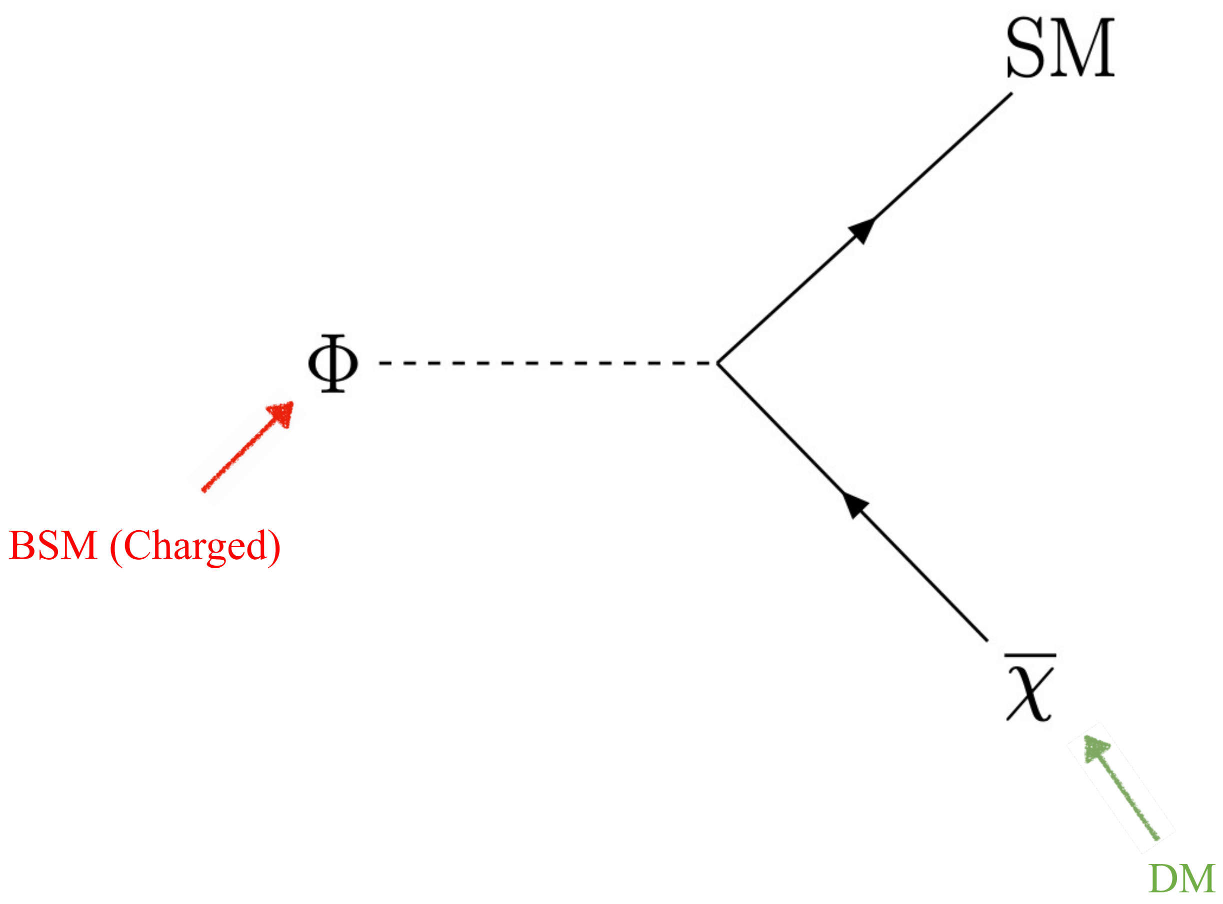
Freeze-in Leptogenesis via Dark Matter Oscillations

Justin Berman

Work in progress with Brian Shuve and Dave Tucker-Smith

Freeze-in DM To Freeze-in Leptogenesis



McDonald, hep-ph/0106249
Hall et al., arXiv:0911.1120
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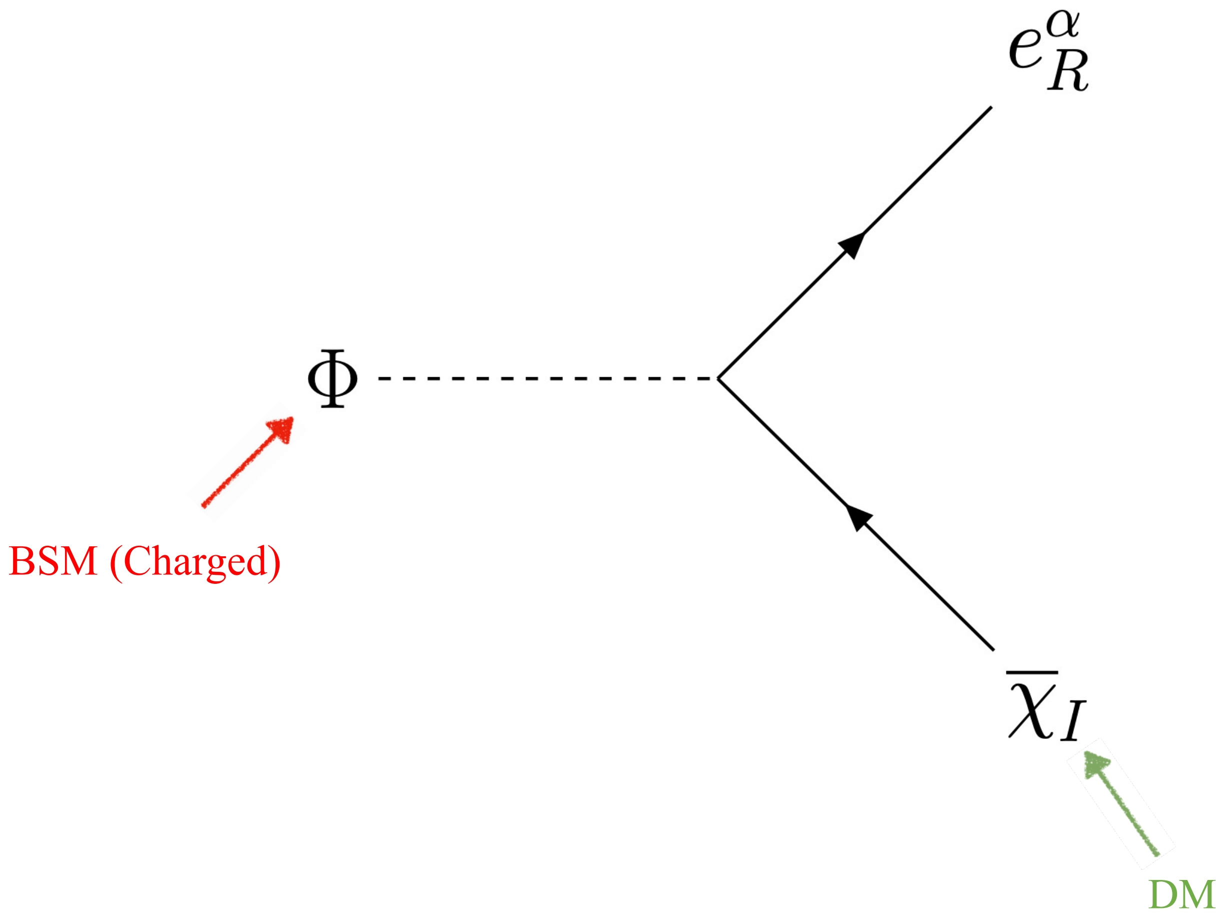

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Akhmedov et al., hep-ph/9803255

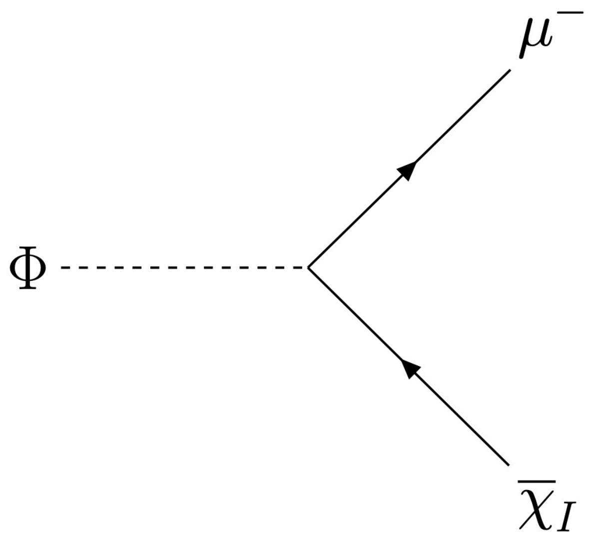
Shuve and Tucker-Smith, arXiv:2004.00636

Main Questions

- Is it possible to produce both the observed DM energy density and baryon asymmetry?
- What is the viable mass-lifetime parameter space for Φ?
  - What are the prospects for probing our model at colliders?
- How heavy can the dark matter mass eigenstates be?
  - Can we satisfy structure formation constraints?

Basic Mechanism

Step 1: Produce DM



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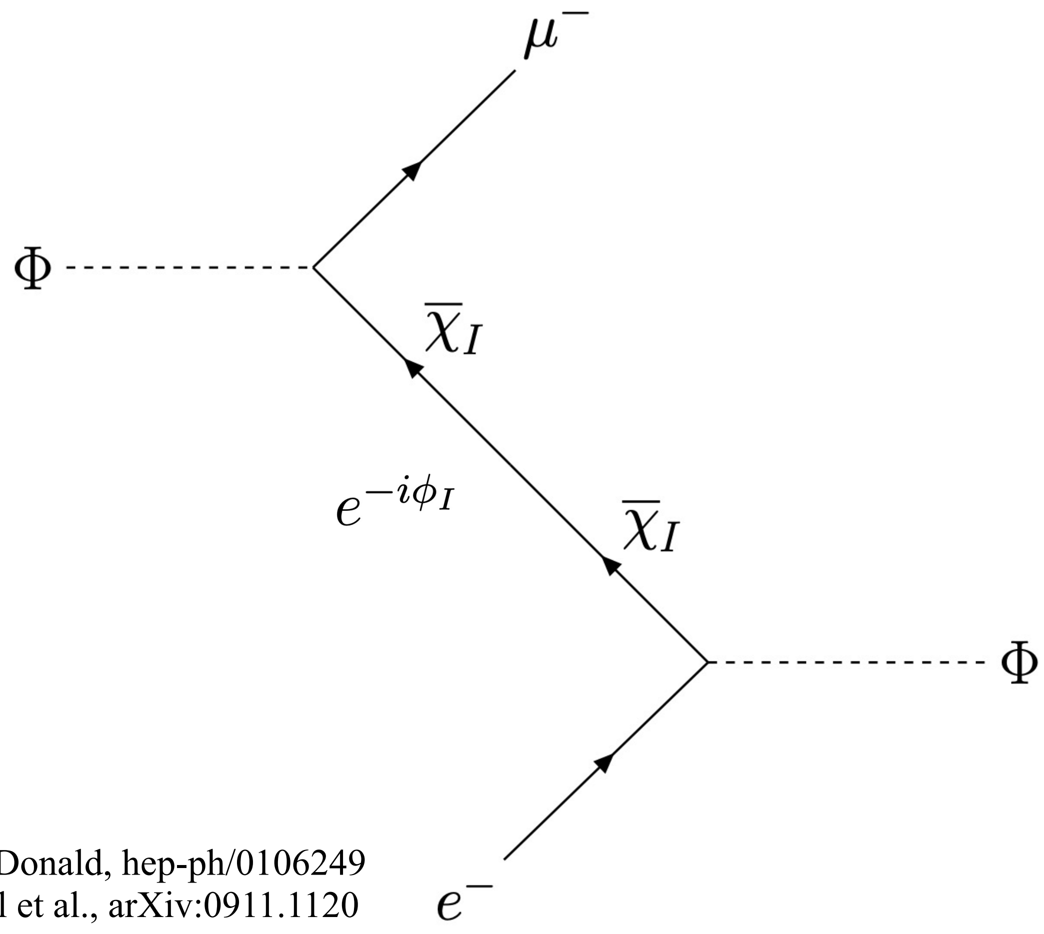
Step 2: Produce lepton flavor asymmetry



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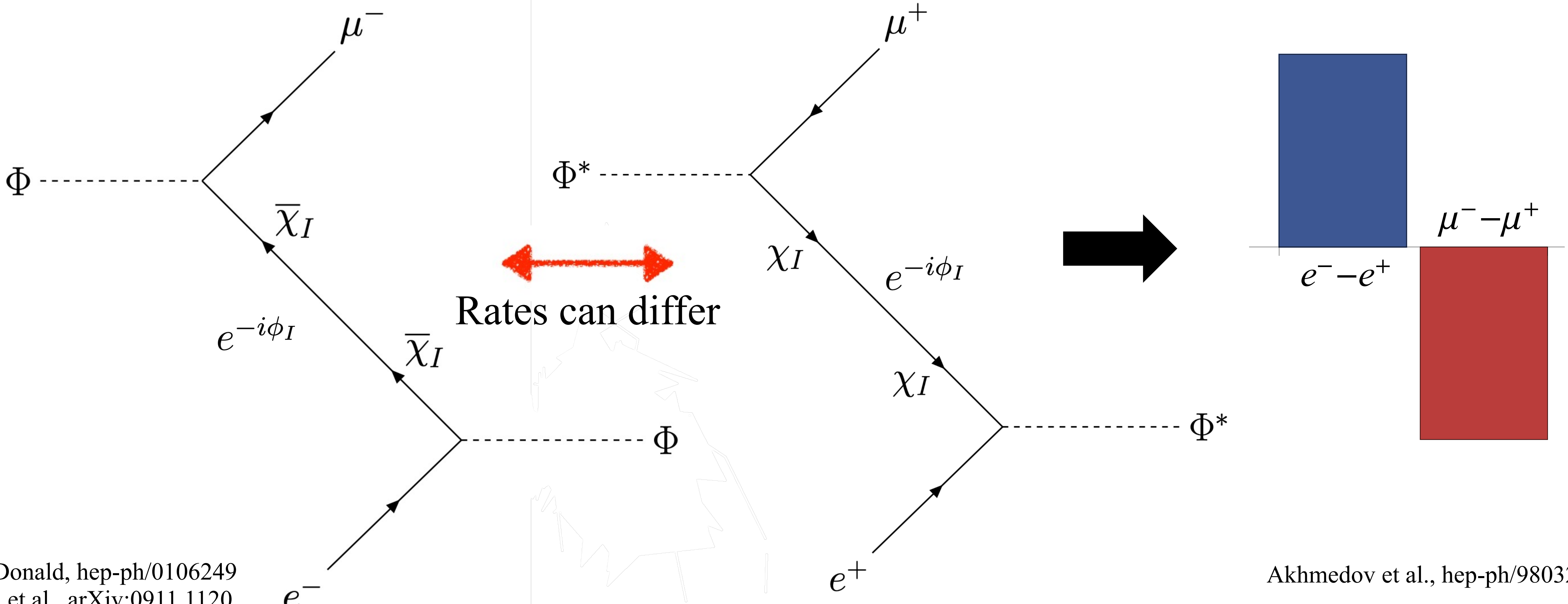

Produces nonzero $\mathcal{X}^\alpha = B/3\text{-}L^\alpha$ charge densities

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Quantum Kinetic Equations

$$\frac{d}{d\ln z}Y^{\chi}_{IJ} = \sum_{\alpha}\Bigg(-\frac{1}{2}\left\{\tilde{\gamma}_{0,\alpha}, Y^{\chi} - Y^{\chi}_{eq}\right\} + \frac{\mu_{e_R^\alpha}}{T}\left[Y^{\chi}_{eq}\tilde{\gamma}_{\psi 1,\alpha} + \frac{1}{2}\left\{\tilde{\gamma}_{\psi 2,\alpha}, Y^{\chi}\right\}\right]$$

$$+\frac{1}{2}\left(1-\cosh\left(\frac{\mu_\Phi}{T}\right)\right)\left\{\tilde{\gamma}_{0,\alpha}, Y^{\chi} - Y^{\chi}_{eq}\right\} - \sinh\left(\frac{\mu_\Phi}{T}\right)\left[Y^{\chi}_{eq}\tilde{\gamma}_{\Phi 1,\alpha} - \frac{1}{2}\left\{\tilde{\gamma}_{\Phi 2,\alpha}, Y^{\chi}\right\}\right]\Bigg)_{IJ}$$

$$\frac{d}{d\ln z}Y^{\overline{\chi}}_{IJ} = \sum_{\alpha}\Bigg(-\frac{1}{2}\left\{\tilde{\gamma}^*_{0,\alpha}, Y^{\overline{\chi}} - Y^{\chi}_{eq}\right\} - \frac{\mu_{e_R^\alpha}}{T}\left[Y^{\chi}_{eq}\tilde{\gamma}^*_{\psi 1,\alpha} - \frac{1}{2}\left\{\tilde{\gamma}^*_{\psi 2,\alpha}, Y^{\overline{\chi}}\right\}\right]$$

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$$\frac{d}{d\ln z}Y_{\mathcal{X}^\alpha} = -\operatorname{Tr}\left[\tilde{\gamma}_{0,\alpha}Y^{\chi} - \tilde{\gamma}^*_{0,\alpha}Y^{\overline{\chi}}\right] + 2Y^{\chi}_{eq}\frac{\mu_{e_R^\alpha}}{T}\operatorname{Tr}[\tilde{\gamma}_{\psi 1,\alpha}] + \frac{\mu_{e_R^\alpha}}{T}\operatorname{Tr}[\tilde{\gamma}_{\psi 2,\alpha}Y^{\chi} + \tilde{\gamma}^*_{\psi 1,\alpha}Y^{\overline{\chi}}]$$

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Similar to Hambye and Teresi, arXiv: 1705.00016 in the ARS context

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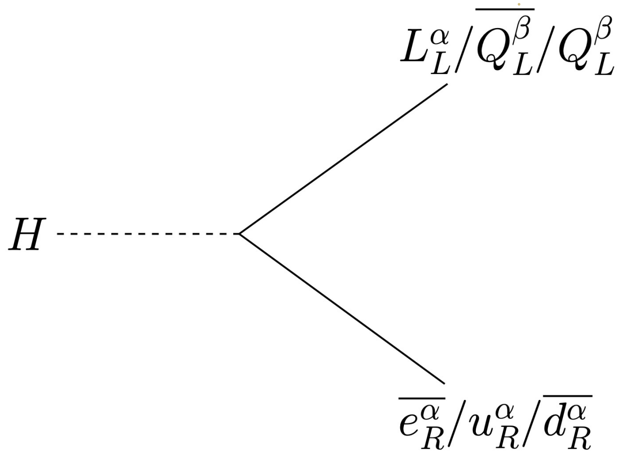
SM Processes

$\mathcal{X}^\alpha$ asymmetries "seed" a flavor summed asymmetry, which is converted to a baryon asymmetry

SM Yukawas

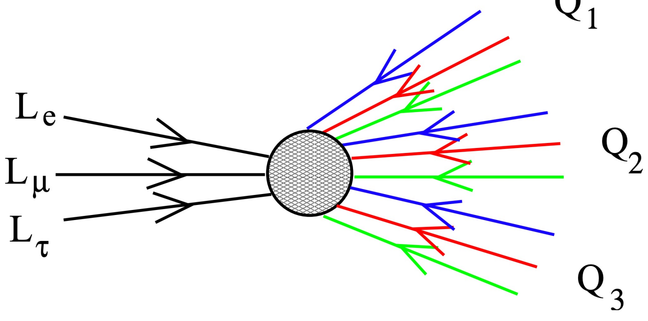
$Y_{\mathcal{X}^\alpha}$ ⇒



$$0 = \mu_H - \mu_{Q_L} + \mu_{d_R}$$
$$0 = \mu_H + \mu_{Q_L} - \mu_{u_R}$$
$$0 = \mu_H - \mu_{L_L^\alpha} + \mu_{e_R^\alpha}$$

⇒ Y_B

Sphalerons

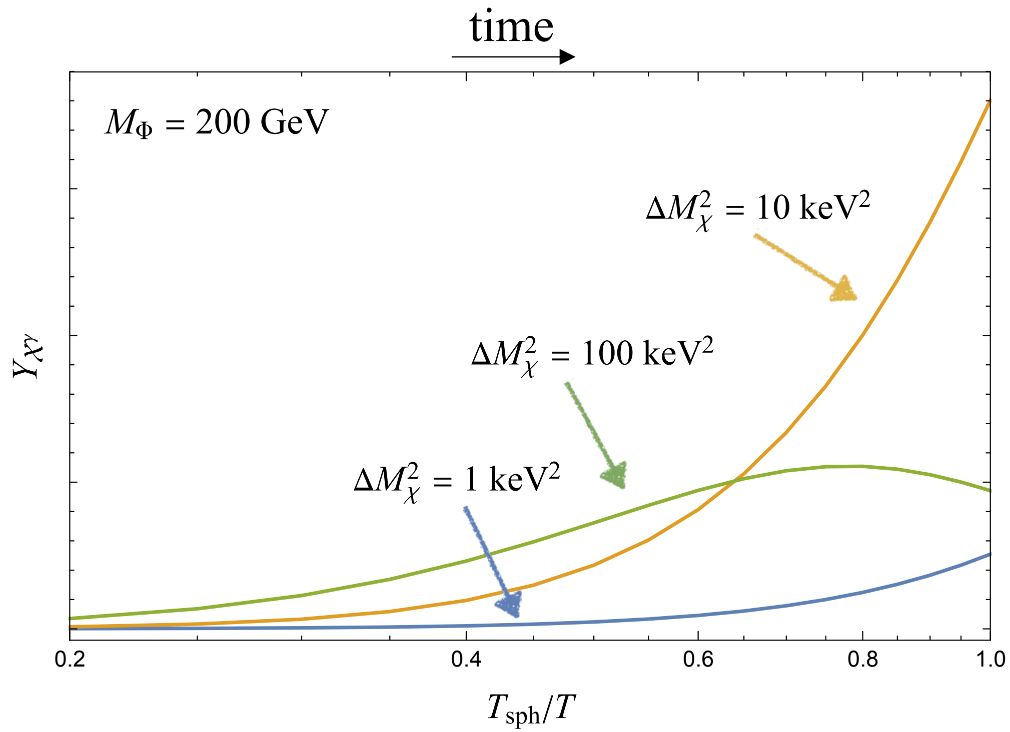


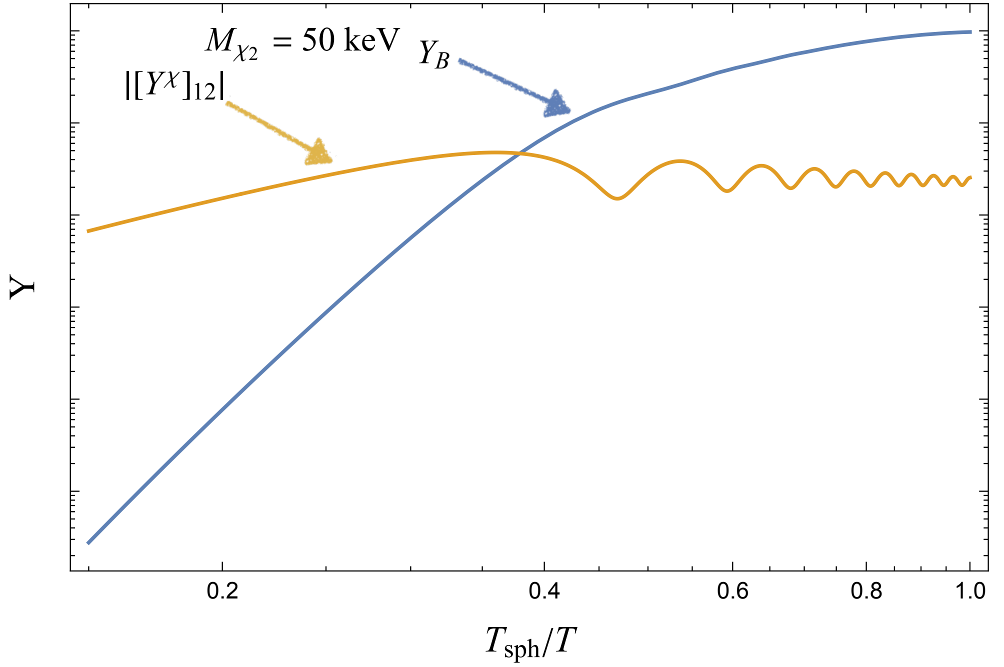
$$0 = 9\mu_{Q_L} + \sum_\alpha \mu_{L_L^\alpha}$$

Cline, arXiv:0609145

Favored Parameters

1. Heavier χ means smaller couplings to match DM energy density. To have large enough asymmetry, typically need $M_{\chi_2} < 100$ keV
2. Oscillation timescale $\propto 1/\Delta M_\chi^2$, want appreciable fraction of an oscillation to occur by T ~ M_Φ for leptogenesis
3. (1) and (2) make optimal Φ masses in the hundreds of GeV to TeV range





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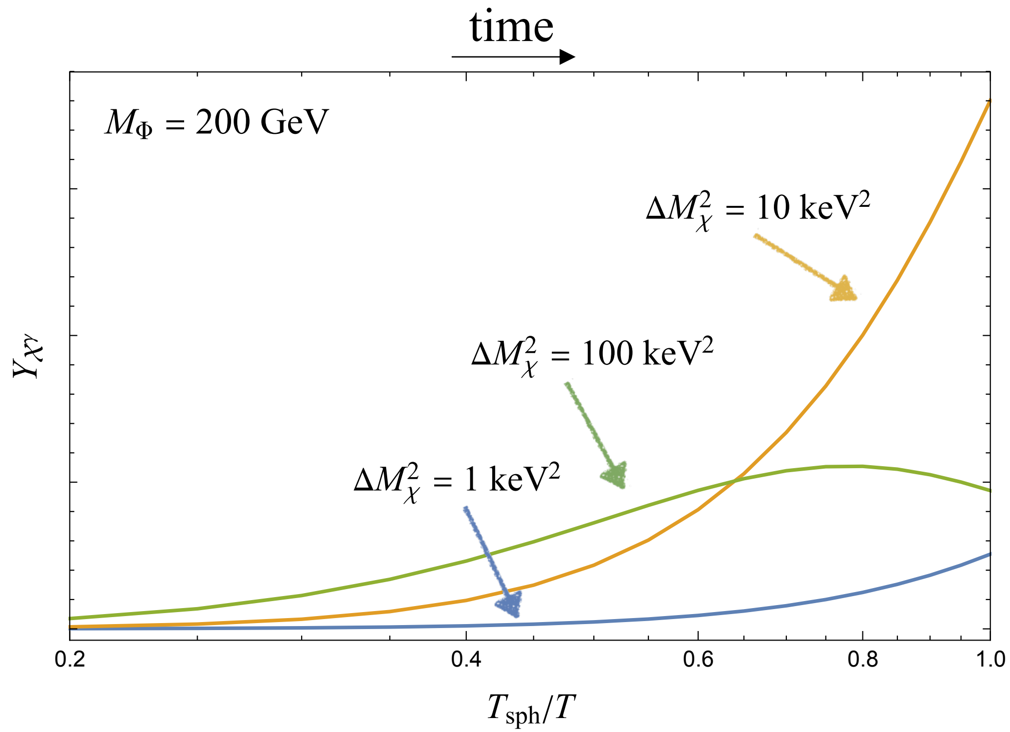
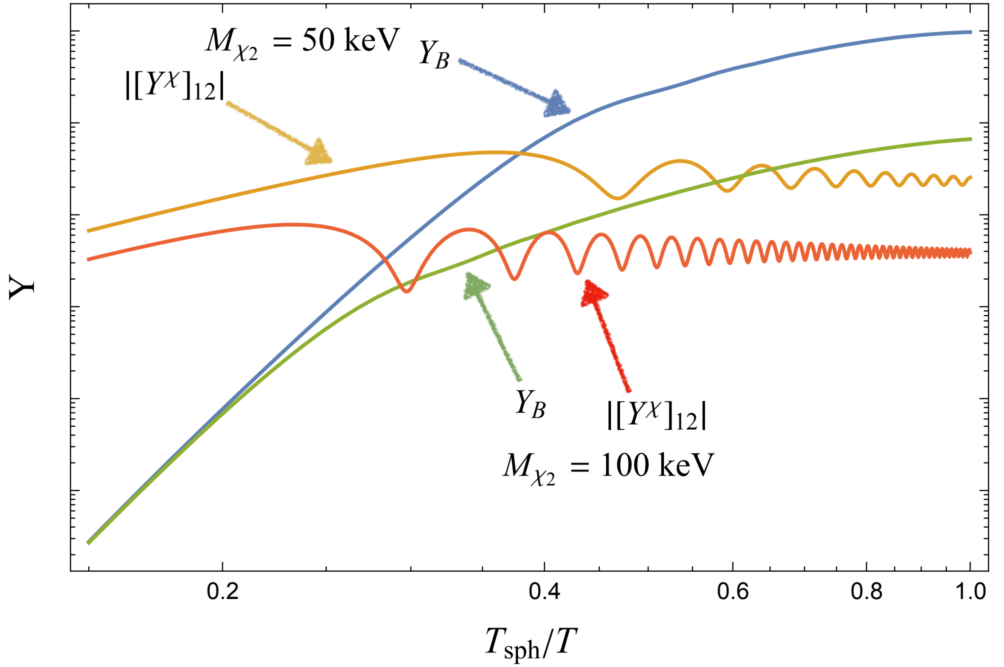


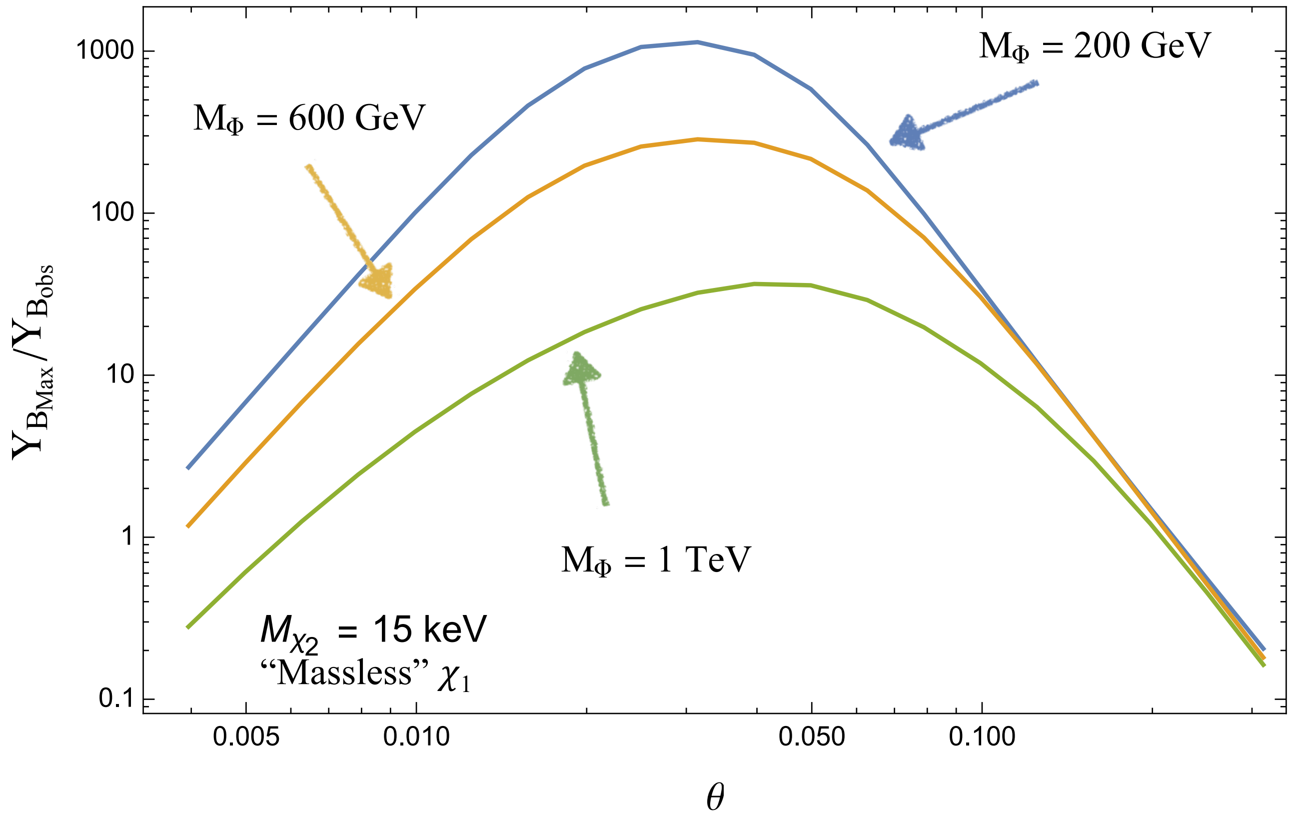


Asymmetry Generating Scenarios: $\mathbb{Z}_2$

$$\mathcal{L} \supset -F^i_{\alpha I}\overline{e^\alpha_R}\Phi_i\chi_I + \text{h.c.}$$

Single Scalar

- Asymmetry arises at order F^6, making it challenging to get large enough asymmetry without overproducing DM
- Loophole: Φ might preferentially decay to a very light (sub-keV) χ mass eigenstate, suppressing the DM energy density
    - Small θ means Φ prefers to decay to χ_1



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Two Scalar

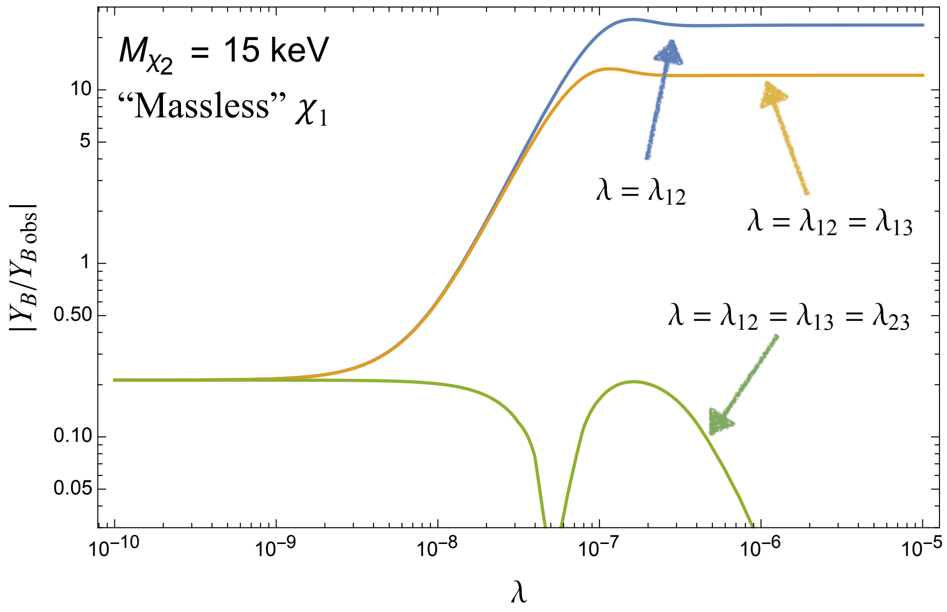
- Φ_2: a stand-in for unspecified source of coherent χ background
- Asymmetry is generated at order F^4 from Φ_2 decays and Φ_1 inverse decays
- Small F coupling ($F \lesssim 10^{-7}$) leads to long Φ_1 lifetimes, ($c\tau \gtrsim 1$ cm are favored if Φ_1 couples indiscriminately to χ_1 vs. χ_2)

Asymmetry Generating Scenarios: $\not{\mathbb{Z}}_2$

$$\mathcal{L} \supset -F_{\alpha I}\overline{e_R^\alpha}\Phi\chi_I - h_{\alpha I}\overline{L_L^\alpha}H\chi_I - \frac{\lambda_{\alpha\beta}}{2}\Phi^*\overline{L_L^{\alpha C}}L_L^\beta + \text{h.c.}$$

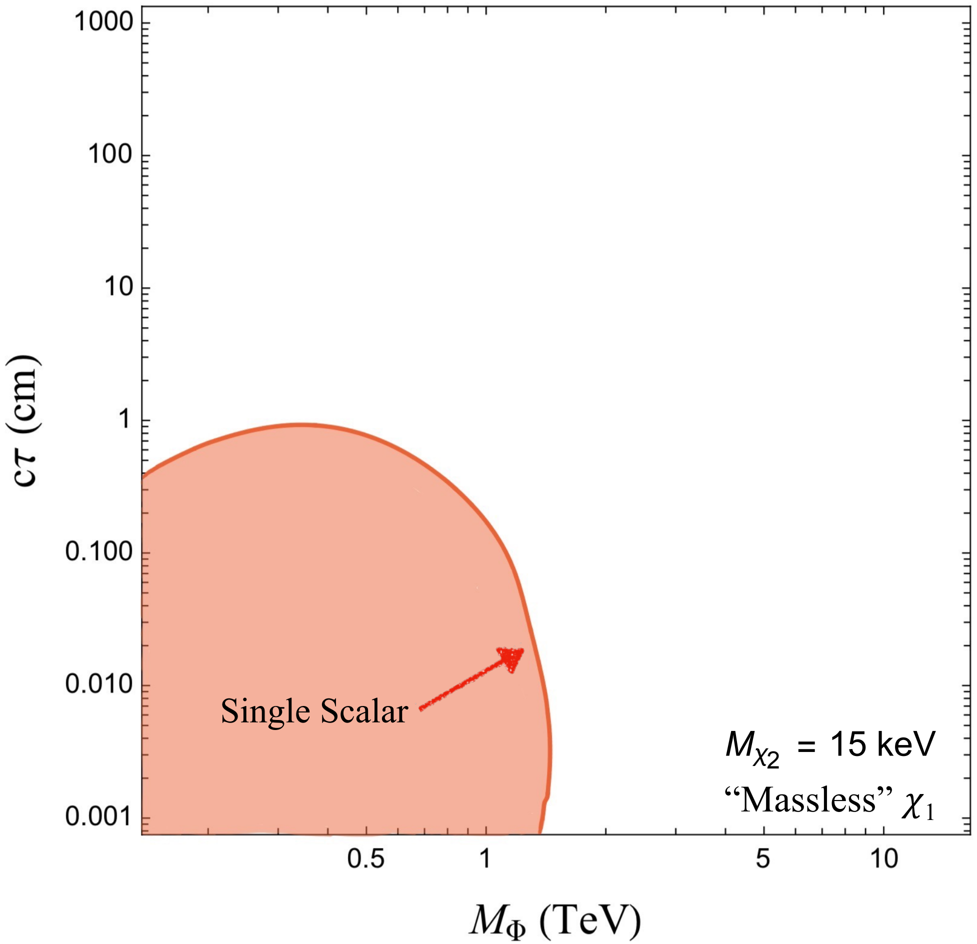
Must be tiny, $\lesssim 10^{-12}$

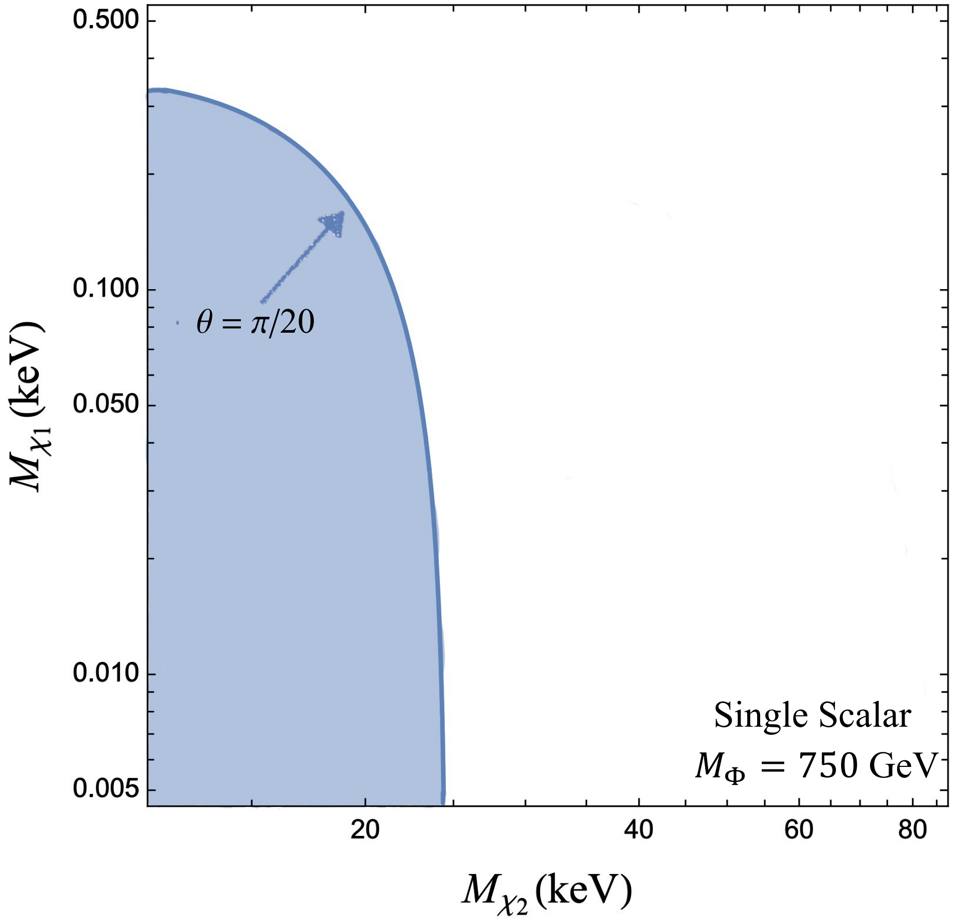
- Asymmetry at order $F^4\lambda^2$
- If λ coupling large enough, it comes into equilibrium, so asymmetry effectively arises at order F^4 (details depend on flavor structure of λ)
  - No longer need to take θ to be small, though smaller θ leads to an increase in the allowed parameter space



Adhikari et al., arXiv: 1602.04816

Results: $\mathbb{Z}_2$





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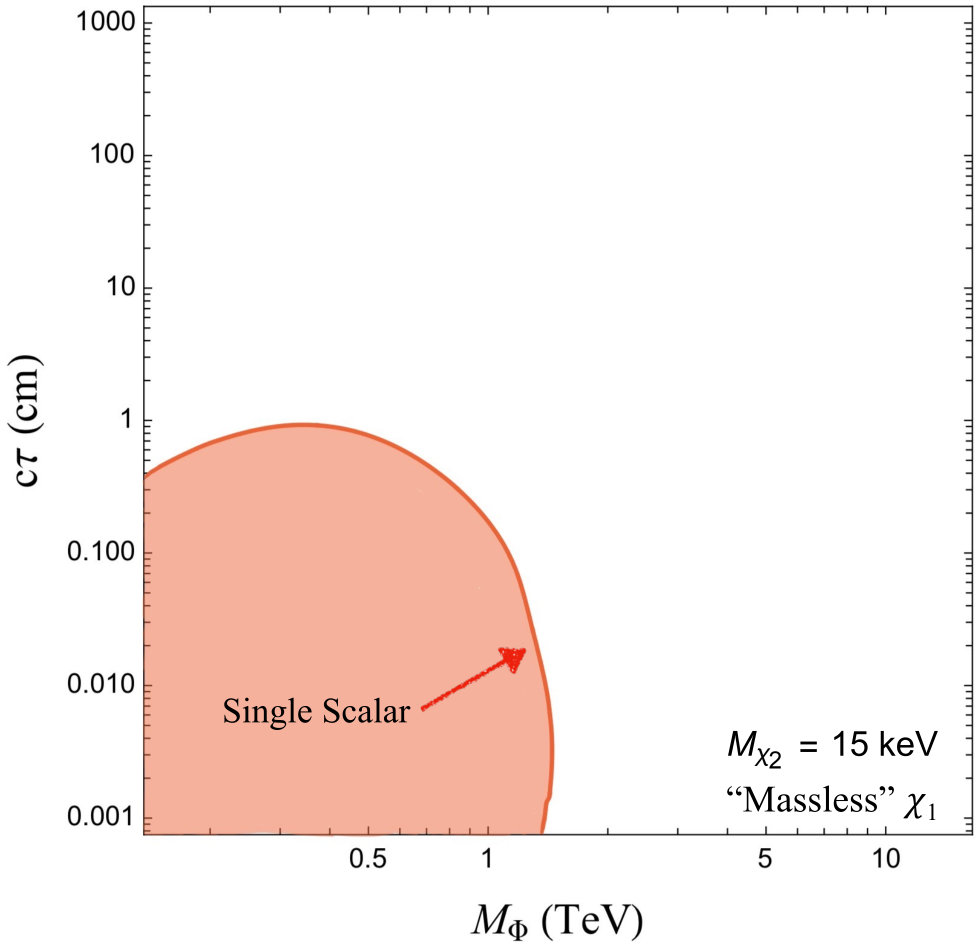

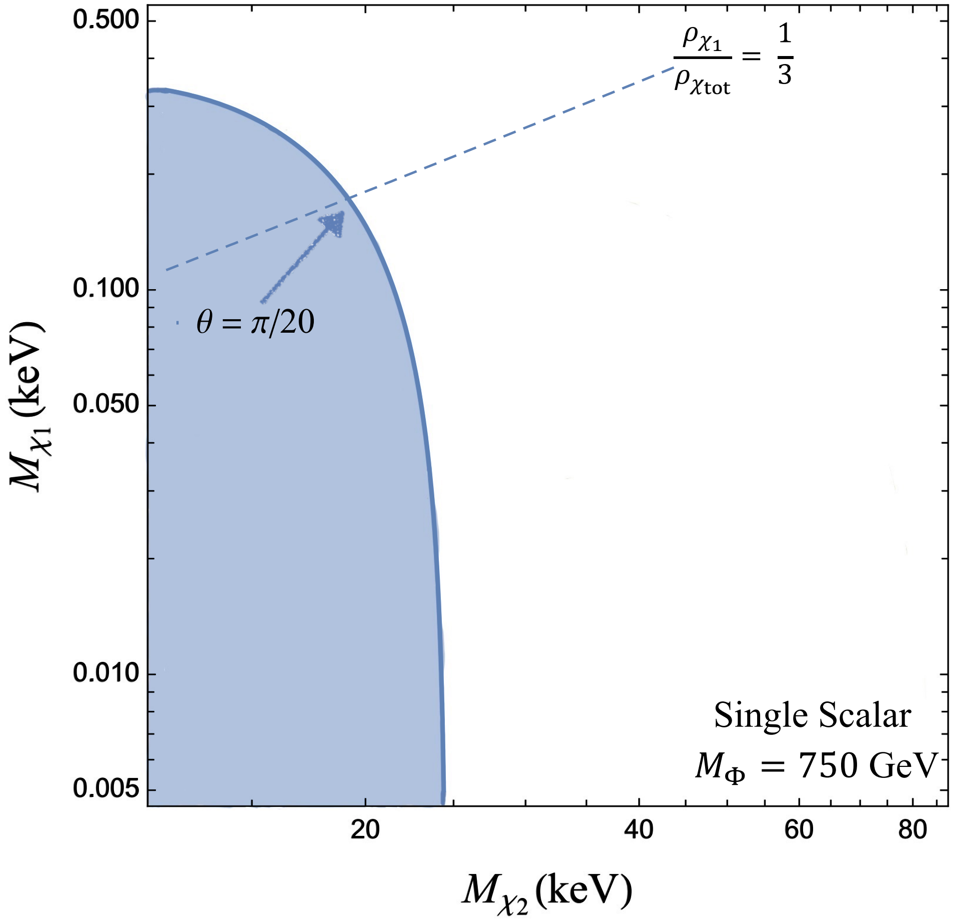

Structure formation constraints on mixed cold/warm DM are discussed in Kamada, arXiv: 1604.01489

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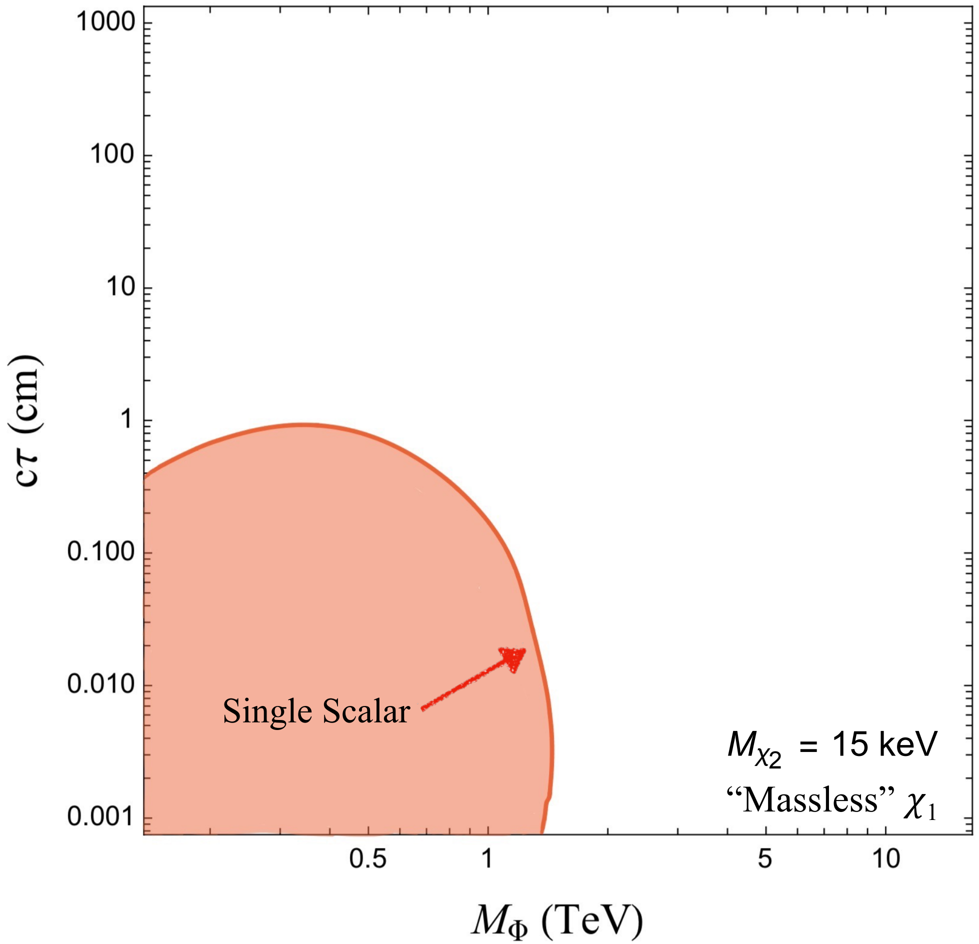

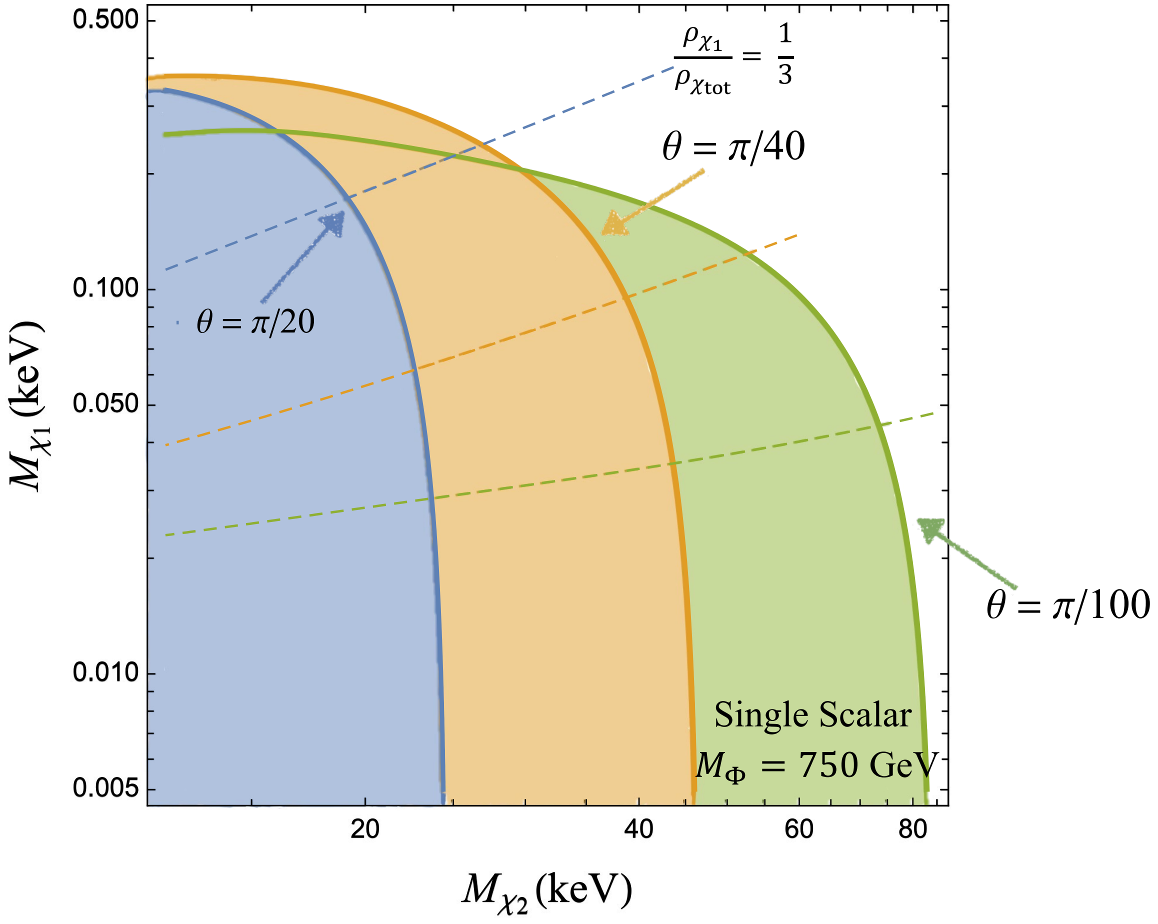

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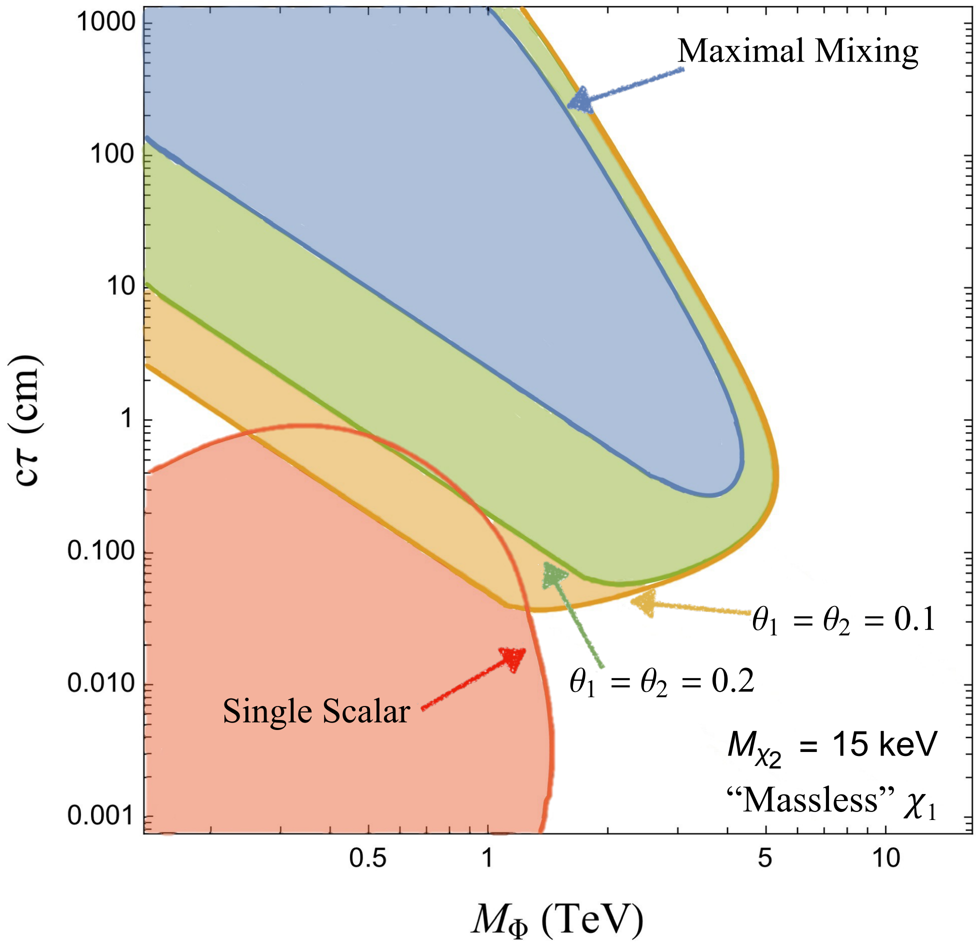

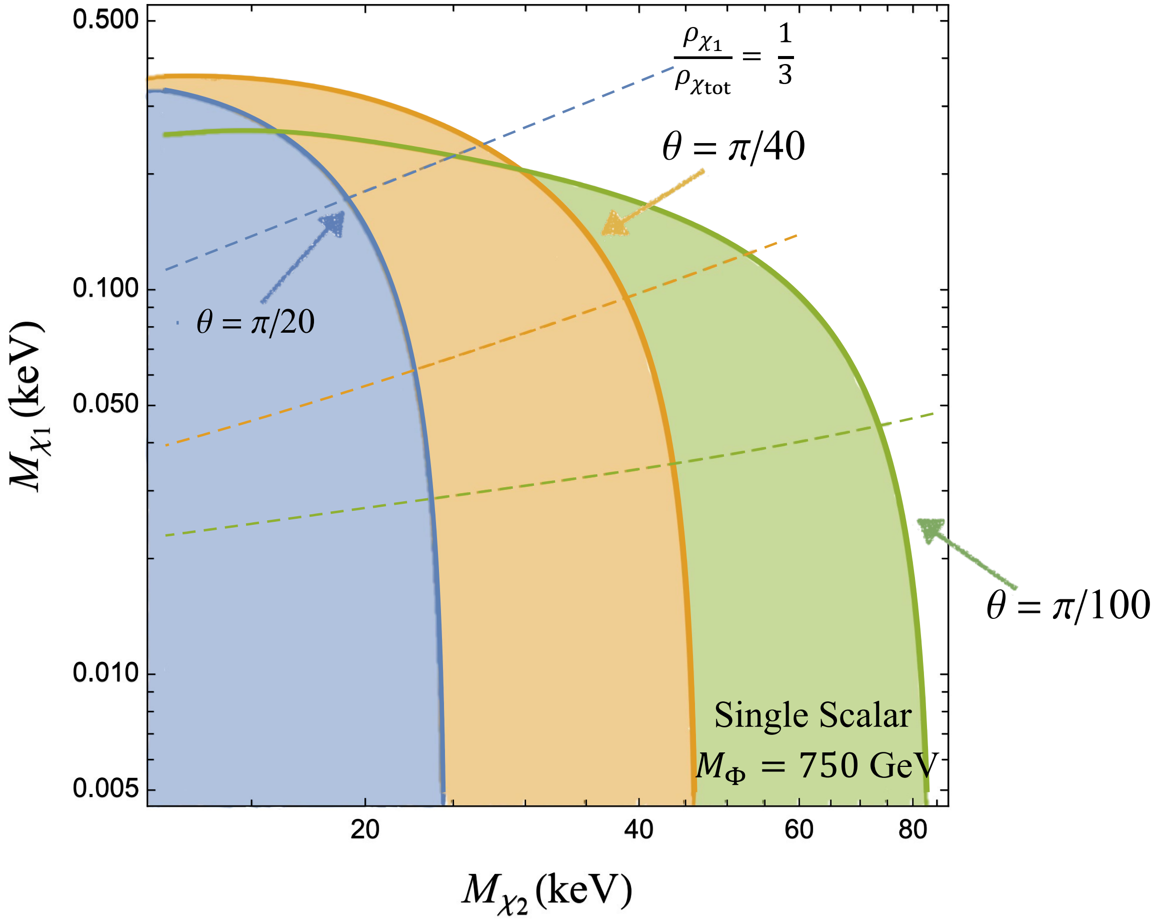

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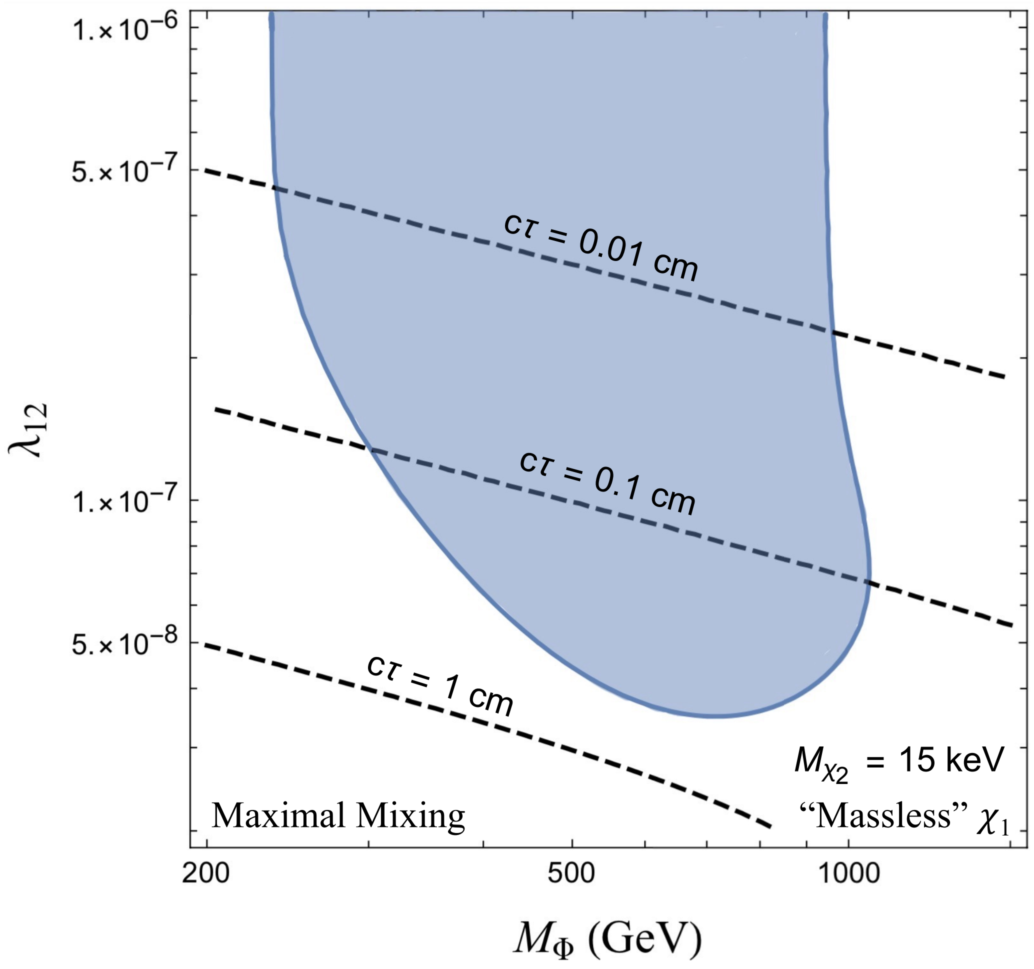

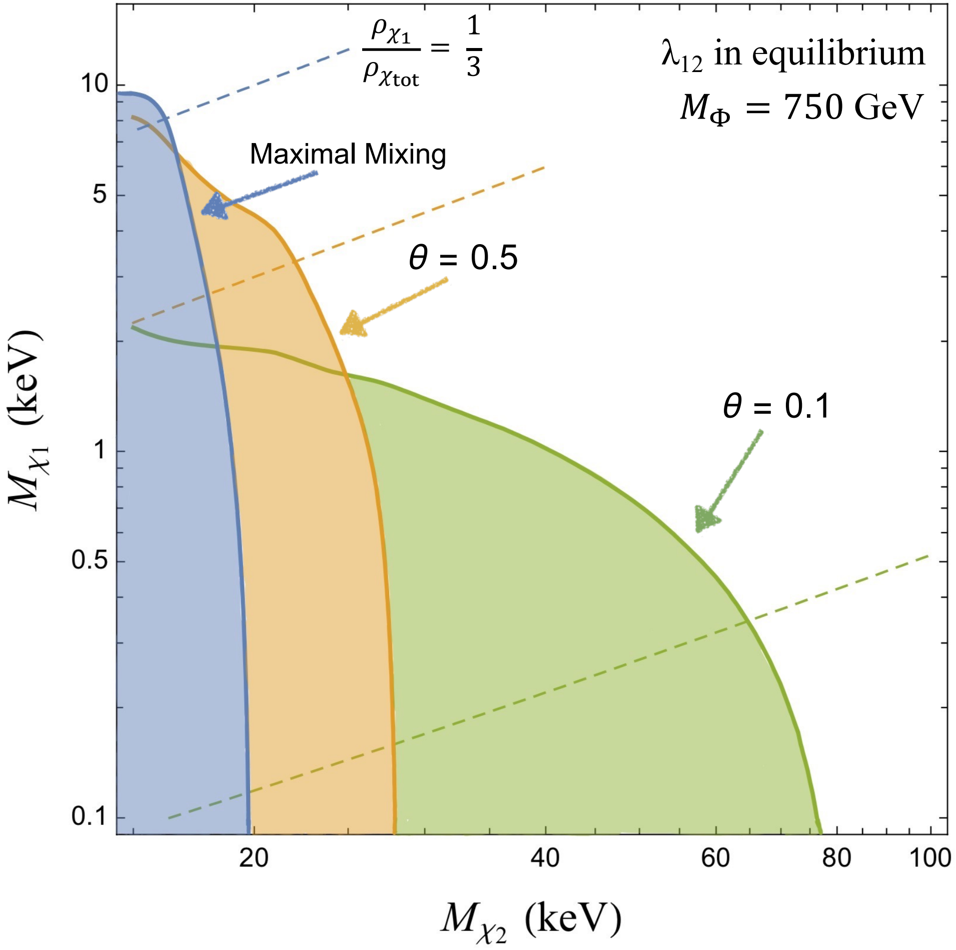

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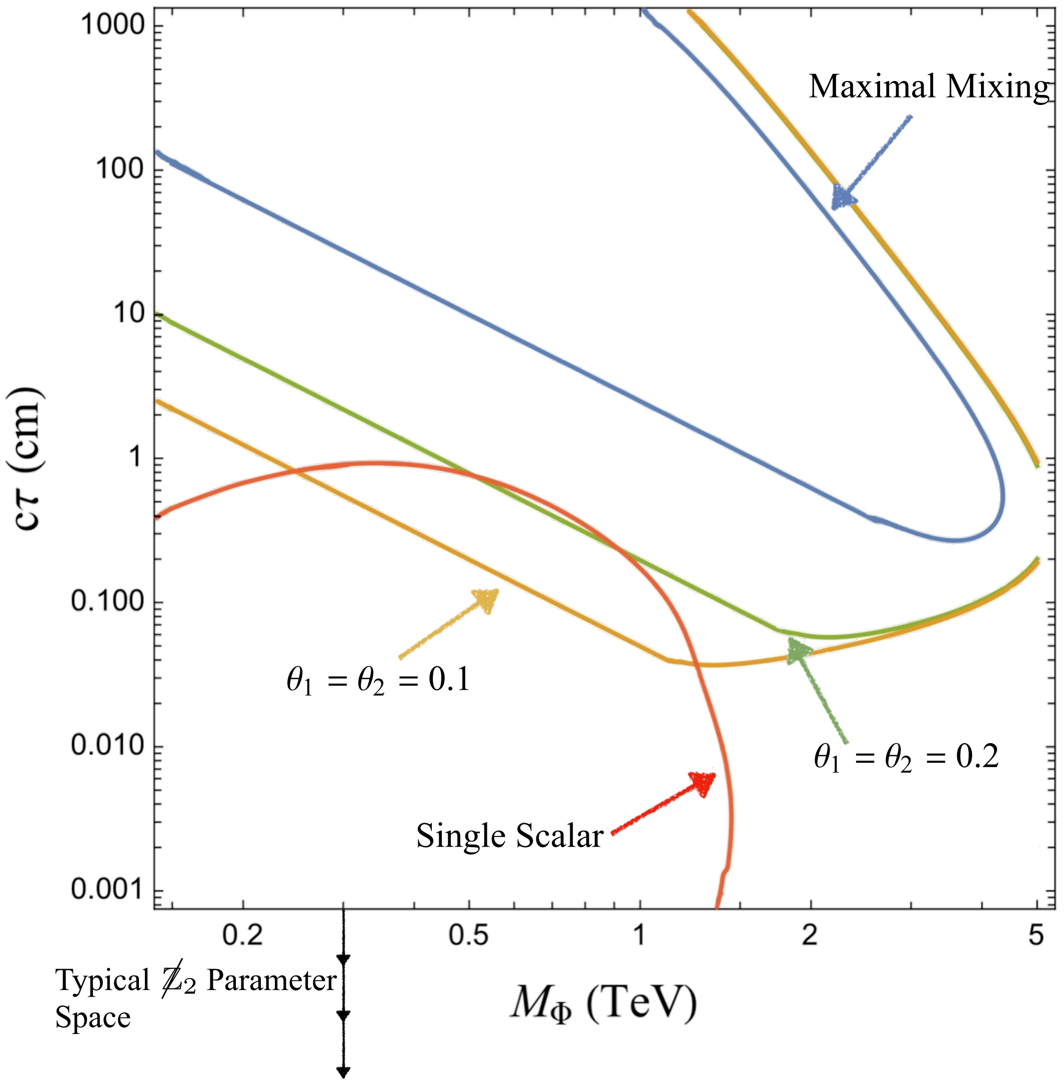
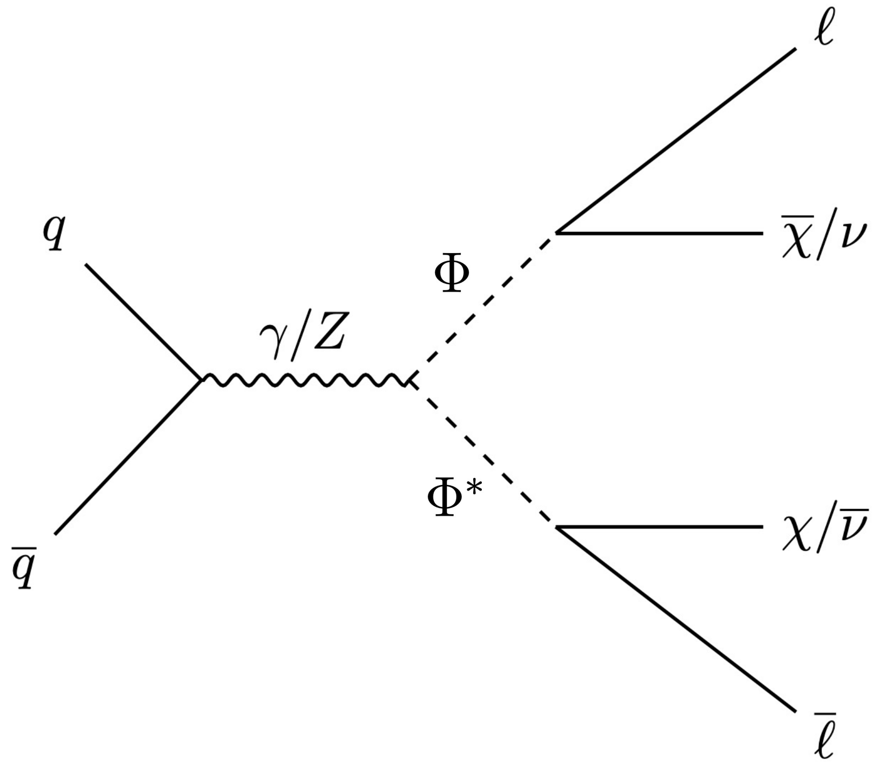
Experimental Constraints: Colliders





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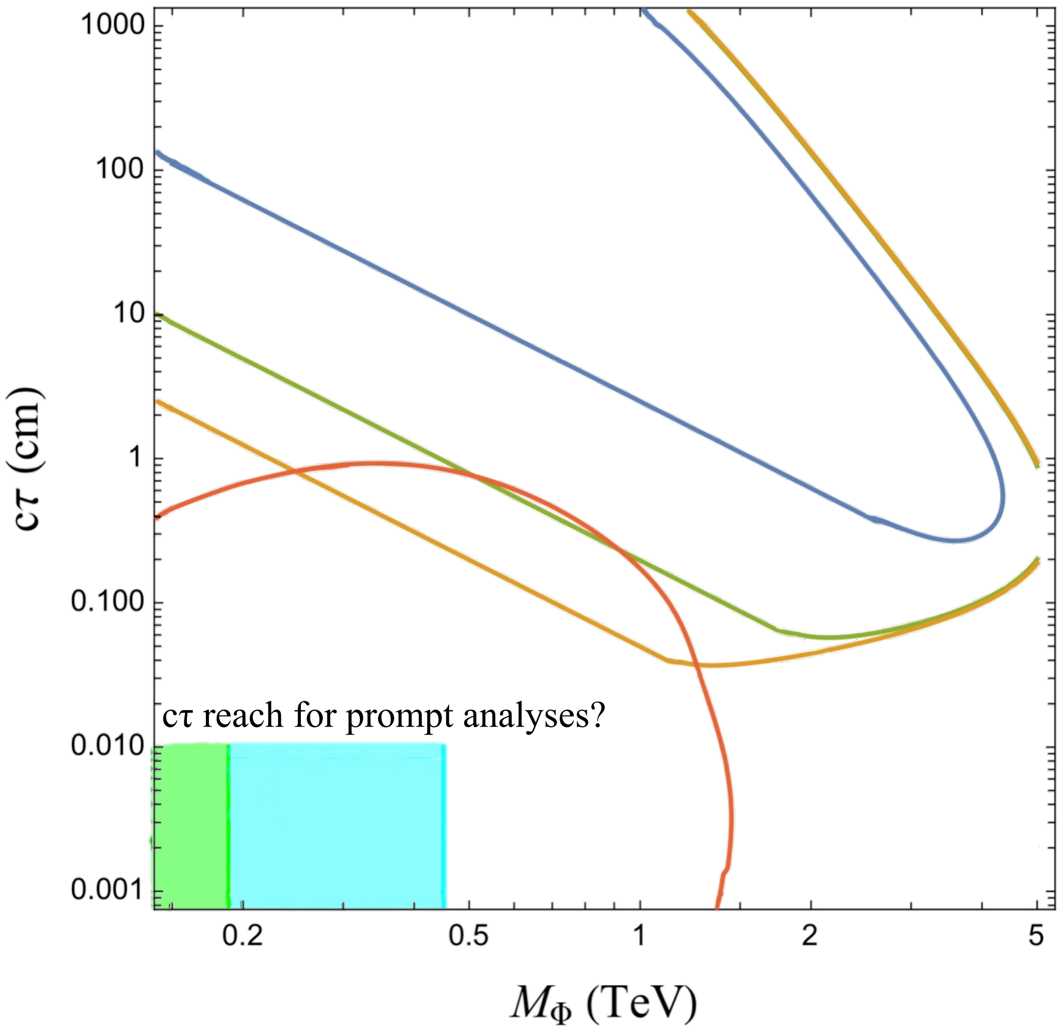

Prompt Decay (Φ decays 100% to μ)

Prompt Decay (Φ decays 50% to μ)

CMS Collaboration, arXiv:2012.08600
ATLAS Collaboration, arXiv: 1908.08215

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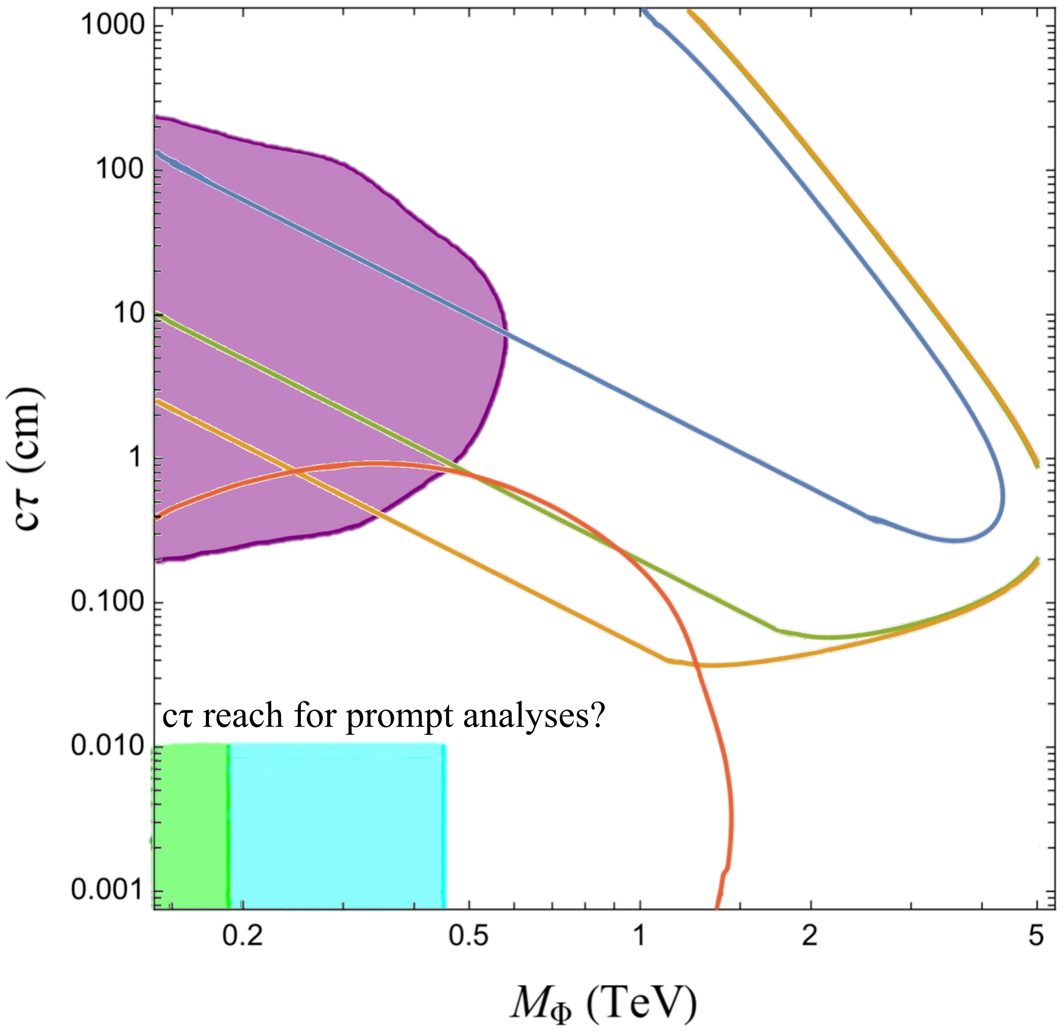

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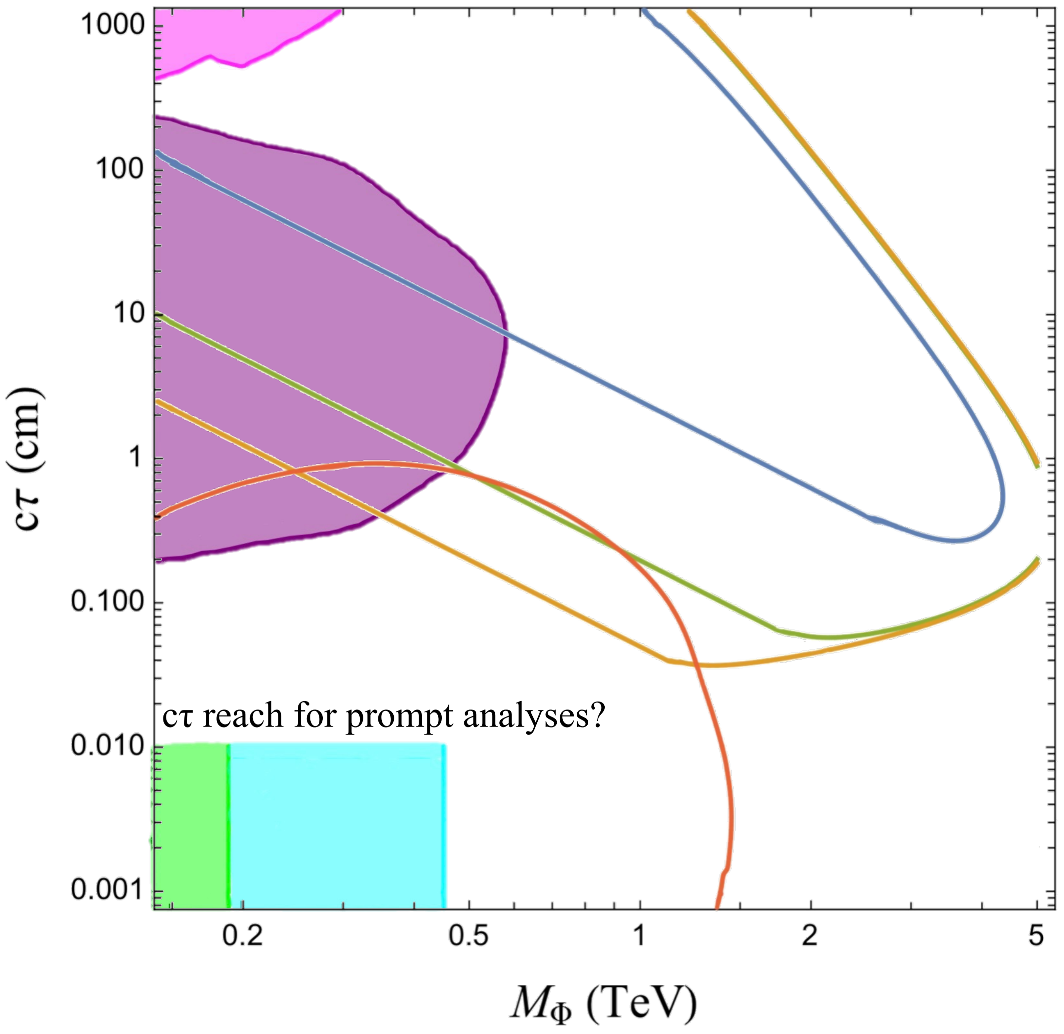

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ATLAS Collaboration, arXiv: 2011.07812

Decays Outside Detector (CMS HSCP)

CMS Collaboration, EXO-16-036-pas

Summary

- We propose a simple model that combines mechanisms for DM production and leptogenesis
- Various asymmetry generating scenarios lead to a broad range of possibilities for the scalar lifetime
- DM and leptogenesis constraints favor scalar masses in the hundreds of GeV to TeV range