Conversion-Driven Baryogenesis with Quark-Philic Flavored Dark Matter

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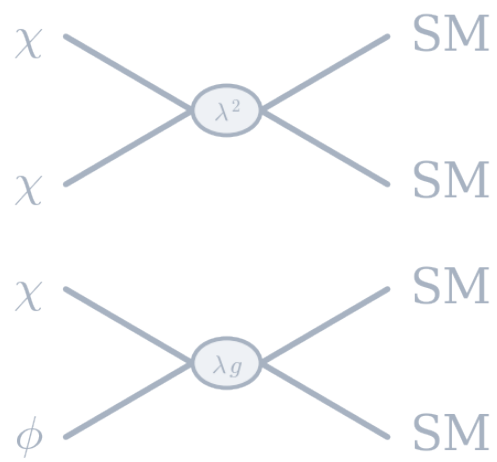
B. Belfatto, M. Blanke, J. Heisig, L. Rathmann, F. Wilsch, arXiv:2607.11147

Dark Matter and Baryogenesis with Flavored Dark Matter

Dark Matter abundance	**Conversion driven freeze-out**	small mediator-dark matter mass splitting $\Delta m = m_\phi - m_\chi$, couplings $\bar{\lambda} \sim 10^{-7}$–$10^{-6}$
CP violation	**Flavored Dark Matter**	Very small mass splitting $m_{\chi_2} - m_{\chi_1}$ between dark matter species → resonant regime
Baryon Asymmetry	**CP violating conversions + Electroweak sphalerons**	Semi-inefficient conversions provide out-of-equilibrium, B and L perturbatively conserved

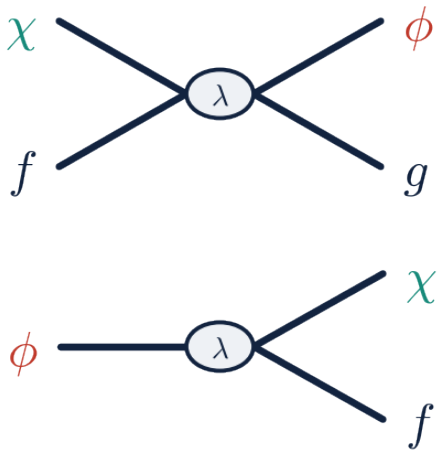
Conversion driven freeze-out

annihilation & coannihilation

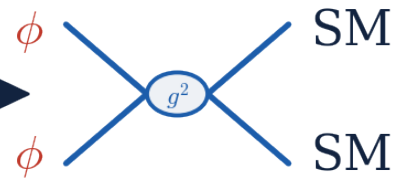


suppressed $(\propto \lambda^2, \lambda^4)$

conversions $\chi \leftrightarrow \phi$



mediator annihilation



scatterings + (inverse) decays

- Tiny Yukawa: annihilations and coannihilations are strongly suppressed
- **Conversions χ ↔ ϕ — decays, inverse decays, scatterings off the plasma — become semi-inefficient near freeze-out, and chemical equilibrium breaks down**
- **Mediator pair-annihilation**, driven by QCD charge of the mediator, is what actually depletes the dark sector
- Realized in **t-channel mediator DM models**

Flavored dark matter

CPT invariance ⇒ a non-vanishing CP asymmetry needs more particle fields

Minimal t-channel mediator models not enough ⇒ Flavored DM

Minimal working setup: 2 dark flavors × 2 SM flavors

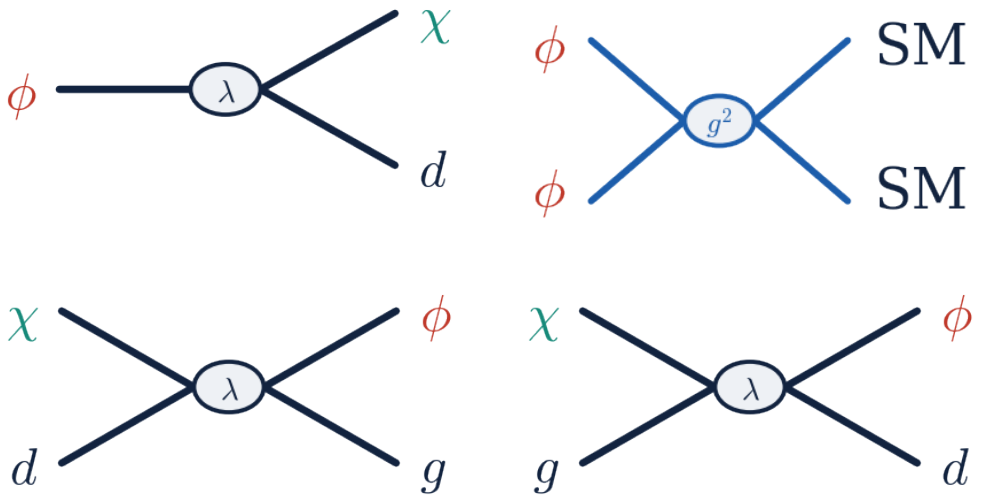
- gauge-singlet **Majorana DM** multiplet χ_i + **t-channel mediator ϕ**, both **Z_2-odd,** (SM Z_2-even)
- ϕ carries the gauge quantum numbers of the SM fermions it couples to
- New **complex Yukawa matrix λ** coupling the mediator and dark flavors to SM fermions
- ϕ couples to right-handed down-type quarks, two dark flavors $\chi_{1,2}$

$$\mathcal{L} \supset \frac{1}{2}\bar{\chi}_i\, i\partial\!\!\!/\, \chi_i - \frac{M_\chi^{ij}}{2}\bar{\chi}_i\chi_j + (D_\mu\phi)^\dagger D^\mu\phi - m_\phi^2|\phi|^2 - \left(\lambda_{\alpha i}\,\phi\,\bar{f}_{\mathrm{R},\alpha}\chi_i + \mathrm{h.c.}\right) - \lambda_H H^\dagger H\,\phi^\dagger\phi$$

$\bar{\lambda} \equiv \sqrt{\mathrm{tr}(\lambda^\dagger\lambda)}$ overall coupling strength, sets the total mediator width

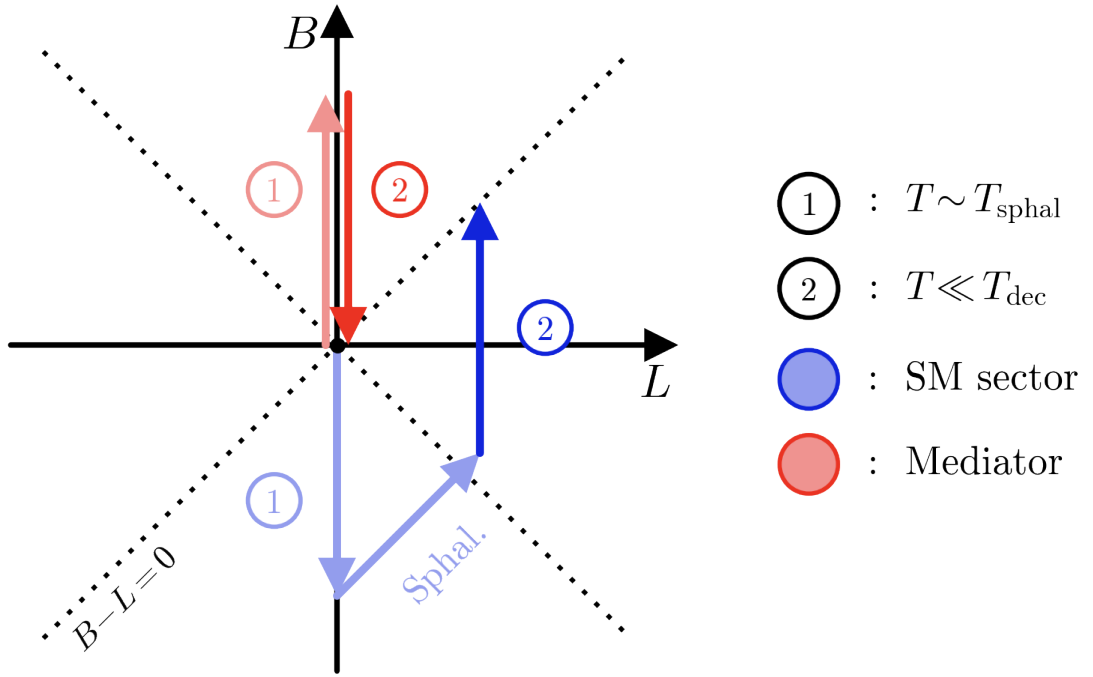
- $m_{\chi_2} - m_{\chi_1} \sim \bar{\lambda}^2 m_\chi$ ⟶ resonant regime

Conversion driven baryogenesis



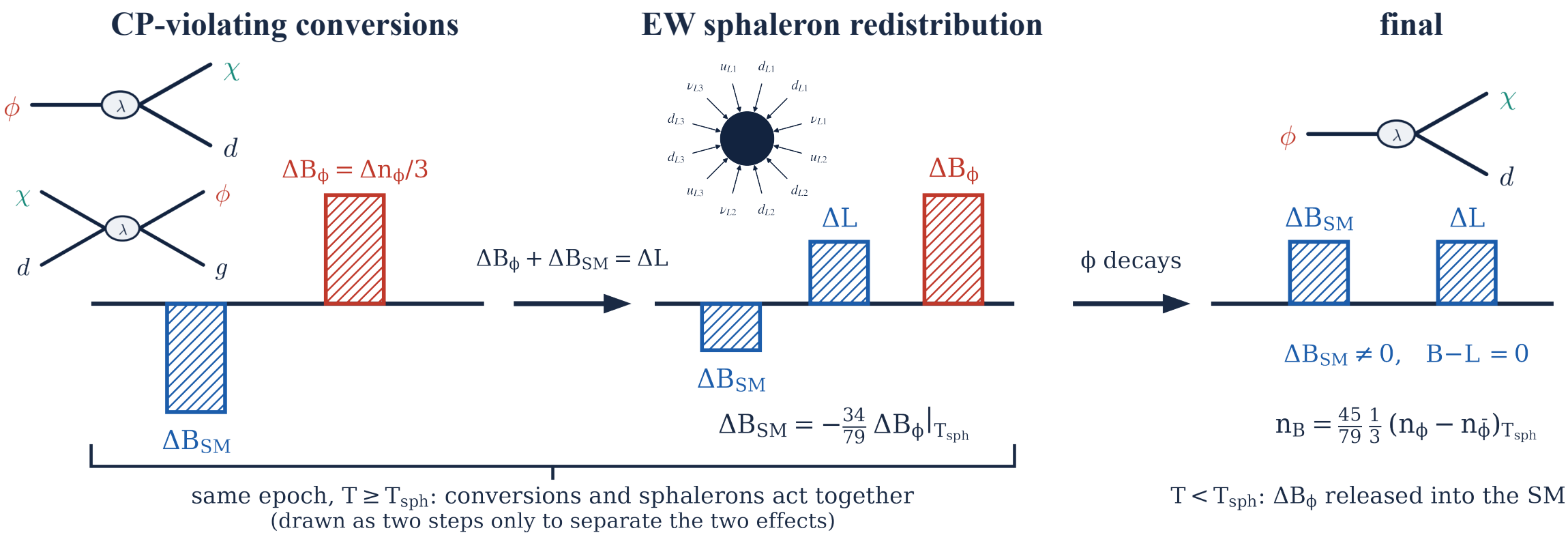
Quarkphilic model, d_R

$n_{\Delta B} = \frac{45}{79}\frac{1}{3}(n_\phi - n_{\bar{\phi}})_{T_{\rm sphal}}$



- ϕ carries the baryon (or lepton) number of the fermion it couples to ⇒ **B and L perturbatively conserved**
- Gauge interactions keep ϕ in equilibrium; χ leaves equilibrium before sphaleron decoupling
- SM Yukawas pass the right-handed asymmetry to the sphaleron-active left-handed sector
- **ϕ decays later and transfers asymmetry to SM; sphalerons have reshaped the rest ⇒ a net B survives**

Baryon number

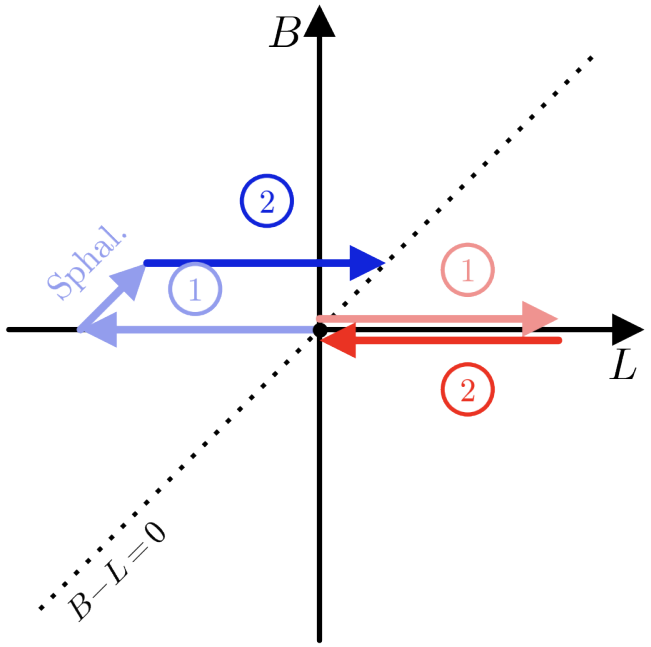


- ϕ carries the baryon (or lepton) number of the fermion it couples to $\Rightarrow$ **B and L perturbatively conserved**
- **CP-violating conversions** generate baryon asymmetries in the SM and mediator sectors.
- **Electroweak sphalerons** redistribute the SM asymmetry before decoupling.
- **Mediator**'s equilibrium gauge interactions **do not transfer its B−L asymmetry** to the sphaleron-active sector.
- Subsequent mediator decays release the remaining baryon asymmetry to the SM, while total B−L remains zero.

B–L

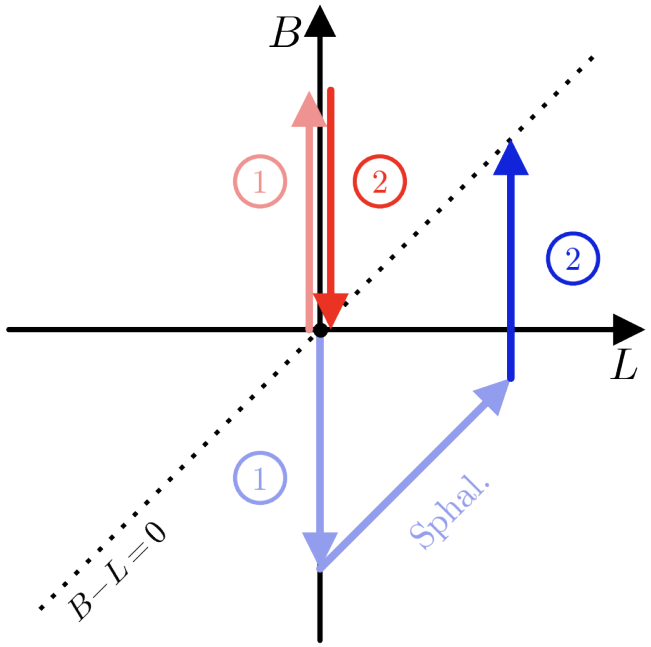
Leptophilic model

$n_{\Delta B} = \frac{22}{79}(n_\phi - n_{\bar{\phi}})_{T_{\rm sphal}}$



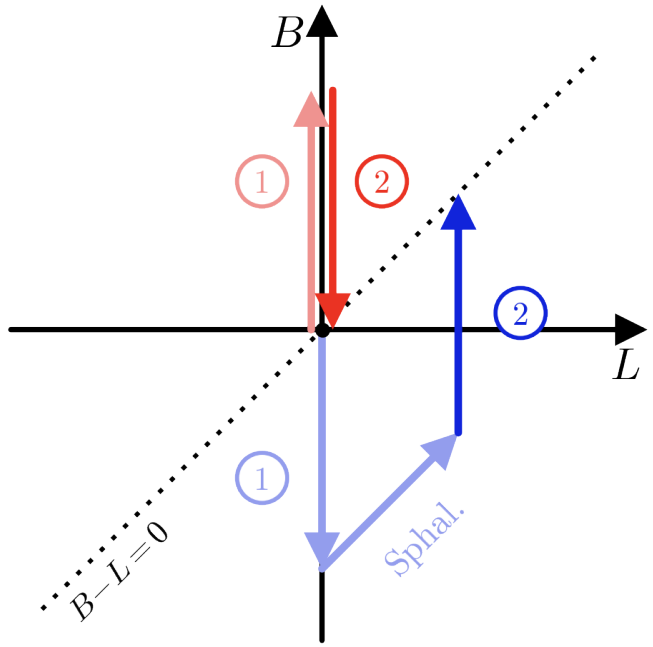
Quarkphilic model, u_R

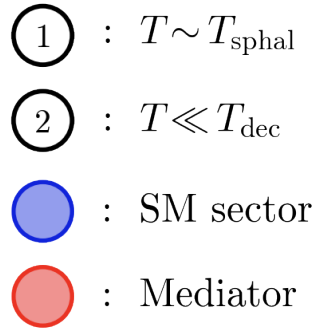
$n_{\Delta B} = \frac{63}{79}\frac{1}{3}(n_\phi - n_{\bar{\phi}})_{T_{\rm sphal}}$



Quarkphilic model, d_R

$n_{\Delta B} = \frac{45}{79}\frac{1}{3}(n_\phi - n_{\bar{\phi}})_{T_{\rm sphal}}$

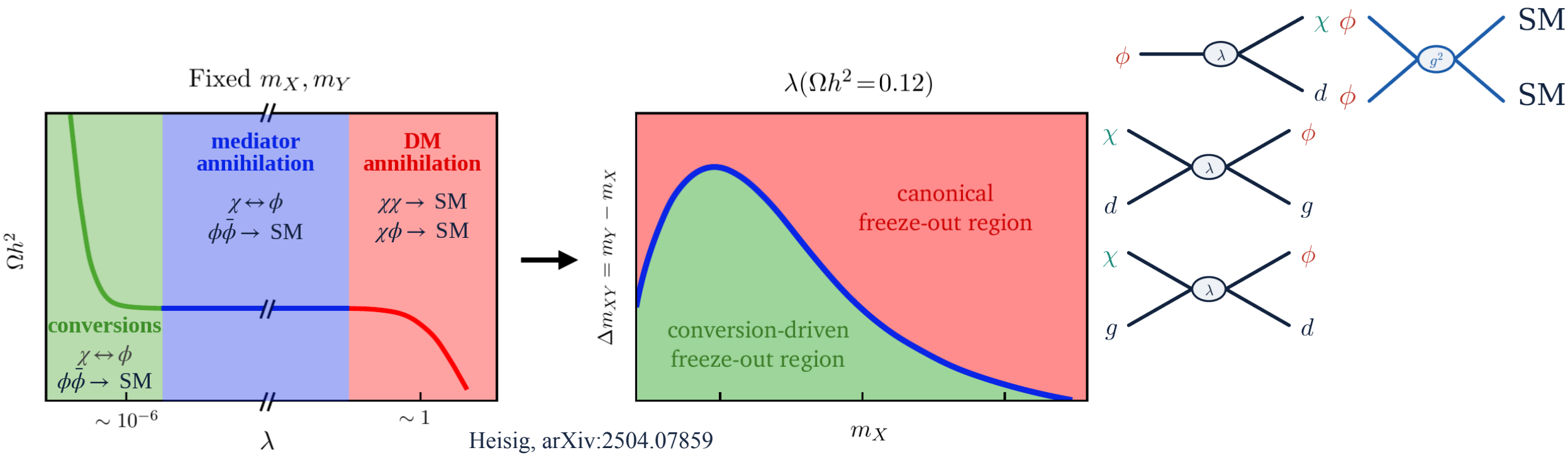




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- **Mediator**'s equilibrium gauge interactions **do not transfer its B−L asymmetry** to the sphaleron-active sector.
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$\bar{\lambda}$ - Δm interplay

CONVERSION-DRIVEN FREEZE-OUT

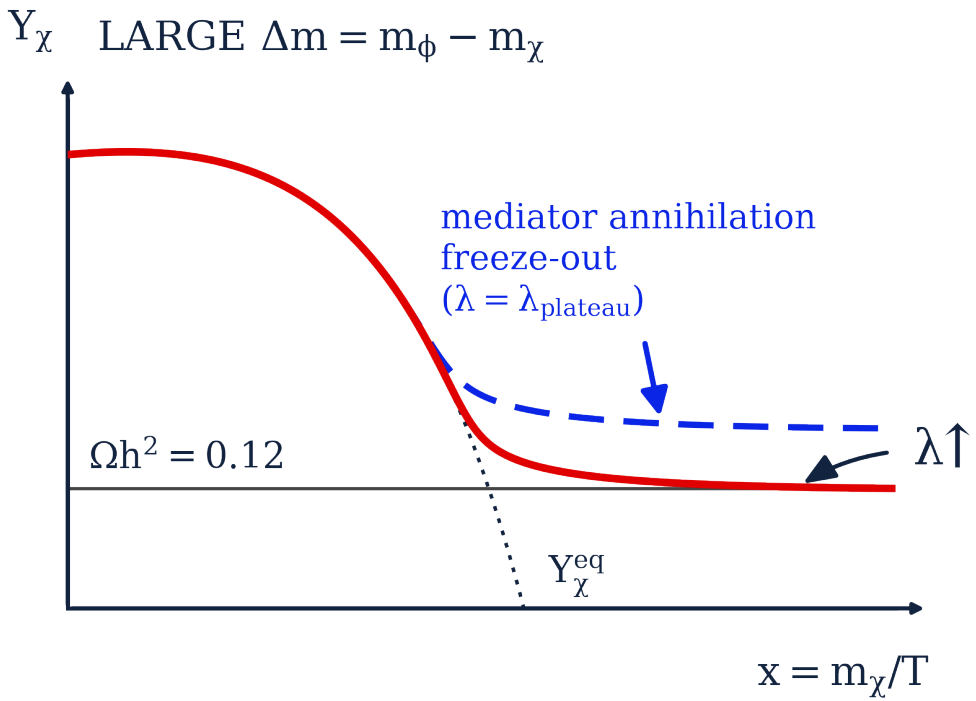


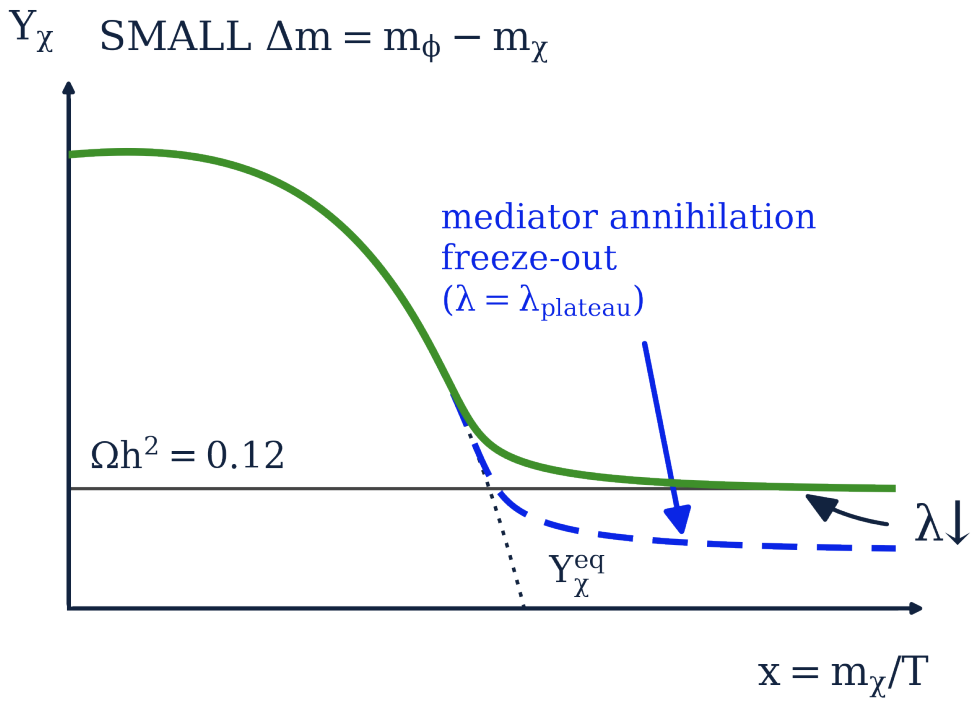
Heisig, arXiv:2504.07859

- Three regimes as λ falls: canonical annihilation (red), a plateau where mediator annihilation does the work (blue), and conversion-driven freeze-out (green)
- Requiring $\Omega\, h^2 = 0.12$ turns this into a boundary in the mass plane: the coupling drops by orders of magnitude across it

$\bar{\lambda}$ - Δm interplay

Schematic DM yield for λ at its plateau value (dashed) and for the λ that gives $\Omega\, h^2 = 0.12$ (solid): red = canonical, green = conversion-driven



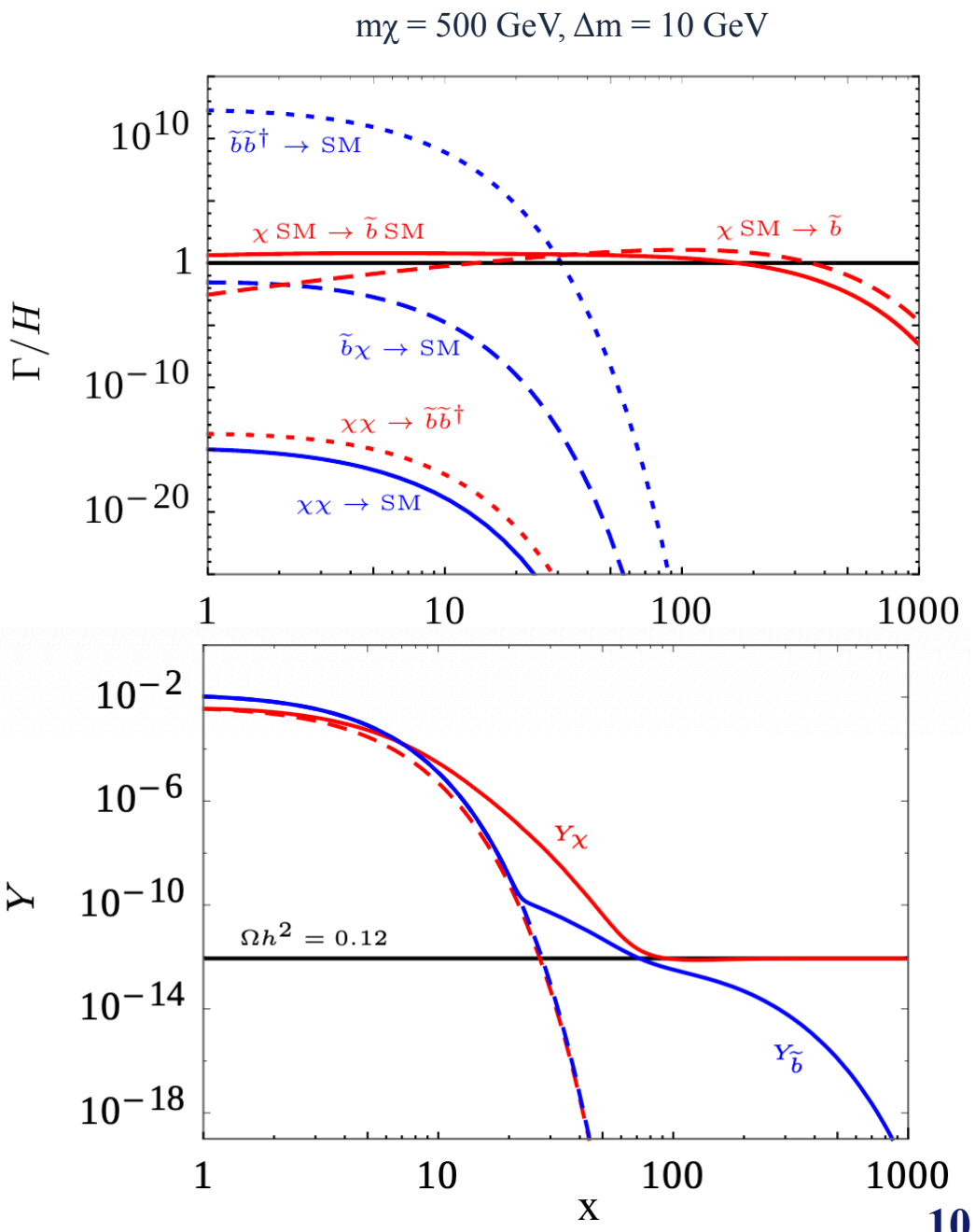


Large Δm: the plateau lies above $\Omega\, h^2 = 0.12$: a sizeable λ is needed so that DM annihilation ($\chi\chi$, $\chi\phi \to$ SM) is efficient: canonical freeze-out

Small Δm: the plateau falls below $\Omega\, h^2 = 0.12$: solutions exist for small λ, where conversions become semi-efficient and χ decouples chemically from ϕ before being fully diluted: conversion-driven freeze-out

Conversion-driven freeze-out

- Conversions are **not Boltzmann-suppressed** — a single heavy particle in the initial state — they stay efficient
- **Annihilation** and pair production rates **negligible** (two heavy particles)
- Γconv has a shallow T-dependence: it hovers just above H from the relativistic to the non-relativistic regime
- **early gradual decoupling** that starts while χ is still **semi-relativistic** and abundant — this is what makes the asymmetry sizable
- **DM dilution**: $\chi \to \phi$ followed by efficient annihilation $\phi\phi \to SM$
- needs a **small DM–mediator** splitting
- Relic abundance is enhanced for small couplings ⇒ $\bar{\lambda} \sim 10^{-6}$
- DM thermalizes first ⇒ abundances and asymmetries are **insensitive to initial conditions**
- very **weak DM couplings** evade experiments
- one of the simplest realization: **t-channel mediator** models



Garny, Heisig, Lülf, Vogl, arXiv:1705.09292

Sakharov conditions

the conversion driven freeze-out regime	⇨	**Out of equilibrium**
CP-violating conversions, Flavored dark matter	⇨	**C and CP violation**
electroweak sphalerons: B−L conserved, active until T ≈ 130 GeV; B and L perturbatively conserved	⇨	**B violation**

Equilibrium conditions and neutrality conditions

$$n_{\Delta X} \equiv n_X - n_{\bar{X}} = \frac{g_X T^3}{6} \frac{\mu_X}{T} k_X \qquad k_X = \begin{cases} 1 & \text{relativistic fermions} \\ 2 & \text{relativistic bosons} \\ \frac{6}{\pi^2}\left(\frac{m_X}{T}\right)^2 K_2\left(\frac{m_X}{T}\right) \underset{m_X \gg T}{\approx} \frac{6\, e^{-m_X/T} m_X^{3/2}}{\sqrt{2}\,\pi^{3/2} T^{3/2}} & \text{non rel.} \end{cases}$$

- **Fast processes** and **conservation laws** fix equilibrium conditions on chemical potentials
- **Slow processes** need to be taken into account in Boltzmann equations
- SM Yukawa equilibrium, sphaleron equilibrium $3\mu_q + \mu_\ell = 0$, hypercharge neutrality
- Additional condition from **conserved quantum number B-L**: assumption $B - L = (B - L)_{\text{initial}}$
- **Everything reduces to one chemical potential, μ_ϕ**

Right-handed down-type quarks ($y_\phi = -1/3$, $g_\phi = 3$, baryon number 1/3):

$$n_{\Delta B} = \frac{1}{3}\left(n_\phi - n_{\bar{\phi}}\right)_{T=T_{\text{sphal}}} \times \frac{45}{79}$$

The Boltzmann system

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

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

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

- CPT $\Rightarrow \varepsilon_1 = -\varepsilon_2\, B_2/B_1 \equiv \varepsilon$
- $n_d - n_{\bar{d}} = -\left(n_\phi - n_{\bar{\phi}}\right) n_F\ \frac{40}{237}$ from equilibrium conditions
- Dividing by ε factorizes the density dynamics from the CP-asymmetry computation: one solves once for $\Delta\phi/\varepsilon$
- Scatterings enter as

$$\Gamma_i \longrightarrow \Gamma_i + \Gamma_{\mathrm{scat,\,i}}$$

Rates and CP asymmetries

$$\Gamma_i \equiv \frac{1}{2}\sum_\alpha\left(\langle\Gamma_{\phi\to\chi_i f_\alpha}\rangle + \langle\Gamma_{\bar{\phi}\to\chi_i \bar{f}_\alpha}\rangle\right)$$

$$\epsilon_i \equiv \frac{1}{2\Gamma_i}\sum_\alpha\left(\langle\Gamma_{\phi\to\chi_i f_\alpha}\rangle - \langle\Gamma_{\bar{\phi}\to\chi_i \bar{f}_\alpha}\rangle\right)$$

$$\Gamma_\phi \equiv \sum_i \Gamma_i$$

- $\Sigma\phi = Y\phi + Y\bar{\phi}$
- $\Delta\phi = Y\phi - Y\bar{\phi}$
- $x = m\chi_1 / T$
- **inputs: $\bar{\lambda}$, ε, B_1**
- $m\chi_1 = m\chi_2$ in the numerics

Boltzmann equations with scatterings

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

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

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

$$\Gamma_{\mathrm{scat},i} = \frac{1}{2}\sum_{k,m}\left(\langle\sigma_{\phi\bar{k}\to\chi_i m}v\rangle + \langle\sigma_{\bar{\phi}k\to\chi_i\bar{m}}v\rangle\right)n_k^{\mathrm{eq}}, \qquad \epsilon_{\mathrm{scat},i} = \frac{1}{2\Gamma_{\mathrm{scat},i}}\sum_{k,m}\left(\langle\sigma_{\phi\bar{k}\to\chi_i m}v\rangle - \langle\sigma_{\bar{\phi}k\to\chi_i\bar{m}}v\rangle\right)n_k^{\mathrm{eq}}$$

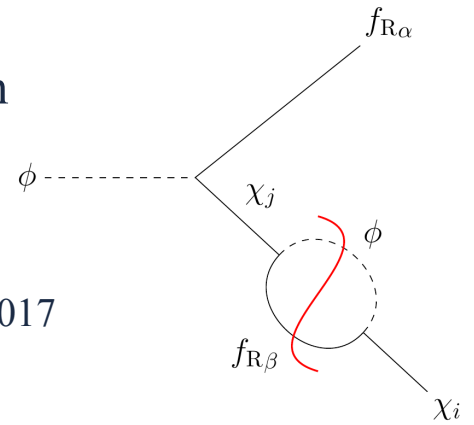
- CP violation in scatterings approximated by $\varepsilon_{\mathrm{scat,i}} \simeq \varepsilon_i$; the SM asymmetry Δ_f is traded for Δ_ϕ through the chemical-potential relations and, after CPT, one solves once for Δ_ϕ/ε
- Scatterings off gluons and quarks reach rates comparable to decays: relativistic SM particles, large phase space

Thermal effects: the CP asymmetry

- At T = 0 the interference is CP-conserving: the absorptive part is generated by the bath
- Resonantly enhanced for nearly degenerate χ_1, χ_2, with Δm_{12} of order $\bar{\lambda}^2$ m_χ

$$\epsilon(T) = I_1 \frac{2\,\Delta m_{12}\,\Gamma^0_{\chi_2}\,\gamma(T)}{\left[2\,\Delta m_{12}(T)\right]^2 + \left[\Gamma^0_{\chi_2}\,\gamma(T)\right]^2} \simeq I_1 \frac{\Gamma^0_{\chi_2}\,\gamma(T)}{2\,\Delta m_{12}}$$

Hambye, Teresi, arXiv:1606.00017



self-energy diagram with thermal cut

$$I_1 = \frac{\mathrm{Im}\left[(\lambda^\dagger\lambda)^2_{12}\right]}{(\lambda^\dagger\lambda)_{11}(\lambda^\dagger\lambda)_{22}} = \frac{\mathrm{Im}\left[(\lambda^\dagger\lambda)^2_{12}\right]}{\bar{\lambda}^4\mathcal{B}_1(1-\mathcal{B}_1)} \qquad \Gamma^0_{\chi_2} = \frac{m_\chi\,(\lambda^\dagger\lambda)_{22}}{8\pi} = \frac{m_\chi\,\bar{\lambda}^2\,(1-\mathcal{B}_1)}{8\pi}$$

$$\xi = 2\,\frac{\Delta m_{12}}{\Gamma^0_{\chi_2}} \qquad \boxed{\frac{\epsilon(T)}{\gamma(T)} \simeq \frac{I_1}{\xi} \simeq \frac{\mathrm{Im}\left[(\lambda^\dagger\lambda)^2_{12}\right]}{(\lambda^\dagger\lambda)_{11}}\,\frac{m_\chi}{16\pi\,\Delta m_{12}}}$$

- $\gamma(T)$: spectral loop integral entering the self-energy diagram; $\Gamma^0_{\chi_2}\gamma(T)$ corresponds to the **absorptive part of the self-energy**.
- Approximation in the limit $\xi \gg \gamma(T), x^{-2}$
  - semi-relativistic regime $x \gtrsim 2$, assuming $\boxed{\Delta m_{12} \gg \Gamma^0_{\chi_2} = \frac{m_\chi\,(\lambda^\dagger\lambda)_{22}}{8\pi}}$; $\gamma(T)$ falls steeply with $x = m_{\chi_1}/T$.
  - $\varepsilon/\gamma \simeq I_1/\xi$ is **temperature-independent** in this limit

Thermal effects

- Finite T: kinematic blocking of decay channels, and scatterings feeding the CP source
- two benchmark setups to assess sensitivity to thermal effects

Minimal setup

- thermal masses: gluon + light quarks, only to delimit phase space and to regulate the soft divergences of the scatterings
- scatterings: in the $\Sigma\phi$ and $Y\chi$ equations only
- no CP asymmetry from scatterings

Thermal-mass setup

- thermal masses in propagators and phase space
- scatterings: in all three equations
- CP asymmetry from scatterings set equal to the one from decays

Thermal effects

Thermal masses

- High-momentum regime E ~ p ~ T ≫ m_0: fields treated as free massive particles carrying the asymptotic thermal mass

$$m_q^2(T) = 2\, m_q^{\mathrm{th}\,2}(T) = \frac{2}{6}\, g_s^2 T^2\,, \qquad m_g^2(T) = \frac{1}{2}\left(1 + \frac{N_f(T)}{6}\right) g_s^2 T^2 \qquad M_\Phi^2(T) = M_\Phi^2 + \frac{2}{3}\, g_s^2 T^2$$

Resummed propagators, real-time formalism

- The second setup additionally uses one-loop resummed propagators in the real-time formalism, for the colored scalar and the fermions [Niemi, Semenoff 1984; Kobes, Semenoff 1985; Giudice et al. 2004]

Scalar (11 component of the 2×2 real-time matrix; the thermal mass is the one-loop self-energy):

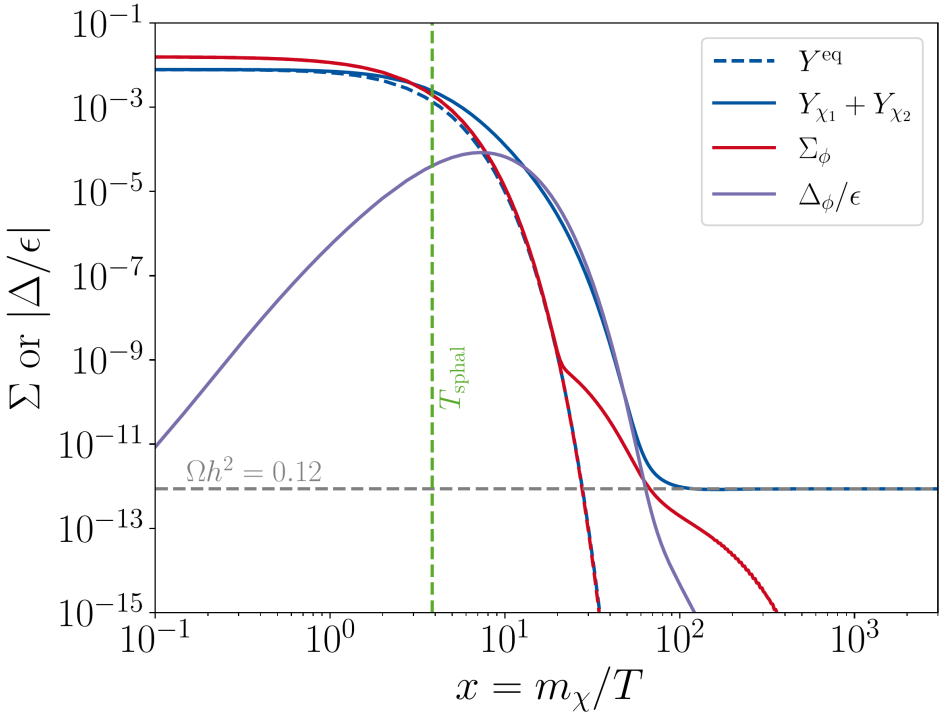
$$D_{11}(K) = \big(D_{22}(K)\big)^* = \frac{i}{K^2 - M_\Phi^2(T) + i\eta} + 2\pi\, n_B(\omega)\, \delta\big(K^2 - M_\Phi^2(T)\big), \qquad n_B(\omega) = \frac{1}{e^{|\omega|/T} - 1}$$

Fermion: in the high-momentum regime the dispersion relation is that of a free particle with the asymptotic mass

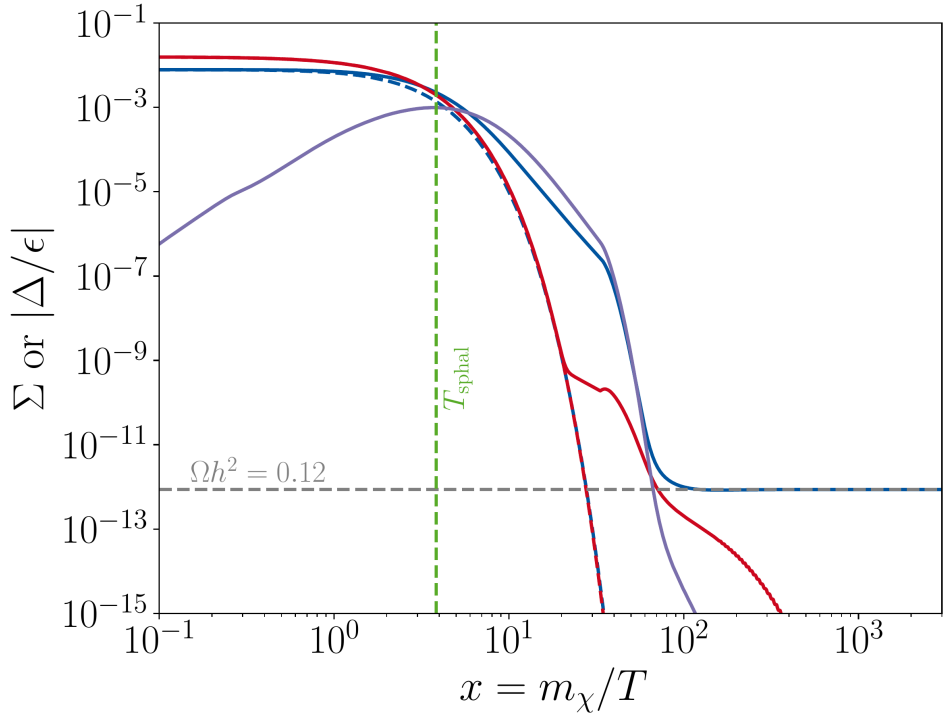
$$S^{11}(K) \approx \not{K}\left[\frac{i}{K^2 - 2\, m_q^{\mathrm{th}}(T)^2 + i\epsilon} - 2\pi\, n_F(\omega)\, \delta\big(K^2 - 2\, m_q^{\mathrm{th}}(T)^2\big)\right], \qquad n_F(\omega) = \frac{1}{e^{|\omega|/T} + 1}$$

Solving the system

Minimal setup



Thermal-mass setup



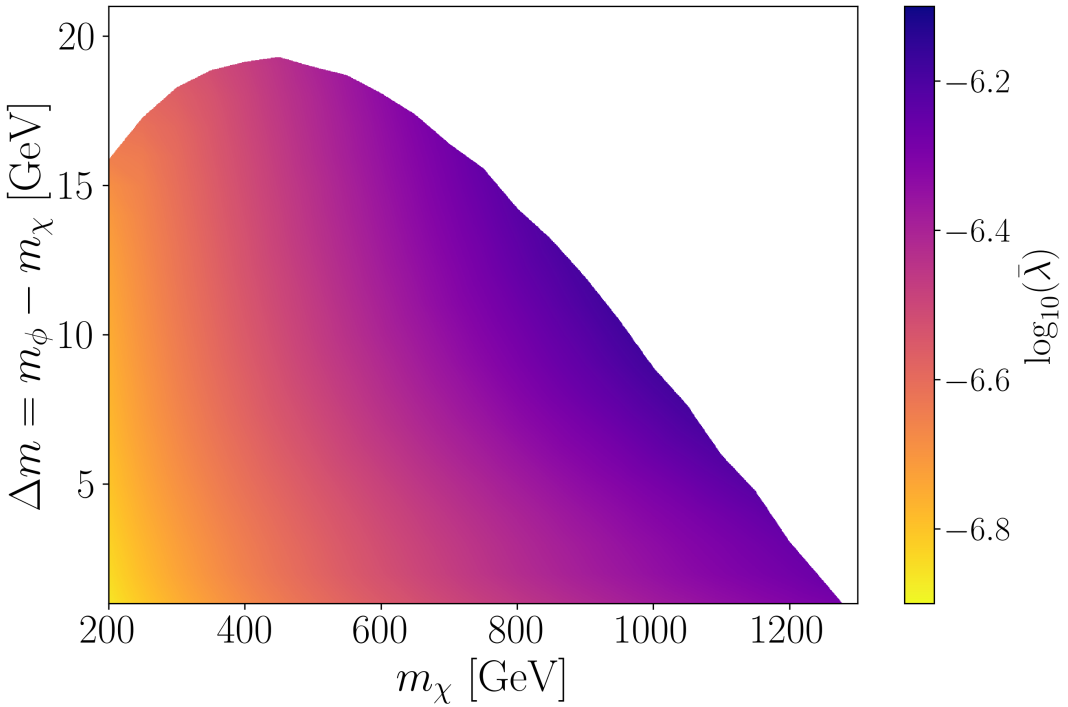
blue: $Y_{\chi_1} + Y_{\chi_2}$ **red: Σ_ϕ** **purple: $|\Delta_\phi/\varepsilon|$** dashed: equilibrium **green: $T_{\rm sphal}$**

$m\chi = 500$ GeV, $m\phi = 510$ GeV, $B_1 = 0.75$, $\lambda H = 0$, $\bar{\lambda}$ fixed by $\Omega\, h^2 = 0.12$

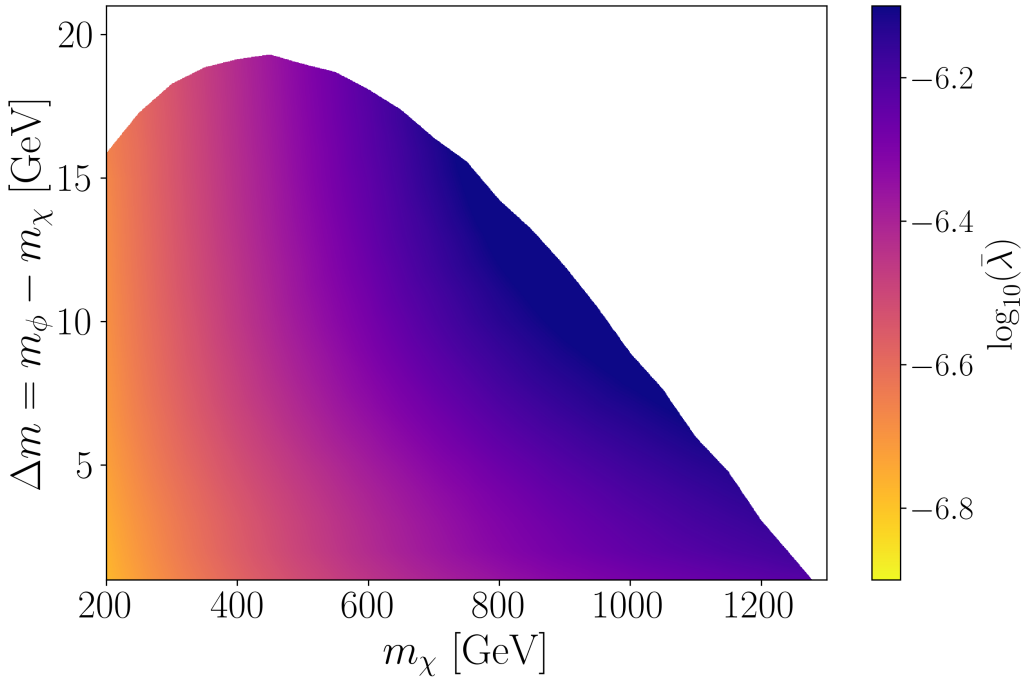
- The kinks are thermal blocking: the **decay channel closing and reopening**.
- In the thermal-mass setup the asymmetry starts to build up at higher T: the scatterings feed the CP source term

Coupling required for the relic density

Minimal setup



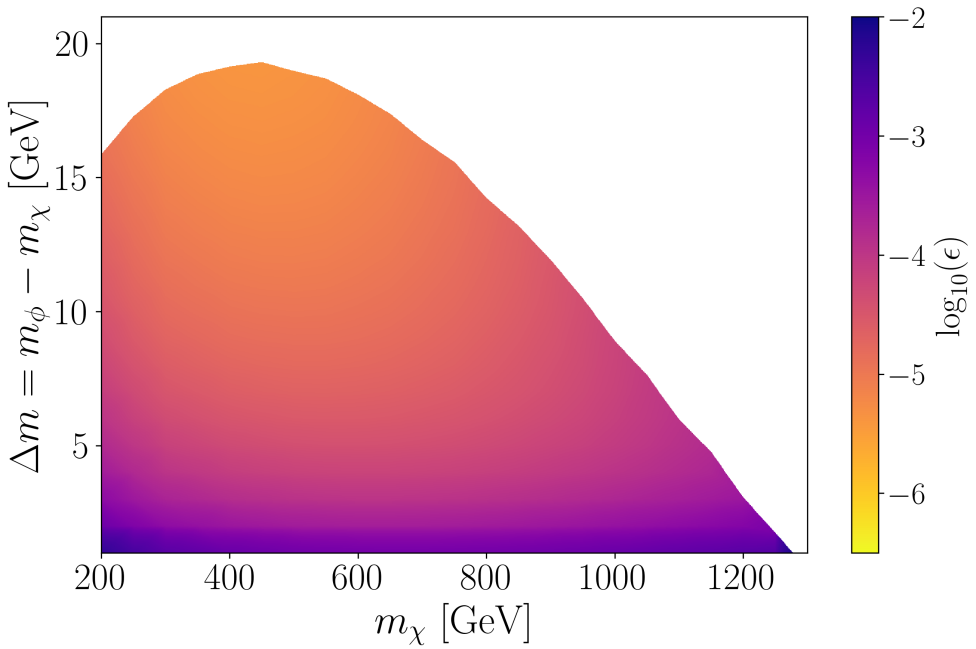
Thermal-mass setup



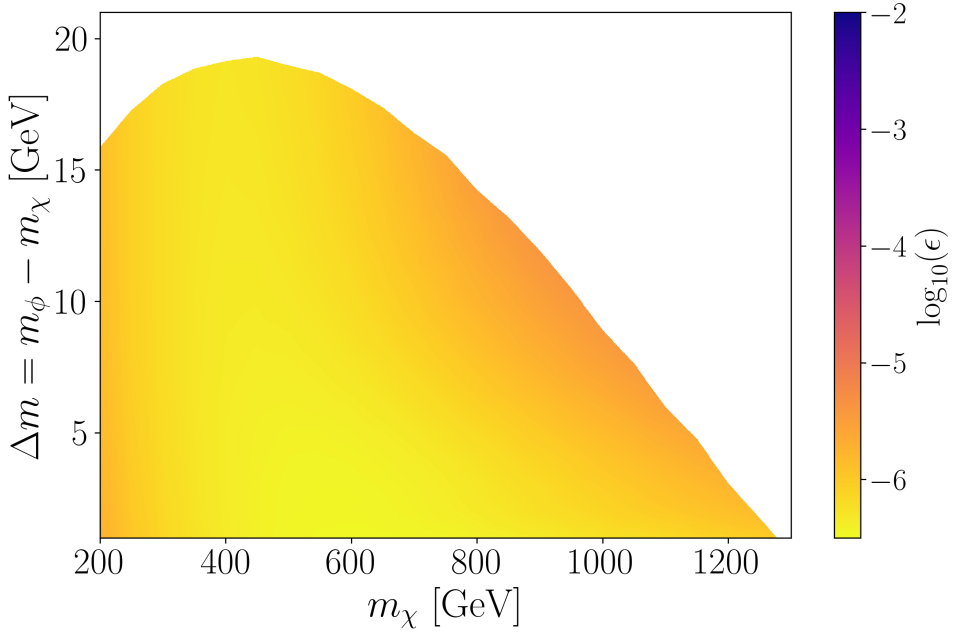
- **$\bar{\lambda} \sim 10^{-7}$–$10^{-6}$ across the whole CDFO region**
- minor difference between the two thermal treatments
- White region above the boundary: the WIMP regime of the same model

CP asymmetry required for the baryon asymmetry

Minimal setup

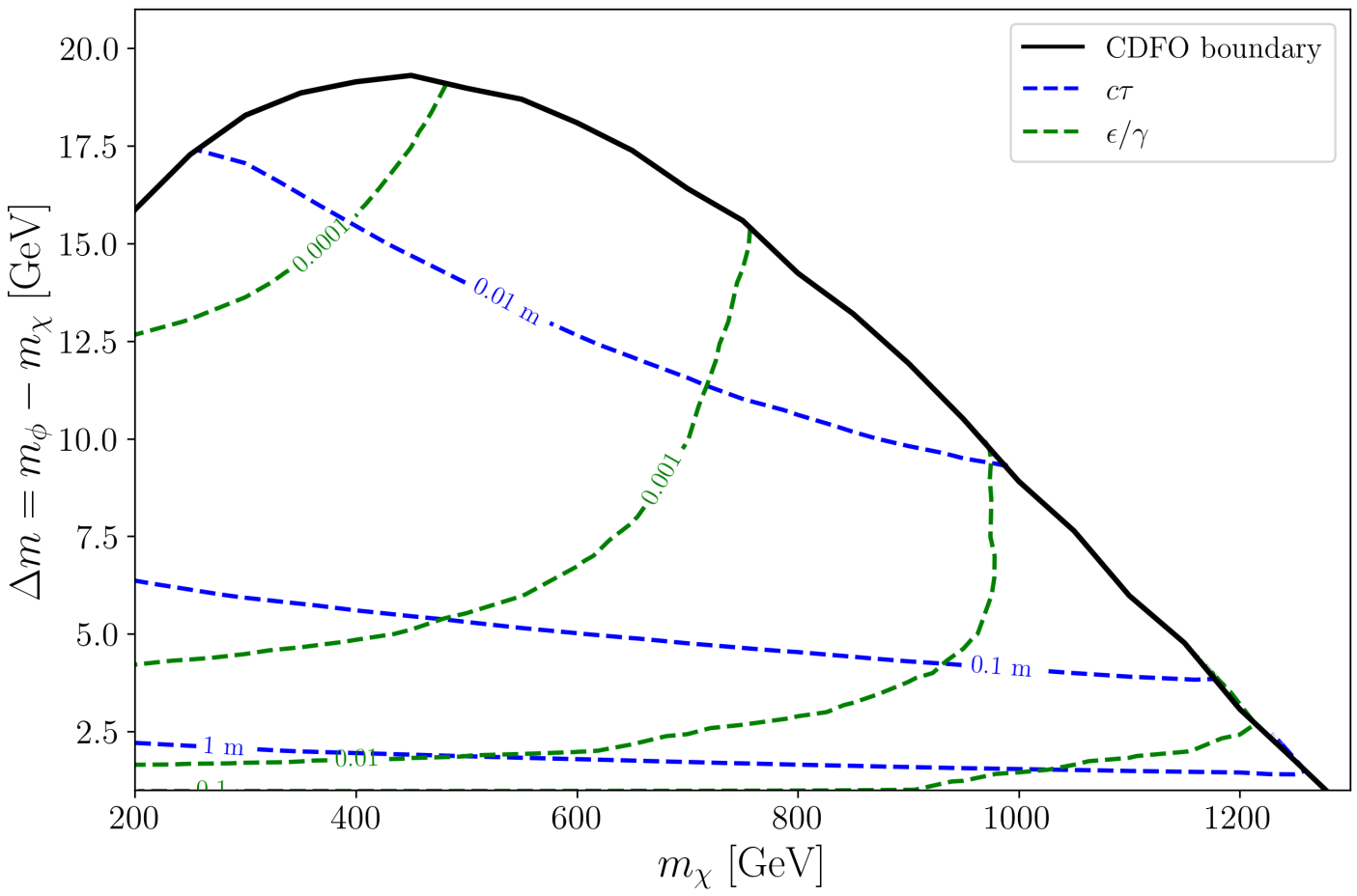


Thermal-mass setup



- Minimal setup: $\epsilon \sim 10^{-6}$ - 10^{-3} ; thermal-mass setup: $\epsilon \sim 10^{-7}$ - 10^{-6}
- In the thermal-mass setup, most of the viable region satisfies $\varepsilon/\gamma < 0.1$.
- $\varepsilon/\gamma \simeq I_1/\xi$ with $|I_1| \leq 1$: we focus on $\varepsilon/\gamma < 0.1$. Beyond it the two near-degenerate states would need a density-matrix treatment

Viable parameter space

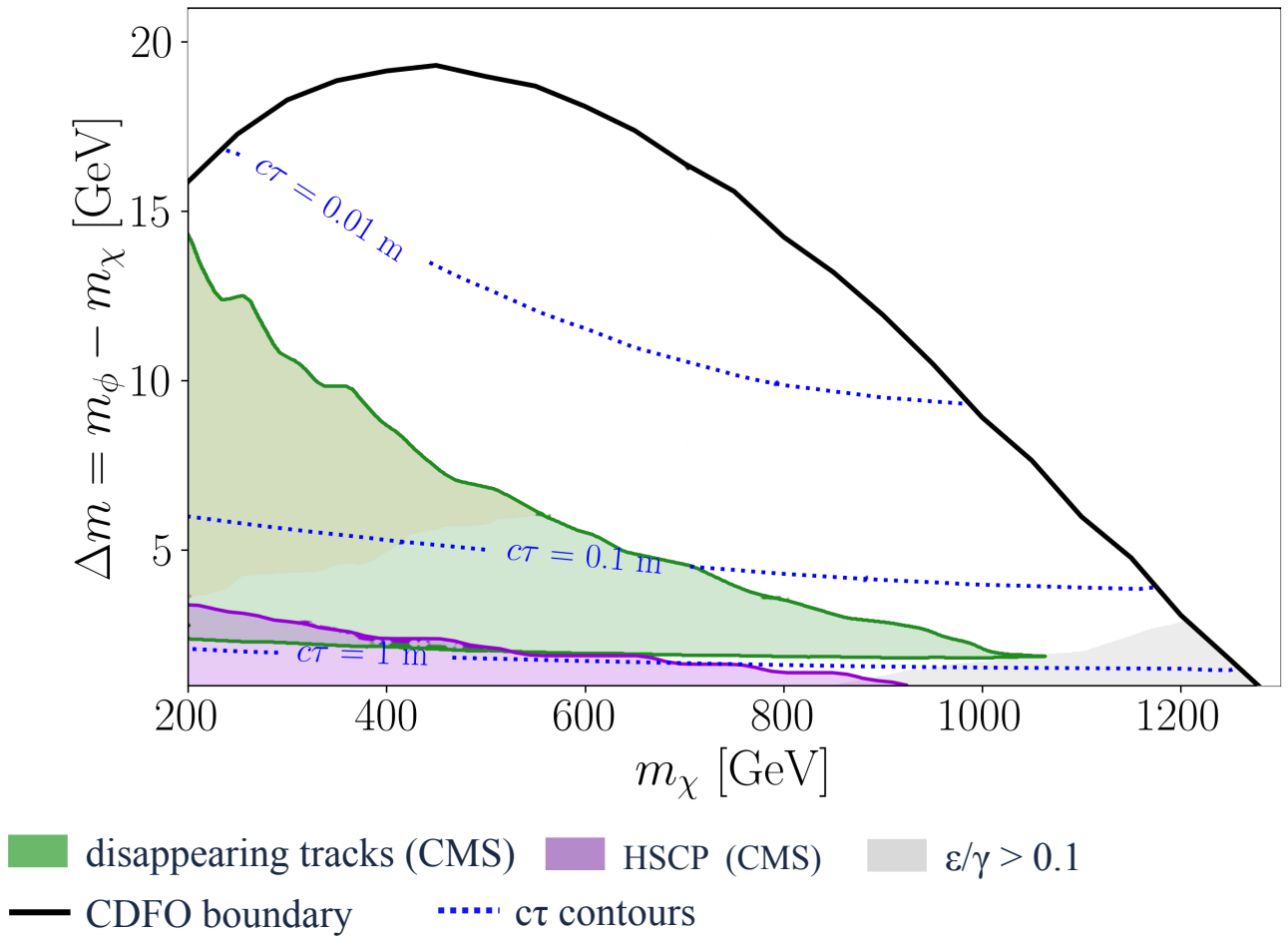


thermal-mass setup, $B_1 = 0.75$

- Viable solutions in the entire region below the CDFO boundary
- mχ from a few hundred GeV to **≈ 1.2 TeV, Δm up to ≈ 20 GeV**
- **strong QCD interactions of the colored mediator** (including bound states) enlarge the range well beyond the leptophilic case (≈ 500–640 GeV with λH = 1, below 150 GeV without it [Heisig 2024])
- Higgs portal: even $\lambda_H = 1$changes little — unlike leptophilic
- Mediator lifetime reaches cτ ~ O(1) m
- ε/γ > 0.1: viability requires a more complete treatment of mixing and coherence.

Long-lived particle signatures

The small Yukawa couplings lead to macroscopic mediator decay lengths.

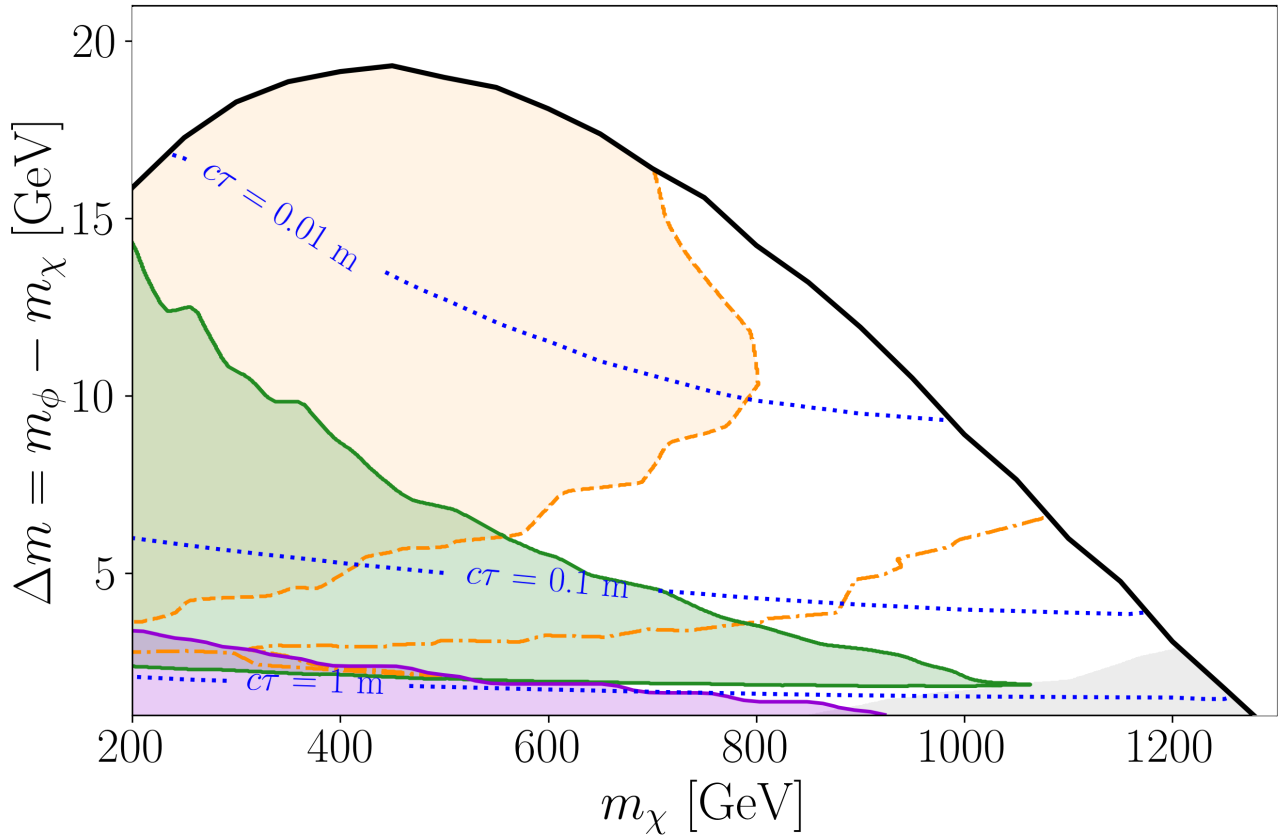


thermal-mass setup, $B_1 = 0.75$

- $c\tau \gtrsim 1$ m → **heavy stable charged particles,** detector-stable R-hadrons
- 10 cm $\lesssim c\tau \lesssim 1$ m → **disappearing tracks**
- $c\tau \lesssim 10$ cm → **displaced vertices**
- Existing limits carve out only small regions: disappearing tracks are the strongest constraint at low and intermediate mχ and lose sensitivity towards 1 TeV, HSCP only reach very small Δm
- Other searches (missing energy, standard disappearing-track cuts) stay below mχ ~ 400 GeV for such small Δm
- Gray: ε/γ > 0.1; viability requires a more complete treatment of mixing and coherence.

Long-lived particle signatures

The small Yukawa couplings lead to macroscopic mediator decay lengths.



- **cτ ≳ 1 m → heavy stable charged particles,** detector-stable R-hadrons
- **10 cm ≲ cτ ≲ 1 m → disappearing tracks**
- **cτ ≲ 10 cm → displaced vertices**
- Existing limits carve out only small regions: small Δm, large lifetime
- Proposed search: the ATLAS DV analysis with a lower cut on the displaced invariant mass — soft displaced objects are the CDFO signature
- The HL-LHC projection covers most of the cosmologically viable region
- **Limits nearly identical in the two setups: cτ is fixed by $\bar{\lambda}$, which barely changes**

disappearing tracks (CMS) HSCP (CMS) $\varepsilon/\gamma > 0.1$

CDFO boundary cτ contours DV search, 32.8 fb^{-1} DV search, HL-LHC 3 ab^{-1}

thermal-mass setup, $B_1 = 0.75$

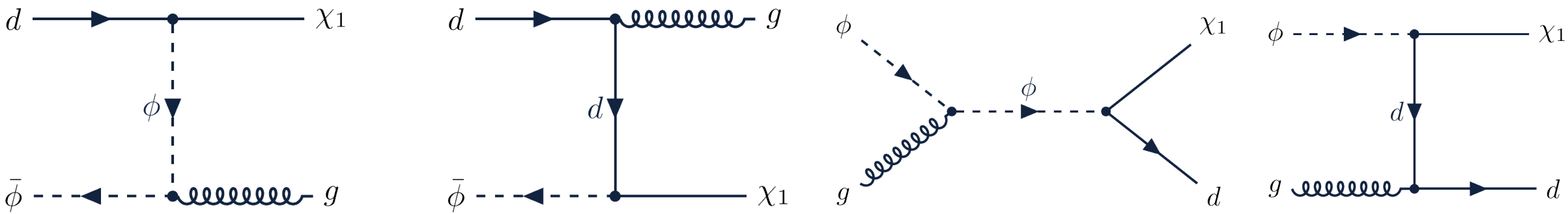
Conclusions

- **Conversion-driven freeze-out** gives dark matter relic abundance
- Semi-inefficient conversions provide out-of-equilibrium condition while state are **semi-relativistic**
- Realized for small mediator-dark matter mass splitting $\Delta m = m_\phi - m_\chi$ with coupling $\bar{\lambda} \sim 10^{-7}$–$10^{-6}$
- **Flavored dark matter** gives CP-violating conversions
- Very small mass splitting $m_{\chi_2} - m_{\chi_1}$ between dark matter species → resonant regime
- **Electroweak sphaleron** action gives baryon number noncoservation — with B and L perturbatively conserved
- The quark-philic realization works up to $m\chi \approx 1.2$ TeV
- $\bar{\lambda} \sim 10^{-7}$–$10^{-6}$ ⇒ proposed soft displaced-vertex search at the HL-LHC is projected to cover most of the viable region.

Backup

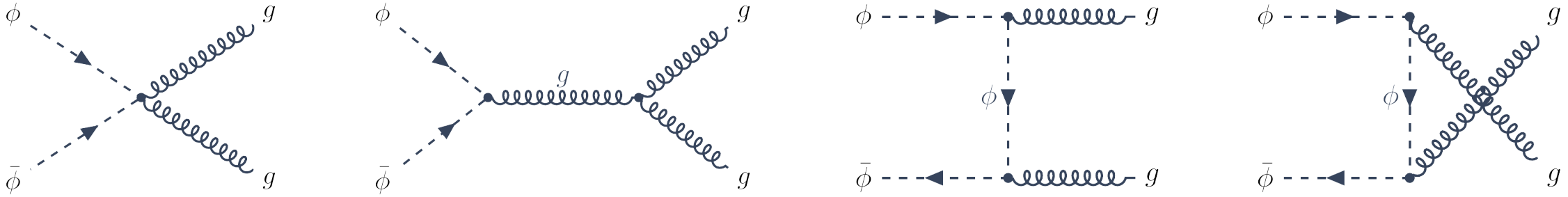
Annihilation and conversion processes

Conversions $d\,\bar{\phi} \to \chi_1\, g$ and $g\,\phi \to \chi_1\, d$ (Conversion rates $\propto \lambda^2$, less Boltzmann-suppressed)



Together with decays and inverse decays $\phi \leftrightarrow \chi_1\, d$.

Mediator pair-annihilation $\phi\,\bar{\phi} \to g\,g$ (sets the depletion rate)



Chemical potentials: symmetric phase, three cases

Asymmetry ↔ chemical potential, first order in μ/T:

$$k_X = \begin{cases} 1 & \text{relativistic fermions} \\ 2 & \text{relativistic bosons} \\ \dfrac{6}{\pi^2}\left(\dfrac{m_X}{T}\right)^2 K_2\left(\dfrac{m_X}{T}\right) \underset{m_X \gg T}{\approx} \dfrac{6\, e^{-m_X/T} m_X^{3/2}}{\sqrt{2}\,\pi^{3/2}\, T^{3/2}} & \text{non-relativistic} \end{cases}$$

Fast processes (Yukawa, sphalerons, hypercharge neutrality):

$$\mu_q + \mu_H - \mu_u = 0, \qquad \mu_q - \mu_H - \mu_d = 0, \qquad \mu_\ell - \mu_H - \mu_e = 0, \qquad 3\mu_q + \mu_\ell = 0$$

$$y = 3(\mu_q + 2\mu_u - \mu_d - \mu_\ell - \mu_e) + 2\mu_H + y_\phi\, g_\phi k_\phi \mu_\phi = 0$$

$$B = 12\mu_q + N_B^\phi\, g_\phi k_\phi \mu_\phi\,, \qquad L = -\frac{153}{7}\mu_q + \left(\frac{3}{14} y_\phi + N_L^\phi\right) g_\phi k_\phi \mu_\phi\,, \qquad B - L = 0$$

With rapid quark Yukawas the QCD-instanton relation $\Sigma(2\mu_q - \mu_u - \mu_d) = 0$ is automatic

Baryon asymmetry in terms of the mediator asymmetry at sphaleron decoupling, symmetric (SP) and broken (BP) phase:

$$n_{\Delta B} = \left(n_\phi - n_{\bar\phi}\right)_{T_{\rm sphal}} \times \begin{cases} \frac{22}{79}\ (\text{SP}),\ \frac{11}{37}\ (\text{BP}) & \text{leptons: } y_\phi = -1,\ g_\phi = 1,\ N_L^\phi = 1 \\ \frac{1}{3}\cdot\frac{63}{79}\ (\text{SP}),\ \frac{1}{3}\cdot\frac{27}{37}\ (\text{BP}) & \text{up-type quarks: } y_\phi = \frac{2}{3},\ g_\phi = 3,\ N_B^\phi = \frac{1}{3} \\ \frac{1}{3}\cdot\frac{45}{79}\ (\text{SP}),\ \frac{1}{3}\cdot\frac{24}{37}\ (\text{BP}) & \text{down-type quarks: } y_\phi = -\frac{1}{3},\ g_\phi = 3,\ N_B^\phi = \frac{1}{3} \end{cases}$$

Induced asymmetries in the SM fermions coupled to ϕ (n_F = number of SM families coupling to ϕ):

$$n_{e^-} - n_{e^+} = -(n_\phi - n_{\bar\phi})\, n_F \begin{cases} \frac{8}{79} \\ \frac{19}{222} \end{cases} \qquad n_u - n_{\bar u} = -(n_\phi - n_{\bar\phi})\, n_F \begin{cases} \frac{31}{237} \\ \frac{7}{111} \end{cases} \qquad n_d - n_{\bar d} = -(n_\phi - n_{\bar\phi})\, n_F \begin{cases} \frac{40}{237}\ (\text{SP}) \\ \frac{17}{222}\ (\text{BP}) \end{cases}$$

Chemical potentials: broken phase

- Below the electroweak crossover: SM fermions are massive, the neutral Higgs component has $\mu_0 = 0$, and the chemical potential μ_W of the charged gauge bosons enters [Harvey, Turner 1990]
- Weak equilibrium within multiplets, Yukawa equilibrium, and rapid sphalerons:

$$\mu_{u_L} = \mu_{d_L} - \mu_W\,, \qquad \mu_{e_L} = \mu_{\nu_L} + \mu_W\,, \qquad 3(\mu_{u_L} + 2\mu_{d_L}) + 3\mu_{\nu_L} = 0$$

$$\mu_{u_L} + \mu_0 - \mu_{u_R} = 0, \qquad \mu_{d_L} - \mu_0 - \mu_{d_R} = 0, \qquad \mu_{e_L} - \mu_0 - \mu_{e_R} = 0$$

Electric-charge neutrality (k_t accounts for the top-quark mass):

$$Q = (4 + 2k_t)(\mu_{u_L} + \mu_{u_R}) - 3(\mu_{d_L} + \mu_{d_R}) - 3(\mu_{e_L} + \mu_{e_R}) - 6\mu_W + Q_\phi\, g_\phi k_\phi \mu_\phi = 0$$

Baryon and lepton number, with $B - L = 0$ fixing everything in terms of μ_ϕ:

$$B = \frac{4}{3}\left(16 + 10k_t + k_t^2\right)\mu_{u_L} + \left(\tfrac{1}{3}(2 + k_t)Q_\phi + N_B^\phi\right) g_\phi k_\phi \mu_\phi\,, \qquad L = -75\,\mu_{u_L} + \left(N_L^\phi - 2Q_\phi\right) g_\phi k_\phi \mu_\phi$$

- Right-handed down-type quarks: the conversion factor is 24/37 in the broken phase against 45/79 in the symmetric phase
- The mediator mass term is shifted by the Higgs vev through λ_H; the non-relativistic k_ϕ carries the Boltzmann suppression of ϕ

Resummed propagators, real-time formalism

Thermal-mass setup: one-loop resummed propagators for the colored scalar and the fermions [Niemi, Semenoff 1984; Kobes, Semenoff 1985; Giudice et al. 2004]

Scalar (11 component of the 2×2 real-time matrix; the thermal mass is the one-loop self-energy):

$$D_{11}(K) = \big(D_{22}(K)\big)^* = \frac{i}{K^2 - M_\Phi^2(T) + i\eta} + 2\pi\, n_B(\omega)\,\delta\big(K^2 - M_\Phi^2(T)\big), \qquad n_B(\omega) = \frac{1}{e^{|\omega|/T} - 1}$$

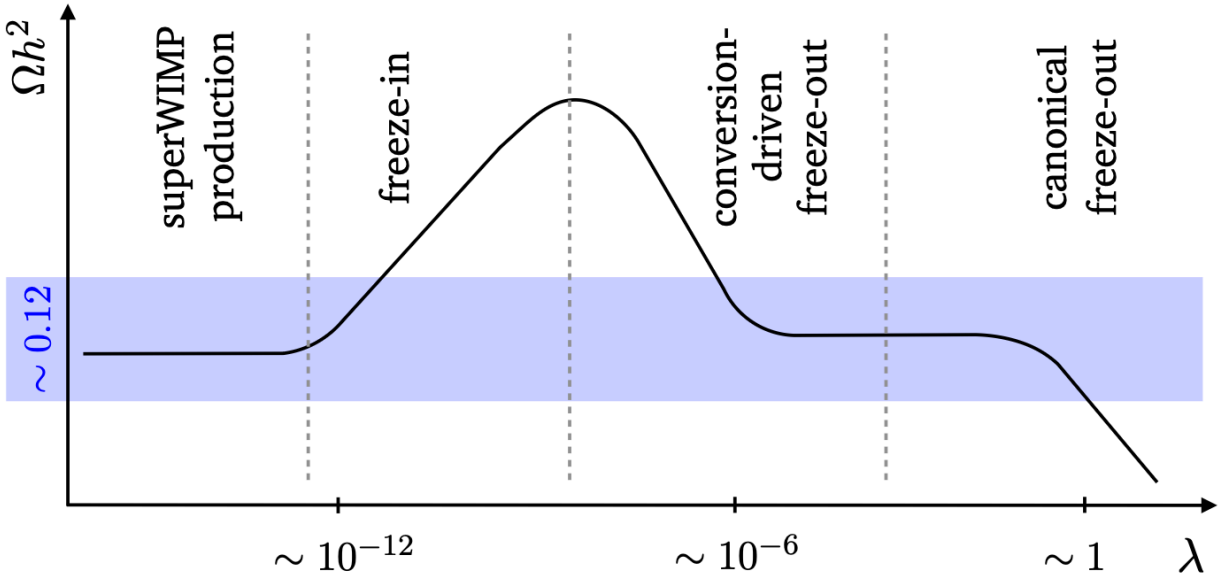
Fermion: in the high-momentum regime the dispersion relation is that of a free particle with the asymptotic mass

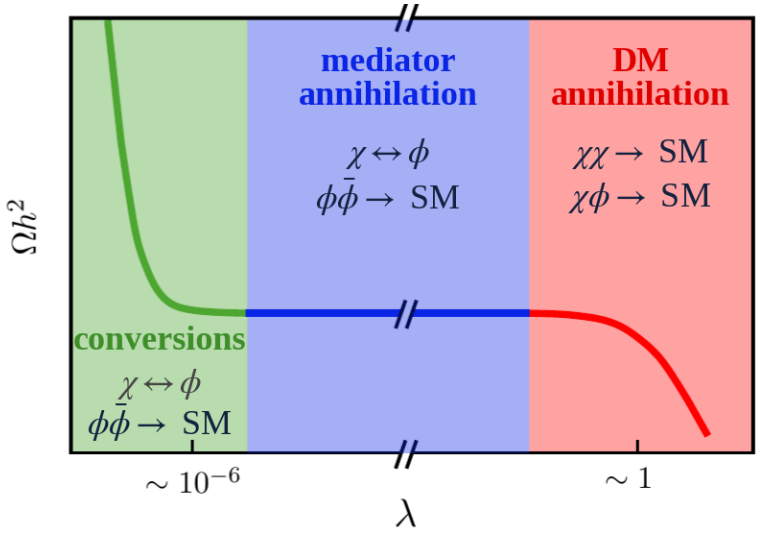
$$S^{11}(K) \approx \not{K}\left[\frac{i}{K^2 - 2\,m_q^{\rm th}(T)^2 + i\epsilon} - 2\pi\, n_F(\omega)\,\delta\big(K^2 - 2\,m_q^{\rm th}(T)^2\big)\right], \qquad n_F(\omega) = \frac{1}{e^{|\omega|/T} + 1}$$

$$\Sigma_F(K) = -a\,\not{K} - b\,\not{u}\,, \qquad \omega = K^\alpha u_\alpha\,, \quad k = \left[(K^\alpha u_\alpha)^2 - K^2\right]^{1/2}, \qquad 2\,m_f^{\rm th\,2} = \frac{2\,g^2 T^2\,C(R)}{8}$$

- a, b are Lorentz-invariant functions of ω and k; u is the bath four-velocity
- Gauge bosons propagate as transverse modes with thermal mass equal to the Debye mass over √2, of order gT; fermions resemble vacuum particles of mass √2 times their thermal mass
- These propagators are used to estimate the **CP-conserving part of the scattering processes**

WIMP, coannihilation, coscattering and conversions





C.~Arina, B.~Fuks, L.~Panizzi, et al., ``t-channel dark matter models - a whitepaper,'' 2504.10597.

Heisig, arXiv:2504.07859

- very **weak DM couplings** evade experiments
- **thermalization** of DM
- one of the simplest realization: **t-channel mediator** models
- DM particle χ, **slightly heavier mediator** ϕ
- **both odd** under Z_2 stabilizing DM
- **annihilation** and pair production rates **negligible**
- **DM dilution**: $\chi \rightarrow \phi$ followed by efficient annihilation $\phi\phi \rightarrow SM$

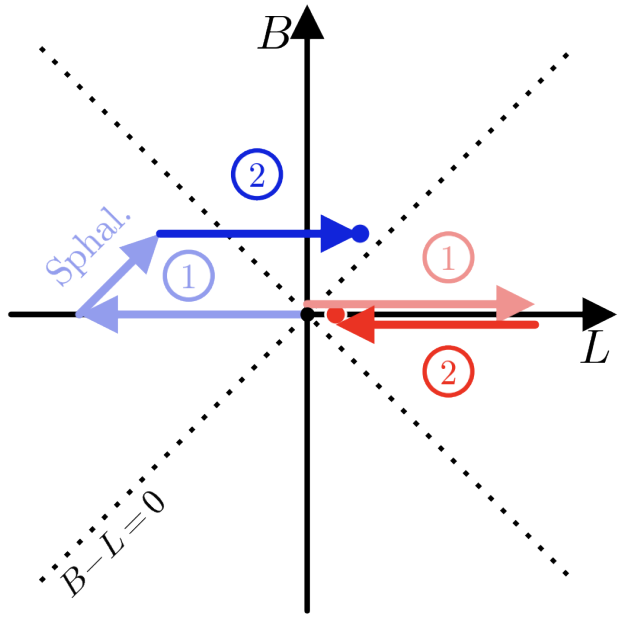
Related mechanisms

A recurring idea: to obtain $B \neq 0$ without $B-L$ violation, part of the asymmetry must sit where sphalerons cannot reach it. An asymmetry stored in e_R alone does not survive in the SM — e_R equilibrates through its Yukawa coupling at $T \sim 10^4$ GeV [Campbell, Davidson, Ellis, Olive 1992; Cline, Kainulainen, Olive 1993]. Dirac leptogenesis stores it in ν_R instead [Dick, Lindner, Ratz, Wright 2000].

Dirac leptogenesis — Dick, Lindner, Ratz, Wright, PRL 84 (2000) 4039, hep-ph/9907562.

Cloistered baryogenesis — Aristizabal Sierra, Fong, Nardi, Peinado, JCAP 1402 (2014) 021, arXiv:1309.4770

Dirac leptogenesis



① : $T \sim T_{\text{sphal}}$

② : $T \ll T_{\text{LR}}$

: SM sector

: ν_R (decoupled)

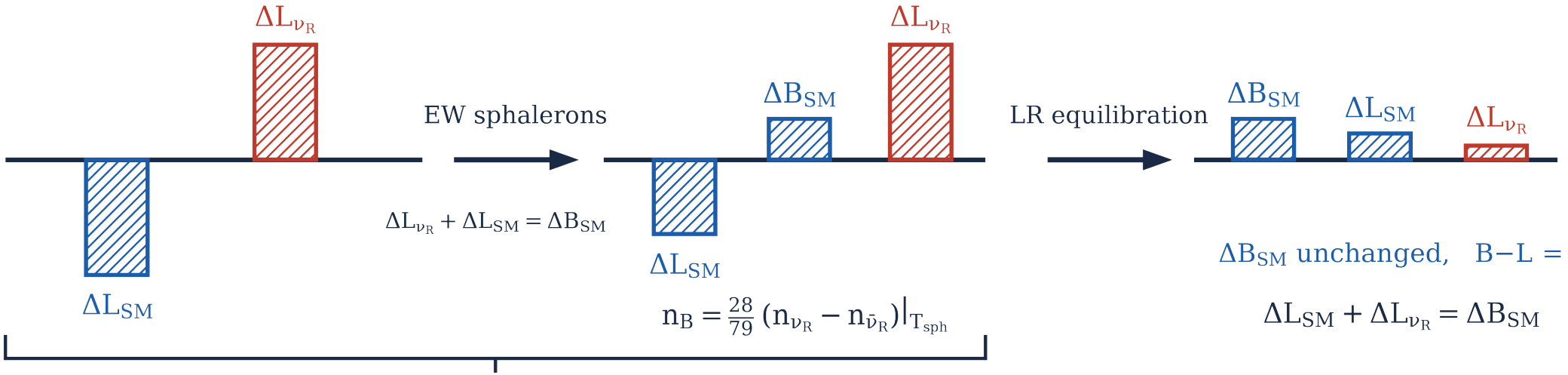
: final SM sector

: final ν_R

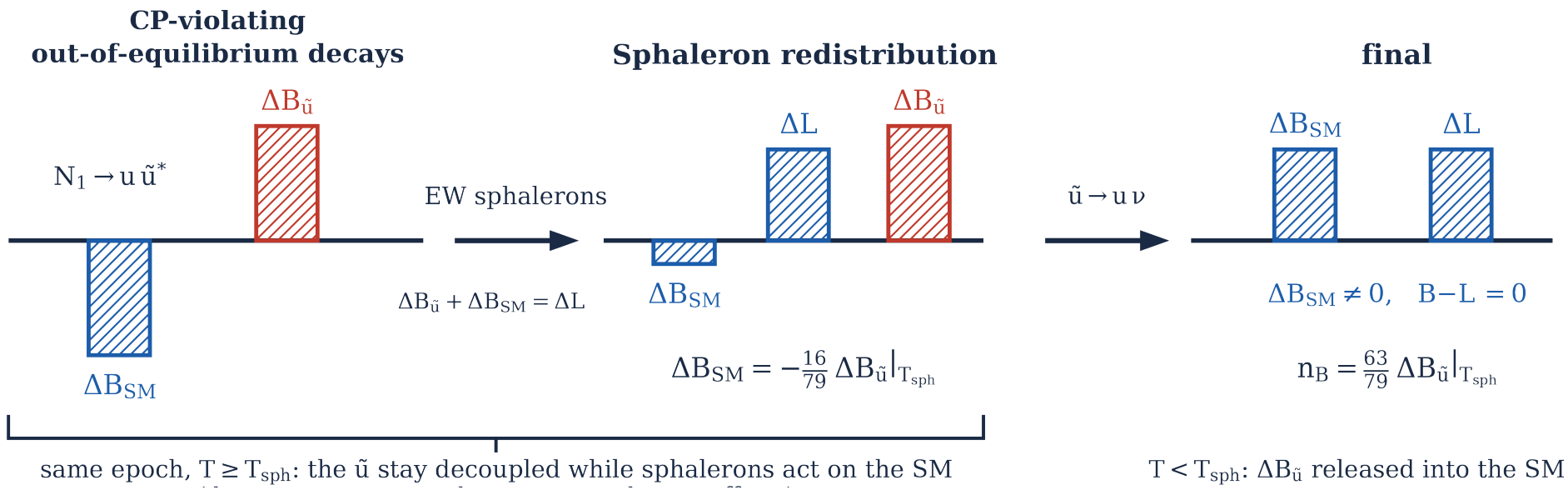
CP-violating out-of-equilibrium decays

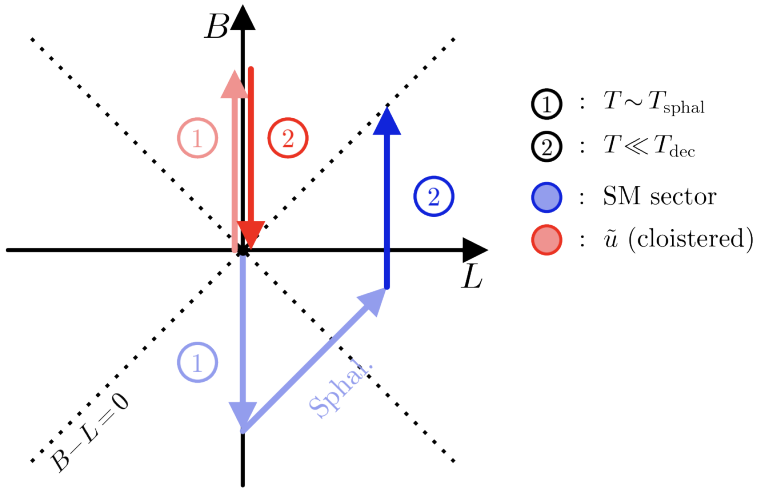
Sphaleron redistribution

final

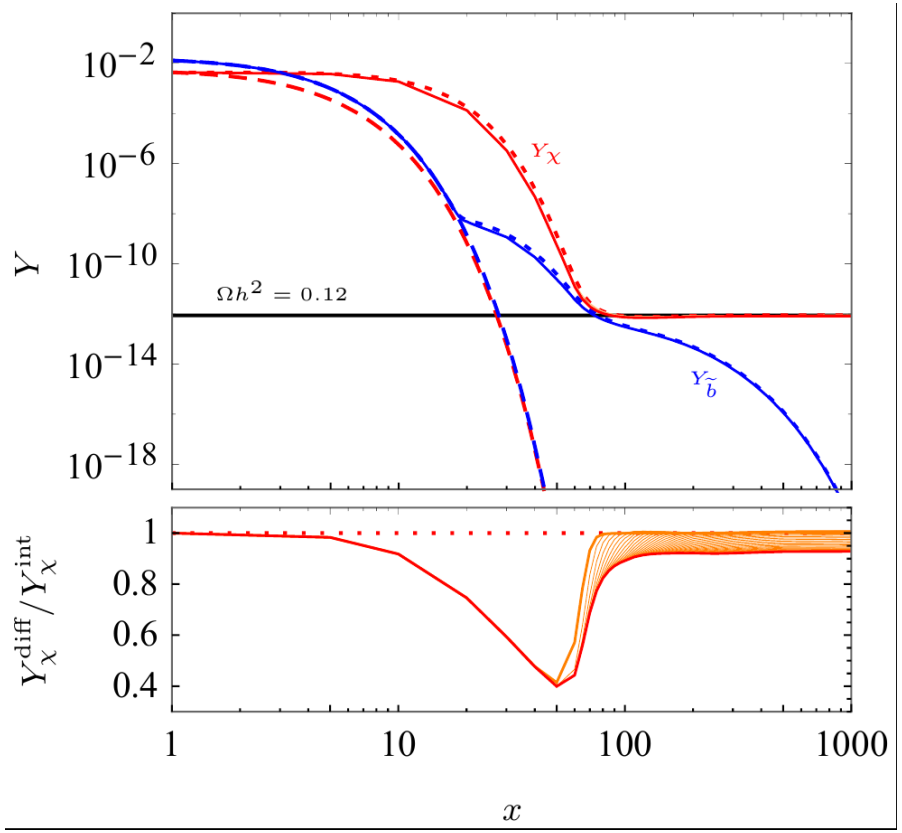


Cloistered baryogenesis





Kinetic equilibrium of χ



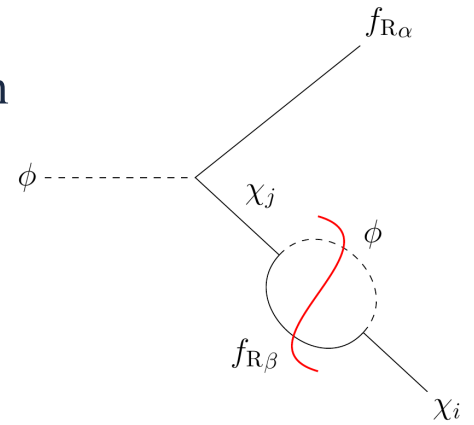
Garny, Heisig, Lülf, Vogl, arXiv:1705.09292, Fig. 7 — $\tilde{b}$ model, $m\chi = 500$ GeV, $\Delta m = 10$ GeV, $\lambda \approx 4 \times 10^{-7}$. Solid: momentum-dependent Boltzmann equation; dotted: integrated one. Bottom: ratio of the two Yχ.

- Our Boltzmann equations are integrated over momentum ⇒ they assume χ keeps a thermal momentum distribution (kinetic equilibrium), with rates averaged over the equilibrium phase-space distribution
- Not automatic here: elastic scatterings $\chi q \to \chi q$ scale as λ^4 and are negligible; kinetic equilibrium is kept by the same conversions $\chi \leftrightarrow \phi$ that keep chemical equilibrium, so kinetic and chemical decoupling happen together
- **Garny et al. 2017 (App. C):** solving the full momentum-dependent equation for χ, f_χ departs from thermal at intermediate x, but the final Yχ changes by less than 10% — the collision operator depends only weakly on the momentum mode, so all modes freeze out together
- **D'Agnolo, Pappadopulo, Ruderman 2017:** larger corrections in their coscattering setup, where the upscattering $\chi\phi \to \psi\phi$ is endothermic with large splittings, $\Delta = (m\psi - m\chi)/m\chi$ up to 0.7 — the correction grows with Δ, but the integrated treatment still captures the abundance at the order-of-magnitude level
- **Our case:** Δm/mχ of a few per cent and the same conversion processes as Garny et al. ⇒ corrections expected at the ≲ 10% level, below the spread between the minimal and thermal-mass setups

Thermal effects: the CP asymmetry

- At T = 0 the interference is CP-conserving: the absorptive part is generated by the bath
- Resonantly enhanced for nearly degenerate χ_1, χ_2, with Δm_{12} of order $\bar{\lambda}^2$ m_χ

$$\epsilon(T) = \frac{1}{8\pi}\,\frac{\mathrm{Im}\left[(\lambda^\dagger\lambda)^2_{12}\right]}{(\lambda^\dagger\lambda)_{11}}\,\frac{2\,\Delta m_{12}\,m_\chi\,\gamma(T)}{\left[2\,\Delta m_{12}(T)\right]^2+\left[\frac{m_\chi\,(\lambda^\dagger\lambda)_{22}\,\gamma(T)}{8\pi}\right]^2} \simeq \frac{\mathrm{Im}\left[(\lambda^\dagger\lambda)^2_{12}\right]}{(\lambda^\dagger\lambda)_{11}}\,\frac{m_\chi\,\gamma(T)}{16\pi\,\Delta m_{12}}$$



self-energy diagram with thermal cut

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

Hambye, Teresi, arXiv:1606.00017

$$I_1 = \frac{\mathrm{Im}\left[(\lambda^\dagger\lambda)^2_{12}\right]}{(\lambda^\dagger\lambda)_{11}(\lambda^\dagger\lambda)_{22}} = \frac{\mathrm{Im}\left[(\lambda^\dagger\lambda)^2_{12}\right]}{\bar{\lambda}^4\mathcal{B}_1(1-\mathcal{B}_1)} \qquad \xi = 2\,\frac{\Delta m_{12}}{\Gamma^0_{\chi_2}}$$

$\varepsilon/\gamma \simeq I_1/\xi$ is temperature-independent in the limit $\xi \gg \gamma(T)$, x^{-2}
valid for $x \gtrsim 2$ (semi-relativistic) and $\Delta m_{12} \gg \Gamma^0\chi_2$, since $\gamma(T)$ falls steeply with x

$\Gamma^0\chi_2$: would-be width of $\chi_2 \to \phi$ f for massless final states; $\gamma(T)$: spectral loop integral entering the self-energy
their product $\Gamma^0\chi_2\,\gamma(T)$ is the absorptive part of the self-energy, so $\varepsilon(T) \simeq I_1\,\Gamma^0\chi_2\,\gamma(T)\,/\,(2\,\Delta m_{12})$

Conversions via scatterings

Symmetric and CP-violating parts of the scattering rate, written out (γ is the relevant gauge boson):

$$\Gamma_{\text{scat},\,i} = \sum\nolimits_{\alpha} \left(s\, Y_{\gamma}^{\text{eq}}\, \frac{\langle \sigma_{\phi\gamma\to\chi_i f_\alpha} v\rangle + \langle \sigma_{\overline{\phi}\gamma\to\chi_i \bar{f}_\alpha} v\rangle}{2} + s\, Y_{f}^{\text{eq}}\, \frac{\langle \sigma_{\phi \bar{f}_\alpha\to\chi_i\gamma} v\rangle + \langle \sigma_{\overline{\phi} f_\alpha\to\chi_i\gamma} v\rangle}{2} \right)$$

$$\epsilon_{\text{scat},\,i}\,\Gamma_{\text{scat},\,i} = \sum_{\alpha} \left(s\, Y_{\gamma}^{\text{eq}}\, \frac{\langle \sigma_{\phi\gamma\to\chi_i f_\alpha} v\rangle - \langle \sigma_{\overline{\phi}\gamma\to\chi_i \bar{f}_\alpha} v\rangle}{2} + s\, Y_{f_\alpha}^{\text{eq}}\, \frac{\langle \sigma_{\phi \bar{f}_\alpha\to\chi_i\gamma} v\rangle - \langle \sigma_{\overline{\phi} f_\alpha\to\chi_i\gamma} v\rangle}{2} \right)$$

They enter the evolution equations as $\Gamma_i \to \Gamma_i + \Gamma\text{scat},_i$, exactly like (inverse) decays

In the thermal-mass setup we take $\varepsilon\text{scat},_i \simeq \varepsilon_i$ [Pilaftsis, Underwood 2003]; in the minimal setup the scatterings carry no CP asymmetry

Terms of relative order $\mu\alpha/T$ are neglected — $\mu\alpha\mu\beta/T^2$ in the equation for $Y\chi_i$