Karlsruhe Institute of Technology

Conversion-Driven Baryogenesis with Quark-Philic Flavored Dark Matter

Based on ArXiv:26XX.XXXXX

Lena Rathmann

In collaboration with B. Belfatto, M. Blanke, J. Heisig, and F. Wilsch

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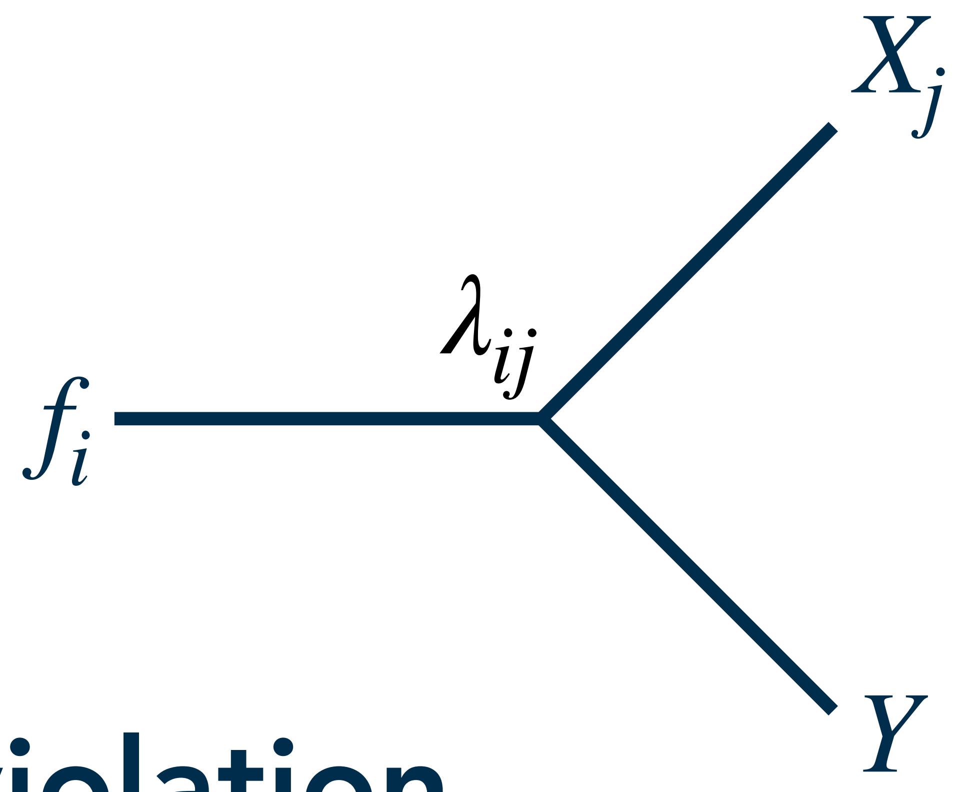
Why Flavored Dark Matter?

- Traditional WIMP models under severe pressure

  → Assume **DM has non-trivial flavor structure** like SM

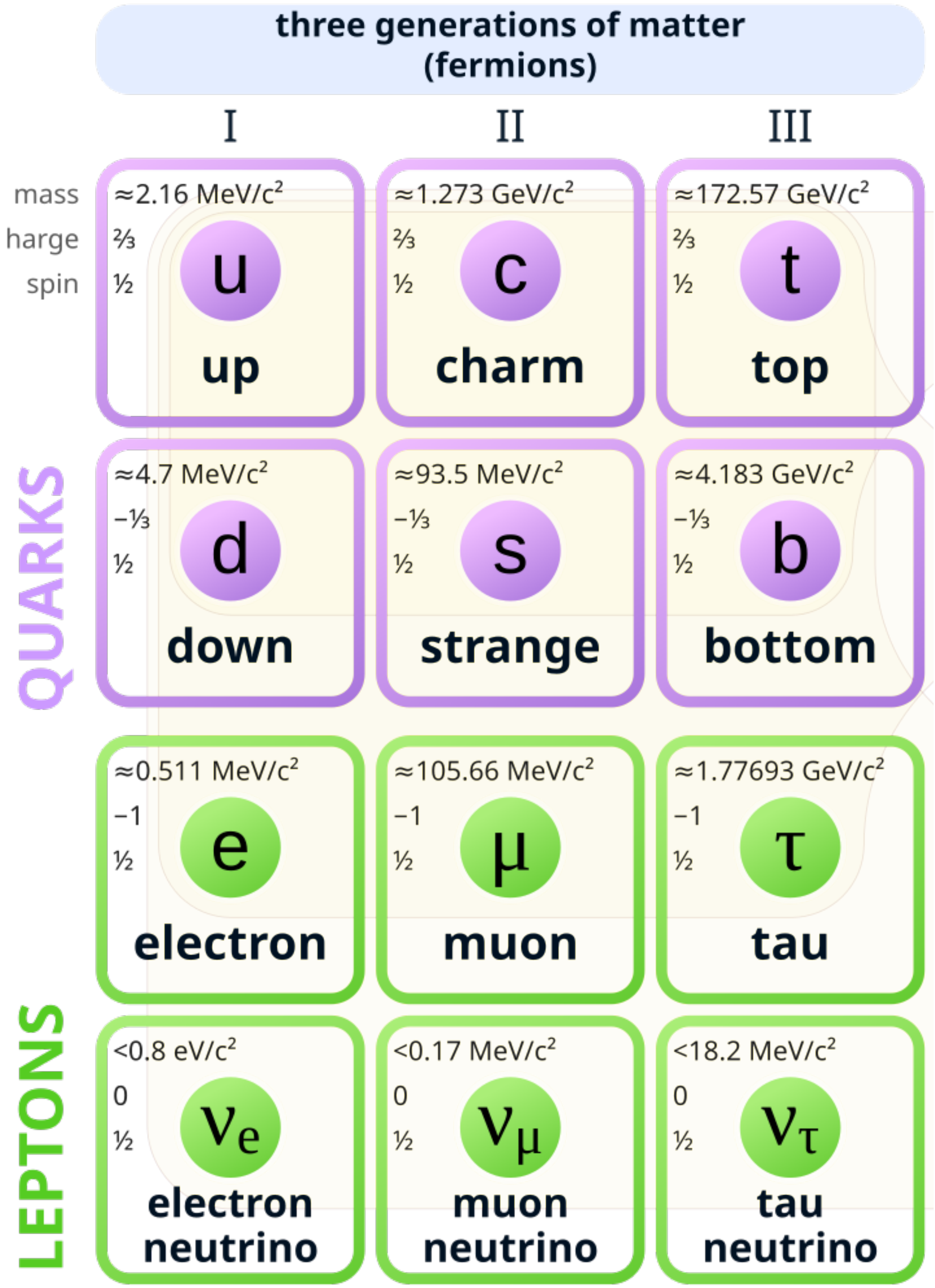
- **Couple to SM fermions** f through complex 3×3 matrix λ

$$\mathscr{L}_{\text{int}} = -\lambda_{ij}\bar{f}_i X_j Y + \text{h.c.}$$



- New source of **flavor and CP violation**

  → Different phenomenology like more complex freeze-out mechanism

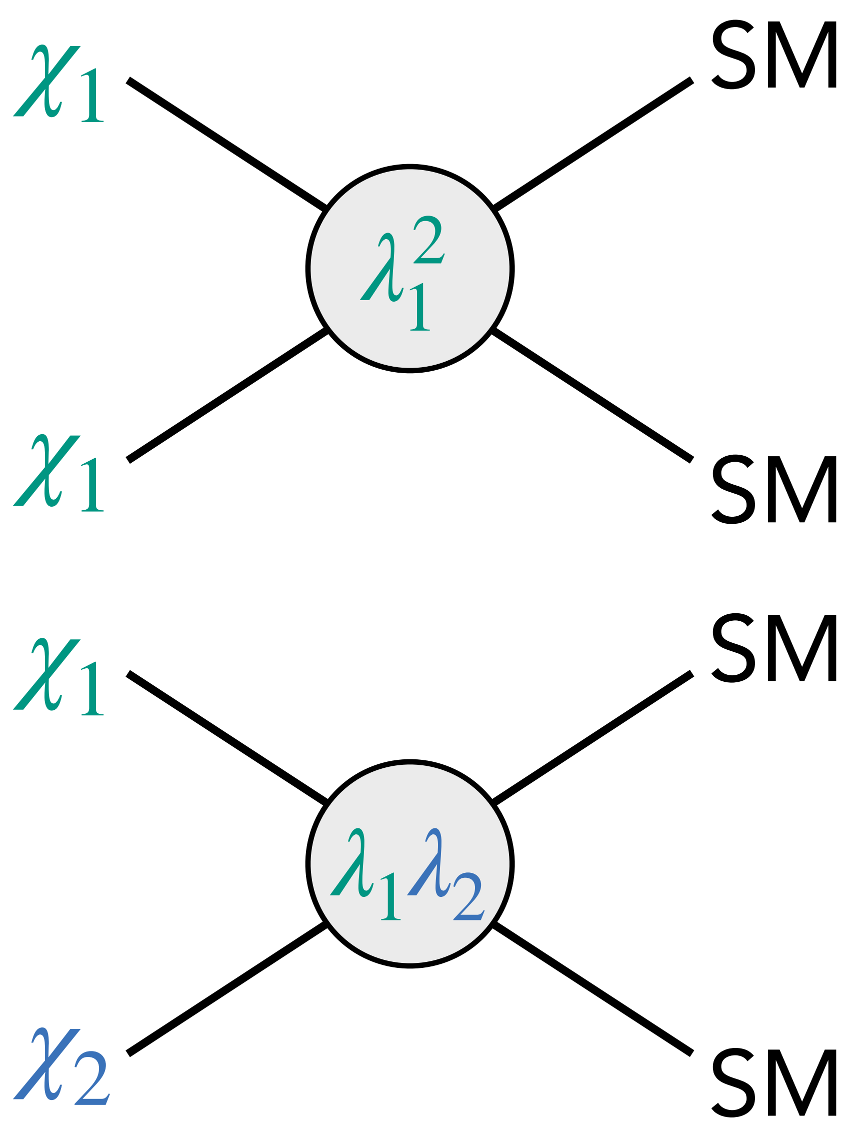


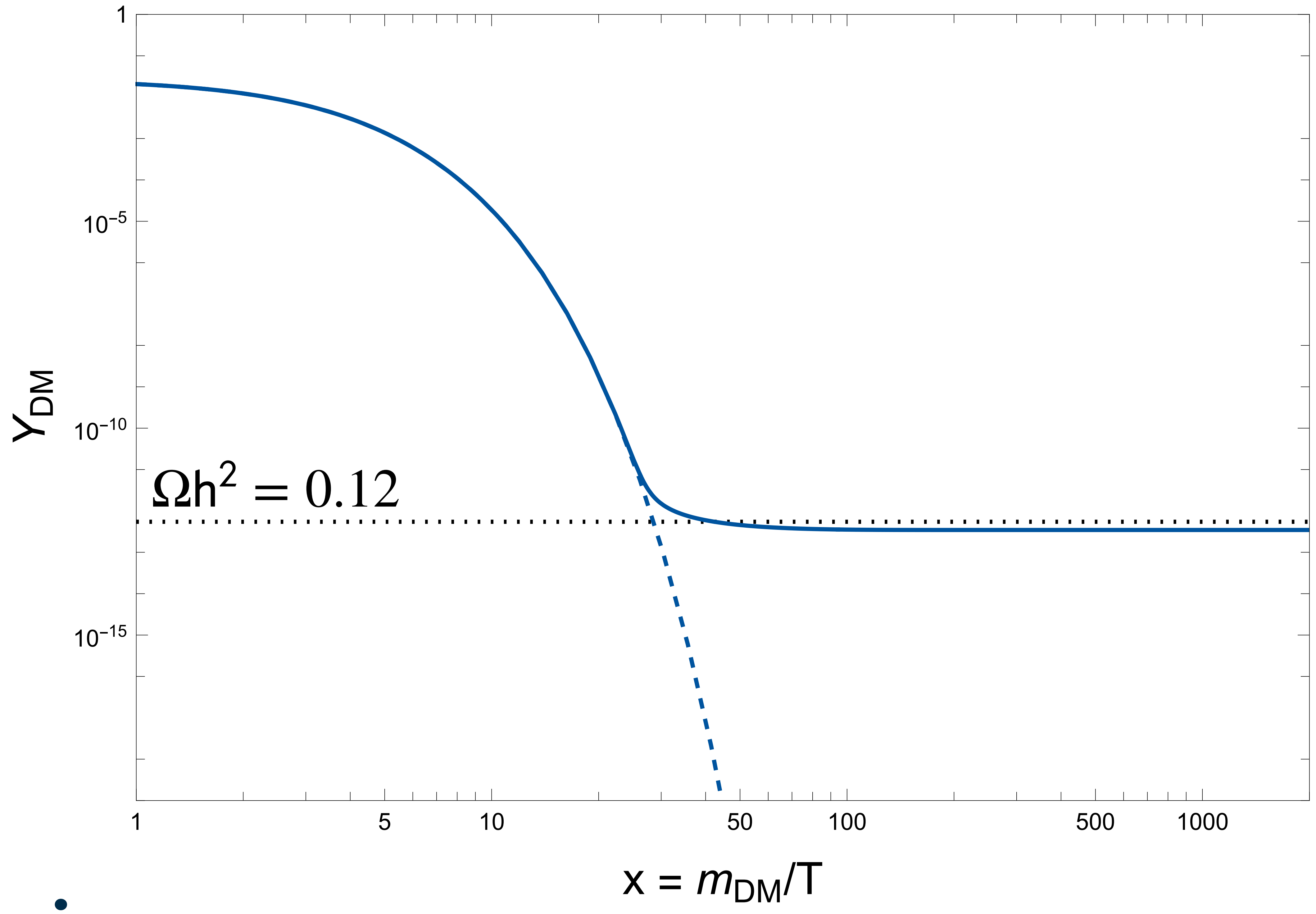
[Wikipedia]

Freeze-Out with Coannihilations

$\lambda_1 \sim \lambda_2$, couplings large

Dark Matter depletes through





Dark sector particles in **chemical equilibrium**

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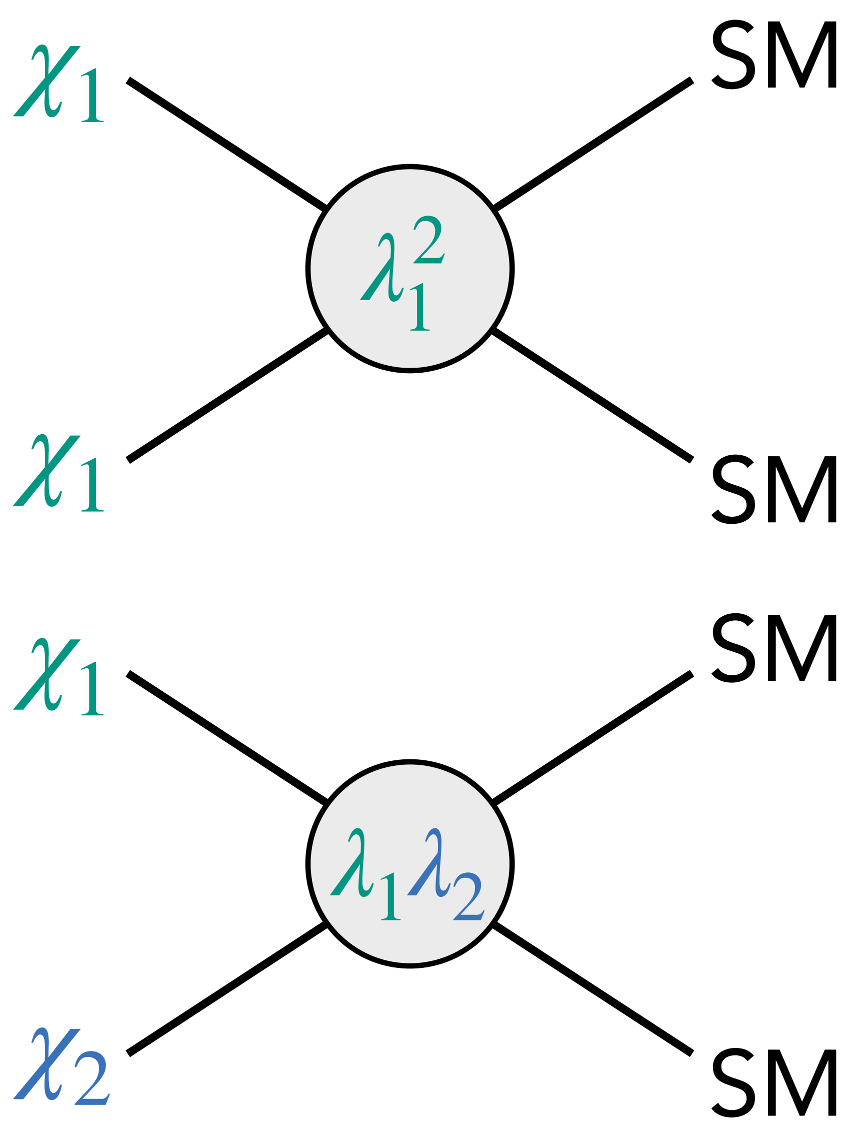
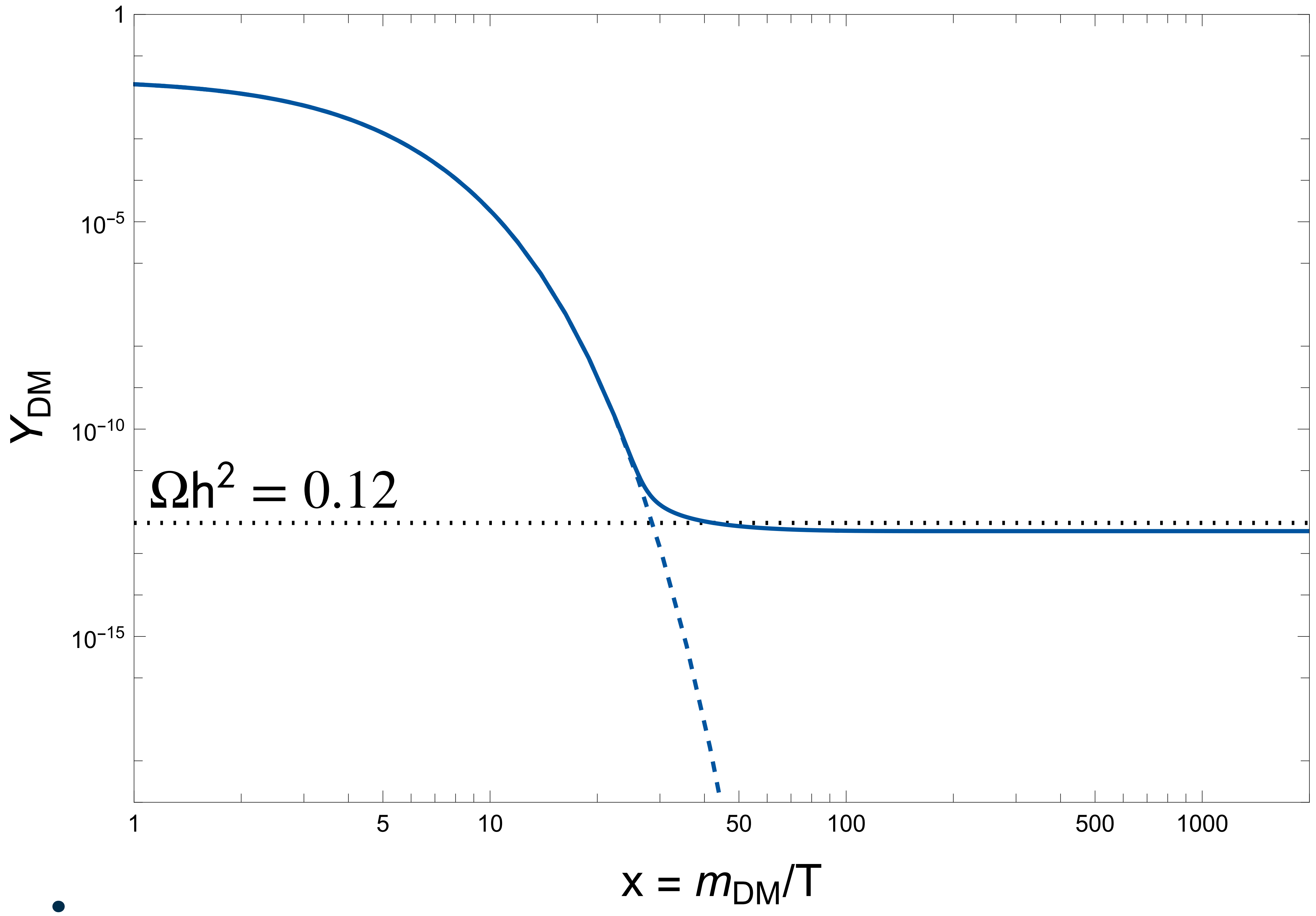


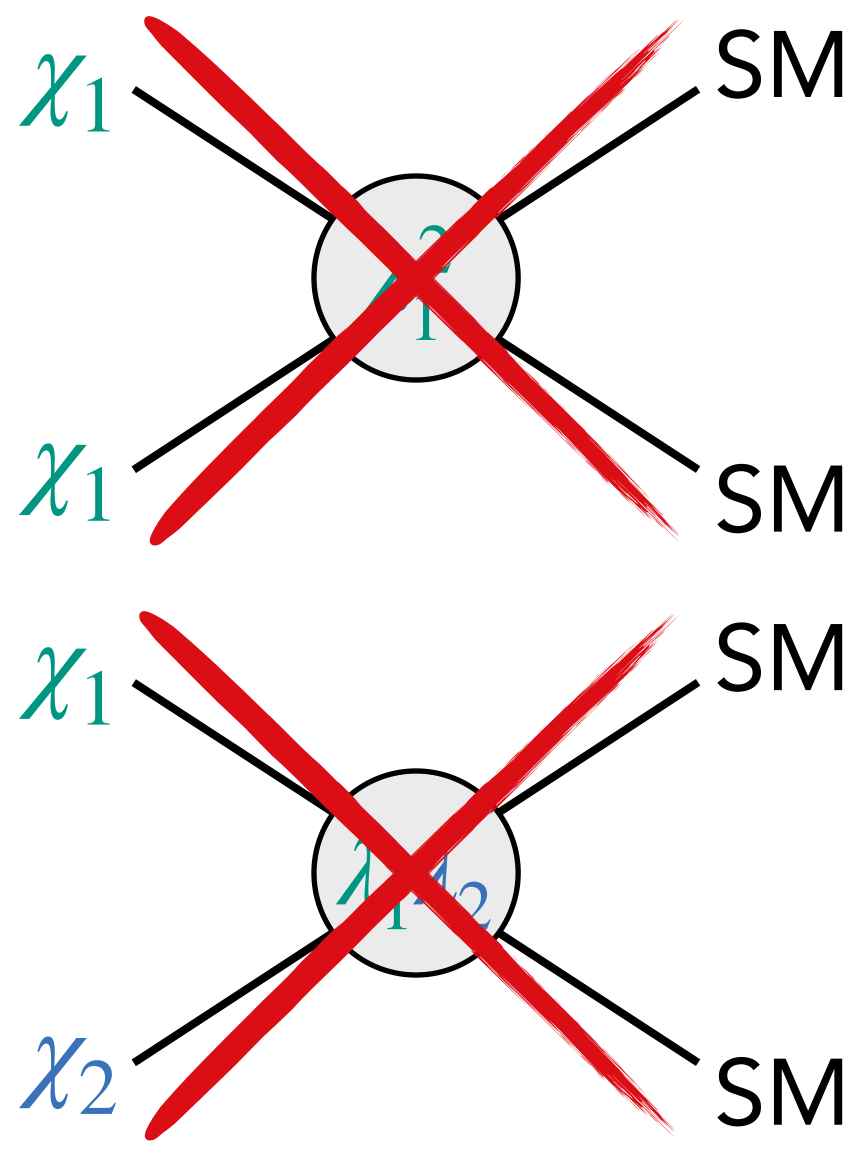


Dark sector particles in **chemical equilibrium**

→ Solve $$\frac{dY}{dx} = -\frac{1}{3H}\frac{ds}{dx}\langle\sigma_{\text{eff}}v\rangle(Y^2 - Y_{\text{eq}}^2)$$ where $$\langle\sigma_{\text{eff}}v\rangle = \sum_{ij}\langle\sigma_{ij}v_{ij}\rangle\frac{n_i^{\text{eq}}}{n^{\text{eq}}}\frac{n_j^{\text{eq}}}{n^{\text{eq}}}$$

Conversion-Driven Freeze-Out

λ_1 very small, λ_2 large



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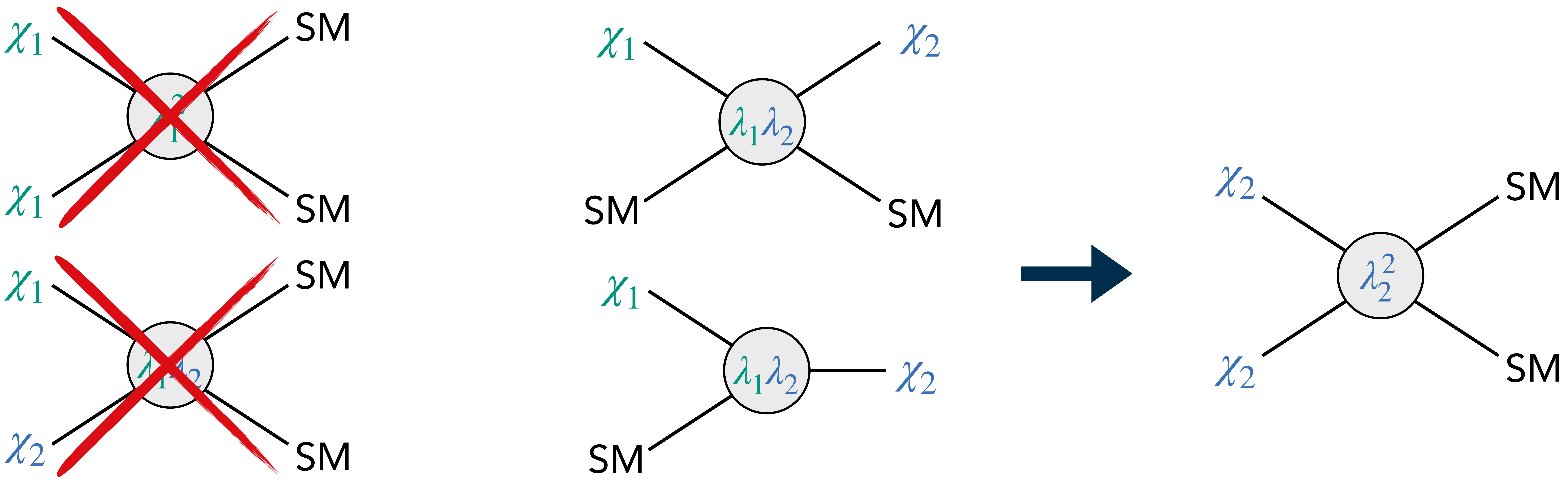
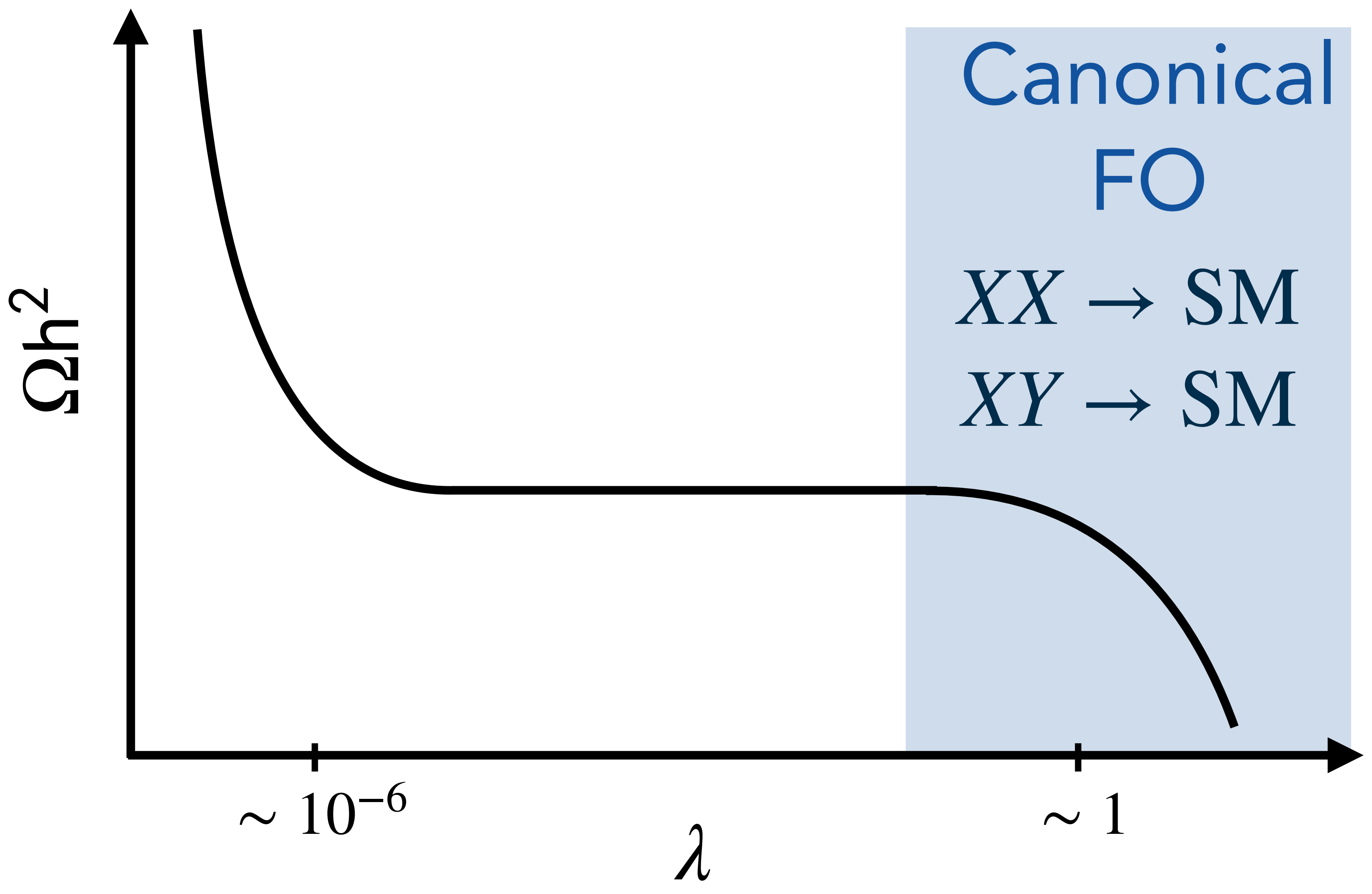


$\Gamma_{\text{conv}} \sim H \rightarrow$ **no chemical equilibrium**

→ Set of coupled Boltzmann equations needs to be solved for all contributing particles

Conversion-Driven Freeze-Out



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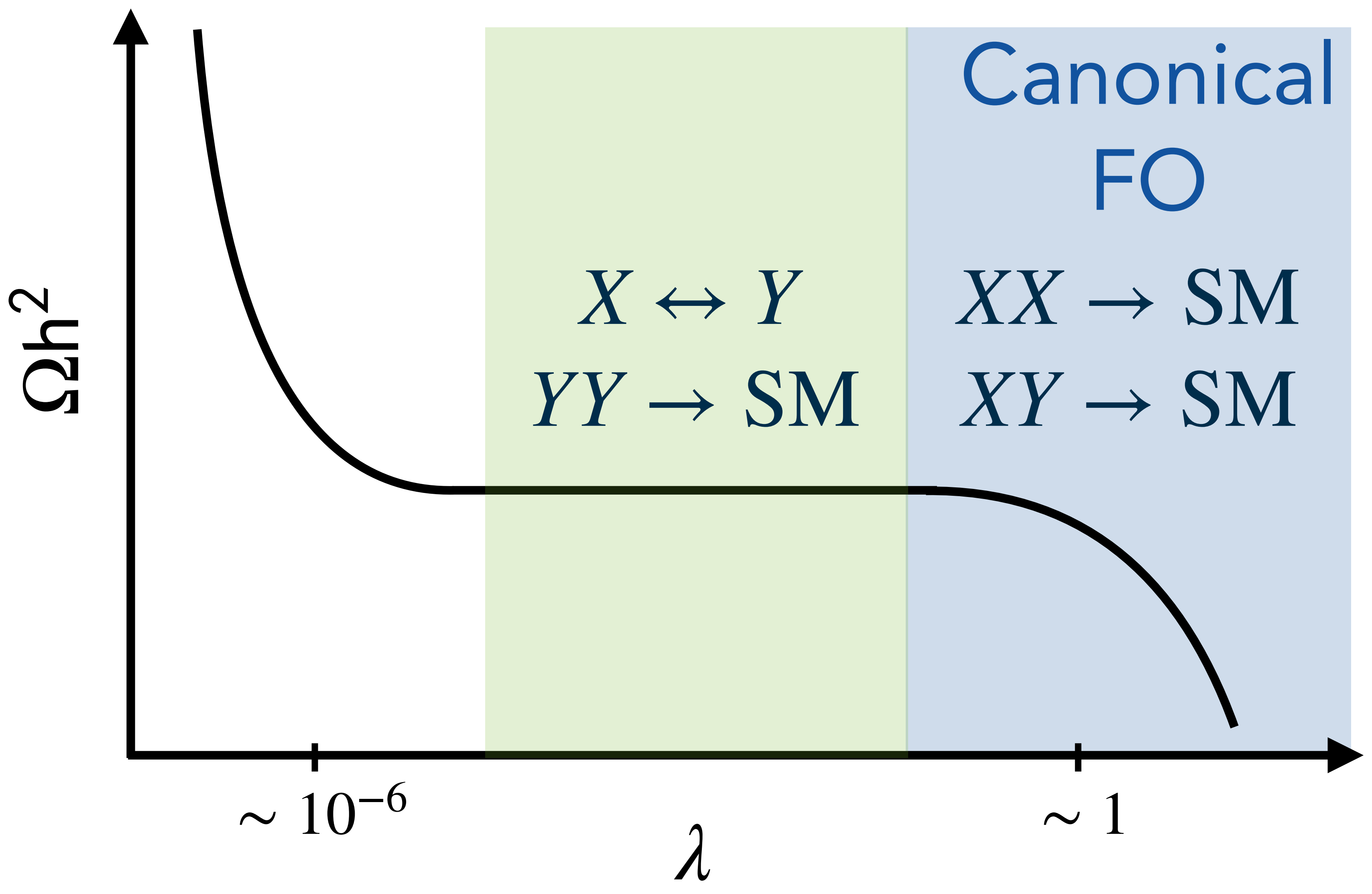

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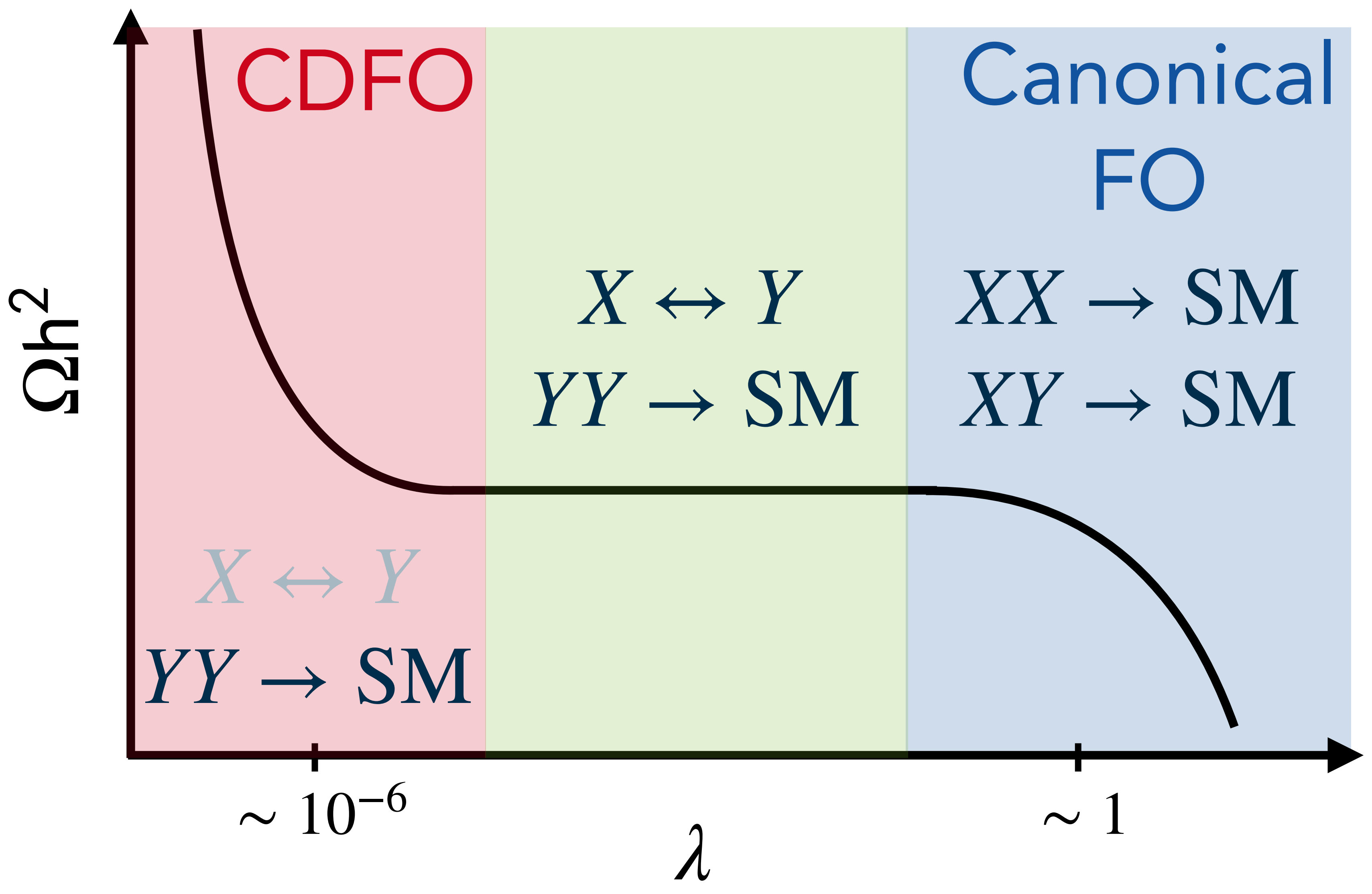
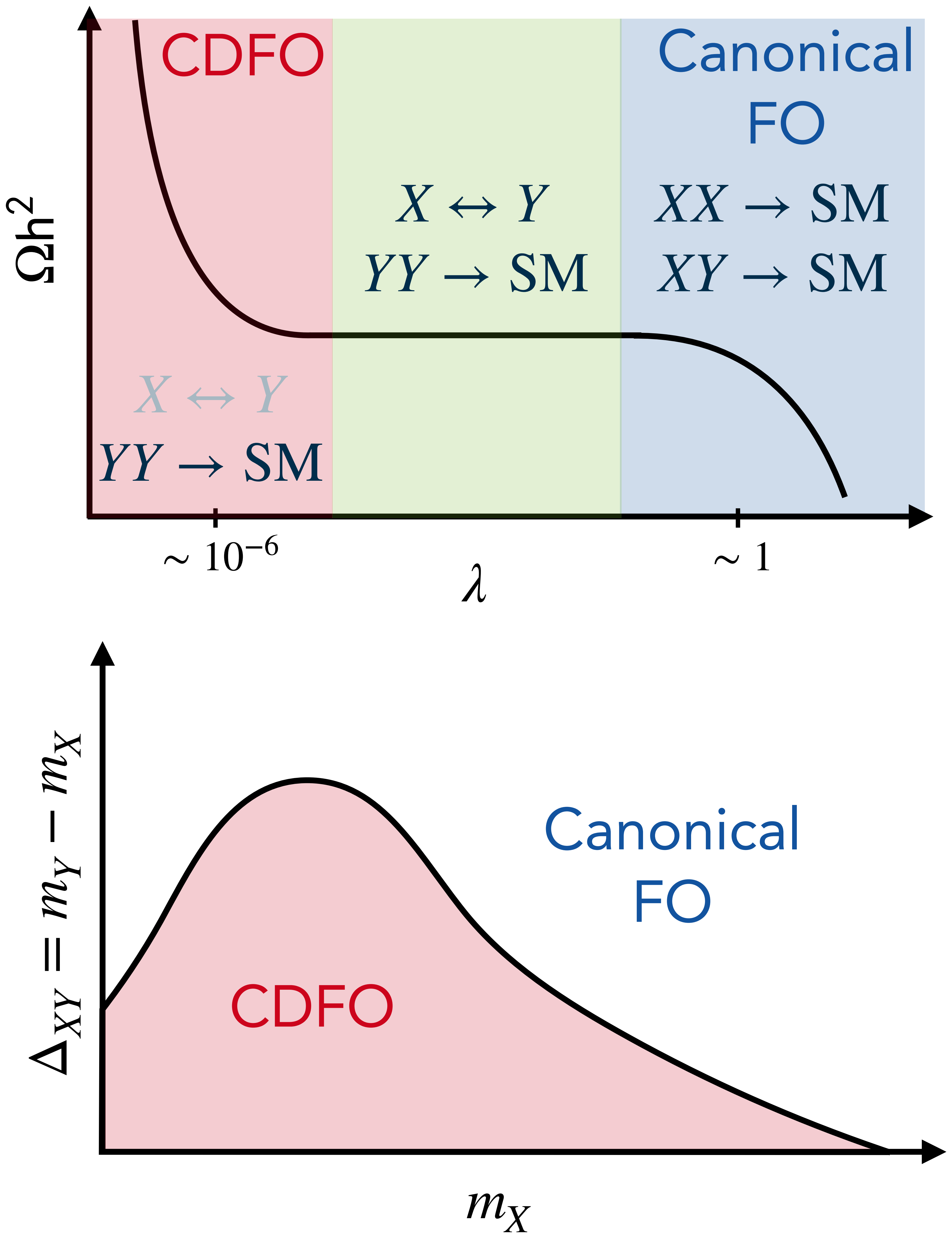


→ **Relic abundance is enhanced** for very small couplings

Conversion-Driven Freeze-Out



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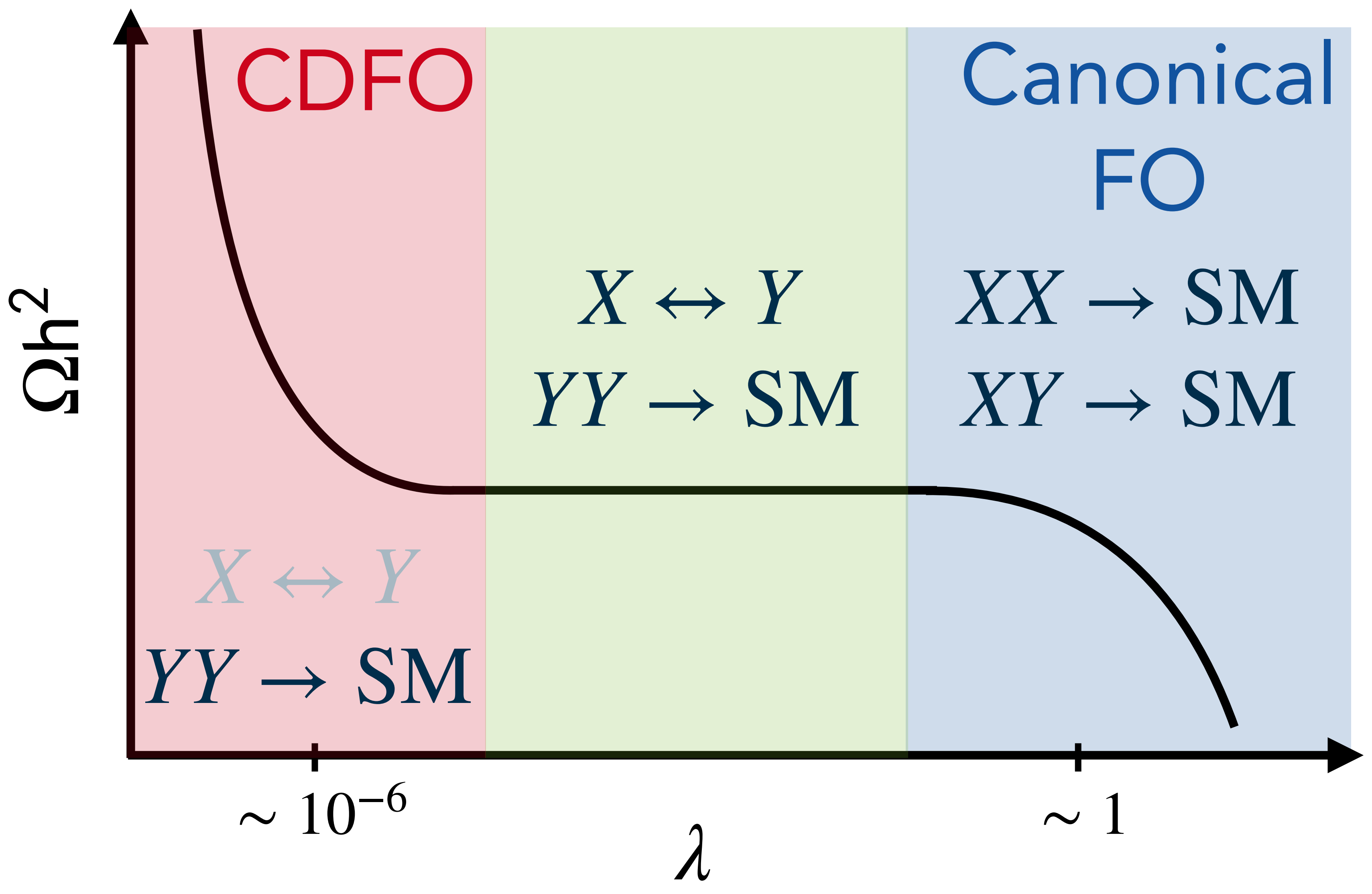

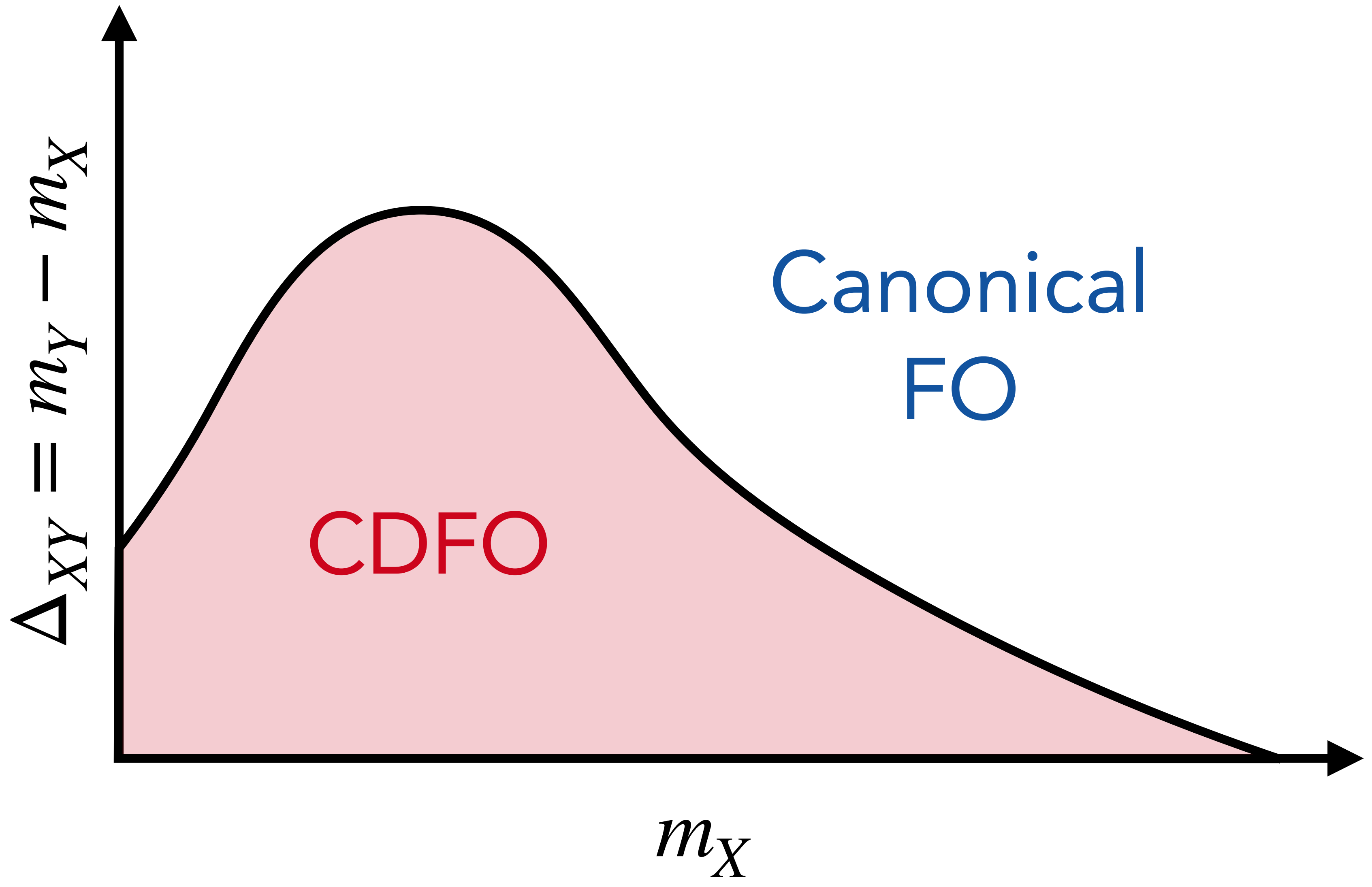

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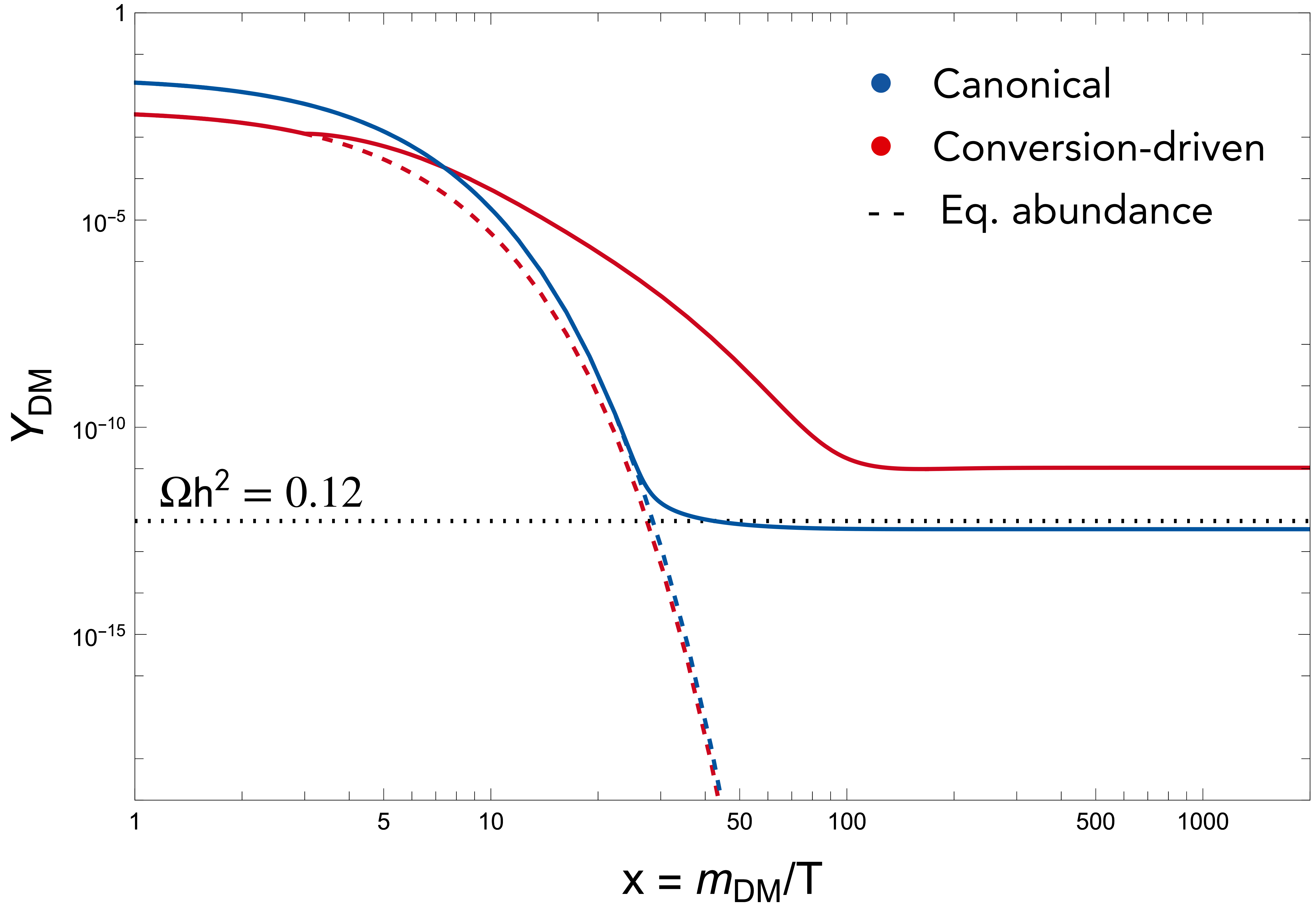
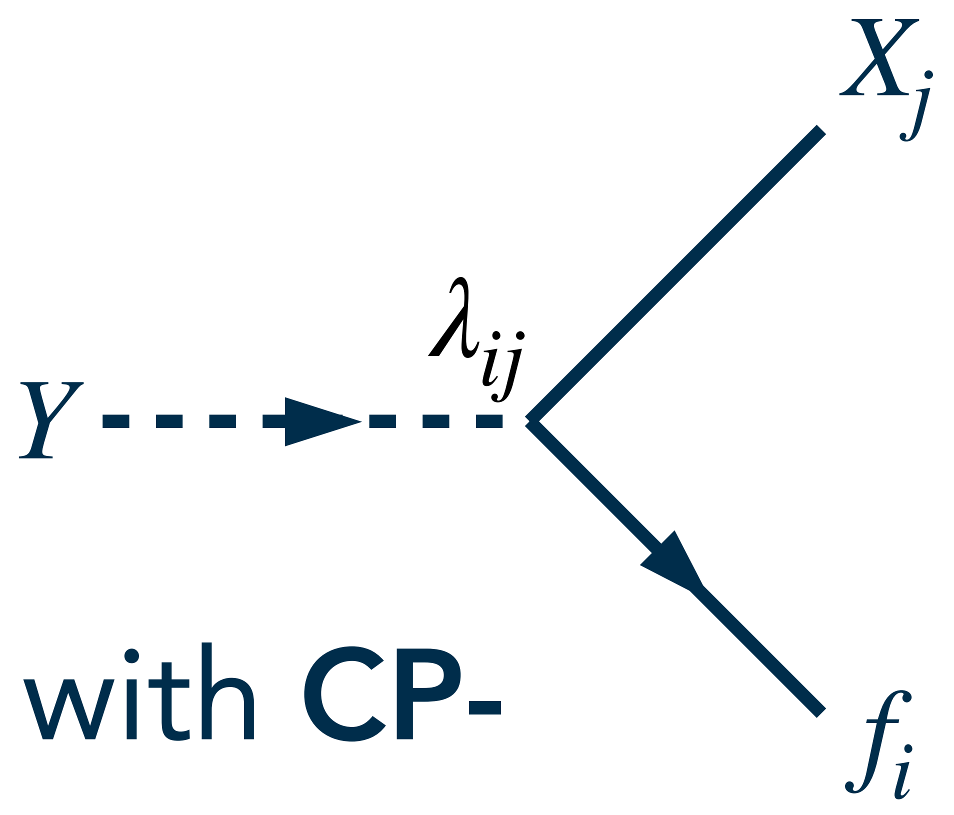


Baryon Asymmetry with Flavored DM



- **Sakharov conditions:**
  - C- and CP-symmetry violation — ✅ From conversion process with **CP-violating coupling**
  - Interactions out of equilibrium — ✅ **Early DM departure from equilibrium** because of very small couplings
  - Baryon number violation — ✅ **Sphaleron processes** violate $B + L$ in SM sector (but conserve $B - L$)

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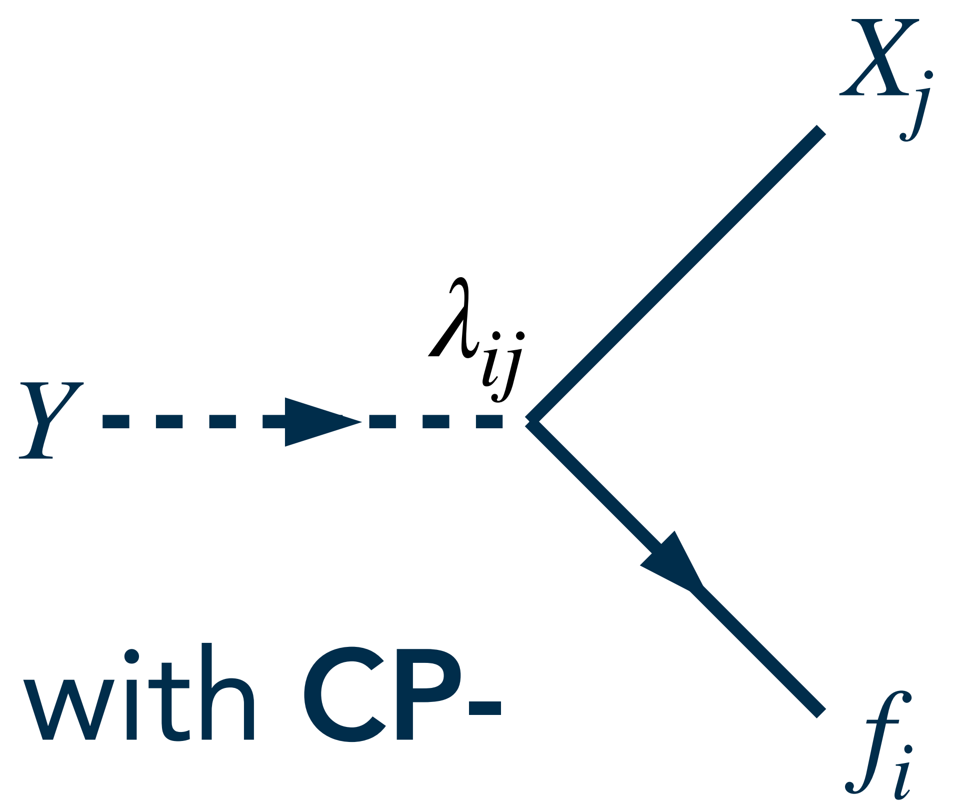

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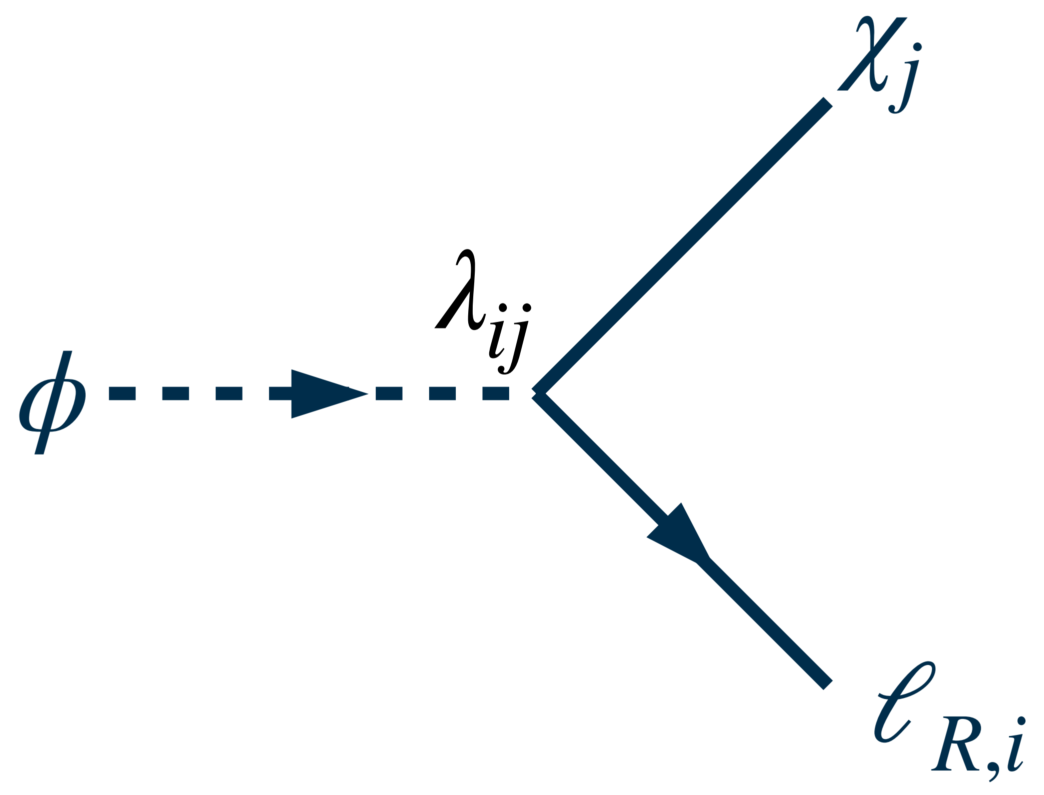
  - Baryon number violation — ✅ **Sphaleron processes** violate $B + L$ in SM sector (but conserve $B - L$)
- **Sphaleron processes:** non-perturbative transitions in the electroweak theory between topologically distinct vacua, active at high temperatures (until $T \sim 130$ GeV)

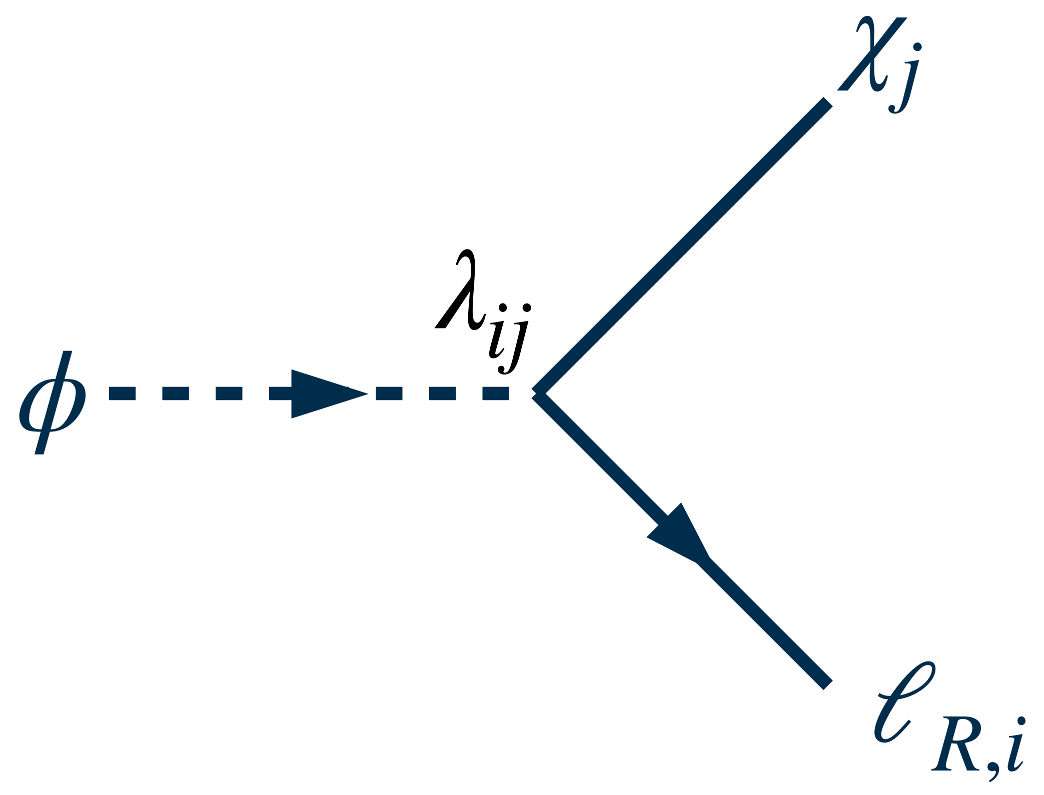
Conversion-Driven Leptogenesis

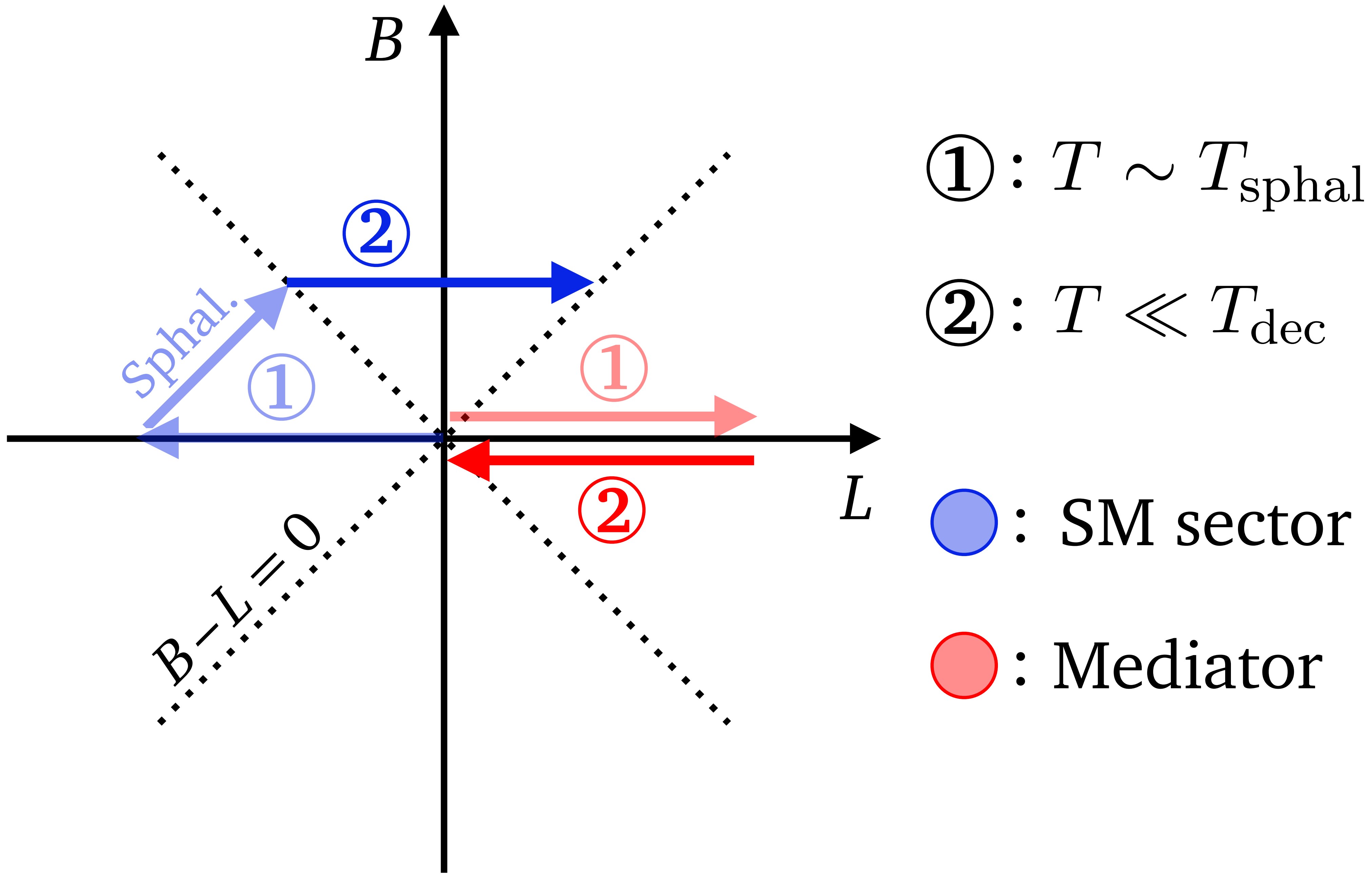
- Studied already using leptophilic flavored DM with 2 nearly mass-degenerate χ flavors



Conversion-Driven Leptogenesis

- Studied already using leptophilic flavored DM with 2 nearly mass-degenerate χ flavors
- Generate Δ_ϕ and Δ_{ℓ_R} through **CP-violating conversion** where $\Delta_A = Y_A - Y_{\bar{A}}$
- Lepton number conserved overall
  $\rightarrow \Delta_\phi = -\Delta_{\ell_R} = -\Delta L$
- **Sphaleron processes convert ΔL to ΔB,** only affecting SM
- After sphaleron decoupling, ϕ decays and asymmetry is removed





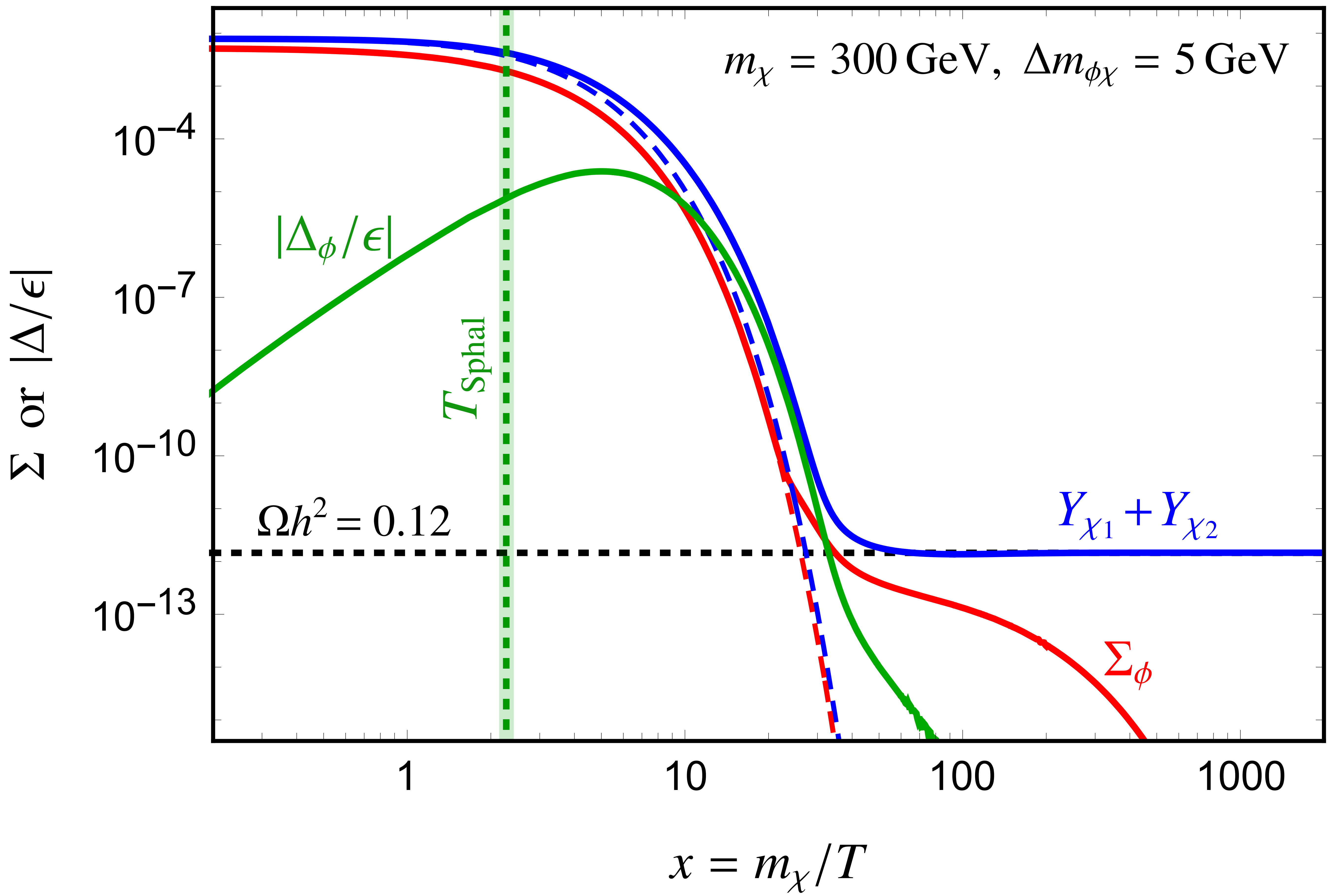
Conversion-Driven Leptogenesis

- CP-asymmetry in $\phi \to \chi_i \ell_R$ decay

$$\epsilon_i = \frac{\Gamma_i^- - \Gamma_i^+}{2\Gamma_i},\ \epsilon \equiv \epsilon_1$$

- **Asymmetry $\Delta_\phi = Y_\phi - Y_{\bar\phi}$ large** at sphaleron decoupling temperature
- Can be converted into Baryon asymmetry with

$$Y_{\Delta B} \approx -\frac{28}{79}\epsilon \left.\frac{\Delta_\phi}{\epsilon}\right|_{T=T_{\mathrm{Sphal}}}$$



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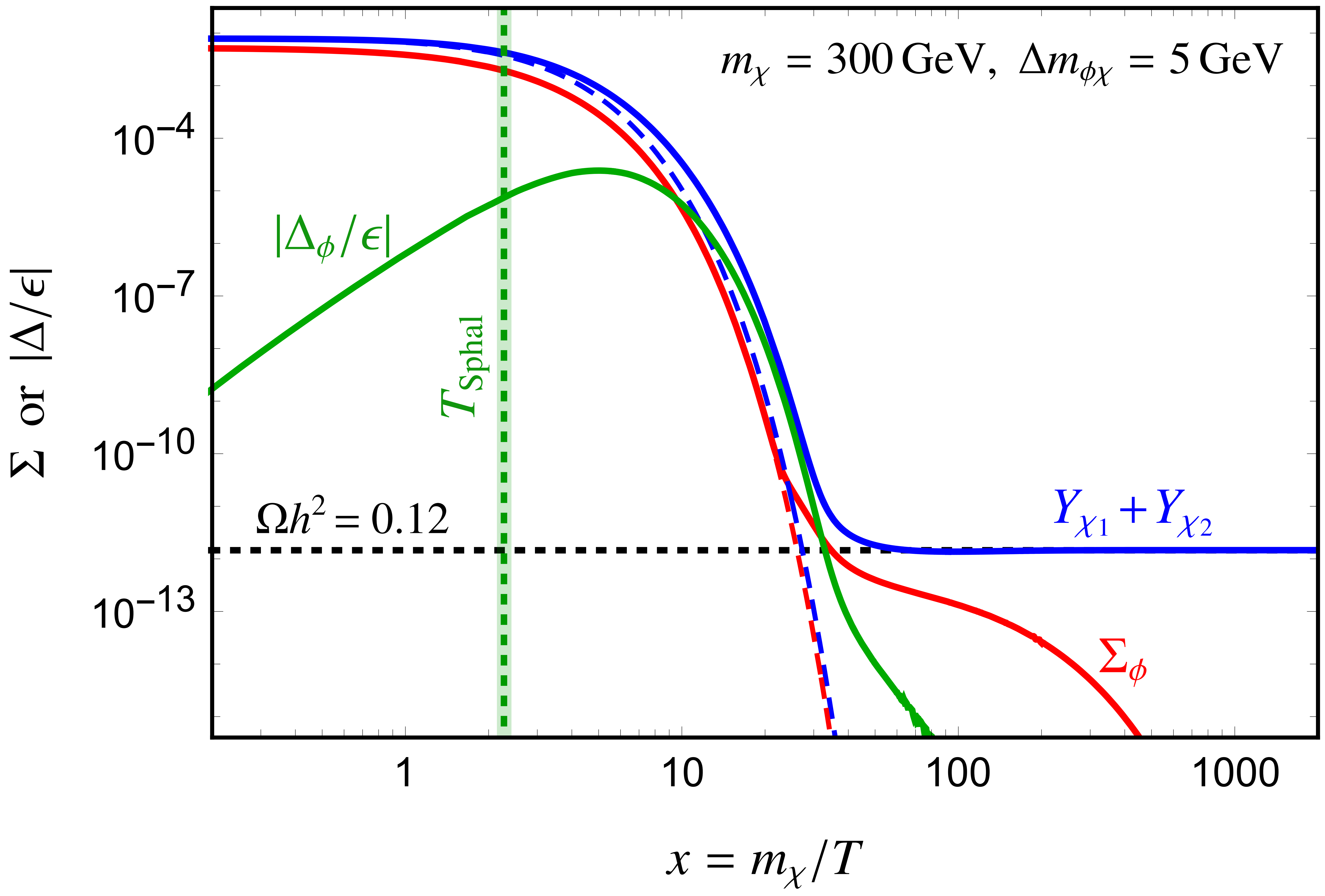
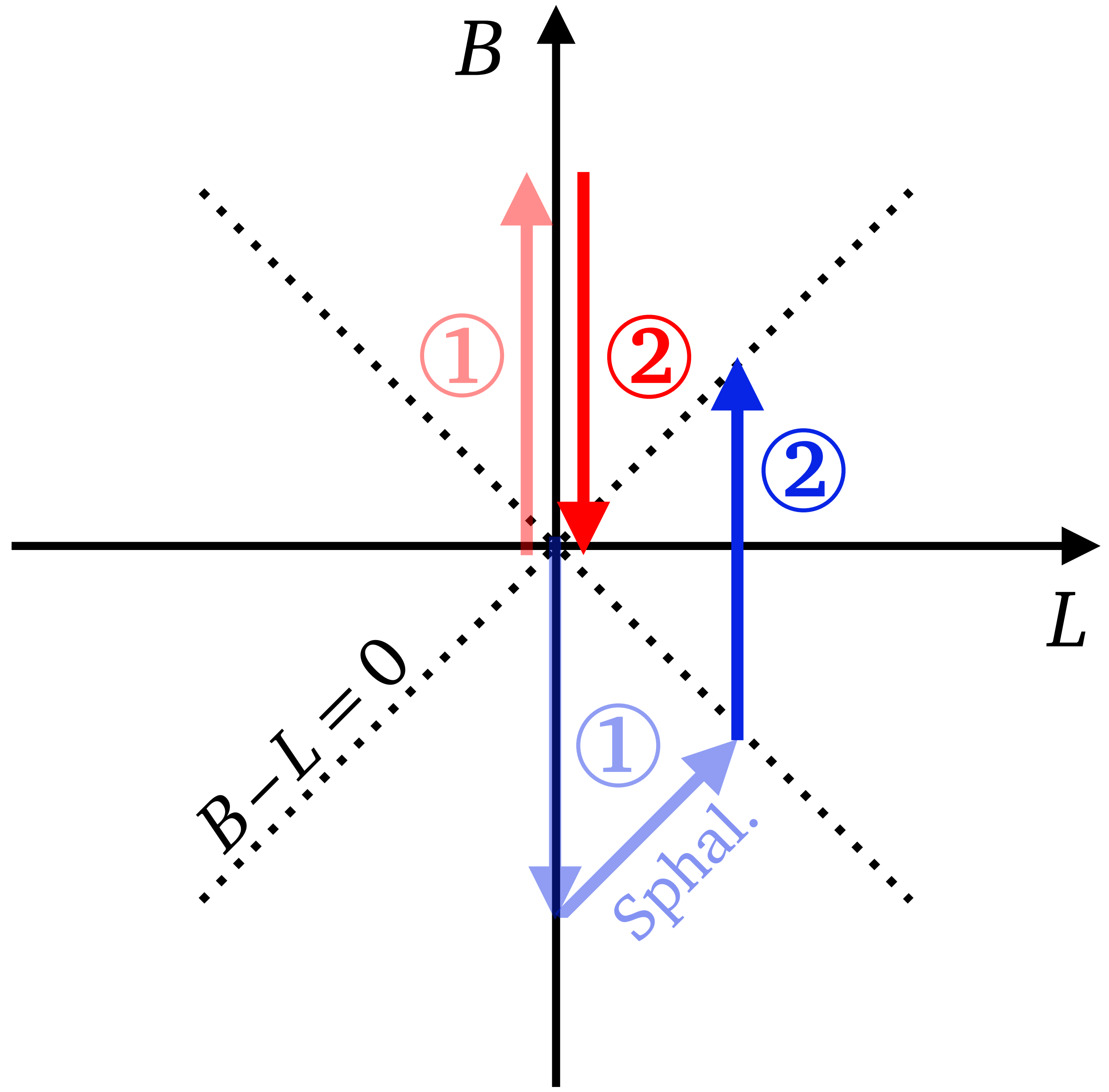


→ Study case for quark-philic model, include thermal corrections

Preliminary

Conversion-Driven Baryogenesis



①: $T \sim T_{\text{sphal}}$

②: $T \ll T_{\text{dec}}$

●: SM sector

●: Mediator

- Use flavored DM model **coupling to right-handed down-type quarks** with 2 flavors
- **Include Sommerfeld enhancement** and **bound state formation effects** from [Binder et al. 2025] for $\phi\phi$ pair-annihilation

Conversion-Driven Baryogenesis

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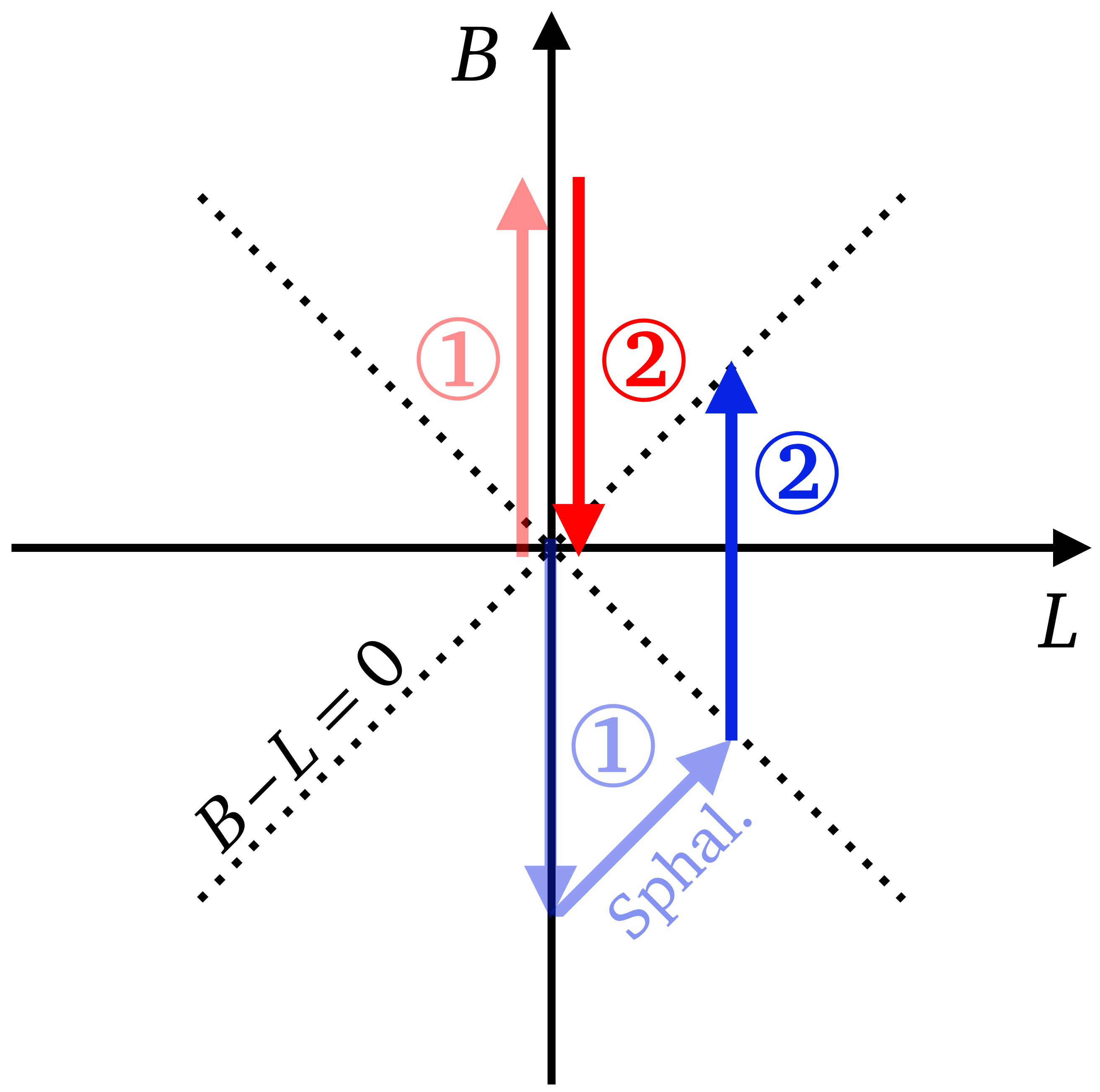

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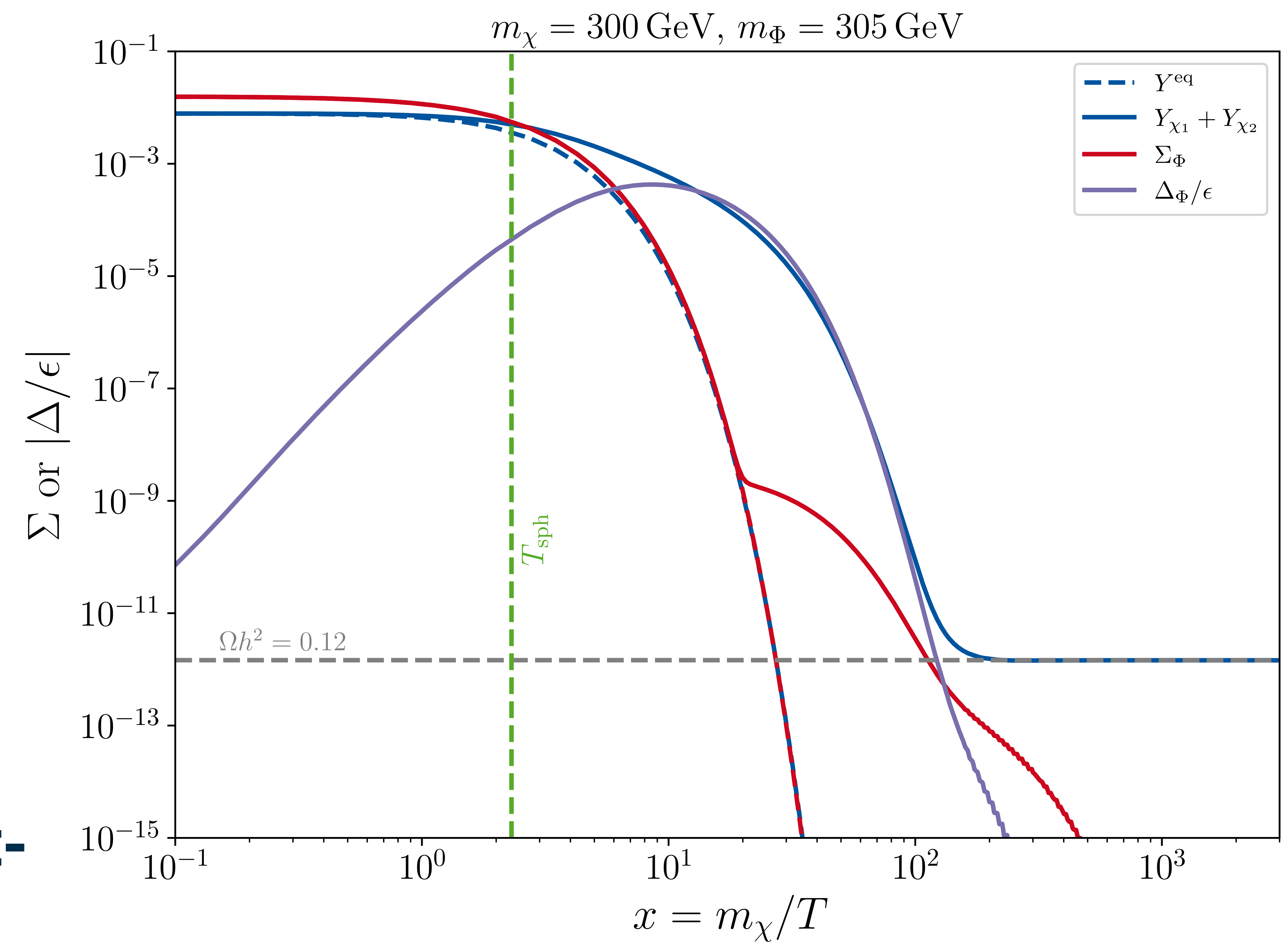
SM sector

Mediator



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Convert into baryon asymmetry:

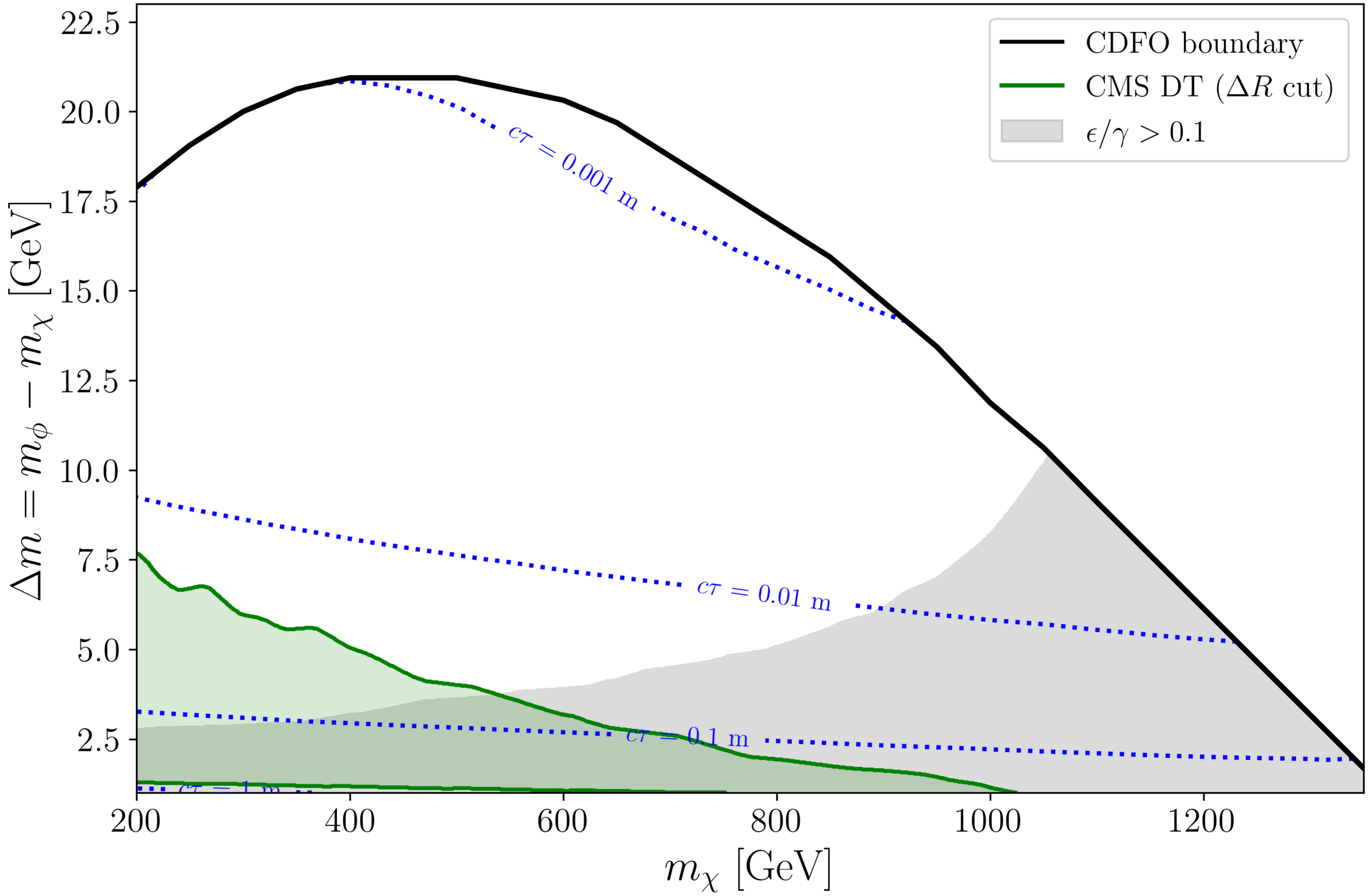
$$Y_{\Delta B} = -\frac{21}{79}\epsilon \left.\frac{\Delta_\phi}{\epsilon}\right|_{T=T_{\rm Sphal}}$$

Viable Parameter Space

Preliminary

- Solution possible for $\Omega h^2 = 0.12$ **and** $Y_{\Delta B} = 0.9 \times 10^{-10}$ with $\epsilon \sim 10^{-6} - 10^{-3}$
- Couplings of order $\mathcal{O}(10^{-7})$ $\rightarrow$ evade direct and indirect searches, possible to **look for disappearing tracks** (DT) at LHC
- For $\epsilon/\gamma > 0.1$ validity of computation questionable

Branching fraction $\phi \rightarrow \chi_1$: 0.95



Limits reinterpreted from [Heisig et al. 2024]

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- Proposed displaced vertices (DV) +MET search could cover most of parameter space

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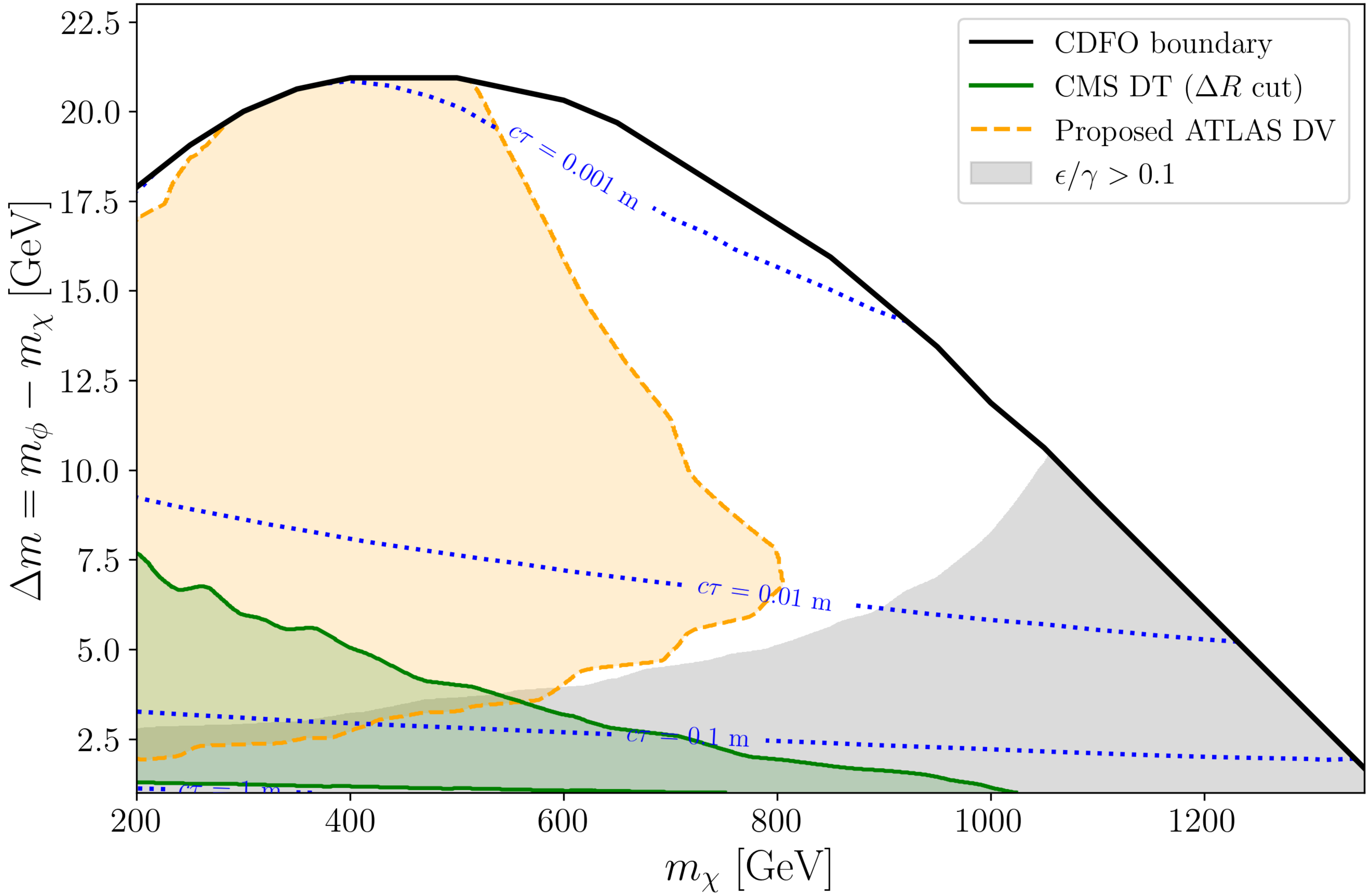
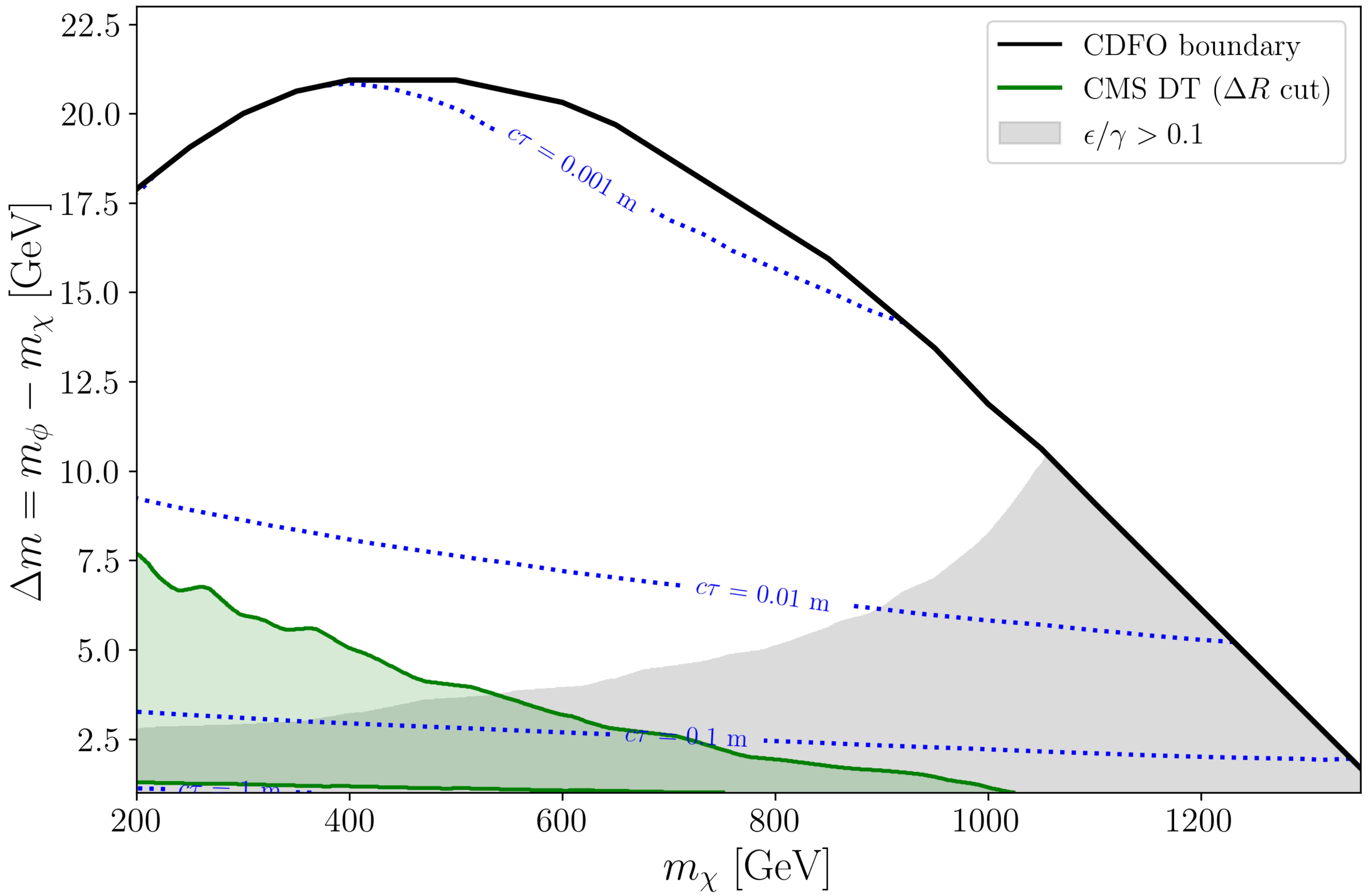


Limits reinterpreted from [Heisig et al. 2024]

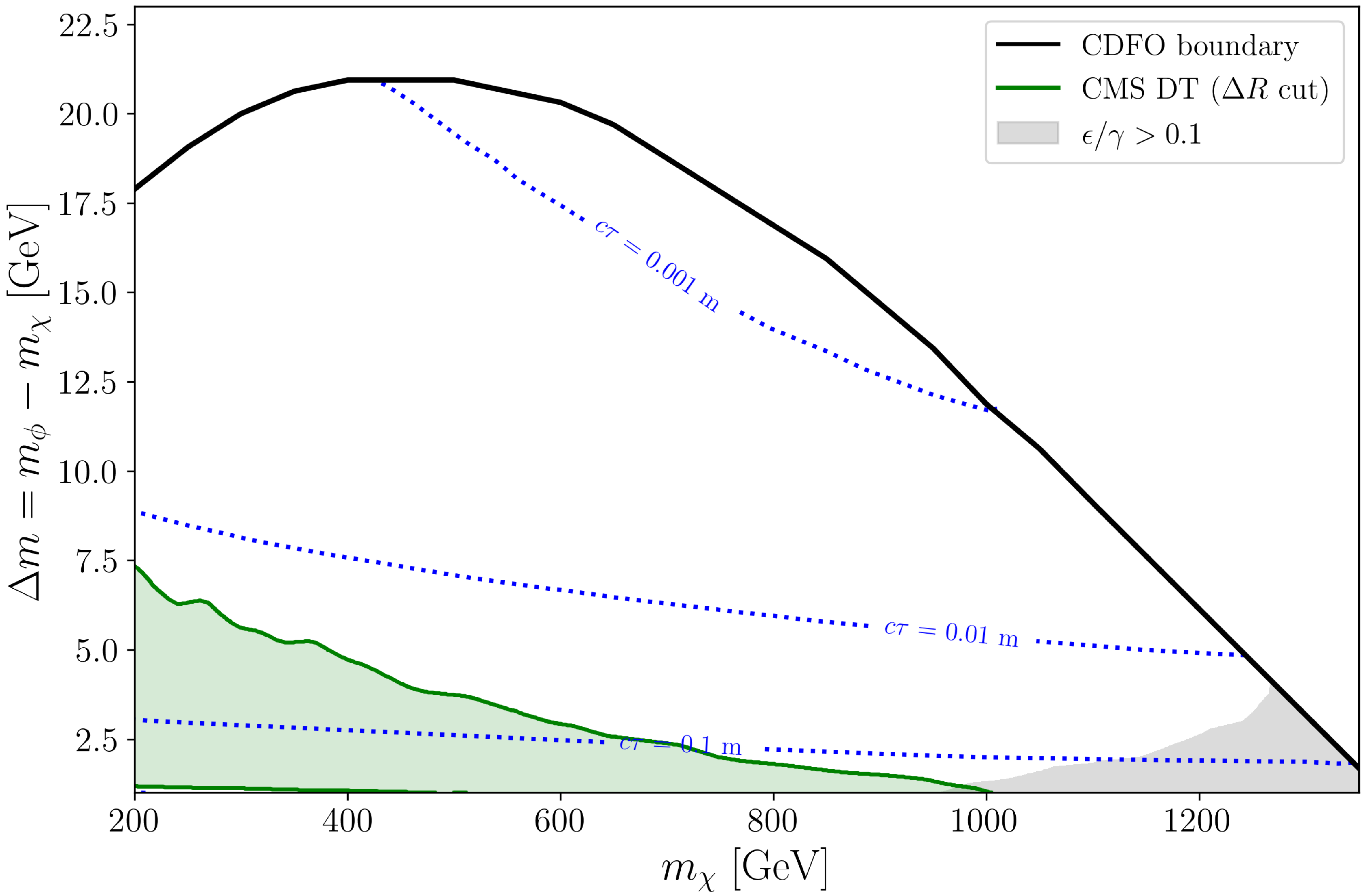
Thermal Effects

- Include **thermal effects for propagators** using real time formalism and include **thermal masses** of particles

Without thermal masses



With thermal masses



Conclusions

- **Conversion-driven freeze-out** scenario in flavored DM models allows for couplings $\lambda \sim 10^{-7}$ $\rightarrow$ provides **correct relic abundance** while **evading WIMP constraints** and **fulfills Sakharov conditions**
- **Conversion-driven baryogenesis** can produce viable dark matter candidate and baryon asymmetry at the same time in large region of parameter space
- **Solution possible up to DM masses of $\sim$ 1200 GeV** (compared to leptogenesis case with DM masses only up to 500 GeV)
- Most of the parameter space is **testable at colliders** with existing DV or proposed DT searches

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Thank you!

Backup Slides

Majorana DM Coupling to d_R

- Dark matter flavor triplet $\tilde{\chi}$, mediator φ
- New physics contribution with flavor and CP violating interaction:

$$\mathcal{L}_{\text{NP}} \supset \frac{1}{2}\bar{\tilde{\chi}}(i\partial\!\!\!/ - M_{\tilde{\chi}})\tilde{\chi} + (D_\mu\varphi)^\dagger(D^\mu\varphi) - M_\varphi^2\varphi^\dagger\varphi + (\lambda_{ij}\,\bar{d}_{R,i}\,\tilde{\chi}_j\,\varphi + \text{h.c.})$$
$$+\lambda_{\varphi\varphi}(\varphi^\dagger\varphi)^2 + \lambda_{\varphi H}(\varphi^\dagger\varphi)(H^\dagger H)$$

Conversion Driven Freeze-Out

- Conversions $\chi_i \leftrightarrow \chi_j$ or $\chi_i \leftrightarrow \phi$ can become inefficient during freeze-out when conversion rate $\Gamma \sim H$
- Chemical equilibrium breaks down $\rightarrow$ coupled BME of all particles need to be solved

$$\frac{dY_{\chi_i}}{dx} = \frac{1}{3H}\frac{ds}{dx}\left(\langle\sigma_{\chi_i\chi_j}v\rangle(Y_{\chi_i}Y_{\chi_j} - Y^{\rm eq}_{\chi_i}Y^{\rm eq}_{\chi_j}) + \frac{\Gamma_{\chi_i\to\chi_j}}{s}\left(Y_{\chi_i} - Y_{\chi_j}\frac{Y^{\rm eq}_{\chi_i}}{Y^{\rm eq}_{\chi_j}}\right) + \langle\sigma_{\phi\chi_i}v\rangle(Y_{\chi_i}Y_{\phi} - Y^{\rm eq}_{\chi_i}Y^{\rm eq}_{\phi}) - \frac{\Gamma_{\phi\to\chi_i}}{s}\left(Y_{\phi} - Y_{\chi_i}\frac{Y^{\rm eq}_{\phi}}{Y^{\rm eq}_{\chi_i}}\right)\right)$$

$$\frac{dY_{\phi}}{dx} = \frac{1}{3H}\frac{ds}{dx}\left(\frac{1}{2}\langle\sigma_{\phi\phi}v\rangle(Y_{\phi}^2 - (Y^{\rm eq}_{\phi})^2) + \langle\sigma_{\phi\chi_i}v\rangle(Y_{\chi_i}Y_{\phi} - Y^{\rm eq}_{\chi_i}Y^{\rm eq}_{\phi}) + \frac{\Gamma_{\phi\to\chi_i}}{s}\left(Y_{\phi} - Y_{\chi_i}\frac{Y^{\rm eq}_{\phi}}{Y^{\rm eq}_{\chi_i}}\right)\right)$$

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All coannihilations

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All conversions including decays

BME for Conversion-Driven Baryogenesis

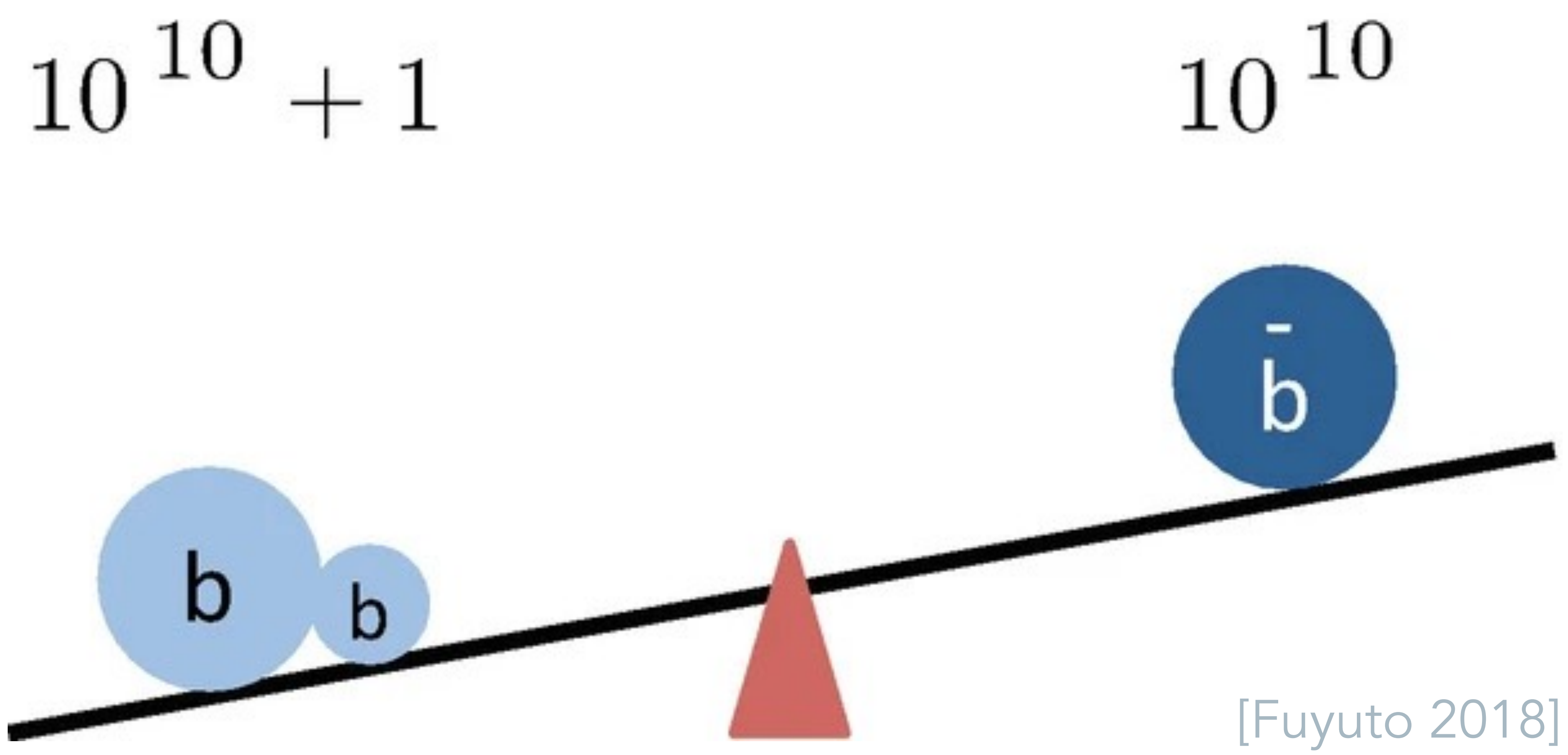
$$x\mathcal{H}Z\,\frac{\mathrm{d}\Sigma_\phi}{\mathrm{d}x} = -\,\Gamma_\phi\,\Sigma_\phi + \frac{1}{2}\,\Sigma_\phi^{\mathrm{eq}}\sum_i \Gamma_i\,\frac{Y_{\chi_i}}{Y_{\chi_i}^{\mathrm{eq}}} - \frac{1}{2}\langle\sigma v\rangle\, s\left(\Sigma_\phi^2 - \Sigma_\phi^{\mathrm{eq}2}\right)$$

$$x\mathcal{H}Z\,\frac{\mathrm{d}\Delta_\phi}{\mathrm{d}x} = -\,\Gamma_\phi\,\Delta_\phi + \Gamma_\phi\,Y_\phi^{\mathrm{eq}}\sum_i \frac{Y_{\chi_i}}{Y_{\chi_i}^{\mathrm{eq}}}\left(-\,\epsilon_i + \frac{\Gamma_i}{\Gamma_\phi}\,\frac{\Delta_f}{\Sigma_f^{\mathrm{eq}}}\right)$$

$$x\mathcal{H}Z\,\frac{\mathrm{d}Y_{\chi_i}}{\mathrm{d}x} = \frac{1}{2}\,\Gamma_i\left(\Sigma_\phi - \Sigma_\phi^{\mathrm{eq}}\,\frac{Y_{\chi_i}}{Y_{\chi_i}^{\mathrm{eq}}}\right)$$

Baryon Asymmetry

- **Sakharov conditions** for baryon-generating interactions:
  - C- and CP-symmetry violation
  - Interactions out of equilibrium
  - Baryon number violation



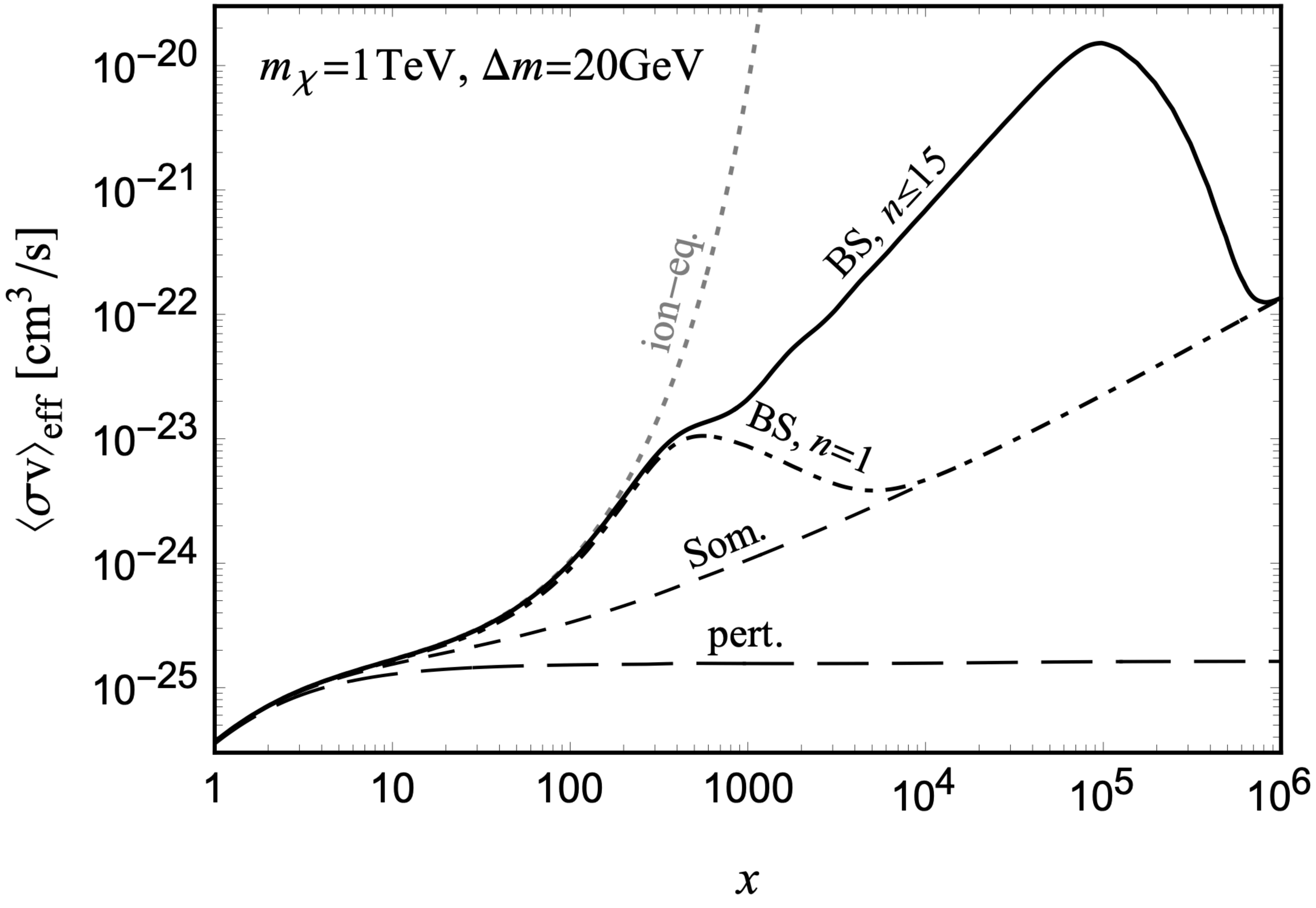
[Fuyuto 2018]

- Possible solutions linking DM and baryon asymmetry: sterile neutrino, [Canetti et al. 2013] asymmetric DM [Petraki, Volkas 2013]

Sommerfeld Enhancement and Bound State Effects

- Occur in models with t-channel mediators, can become relevant in conversion-driven freeze-out when mediator annihilation is dominant
- **Sommerfeld enhancement:** two-body wave-function of $\phi\phi$ is distorted by long-range potential → enhanced wave-function at short distance
- **Bound State Effects:** particles can form bound states which increases annihilation cross section

[Garny, Heisig 2022]



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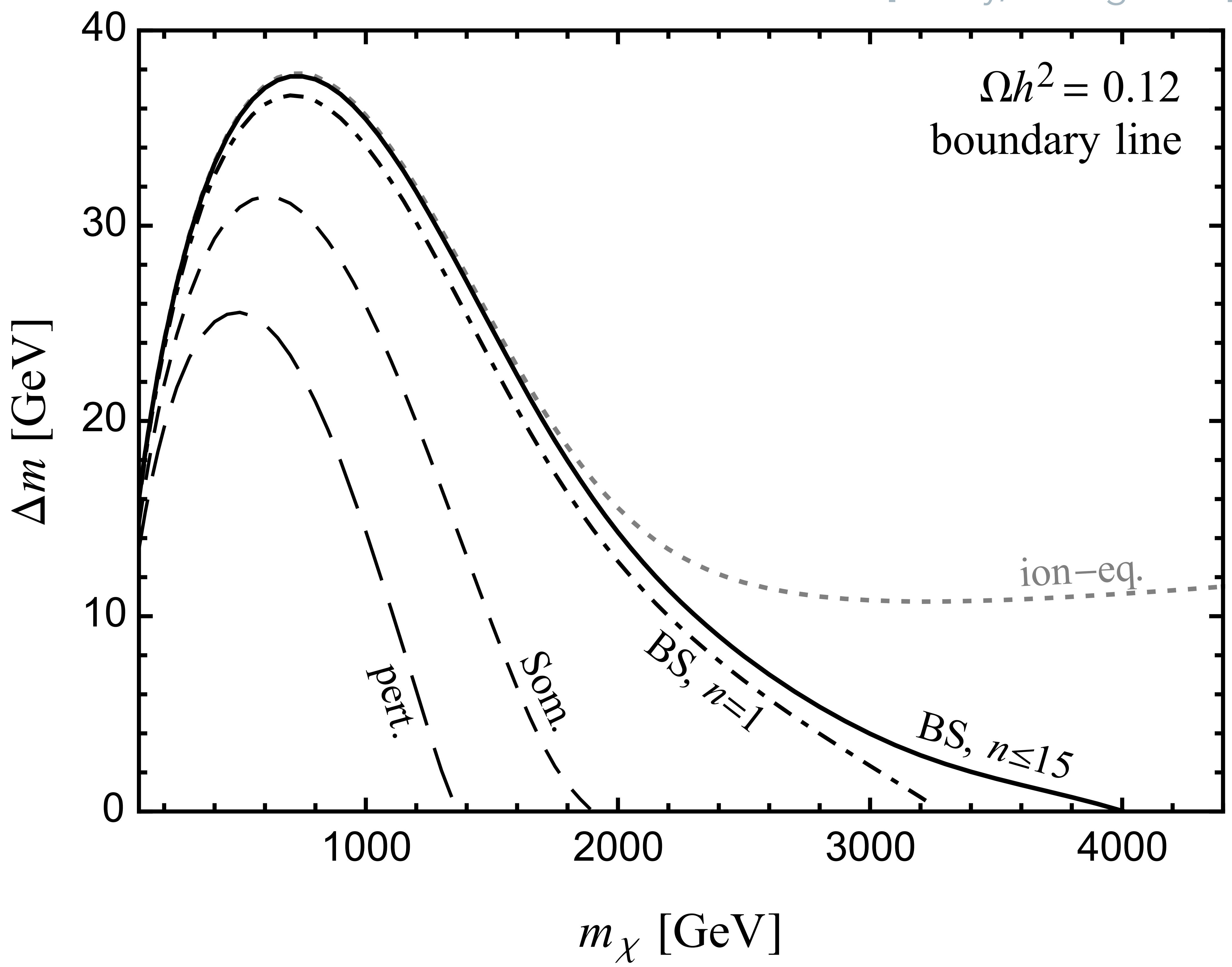
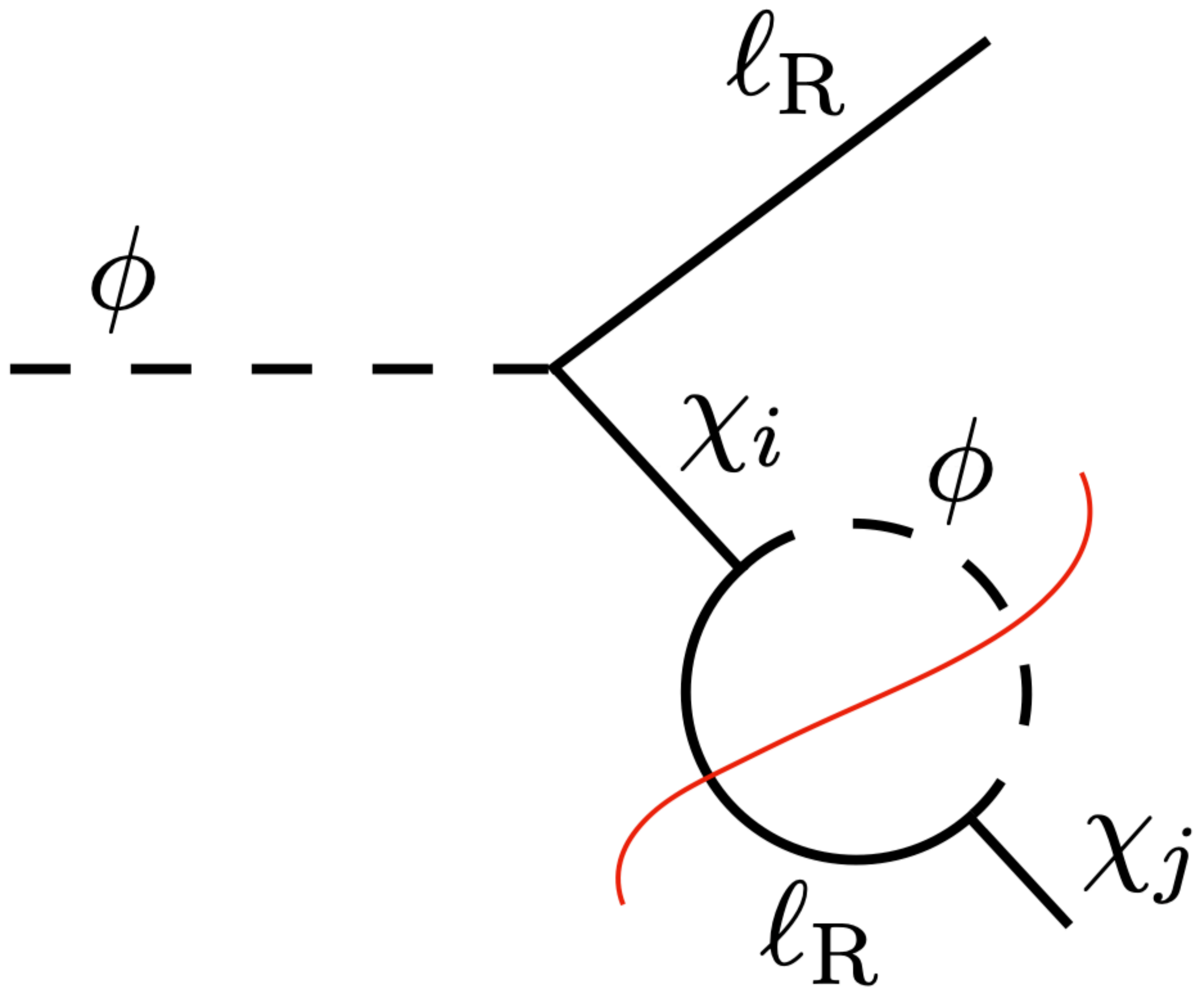


[Heisig 2024]

CP-Asymmetry in Decay

- Leading contribution to CP-asymmetry from interference of tree-level and one-loop diagram at finite temperatures



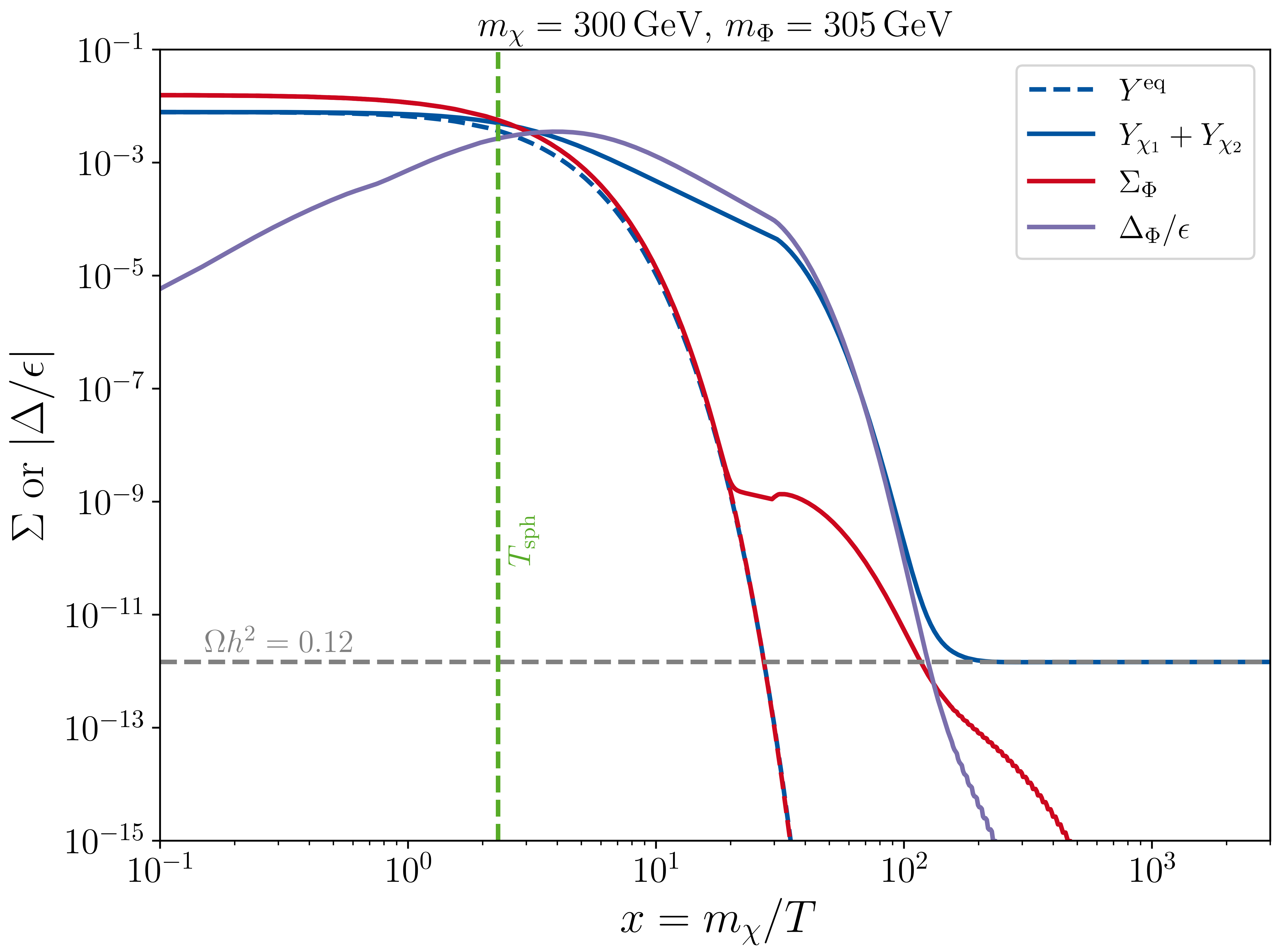
$$\epsilon(T) = I_1 \frac{\xi\,\gamma(T)}{\left(\xi + \pi\varphi/(2x)^2\right)^2 + \gamma(T)^2} \simeq I_1 \frac{\gamma(T)}{\xi}$$

$$I_1 = \Im[(\lambda^\dagger\lambda)^2_{12}]/(|\lambda^\dagger\lambda|_{11}|\lambda^\dagger\lambda|_{22}),\ \xi = 2\Delta m_{12}/\Gamma^0_{\chi_2}$$

- I_1: complex phase, should be smaller than 1
- ξ: decay width should be smaller than mass splitting $\rightarrow \xi > 10$

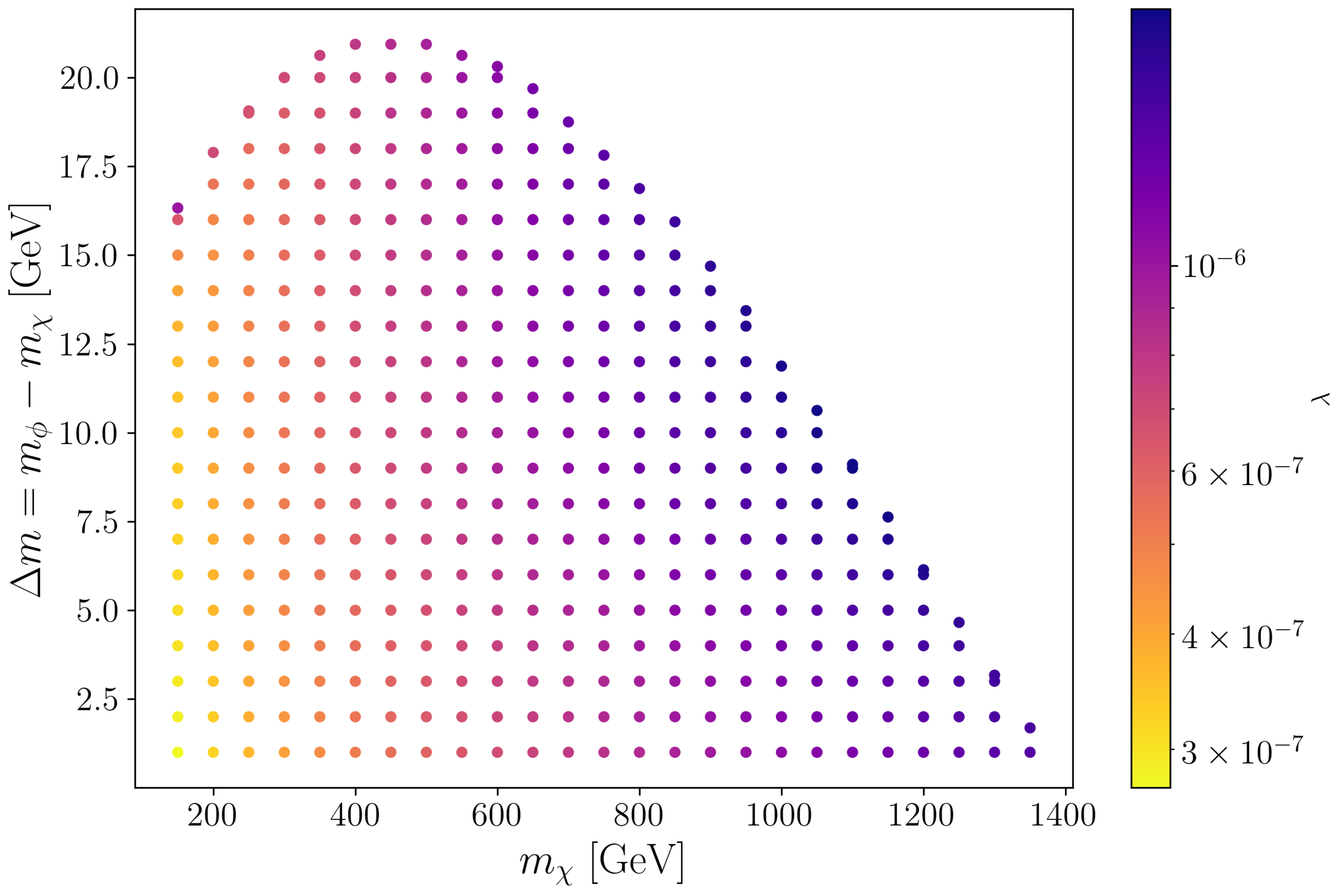
BME Solutions Including Thermal Effects

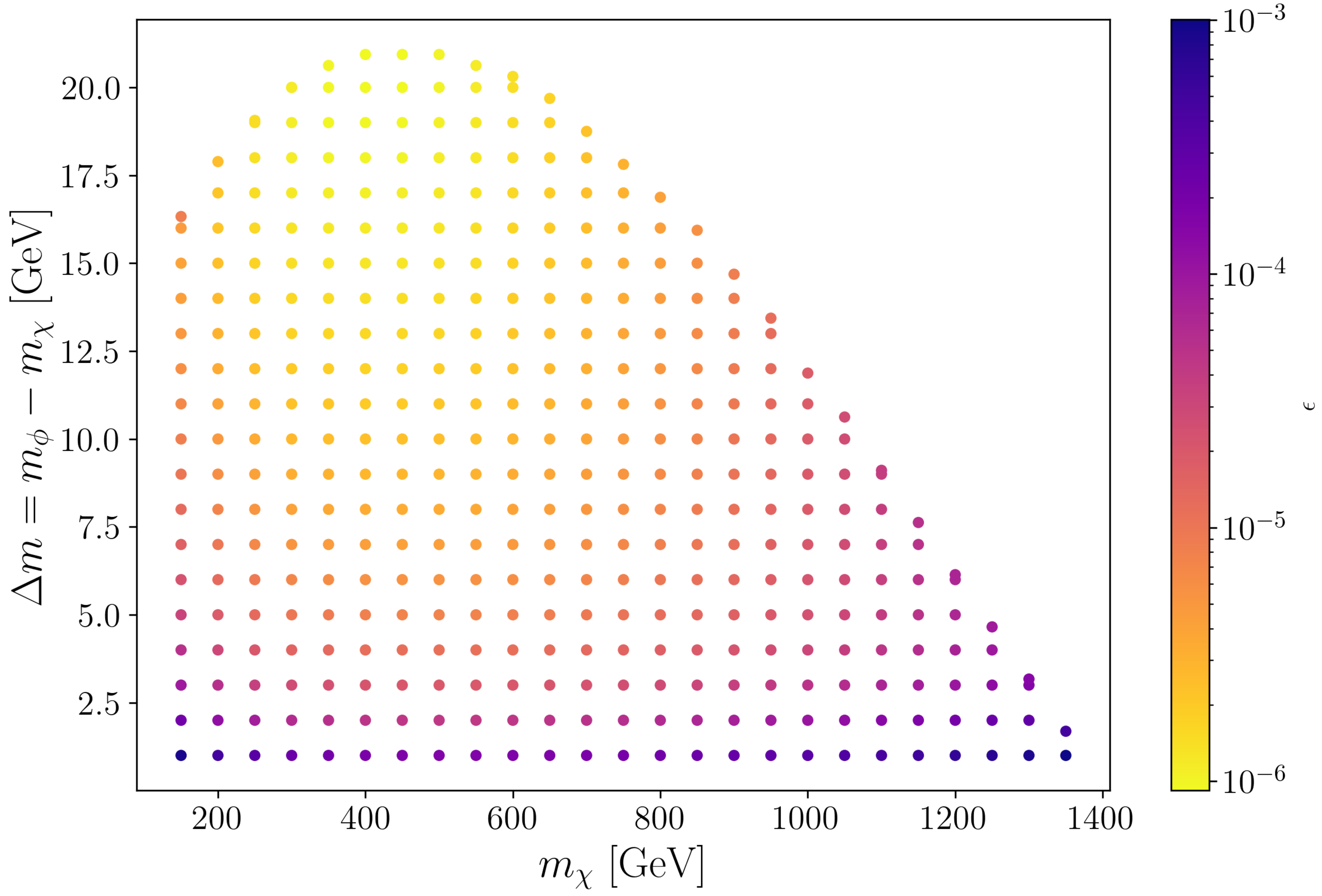
- …



Parameter Values

- Needed coupling and ϵ values to obtain $\Omega h^2 = 0.12$ and $Y_{\Delta B} = 0.9 \times 10^{-10}$



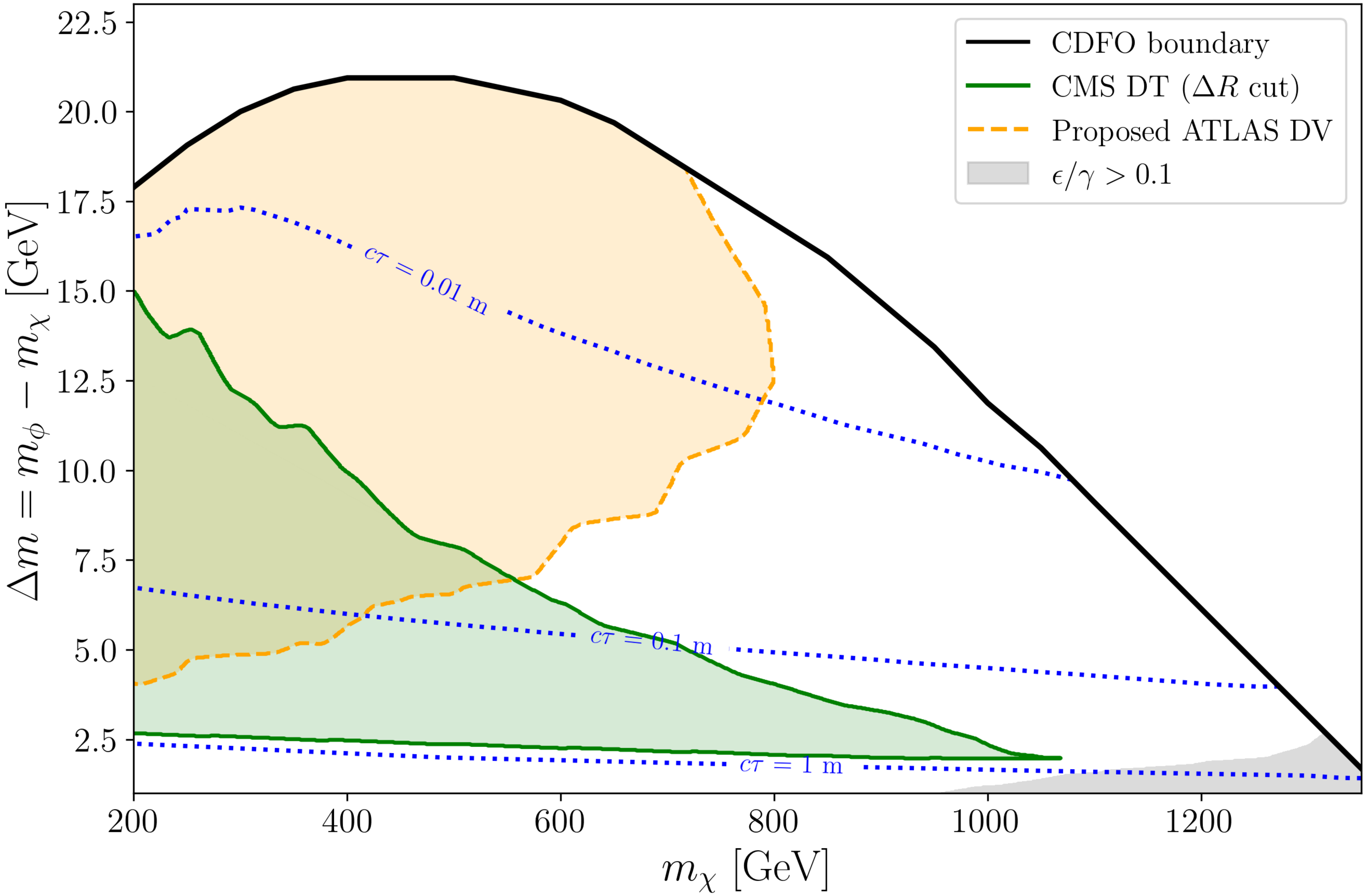


Viable Parameter Space

Preliminary

- Solution possible for $\Omega h^2 = 0.12$ **and** $Y_{\Delta B} = 0.9 \times 10^{-10}$ with $\epsilon \sim 10^{-6} - 10^{-3}$
- For $\epsilon/\gamma > 0.1$ validity of computation questionable
- Couplings of order $\mathcal{O}(10^{-7})$ $\rightarrow$ evade direct and indirect searches, possible to **look for disappearing tracks** (DT) at LHC

Branching fraction $\phi \rightarrow \chi_1$: 0.75



Limits reinterpreted from [Heisig et al. 2024]

Viable Parameter Space

Preliminary

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- For $\epsilon/\gamma > 0.1$ validity of computation questionable
- Couplings of order $\mathcal{O}(10^{-7})$ → evade direct and indirect searches, possible to **look for disappearing tracks** (DT) at LHC
- Proposed displaced vertices (DV) +MET search could cover most of parameter space

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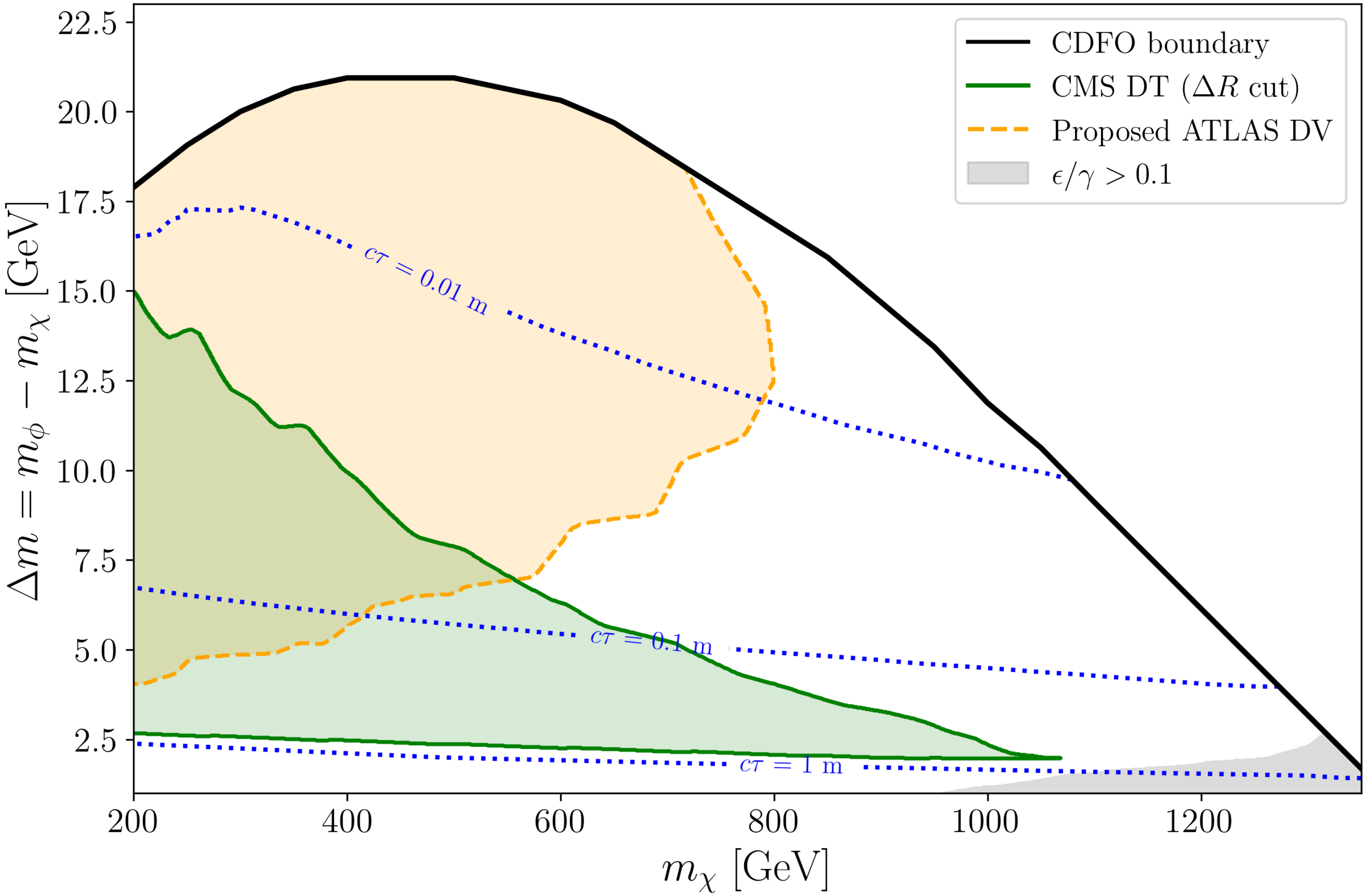

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