# Ultraheavy Atomic Dark Matter

## Freeze-out through Rearrangement

**Yu-Cheng Qiu**
Tsung-Dao Lee Institute,
Shanghai Jiao Tong University

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

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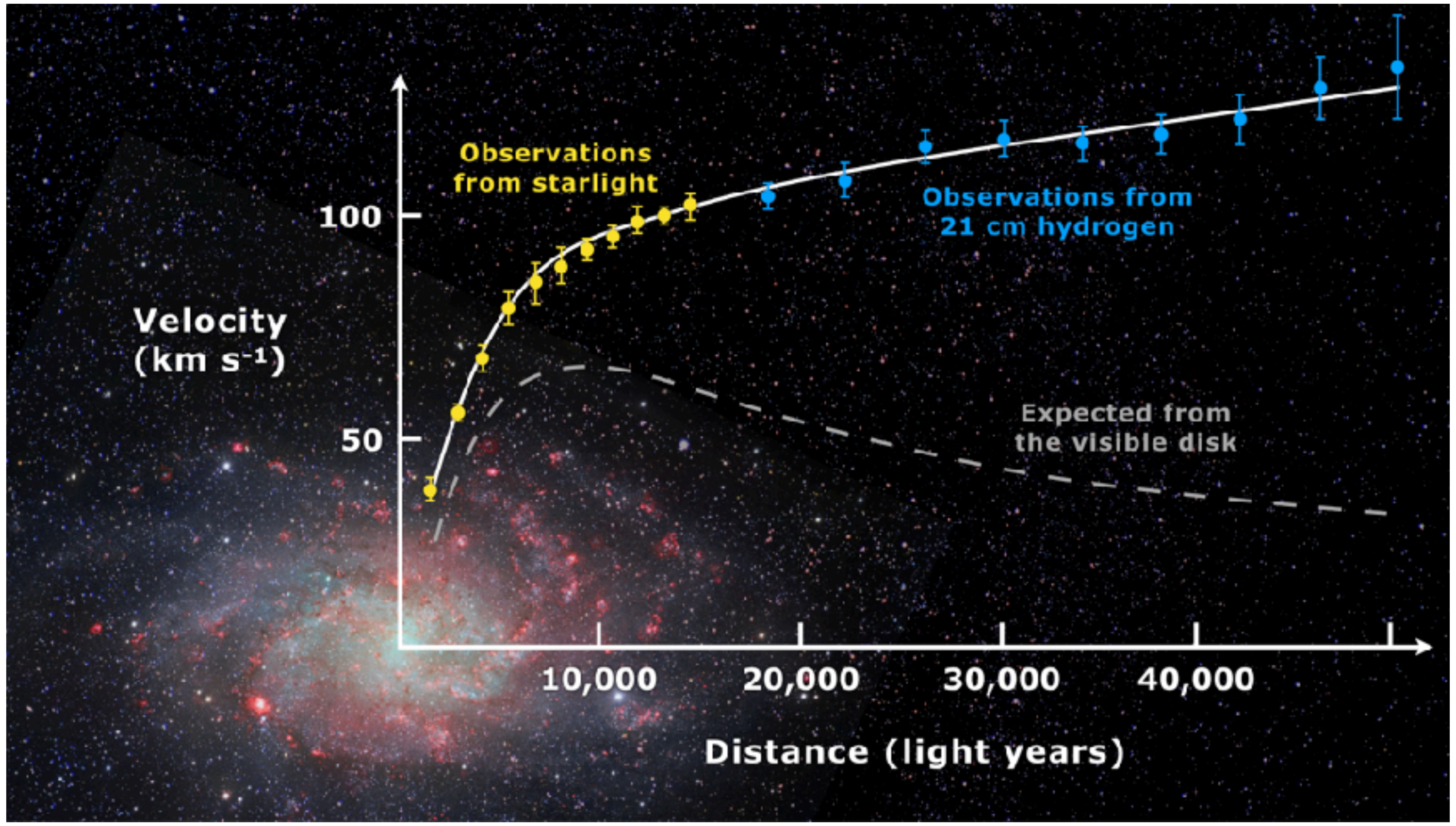
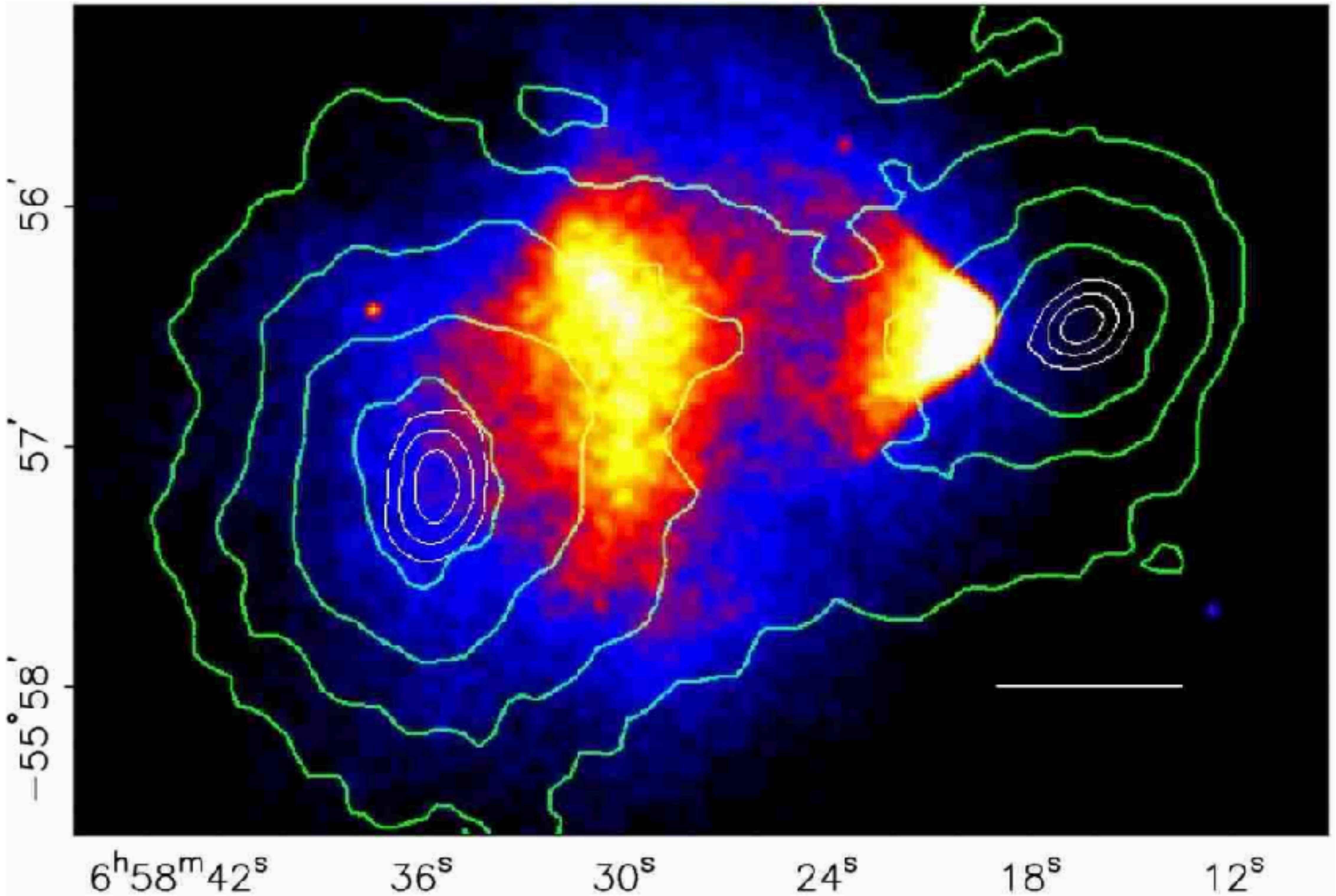
# Why DM?

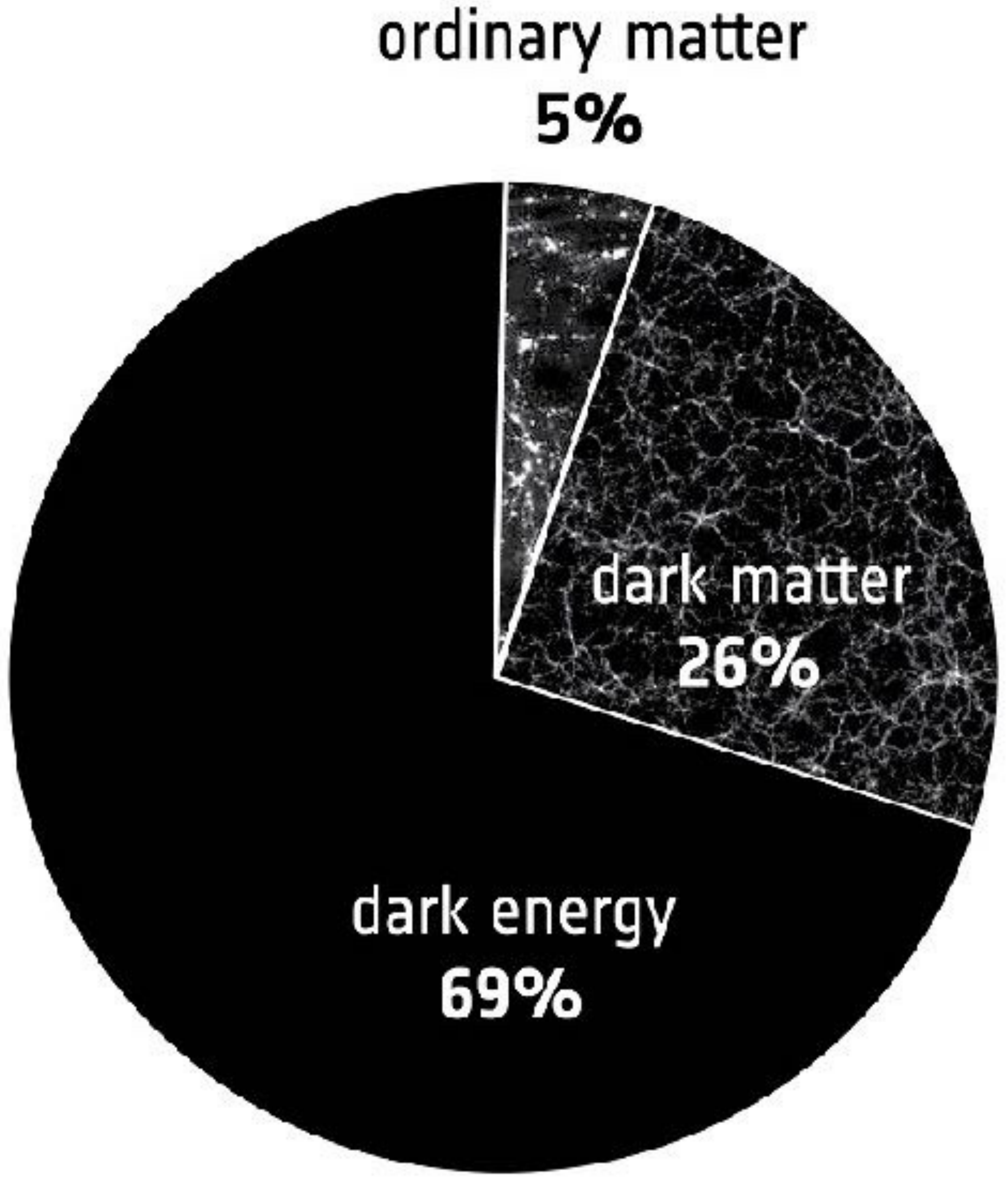



Galaxy rotation curve. Credit: Mario De Leo




Bullet Cluster. From astro-ph/0608407

# What is DM?




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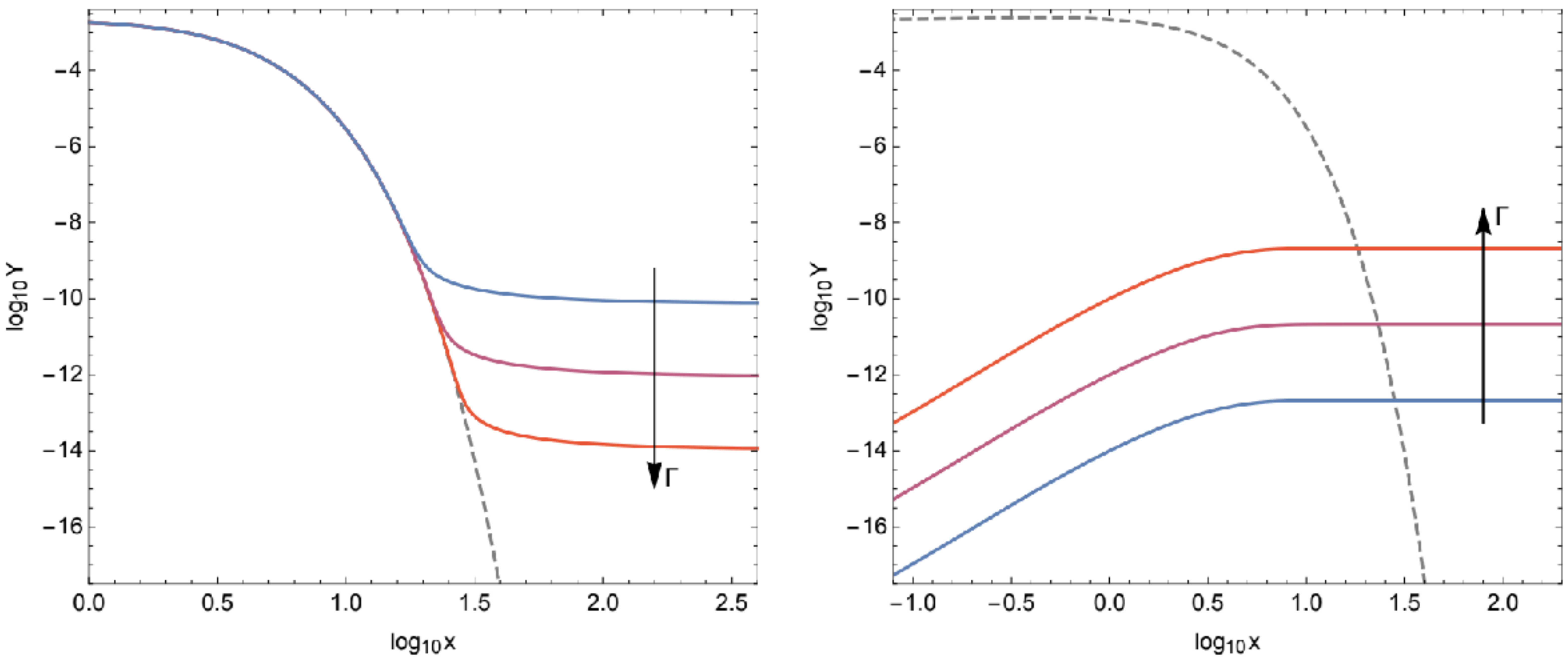
- Mass?
- Coupling with baryon?
- Spectrum?
- Elementary or composite?

# DM Production

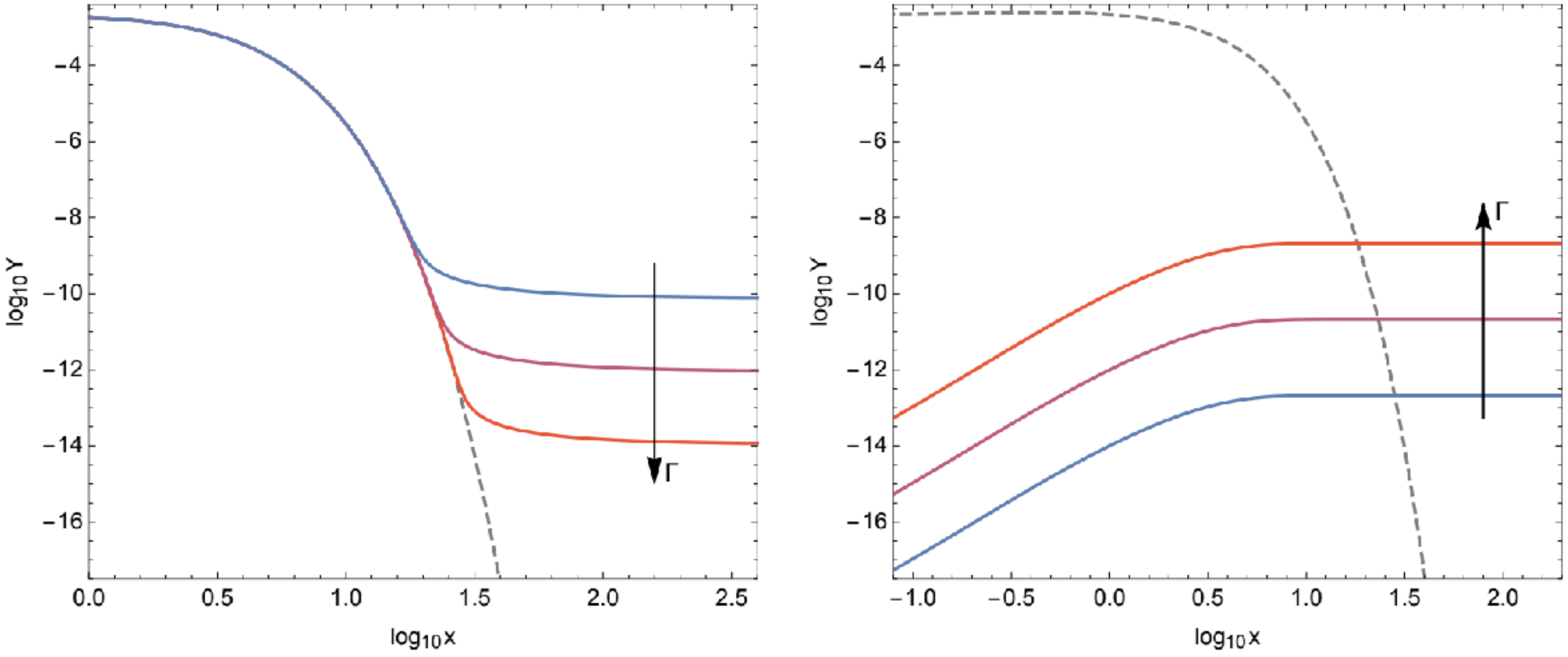
- Thermal Freeze-out.
- Freeze-in.
- Misalignment.
- Decay.
- PBH.




From 1705.01987

# DM Production

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




From 1705.01987

# Unitarity Bound

VOLUME 64, NUMBER 6 PHYSICAL REVIEW LETTERS 5 FEBRUARY 1990

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

Kim Griest

*Center for Particle Astrophysics, University of California, Berkeley, California 94720*

Marc Kamionkowski

*Physics Department, Enrico Fermi Institute, The University of Chicago, Chicago, Illinois 60637-1433 and NASA/Fermilab Astrophysics Center, Fermi National Accelerator Laboratory, Batavia, Illinois 60510-0500*

(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 $7.5\times10^{-7}$ fm. A lower limit to the relic abundance of such particles is also found.

PACS numbers: 98.80.Cq, 11.80.Et

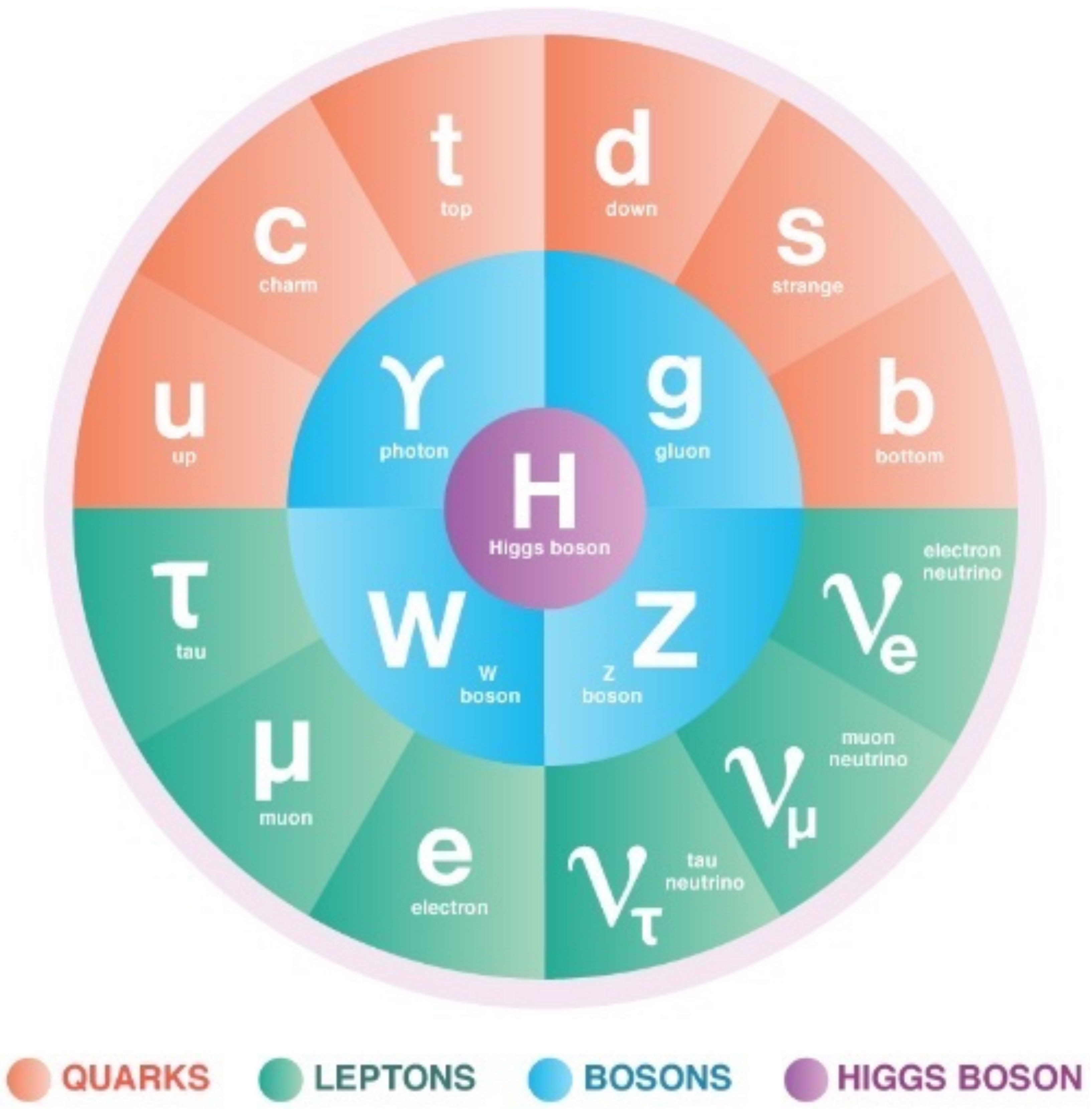
Model-independent

Thermal freezeout DM Mass should be bounded from above:

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

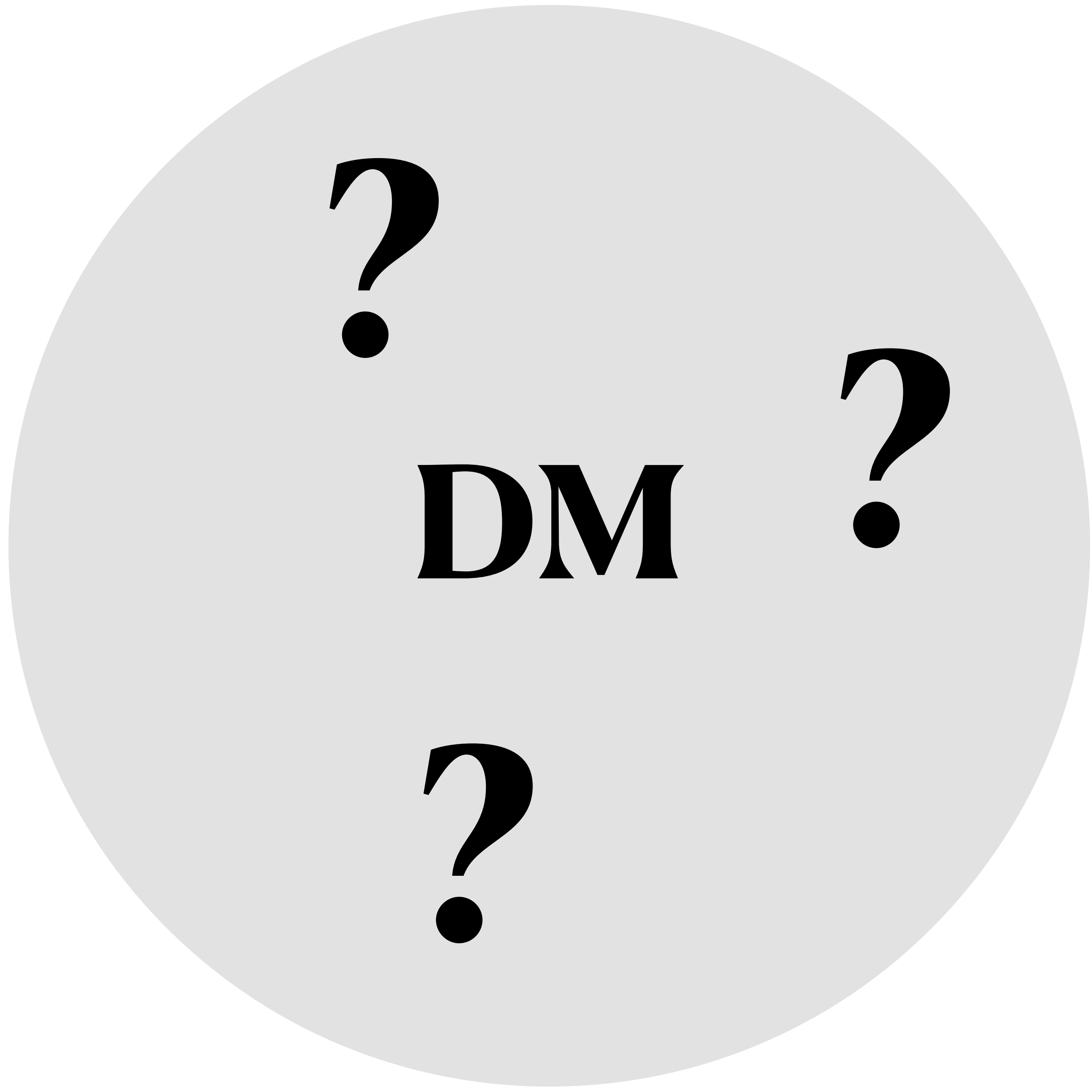
The Unitarity bound could be violated if there is a secondary stage of freeze out.

# 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

David E. Kaplan, Gordan Z. Krnjaic, Keith R. Rehermann and Christopher M. Wells

Department of Physics and Astronomy, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218-2686, U.S.A.

E-mail: dkaplan@pha.jhu.edu, gordan@pha.jhu.edu, keith@pha.jhu.edu, cwells13@pha.jhu.edu

Journal of Cosmology and Astroparticle Physics
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# Dark atoms: asymmetry and direct detection

David E. Kaplan,[a] Gordan Z. Krnjaic,[a,b] Keith R. Rehermann[c] and Christopher M. Wells[d]

[a]Department of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD, U.S.A.

[b]Theoretical Physics Group, Fermi National Accelerator Laboratory, Batavia, IL, U.S.A.

[c]Center for Theoretical Physics, MIT, 77 Mass Ave., Cambridge, MA, U.S.A.

[d]Department of Physics, Houghton College, 1 Willard Avenue, Houghton, NY, U.S.A.

E-mail: dkaplan@pha.jhu.edu, gordan@pha.jhu.edu, krmann@mit.edu, christopher.wells@houghton.edu

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

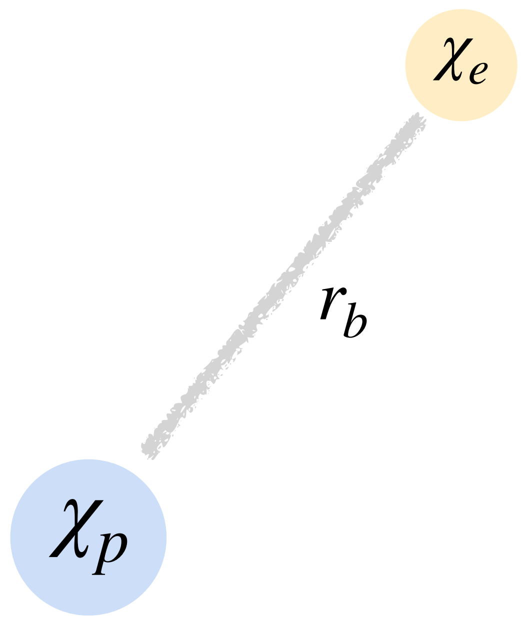
$$+\bar{\chi}_p\left(i\gamma\cdot D - m_{\chi_p}\right)\chi_p + \bar{\chi}_e\left(i\gamma\cdot D - m_{\chi_e}\right)\chi_e$$ Dark proton and electron

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

---

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

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




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

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

# Dark Plasma

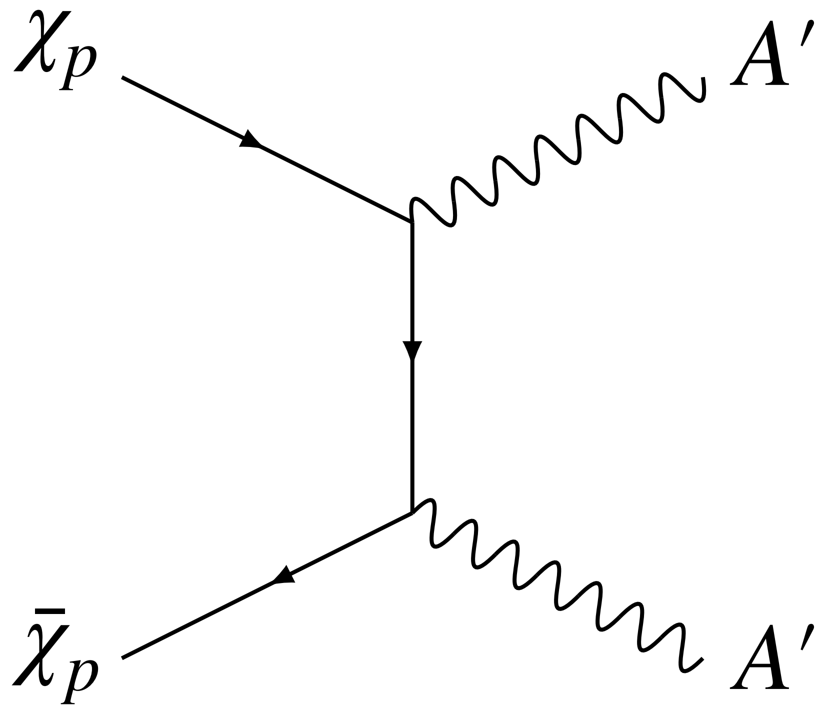
- To protect the BBN, we tune the kinetic mixing $\epsilon < 10^{-12}$ ,
- And let $T_\chi = T_\gamma \xi$, where $\xi = 0.2$.

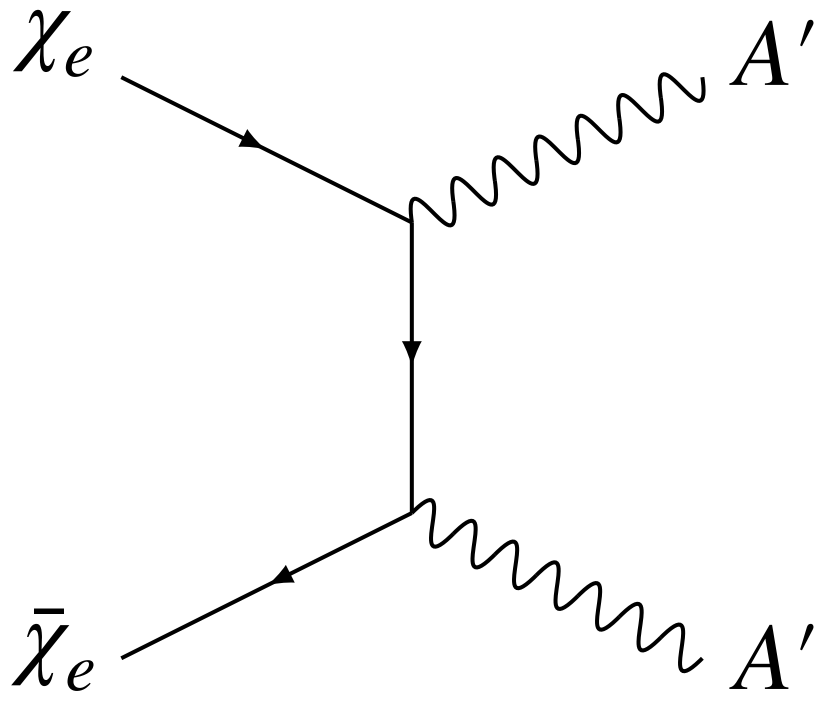
$$\chi_p + \bar{\chi}_p \leftrightarrow 2A'$$

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

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

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




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

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

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

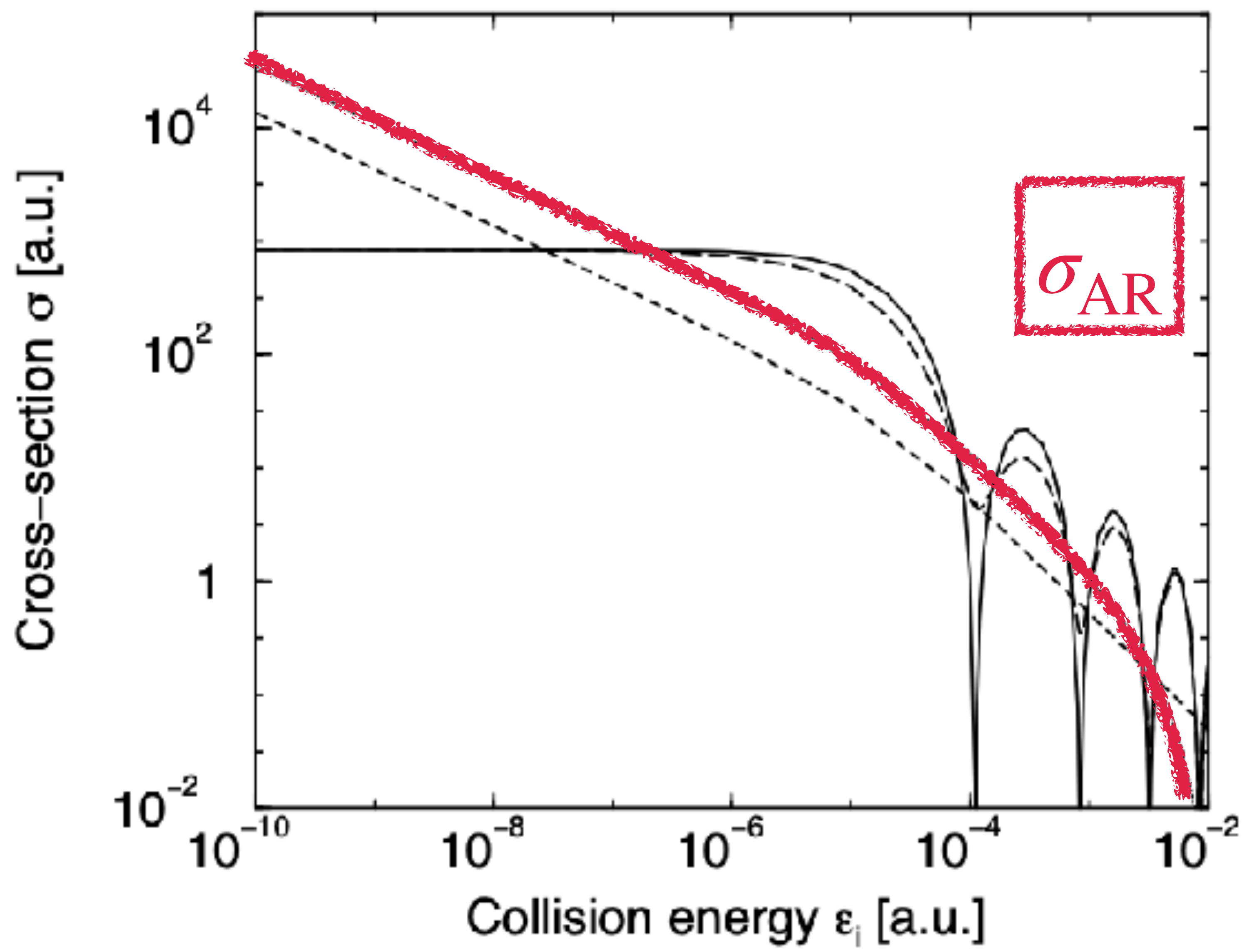
# Atomic Rearrangement

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

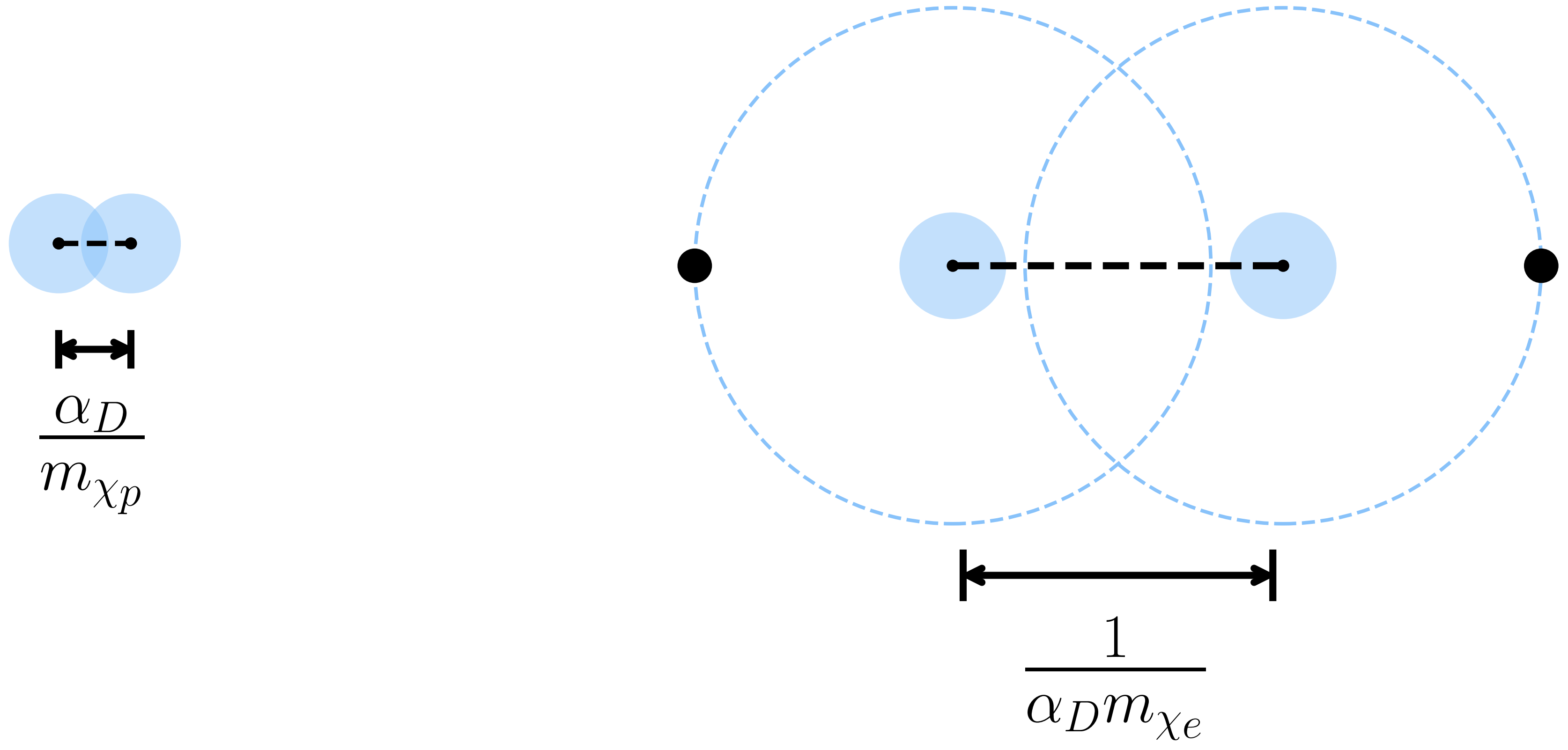
$$\sigma_{p\bar{A}} \left( \begin{array}{l} \chi_p + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + \bar{\chi}_e \\ \bar{\chi}_p + (\chi_p\chi_e) \to (\bar{\chi}_p\chi_p) + \chi_e \end{array} \right.$$

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

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




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




Geometric cross section

# Atomic Rearrangement

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

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

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

Binding Energy $E_b(\bar\chi_e\chi_e)<E_b(\bar\chi_p\chi_e)$

So it is an endothermic reaction.

Kinetically forbidden

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

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

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 $\chi_p$ than $\chi_e$ after their freezeout through direct annihilation. One has to produce more $\chi_e$ to form $(\chi_p \chi_e)$ and deplete $\chi_p$. Therefore, $\phi$ is introduced to slowly produce $\chi_e$ via

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

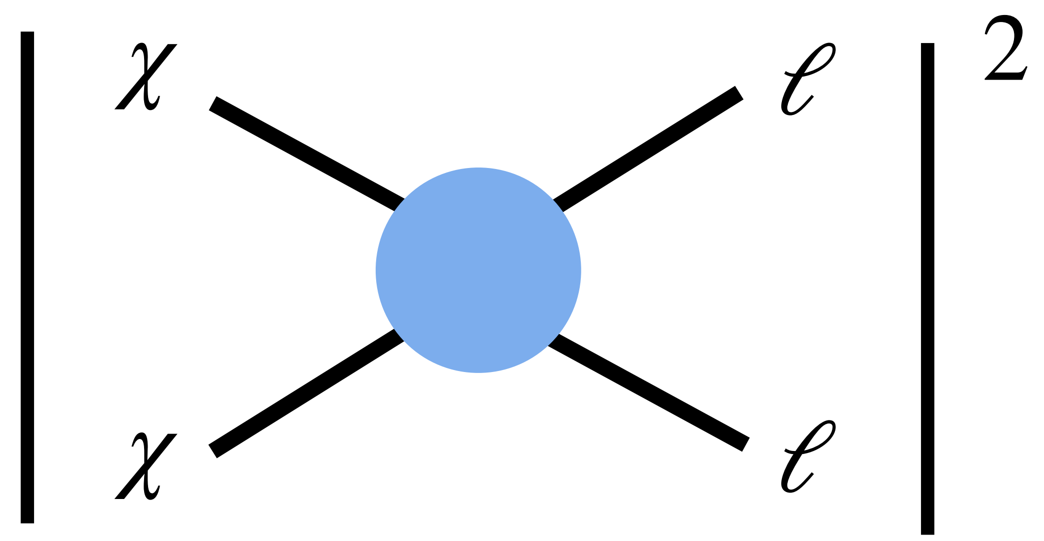
# Production

**Boltzmann equations for general $\chi$**

(1) Number density $n(t)$

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

$$\sigma_{\chi\chi} =$$




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

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

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

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

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

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

# Production

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

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

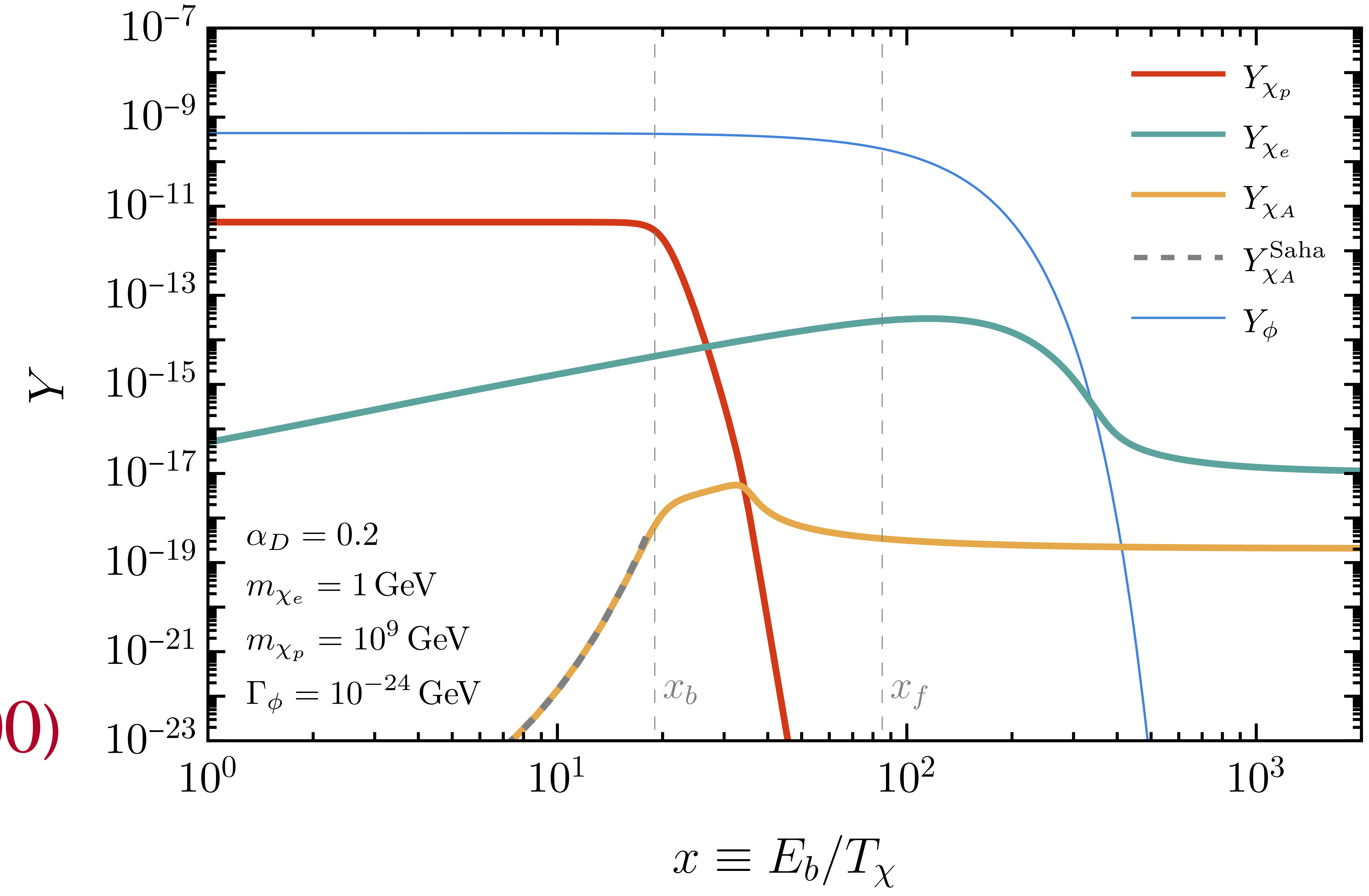
$$\frac{dY_e}{dt} = -s\langle\sigma_{\mathrm{anni}}^{e}v\rangle\left(Y_e^2 - (Y_e^{\mathrm{eq}})^2\right) - s\langle\sigma_{\mathrm{AF}}v\rangle\left(Y_pY_e - Y_p^{\mathrm{eq}}Y_e^{\mathrm{eq}}\frac{Y_{\chi_A}}{Y_{\chi_A}^{\mathrm{eq}}}\right) + \langle\Gamma_\phi\rangle Y_\phi + s\langle\sigma_{\mathrm{AR}}v\rangle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

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

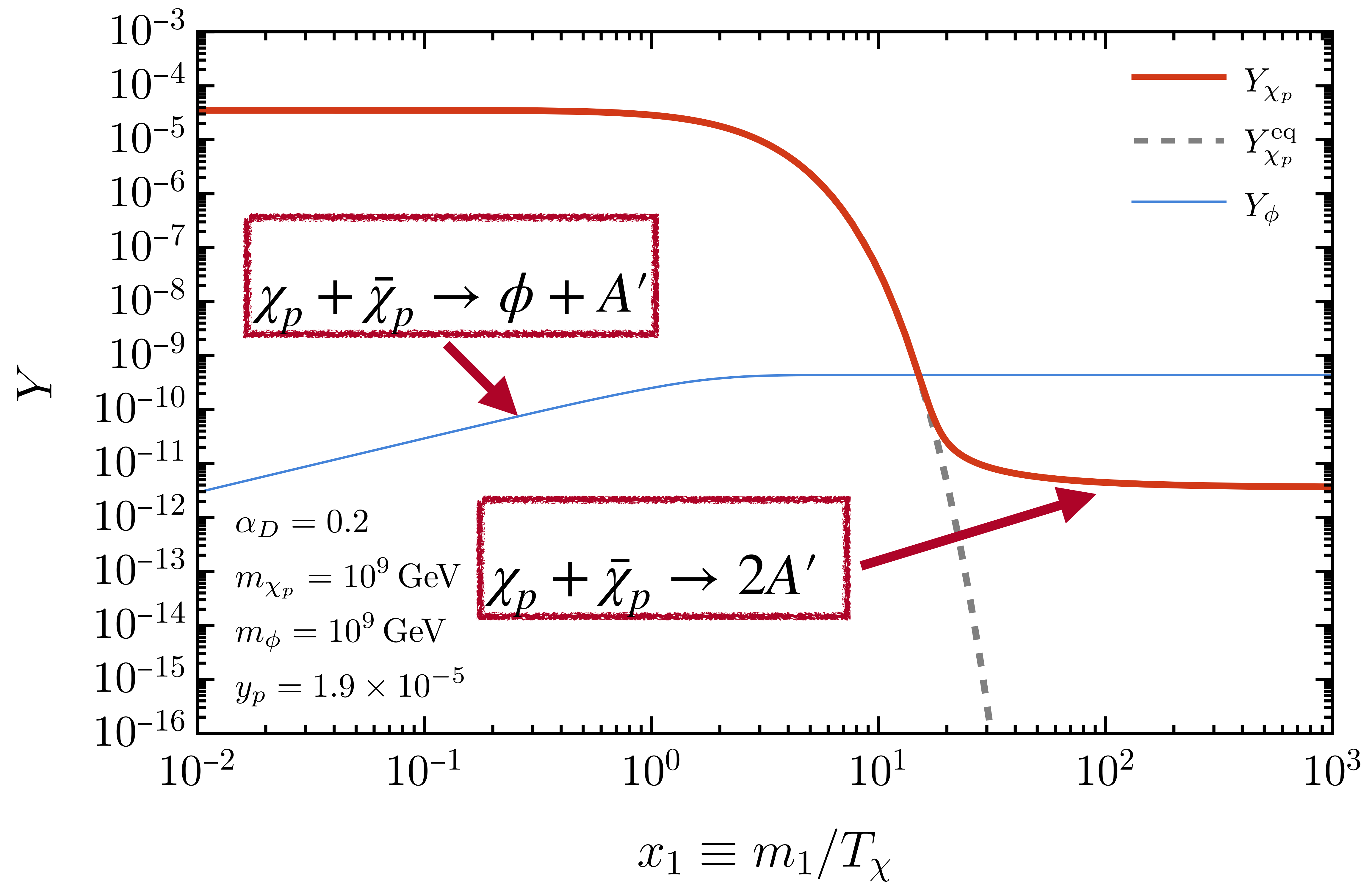
Consider $2m_{\chi_p} > m_\phi > 2m_{\chi_e}$, so that only $\phi \to \chi_e + \bar{\chi}_e$ is kinetically allowed.

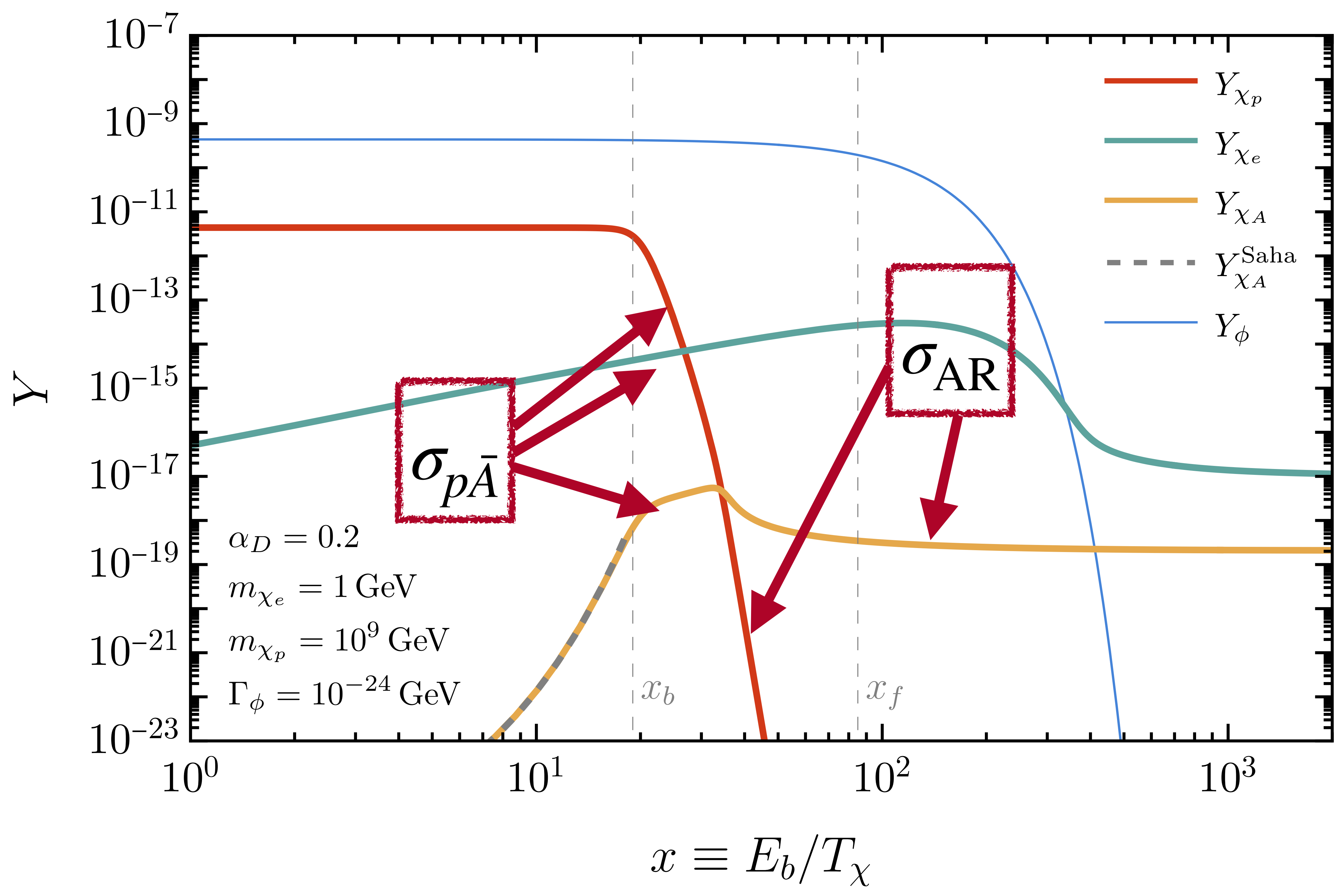
# Production (stages)

- (1) $\chi_p$ freezeout ($E_b \lesssim T_\chi \lesssim m_{\chi_p}$)
  - $\chi_p$ stays constant yield.
  - $\chi_e$ 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 ($T_\chi \sim E_b/100$)
  - $(\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + (\bar{\chi}_e\chi_e)$
  - $(\chi_p\chi_e) + (\bar{\chi}_p\bar{\chi}_e) \to (\bar{\chi}_p\chi_p) + \chi_e + \bar{\chi}_e$

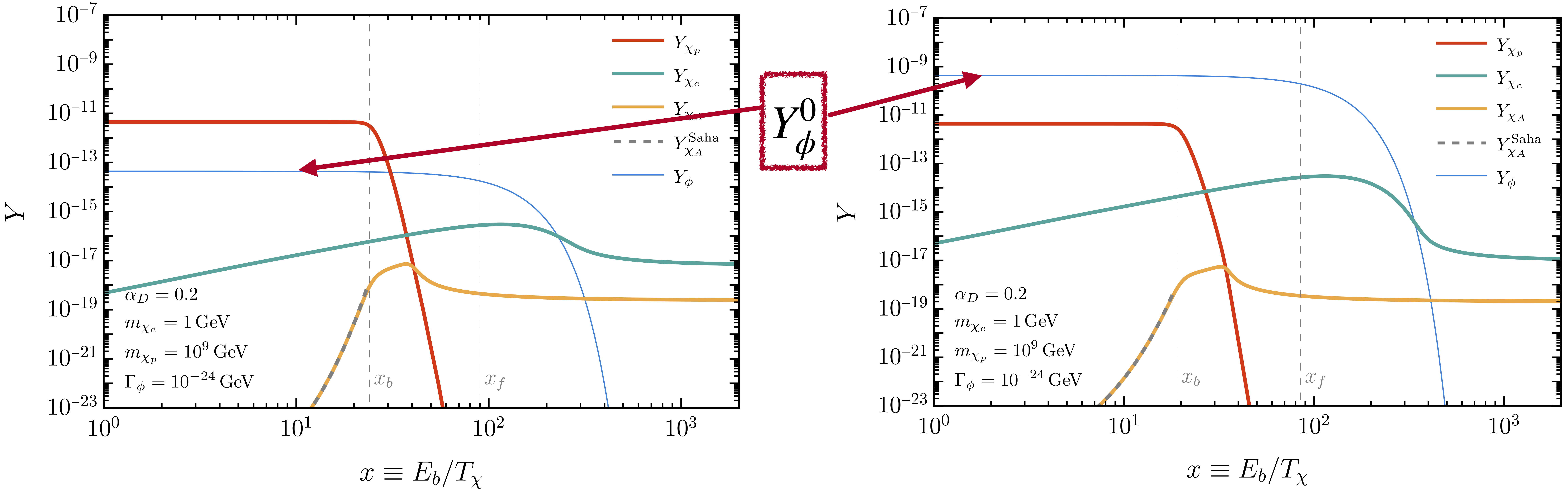


# Production (full picture)



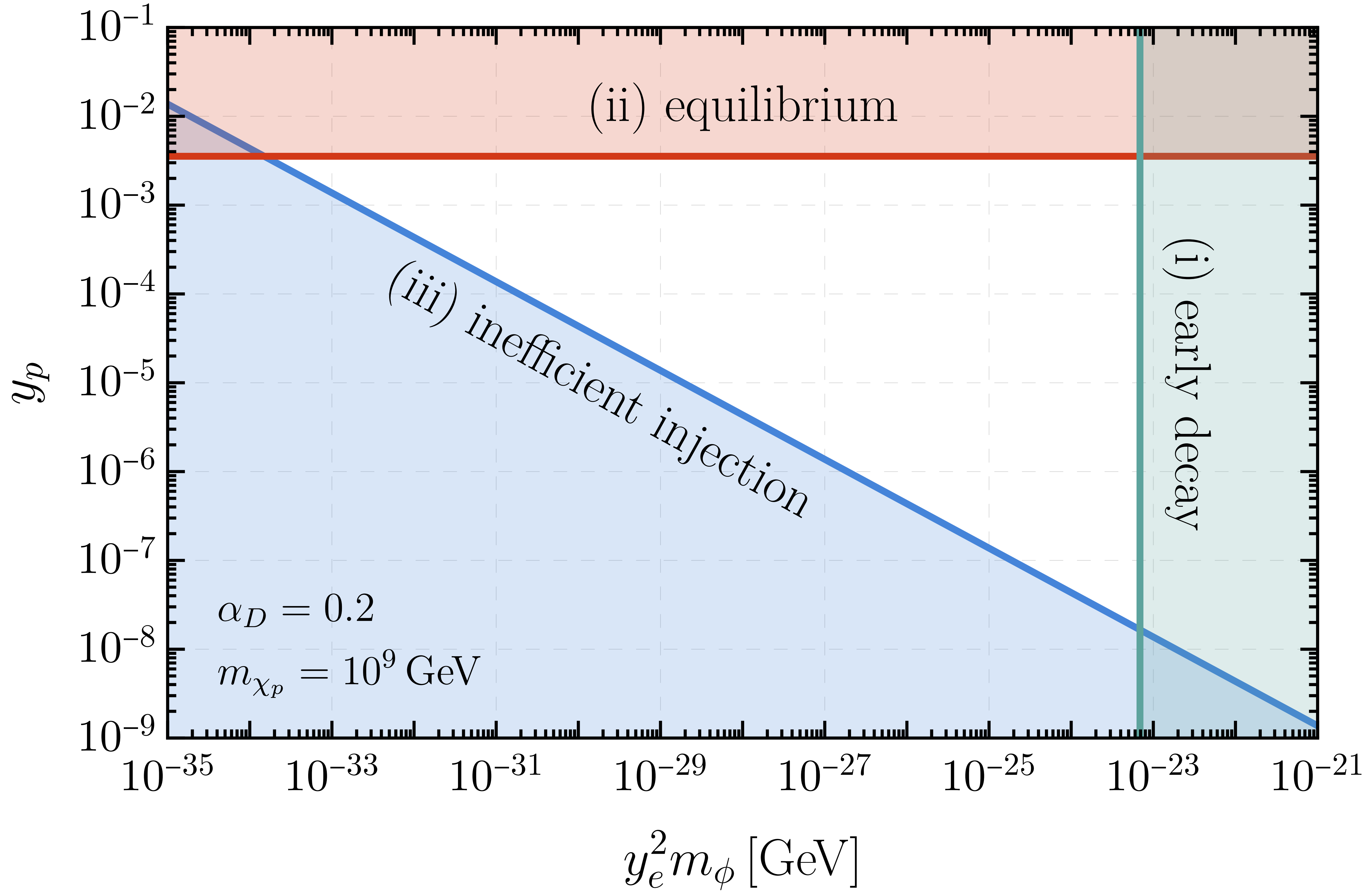
# Production




Different $Y_\phi^0$ 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

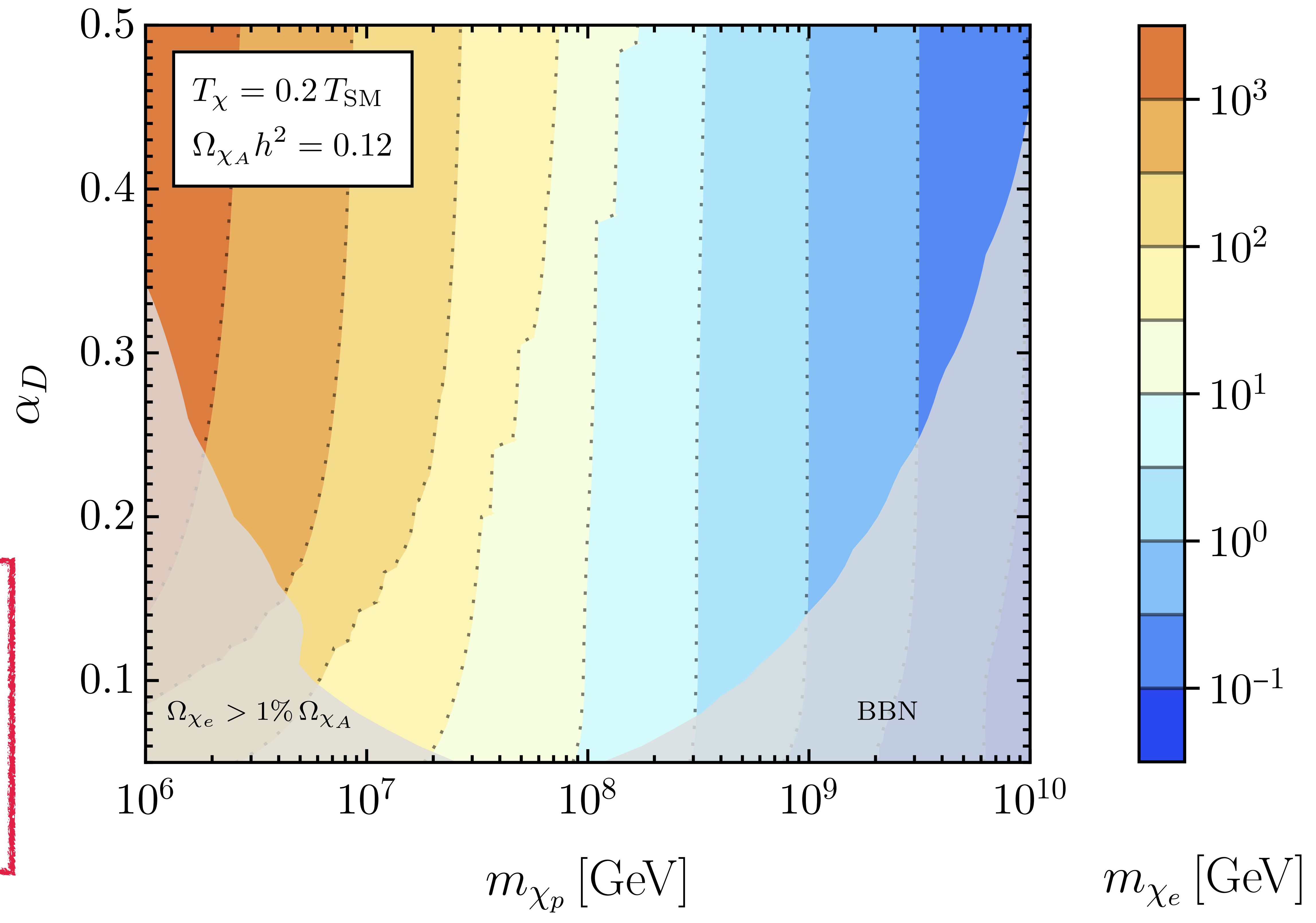



1. Decay of $\phi$ happen after $\chi_A$ freezes out. $\Gamma_\phi < H(x_f)$.
2. $\phi$ produced through freeze in, and it never enters equilibrium.
3. Production of $\chi_e$ from $\phi$ should be sufficient.

# Parameters

- Choose the initial condition of $\phi$ 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