A Taste of Dark Matter.

Flavour Constraints on Pseudoscalar Mediators

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Based on arXiv:1412.5174 in collaboration
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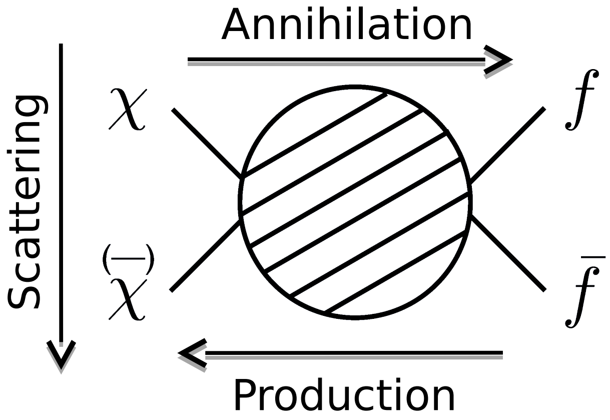
DESY

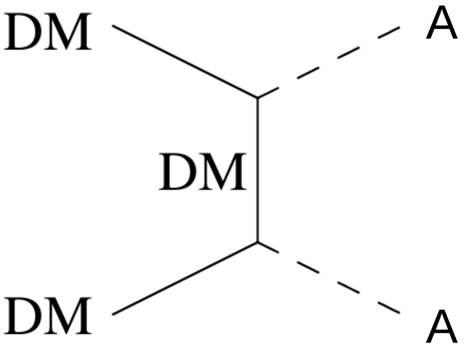
Why light mediators?

- It is tempting to assume that dark matter (DM) freeze-out is directly linked to dark matter direct and indirect detection and collider searches via the crossing symmetry of a single diagram describing the interactions between DM and Standard Model (SM) fermions.



- Experimental and observational constraints, however, make it increasingly difficult (in particular for low-mass DM) to achieve a sufficiently large annihilation rate in the early Universe to avoid overproduction of DM.

- If DM interacts via a new state *A*, which has a smaller mass than the DM particle ($m_A < m_\chi$) and only weak couplings to the visible sector, DM can directly annihilate into pairs of mediators, which subsequently decay into SM states.



Why pseudoscalars?

- A pseudoscalar particle is a particularly interesting possibility for such a new light mediator:
  - We now have convincing evidence that fundamental scalars exist in nature, so it is a well-motivated task to search for further light scalar or pseudoscalar states.
  - Pseudoscalars naturally arise in many extensions of the Higgs sector (such as Two-Higgs Doublet Models) and they can easily be lighter than the CP-even SM-like Higgs at 125 GeV (for example in the NMSSM).
  - Light pseudoscalars can also arise as pseudo–Nambu-Goldstone bosons from a broken *U*(1) symmetry. These axion-like particles typically couple derivatively to SM fermions:

$$\sum_{f=q,\ell} \frac{C_{Af}}{2\,f_A} \bar{f}\gamma^\mu\gamma^5 f\,\partial_\mu A$$

  - Integrating by parts and using the equations of motion, this can be written as

$$i \sum_{f=q,\ell} g_{Af} \frac{m_f}{v} A\,\bar{f}\gamma_5 f \qquad\qquad g_{Af} \equiv -C_{Af}\frac{v}{f_A}$$

Why pseudoscalars?

- Pseudoscalar mediators are also attractive from a purely phenomenological point of view, because they predict a strong suppression of the event rate in direct detection experiments, due to three separate effects:
  - In the non-relativistic limit, scattering via pseudoscalar exchange is momentum suppressed. Event rates are proportional to $q^4/(m_\chi^2\, m_N^2)$ where $q \sim \mu\, v$ and $v \simeq 10^{-3} c$.
  - Moreover, in contrast to scalars pseudoscalars couple to the nucleus spin rather than its mass, so that there is no large enhancement for heavy target nuclei.
  - Finally, it turns out that for typical coupling structures pseudoscalars have strongly suppressed couplings to neutrons, further reducing the sensitivity of experiments with unpaired neutrons (in particular xenon-based experiments).

$$g_N = \sum_{q=u,d,s} \frac{m_N}{m_q} \left[g_q - \sum_{q'=u,\dots,t} g_{q'} \frac{\overline{m}}{m_{q'}} \right] \Delta_q^{(N)}$$

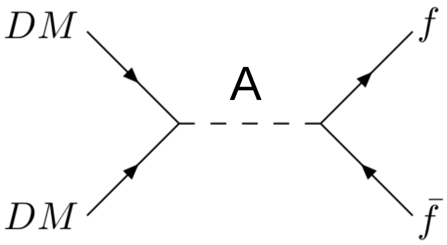
For Yukawa-like couplings:

$$-0.4 \lesssim g_n/g_p \lesssim 0$$

Freytsis & Ligeti, arXiv:1012.5317

Why pseudoscalars?

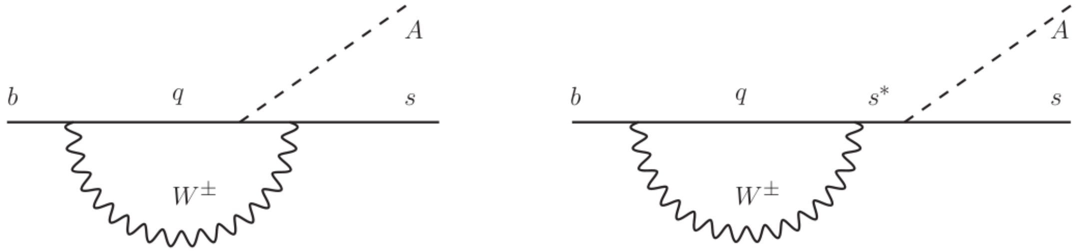
- Since constraints from direct detection experiments are largely absent, pseudoscalars can potentially give rise to a range of interesting signals:
  - It is possible to obtain observable indirect detection signals and for example explain the Fermi-LAT Galactic Centre gamma-ray excess.
    - Coy Dark Matter (Boehm et al., arXiv:1401.6458)



  - A light pseudoscalar mediator offers the possibility to obtain large self-interactions in the dark sector and to explain the discrepancies between *N*-body simulations and the observations of small-scale structures.
    - Enhanced by non-perturbative effects (temporary bound states of DM, see e.g. Loeb & Weiner, arXiv:1011.6374, Tulin et al., arXiv:1302.3898)
  - Finally, a pseudoscalar mediator can potentially provide an explanation of the annual modulation observed by DAMA while evading the constraints from other direct detection experiments, provided a sufficiently large cross section can be obtained.
    - Not so Coy Dark Matter (Arina et al., arXiv:1406.5542)

Why flavour constraints?

- Of course, there are stringent constraints on new light states coupling to SM particles (see e.g. Andreas et al., arXiv:1005.3978):



  - Experimental searches for rare meson decays resulting from flavour-changing processes such as $K \to \pi A$ or $B \to K A$.
  - Fixed target experiments with a far detector searching for long-lived weakly-coupled states.
  - For very small couplings (long pseudoscalar lifetimes), constraints from Big Bang Nucleosynthesis (BBN) become relevant.
- Key question: Is it possible to obtain an interesting DM phenomenology from a light pseudoscalar in spite of all these constraints?

Typical experimental signatures

- Typical observable: Rare kaon decays

$$\mathrm{BR}(K^+ \to \pi^+\gamma\gamma) = \frac{\Gamma(K^+ \to \pi^+\gamma\gamma)}{\Gamma_{K^+}}$$

$$= \frac{\Gamma(K^+ \to \pi^+ A) \times \mathrm{BR}(A \to \gamma\gamma)}{\Gamma_{K^+}} + \mathrm{BR}(K^+ \to \pi^+\gamma\gamma)_{\mathrm{SM}}$$

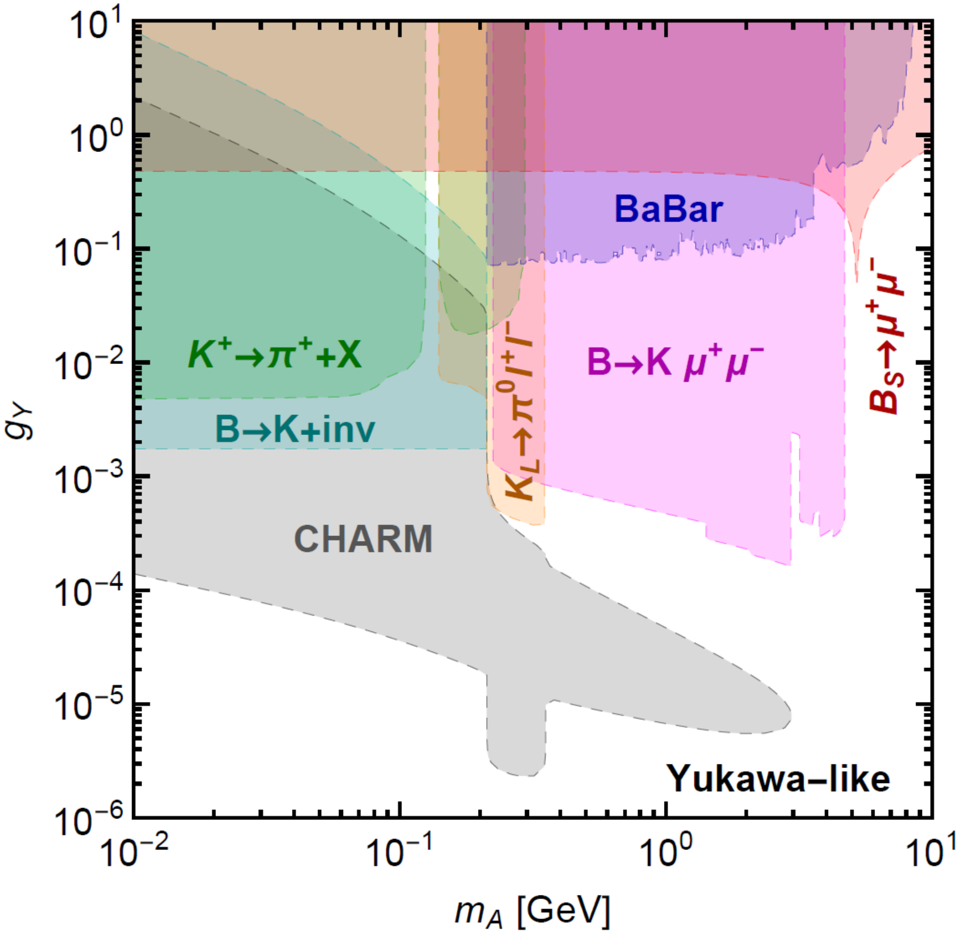
Step 1: Determine the amplitude h_{ds} for the flavour-changing transition $s \to d\,A$.

Step 2: Calculate the partial kaon decay width in terms of this amplitude.

Step 1: Determine the partial decay width for loop-induced decays into photons.

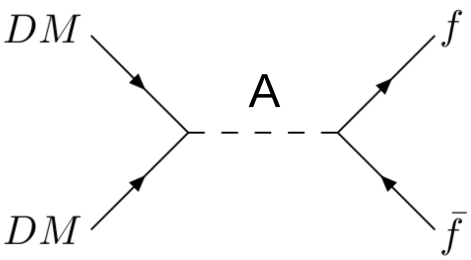
Step 2: Determine the total pseudoscalar decay width by summing all other decay channels.

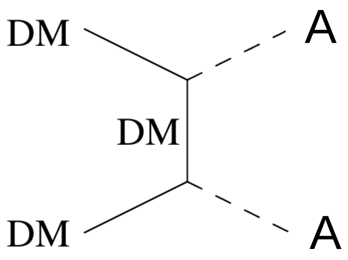
Experimental results



The dark matter connection

- Two processes can be relevant for the freeze-out of DM in the early Universe:





$$\langle\sigma v\rangle_{\bar\chi\chi\to\bar f f} \simeq \sum_f \frac{N_c}{2\pi}\frac{g_f^2\, g_\chi^2\, m_\chi^2}{(4m_\chi^2-m_A^2)^2}\sqrt{1-\frac{m_f^2}{m_\chi^2}}$$

$$\langle\sigma v\rangle_{\bar\chi\chi\to AA} \simeq \frac{g_\chi^4}{24\pi}\frac{m_\chi(m_\chi^2-m_A^2)^{5/2}}{(m_A^2-2\,m_\chi^2)^4}\frac{6}{x}$$

→ s-wave annihilation
→ depends on g_f and g_x

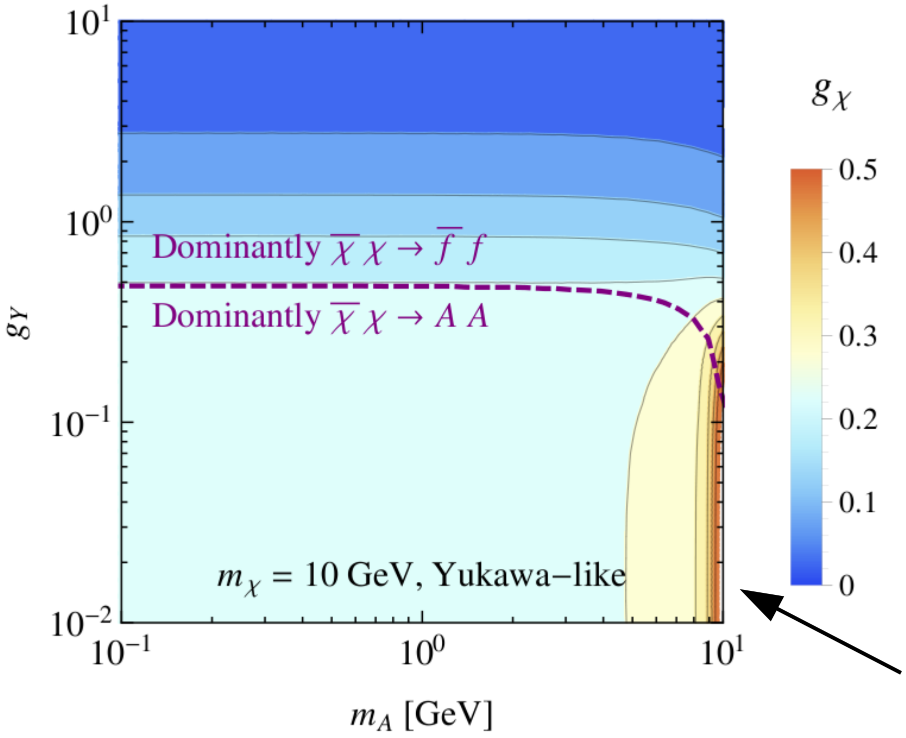
→ p-wave annihilation
→ depends only on g_x

- Which process dominates at high temperatures depends on the combination of g_x and g_f.

- If the relic density is set by annihilation into pseudoscalars, there are typically no constraints from indirect detection experiments.

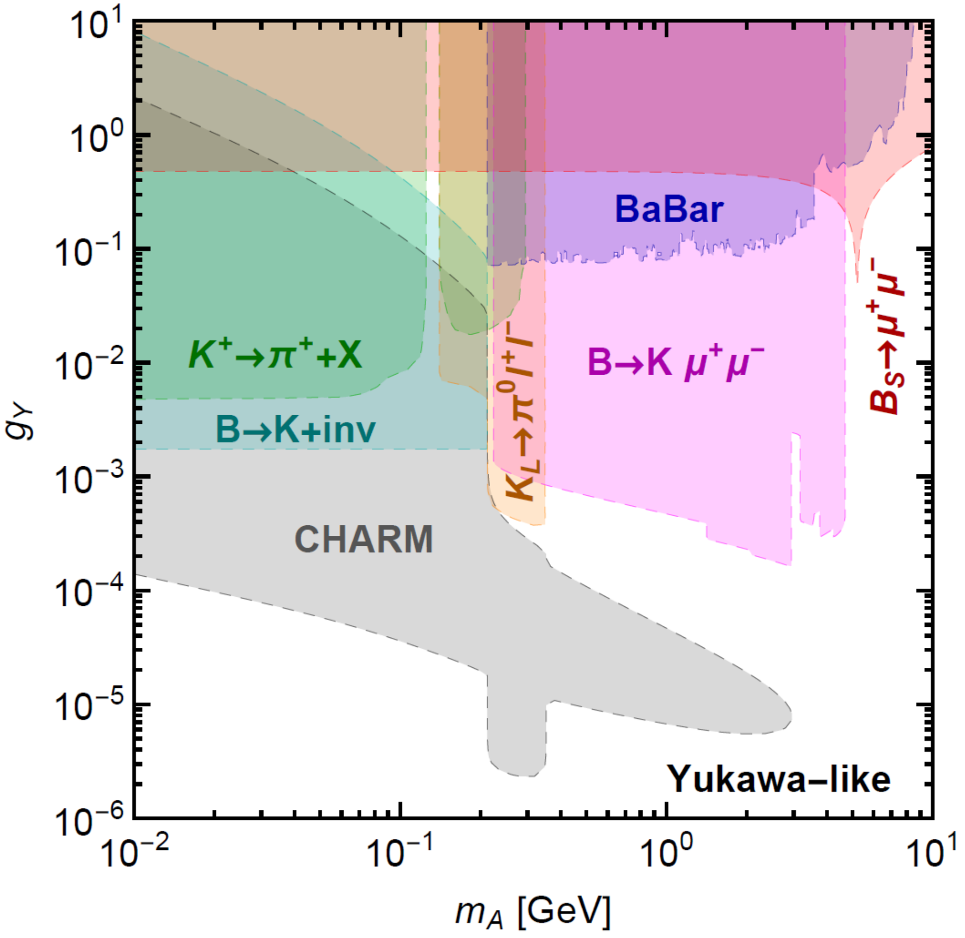
Relic density calculation

- We can fix g_χ (for given m_A, m_χ and g_Y) by the requirement that DM freeze-out yields the observed relic abundance.

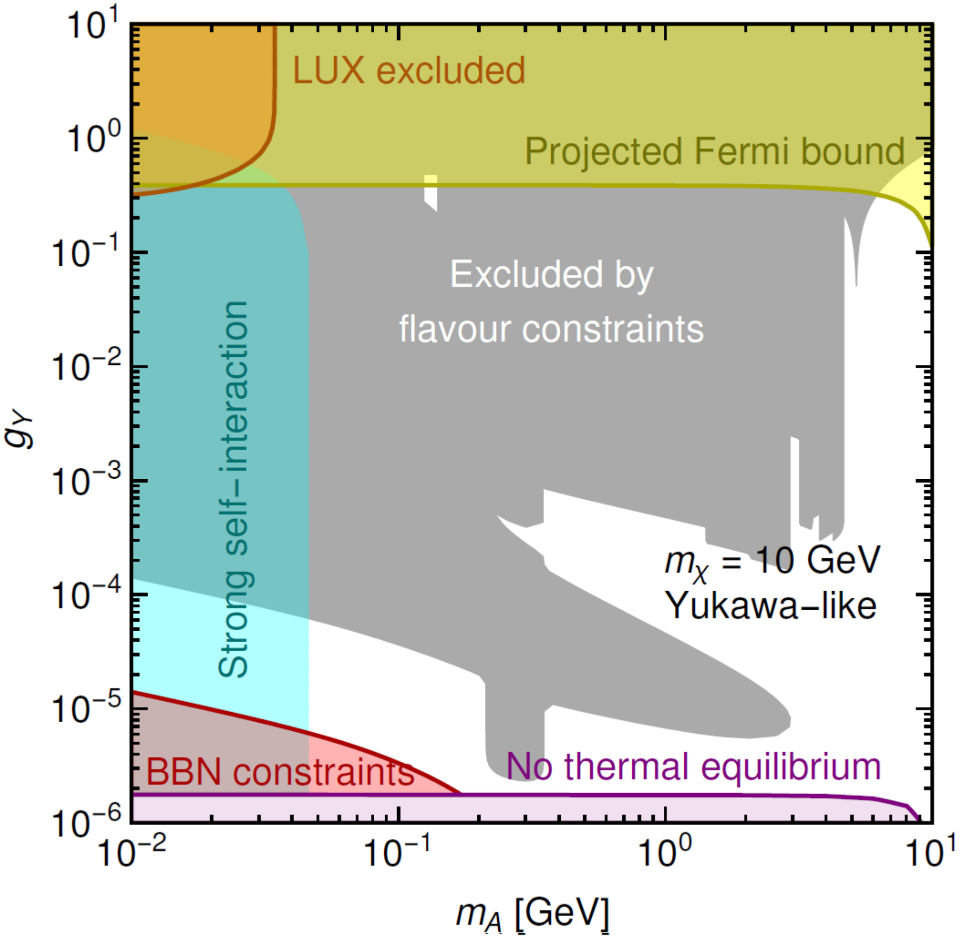


Phase-space suppression of annihilation into pseudoscalars for $m_A \sim m_\chi$.

Dark matter constraints

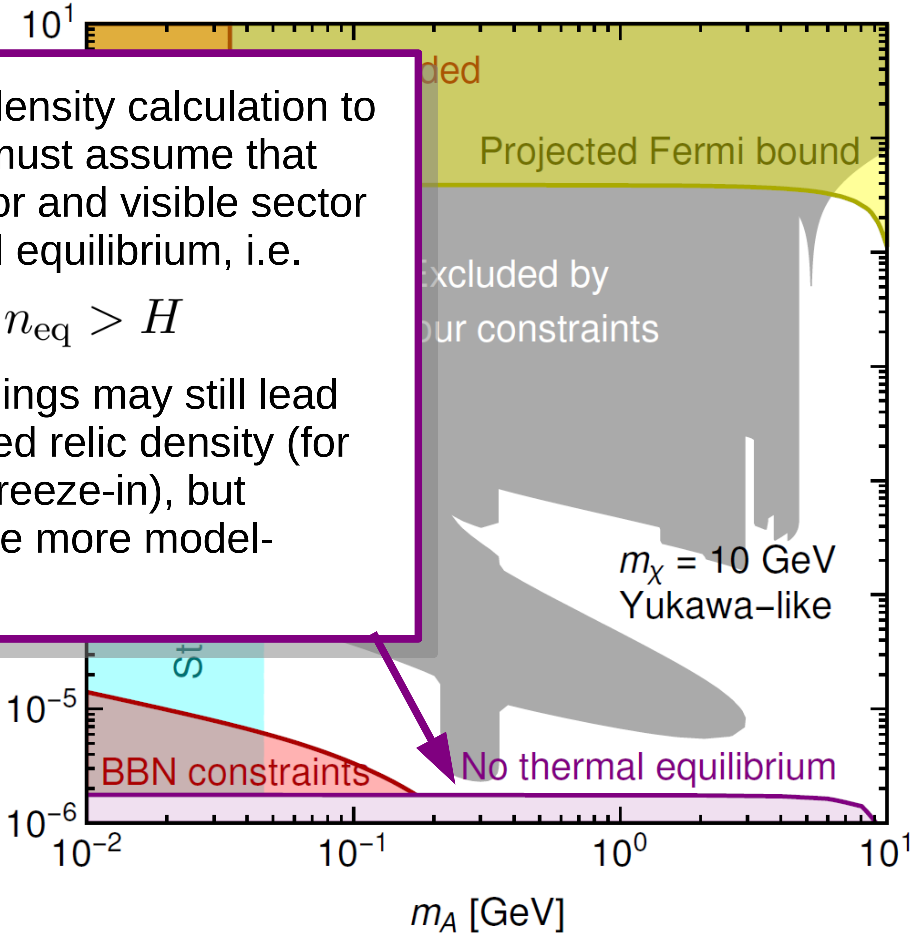


Dark matter constraints



g_χ fixed by relic density requirement!

Dark matter constraints

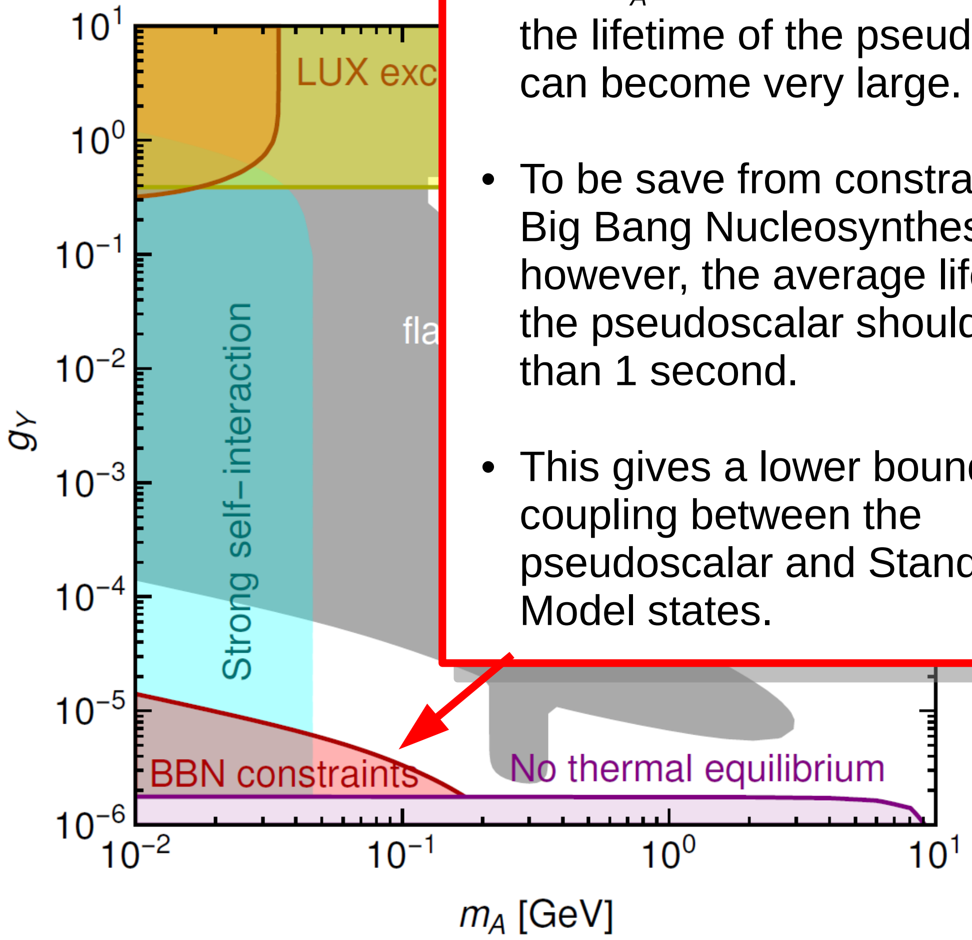


- For the relic density calculation to be valid, we must assume that the dark sector and visible sector reach thermal equilibrium, i.e.

$$\langle \sigma v \rangle n_{\mathrm{eq}} > H$$

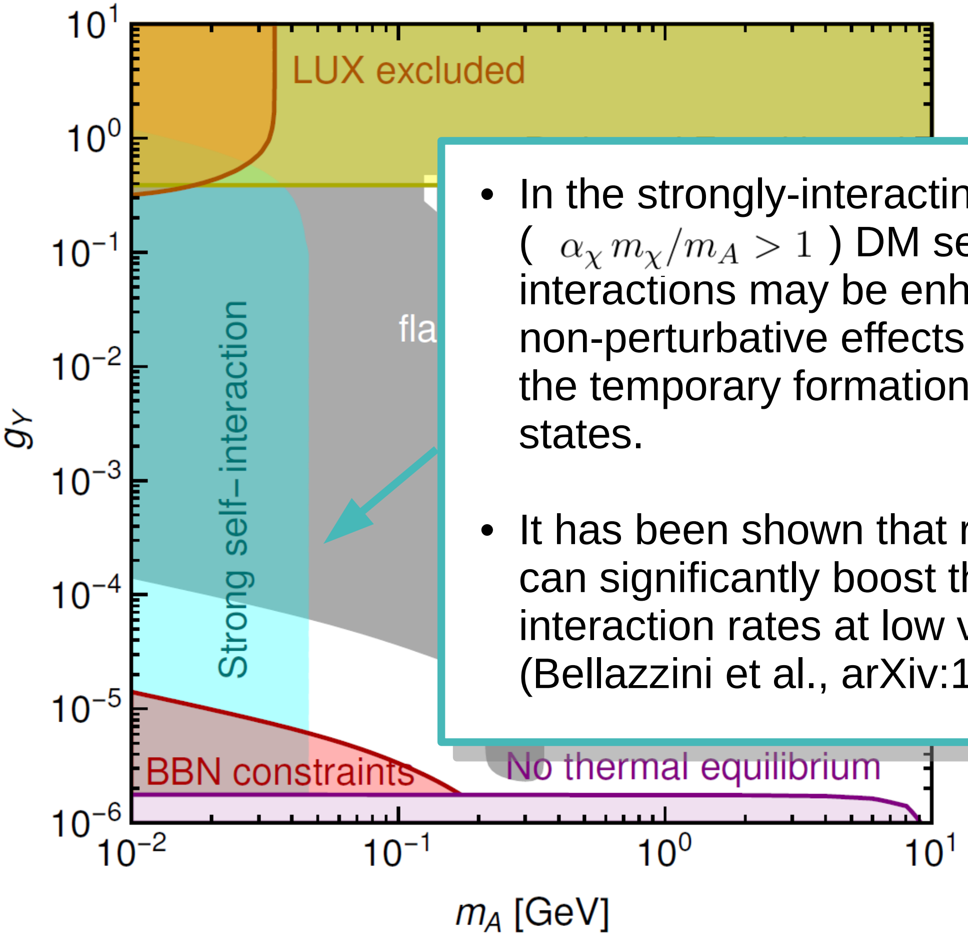
- Smaller couplings may still lead to the observed relic density (for example via freeze-in), but predictions are more model-dependent.

Dark matter constraints



- For m_A below the muon mass, the lifetime of the pseudoscalar can become very large.
- To be save from constraints from Big Bang Nucleosynthesis, however, the average lifetime of the pseudoscalar should be less than 1 second.
- This gives a lower bound on the coupling between the pseudoscalar and Standard Model states.

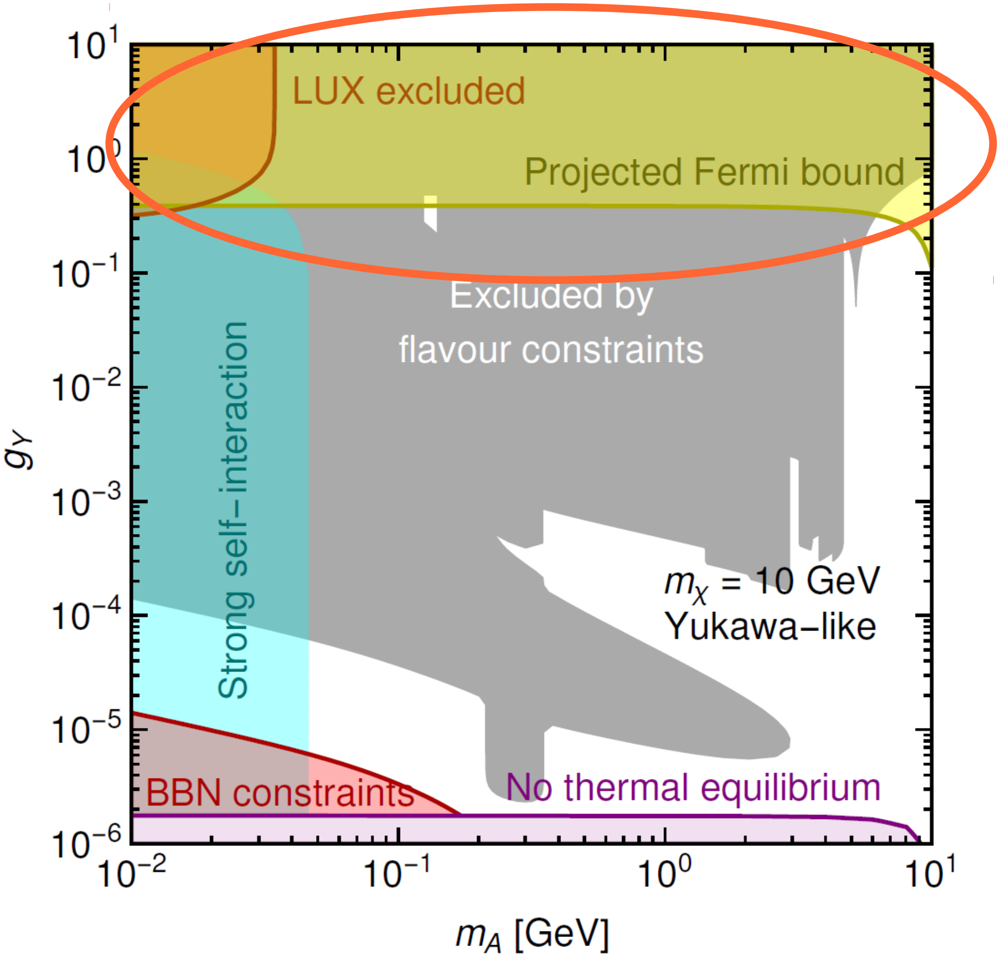
Dark matter constraints



- In the strongly-interacting regime ($\alpha_\chi m_\chi / m_A > 1$) DM self-interactions may be enhanced by non-perturbative effects such as the temporary formation of bound states.

- It has been shown that resonances can significantly boost the interaction rates at low velocities (Bellazzini et al., arXiv:1307.1129).

Dark matter constraints

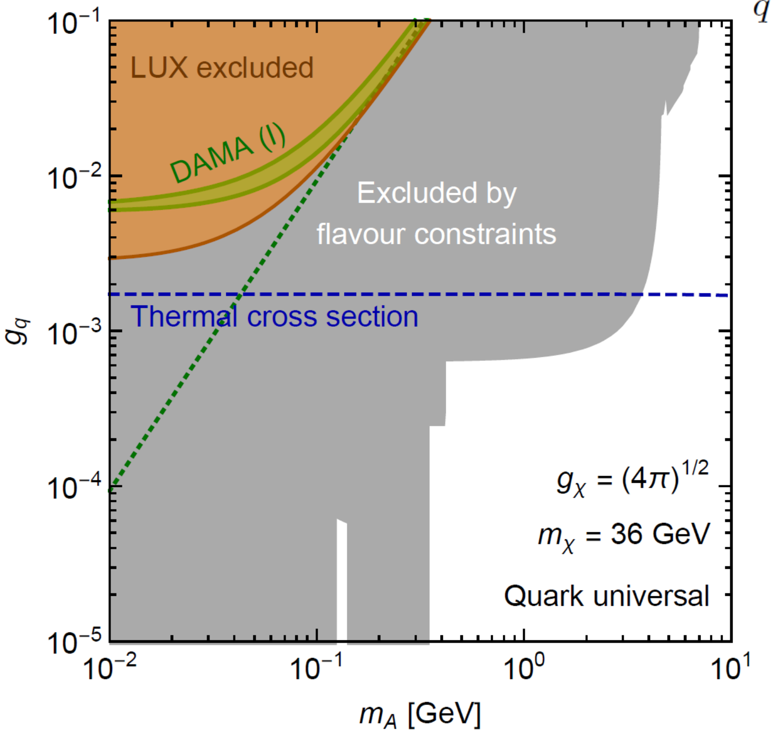


- Parameter region with sizeable g_Y.
- Potentially probed by direct and indirect detection experiments.

DAMA and LUX

- The ratio $g_p \,/\, g_n \sim -4$ obtained for Yukawa-like couplings is insufficient to reconcile DAMA and LUX.
- For different coupling structures, a much larger ratio can be obtained, for example $g_p/g_n \sim -16$ for couplings of the form

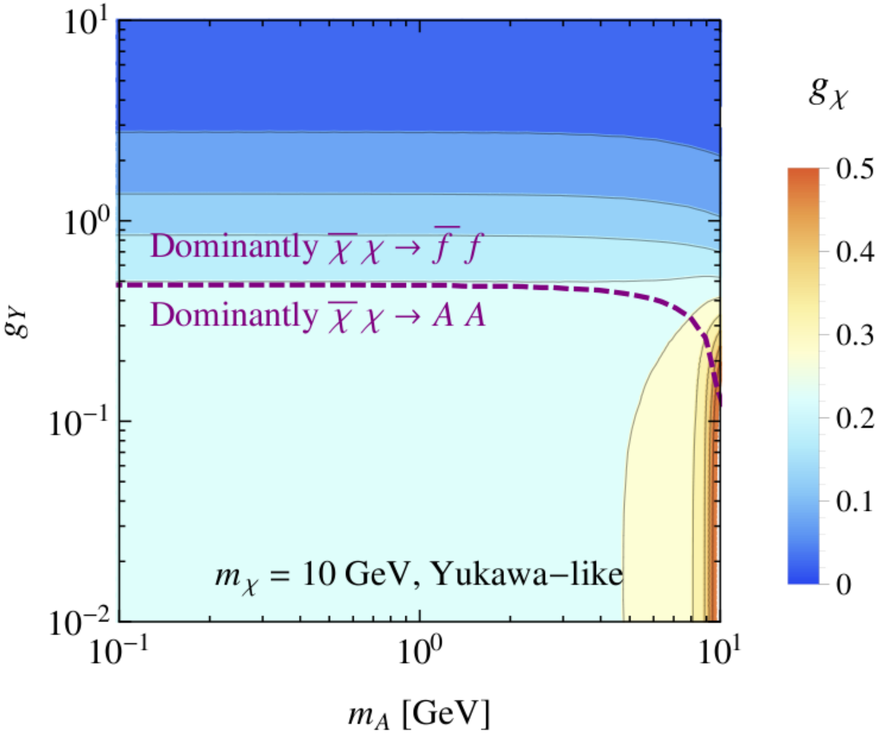
$$\mathcal{L}_{\mathrm{SM}}^{(q)} = i\, g_q \sum_q A\, \bar{q} \gamma^5 q$$



- Even in the most optimistic case that we make the DM coupling g_χ as large as possible (e.g. $g_\chi = (4\pi)^{1/2}$), the quark coupling gq still has to be so large, that it is excluded by flavour constraints by many orders of magnitude.
- Moreover, the required coupling strength would have to be so large, that DM would be underproduced in the early universe.

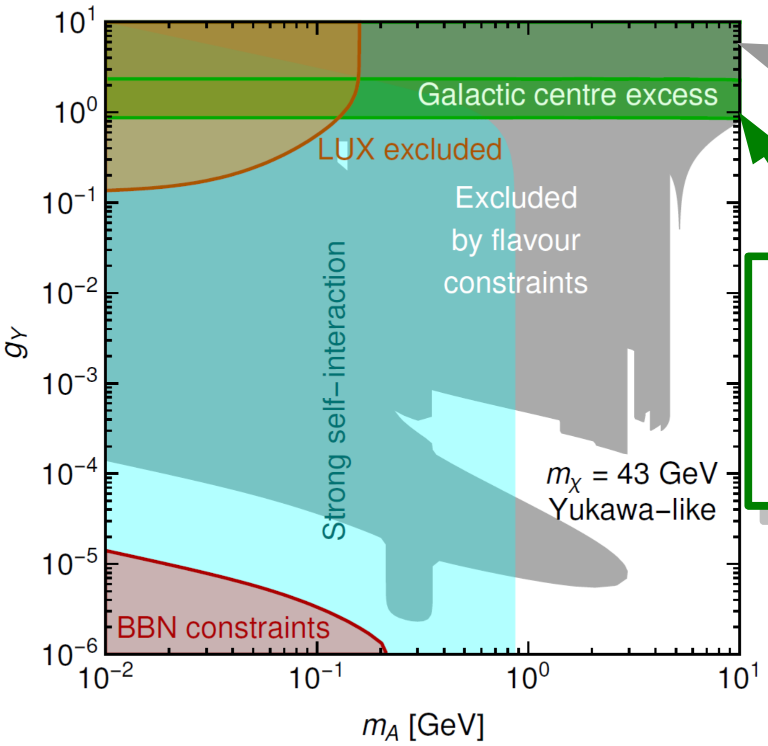
Indirect detection

- If dark matter freeze-out is dominated by *p*-wave annihilation into pseudoscalar no annihilation signals will be observable in the present universe.
- If freeze-out is dominated by *s*-wave annihilation into SM fermions, the annihilation rate in the present universe will be given by the thermal cross section.



- If both annihilation channels contribute in the early universe, we expect to see an annihilation signal slightly below the standard expectation for a thermal relic.
  - Perfect for explaining the Galactic Centre Excess

The Galactic Centre Excess from pseudoscalars



- Conventional explanation of the Galactic centre excess, but strong constraints from dwarf spheroidals.

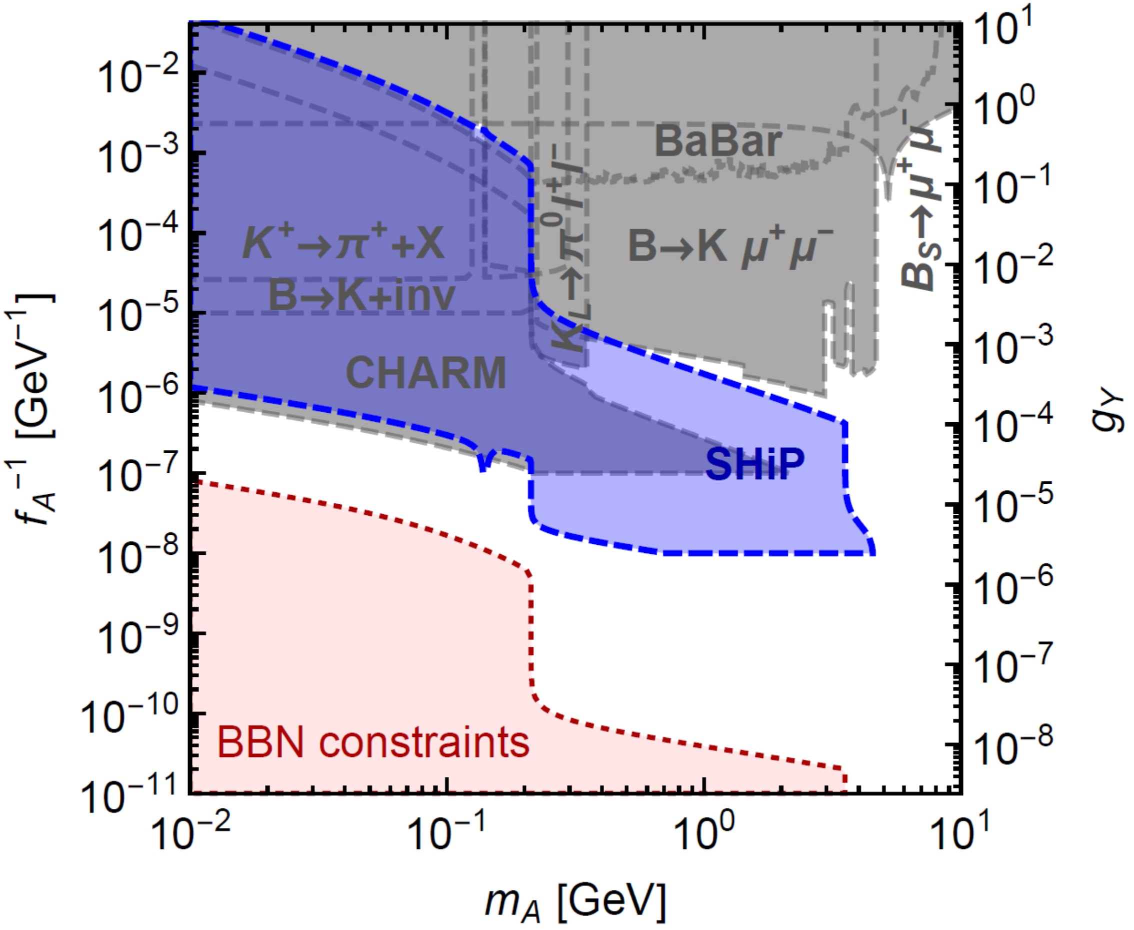
- Potential explanation of the Galactic centre excess within astrophysical uncertainties while at the same time being save from dwarf spheroidal constraints.

> For m_A > 10 GeV it is possible to explain the Galactic centre excess in terms of a pseudoscalar mediator while evading flavour constraints.

> However, due to these constraints it is impossible to explain the Galactic centre excess and at the same time have observable direct detection signals and/or strong dark matter self-interactions.

Future prospects

- For pseudoscalar masses of about 1 GeV, future proton beam-dump experiments (e.g. SHiP) have great potential to improve existing constraints and explore new regions of parameter space.
- Another very promising strategy are searches for displaced vertices at the LHC.



Alekhin, FK et al., arXiv:1504.04855

Conclusions

- Pseudoscalar mediators coupling the visible and dark sectors are interesting from both the model-building and phenomenological perspectives.
- Flavour physics is an interesting and rarely studied tool to constrain these types of models and yields relevant and highly complementary information.
- There are many interesting ways to further constrain the parameter space, e.g. $B_s \rightarrow \mu^+ \mu^-$, searches for displaced vertices and future beam-dump experiments.
- Cosmological and astrophysical measurements enable us to set constraints on the direct couplings of such a pseudoscalar to dark matter and on the interactions between dark matter and Standard Model quarks mediated by it:
  - It does not seem possible to obtain both large self-interactions and at the same time a dark matter signal from direct or indirect detection experiments given current bounds.
  - Our results rule out an interpretation of DAMA (and indeed of any direct detection signal observed in the foreseeable future) in terms of pseudoscalar exchange.
  - A pseudoscalar mediator with 10 GeV $< m_A < m_\chi$ remains one of the most attractive explanations for the Galactic centre gamma-ray excess.

Backup

The general set-up

- We are interested in the interactions of a light real pseudoscalar A with the DM particle χ (a Dirac fermion) and SM fermions:

$$\mathcal{L}_{\mathrm{DM}} = i\, g_\chi\, A\, \bar{\chi}\gamma^5\chi$$

- The most well-motivated scenario is that DM has couplings to all charged SM fermions proportional to the SM Yukawa couplings:

$$\mathcal{L}_{\mathrm{SM}}^{(Y)} = i\, g_Y \sum_{f=q,\ell} \frac{\sqrt{2}\, m_f}{v} A\, \bar{f}\gamma^5 f$$

- This coupling structure is expected for pseudoscalars arising from extended Higgs sectors. Furthermore, it is consistent with the assumption of Minimal Flavour Violation and therefore typically less constrained than other kinds of couplings.

- Another interesting possibility: Yukawa-like couplings only to quarks (no couplings to leptons) – see arXiv:1412.5174 for more details.

Flavour-changing processes

- The relevant terms in the effective Lagrangian for flavour-changing processes can be parameterised as

$$\mathcal{L}_{\mathrm{FCNC}} \supset h^R_{ds} A\, \bar{d}_L s_R + h^L_{ds} A\, \bar{d}_R s_L + h^R_{sb} A\, \bar{s}_L b_R + h^L_{sb} A\, \bar{s}_R b_L + \mathrm{h.c.}$$

- For Yukawa-like couplings to quarks, we find

$$\boxed{h^R_{sb} = -\frac{\alpha\, g_Y\, m_b\, m_t^2}{2\sqrt{2}\pi\, m_W^2\, \sin(\theta_W)^2\, v} V_{tb} V^*_{ts} \log\left(\frac{\Lambda^2}{m_t^2}\right)}$$

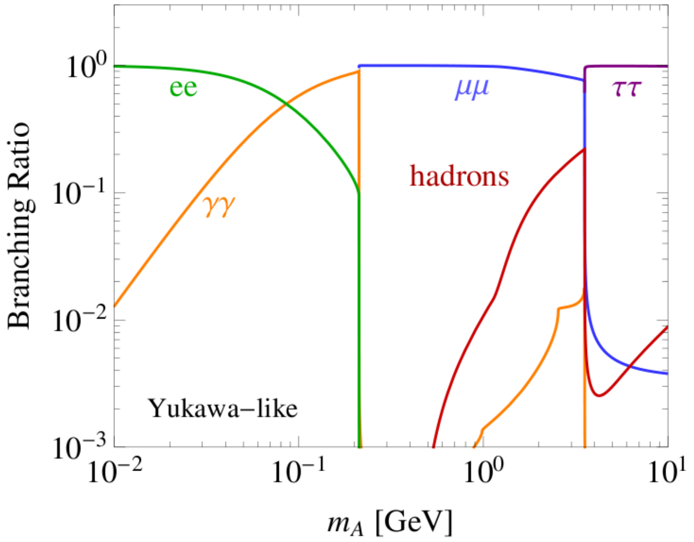
- It is well-known how to calculate the partial kaon decay width in terms of these effective couplings:

$$\Gamma(K^+ \to \pi^+ A) = \frac{1}{16\pi\, m^3_{K^+}} \lambda^{1/2}(m^2_{K^+}, m^2_{\pi^+}, m^2_A) \left(\frac{m^2_{K^+} - m^2_{\pi^+}}{m_s - m_d}\right)^2 |h^S_{ds}|^2$$

$$h^S_{qq'} = (h^R_{qq'} + h^L_{qq'})/2$$

Pseudoscalar decays

- In principle, the pseudoscalar can decay into leptons, photons and hadrons.
- For $m_A < 2\,m_\pi$, hadronic decays are kinematically forbidden. But even for $m_A > 2\,m_\pi$ the decay $A \to \pi\pi$ is forbidden by *CP*. Hiller, arXiv:hep-ph/0404220
- Using the perturbative spectator model, we estimate the decay width for hadronic final states and find it to be significantly smaller than the corresponding widths for decays into leptons and photons due to the phase-space suppression for three-body final states.



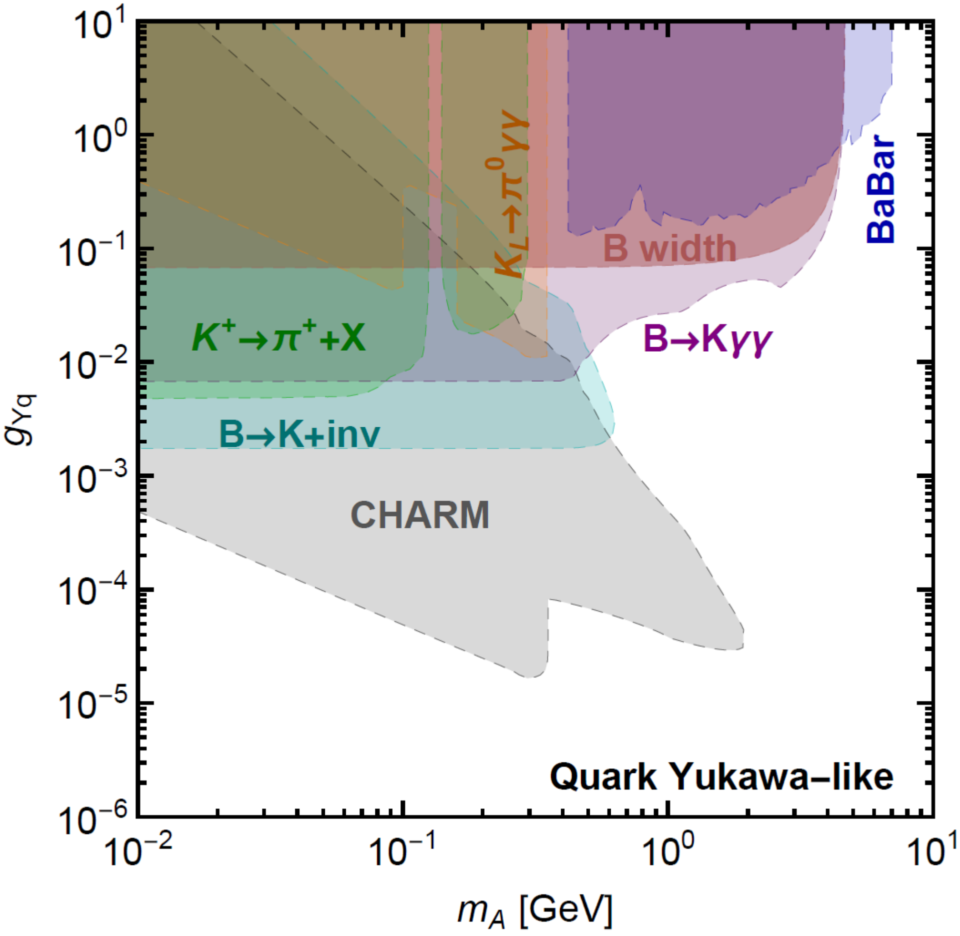
$$\Gamma(A \to \ell^+\ell^-) = \frac{g_f^2}{8\pi}\, m_A \sqrt{1 - \frac{1}{\tau_\ell}}\,,$$

$$\Gamma(A \to \gamma\gamma) = \frac{\alpha^2\, m_A^3}{256\pi^3} \left| \sum_f \frac{N_c\, Q_f^2\, g_f}{m_f} F_A(\tau_f) \right|^2$$

$$\tau_f = m_A^2/(4\, m_f^2)$$

Yukawa-like couplings only to quarks

- Bounds are generally weaker, since there are no constraints from pseudoscalar decays into leptons.
- However, escaping particles and loop-induced decays into photons still give relevant constraints.
- Bounds from CHARM even get stronger because of the longer pseudoscalar lifetime.
- A promising search for these kinds of models is $B \to K\gamma\gamma$.
- All of the general conclusions remain unchanged.

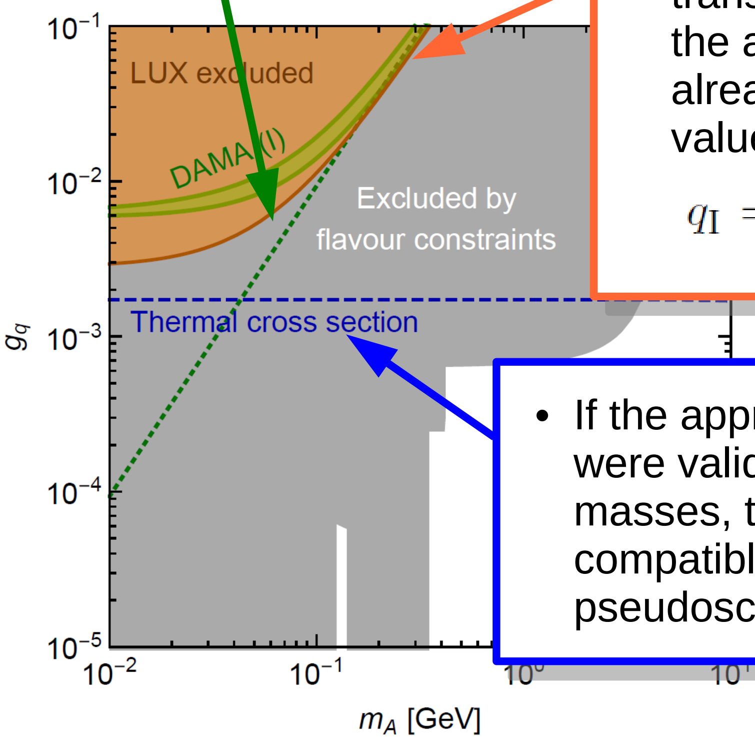


DAMA and LUX: Some additional observations

- The green dashed line indicates the naive extrapolation of contact interactions (R ~ m_A^{-4}).

- While DAMA and LUX are (marginally) compatible for $m_A \gg q$, DAMA is clearly excluded for low pseudoscalar masses.
- The reason is that the typical momentum transfer in DAMA is larger than in LUX, so the approximation of contact interactions already breaks down already for larger values of m_A:

$$q_{\mathrm{I}} = \sqrt{2\, m_{\mathrm{I}}\, E_{\mathrm{ee}}/Q_{\mathrm{I}}} = (70\text{–}100)\ \mathrm{MeV}$$

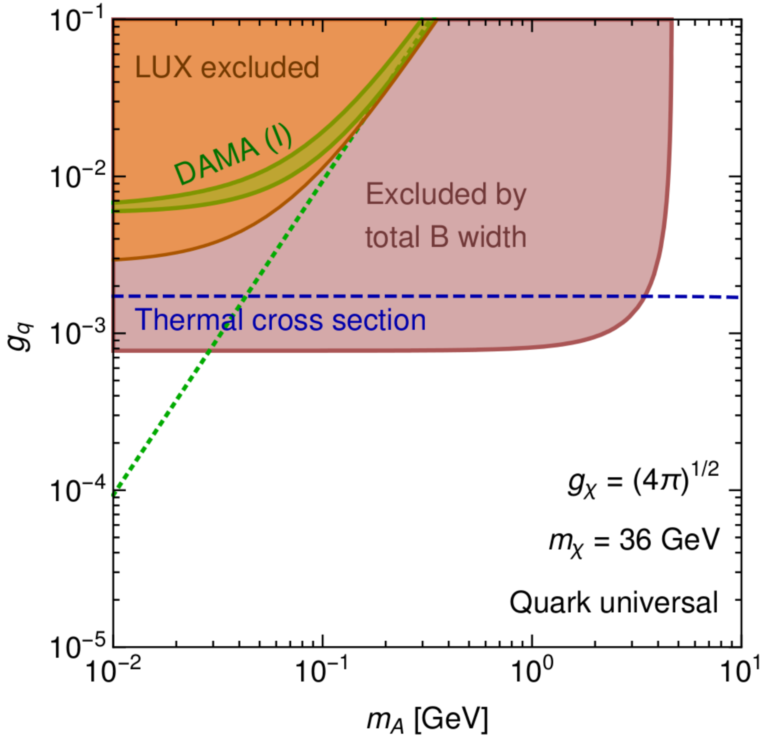


- If the approximation of contact interactions were valid down to small pseudoscalar masses, the DAMA modulation could be compatible with thermal freeze-out for pseudoscalar masses around 30-40 MeV.

DAMA and LUX: Some additional observations

- In fact, an interpretation of DAMA in terms of pseudoscalar exchange with universal quark couplings is solidly excluded even my the simplest and most conservative bound, namely the requirement that

$$\mathrm{BR}(B \rightarrow X_s A) < 1.$$



- This constraint is completely independent of the mass of A (as long as $m_A << m_B$) and its subsequent decays and it does not require any matching to chiral perturbation theory.
- Taking into account that B mesons are observed to decay almost exclusively into c-quarks, this constraint could be improved by another order of magnitude.