Higgs-coupled freeze-in baryogenesis

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Work in progress with B. Halcomb, N. Kirby, and B. Shuve

Freeze-in DM

McDonald, hep-ph/0106249
Hall *et al.*, arXiv:0911.1920
review by Bernal *et al.*, arXiv:1706.07442

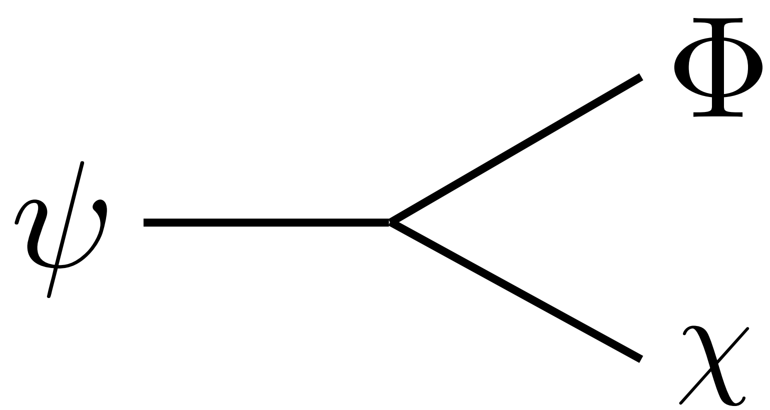
$$\mathcal{L} \supset -F\psi\chi\Phi + \text{ h.c.}$$

feeble interaction

BSM (charged)

DM

SM



$$\frac{\rho_{\rm DM}}{\rho_{\rm DM,obs}} \simeq \left(\frac{F}{10^{-8}}\right)^2 \left(\frac{\rm TeV}{M_\psi}\right) \left(\frac{M_\chi}{10 \text{ eV}}\right)$$

Freeze-in baryogenesis

$$\mathcal{L} \supset -F_i \psi \chi_i \Phi + \text{ h.c.}$$

J. Berman, B. Shuve, DTS, arXiv 2201.11502: $\Phi = e_R$ (electroweak-charged ψ)
B. Shuve, DTS, arXiv 2004.00363: $\Phi = u_R$ (QCD-charged ψ)

Combined baryogenesis and DM constraints prefer $M_\psi \sim$ TeV scale and $M_\chi \sim$ 10's of keV

$\psi =$ collider target

Cosmological probes of structure formation are relevant for χ

The Higgs-coupled case

Introduce $\begin{cases} \chi_{1,2} : \text{ Majorana fermion DM} \\ \Psi = (\psi, \psi^c) : \text{ vector-like electroweak-doublet fermion} \sim (1, 2, \mp 1/2) \end{cases}$

$$\mathcal{L}_{\chi \text{ int}} = -F_{1i}\, \psi \chi_i H - F_{2i}\, \psi^c \chi_i \tilde{H} \; + \; \text{h.c.}$$

This is “singlet-doublet” freeze-in DM, but with two DM particles.

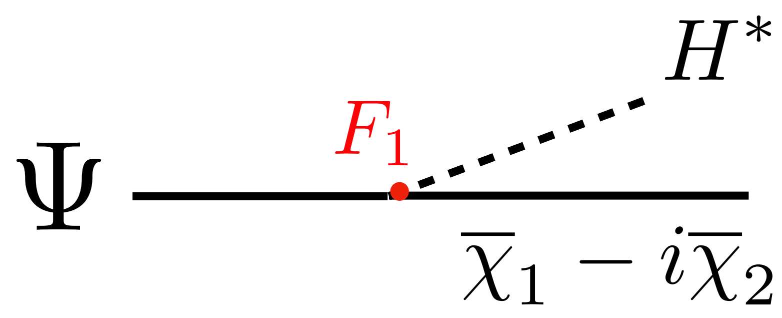
L. Calibbi, L. Lopez-Honorez, S. Lowette,
A. Mariotti, arXiv:1805.04423

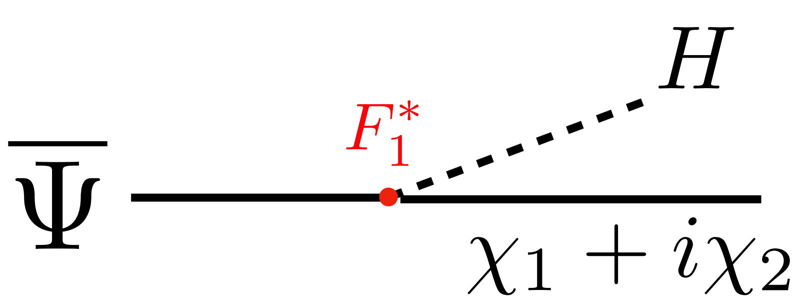
$\mathcal{L}_{\chi \text{ int}}$ “seeds” asymmetries in $\Psi/\overline{\Psi}$ and in H/H^*, which are converted to a baryon asymmetry via spectator processes.

Asymmetry generation: heuristic illustration

Akhmedov, Rubakov, Smirnov, hep-ph/9803255
Asaka, Shaposhnikov, hep-ph/0505013
Shuve, DTS, arXiv:2004.00636

$$\mathcal{L} \supset -F_1\psi(\chi_1 - i\chi_2)H - F_2\psi^c(\chi_1 + \chi_2)\tilde{H} + \text{h.c.}$$





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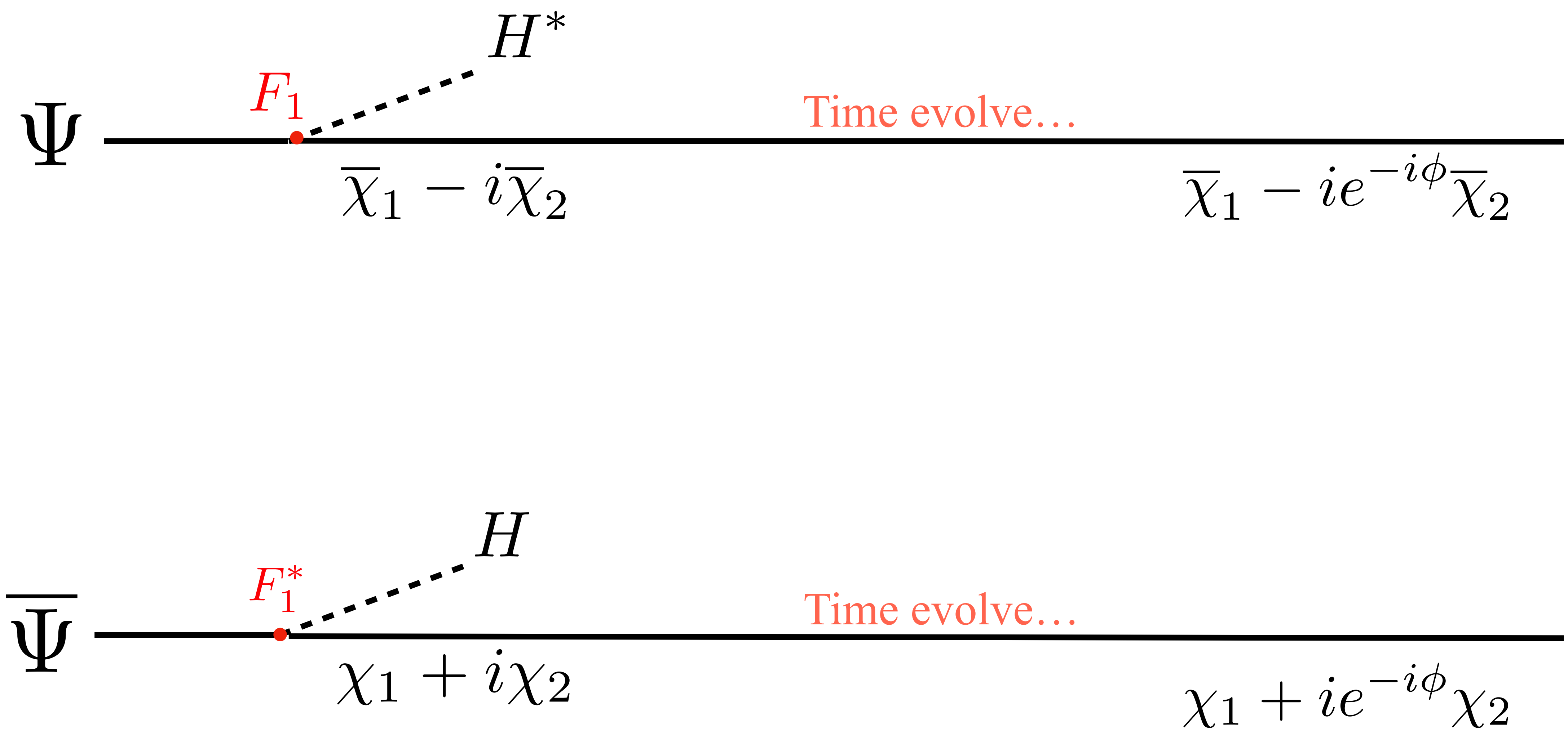

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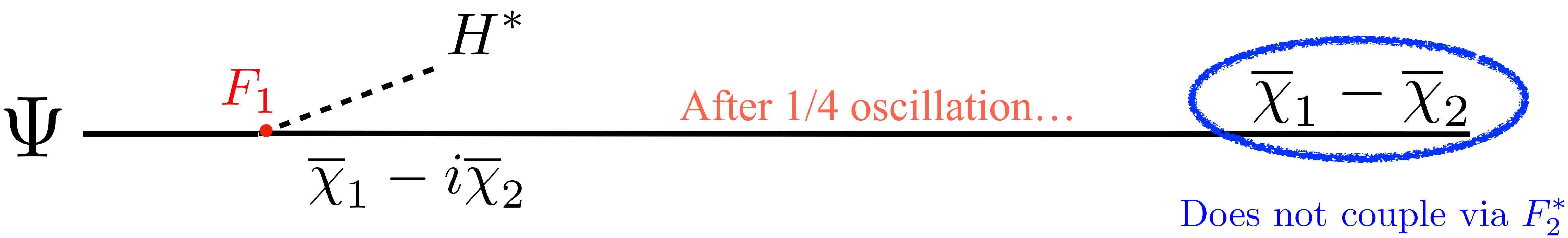
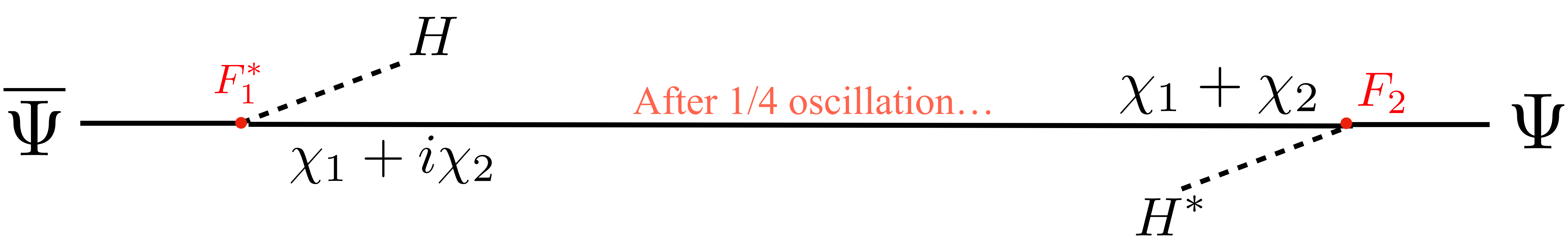




Perturbative solution of quantum kinetic equations

$$\frac{df_\chi}{dt} = -i\left[E_\chi, f_\chi\right] + \frac{1}{2}\left\{\frac{\Gamma^<}{2E_\chi}, 1 - f_\chi\right\} - \frac{1}{2}\left\{\frac{\Gamma^>}{2E_\chi}, f_\chi\right\}$$

See *e.g.* T. Hambye and D. Teresi, arXiv:1705.00016; Abada *et. al.* arXiv 1810.12463

A net asymmetry arises at $\mathcal{O}(F^4)$:

$$\beta_{\rm osc} \simeq 0.047 \times \left(\frac{\rm TeV}{M_\Psi}\right)^3 \frac{\Delta M^2}{(20\ {\rm keV})^2}$$

$$(Y_\Psi - Y_{\overline{\Psi}})|_{T{\rm ew}} = \frac{45}{32 g_* \pi^6}\left(\frac{M_0}{M_\Psi}\right)^2 {\rm Im}\left[F_{11}F^*_{12}F^*_{21}F_{22}\right]$$

$$\times \int_0^\infty \frac{dy}{y^2 f_+(y)} \int_0^{M_\Psi/T_{\rm ew}} dx_1\, x_1^2\, g_0(x_1, y) \times \int_0^{x_1} dx_2\, x_2^2\, g_0(x_2, y)\ \sin\left[\frac{\beta_{\rm osc}}{y}(x_1^3 - x_2^3)\right]$$

$y = E_\chi/T$

$x_1 = M_\Psi/T$
at inverse decay time

$x_2 = M_\Psi/T$
at decay time

For the perturbative treatment to be valid, we need

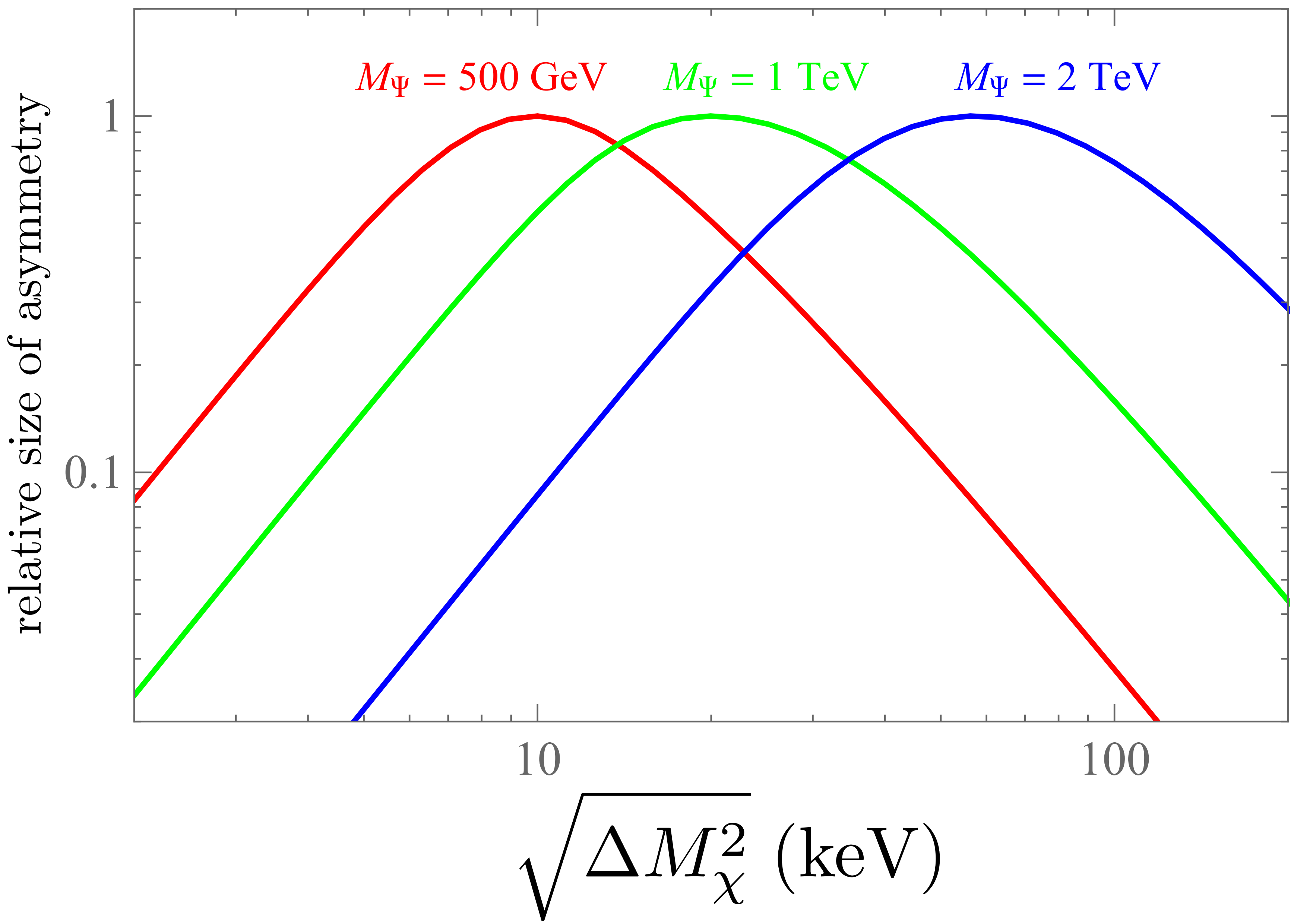
1. $\Gamma_{\Psi\to H^*\chi} \lesssim H_{\rm ew} \implies \Gamma^{-1}_{\Psi\to H^*\chi} \gtrsim 1\ {\rm cm}$

2. $\dfrac{Y_\chi}{Y_\chi^{\rm eq}} \simeq 0.23 \times \left(\dfrac{\rm TeV}{M_\Psi}\right)^2 \left(\dfrac{\Gamma_{\Psi\to H^*\chi}}{H_{\rm ew}}\right) \ll 1$

Asymmetry versus ΔM_χ^2

- Oscillation timescale is set by ΔM_χ^2. Very roughly, the asymmetry is maximized for $\sim \mathcal{O}(1)$ oscillations while $T \sim M_\Psi$.

- Together, DM and baryogenesis requirements prevent scaling the whole mechanism up to arbitrarily high mass scales.



Two scenarios for generating a baryon asymmetry

1. Z_2–preserving scenario

$$\mathcal{L}_{\psi \text{ int}} = \mathcal{L}_{\chi \text{ int}} = -F_{1i}\,\psi\chi_i H - F_{2i}\,\psi^c\chi_i\tilde{H} \;+\; \text{h.c.}$$

$$Y_B \simeq 0.03 \times (Y_\Psi - Y_{\overline{\Psi}})$$

$$\Psi^- \to \Psi^0 + \pi^-, \quad \Psi^0 \to h/Z + \chi \text{ at colliders (displaced)}$$

L. Calibbi, L. Lopez-Honorez, S. Lowette, A. Mariotti, arXiv:1805.04423

2. Z_2–violating scenario

$$\mathcal{L}_{\psi \text{ int}} = \mathcal{L}_{\chi \text{ int}} - \left(\lambda_\alpha \psi e^c_\alpha \tilde{H} + \text{h.c.}\right)$$

$$Y_B \simeq 0.3 \times (Y_\Psi - Y_{\overline{\Psi}})$$

$$\Psi^- \to l^- + Z/h, \quad \Psi^0 \to l^- + W^+ \quad \text{(potentially prompt; } \Psi = \text{VLL)}$$

Potential x-ray signals from DM decay

Z_2-preserving scenario: spectator effects

$$\mathcal{L}_{\rm int} = -F_{1i}\,\psi\chi_i H - F_{2i}\,\psi^c\chi_i\tilde{H} \; + \; \text{h.c.}$$

The baryon asymmetry is frozen in at sphaleron decoupling, $T_{\rm sph} \simeq 130\ \text{GeV}$. With sphalerons in equilibrium:

M. D'Onofrio, K. Rummukainen, A. Tranberg, arXiv:1404.3565

Unbroken phase relations $(T \ll v(T))$**:** ~ 4% conversion of $\Psi/\overline{\Psi}$ asymmetry to baryon asymmetry:

$$Y_B = \frac{28}{79}\cancelto{0}{Y_{B-L}} - \frac{6}{79}(Y_y)_{\rm sm} \simeq -\frac{3}{79}\left(Y_\Psi - Y_{\overline{\Psi}}\right)$$

J.A. Harvey, M.S. Turner (1990)

Broken phase relations $(T \ll v(T))$**:** conversion of $\Psi/\overline{\Psi}$ asymmetry to baryon asymmetry is a factor of ~3 smaller:

$$Y_B = \frac{12}{37}\cancelto{0}{Y_{B-L}} - \frac{1}{37}(Y_Q)_{\rm sm} \simeq -\frac{1}{74}\left(Y_\Psi - Y_{\overline{\Psi}}\right)$$

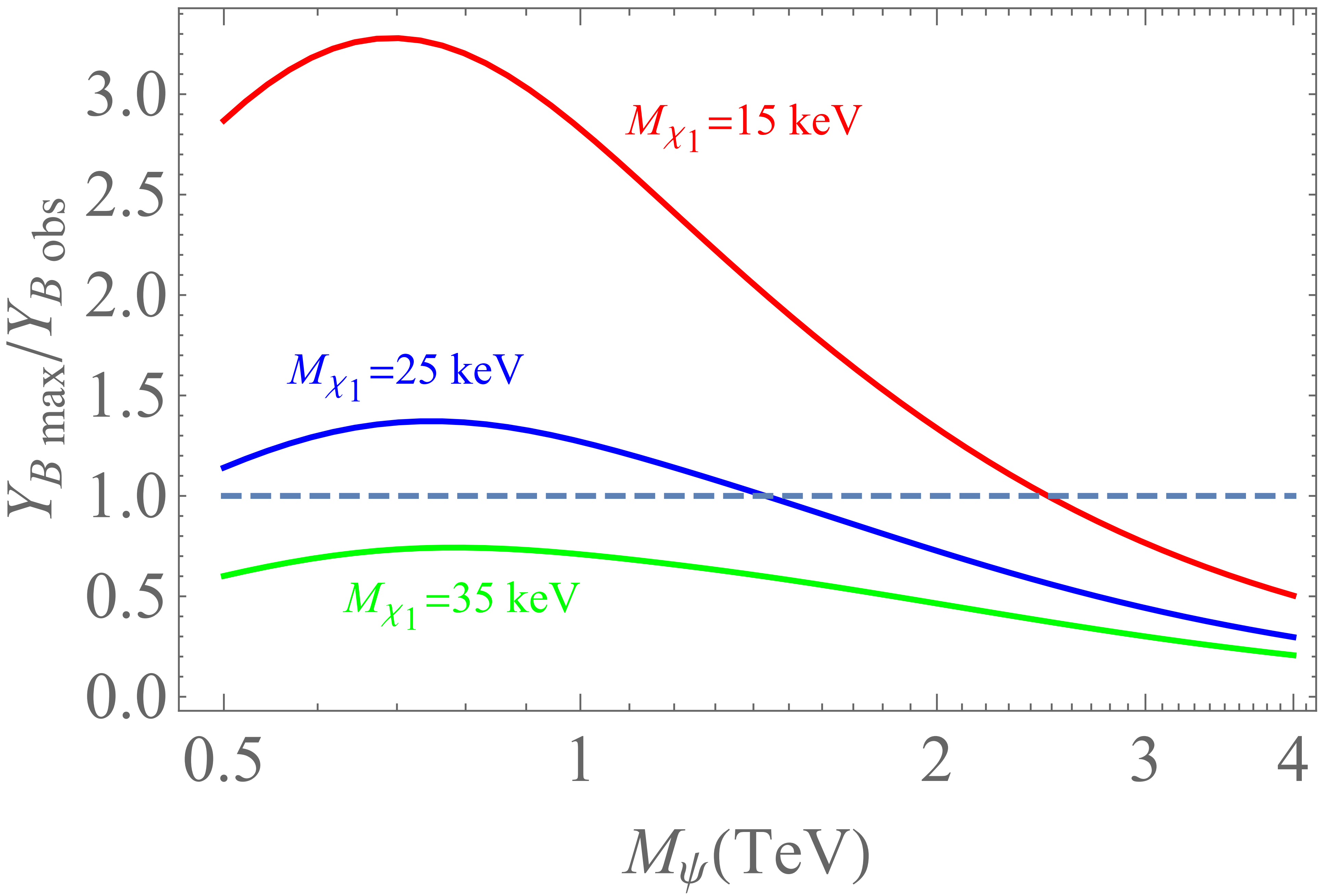
General case (take into account that Higgs vev is turning on as sphalerons decouple)

S. Yu. Khlebnikov, M. E. Shaposhnikov, hep-ph/9607386

$$Y_B = -\frac{66 + 9v^2(T)/T^2}{1738 + 666v^2(T)/T^2}\left(Y_\Psi - Y_{\overline{\Psi}}\right) \simeq -0.29\left(Y_\Psi - Y_{\overline{\Psi}}\right) \text{ at sphaleron decoupling}$$

Non-instantaneous sphaleron decoupling can be taken into account using the prescription of S. Eijima, M. Shaposhnikov, I. Timiryasov, arXiv:1709.07834.

Results for the Z_2-preserving scenario



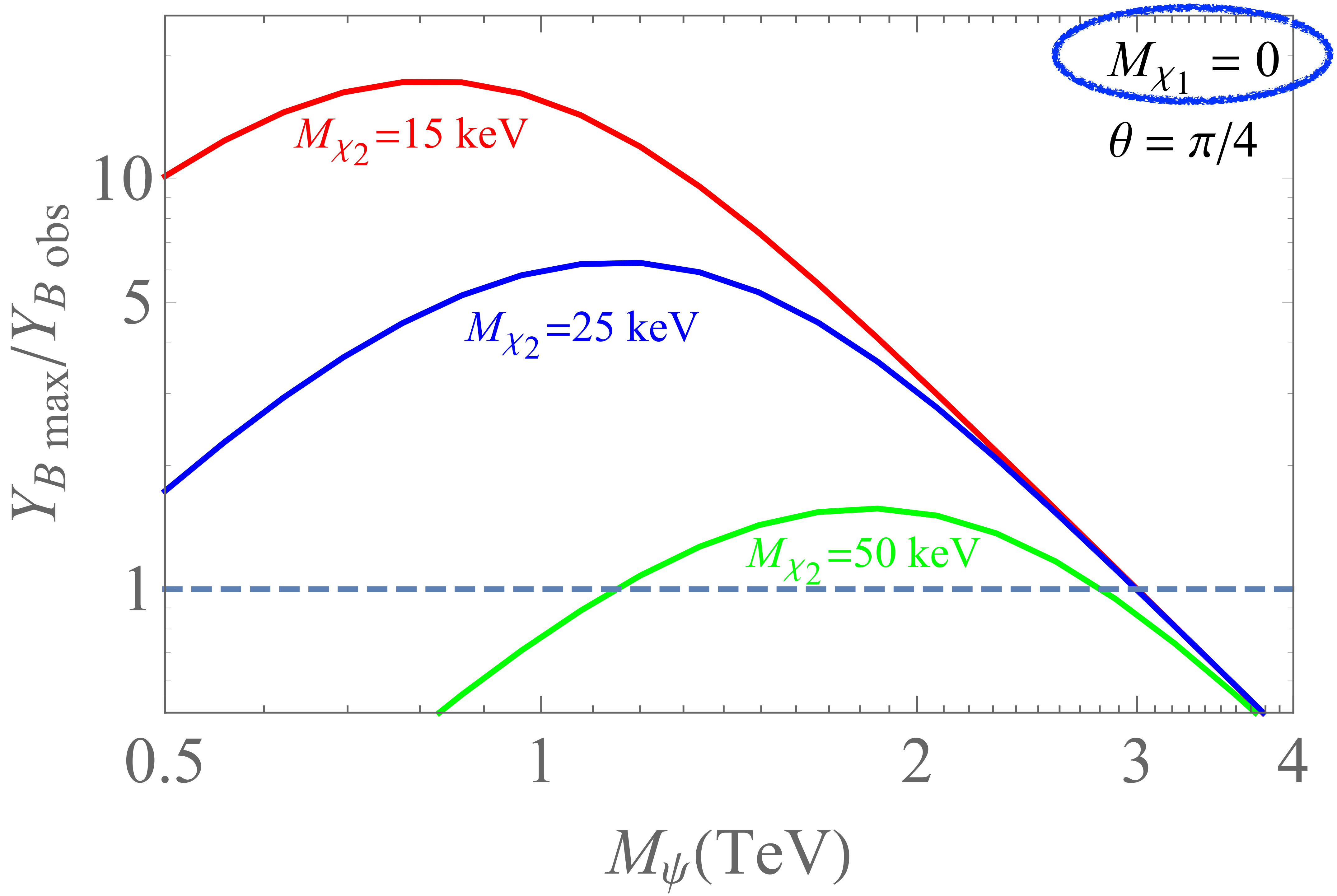
Structure formation constraints require $M_\chi \gtrsim 10 - 25$ keV.

See e.g. Palanque-Delabrouille et al., JCAP (2016); Kamada and Yanagi JCAP (2019); Ballesteros, Garcia, and Pierre, JCAP (2021), Villasenor et al., PRD (2023), Nadler et al., ApJ (2021); Zelko et al., PRL (2022), Dekker et al., PRD (2022), Keeley et al., arXiv:2405.01620.

Results for the Z_2-preserving scenario

For $M_\chi \lesssim 2$ eV, cosmological constraints on LiMRs are evaded.

Xu, Munoz, and Dvorkin, PRD (2022)



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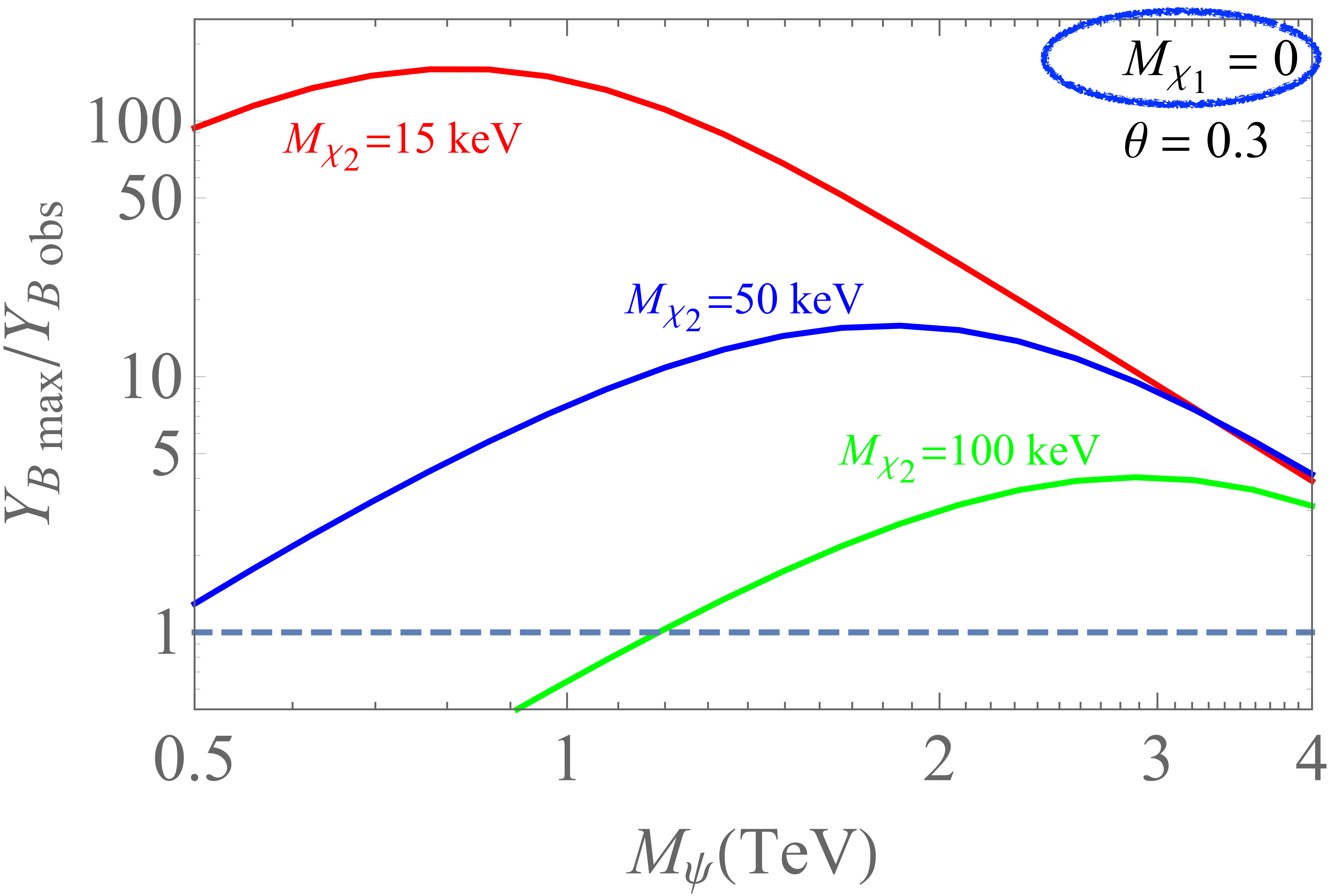

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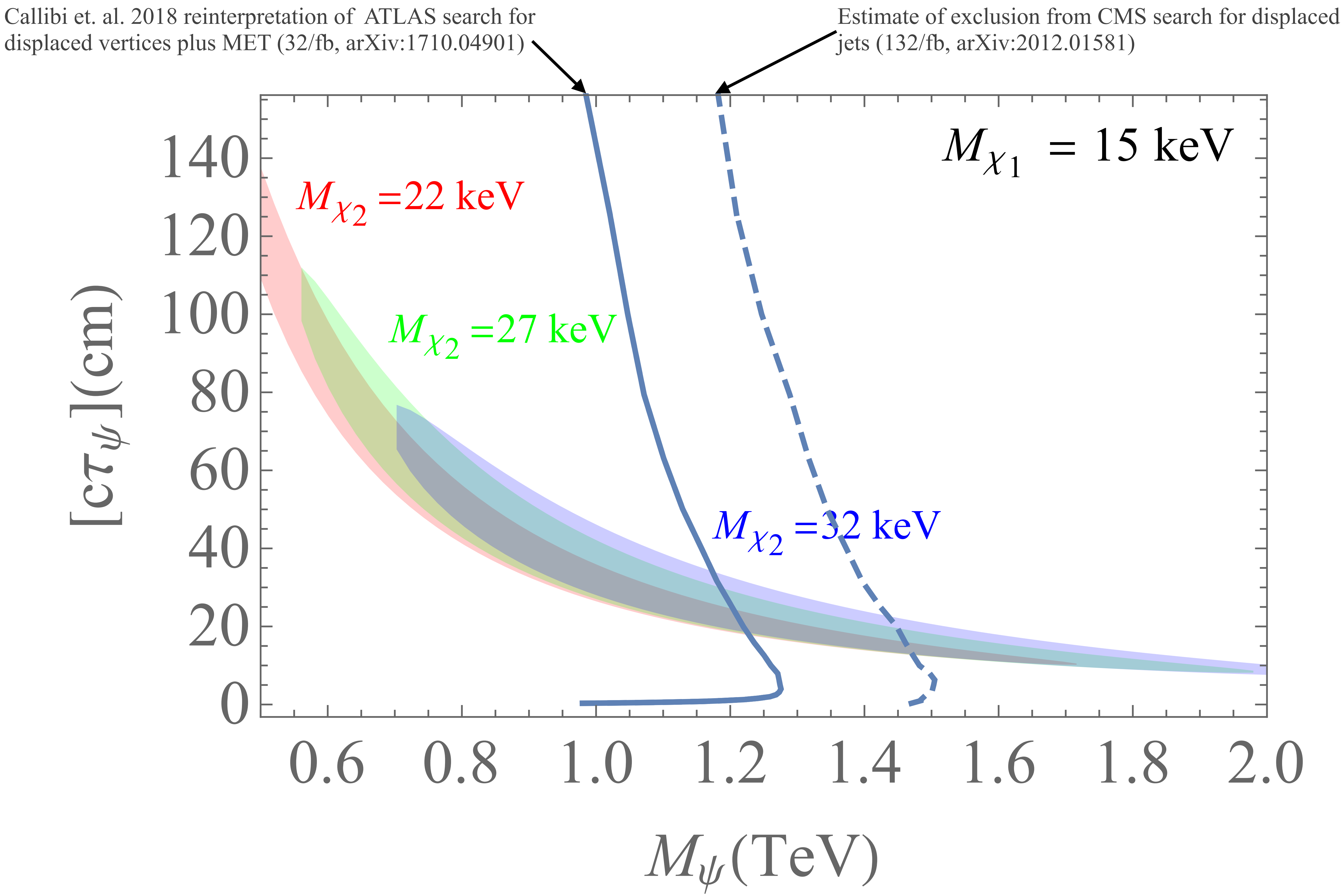

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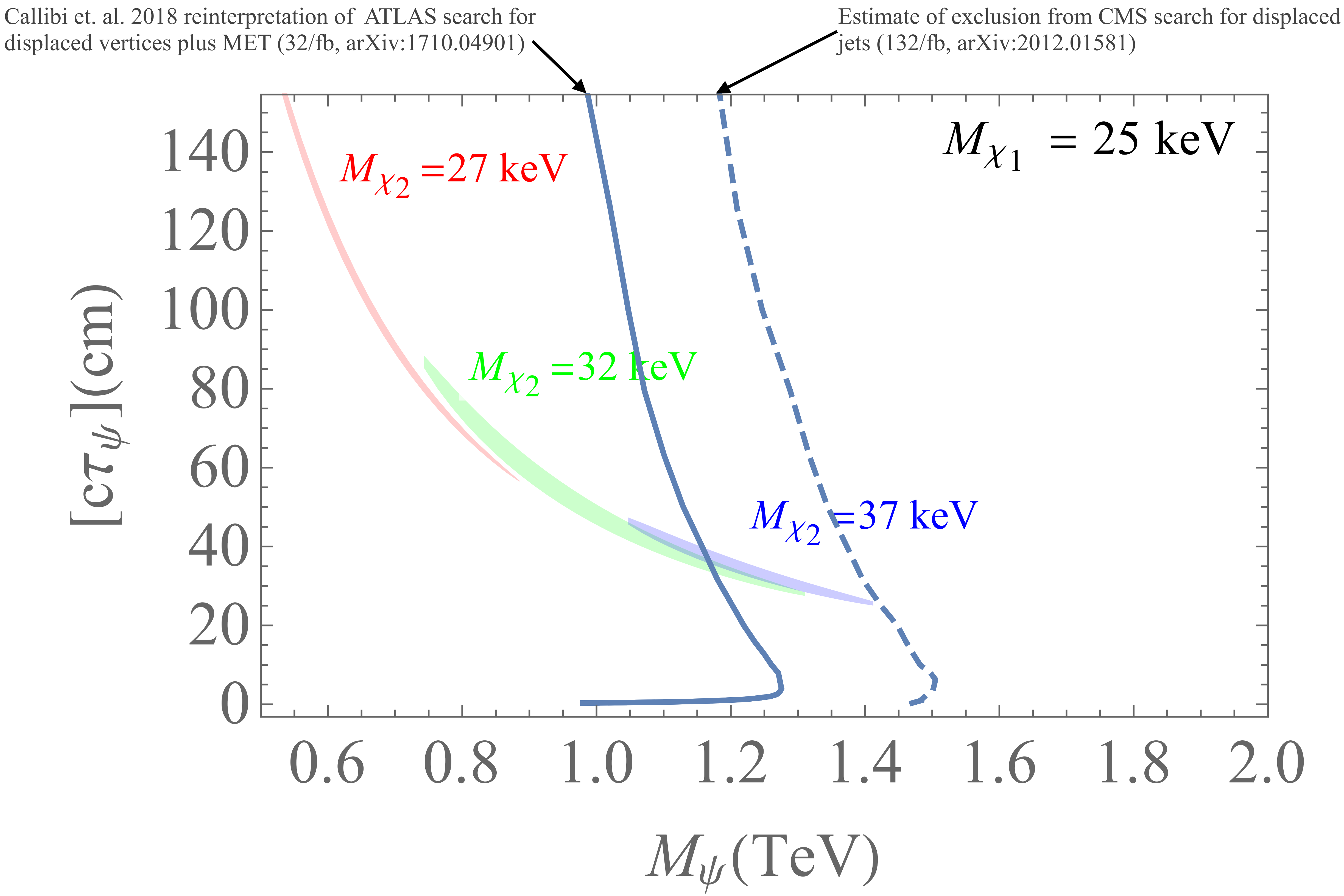


Z_2-violating scenario: spectator effects and DM decay

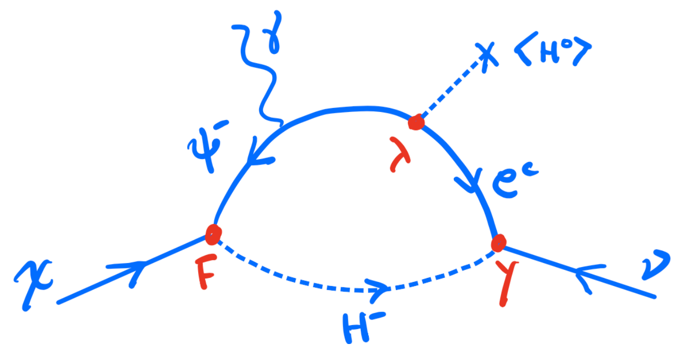
$$\mathcal{L}_{\rm int} = -F_{1i}\,\psi\chi_i H - F_{2i}\,\psi^c\chi_i\tilde{H} - \lambda_\alpha\,\psi e^c_\alpha\tilde{H} \ + \ \text{h.c.}$$

Z_2-violating interactions to come into equilibrium for $\lambda \gtrsim 5\times 10^{-8}\left(\frac{\text{TeV}}{M_\Psi}\right)^{1/2}$

QKEs are modified and asymmetry is enhanced:

$$(Y_\Psi - Y_{\overline{\Psi}}) \to -Y_{B-L} \qquad\qquad Y_B \sim -\frac{28}{79}\times(\text{asymmetry calculated by QKEs})$$

Constraints from NuSTAR and INTEGRAL X-ray observations can be as strong as $\lambda_\tau \lesssim 10^{-4}$

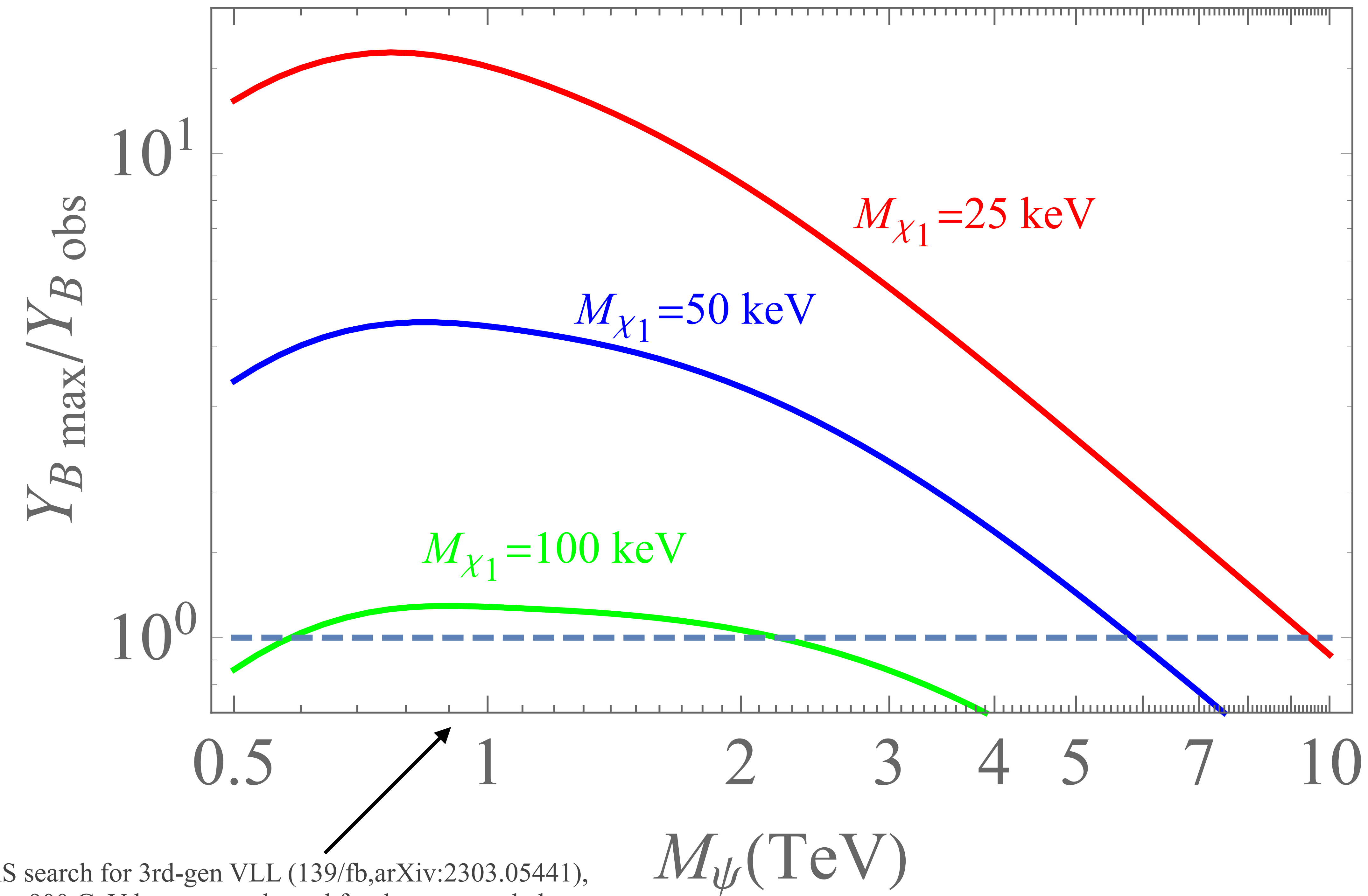


Perez *et al.*, PRD (2017); Neronov, Malyshev, and Eckert, PRD (2016); Ng *et al.*, PRD (2019); Roach *et al.*, PRD (2020); Laha, Muñoz, and Slatyer, PRD (2020).

At colliders: $\Psi^- \to l^- + Z/h,\ \ \Psi^0 \to l^- + W^+$

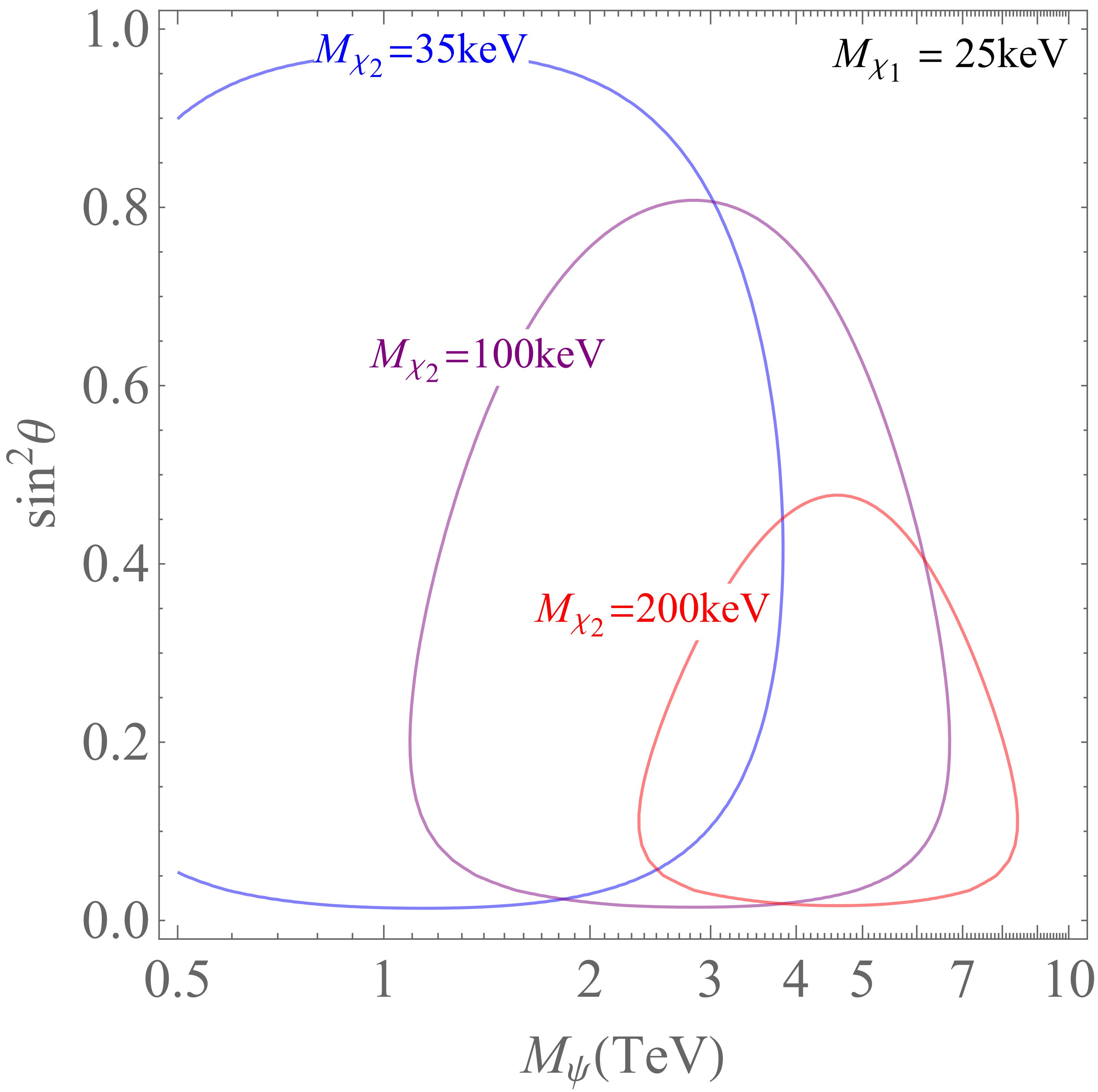
$$\frac{c\tau}{\text{cm}} \simeq \left(\frac{4.5\times 10^{-8}}{\lambda}\right)^2\left(\frac{M_\Psi}{\text{TeV}}\right)$$

Results for the Z_2-violating scenario



ATLAS search for 3rd-gen VLL (139/fb,arXiv:2303.05441), imposes 900 GeV lower mass bound for the tau-coupled case.

Results for the Z_2-violating scenario



Summary

- Models of freeze-in DM can easily be extended to incorporate baryogenesis.
- Higgs-coupled models with a BSM vector-like fermion doublet tend to have an enhanced asymmetry relative to other freeze-in baryogenesis scenarios.
- Potential for collider signals, observable impact on cosmological structure formation, and X-ray lines from DM decay.