Axion-like Particles as Mediators for Dark Matter: Beyond Freeze-out

In collaboration with Aoife Bharucha, Felix Brümmer and Nishita Desai

Sophie Mutzel

Centre de Physique Théorique Marseille

International School of Subnuclear Physics
58th Course: Gravity and Matter in the Subnuclear World
Erice, June 15-24, 2022

Introduction

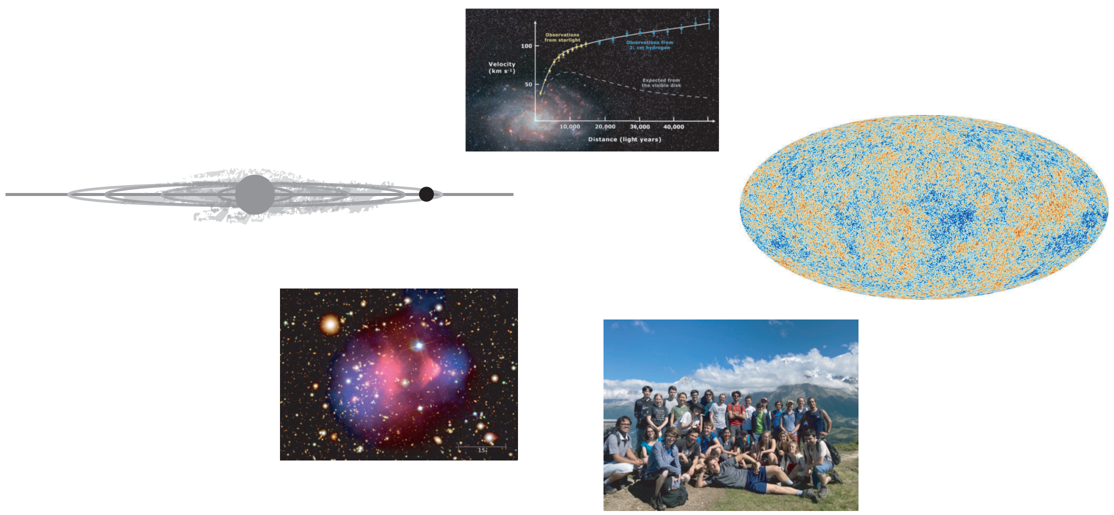
*Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass **dunkle Materie** in sehr viel größerer Dichte vorhanden ist als leuchtende Materie.*

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

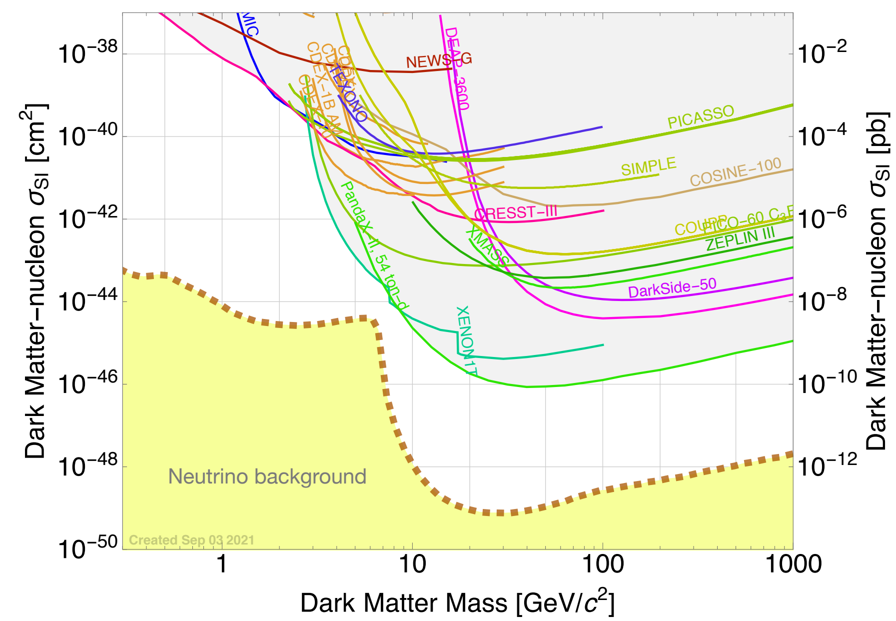
Zwicky 1933

Introduction

Gravitational evidence for Dark Matter (DM)

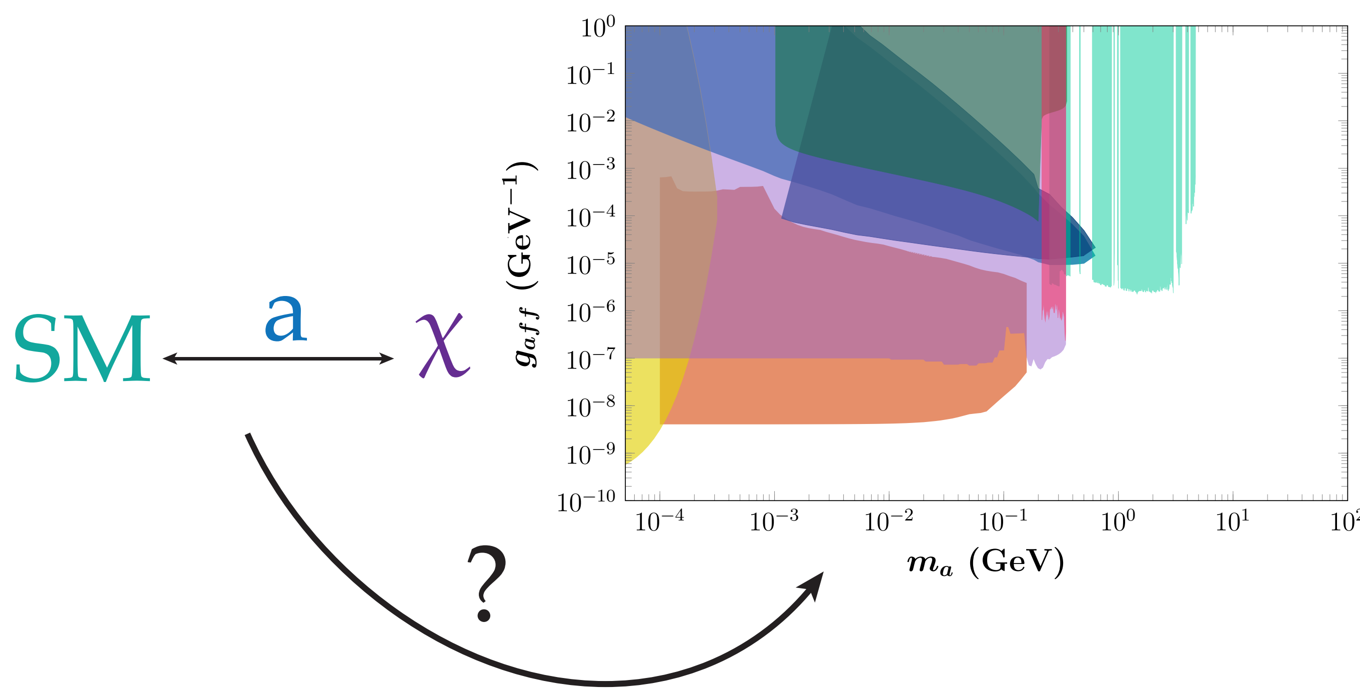


Freeze-out and WIMPs require large couplings



[1]

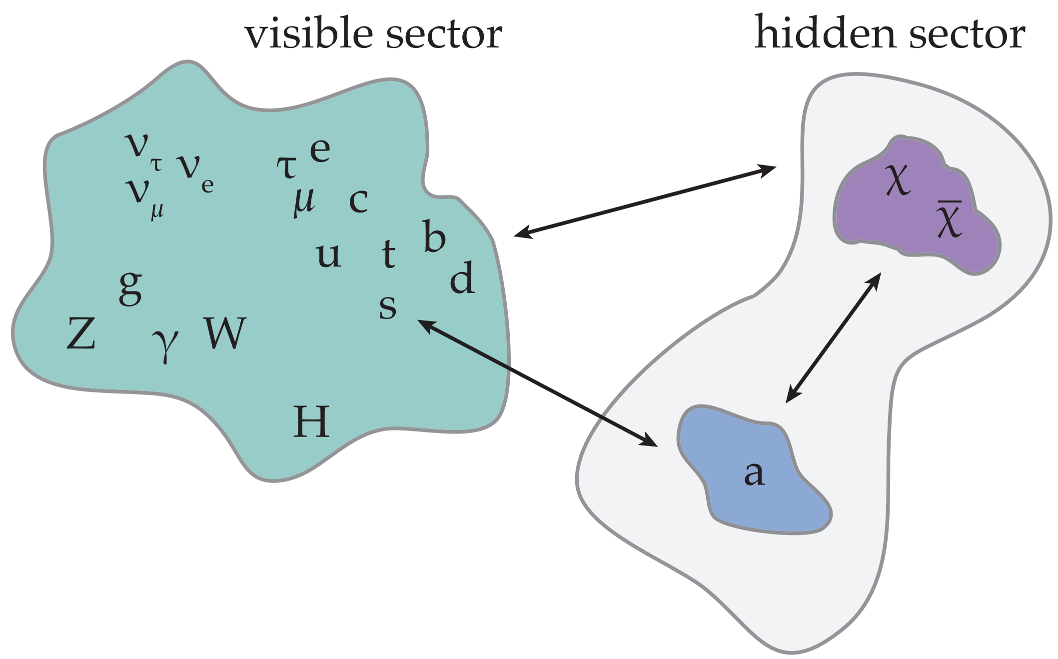
Look at different scenarios & explore parameter space



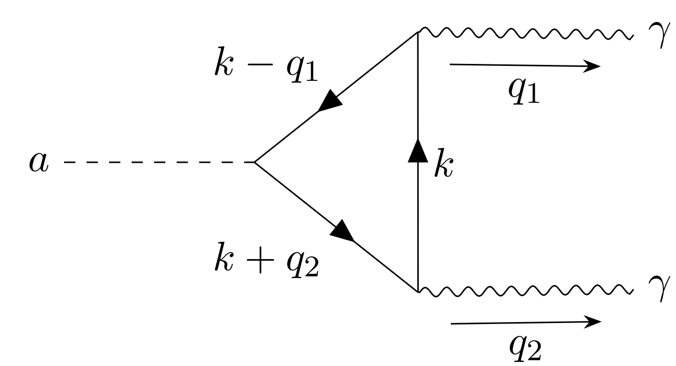
[1] figure created using https://supercdms.slac.stanford.edu/dark-matter-limit-plotter

The Model

Axion-like particle (a) mediator between the SM fermions (f) and the DM (χ), a Dirac fermion



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



Lagrangian:

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

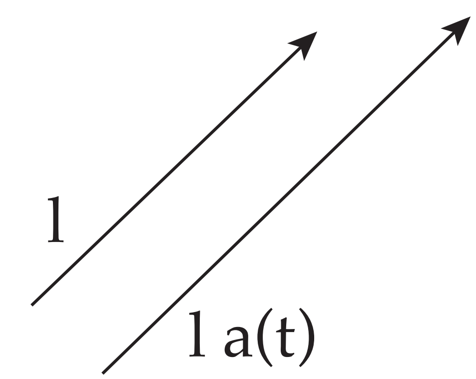
$g_{a\chi\chi} \equiv C_\chi / f_a$ (hidden sector coupling), $g_{aff} \equiv C_f / f_a$ (connector coupling)

Boltzmann equation - general

Consider a system without collisions (free particles): $\frac{\partial N}{\partial t} = 0 \qquad N = nV$

$$\frac{\partial (nV)}{\partial t} = V\frac{\partial n}{\partial t} + n\frac{\partial V}{\partial t} = 0$$

In an expanding universe $V \propto a^3$ and thus $\frac{1}{V}\frac{\partial V}{\partial t} = \frac{3}{a}\frac{\partial a}{\partial t}$

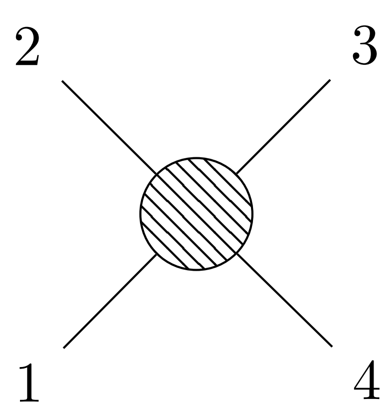


$$\frac{\partial n}{\partial t} + 3n\underbrace{\left(\frac{\dot{a}}{a}\right)}_{H} = 0$$

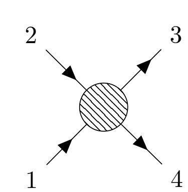
H is the Hubble function characterizing the rate of expansion of the universe

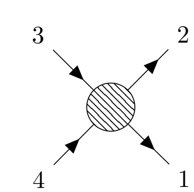
$$\boxed{\frac{\partial n}{\partial t} + 3nH = -C[n]}$$

$C[n]$ collision term



Introduce thermally averaged cross section $\langle \sigma_{12\to 34} v \rangle$



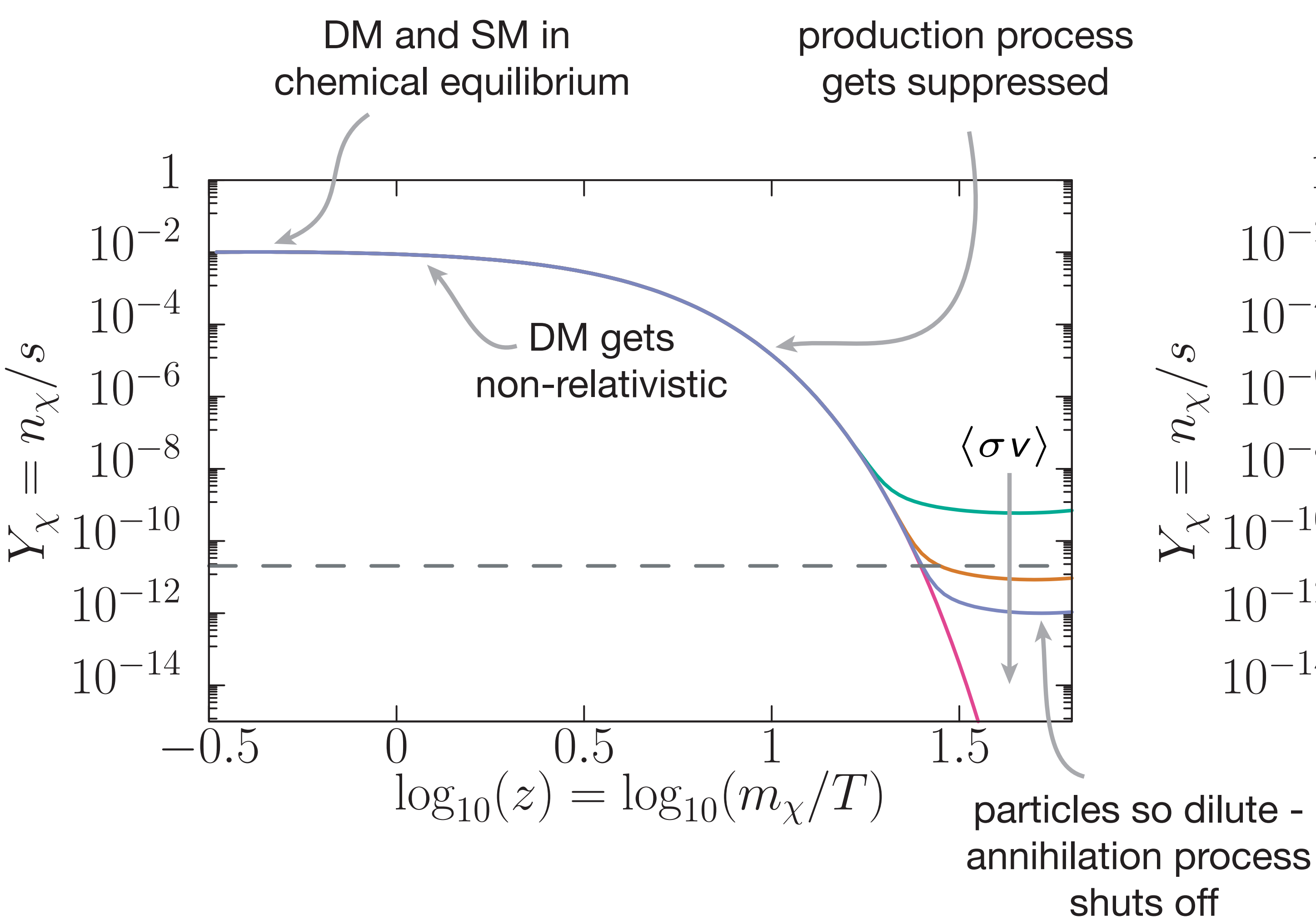


$$C[n_1] = \overbrace{\langle \sigma_{12\to 34} v \rangle\, n_1 n_2} - \overbrace{\langle \sigma_{34\to 12} v \rangle\, n_3 n_4}$$

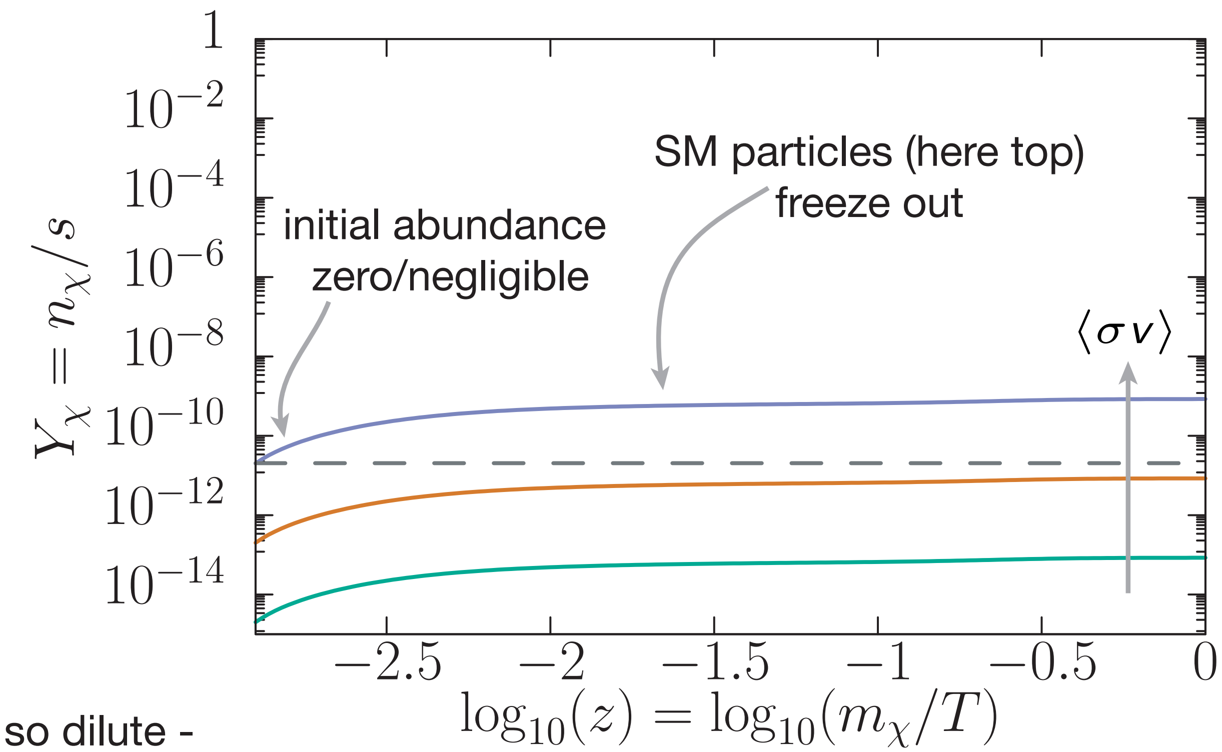
Alternative DM Genesis Scenarios

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

Freeze-out

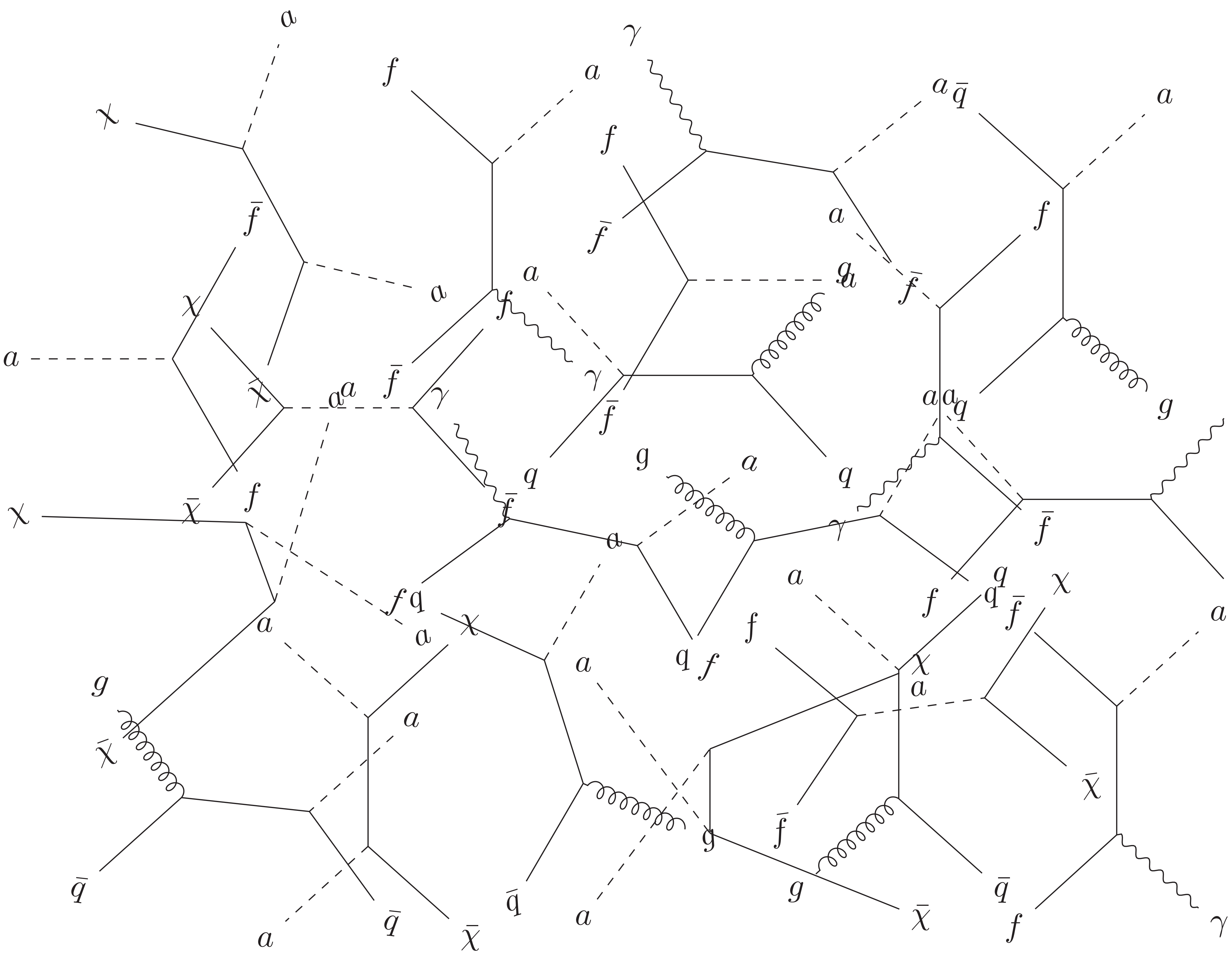


Freeze-in

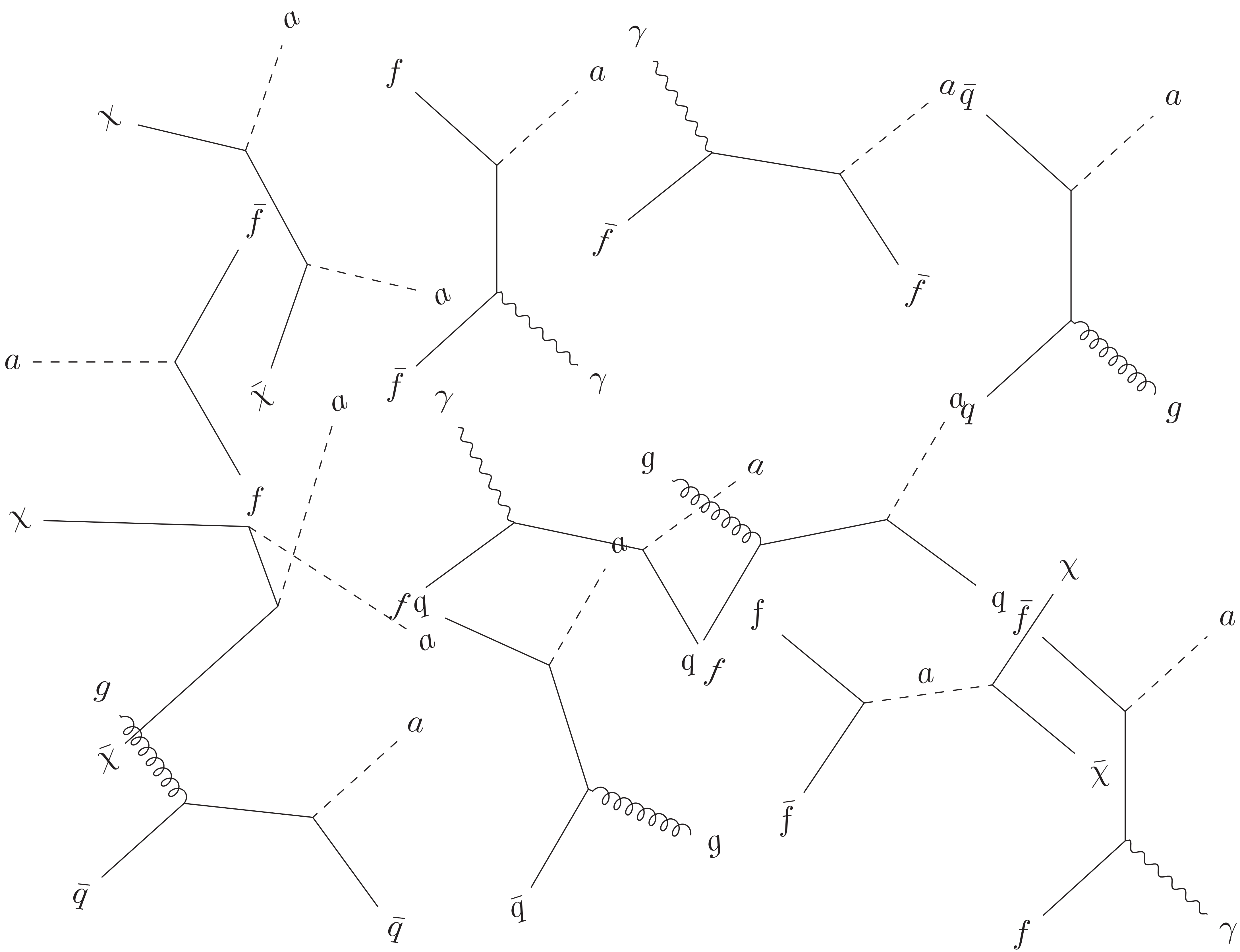


Unfortunately things not so simple! ALP also has a say...

DM and ALP number changing interactions

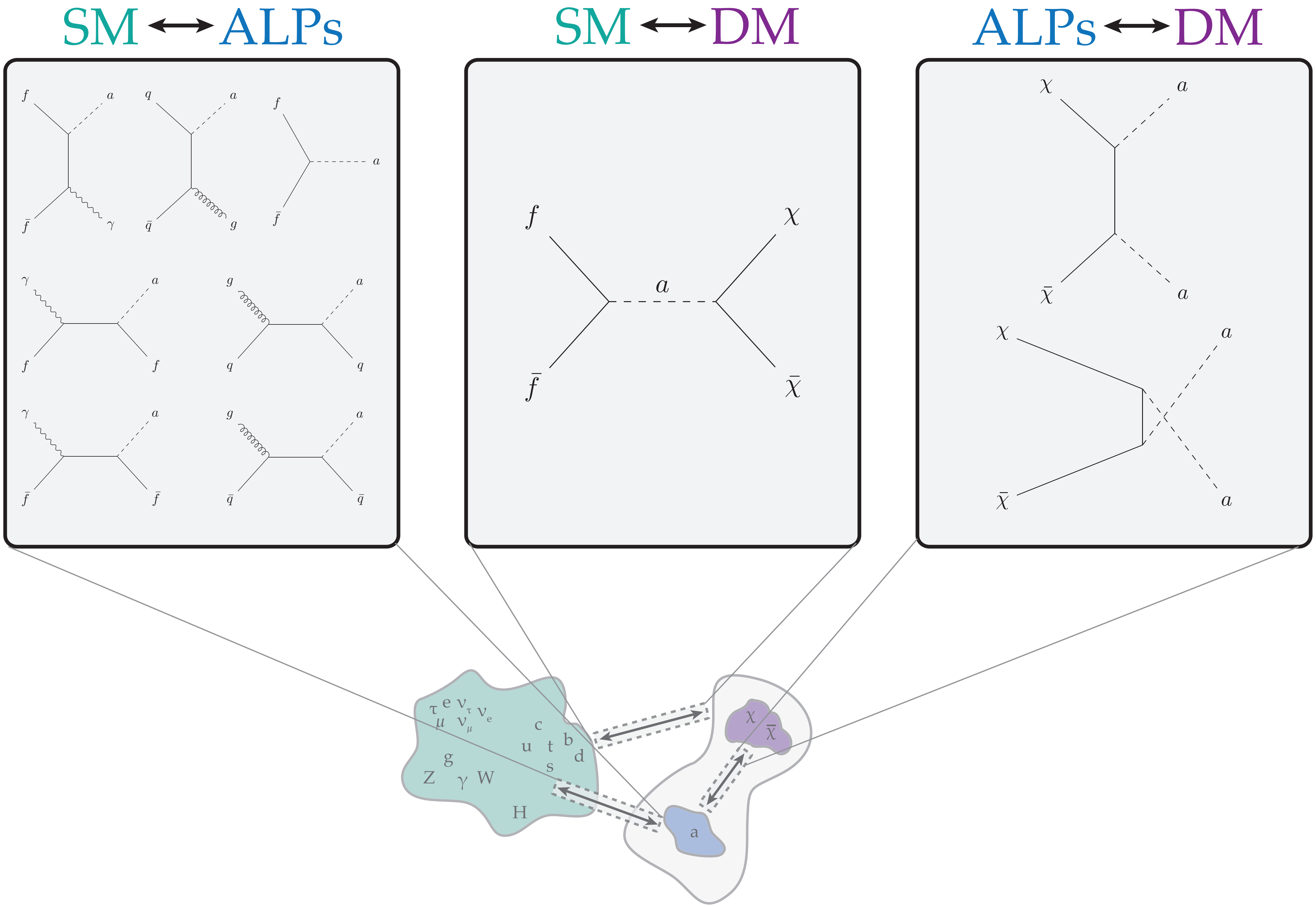


DM and ALP number changing interactions

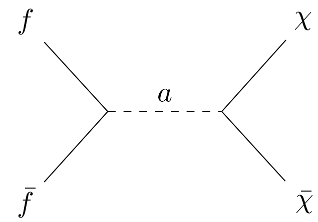


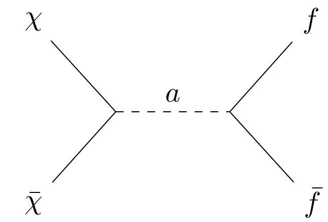
DM and ALP number changing interactions

$\propto g_{aff}^2$ $\propto (g_{aff}\, g_{a\chi\chi})^2$ $\propto g_{a\chi\chi}^4$



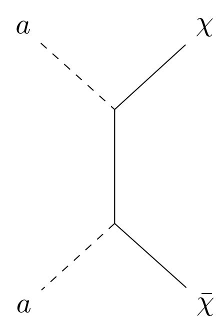
Coupled Boltzmann equations

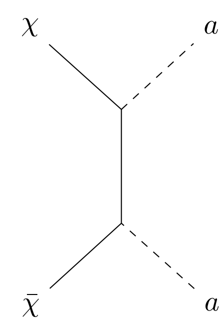




$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t}+3Hn_\chi=\sum_f\left\langle\sigma_{\chi\bar\chi\to f\bar f}v\right\rangle\Big(\overbrace{\left(n_\chi^{\mathrm{eq}}(T)\right)^2}-\overbrace{n_\chi^2}\Big)$$

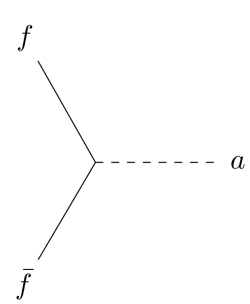
$$+\underbrace{\langle\sigma_{aa\to\chi\bar\chi}v\rangle\, n_a^2}-\underbrace{\langle\sigma_{\chi\bar\chi\to aa}v\rangle\, n_\chi^2}$$

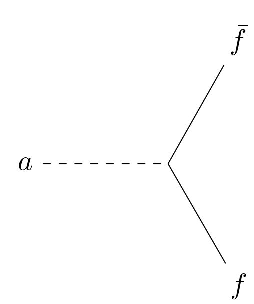


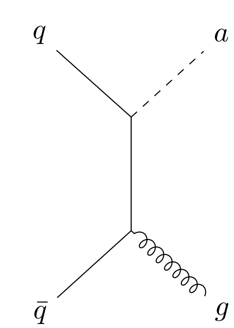


$$\frac{\mathrm{d}n_a}{\mathrm{d}t}+3Hn_a=-\overbrace{\langle\sigma_{aa\to\chi\bar\chi}v\rangle\, n_a^2}+\overbrace{\langle\sigma_{\chi\bar\chi\to aa}v\rangle\, n_\chi^2}$$

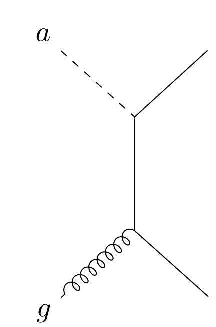
$$+\langle\Gamma_a\rangle\Big(\underbrace{n_a^{\mathrm{eq}}(T)}-\underbrace{n_a}\Big)+\sum_{i,j,k}\left\langle\sigma_{ai\to jk}v\right\rangle\Big(\underbrace{n_a^{\mathrm{eq}}(T)n_i^{\mathrm{eq}}(T)}-\underbrace{n_a n_i^{\mathrm{eq}}(T)}\Big)$$





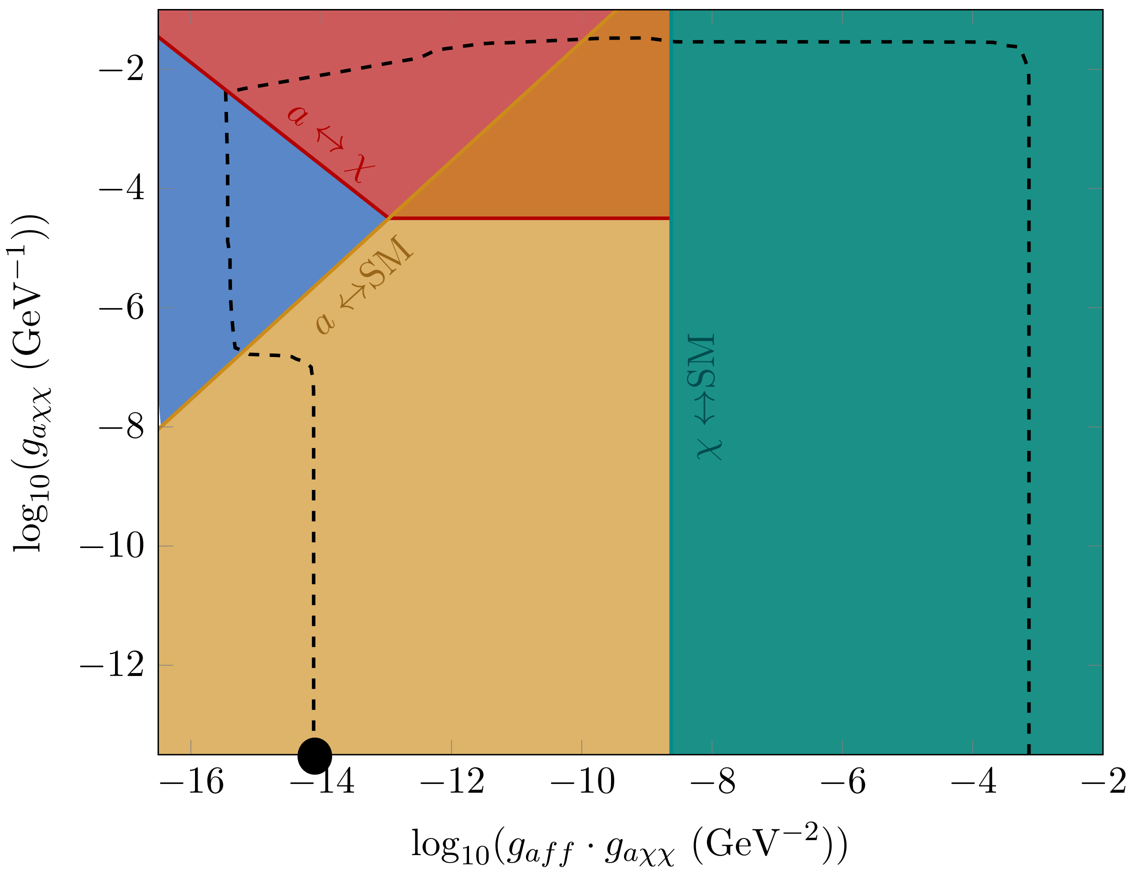


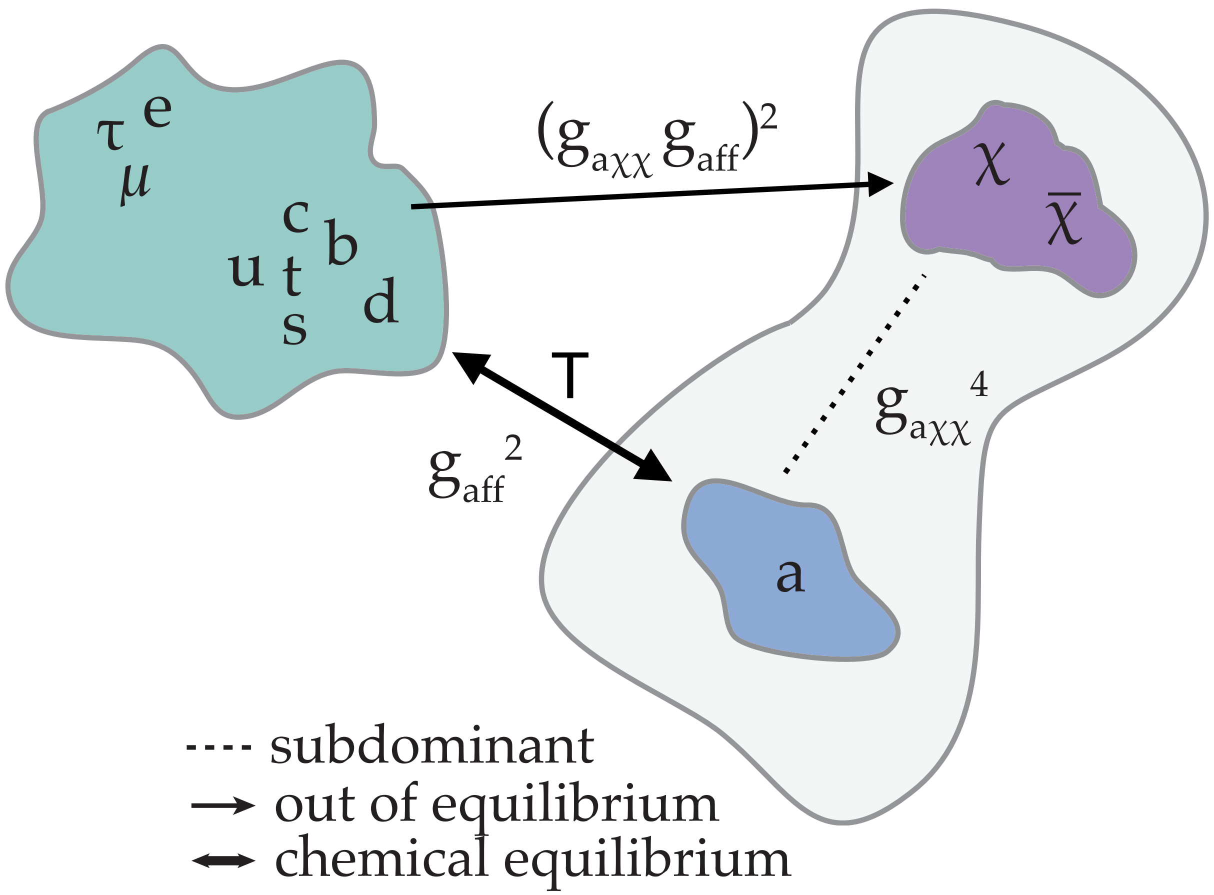
...



...

Freeze-in from SM

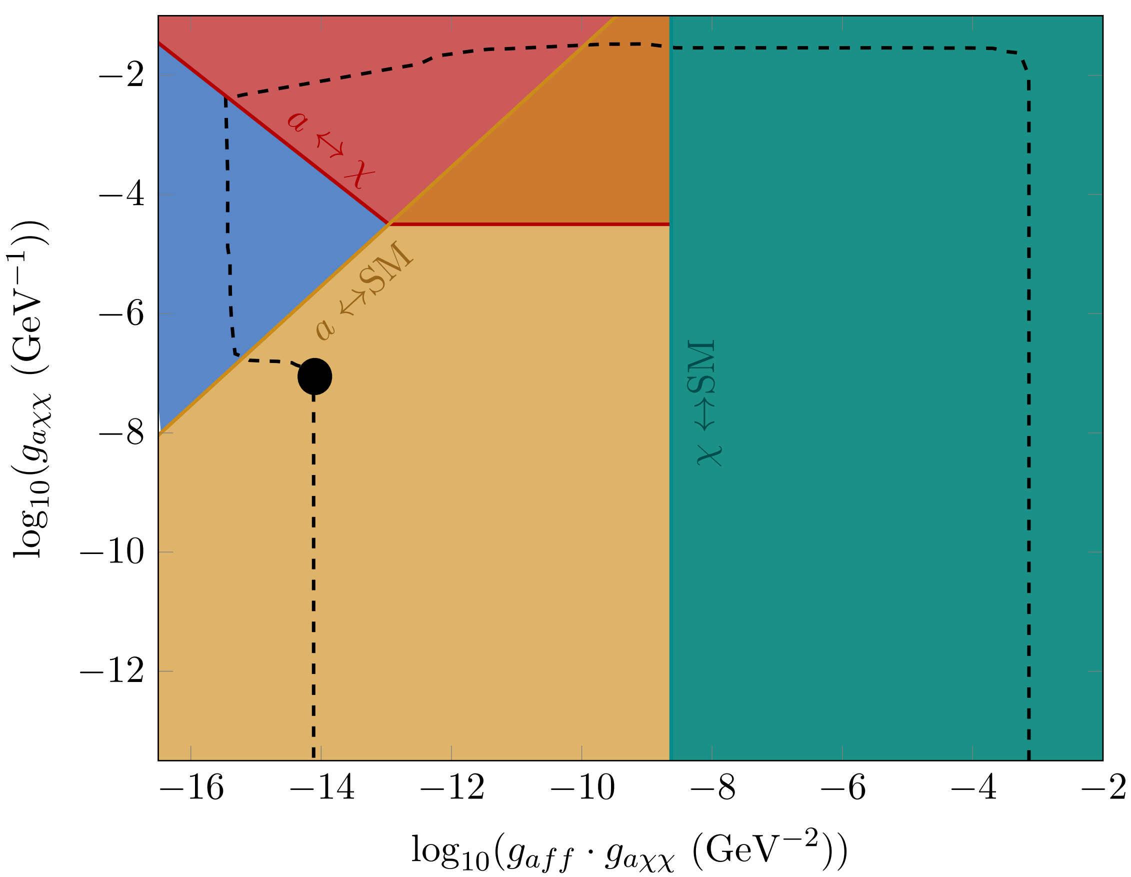


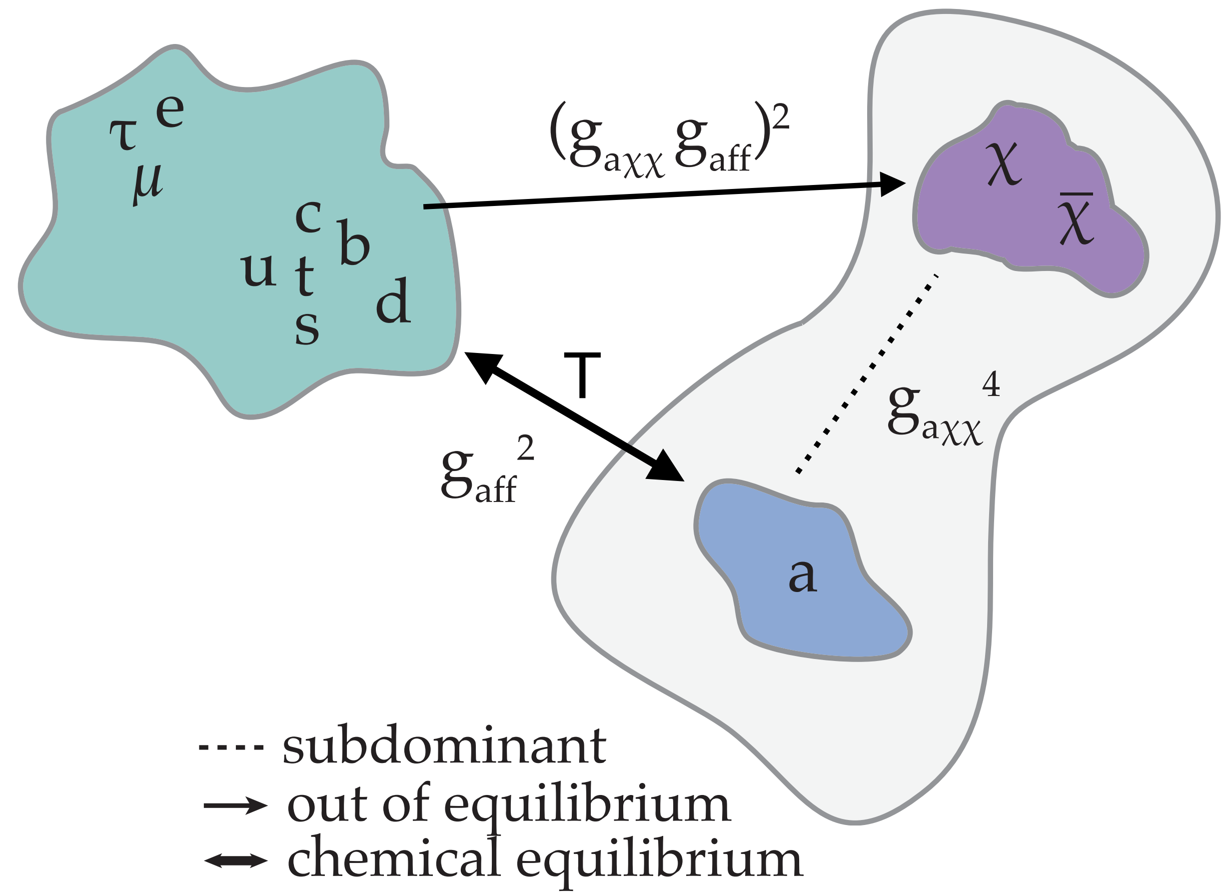


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-in from SM

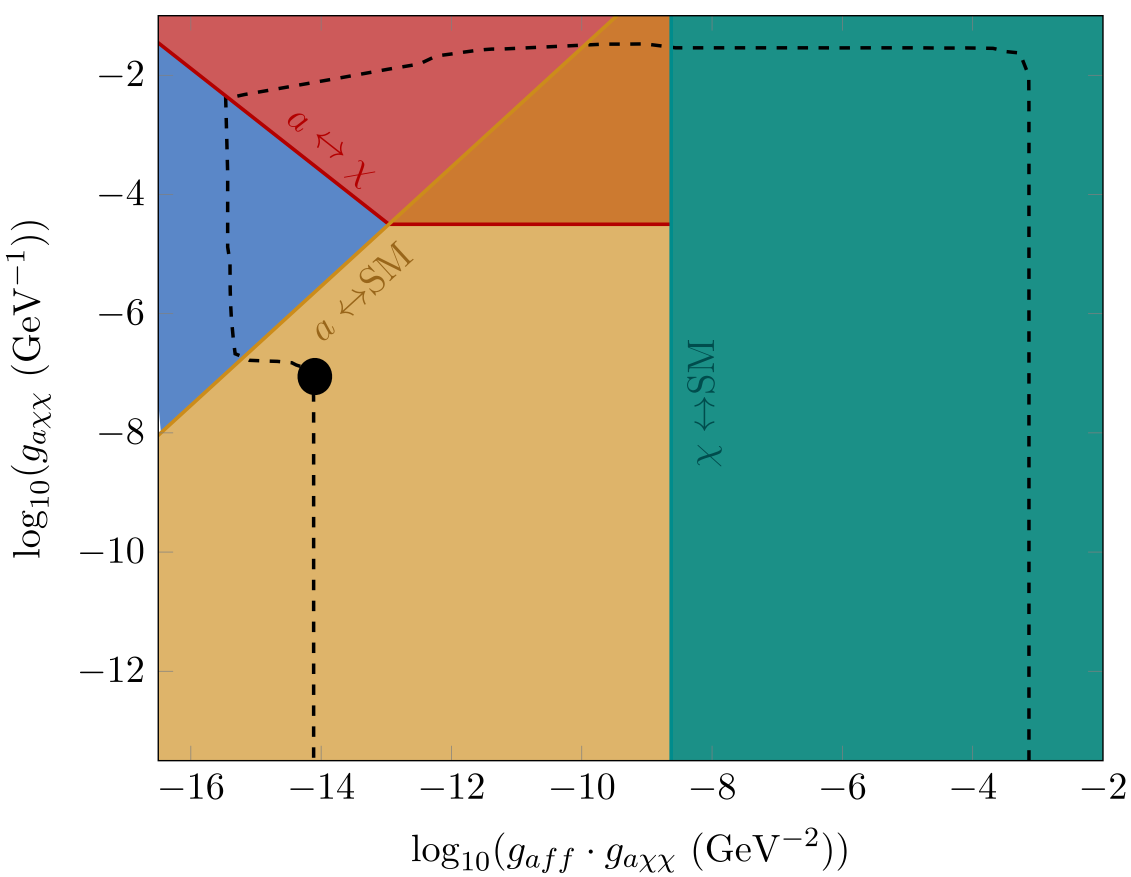


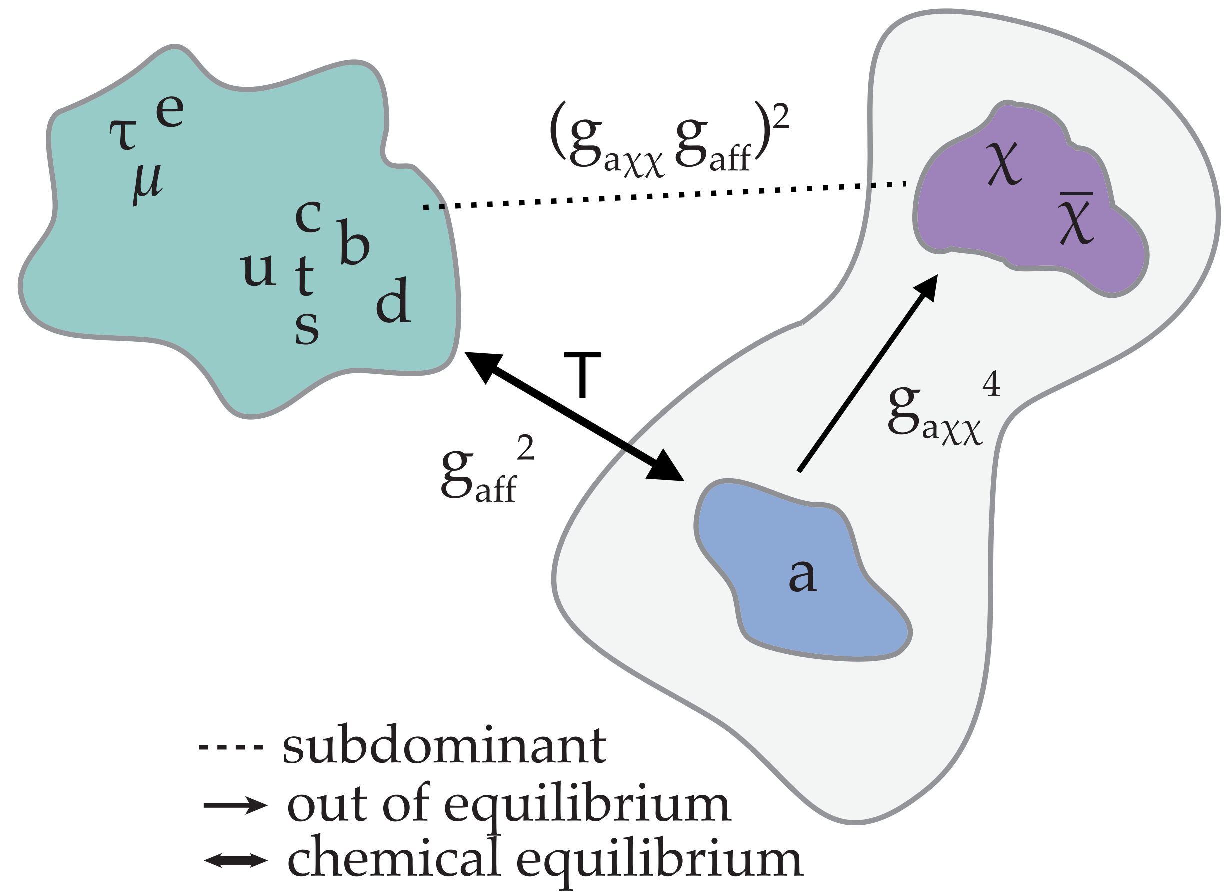


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-in from the mediator

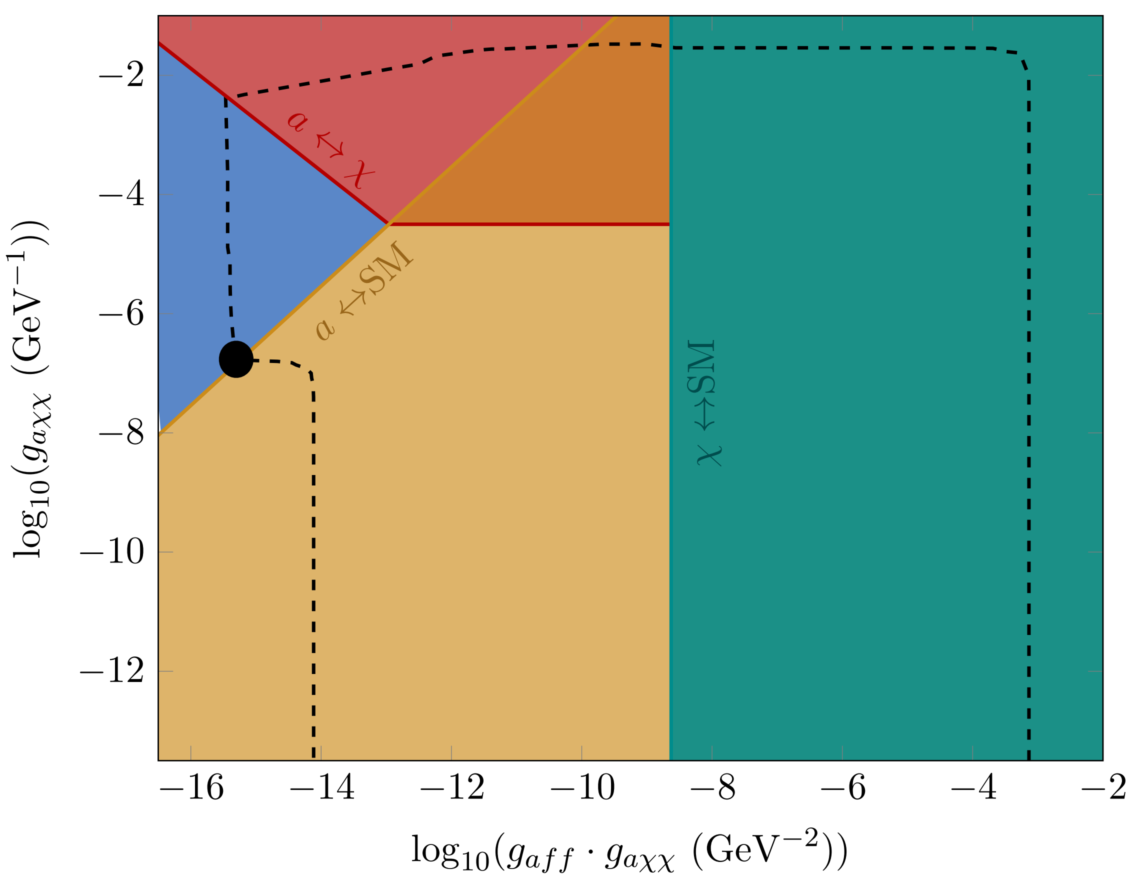


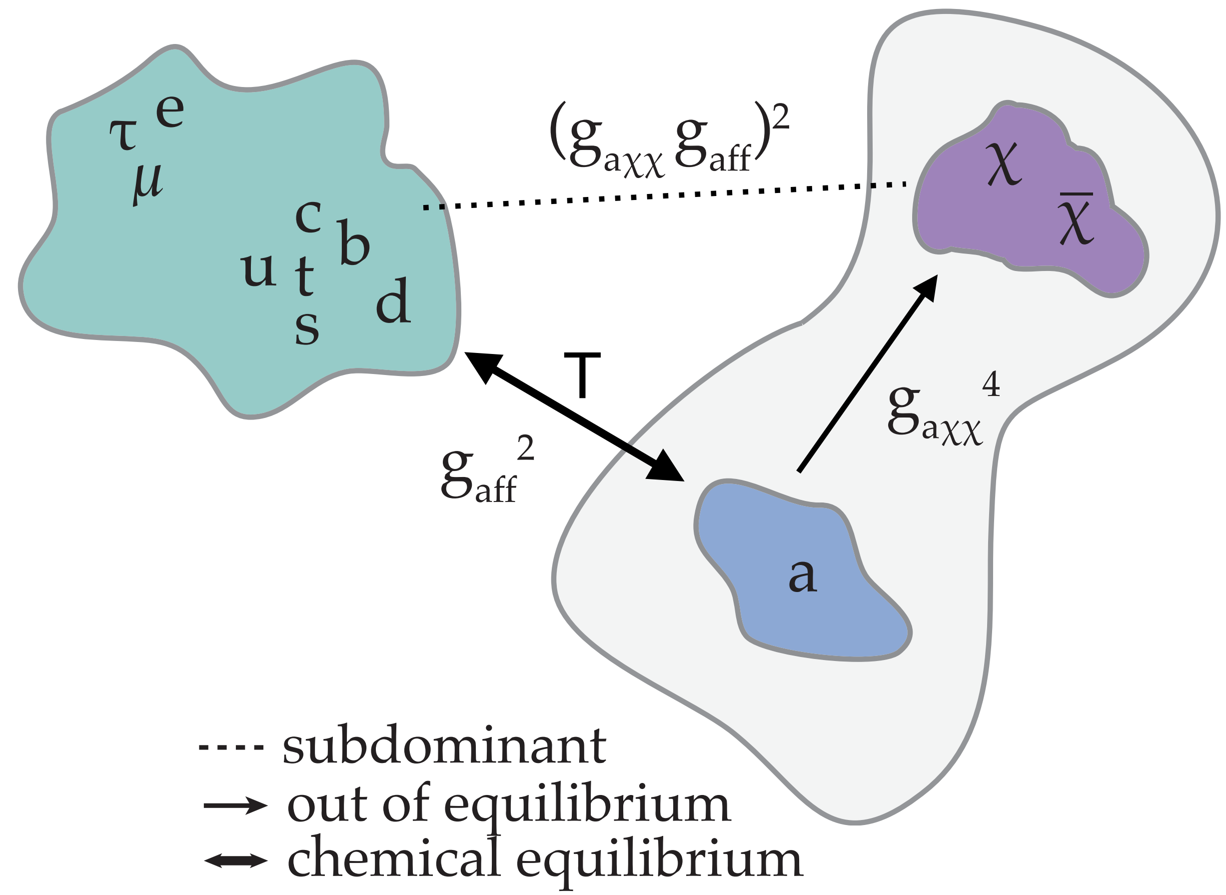


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-in from the mediator

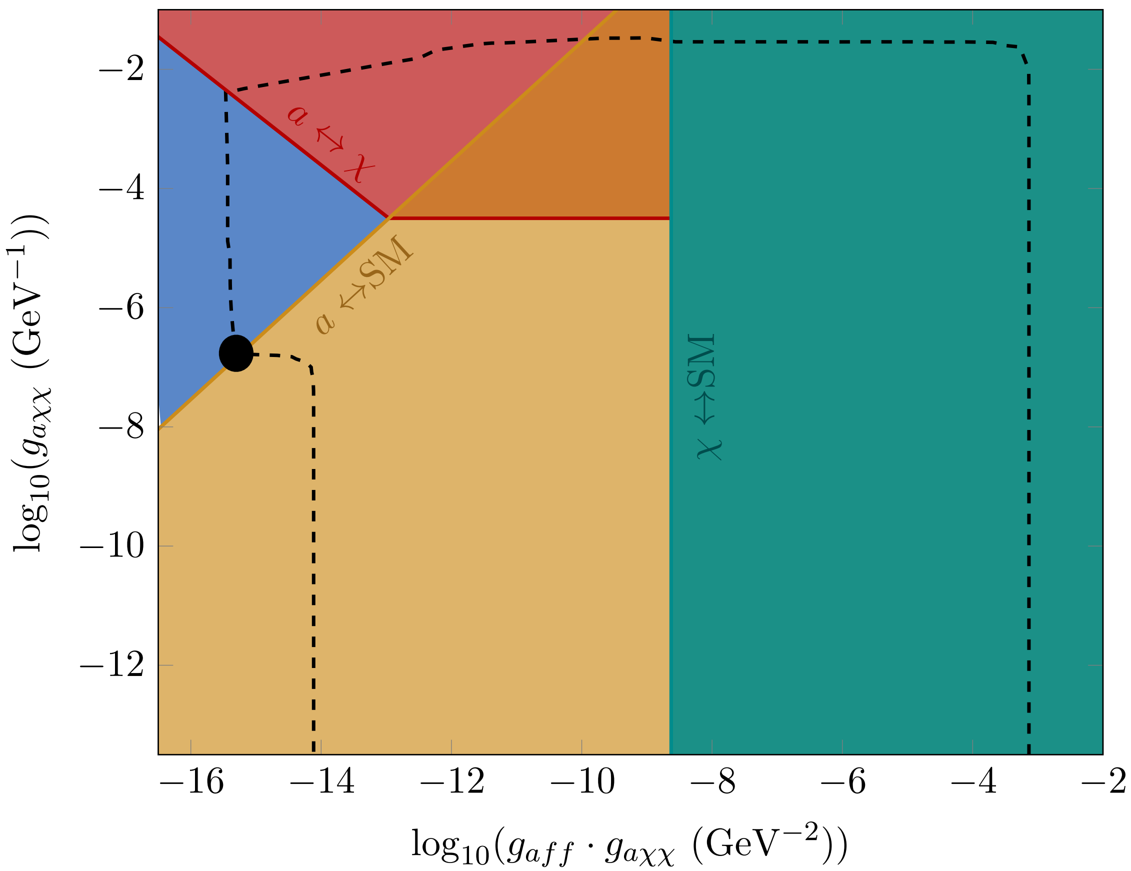


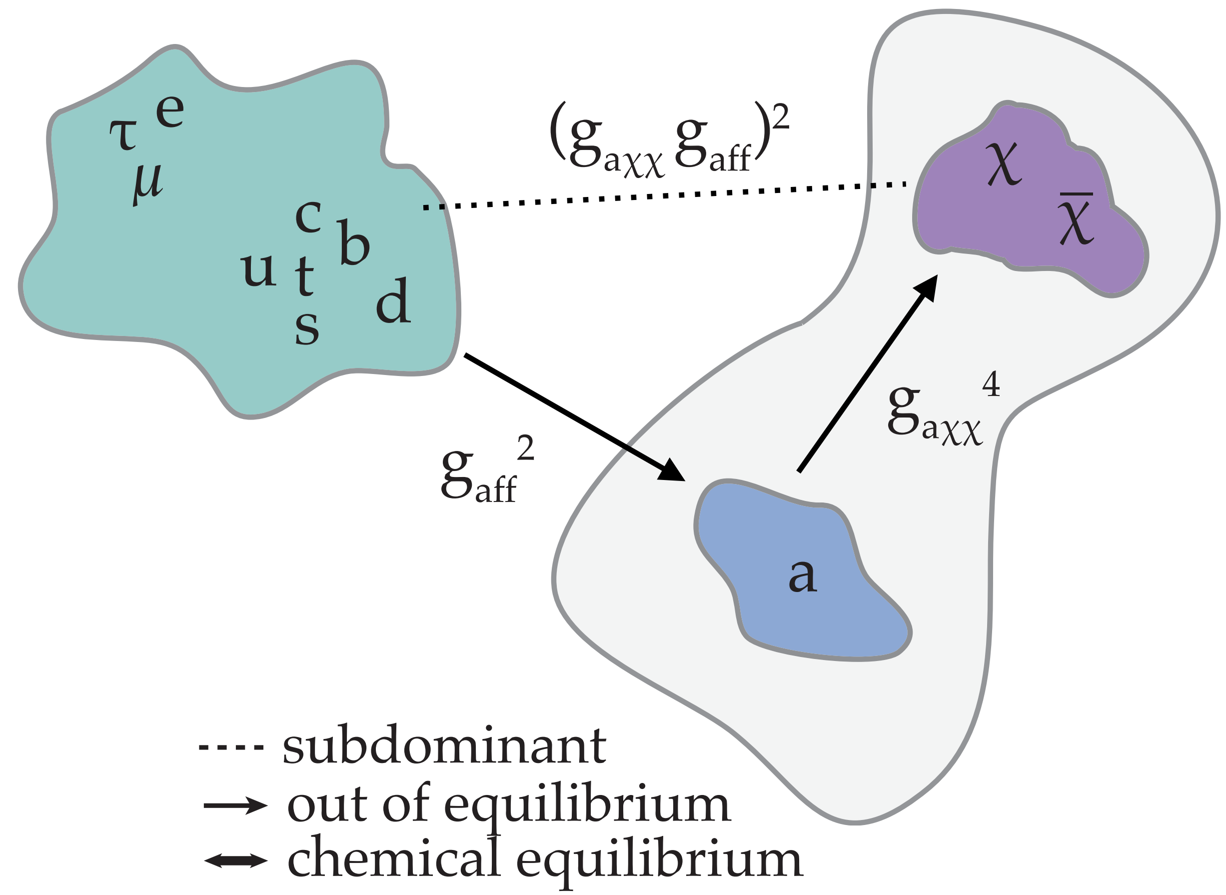


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Sequential freeze-in

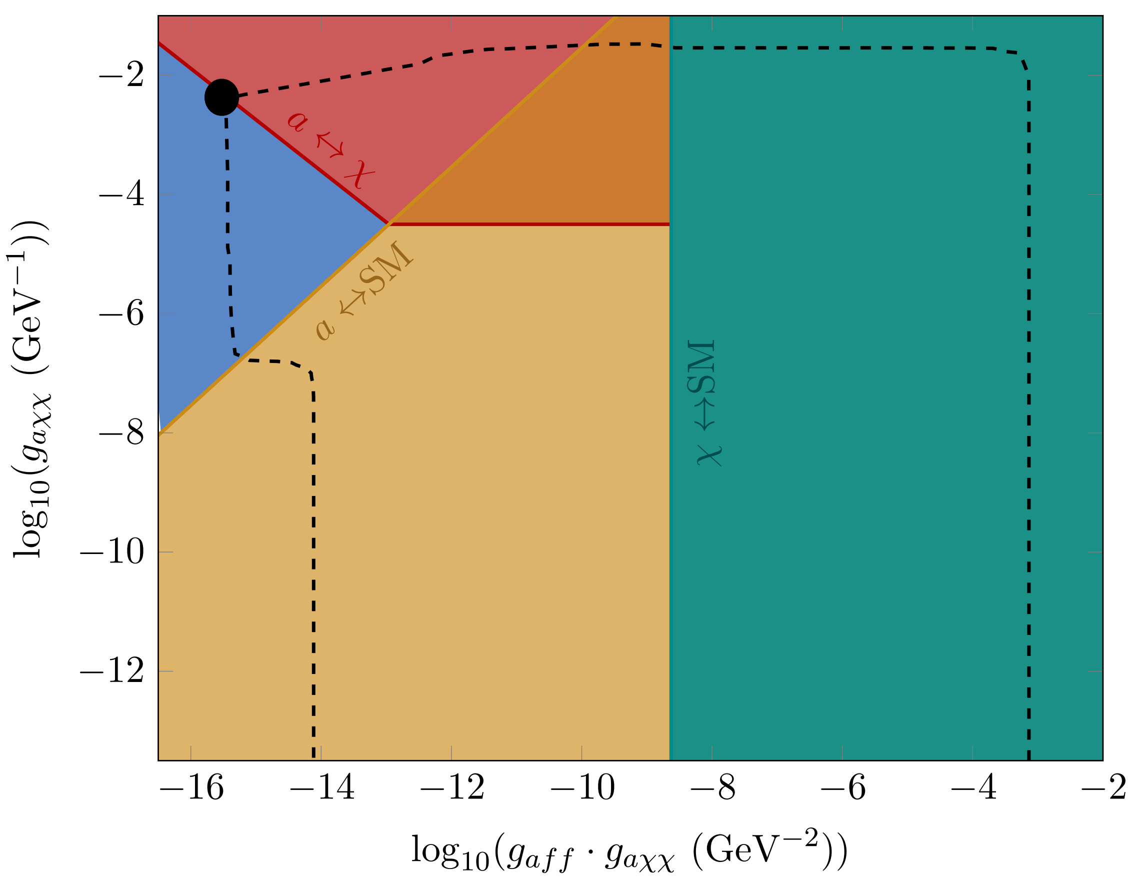


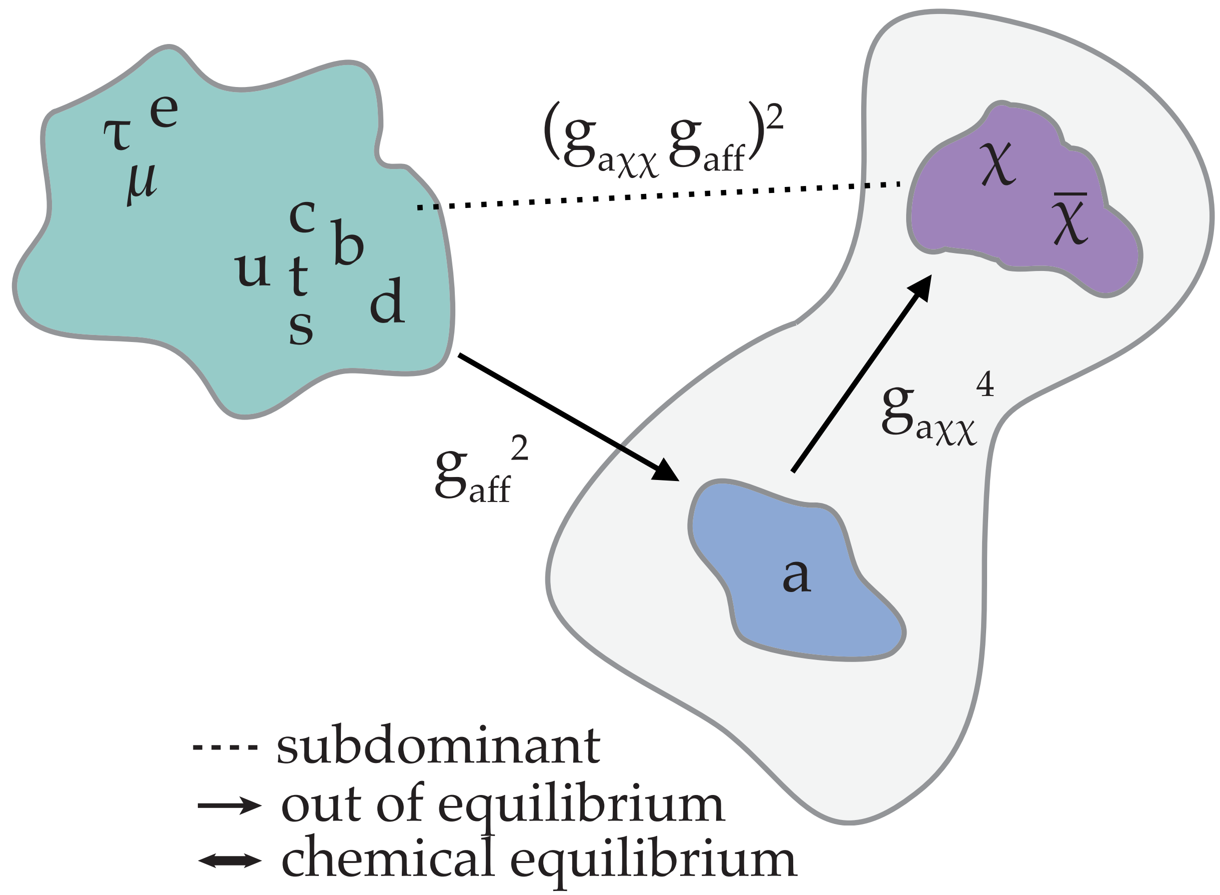


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Sequential freeze-in

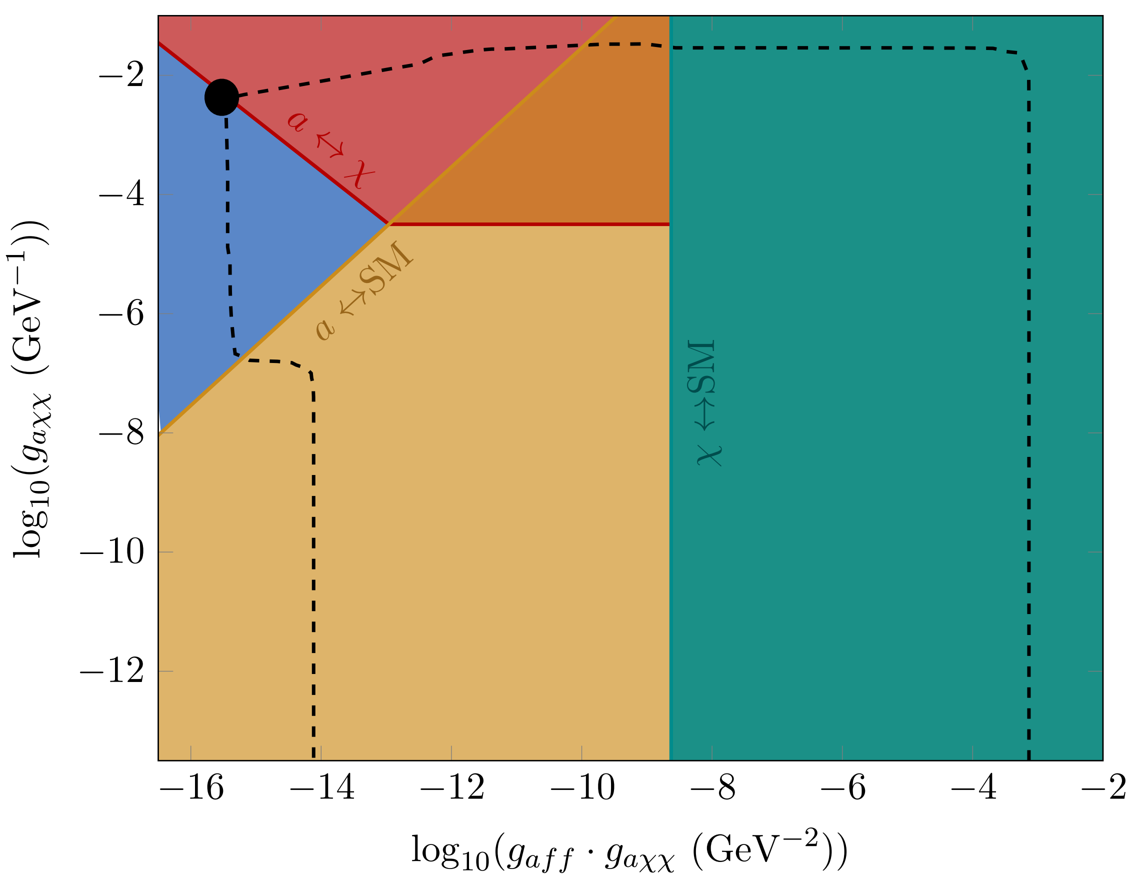


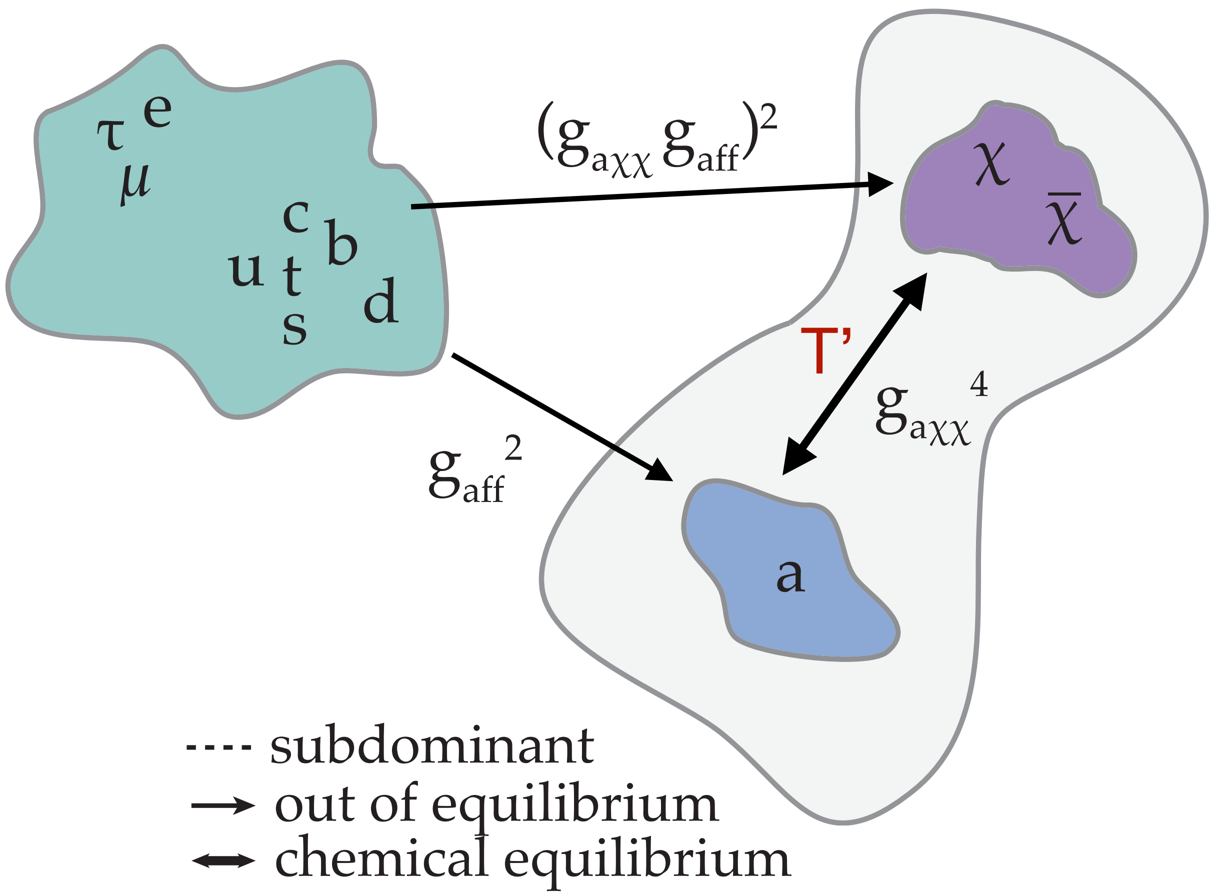


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-out from a decoupled dark sector (FODDS)





$m_\chi = 10$ 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]

Freeze-out from a decoupled dark sector (FODDS)

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

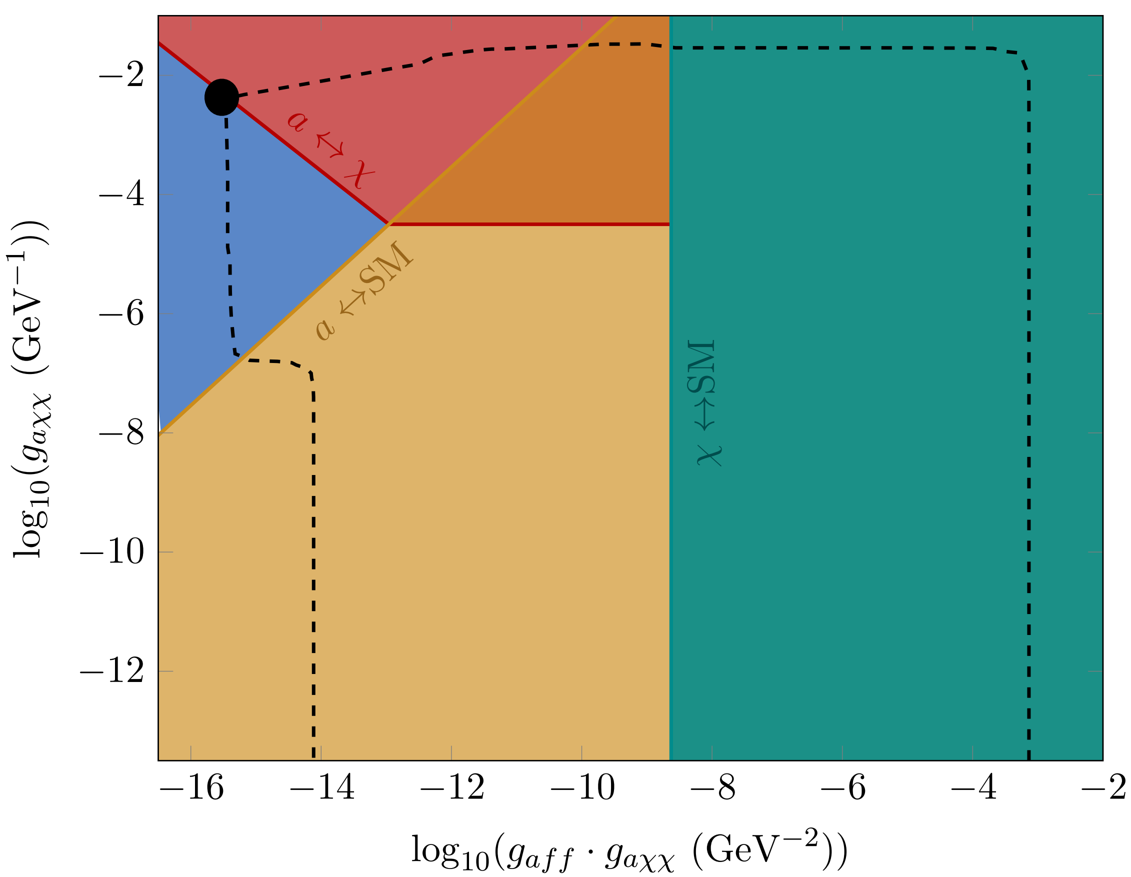
$$\frac{\partial \rho'(T')}{\partial t} + 3H\ (\rho' + P')\,(T') = \int \frac{d^3p}{(2\pi)^3} C[f(p,t)]$$

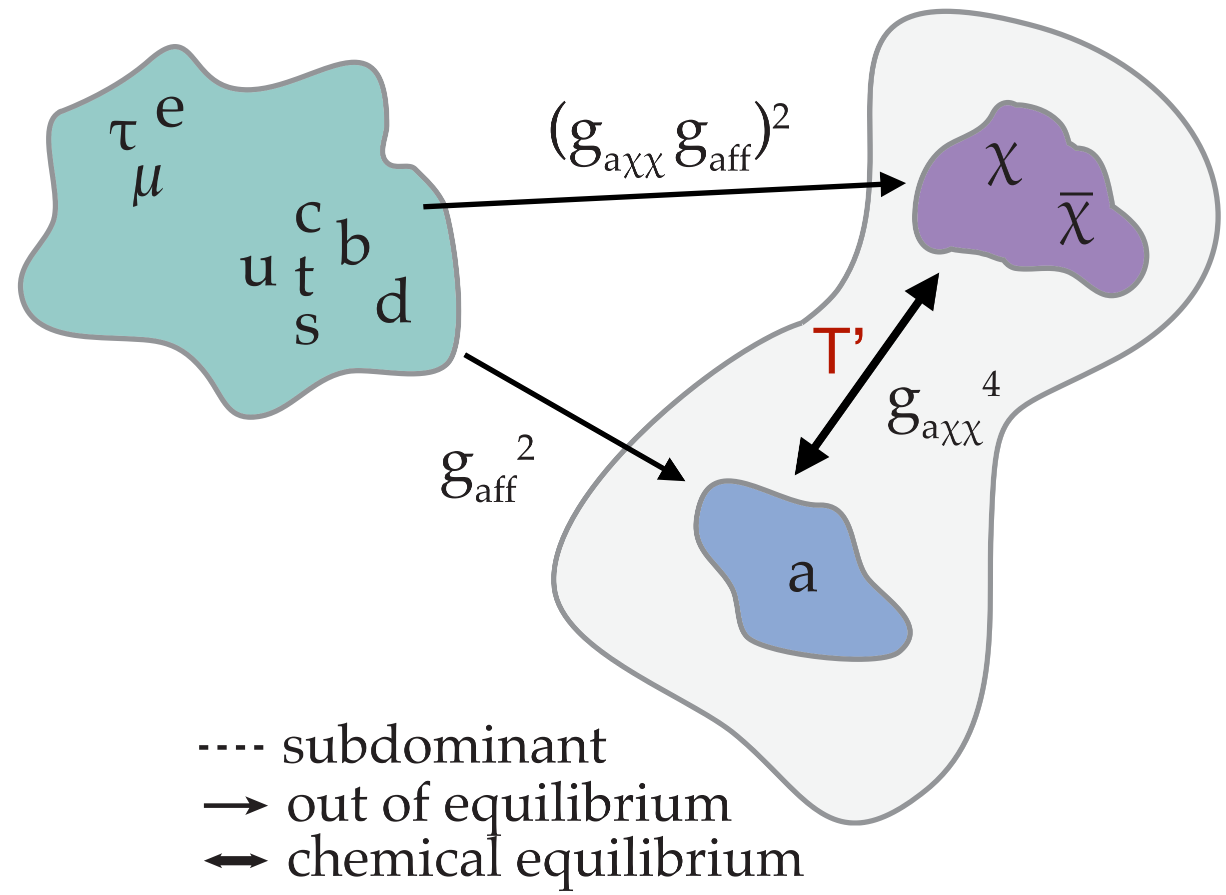
Need to solve system of 3 (unfortunately stiff) coupled differential equations

$m_\chi = 10$ 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]

Freeze-out from a decoupled dark sector (FODDS)

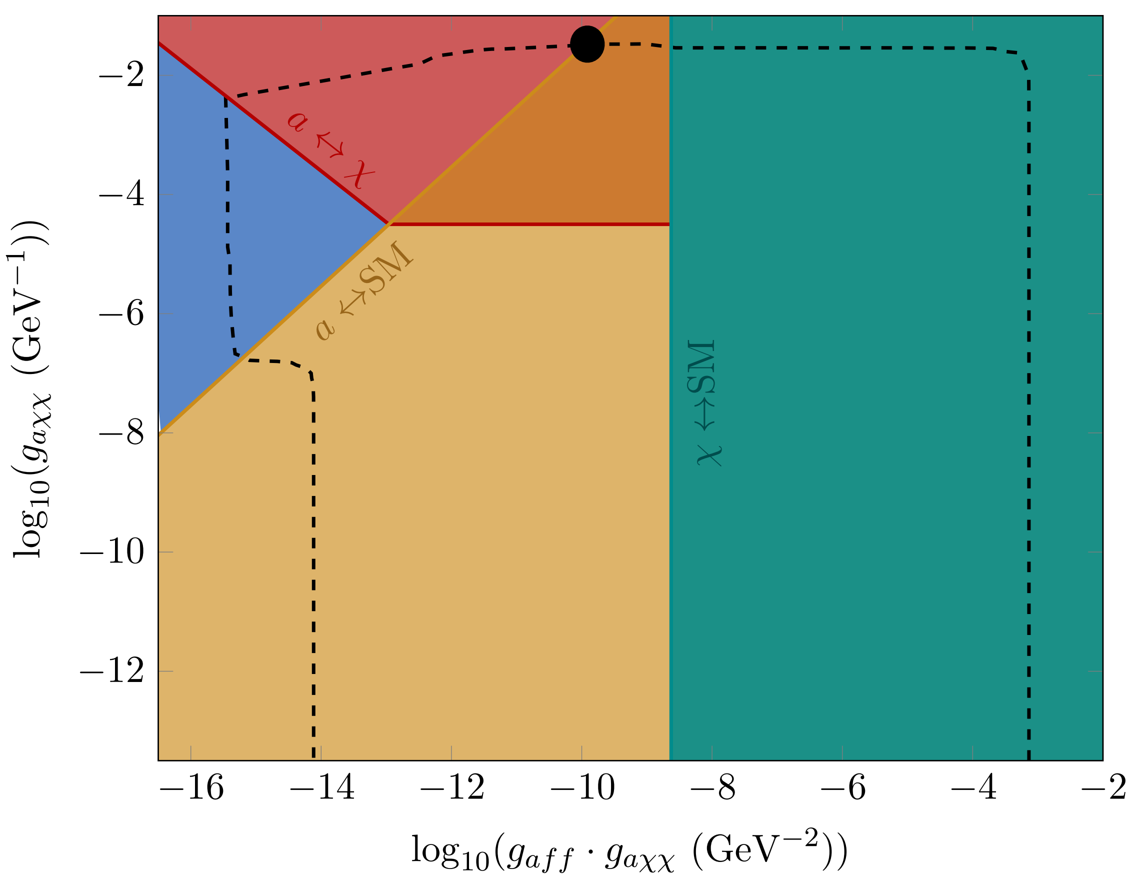


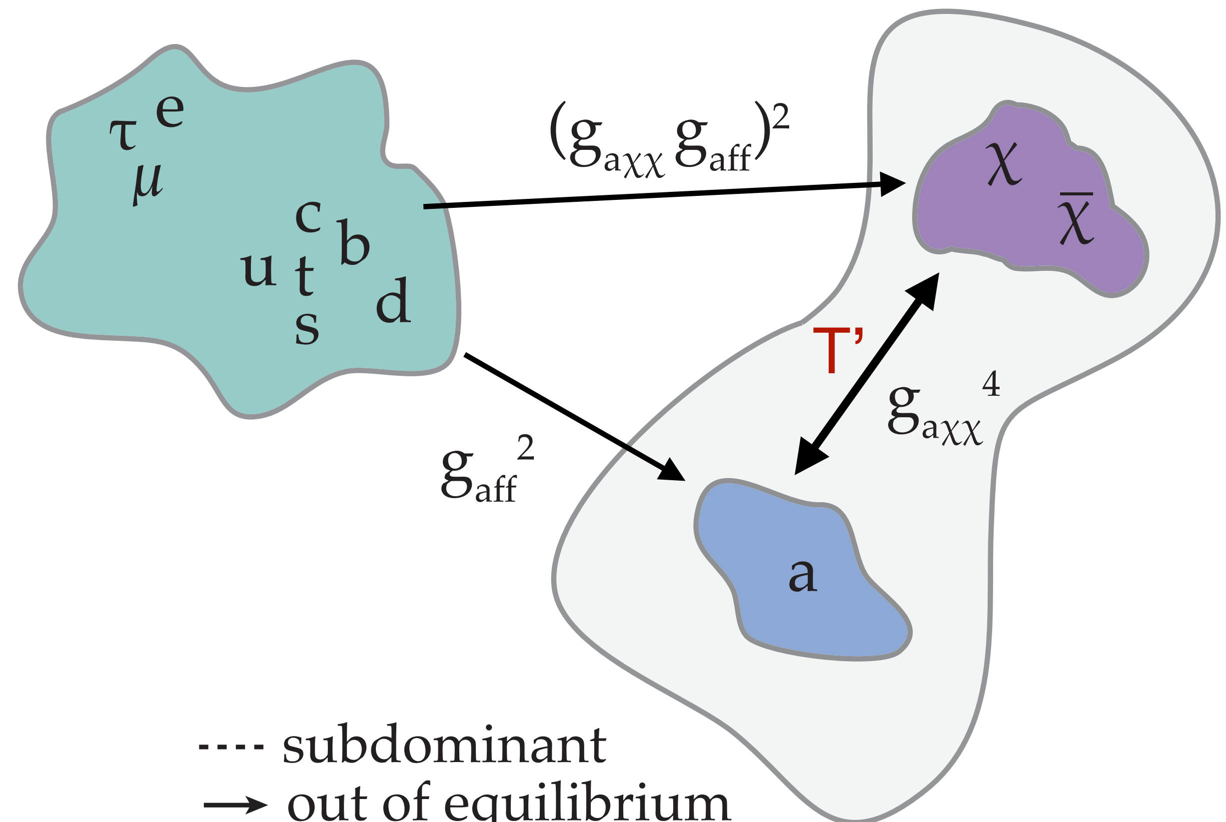


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-out from a decoupled dark sector (FODDS)

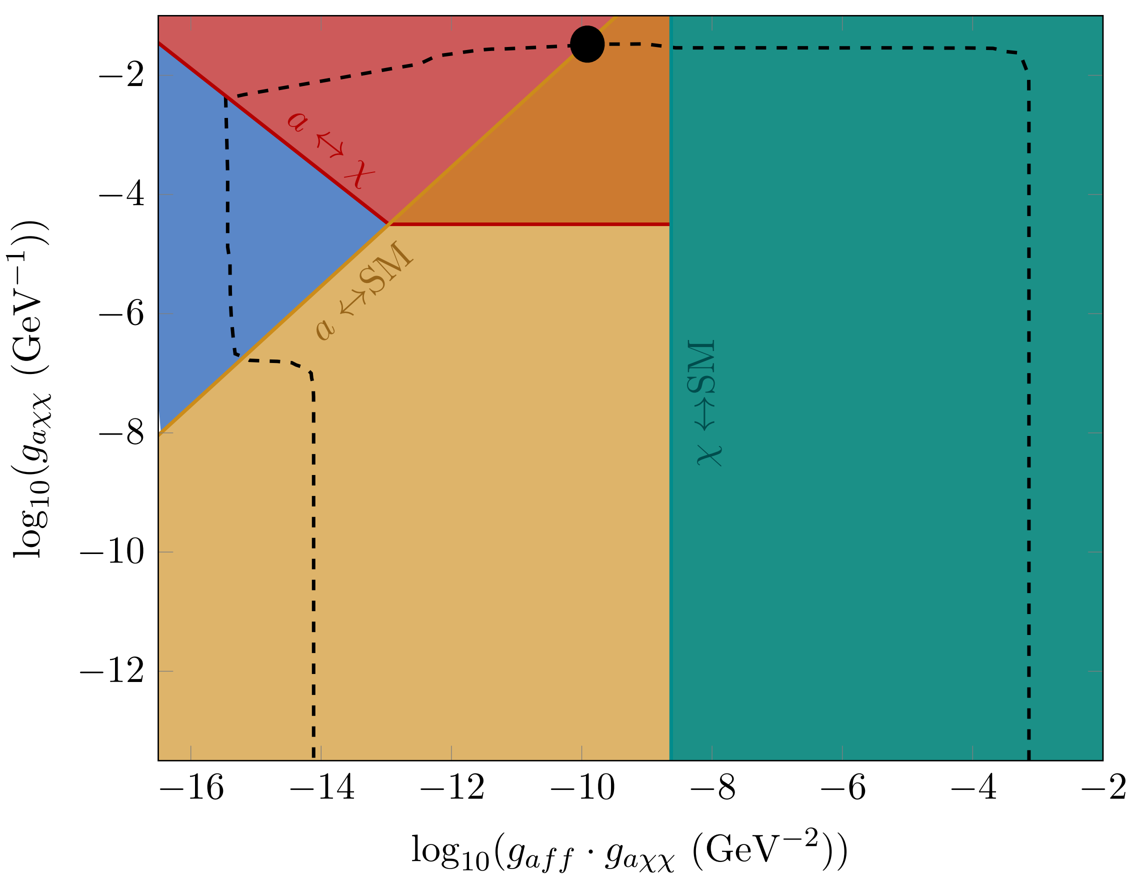


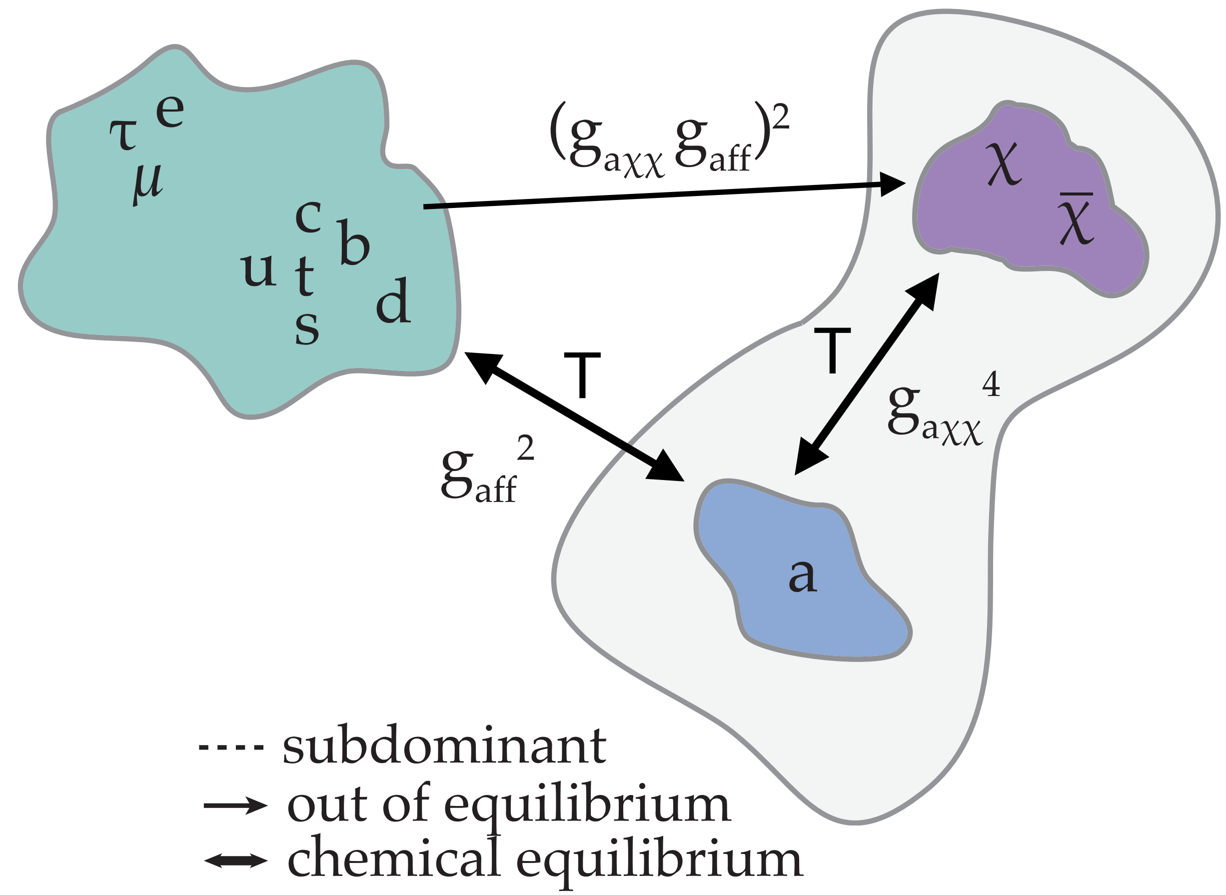


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-out from the mediator

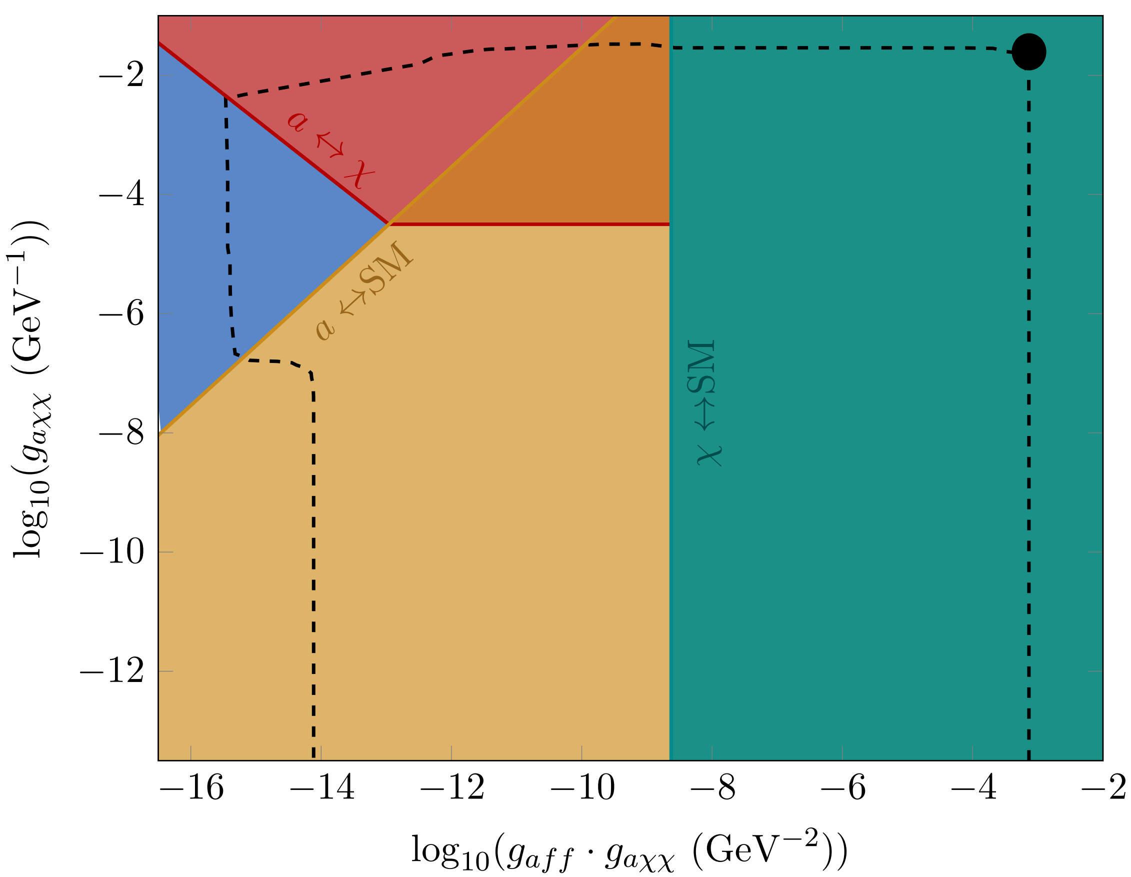


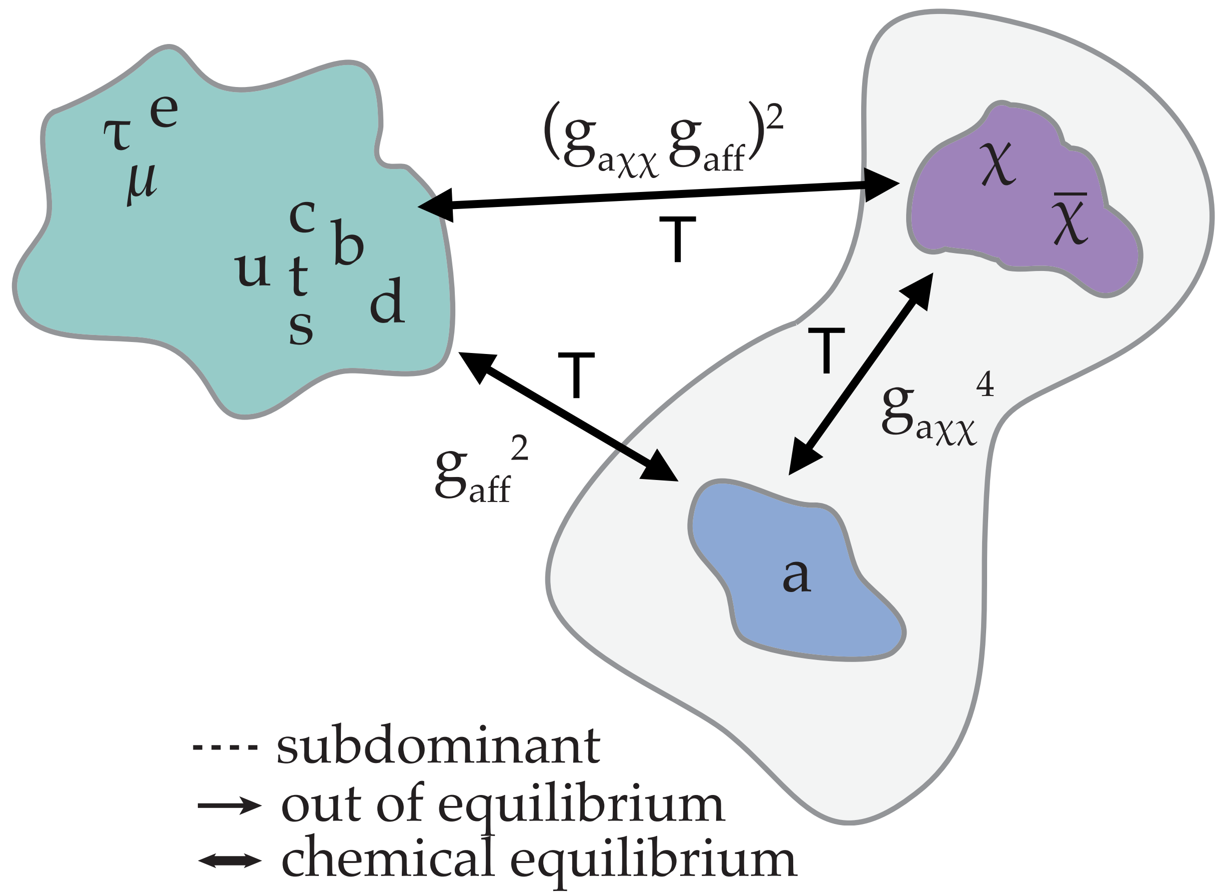


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-out from SM

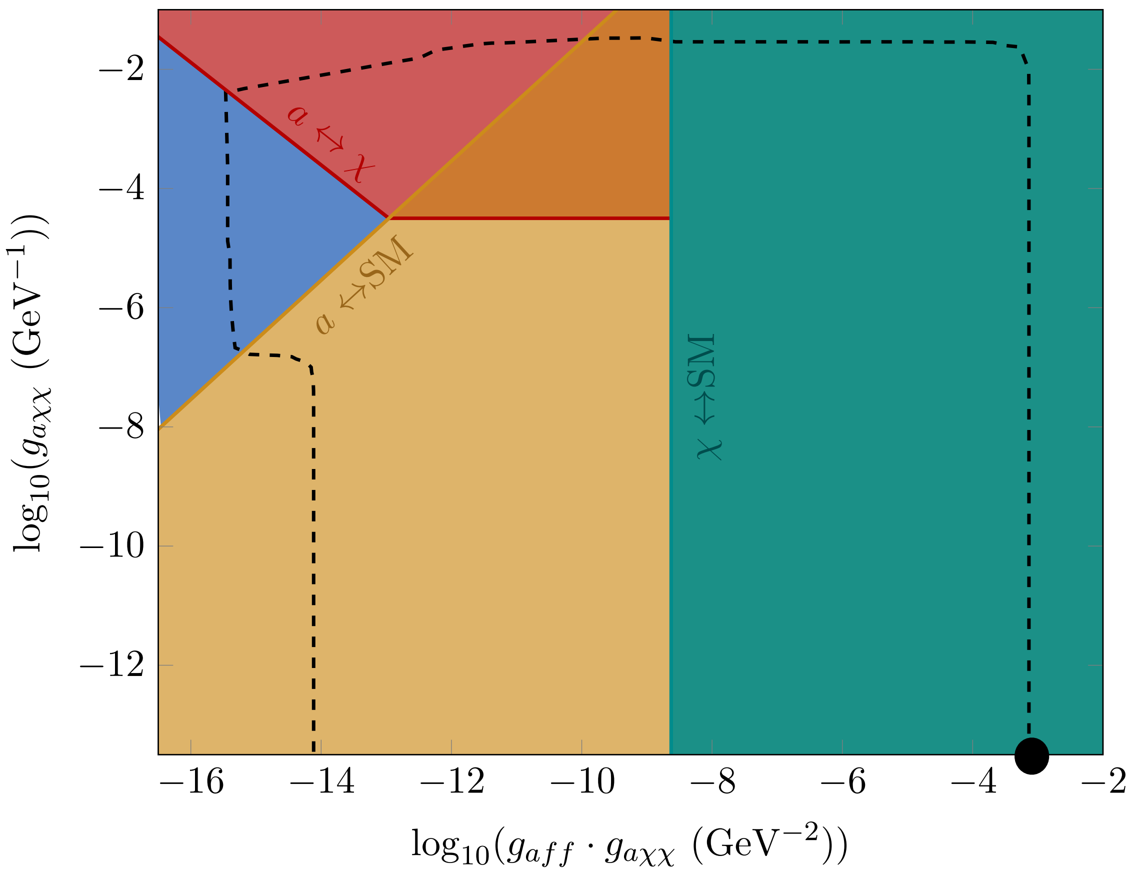


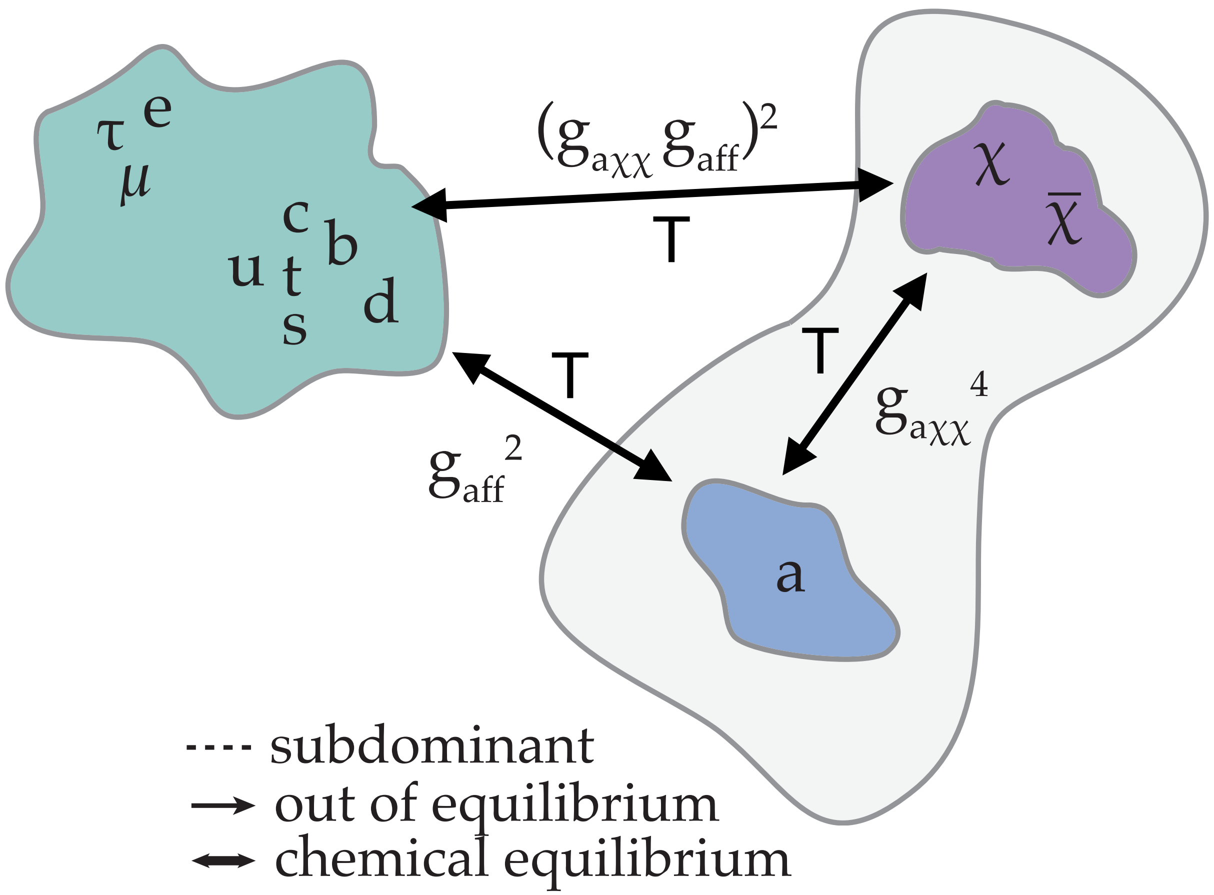


$m_\chi = 10$ GeV, $m_a = 1$ GeV

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

Freeze-out from SM



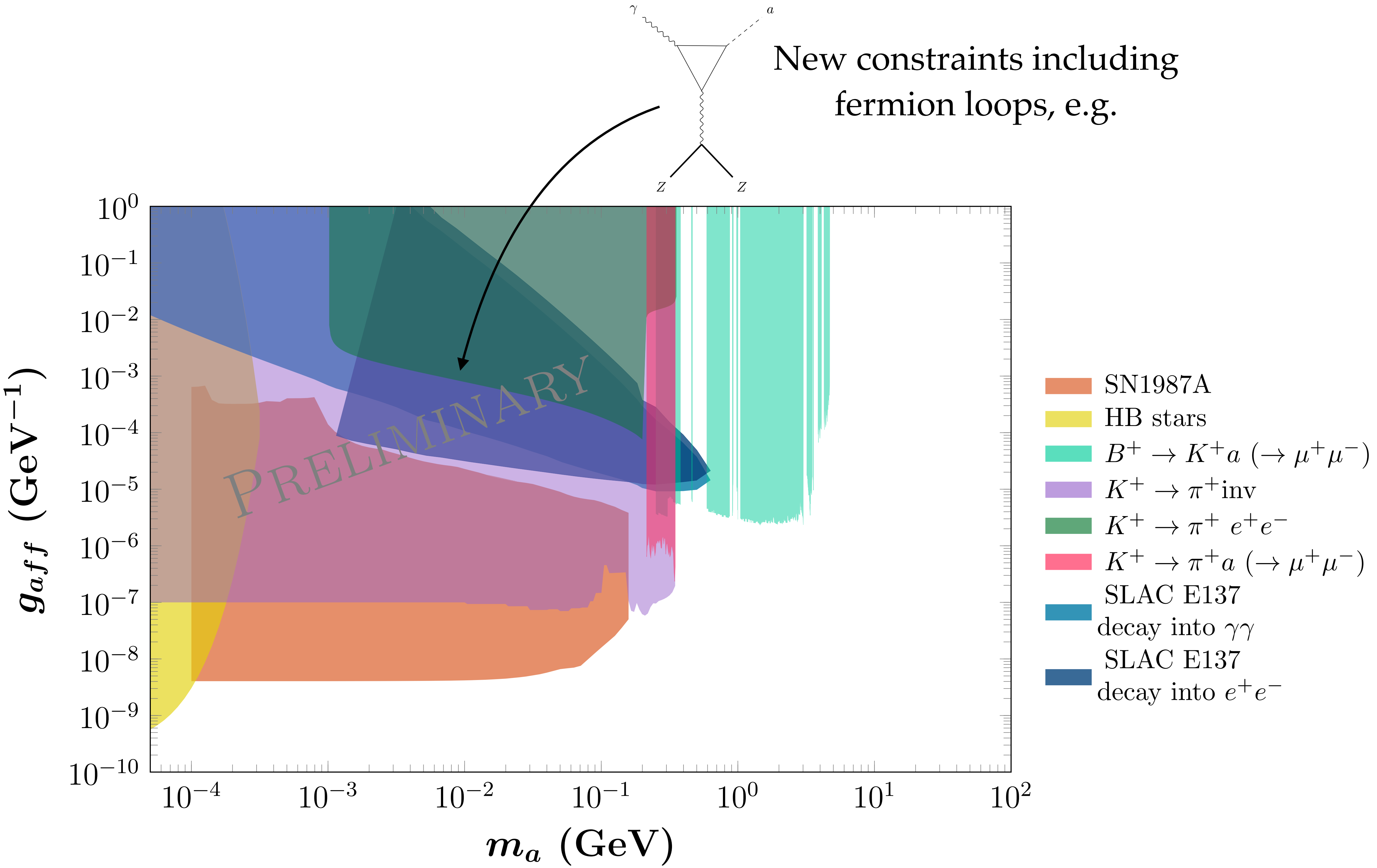


$m_\chi = 10$ GeV, $m_a = 1$ GeV

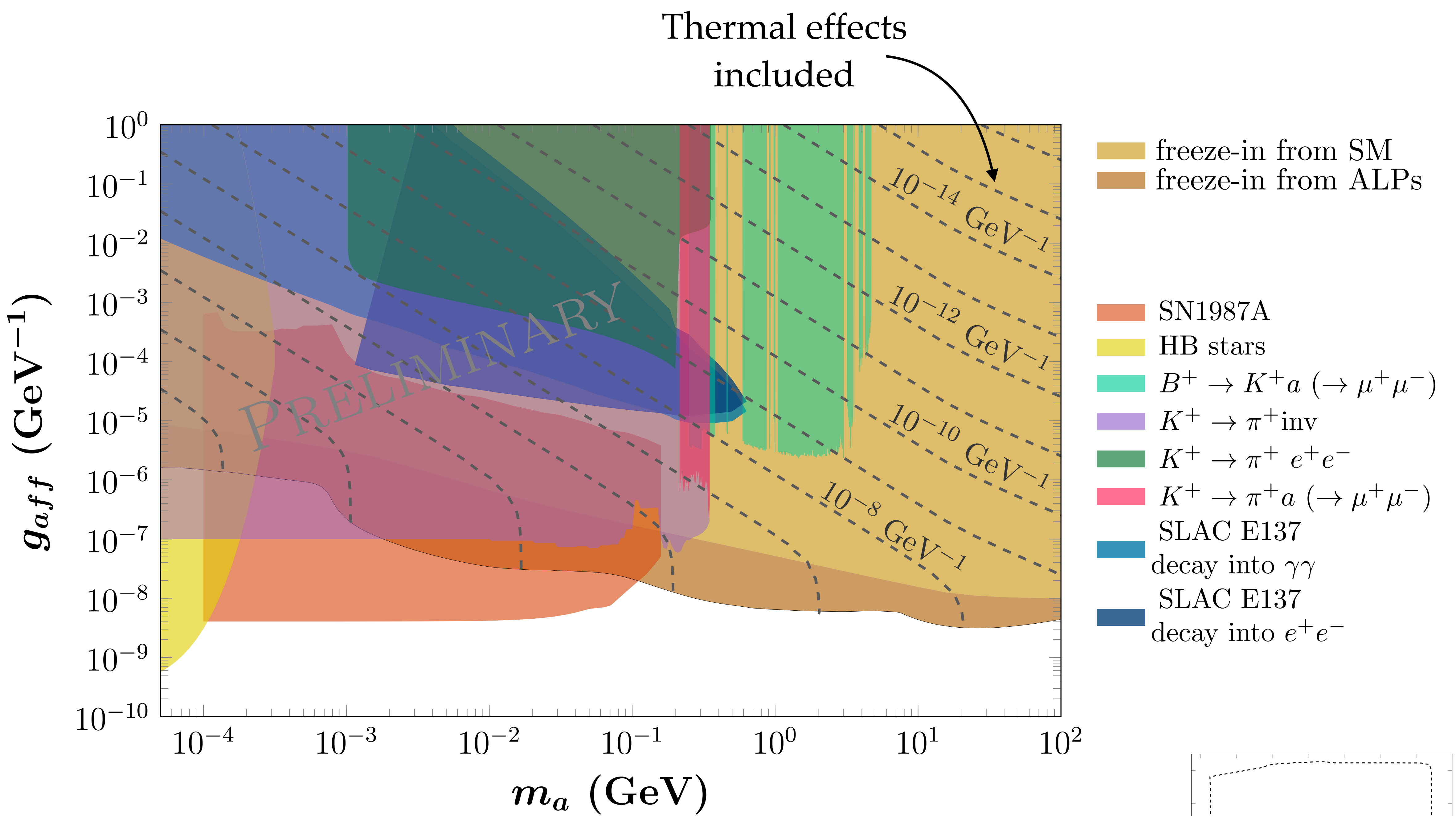
[Chu, Hambye, Tytgat. JCAP, 2012], [Hambye, Tytgat, Vandecasteele, Vanderheyden. Phys. Rev. D, 2019], [Bélanger, Delaunay, Pukhov, Zaldivar. Phys. Rev. D, 2020]

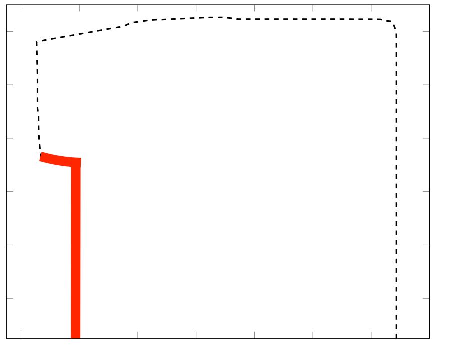
Constraints on our ALP

New constraints including fermion loops, e.g.

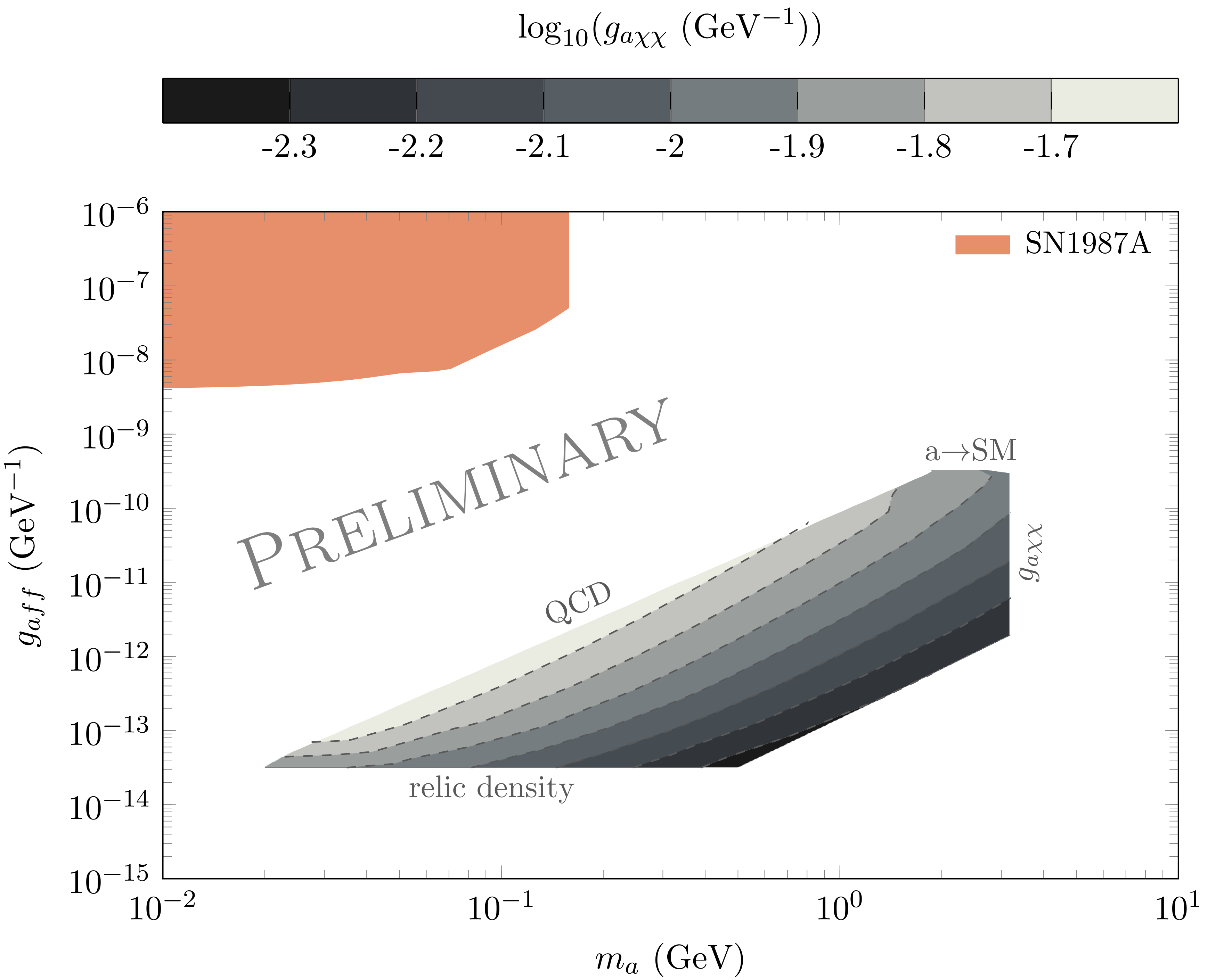


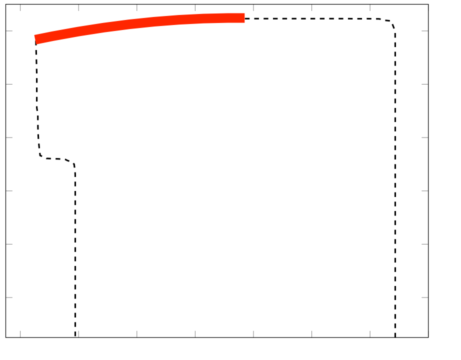
Freeze-in vs. constraints on our ALP ($m_\chi / m_a = 10$)





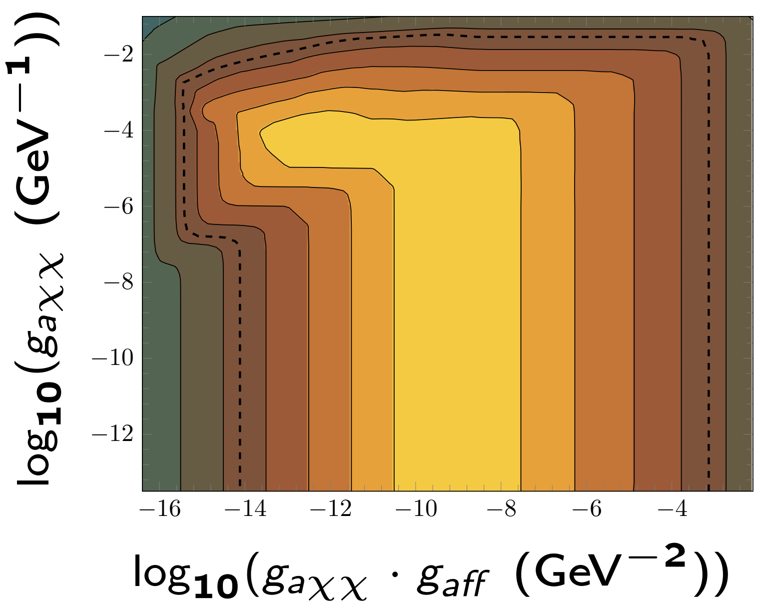
FODDS vs. constraints on our ALP ($m_\chi/m_a = 10$)





Conclusion

What we have done



- Our simple 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 FODDS 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

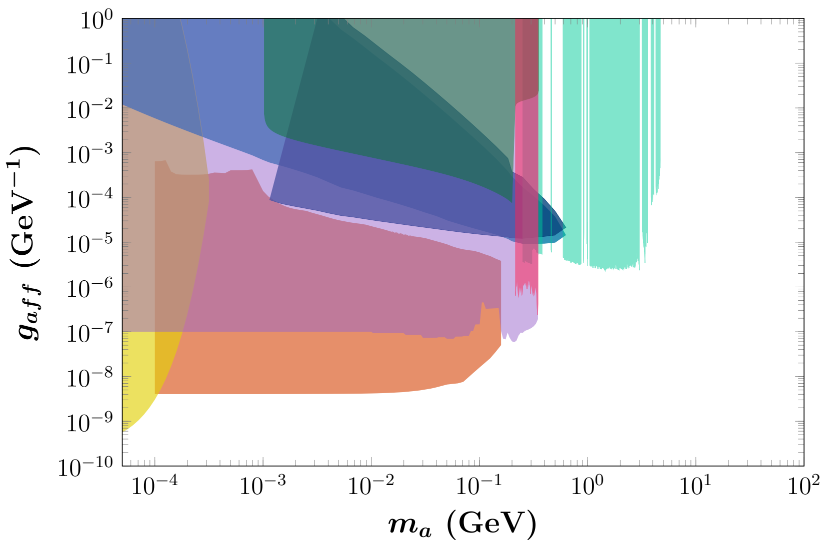
Future work

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

- 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

Conclusion

What we have done



- Our simple 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 FODDS 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

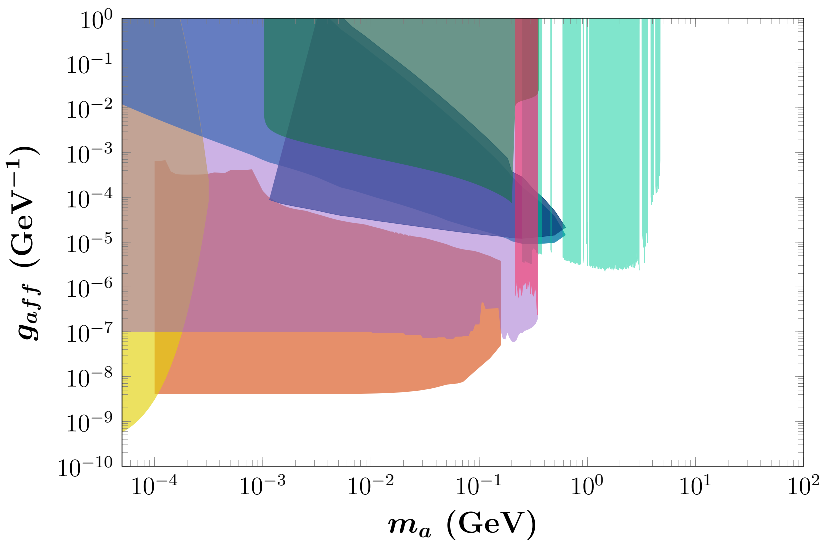
- Improve accuracy, in particular in sequential freeze-in region, by solving unintegrated Boltzmann equation

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

- Assess the potential sensitivity of future experiments to the region of interest

Conclusion

What we have done



- Our simple 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 FODDS 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

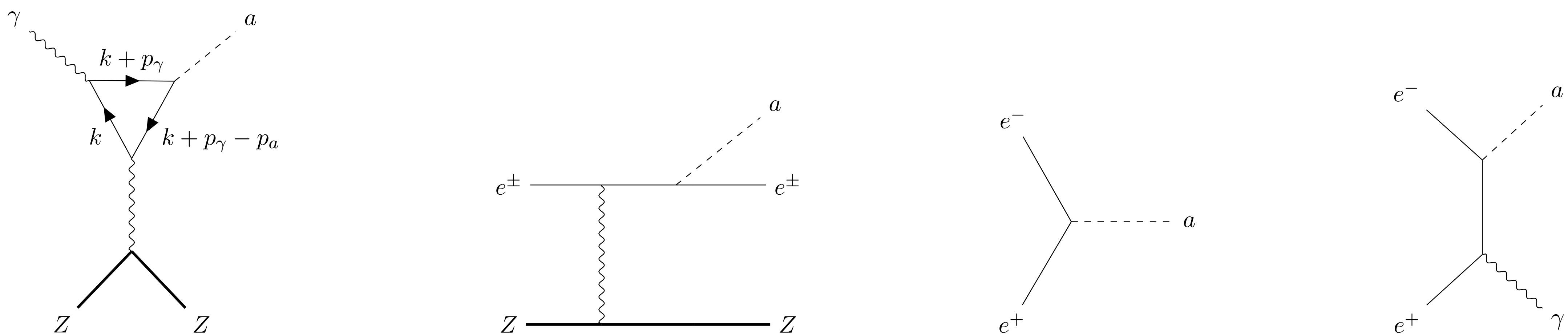
$$E\left(\partial_t - Hp\partial_p\right) f = C\left[f\right]$$

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

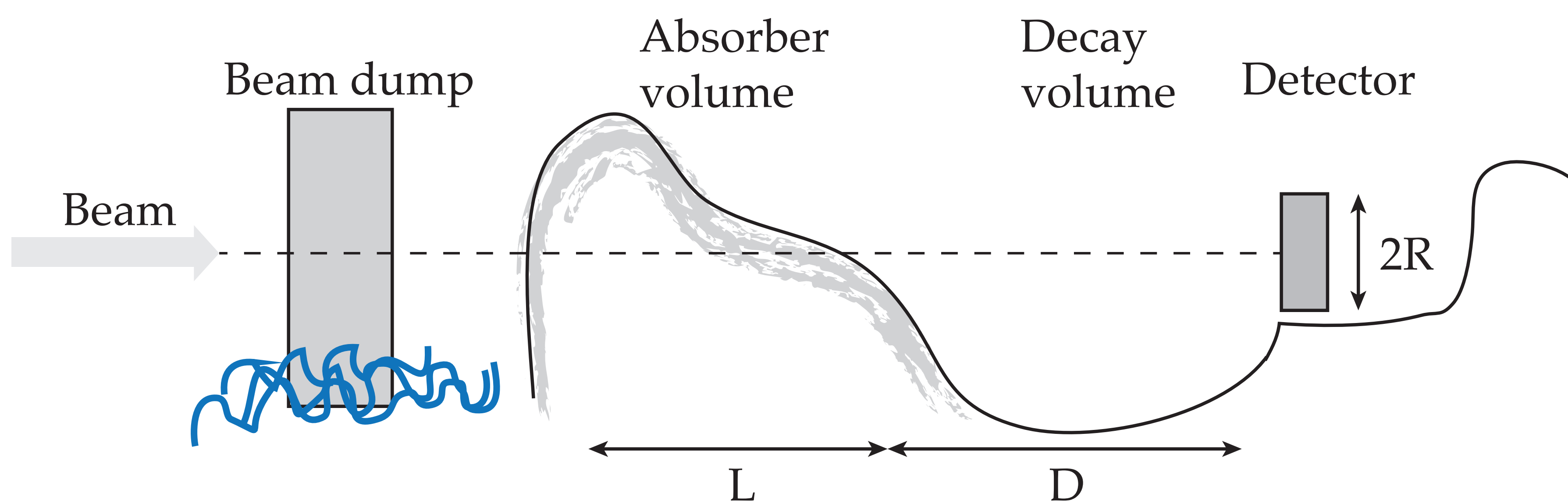
Backup Slides

Electron Beam Dump Constraint

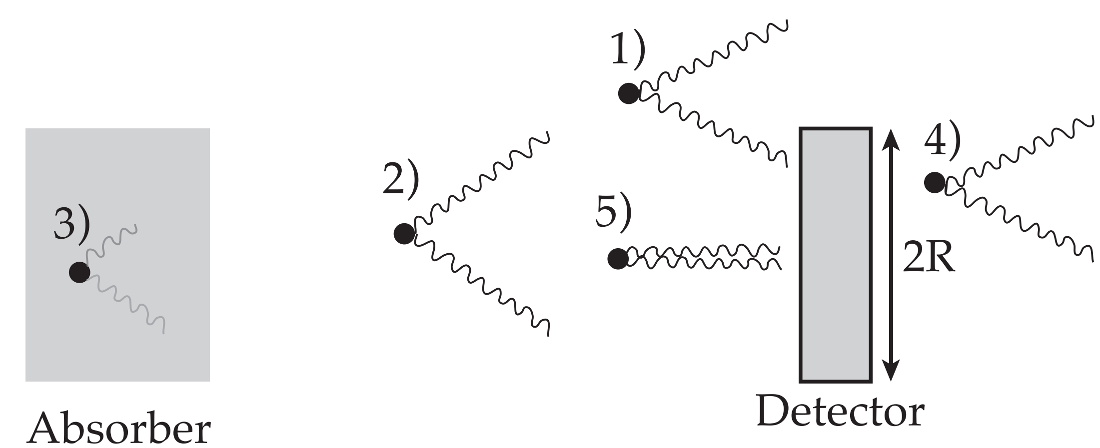
SLAC E137 Experiment: 20 GeV Electrons bumped



Fold **detector geometry**

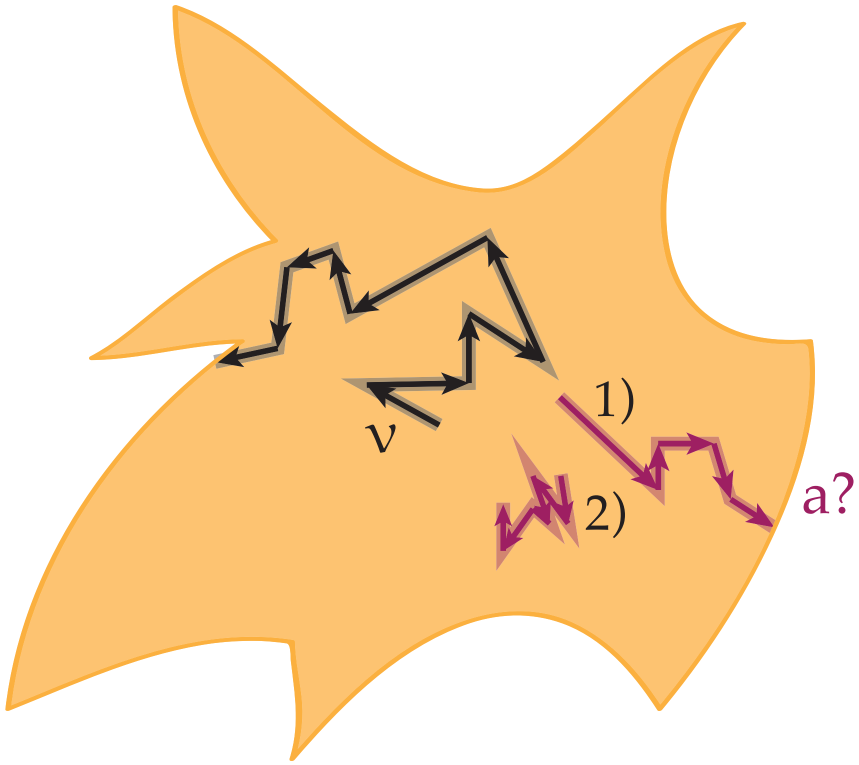


with **ALP decay probability**



Astrophysical Constraints

ALPs inside stars



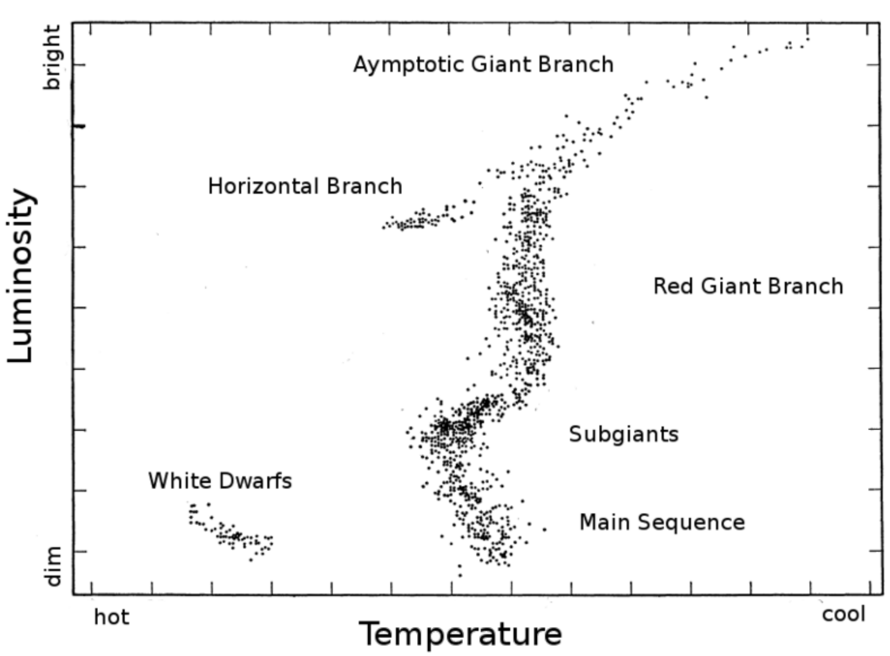
1) Energy Loss

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

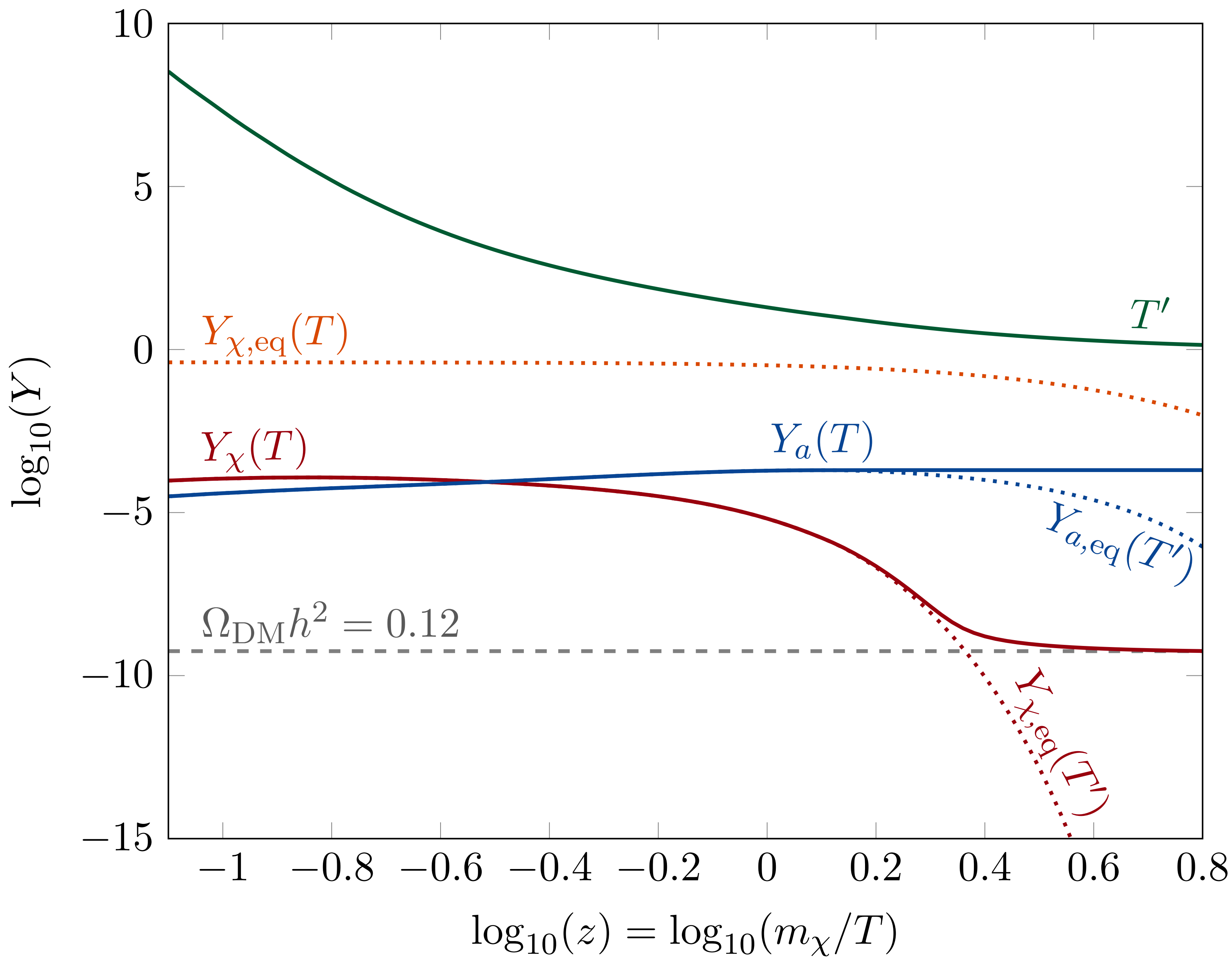
Horizontal Branch Stars



$R = N_{HB}/N_{RG}$ 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



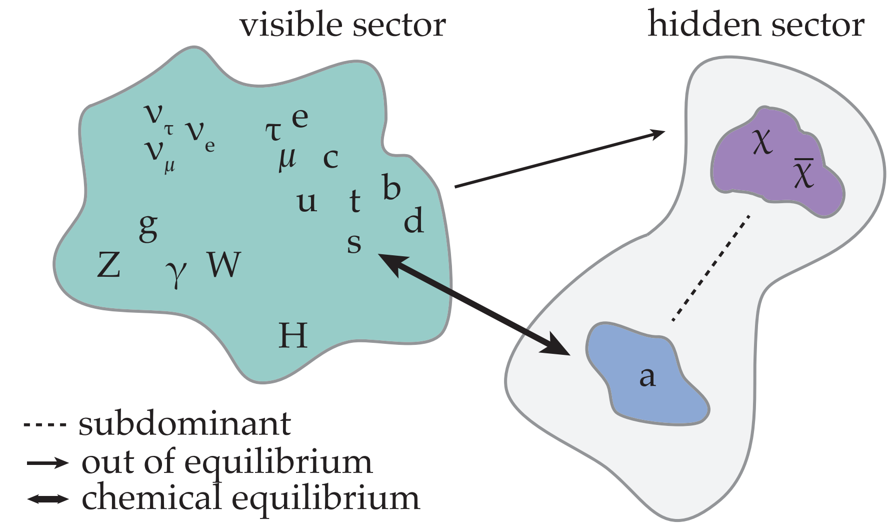
for $m_\chi = 10$, $m_a = 1$ GeV, $g_{a\chi\chi} = 1.3 \cdot 10^{-2}$ GeV^{-1}, $g_{aff} = 10^{-13}$ GeV^{-1}

Freeze-in ...

... from SM particles

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

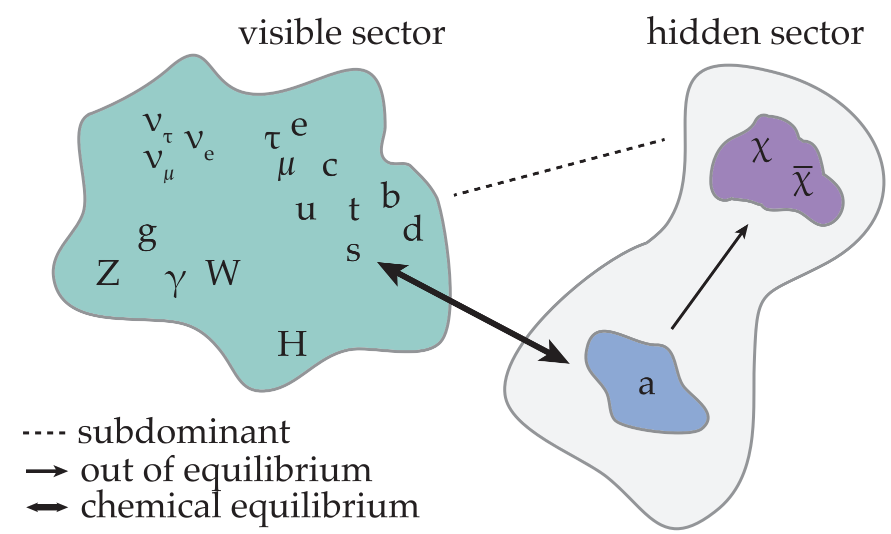
$$+ \underbrace{\cancel{\langle \sigma_{\chi\bar{\chi}\to aa} v\rangle}}_{\propto g_{a\chi\chi}^4} (n_\chi^{\mathrm{eq}2} - n_\chi^2)$$



... from the mediator

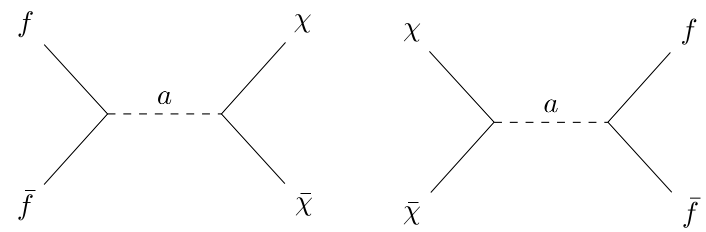
$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \underbrace{\cancel{\sum_f \langle \sigma_{\chi\bar{\chi}\to f\bar{f}} v\rangle}}_{\propto (g_{aff}\, g_{a\chi\chi})^2} (n_\chi^{\mathrm{eq}2} - n_\chi^2)$$

$$+ \langle \sigma_{\chi\bar{\chi}\to aa} v\rangle \left(n_\chi^{\mathrm{eq}2} - \underbrace{\cancel{n_\chi^2}}_{n_\chi \ll n_\chi^{\mathrm{eq}}}\right)$$



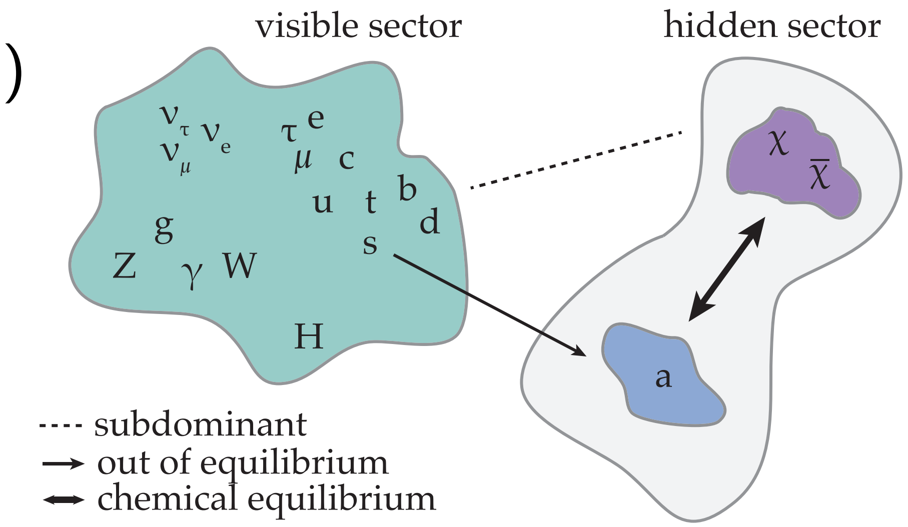
$$\boxed{Y_0 = \int_0^\infty \frac{\langle \sigma_{\mathrm{connector}} v\rangle n_\chi^{\mathrm{eq}2}}{sHT}\, \mathrm{d}T}$$

FODDS region



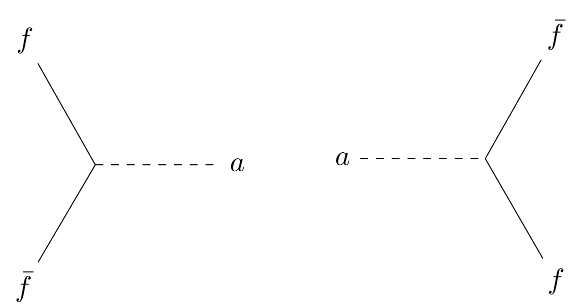
$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar\chi\to f\bar f} v \right\rangle \left(\overbrace{(n_\chi^{\mathrm{eq}}(T))^2} - \overbrace{n_\chi^2} \right)$$

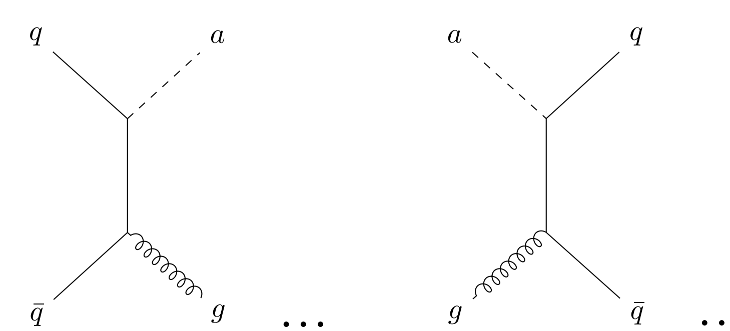
$$+ \underbrace{\langle \sigma_{aa\to\chi\bar\chi} v\rangle \, ({\color{red}T'}) n_a^2} - \underbrace{\langle \sigma_{\chi\bar\chi\to aa} v\rangle \, ({\color{red}T'}) n_\chi^2}$$



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

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



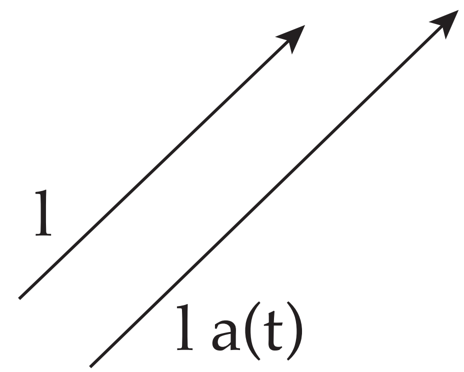


[Chu, Hambye, Tytgat. JCAP, 2012], [Hambye, Tytgat, Vandecasteele, Vanderheyden. Phys. Rev. D, 2019], [Bélanger, Delaunay, Pukhov, Zaldivar. Phys. Rev. D, 2020]

Boltzmann equation - general

Consider a system without collisions (free particles): $\frac{\partial N}{\partial t} = 0 \qquad N = nV$

$$\frac{\partial(nV)}{\partial t} = V\frac{\partial n}{\partial t} + n\frac{\partial V}{\partial t} = 0$$

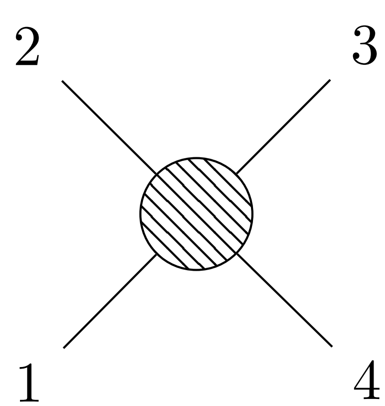


In an expanding universe $V \propto a^3$ and thus $\frac{1}{V}\frac{\partial V}{\partial t} = \frac{3}{a}\frac{\partial a}{\partial t}$

$$\frac{\partial n}{\partial t} + 3n\underbrace{\left(\frac{\dot{a}}{a}\right)}_{H} = 0$$

H is the Hubble function characterizing the rate of expansion of the universe

$$\boxed{\frac{\partial n}{\partial t} + 3nH = -C[n]}$$ $C[n]$ collision term



$$C[n_1] = \int \prod_{i=1}^{4} \frac{g_i d^3 p_i}{(2\pi)^3 2E_i}(f_1 f_2 - f_3 f_4)\overline{|i\mathcal{M}_{12\leftrightarrow 34}|}^2 \times$$
$$(2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4)$$