

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

In collaboration with Aoife Bharucha, Felix Brümmer and Nishita

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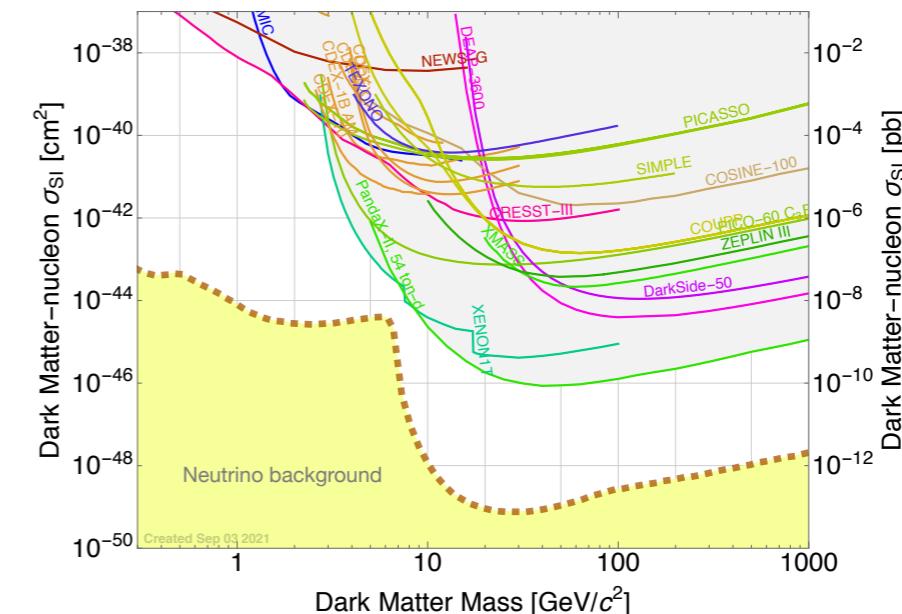
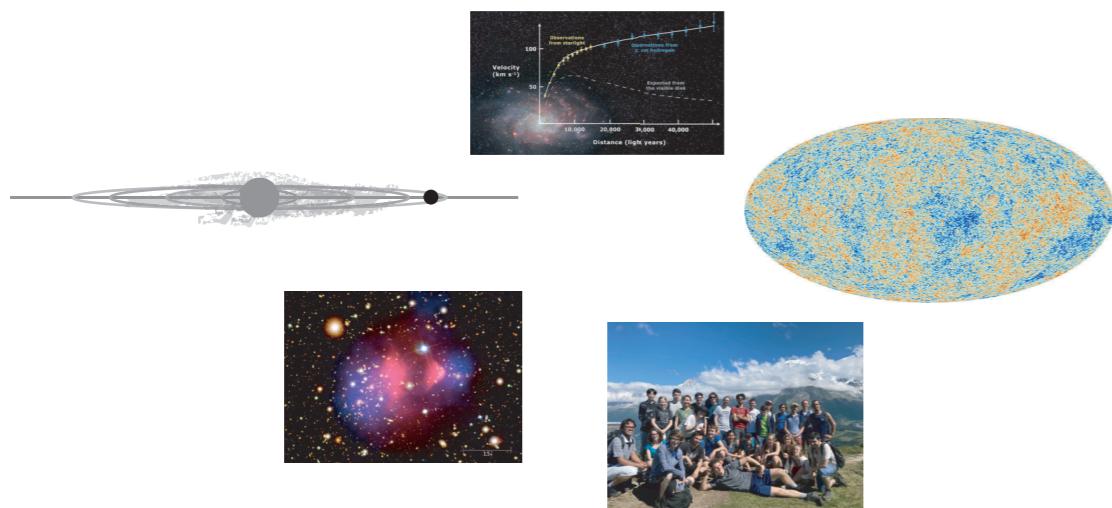
November 15, 2021

Annual workshop GDR Intensity Frontier

Introduction

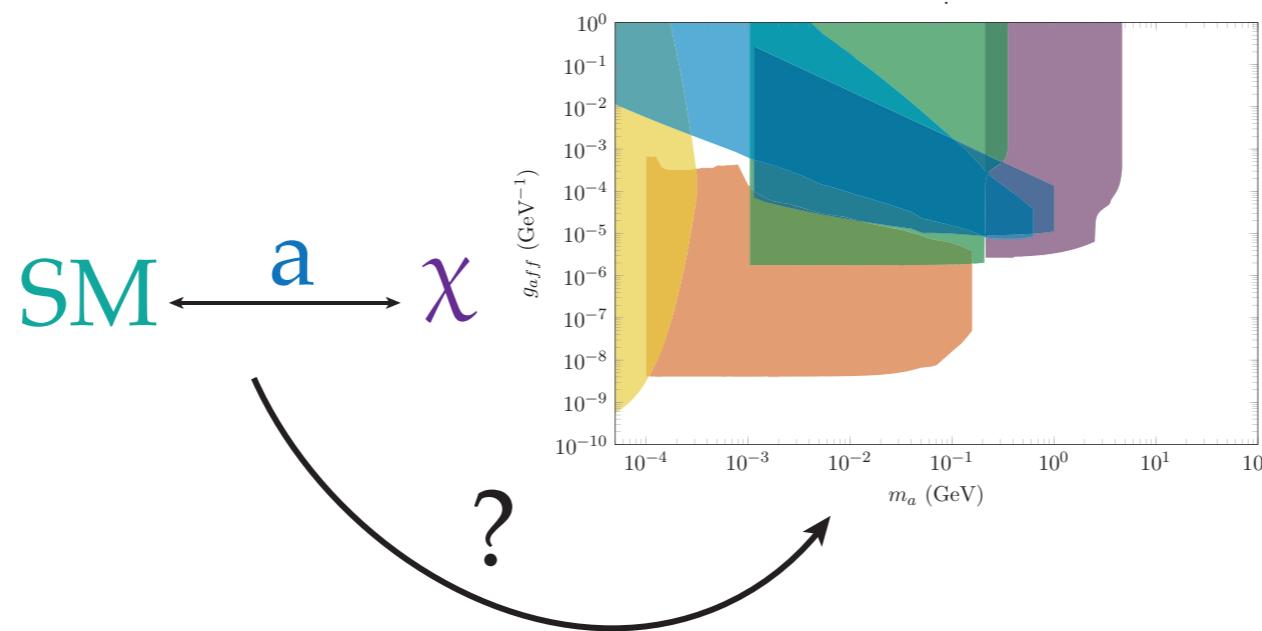
Gravitational evidence for Dark Matter (DM)

Freeze-out and WIMPs require large couplings



[1]

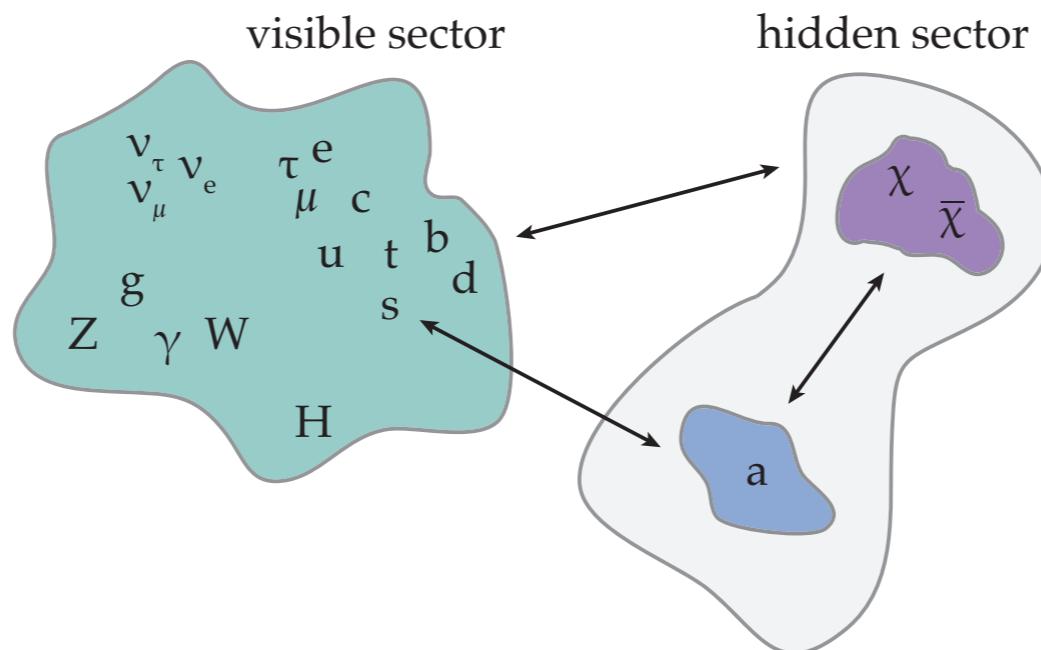
Look at different scenarios & explore parameter space



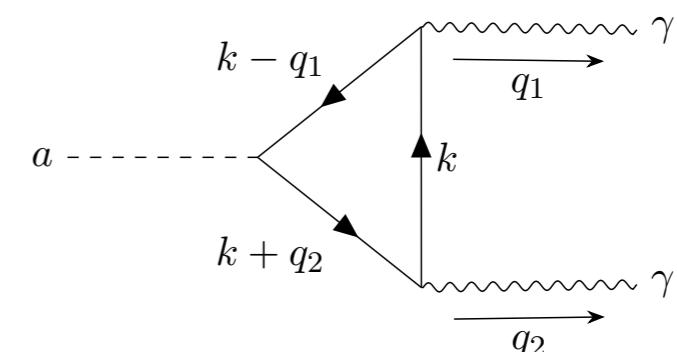
[1] figure created using <https://supercdms.slac.stanford.edu/dark-matter-limit-plotter>

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:

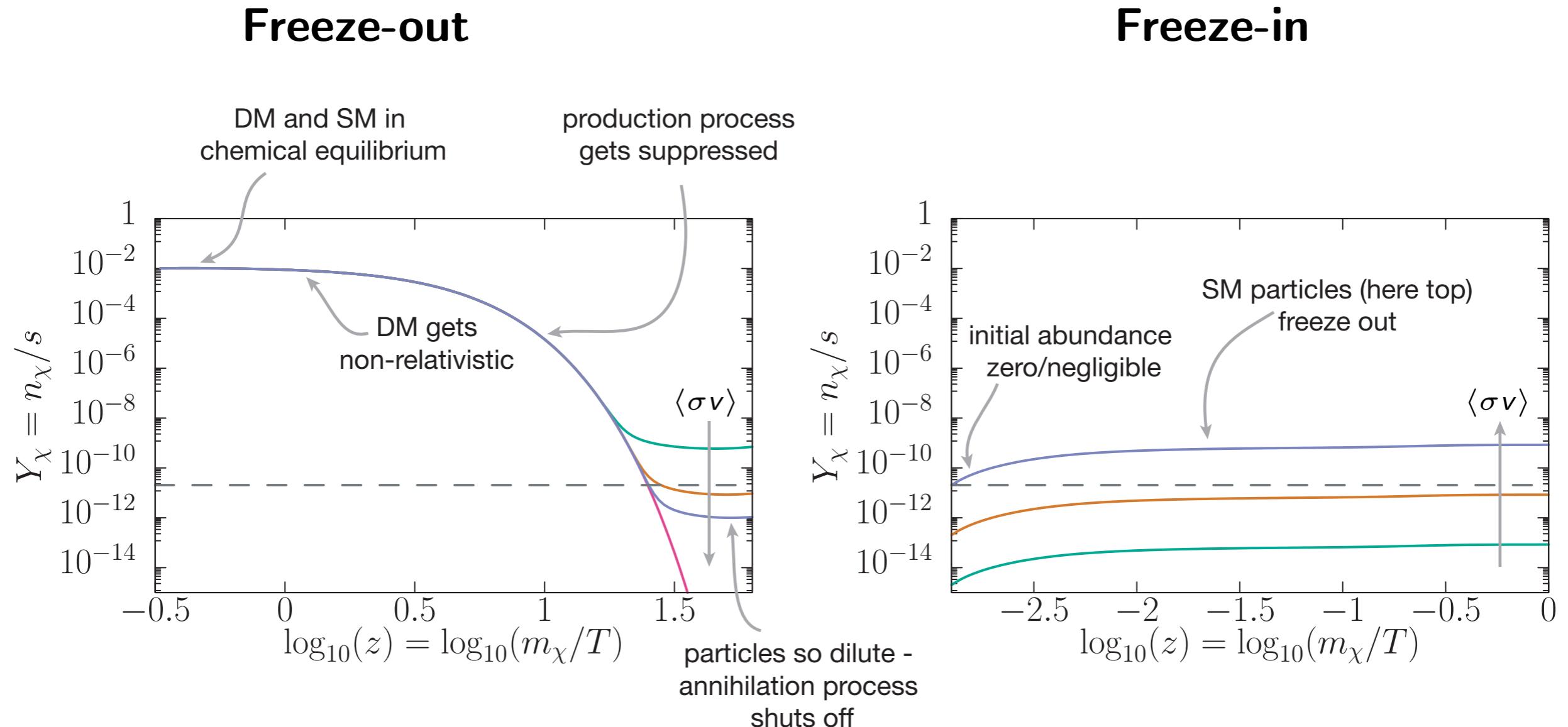
$$\mathcal{L} \supset \frac{1}{2} \partial_\mu a \partial^\mu a + \bar{\chi}(i\partial^\mu - m_\chi)\chi - \frac{1}{2} m_a^2 a^2 + ia \sum_f \frac{m_f}{f_a} C_f \bar{f} \gamma_5 f + ia \frac{m_\chi}{f_a} C_\chi \bar{\chi} \gamma_5 \chi$$

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

Alternative DM Genesis Scenarios

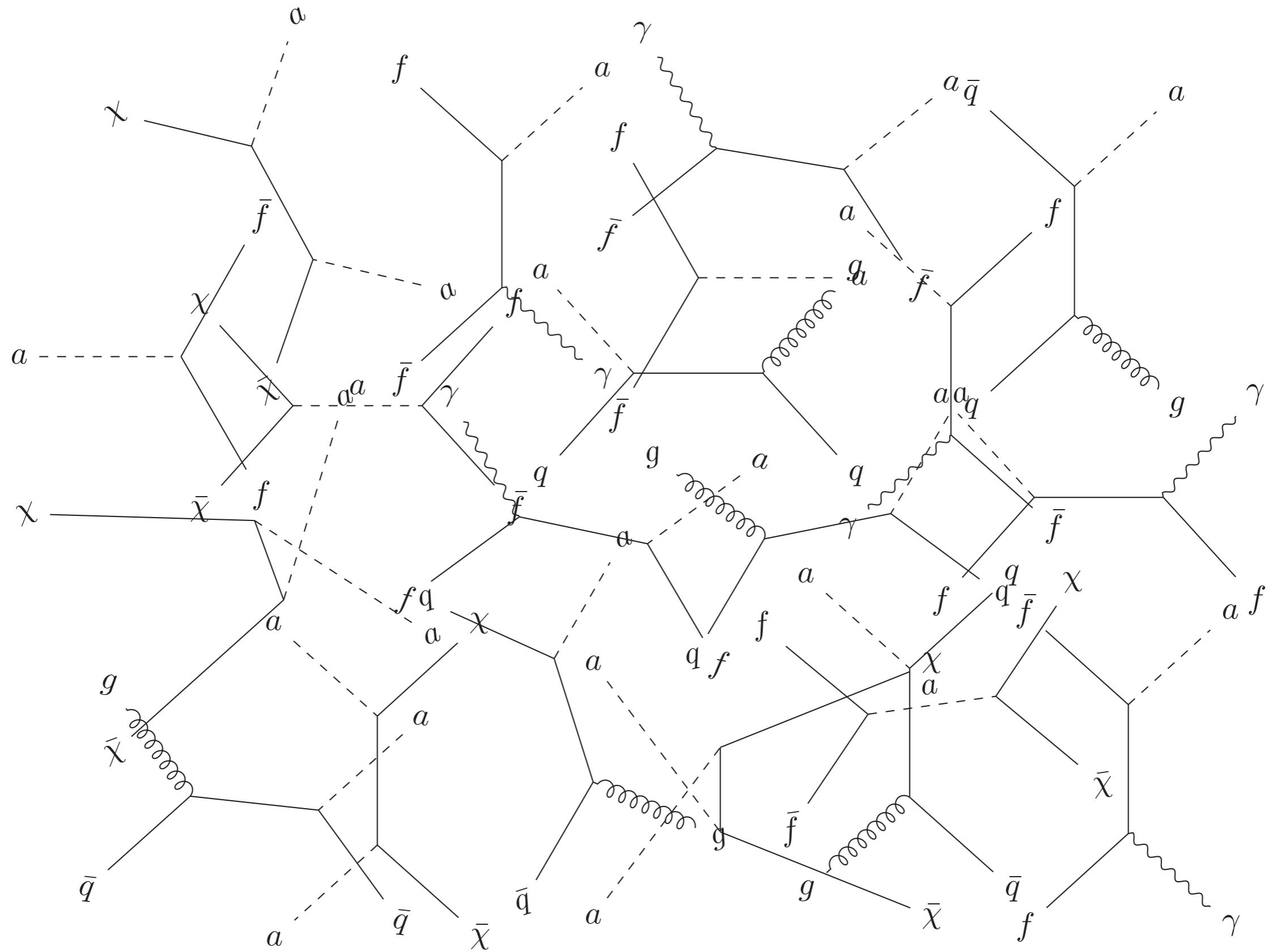
Consider simpler toy model:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \rangle (n_\chi^{\text{eq}}(T)^2 - n_\chi^2)$$

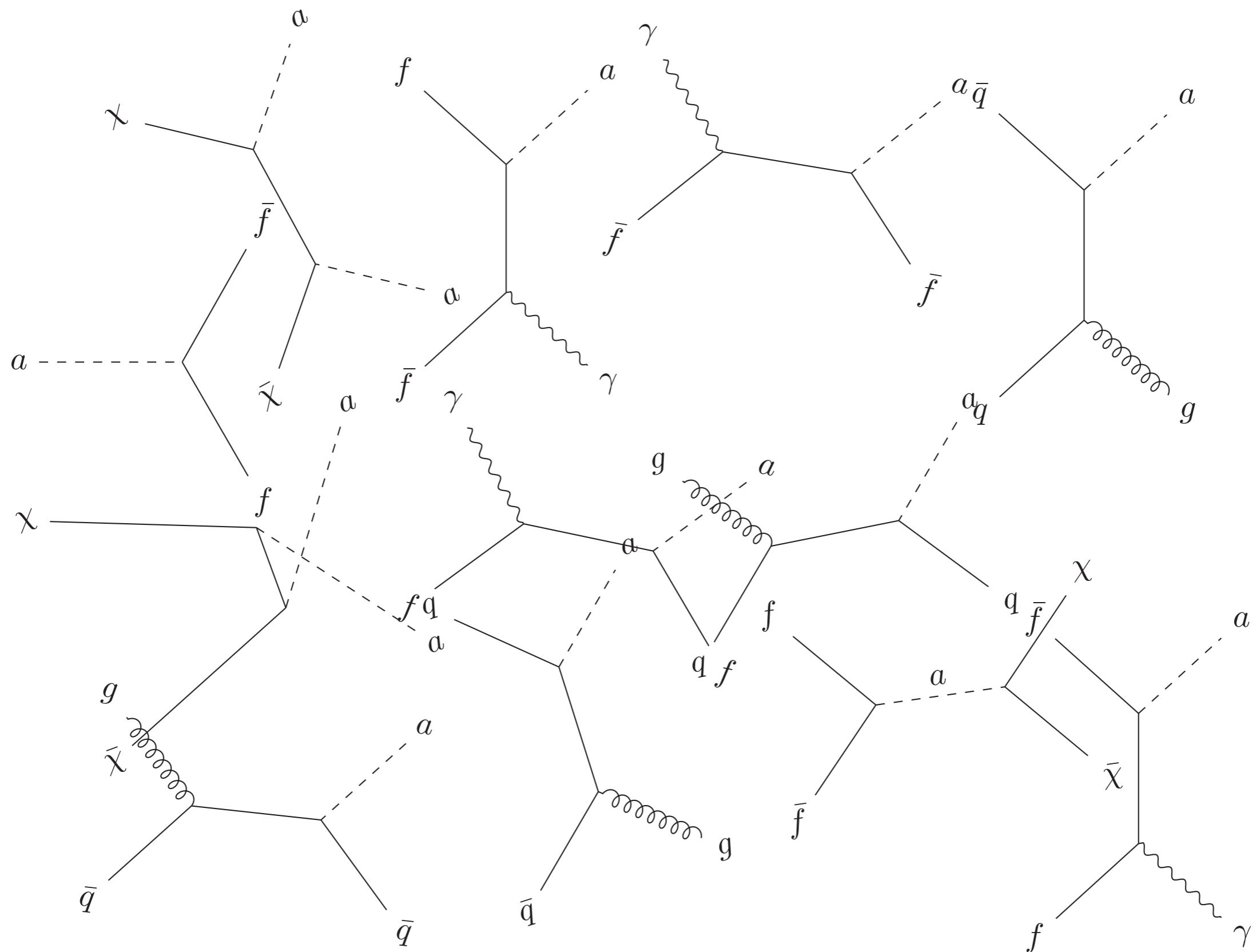


Unfortunately things not so simple! ALP also has a say...

DM and ALP number changing interactions



DM and ALP number changing interactions



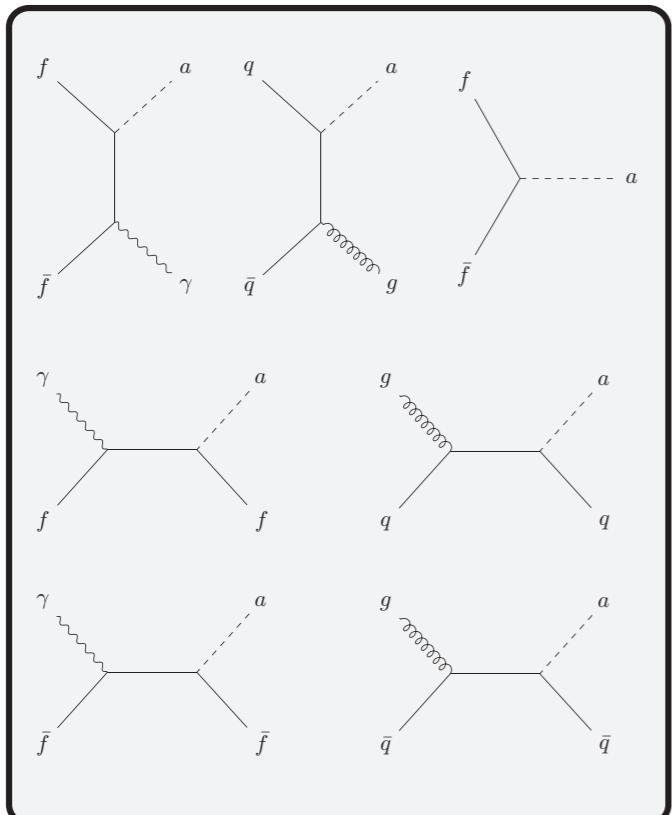
DM and ALP number changing interactions

$$\propto g_{aff}^2$$

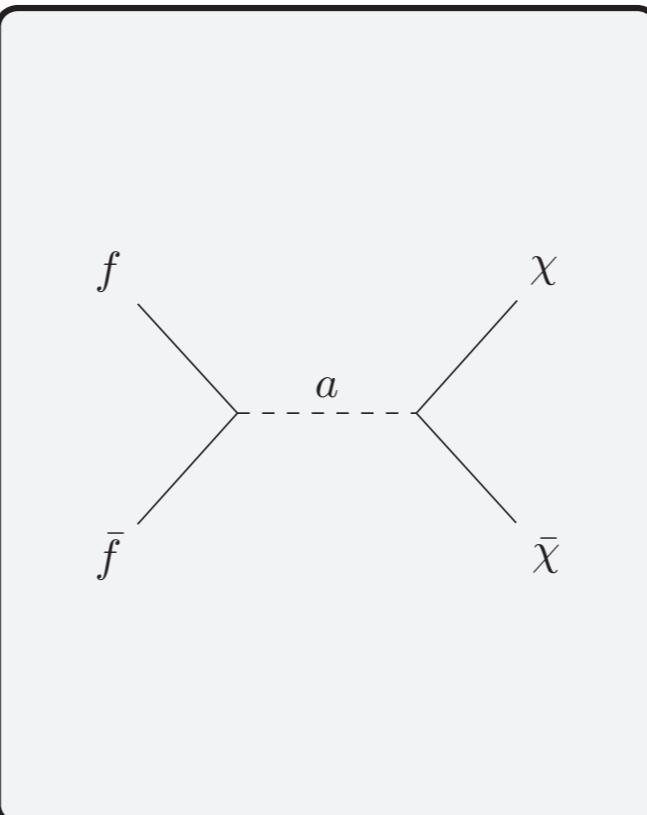
$$\propto (g_{aff} g_{a\chi\chi})^2$$

$$\propto g_{a\chi\chi}^4$$

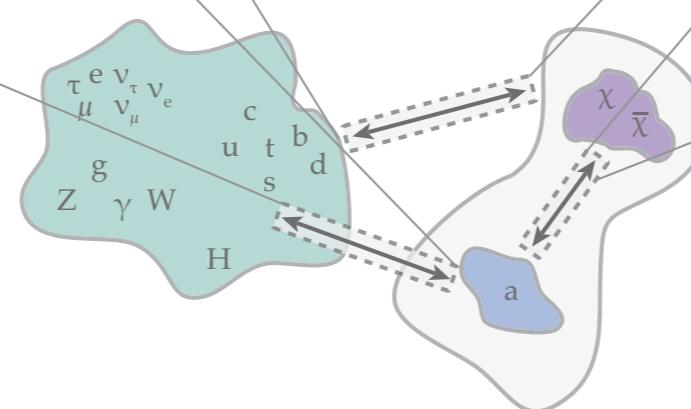
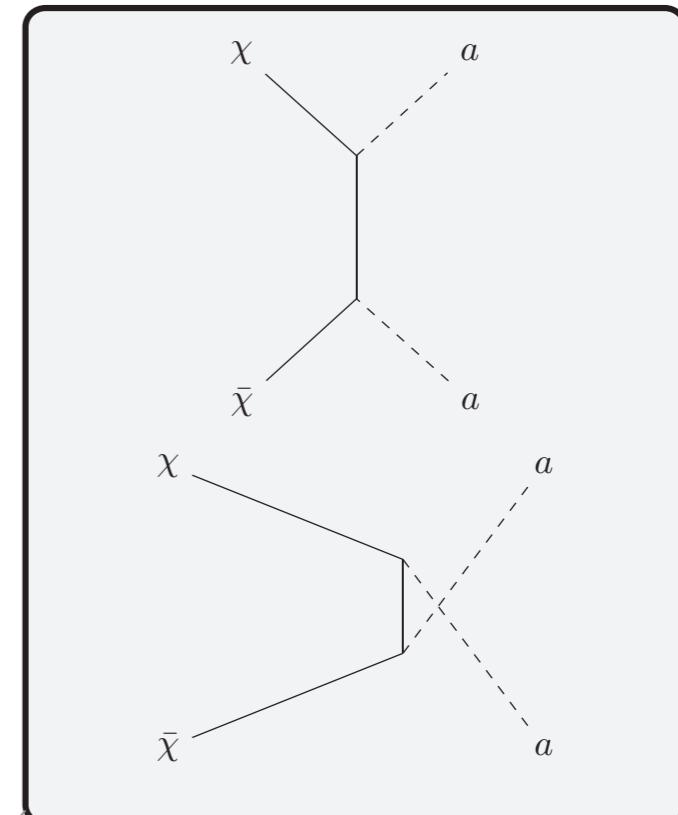
SM \leftrightarrow ALPs



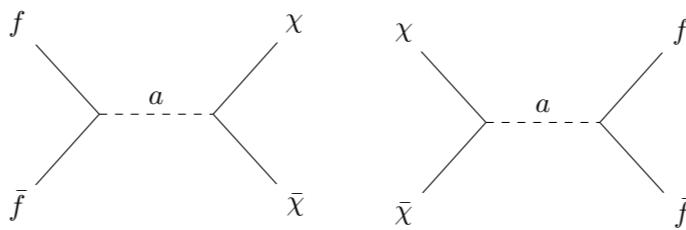
SM \leftrightarrow DM



ALPs \leftrightarrow DM

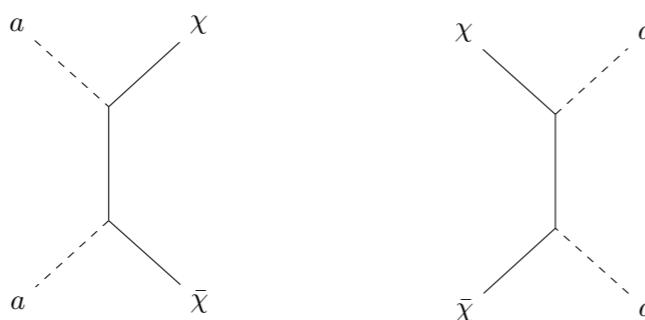


Coupled Boltzmann equations

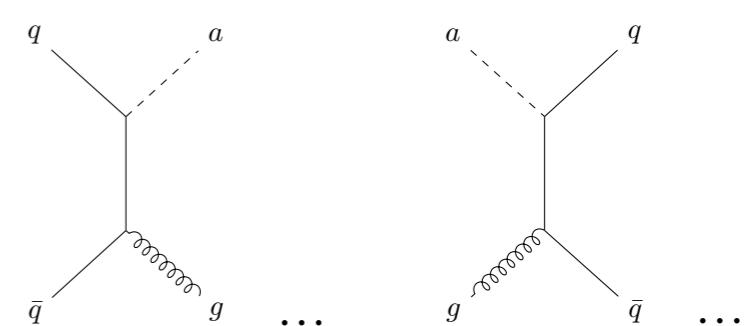
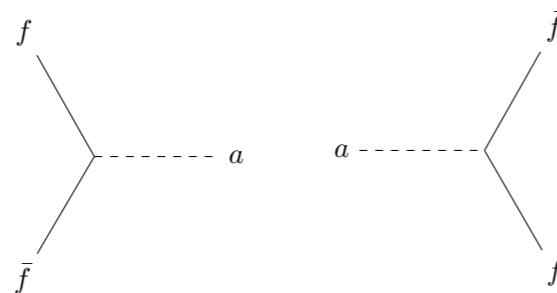


$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \right\rangle \left(\overbrace{(n_\chi^{\text{eq}}(T))^2}^{} - \overbrace{n_\chi^2}^{} \right)$$

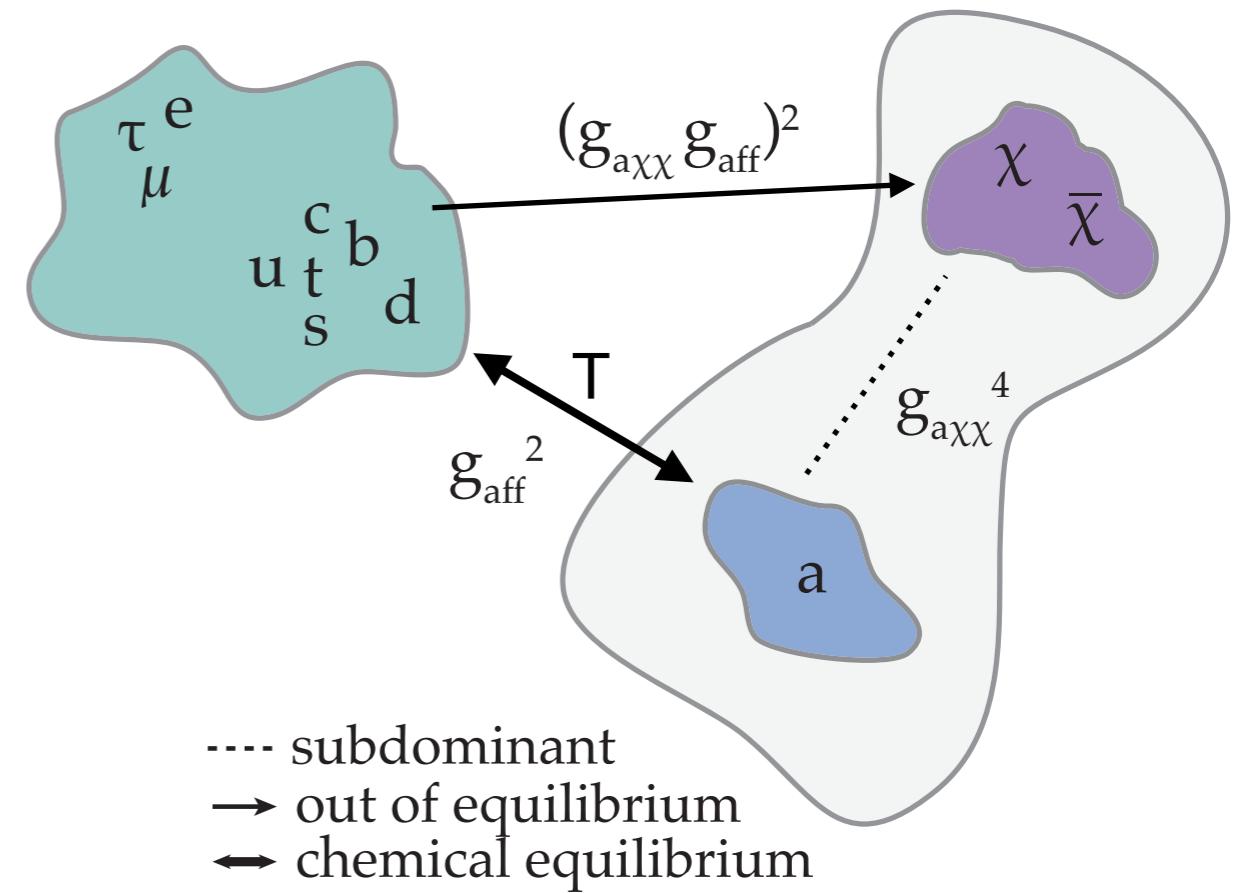
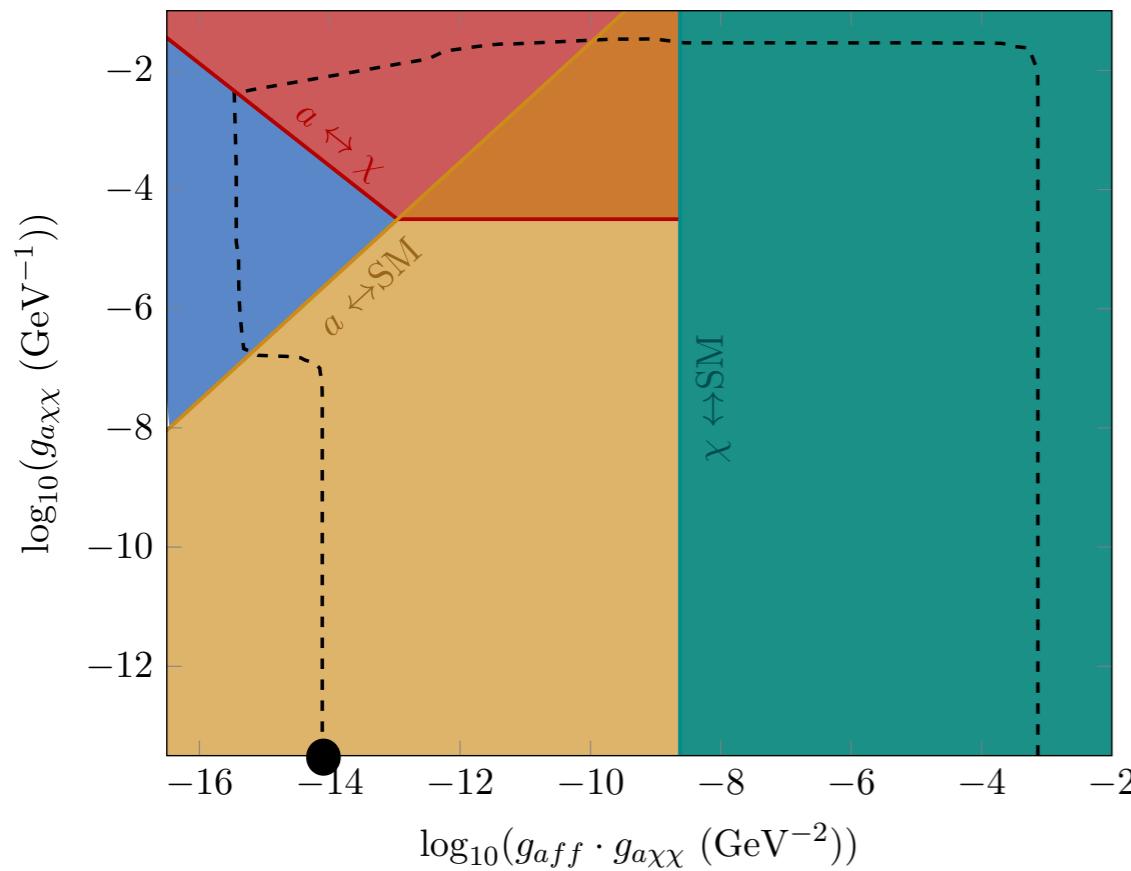
$$+ \underbrace{\left\langle \sigma_{aa \rightarrow \chi\bar{\chi}} v \right\rangle n_a^2}_{\text{annihilation}} - \underbrace{\left\langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \right\rangle n_\chi^2}_{\text{creation}}$$



$$\frac{dn_a}{dt} + 3Hn_a = - \overbrace{\left\langle \sigma_{aa \rightarrow \chi\bar{\chi}} v \right\rangle n_a^2}^{} + \overbrace{\left\langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \right\rangle n_\chi^2}^{} + \langle \Gamma_a \rangle \left(\underbrace{n_a^{\text{eq}}(T)}_{} - \underbrace{n_a}_{} \right) + \sum_{i,j,k} \left\langle \sigma_{ai \rightarrow jk} v \right\rangle \left(\underbrace{n_a^{\text{eq}}(T)n_i^{\text{eq}}(T)}_{} - \underbrace{n_a n_i^{\text{eq}}(T)}_{} \right)$$



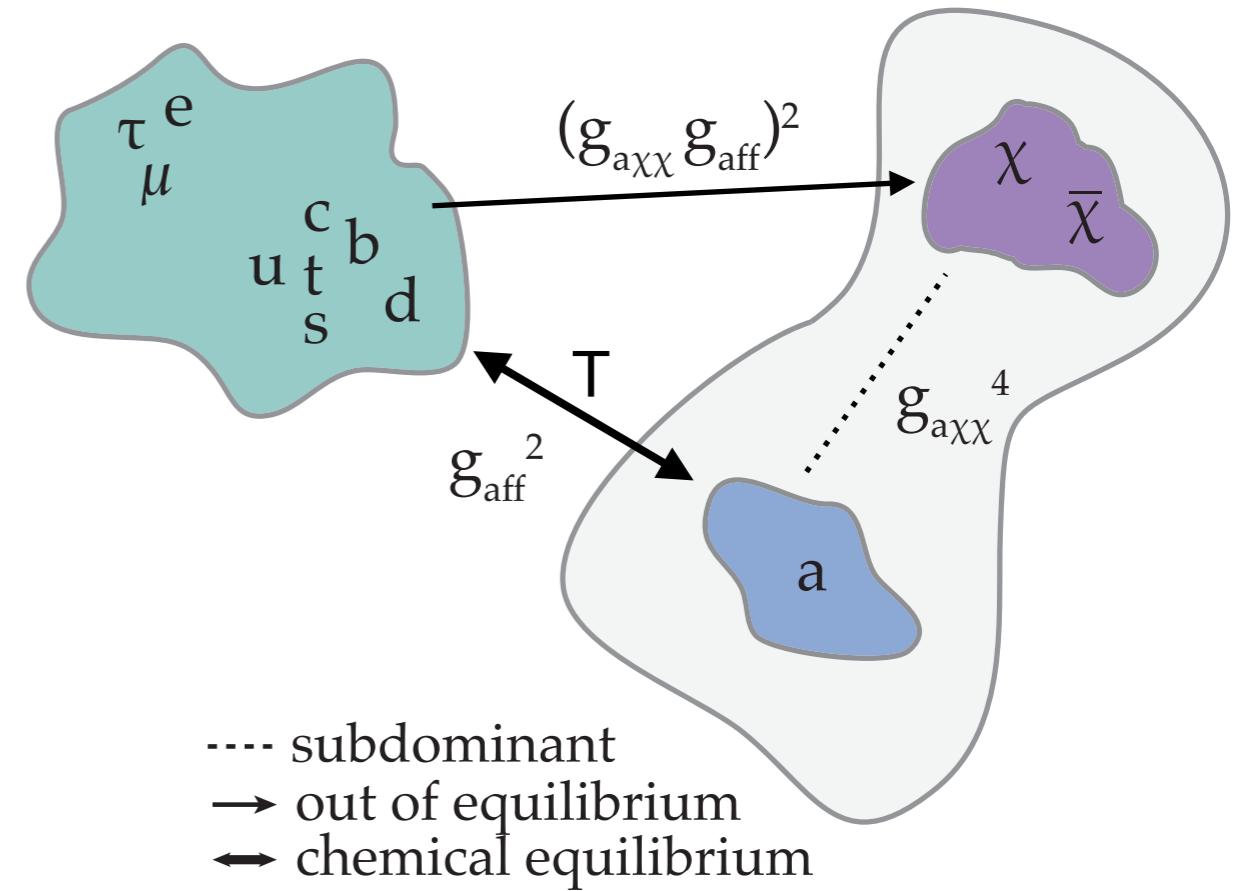
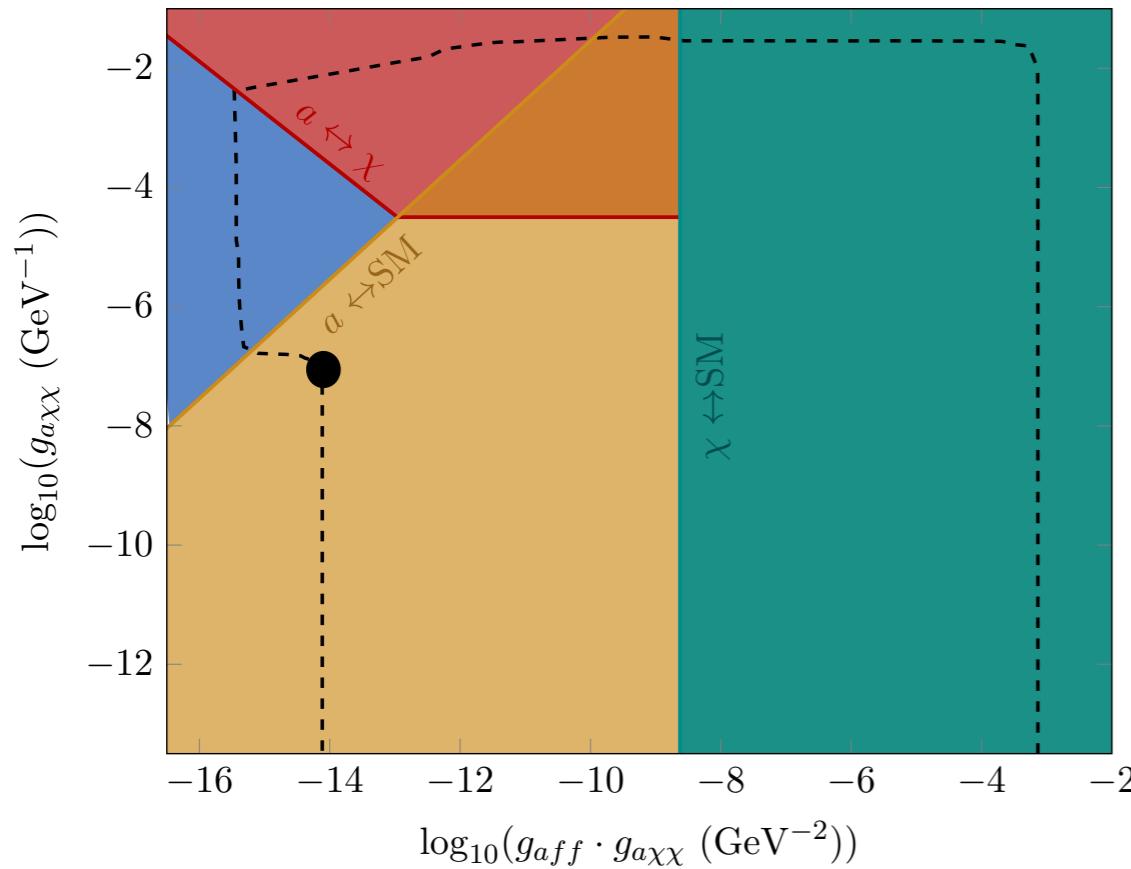
Freeze-in from SM



$$m_\chi = 10 \text{ GeV}, m_a = 1 \text{ GeV}$$

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

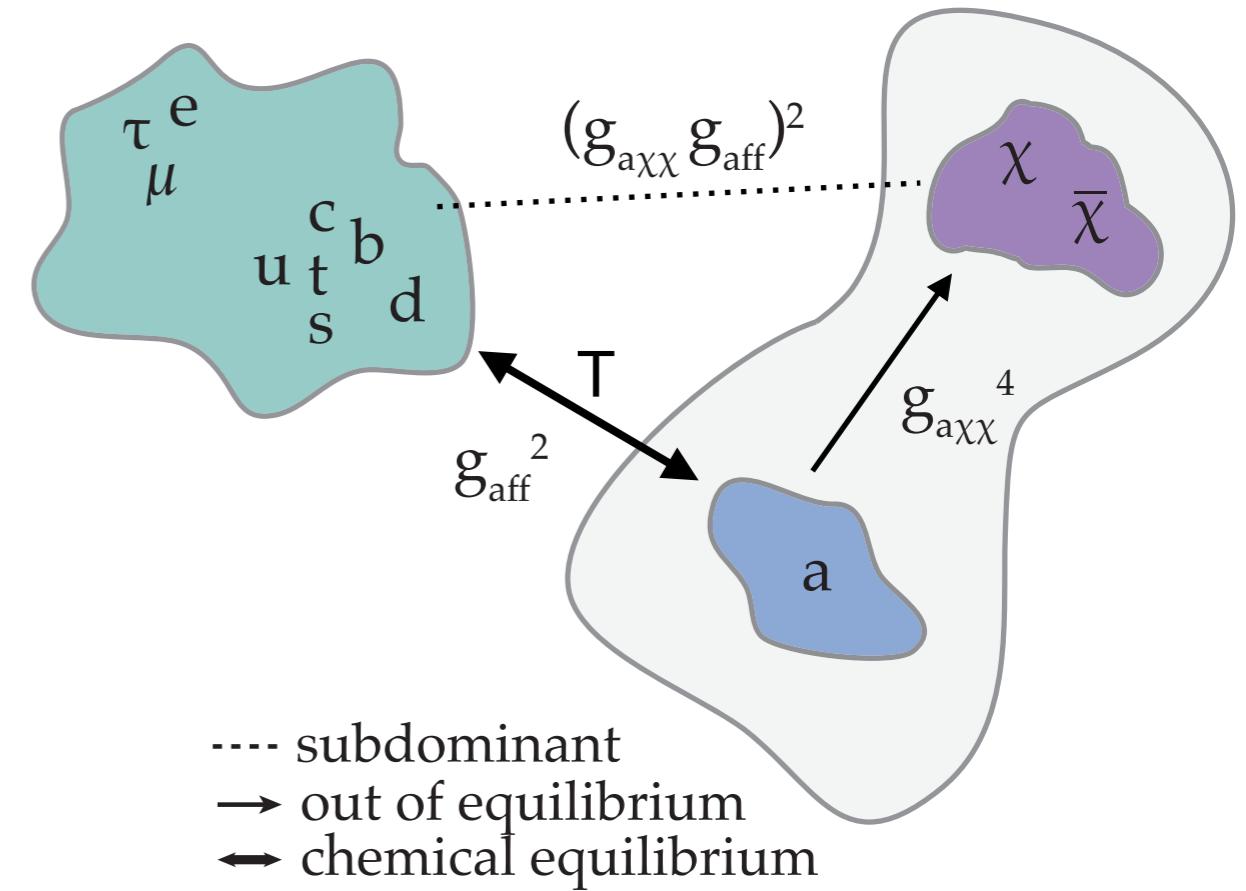
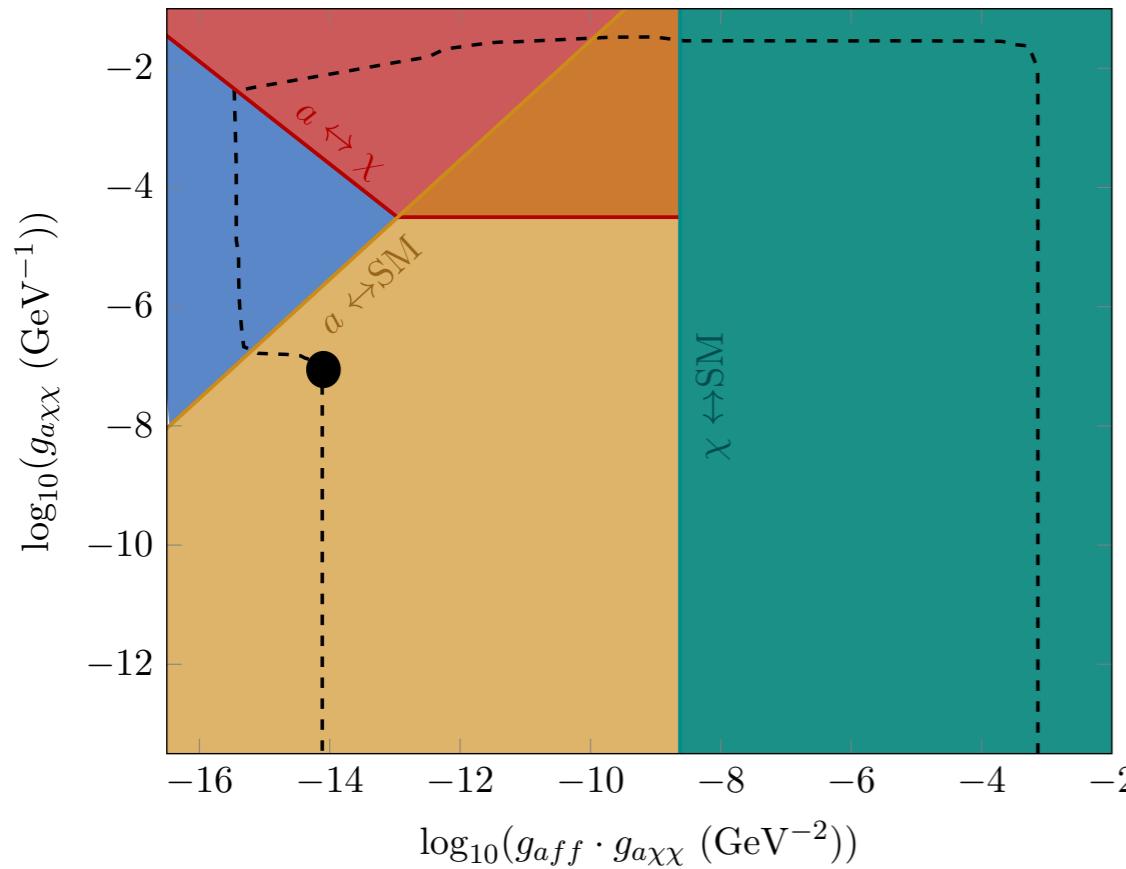
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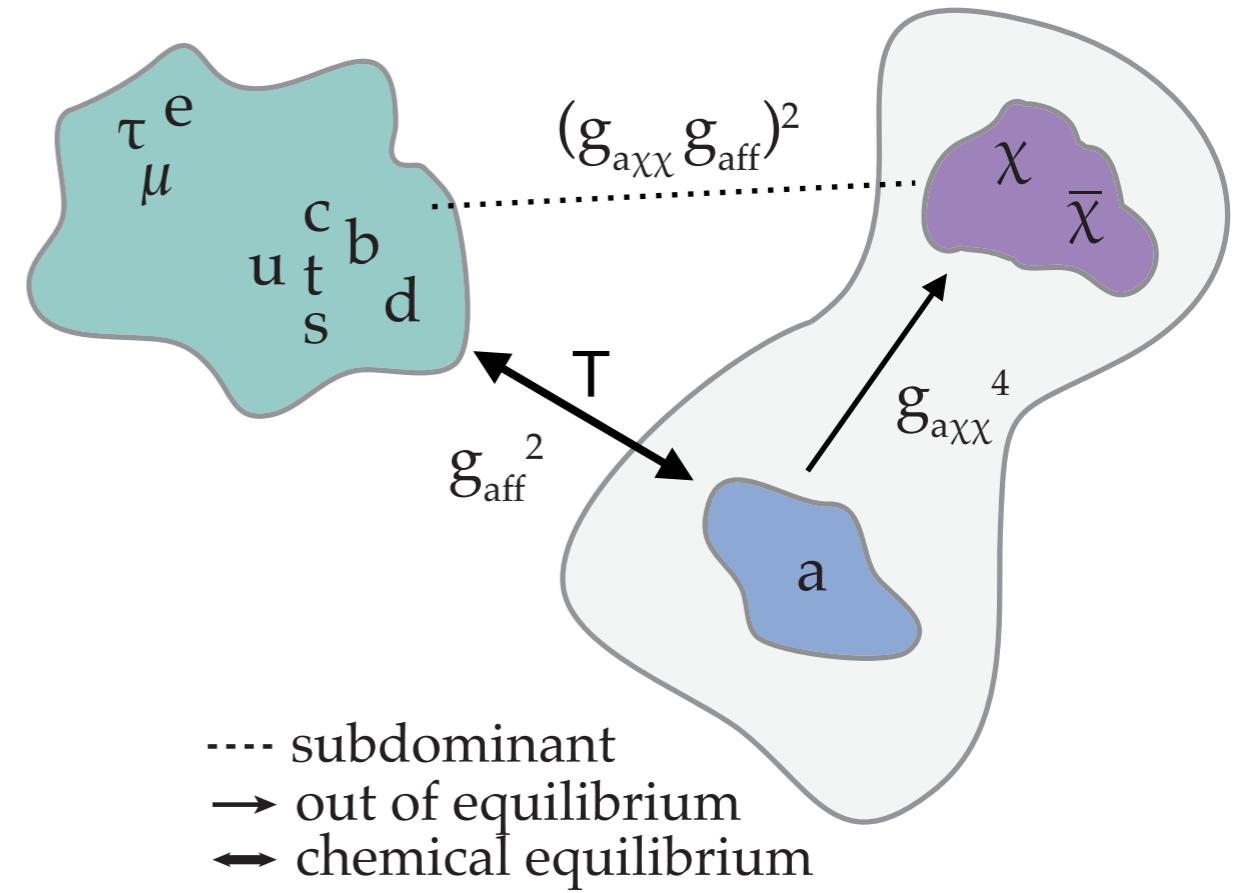
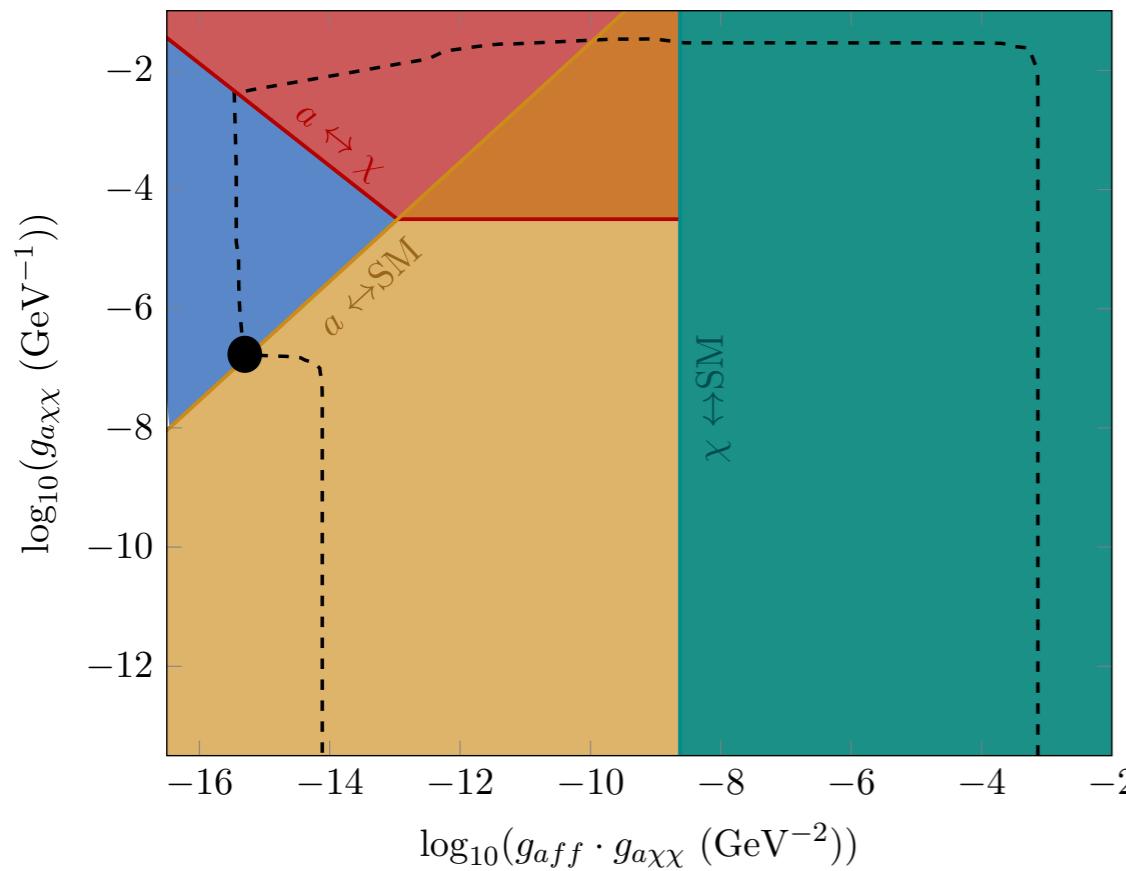
Freeze-in from the mediator



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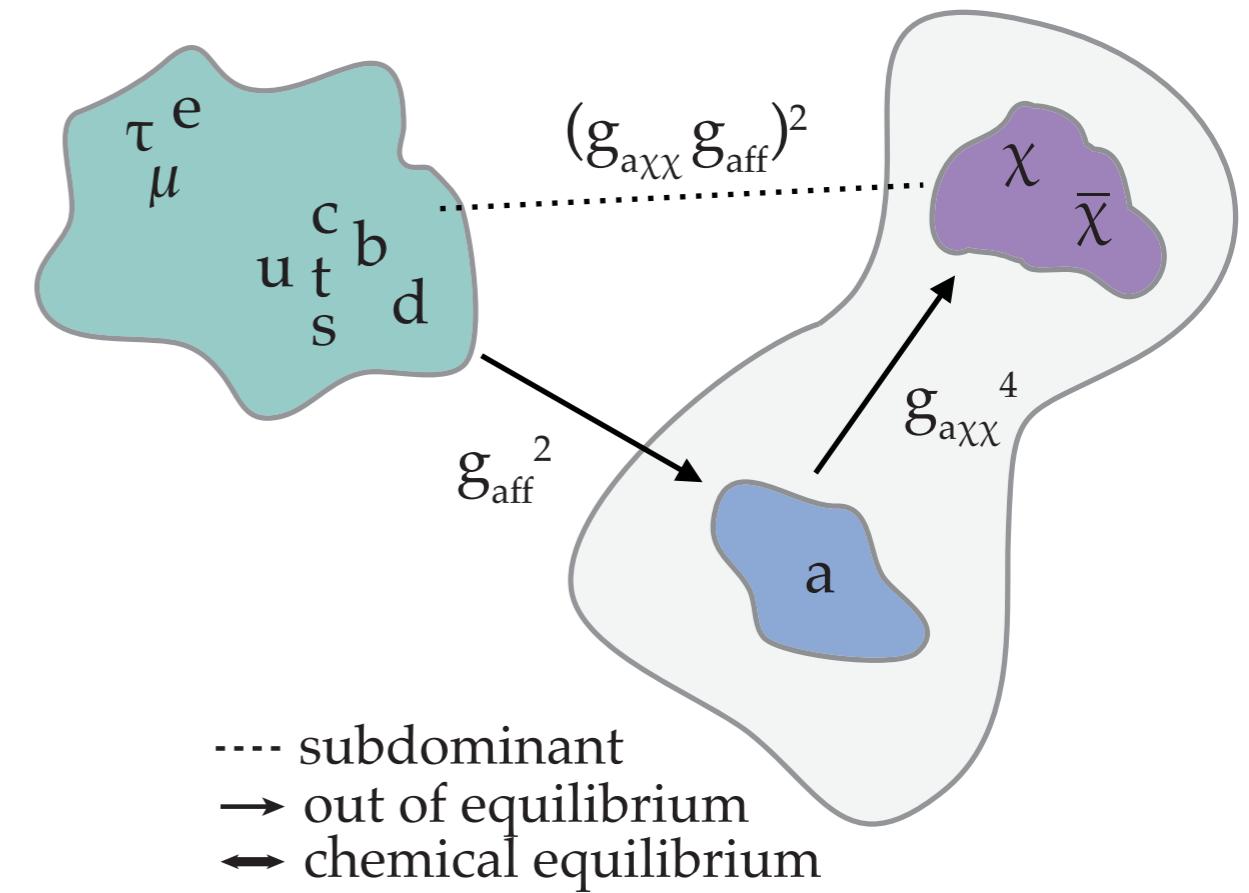
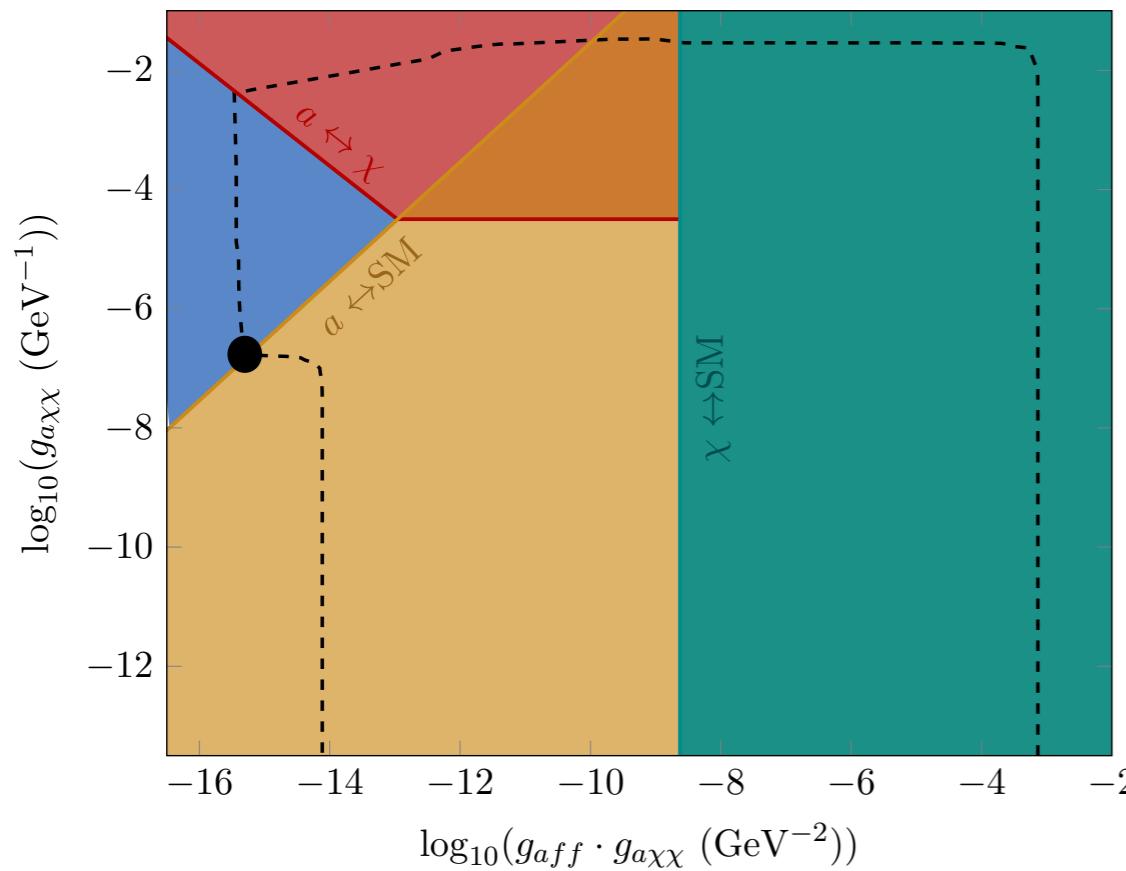
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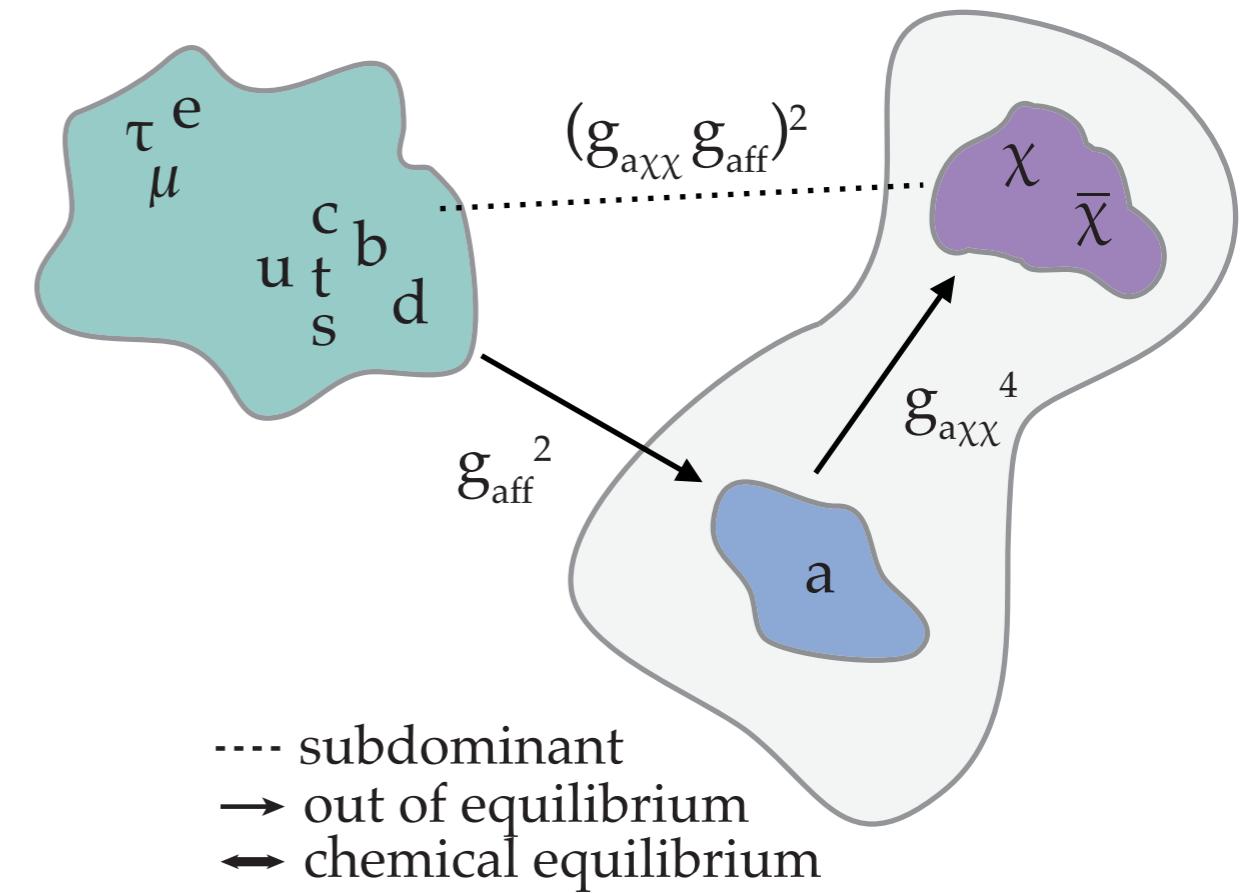
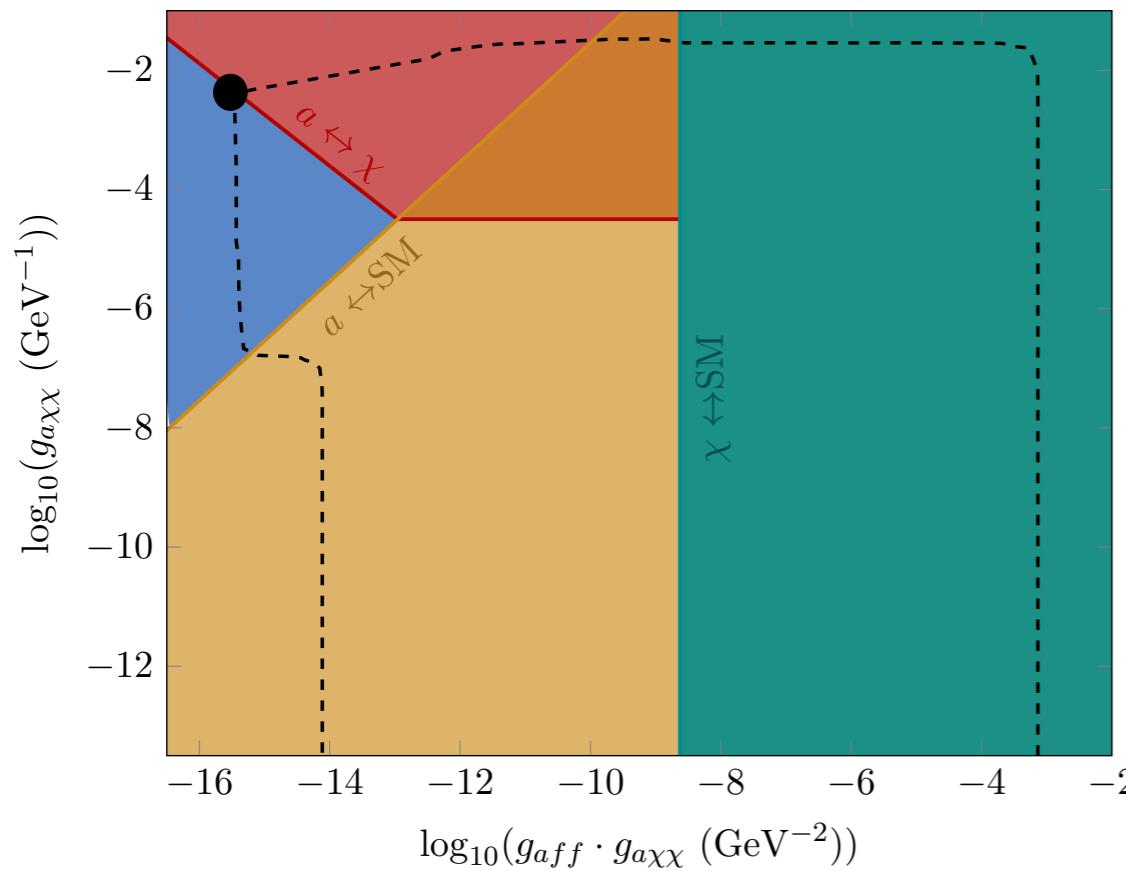
Sequential freeze-in



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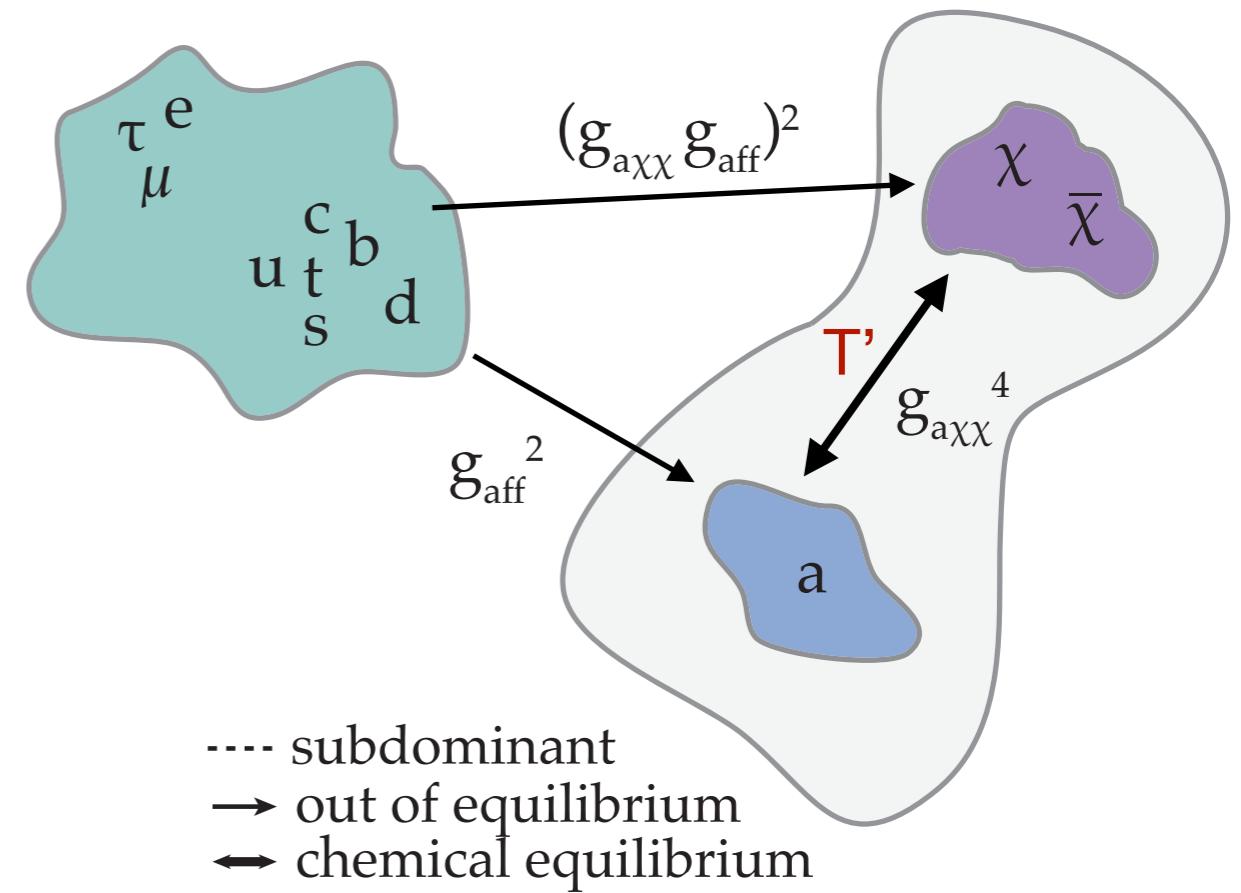
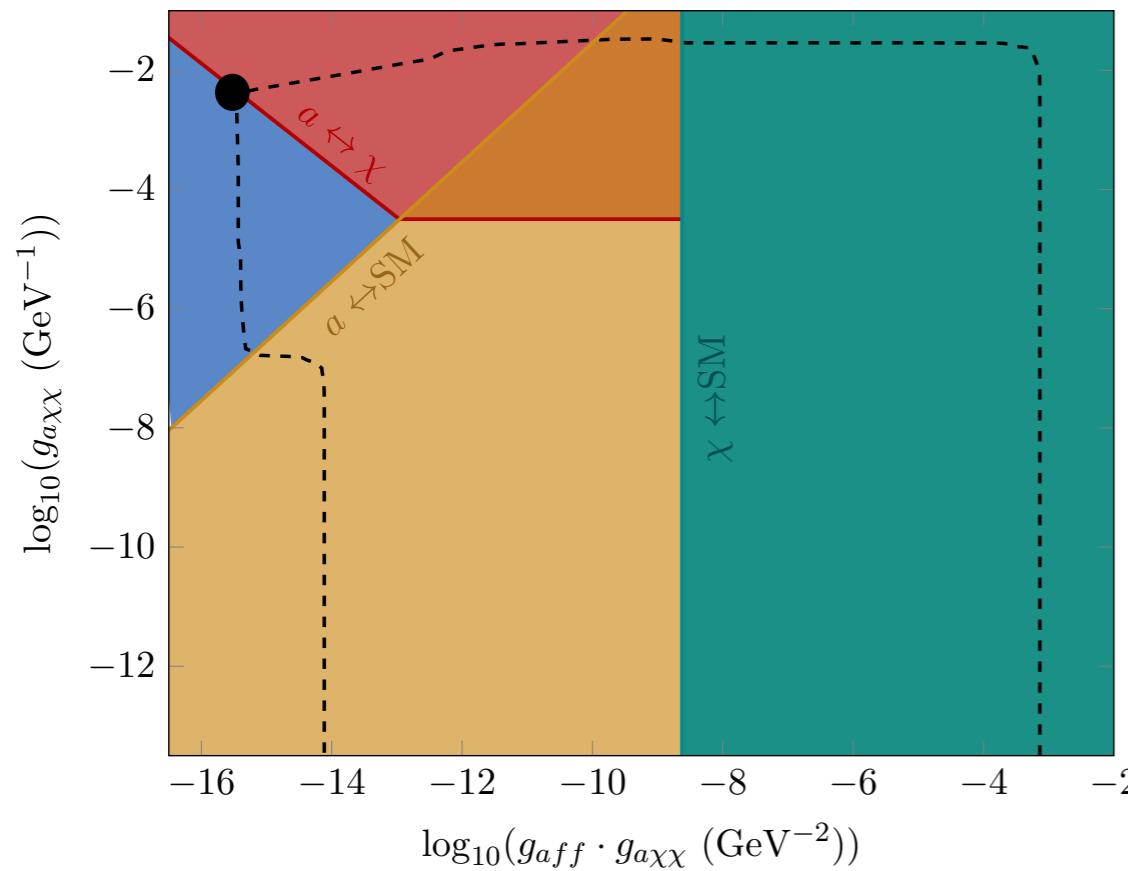
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Freeze-out from a decoupled dark sector (FODDS)



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Freeze-out from a decoupled dark sector (FODDS)

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

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

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

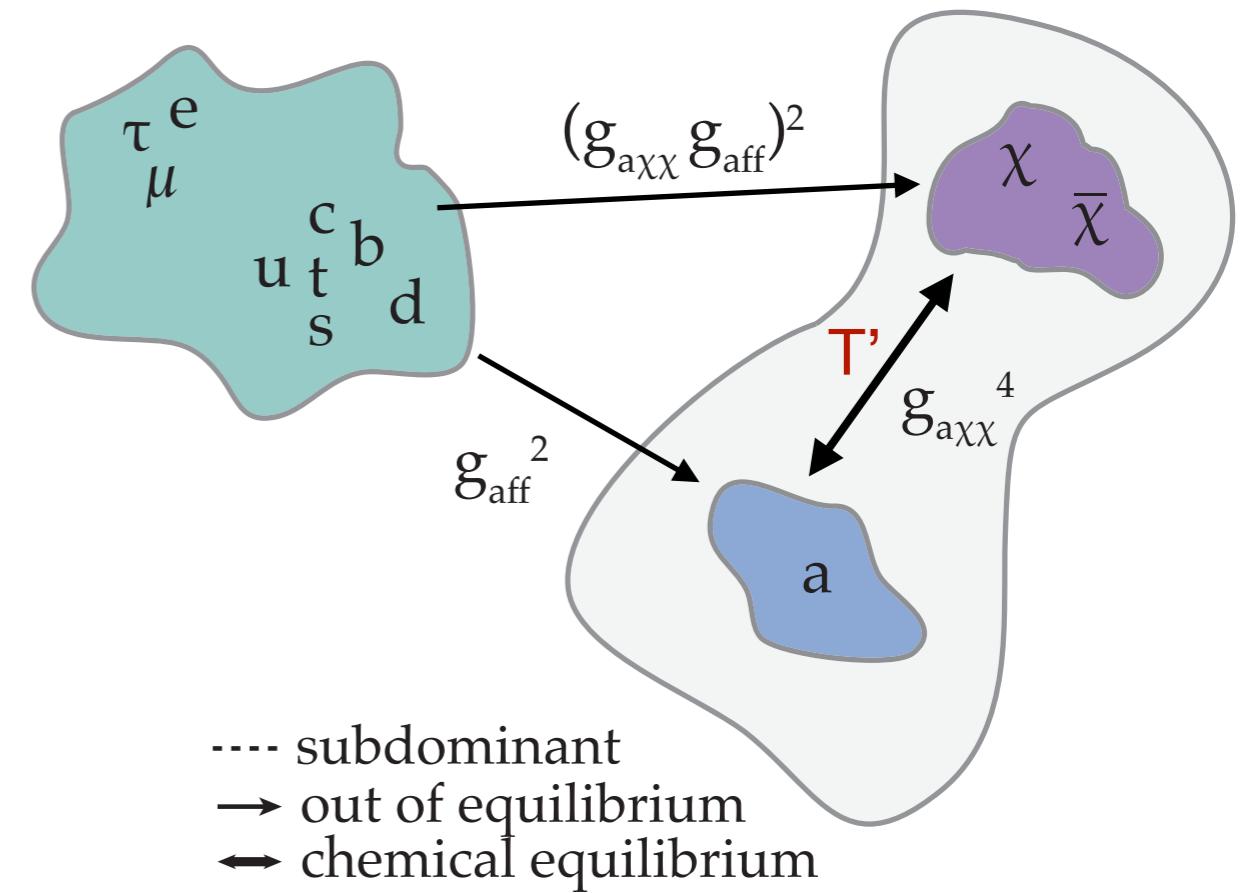
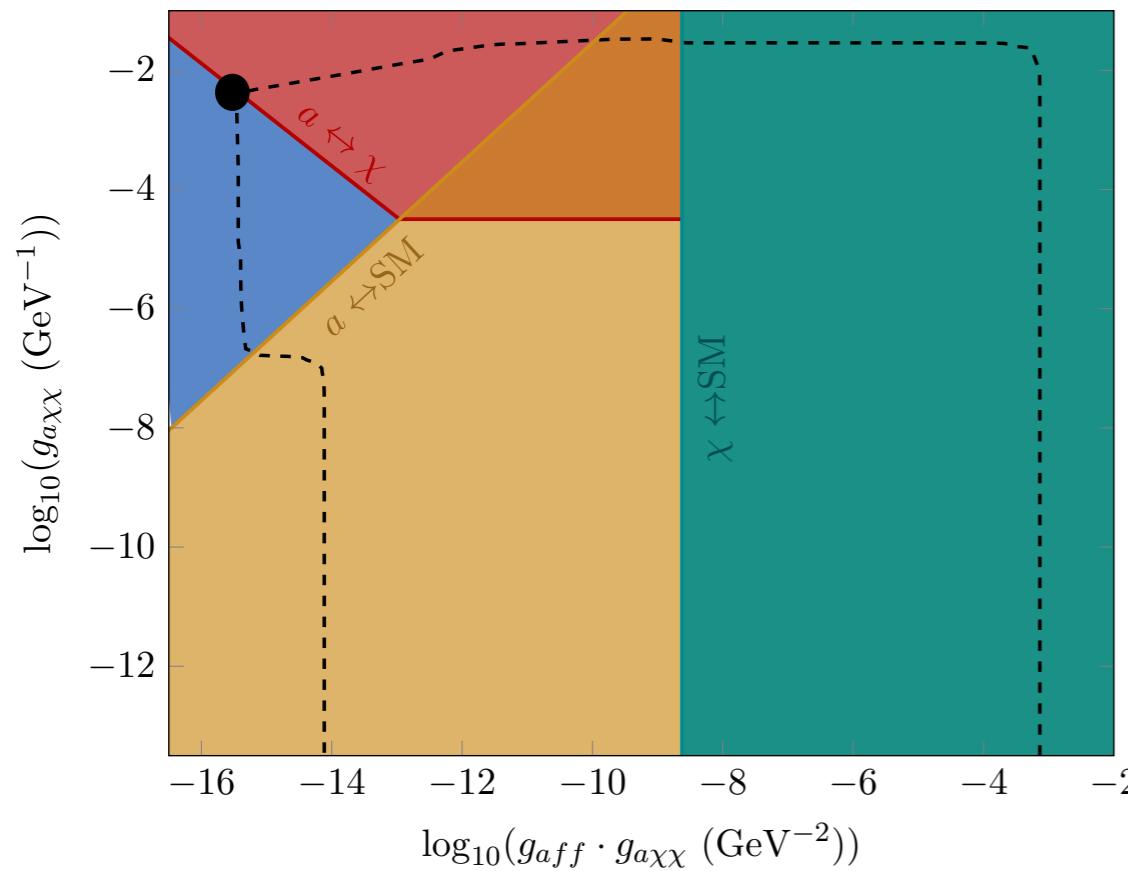
$\log_{10}(g_{aff} \cdot g_{a\chi\chi} \text{ (GeV}^{-2}))$

\longleftrightarrow chemical equilibrium

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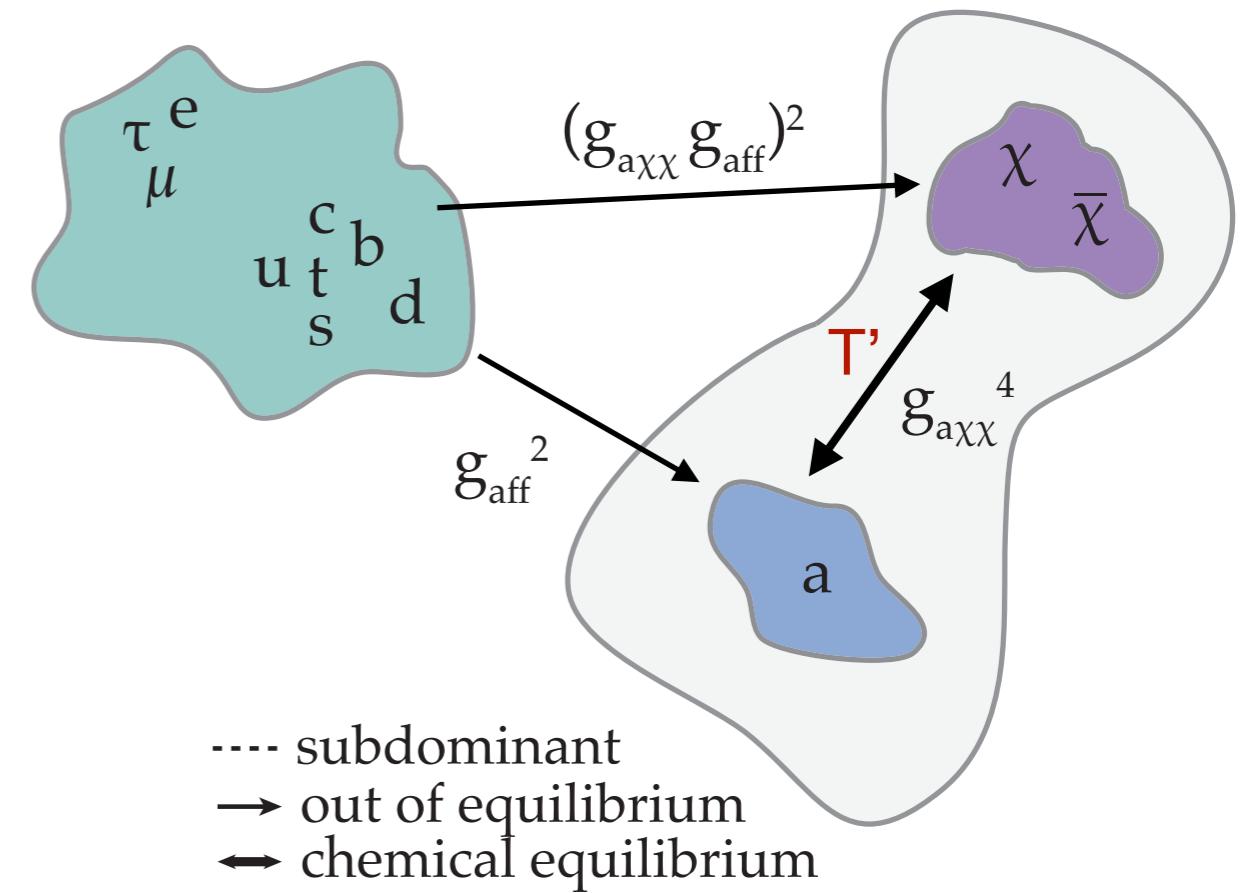
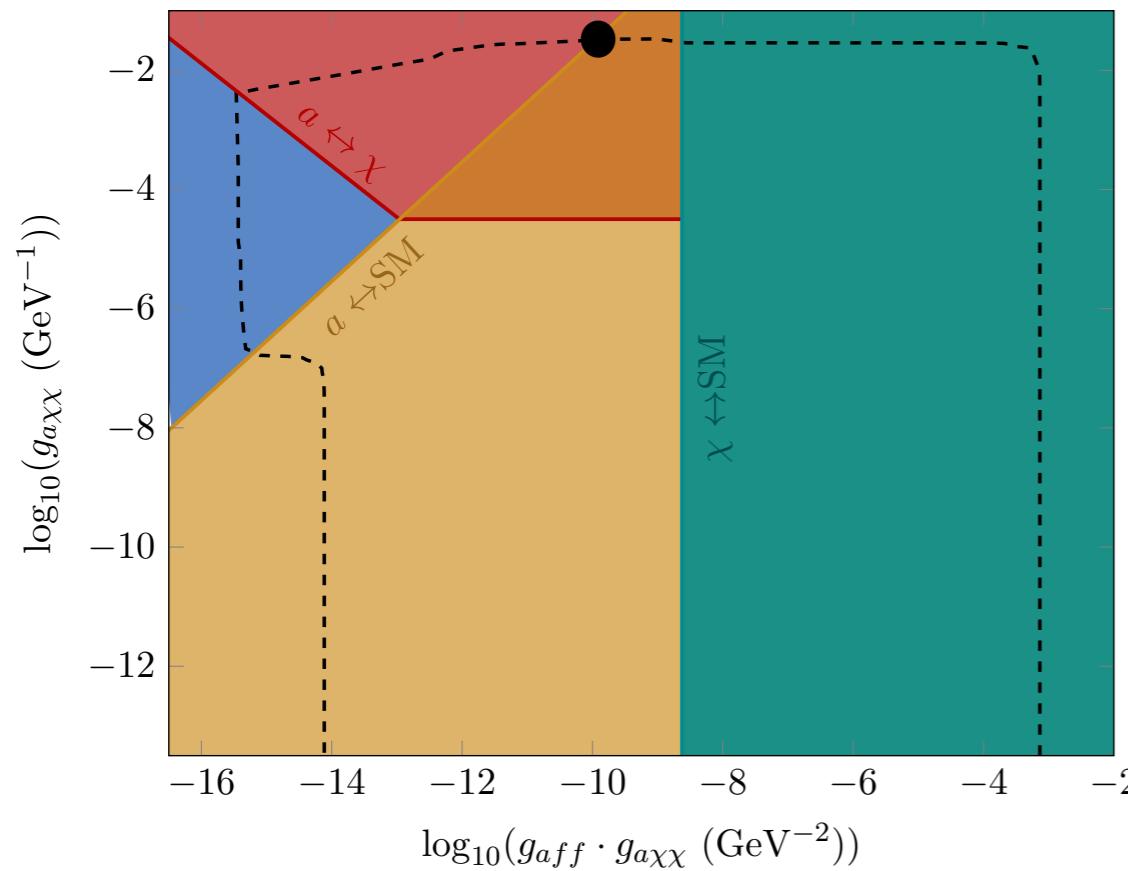
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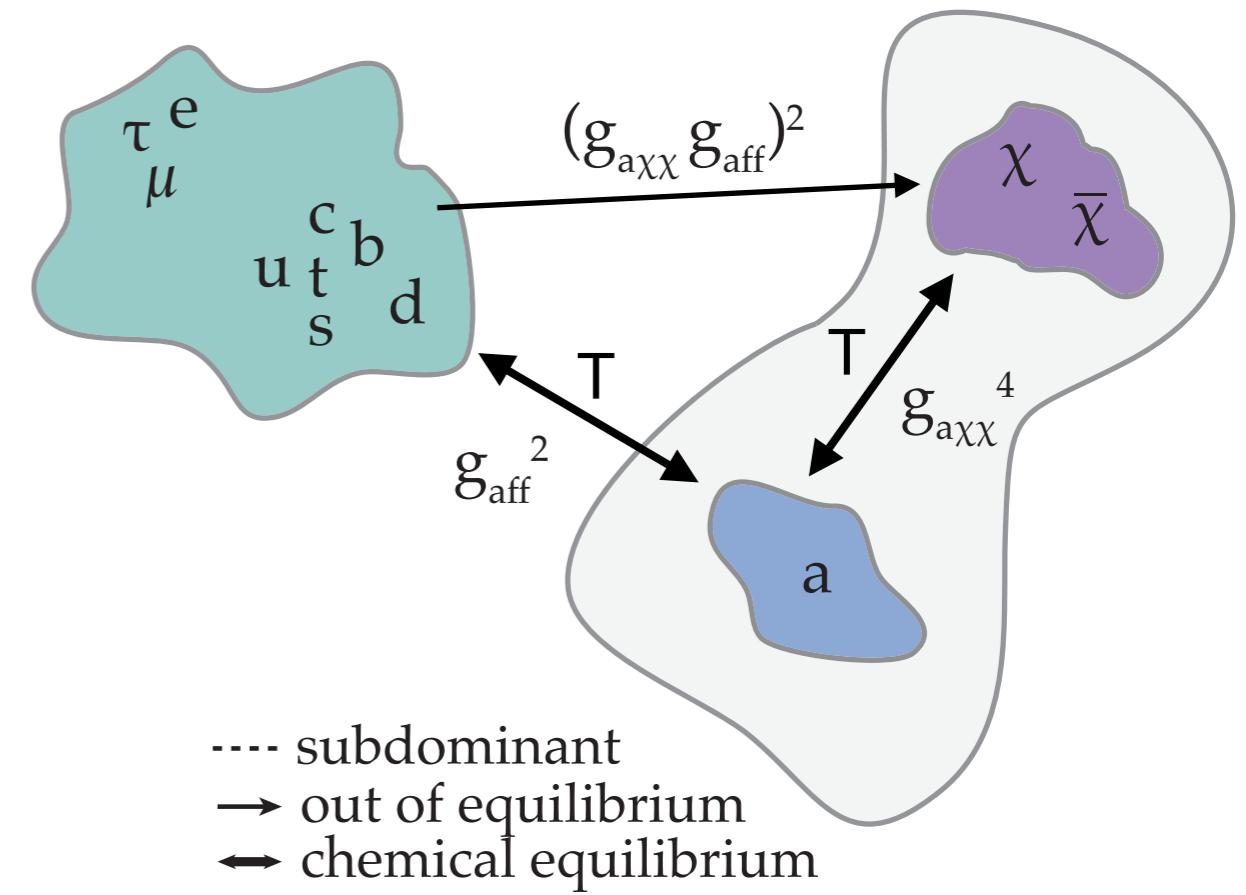
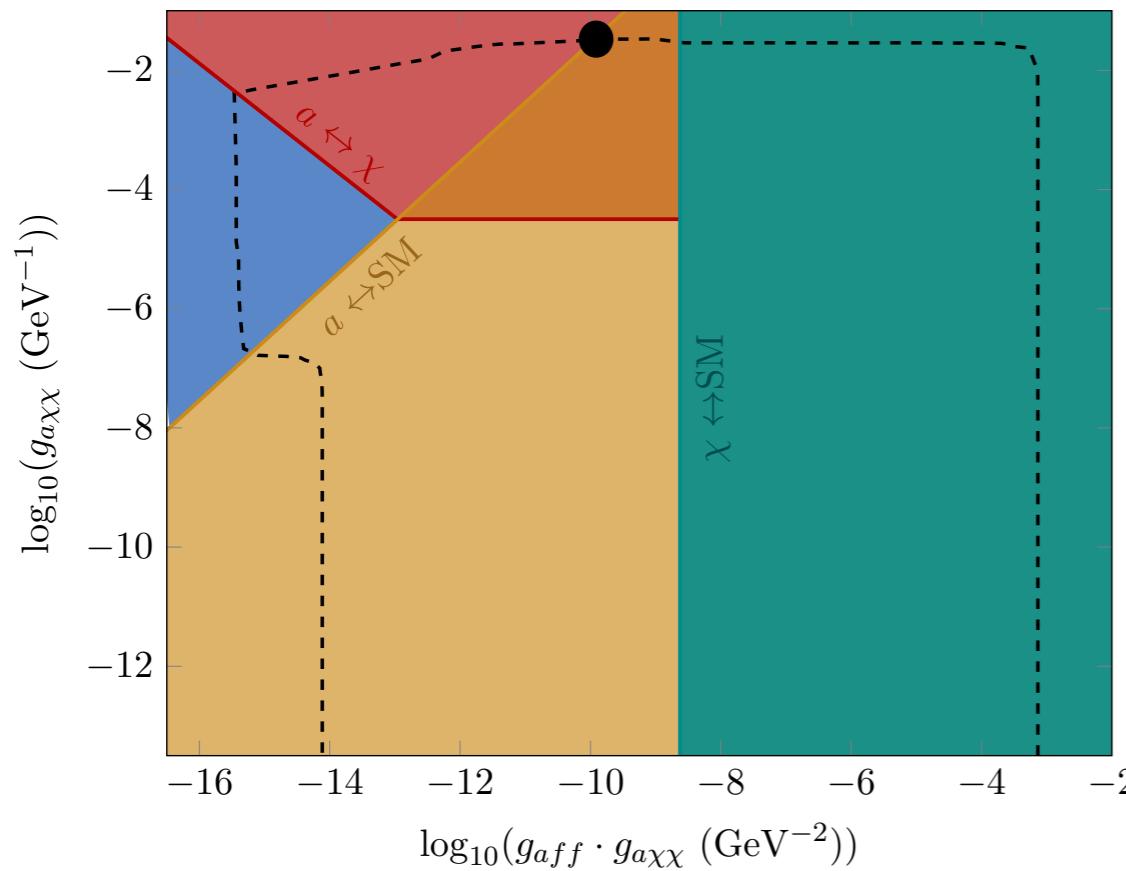
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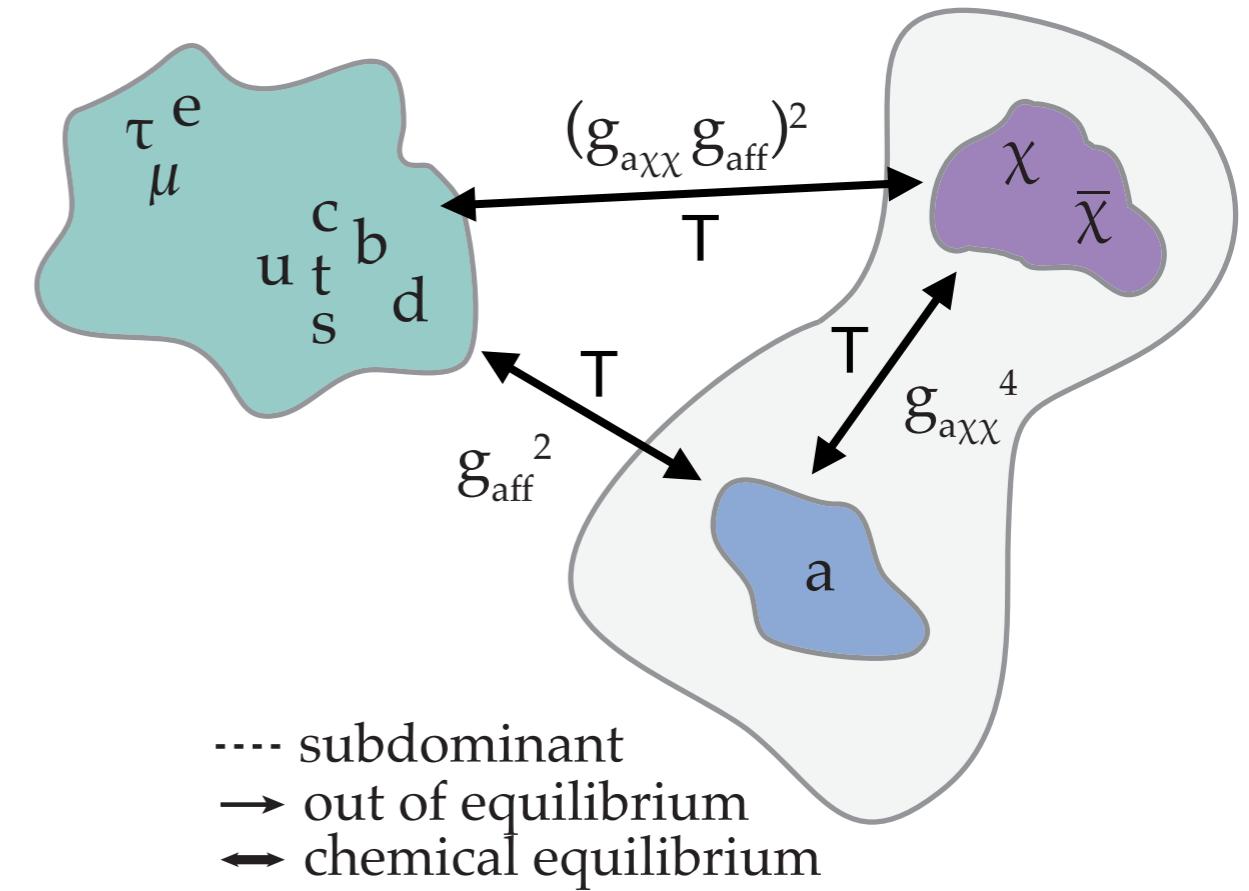
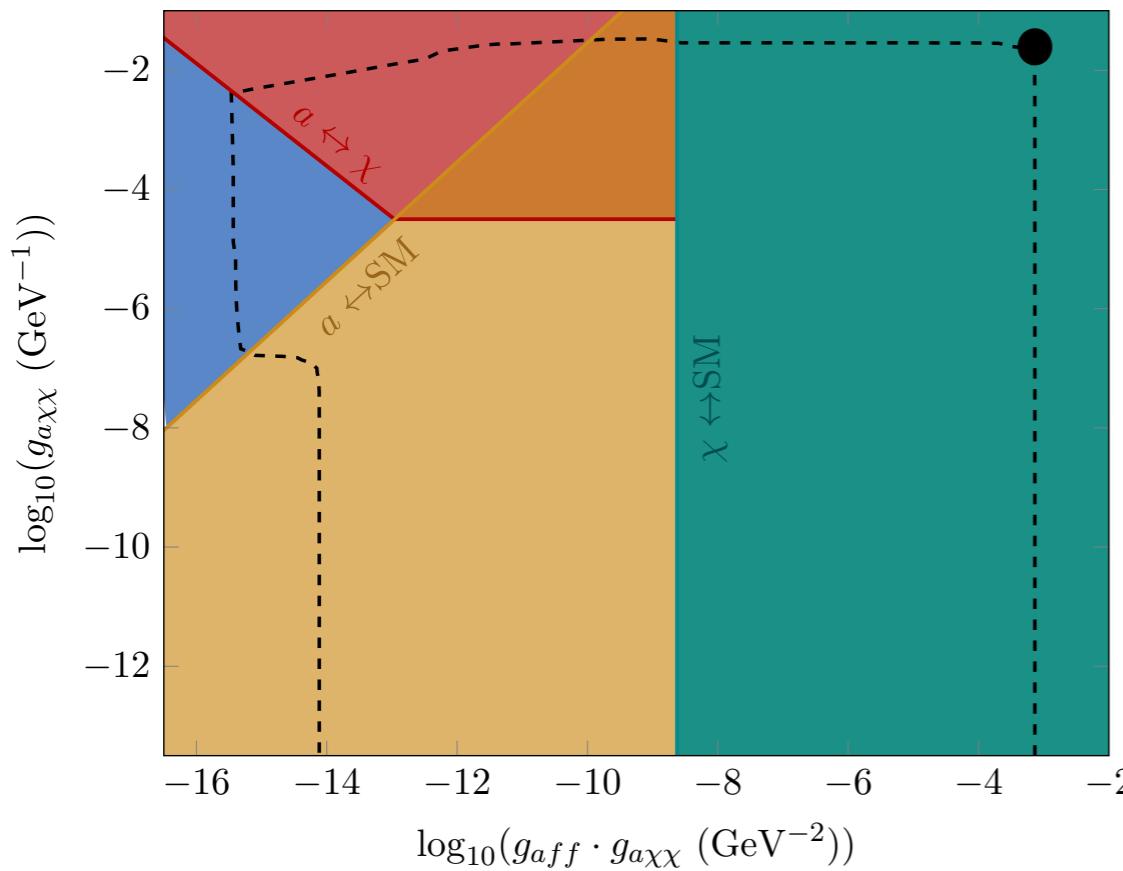
Freeze-out from the mediator



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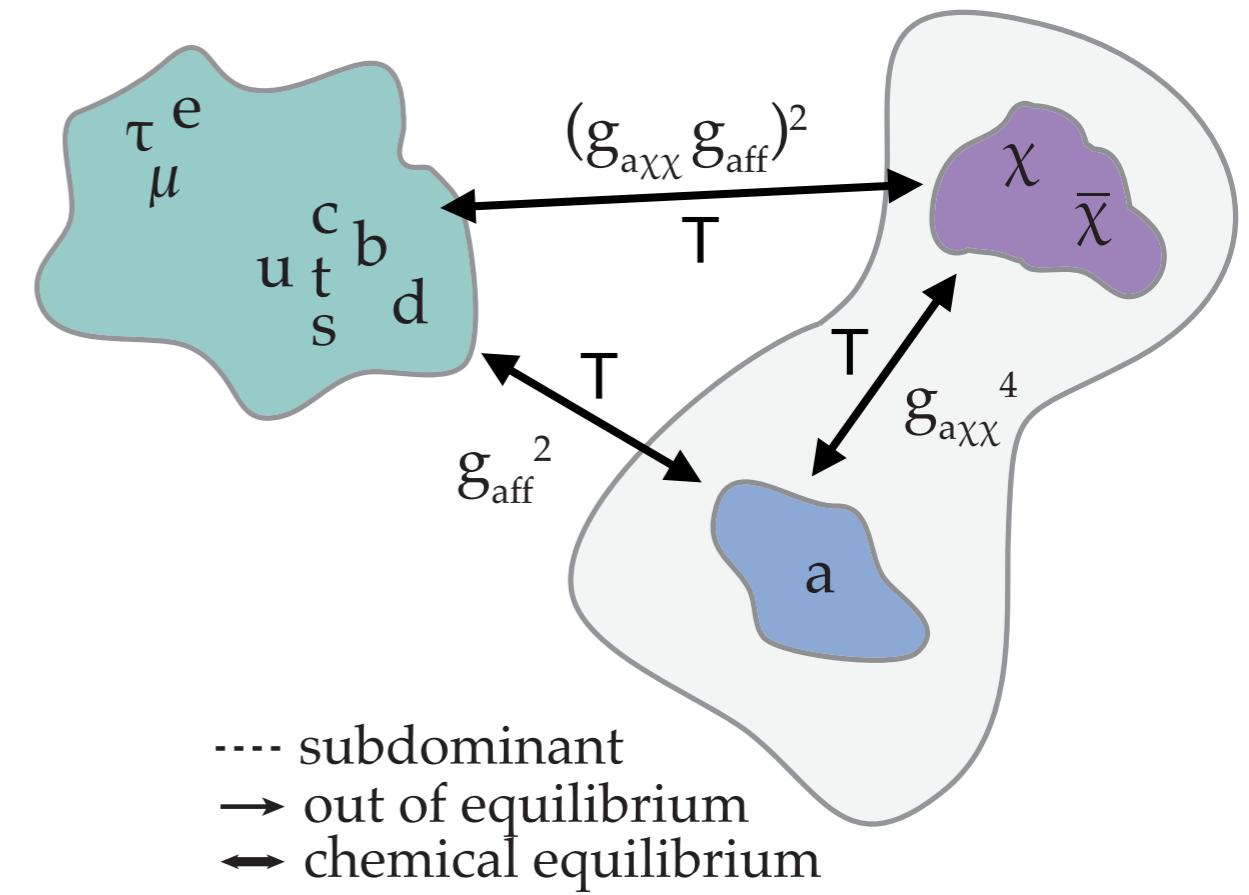
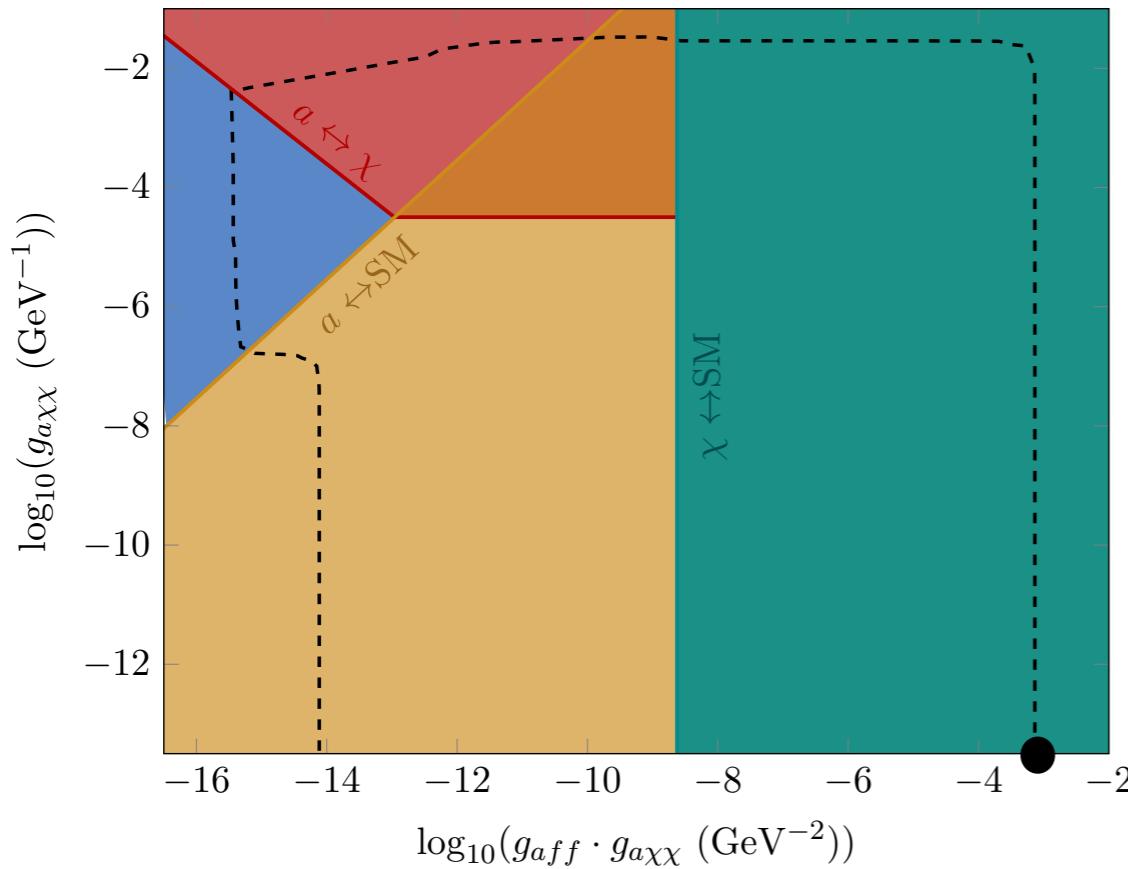
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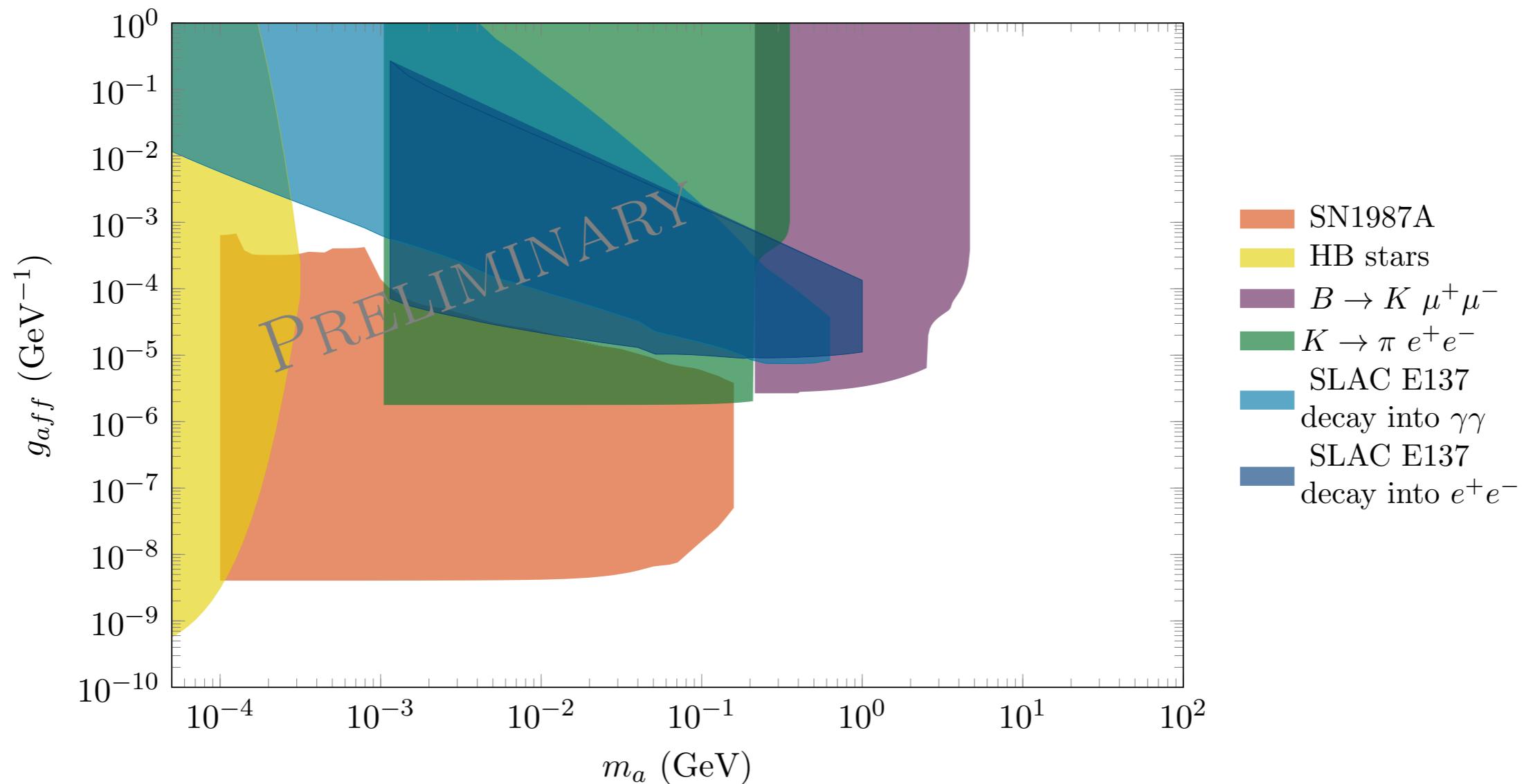
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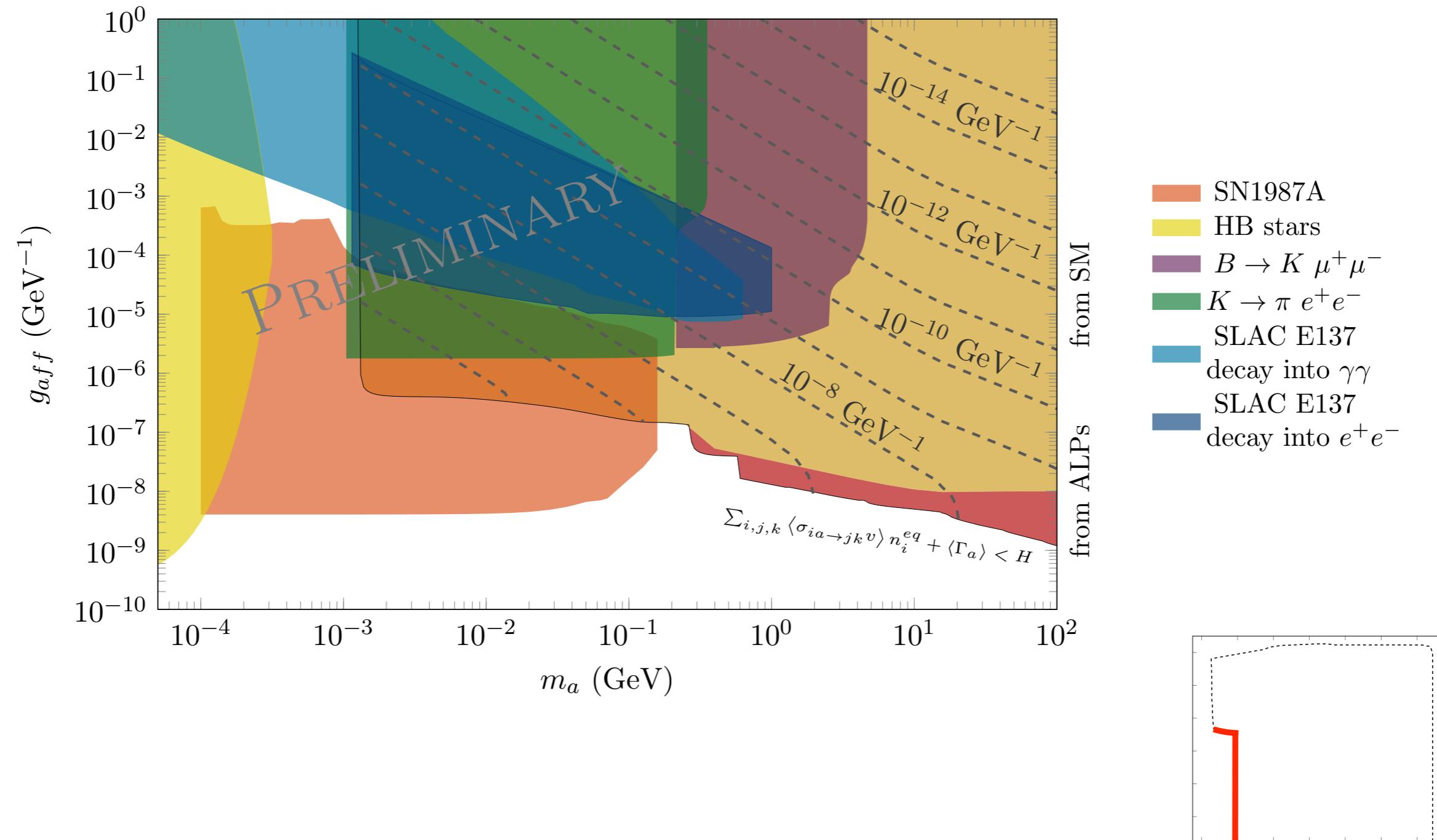
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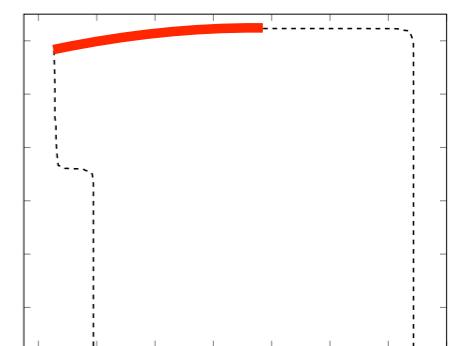
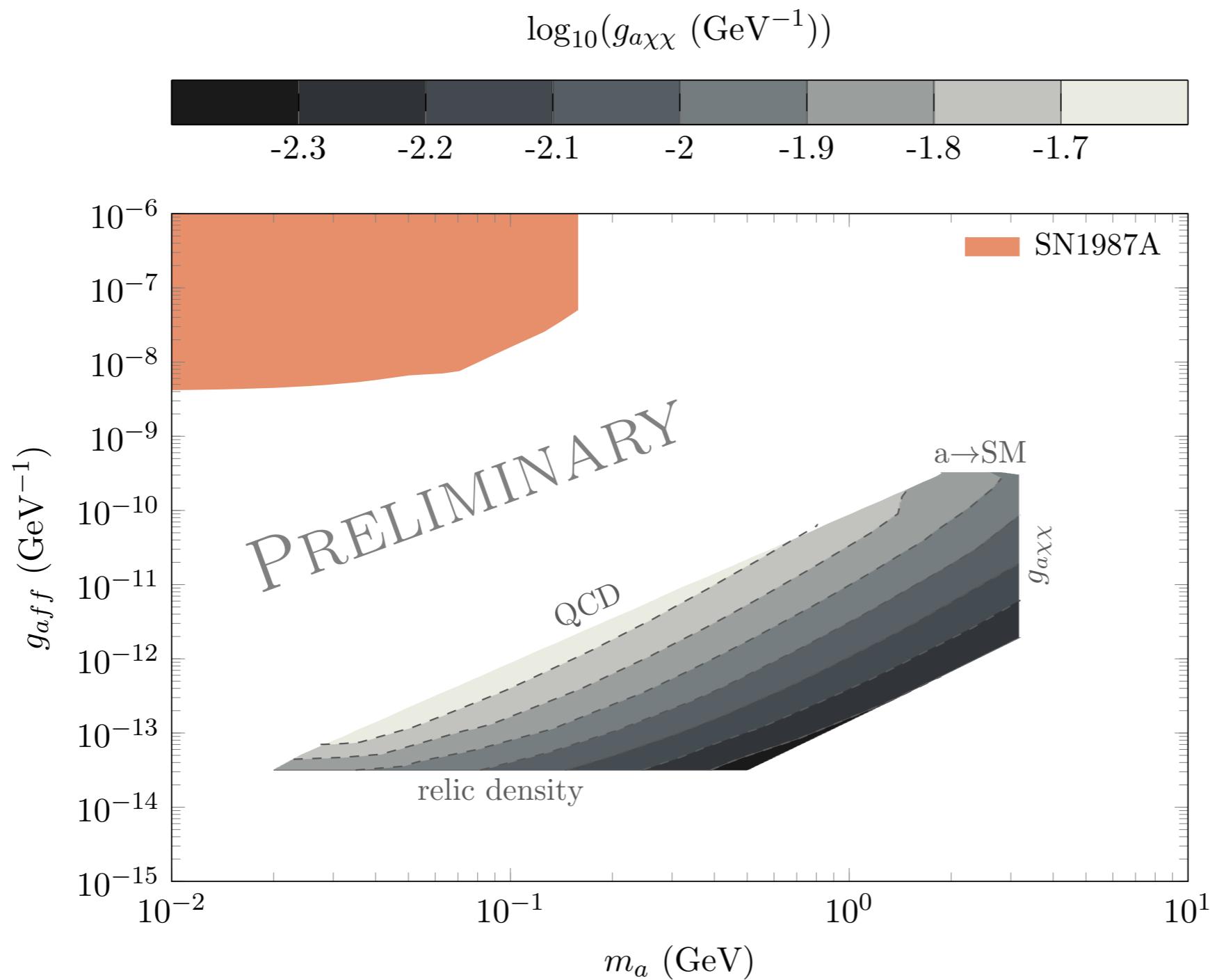
Constraints on our ALP



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

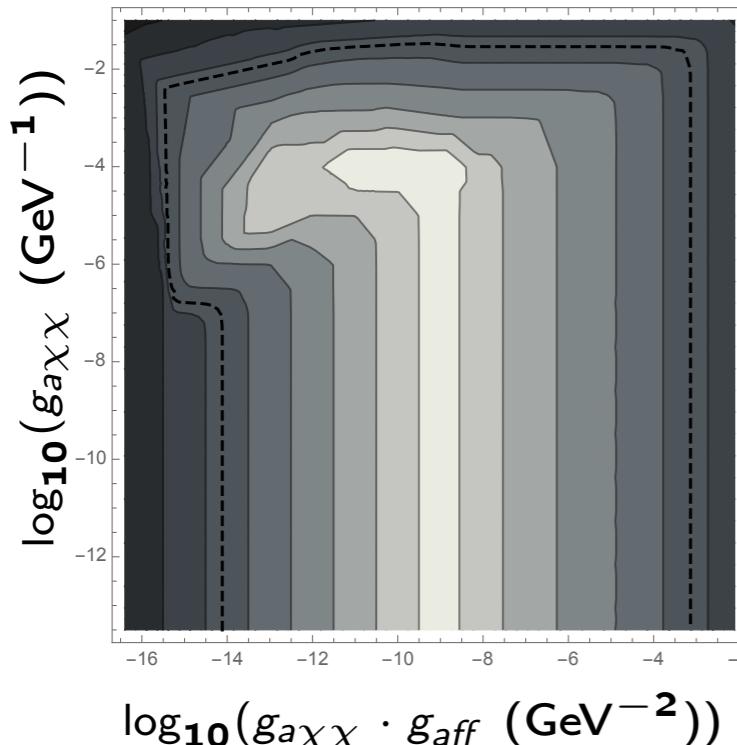


FODDS vs. constraints on our ALP ($m_\chi/m_a = 10$)



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

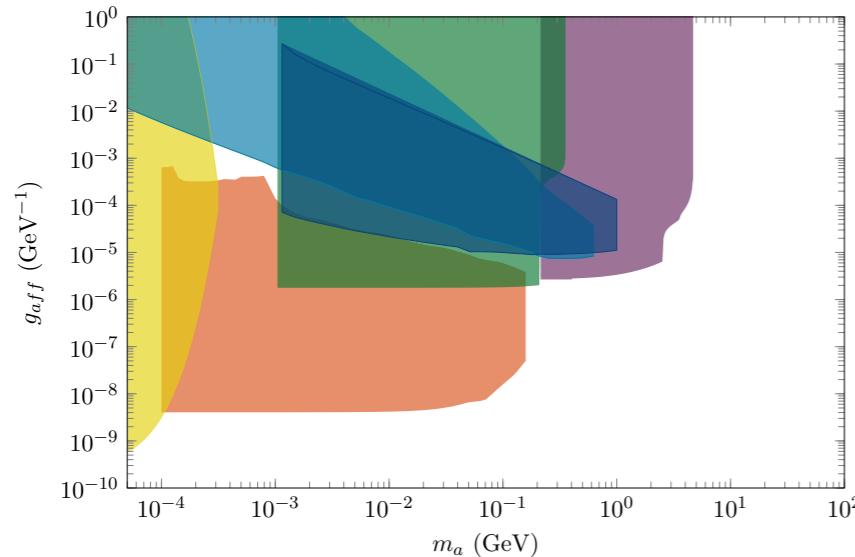
Future work

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

- 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

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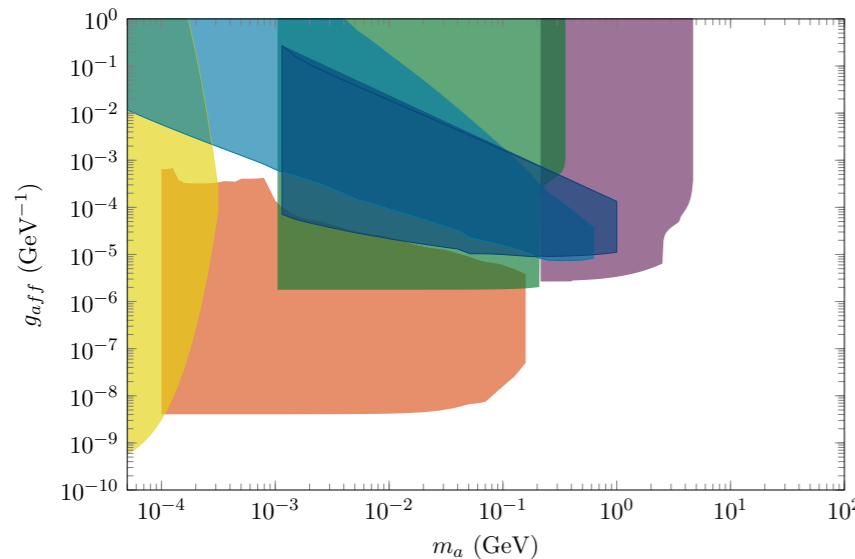
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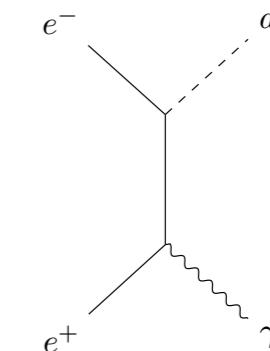
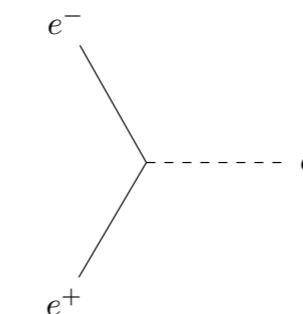
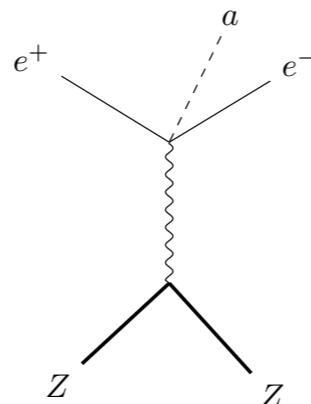
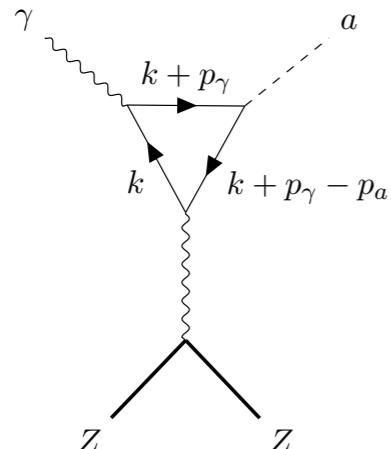
$$E(\partial_t - H p \partial_p) f = C[f]$$

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

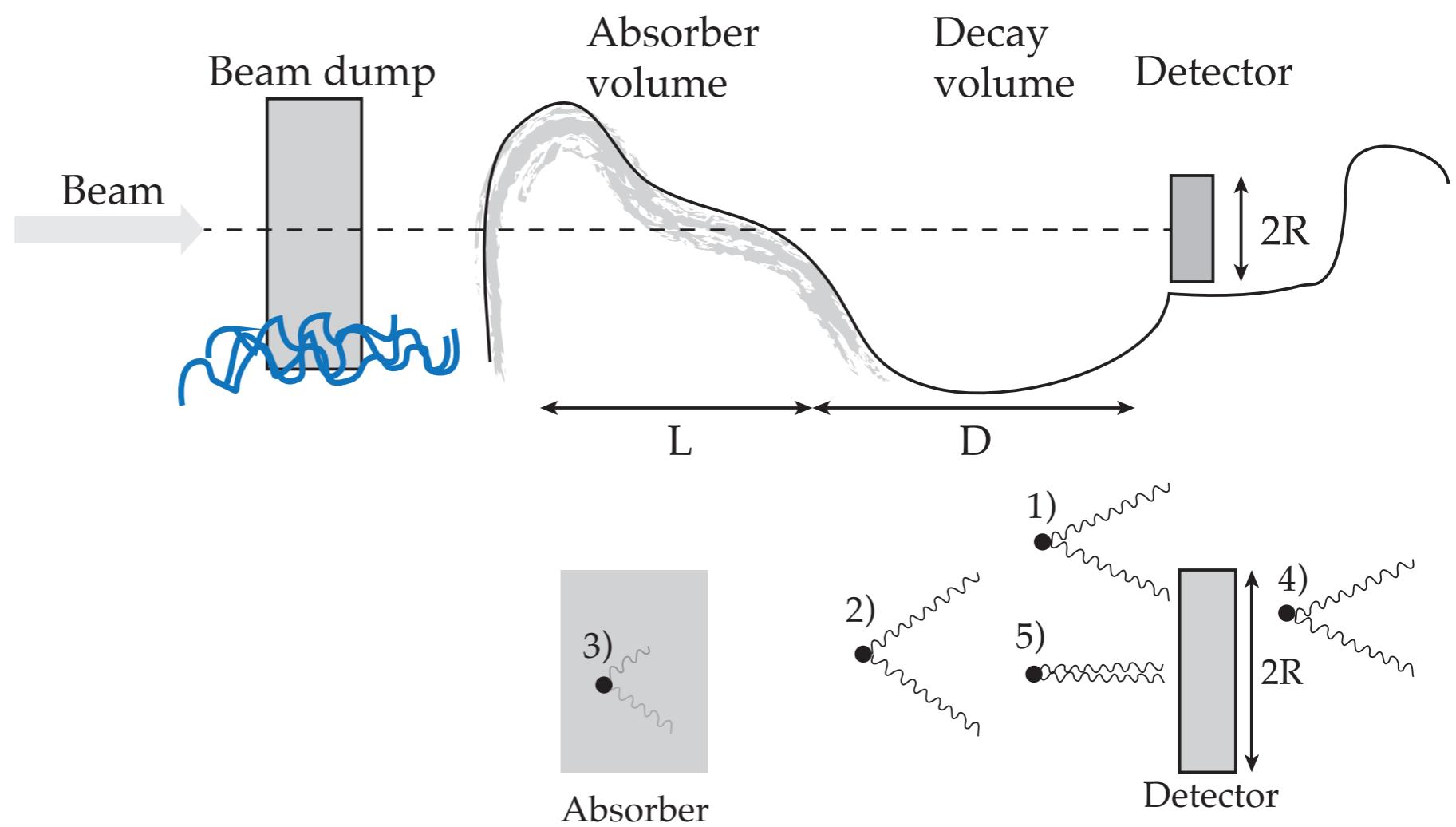
Backup Slides

Electron Beam Dump Constraint

SLAC E137 Experiment: 20 GeV Electrons bumped



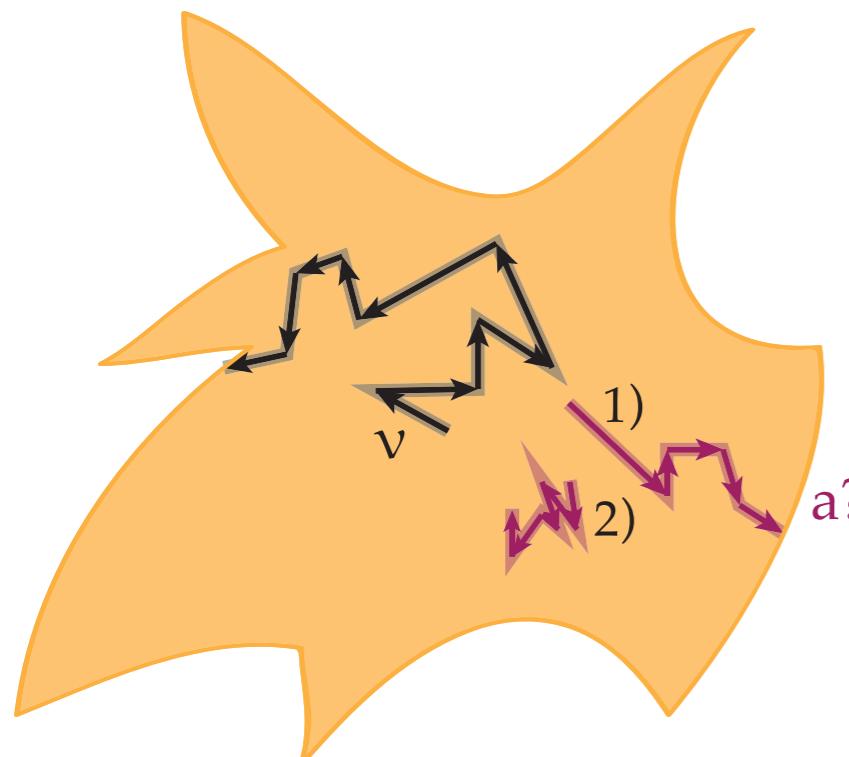
Fold detector geometry



with ALP decay probability

Astrophysical Constraints - HB stars and SN1987A

ALPs inside stars



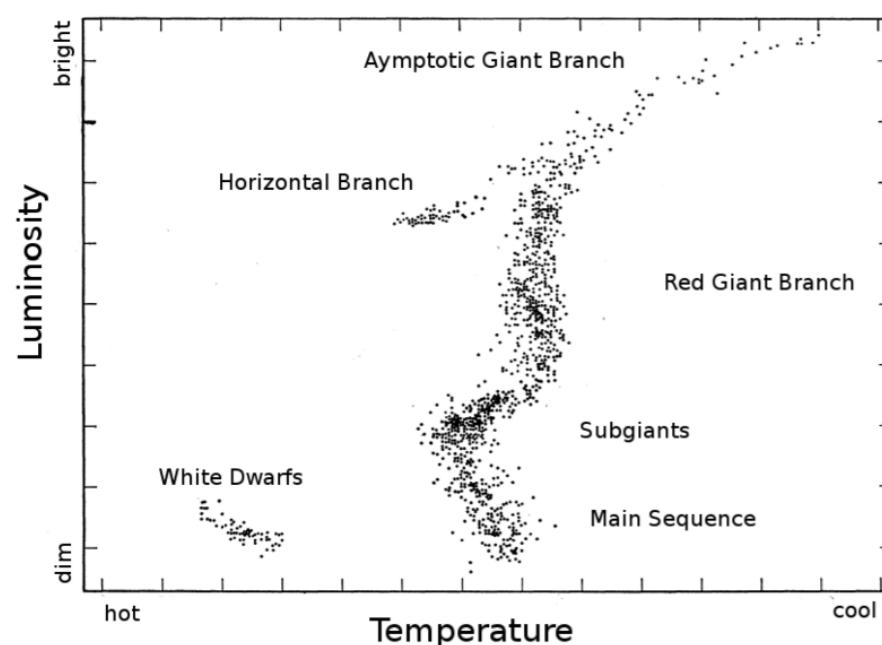
1) Energy Loss

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



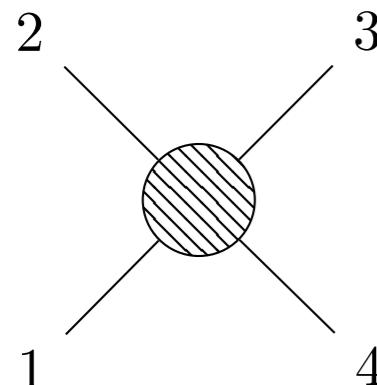
$$R = N_{HB}/N_{RG} \text{ well described} \Rightarrow L_a \lesssim L_{3\alpha}$$

Energy emitted per unit mass and time
 $\langle \epsilon_a \rangle \lesssim 0.1 \langle \epsilon_{3\alpha} \rangle = 100 \text{ g}^{-1} \text{ erg s}^{-1}$

Boltzmann equation - general

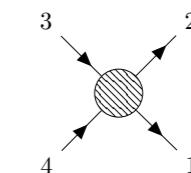
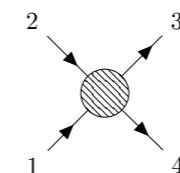
$$\frac{\partial n}{\partial t} + 3nH = -C[n]$$

$C[n]$ collision term



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

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



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

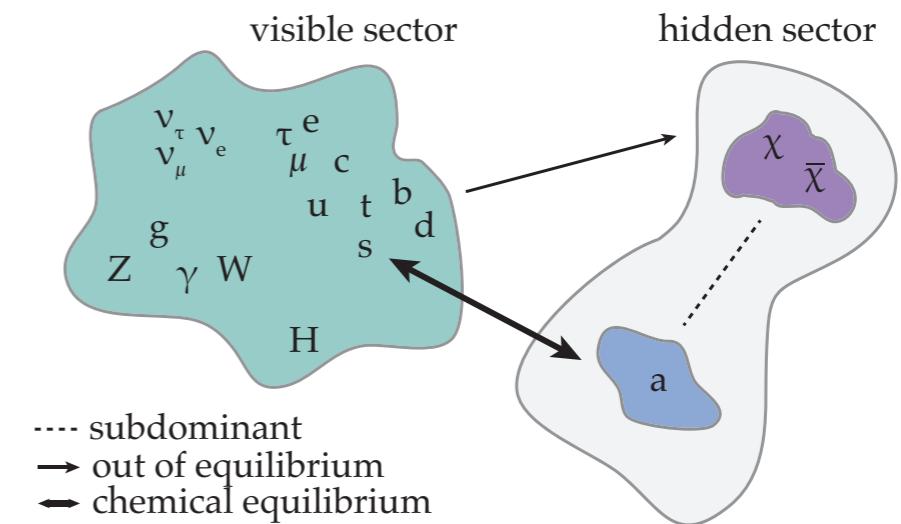
chemical equilibrium as long as $\langle \sigma v \rangle n^{\text{eq}} \gtrsim H$

detailed balance $\langle \sigma_{ij \rightarrow kl} v \rangle n_i^{\text{eq}} n_j^{\text{eq}} = \langle \sigma_{kl \rightarrow ij} v \rangle n_k^{\text{eq}} n_l^{\text{eq}}$

Freeze-in ...

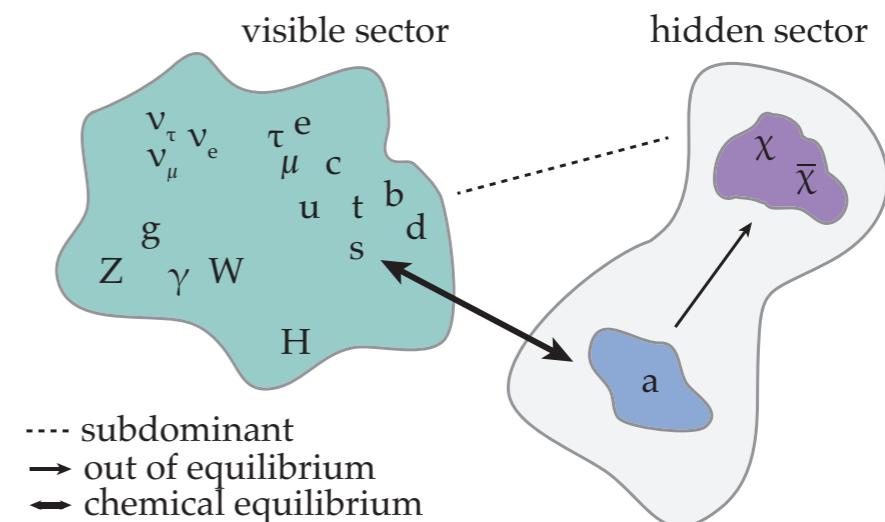
... from SM particles

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \rangle (n_\chi^{\text{eq}2} - \underbrace{n_\chi^2}_{n_\chi \ll n_\chi^{\text{eq}}}) + \underbrace{\langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \rangle}_{\propto g_{a\chi\chi}^4} (n_\chi^{\text{eq}2} - n_\chi^2)$$



... from the mediator

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \underbrace{\sum_f \langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \rangle}_{\propto (g_{aff} g_{a\chi\chi})^2} (n_\chi^{\text{eq}2} - n_\chi^2) + \langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \rangle (n_\chi^{\text{eq}2} - \underbrace{n_\chi^2}_{n_\chi \ll n_\chi^{\text{eq}}})$$



$$Y_0 = \int_0^\infty \frac{\langle \sigma_{\text{connector}} v \rangle n_\chi^{\text{eq}2}}{sHT} dT$$

FODDS region

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \sum_f \left\langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \right\rangle \left(\overbrace{(n_\chi^{\text{eq}}(T))^2}^{\text{underbrace}} - \overbrace{n_\chi^2}^{\text{overbrace}} \right)$$

$$+ \underbrace{\left\langle \sigma_{aa \rightarrow \chi\bar{\chi}} v \right\rangle (\mathcal{T}') n_a^2}_{\text{underbrace}} - \underbrace{\left\langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \right\rangle (\mathcal{T}') n_\chi^2}_{\text{underbrace}}$$



$$\frac{dn_a}{dt} + 3Hn_a = - \underbrace{\left\langle \sigma_{aa \rightarrow \chi\bar{\chi}} v \right\rangle (\mathcal{T}') n_a^2}_{\text{underbrace}} + \underbrace{\left\langle \sigma_{\chi\bar{\chi} \rightarrow aa} v \right\rangle (\mathcal{T}') n_\chi^2}_{\text{underbrace}}$$

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

