JUNO sensitivity to resonance-enhanced MeV dark matter annihilation in the galactic halo

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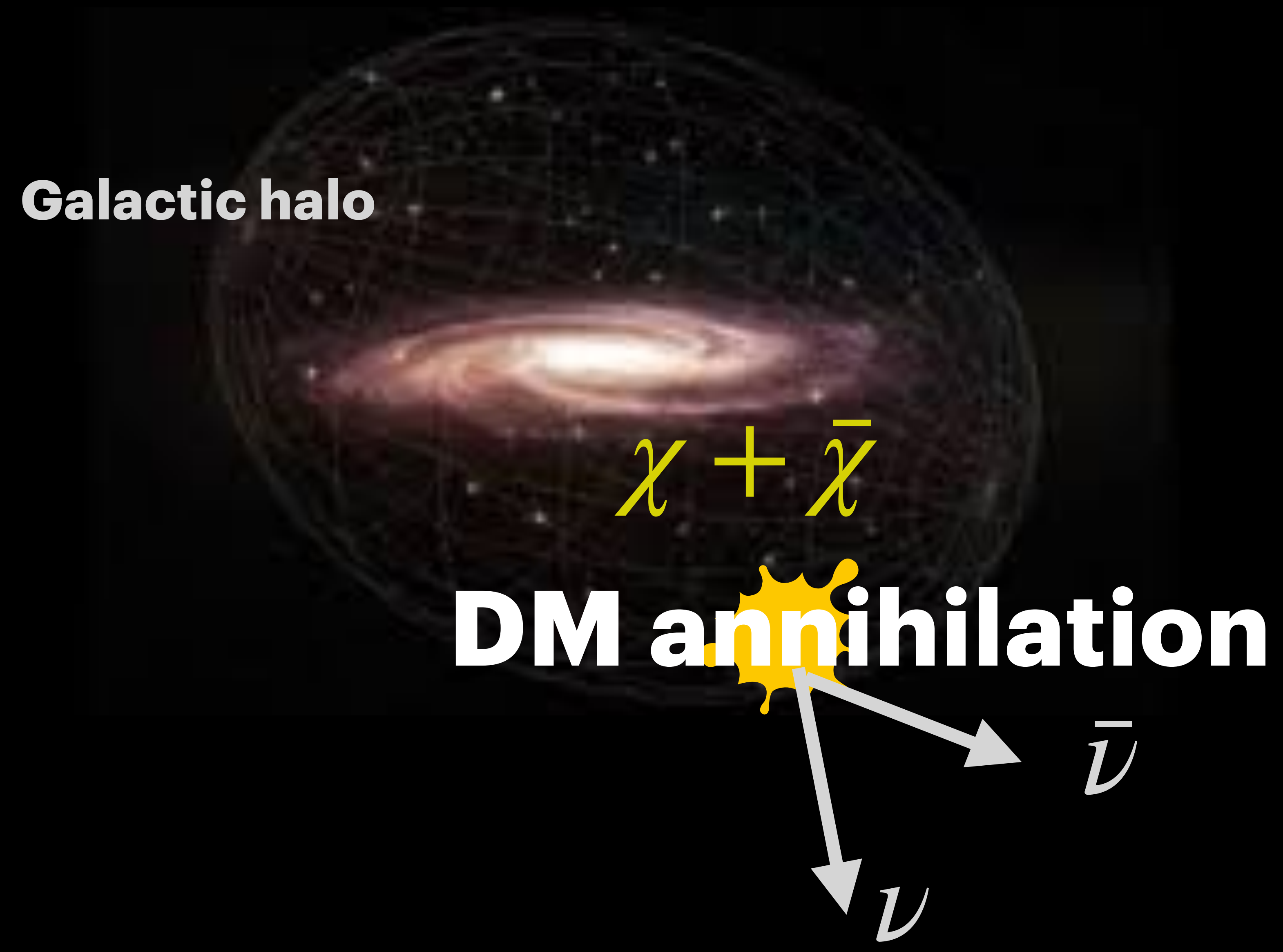
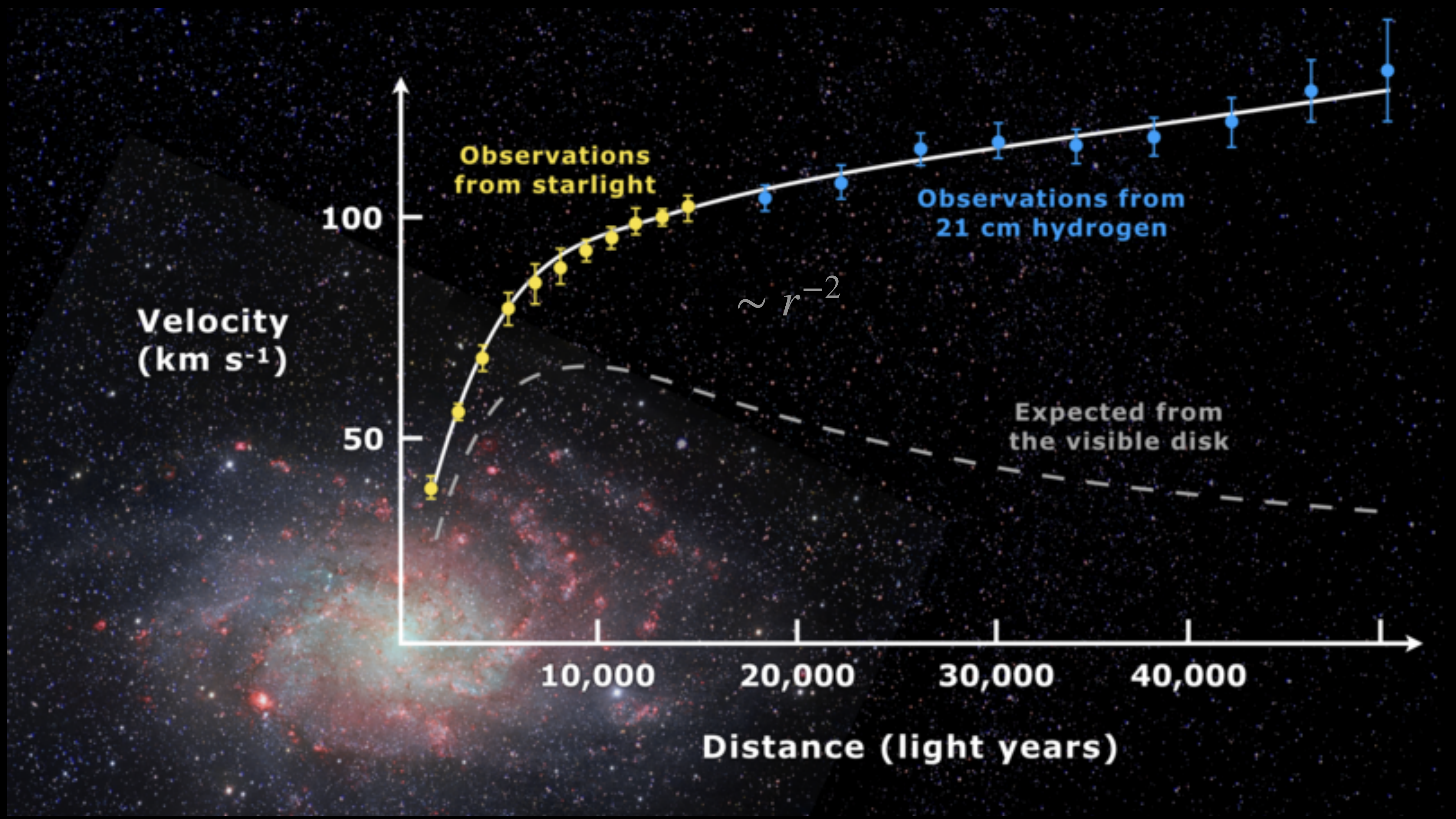
OUTLINE

- I — Introduction and Motivation
- II — Constrain the $U(1)_{L_\mu - L_\tau}$ model and the enhancement
- III — Conclusion

INTRODUCTION & MOTIVATION

Why Dark Matter (DM) ?





JUNO detector figure

The Jiangmen Underground Neutrino Observatory (JUNO) detector

INTRODUCTION & MOTIVATION

The Jiangmen Underground Neutrino Observatory (JUNO) detector

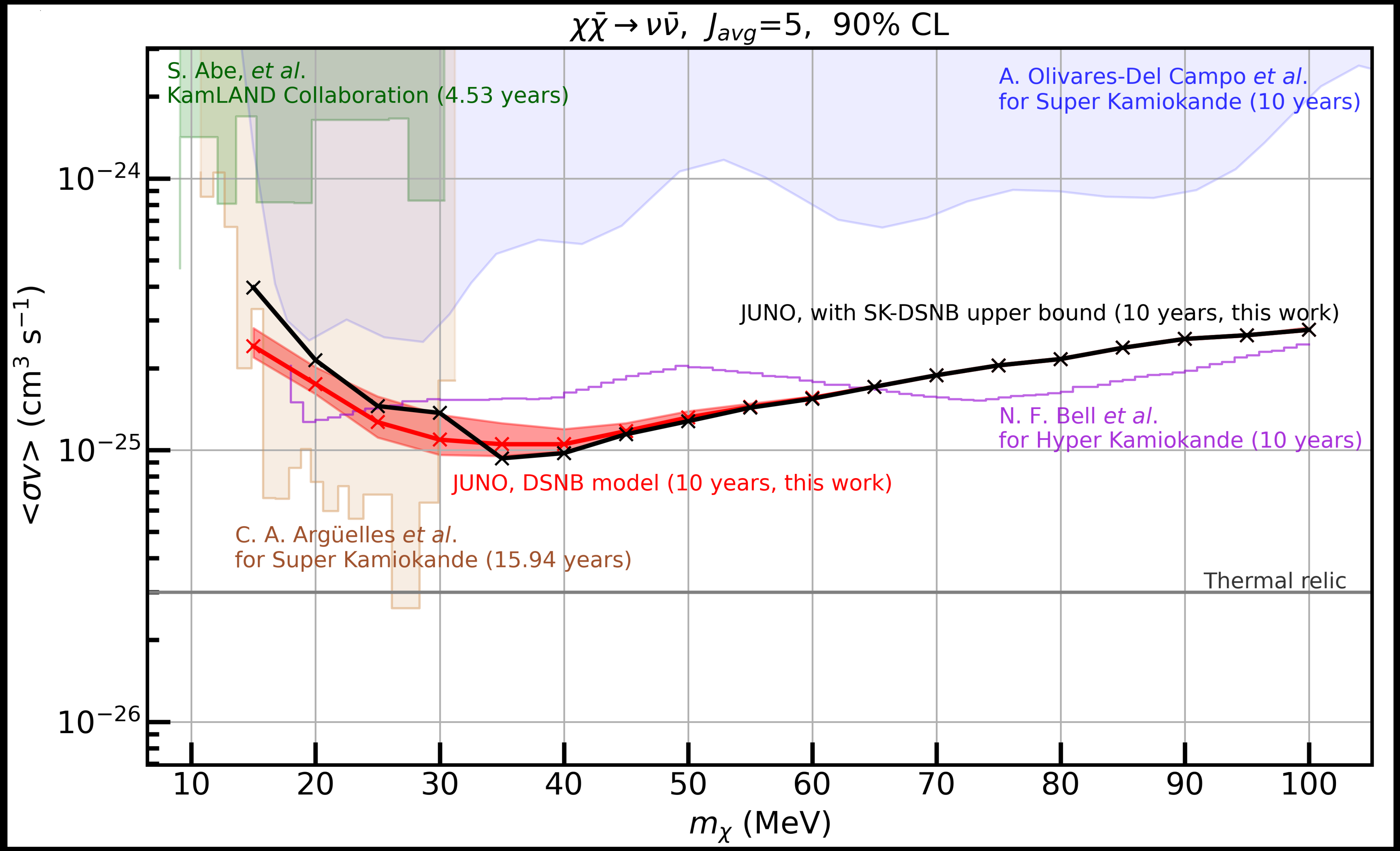
A central acrylic sphere containing 20 kt of liquid scintillator (LS) will significantly improve the sensitivity $\langle \sigma v \rangle$.

JUNO sensitivity to the detection of neutrinos from DM annihilation from galactic halo.

$$m_\chi : 15\text{MeV} - 100\text{MeV}$$

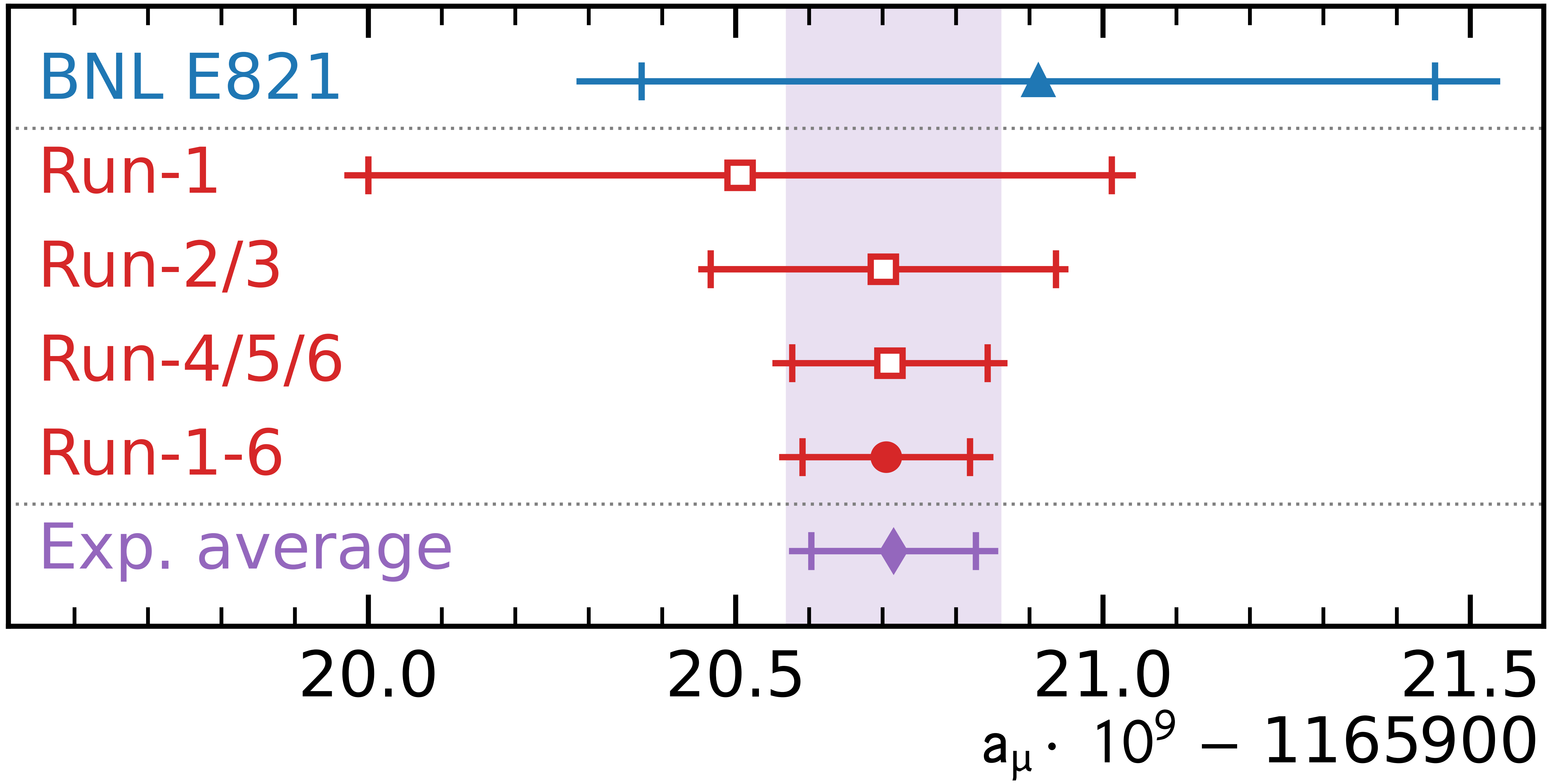
The thermally averaged Dark Matter (DM) annihilation cross section

$$\langle \sigma v \rangle_{present-day} \sim 10^{-25} cm^3 s^{-1}$$



A. Abusleme et al JCAP09(2023)001

The measurement of the muon anomalous magnetic moment result (June 3rd, 2025)



$$a_\mu^{SM} \times 10^{-9} - 1165900 = 20.33 \pm 0.62$$

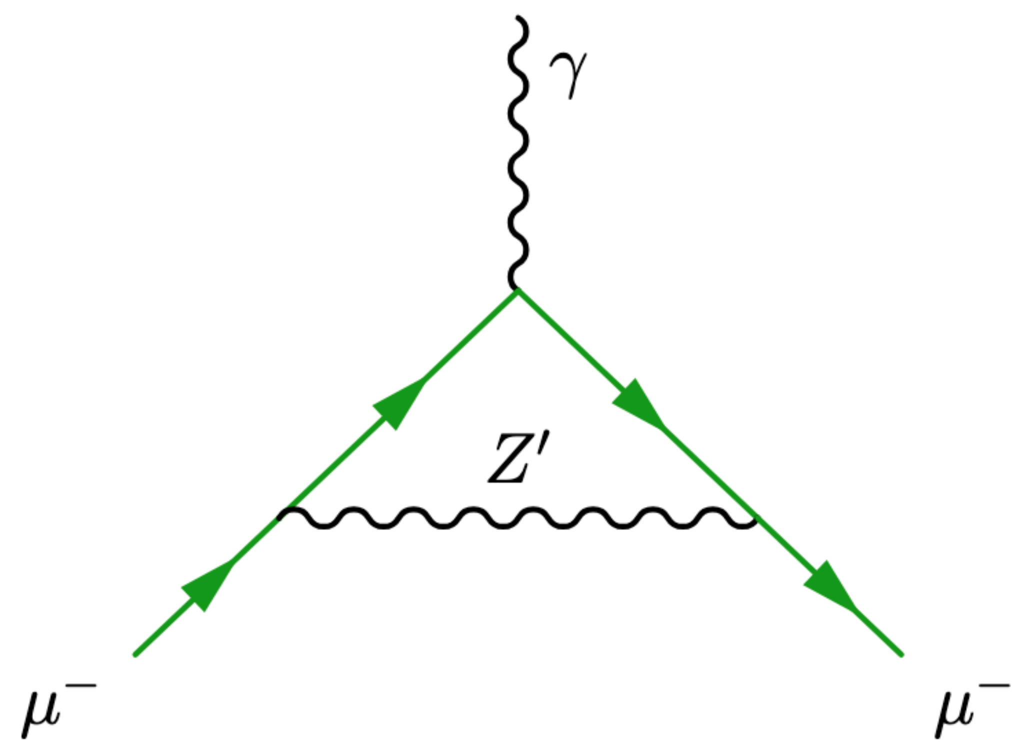
$$a_\mu^{Ex} \times 10^{-9} - 1165900 = 20.715 \pm 0.113$$

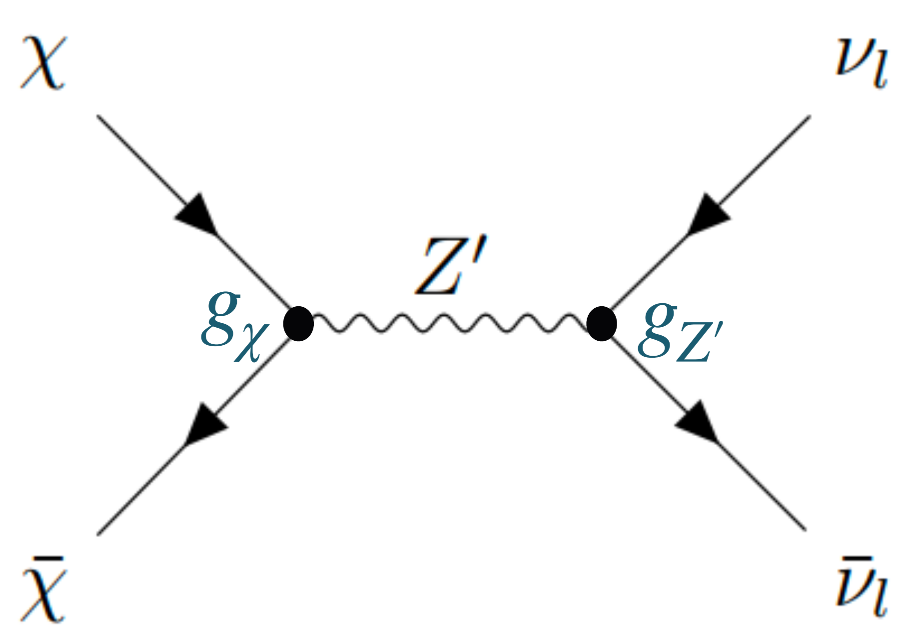
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (0.385 \pm 0.63) \times 10^{-9}$$

R. Aliberti et al., The anomalous magnetic moment of the muon in the Standard Model: an update (2025), arXiv:2505.21476 [hep-ph].

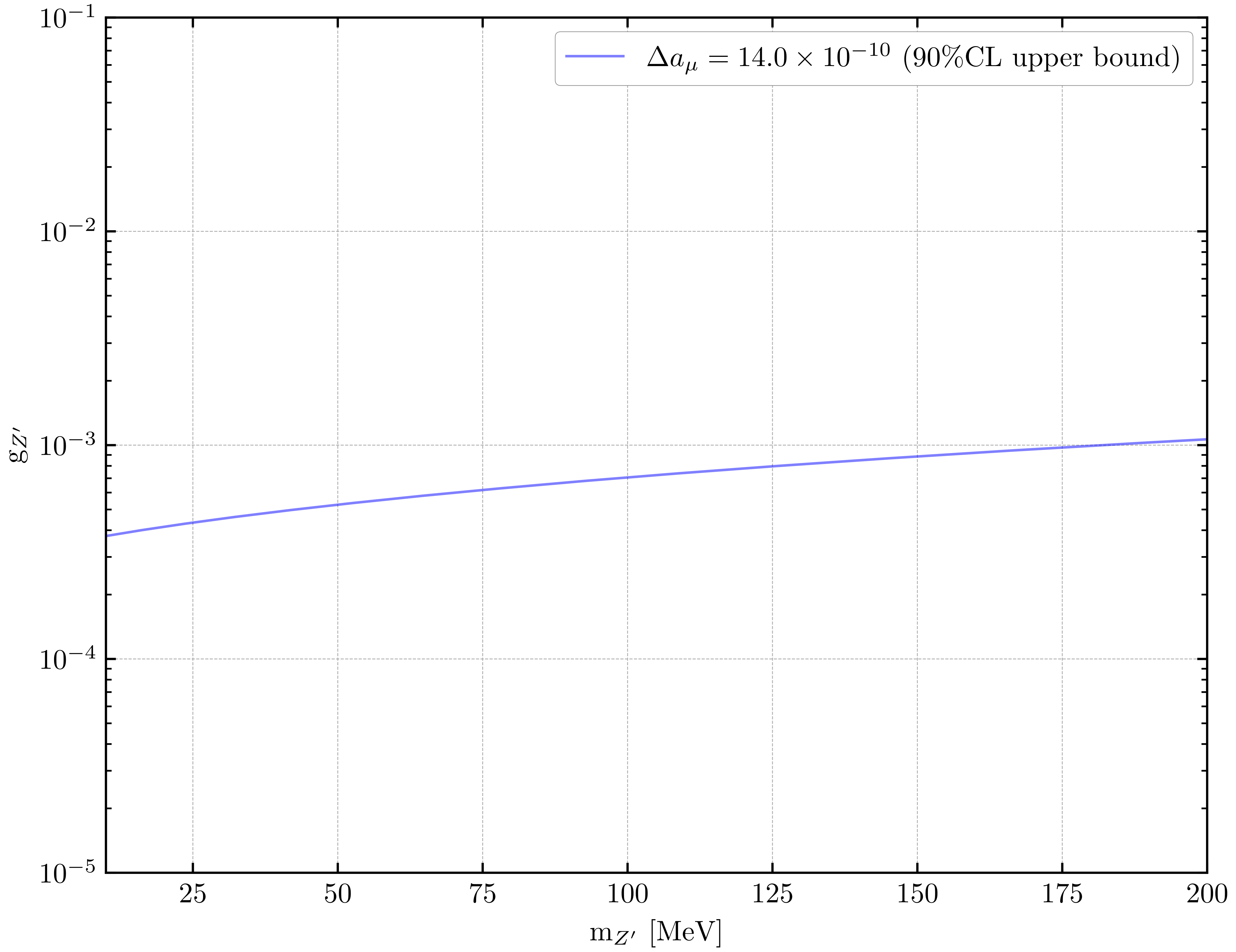
Aguillard, D. P. and others, Measurement of the Positive Muon Anomalous Magnetic Moment to 127 ppb (2025), arXiv:2506.03069 [hep-ex]

The $U(1)_{L_\mu - L_\tau}$ model





$g_\chi = g_{Z'}$



$U(1)_{L_\mu - L_\tau}$ model contributes to $(g-2)_\mu$ at one-loop level:

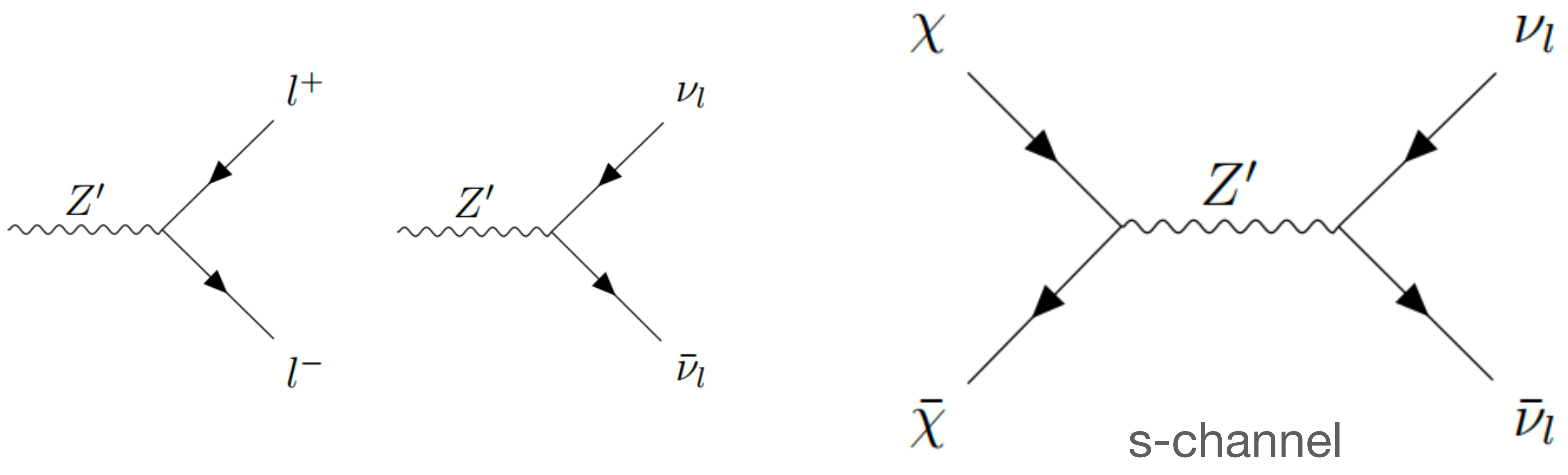
$$\Delta a_\mu = \frac{g_{Z'}^2}{8\pi^2} \int_0^1 dx \frac{2m_\mu^2 x^2 (1-x)}{x^2 m_\mu^2 + (1-x) m_{Z'}^2} .$$

*P. Fayet, Phys. Rev. D **75**, 115017,*
*M. Pospelov, Phys. Rev. D **80**, 095002*

The new gauge boson Z′ acts as a mediator between the Standard Model (SM) and Dark Matter (DM).

In the mass range of $\mathcal{O}$MeV $\leq m_{Z'} \leq 200$MeV, and the required coupling $g_{Z'}$ is necessary to constraint.

For DM $m_\chi < m_\mu$ —> mainly annihilate to neutrinos $\chi\bar{\chi} \rightarrow \nu_l \bar{\nu}_l$, $l = \mu, \tau$.



M. Drees, Physics Letters B 827 (2022) 136948
H. Murayama, Physics Review D 79, 095009 (2009)

The thermally averaged Dark Matter (DM) annihilation cross section

$m_\chi < m_{Z'}/2$:

$$\langle \sigma v \rangle = \frac{g_{Z'}^4 q_\chi^2}{12\pi (8 m_\chi^4) T K_2^2(m_\chi/T)} \int_{y_{min}}^{y_{max}} \mathrm{d}\, y \sqrt{s - 4m_\chi^2}\, \frac{s(s+2m_\chi^2)}{\Gamma_{Z'} m_{Z'}} K_1\left(\frac{\sqrt{s}}{T}\right) ,$$

$$\text{with } \mathrm{y(s)} = \tan^{-1}\left(\frac{\mathrm{s} - \mathrm{m}_{Z'}^2}{\Gamma_{Z'} \mathrm{m}_{Z'}}\right) ,$$

$$s = m_{Z'}^2 + \tan(y)\Gamma_{Z'} m_{Z'} ,$$

$$y_{min} = y(s = max(0.9 m_{Z'}^2, 4m_\chi^2), \; y_{max} = y(s = 1.1 m_{Z'}^2) .$$

$m_\chi > m_{Z'}/2$:

$$\langle \sigma v \rangle = \frac{1}{8 m_\chi^4 T K_2^2(m_\chi/T)} \int_{4m_\chi^2}^{\infty} \mathrm{d}\, s \sigma(s) \sqrt{s} (s - 4m_\chi^2) K_1\left(\frac{\sqrt{s}}{T}\right) ,$$

where the $K_n(x)$ are modified Bessel functions of order n, can be computed when x>0

$$\sigma(s)_{\chi\bar{\chi}\rightarrow\nu\bar{\nu}} = \frac{g_{Z'}^4 q_\chi^2}{12\pi} \sqrt{\frac{s}{s - 4m_\chi^2}}\, \frac{s^2 + 2m_\chi^2 s}{s\left[(s - m_{Z'}^2)^2 + \Gamma_{Z'}^2 m_{Z'}^2\right]} .$$

$$\Gamma_{Z' \rightarrow \bar{\nu}_l \nu_l} = \frac{2 g_{Z'}^2 m_{Z'}}{24\pi} = \frac{g_{Z'}^2 m_{Z'}}{12\pi} .$$

P. Gondolo, Nucl. Phys. B 360 (1) (1991) 145–179

The freeze-out point is given in terms of the scaled inverse temperature $x_f = \frac{m_\chi}{T}$:

$$x_f = ln \frac{0.076\, M_{pl}\, m_\chi \,\langle \sigma v \rangle}{g_*^{1/2} x_f^{1/2}} \,.$$

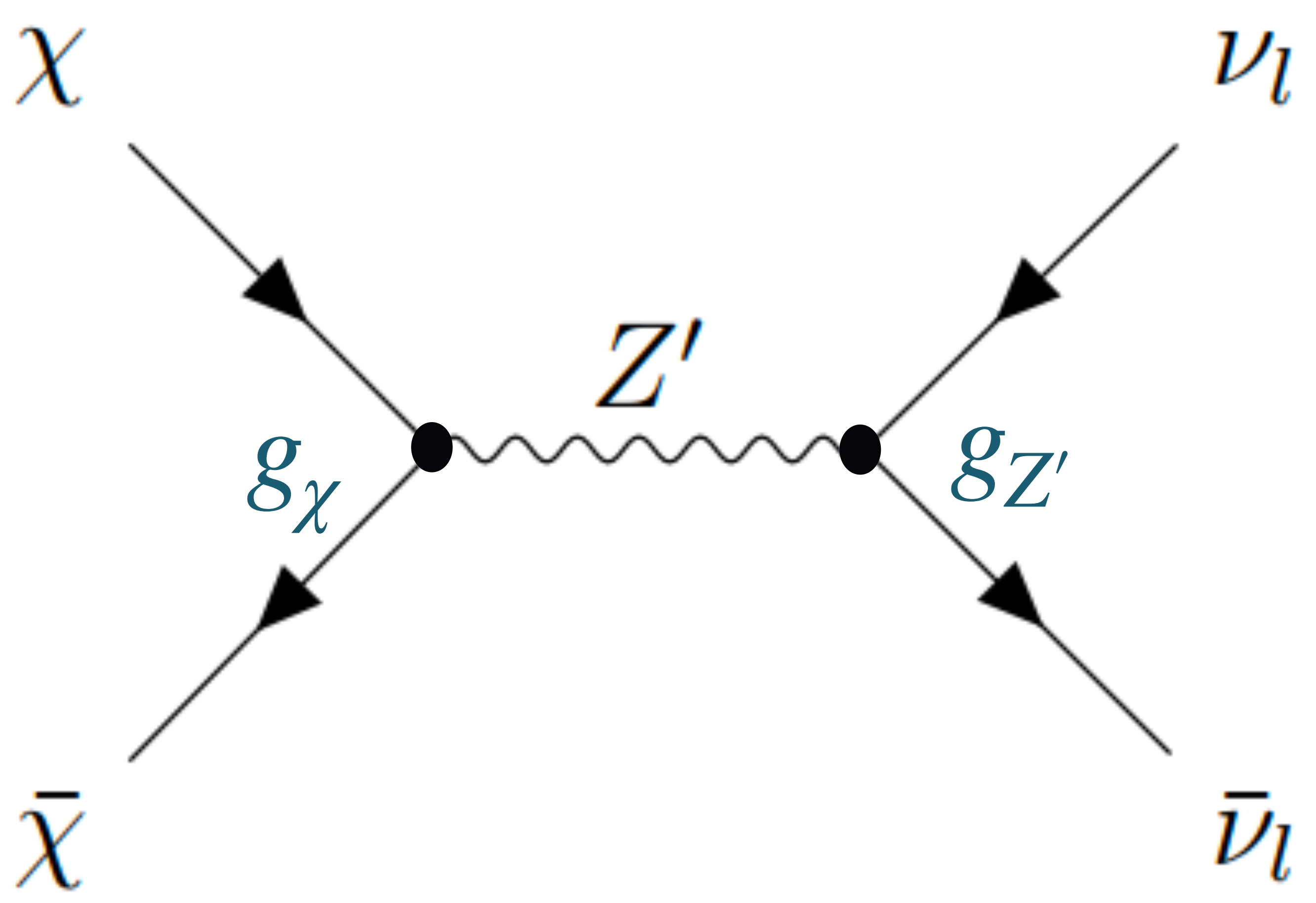
$M_{pl} = 1.22 \times 10^{19} \mathrm{GeV}$ and g_* is the total number of effectively relativistic degrees of freedom at the time of freeze-out.

The present-day mass density of χ is then given by

$$\Omega_\chi h^2 = \frac{1.07 \times 10^9 \ \mathrm{GeV}^{-1}}{J g_*^{1/2} M_{pl}} \,.$$

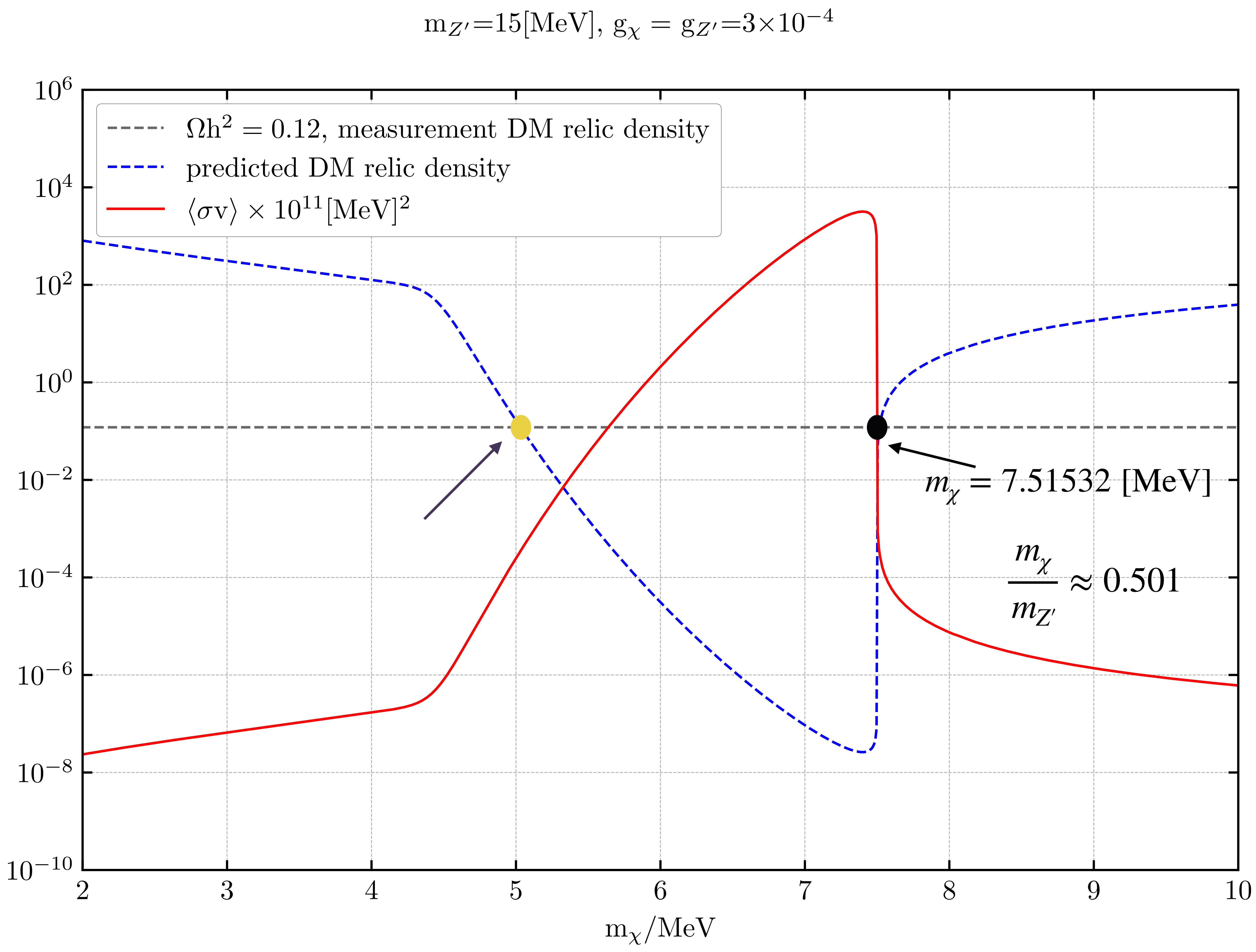
The efficiency of freeze-out annihilation is expressed through the integral $J = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle}{x^2} \, dx$,

K. Griest, Phys. Rev. D 43 (1991) 3191–3203



$g_\chi = g_{Z'} = 3 \times 10^{-4}$

If $m_\chi < m_{Z'}/2 \rightarrow \langle \sigma v \rangle$ will fall after DM decoupling, making DM annihilation in the present-day Universe smaller than the one in the early Universe.



Near the resonance, DM annihilation is needed to reproduce the DM relic abundance in the parameter space region of m_χ , g_χ.

Two intersection points

M. Drees, Physics Letters B 827 (2022) 136948
H. Murayama, Physics Review D 79, 095009 (2009)

Early Universe

$$\langle \sigma v \rangle_{early} = \frac{1}{8m_\chi^4 T K_2^2(m_\chi/T)} \int_{4m_\chi^2}^{\infty} ds\ \sigma(s)\ \sqrt{s}(s - 4m_\chi^2) K_1\left(\frac{\sqrt{s}}{T}\right),$$

$$x_f = \frac{m_\chi}{T}$$

$$K_n(x) = \sqrt{\frac{\pi}{2x}}\ e^{-x}$$

With parameters $(m_{Z'}, g_{Z'}, m_\chi)$ producing the measured relic abundance of [*]

$$\Omega_\chi h^2 = 0.12$$

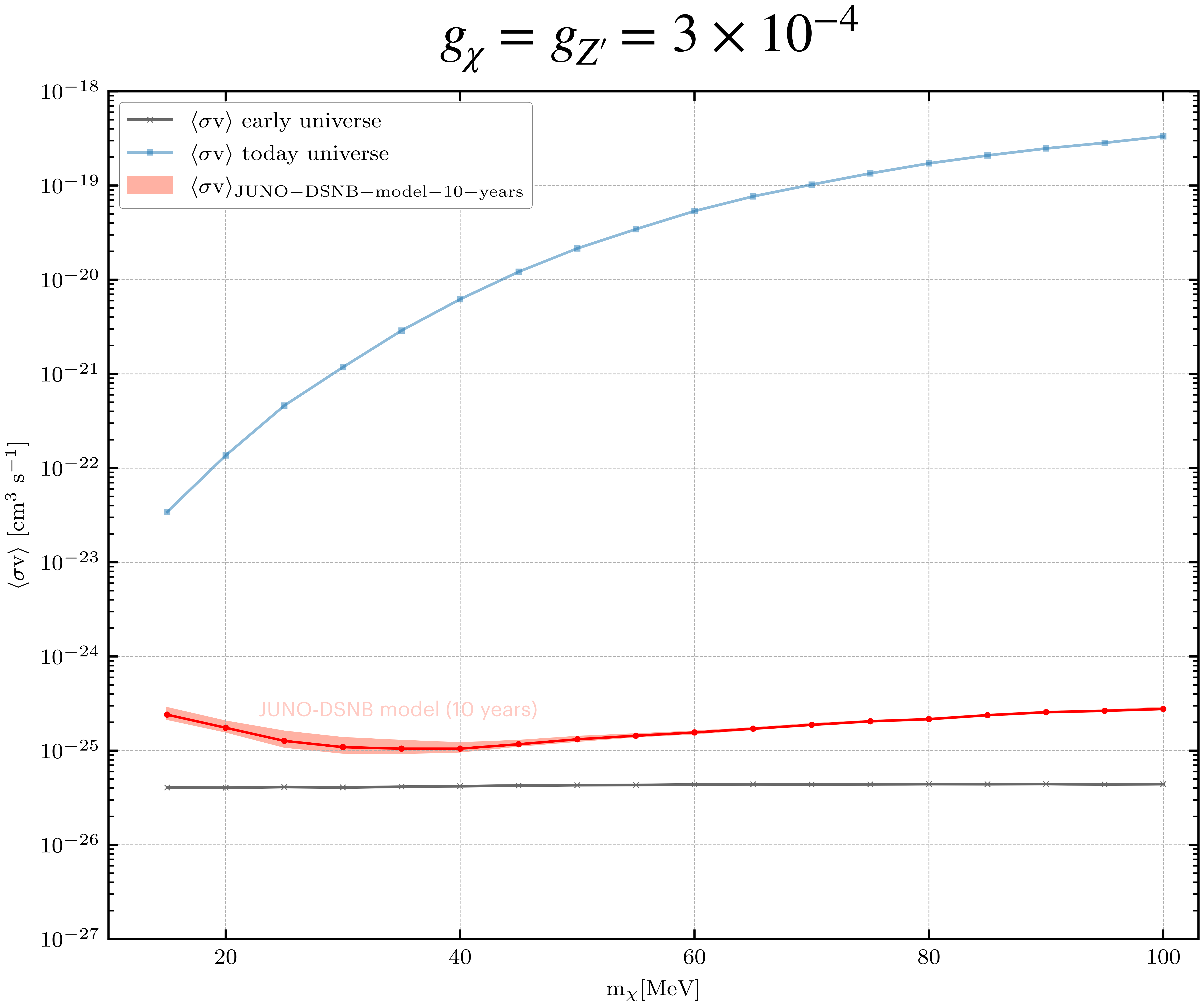
*P.A. Zyla, et al., PTEP 2020 (8) (2020) 083C01

Present-day Universe

$v_0/c = 220/(3 \times 10^5)$

$$\langle \sigma v \rangle = \sqrt{\frac{2}{\pi}} \frac{g_{Z'}^4}{96\pi m_\chi^3 T^{3/2}} \int_{4m_\chi^2}^{\infty} ds\ s^{3/4} \sqrt{s - 4m_\chi^2} \frac{s + 2m_\chi^2}{(s - m_{Z'}^2)^2 + \Gamma_{Z'}^2 m_{Z'}^2}\ e^{\frac{2m_\chi - \sqrt{s}}{T}}$$

The annihilation process through Z' : $\chi\chi \to Z' \to \nu\bar{\nu}$.



Here we did not show the WIMP particles with canonical $\langle\sigma v\rangle \sim 3 \times 10^{-26} \mathrm{cm}^3\mathrm{s}^{-1}$

RESULTS

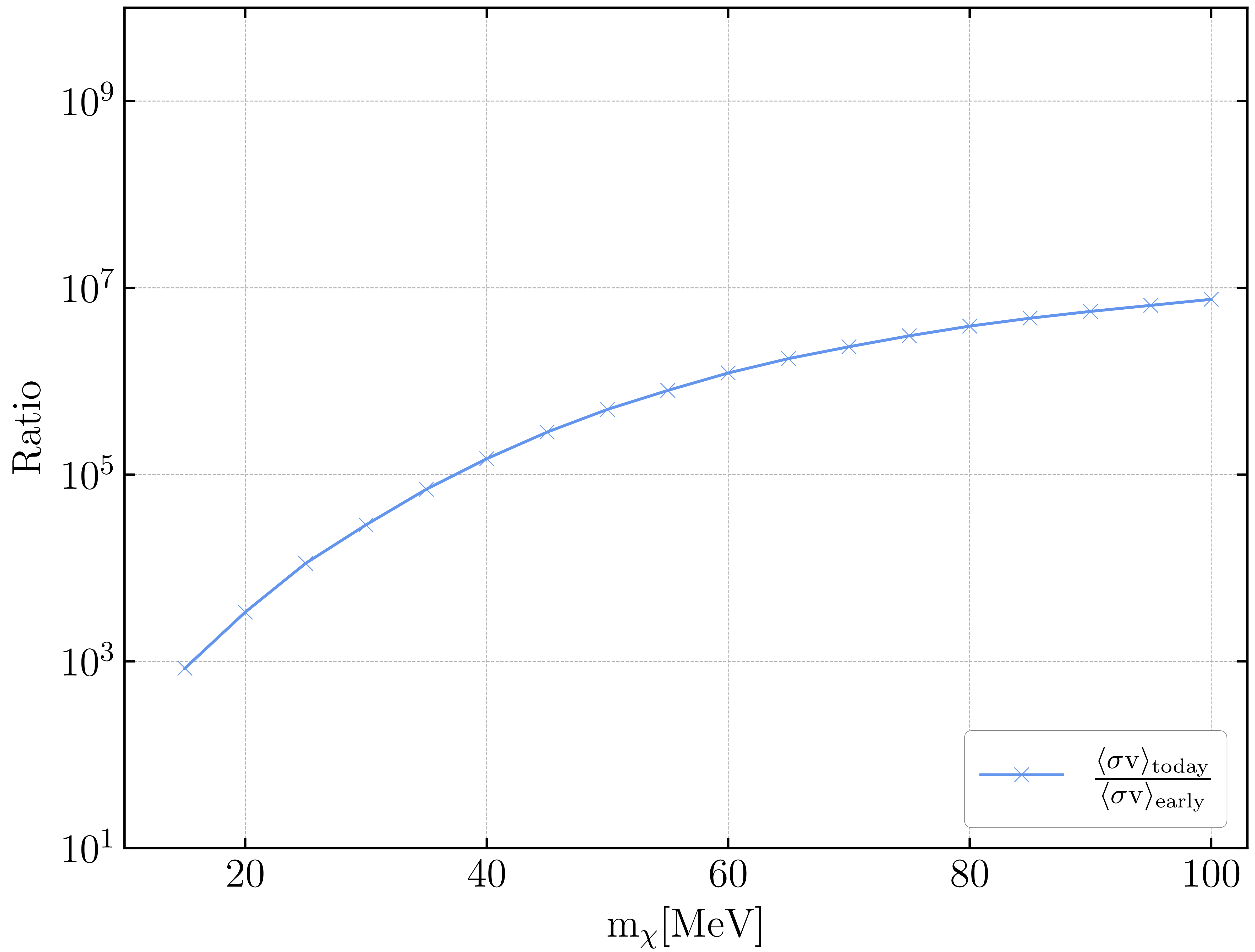
Define:

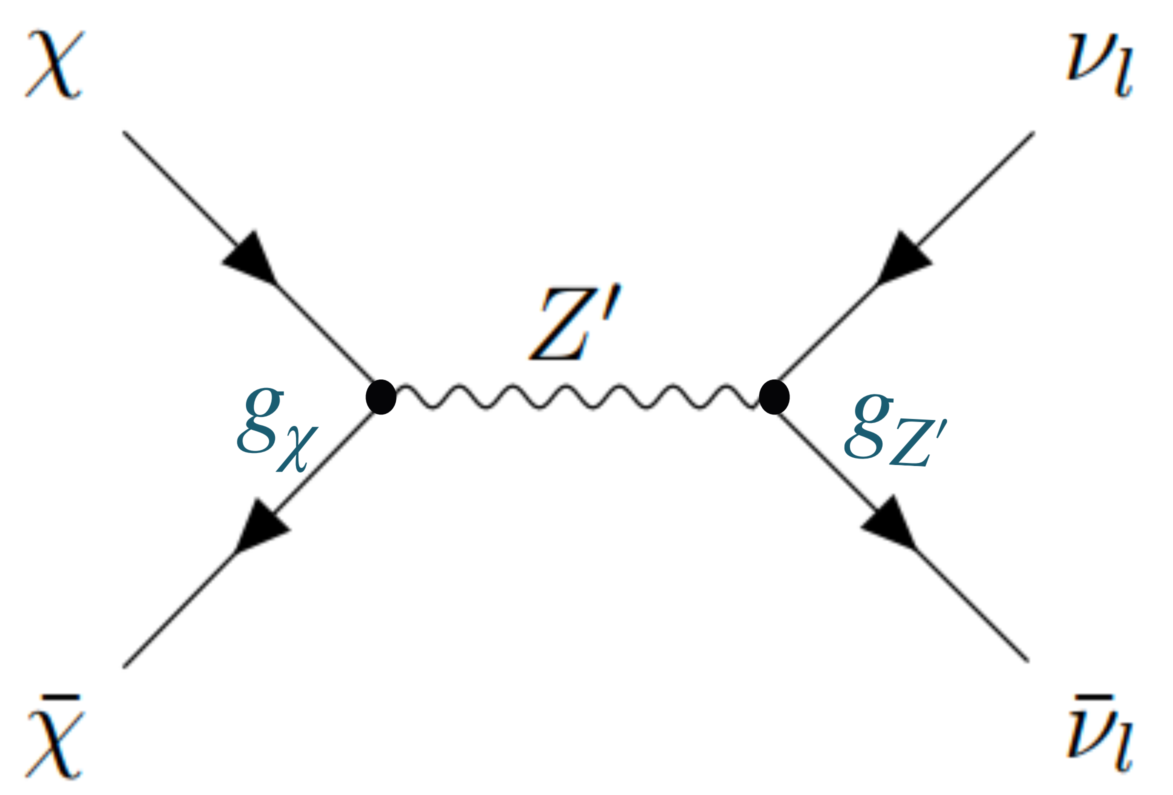
$$Ratio = \frac{\langle \sigma \mathrm{v} \rangle_{\mathrm{today}}}{\langle \sigma \mathrm{v} \rangle_{\mathrm{early}}}$$

At the desired DM relic density, $\Omega_\chi h^2 = 0.12$

→ The thermally averaged DM annihilation cross section $\langle \sigma v \rangle_{\mathrm{today-universe}}$ is enhanced compared to $\langle \sigma v \rangle_{\mathrm{early-universe}}$.

→The predicted $\langle \sigma v \rangle_{\mathrm{today-universe}}$ is testable by JUNO detector.

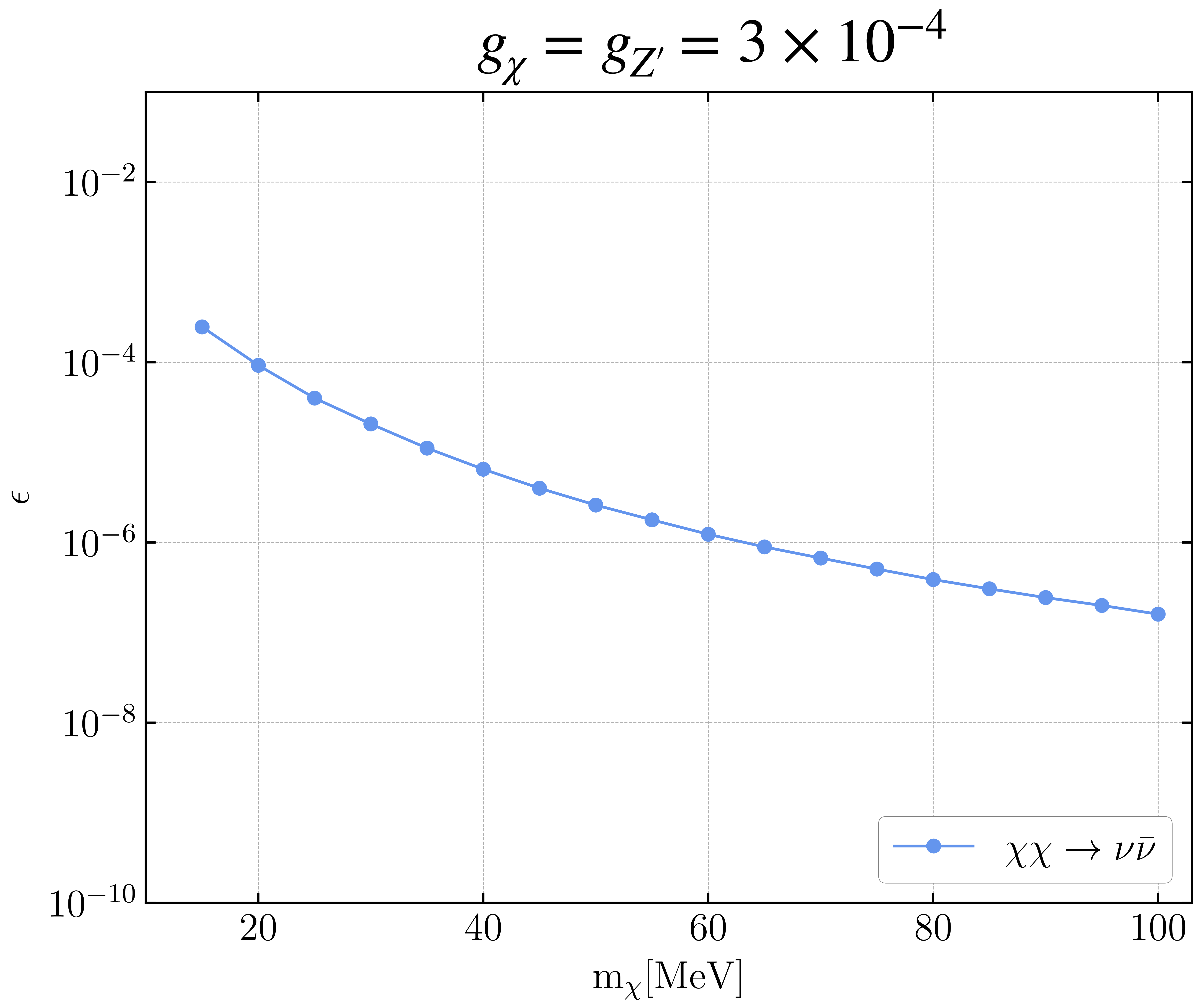




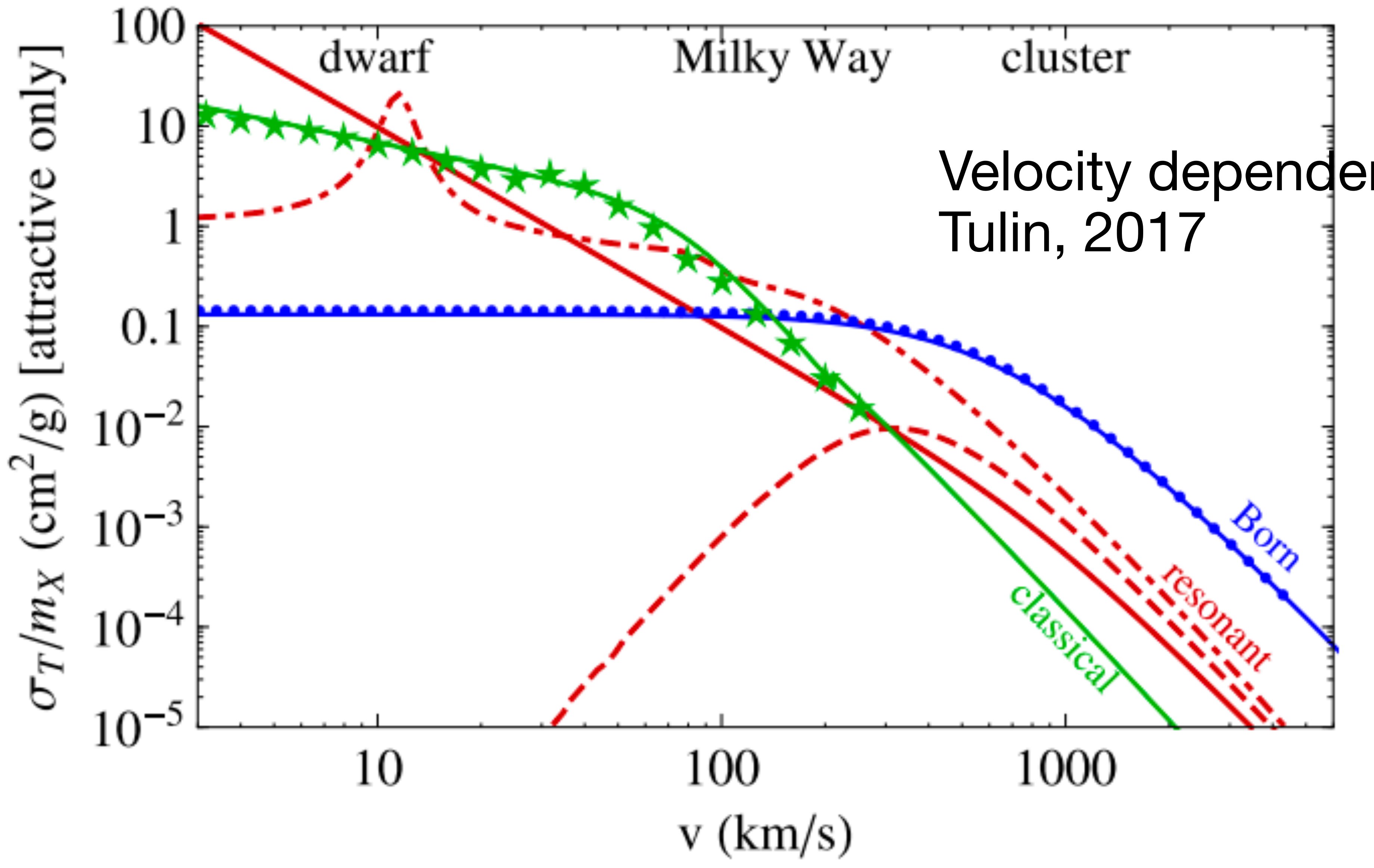
$$\epsilon = \left(\frac{2m_\chi}{m_{Z'}} - 1\right) \gtrsim 0$$

g_χ does not have to be equal to $g_{Z'}$

→ The range of g_χ can be determined by SIDM constraints.



CONSTRAINT ON SELF-INTERACTION DM (SIDM)



Velocity dependence of SIDM
Tulin, 2017

Peter et al., 2013, arXiv:1208.3026. $\sigma_{\chi\chi}/m_\chi \leq 1\ cm^2 g^{-1}$

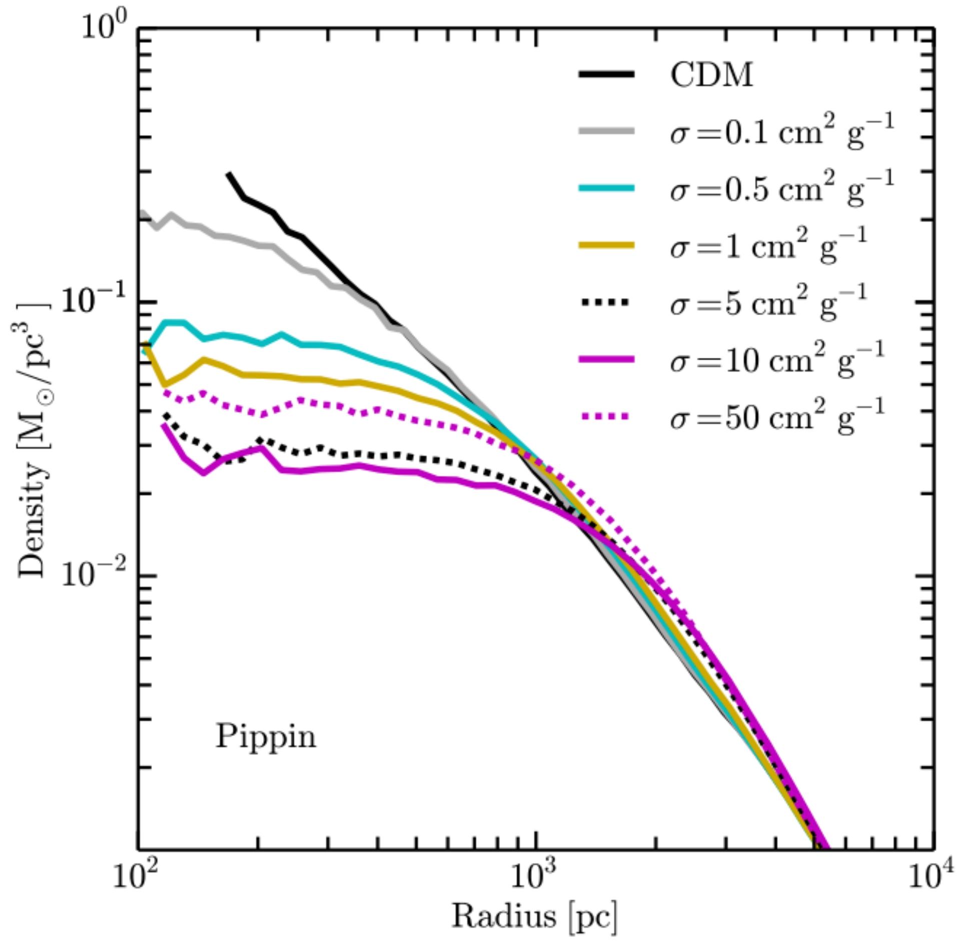
SIDM in merging clusters

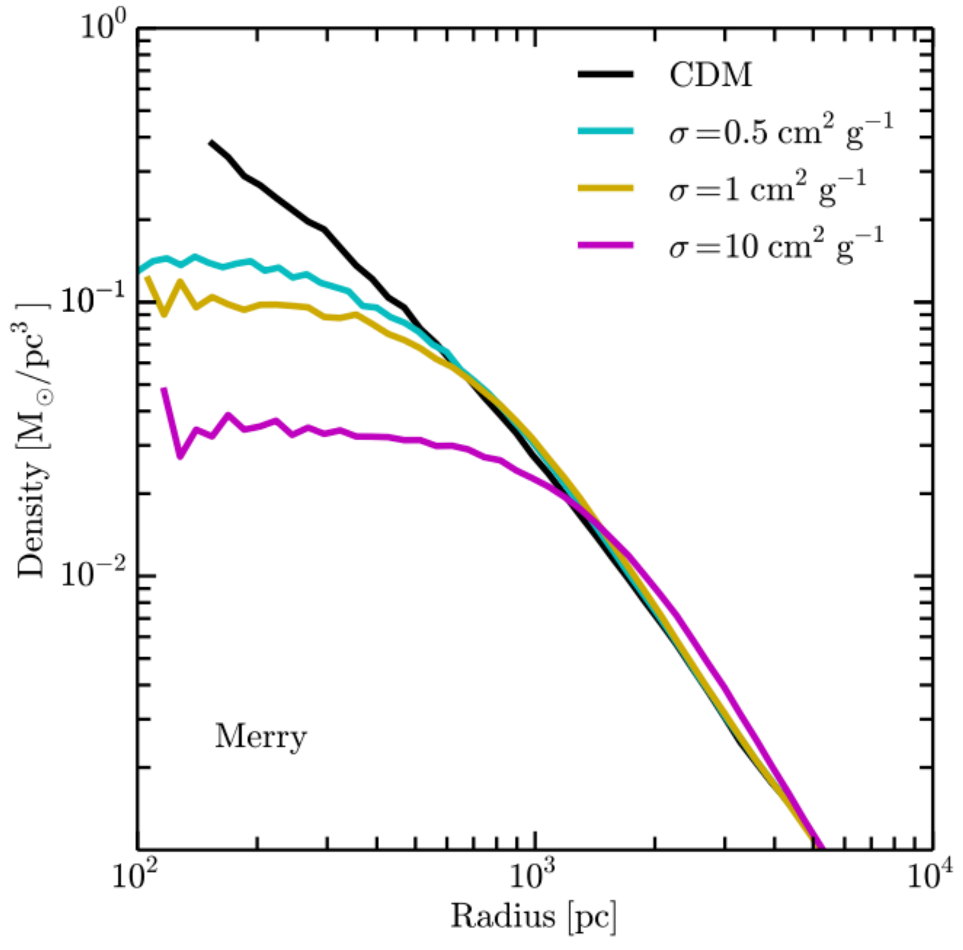
Randall et al., 2007, Astrophys. J. 679 (2008) 1173. arXiv:0704.0261.

$\sigma_{\chi\chi}/m_\chi \leq 1.25\ cm^2 g^{-1}$

Harvey et al., 2015, arXiv:1503.07675v2.

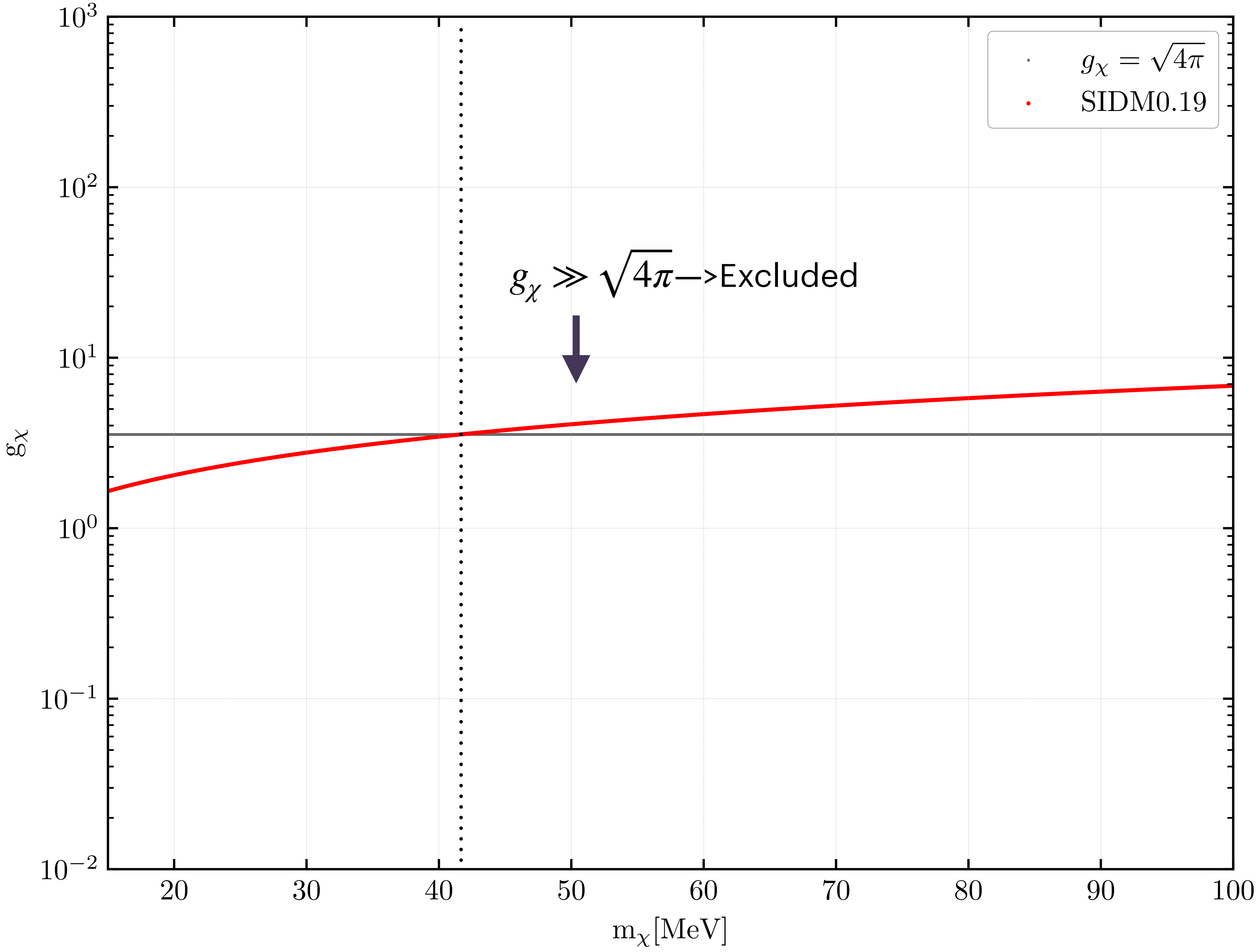
$\sigma_{\chi\chi}/m_\chi \leq 0.47\ cm^2 g^{-1}$





Elbert et al., 2015

The sample: XMM-Newton Cluster Outskirts Project (X-COP, D. Eckert et al. 2017) - 12 massive galaxy clusters with Einasto profile. —> $\sigma_{\chi\chi}/m_\chi \leq 0.19\ cm^2 g^{-1}$ **(2022).**



To constraint the SIDM with the upper bound

$$\sigma_{\chi\chi}/m_\chi \leq 0.19\ cm^2 g^{-1}$$

D. Eckert, A&A 666, A41 (2022), 2205.01123

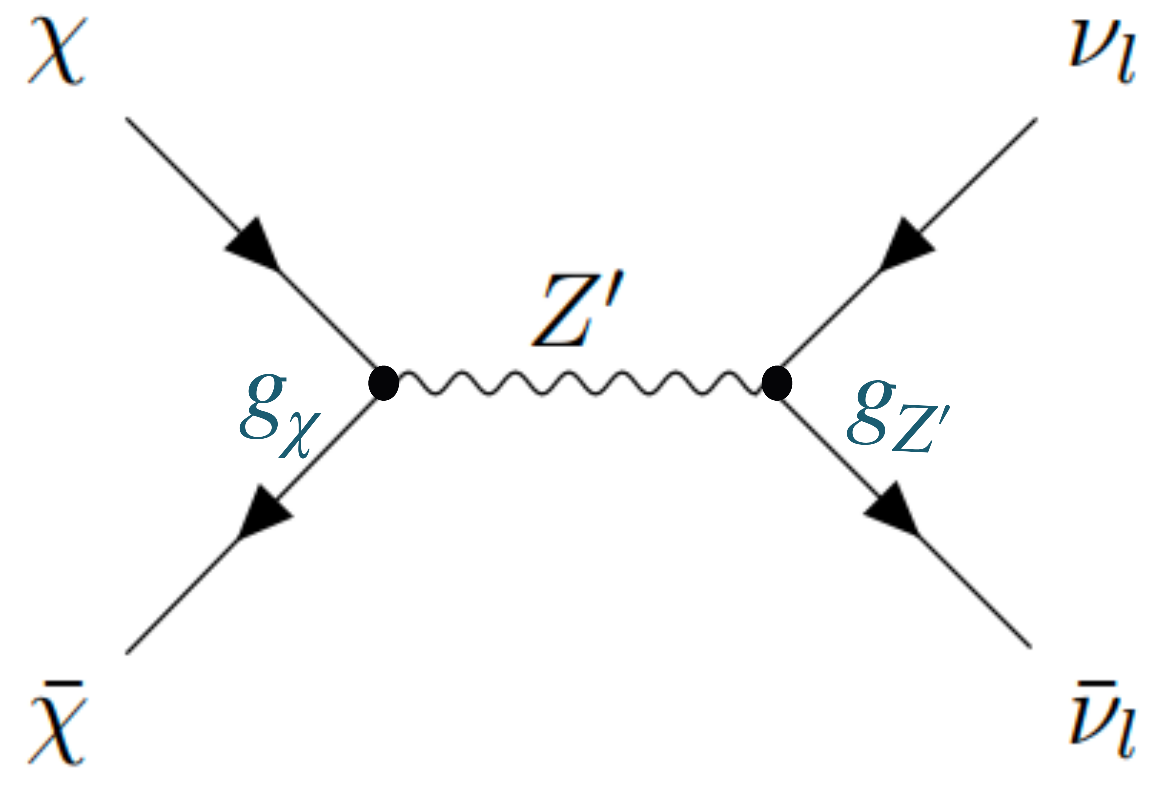
$$m_\chi \sim \frac{m_{Z'}}{2}$$

In the elastic DM self-scattering, consider in the perturbative limit $\alpha_\chi \ll 1$ with $\alpha_\chi = \frac{g_\chi^2}{4\pi}$.

In the case that we consider the g_χ is bigger, so $g_{Z'}$ is smaller.

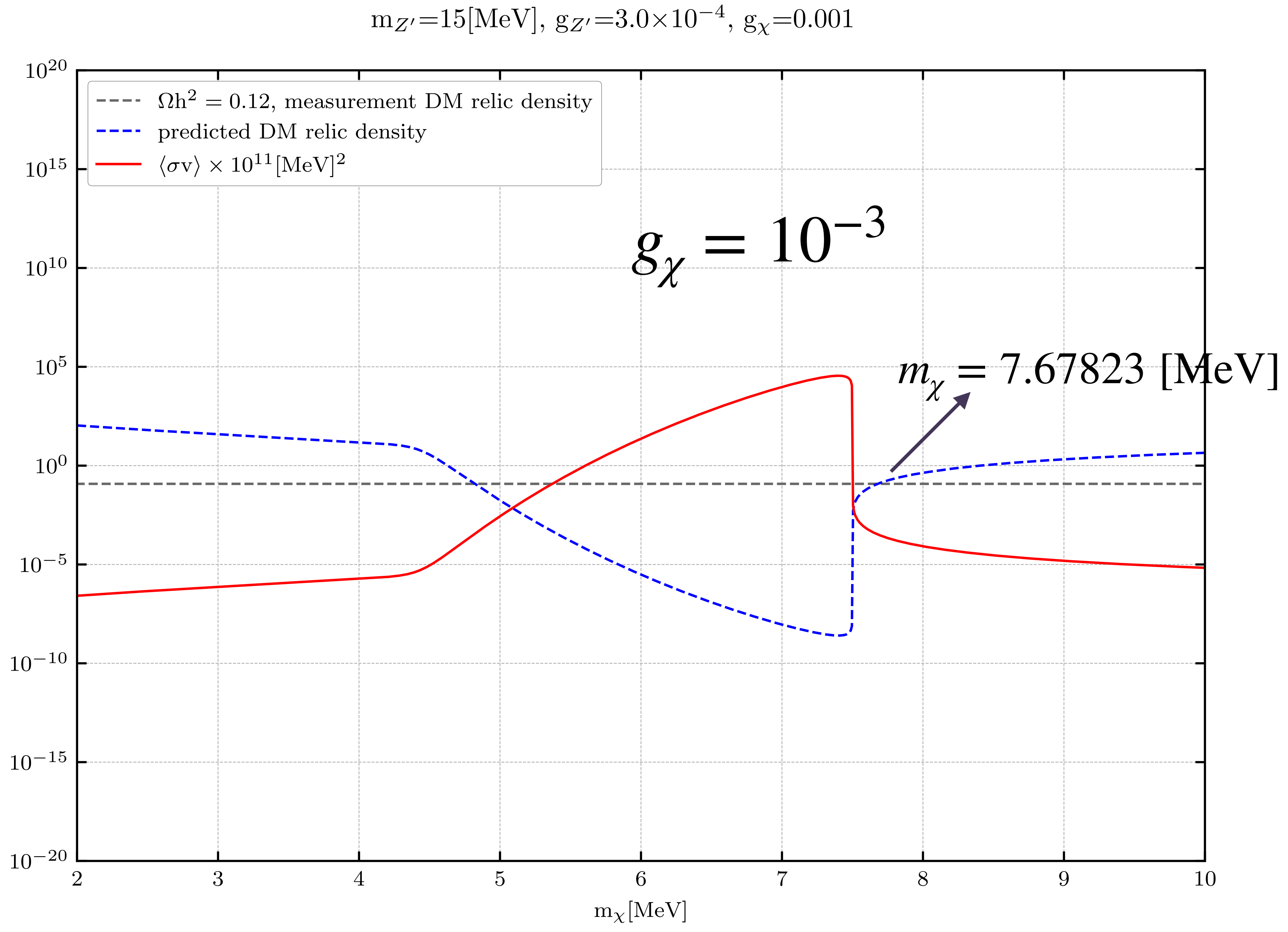
Now, if we assume $g_\chi \neq g_{Z'}$,

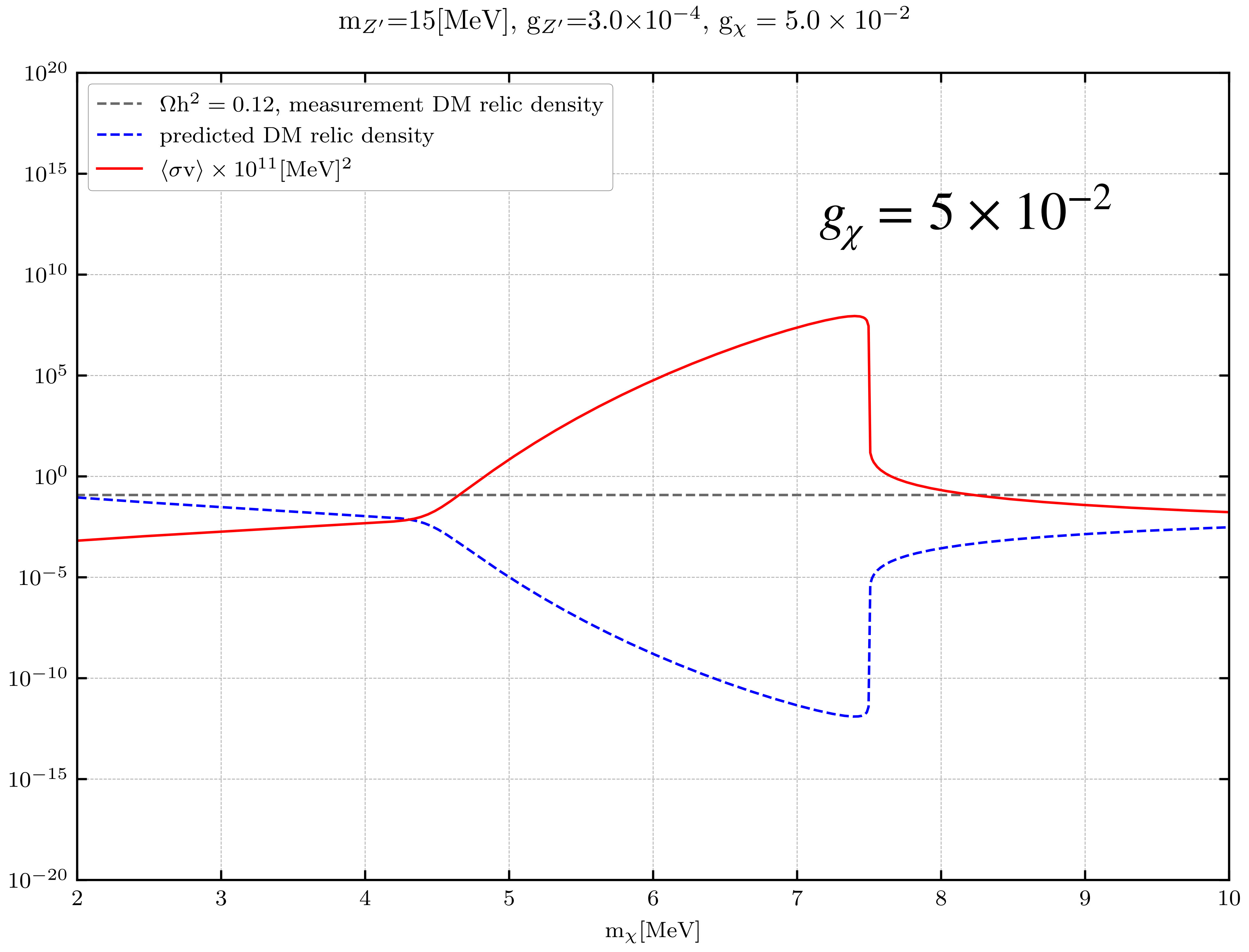
→What will happen?

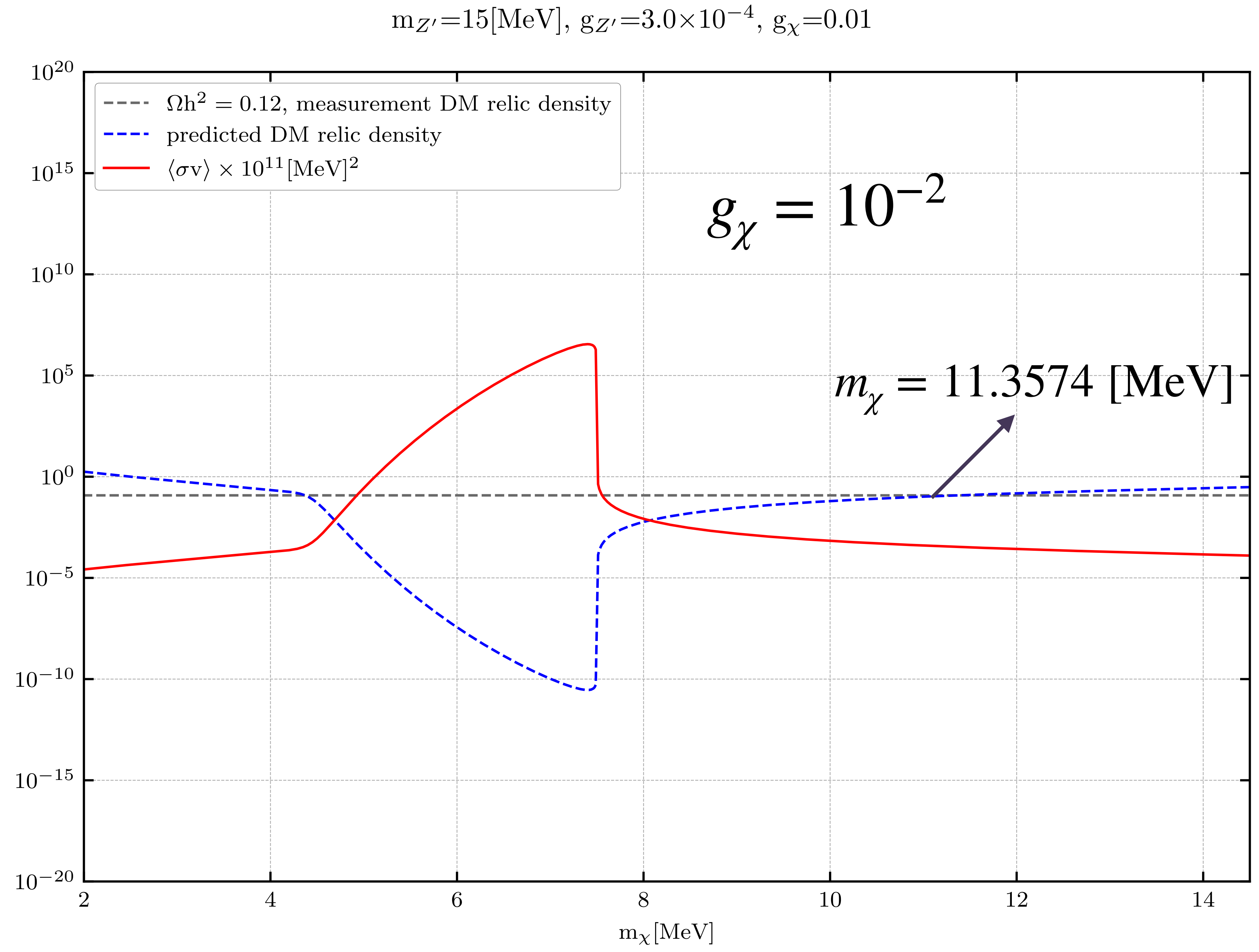


Example: $m_{Z'} = 15$ [MeV], $g_{Z'} = 3 \times 10^{-4}$

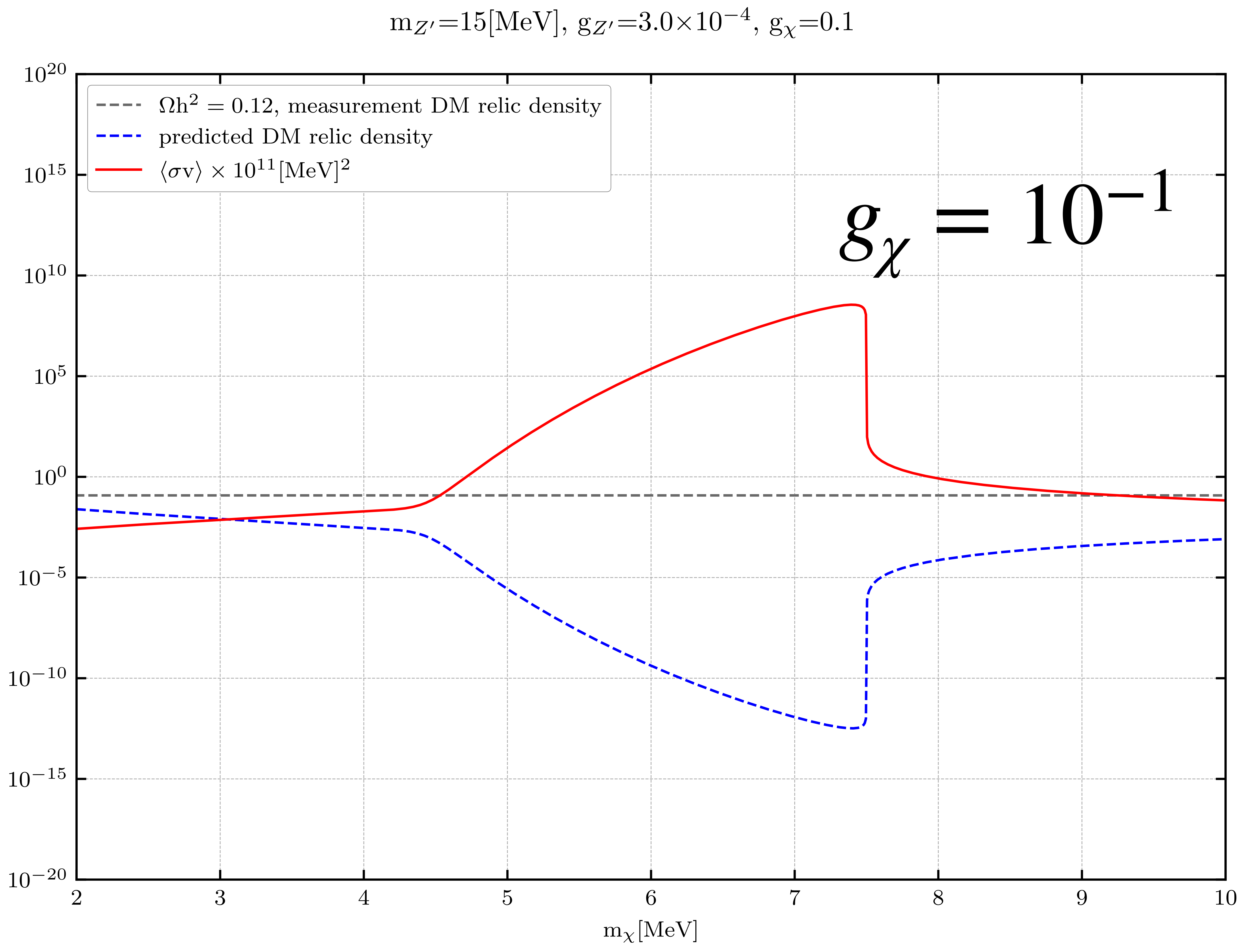
$g_\chi = 10^{-3}, 10^{-2}, 5 \times 10^{-2}, 10^{-1}$ and 1.0

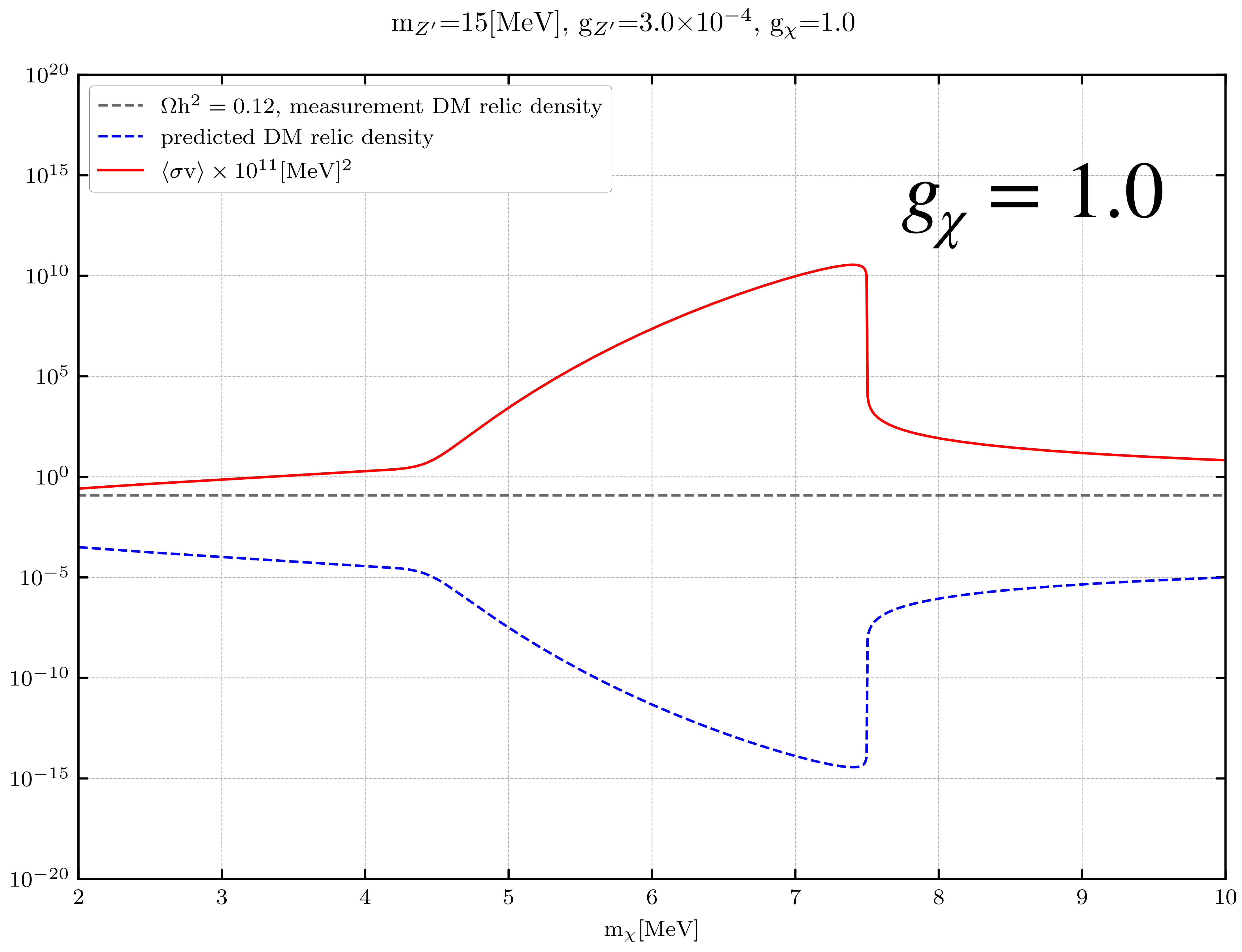






Ex: $m_{Z'} = 15$ [MeV], $g_{Z'} = 3 \times 10^{-4}$

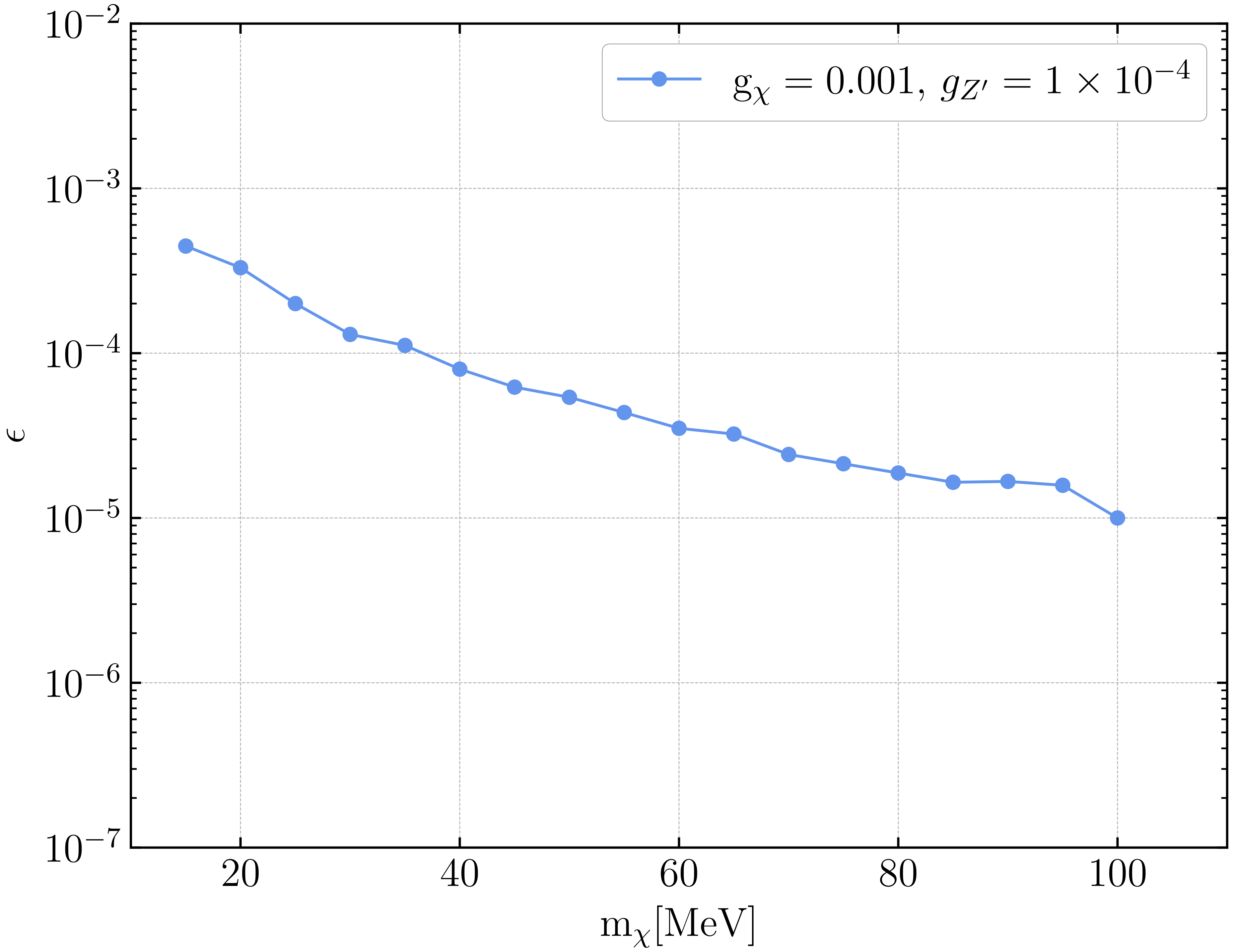


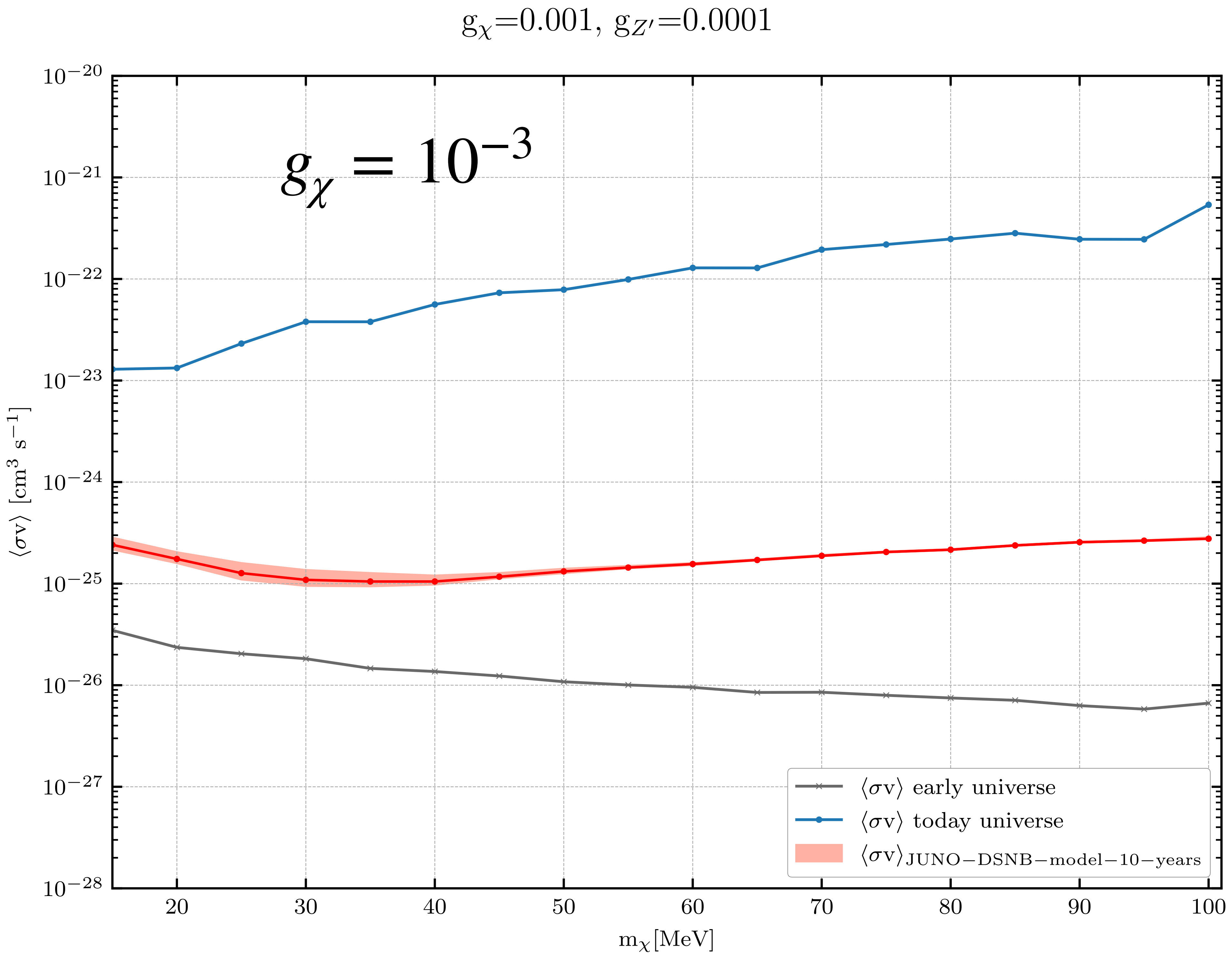


No intersection points

$$\epsilon = \left(\frac{2m_\chi}{m_{Z'}} - 1\right) \gtrsim 0$$

Resonance-enhanced DM annihilation cross section





→ Fine-tune on the ratio $\frac{m_\chi}{m_{Z'}} \sim \frac{1}{2}$.

Resonance-enhanced DM annihilation cross section

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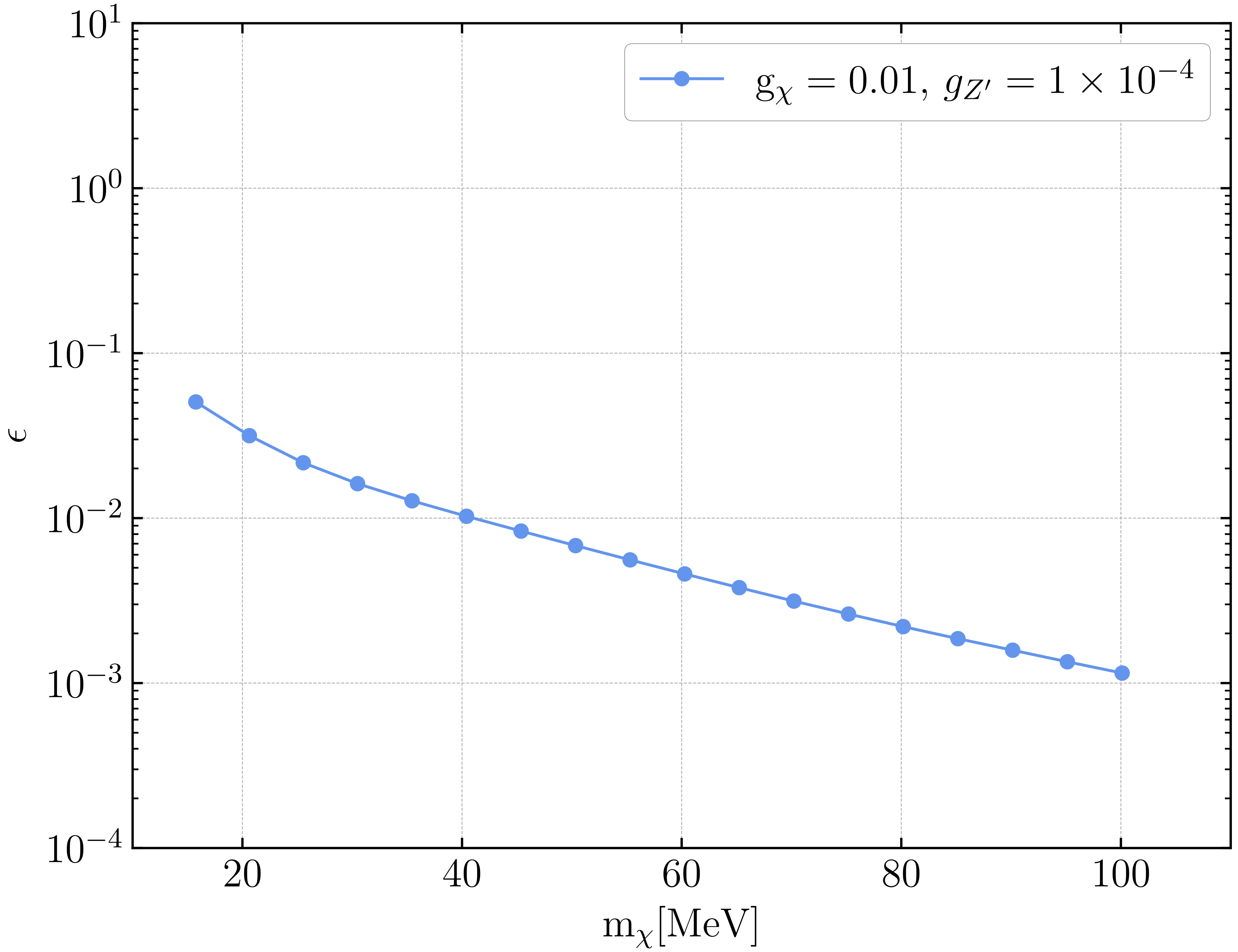

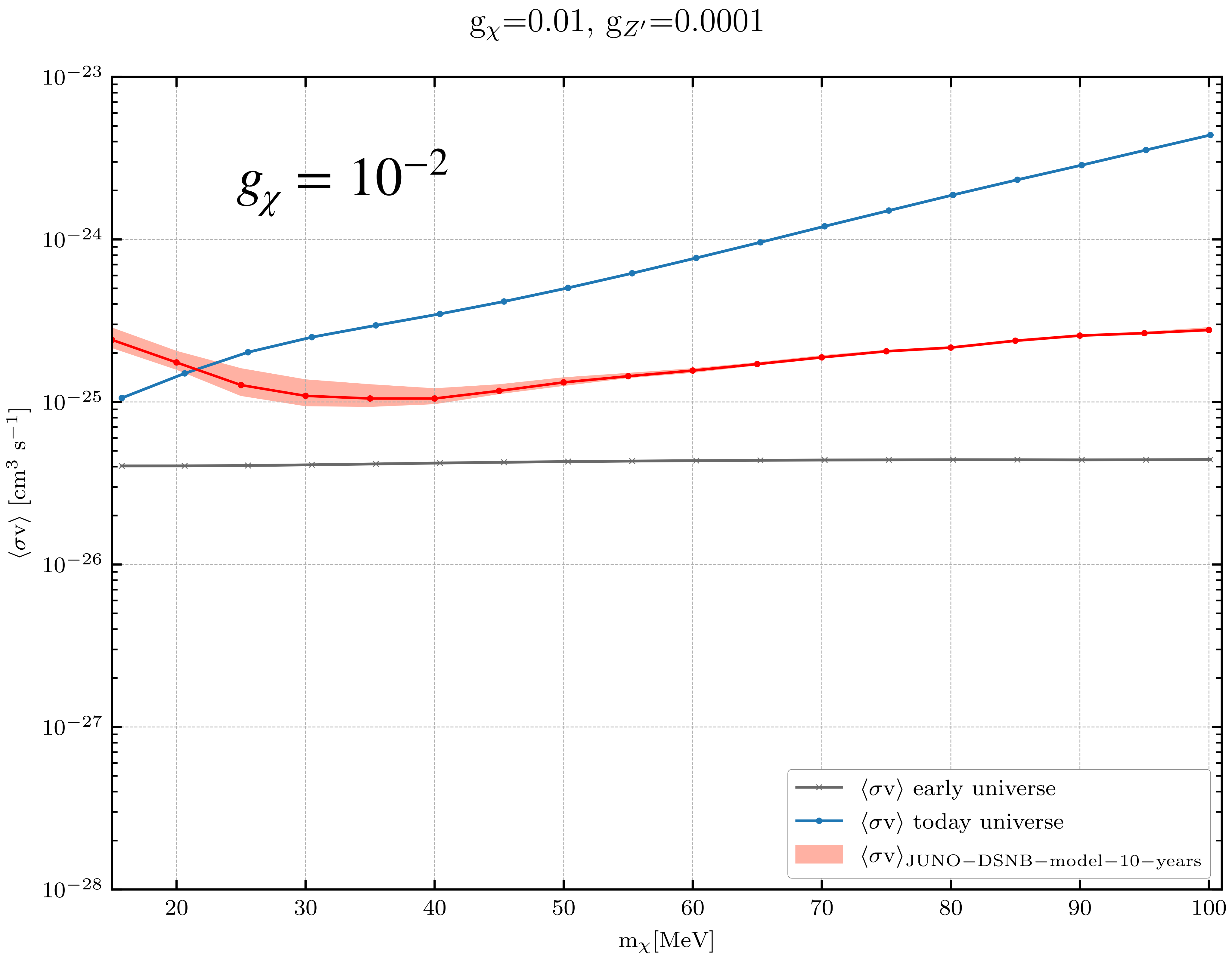

—> Fine-tune on the ratio $\dfrac{m_\chi}{m_{Z'}} \sim \dfrac{1}{2}$.

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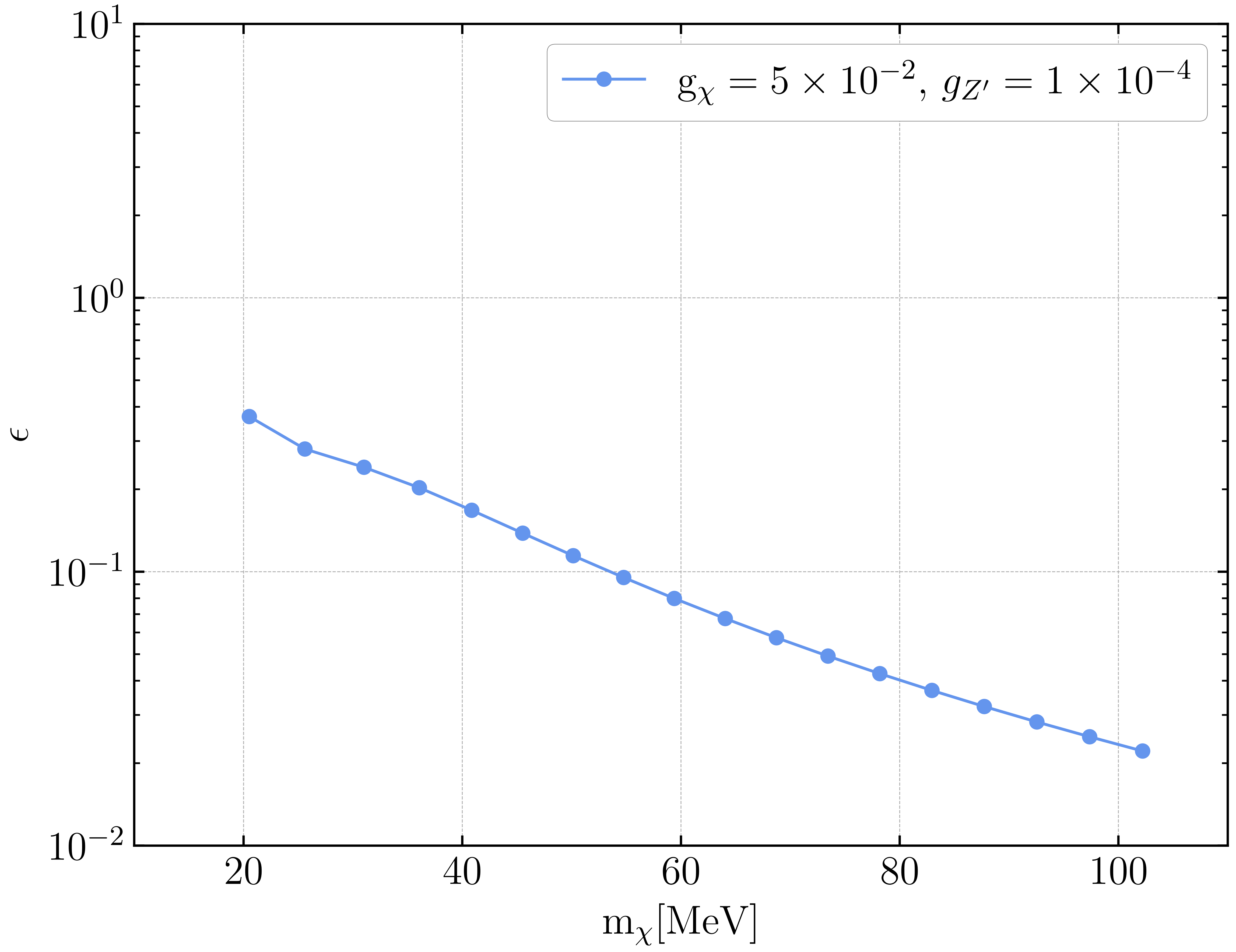
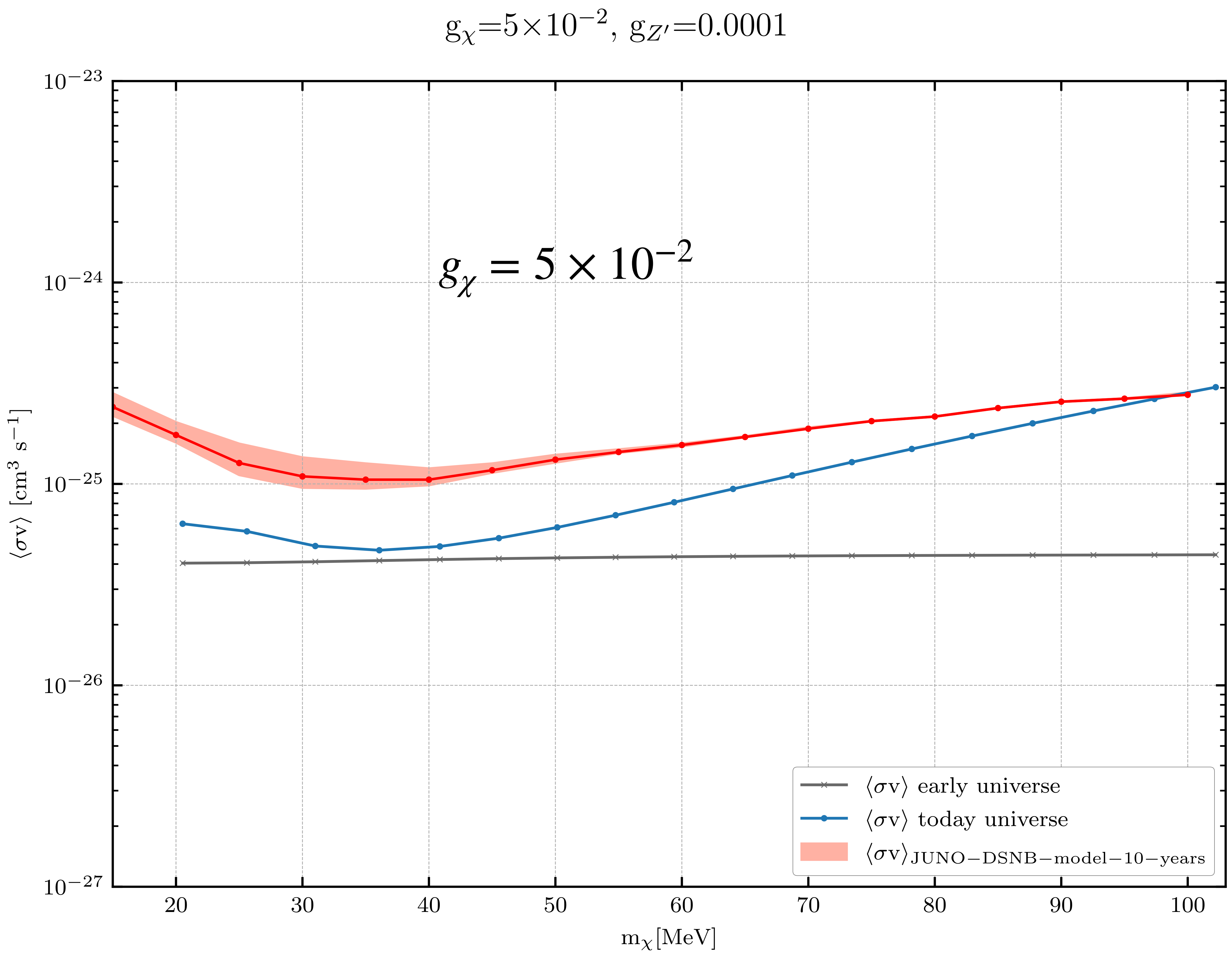




Minor enhancement; not reachable by JUNO (10 years).

JUNO sensitivity and Sommerfeld effect

Define

$$S = \frac{\langle \sigma v \rangle_{Present-day}}{\langle \sigma v \rangle_{Early\ Universe}},$$

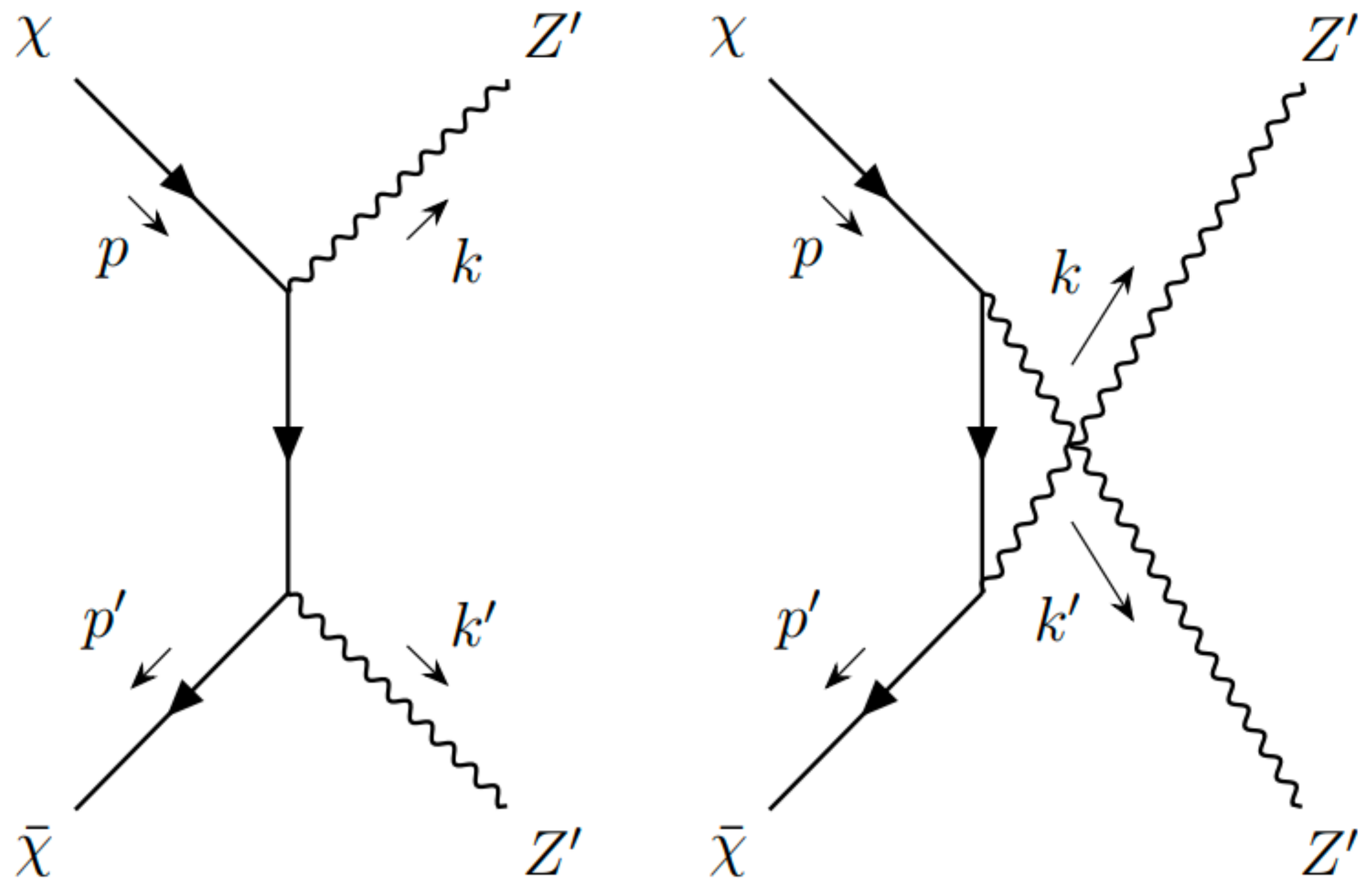
→ S is the Sommerfeld factor, either the DM annihilation rate for s-wave or p-wave annihilation.

In the $U(1)_{L_\mu - L_\tau}$ model, how and why can we apply Sommerfeld?

$$S = ? \rightarrow \langle \sigma v \rangle_S = ?$$

The annihilation process through Z' : $\chi\chi \rightarrow Z'Z' \rightarrow \nu\bar{\nu}\nu\bar{\nu}$.

$$m_\chi \gg m_{Z'}$$



t-channel u-channel

Arnold Sommerfeld

JUNO sensitivity and Sommerfeld effect

In the early universe:

$$m_\chi \gg m_{Z'}$$

$$\langle \sigma v_{rel} \rangle \approx \frac{\pi \alpha_\chi^2}{2 m_\chi^2};$$

+ The DM velocity v_{rel} is high,

$$S = \frac{2\pi\alpha_\chi / v_{rel}}{1 - e^{-2\pi\alpha_\chi / v_{rel}}} \; ; \alpha_\chi = \frac{g_\chi^2}{4\pi}$$

$\rightarrow S \approx 1$

Jonathan L. Feng, Manoj Kaplinghat, and Hai-Bo Yu, PRL 104, 151301 (2010)

For $m_\chi = 100$ MeV, $\alpha_\chi \sim 10^{-6}$ by thermal relic condition

In the present-day universe:

+ The coupling is too small
  $\alpha_\chi \ll v_{rel}, v_{rel} = 10^{-3}$

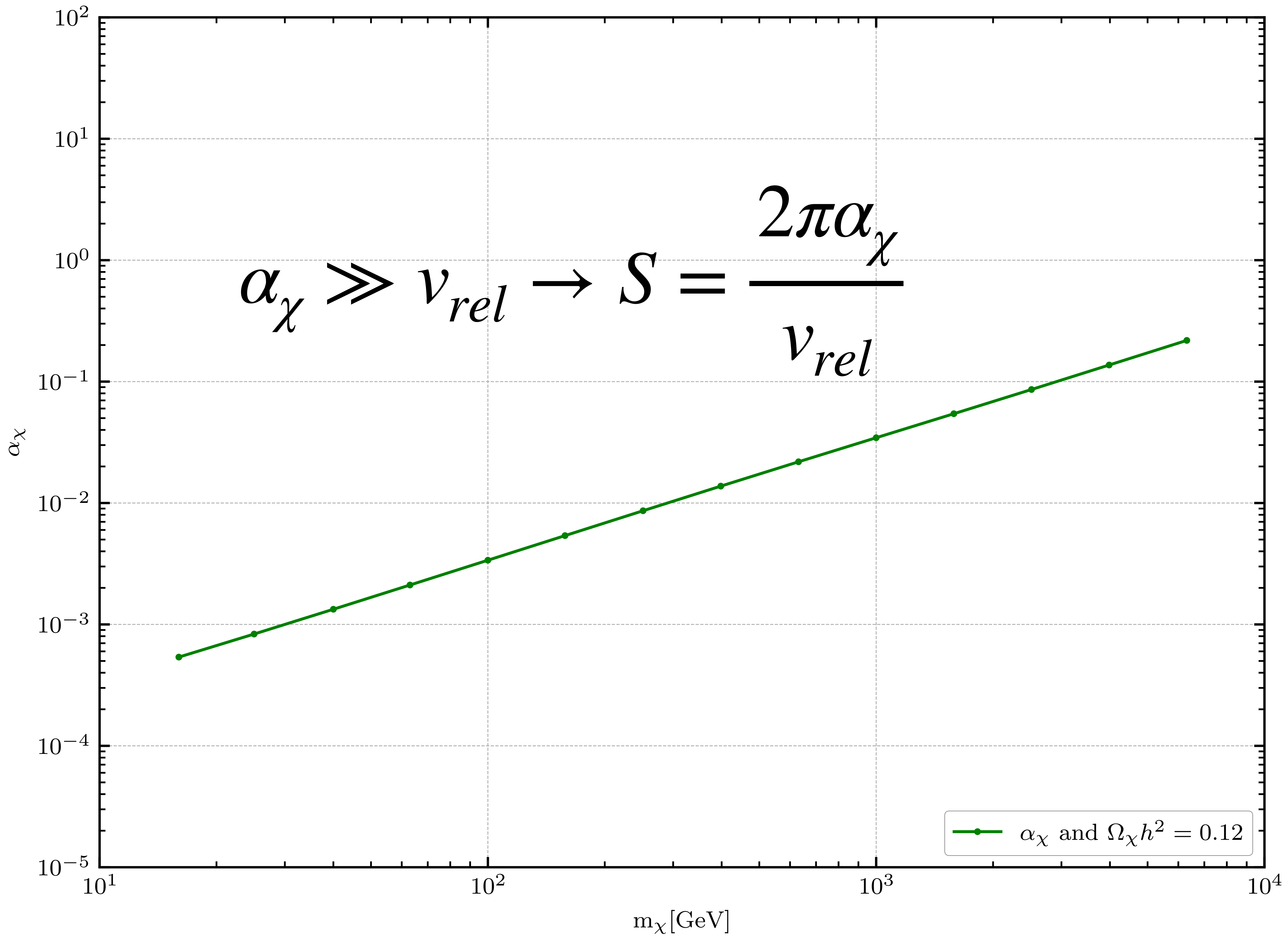
$\rightarrow$ Not satisfy the Coloumb limit below: $\alpha_\chi \gg v_{rel} \rightarrow S = \dfrac{2\pi\alpha_\chi}{v_{rel}}$

$\Rightarrow$ The Sommerfeld enhancement is absent due to small coupling constant, so JUNO is not able to probe this effect.

$$m_\chi \gg m_{Z'}$$

$$\langle \sigma v_{rel} \rangle \approx \frac{\pi \alpha_\chi^2}{2 m_\chi^2};$$

$$\alpha_\chi \gg v_{rel} \rightarrow S = \frac{2\pi\alpha_\chi}{v_{rel}}$$



DM with a mass of 10 GeV- 10 TeV.

To satisfy the thermal relic condition:
α_χ scales linearly with m_χ

JUNO cannot probe the Sommerfeld enhancement due to its operating energy range; higher-energy indirect detection experiments like **IceCube** are better suited for this.

—> work under progress

Summary

> Within $U(1)_{L_\mu - L_\tau}$ model, a comprehensive analysis of $\langle \sigma v \rangle$ in the early Universe and present-day Universe were performed for DM mass between 15 MeV and 100 MeV, which is within the operating energy range of the JUNO detector.

> Due to the resonance-enhanced effect, the predicted $\langle \sigma v \rangle$ in the galactic halo is testable by the JUNO detector under very fine-tuned mass ratio between m_χ and $m_{Z'}$.

> JUNO cannot probe the Sommerfeld enhancement due to its operating energy range. On the other hand, IceCube experiment will be able to test this effect.

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Thank you for your listening

Discussion and Q&A

Backup slides

Data Using from

galaxies

MDPI

Article

On Effective Degrees of Freedom in the Early Universe

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1.0e-2 3.36
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5.0e-1 10.16
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50.0 14.63
100.0 18.0
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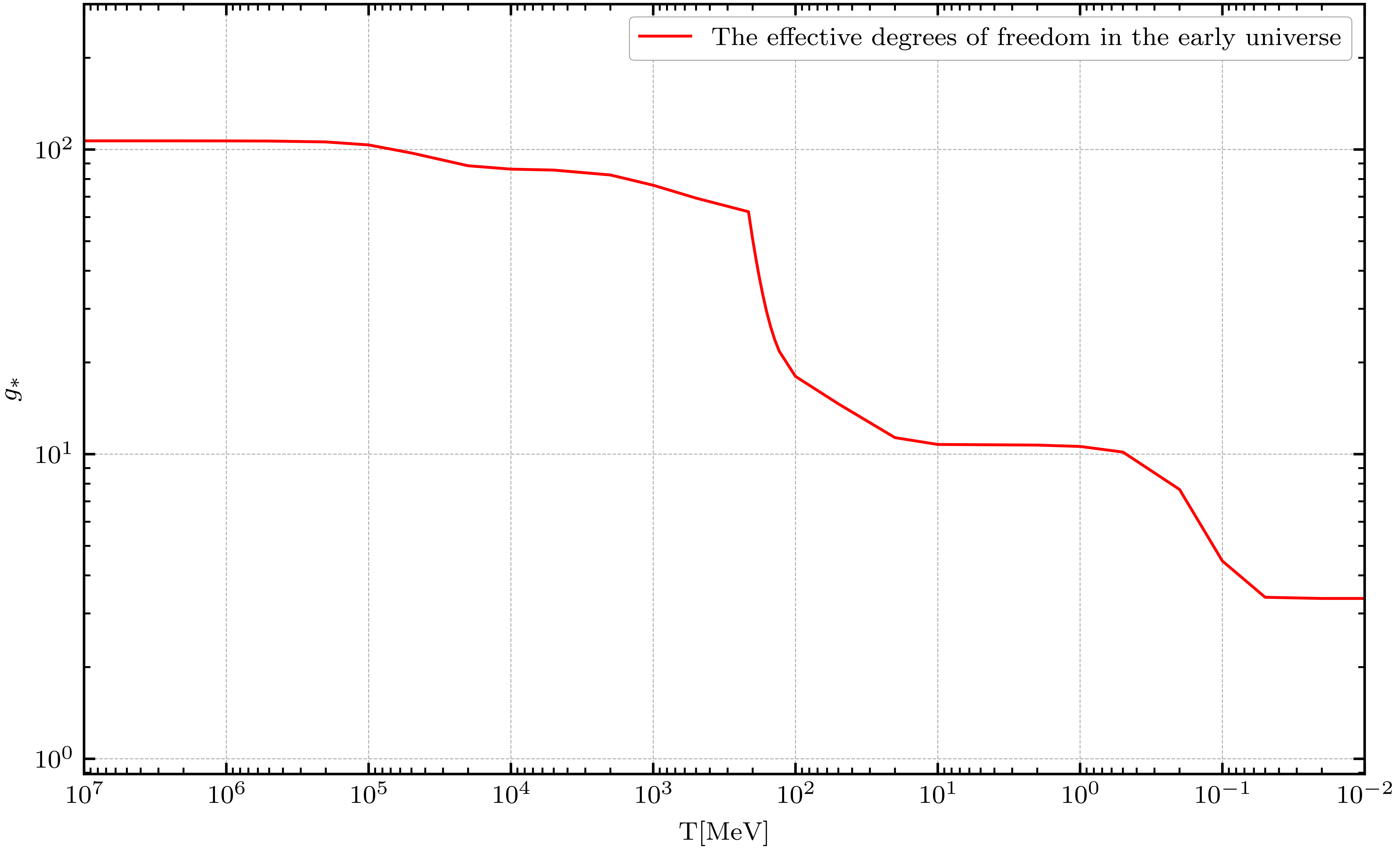

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