Limiting Light Dark Matter-Baryon Interactions

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arXiv:2408.12144

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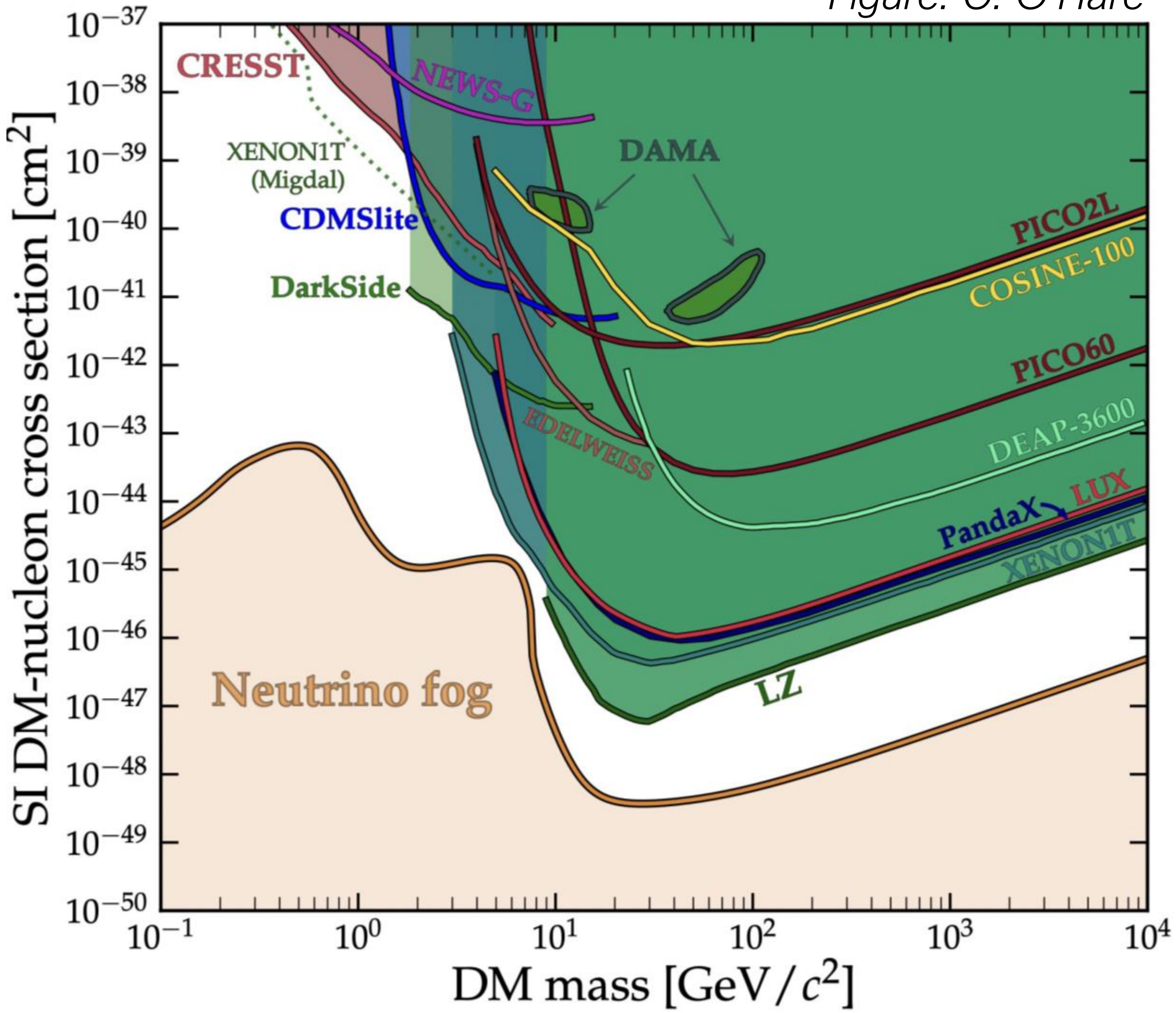
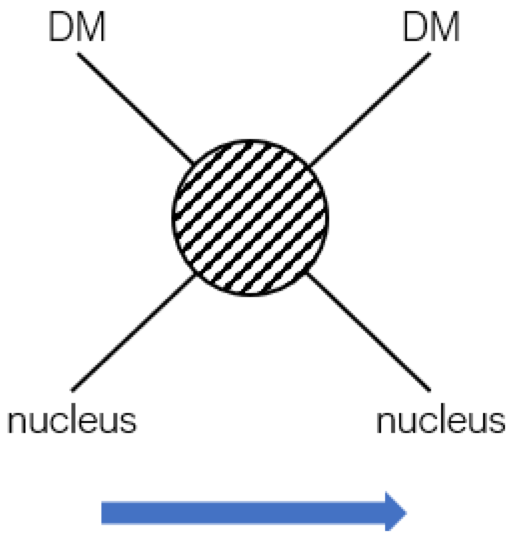
≳ GeV-scale dark matter

Figure: C. O'Hare





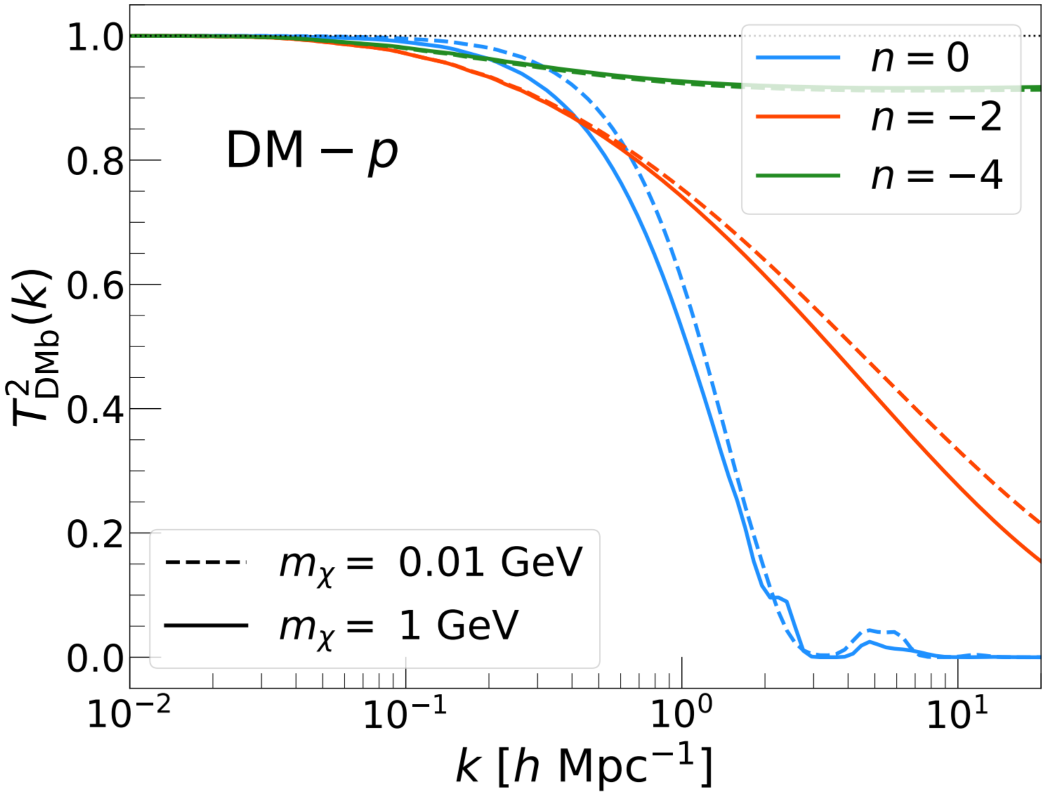
Strong bounds from direct detection for DM above the GeV scale

MeV-scale dark matter

Leading 'model-independent' bound on DM-baryon interactions

comes from effect on matter power spectrum

Buen-Abad el. al. (2021)



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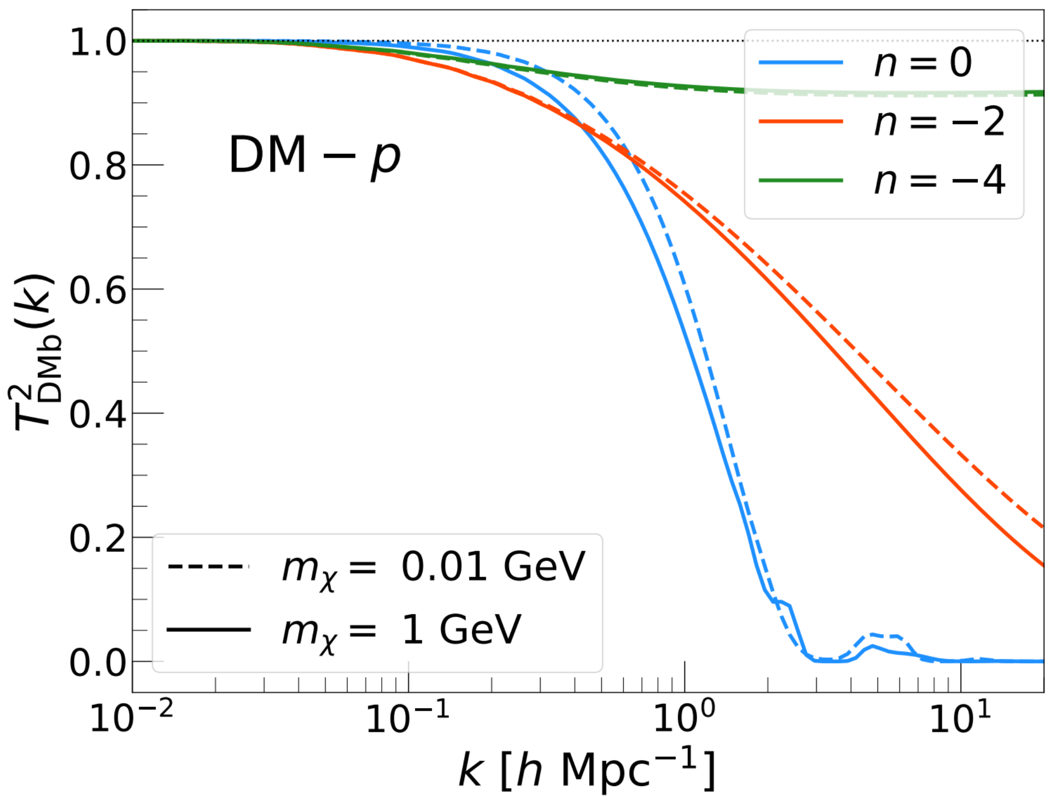

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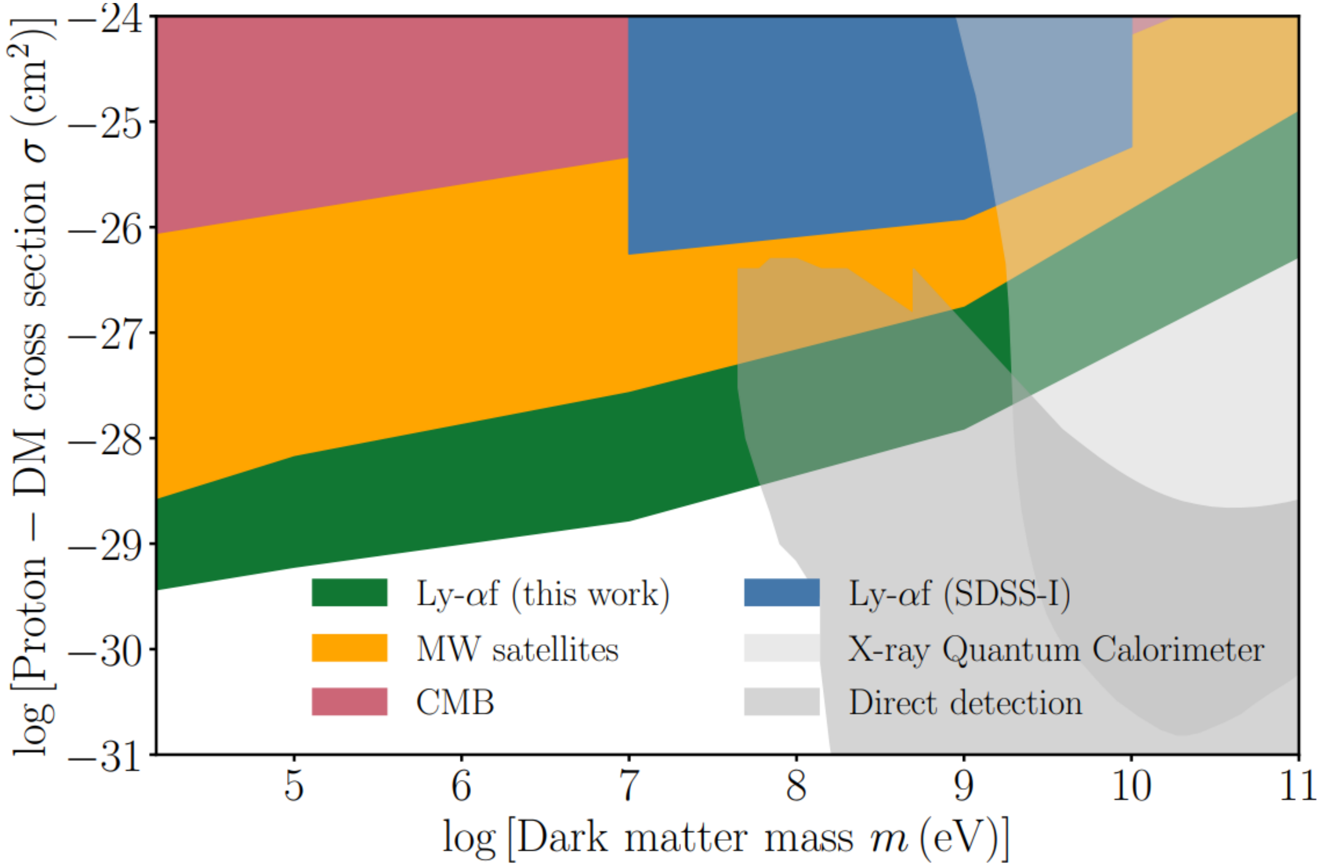

MeV-scale dark matter

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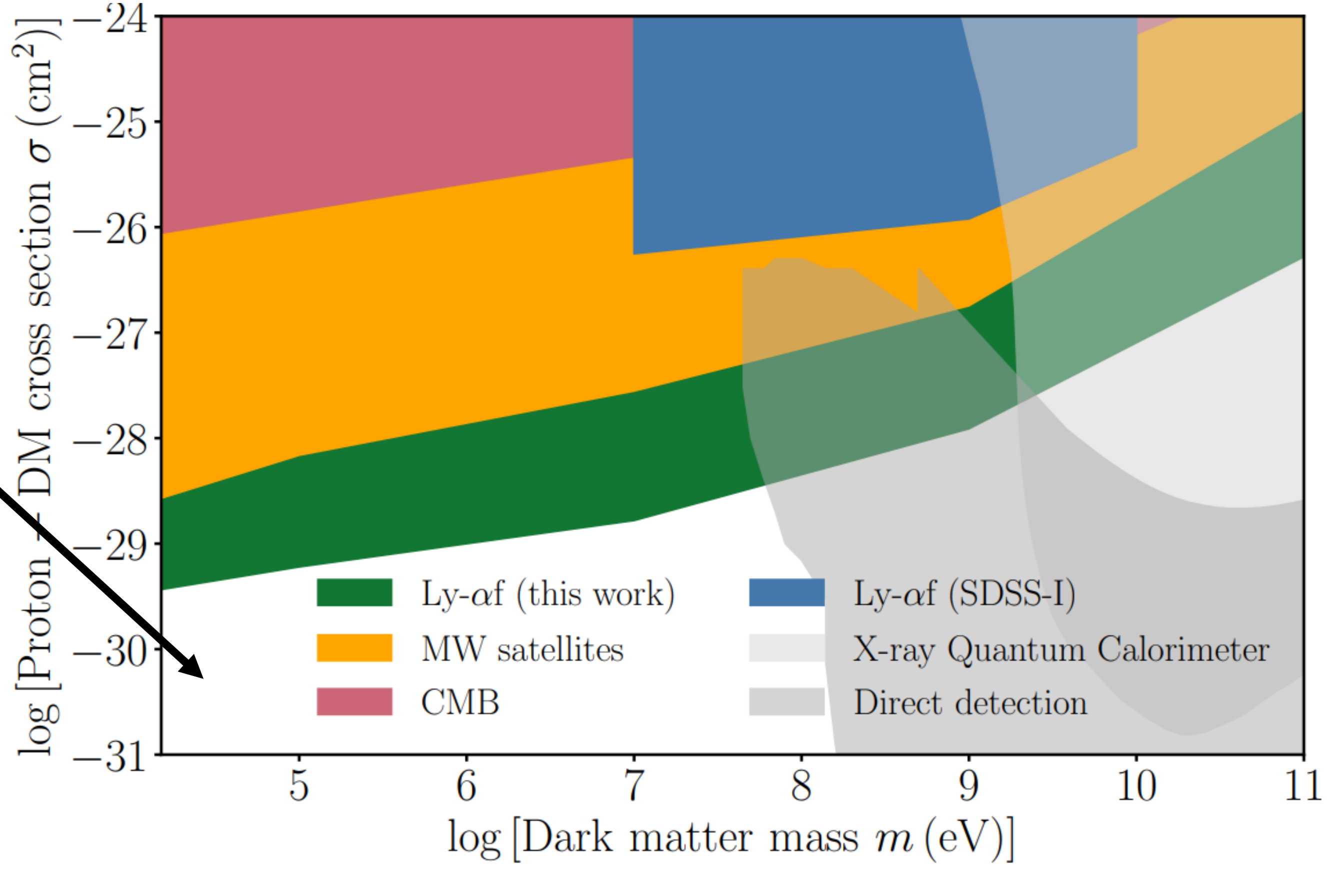
Are such large cross-sections allowed in complete models?



Models & assumptions

Consider DM-SM interactions of the form $$\mathcal{L} \supset \frac{\mathcal{O}_\chi \mathcal{O}_{\rm SM}}{\Lambda^n}$$

- Restrict to scalar operators
- Assume mediator has mass > 500 MeV

$$\Rightarrow \quad \mathcal{O}_\chi = \begin{cases} \chi^\dagger \chi & \text{(complex scalar)} \\ \bar{\chi}\chi & \text{(Dirac fermion)} \end{cases}$$

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Consider two effective models, motivated by UV completions

I. Gluon-coupled $\quad \mathcal{O}^G_{\rm SM} = \dfrac{\alpha_s}{8\pi} G^{a,\mu\nu} G_{a,\mu\nu}$

Integrated out heavy quarks

II. Quark-coupled $\quad \mathcal{O}^q_{\rm SM} = \displaystyle\sum_{q=u,d,s} m_q \bar{q} q + \frac{c_G \alpha_s}{8\pi} G^{a,\mu\nu} G_{a,\mu\nu} + \frac{c_\gamma \alpha}{8\pi} F^{\mu\nu} F_{\mu\nu}$

$c_G = -2 \quad c_\gamma = 3$

Constraints from BBN

Abundance of additional relativistic species during BBN is tightly constrained

Steigman '77, Kolb et. al., '86, Boehm et. al. '13, …

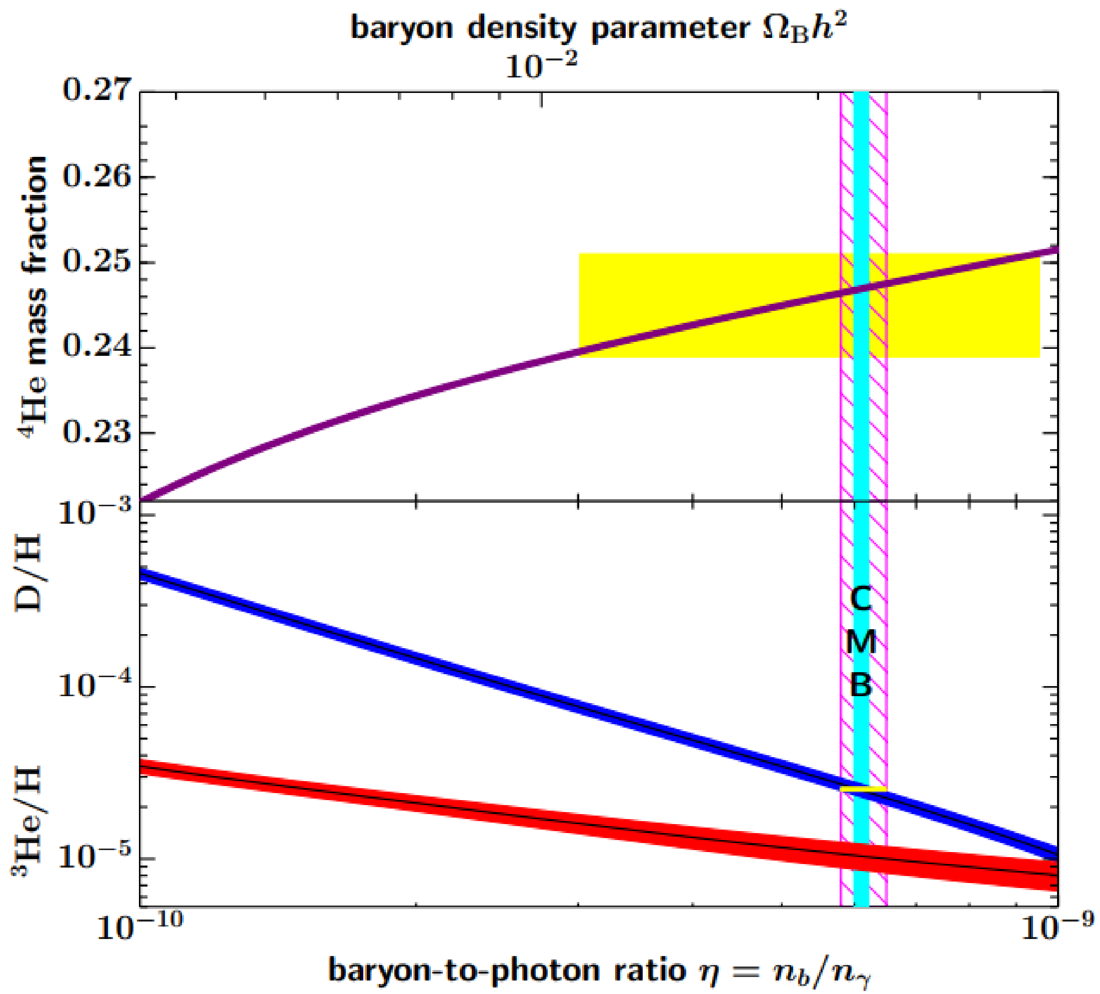
Thermal relic DM annihilating into $e^{\pm}$/photons or neutrinos excluded for

$$m_\chi < 0.5\,\mathrm{MeV}$$

Sabti et. al. '19

What about hadronically-interacting DM?

Figure: Particle Data Group



Constraining $\sigma_{\chi N}$ with BBN

Want to obtain a *conservative* bound on $\sigma_{\chi N}$ that is independent of cosmological history at early times

BBN requires universe reheated to temperature of at least ~10 MeV

Was the dark matter in equilibrium at these temperatures?

Note: stronger bounds can be obtained *if* the universe reheated above the QCD phase transition
(see Green & Rajendran '17, Krnjaic & McDermott '19)

Equilibrium – in or out?

Hadronically interacting DM can (naively) remain out-of-equilibrium at $T \sim$ MeV even for large $\sigma_{\chi N}$

- *Baryon (& meson) abundance is highly suppressed*

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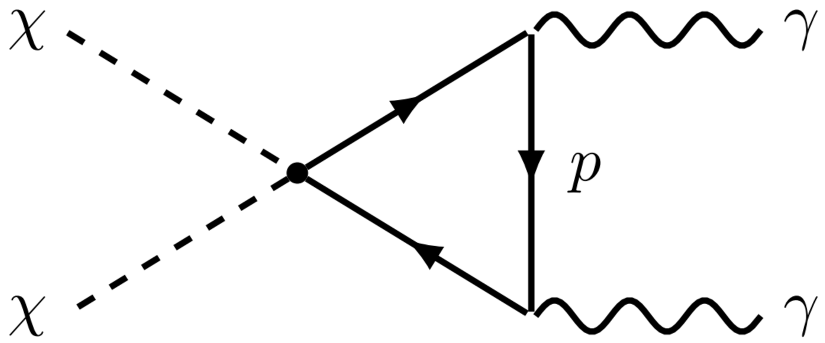
But DM interacts with photons at 1-loop



Processes such as $\gamma\gamma \to \chi\chi$ can equilibrate DM & SM sectors

BBN & CMB bounds

Is MeV-scale DM that was in equilibrium with photons during BBN excluded?

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Three regimes to consider:

I. *DM decouples when relativistic, before $e^{\pm}$ annihilation*

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III. *DM decouples when non-relativistic*

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Existing BBN analyses apply

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Overclose the universe

Existing BBN analyses apply

BBN & CMB bounds

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Effect of DM is to increase expansion rate during BBN

(can be parameterised by contribution to $\Delta N_{\rm eff}^{\rm BBN}$)

- Leads to earlier freeze-out of $n \leftrightarrow p$ and nuclear interactions

$\Rightarrow$ Increase in both Y_P and $D/H|_P$

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Yeh et. al. (2022) : $\Delta N_{\rm eff}^{\rm BBN} < 0.407 \ (95\% \, {\rm CL})$

c.f. real scalar in equilibrium: $\Delta N_{\rm eff} \approx 0.57$

BBN & CMB bounds

II. DM decouples when relativistic, after $e^{\pm}$ annihilation

- DM shares entropy released during $e^{\pm}$ annihilation
- Increases T_ν/T_γ relative to SM:

$$\left(\frac{T_\nu}{T_\gamma}\right)^3 = \frac{4+2g_*^\chi}{11+2g_*^\chi}$$

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$$\left(\frac{T_\nu}{T_\gamma}\right)^3 = \frac{4+2g_*^\chi}{11+2g_*^\chi} \quad \Rightarrow \quad \Delta N_{\text{eff}}^{\text{CMB}} \approx 2.2$$

(real scalar $g_*^\chi = 1$)

Large contribution to ΔN_{eff} at recombination!

BBN & CMB bounds

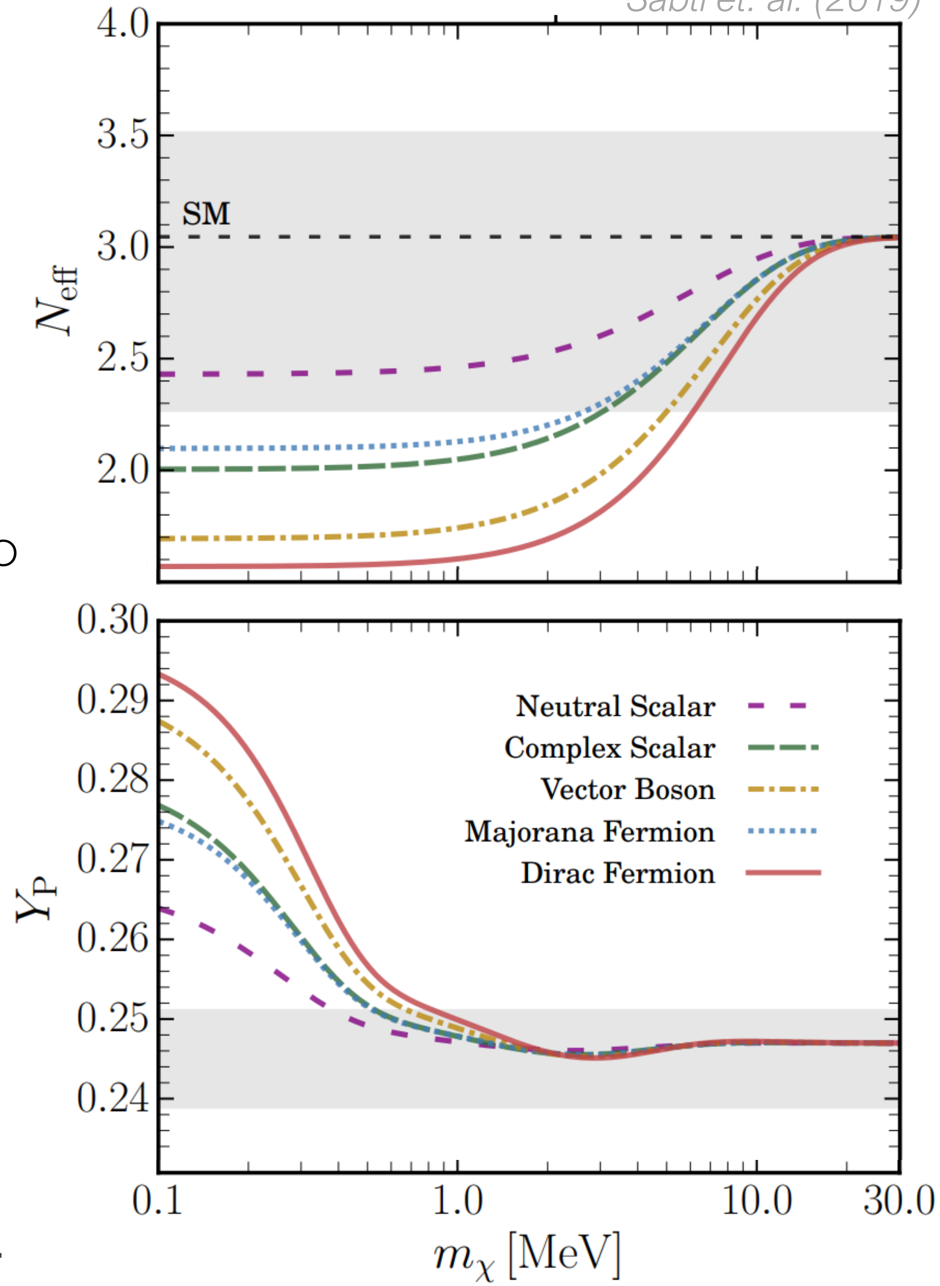
III. DM decouples when non-relativistic

DM modifies expansion rate *and* transfers entropy to photons

- Dilutes baryons $\Rightarrow$ need larger initial baryon-to-photon ratio
- Also decreases T_ν/T_γ

Net effect is increase in Y_P, decrease in $\Delta N_{\rm eff}^{\rm CMB}$

Sabti et. al. (2019)



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Combined BBN+CMB fit excludes $m_\chi < 4.9\,\mathrm{MeV}$

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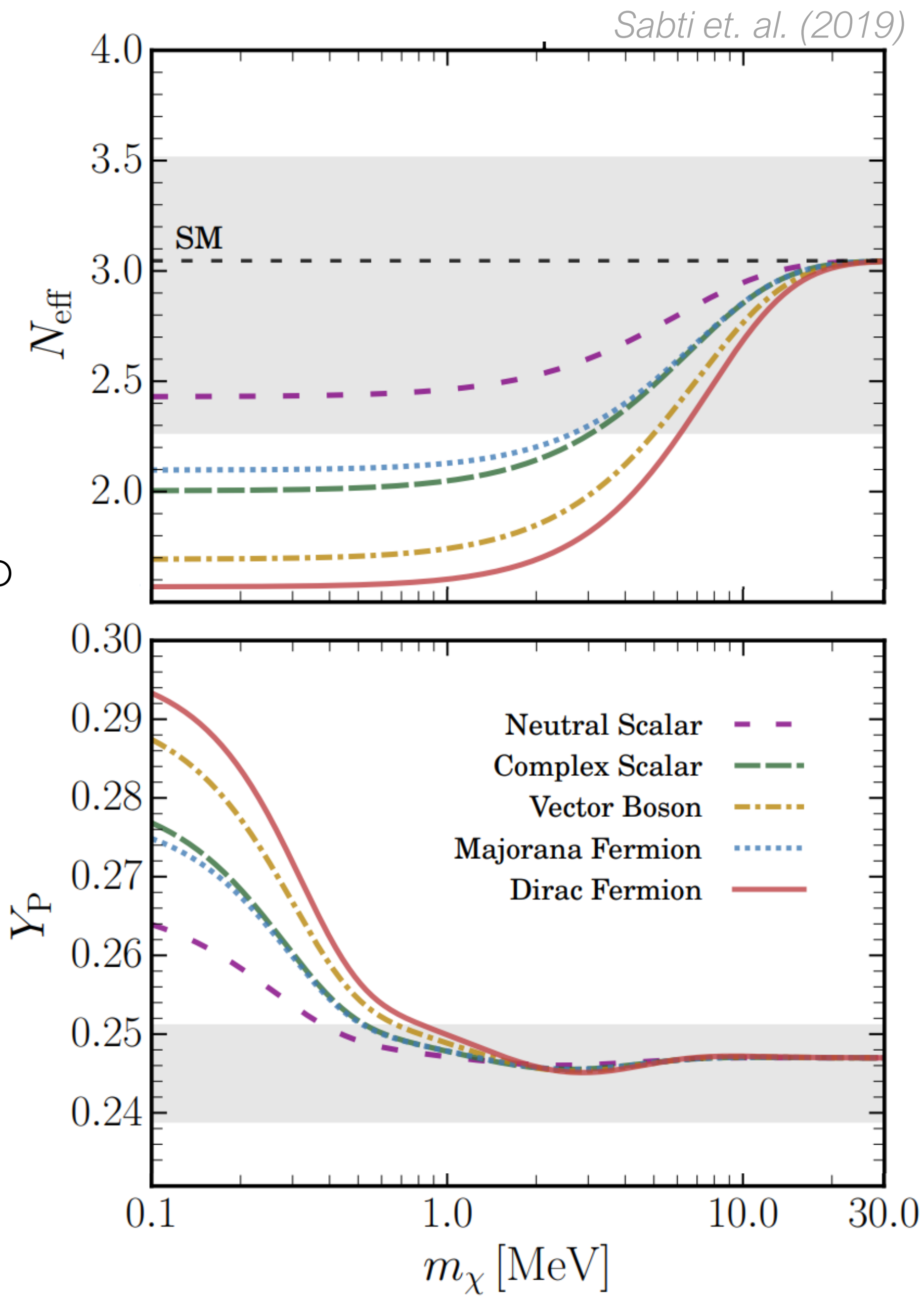

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To convert into bound on $\sigma_{\chi N}$, still need to calculate $\Gamma_{\gamma\gamma\to\chi\chi}$

Matching to ChPT

To calculate rate of $\gamma\gamma \to \chi\chi$ at MeV energies, match onto *SU(3)* Chiral Lagrangian

- Dark matter included via local source terms

$$\mathcal{L} = \mathcal{L}_{\rm QCD} + s_G(x)\frac{\alpha_s}{12\pi}G^{a,\mu\nu}G_{a,\mu\nu} - \bar{q}M_q s_\chi(x) q$$

$$\Downarrow$$

$$\mathcal{L}^{\rm LO}_{\rm ChPT} = \frac{f^2}{4}\left(1+\frac{4}{27}s_G\right)\mathrm{Tr}[D^\mu U^\dagger D_\mu U] + \frac{B_0 f^2}{2}\left(1+s_\chi+\frac{2}{9}s_G\right)\mathrm{Tr}[M_q(U+U^\dagger)]$$

- Coupling structure dictated by symmetries

Matching to ChPT

To calculate rate of $\gamma\gamma \to \chi\chi$ at MeV energies, match onto *SU(3)* Chiral Lagrangian

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$$\mathcal{L}_{\text{ChPT}}^{\text{LO}} \supset \left(1 + \frac{4}{27} s_G\right) \left((D^\mu \pi^+)(D_\mu \pi^-) + (D^\mu K^+)(D_\mu K^-) \right) + \left(1 + s_\chi + \frac{2}{9} s_G\right) \left(m_\pi^2 \pi^+ \pi^- + m_K^2 K^+ K^- \right)$$

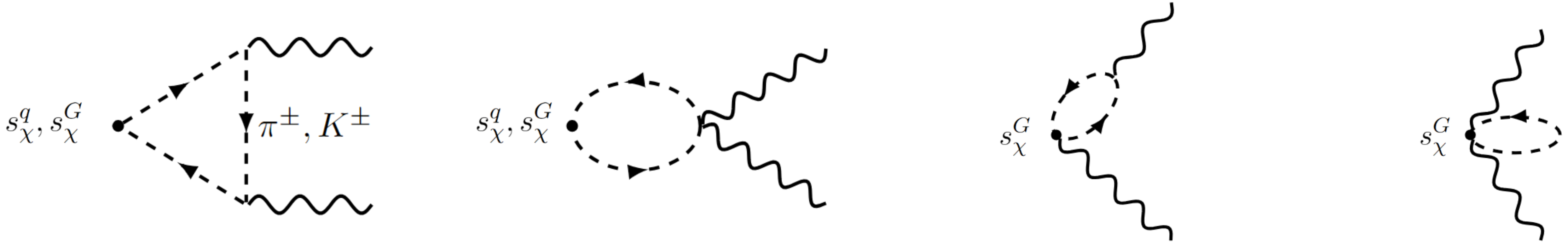
<u>Gluon-coupled</u>

$$s_\chi = 0\,, \quad s_G = \frac{3}{2\Lambda^2} \chi^* \chi$$

<u>Quark-coupled</u>

$$s_\chi = \frac{-1}{\Lambda^2} \chi^* \chi\,, \quad s_G = \frac{3 c_G}{2\Lambda^2} \chi^* \chi$$

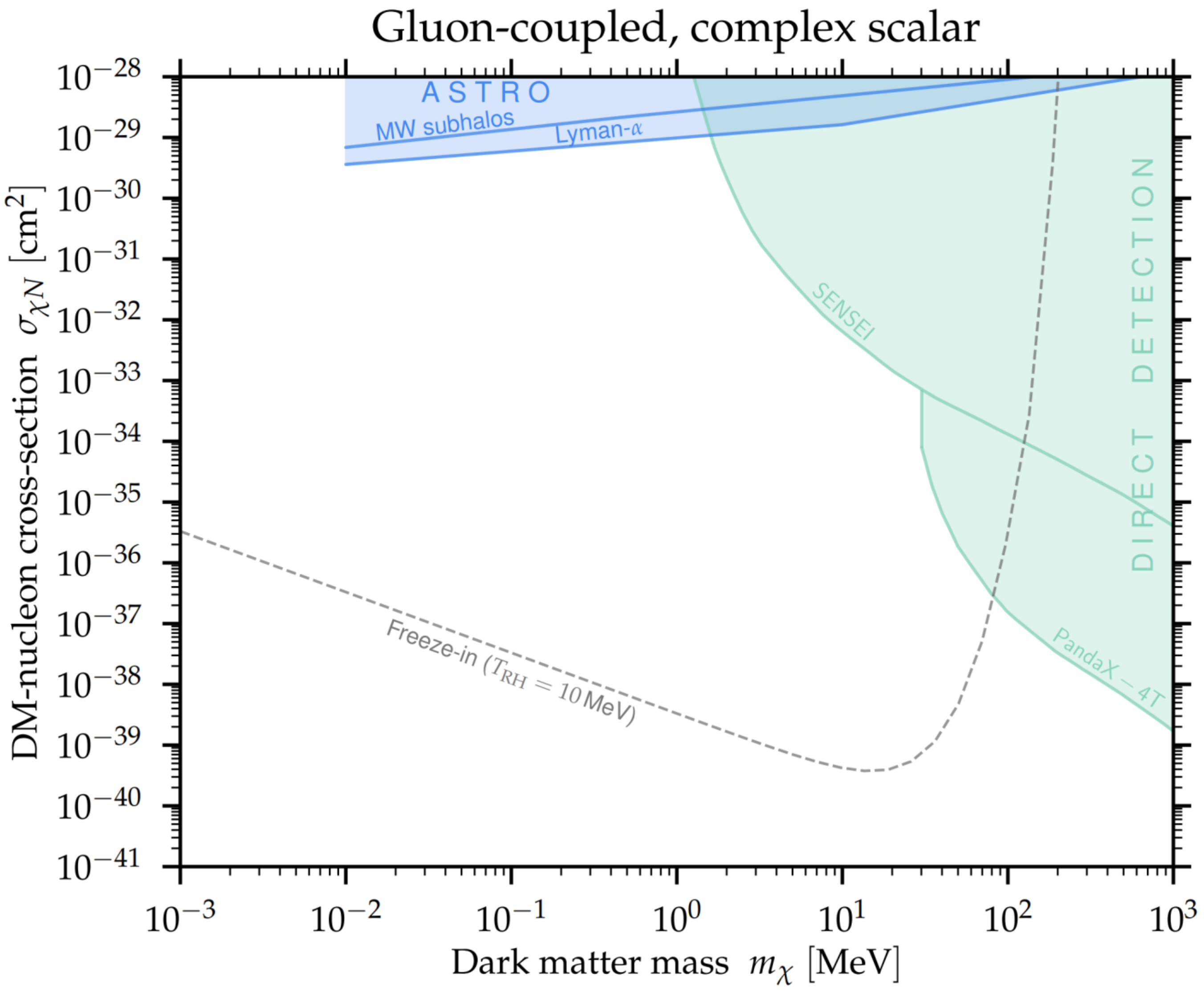
$\gamma\gamma \to \chi\chi$



Thermally averaged rate, expressed in terms of $\sigma_{\chi N}$

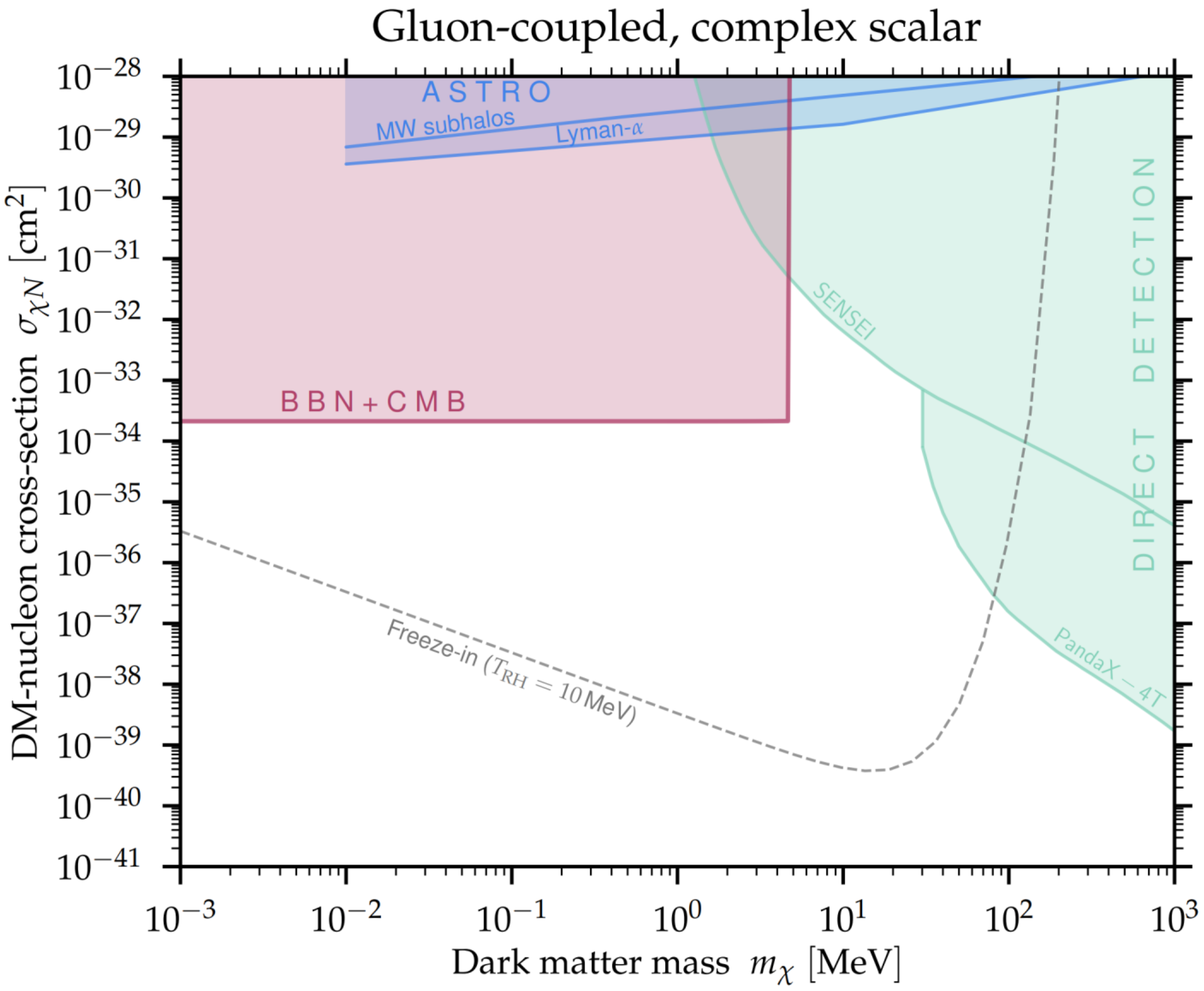
$$\Gamma_{\gamma\gamma\to\bar{\chi}\chi} \propto \sigma_{\chi N} \frac{\alpha^2 T^5}{\Lambda_{\mathrm{QCD}}^2} \begin{cases} 1 & \text{(scalar DM)} \\ 24(T/m_\chi)^2 & \text{(fermion DM)} \end{cases}$$

CMB + BBN constraints



CMB + BBN constraints

$$\Gamma_{\gamma\gamma\to\chi\chi} < H \quad (T = 10\,\mathrm{MeV})$$



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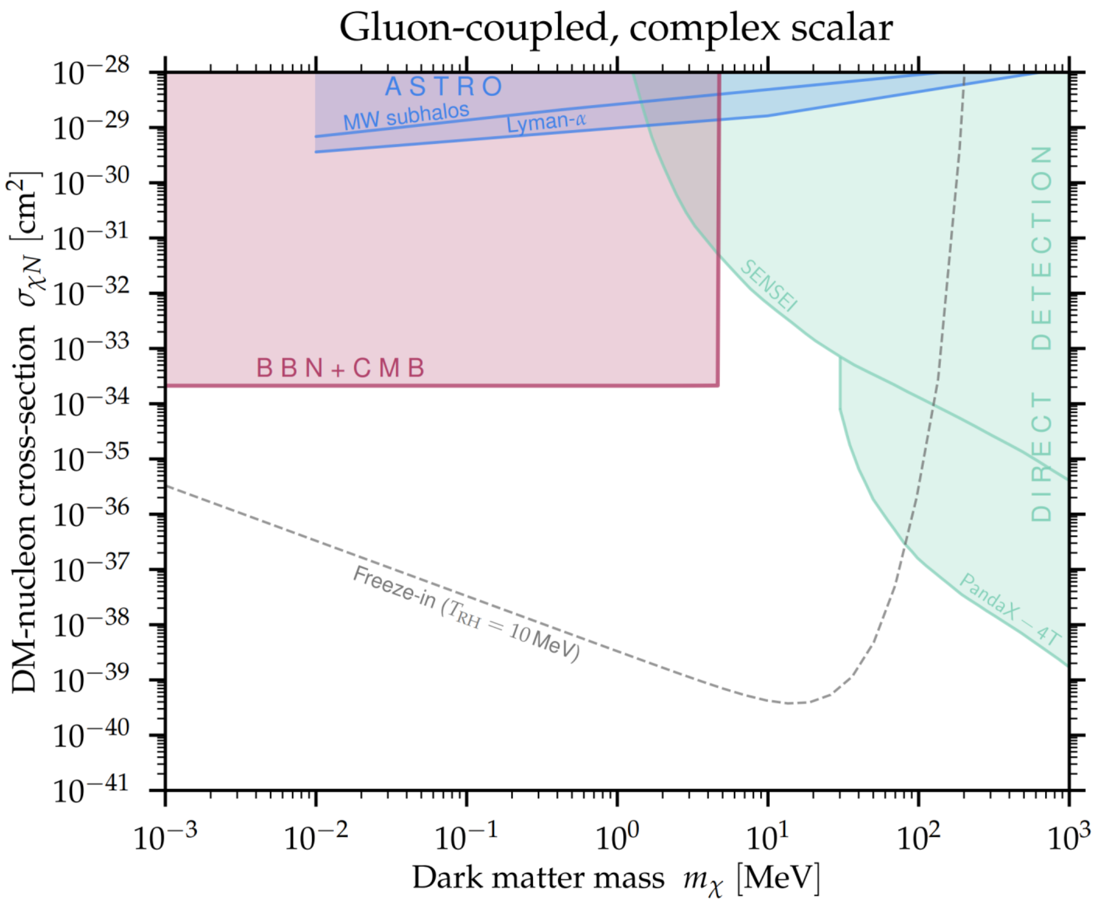
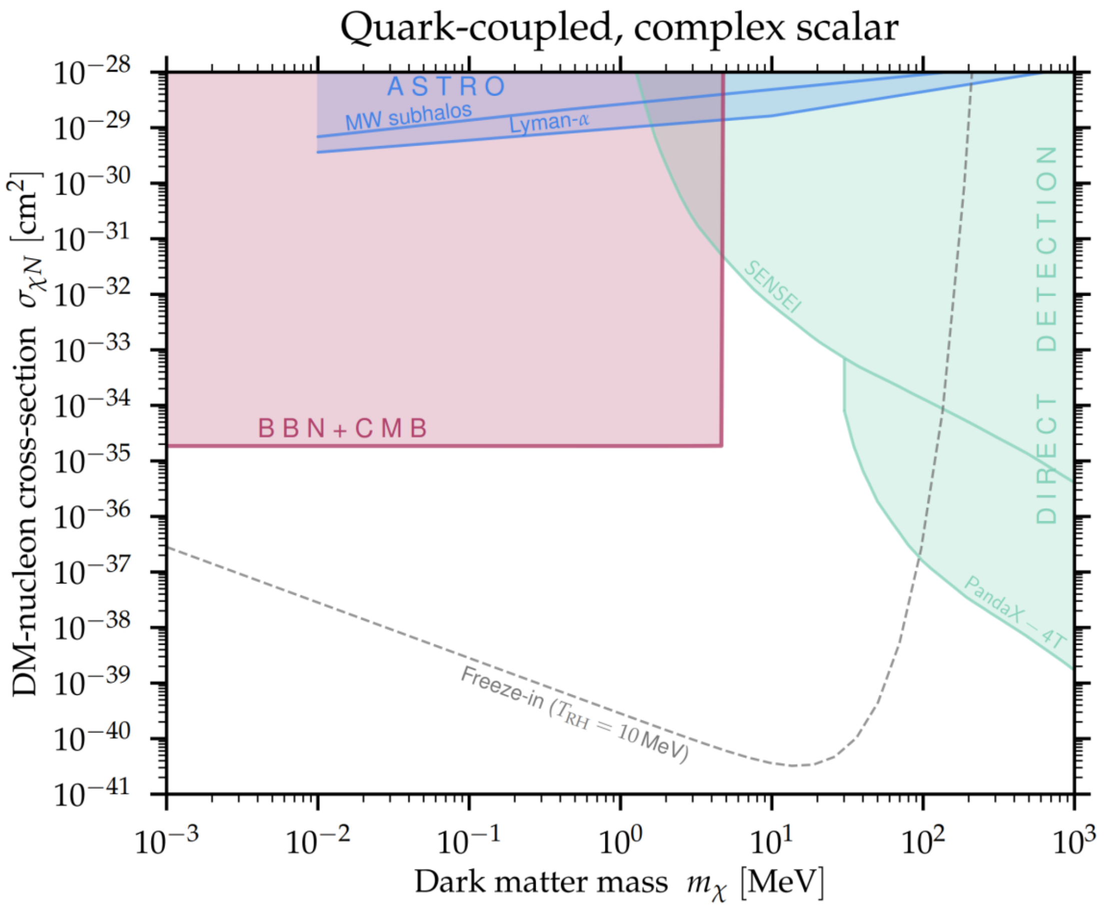




Minimal dependence on the model (*gluon-coupled vs quark-coupled*)

Kaon decay constraints

Dark matter interaction with π, K also leads to bounds from invisible meson decays

NA62 measurement of rare FCNC decay $K^+ \to \pi^+ \bar{\nu}\nu$

$$\mathrm{BR}(K^+ \to \pi^+ \bar{\nu}\nu) = (1.06 \pm 0.4) \times 10^{-10}$$

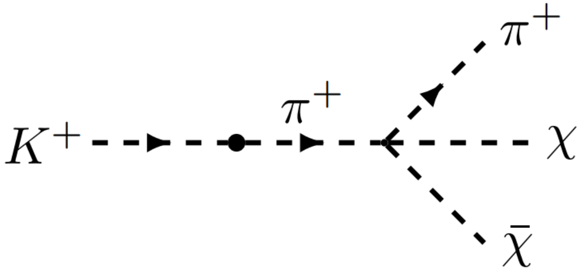
Leads to very strong bound on decay to other "invisible" particles, e.g. dark matter

$$\boxed{\mathrm{BR}(K^+ \to \pi^+ \chi\chi) \lesssim 10^{-10}}$$

Bounds from rare K-decays

Two types of contributions to $K^+ \to \pi^+ \chi\chi$

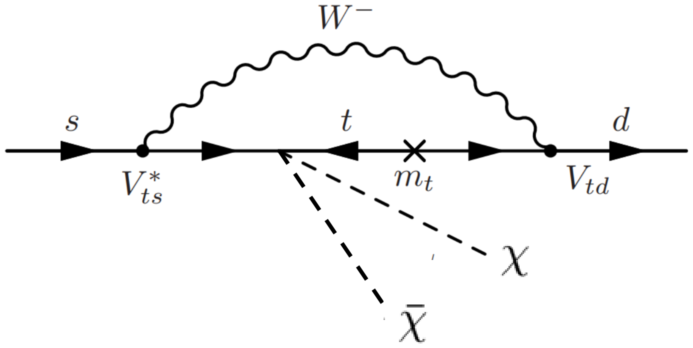
IR contribution:



$s \to d$ transition from SM effective weak Lagrangian

$$\mathcal{L}^{\mathrm{LO}}_{\Delta S=1} \supset -\sqrt{2} G_F V_{ud} V^*_{us}\, g_8 f^2 (\partial^\mu \pi^-)(\partial_\mu K^+) + \mathrm{h.c.}$$

UV contribution:



Additional terms in low-energy Lagrangian from matching

$$\mathcal{L}_{sd} \supset \frac{m_K^2}{2} s_\chi (c_{sd}\, \pi^- K^+ + \mathrm{h.c.})$$

$$c_{sd} = \frac{\sqrt{2} G_F m_t^2 V_{td} V^*_{ts}}{16\pi^2} F_t(m_W^2/m_t^2)$$

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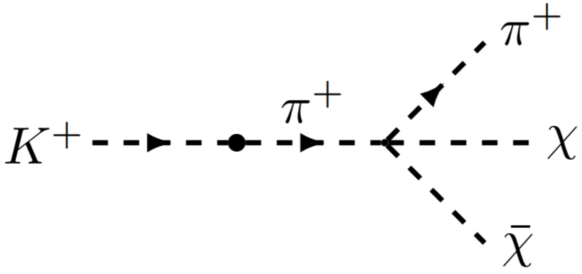
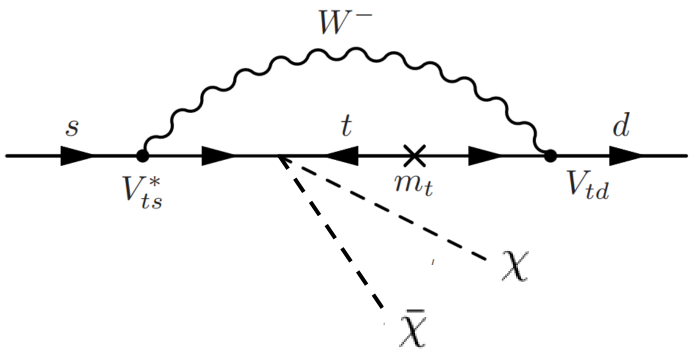


Leading contribution in gluon-coupled case

$$\mathcal{M}(q^2) = \sqrt{2} G_F V_{ud} V_{us}^* g_8 f^2 \frac{c_G}{9\Lambda^2} (m_K^2 + m_\pi^2 - q^2)$$

UV contribution:

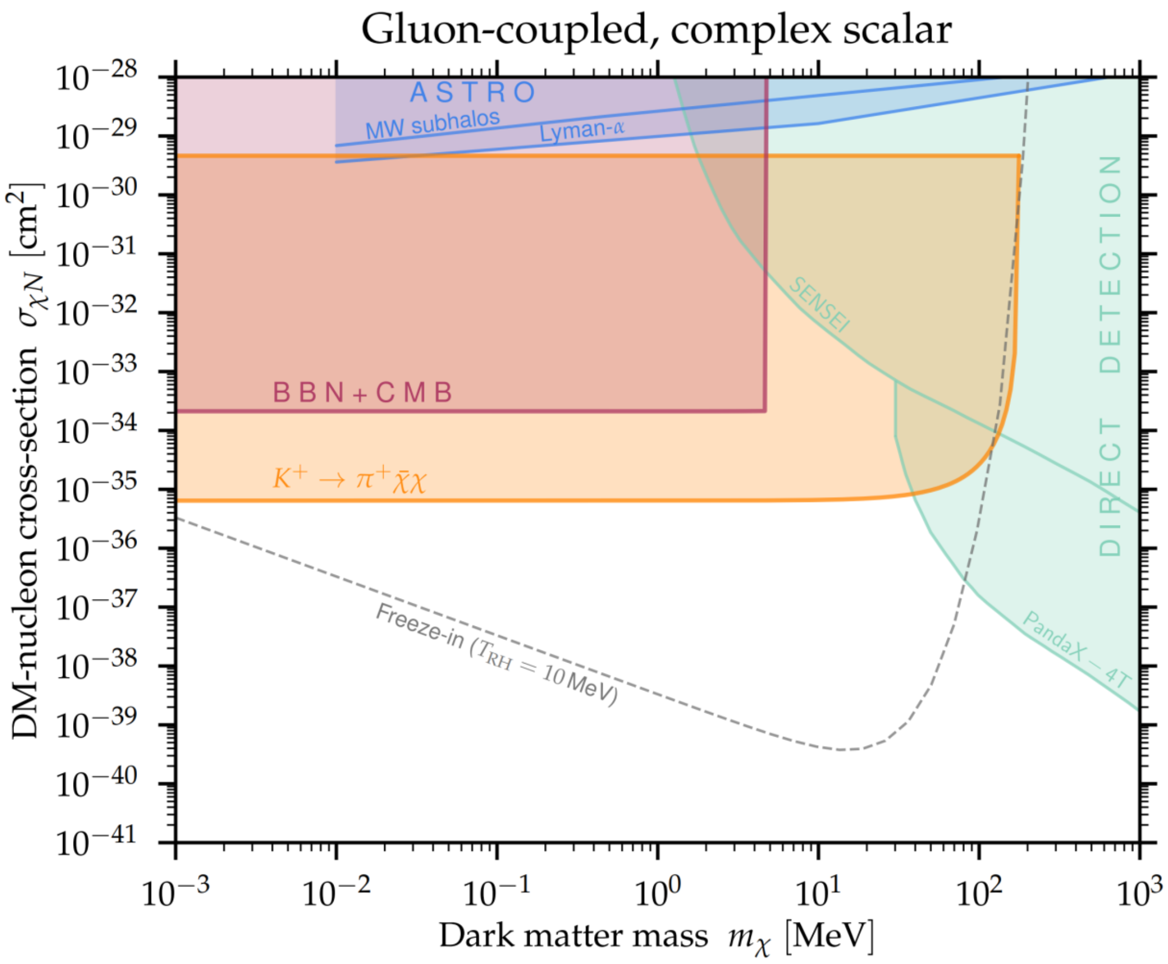


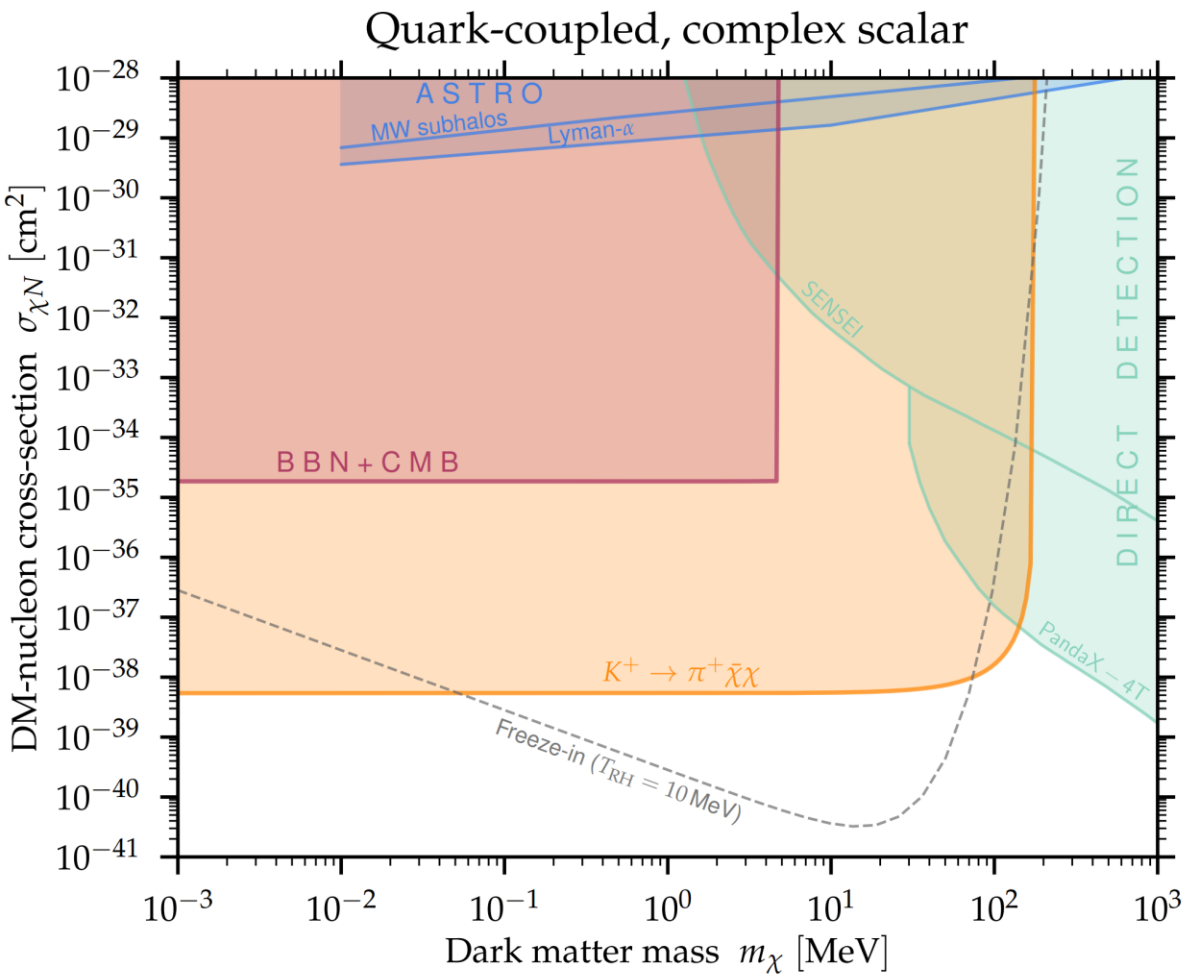
Dominates if coupling to heavy quarks

(e.g. Higgs portal models)

$$\mathcal{M}_{UV}^q = -\frac{\sqrt{2} G_F m_t^2 V_{td} V_{ts}^*}{16\pi^2} \frac{m_K^2}{2\Lambda^2} F_t(m_W^2/m_t^2)$$

Results – scalar DM





Kaon decays give stronger, but more model-dependent bounds

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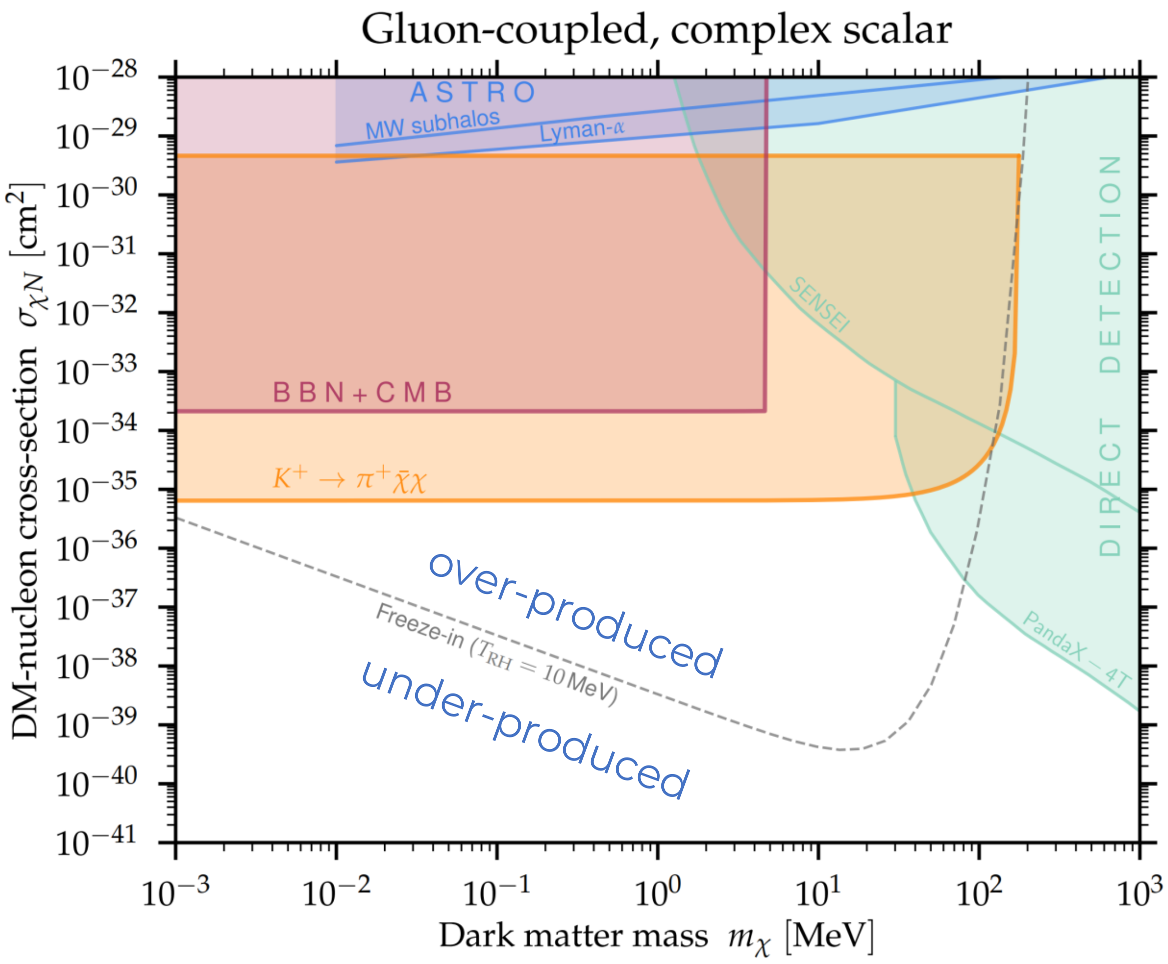
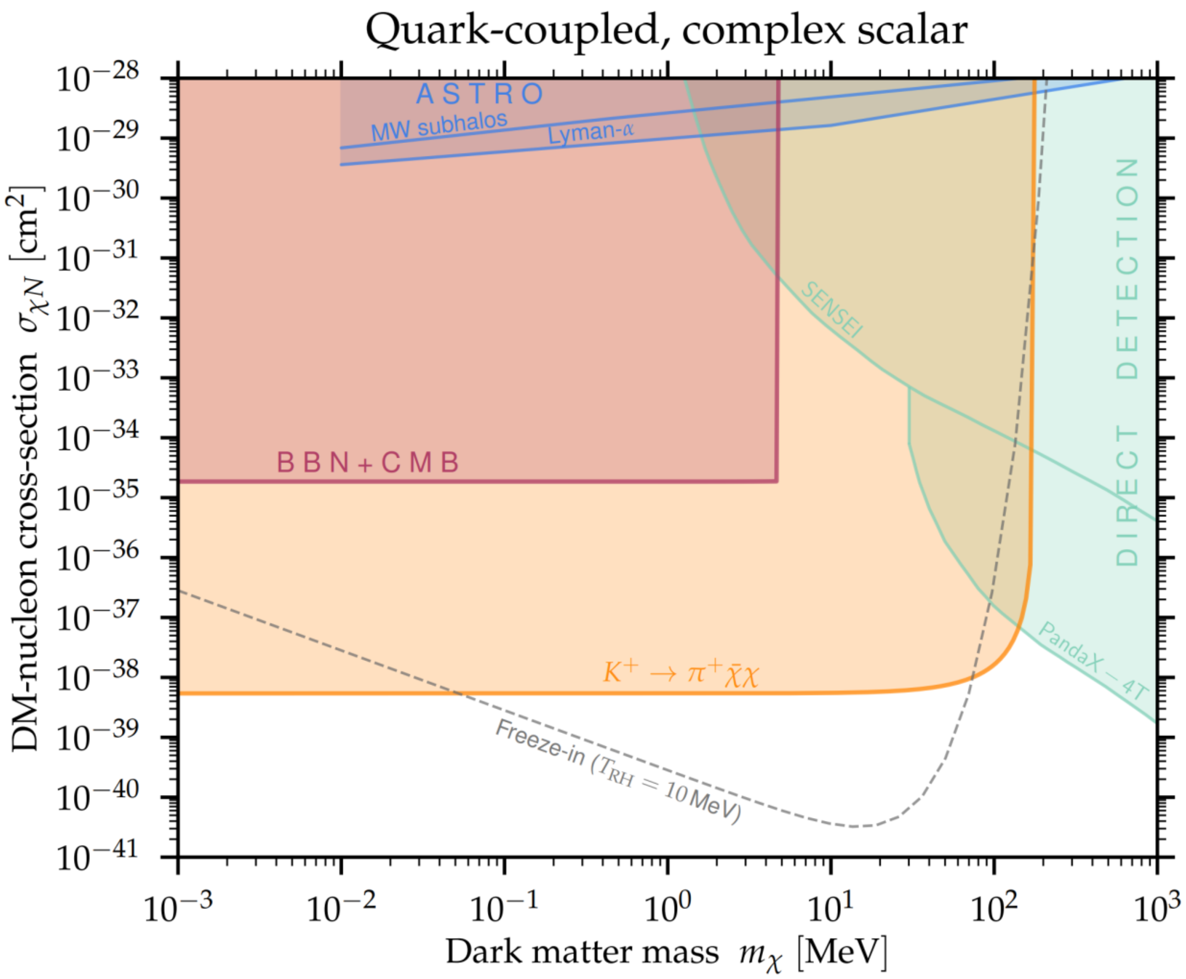
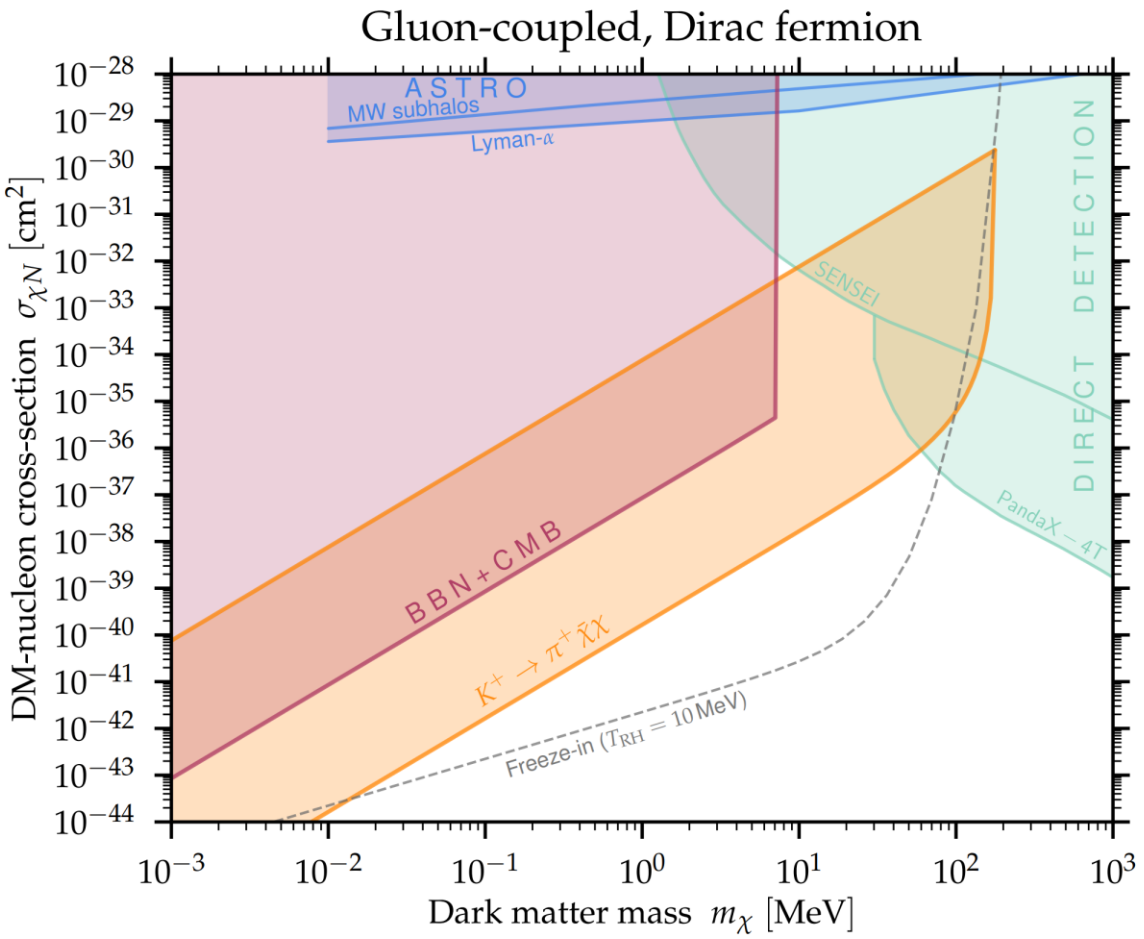
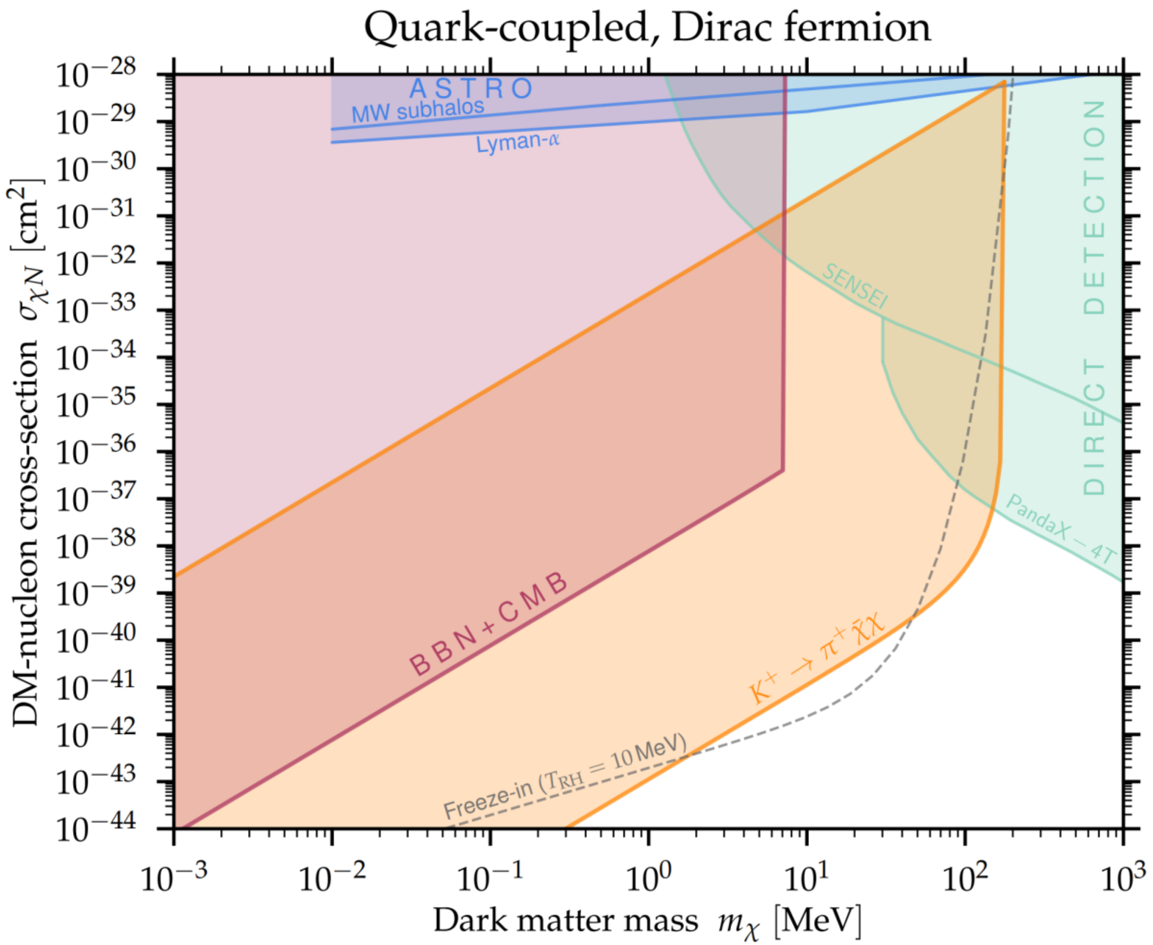




Irreducible freeze-in abundance produced by $\gamma\gamma \to \chi\chi$

Results – fermionic DM





Significantly stronger bounds for fermionic dark matter $\quad \sigma_{\chi N} \propto m_\chi^2/\Lambda^2$

Summary

- BBN/CMB provide strong constraints on light, hadronically-interacting DM
- Significantly stronger than bounds from matter power spectrum
- Rare K decays give stronger, but more model-dependent bounds
- Implications for future low-mass direct detection experiments
- Expect similar bounds to apply to other Lorentz structures (pseudoscalar etc.)