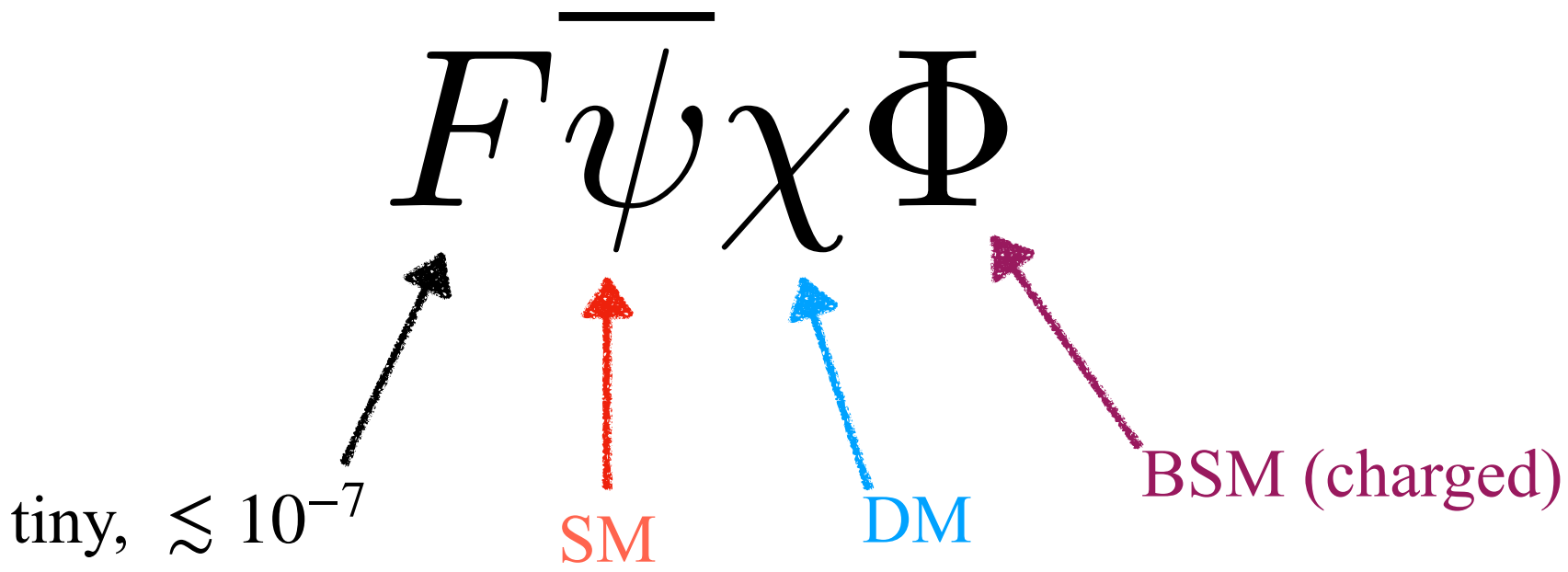
Freeze-in baryogenesis via dark-matter oscillations

Dave Tucker-Smith
Williams College

Berman, Shuve, DTS, arXiv:2201.11502, PRD (2022)
Shuve, DTS, arXiv:2004.00636, PRD (2020)

An interaction for freeze-in DM and baryogenesis



An interaction for freeze-in DM and baryogenesis

$$F\overline{\psi}\chi\Phi$$

tiny, $\lesssim 10^{-7}$

SM

DM

BSM (charged)

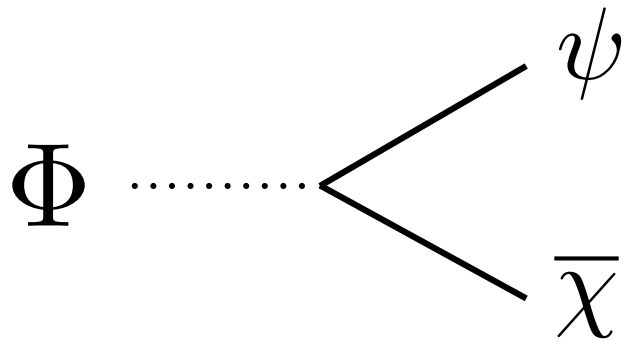
Main focus of this talk ⟶

2201.11502: $\psi = e_R$ (electroweak-charged Φ)

2004.00636: $\psi = u_R$ (QCD-charged Φ)

Basic mechanism

DM production



McDonald, hep-ph/0106249
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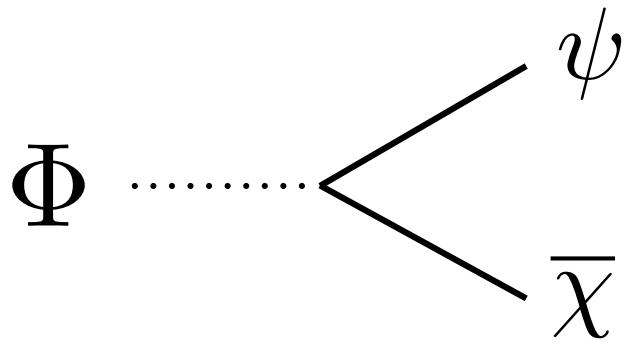

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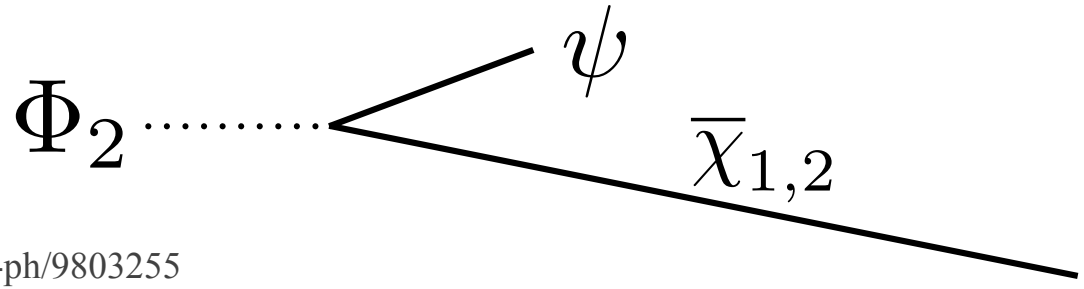
Asymmetry generation



Akhmedov, Rubakov, Smirnov, hep-ph/9803255
Asaka, Shaposhnikov, hep-ph/0505013
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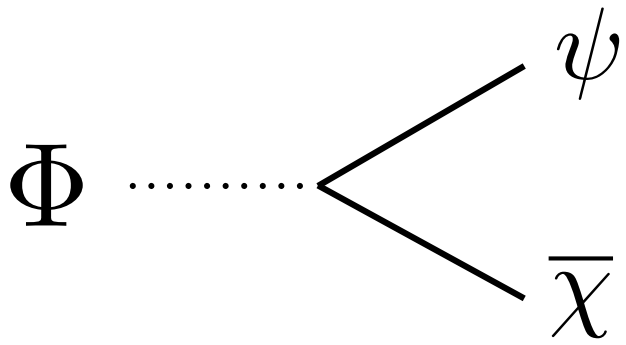

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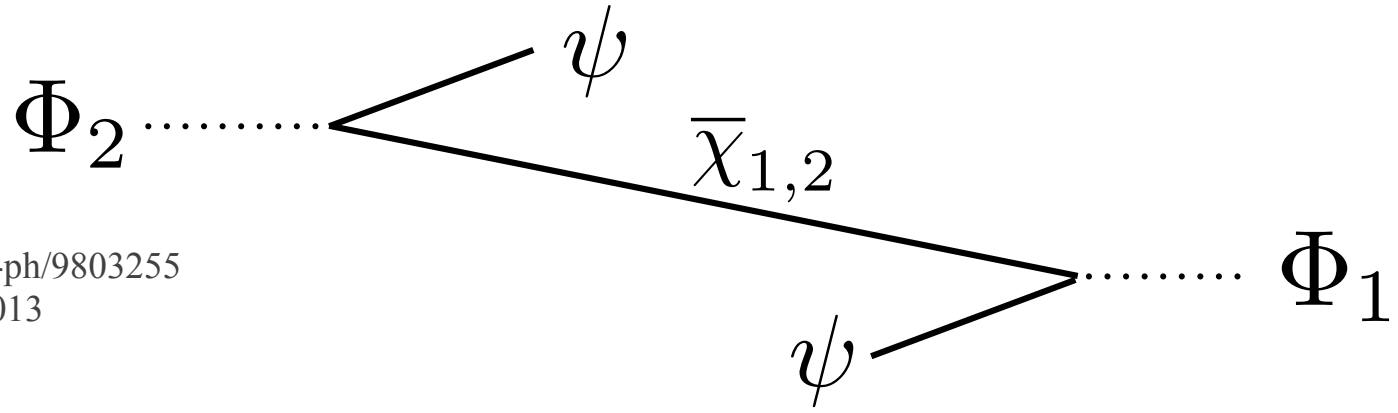

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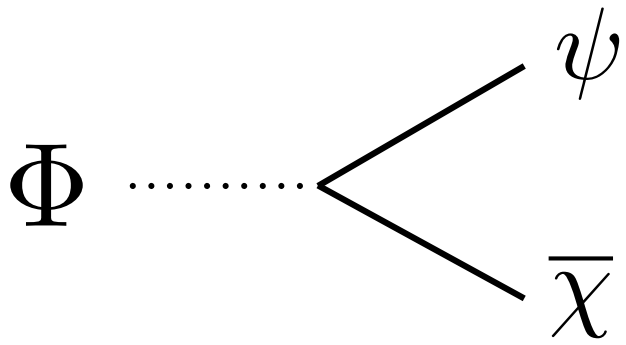

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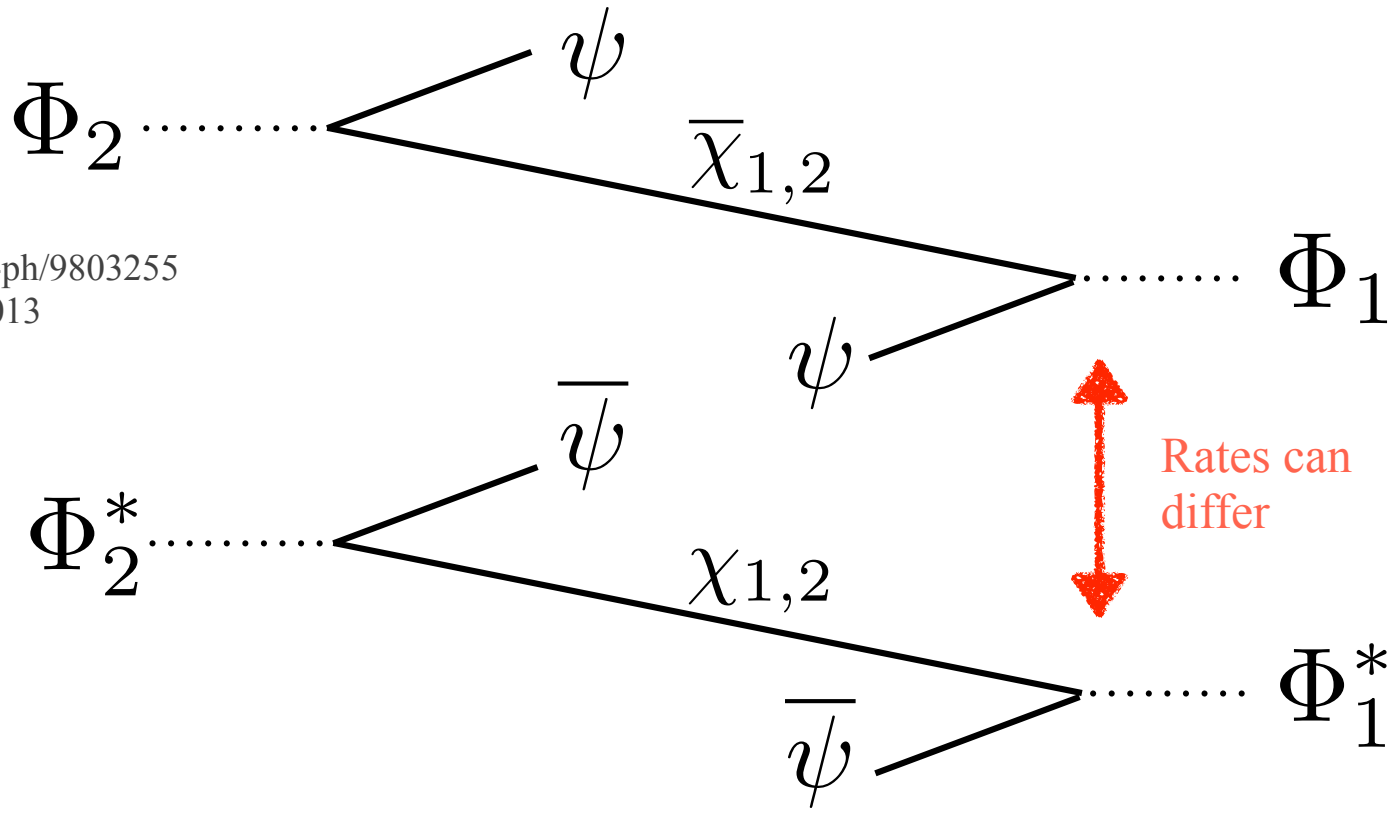

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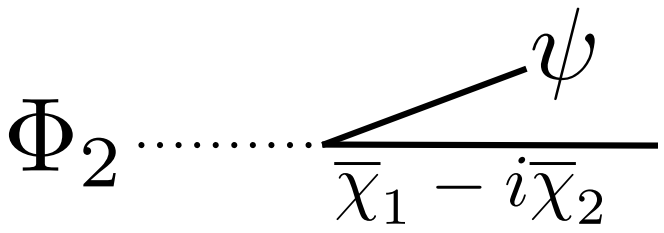
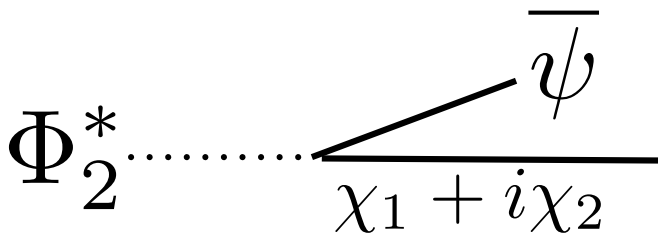
Toy example

$$\mathcal{L} \supset -\lambda_1 \overline{\psi}(\chi_1 + \chi_2)\Phi_1 - \lambda_2 \overline{\psi}(\chi_1 + i\chi_2)\Phi_2 + \text{h.c.}$$





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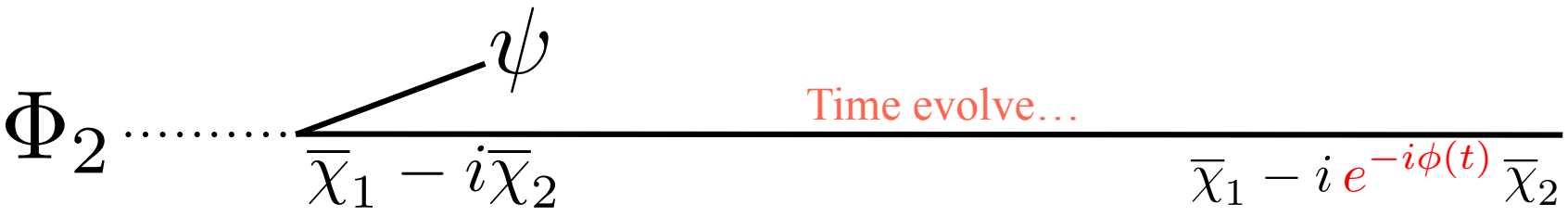

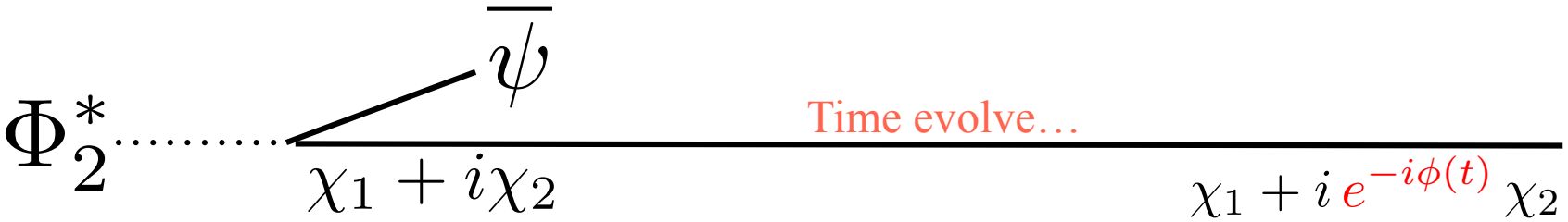

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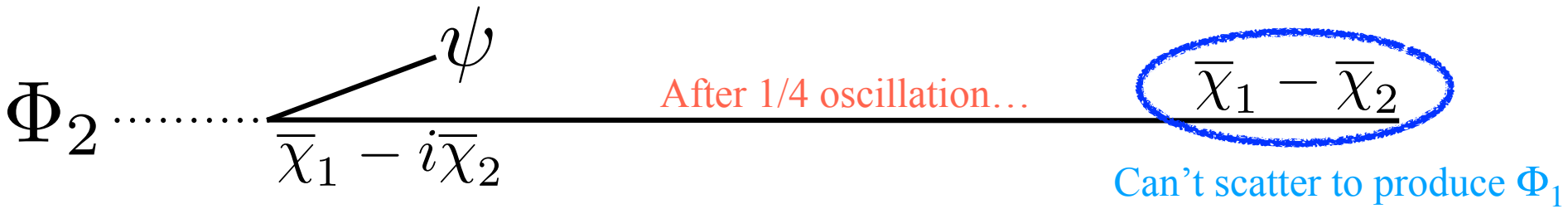
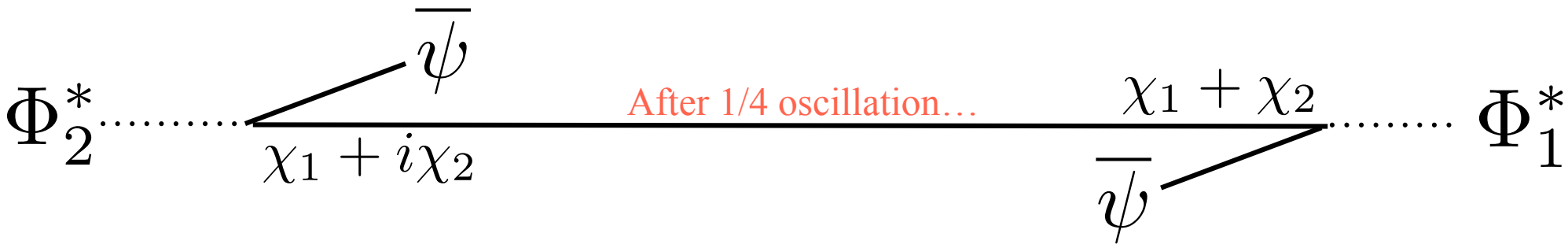
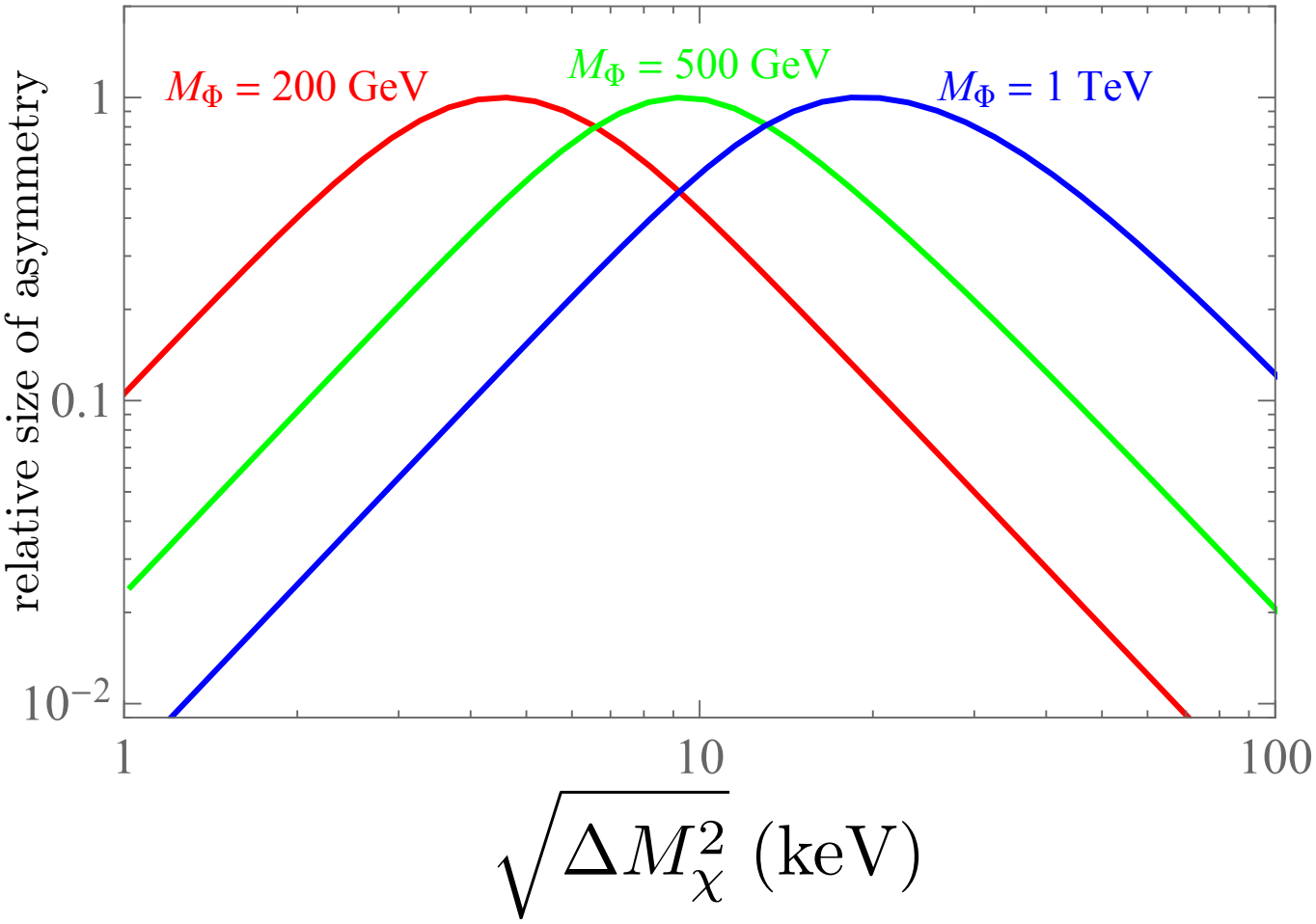




Asymmetry versus ΔM_χ^2

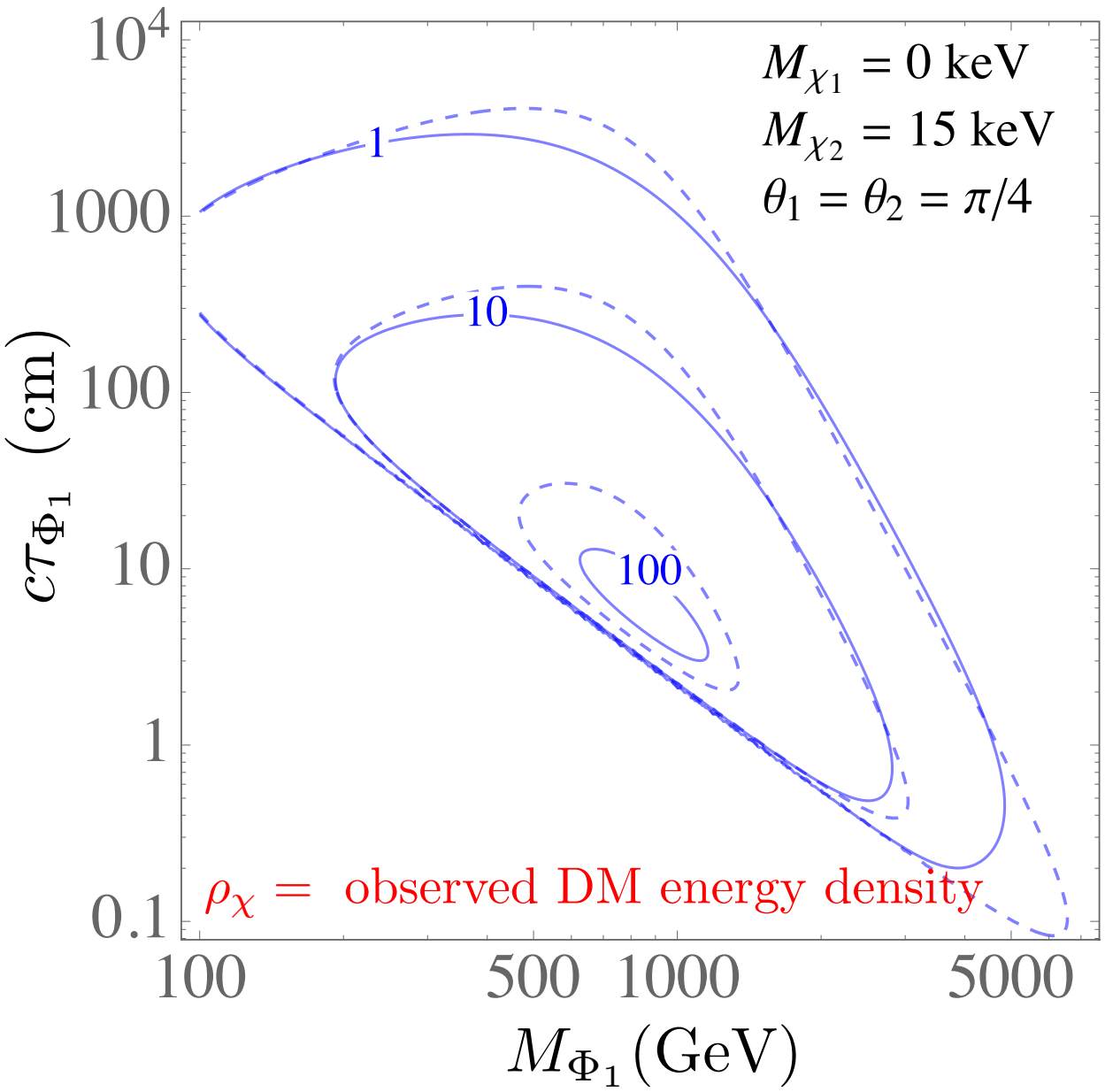
- Oscillation timescale is set by ΔM_χ^2. The asymmetry is maximized for $\sim \mathcal{O}(1)$ oscillations by $T \sim M_{\Phi_1}$.
- Together, DM and baryogenesis requirements prevent scaling the whole mechanism up to arbitrarily high mass scales.



Fine print: the figure shows the leading-order asymmetry in individual lepton flavors (rescaled to peak at 1) in a model with a single BSM scalar.

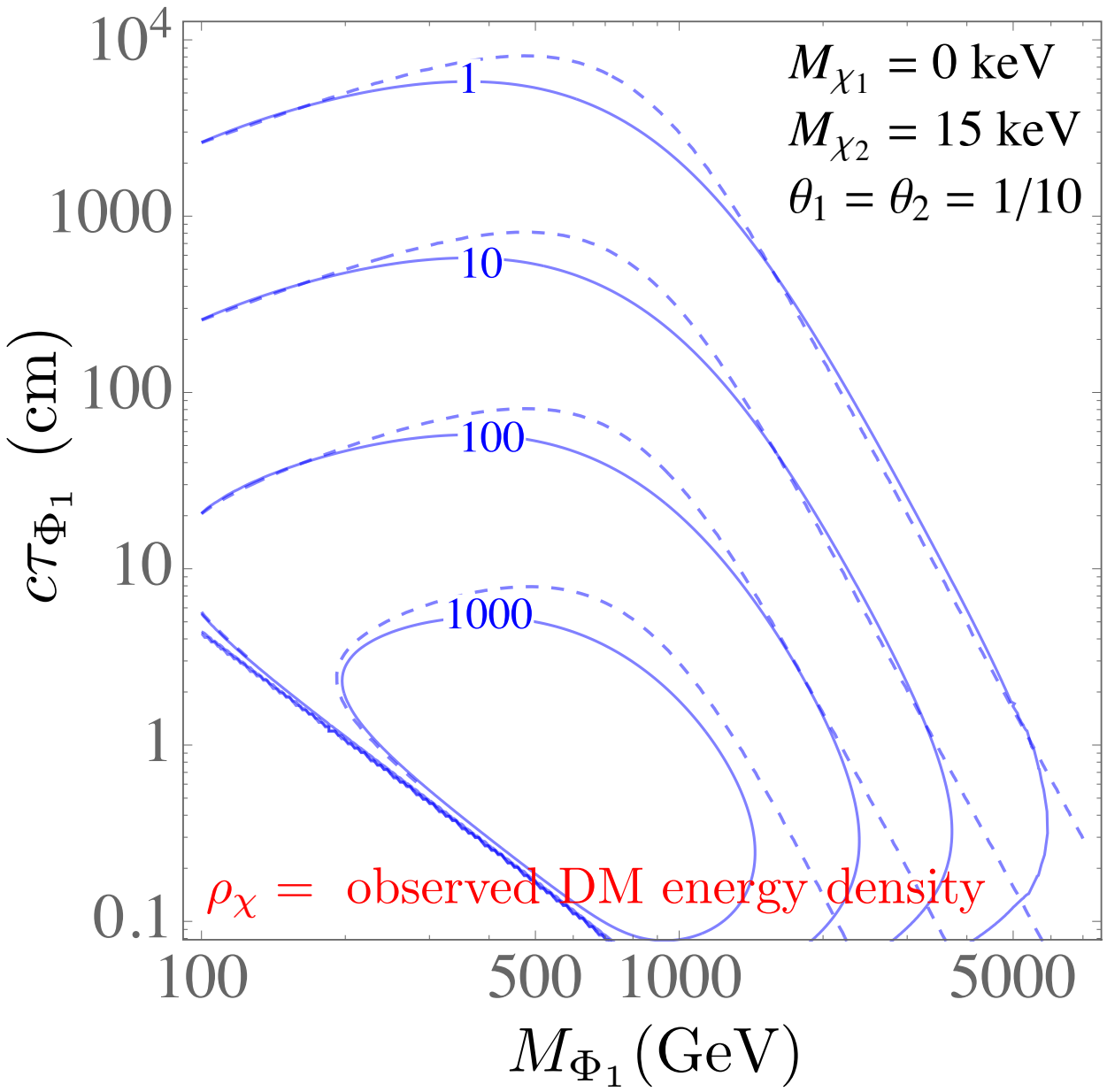
Results for leptogenesis and DM

- We impose $M_{\chi_2} \geq 15$ keV to satisfy structure formation constraints (but see Zelko *et al.*, arXiv:2205.09777)
- $M_{\Phi_2} \gg M_{\Phi_1}$
- Blue contours show the maximum possible baryon asymmetry in units of the observed value.



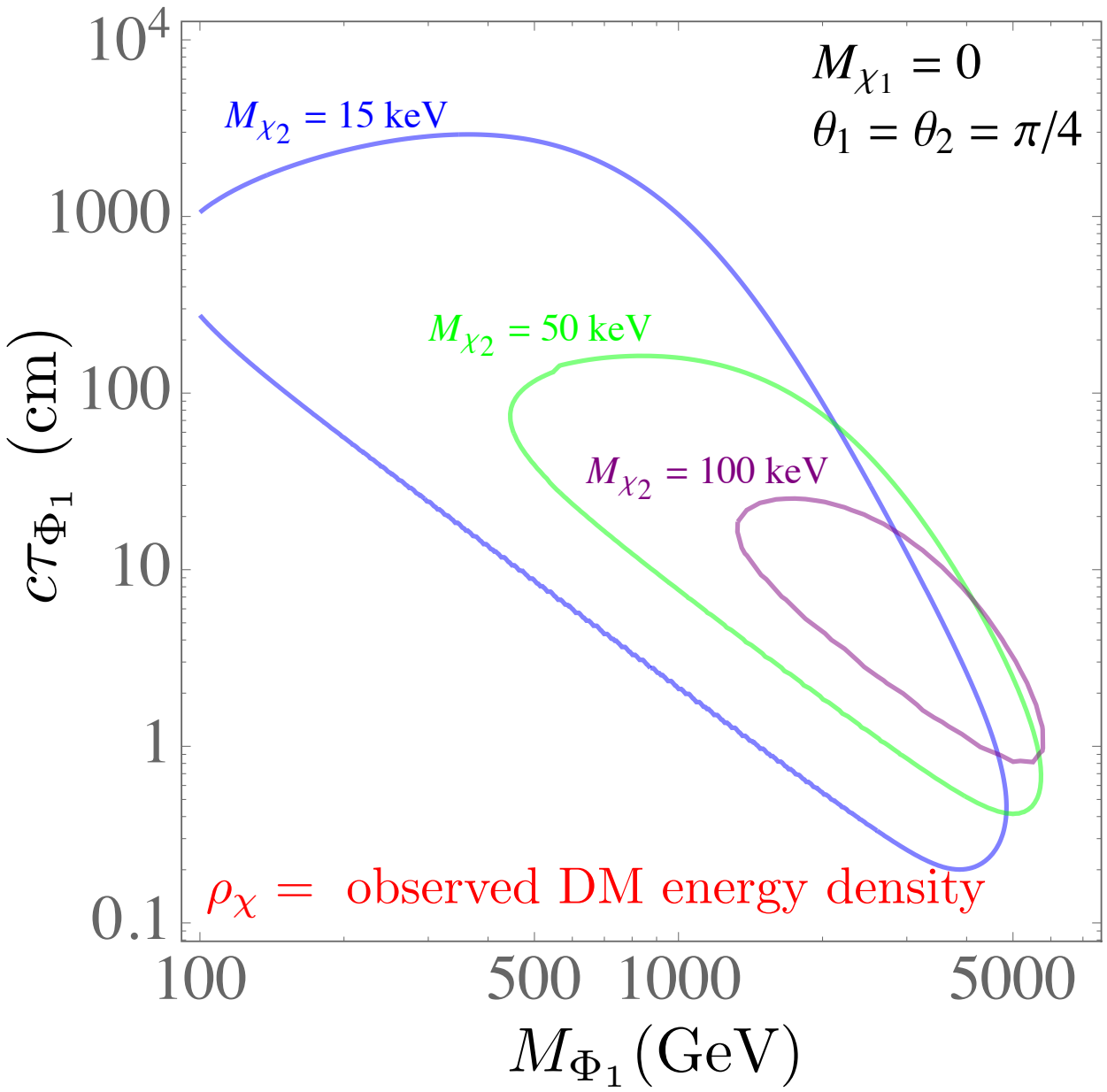
Results for leptogenesis and DM

- The asymmetry can be enhanced if the Φ particles decay predominantly to the lighter DM state.



Results for leptogenesis and DM

- The observed baryon asymmetry can be realized within the contours.
- DM masses above 100 keV are viable.



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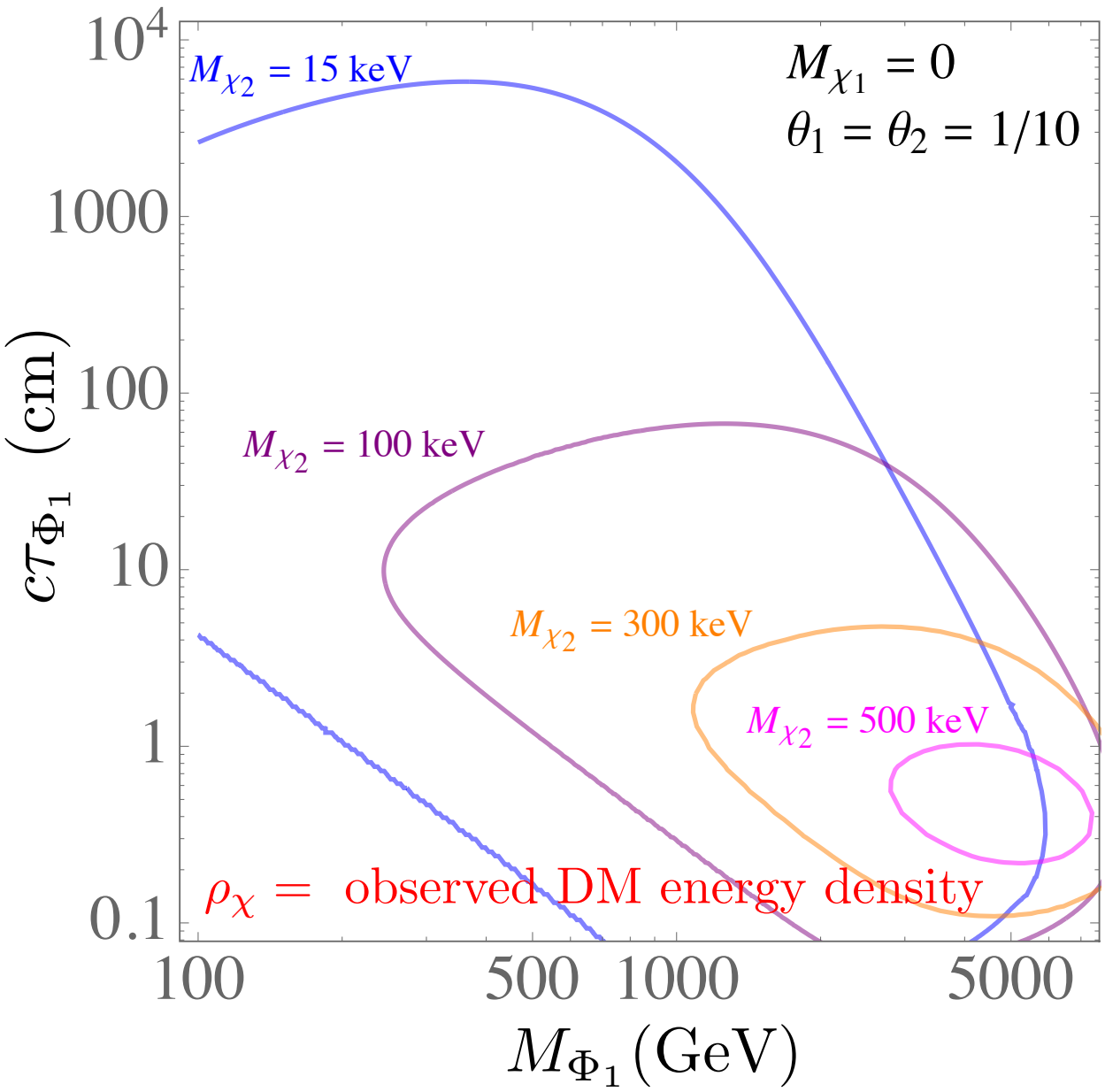
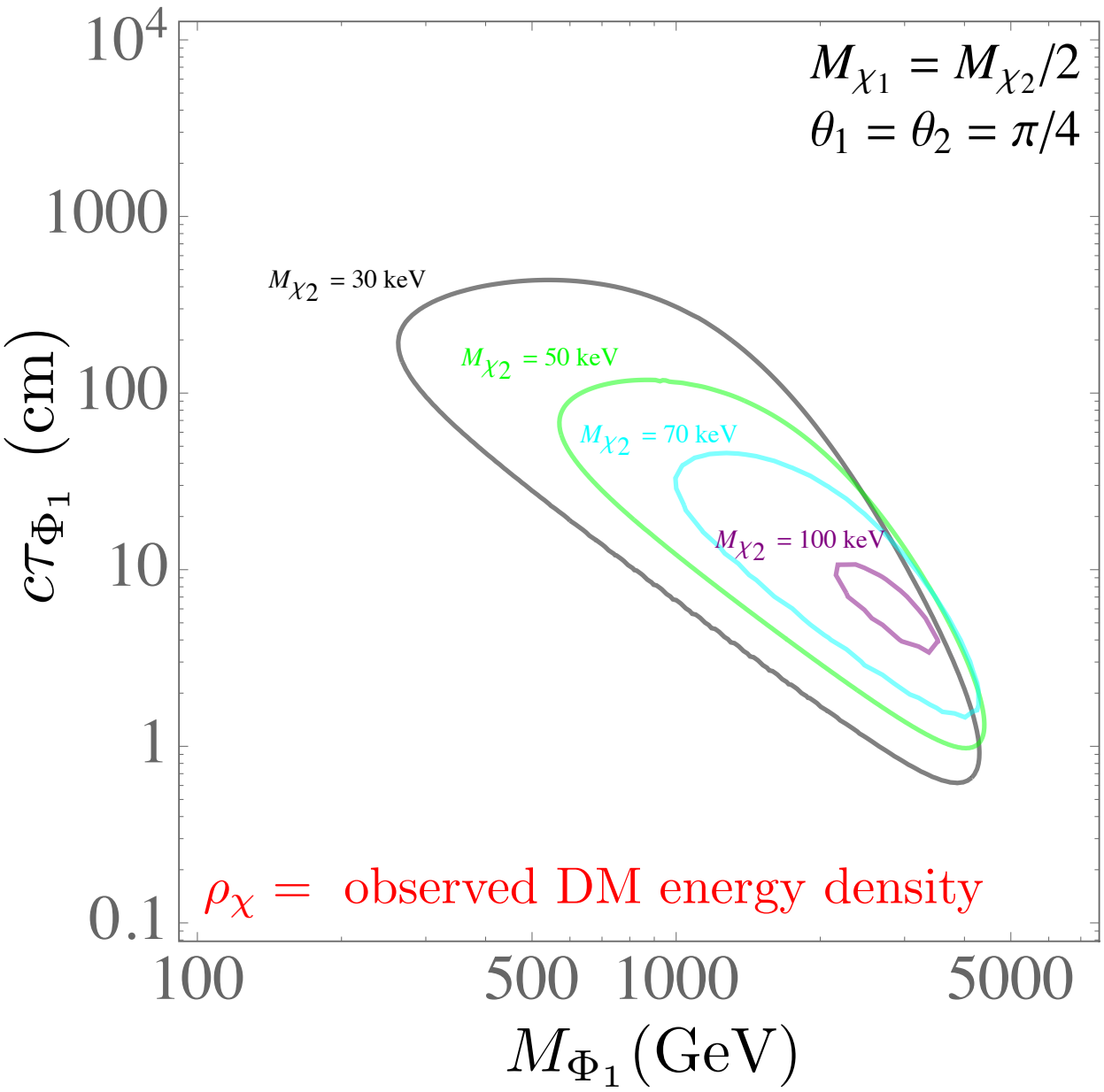


Results for leptogenesis and DM

- Both χ masses can be (well) above 15 keV.



Models

- *UVDM*: DM production at $T \sim M_{\Phi_2}$ followed by asymmetry generation at $T \sim M_{\Phi_1}$. Largest viable parameter space.

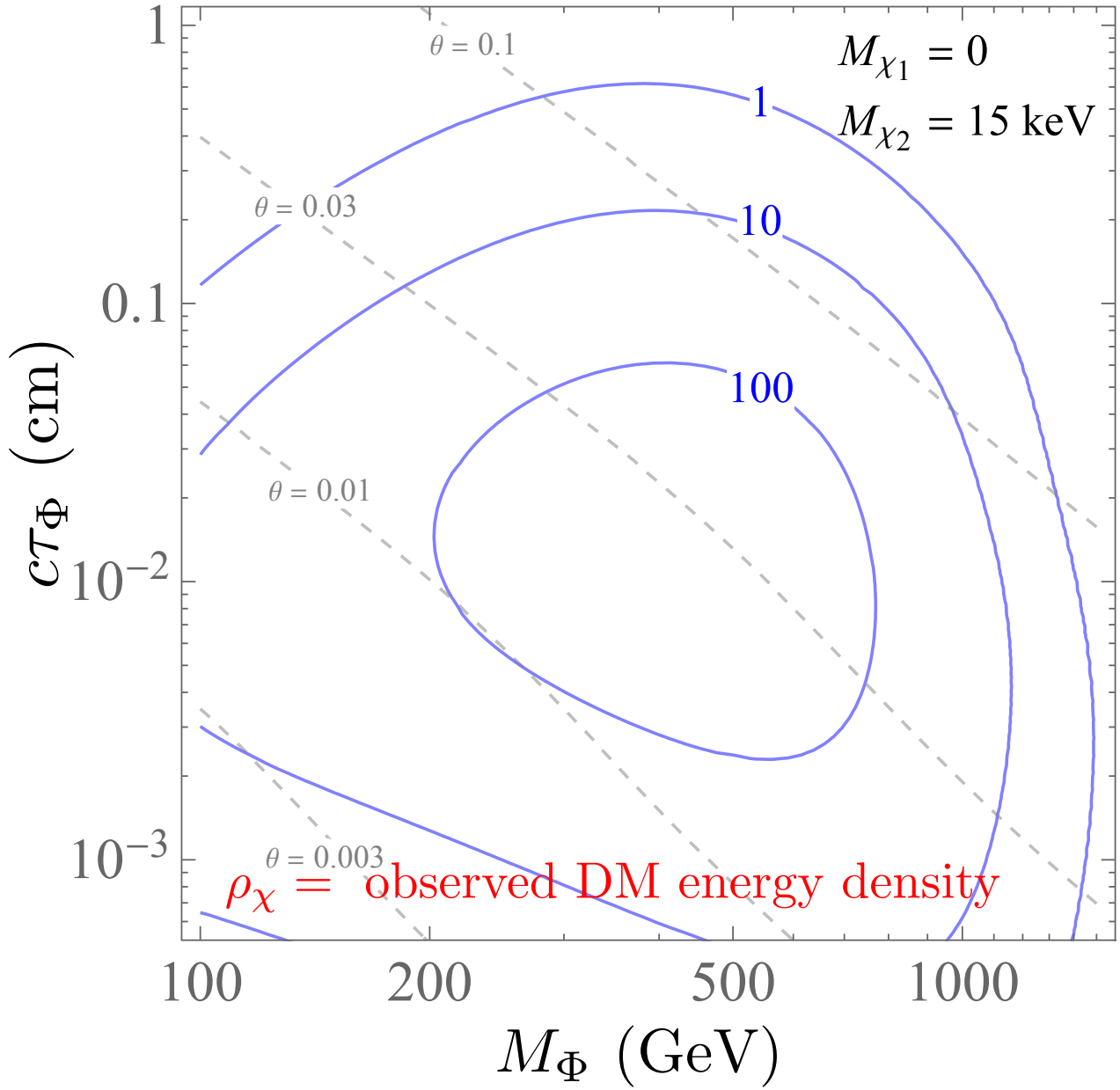
- *Minimal*: single scalar. Fewest model inputs, most constrained. A baryon asymmetry arises at higher-order in *F* compared to UVDM (via standard ARS mechanism).

- *Z2V*: single scalar with additional Φ interactions. Enhanced asymmetry, potential X-ray-line signals from DM decay.

$$\mathcal{L} \supset -\frac{\lambda_{\alpha\beta}}{2} l_\alpha l_\beta \Phi^* + \text{h.c.}$$

Minimal-Model results for leptogenesis and DM

- The viable parameter space has small θ (more production of χ_1 than χ_2) and shorter Φ lifetimes.



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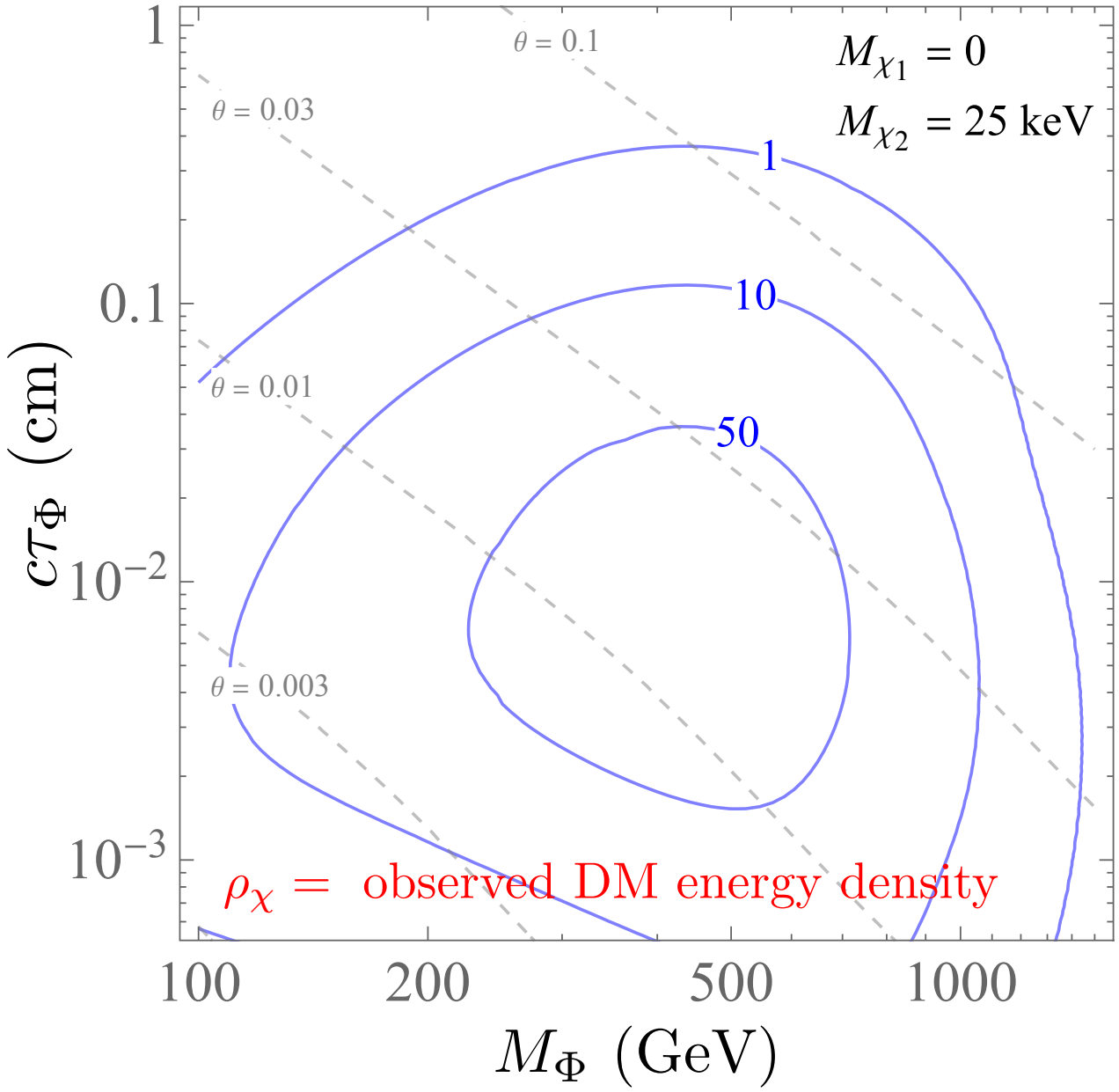

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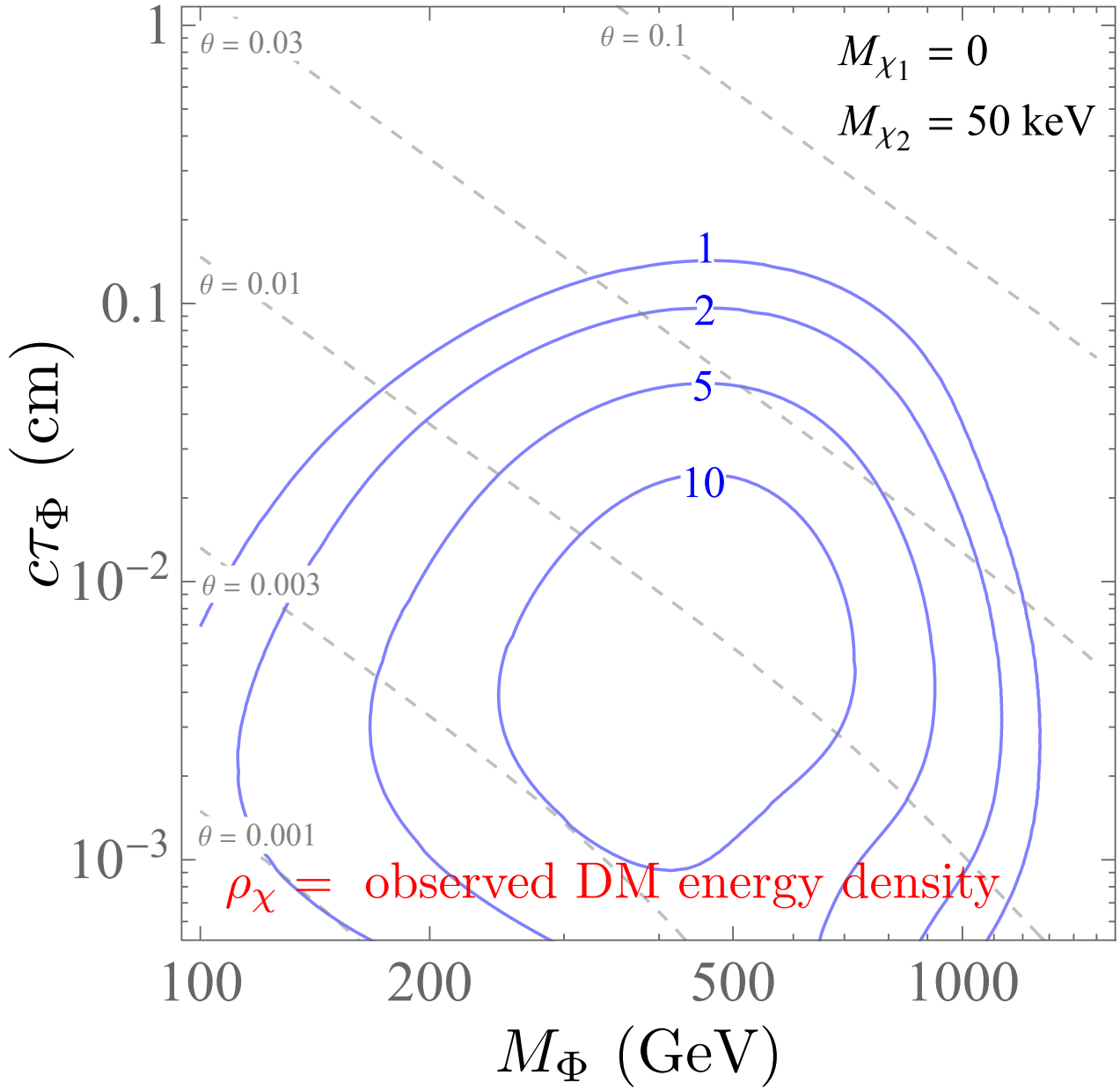

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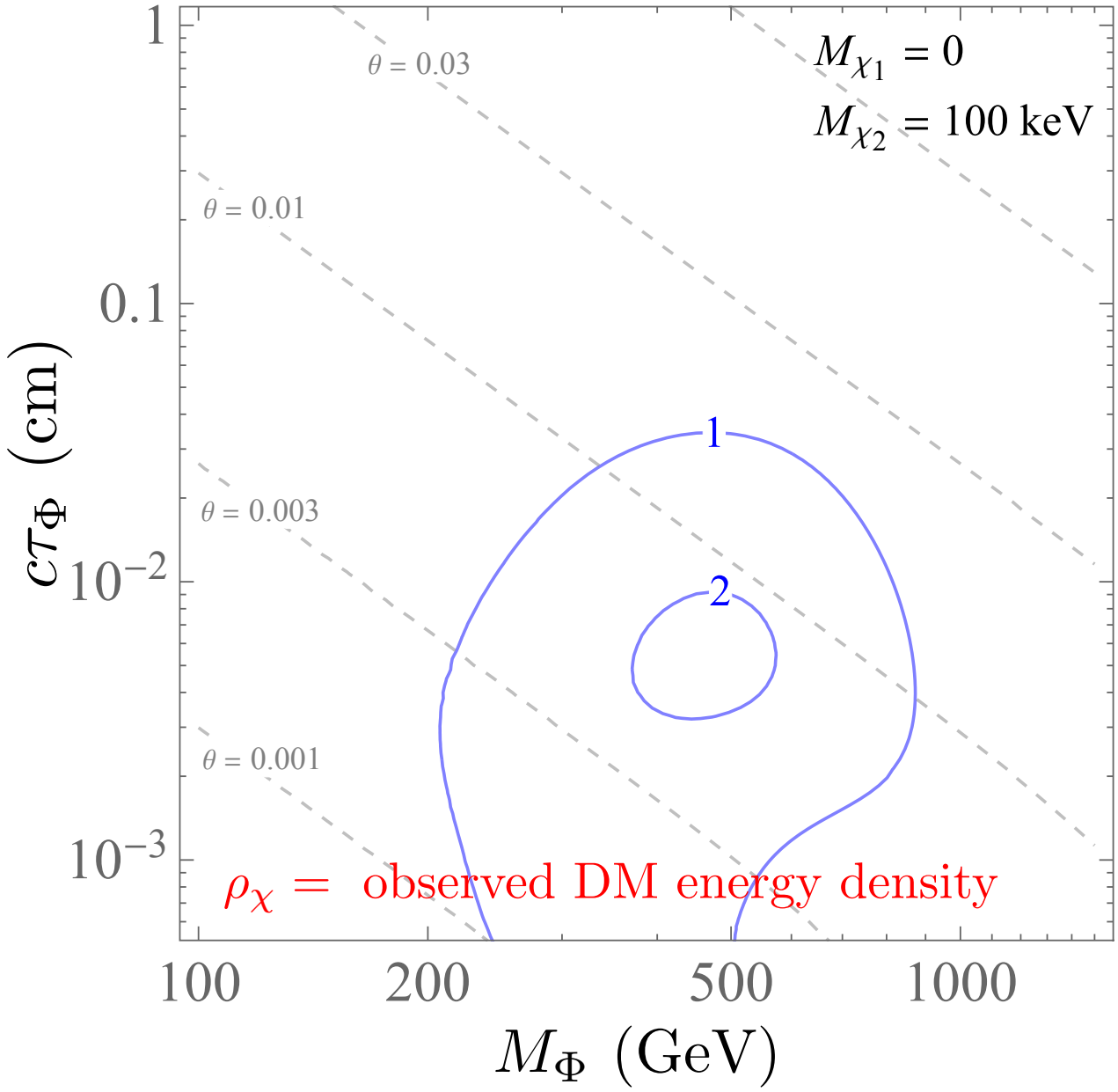
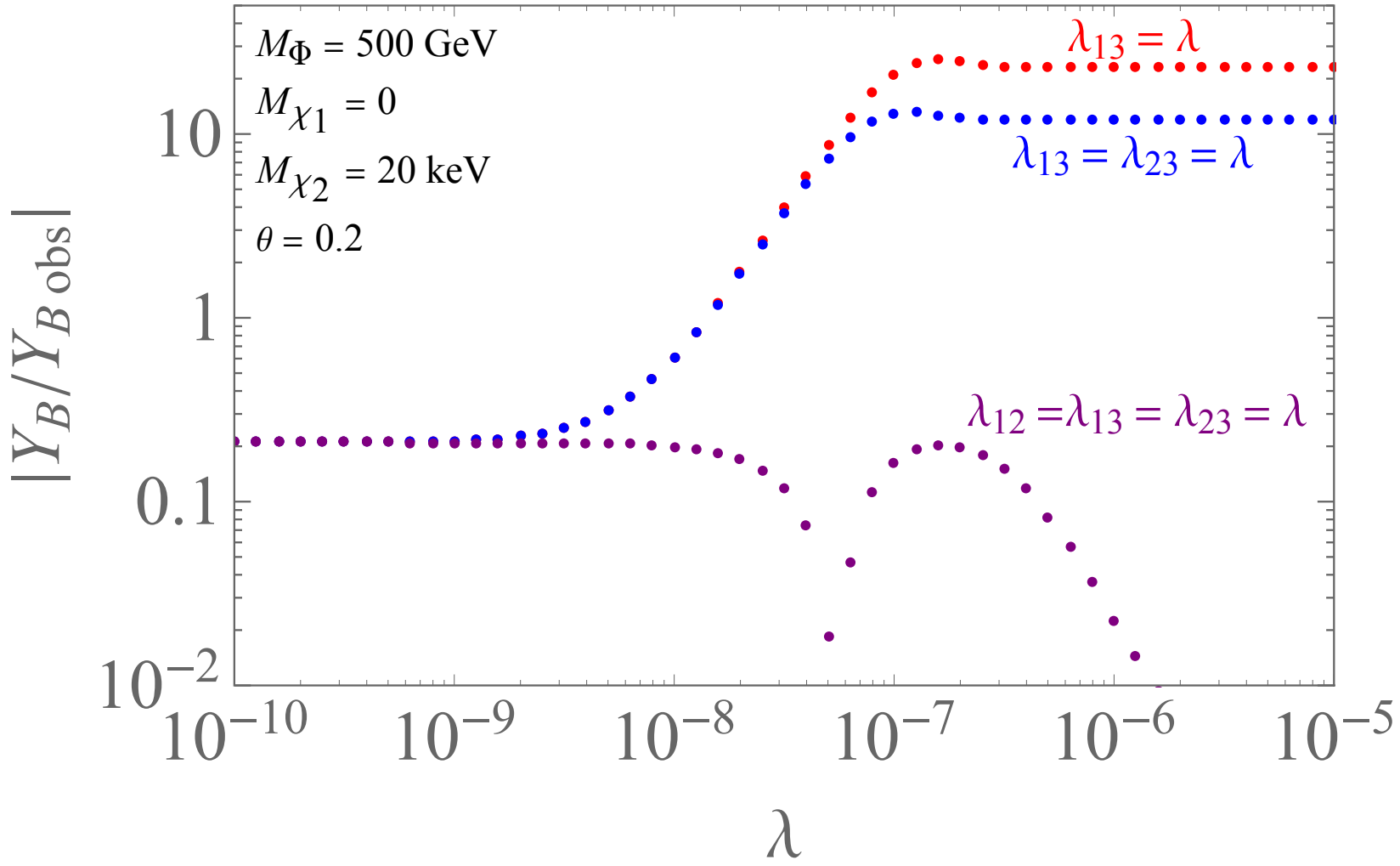


Enhancement of the asymmetry in the Z2V Model

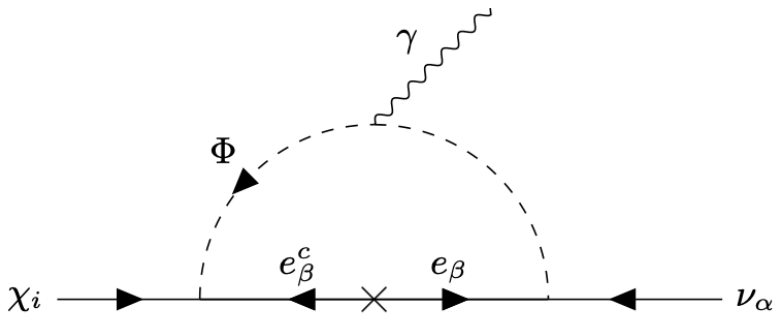
$$\mathcal{L} \supset -\frac{\lambda_{\alpha\beta}}{2} l_\alpha l_\beta \Phi^* + \text{h.c.}$$

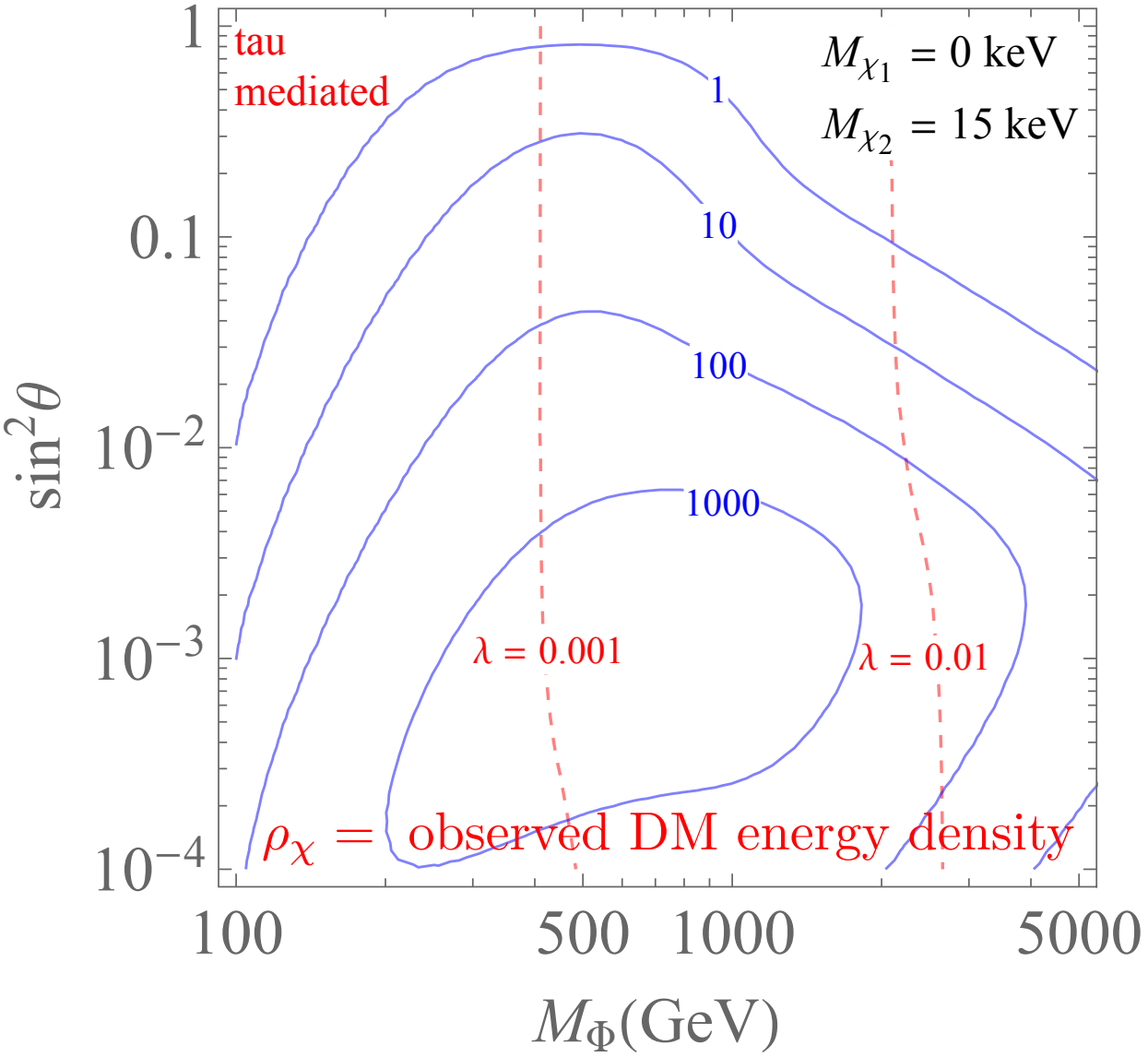


Z2V results for leptogenesis and DM

- Blue contours show the baryon asymmetry in units of the observed value, for a near-optimal benchmark with a single λ coupling in equilibrium.
- Red contours show upper bounds on the Z2V coupling from NuSTAR and INTEGRAL X-ray observations.

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).

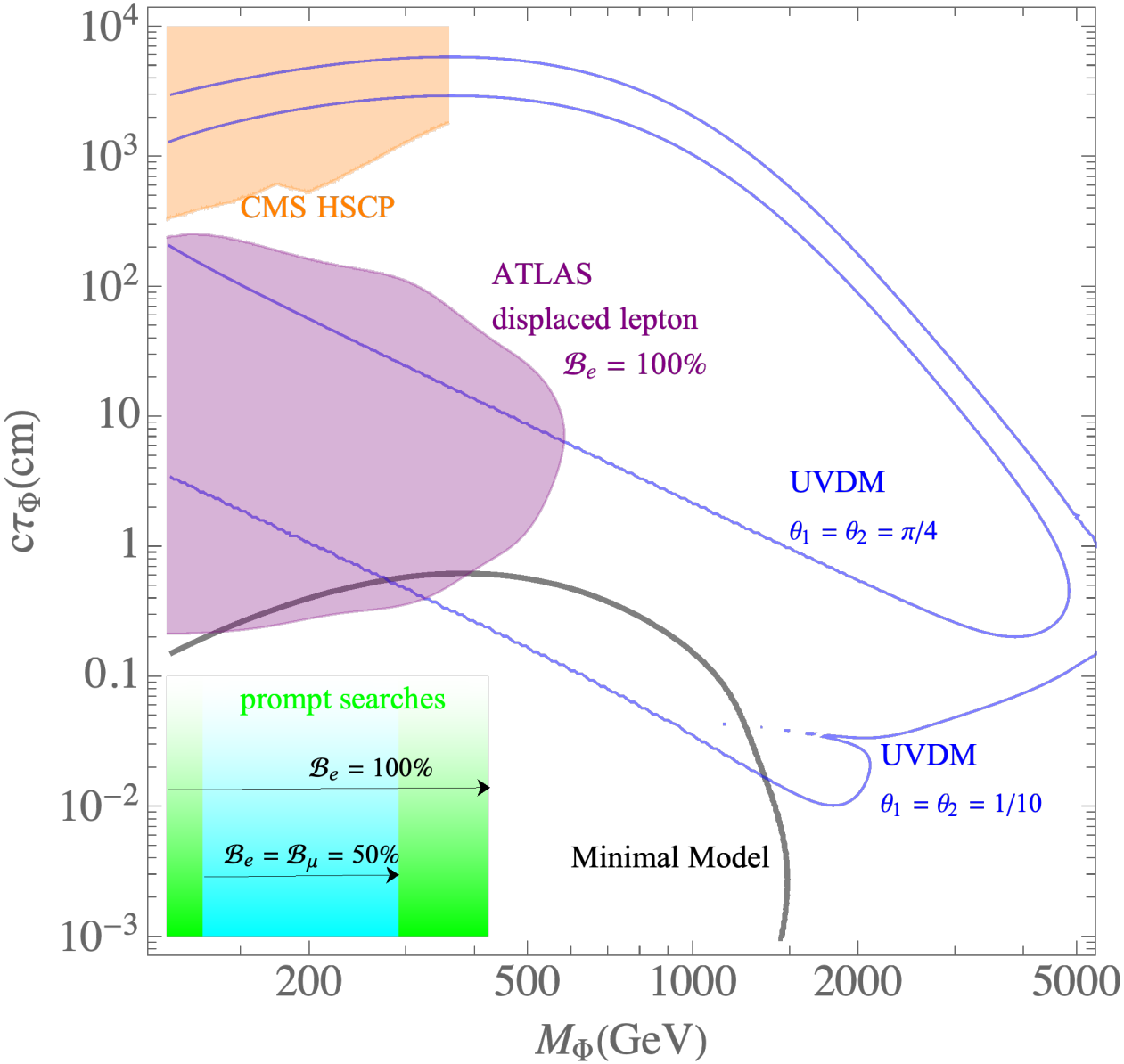




LHC constraints

ATLAS, arXiv:2011.07812; ATLAS, arXiv:1908.08215; ATLAS, arXiv:1403.5294; CMS-PAS-EXO-16-036; CMS, arXiv:2012.08600; CMS, arXiv:1806.05264

- $\Phi \to l + \text{DM}$ or $\Phi \to l + \nu$ leads to events with prompt or displaced leptons + MET
- Or, HSCP signatures for longer lifetimes



Summary

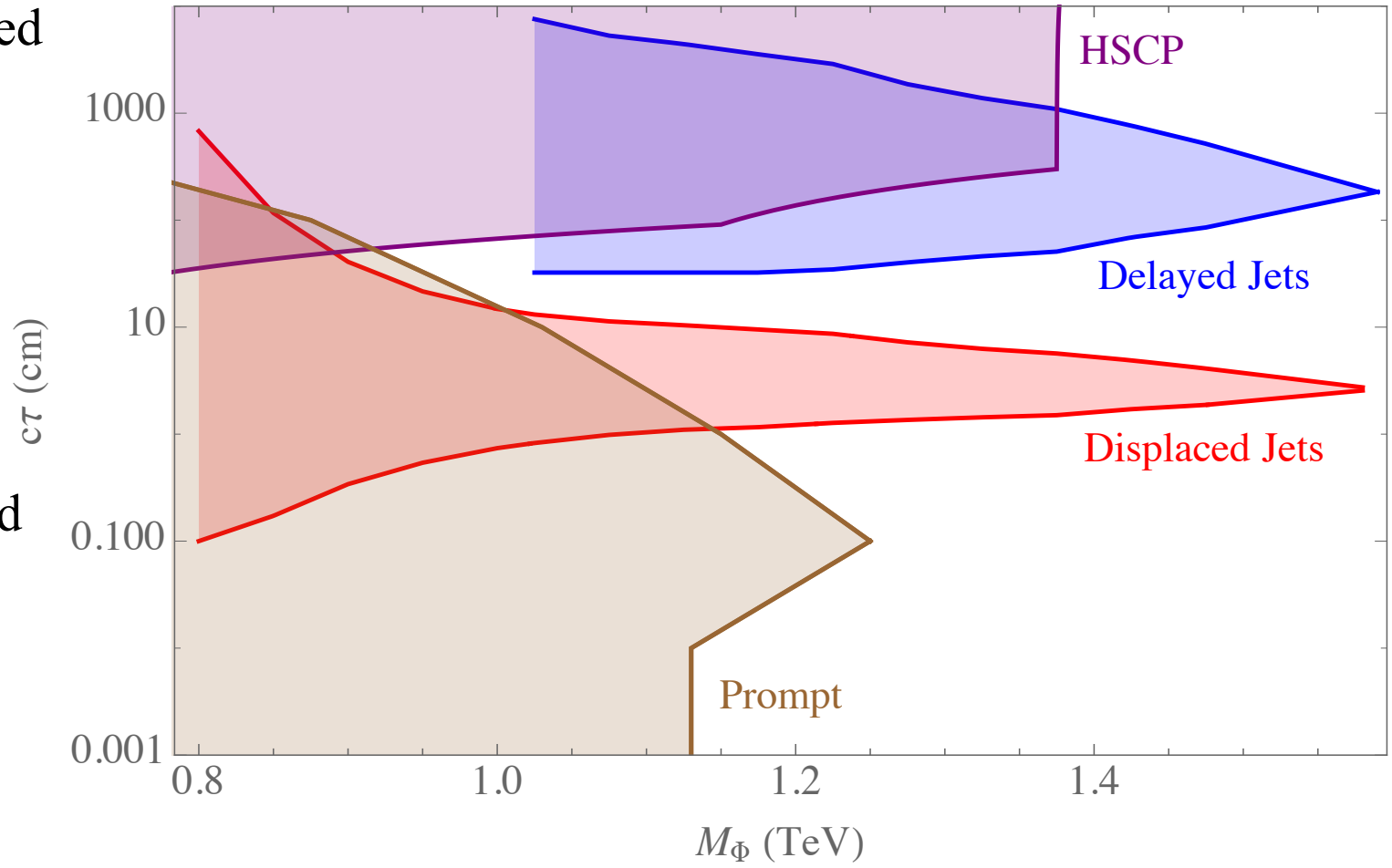
- Models of freeze-in DM can be easily extended to incorporate baryogenesis.
- The framework generally predicts new SM-charged particles with ~TeV-scale masses.
- The viable parameter space has already been impacted by LHC searches and probes of structure formation. Z2V couplings bring into play X-ray observations and low-energy terrestrial experiments.

Backup slides

LHC constraints on the QCD-charged case

ATLAS, arXiv:1710.04901; ATLAS, arXiv:1808.04095; CMS, arXiv:1811.07991; CMS, arXiv:1906.06441; CMS, arXiv:1908.04722

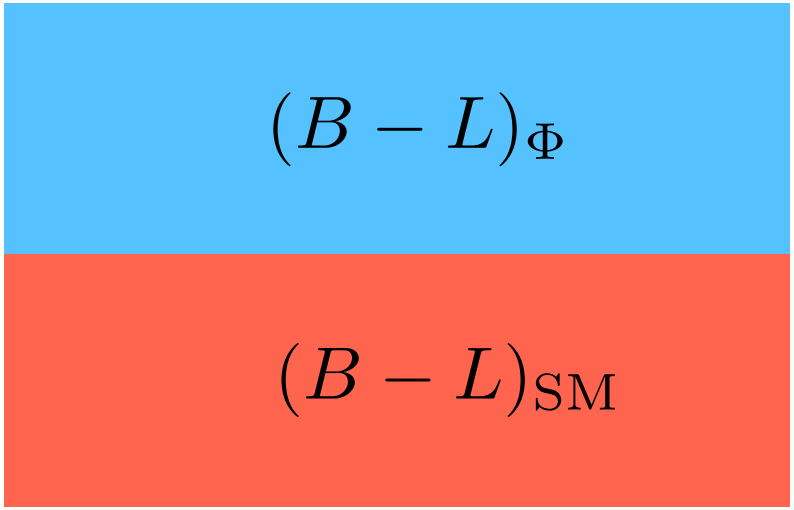
- Φ is pair-produced with a QCD-strength cross section.
- $\Phi \to q + \mathrm{DM}$, leads to events with events with displaced/delayed jets + MET
- Or, HSCP signatures for longer lifetimes



From Φ asymmetry to baryon asymmetry

$$T > T_{\mathrm{ew}}$$

- Neither B nor L is separately conserved.
- $B - L$ *is* conserved.



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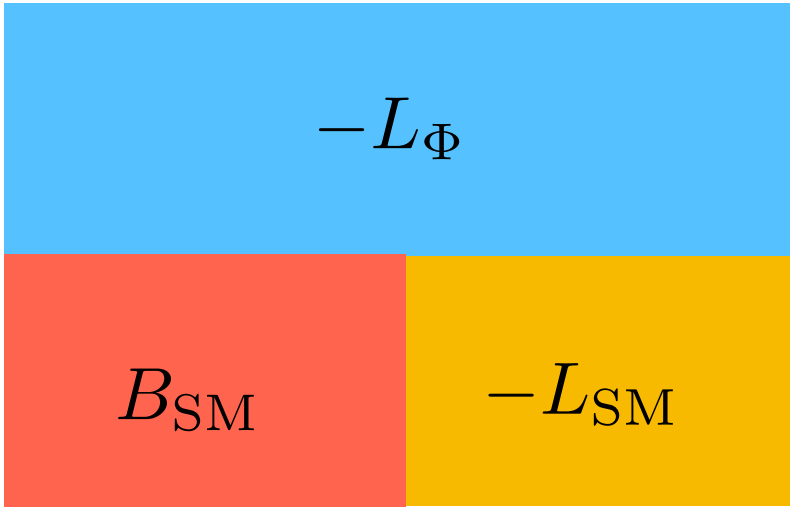

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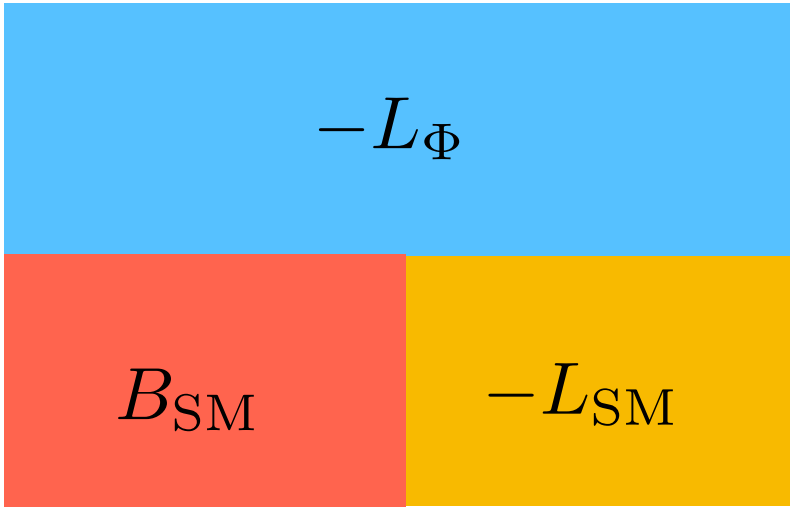

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- B and L are separately conserved.

$$B_{\rm total} = L_{\rm total} \neq 0$$

DM abundance and structure formation constraints

- Smaller DM masses means larger F to realize the observed DM density. Goes in the direction of increasing asymmetry.

- Require $M_{\chi_2} > 15$ keV to satisfy bounds from Lyman-α forest data. See *e.g.* Palanque-Delabrouille *et al.*, JCAP (2016); Kamada and Yanagi JCAP (2019); Ballesteros, Garcia, and Pierre, JCAP (2021).

- A stronger constraint, $M_{\chi_2} \gtrsim 25$ keV, has recently been reported based on strong lensing and satellite galaxy counts. Nadler *et al.*, ApJ (2021); Zelko *et al.*, arXiv:2205.09777.

- χ_1 can be arbitrarily light provided $\rho_{\chi_1}/\rho_{\rm dm} \lesssim 0.1$ (Baur *et al.*, ApJ (2017)). In the "massless-χ_1 limit," $\rho_{\chi_1} \ll \rho_{\rm dm}$ is satisfied even if χ_1 comes into equilibrium ($M_{\chi_1} \ll 0.1$ keV).

- θ parameterizes the relative coupling strengths of χ_1 and χ_2

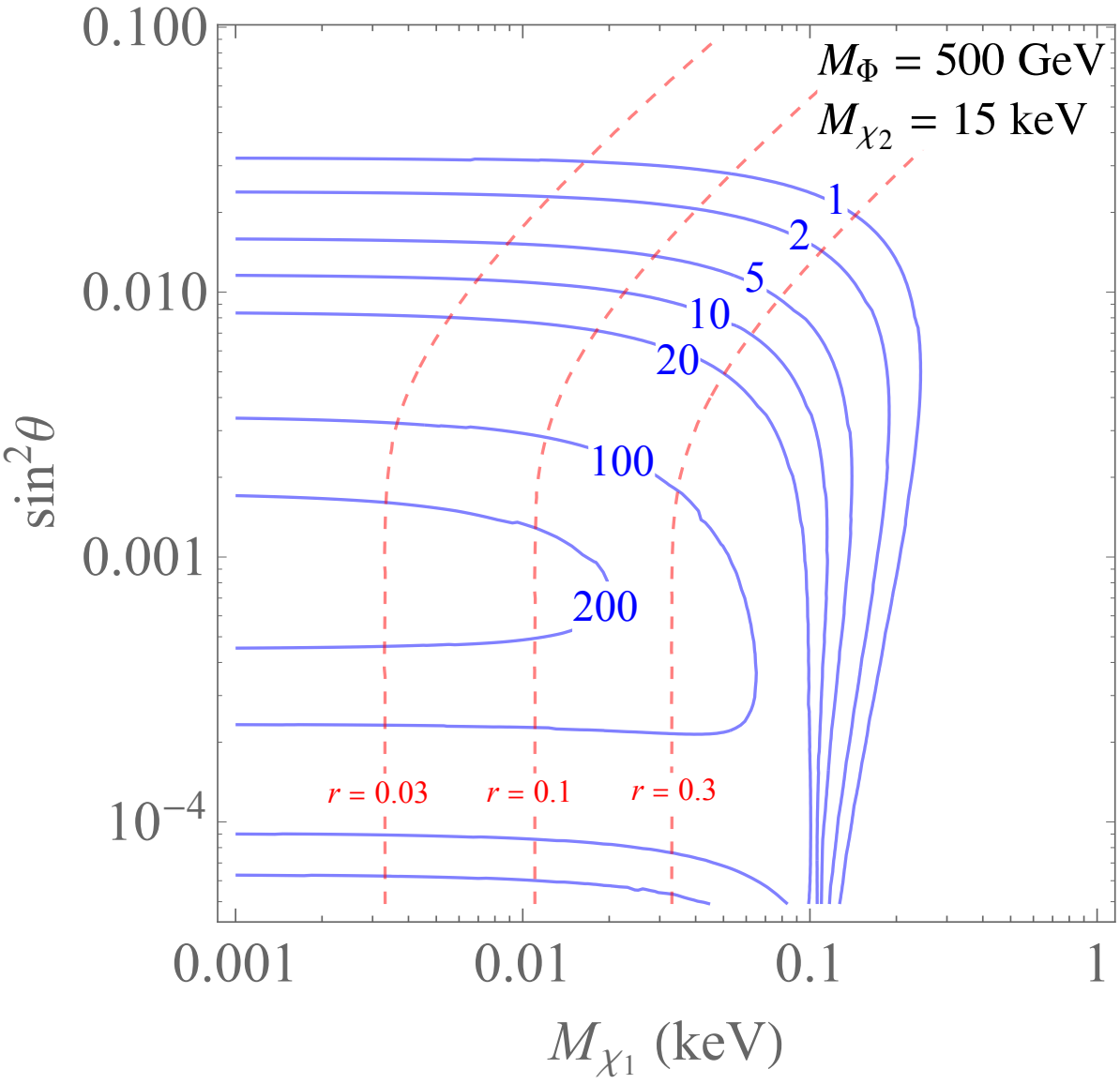
$$\chi_1 \text{ couplings } \propto \cos\theta$$
$$\chi_2 \text{ couplings } \propto \sin\theta$$

(UVDM: $\theta_{1,2}$ for $\Phi_{1,2}$)

Minimal-Model results for leptogenesis and DM

- Even without a constraint on $r \equiv \rho_{\chi_1}/\rho_{\rm dm}$, the viable parameter space has $M_{\chi_1} \lesssim 0.2$ keV.

- Requiring $r < 0.1$ leads to $M_{\chi_1} \lesssim 0.05$ keV.



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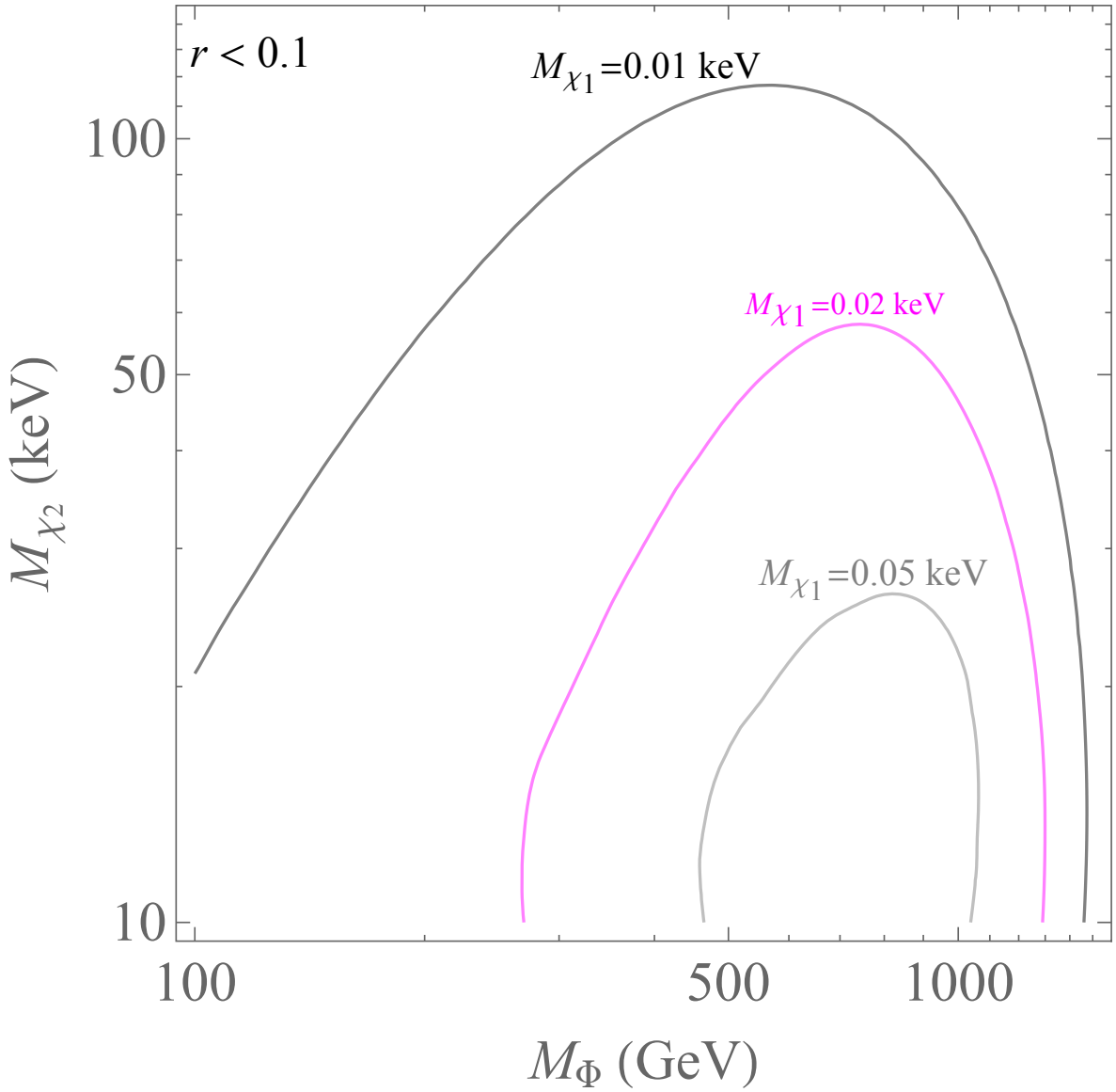

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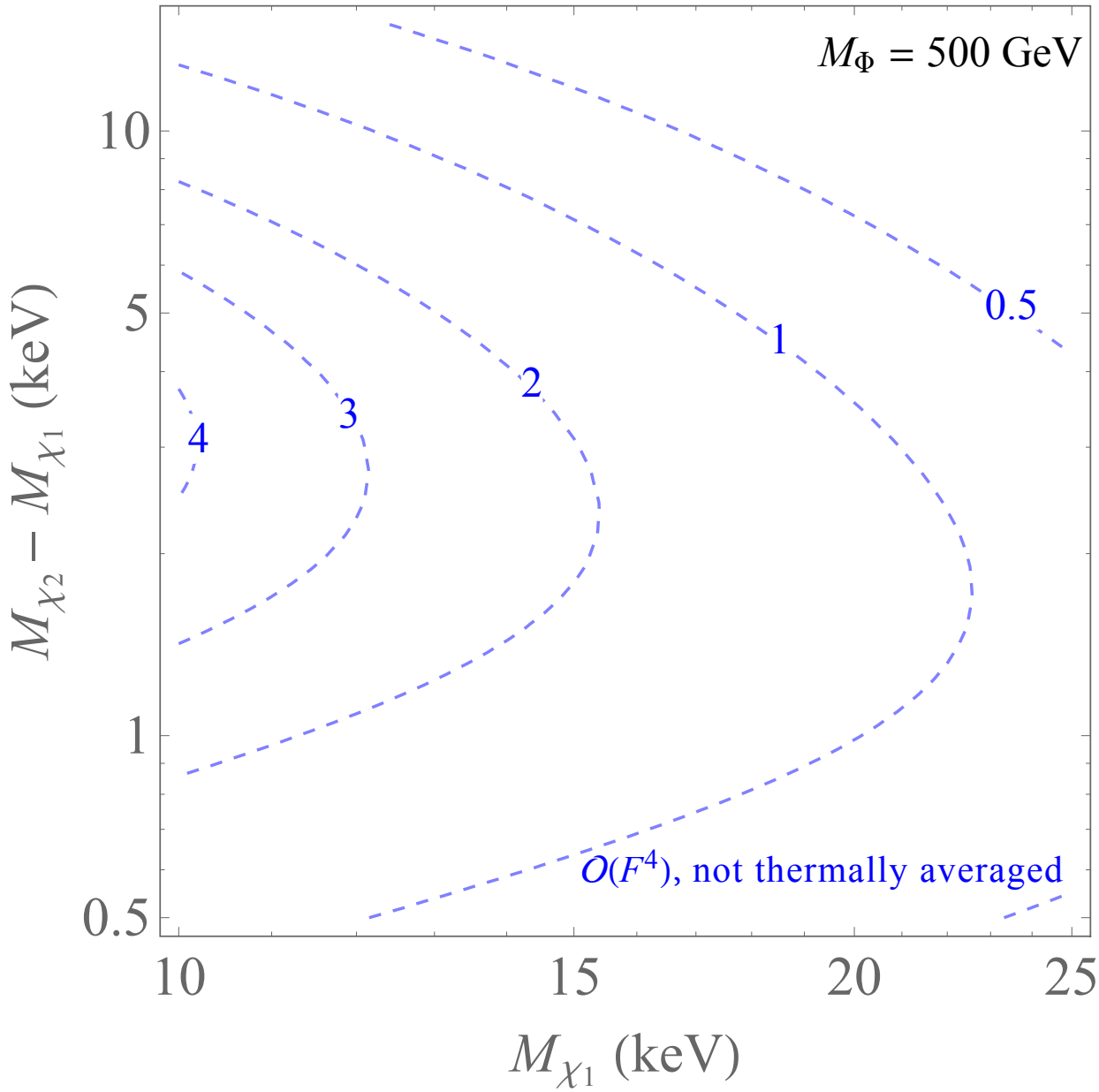

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