Karlsruhe Institute of Technology

Conversion-Driven Baryogenesis with Quark-Philic Flavored Dark Matter

Based on ArXiv:2607.11147

Lena Rathmann

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

Young Scientist Meeting 2026

23.09.2026

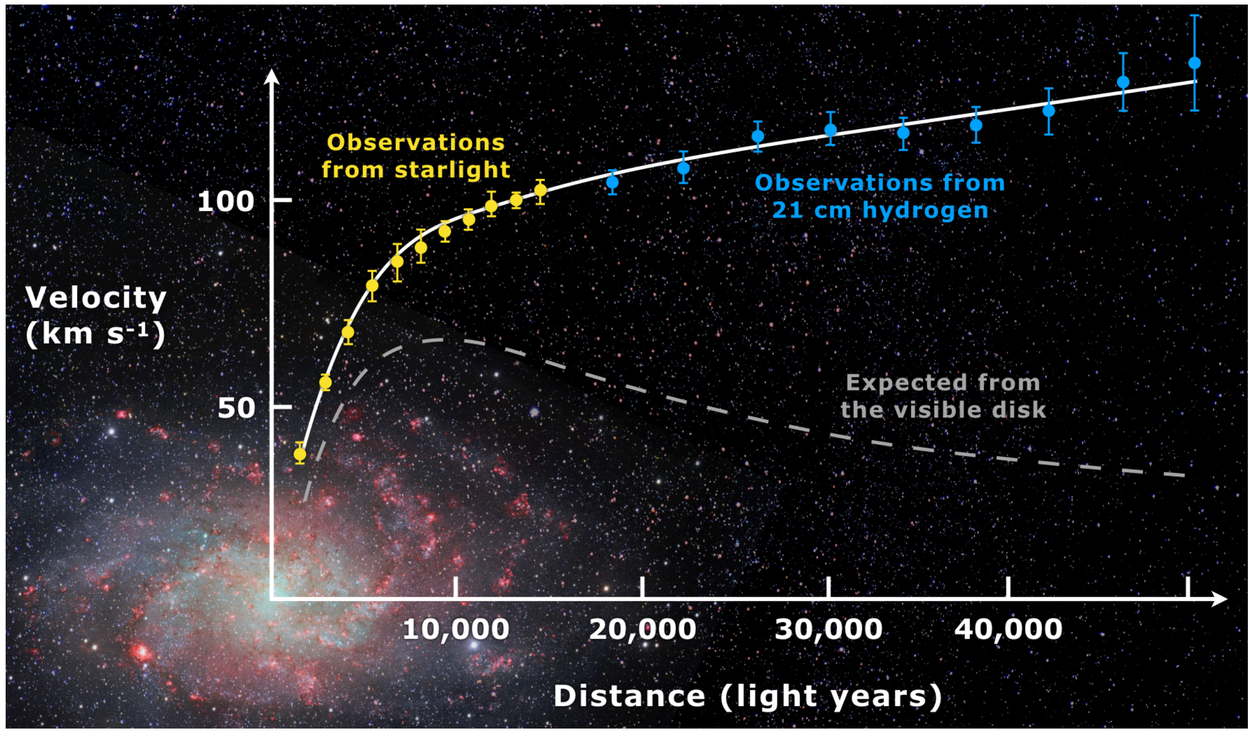
Evidence for Dark Matter

[Zwicky 1933]
[PLANCK collaboration 2018]

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Galaxy rotation curves

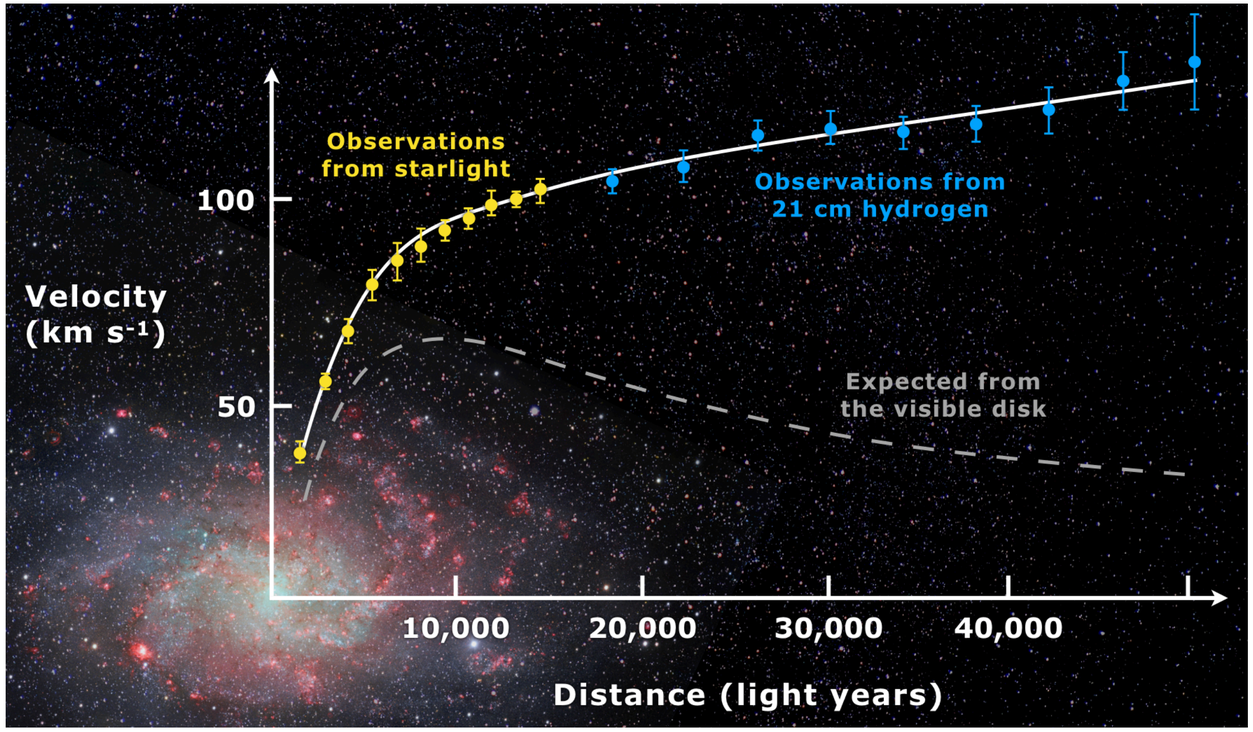


[Wikipedia]

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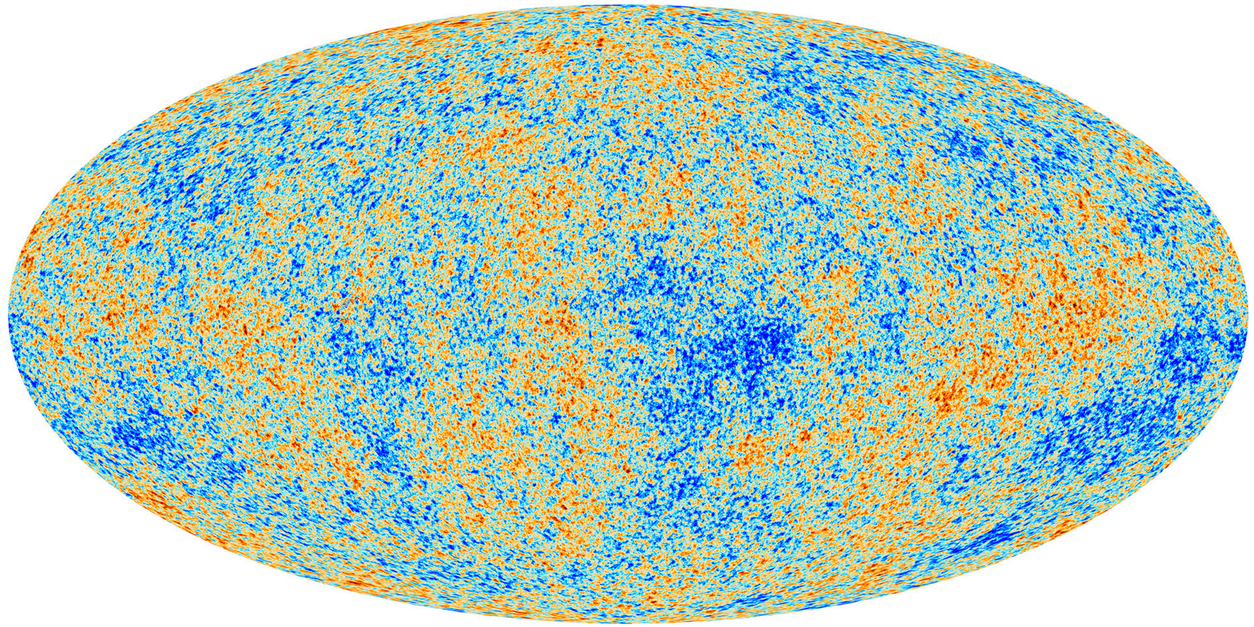
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CMB anisotropies

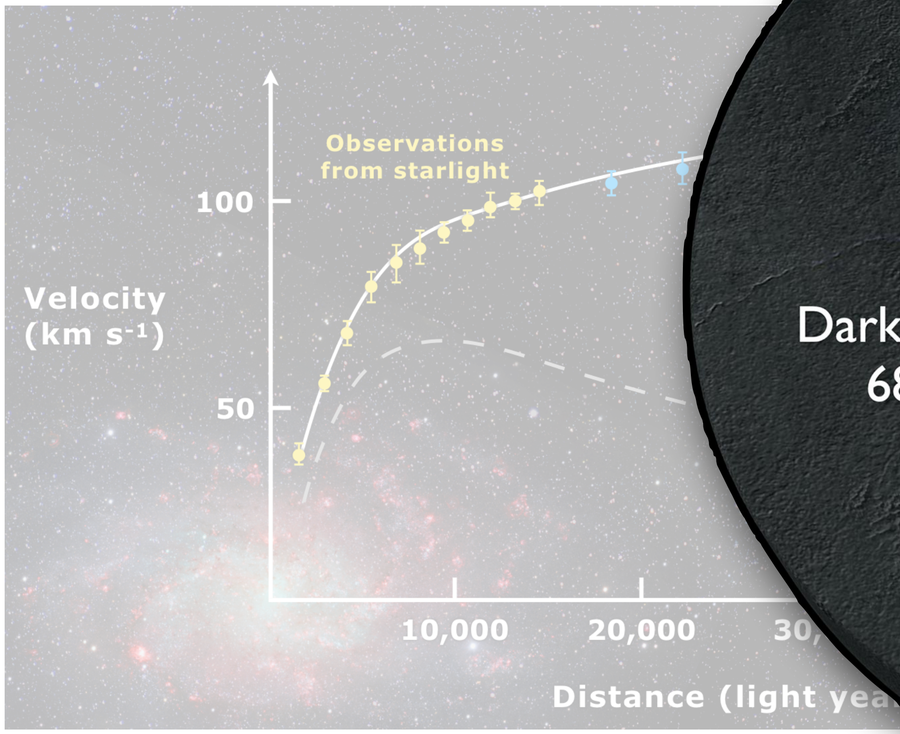


[ESA]

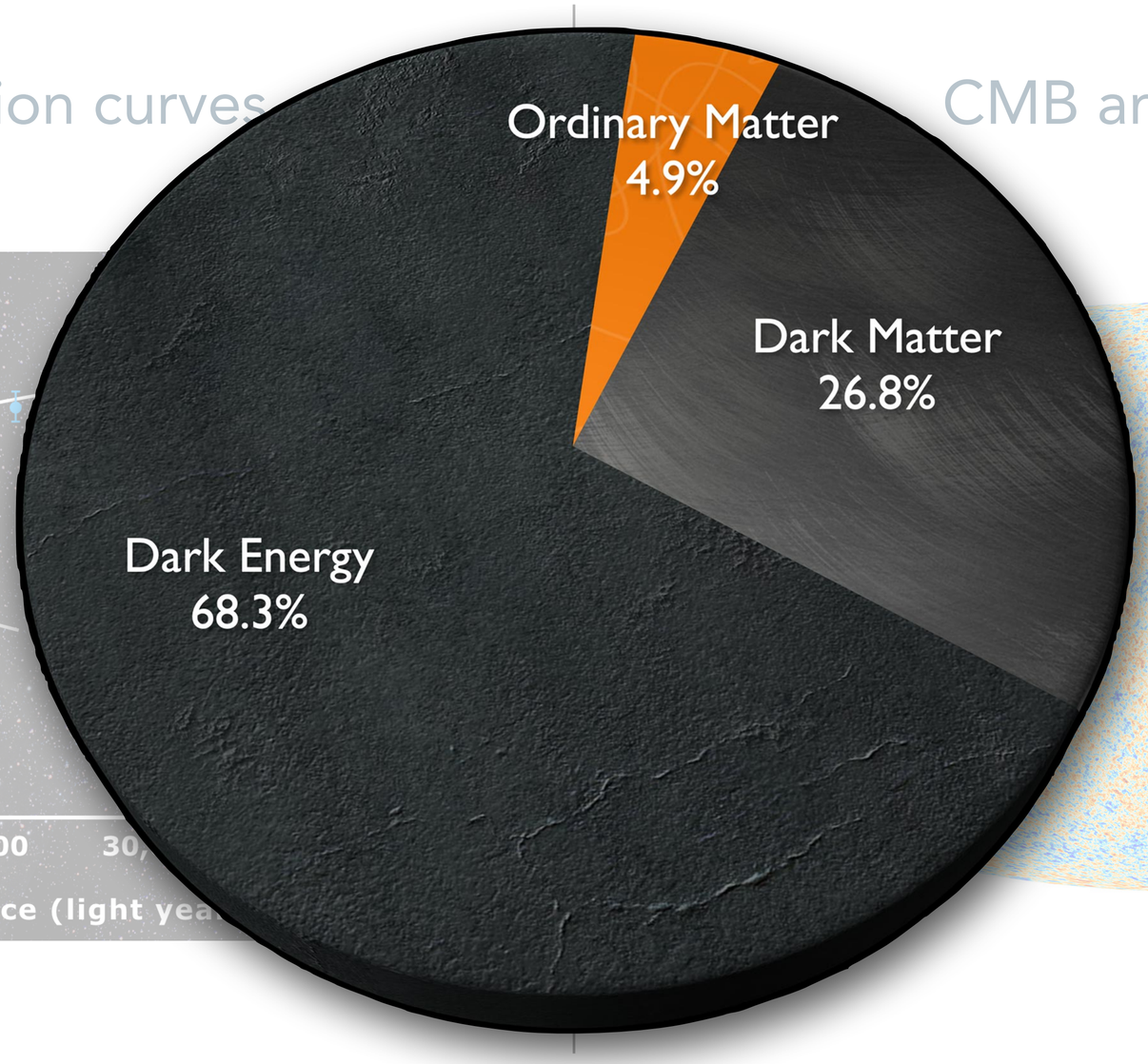
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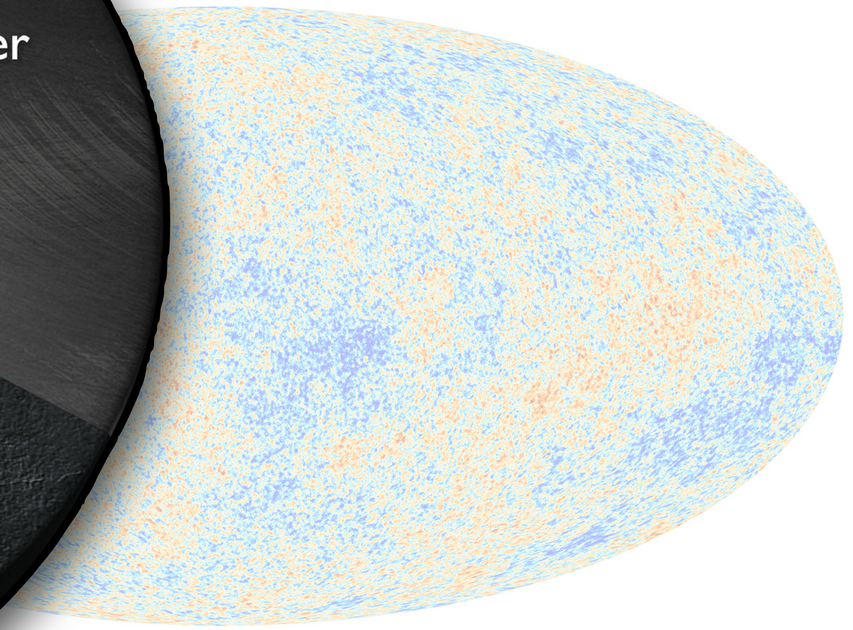
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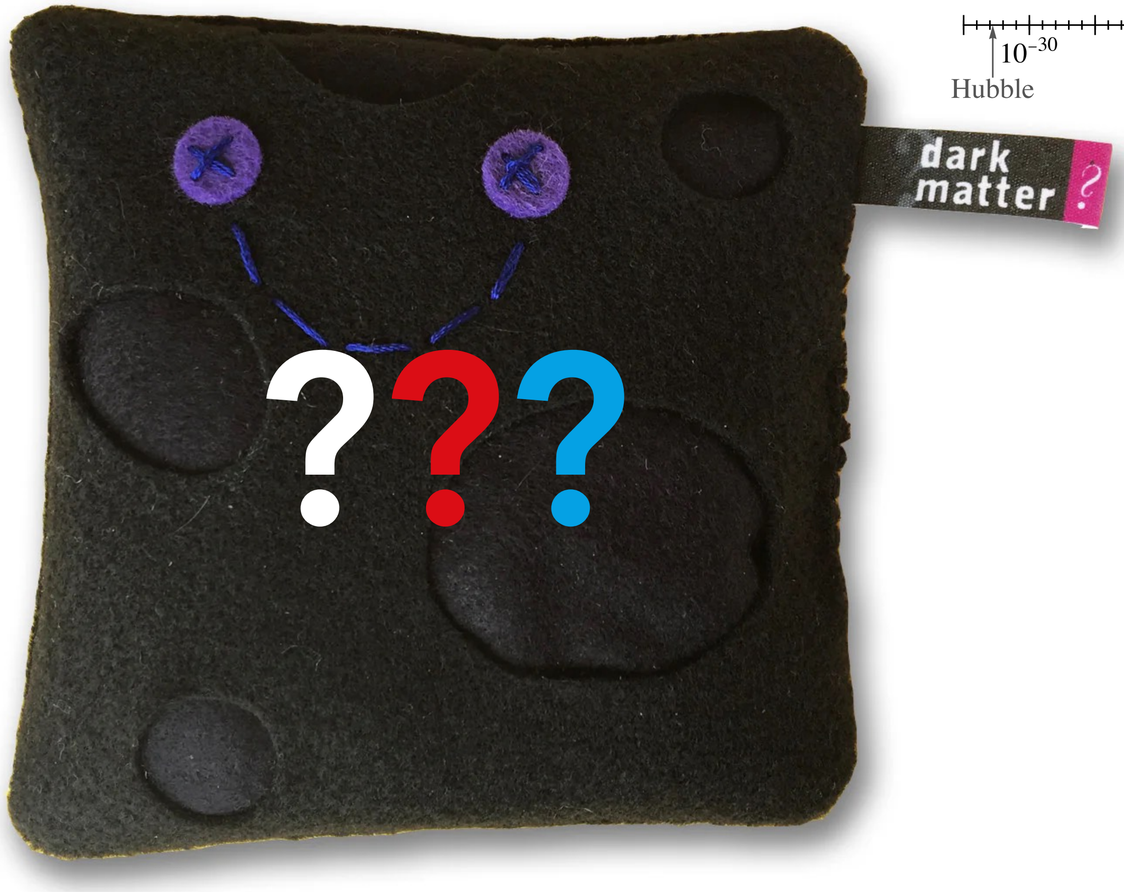


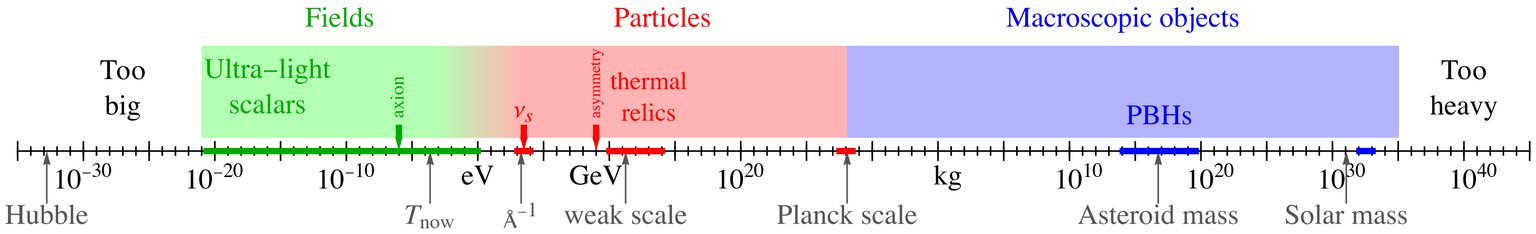


[ESA]

What is Dark Matter?

[Cirelli et al. 2024]



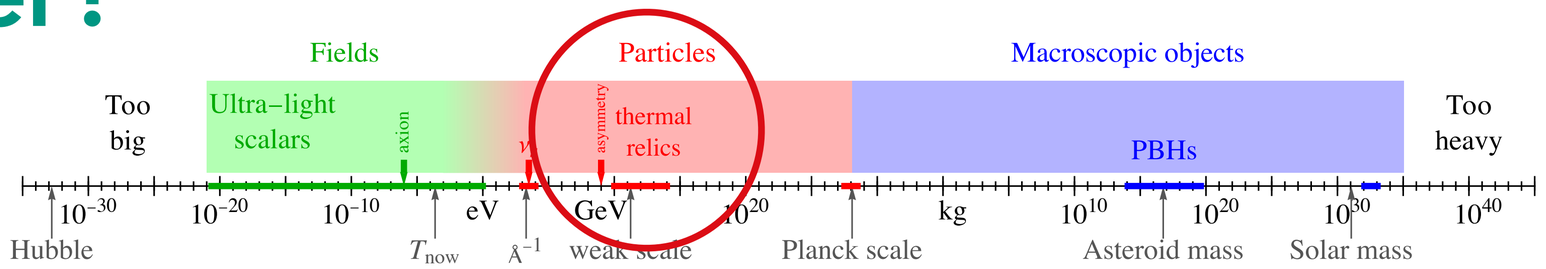


- **We know:** Dark Matter (DM) is non-relativistic, not part of the Standard Model, interacts weakly

What is Dark Matter?

[Cirelli et al. 2024]





- **We know:** Dark Matter (DM) is non-relativistic, not part of the Standard Model, interacts weakly
- **Thermal relics**, especially weakly interacting massive particles (WIMPs), were **extremely successful** as weak-scale cross section gives **correct relic abundance** through **freeze-out**
- Focus on specific model: **flavored DM**

Conversion-Driven Baryogenesis with Quark-Philic Flavored Dark Matter

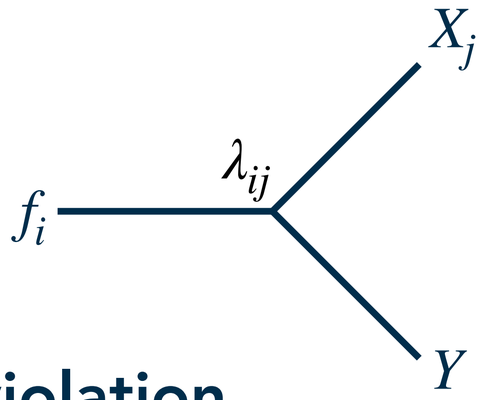
Why Flavored Dark Matter?

- Traditional WIMP models under severe pressure

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

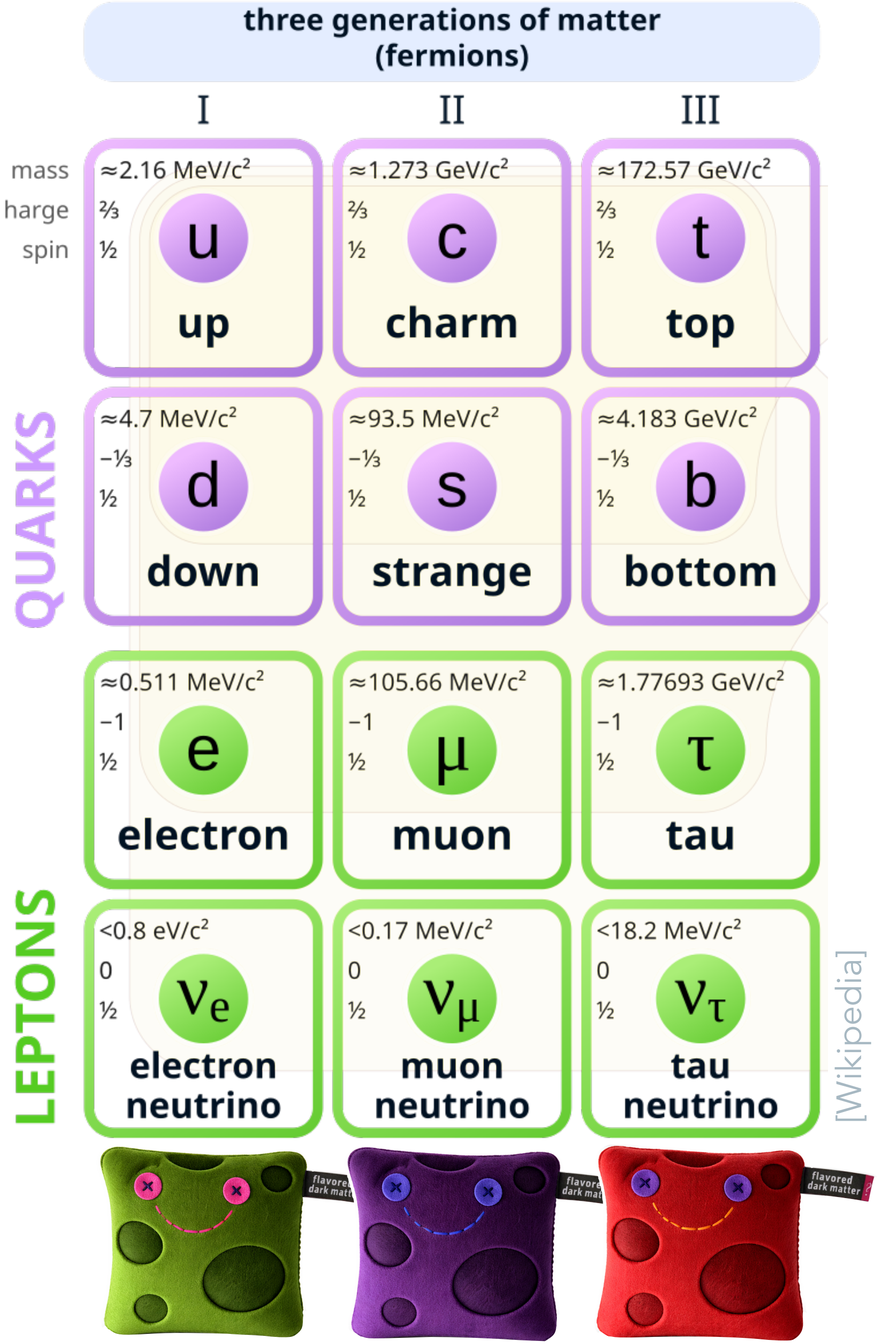
- **Couple to SM fermions** f through complex 3×3 matrix λ

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



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

  → Different phenomenology like more complex freeze-out mechanism



Flavored Dark Matter Models




X_j



Y	f_i

Flavored Dark Matter Models




X_j	Y	f_i
Spin 0	• Real scalar $\tilde{S}$, $G_X = O(3)$ • Complex scalar S, $G_X = U(3)$	• Vector-like fermion ψ	



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Spin 0	• Real scalar $\tilde{S}$, $G_X = O(3)$ • Complex scalar S, $G_X = U(3)$	• Vector-like fermion ψ	
Spin 1/2	• Majorana fermion $\tilde{\chi}$, $G_X = O(3)$ • Dirac fermion χ, $G_X = U(3)$	• Complex scalar φ	



Flavored Dark Matter Models

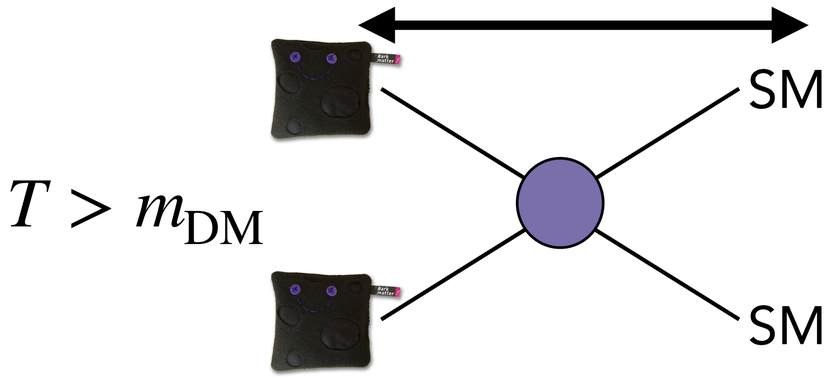



X_j	Y	f_i
Spin 0 • Real scalar $\tilde{S}$, $G_X = O(3)$ • Complex scalar S, $G_X = U(3)$	• Vector-like fermion ψ	• Right-handed up-type quarks u_R • Right-handed down-type quarks d_R • Right-handed charged leptons e_R • Left-handed quark doublet q_L • Left-handed lepton doublet ℓ_L
Spin 1/2 • Majorana fermion $\tilde{\chi}$, $G_X = O(3)$ • Dirac fermion χ, $G_X = U(3)$	• Complex scalar φ	

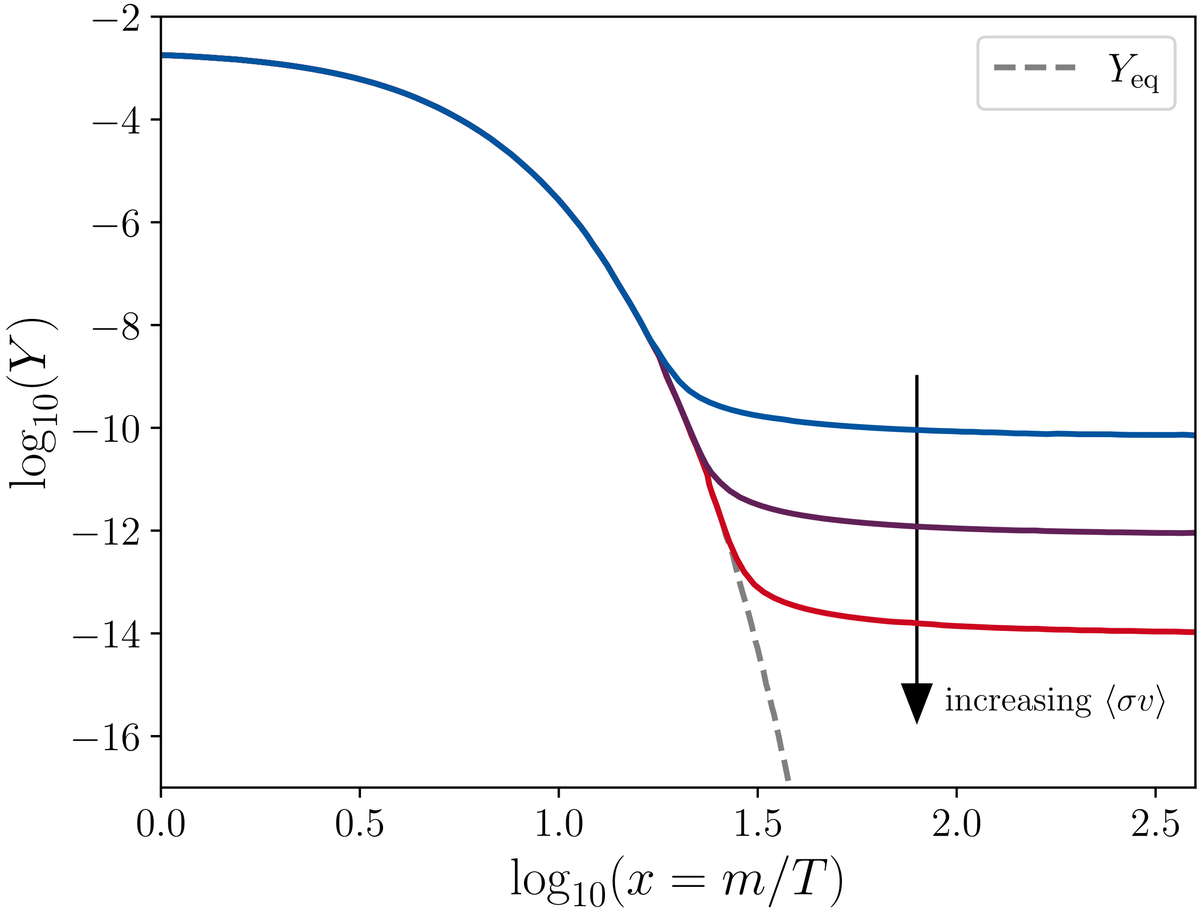


Conversion-Driven Baryogenesis with Quark-Philic Flavored Dark Matter

“Standard” Freeze-Out Mechanism

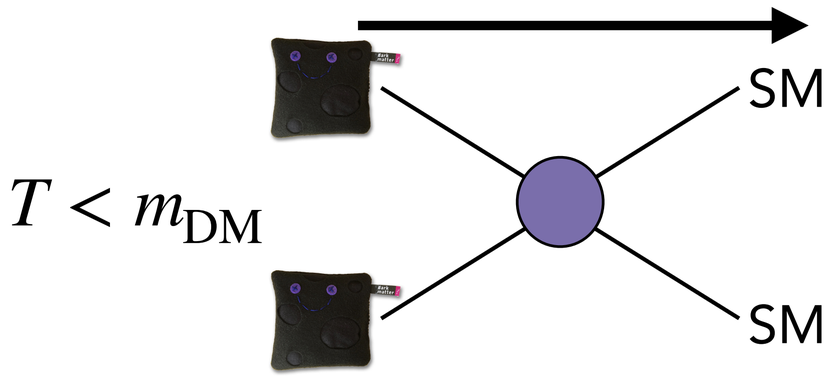


Comoving number density $Y = n/s$

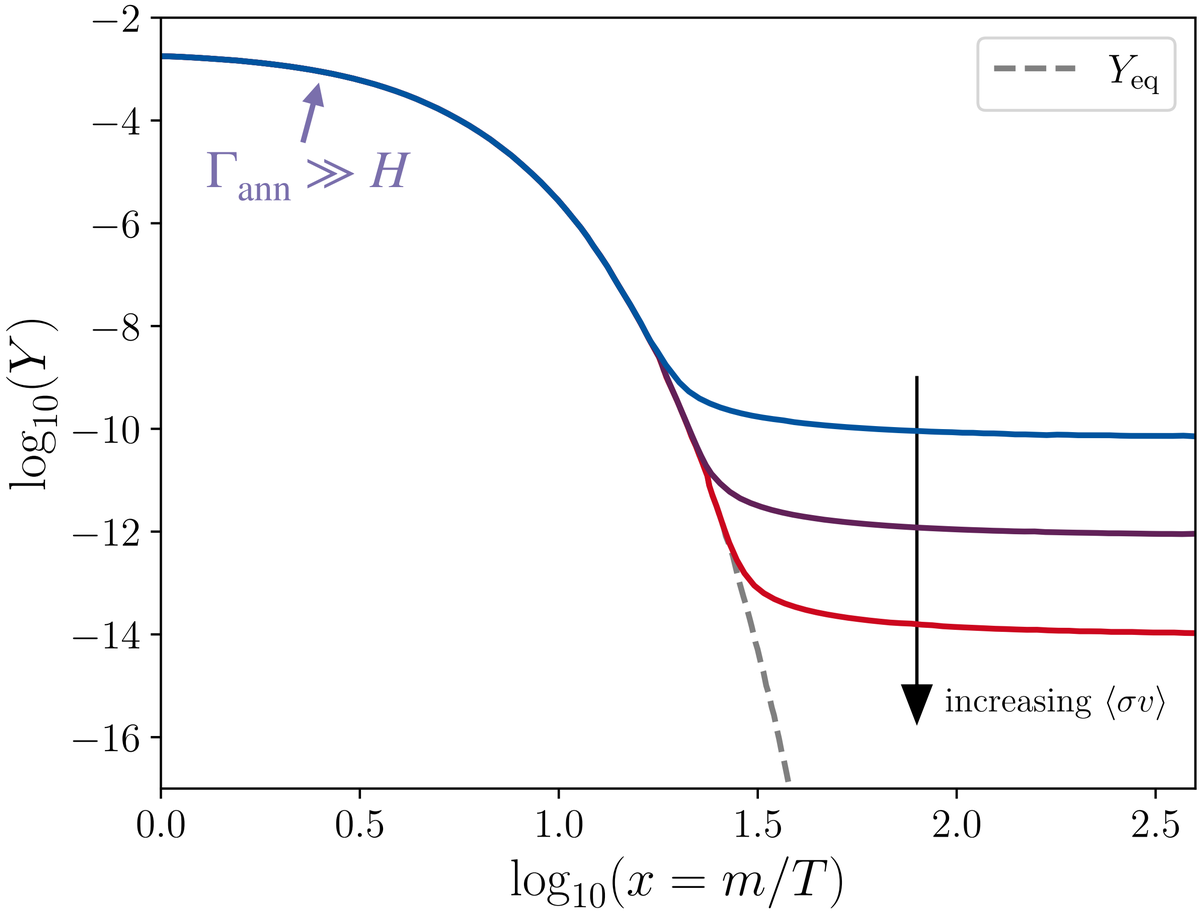


“Standard” Freeze-Out Mechanism

- Three regions for $\Gamma_{\text{ann}} = n_\chi \langle \sigma_{\chi\chi} v \rangle$:
  - $\Gamma_{\text{ann}} \gg H$: DM in thermal equilibrium

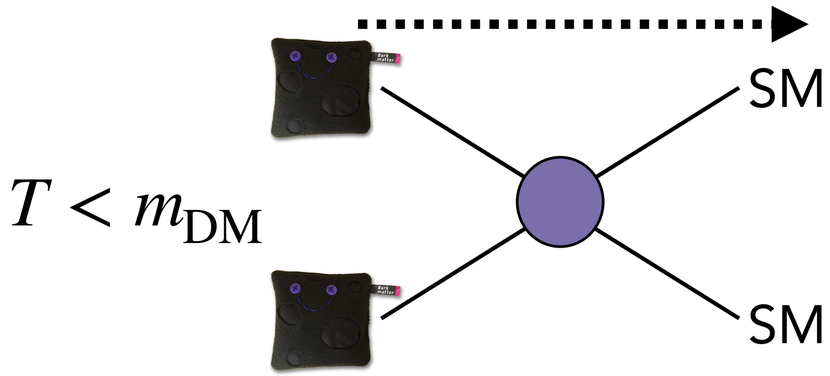


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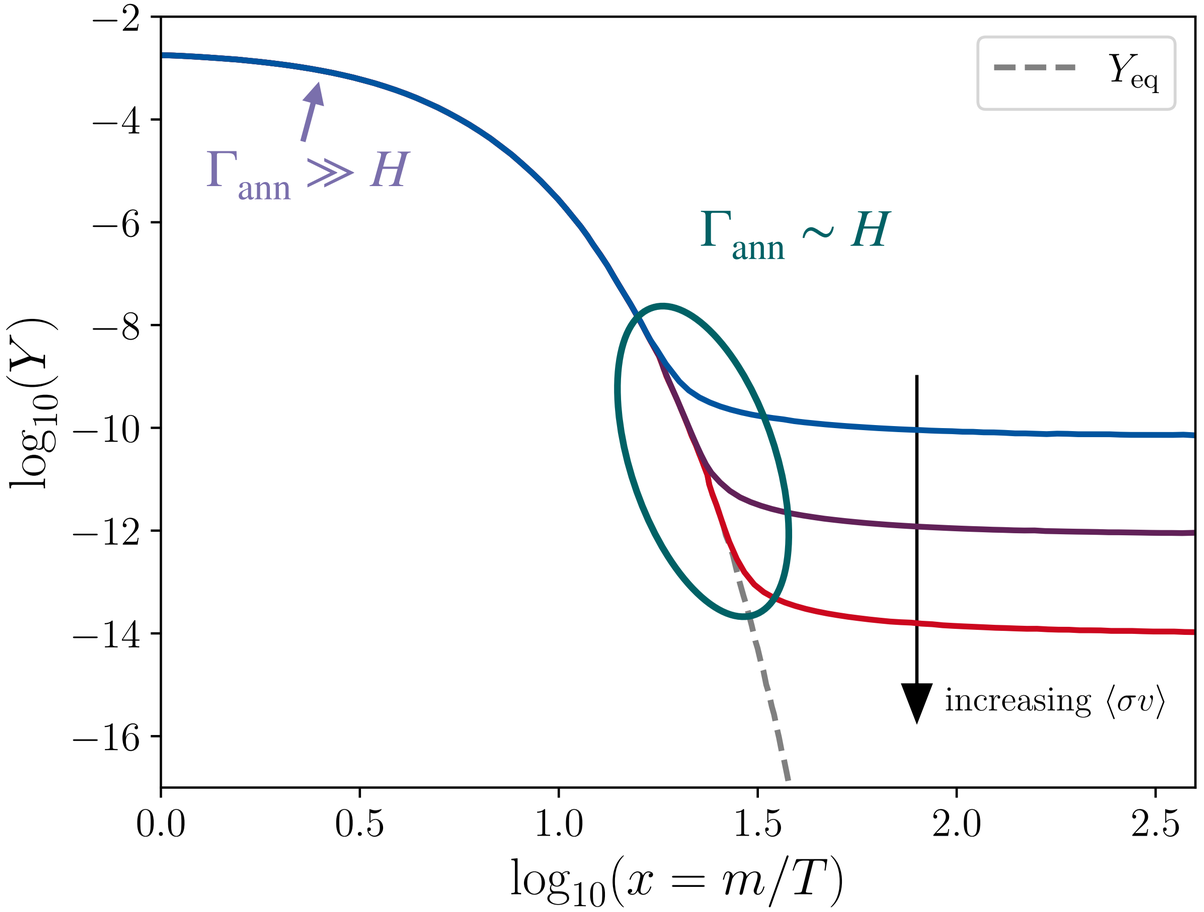


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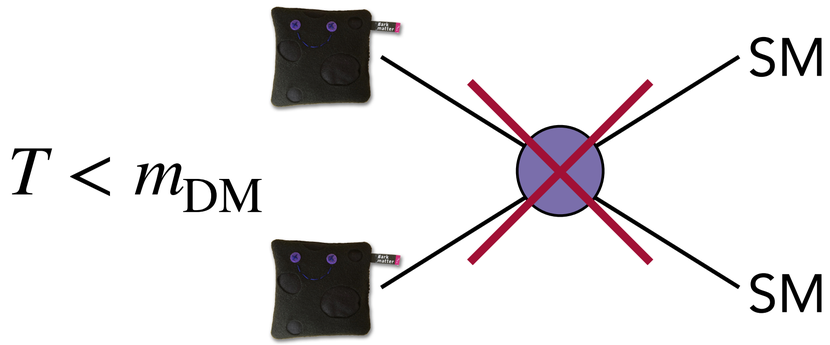


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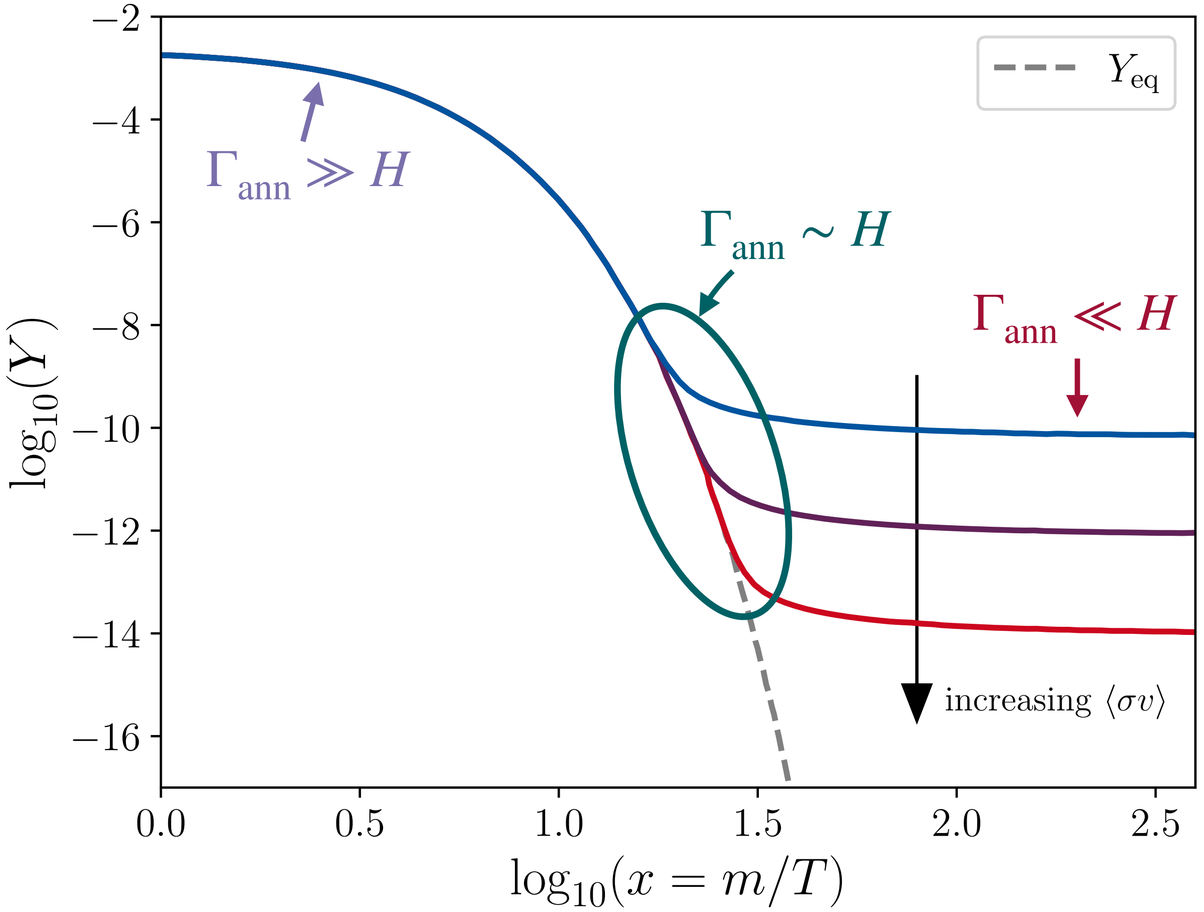
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  - $\Gamma_{\text{ann}} \sim H$: Freeze-out
  - $\Gamma_{\text{ann}} \ll H$: Constant abundance Y



$$\Omega h^2 = 0.12 \propto Y_0$$

Comoving number density $Y = n/s$

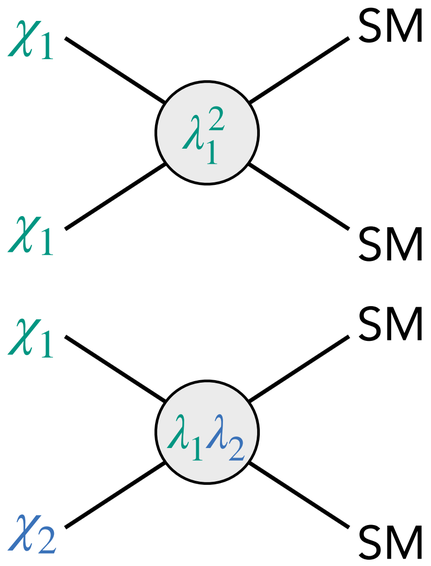


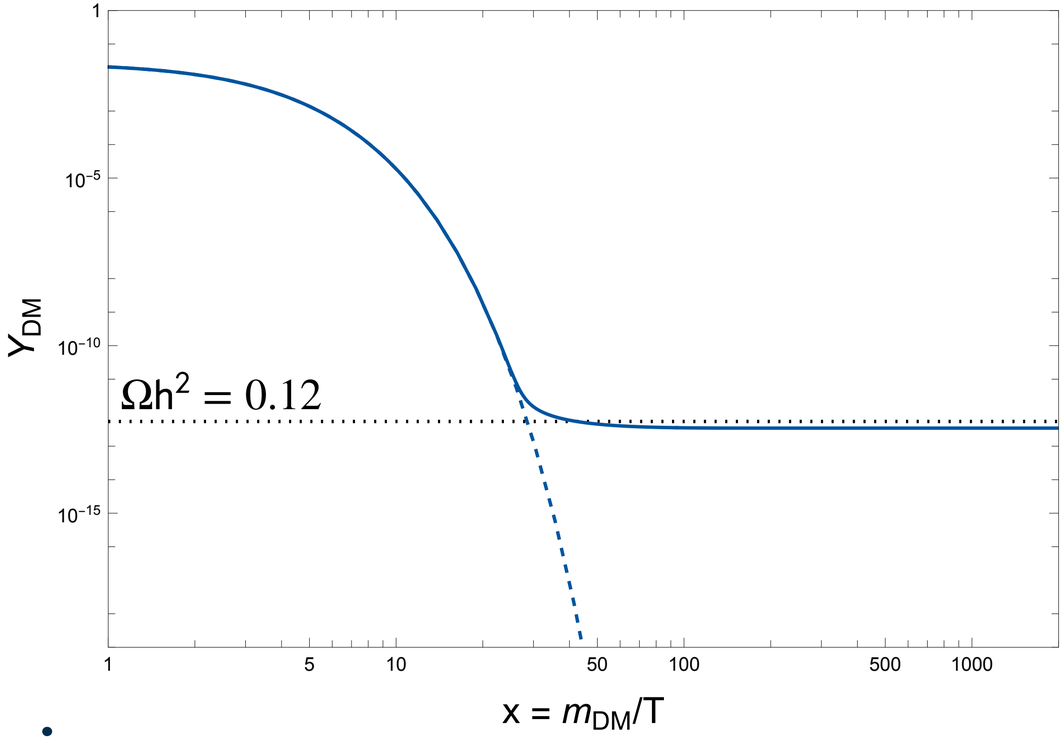
Freeze-Out with Coannihilations

[Griest, Seckel 1991]
[Edsjö, Gondolo 1997]

$\lambda_1 \sim \lambda_2$, couplings large

Dark Matter depletes through





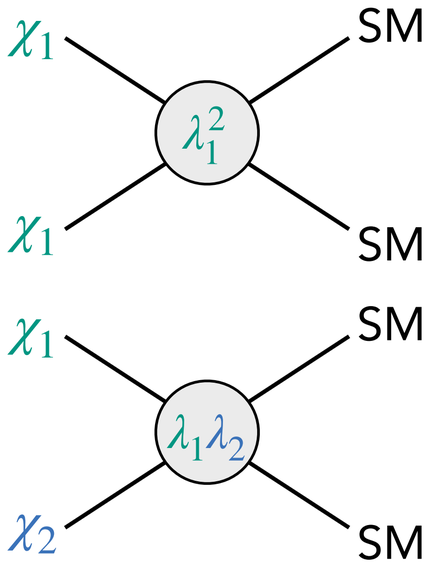
Dark sector particles in **chemical equilibrium**

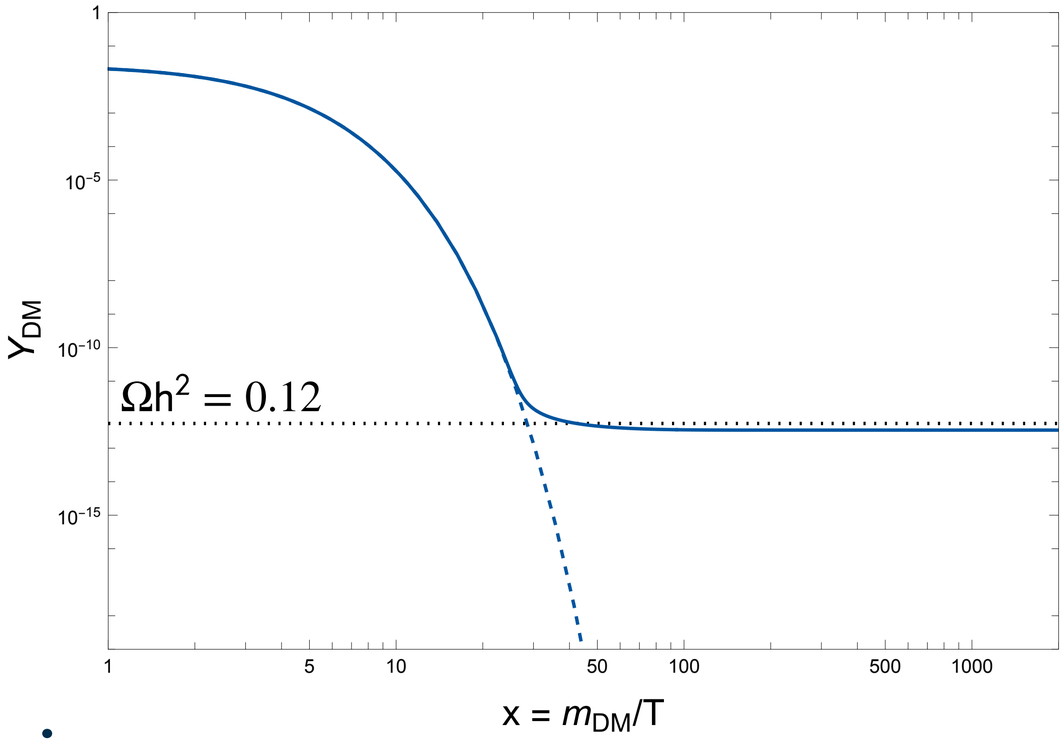
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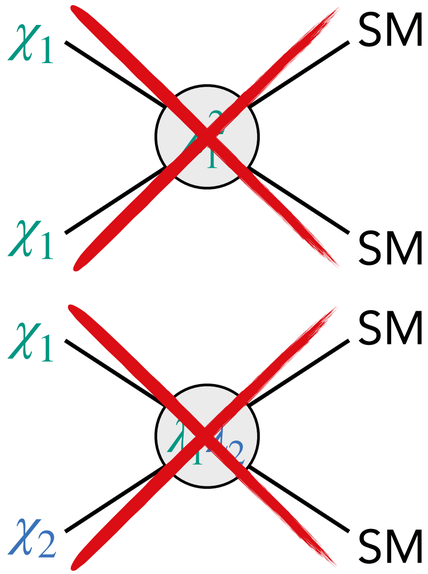
Dark sector particles in **chemical equilibrium**

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

[Garny et al. 2017]

Conversion-Driven Freeze-Out

λ_1 very small, λ_2 large

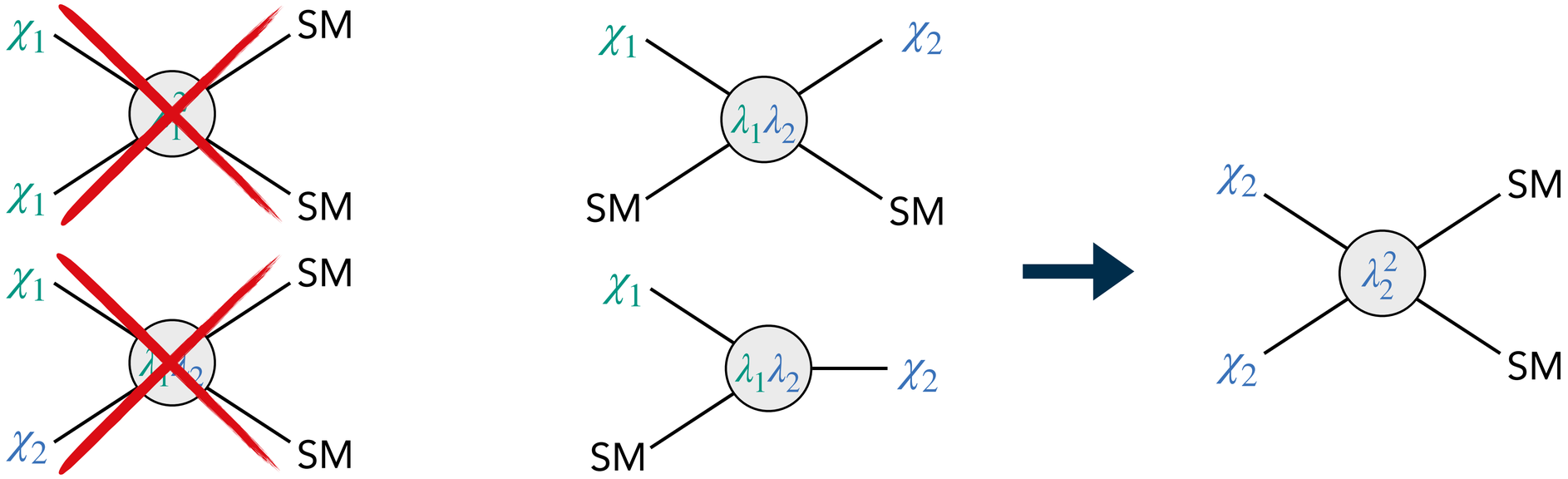


[Garny et al. 2017]

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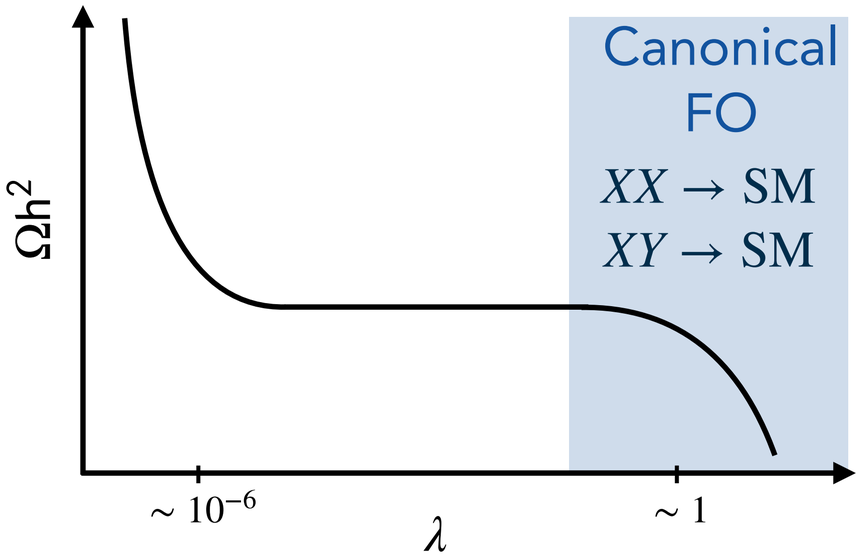
Dark Matter depletes through



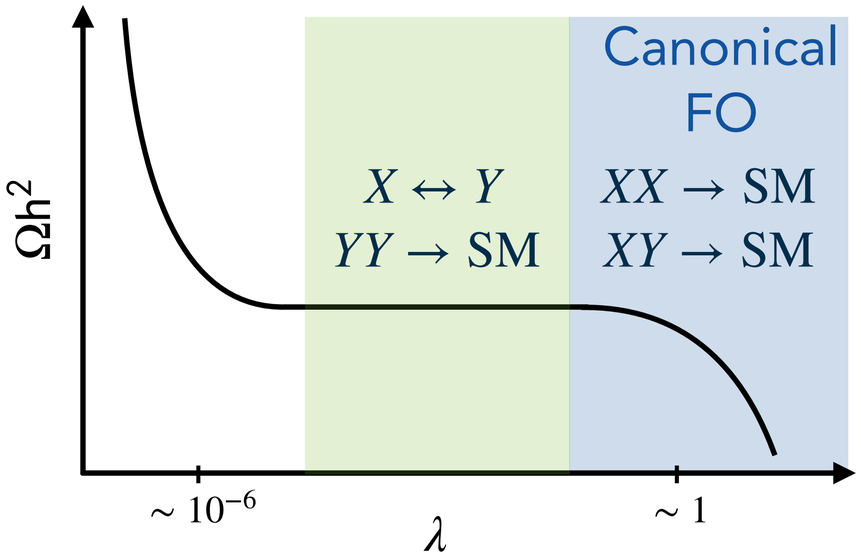
$$\Gamma_{\text{conv}} \sim H \rightarrow \textbf{no chemical equilibrium}$$

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

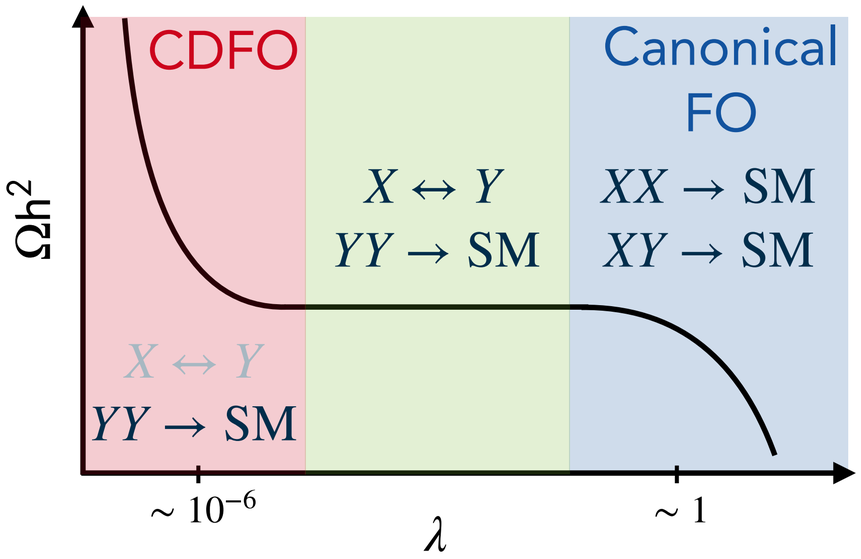
Conversion-Driven Freeze-Out



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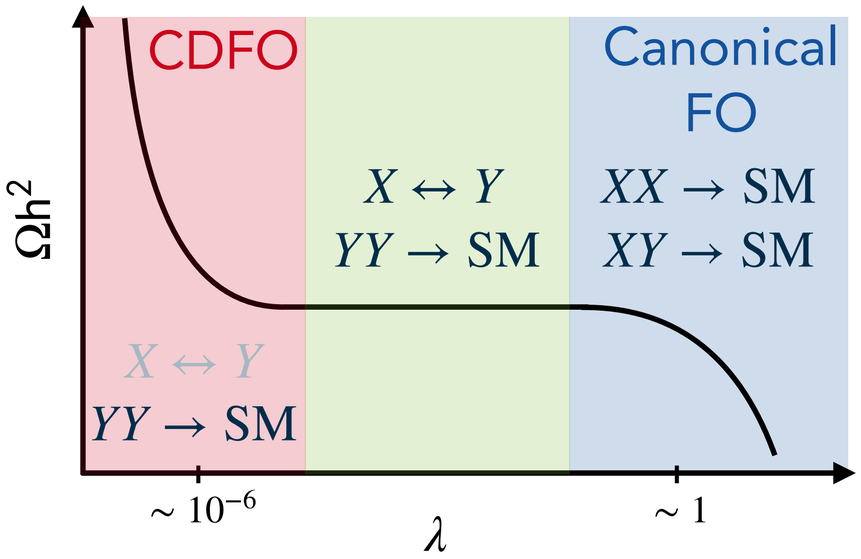


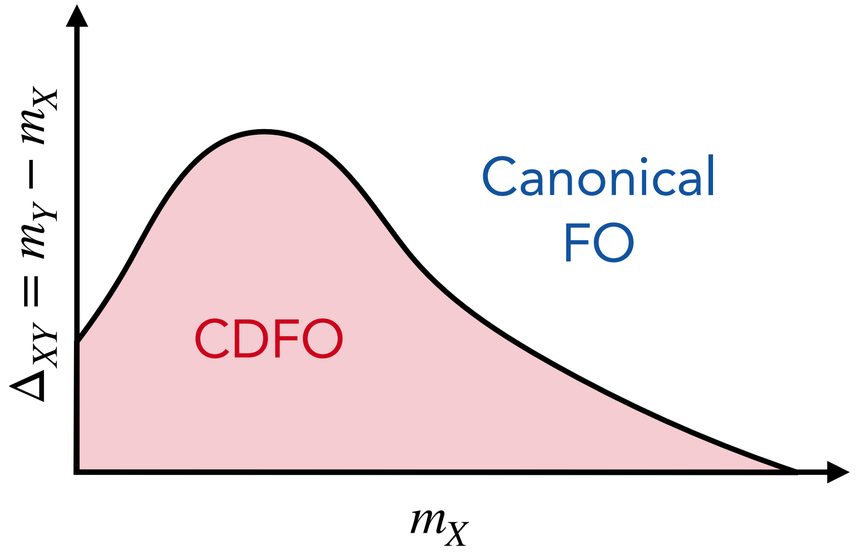
Conversion-Driven Freeze-Out



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

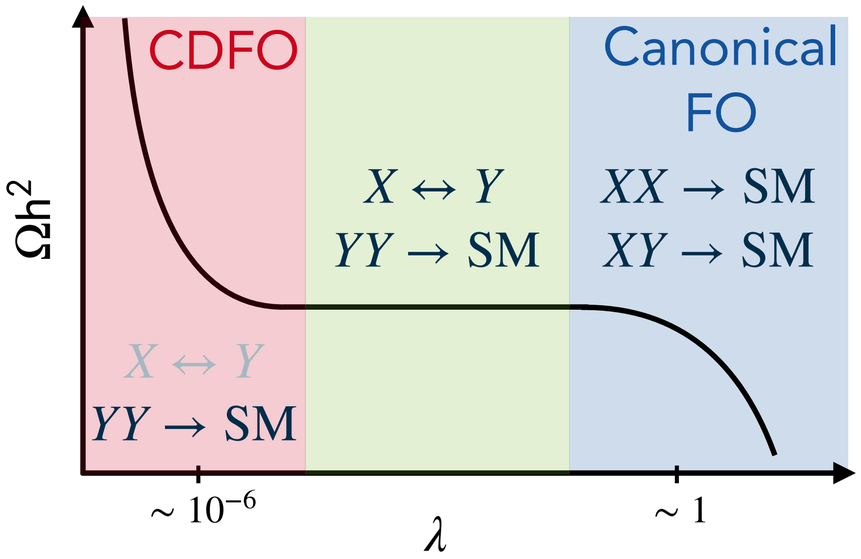
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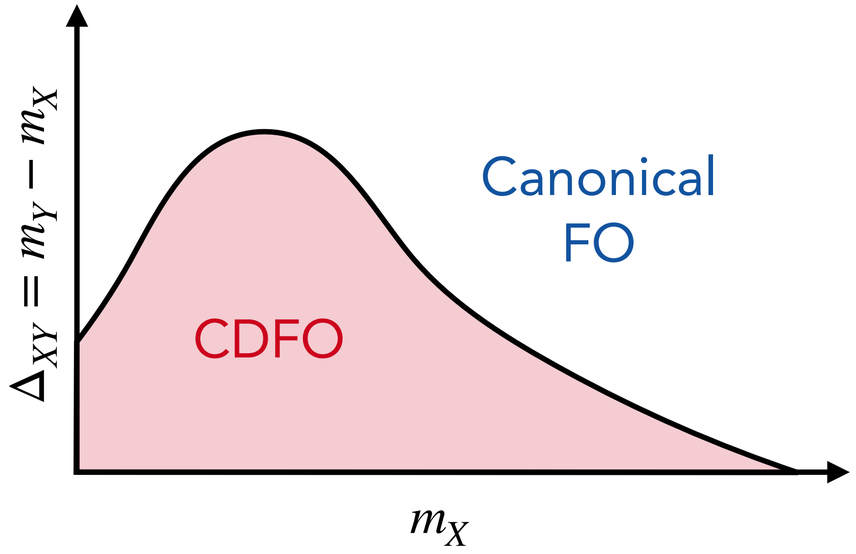




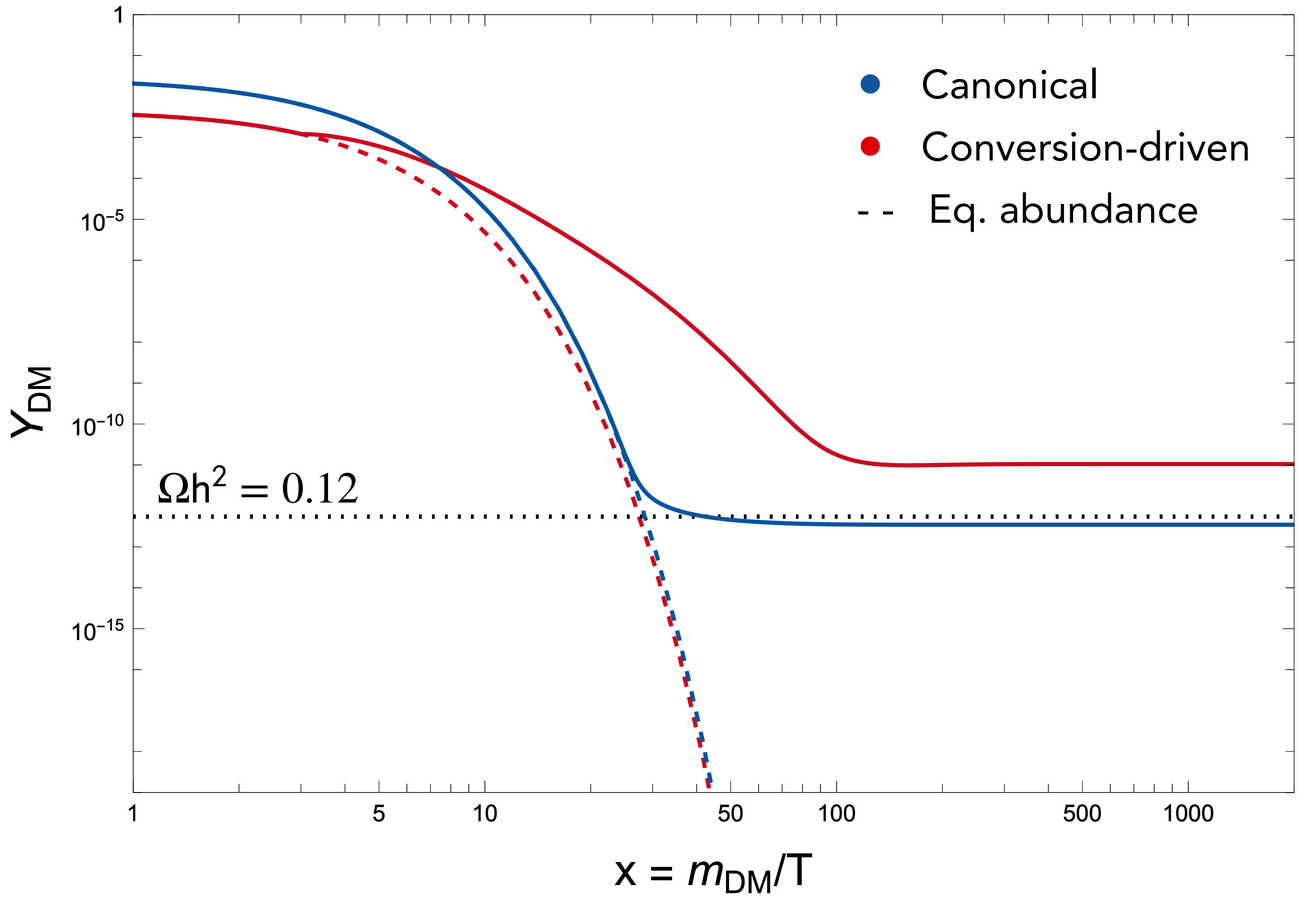
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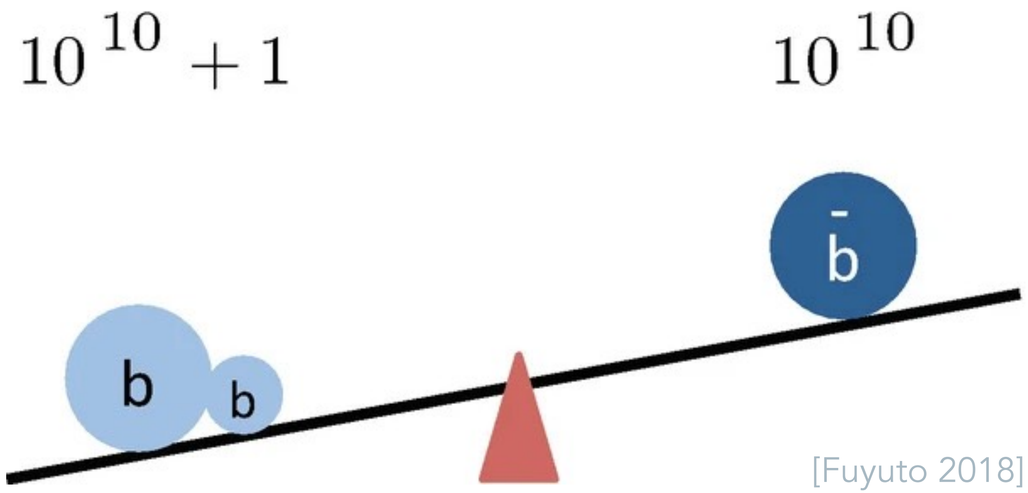
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Conversion-Driven Baryogenesis with Quark-Philic Flavored Dark Matter

Baryon Asymmetry

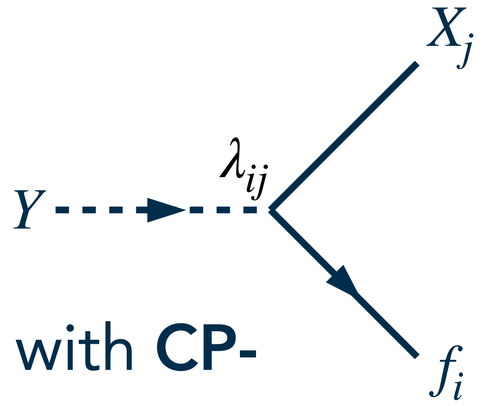
- **Sakharov conditions** for baryon-generating interactions:
  - C- and CP-symmetry violation
  - Interactions out of equilibrium
  - Baryon number violation



[Fuyuto 2018]

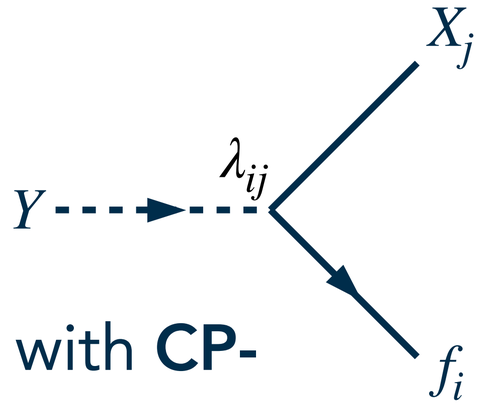
- Possible solutions linking DM and baryon asymmetry: sterile neutrino, [Canetti et al. 2013] asymmetric DM [Petraki, Volkas 2013]
- Here: **use conversion-driven freeze-out in flavored DM models** to generate baryon asymmetry

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 $B - L$)

Baryon Asymmetry with Flavored DM

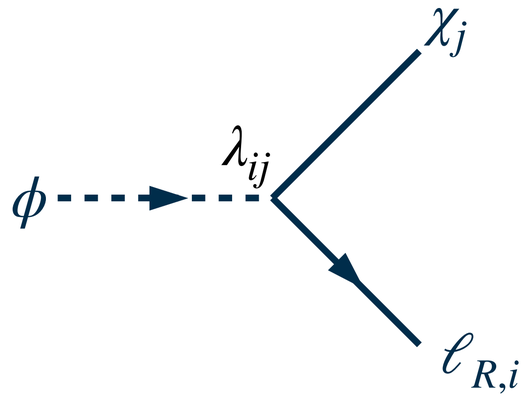


- **Sakharov conditions:**
  - C- and CP-symmetry violation ✅ From conversion process with **CP-violating coupling**
  - Interactions out of equilibrium ✅ **Early DM departure from equilibrium** because of very small couplings
  - Baryon number violation ✅ **Sphaleron processes** violate $B + L$ in SM sector (but conserve $B - L$)
- **Sphaleron processes:** non-perturbative transitions in the electroweak theory between topologically distinct vacua, active at high temperatures (until $T \sim 130$ GeV)

[Heisig 2024]

Conversion-Driven Leptogenesis

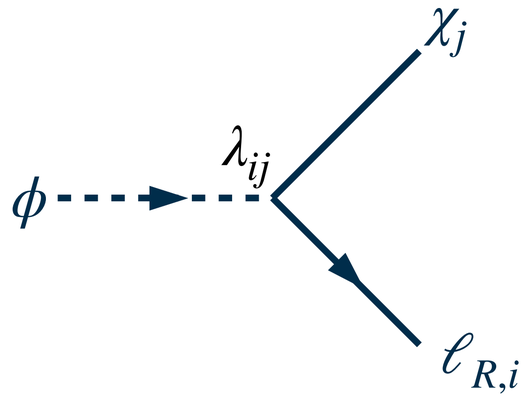
- Studied already using leptophilic flavored DM with 2 nearly mass-degenerate χ flavors

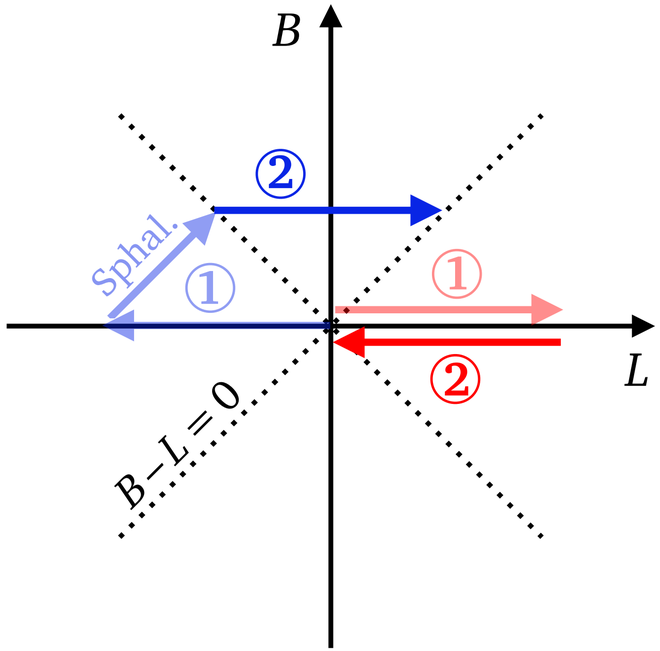


[Heisig 2024]

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





①: $T \sim T_{\text{sphal}}$

②: $T \ll T_{\text{dec}}$

: SM sector

: Mediator

[Heisig 2024]

Conversion-Driven Leptogenesis

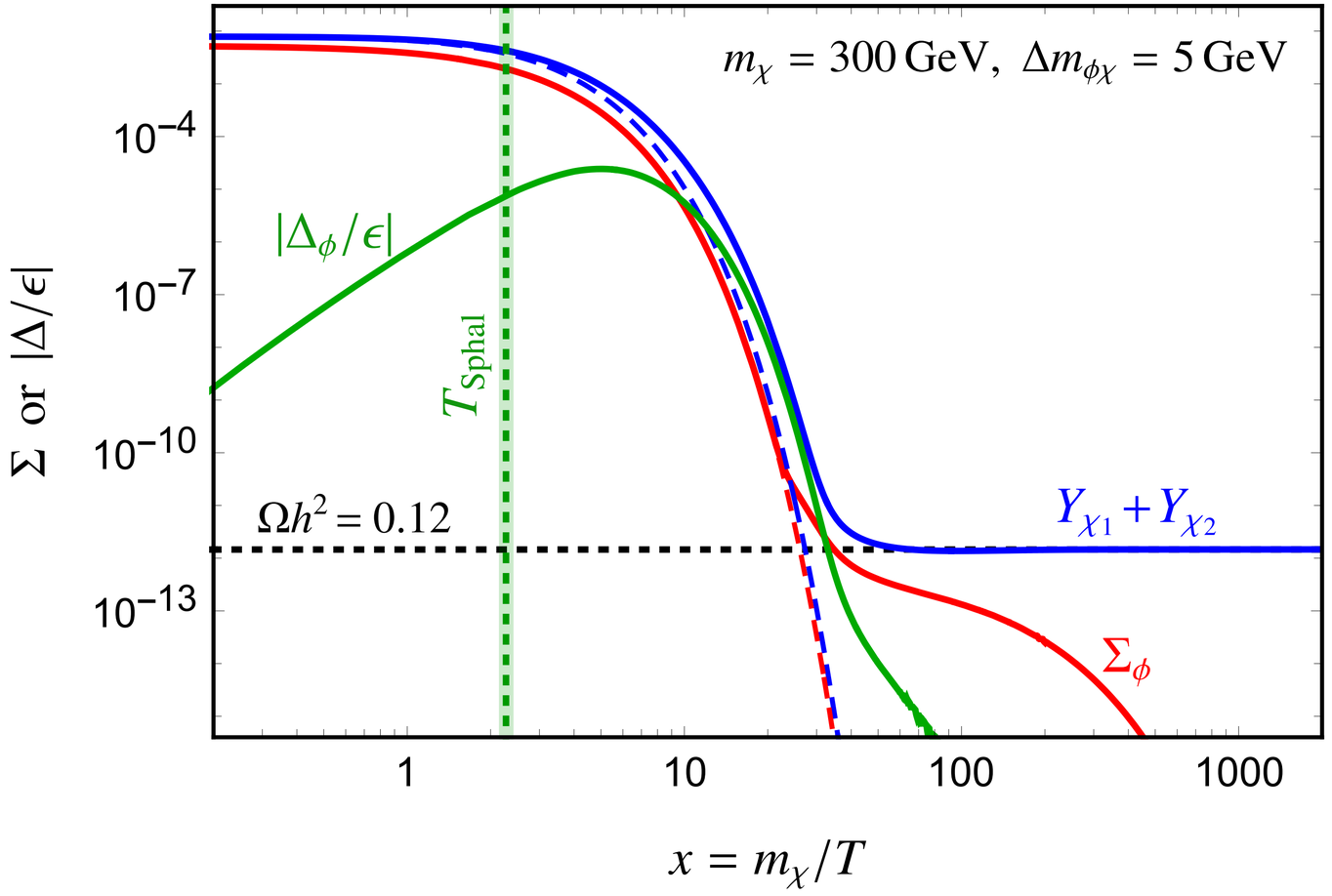
- CP-asymmetry in $\phi \to \chi_i \ell_R$ decay

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

- **Asymmetry $\Delta_\phi = Y_\phi - Y_{\bar{\phi}}$ large** at sphaleron decoupling temperature

- Can be converted into Baryon asymmetry with

$$Y_{\Delta B} \approx -\frac{28}{79}\epsilon \frac{\Delta_\phi}{\epsilon}\bigg|_{T=T_{\text{Sphal}}}$$



[Heisig 2024]

Conversion-Driven Leptogenesis

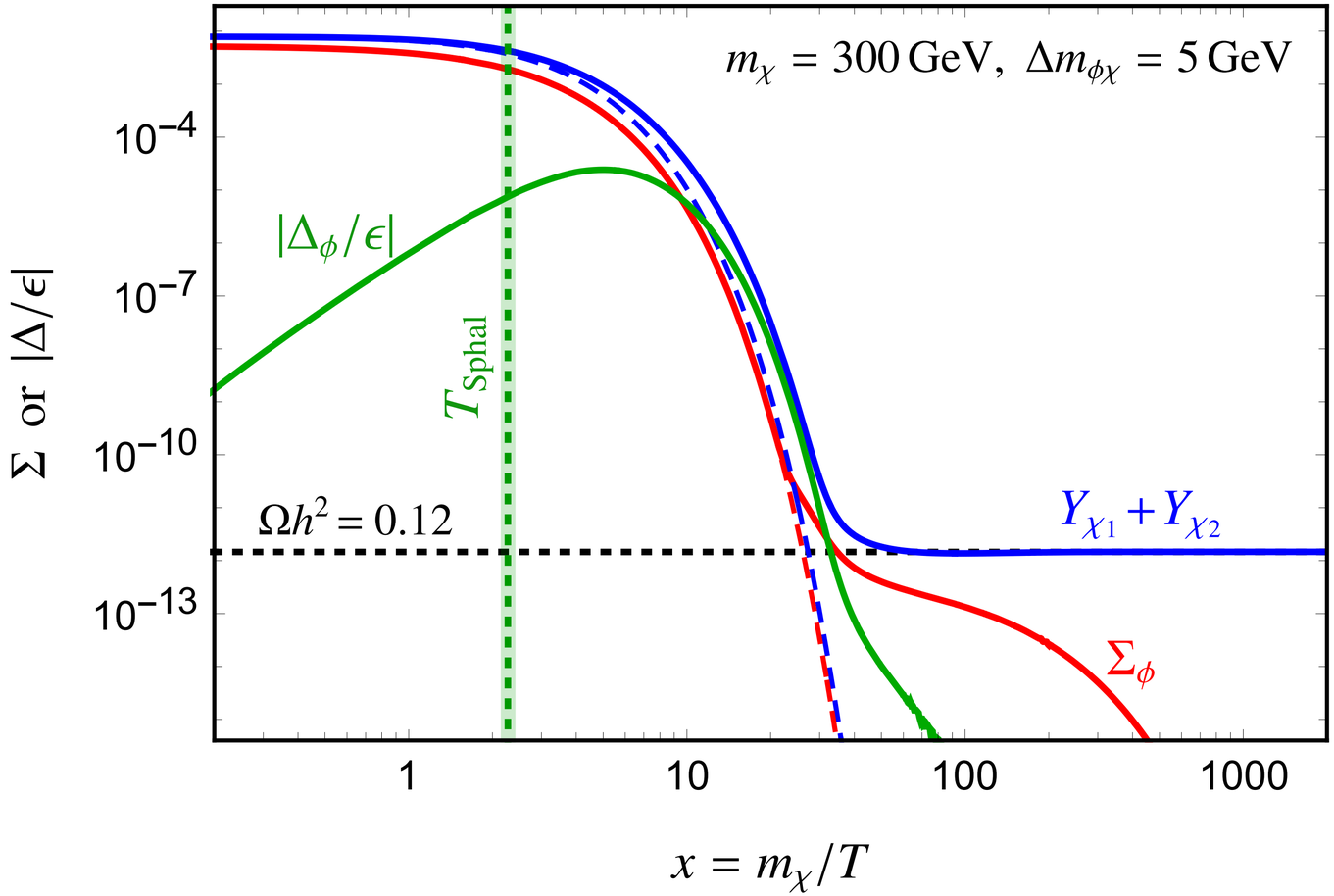
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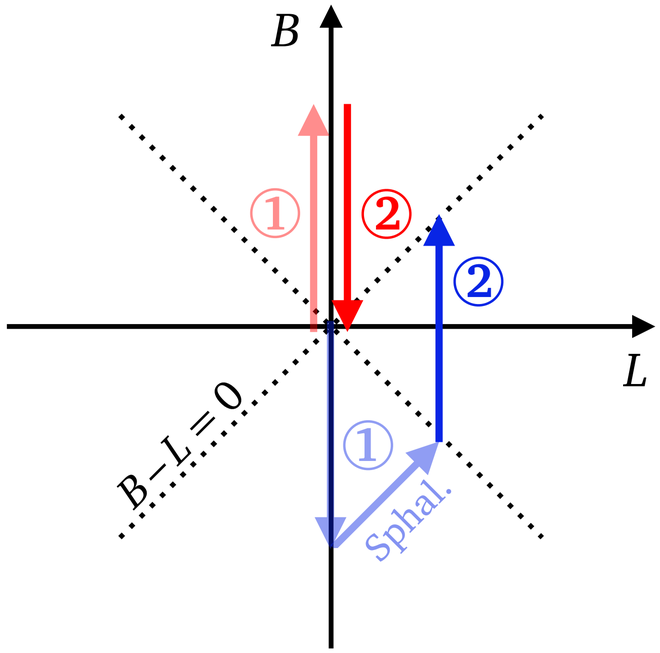
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→ Study case for quark-philic model, include thermal corrections

Conversion-Driven Baryogenesis



①: $T \sim T_{\text{sphal}}$

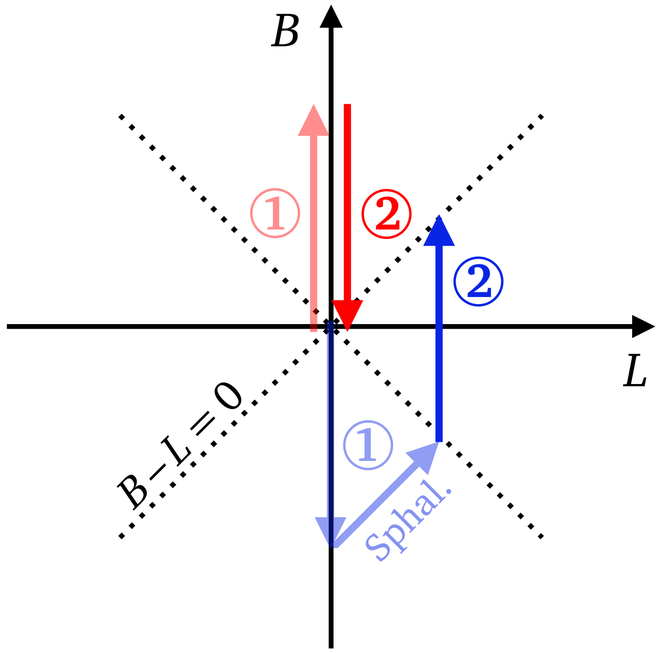
②: $T \ll T_{\text{dec}}$

: SM sector

: Mediator

- Use flavored DM model **coupling to right-handed down-type quarks** with 2 flavors

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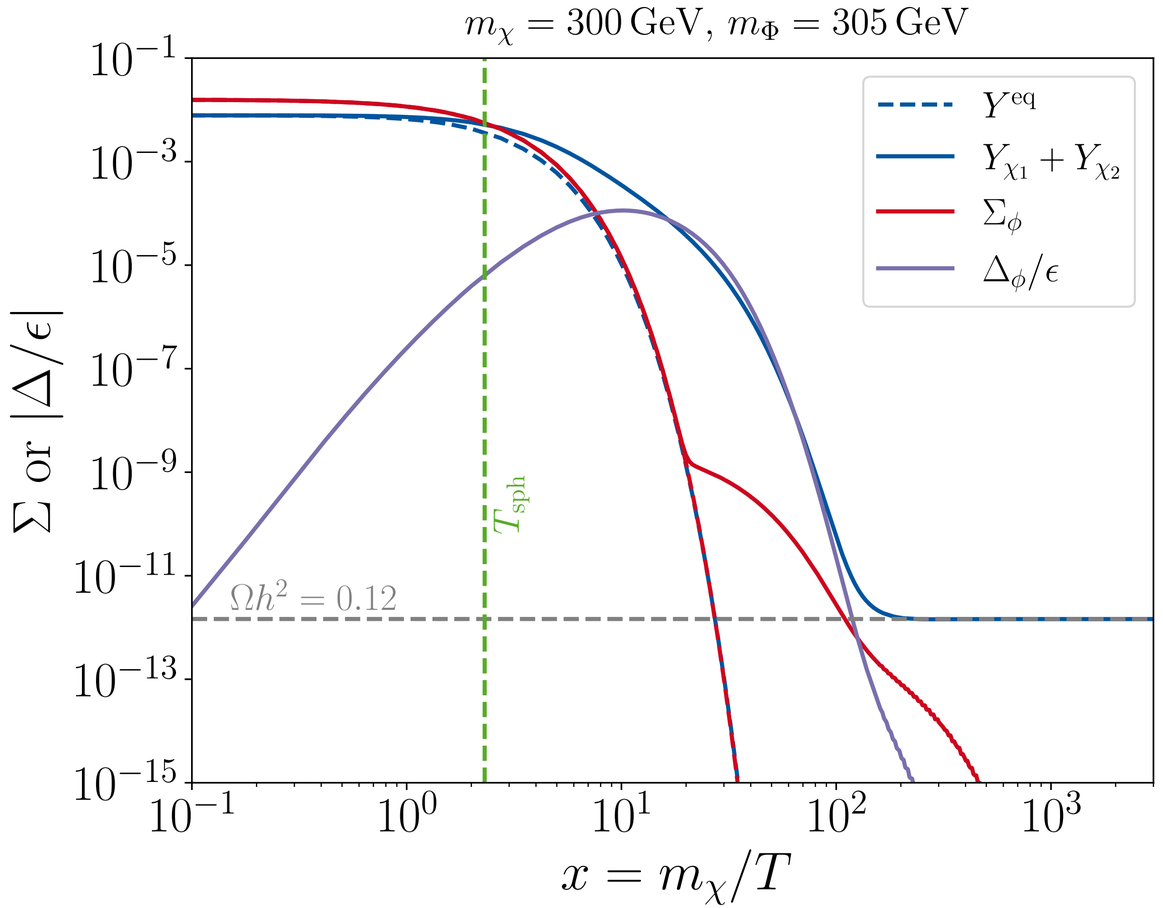


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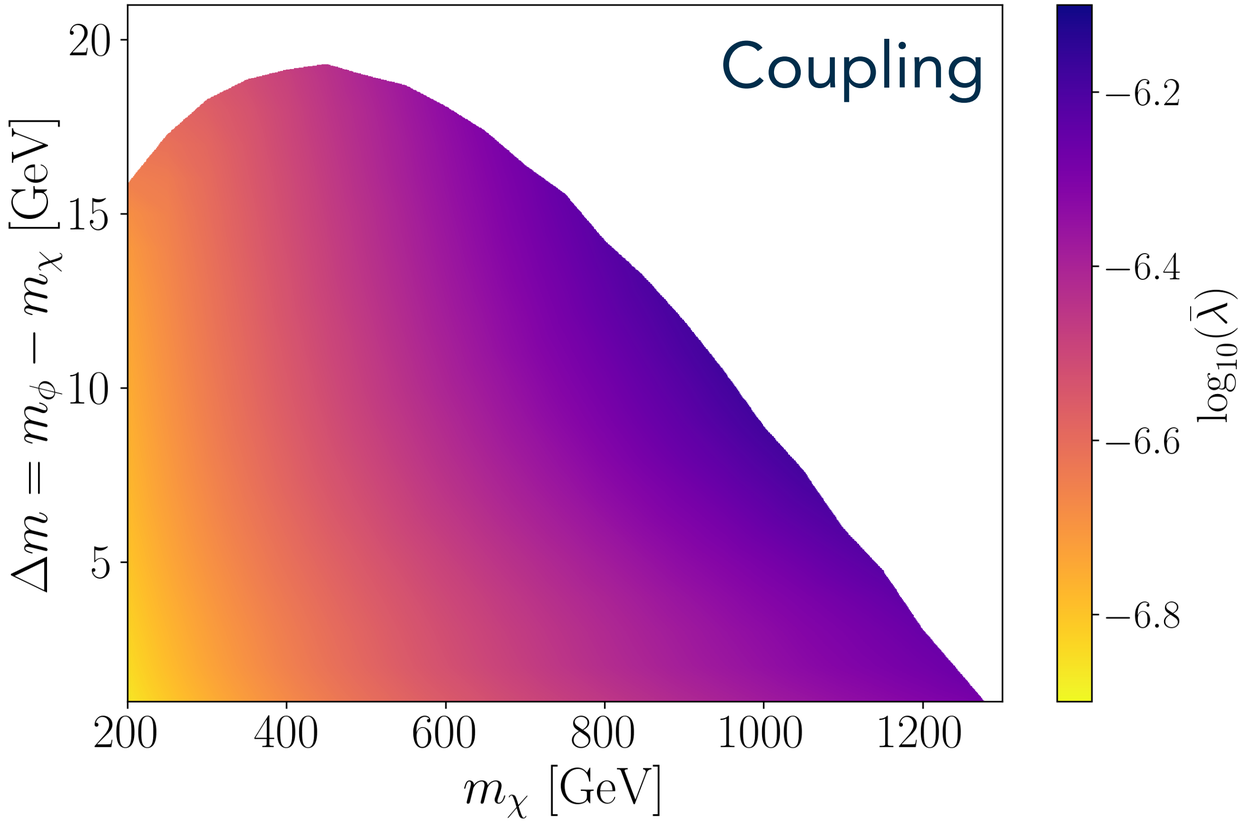


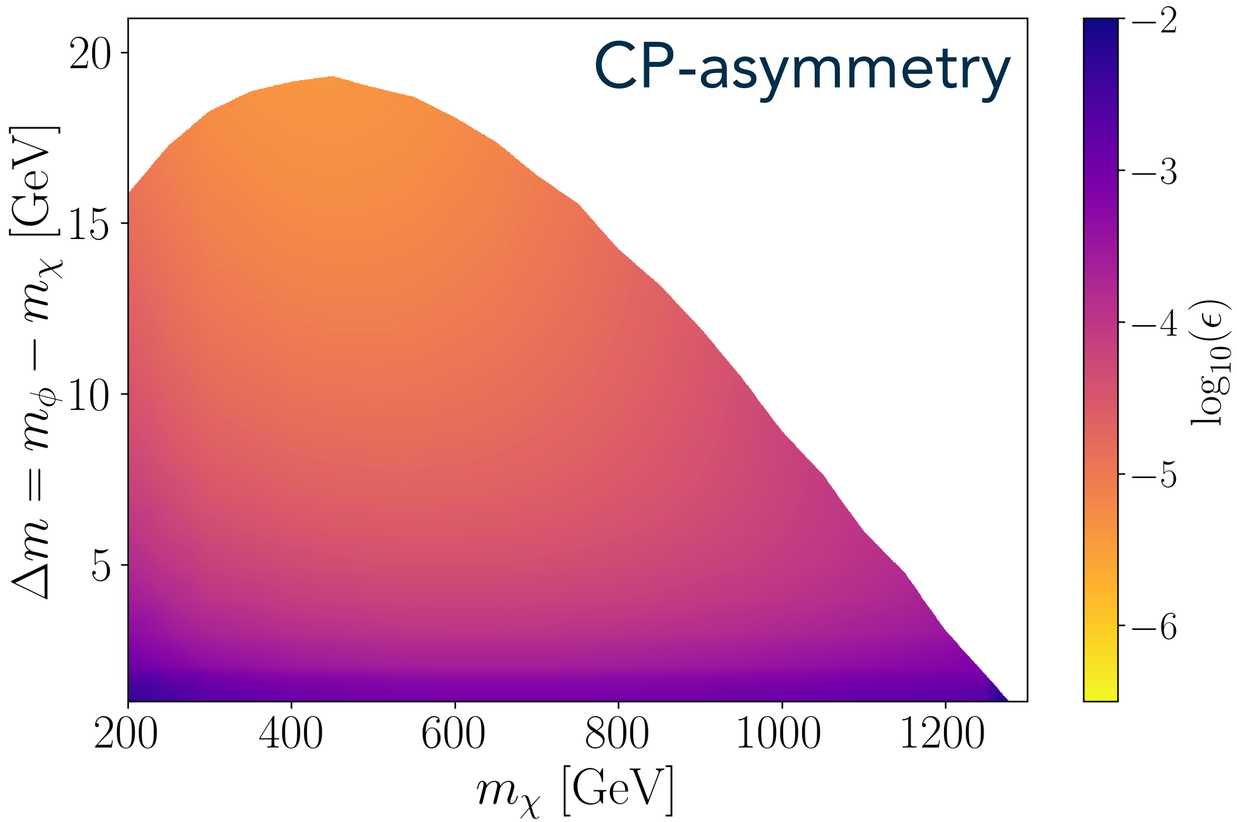
- Use flavored DM model **coupling to right-handed down-type quarks** with 2 flavors

- Convert into baryon asymmetry: $Y_{\Delta B} = -\frac{21}{79}\epsilon \frac{\Delta_\phi}{\epsilon}\Big|_{T=T_{\text{Sphal}}}$

Viable Parameter Space

- Solution possible for $\Omega h^2 = 0.12$ **and** $Y_{\Delta B} = 0.9 \times 10^{-10}$ (here for branching fraction $\mathrm{Br}(\phi \to \chi_1) = 0.75$)

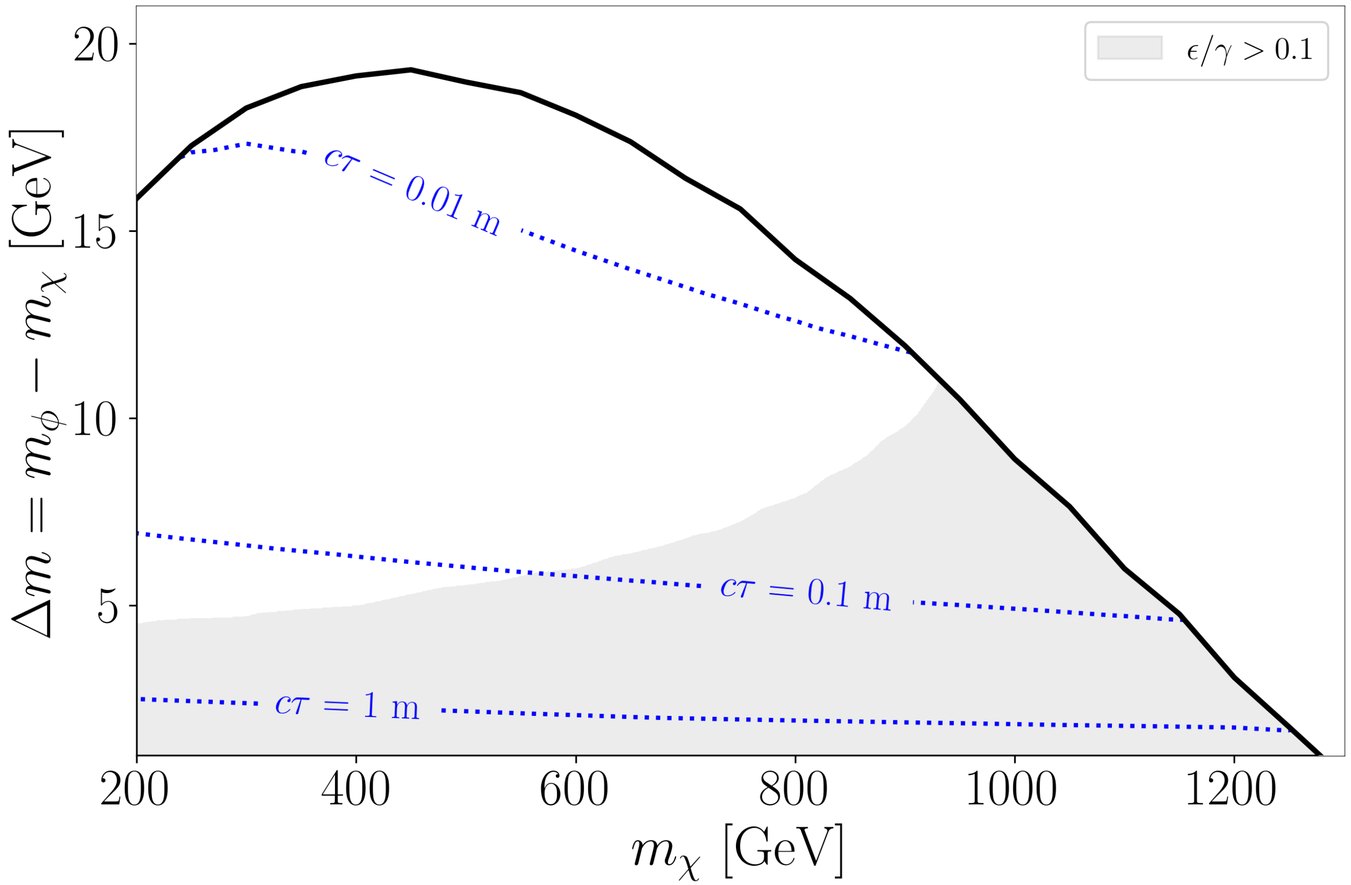




Constraints

- For $\epsilon/\gamma > 0.1$ validity of computation questionable
- Couplings of order $\mathcal{O}(10^{-7})$ → evade direct and indirect searches

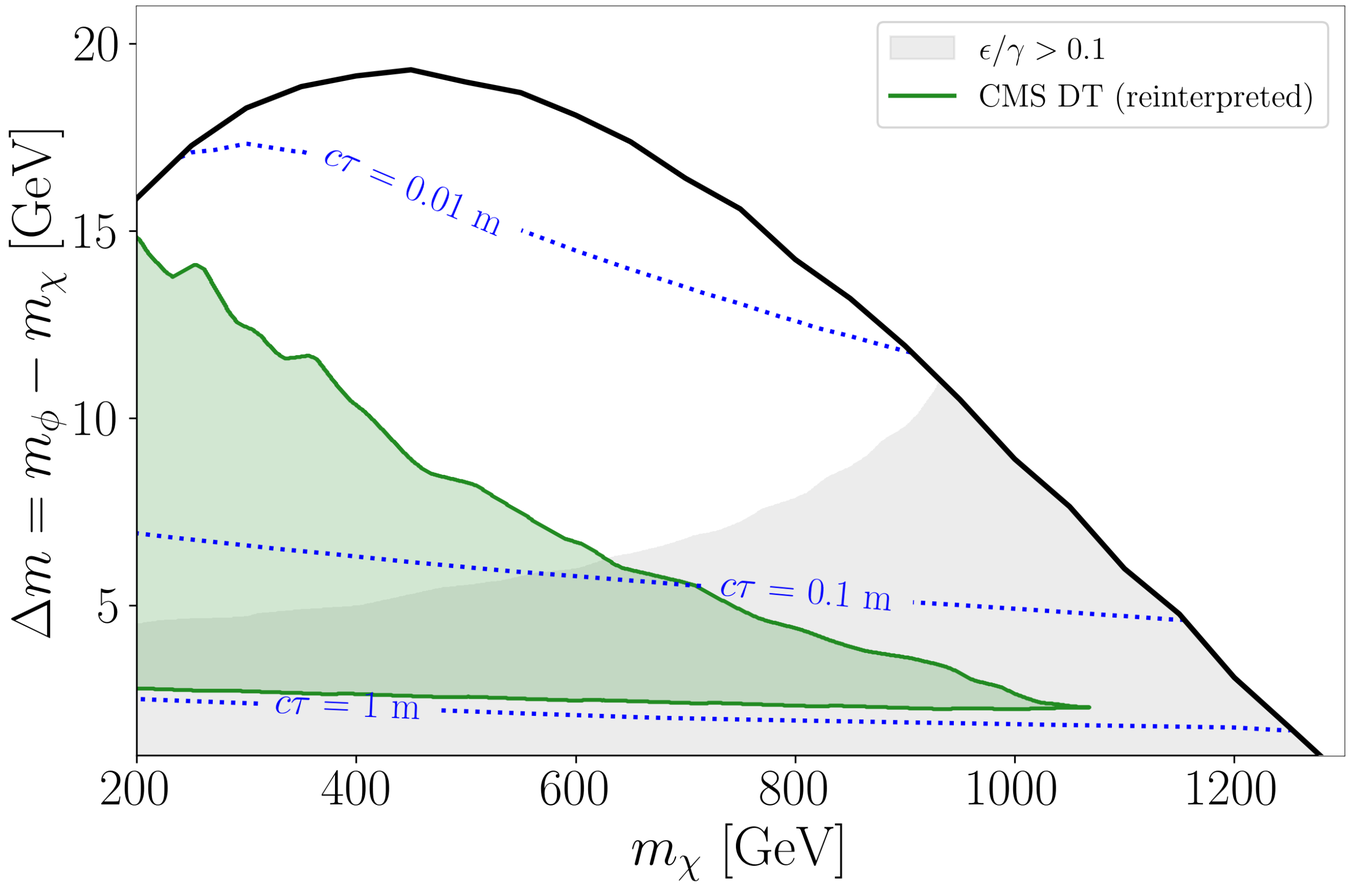
Branching fraction $\mathrm{Br}(\phi \to \chi_1) = 0.75$



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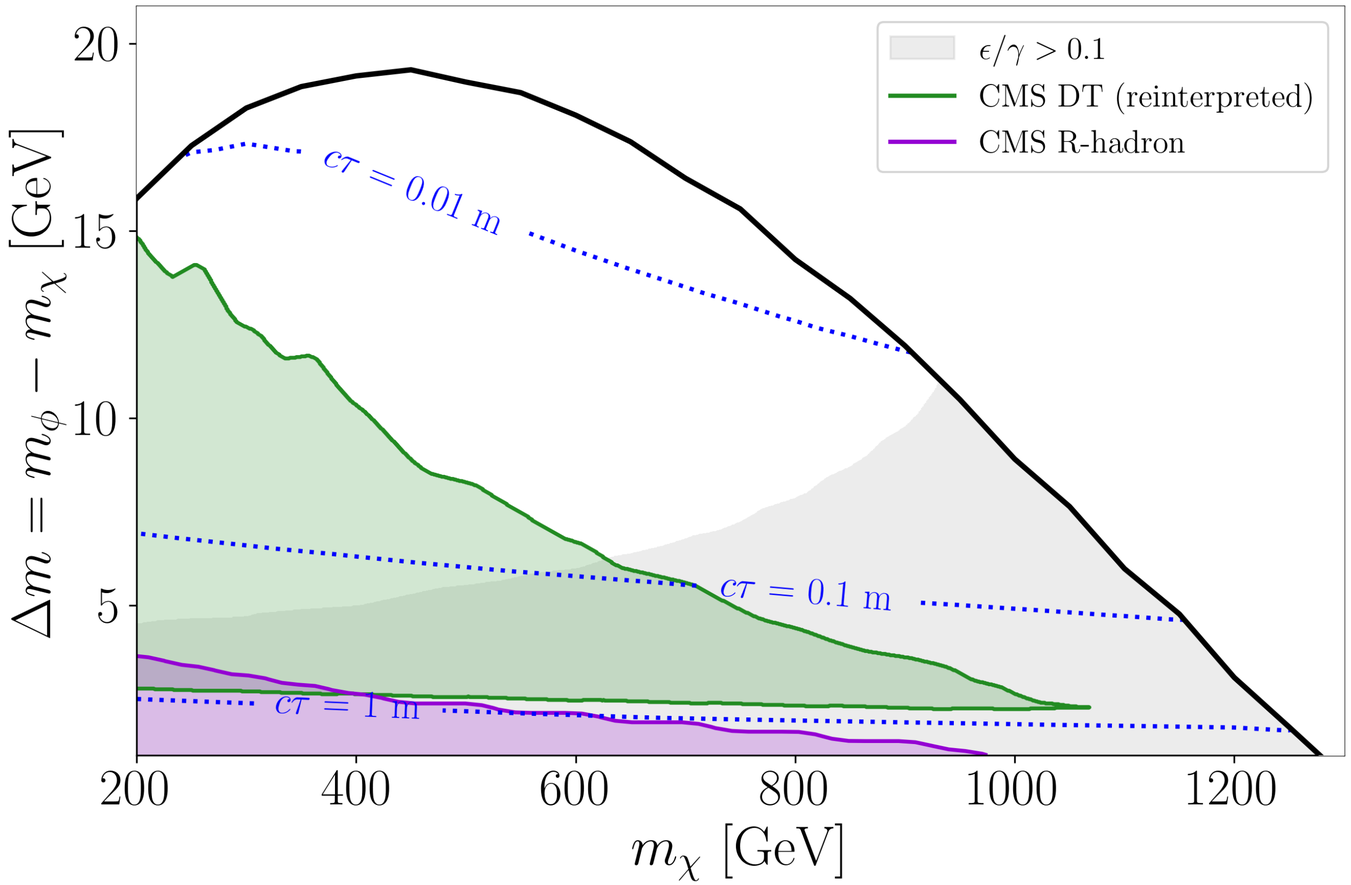


Limits reinterpreted from [Heisig et al. 2024]

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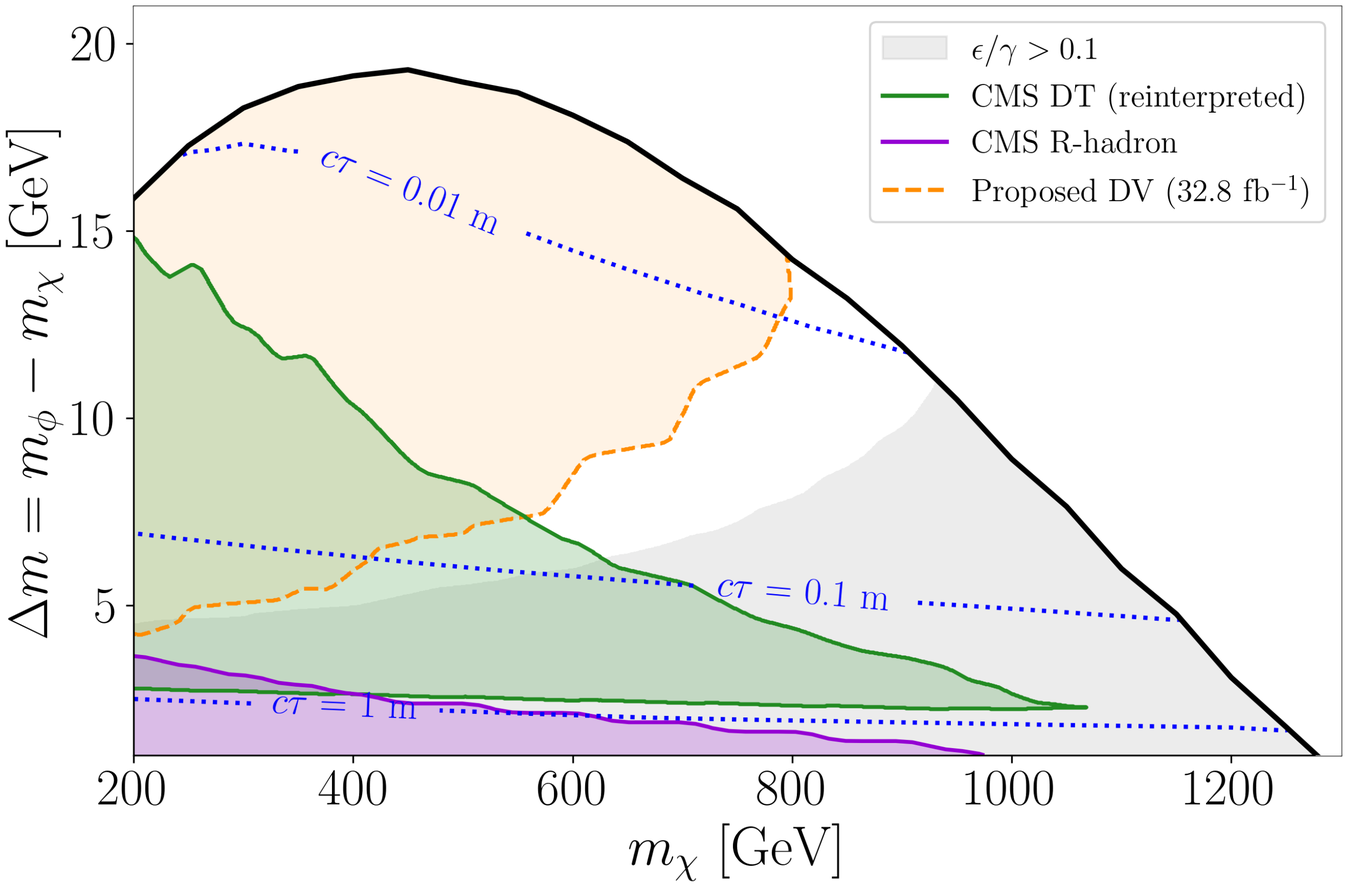


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- Proposed displaced vertices (DV) +MET search could cover most of parameter space

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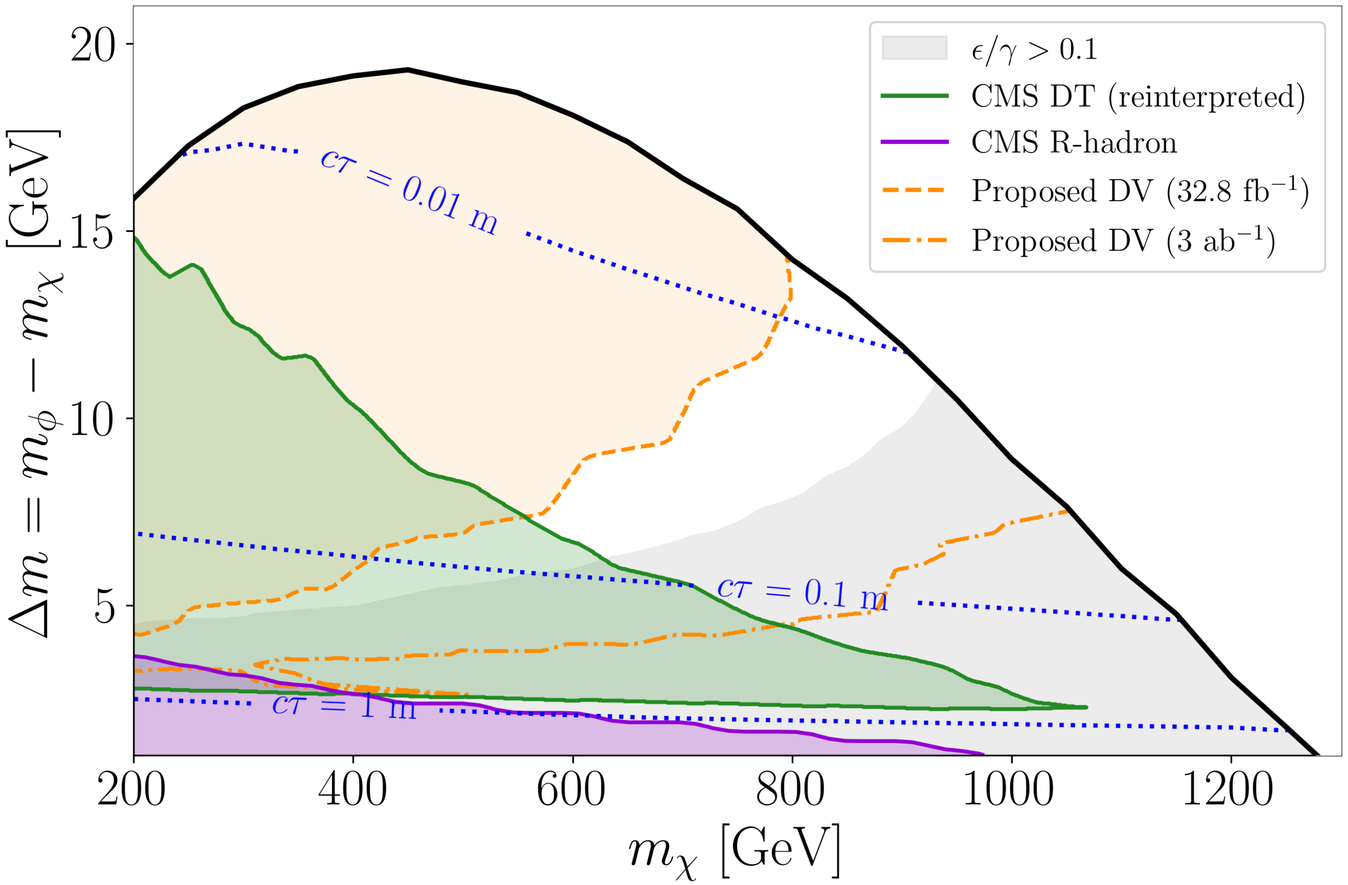


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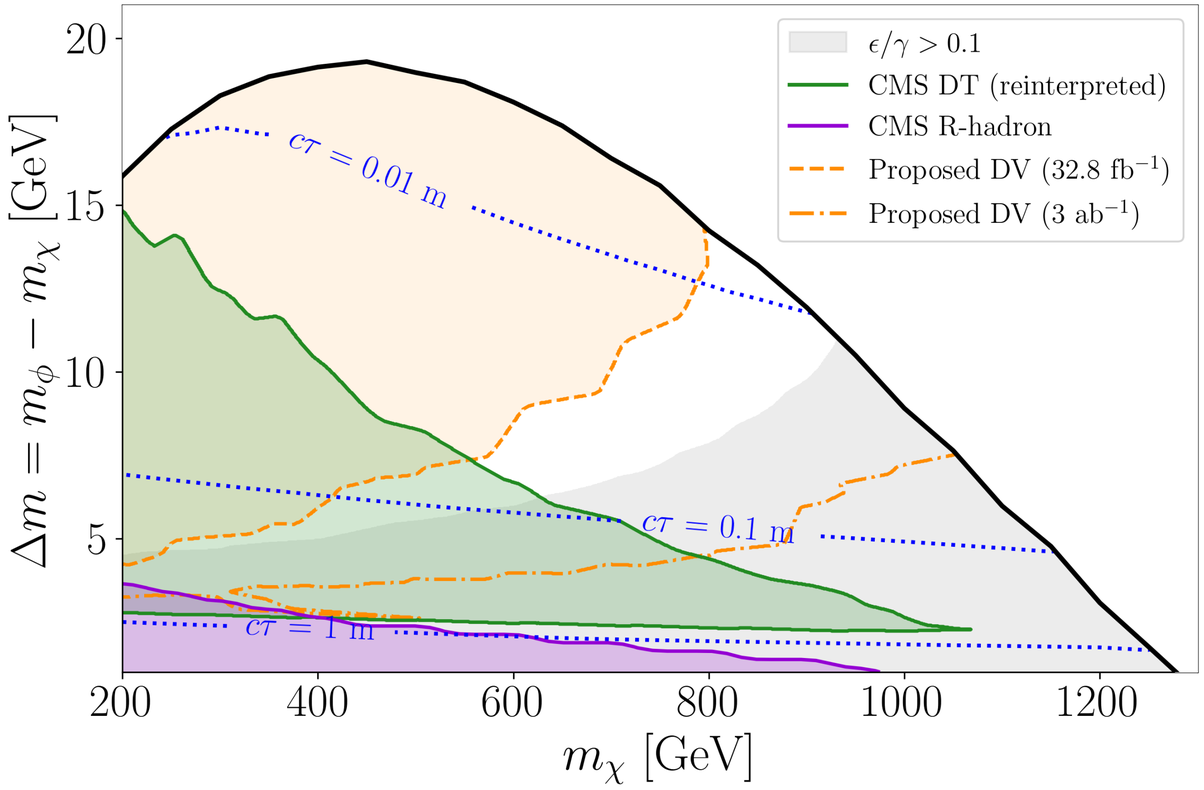


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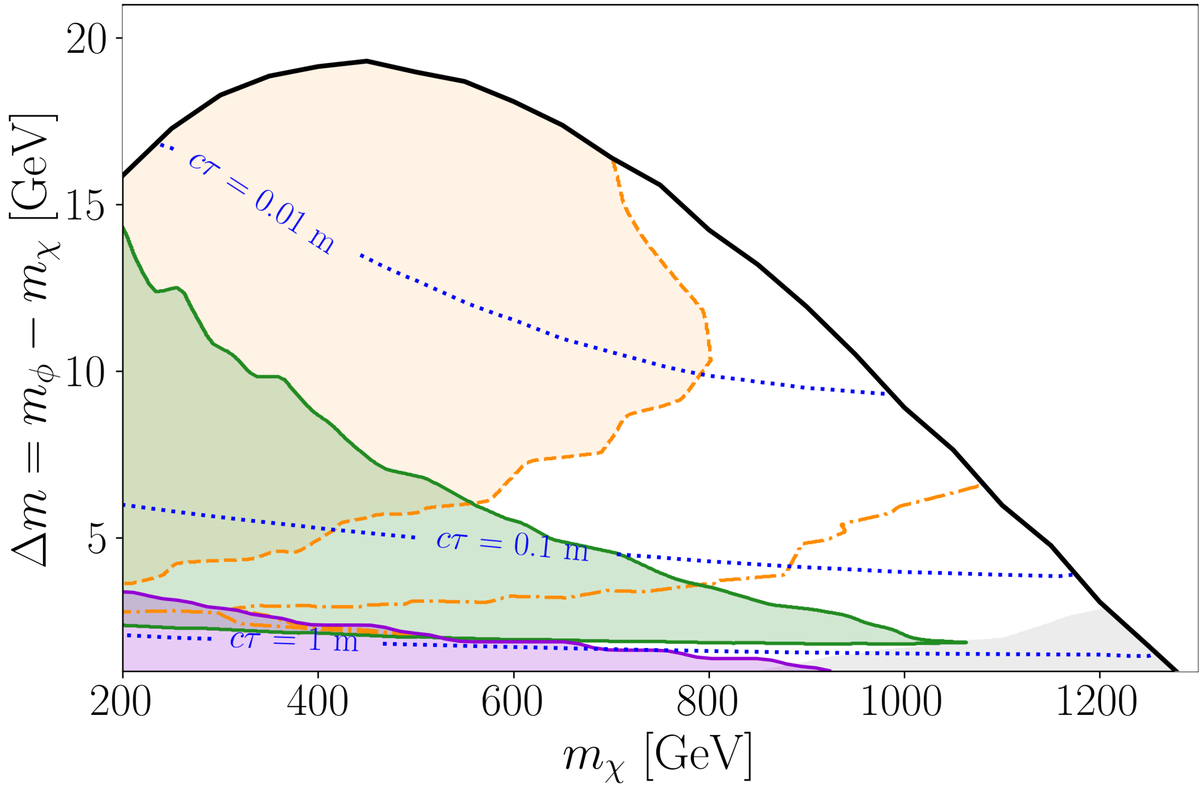
Thermal Effects

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

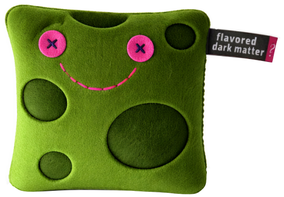
Without thermal masses



With thermal masses



Conclusions

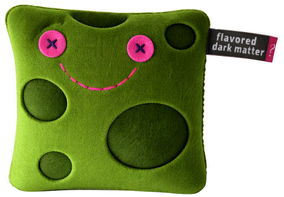


- **Conversion-driven freeze-out** scenario in flavored DM models allows for couplings $\lambda \sim 10^{-7} \rightarrow$ provides **correct relic abundance** while **evading WIMP constraints** and **fulfills Sakharov conditions**
- **Conversion-driven baryogenesis** can produce viable dark matter candidate and baryon asymmetry at the same time in large region of parameter space
- **Solution possible up to DM masses of ~ 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





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**
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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:

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

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

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

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

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

All coannihilations

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All conversions including decays

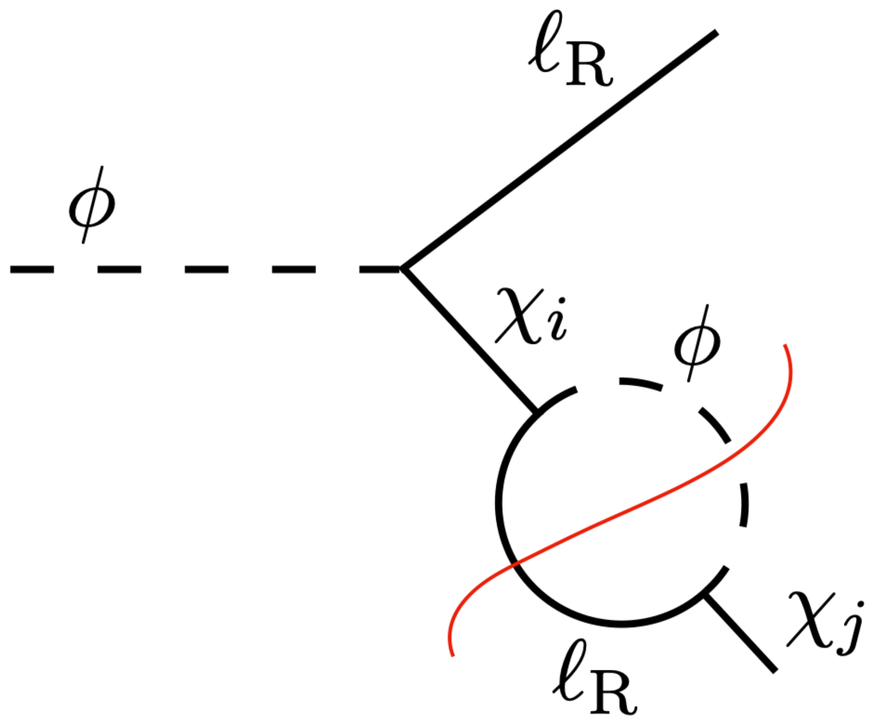
BME for Conversion-Driven Baryogenesis

$$
\begin{aligned}
x\mathcal{H}Z\,\frac{\mathrm{d}\Sigma_\phi}{\mathrm{d}x} &= -\,\Gamma_\phi\,\Sigma_\phi + \frac{1}{2}\,\Sigma_\phi^{\mathrm{eq}} \sum_i \Gamma_i\,\frac{Y_{\chi_i}}{Y_{\chi_i}^{\mathrm{eq}}} \\
&\quad - \frac{1}{2}\langle\sigma v\rangle\, s\left(\Sigma_\phi^2 - \Sigma_\phi^{\mathrm{eq}2}\right) \\
x\mathcal{H}Z\,\frac{\mathrm{d}\Delta_\phi}{\mathrm{d}x} &= -\,\Gamma_\phi\,\Delta_\phi \\
&\quad + \Gamma_\phi\; Y_\phi^{\mathrm{eq}} \sum_i \frac{Y_{\chi_i}}{Y_{\chi_i}^{\mathrm{eq}}}\left(-\,\epsilon_i + \frac{\Gamma_i}{\Gamma_\phi}\,\frac{\Delta_f}{\Sigma_f^{\mathrm{eq}}}\right) \\
x\mathcal{H}Z\,\frac{\mathrm{d}Y_{\chi_i}}{\mathrm{d}x} &= \frac{1}{2}\,\Gamma_i\left(\Sigma_\phi - \Sigma_\phi^{\mathrm{eq}}\,\frac{Y_{\chi_i}}{Y_{\chi_i}^{\mathrm{eq}}}\right)
\end{aligned}
$$

[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

- …

