Limiting Light Dark Matter-Baryon Interactions

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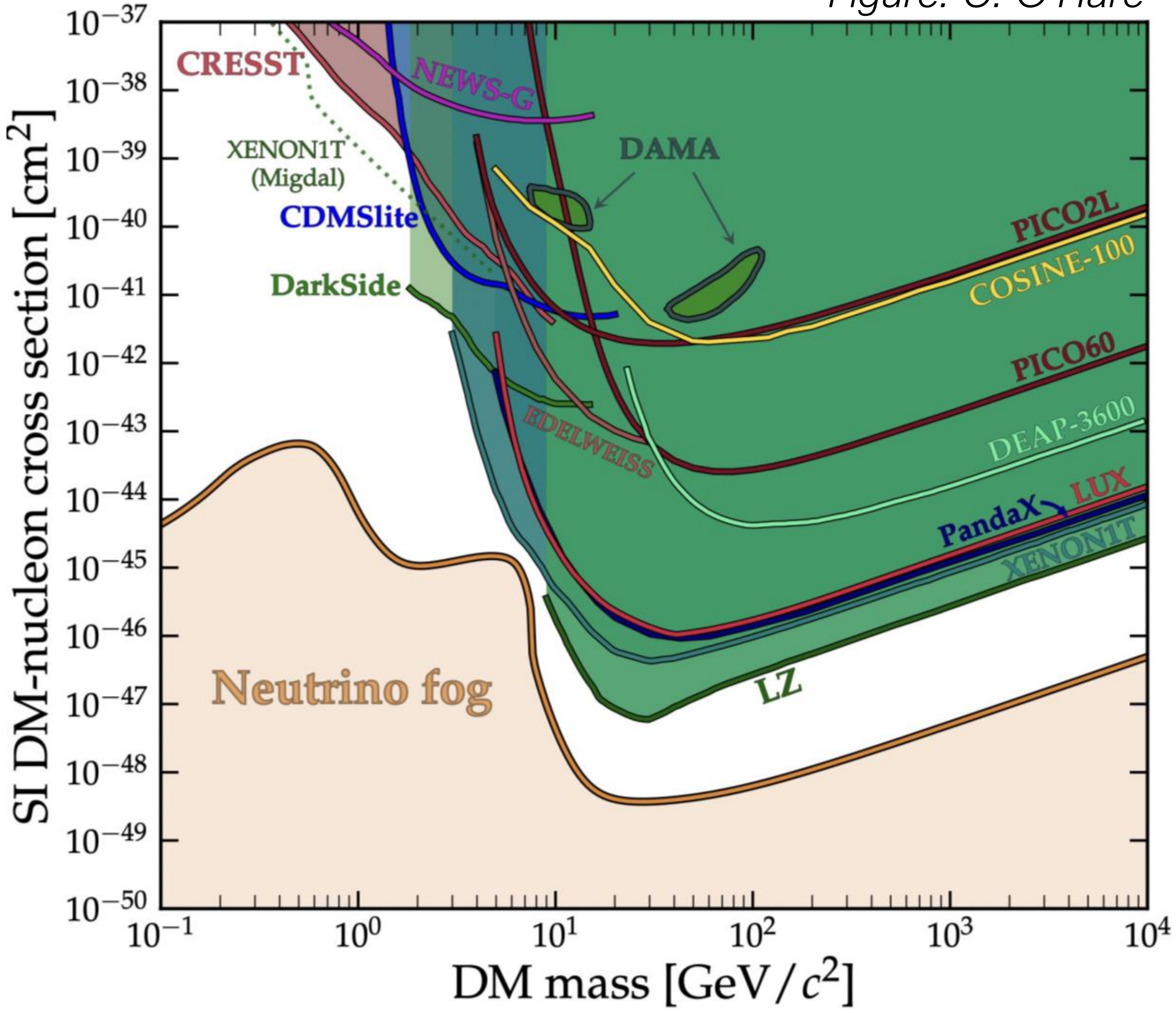
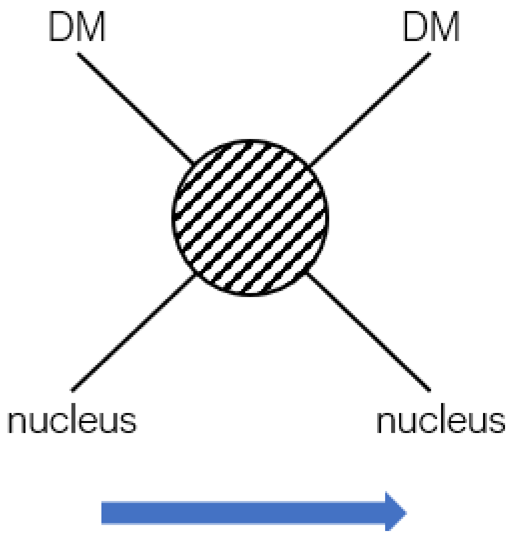
THE UNIVERSITY OF MELBOURNE

DM-baryon interactions: GeV-scale DM

Figure: C. O'Hare



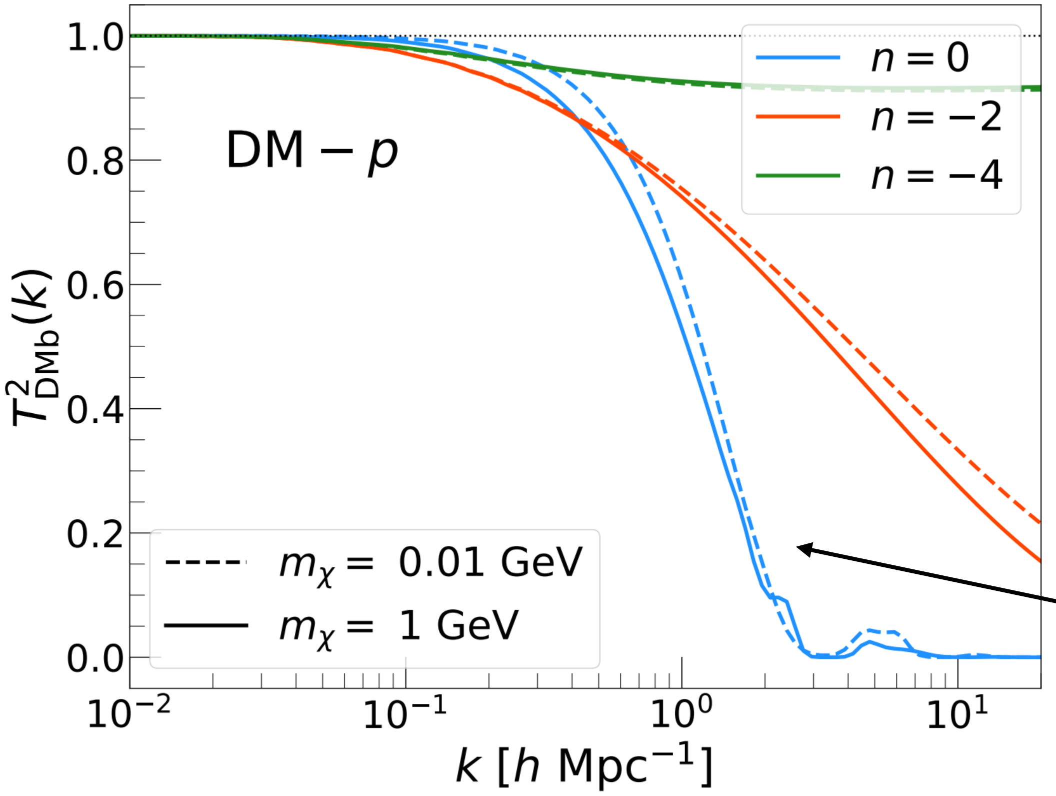


Strong bounds from direct detection for DM masses above the GeV scale

DM-baryon interactions: MeV-scale DM

Leading ‘model-independent’ bound from effect on matter power spectrum

Buen-Abad el. al. (2021)



Suppression of power on small scales

DM-baryon interactions: MeV-scale DM

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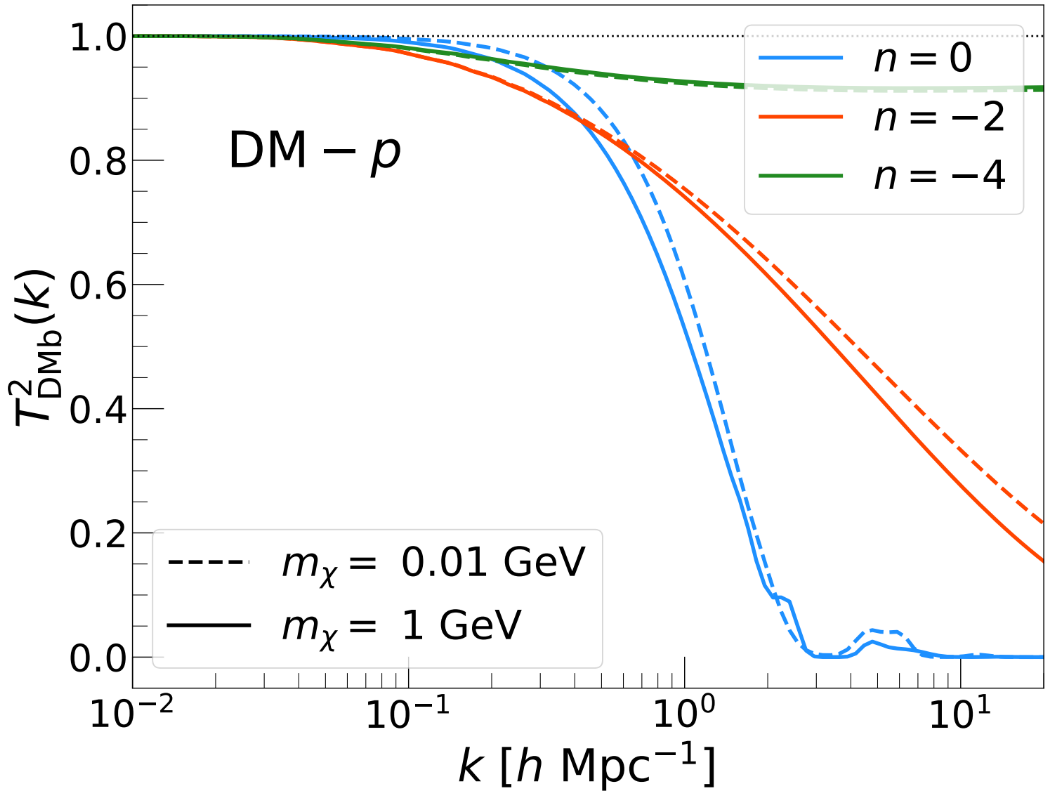
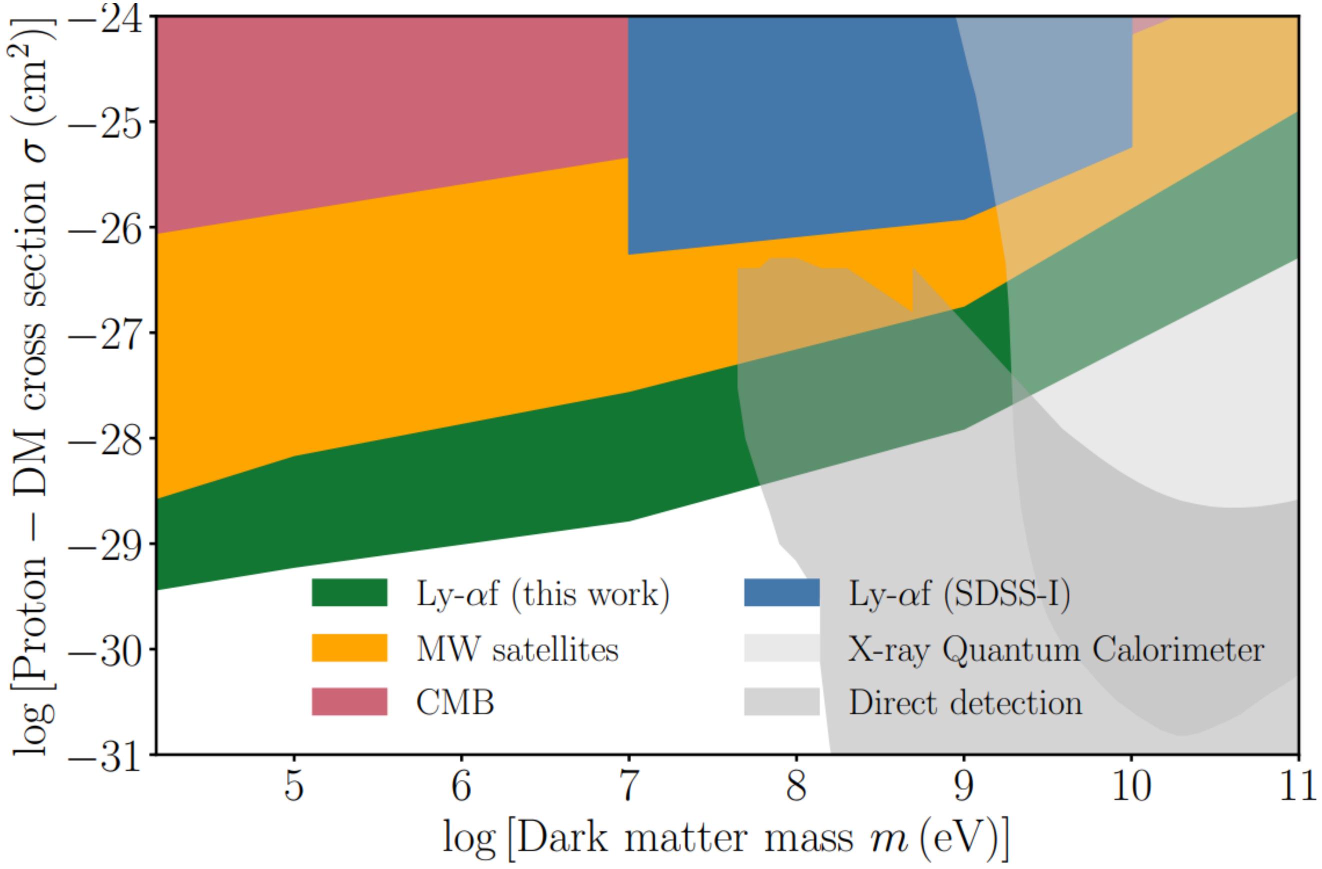


Rogers, Dvorkin, Peiris (2021)



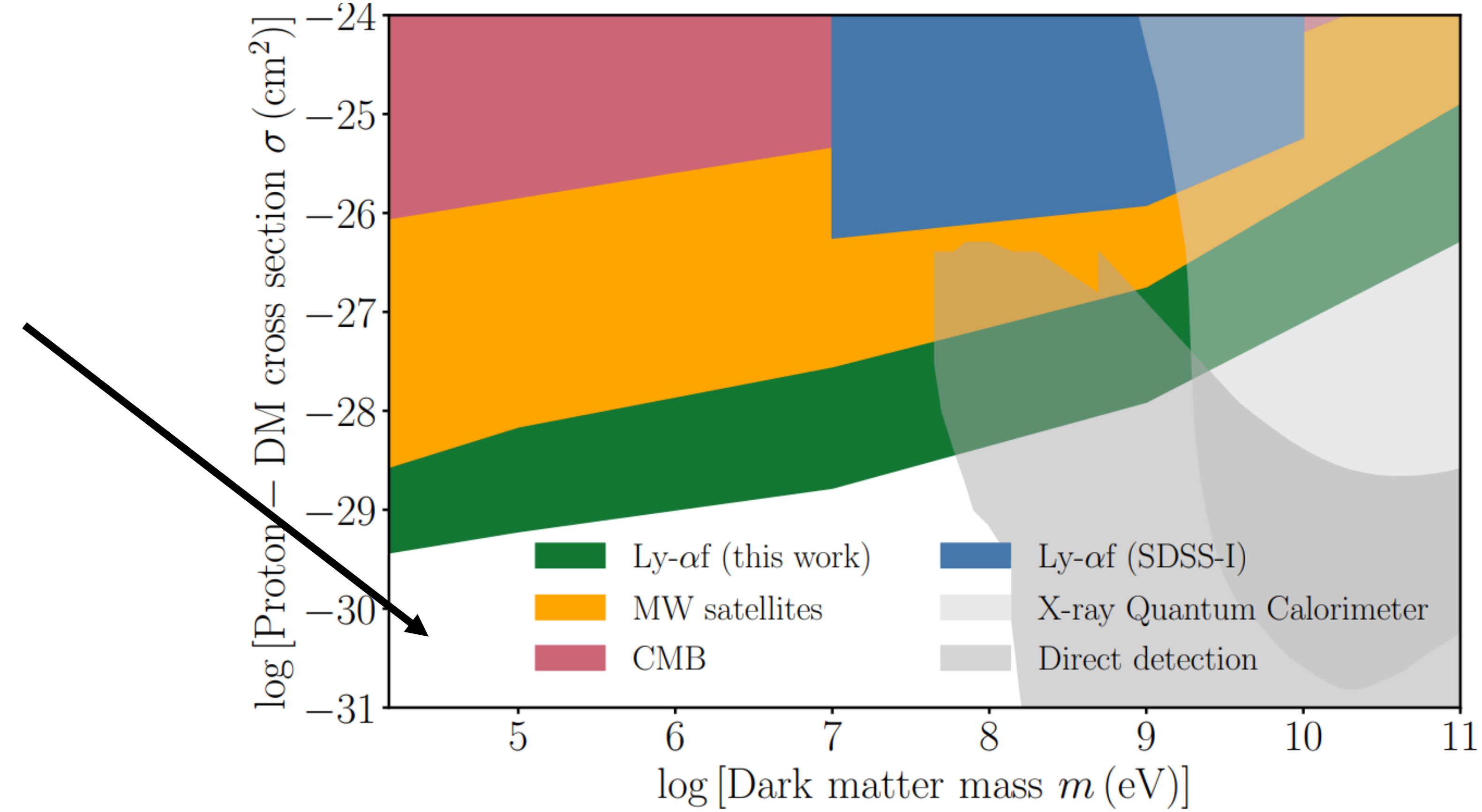
DM-baryon interactions: MeV-scale DM

Leading 'model-independent' bound from effect on matter power spectrum

Rogers, Dvorkin, Peiris (2021)

Are such large cross-sections allowed in complete models?

BBN, CMB, meson decays,
colliders, stars/SNe, … ?



Low-energy effective models

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

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Two effective models, motivated by UV completions

I. Gluon-coupled

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

Integrated out heavy quarks

II. Quark-coupled

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

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

Matching to *SU(3)* Chiral Lagrangian

Focus on *low-energy phenomenology* at sub-GeV scales $\Rightarrow$ *ChPT*

Assume *contact interaction* at low-energies $\mathcal{O}_\chi = \begin{cases} \chi^\dagger \chi & \text{(complex scalar)} \\ \bar{\chi}\chi & \text{(Dirac fermion)} \end{cases}$

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Gluon-coupled, scalar DM

$$\mathcal{L}_{\rm ChPT}^{\rm LO} = \frac{f^2}{4}\left(1 + \frac{2}{9\Lambda^2}\chi^*\chi\right)\mathrm{Tr}\left[D^\mu U^\dagger D_\mu U\right] + \frac{B_0 f^2}{2}\left(1 + \frac{1}{3\Lambda^2}\chi^*\chi\right)\mathrm{Tr}\left[M_q(U + U^\dagger)\right]$$

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Gluon-coupled, scalar DM

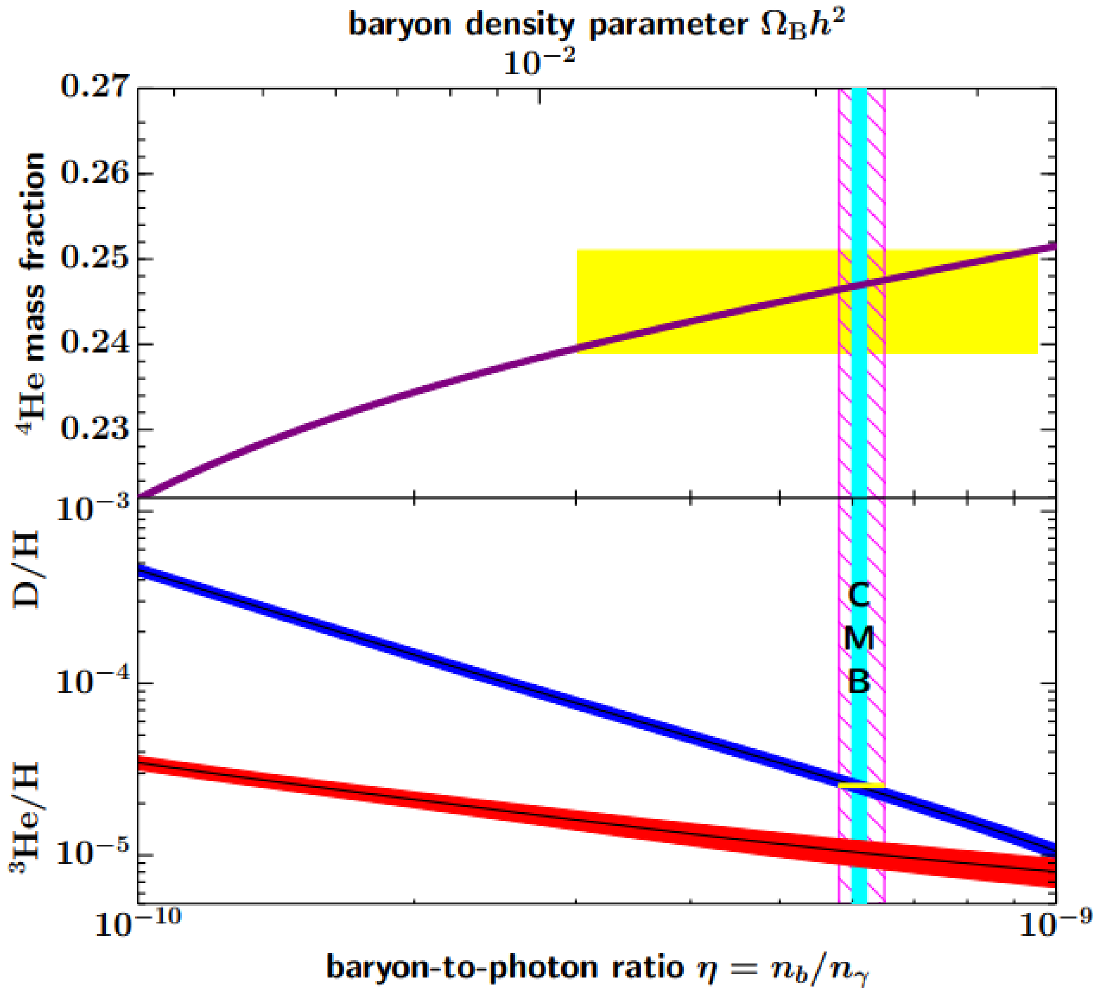
$$\mathcal{L}_{\rm ChPT}^{\rm LO} \supset (1 + \frac{2}{9\Lambda^2}\chi^*\chi)\left((D^\mu \pi^+)(D_\mu \pi^-) + (D^\mu K^+)(D_\mu K^-)\right) + (1 + \frac{1}{3\Lambda^2}\chi^*\chi)\left(m_\pi^2 \pi^+\pi^- + m_K^2 K^+ K^-\right)$$

BBN constraints

BBN restricts abundance of additional relativistic species

Steigman '77, Kolb et. al., '86, …

Figure: Particle Data Group



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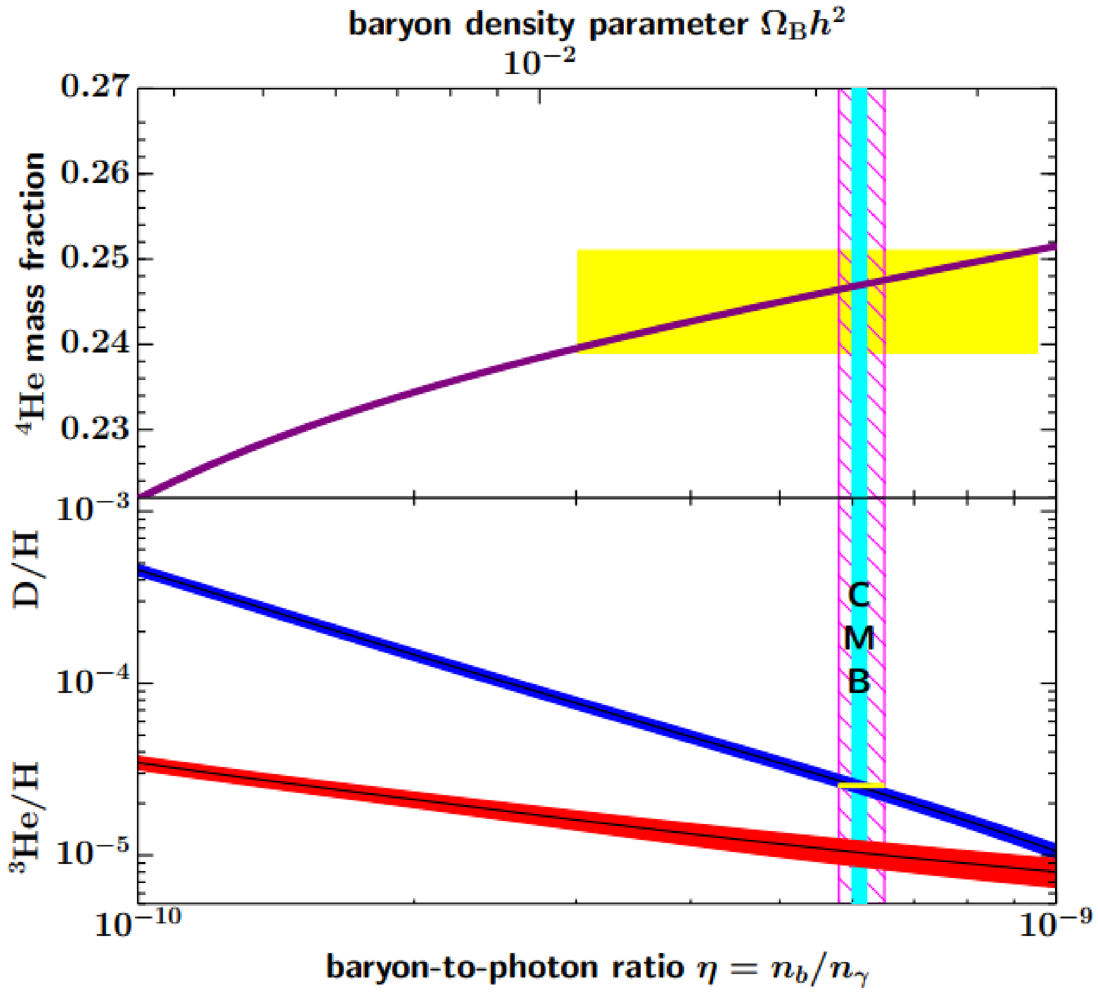

Thermal relic DM annihilating to

$e^{\pm}$/photons or neutrinos excluded if

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

What about hadronically-interacting DM?

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?

Note: stronger bounds can be obtained *if* universe reheated above the QCD phase transition
(see 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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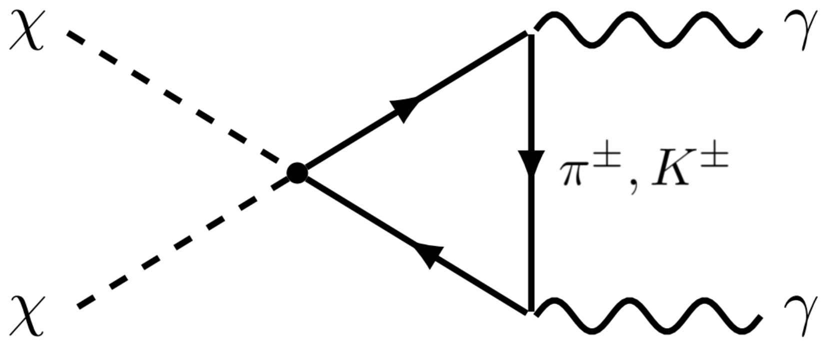
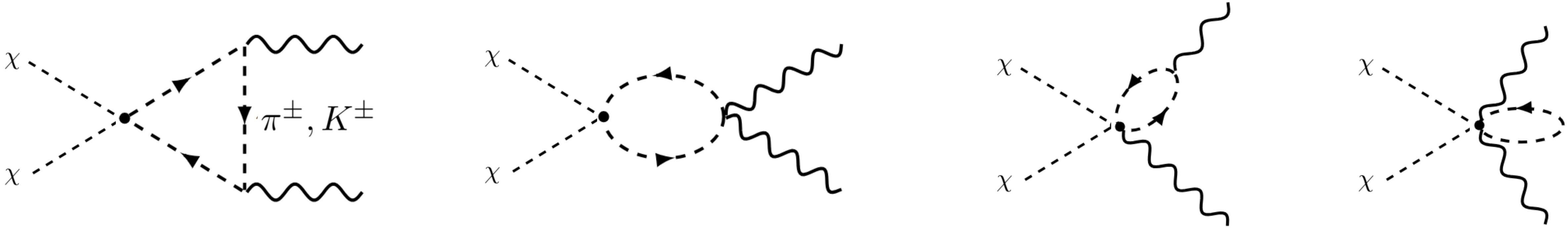
But DM interacts with photons at 1-loop



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

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



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

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

BBN & CMB

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

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Three regimes:

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

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

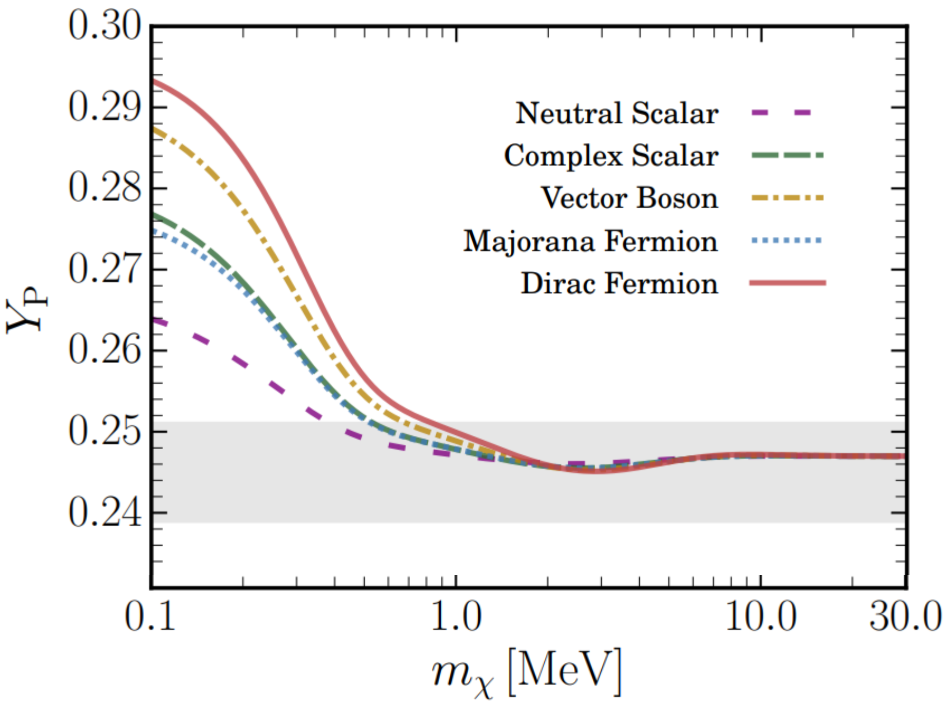
III. *DM decouples when non-relativistic*

Existing BBN analyses apply

BBN & CMB: non-relativistic decoupling

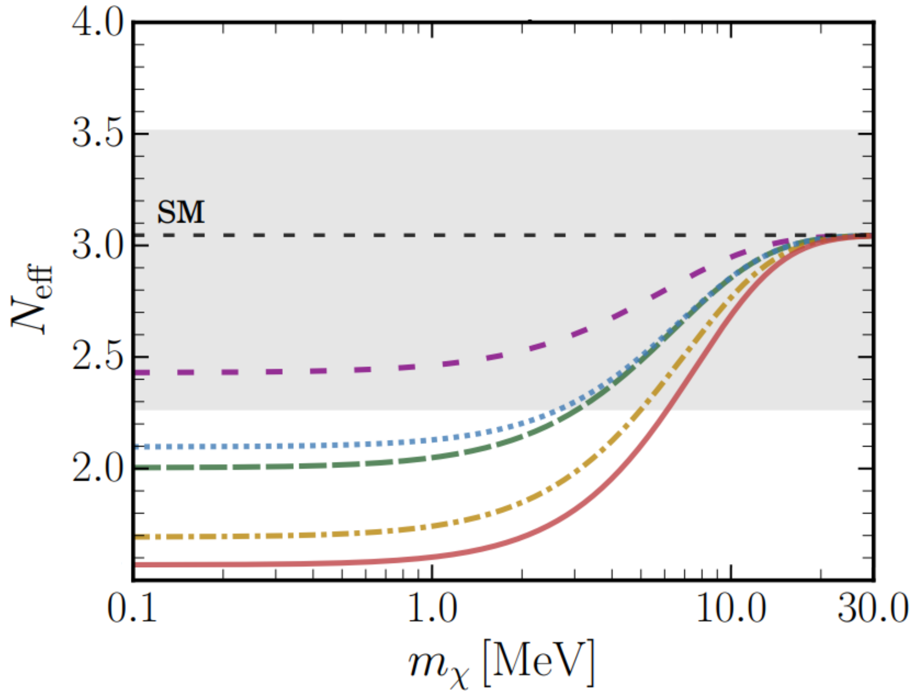
I. *DM initially increases expansion rate*

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



II. *DM transfers entropy to photons*

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



Sabti et. al. (2019)

BBN & CMB: non-relativistic decoupling

I. *DM initially increases expansion rate*
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II. *DM transfers entropy to photons*
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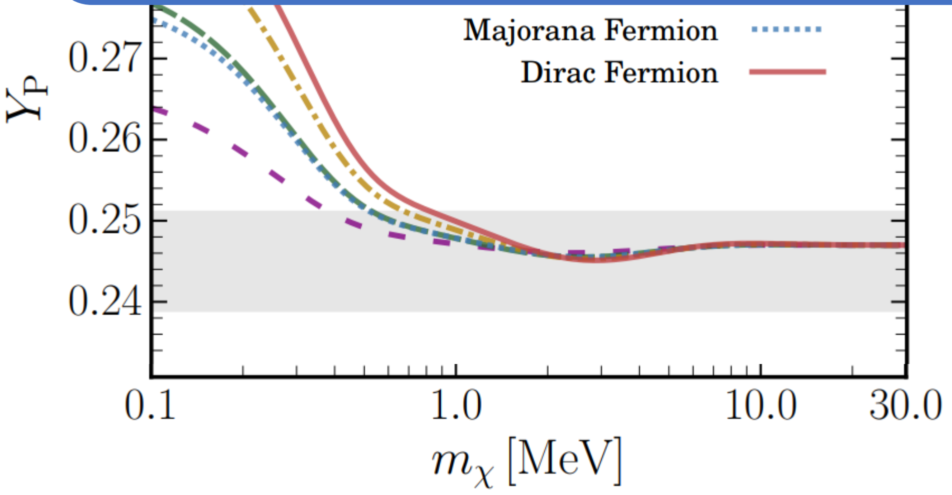
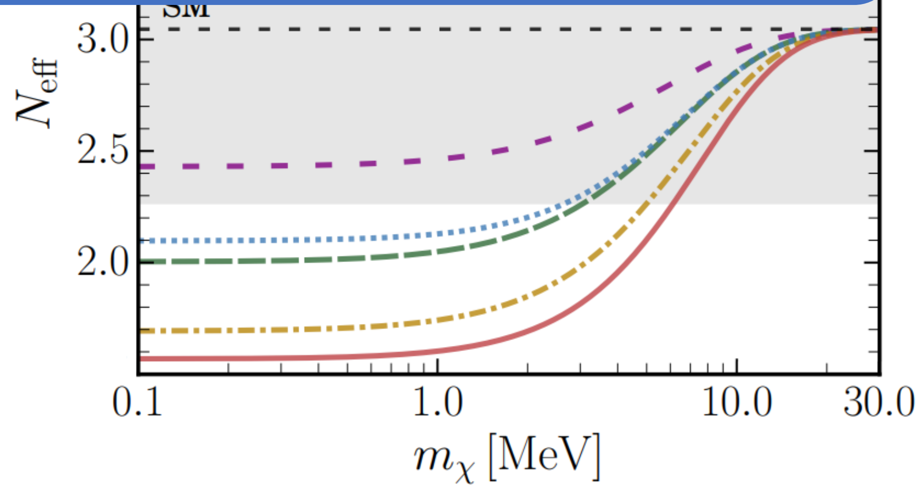
Combined BBN+CMB fit excludes $m_\chi < 4.9\,\mathrm{MeV}$

Sabti et. al. (2019)





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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

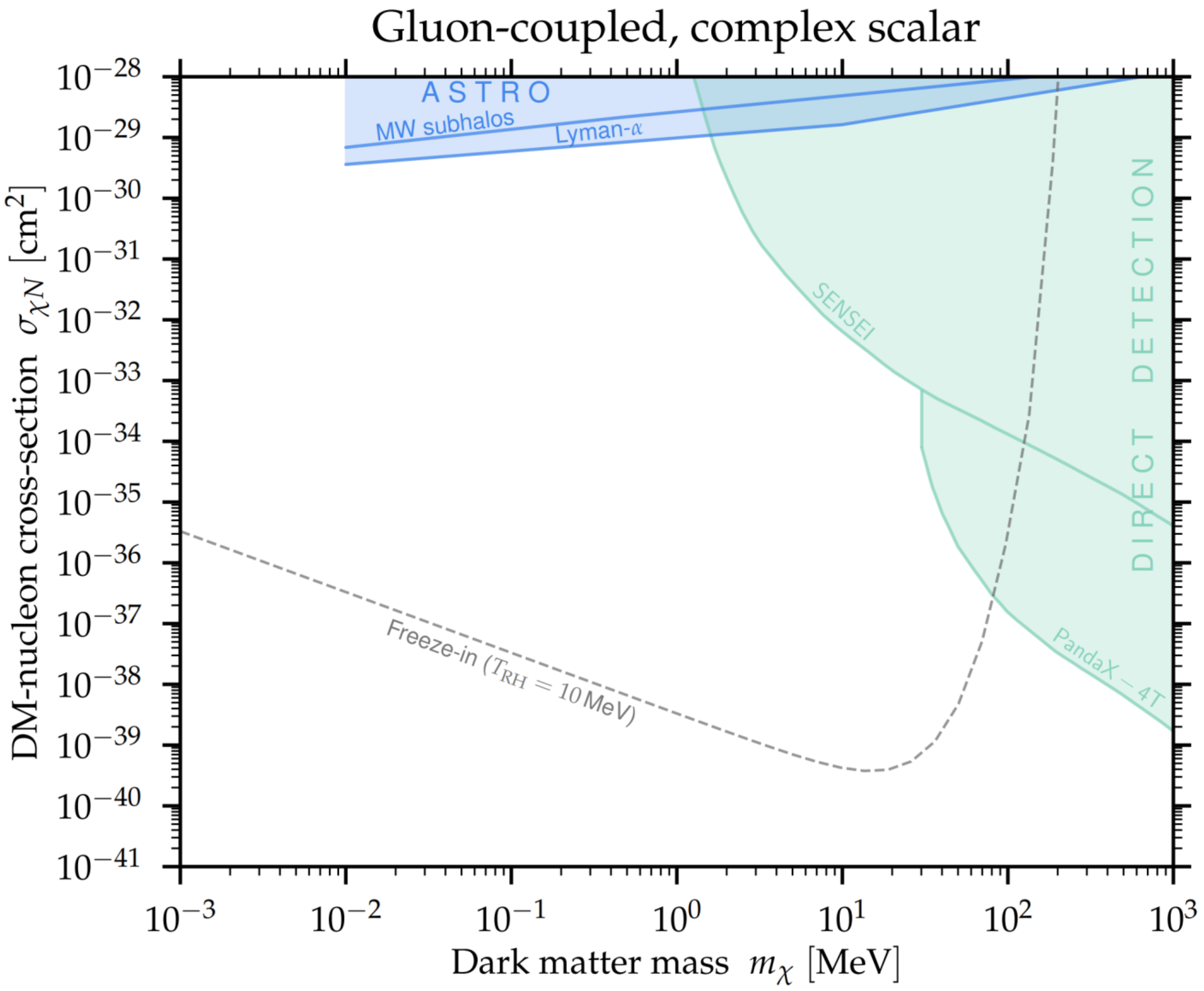
II. *DM decouples when relativistic, after $e^{\pm}$ annihilation*

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

I. *DM decouples when non-relativistic*

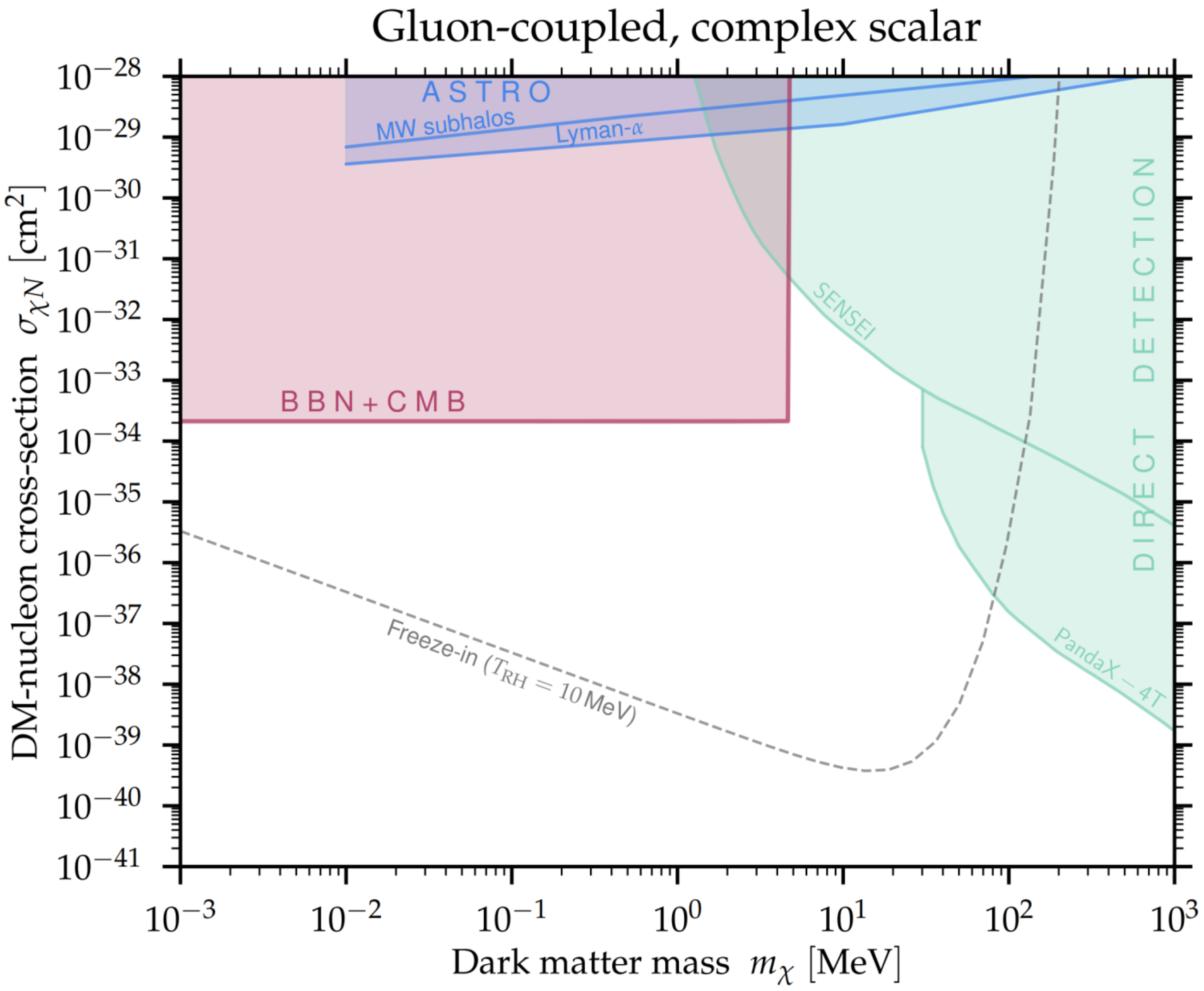
Excluded by BBN & CMB

CMB + BBN constraints



CMB + BBN constraints

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



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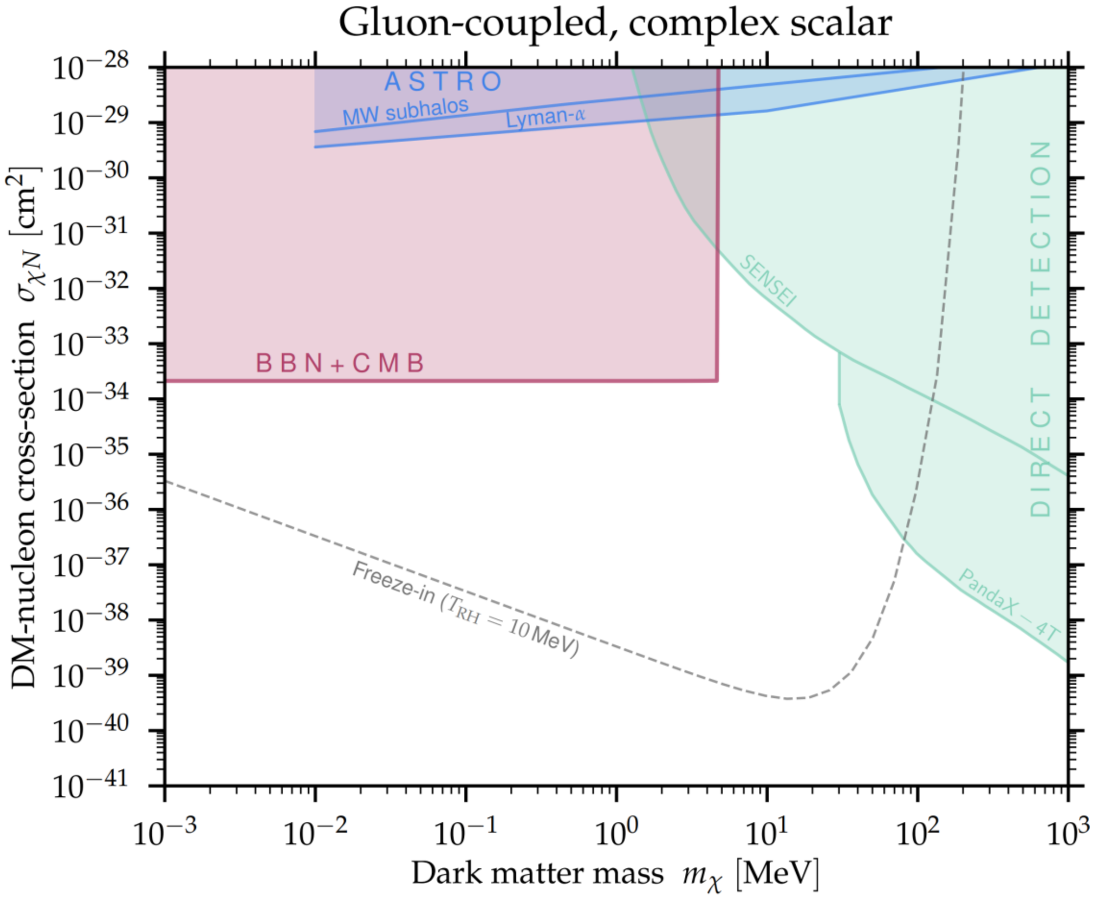
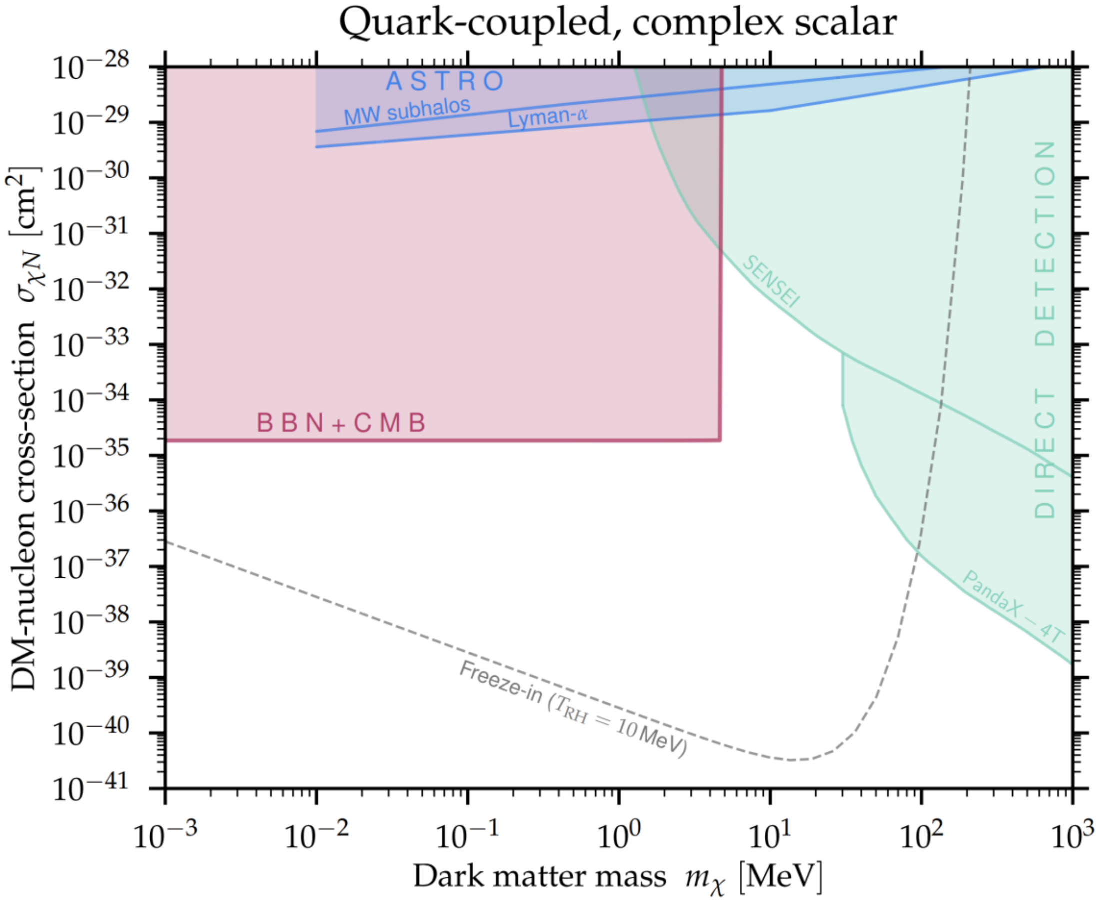




Minimal dependence on the model (*gluon-coupled vs quark-coupled*)

Bounds from rare K-decays

Dark matter can be produced in meson decays

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

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

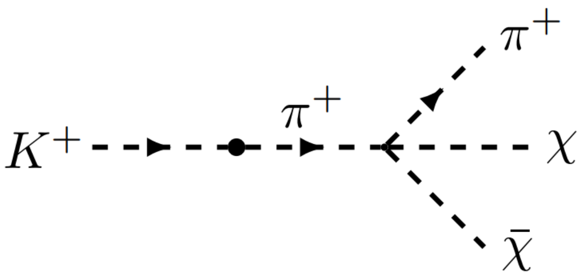
$\Rightarrow$ Strong bound on decays to other “invisible” particles, *e.g. dark matter*

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

Bounds from rare K-decays

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

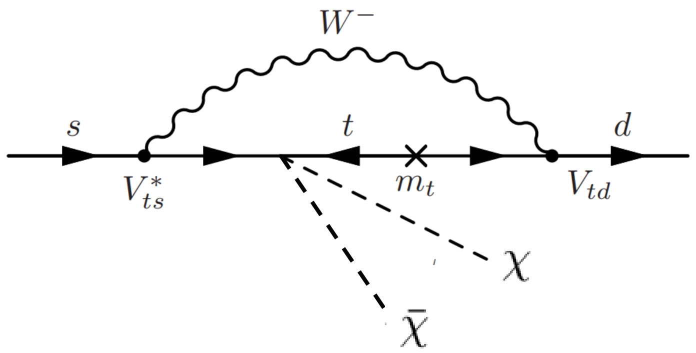
IR contribution:



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

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

UV contribution:



Additional terms in low-energy Lagrangian

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

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

Bounds from rare K-decays

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

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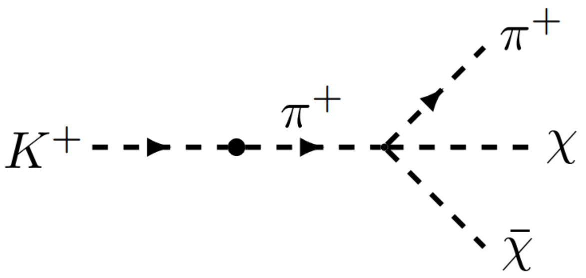
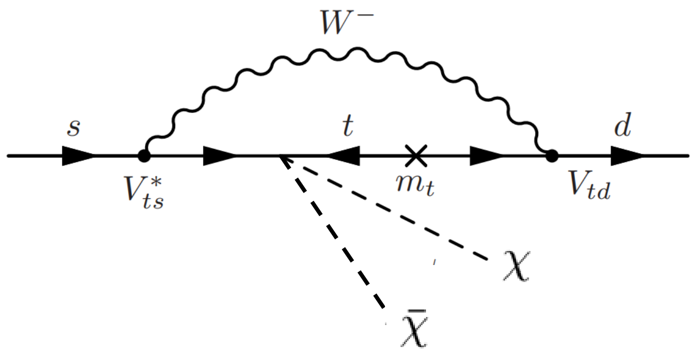


Leading contribution in gluon-coupled case

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

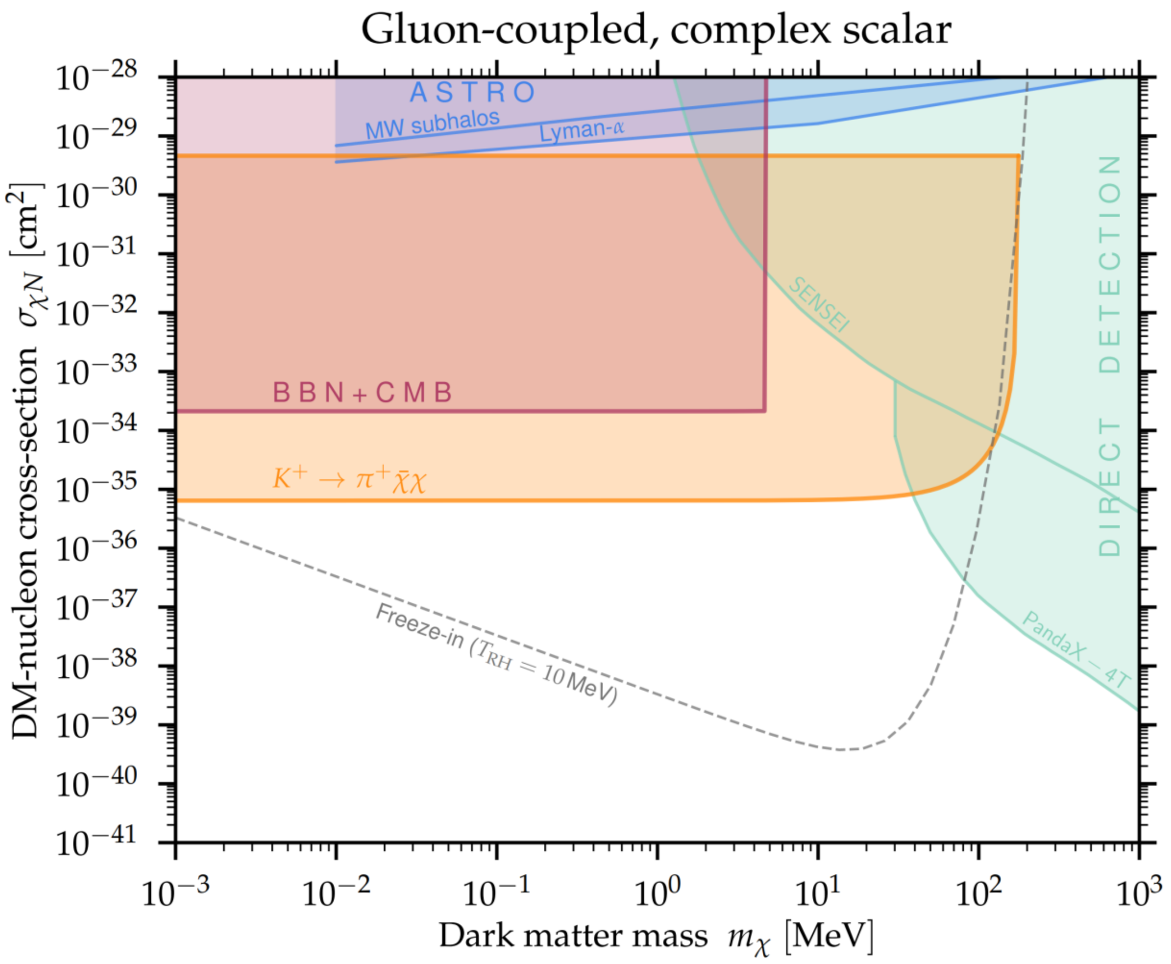
UV contribution:

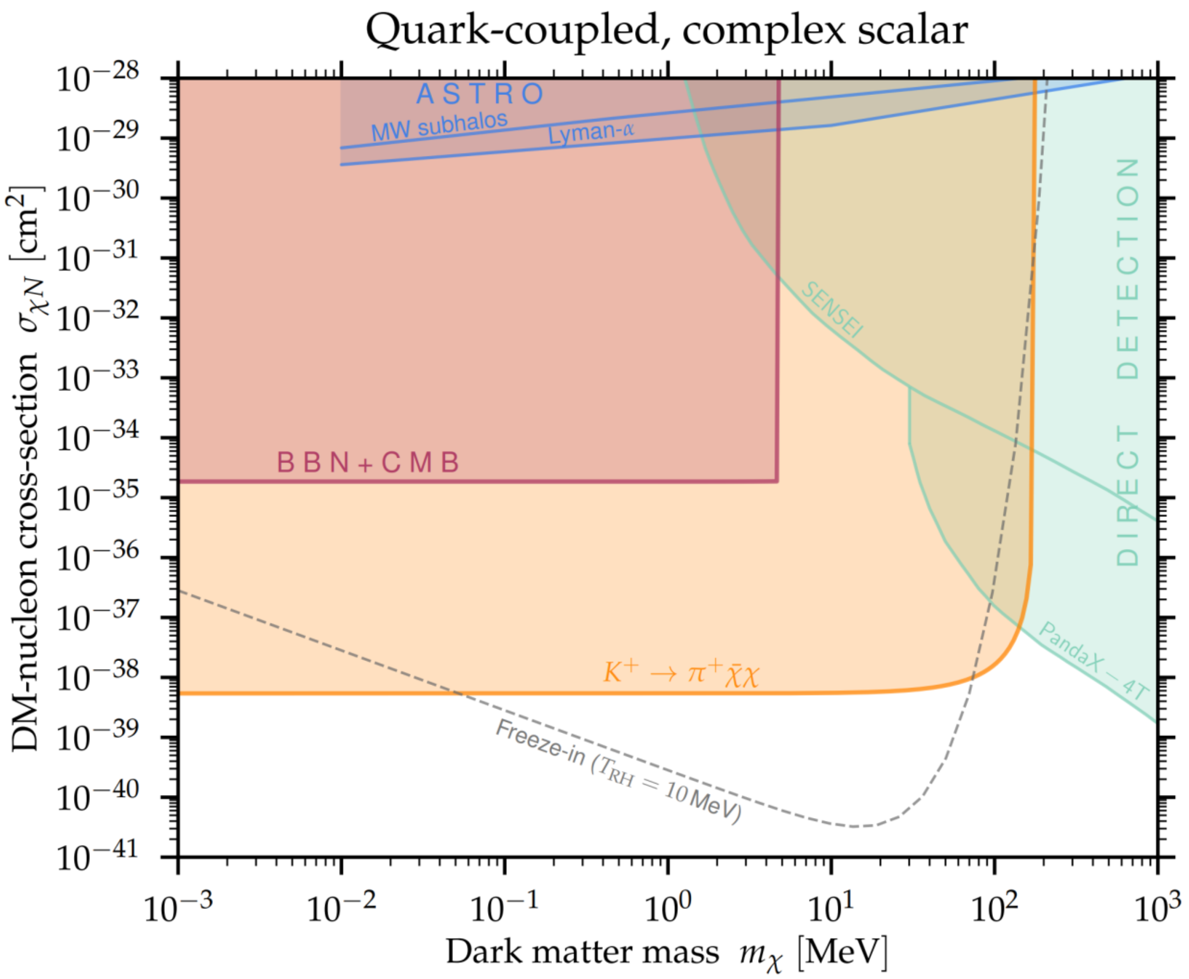


Dominates if coupling to heavy quarks
(e.g. Higgs portal models)

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

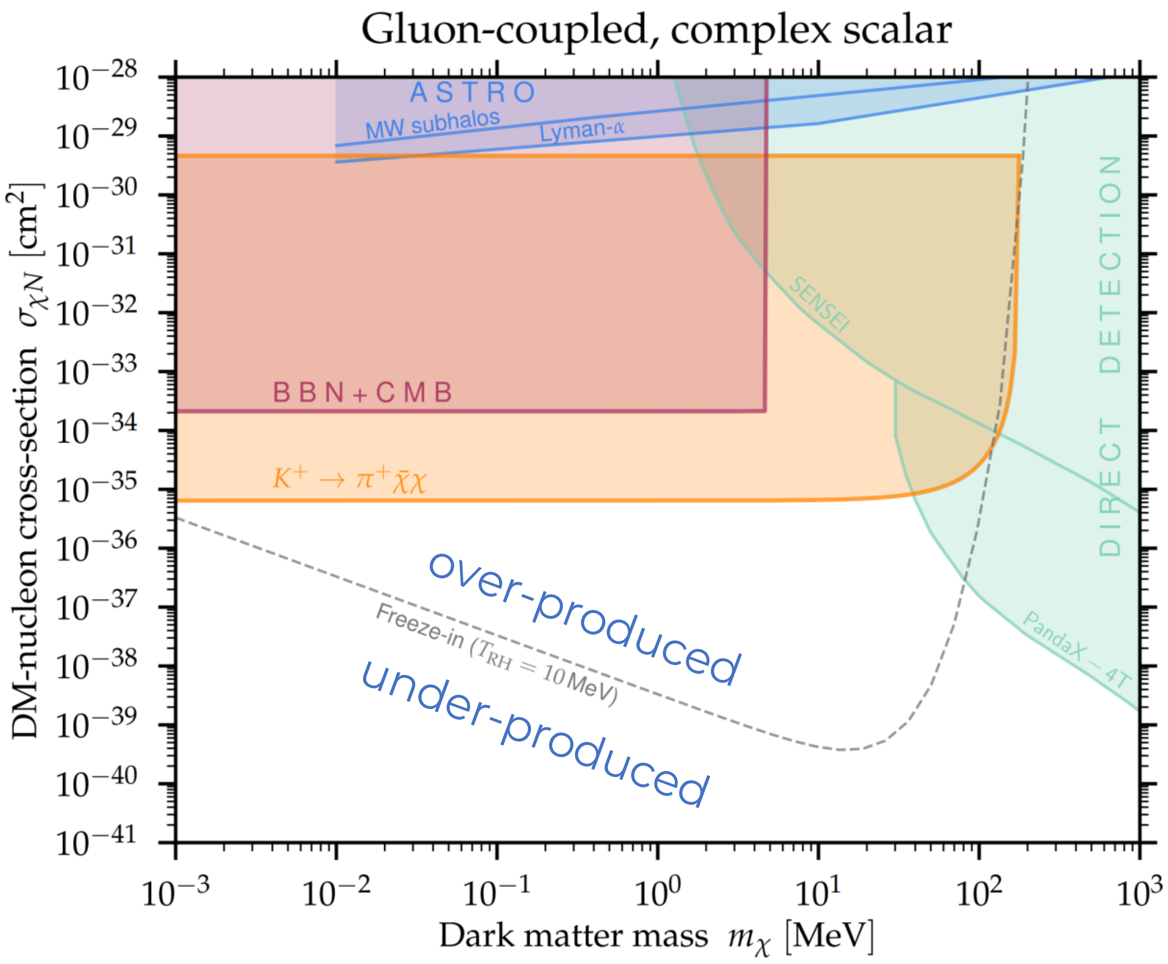
Results – scalar DM

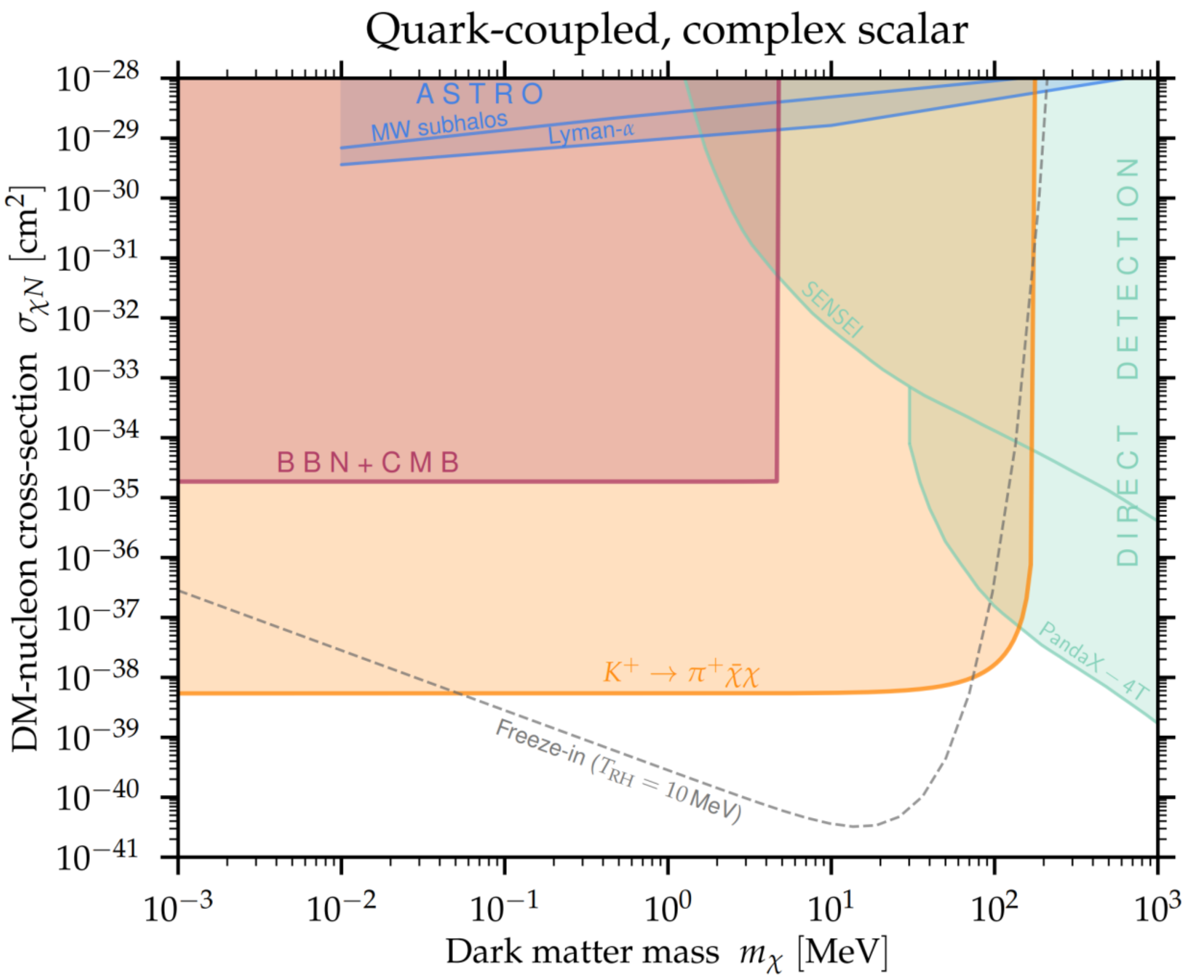




Kaon decays give stronger, but more model-dependent bounds

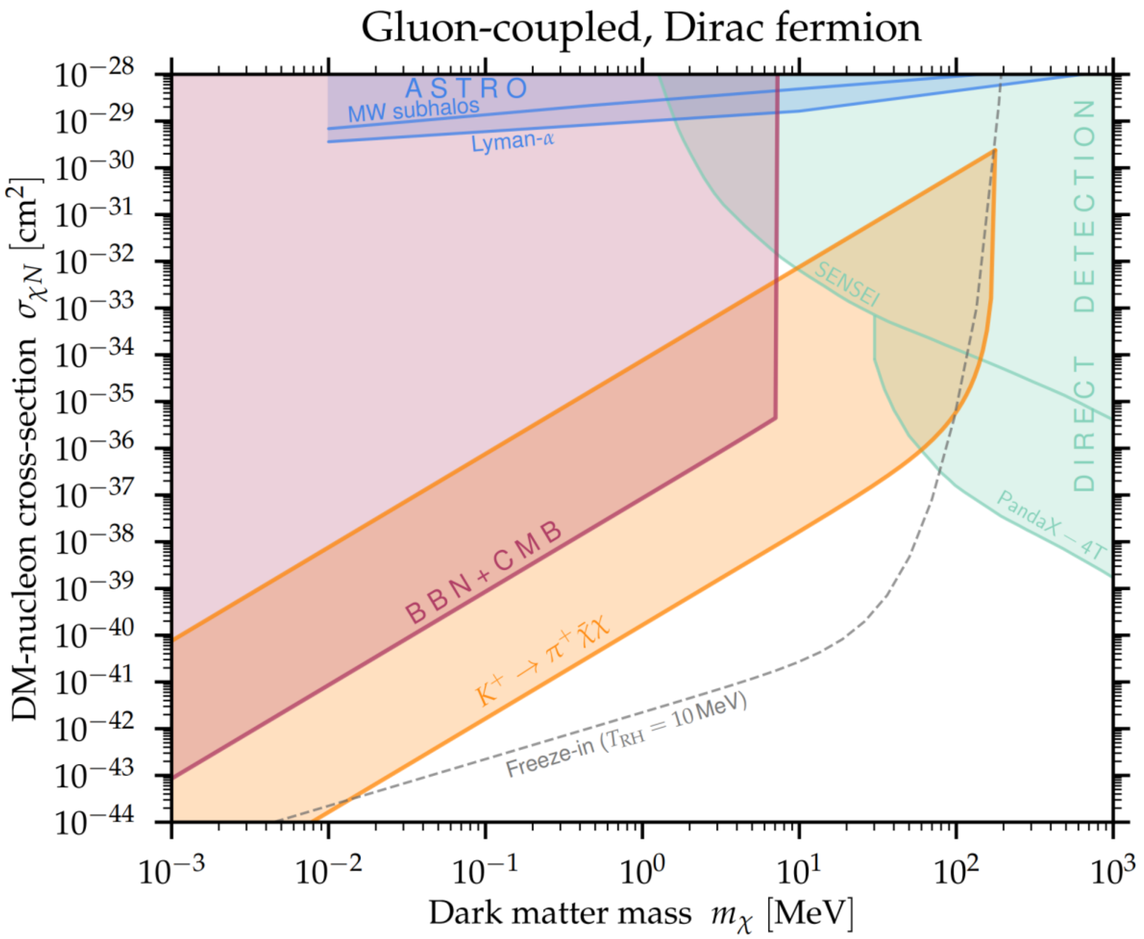
Results – scalar DM

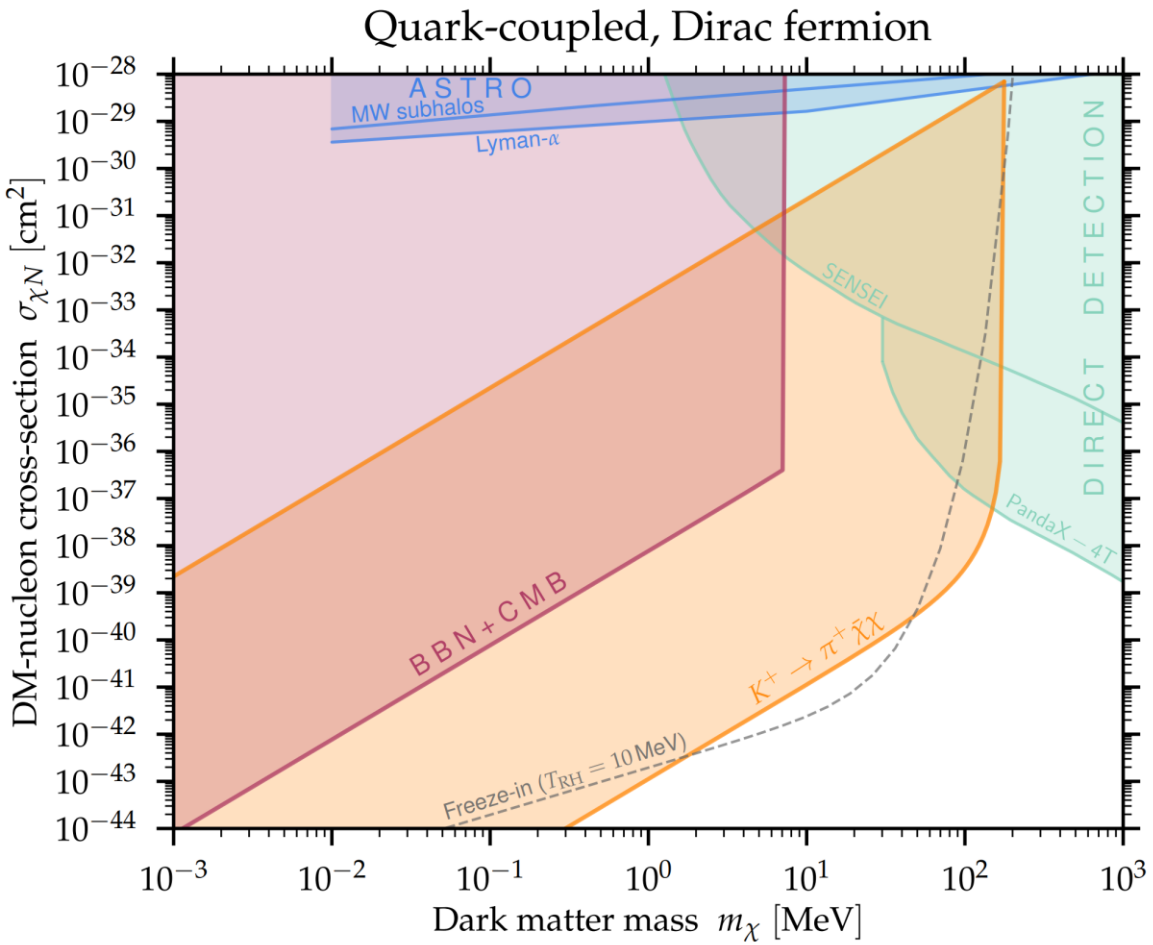




Irreducible freeze-in abundance produced by $\gamma\gamma \to \chi\chi$

Results – fermionic DM





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

Summary

- BBN/CMB provide strong constraints on hadronically-interacting, MeV-scale DM
- Rare K decays give stronger, but more model-dependent bounds
- Significantly stronger than existing bounds from matter power spectrum
- Implications for future low-mass direct detection experiments