Axion-like particles as mediators for dark matter: beyond freeze-out

Based on A. Bharucha, F. Brümmer, N. Desai and S. Mutzel, [arXiv:2209.03932 [hep-ph]], accepted for publication in JHEP

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Introduction

*Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass **dunkle Materie** in sehr viel größerer Dichte vorhanden ist als leuchtende Materie.*

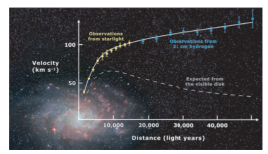
*(If this should be verified, it would lead to the surprising result that **dark matter** exists in much greater density than luminous matter.)*

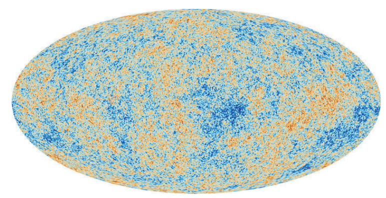
Zwicky 1933

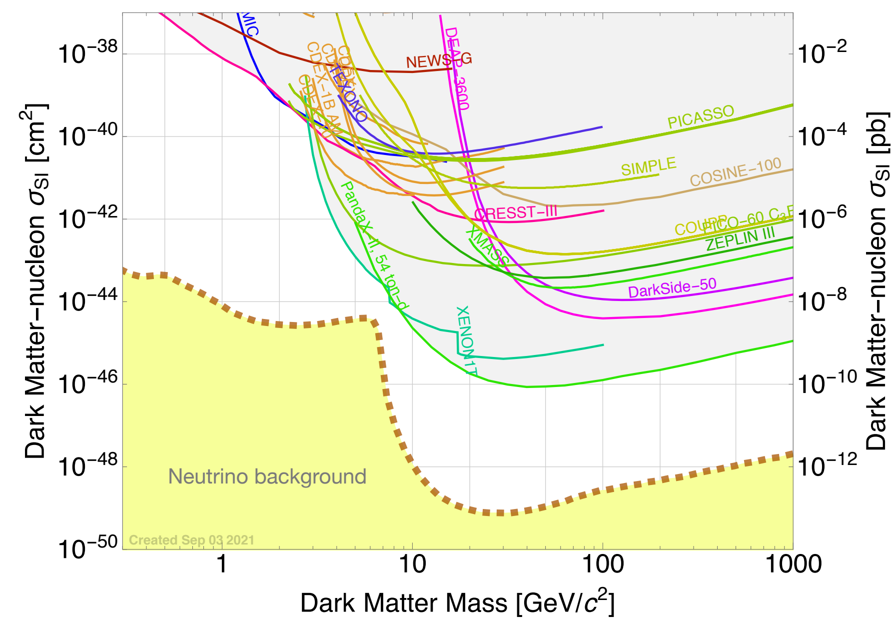
Introduction

Gravitational evidence for Dark Matter (DM)

Freeze-out and WIMPs require large couplings

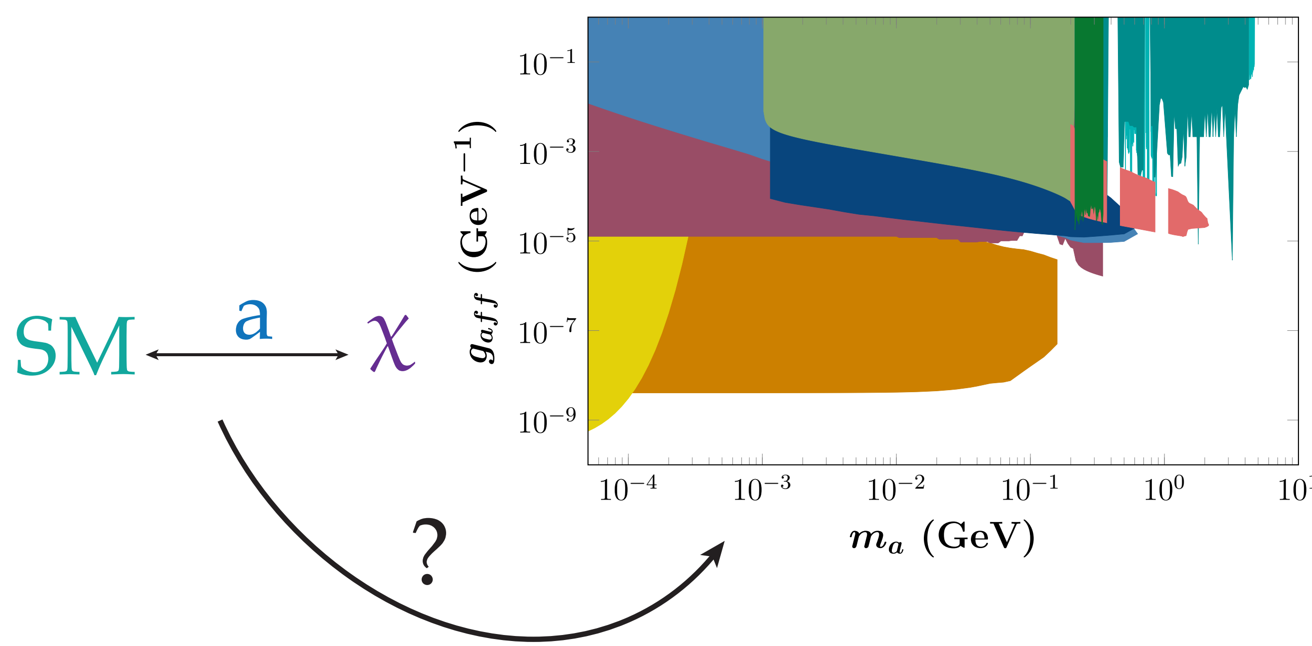






[1]

Look at different scenarios & explore parameter space

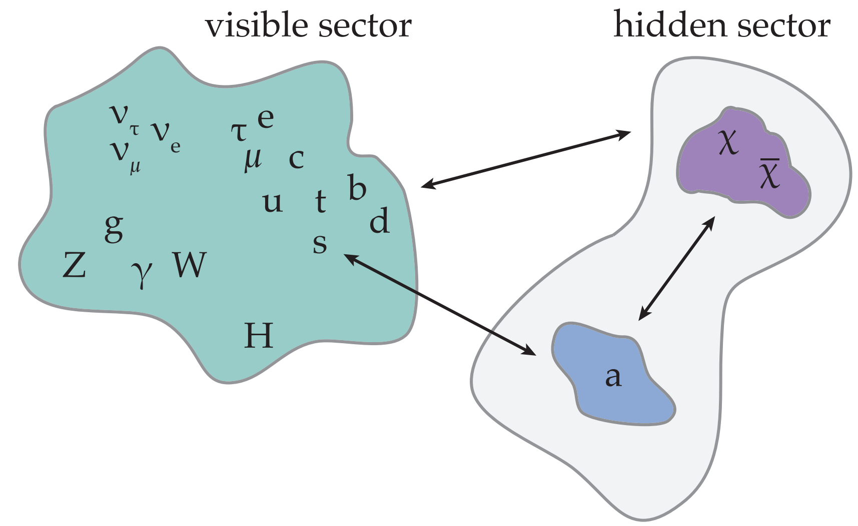


[1] figure created using https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

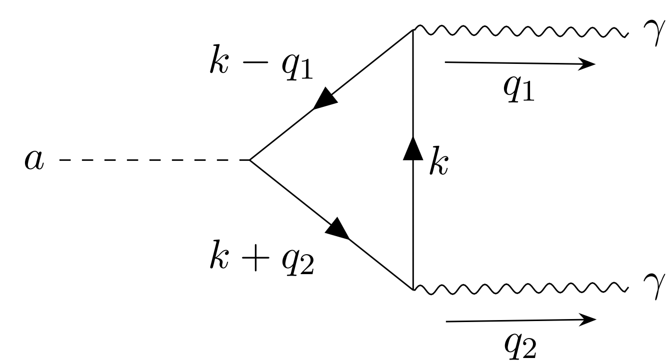
The Model

Axion-like particle (a) mediator between the SM fermions (f) and the DM (χ), a $U(1)_{PQ}$ charged Dirac fermion

a can emerge naturally from extended Higgs sector $\rightarrow$ also expect dim-5 couplings



Do not consider coupling to gauge bosons at tree-level but can couple via loops, e.g.



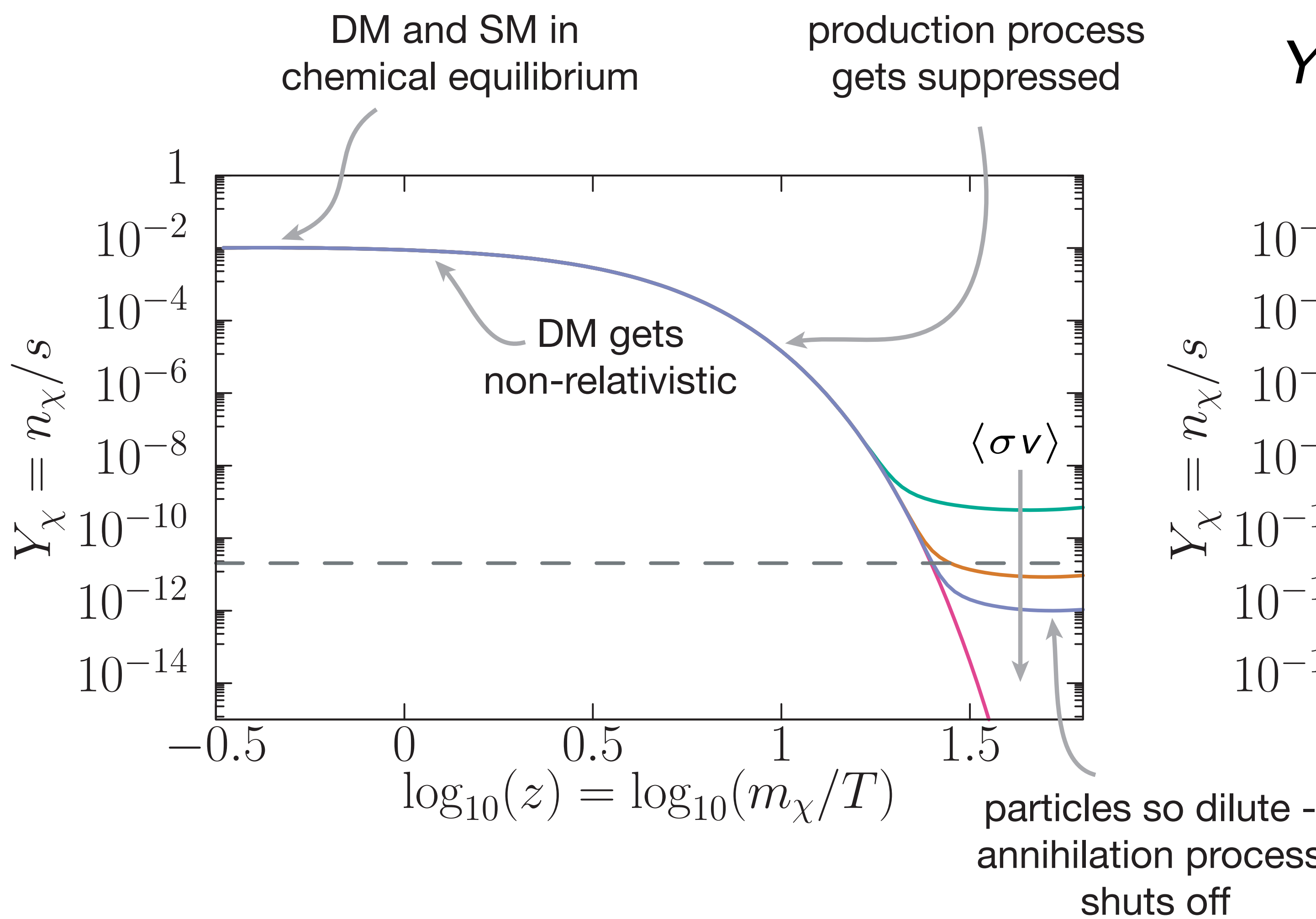
$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a + \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi - \frac{1}{2}m_a^2 a^2 + ia\sum_f \frac{m_f}{f_a} C_f \bar{f}\gamma_5 f + ia\frac{m_\chi}{f_a} C_\chi \bar{\chi}\gamma_5\chi + a\sum_f C_f \frac{y_f}{\sqrt{2}f_a} h\bar{f} i\gamma_5 f + \ldots$$

$g_{a\chi\chi} \equiv C_\chi / f_a$ (hidden sector coupling), $g_{aff} \equiv C_f / f_a$ (connector coupling)

Alternative DM Genesis Scenarios

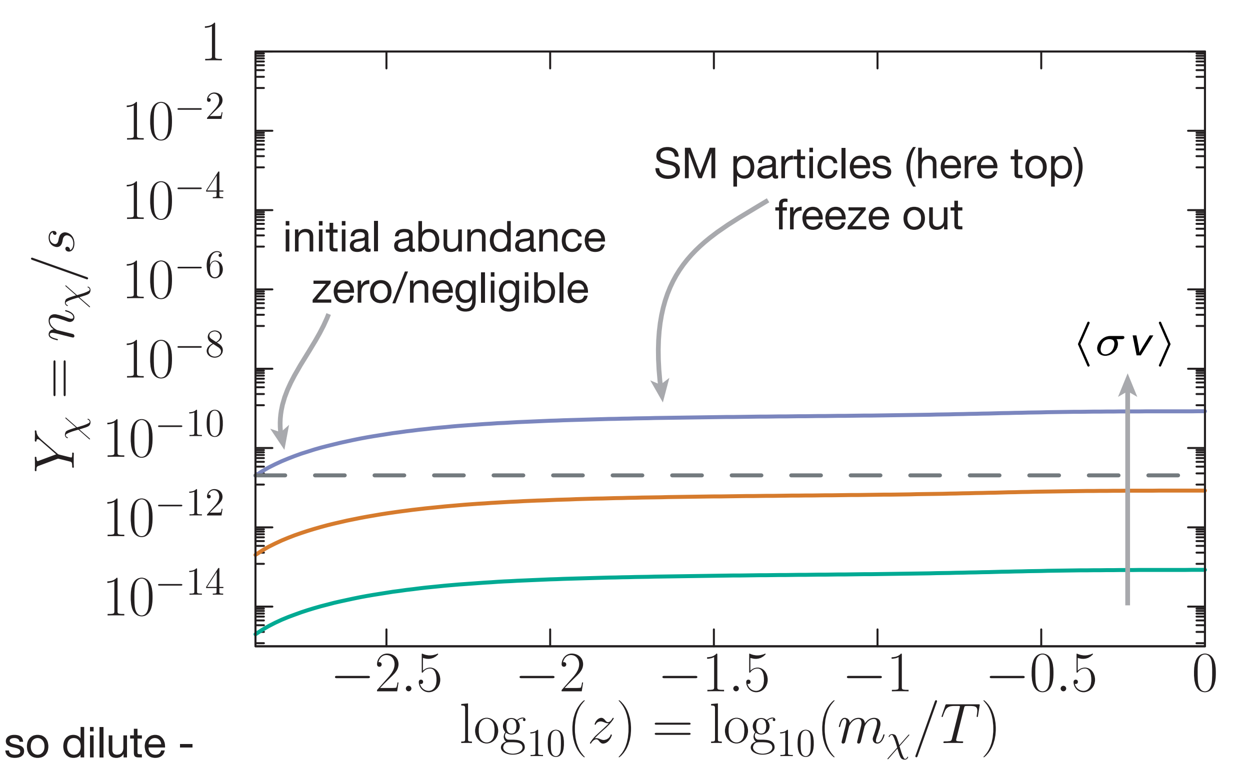
Consider simpler toy model: $$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v \right\rangle \left(n_\chi^{\mathrm{eq}}(T)^2 - n_\chi^2\right)$$

Freeze-out



Freeze-in (IR)

$$Y_{\chi,0} = -\int_0^{T_{RH}} \frac{\left\langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v \right\rangle (n_\chi^{\mathrm{eq}})^2}{3Hs^2} \frac{\mathrm{d}s}{\mathrm{d}T}\, \mathrm{d}T$$



Unfortunately things not so simple! ALP also has a say...

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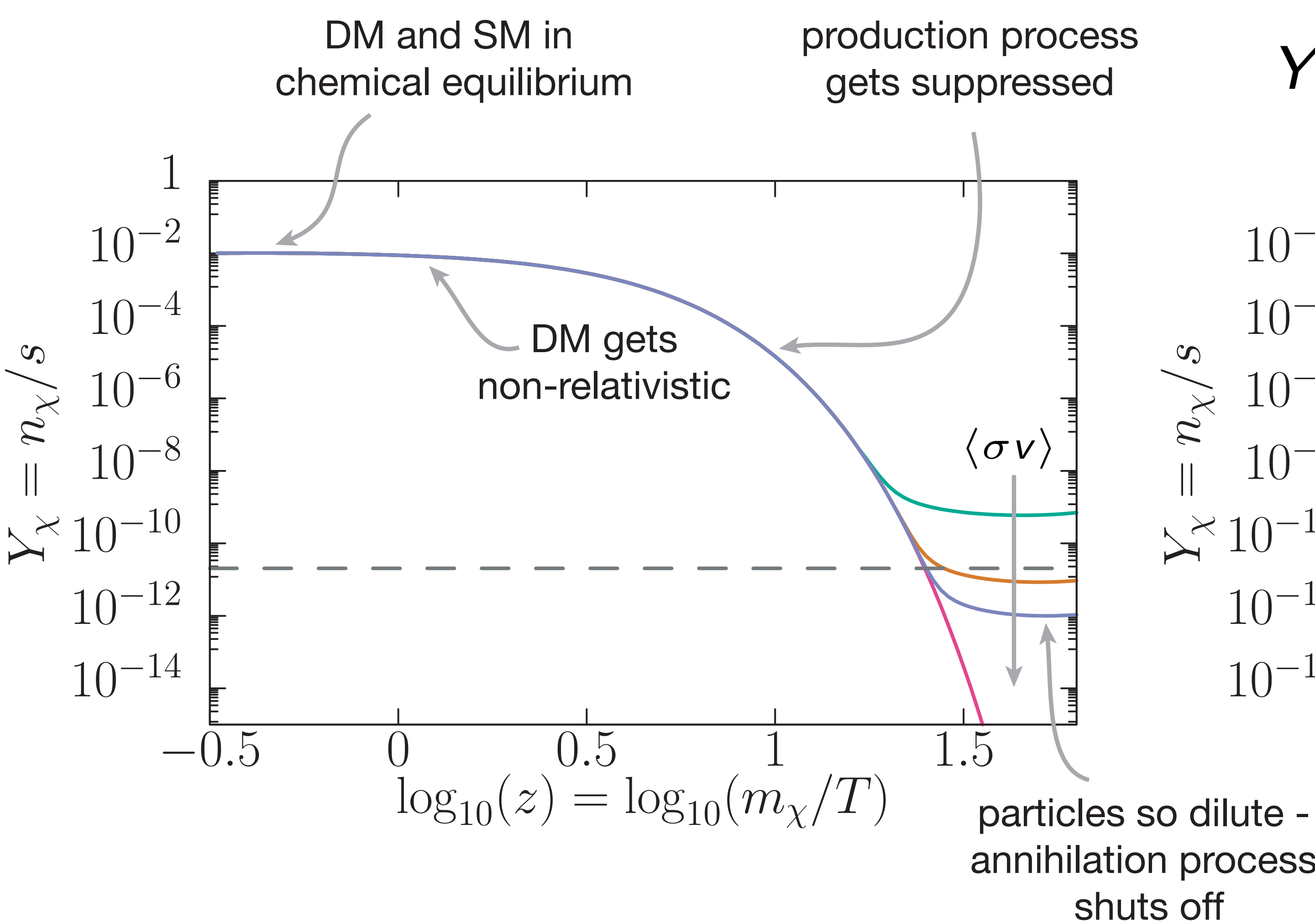
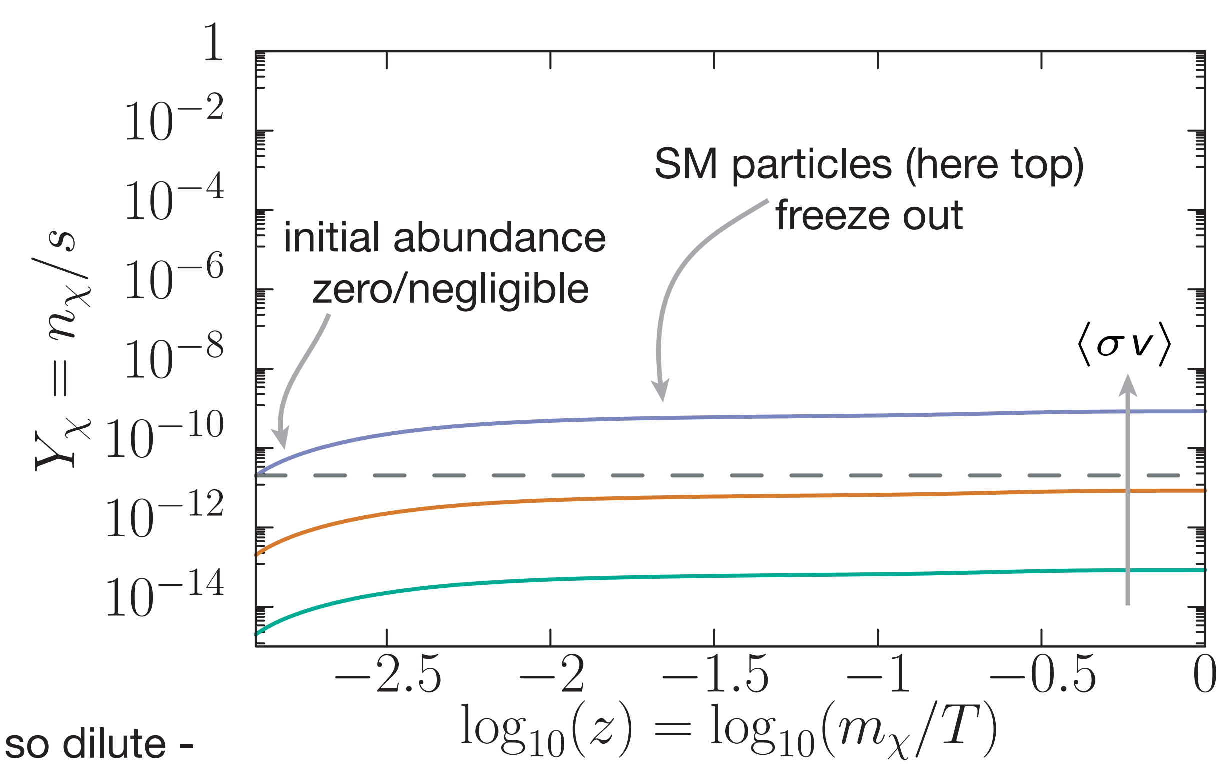


Freeze-in (UV)

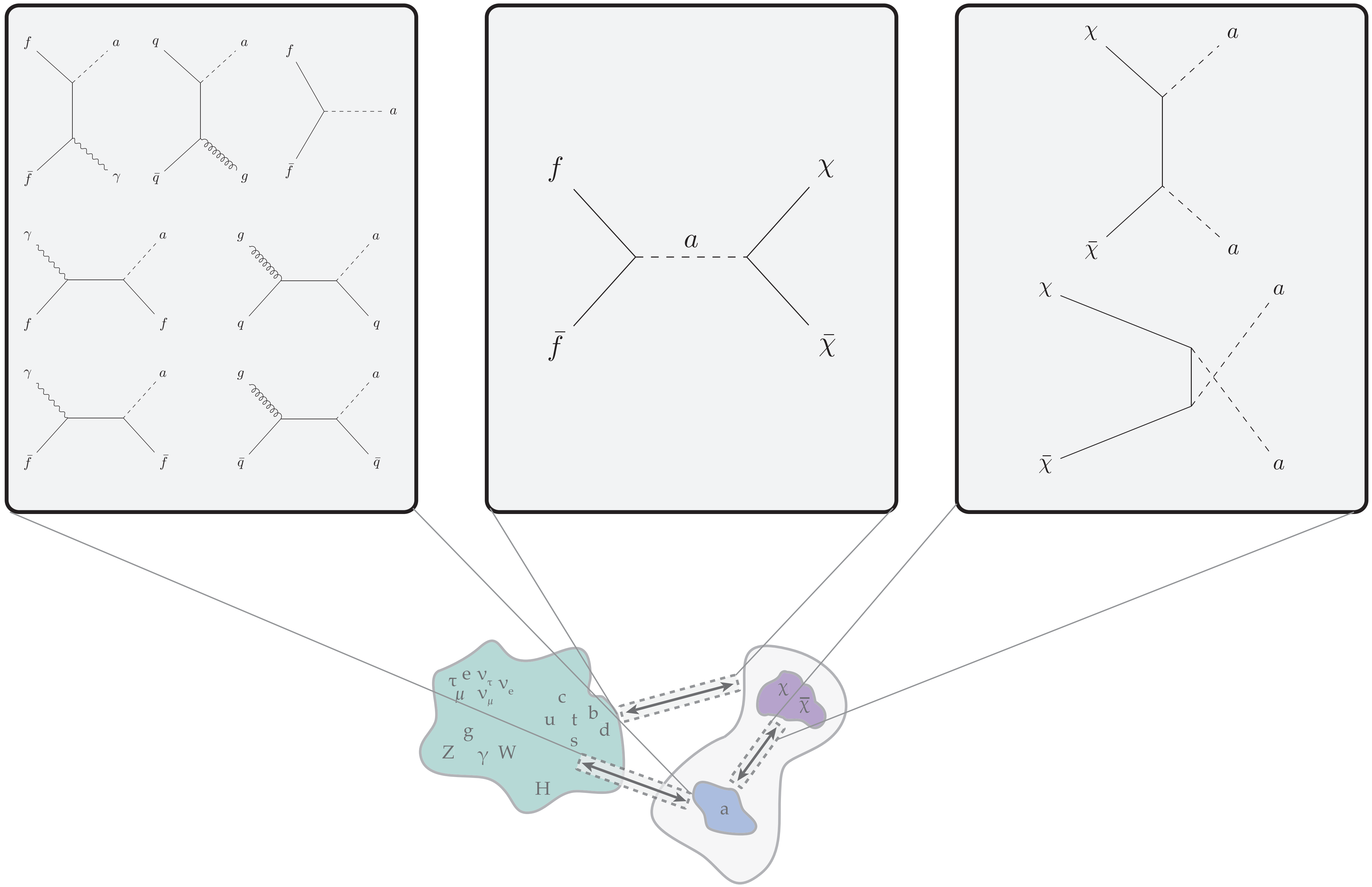
$$Y_{\chi,0} = -\int_0^{T_{RH}} \frac{\left\langle \sigma_{\chi\bar{\chi}\to hf\bar{f}} v \right\rangle (n_\chi^{\mathrm{eq}})^2}{3Hs^2} \frac{\mathrm{d}s}{\mathrm{d}T}\, \mathrm{d}T$$



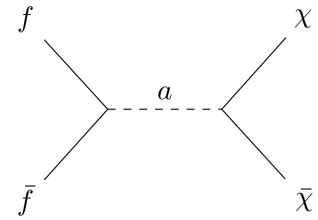
Unfortunately things not so simple! ALP also has a say...

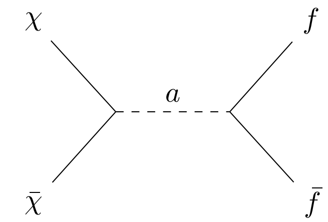
DM and ALP number changing interactions (IR)

$\propto g_{aff}^2$	$\propto (g_{aff}\, g_{a\chi\chi})^2$	$\propto g_{a\chi\chi}^4$
SM ⟷ ALPs	SM ⟷ DM	ALPs ⟷ DM



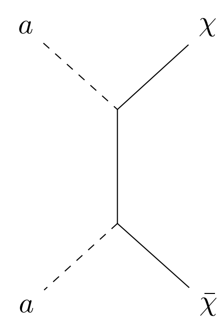
Coupled Boltzmann equations

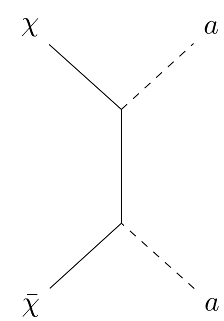




$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi}\to f\bar{f}}\, v \right\rangle \Big(\overbrace{\left(n_\chi^{\mathrm{eq}}(T)\right)^2} - \overbrace{n_\chi^2} \Big)$$

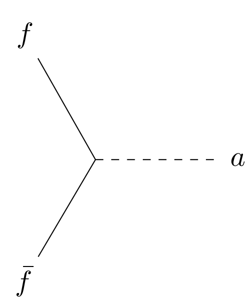
$$+ \underbrace{\langle \sigma_{aa\to\chi\bar{\chi}}\, v\rangle\, n_a^2} - \underbrace{\langle \sigma_{\chi\bar{\chi}\to aa}\, v\rangle\, n_\chi^2}$$

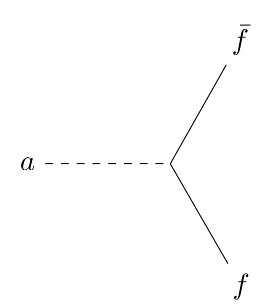


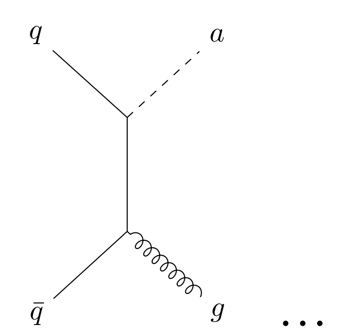


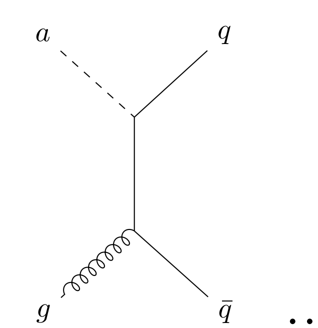
$$\frac{\mathrm{d}n_a}{\mathrm{d}t} + 3Hn_a = -\overbrace{\langle \sigma_{aa\to\chi\bar{\chi}}\, v\rangle\, n_a^2} + \overbrace{\langle \sigma_{\chi\bar{\chi}\to aa}\, v\rangle\, n_\chi^2}$$

$$+ \langle \Gamma_a \rangle \Big(\underbrace{n_a^{\mathrm{eq}}(T)} - \underbrace{n_a} \Big) + \sum_{i,j,k} \left\langle \sigma_{ai\to jk}\, v \right\rangle \Big(\underbrace{n_a^{\mathrm{eq}}(T)\, n_i^{\mathrm{eq}}(T)} - \underbrace{n_a n_i^{\mathrm{eq}}(T)} \Big)$$

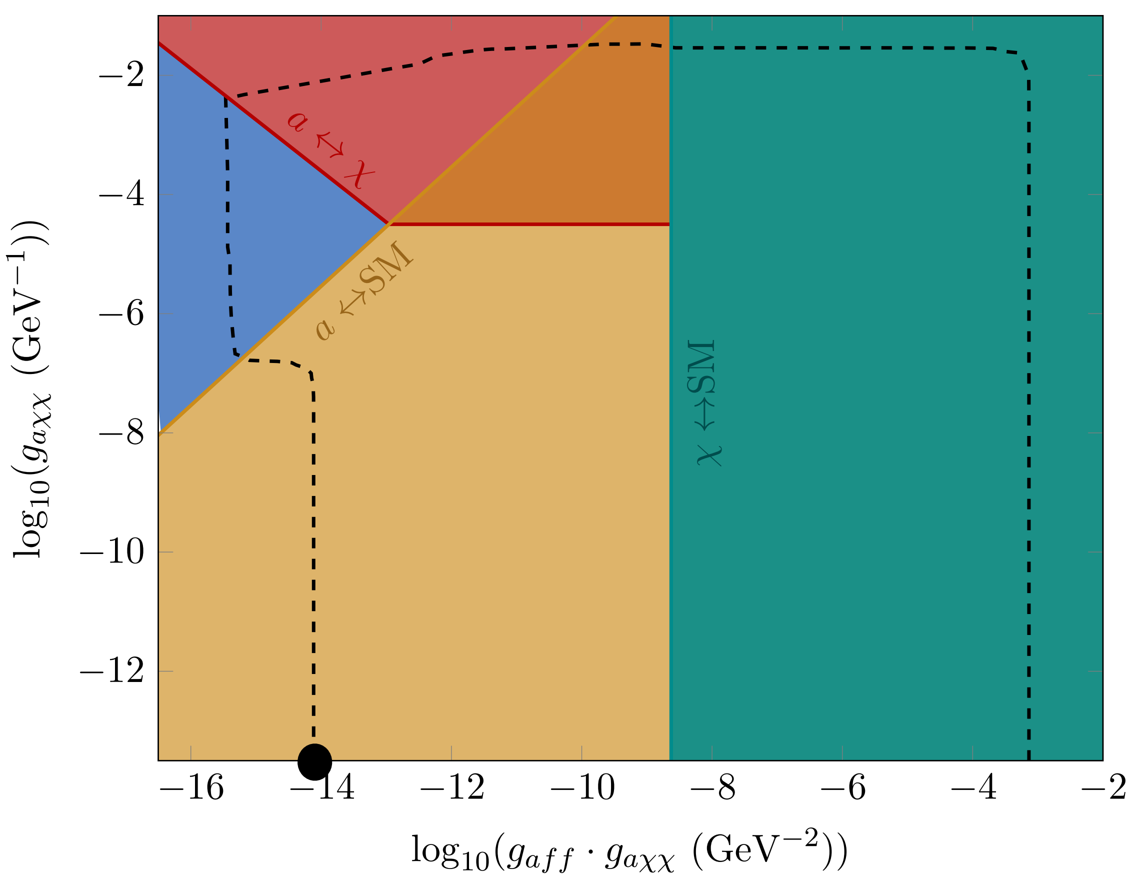


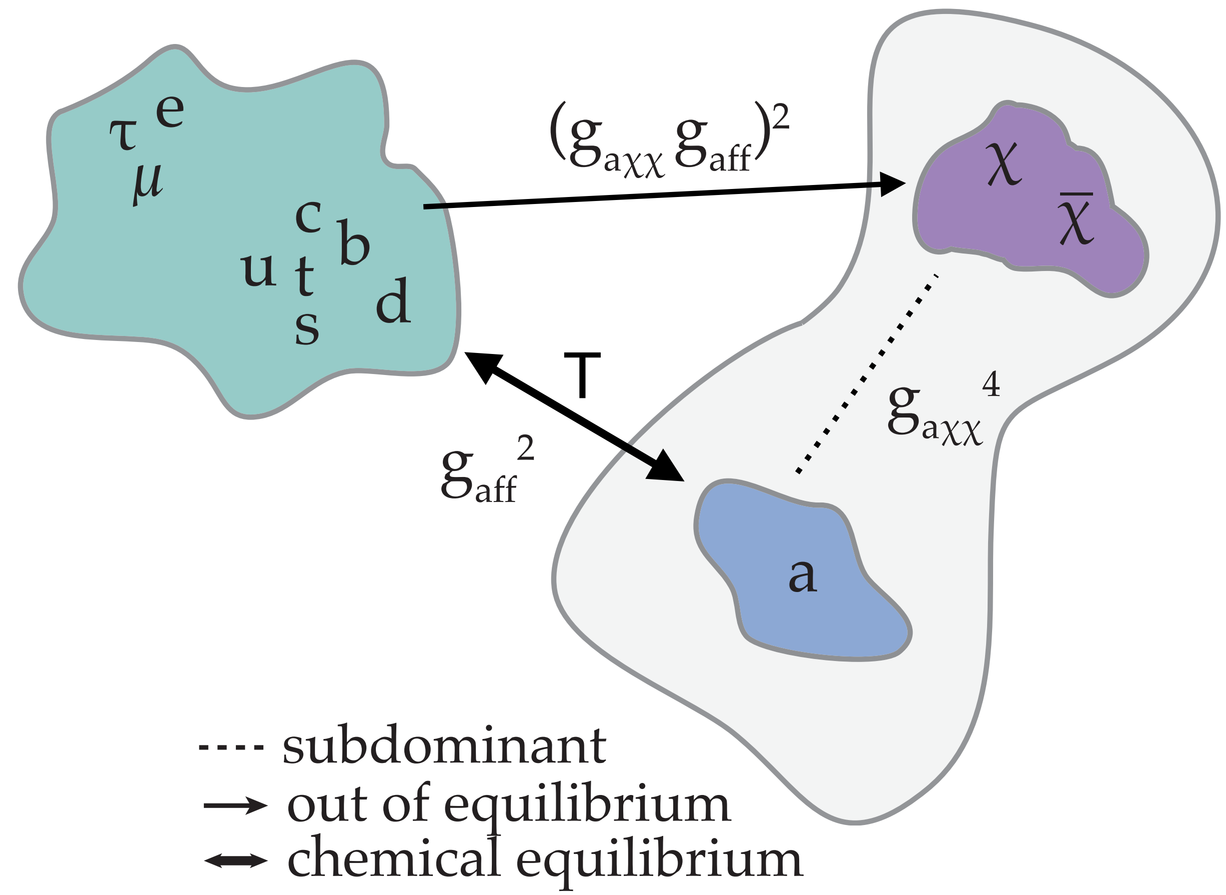






Freeze-in from SM





$m_\chi = 10$ GeV, $m_a = 1$ GeV

[Chu, Hambye, Tytgat. JCAP, 2012], [Hambye, Tytgat, Vandecasteele, Vanderheyden. Phys. Rev. D, 2019], [Bélanger, Delaunay, Pukhov, Zaldivar. Phys. Rev. D, 2020]

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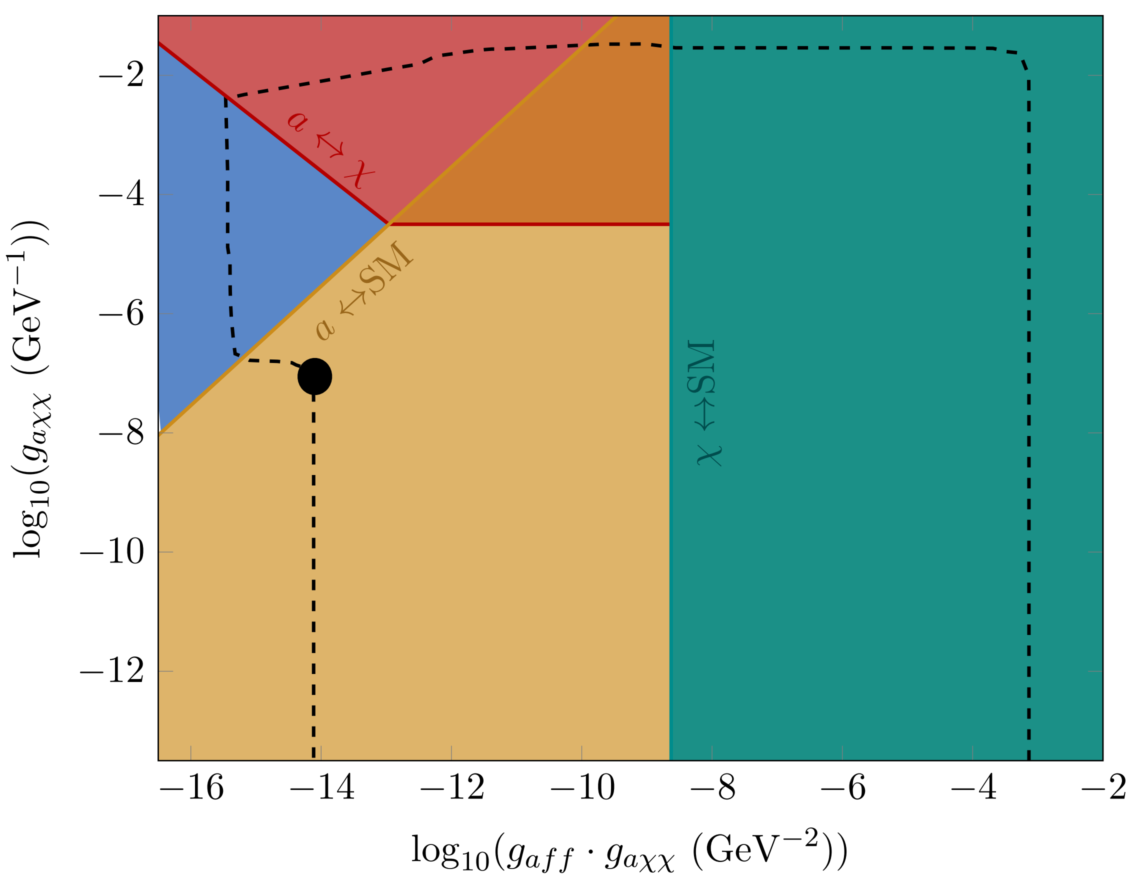

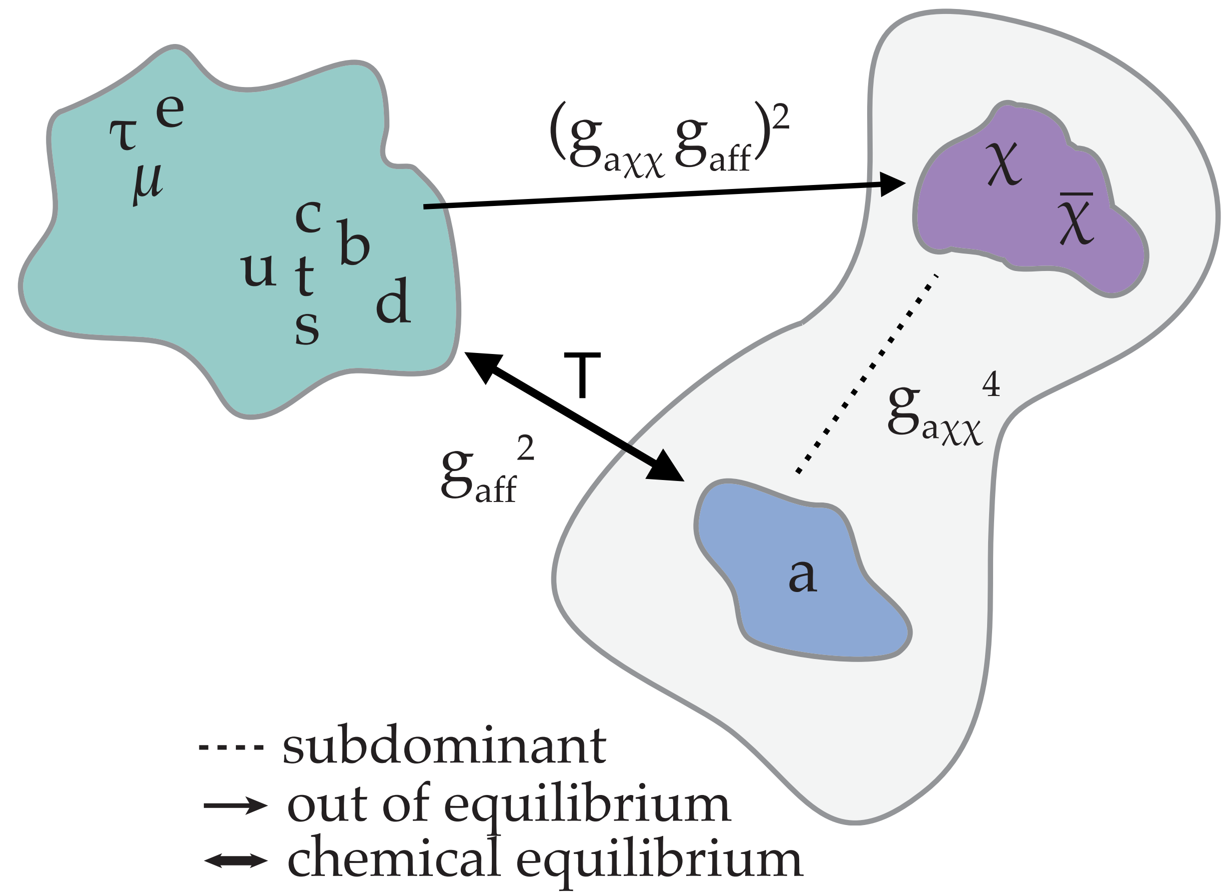

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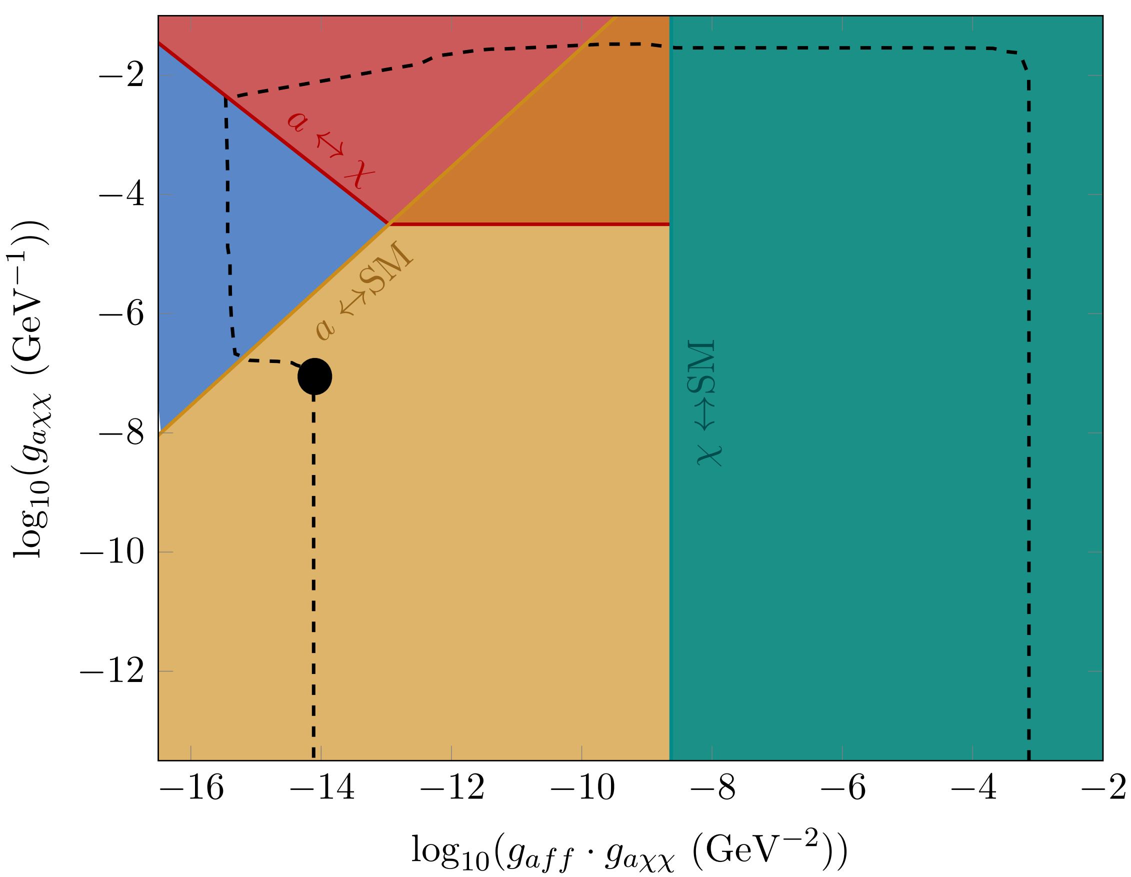
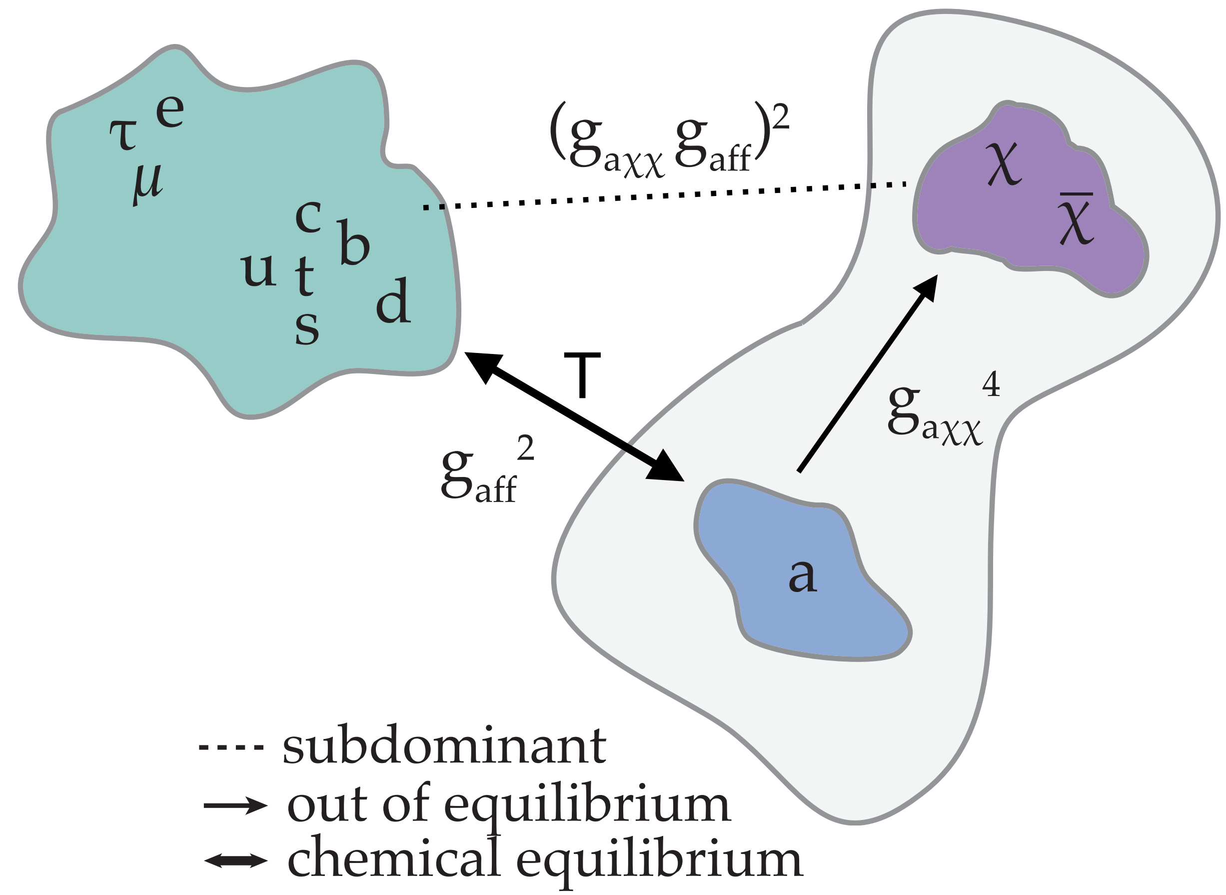
Freeze-in from the mediator





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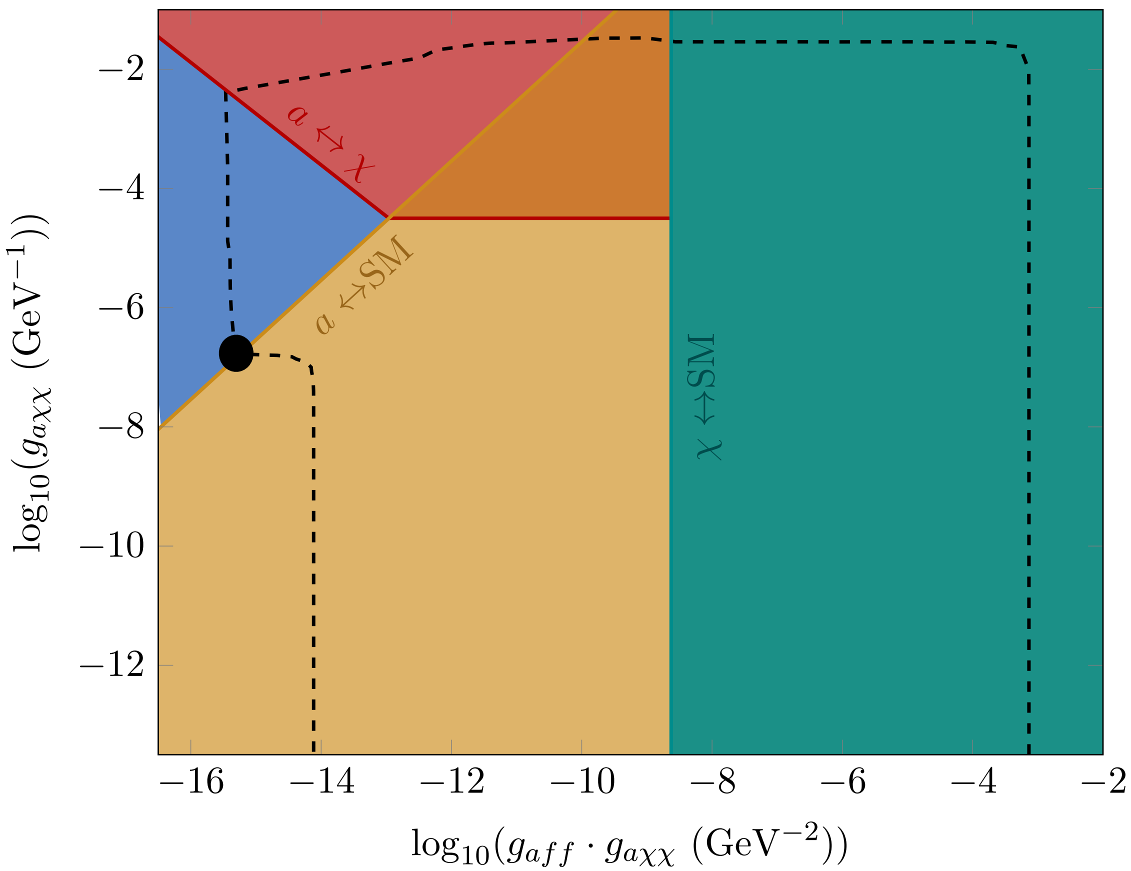

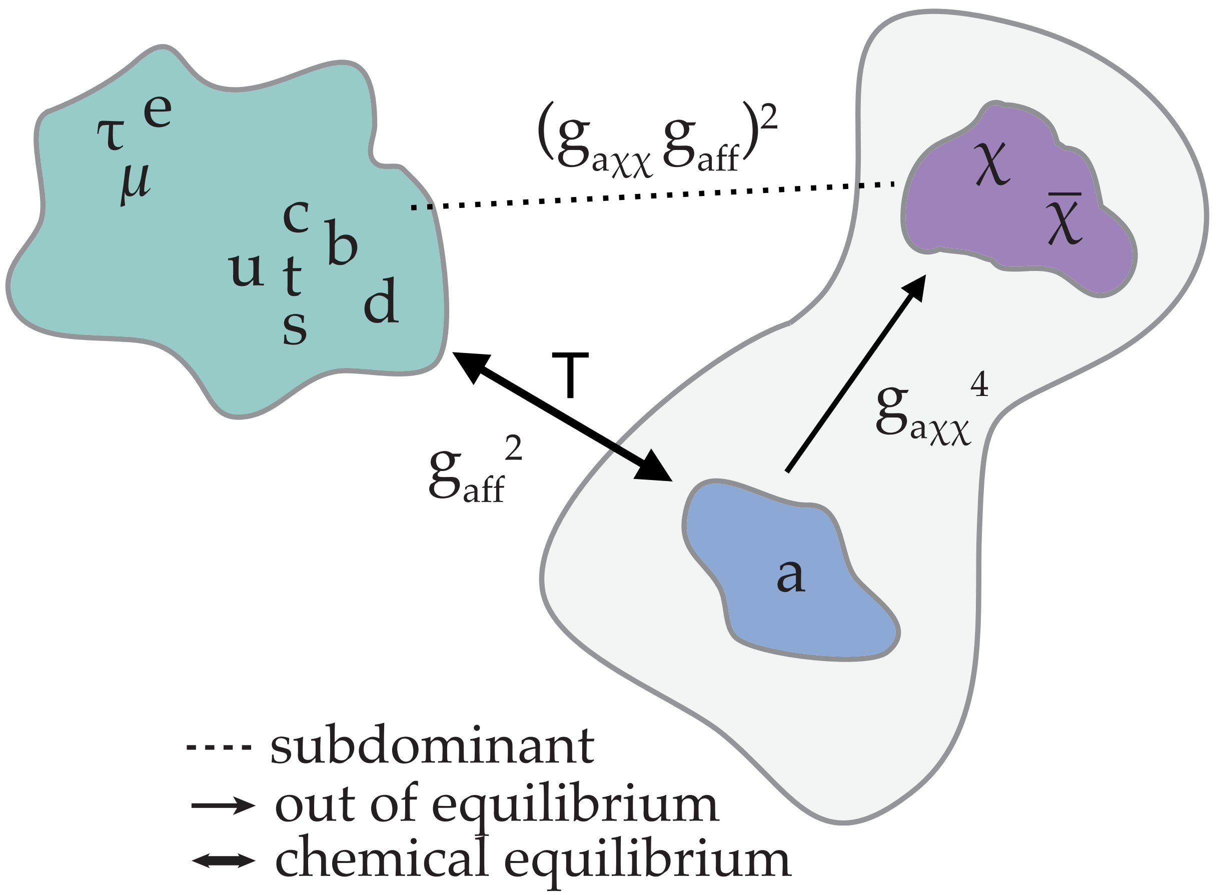

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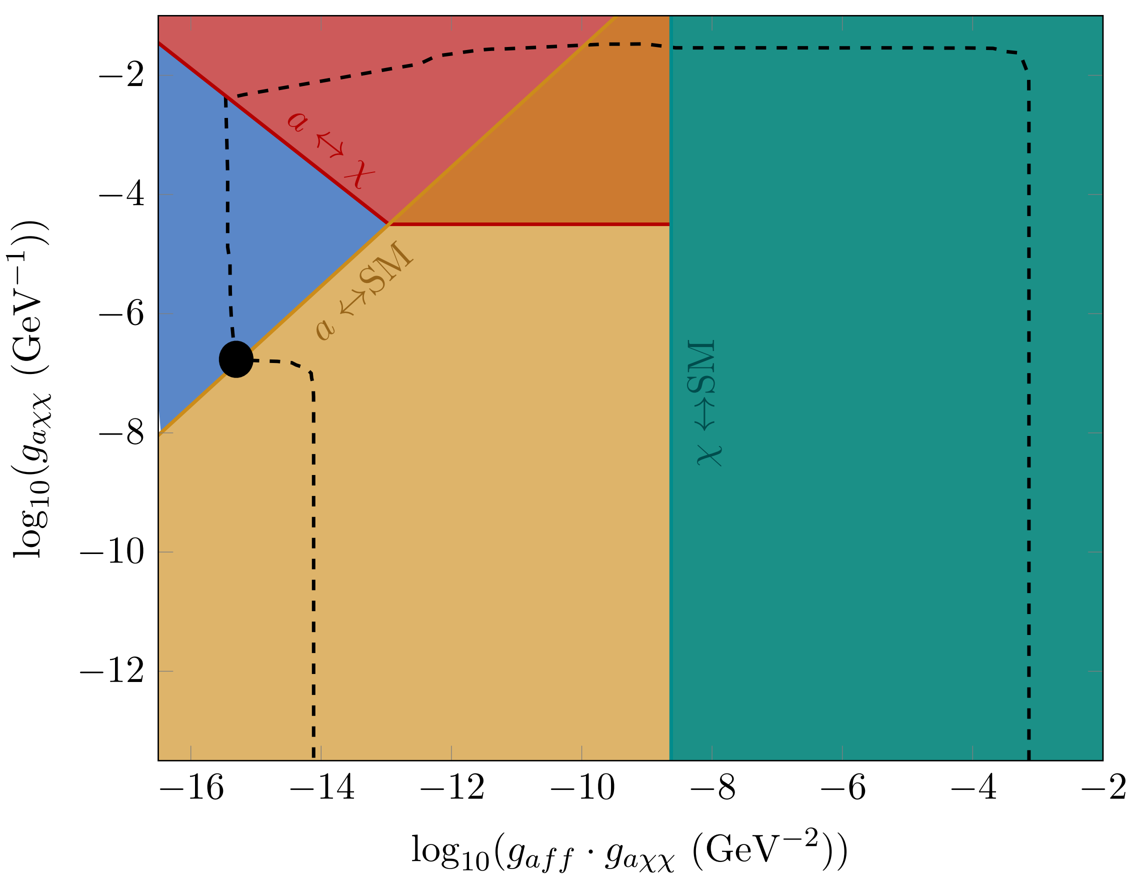
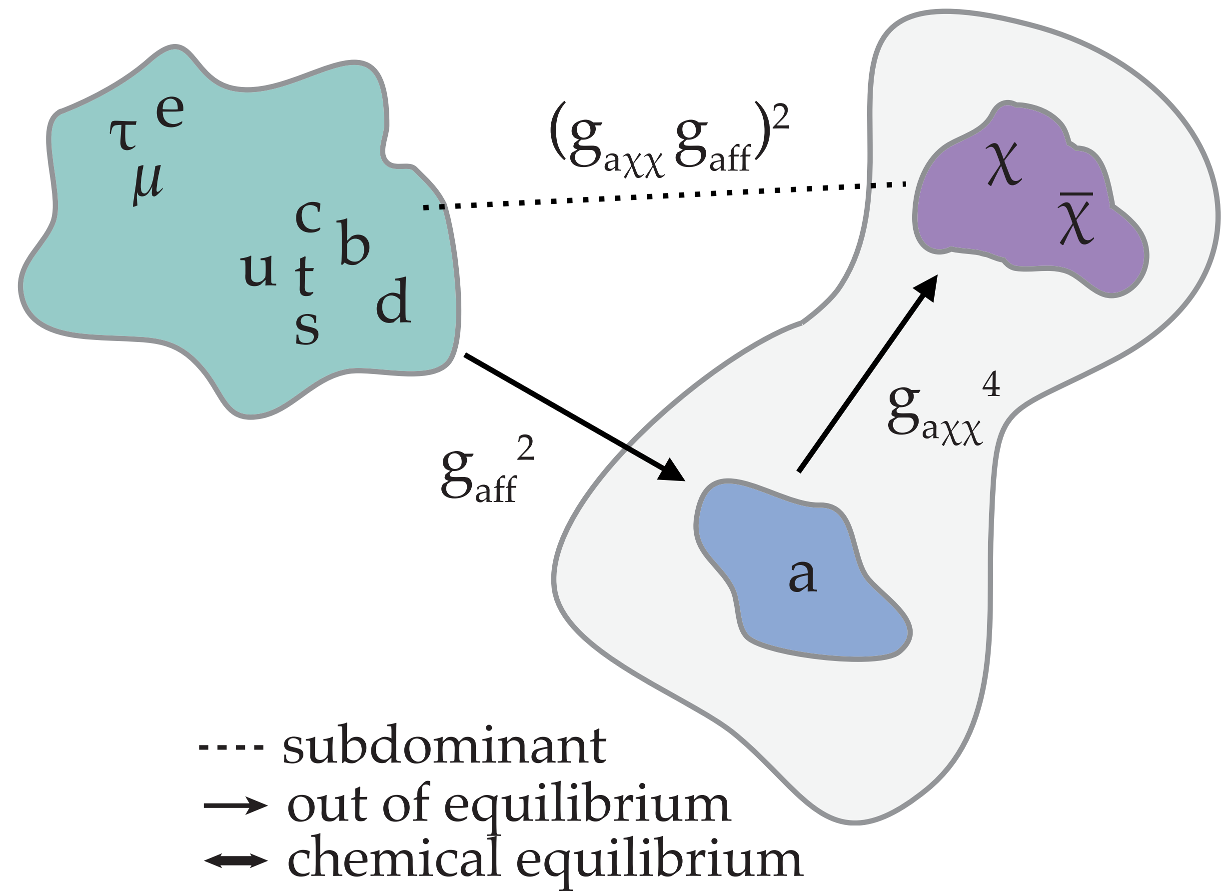
Sequential freeze-in





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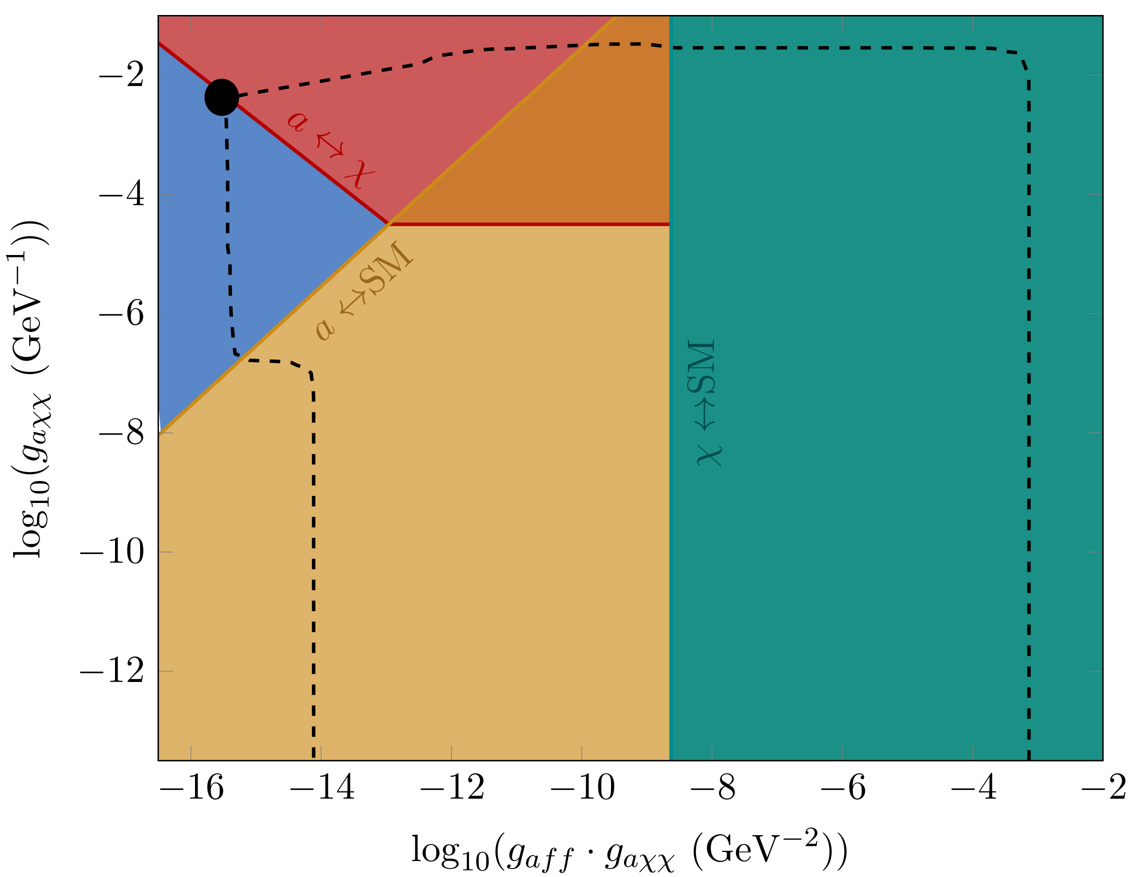

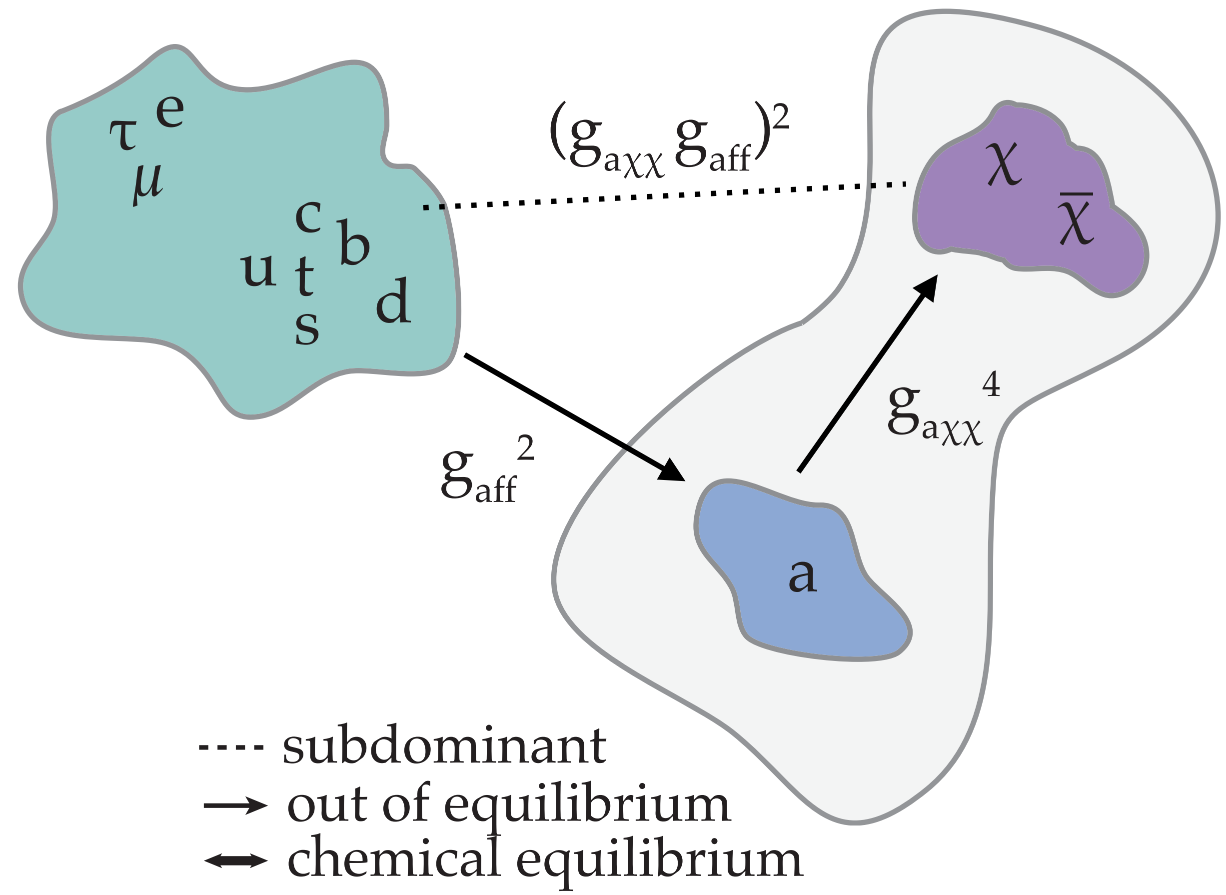

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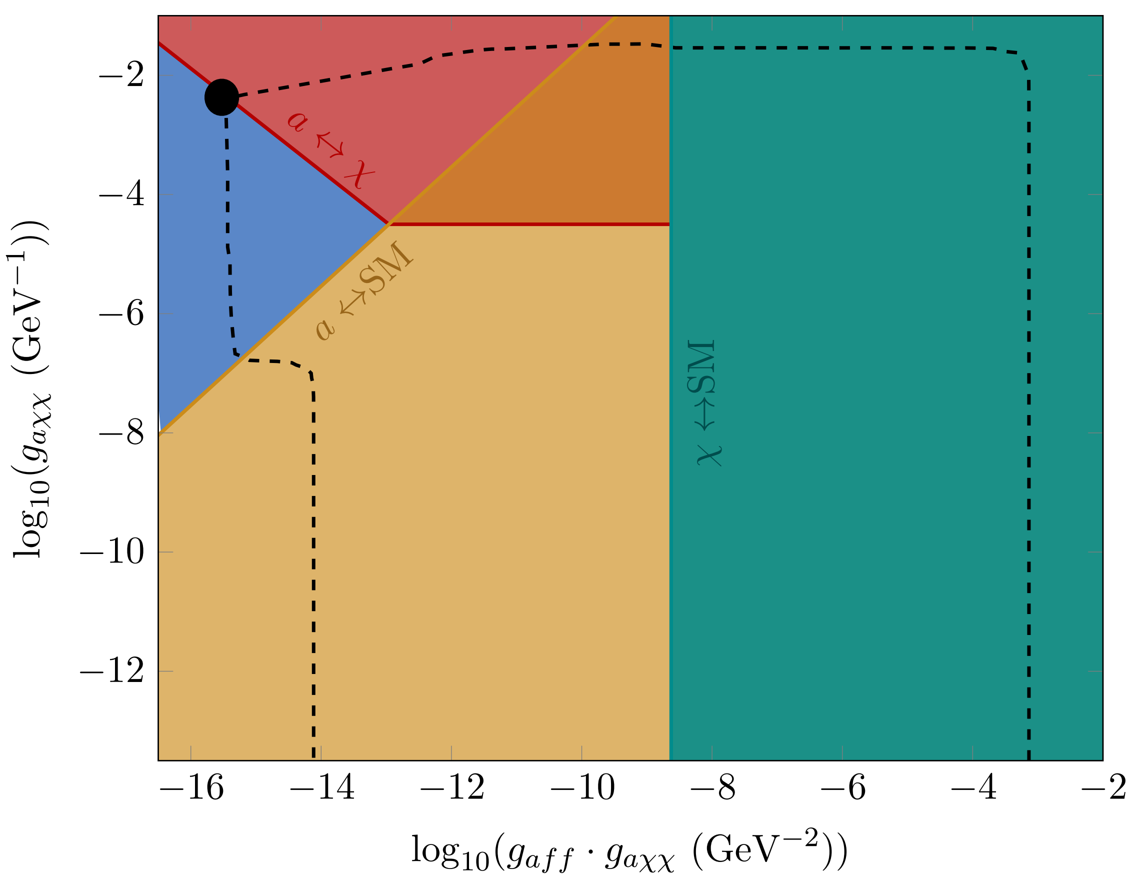
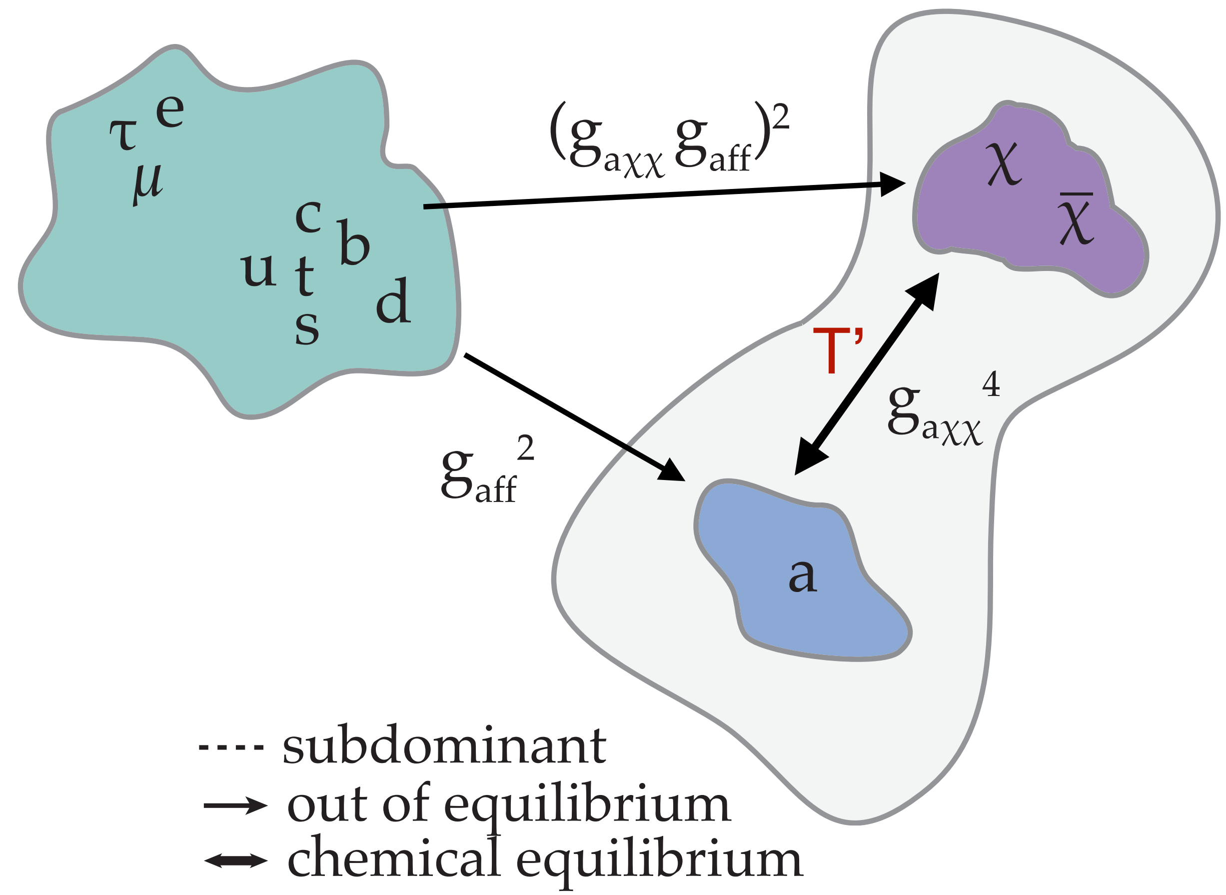
Decoupled freeze-out (DFO)





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Decoupled freeze-out (DFO)

Hidden sector and visible sector thermally decoupled, $T' \ll T$

$$\frac{\partial \rho'(T')}{\partial t} + 3H\left(\rho' + P'\right)(T') = \int \frac{d^3p}{(2\pi)^3} C[f(p,t)]$$

Need to solve system of 3 (unfortunately stiff) coupled differential equations

$m_\chi = 10$ GeV, $m_a = 1$ GeV

[Chu, Hambye, Tytgat. JCAP, 2012], [Hambye, Tytgat, Vandecasteele, Vanderheyden. Phys. Rev. D, 2019], [Bélanger, Delaunay, Pukhov, Zaldivar. Phys. Rev. D, 2020]

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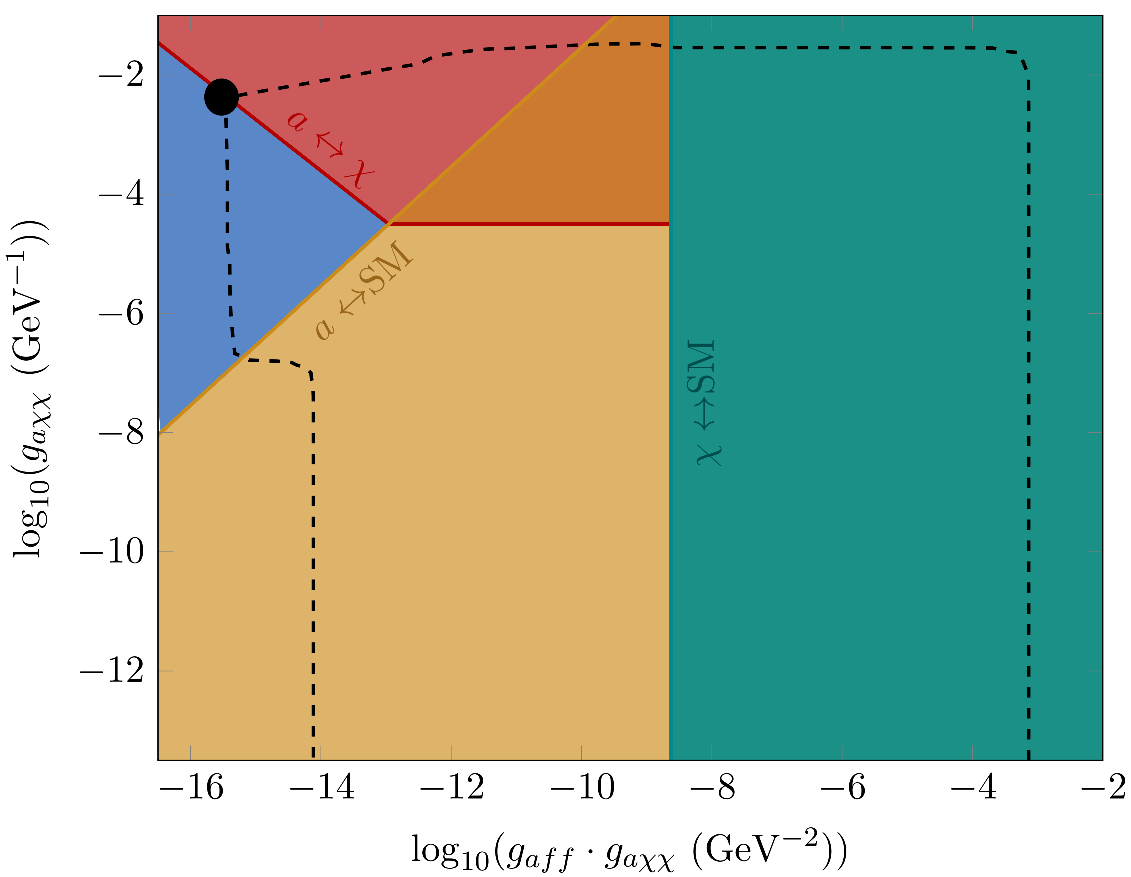

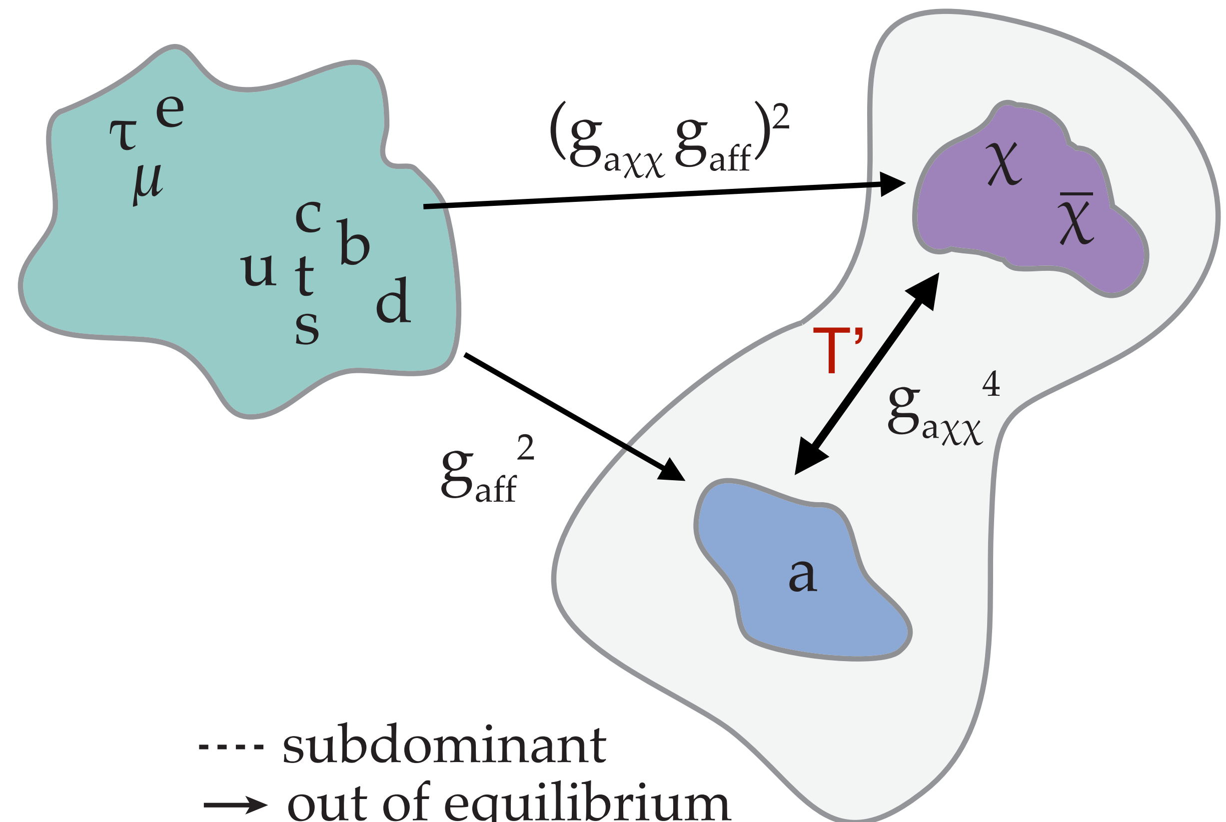

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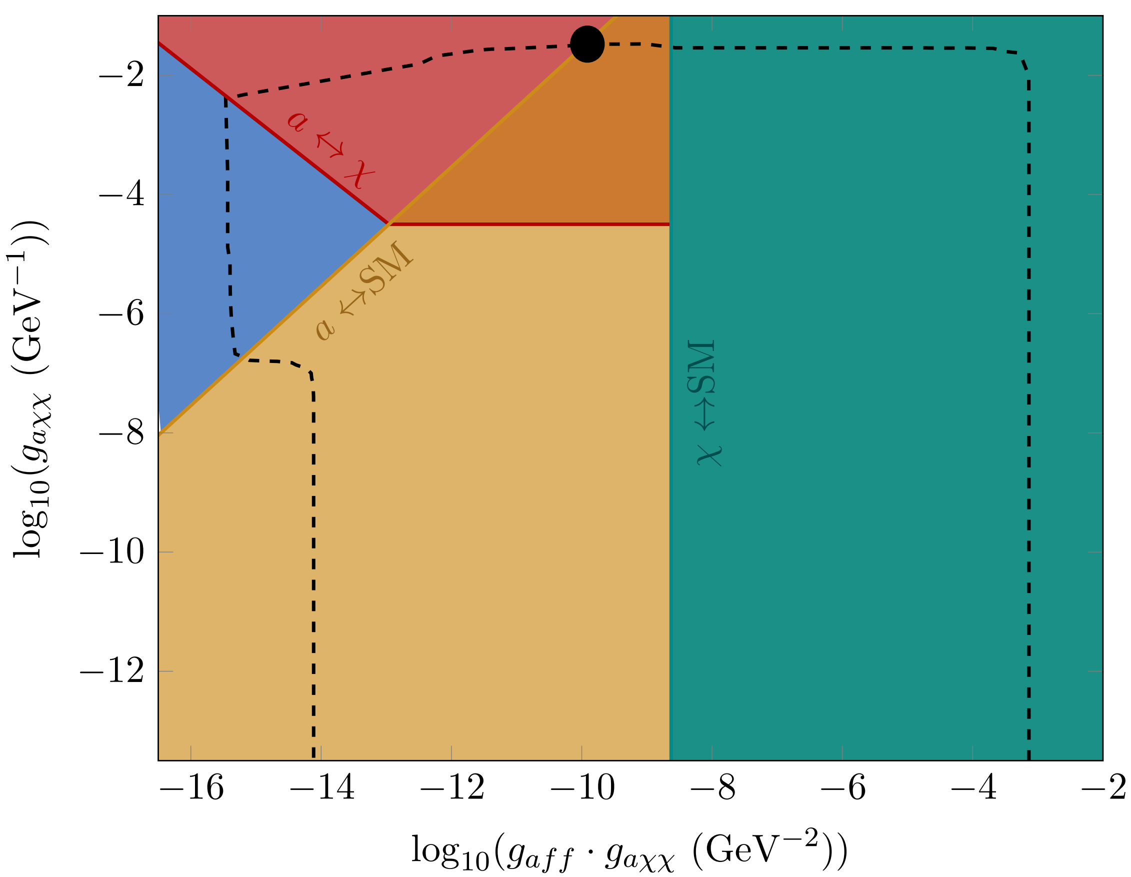

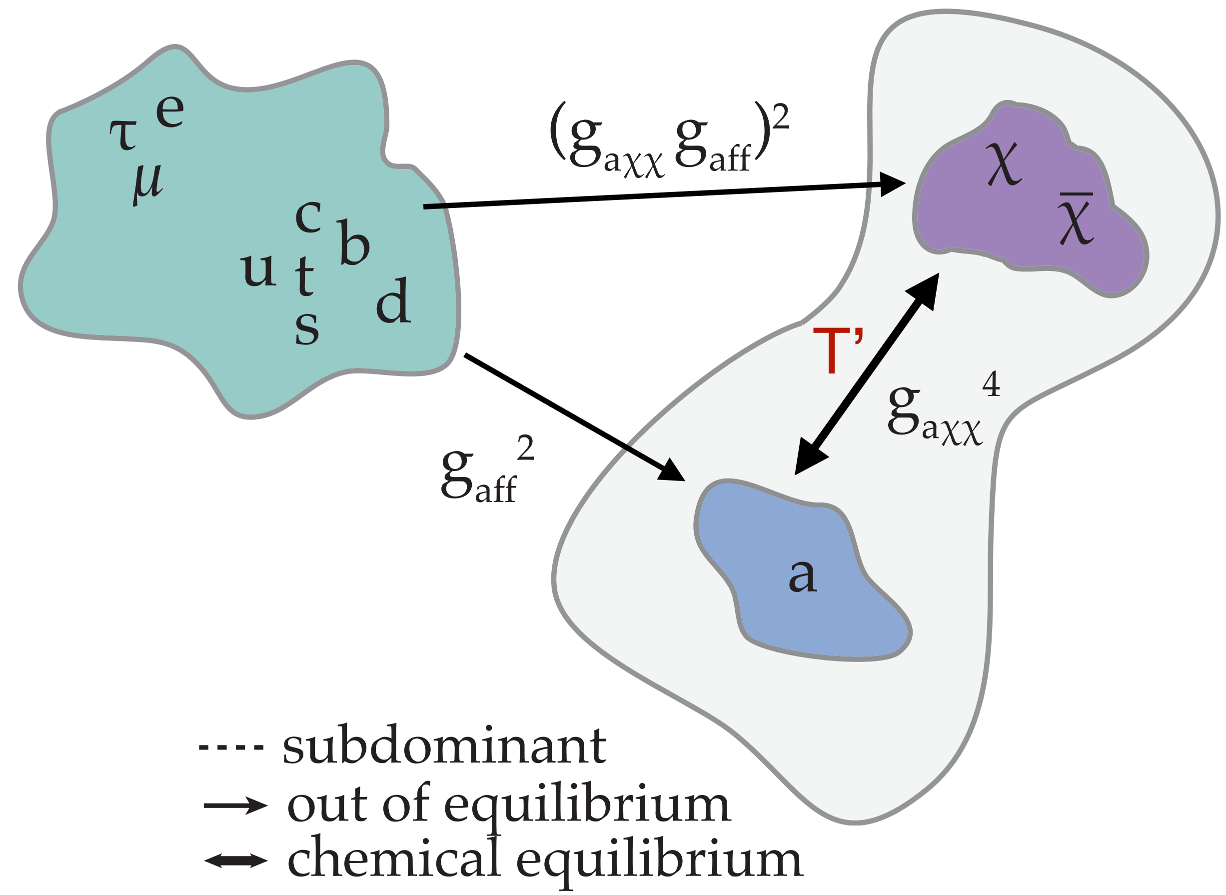

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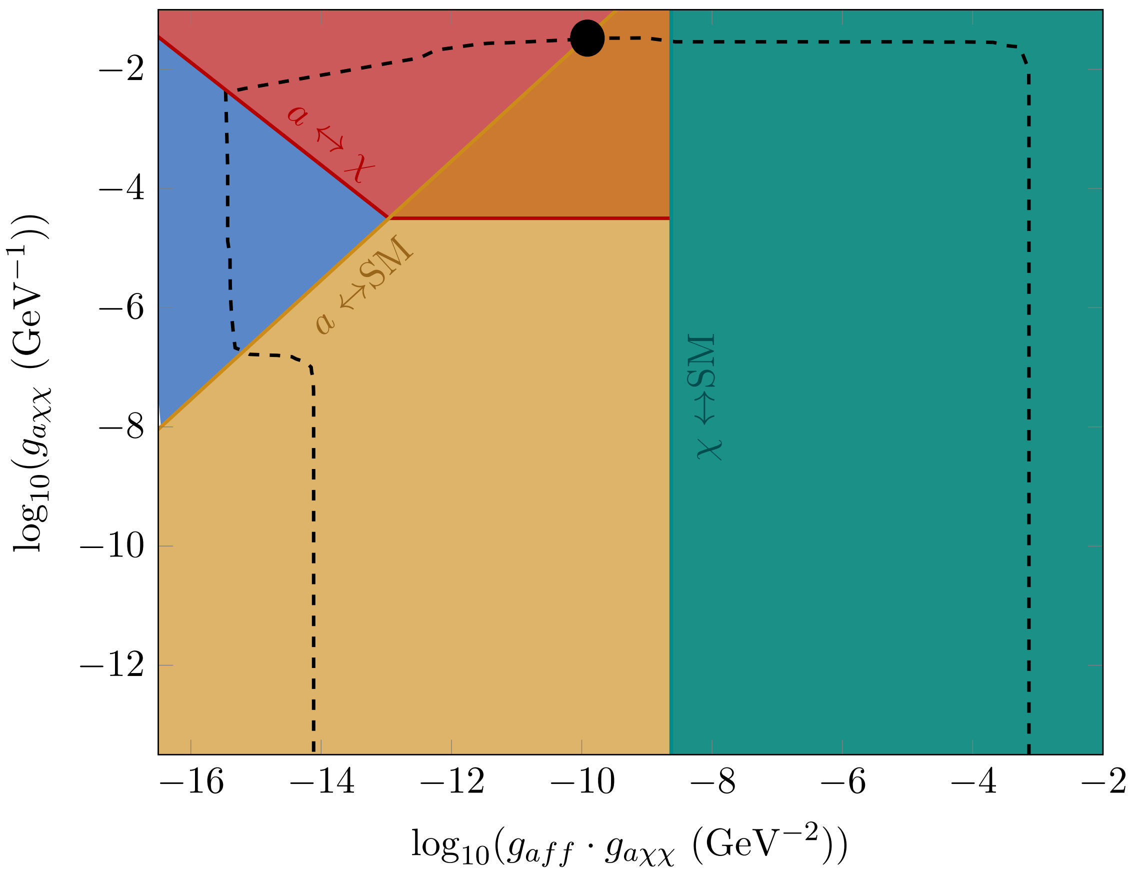
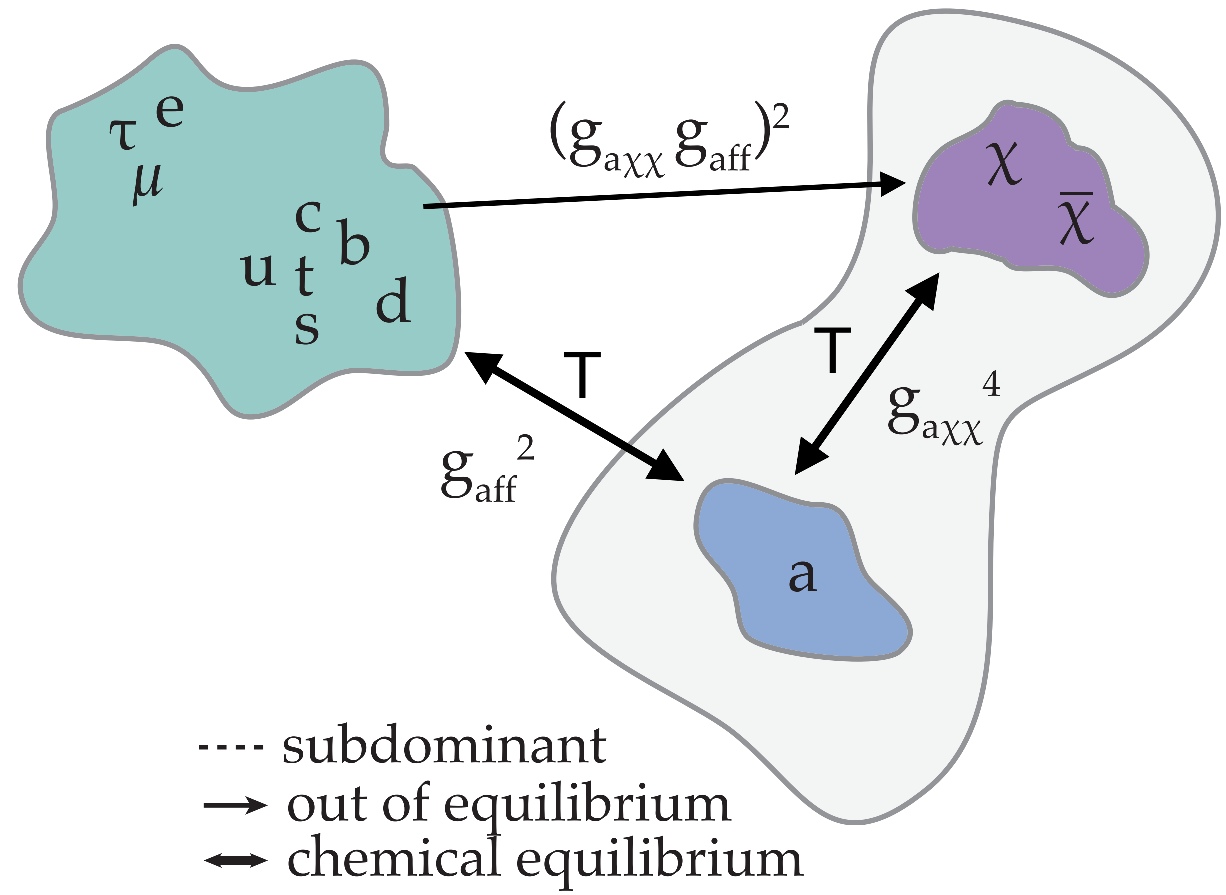
Freeze-out from the mediator





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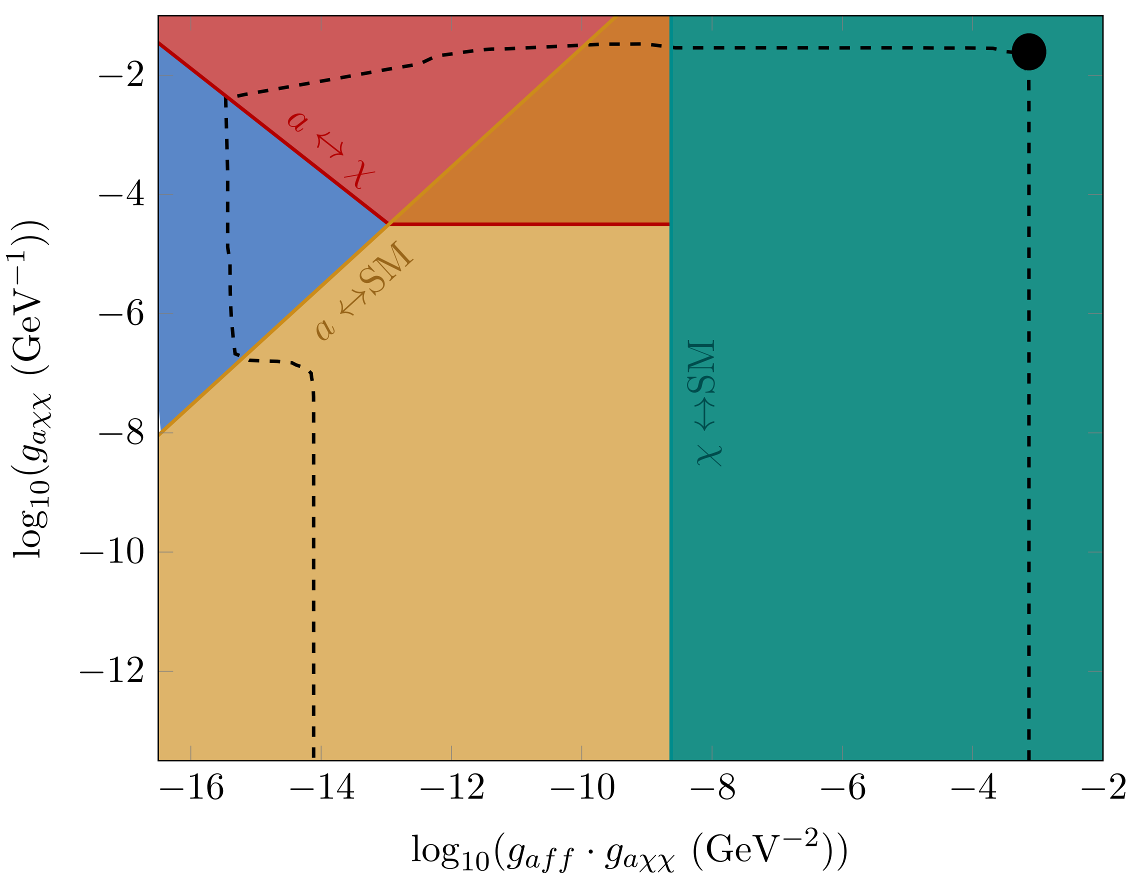
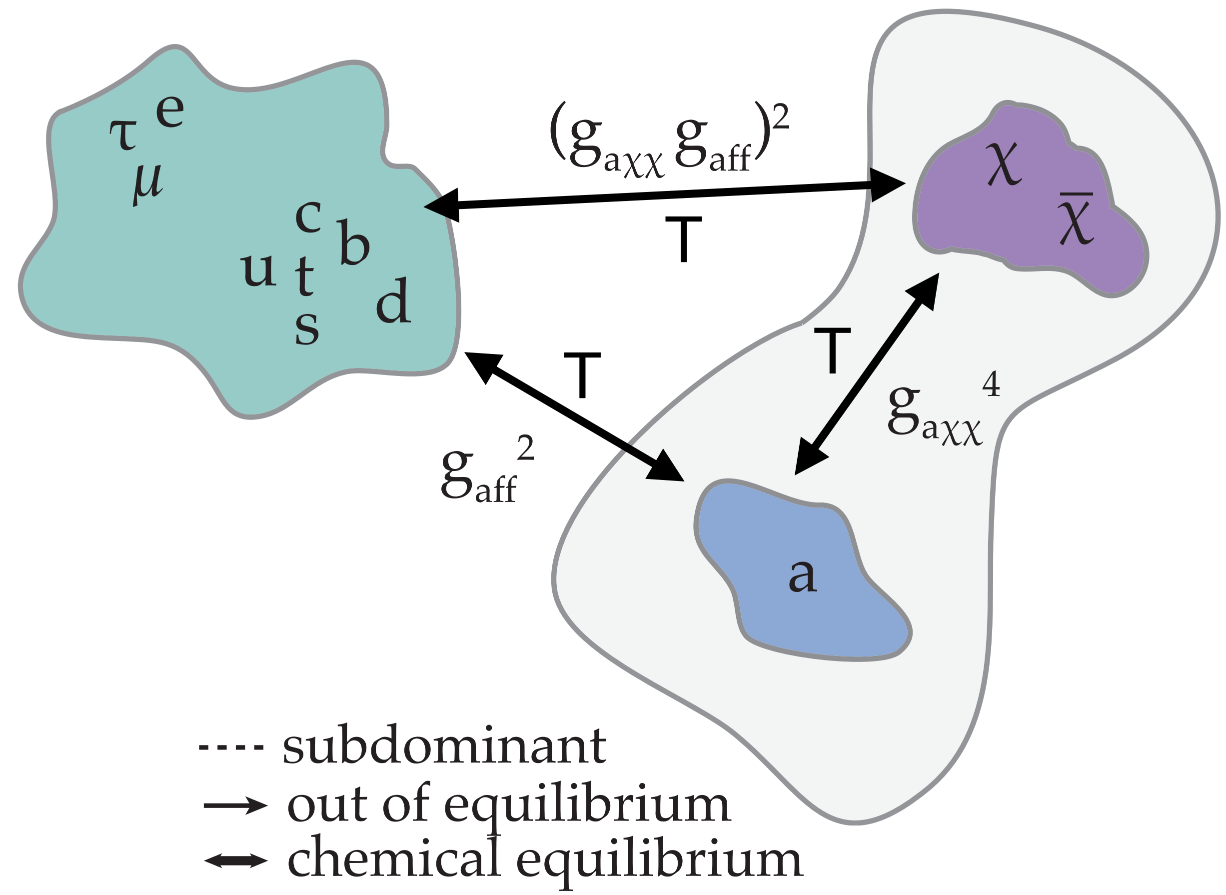
[Chu, Hambye, Tytgat. JCAP, 2012], [Hambye, Tytgat, Vandecasteele, Vanderheyden. Phys. Rev. D, 2019], [Bélanger, Delaunay, Pukhov, Zaldivar. Phys. Rev. D, 2020]

Freeze-out from SM





$m_\chi = 10$ GeV, $m_a = 1$ GeV

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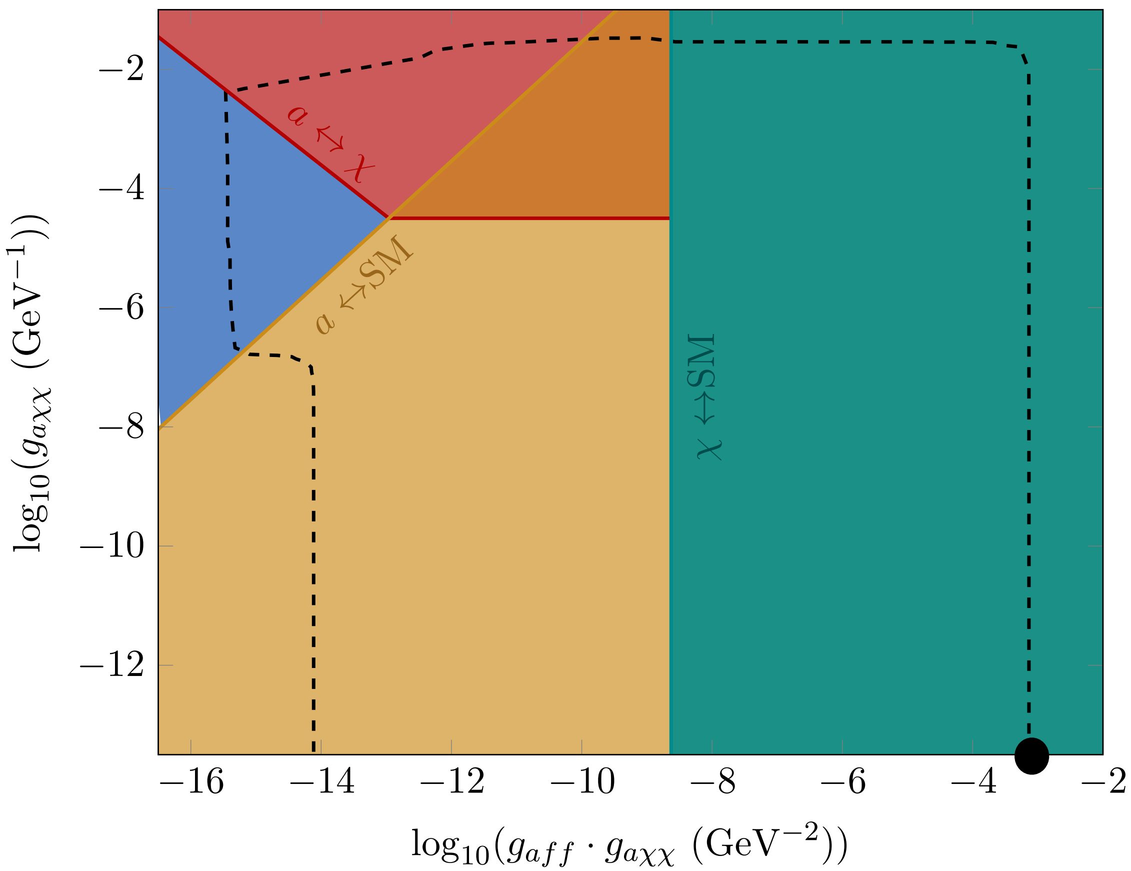

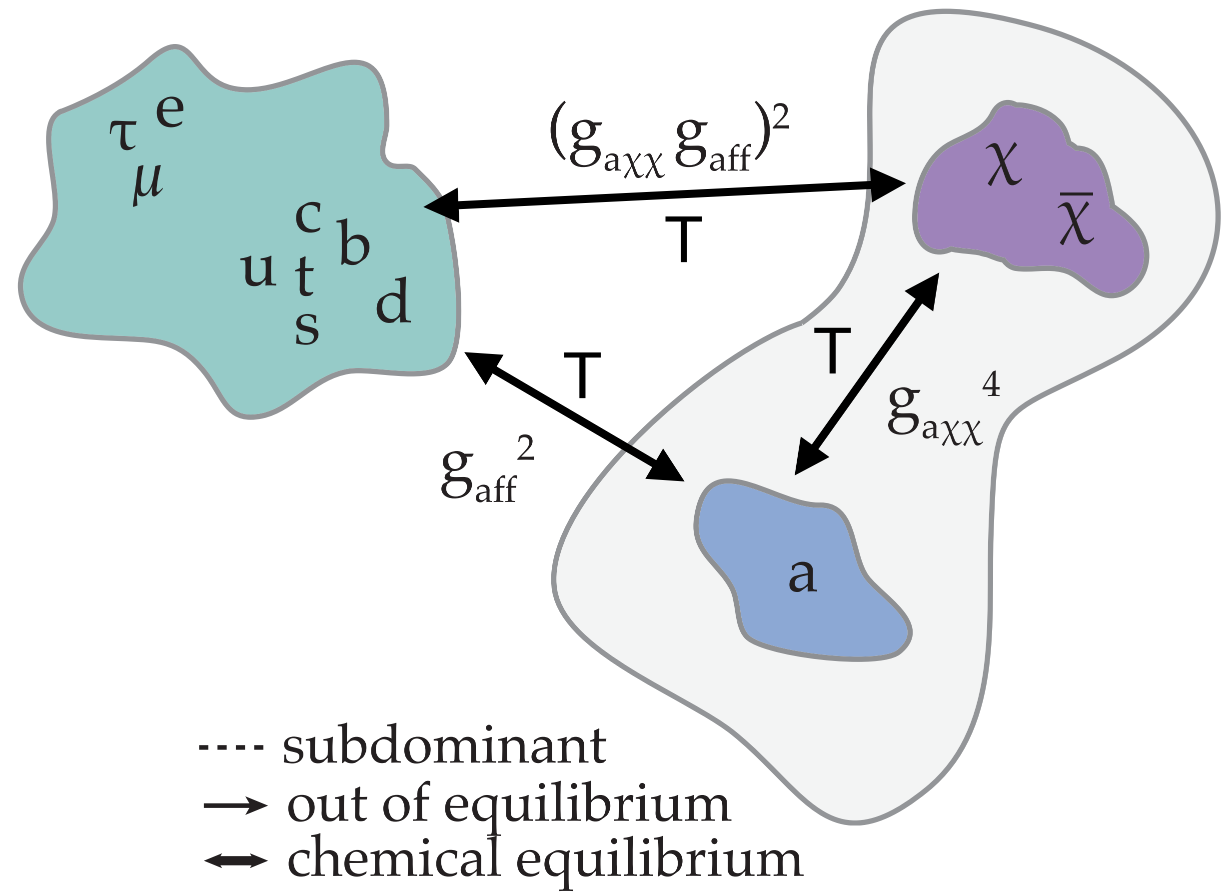

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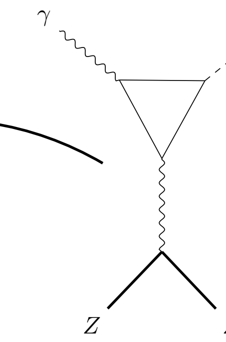
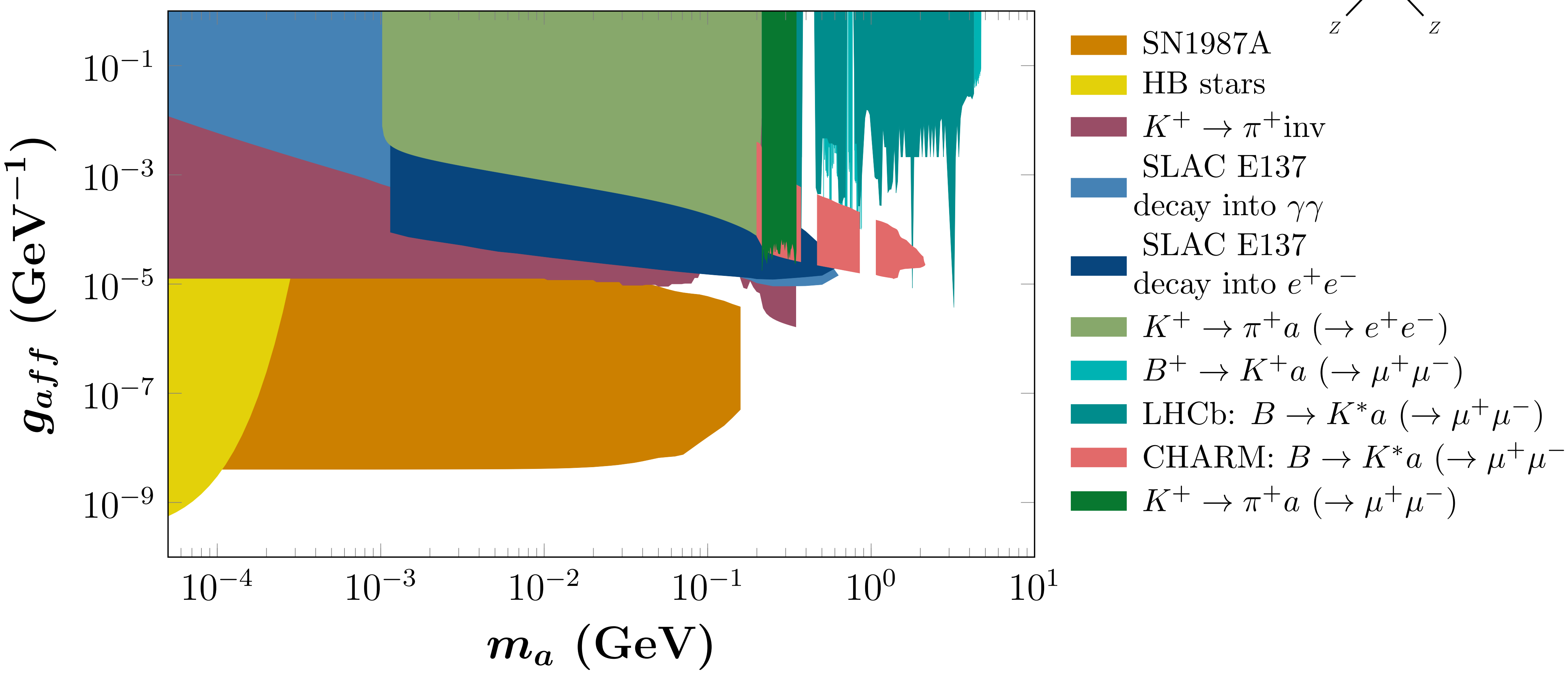
Constraints on our ALP

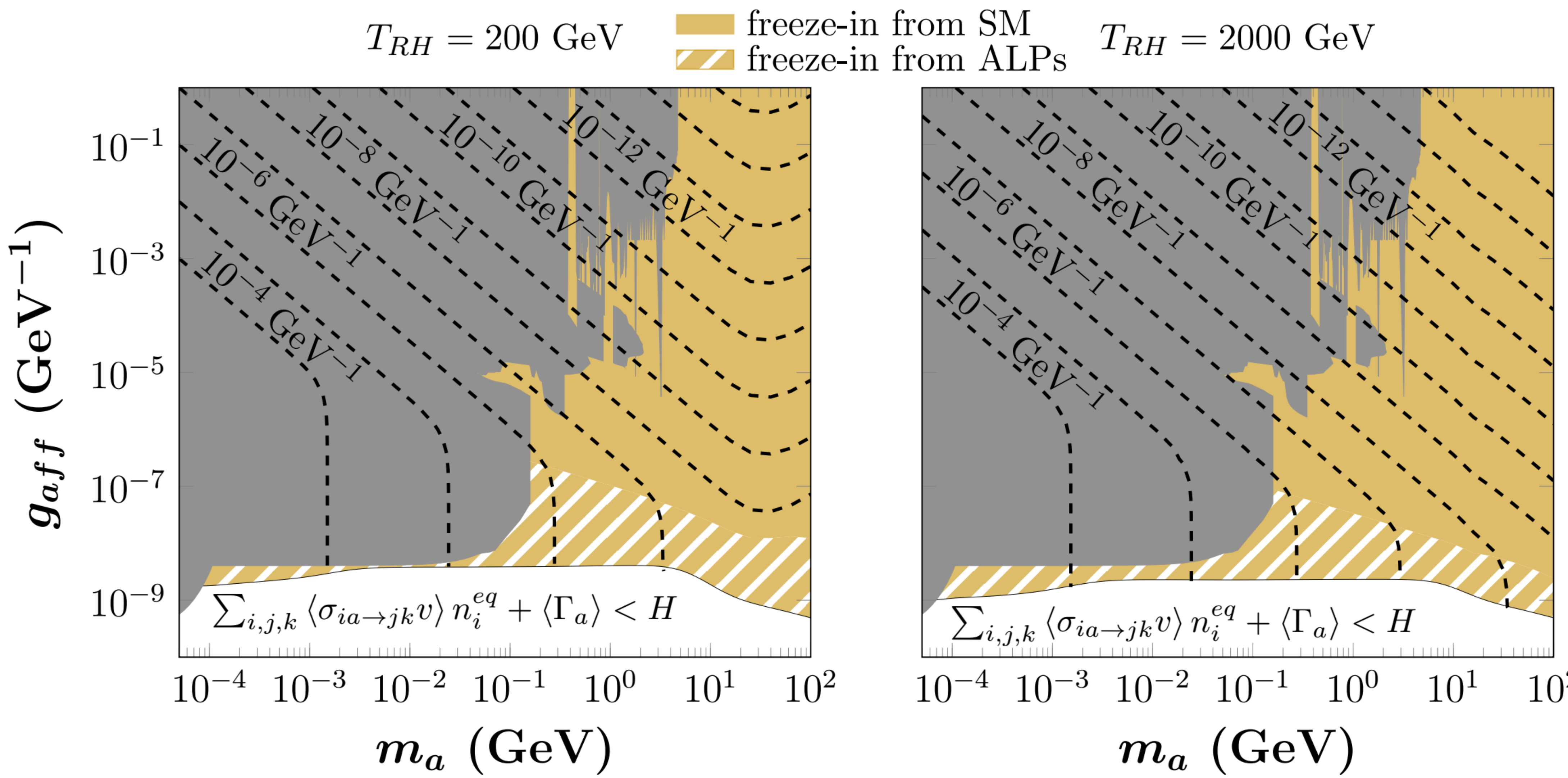


New constraints including fermion loops, e.g.

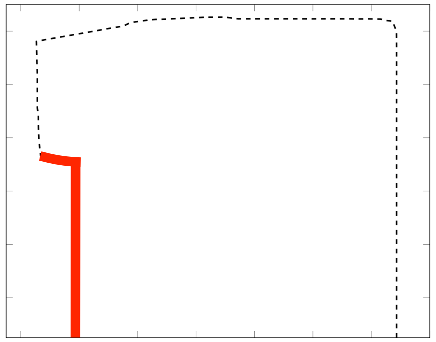


- Revisit constraints from electron beam dumps, rare B and K decays, astrophysics, dark matter searches and cosmology.
- In particular, for our specific ALP scenario we (re)calculate and improve beam dump, flavour and supernova constraints.

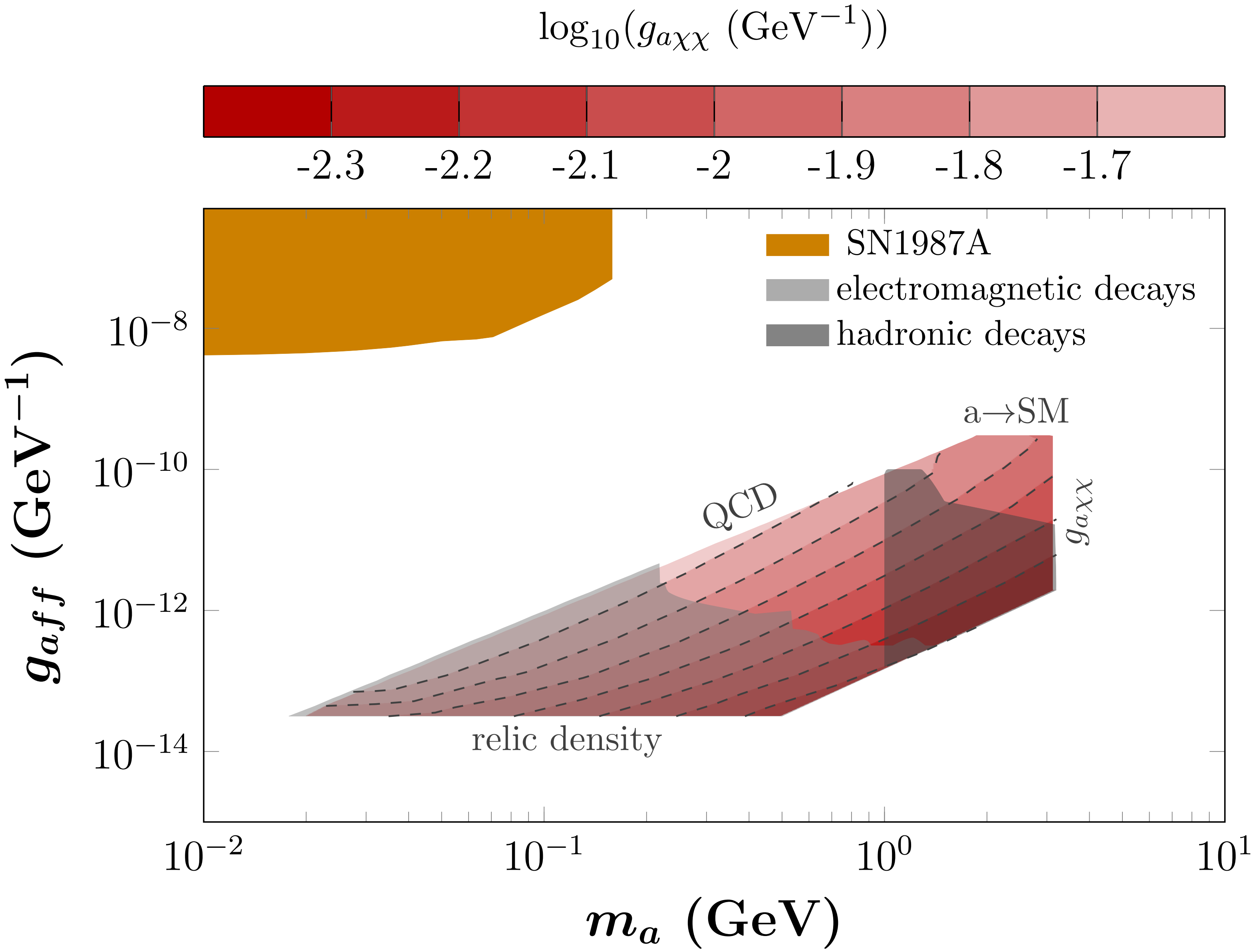
Freeze-in vs. constraints on our ALP ($m_\chi / m_a = 10$)

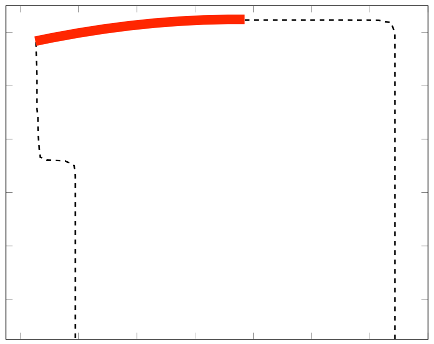


dashed lines: lines of constant $g_{a\chi\chi}$ which reproduce the observed DM relic density



DFO vs. constraints on our ALP ($m_\chi/m_a = 10$)

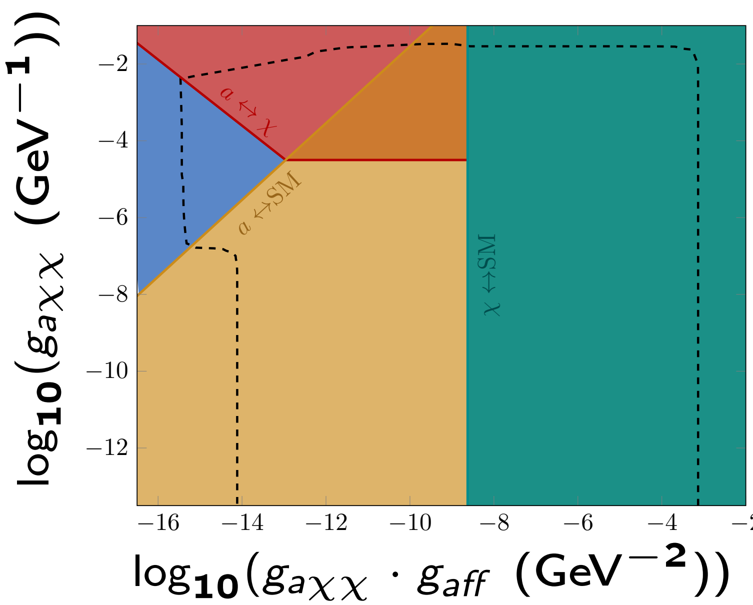




- Tiny g_{aff} ⇒ ALP relatively long lived ⇒ consequences for BBN
- For $m_a \lesssim 2m_\mu$ constraints are very similar, see [Kawasaki et al '20] for very long-lived ALPs with sub-GeV m_a excluding $\tau_a \sim 10^3 - 10^5$ s
- For $2m_\mu \lesssim m_a \lesssim 1$ GeV, EM bounds probably apply too, lifetimes not excluded.
- For hadronic decays $\tau_a \sim 0.1$ s can be excluded, see [Kawasaki et al '17]

Conclusion

What we have done



- Our simple framework of an axion-like particle mediating DM leads to various alternative DM genesis scenarios
- Performed a detailed numerical calculation of full region of parameter space giving the correct relic density in various regimes, in particular DFO regime non-trivial
- Brand-new calculation of constraints (normally constraints for ALPs for photon coupling) to verify if these regions of parameter space are allowed

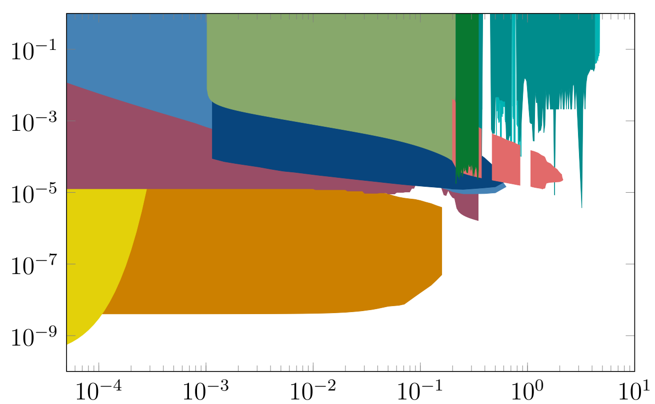
Future work

- Improve accuracy, in particular in sequential freeze-in region, by solving unintegrated Boltzmann equation
- Assess the potential sensitivity of future experiments to the region of interest

$$E\left(\partial_t - Hp\partial_p\right) f = C\left[f\right]$$

Conclusion

What we have done



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Future work

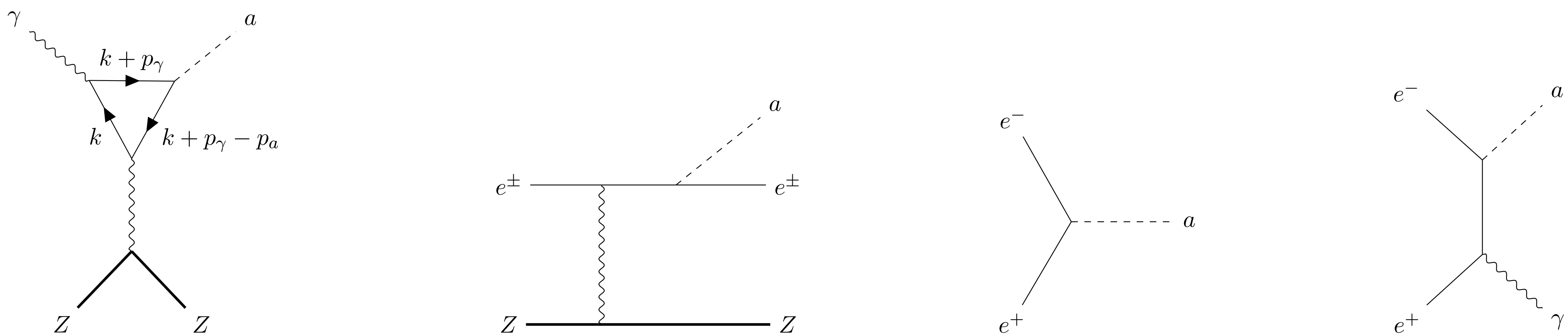
$$E\left(\partial_t - Hp\partial_p\right) f = C\left[f\right]$$

Exciting time for axions! We look forward to seeing the impact of future experimental results on our model!

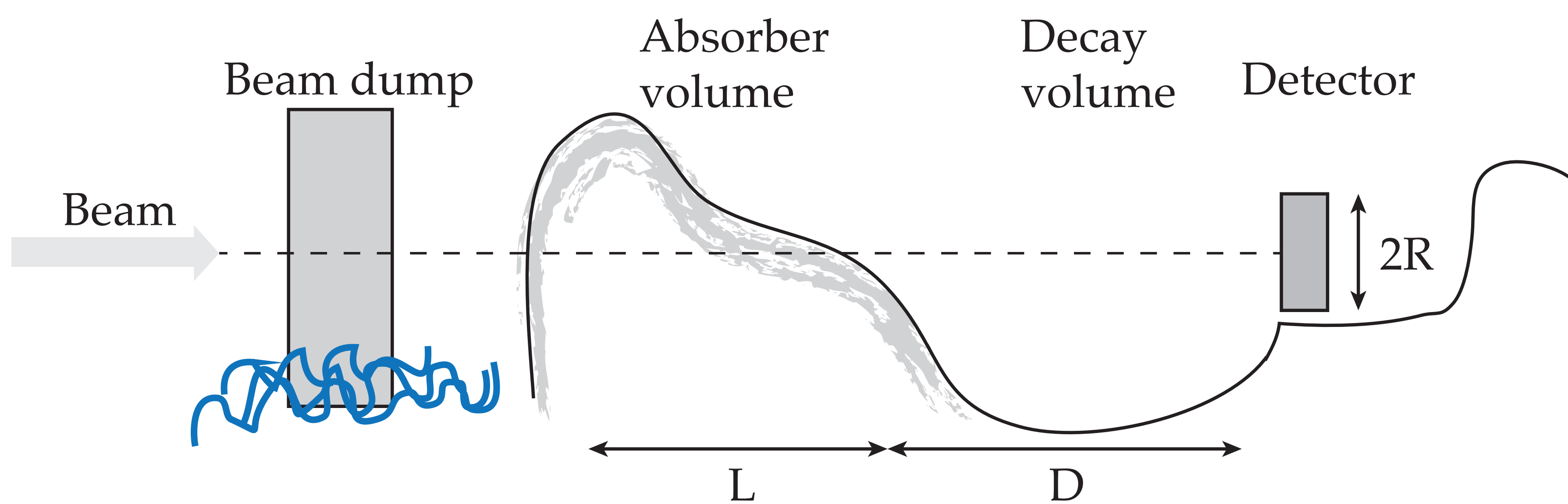
Backup Slides

Electron Beam Dump Constraint

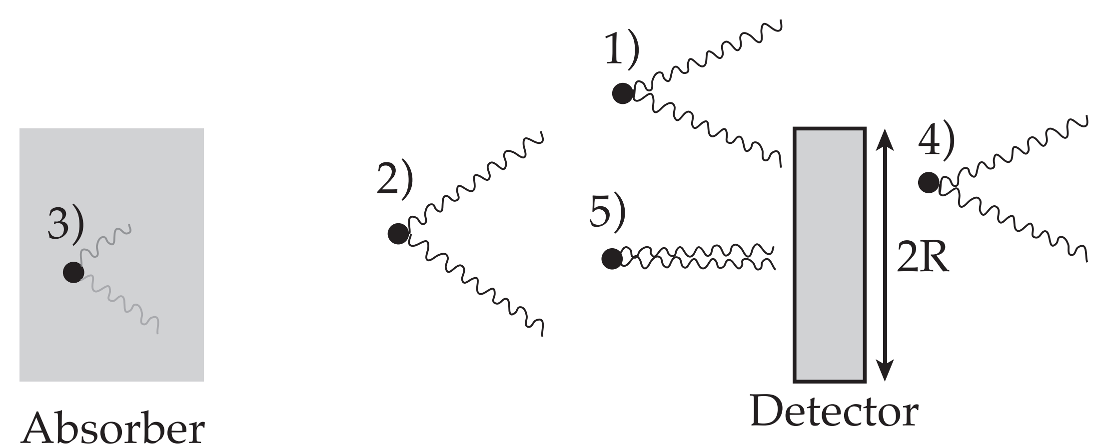
SLAC E137 Experiment: 20 GeV Electrons bumped



Fold **detector geometry**

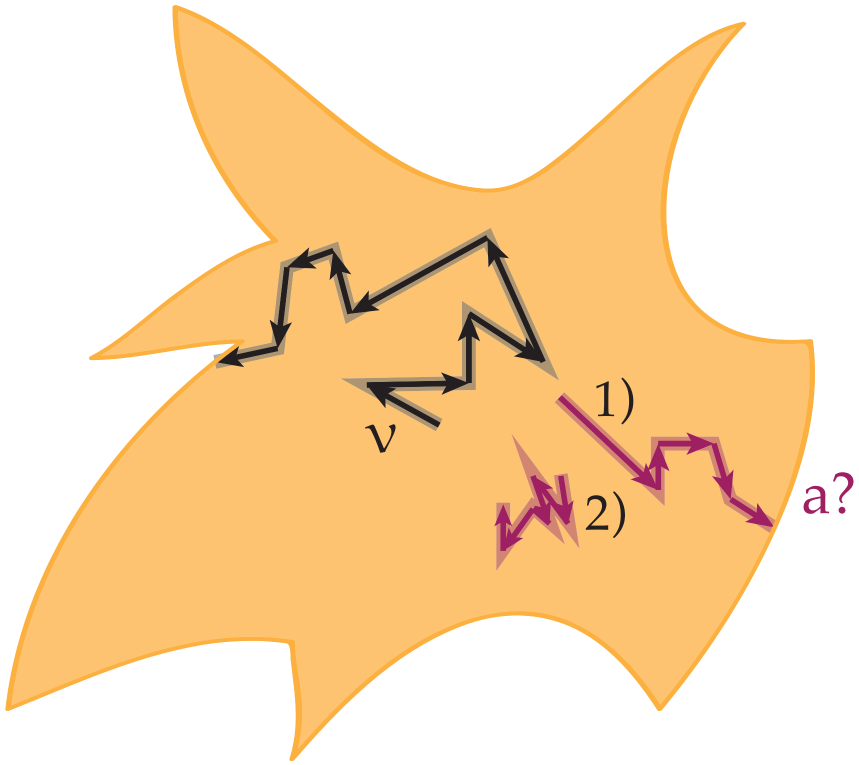


with **ALP decay probability**



Astrophysical Constraints

ALPs inside stars



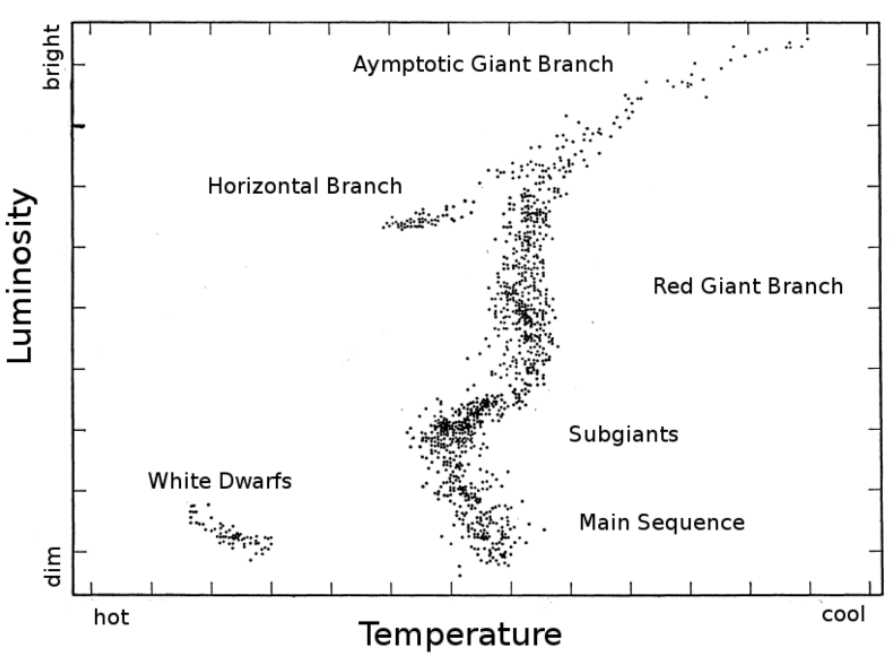
1) Energy Loss

Very weakly interacting ALP would stream out freely of the hot core and accelerate the cooling of the star

2) Radiative Energy Transfer

For larger couplings ALPs will be trapped inside the star and radiate energy

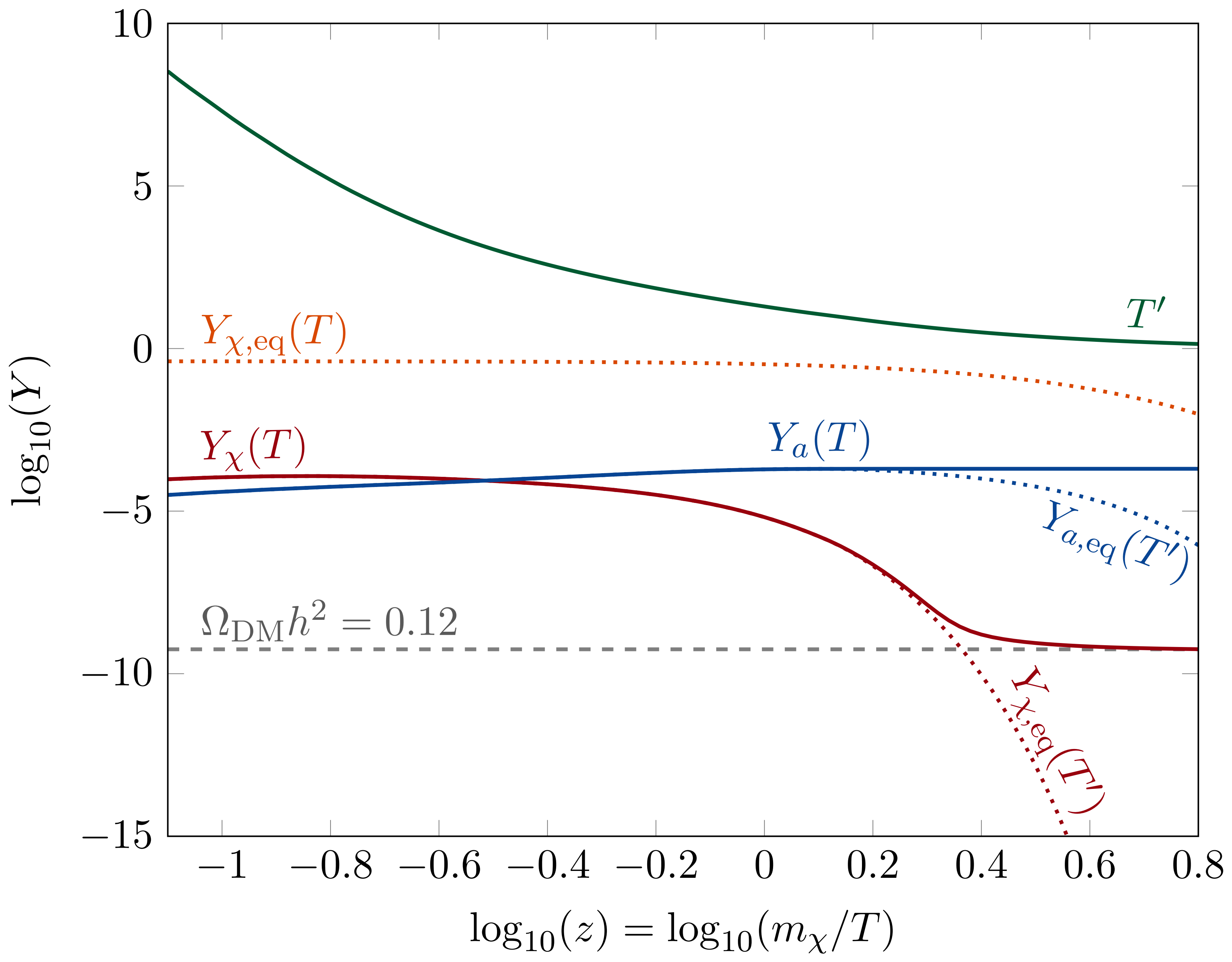
Horizontal Branch Stars



$R = N_{HB}/N_{RG}$ well described $\Rightarrow L_a \lesssim L_{3\alpha}$

Energy emitted per unit mass and time $\langle \epsilon_a \rangle \lesssim \langle \epsilon_{3\alpha} \rangle = 100\,\mathrm{g}^{-1}\,\mathrm{erg}\,\mathrm{s}^{-1}$

FODDS - numerical solution

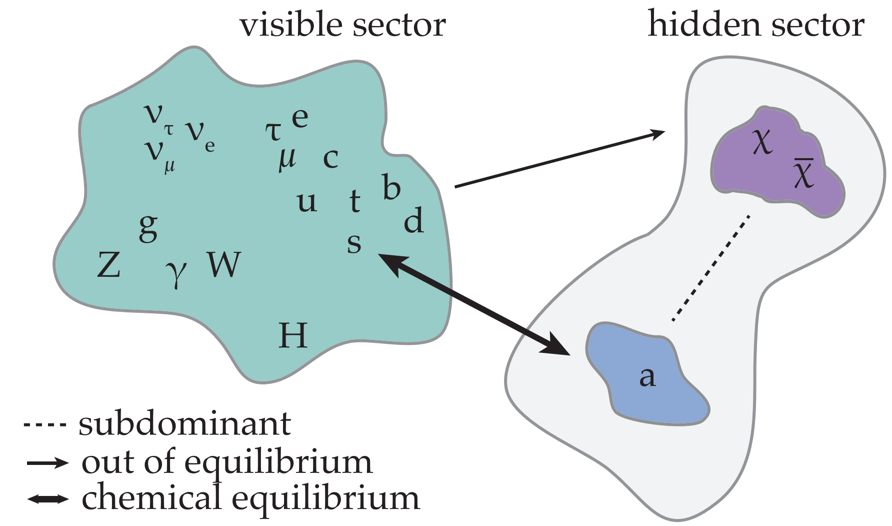


for $m_\chi = 10$, $m_a = 1$ GeV, $g_{a\chi\chi} = 1.3 \cdot 10^{-2}$ GeV^{-1}, $g_{aff} = 10^{-13}$ GeV^{-1}

Freeze-in …

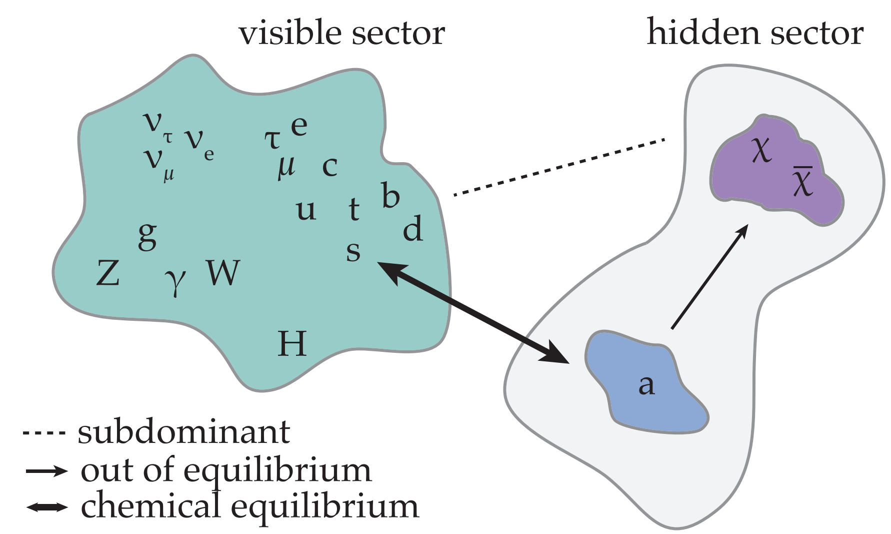
… from SM particles

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_f \langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v\rangle \left(n_\chi^{\mathbf{eq2}} - \underbrace{\cancel{n_\chi^2}}_{n_\chi \ll n_\chi^{\mathrm{eq}}}\right) + \underbrace{\cancel{\langle \sigma_{\chi\bar{\chi}\to aa} v\rangle}}_{\propto g_{a\chi\chi}^{\mathbf{4}}} \left(n_\chi^{\mathbf{eq2}} - n_\chi^2\right)$$



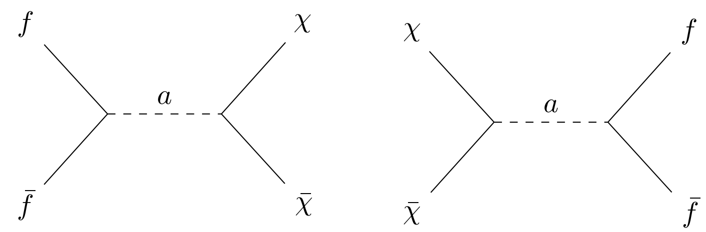
… from the mediator

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \underbrace{\cancel{\sum_f \langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v\rangle}}_{\propto (g_{aff}\, g_{a\chi\chi})^{\mathbf{2}}} \left(n_\chi^{\mathbf{eq2}} - n_\chi^2\right) + \langle \sigma_{\chi\bar{\chi}\to aa} v\rangle \left(n_\chi^{\mathbf{eq2}} - \underbrace{\cancel{n_\chi^2}}_{n_\chi \ll n_\chi^{\mathbf{eq}}}\right)$$



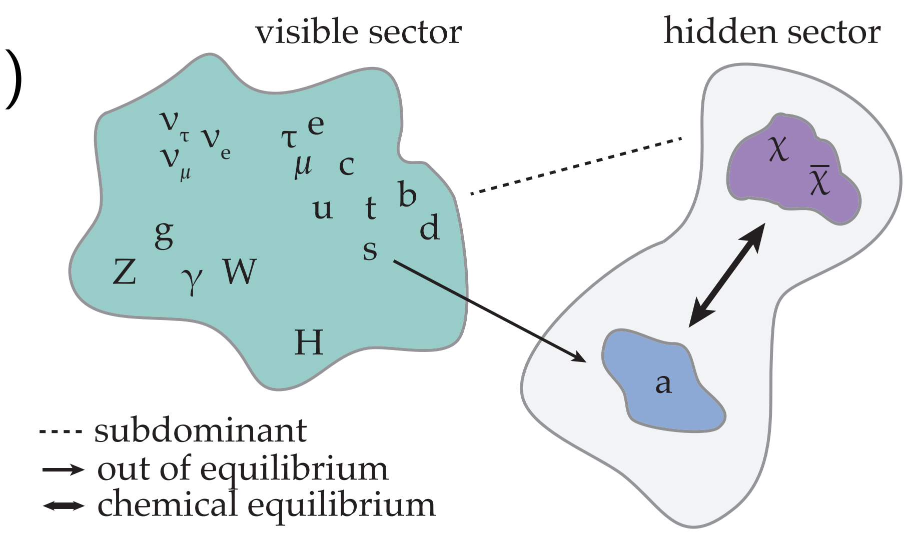
$$Y_0 = \int_0^\infty \frac{\langle \sigma_{\mathbf{connector}} v\rangle\, n_\chi^{\mathbf{eq2}}}{sHT}\, \mathrm{d}T$$

Decoupled freeze-out region



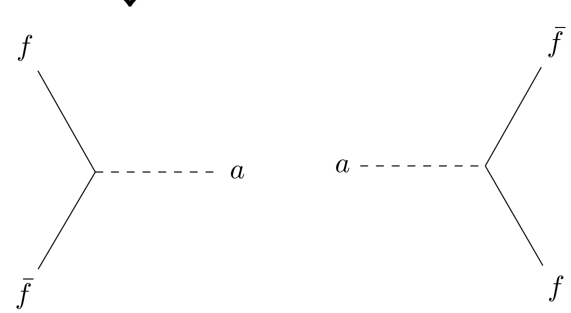
$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t}+3Hn_\chi=\sum_f\left\langle\sigma_{\chi\bar\chi\to f\bar f}v\right\rangle\left(\overbrace{\left(n_\chi^{\mathrm{eq}}(T)\right)^2}-\overbrace{n_\chi^2}\right)$$

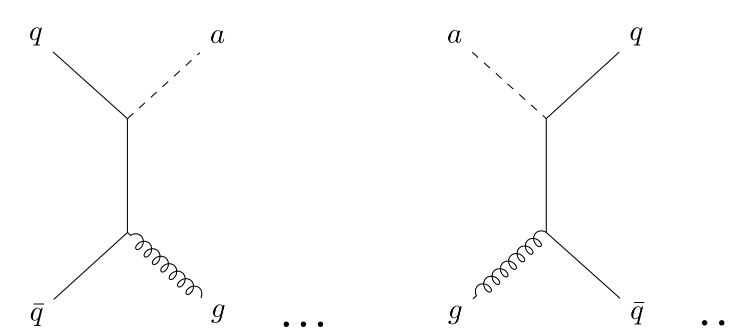
$$+\underbrace{\langle\sigma_{aa\to\chi\bar\chi}v\rangle\,(T')n_a^2}-\underbrace{\langle\sigma_{\chi\bar\chi\to aa}v\rangle\,(T')n_\chi^2}$$



$$\frac{\mathrm{d}n_a}{\mathrm{d}t}+3Hn_a=-\overbrace{\langle\sigma_{aa\to\chi\bar\chi}v\rangle\,(T')n_a^2}+\overbrace{\langle\sigma_{\chi\bar\chi\to aa}v\rangle\,(T')n_\chi^2}$$

$$+\langle\Gamma_a\rangle\left(\underbrace{n_a^{\mathrm{eq}}(T)}-\underbrace{n_a}\right)+\sum_{i,j,k}\left\langle\sigma_{ai\to jk}v\right\rangle\left(\underbrace{n_a^{\mathrm{eq}}(T)n_i^{\mathrm{eq}}(T)}-\underbrace{n_a n_i^{\mathrm{eq}}(T)}\right)$$





[Chu, Hambye, Tytgat. JCAP, 2012], [Hambye, Tytgat, Vandecasteele, Vanderheyden. Phys. Rev. D, 2019], [Bélanger, Delaunay, Pukhov, Zaldivar. Phys. Rev. D, 2020]