New Limits on sub-GeV Dark Matter

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arXiv:2408.12144 with M. Dolan & J. Wood

arXiv:25xx.xxxxx with M. Dolan & A. Ghosh

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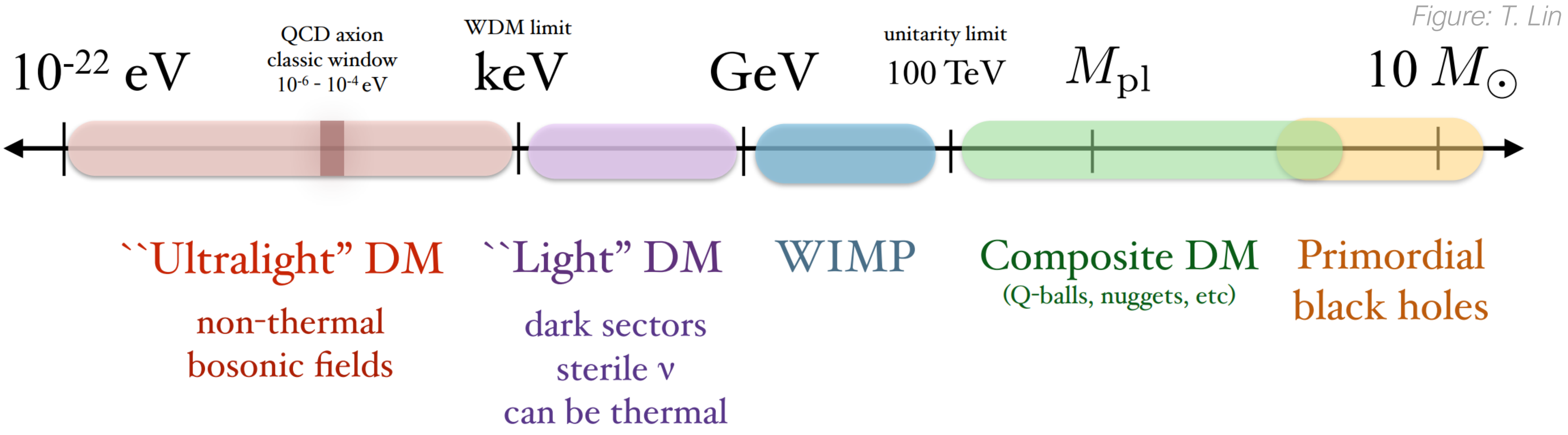
Dark matter landscape

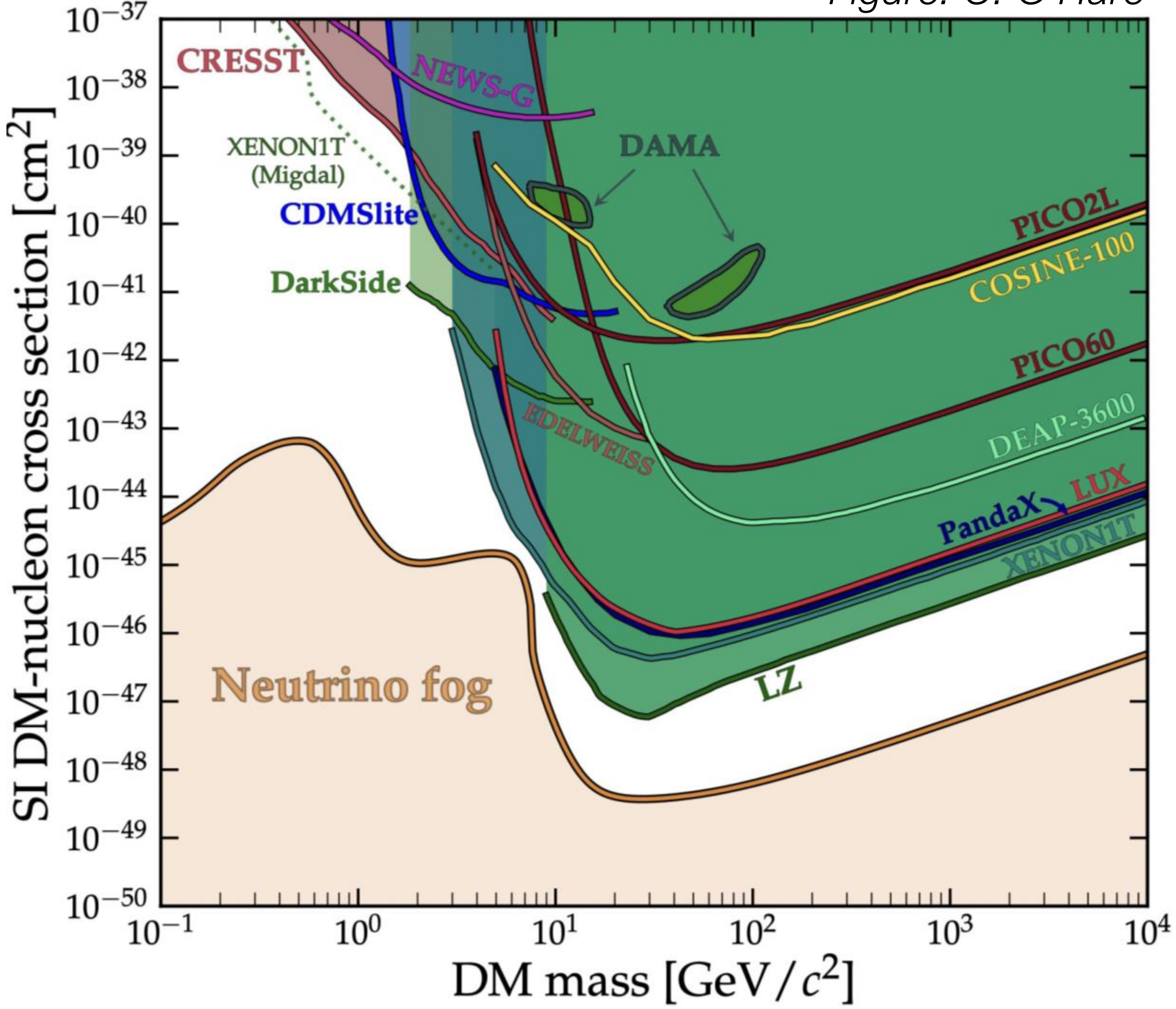


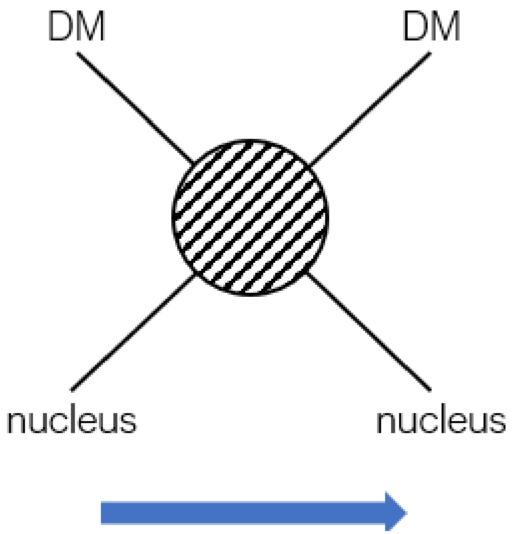
dark matter can't "fit"
in dwarf galaxies

dark matter too discrete

≳ GeV-scale dark matter

Figure: C. O'Hare





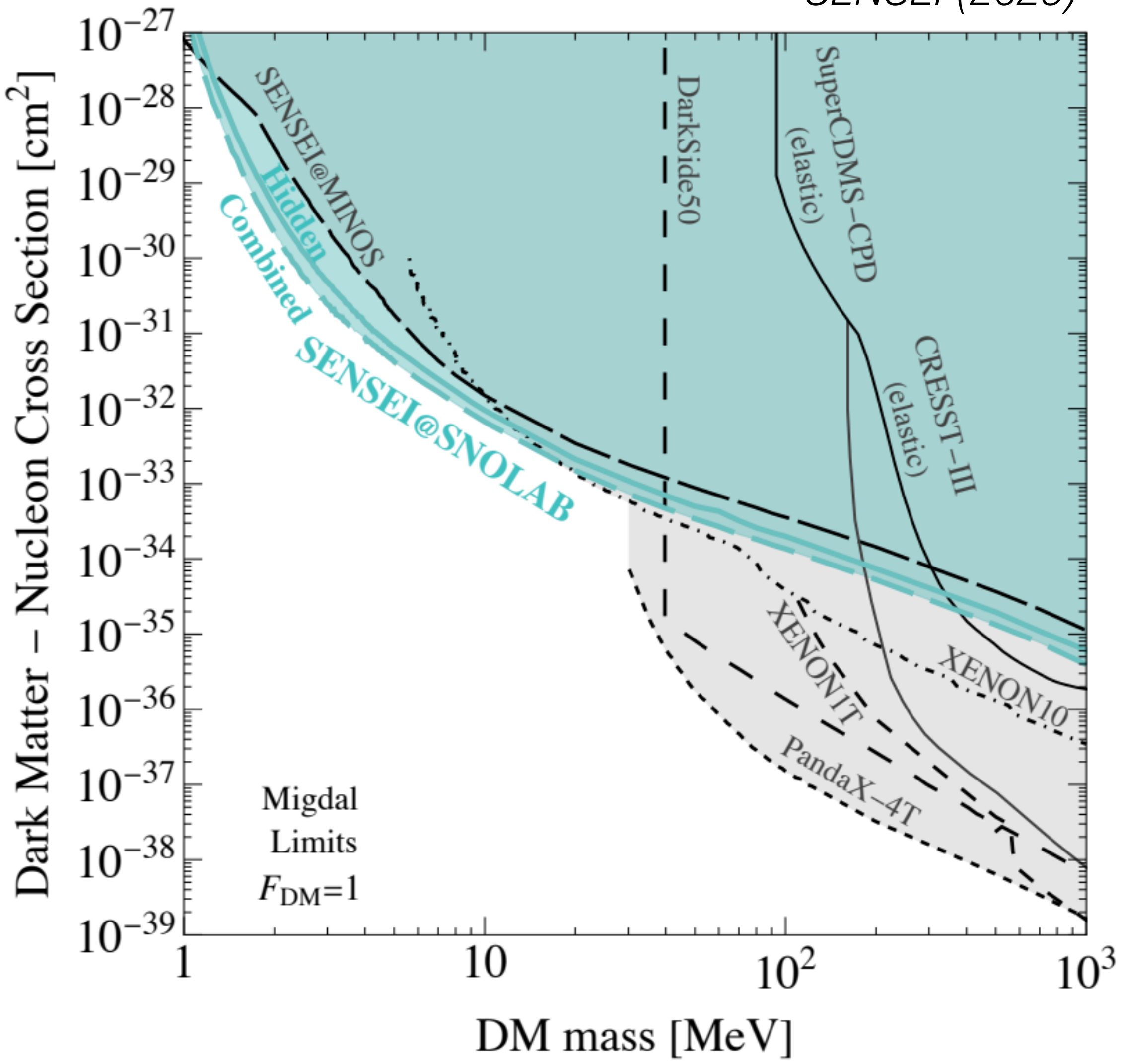
Strong bounds from direct detection for DM above the GeV scale

Sub-GeV direct detection

Significant effort underway to extend direct detection to lower masses

- Migdal effect
- (DM-electron scattering)
- R&D for ultra low-threshold detectors (single phonon sensitivity)

SENSEI (2025)



Sub-GeV direct detection

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What are the model targets?
What cross-sections do we need to reach?

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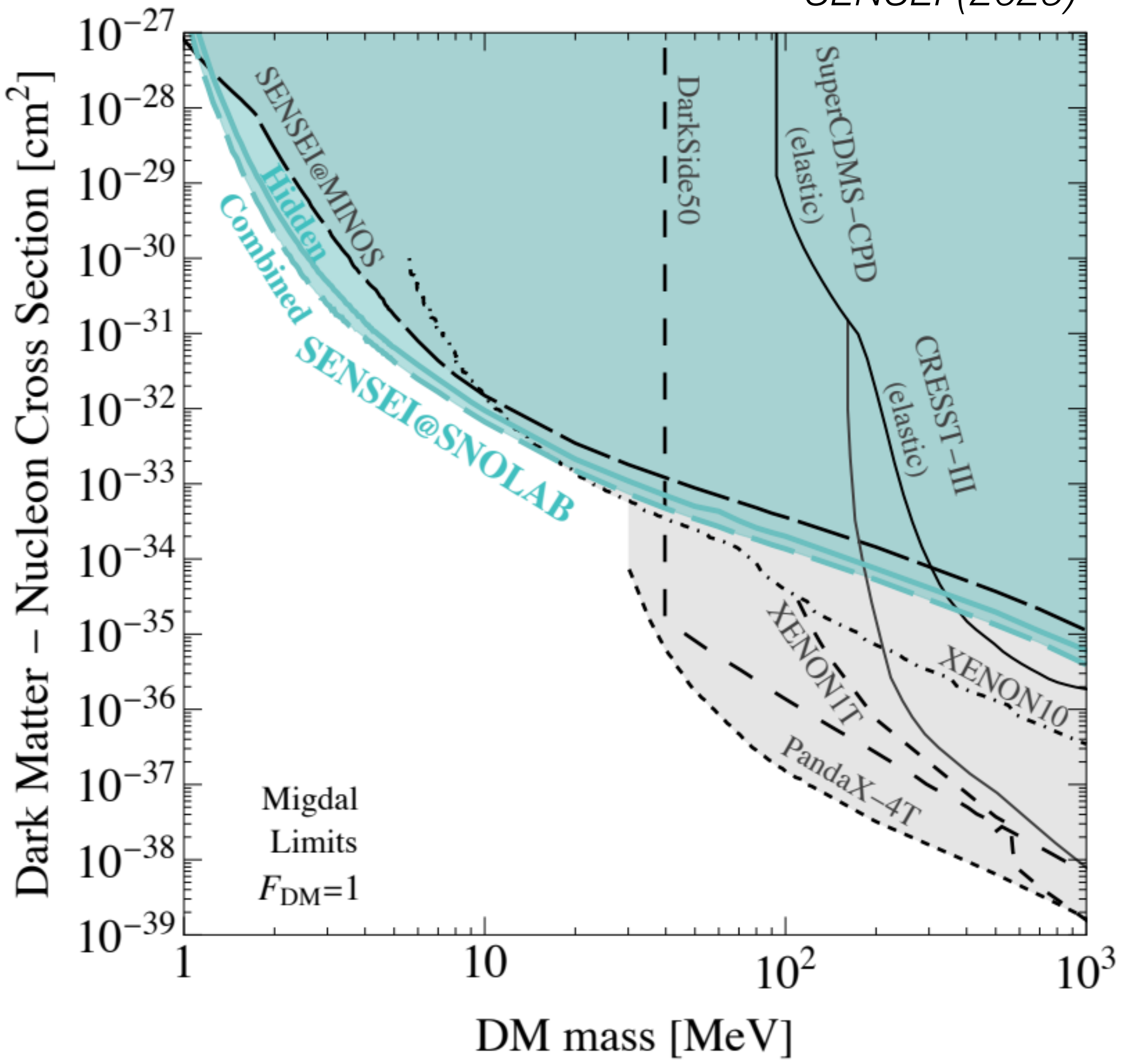


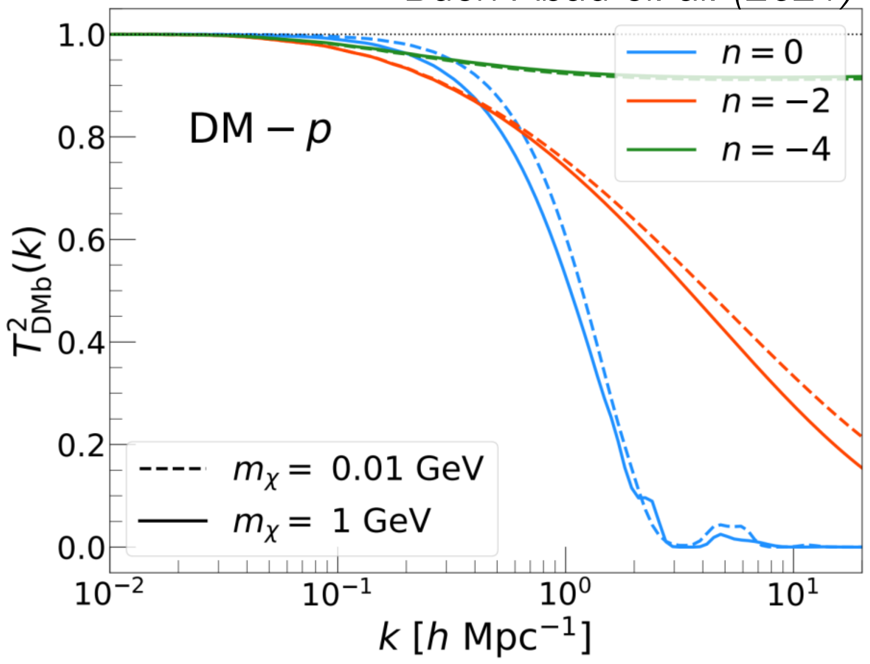
Existing constraints on sub-GeV DM

Leading "model-independent" bounds from cosmology

- *DM-baryon interactions modify matter power spectrum*

  suppress structure on smaller scales - probed by Lyman-α, CMB, MW satellites

Buen-Abad el. al. (2021)



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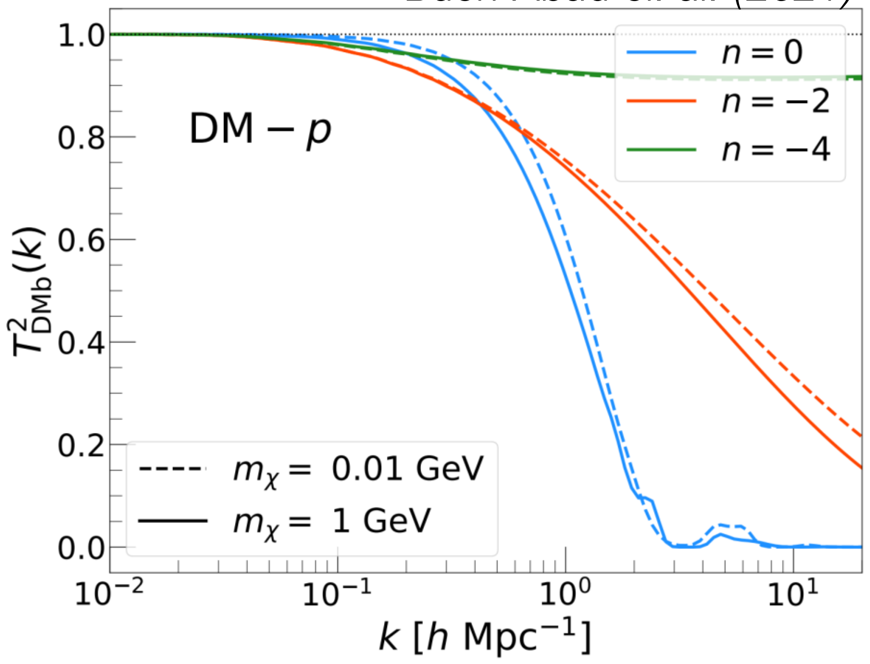

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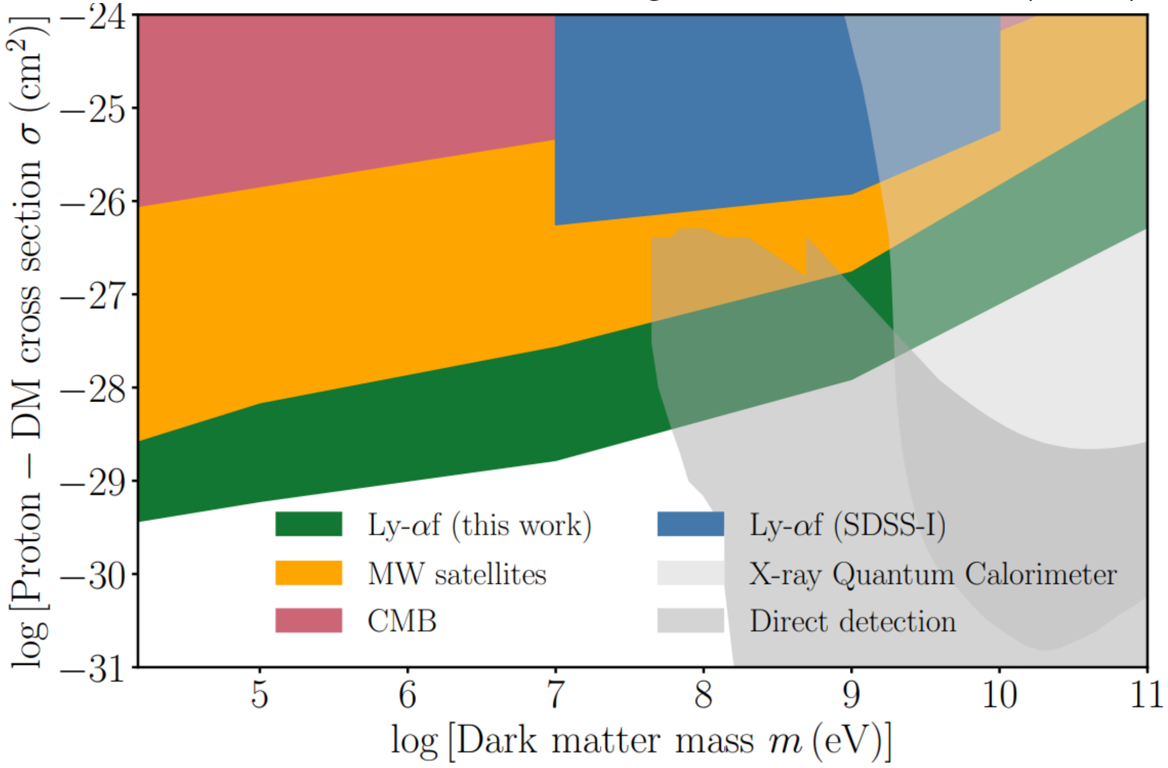

Existing constraints on sub-GeV DM

Expect many additional constraints in complete models:

- *BBN/CMB*
- *Rare meson decays*
- *Stellar/SN cooling*
- *Fifth force*
- *Accelerators/beam dumps*
- *…*

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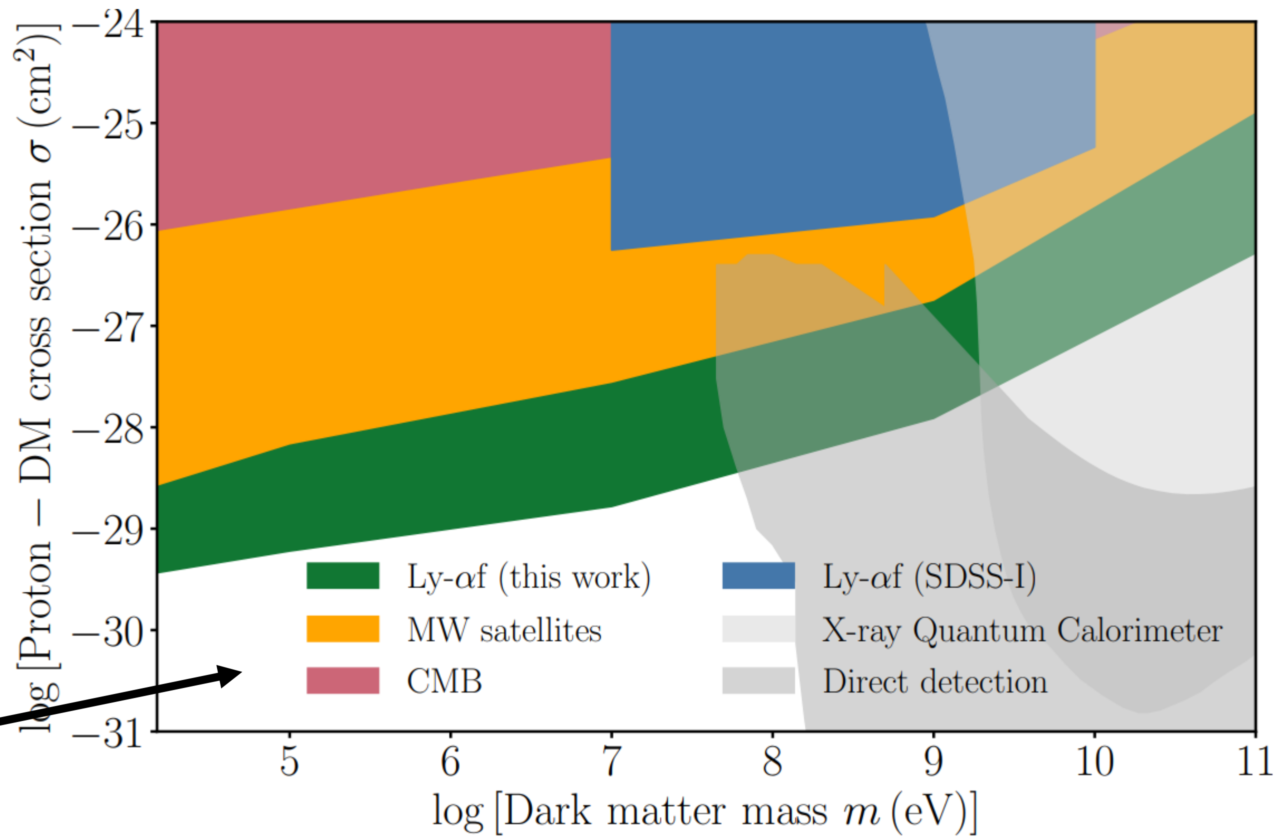
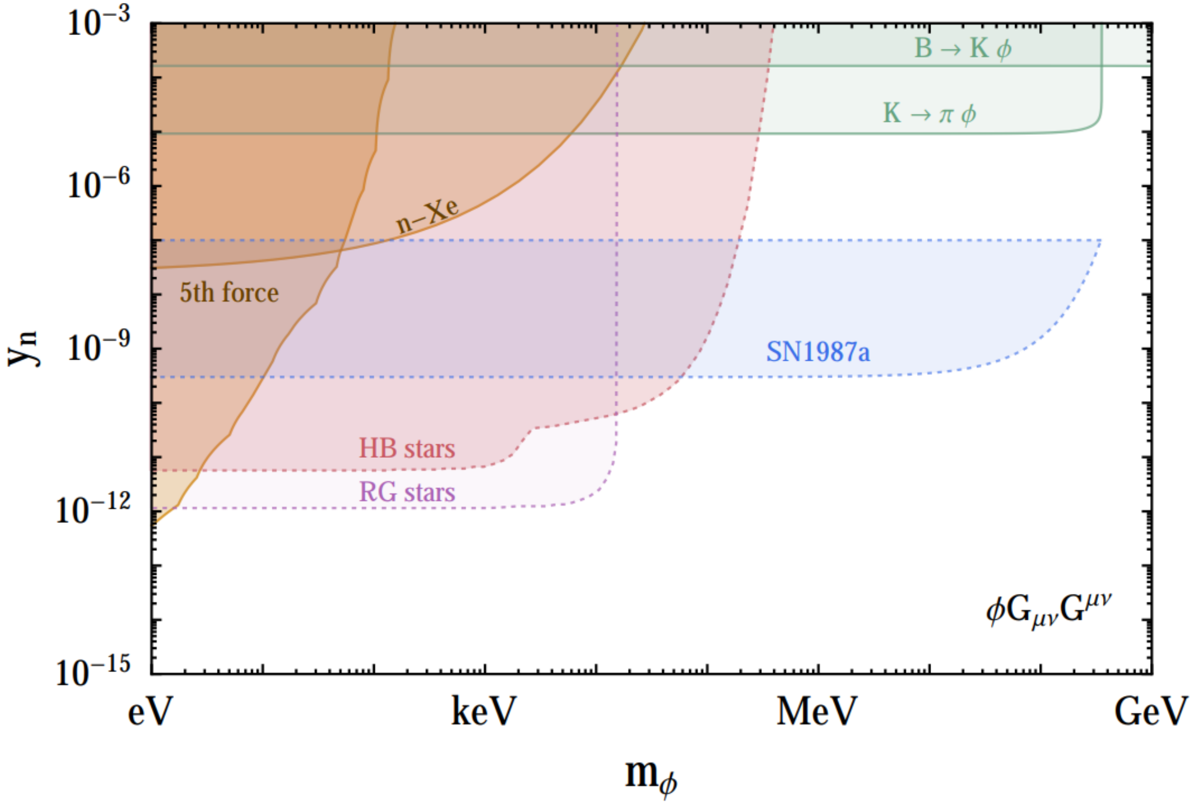


Are such large cross-sections allowed in any complete models?

Light scalar mediator example

Knapen, Lin, Zurek (2018)

$$\mathcal{L} \supset \frac{\alpha_s}{4\Lambda}\phi G^a_{\mu\nu}G^{a\mu\nu} \longrightarrow \mathcal{L} \supset -\frac{1}{2}y_\chi m_\chi \phi\chi^2 - y_n\phi\bar{n}n,$$



Strong bounds on hadronically-interacting scalar mediators from stars and SN1987A

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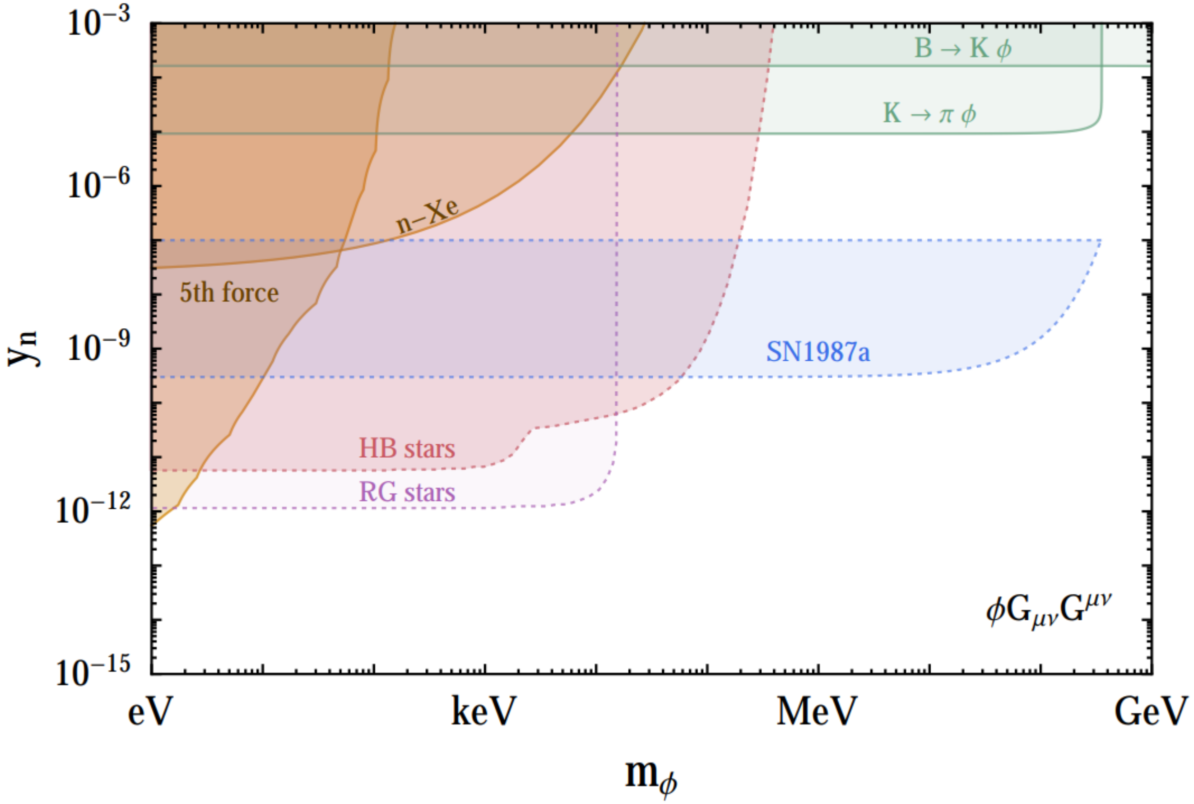
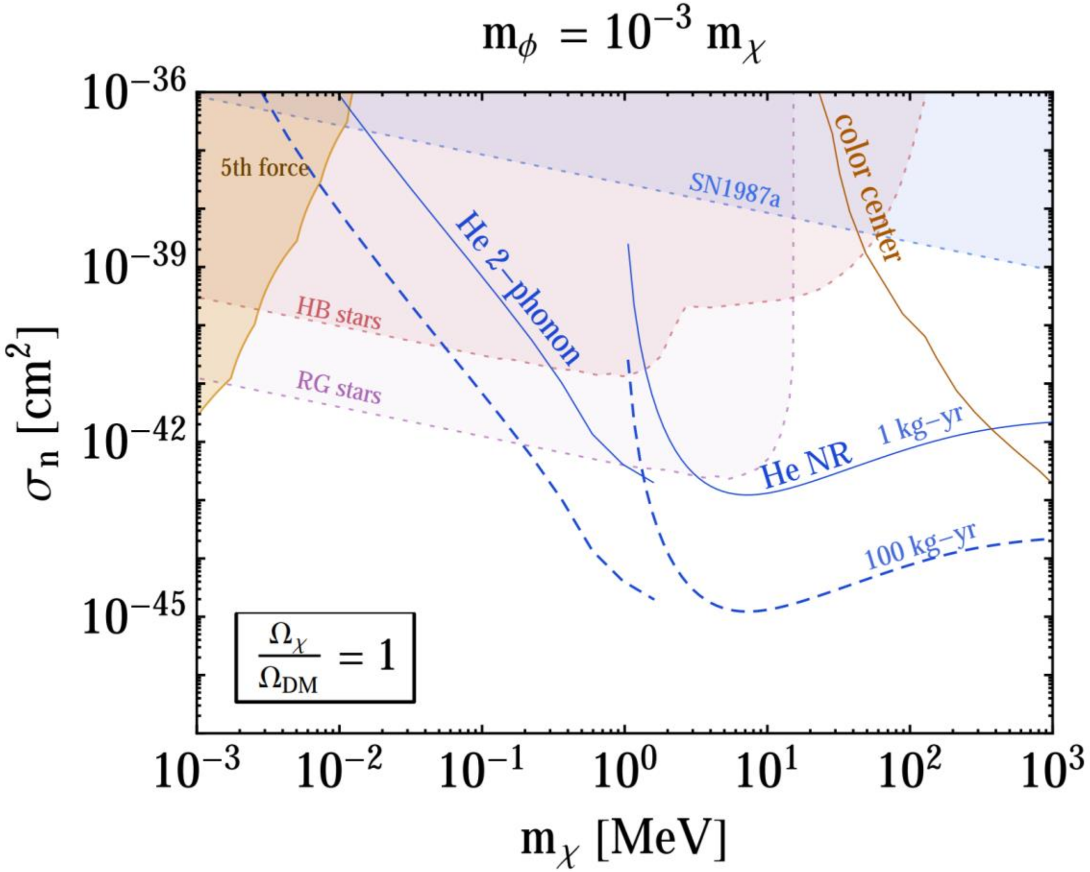




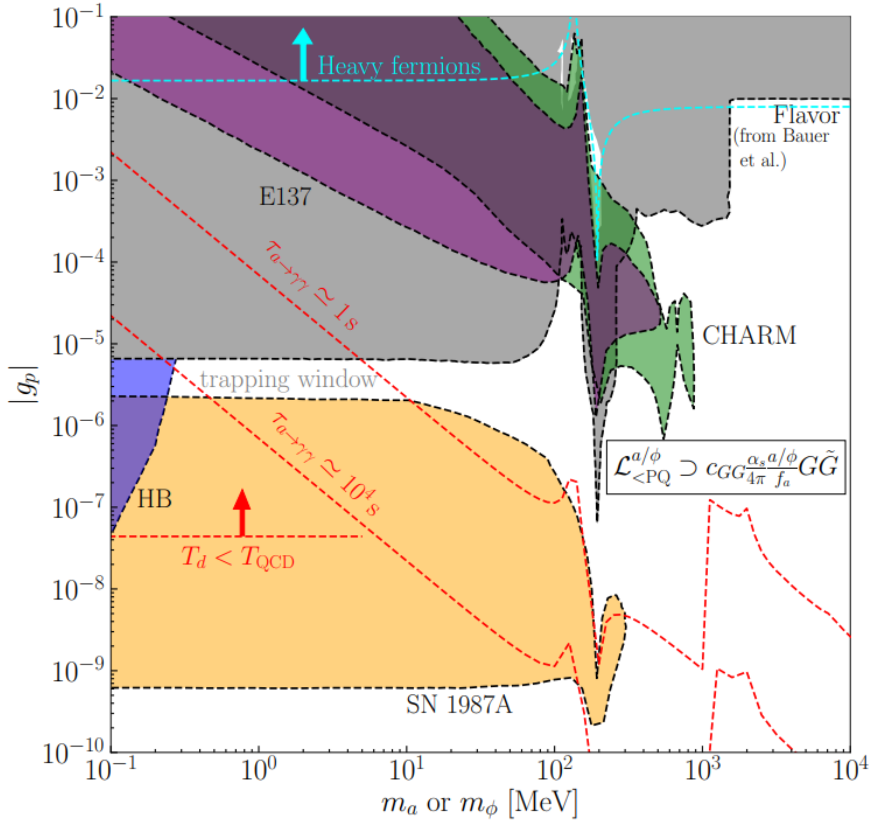
Strong bounds on hadronically-interacting scalar mediators from stars and SN1987A

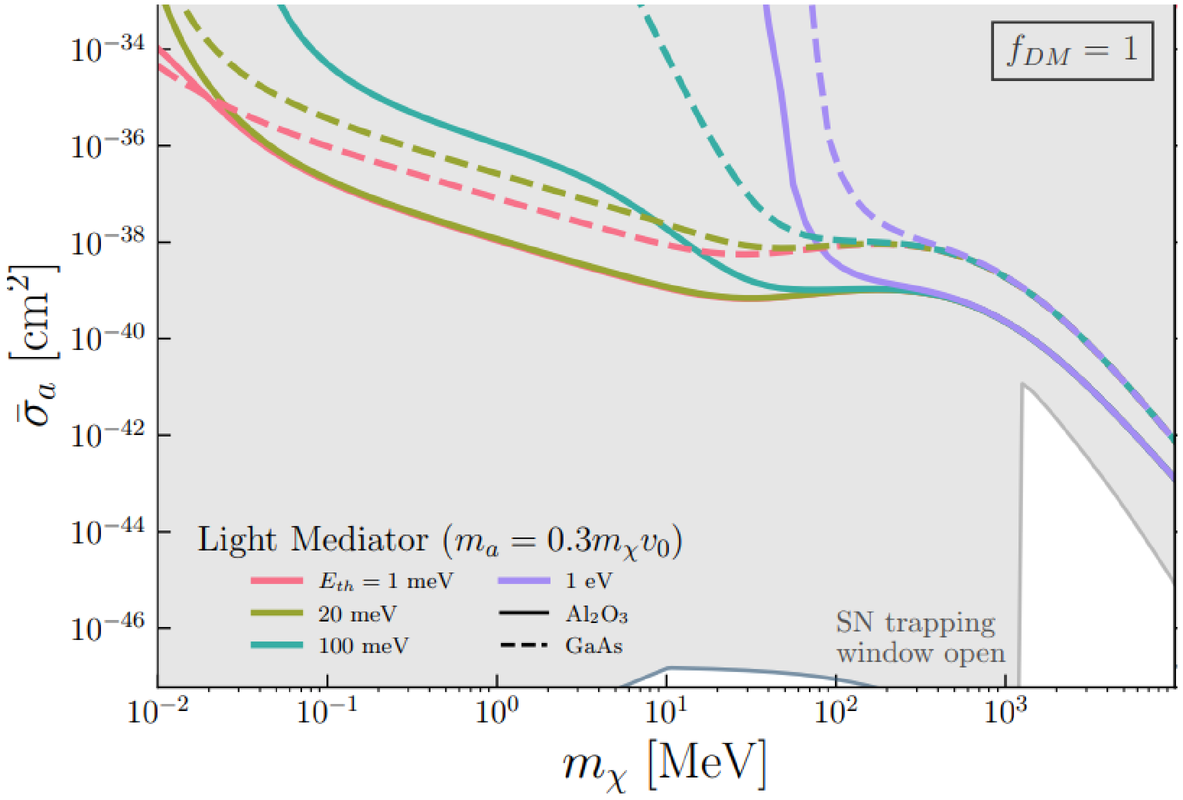
Light pseudo-scalar mediator example

Gori et.al. (2025)

Similarly, spin-dependent scattering via a light pseudoscalar mediator:

$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f_a} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \longrightarrow \mathcal{L}_a = a \left[g_\chi \bar{\chi}\gamma_5\chi + g_p \bar{p}\gamma^5 p + g_n \bar{n}\gamma^5 n \right]$$





This work: massive mediators

We consider the case where mediator mass is $\gtrsim 100$ MeV (i.e. above the SN bounds)

Focus on *low-energy phenomenology*

- Work in low-energy Chiral EFT
- BBN/CMB, rare meson decays
- Obtain *conservative* bounds on DM-nucleon cross-section

DM-SM interactions

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

$\mathcal{O}_{\rm SM}$	$\mathcal{O}_\chi$ (complex scalar DM)	$\mathcal{O}_\chi$ (fermion DM)
$\bar{q} M_q q$	$\chi^* \chi$	$\bar{\chi}\chi$
$G_{\mu\nu} G^{\mu\nu}$	$\chi^* \chi$	$\bar{\chi}\chi$
$\bar{q}\gamma_5 M_q q$	$\not{CP}$	$i\bar{\chi}\gamma^5\chi$
$G_{a\mu\nu}\tilde{G}^{a\mu\nu}$	$\not{CP}$	$i\bar{\chi}\gamma^5\chi$
$\bar{q}\gamma_\mu q$	$i\chi^* \overleftrightarrow{\partial^\mu} \chi$	$\bar{\chi}\gamma^\mu\chi$
$\bar{q}\gamma_\mu\gamma_5 q$	$\not{CP}$	$\bar{\chi}\gamma^\mu\gamma^5\chi$

(Future work: CP-violating couplings)

Scalar operators

Consider two effective models, motivated by UV completions

I. Gluon-coupled

$$\mathcal{O}^G_{\text{SM}} = \frac{\alpha_s}{8\pi} G^{a,\mu\nu} G_{a,\mu\nu}$$

Integrated out heavy quarks

II. Quark-coupled

$$\mathcal{O}^q_{\text{SM}} = \sum_{q=u,d,s} m_q \bar{q} q + \frac{c_G \alpha_s}{8\pi} G^{a,\mu\nu} G_{a,\mu\nu} + \frac{c_\gamma \alpha}{8\pi} F^{\mu\nu} F_{\mu\nu}$$

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

Matching to SU(3) Chiral Lagrangian

Gasser & Leutwyler (1985)
Bishara et. al. (2016)

- Dark matter treated as local source terms added to the QCD Lagrangian

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

- Match onto the low energy $(SU(3)_L \times SU(3)_R)/SU(3)_V$ Chiral Lagrangian

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

$$U(x) = \exp\left(i\sqrt{2}\Pi/f\right)$$

$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}$$

Matching to SU(3) Chiral Lagrangian

- Leading-order DM couplings to mesons

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

Gluon-coupled

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

Quark-coupled

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

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Gluon-coupled

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

- DM couplings to (non-relativistic) nucleons

$$\mathcal{L}_{\text{HBChPT}} \supset (b_0 \, \text{Tr}[M_q] \, s_\chi - \frac{2}{27} m_G s_G)(\bar{p}p + \bar{n}n)$$

Quark-coupled

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

Constraints from BBN

Abundance of additional relativistic species during BBN is tightly constrained

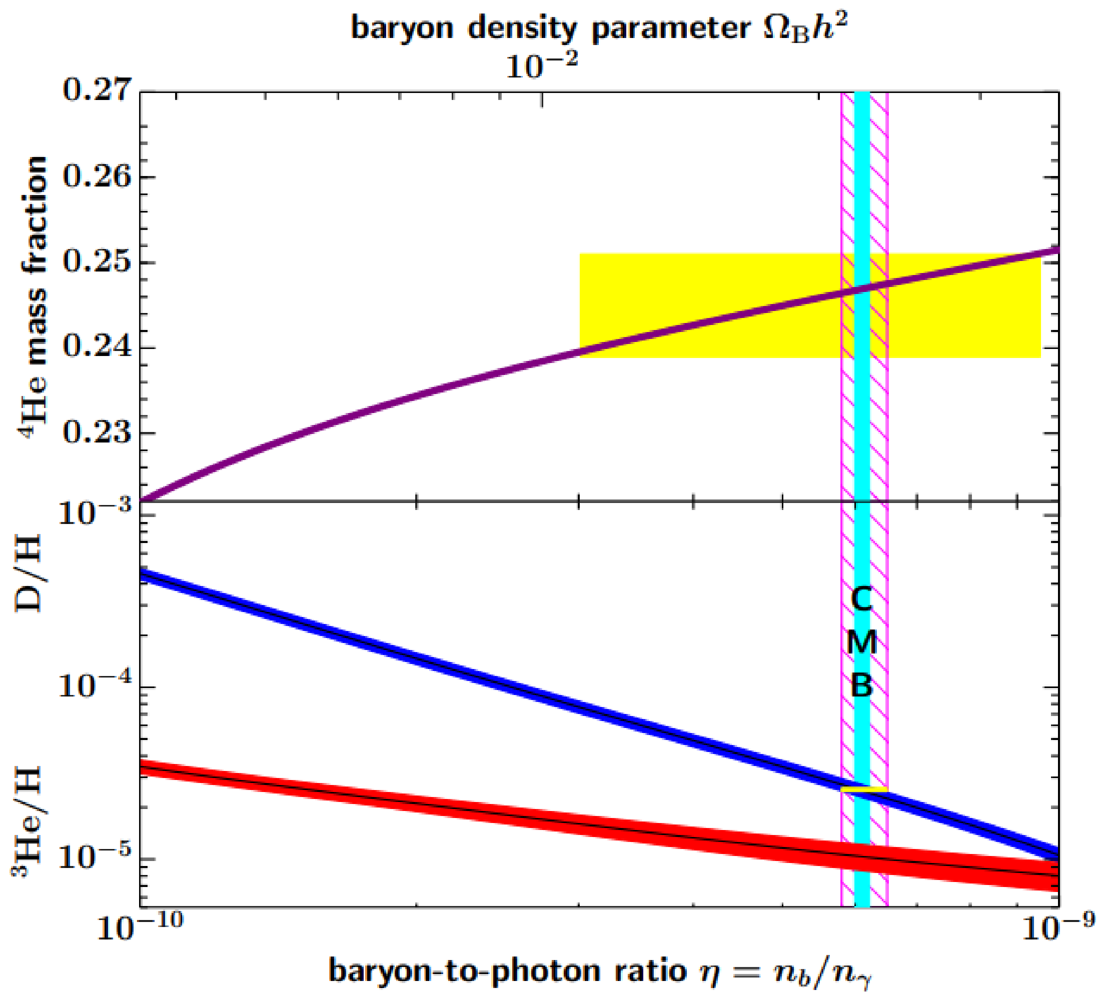
Steigman '77, Kolb et. al., '86, Boehm et. al. '13, …

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

$$m_\chi < 0.5\,\text{MeV}$$ *Sabti et. al. '19*

What about hadronically-interacting DM?

Figure: Particle Data Group



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

Aim: *conservative* bound on DM-nucleon cross-section,

independent of early cosmological history

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

Was the dark matter in equilibrium at 10 MeV?

Stronger bounds can be obtained *if* universe reheated to higher temperatures

(see e.g. Knapen et. al. '17, Green & Rajendran '17, …)

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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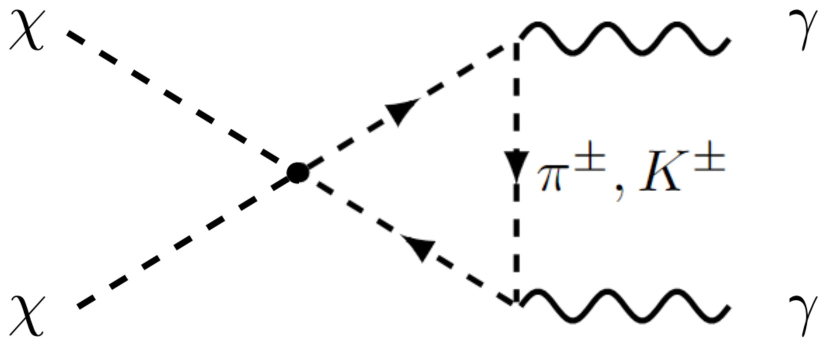
But DM interacts with photons at 1-loop



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*

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

III. *DM decouples when non-relativistic*

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Existing BBN analyses apply (I, III)

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Overclose the universe (I, II)

Existing BBN analyses apply (I–III)

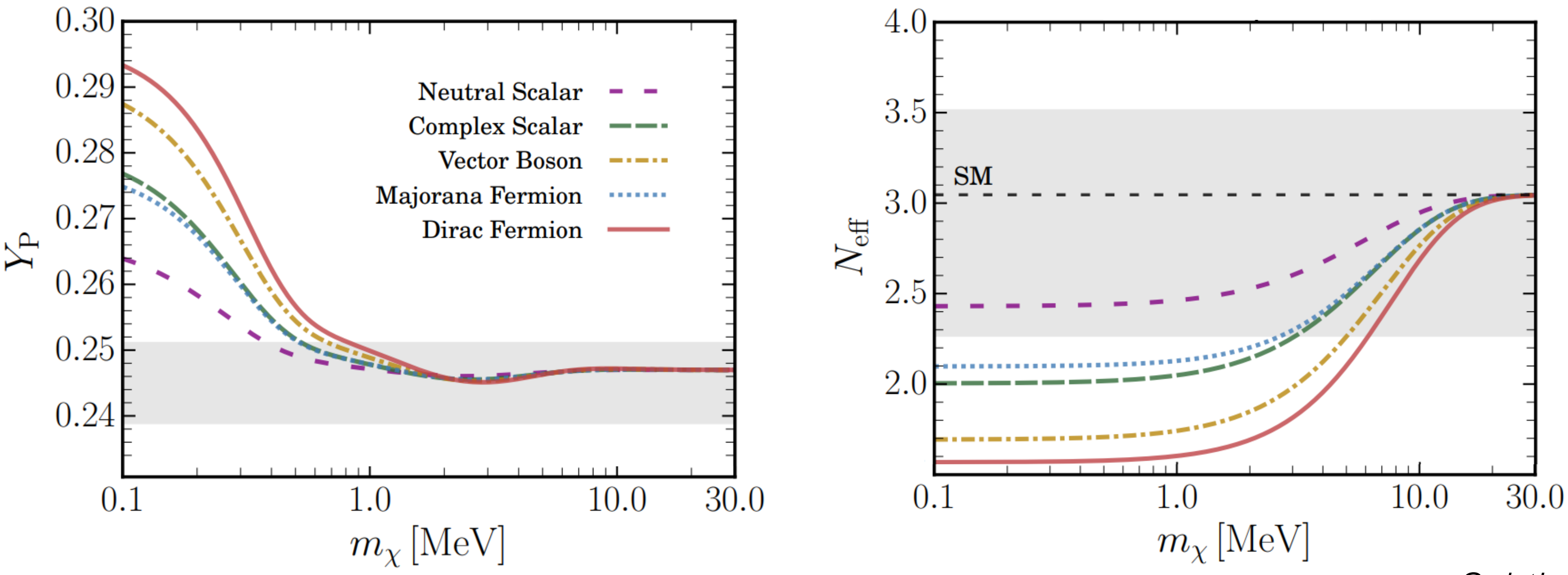
BBN & CMB: non-relativistic decoupling

I. DM initially increases expansion rate

- *Earlier freeze out of of* $n \leftrightarrow p$
- *Increases* Y_P

II. DM transfers entropy to photons

- *Dilutes baryons* $\Rightarrow$ *need larger initial* η
- *Decreases* T_ν / T_γ



Sabti et. al. (2019)

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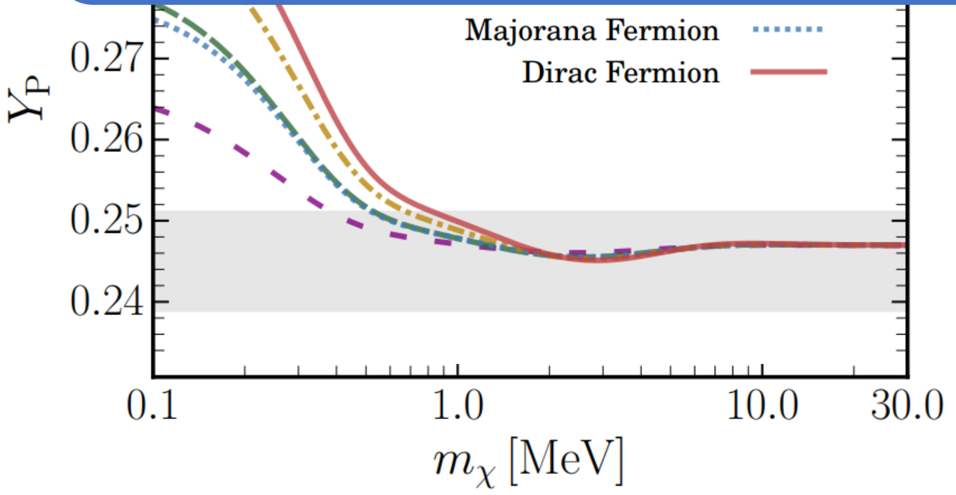
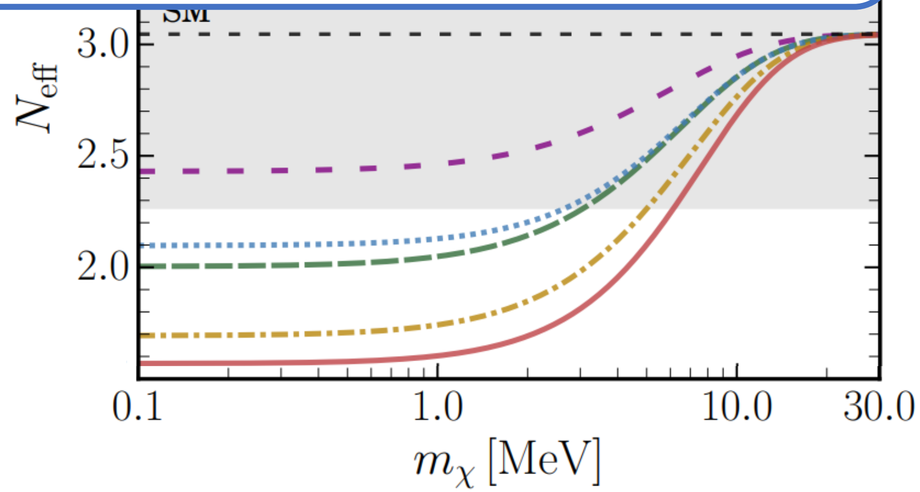
BBN only: $m_\chi > 0.4\,\mathrm{MeV}$

Combined BBN+CMB fit: $m_\chi > 4.9\,\mathrm{MeV}$

Sabti et. al. (2019)





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BBN & CMB bounds: relativistic decoupling

before $e^{\pm}$ annihilation

- Increased expansion rate during BBN

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

- Increase in both Y_P and $D/H|_P$

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

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

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after $e^{\pm}$ annihilation

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

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

$\Rightarrow \Delta N_{\rm eff}^{\rm CMB} \approx 2.2$ (real scalar $g_*^\chi = 1$)

BBN & CMB bounds

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

Three regimes:

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

Overcloses the universe & excluded by BBN

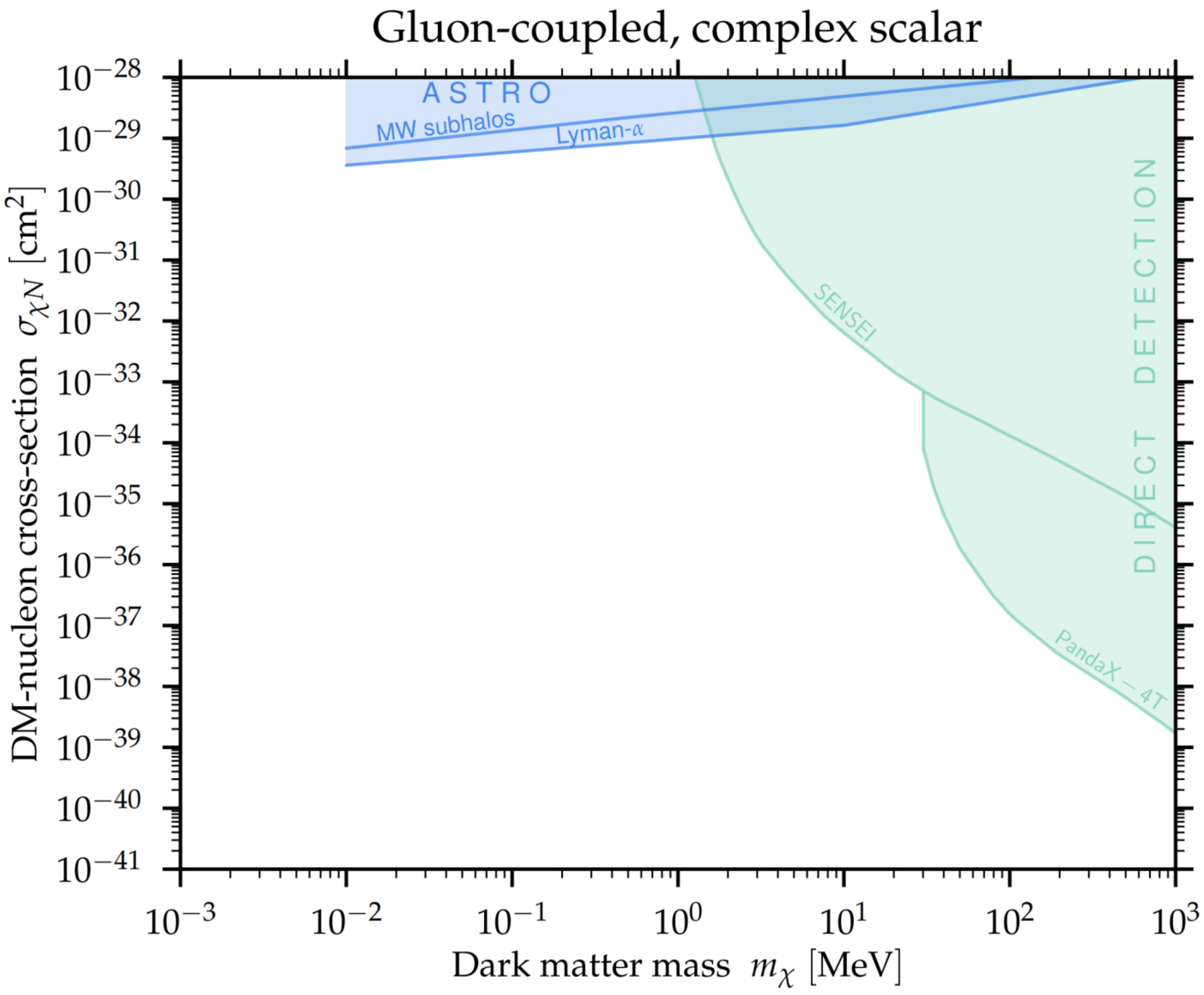
II. *DM decouples when relativistic, after $e^{\pm}$ annihilation*

Overcloses the universe & large contribution to $\Delta N_{\rm eff}^{\rm CMB}$

I. *DM decouples when non-relativistic*

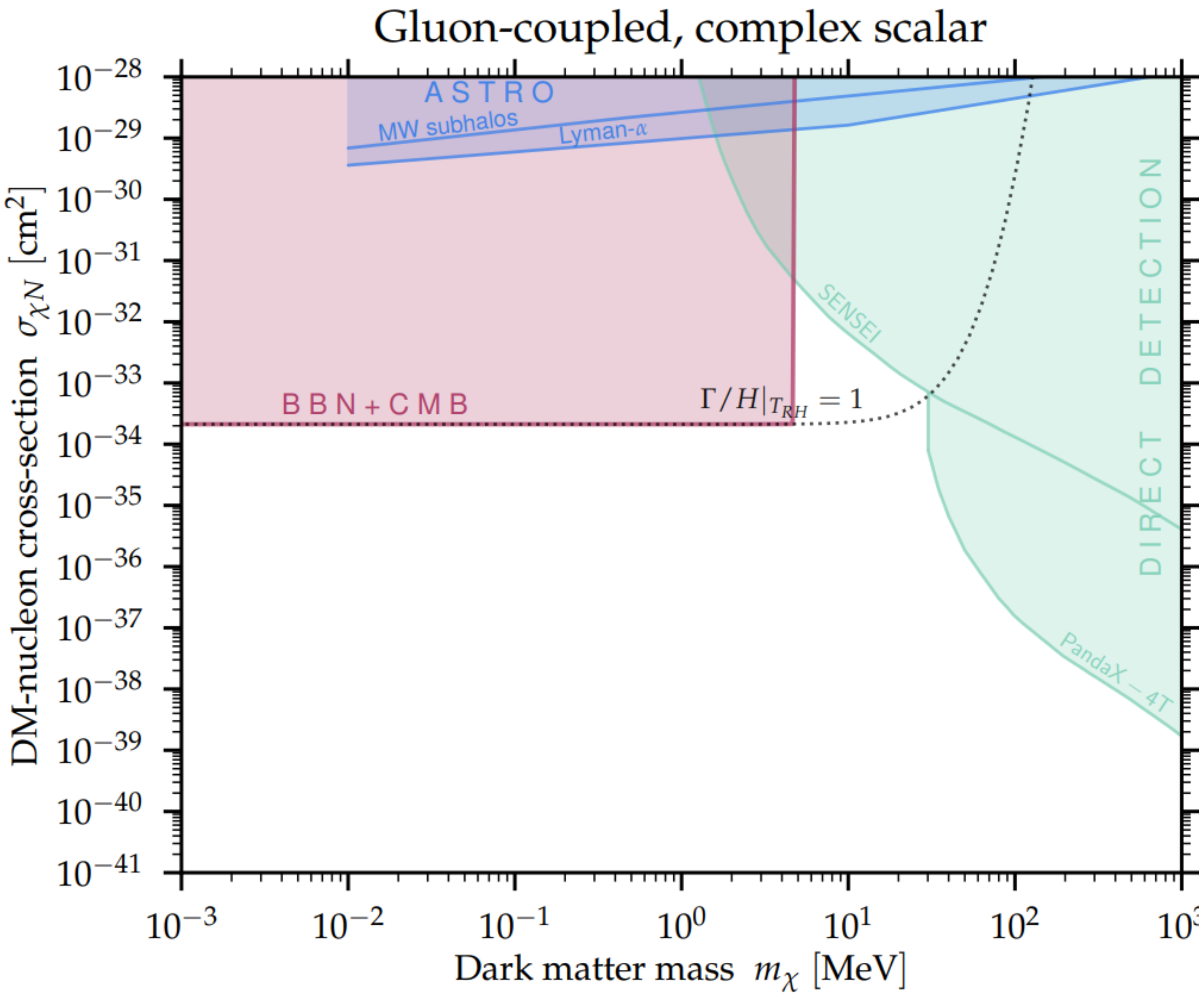
Excluded by BBN

Existing constraints



BBN constraints

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



$$\Gamma_{\gamma\gamma\to\bar{\chi}\chi} \propto \sigma_{\chi N} \frac{\alpha^2 T^5}{\Lambda_{\mathrm{QCD}}^2}$$

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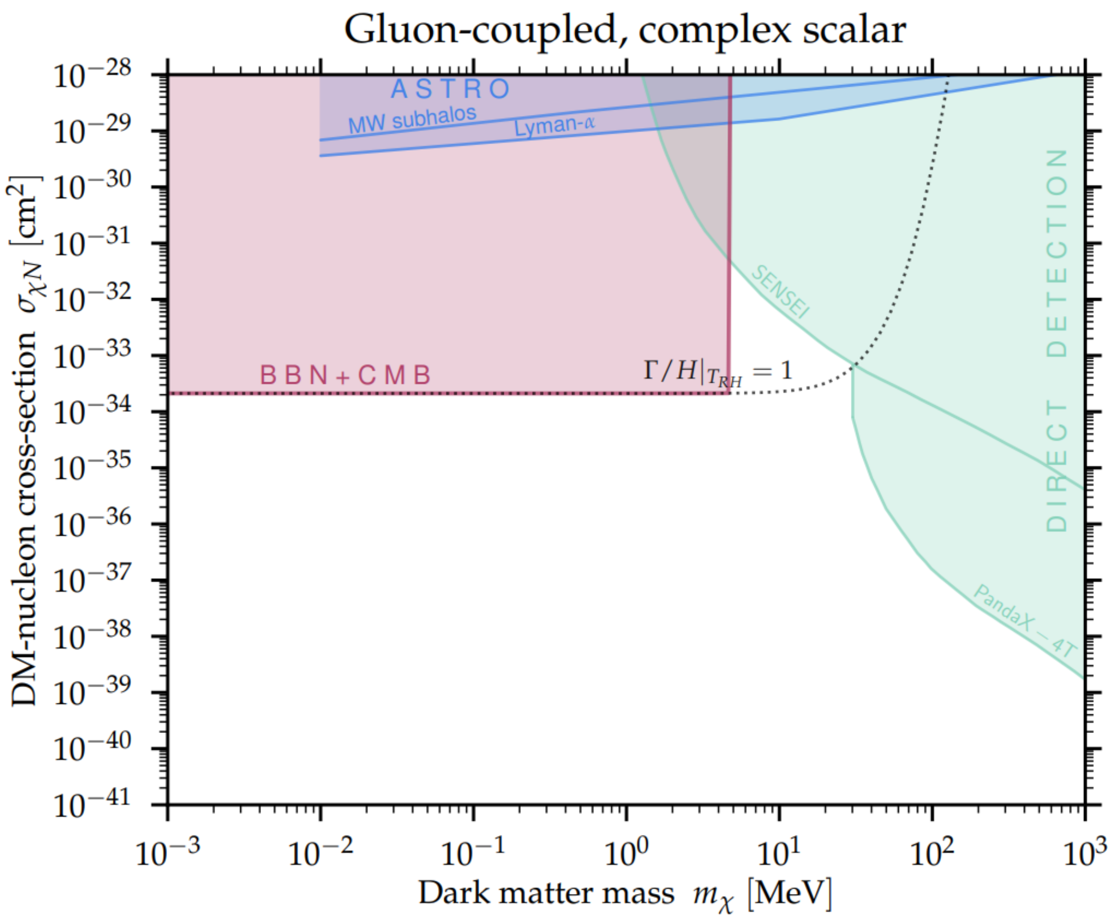
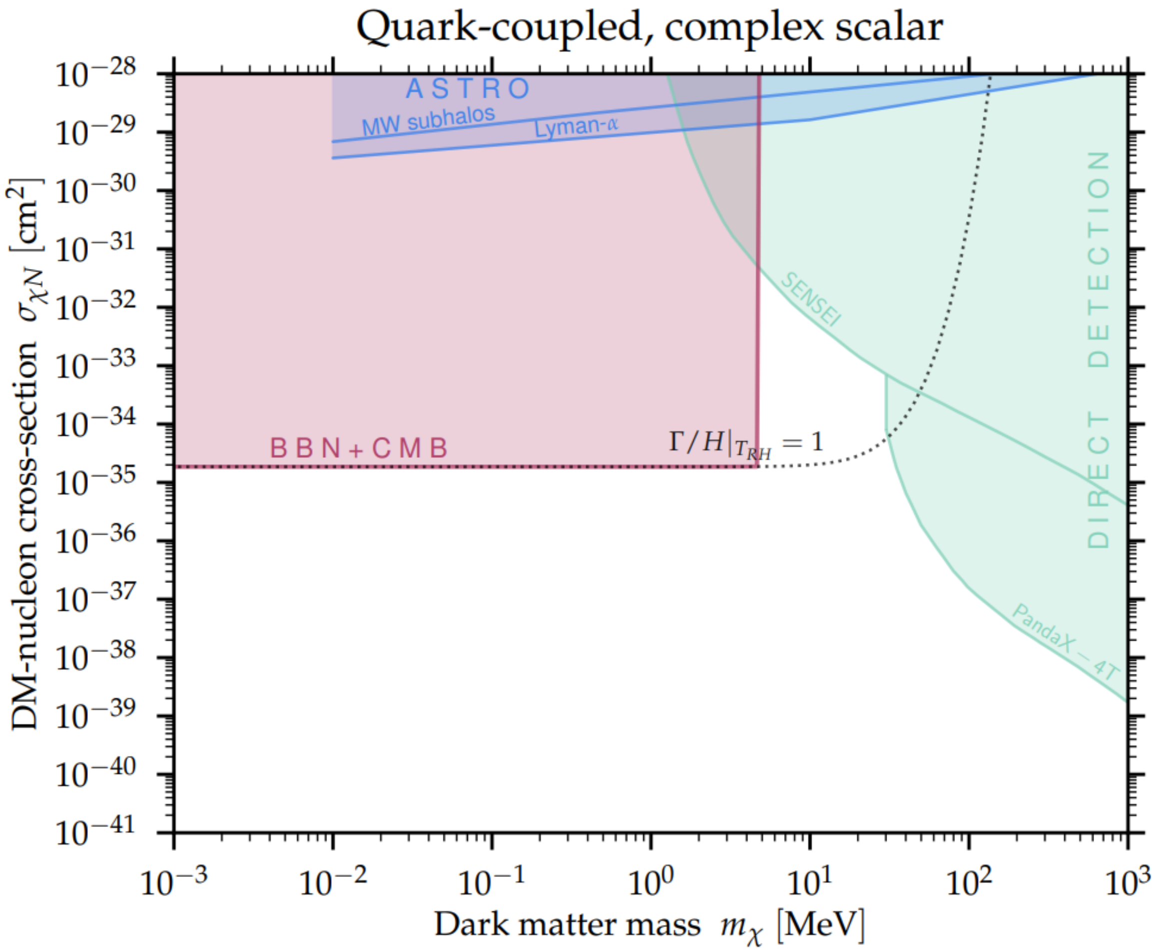




Minimal dependence on the model (*gluon-coupled vs quark-coupled*)

Kaon decay constraints

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

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

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

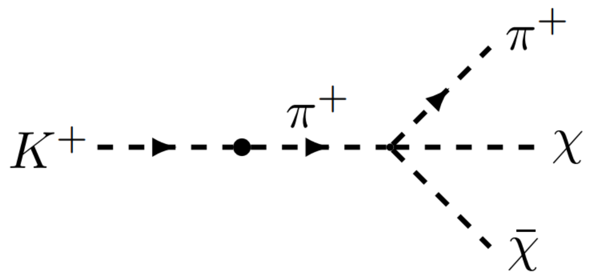
Leads to very strong bound on decay to other "invisible" particles, e.g. dark matter

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

Bounds from rare K-decays

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

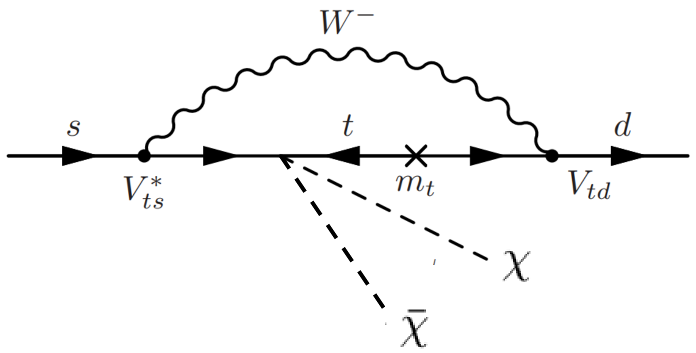
IR contribution:



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

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

UV contribution:



Additional terms in low-energy Lagrangian from matching

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

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

Bounds from rare K-decays

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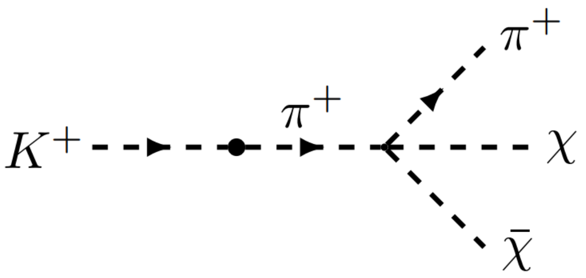
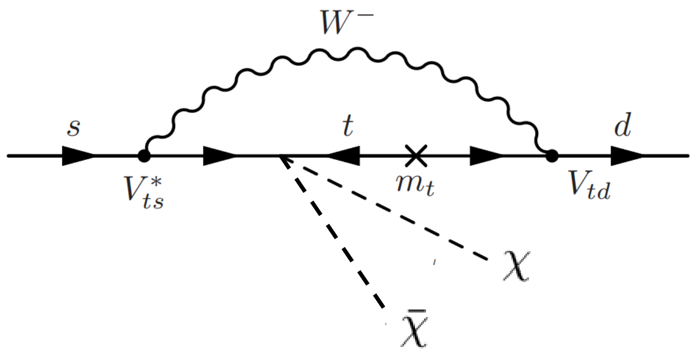


Leading contribution in gluon-coupled case

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

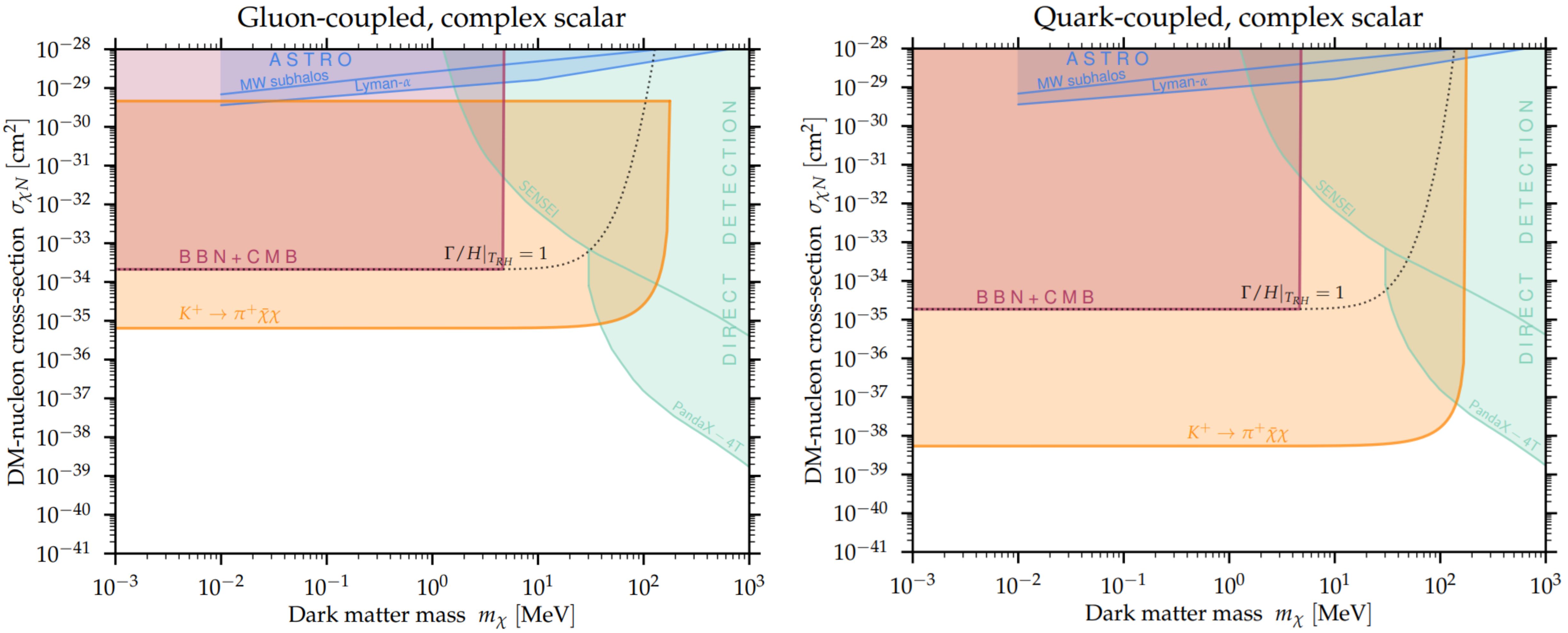
UV contribution:



Dominates if coupling to heavy quarks
(e.g. Higgs portal models)

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

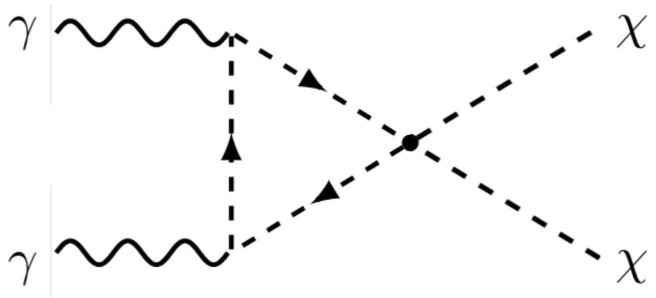
Kaon decay constraints



Kaon decays give stronger, but more model-dependent bounds

Freeze-in DM abundance

- *Dark* matter produced via freeze-in *below* $T\sim 10$ MeV



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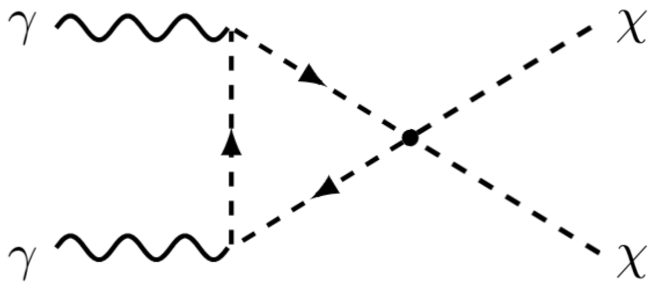
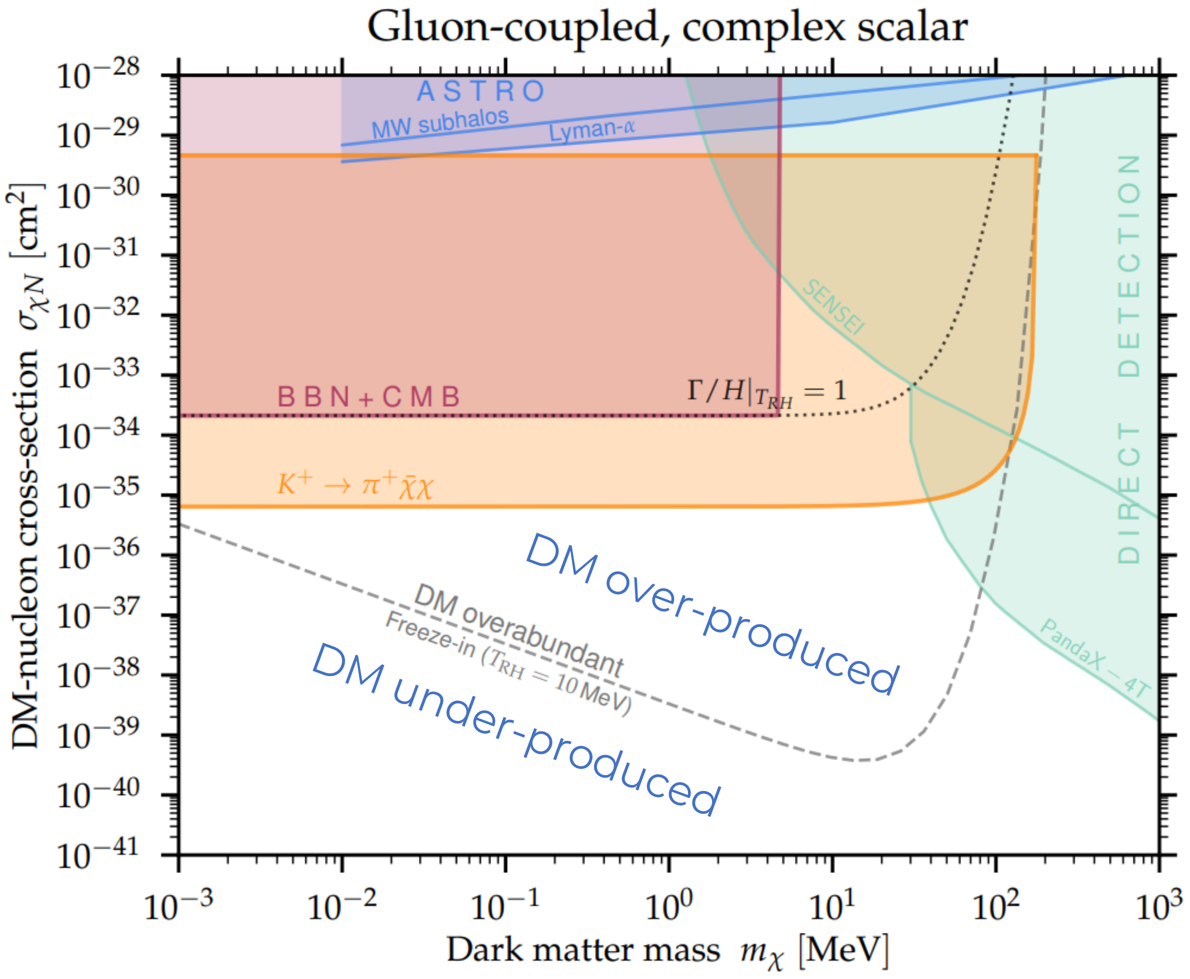


Irreducible abundance: very difficult to deplete this DM prior to CMB

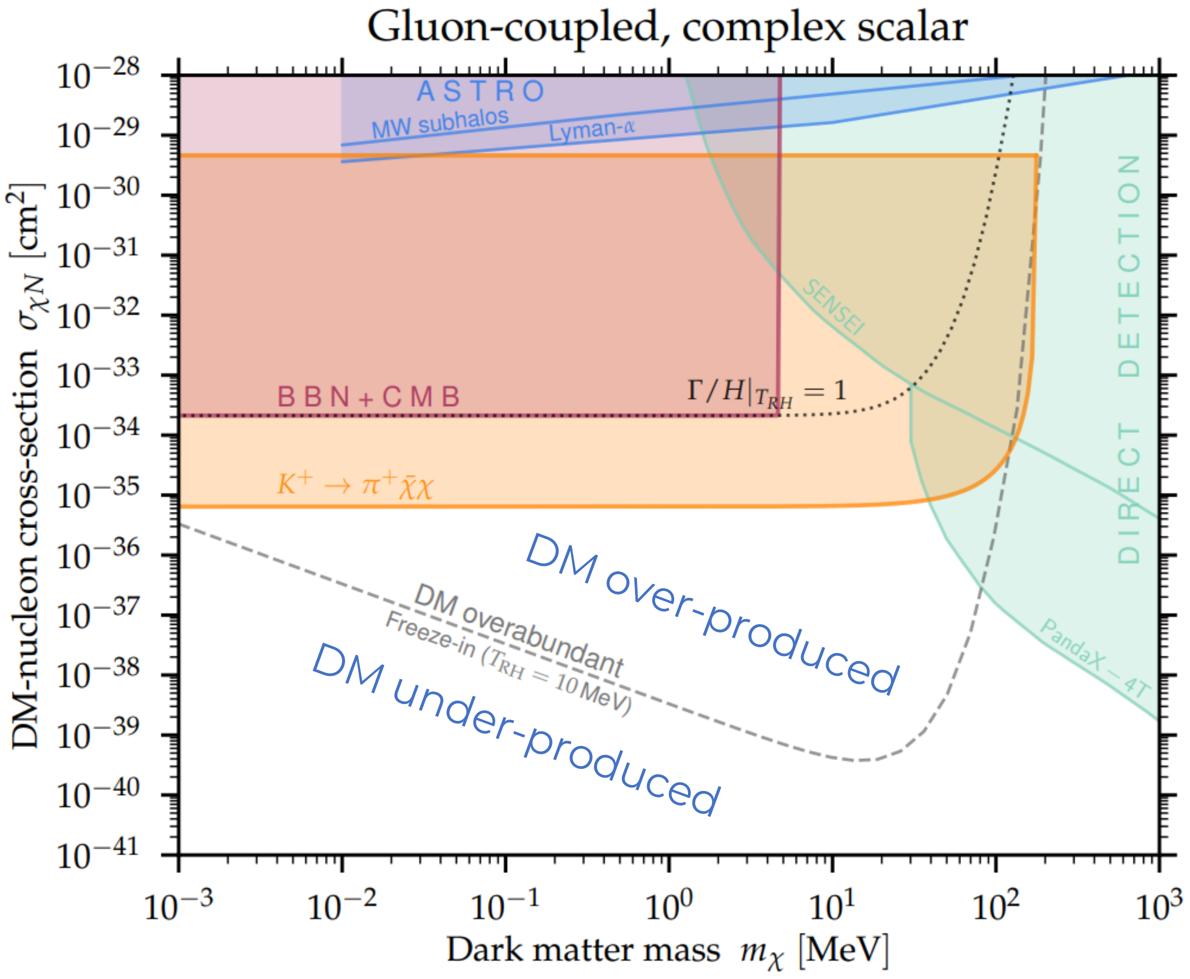
- Decay/annihilate to SM sector: *dilutes baryons*
- Decay/annihilate to dark sector: *contribution to* ΔN_{eff}^{CMB}

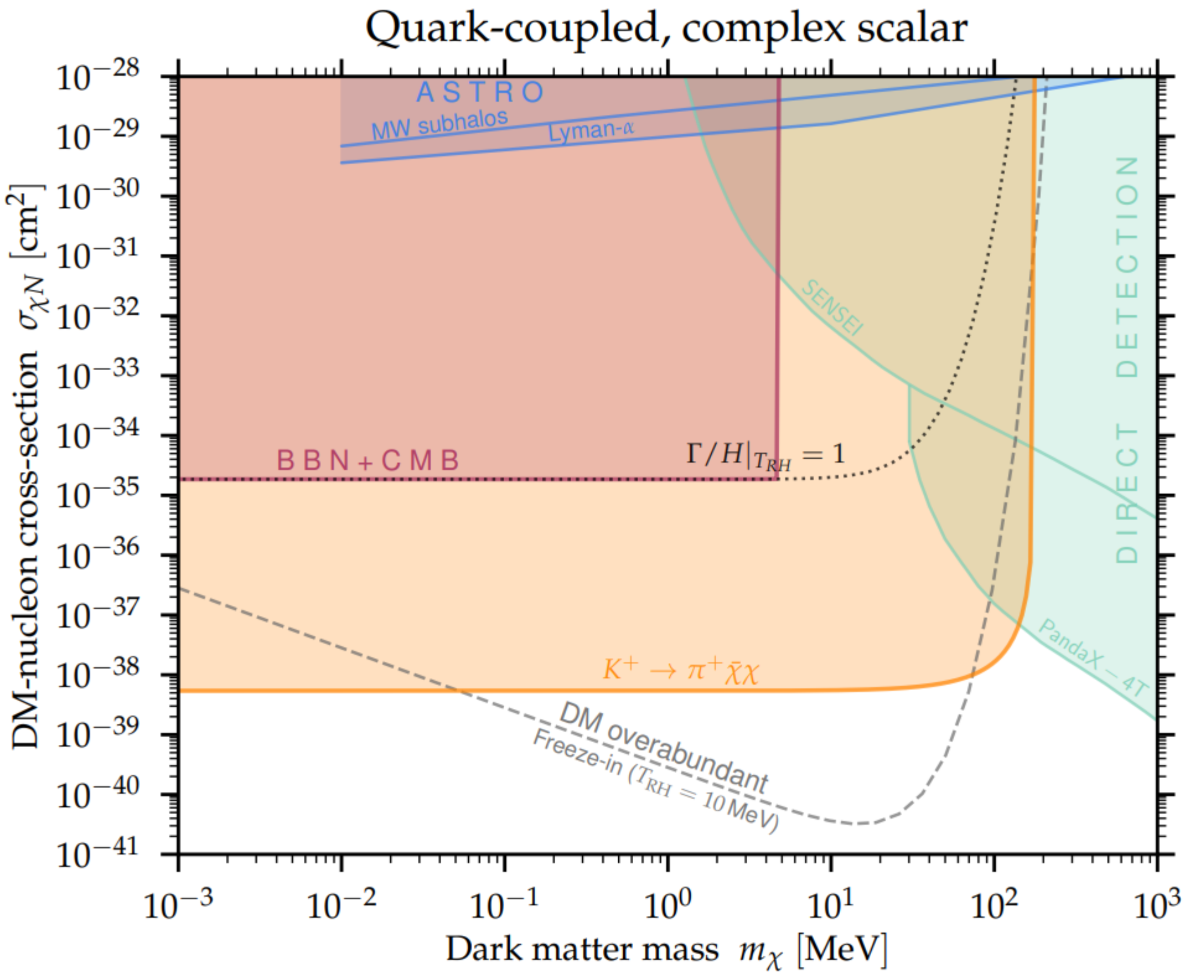
Results: scalar operators, scalar DM



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

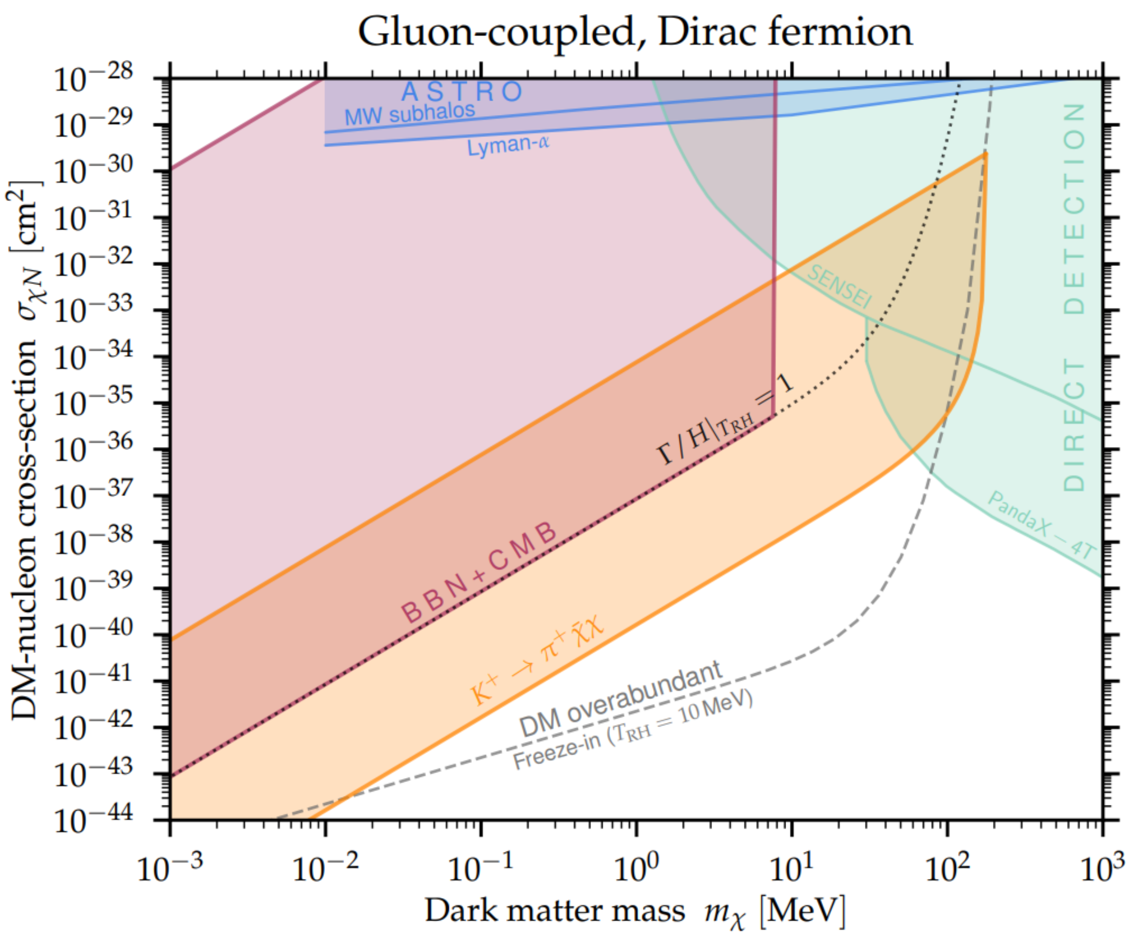
Results: scalar operators, scalar DM

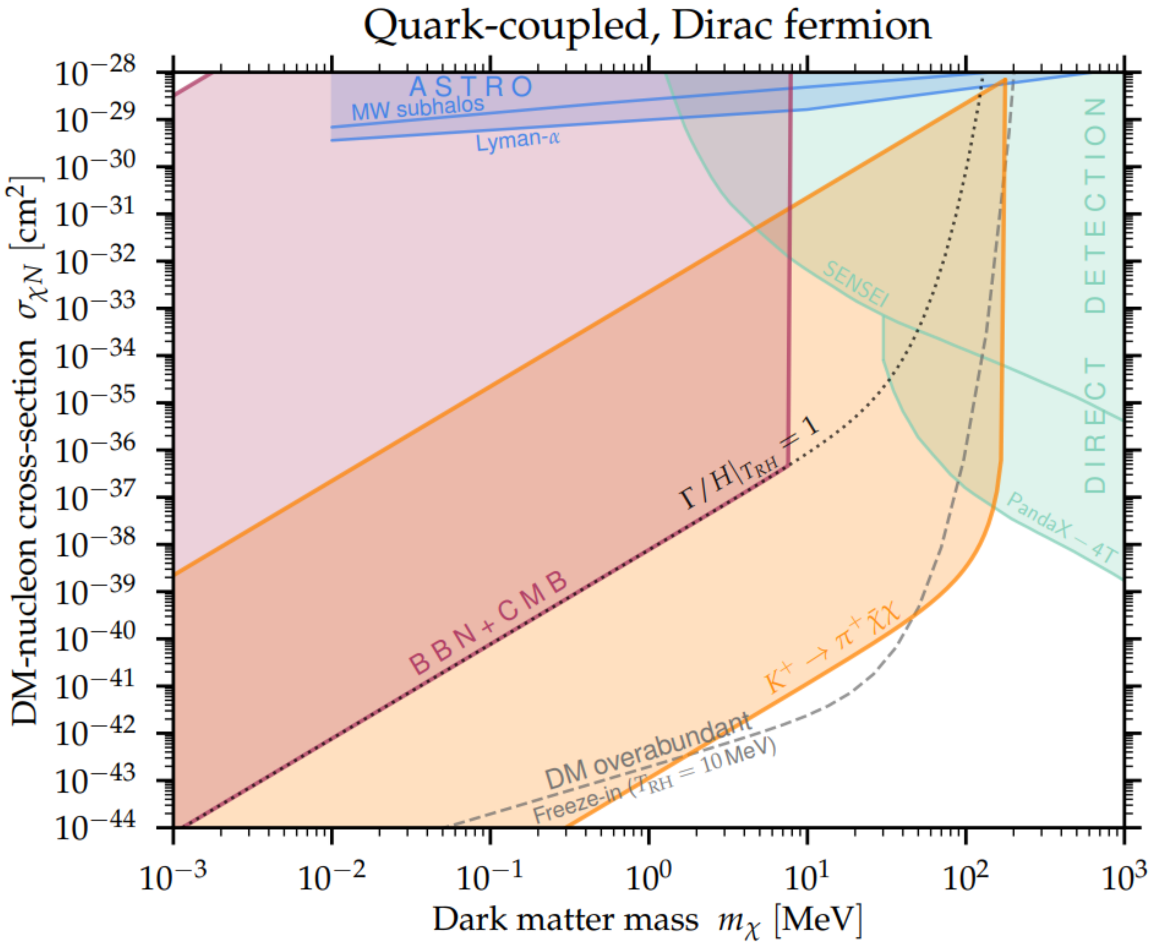




Irreducible freeze-in abundance produced by $\gamma\gamma \to \chi\chi$

Results: scalar operators, fermionic DM





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

Vector operators

$$\mathcal{L} = \mathcal{L}_{\rm QCD} + \bar{q}\gamma^\mu v_\mu(x) q \qquad v_{\mu,a} = C_a^V \begin{cases} \frac{1}{\Lambda^2} i\chi^* \overleftrightarrow{\partial^\mu}\chi & \text{(scalar DM)} \\ \frac{1}{\Lambda^2} \chi\bar{\gamma}^\mu\chi & \text{(fermion DM)} \end{cases}$$

$$\Downarrow$$

$$\mathcal{L}_V = \frac{i}{\Lambda^2}\left(\left(C_u^V - C_d^V\right)\pi^- \overleftrightarrow{D}_\mu \pi^+ + \left(C_u^V - C_s^V\right) K^- \overleftrightarrow{D}_\mu K^+ + \left(C_s^V - C_d^V\right) K^0 \overleftrightarrow{D}_\mu \bar{K}^0\right) \begin{cases} i\chi^* \overleftrightarrow{\partial^\mu}\chi & \text{(scalar DM)} \\ \chi\bar{\gamma}^\mu\chi & \text{(fermion DM)} \end{cases}$$

Vector operators

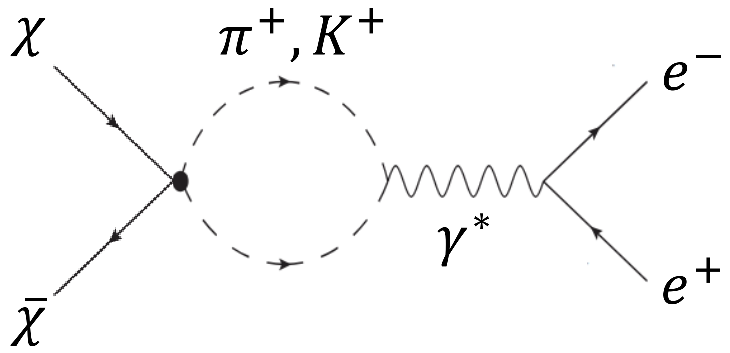
$$\mathcal{L} = \mathcal{L}_{\text{QCD}} + \bar{q}\gamma^\mu v_\mu(x) q \qquad v_{\mu,a} = C_a^V \begin{cases} \frac{1}{\Lambda^2} i\chi^* \overleftrightarrow{\partial^\mu}\chi & \text{(scalar DM)} \\ \frac{1}{\Lambda^2}\chi\bar{\gamma}^\mu\chi & \text{(fermion DM)} \end{cases}$$

$$\Downarrow$$

$$\mathcal{L}_V = \frac{i}{\Lambda^2}\left((C_u^V - C_d^V)\,\pi^- \overleftrightarrow{D}_\mu \pi^+ + (C_u^V - C_s^V)\,K^- \overleftrightarrow{D}_\mu K^+ + (C_s^V - C_d^V)\,K^0 \overleftrightarrow{D}_\mu \bar{K}^0 \right) \begin{cases} i\chi^* \overleftrightarrow{\partial^\mu}\chi & \text{(scalar DM)} \\ \chi\bar{\gamma}^\mu\chi & \text{(fermion DM)} \end{cases}$$

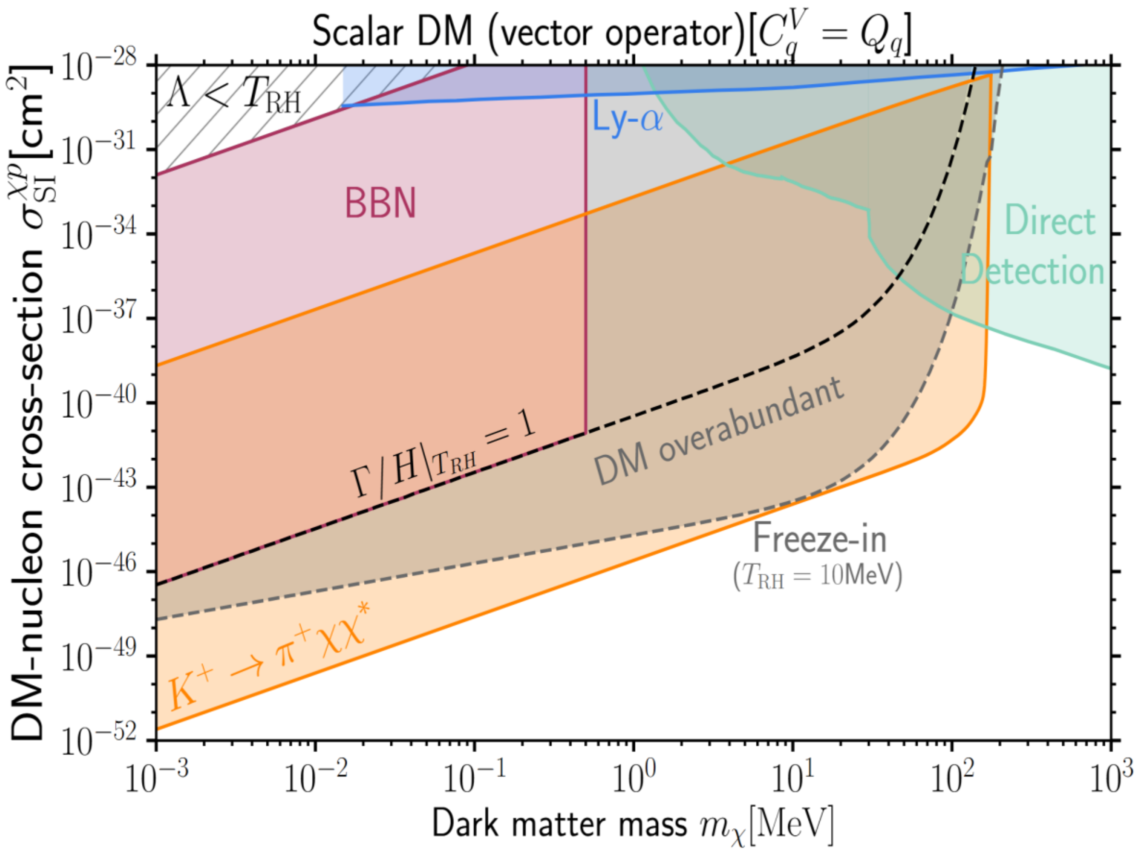
Coupling to two photons vanishes by Landau-Yang theorem

Coupling to electrons induced at one-loop



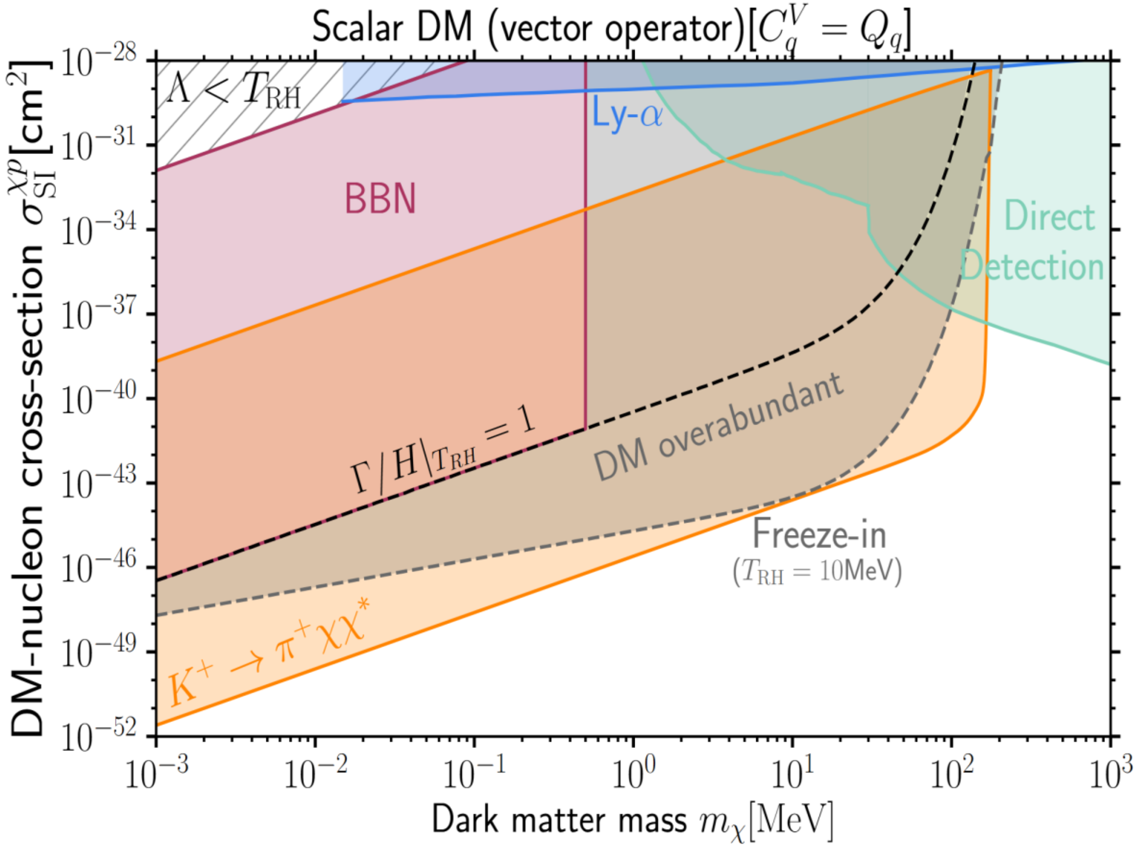
Results: vector operator

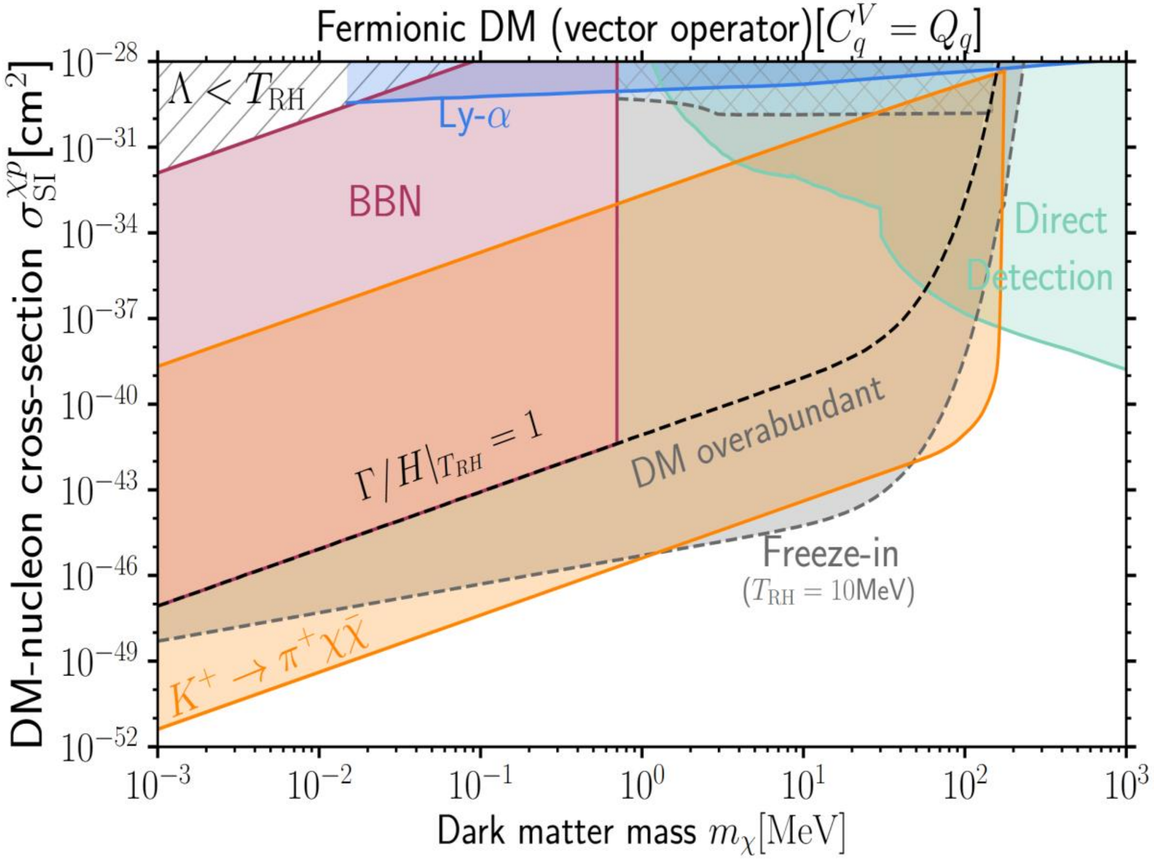
Preliminary!



Results: vector operator

Preliminary!

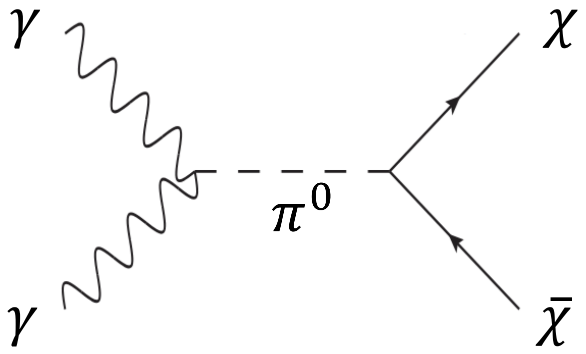




Axial-vector operator

$$\mathcal{L} = \mathcal{L}_{\text{QCD}} + \bar{q}\gamma^\mu\gamma^5 a_\mu(x) q \quad \Rightarrow \quad \mathcal{L}_A = -\frac{1}{\Lambda^2}\left(C_u^A - C_d^A\right) f\,(\partial_\mu \pi^0)(\bar{\chi}\gamma^\mu\gamma^5\chi)$$

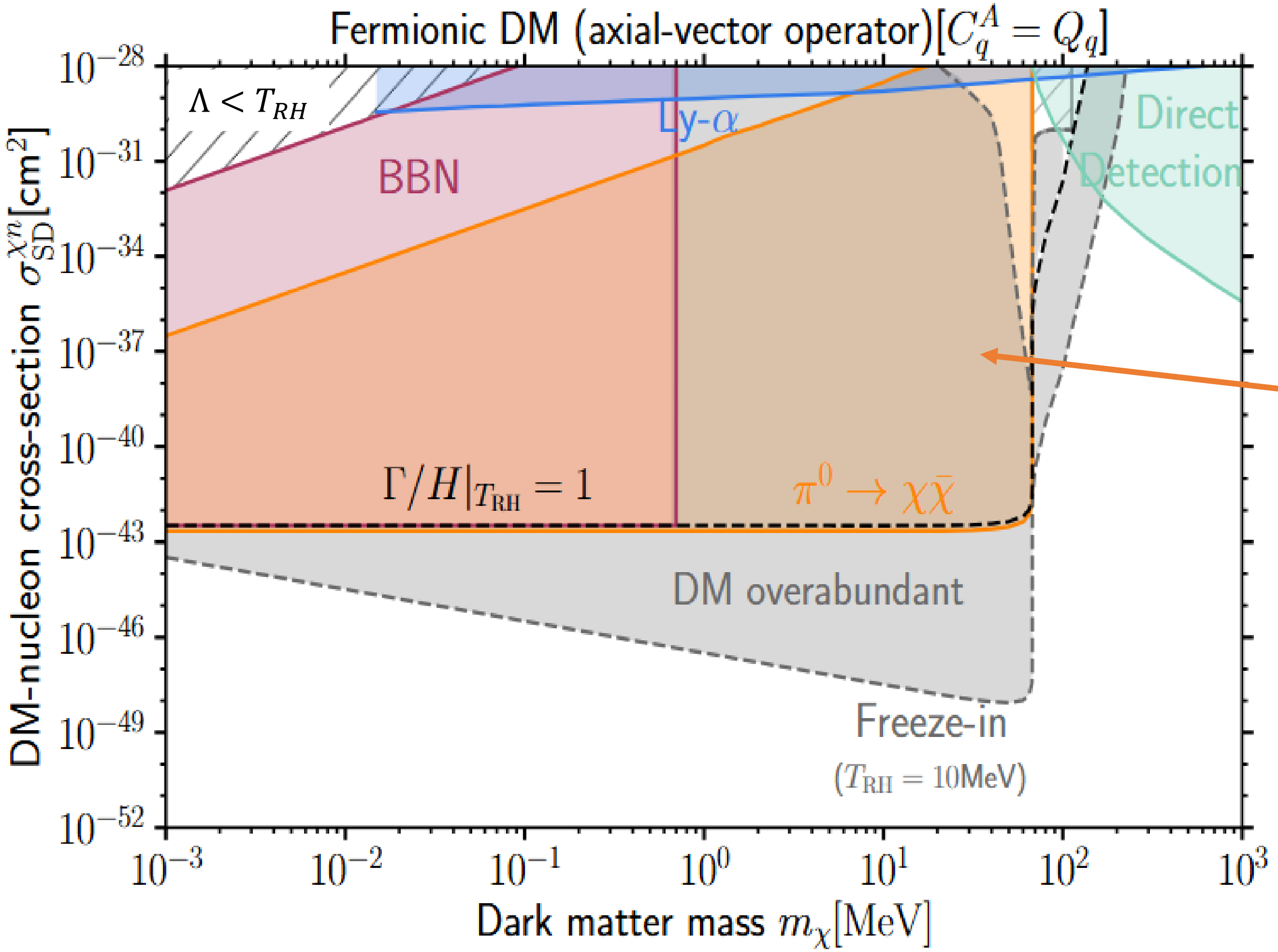
DM couples to a single π^0



Results: axial-vector operator

Preliminary!

Spin-dependent cross-section



$\mathrm{BR}(\pi^0 \to \mathrm{invisible}) < 4.4 \times 10^{-9}$

(NA62)

Special case: flavour universal couplings

For vector/axial-vector operators with *flavour-universal* couplings,
couplings to mesons *vanish* at leading order

$$\mathcal{L}_V = \frac{i}{\Lambda^2}\left(\left(C_u^V - C_d^V\right)\pi^- \overleftrightarrow{D}_\mu \pi^+ + \left(C_u^V - C_s^V\right) K^- \overleftrightarrow{D}_\mu K^+ + \left(C_s^V - C_d^V\right) K^0 \overleftrightarrow{D}_\mu \bar{K}^0\right) \begin{cases} i\chi^* \overleftrightarrow{\partial^\mu} \chi & \text{(scalar DM)} \\ \chi \bar{\gamma}^\mu \chi & \text{(fermion DM)} \end{cases}$$

$$\mathcal{L}_A = -\frac{1}{\Lambda^2}\left(C_u^A - C_d^A\right) f\,(\partial_\mu \pi^0)(\bar{\chi}\gamma^\mu\gamma^5\chi)$$

Need to go to NLO in Chiral Lagrangian $\Rightarrow$ *weaker constraints*

Special case: flavour universal couplings

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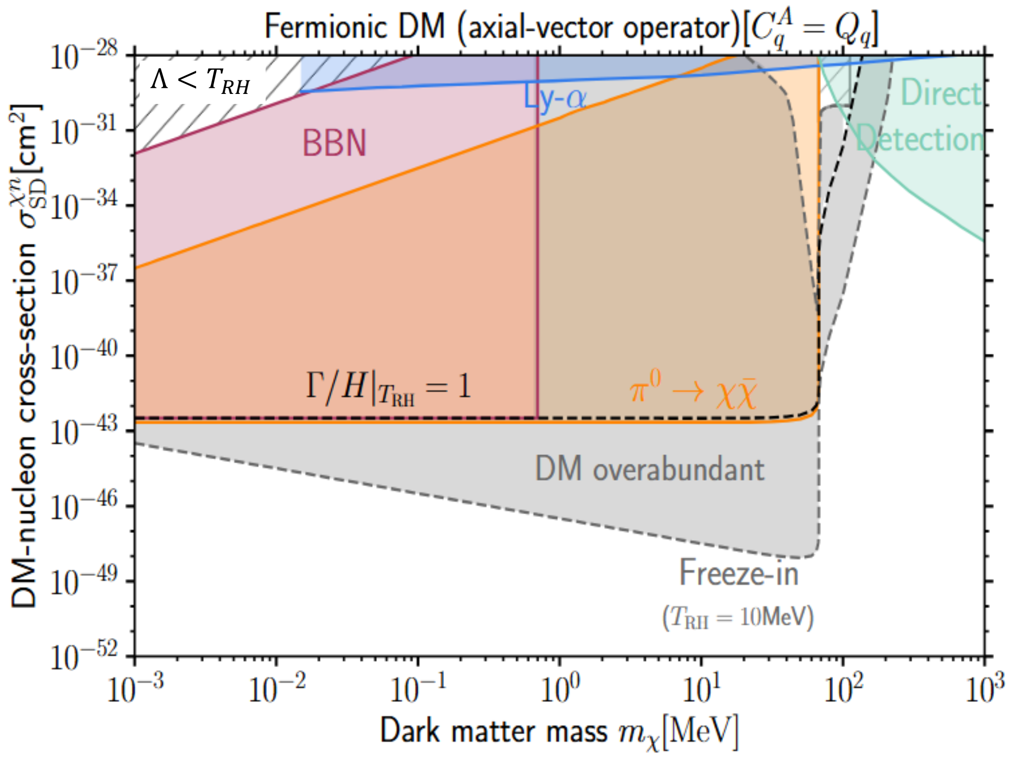
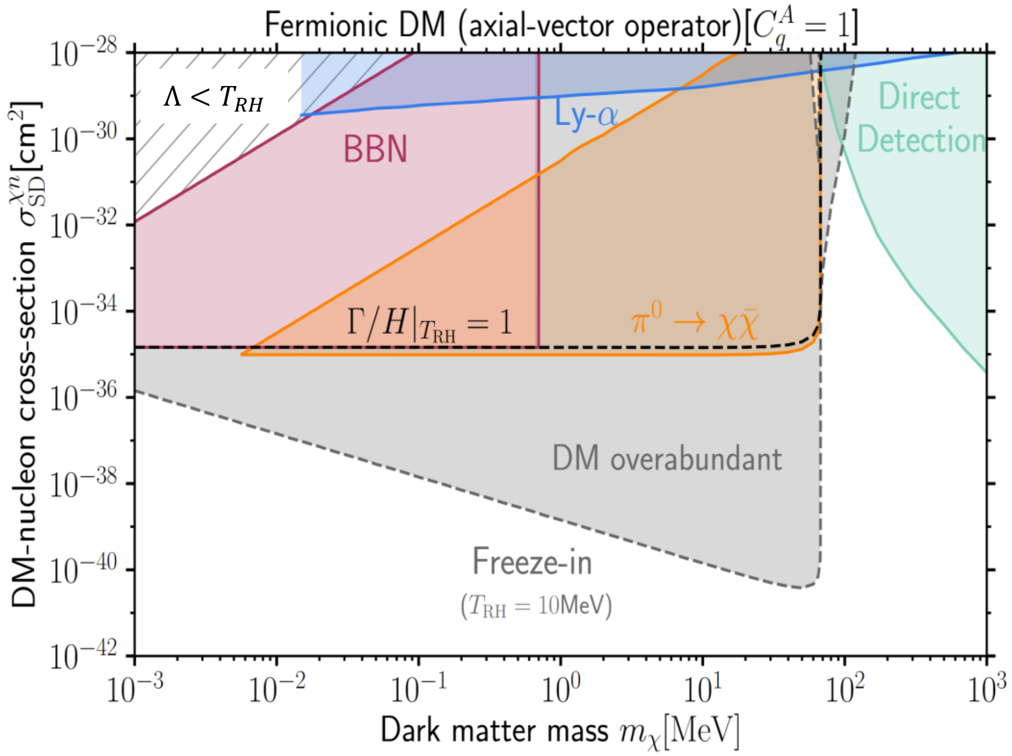




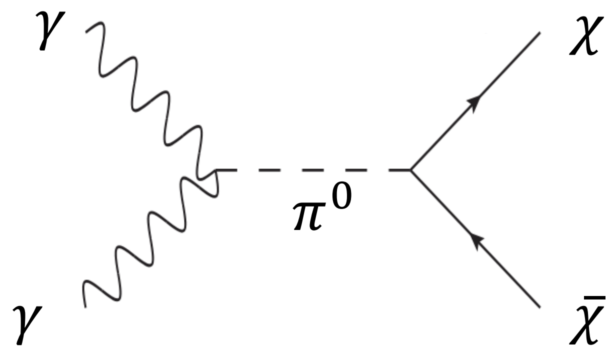
Pseudoscalar operators

$$\mathcal{L} = \mathcal{L}_{\mathrm{QCD}} + \theta(x)\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}_{a,\mu\nu} - i\bar{q}\gamma^5 M_q p(x) q$$

$$\Downarrow$$

$$\mathcal{L}_P = \frac{i}{\Lambda^3}m_{\pi^\pm}^2\left(\frac{m_u - m_d}{m_u + m_d}\right) f\,\pi^0(\chi\bar{\gamma}^5\chi)$$

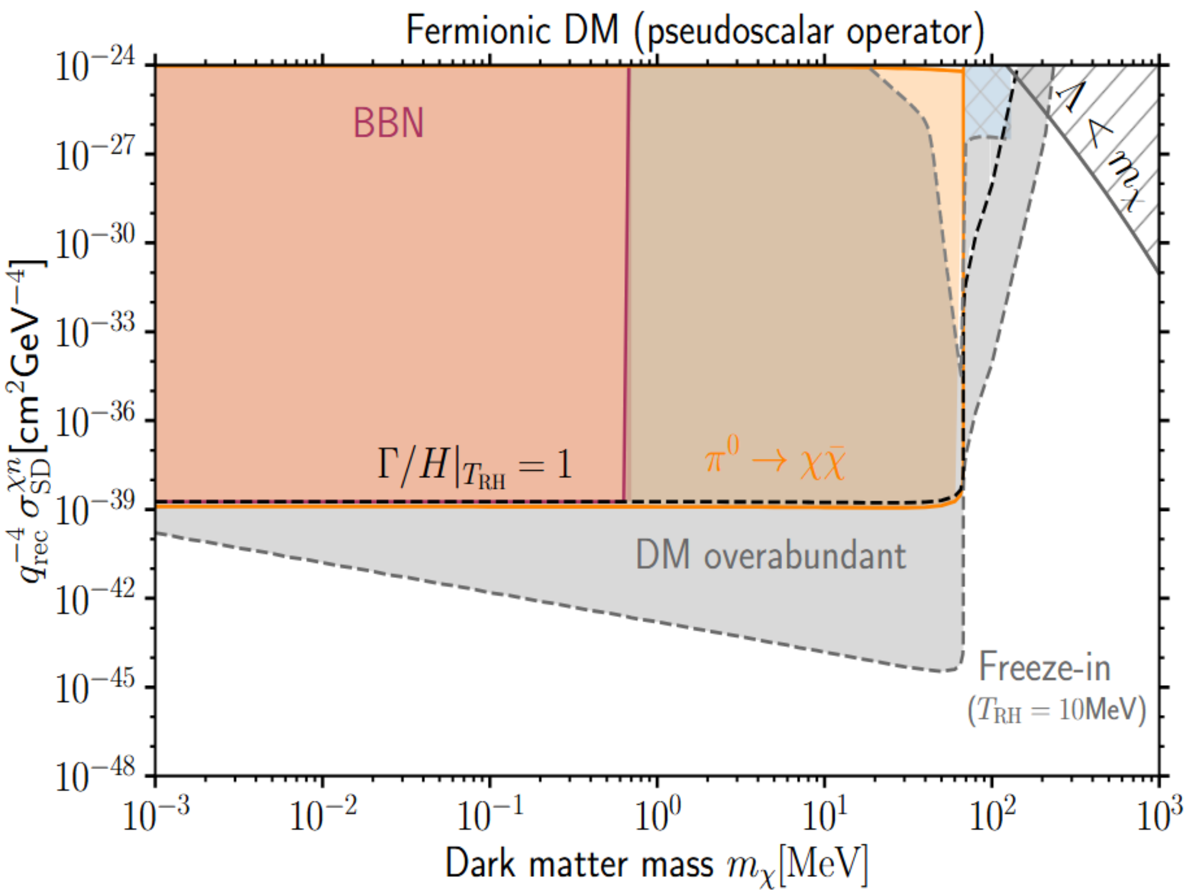
$$\mathcal{L}_{G\tilde{G}} = \frac{if}{2\Lambda^3}\tilde{m}\left(\frac{1}{m_u} - \frac{1}{m_d}\right)(\partial^2\pi^0)(\chi\bar{\gamma}^5\chi)$$

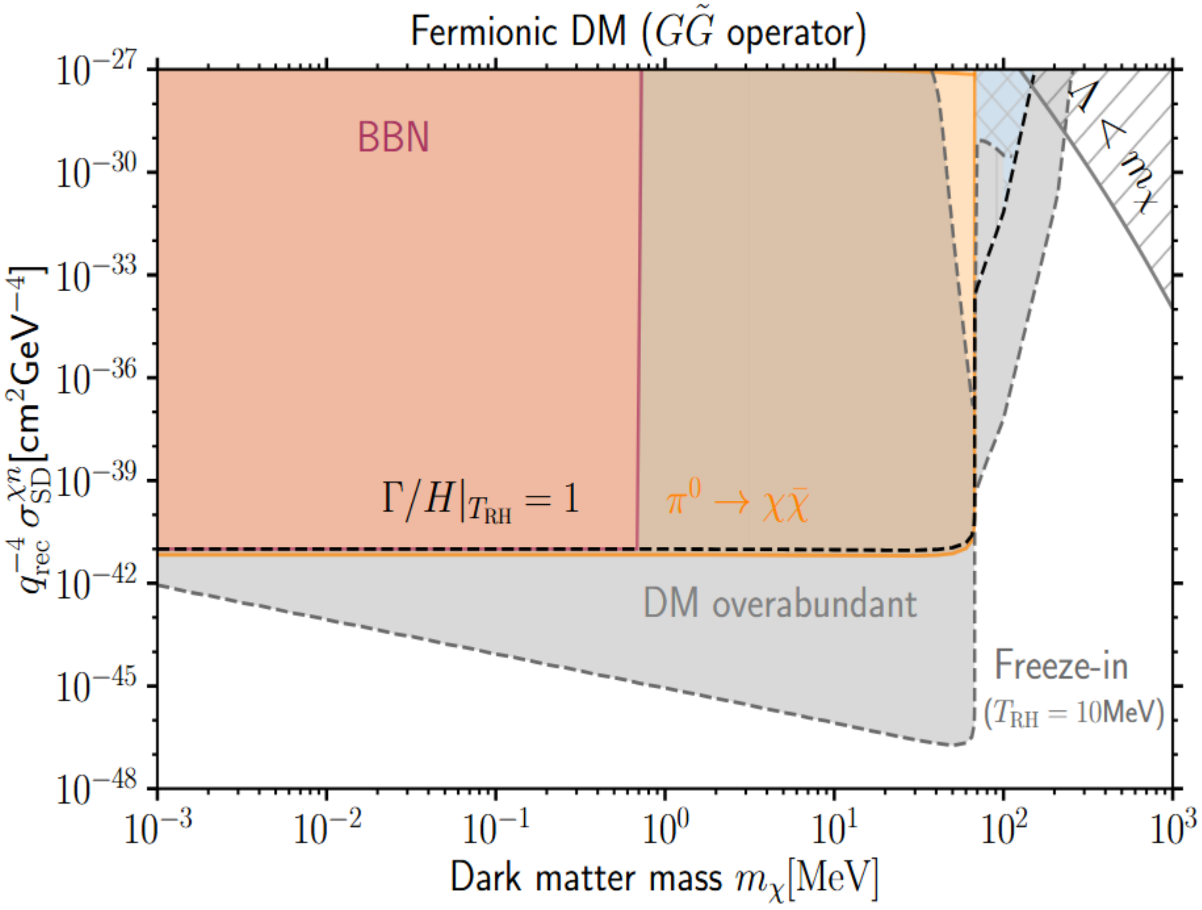


Pseudoscalar operators

Preliminary!

DM-nucleon cross-section is spin-dependent & *momentum-suppressed*





Summary

- Light, hadronically-interacting DM is strongly constrained by BBN, meson decays, irreducible freeze-in abundance

- Bounds orders of magnitude stronger than existing constraints from matter power spectrum

- Implications for future low-mass direct detection experiments