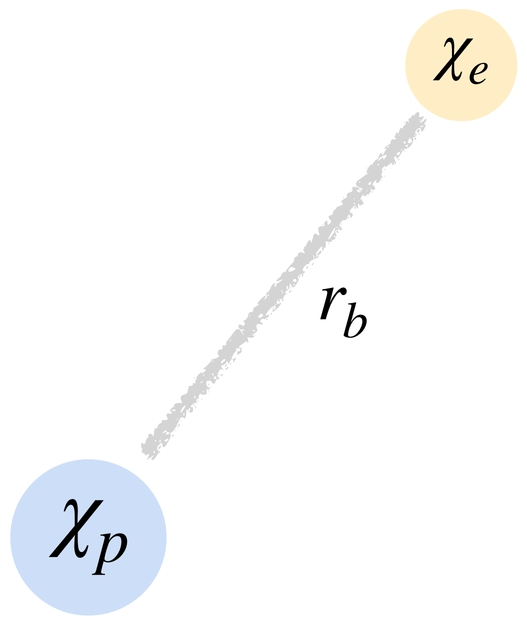
Dark proton and electron

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

Dark Higgs

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

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



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

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

Dark Plasma

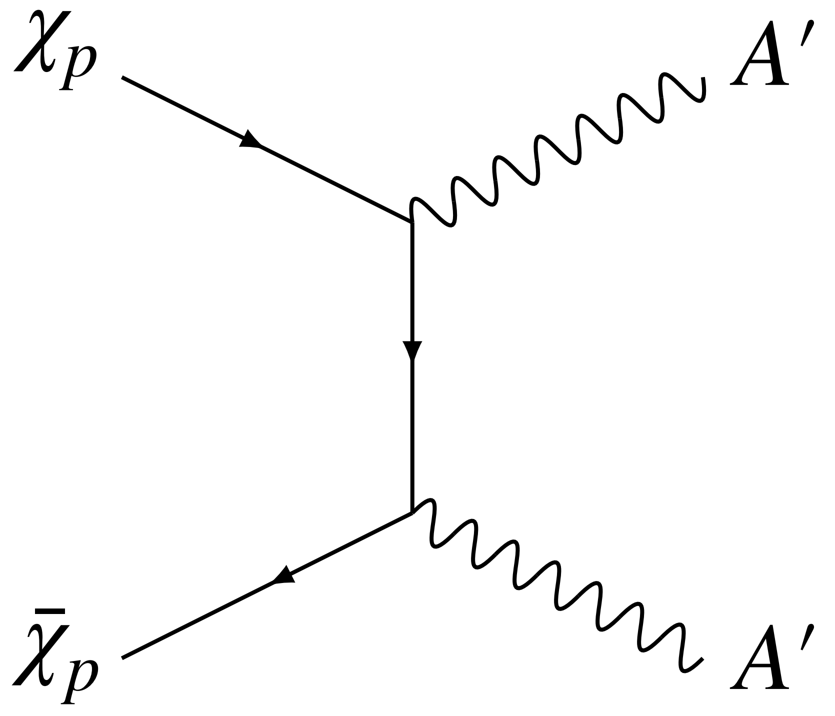
- To protect the BBN, we tune the kinetic mixing $\epsilon < 10^{-12}$,
- And let $T_\chi = T_\gamma \xi$, where $\xi = 0.2$.

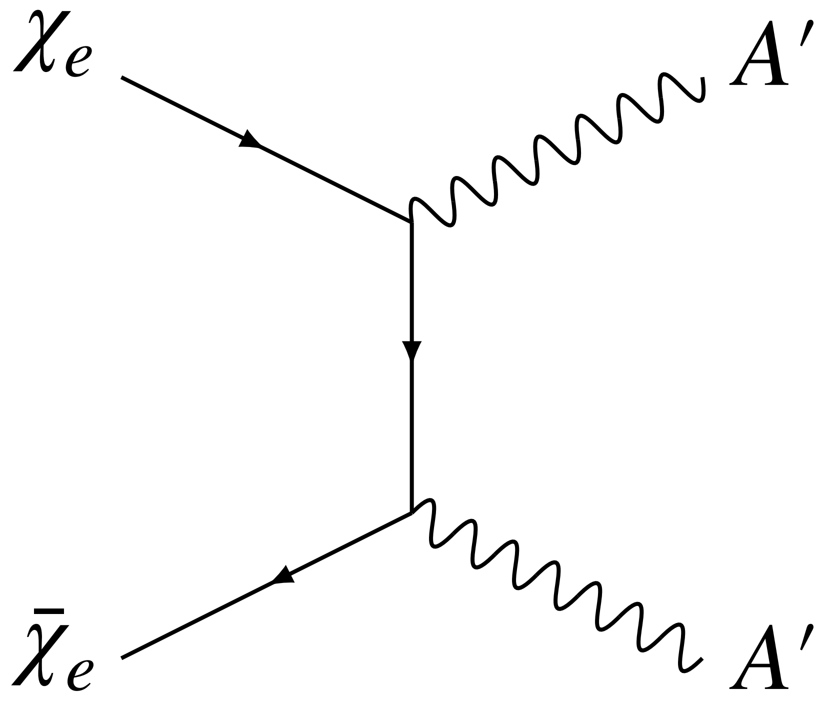
$$\chi_p + \bar{\chi}_p \leftrightarrow 2A'$$

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

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

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





$$\langle \sigma^{p(e)}_{\mathrm{anni}} v \rangle \simeq \frac{\alpha_D^2}{m^2_{\chi_{p(e)}}} \times \mathcal{S}$$

$$\mathcal{S} \sim \mathcal{O}(10^2)$$

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

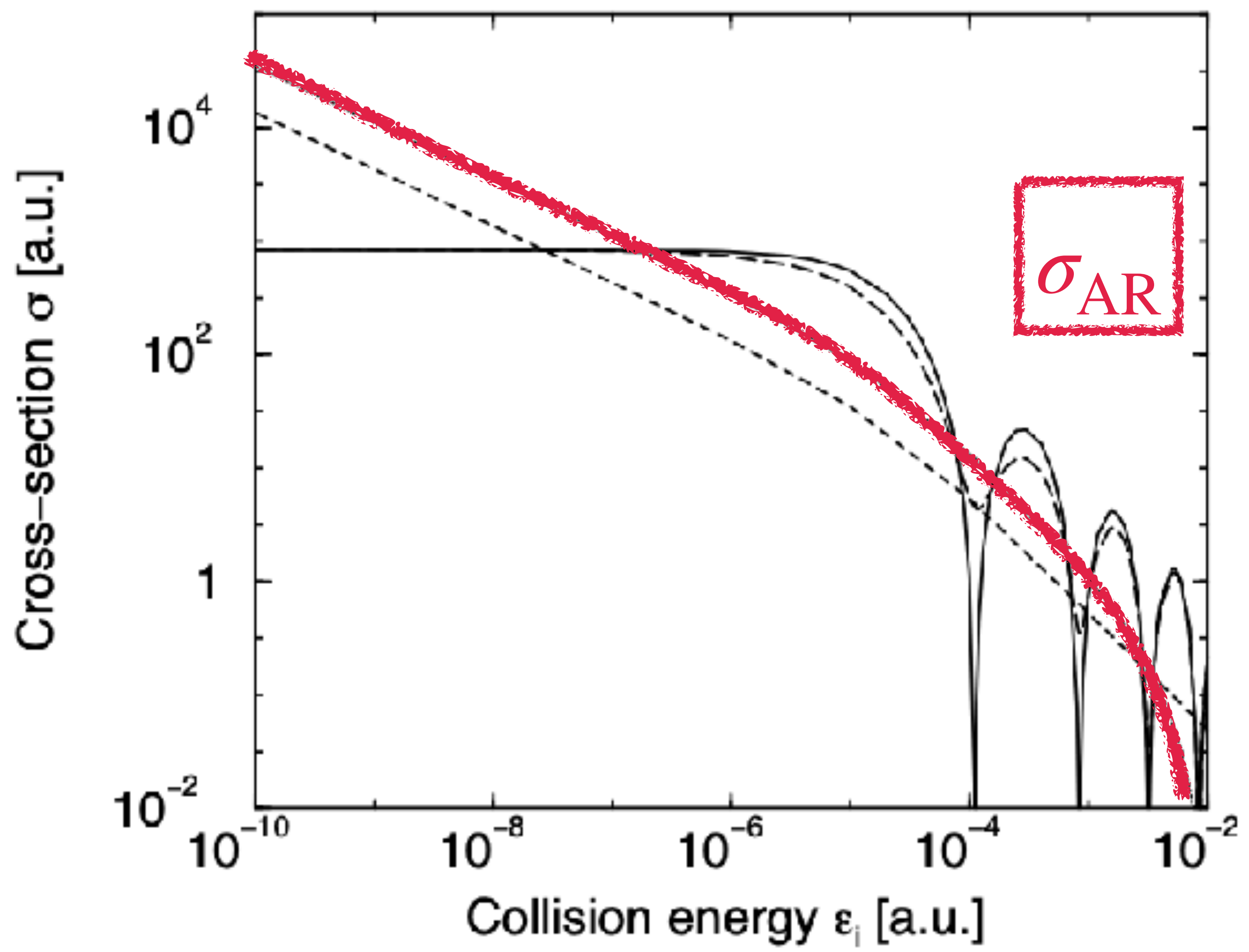
Atomic Rearrangement

$$\sigma_{\rm AR}\left(\boxed{\begin{array}{l}(\chi_p\chi_e)+(\bar\chi_p\bar\chi_e)\to(\bar\chi_p\chi_p)+\chi_e+\bar\chi_e\\(\chi_p\chi_e)+(\bar\chi_p\bar\chi_e)\to(\bar\chi_p\chi_p)+(\bar\chi_e\chi_e)\end{array}}\right.$$

$$\sigma_{p\bar A}\left(\begin{array}{l}\chi_p+(\bar\chi_p\bar\chi_e)\to(\bar\chi_p\chi_p)+\bar\chi_e\\\bar\chi_p+(\chi_p\chi_e)\to(\bar\chi_p\chi_p)+\chi_e\end{array}\right.$$

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

$$\langle\sigma^p_{\rm anni}v\rangle\ll\langle\sigma_{\rm AR}v\rangle\approx\langle\sigma_{p\bar A}v\rangle$$



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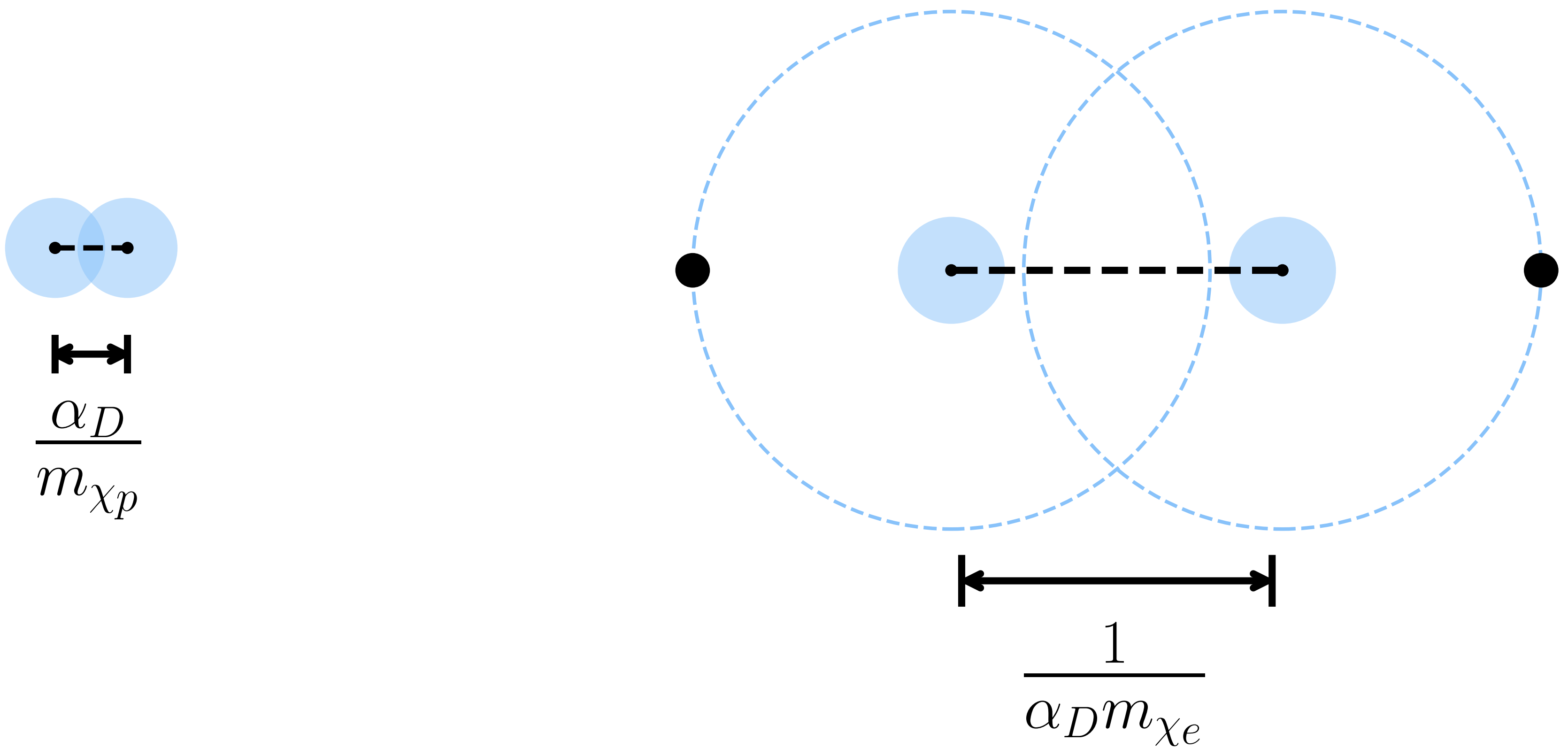


Geometric cross section

Atomic Rearrangement

$$\sigma_{\mathrm{AR}} \left(\begin{array}{l} (\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + \chi_e + \bar{\chi}_e \\ (\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + (\bar{\chi}_e\chi_e) \end{array} \right.$$

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

$$\sigma_{p\bar{A}} \left(\begin{array}{l} \chi_p + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + \bar{\chi}_e \\ \bar{\chi}_p + (\chi_p\chi_e) \to (\bar{\chi}_p\chi_p) + \chi_e \end{array} \right.$$

Binding Energy $E_b(\bar{\chi}_e\chi_e) < E_b(\bar{\chi}_p\chi_e)$

So it is an endothermic reaction.

Kinetically forbidden

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

$$\langle \sigma^p_{\mathrm{anni}} v \rangle \ll \langle \sigma_{\mathrm{AR}} v \rangle \approx \langle \sigma_{p\bar{A}} v \rangle$$

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

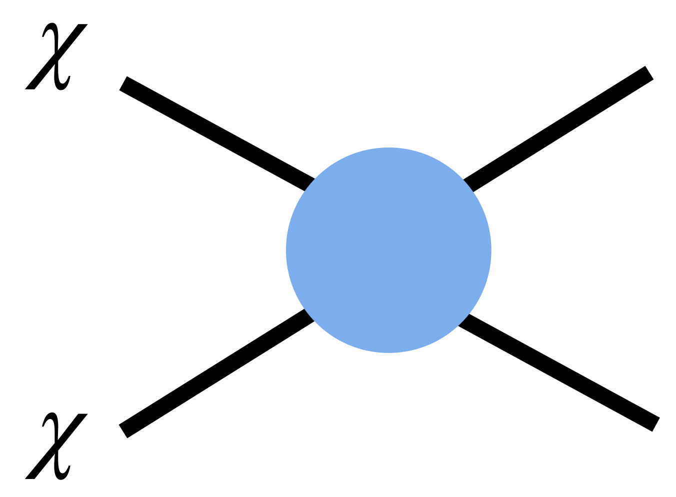
(1) Number density $n(t)$

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

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

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

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

$\sigma_{\chi\chi} = \Big|$  $\Big|^2$

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

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

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

Production

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

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

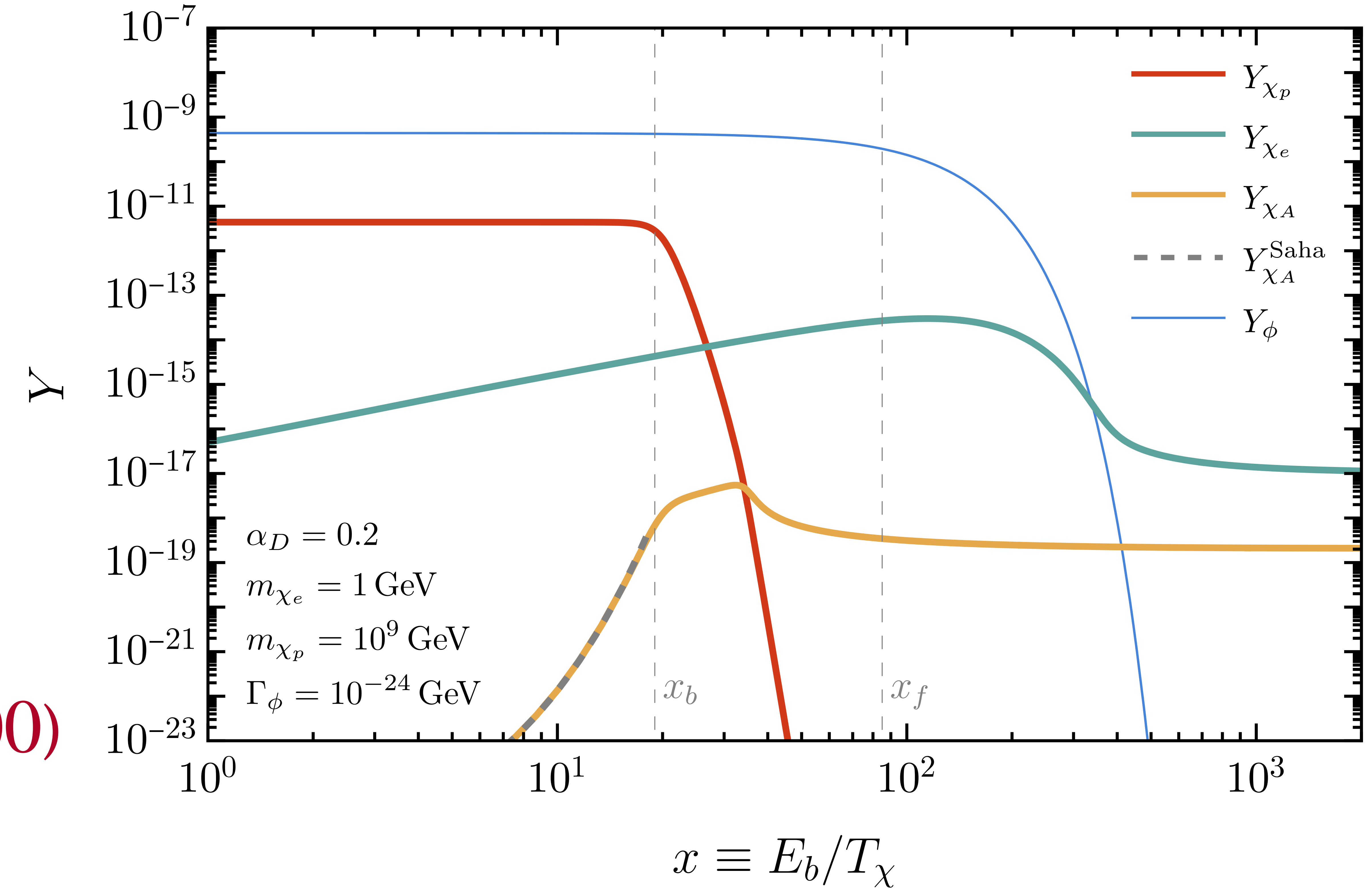
$$\frac{dY_e}{dt} = -\, s\langle\sigma_{\mathrm{anni}}^{e}v\rangle\left(Y_e^2 - (Y_e^{\mathrm{eq}})^2\right) - s\langle\sigma_{\mathrm{AF}}v\rangle\left(Y_pY_e - Y_p^{\mathrm{eq}}Y_e^{\mathrm{eq}}\frac{Y_{\chi_A}}{Y_{\chi_A}^{\mathrm{eq}}}\right) + \langle\Gamma_\phi\rangle Y_\phi + s\langle\sigma_{\mathrm{AR}}v\rangle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

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

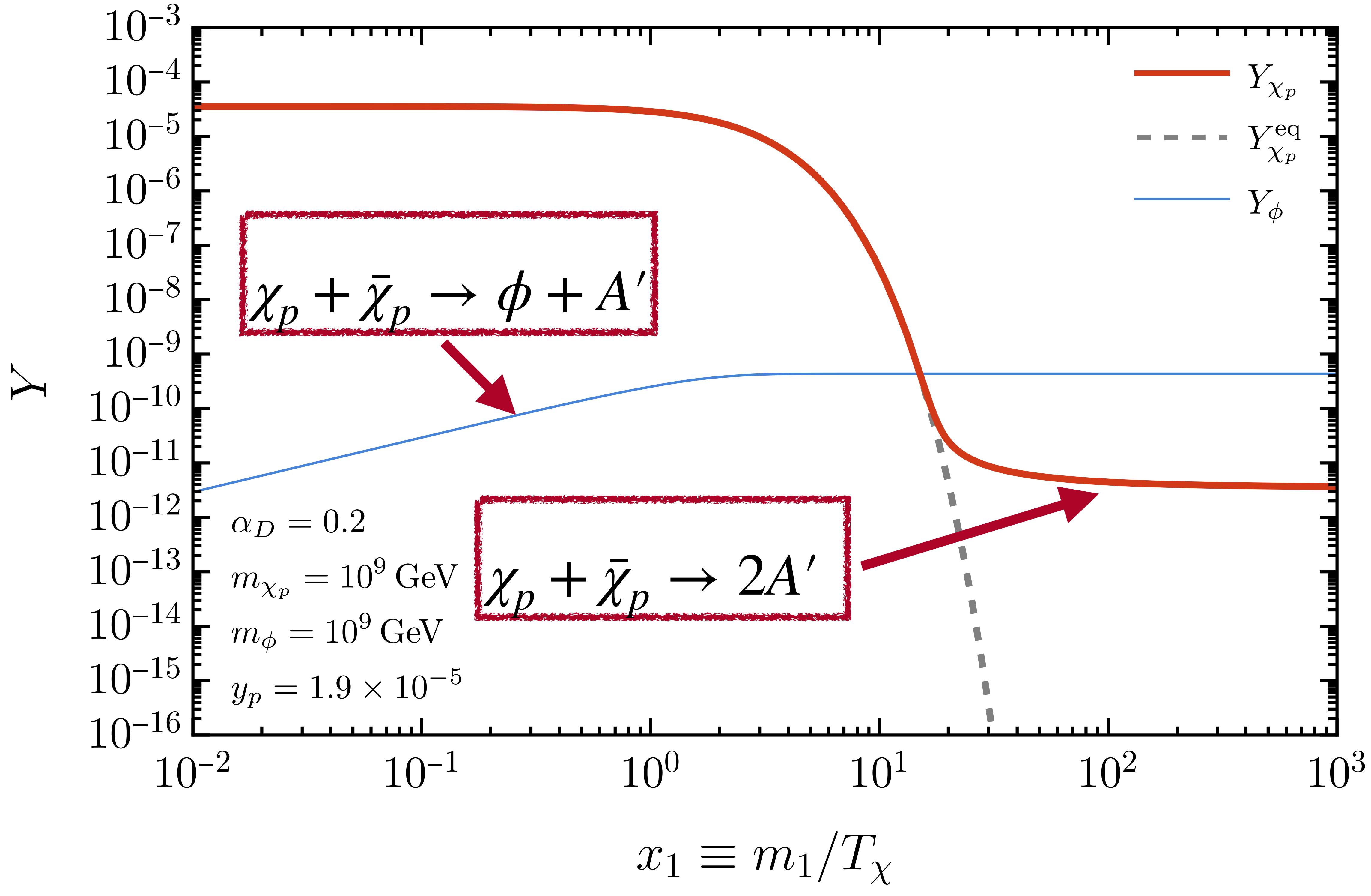
Consider $2m_{\chi_p} > m_\phi > 2m_{\chi_e}$, so that only $\phi \to \chi_e + \bar{\chi}_e$ is kinetically allowed.

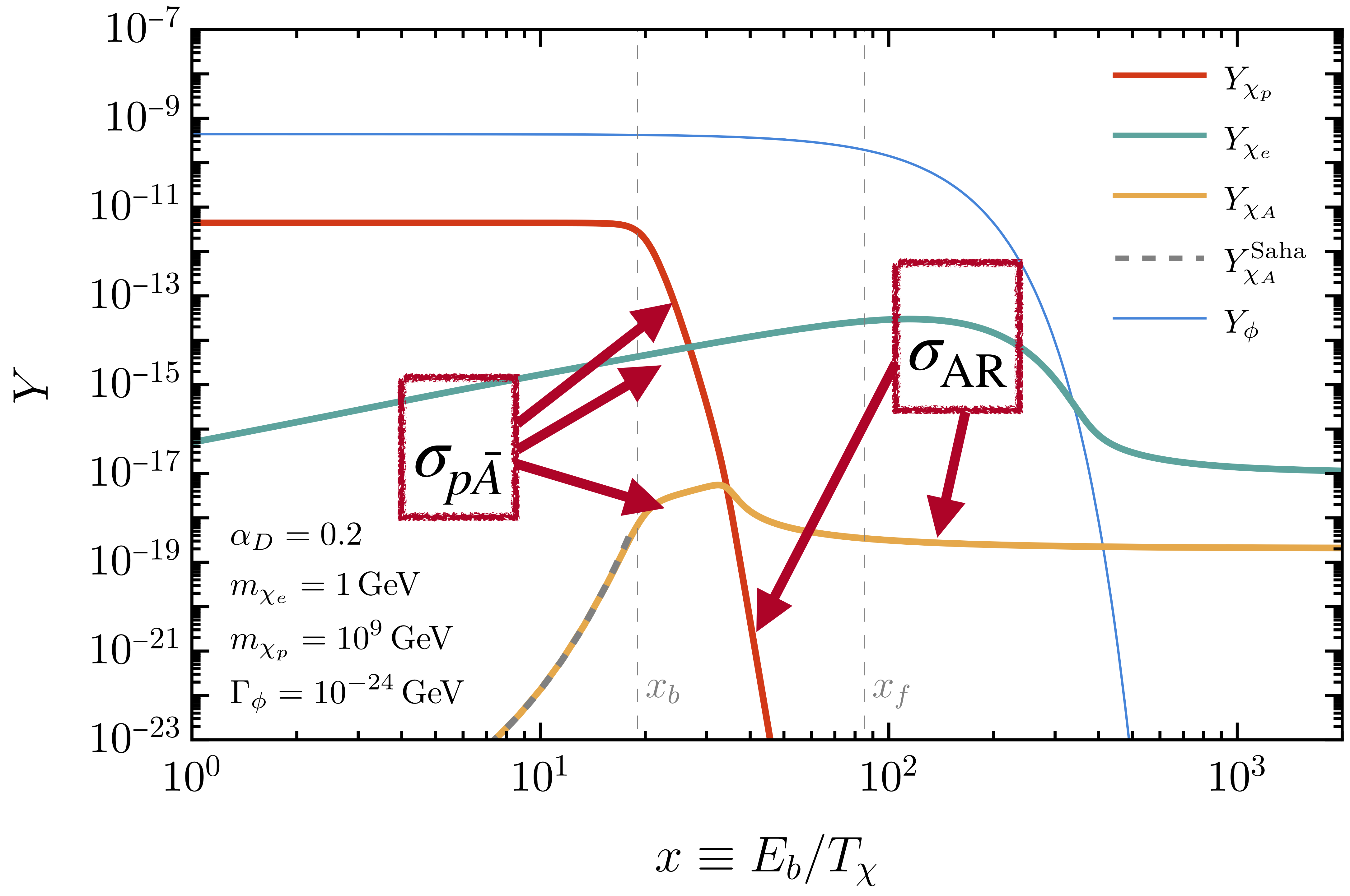
Production (stages)

- (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 ($T_\chi \sim E_b/100$)
  - $(\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + (\bar{\chi}_e\chi_e)$
  - $(\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + \chi_e + \bar{\chi}_e$

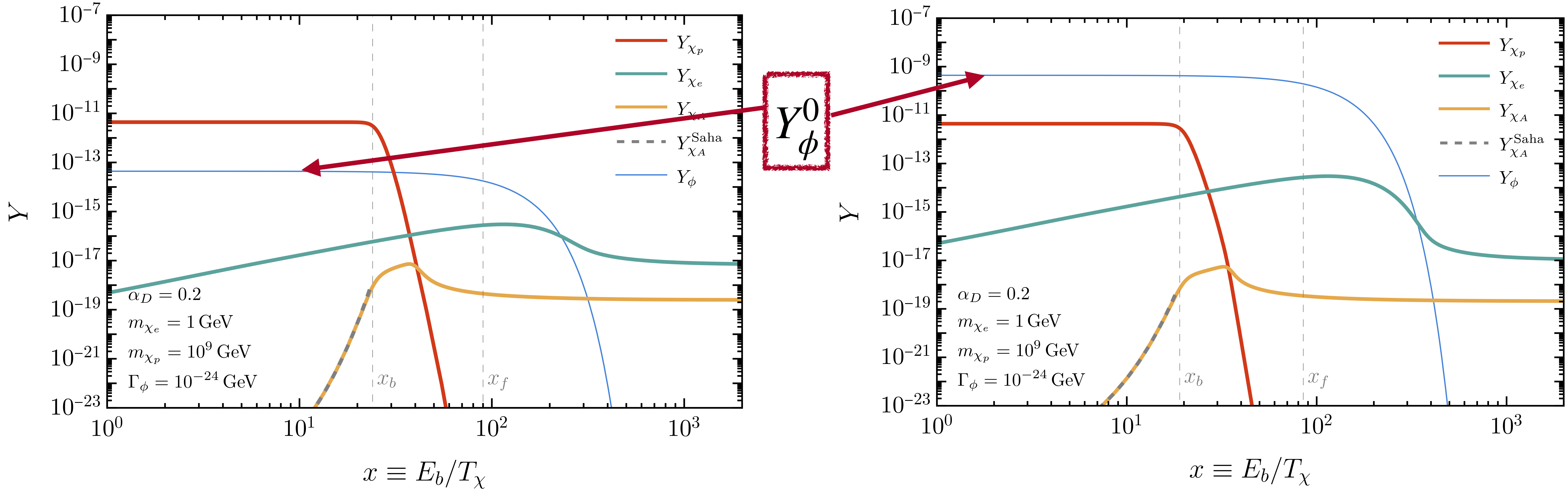


Production (full picture)





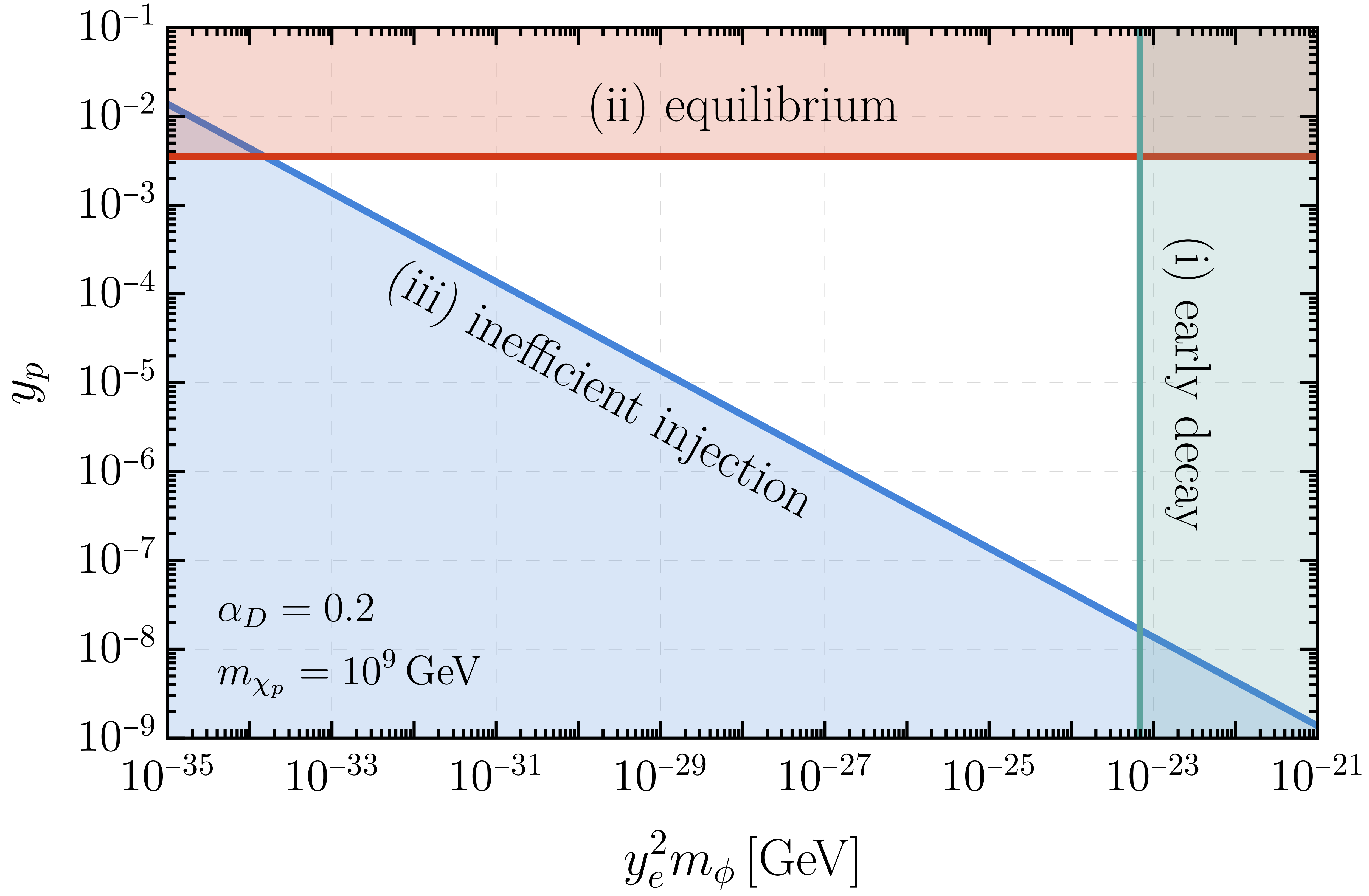
Production



Different Y_ϕ^0 makes minor difference on final $Y_{\chi_e}^\infty$

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

Parameters

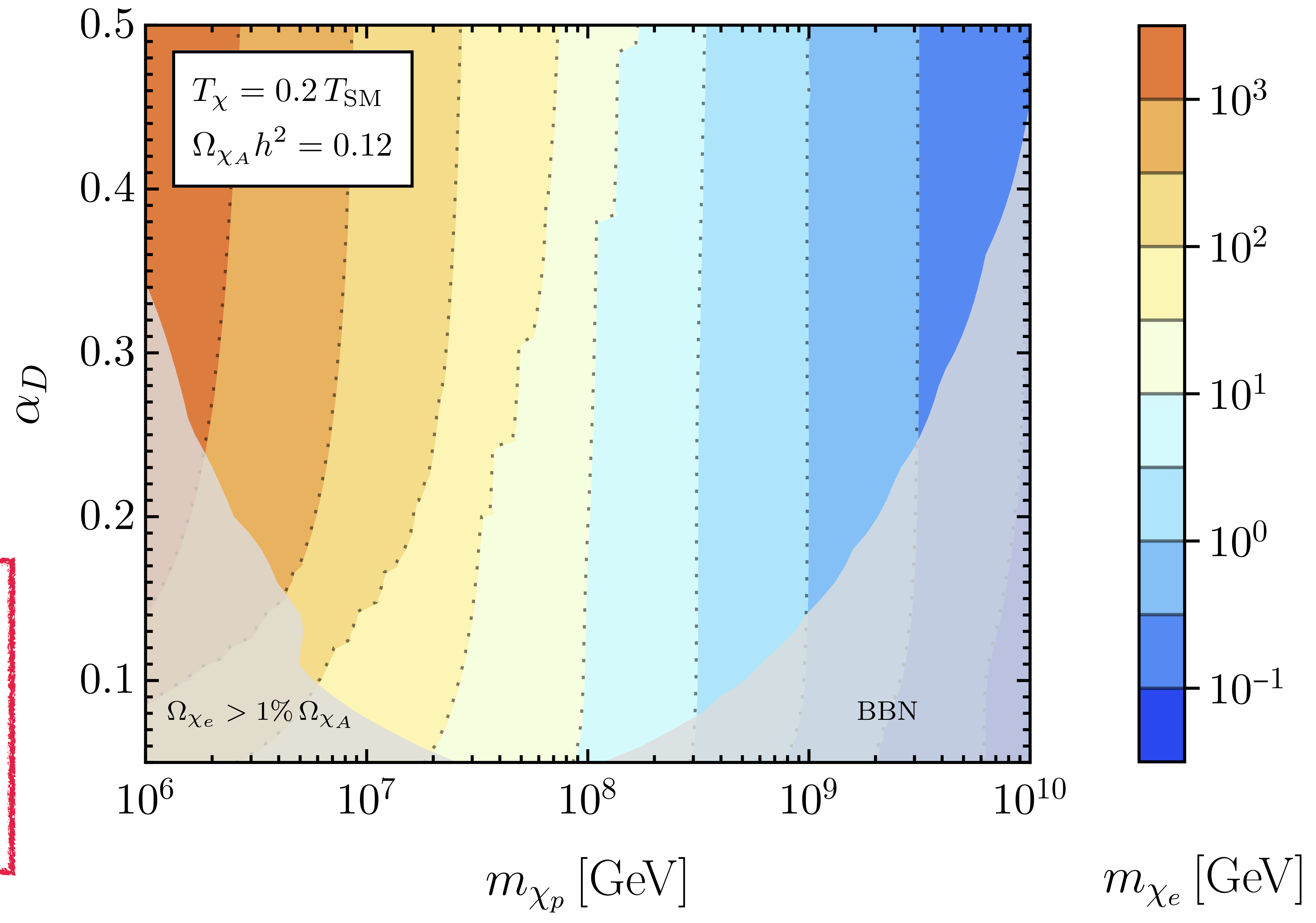


1. Decay of ϕ happen after χ_A freezes out. $\Gamma_\phi < H(x_f)$.
2. ϕ produced through freeze in, and it never enters equilibrium.
3. Production of χ_e from ϕ should be sufficient.

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 $\{\alpha_D, m_{\chi_p}, m_{\chi_e}\}$.

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



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