A Taste of Dark Matter.

Flavour Constraints on Pseudoscalar Mediators

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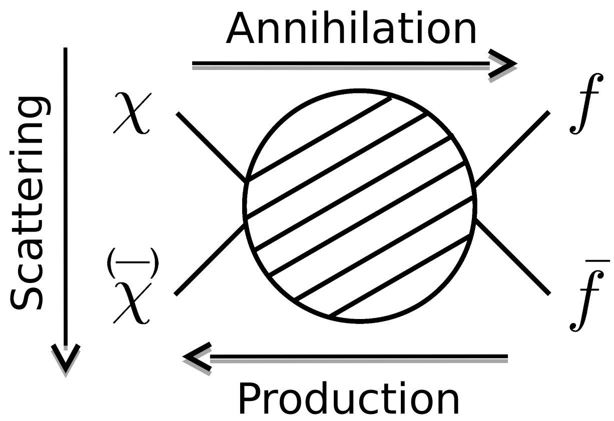
Based on arXiv:1412.5174 in collaboration with Matthew Dolan, Christopher McCabe and Kai Schmidt-Hoberg

Outline

- Motivation for studying light pseudoscalars
- General set-up and potential signatures
- Experimental and observational constraints
  - Involving Standard Model particles
  - Including Dark Matter
- Implications for dark matter signals
  - Direct detection
  - Indirect detection
- Future prospects
- Conclusions

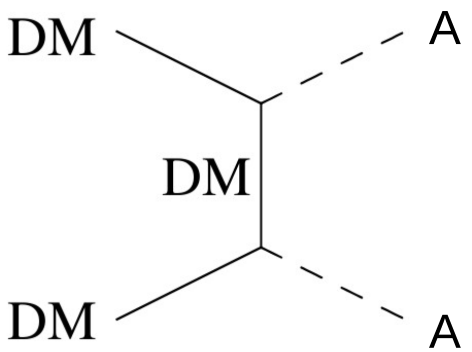
Why light mediators?

- 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).

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

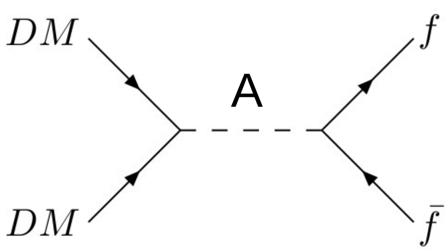
For Yukawa-like couplings:

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

Freytsis & Ligeti, arXiv:1012.5317

Why pseudoscalars?

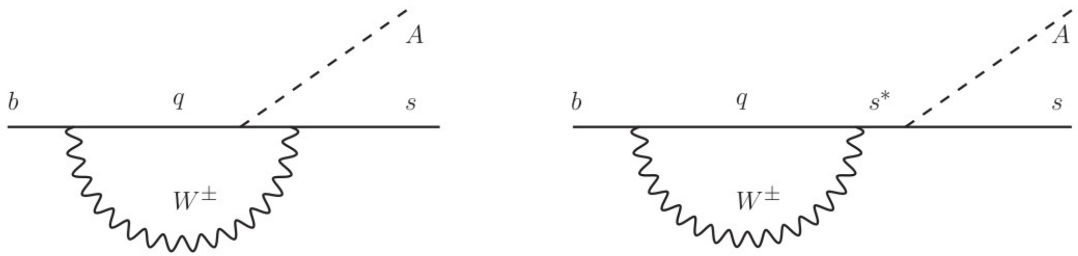
- Since constraints from direct detection experiments are largely absent, pseudoscalars can potentially give rise to a range of interesting signals:
  - It is possible to obtain observable indirect detection signals and for example explain the Fermi-LAT Galactic Centre gamma-ray excess.
    - Coy Dark 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 dark matter phenomenology from a light pseudoscalar in spite of all these constraints?

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:

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

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

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

- 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.

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.

Flavour-changing processes

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

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

- For Yukawa-like couplings to quarks, we find

$$h^R_{sb} = i \frac{\alpha\, m_b}{4\sqrt{2}\pi\ \sin(\theta_W)^2\, v} f(x_t)\, V_{tb} V^*_{ts}\,,$$

$$h^L_{sb} = -\,i \frac{\alpha\, m_s}{4\sqrt{2}\pi\ \sin(\theta_W)^2\, v} f(x_t)\, V_{tb} V^*_{ts}$$

$$f(x_t) = x_t\,(x_t - 2)\left[-\frac{1}{x_t - 1} + \frac{\log x_t}{(x_t - 1)^2}\right]$$

$$x_t \equiv m_t^2 / m_W^2$$

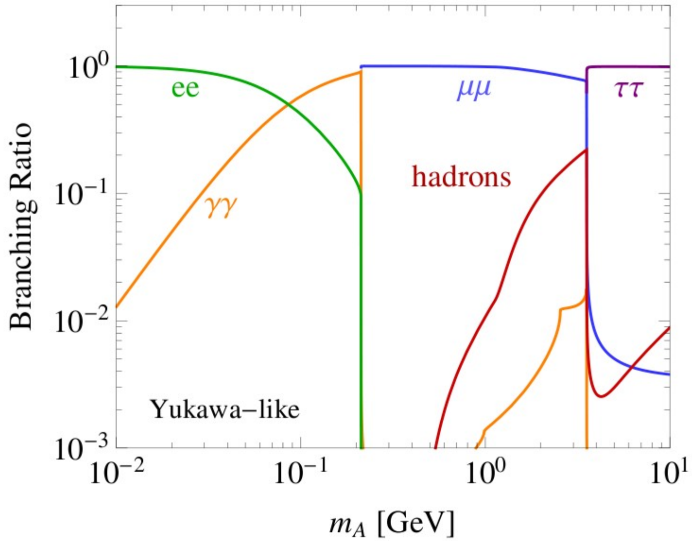
- It is well-known how to calculate the partial kaon decay width in terms of these effective couplings:

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

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

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.

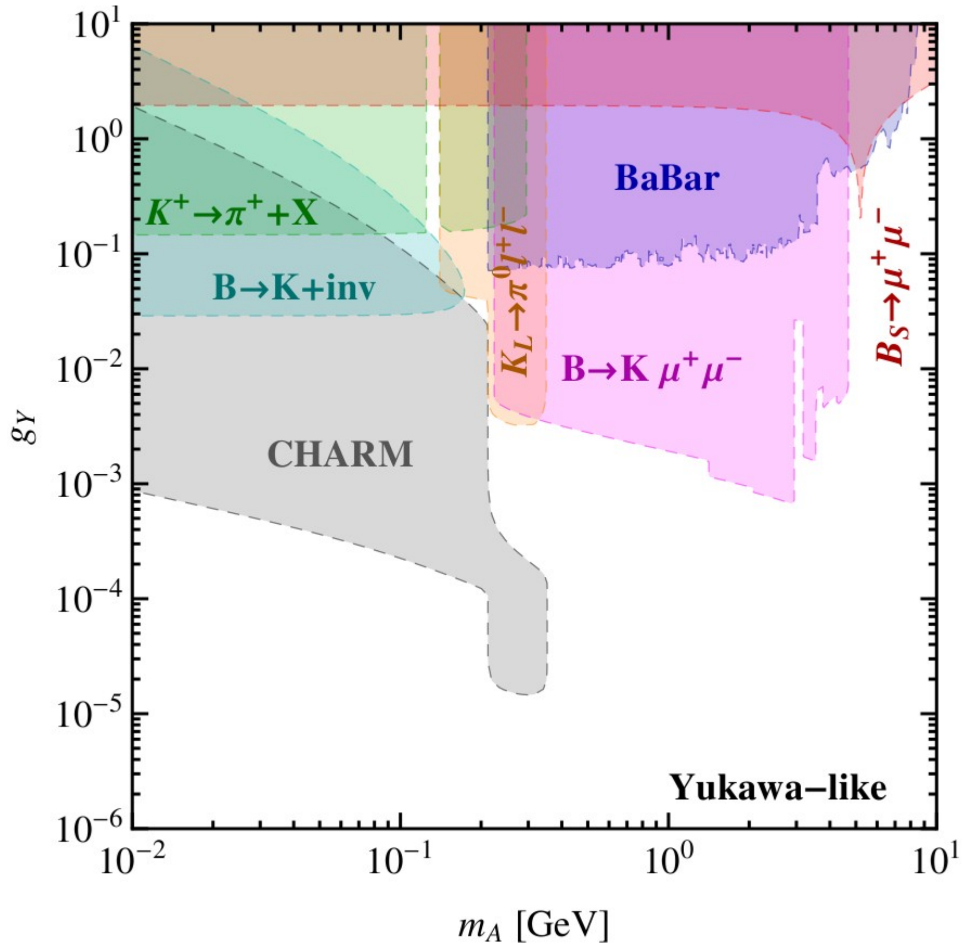


$$\Gamma(A \to \ell^+\ell^-) = \frac{g_f^2}{8\pi}\, m_A \sqrt{1 - \frac{1}{\tau_\ell}}\,,$$

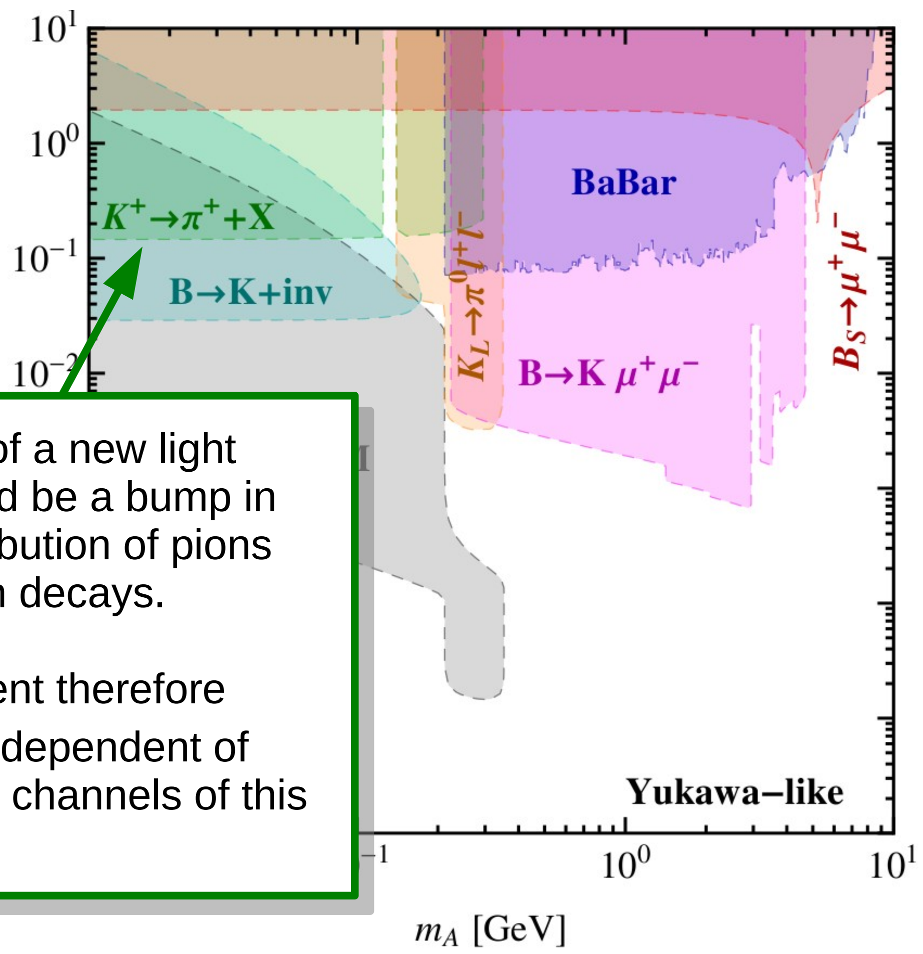
$$\Gamma(A \to \gamma\gamma) = \frac{\alpha^2\, m_A^3}{256\pi^3} \left| \sum_f \frac{N_c\, Q_f^2\, g_f}{m_f} F_A(\tau_f) \right|^2$$

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

Experimental results

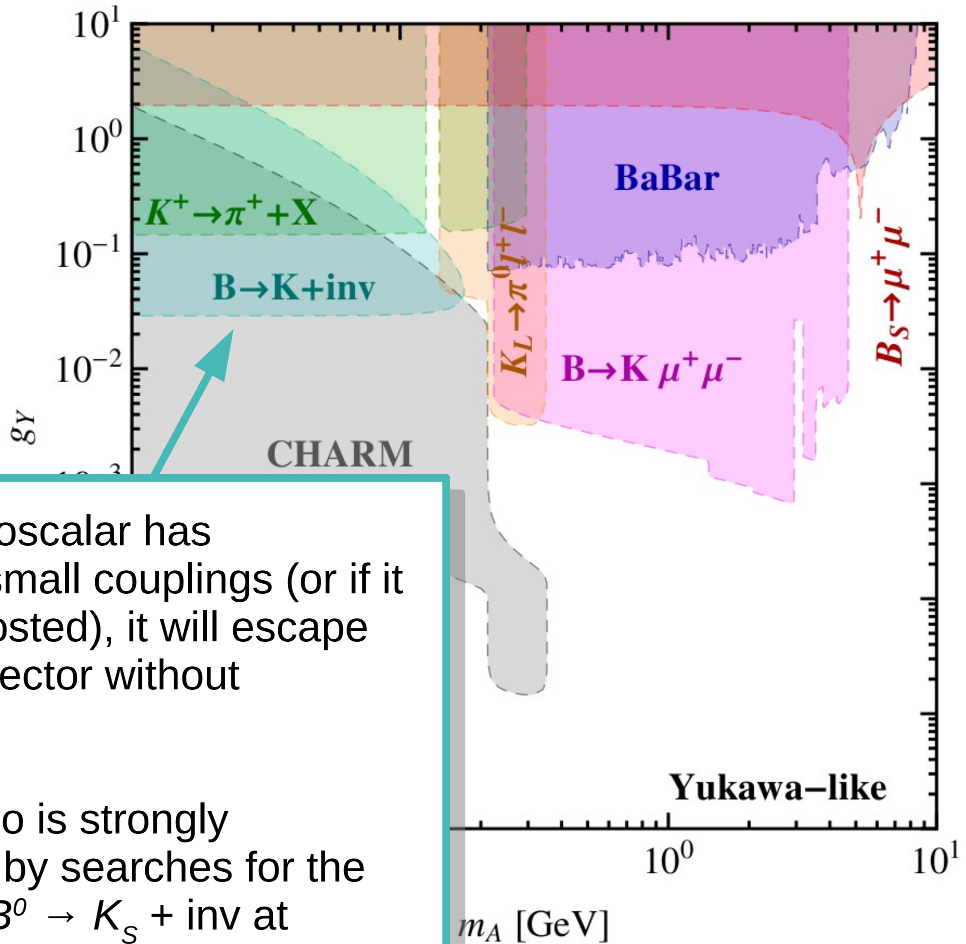


Experimental results



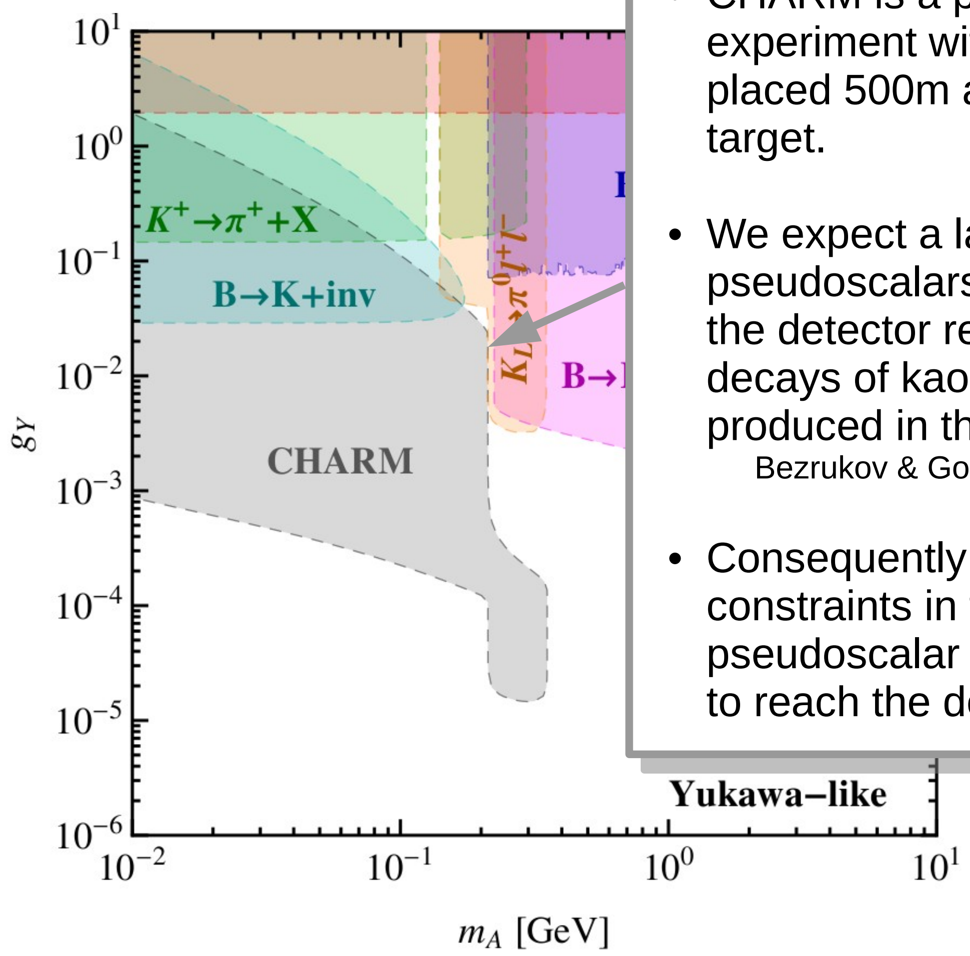
- In the presence of a new light state there should be a bump in momentum distribution of pions produced in kaon decays.
- The $K_{\mu 2}$ experiment therefore places bounds independent of the further decay channels of this new state.

Experimental results



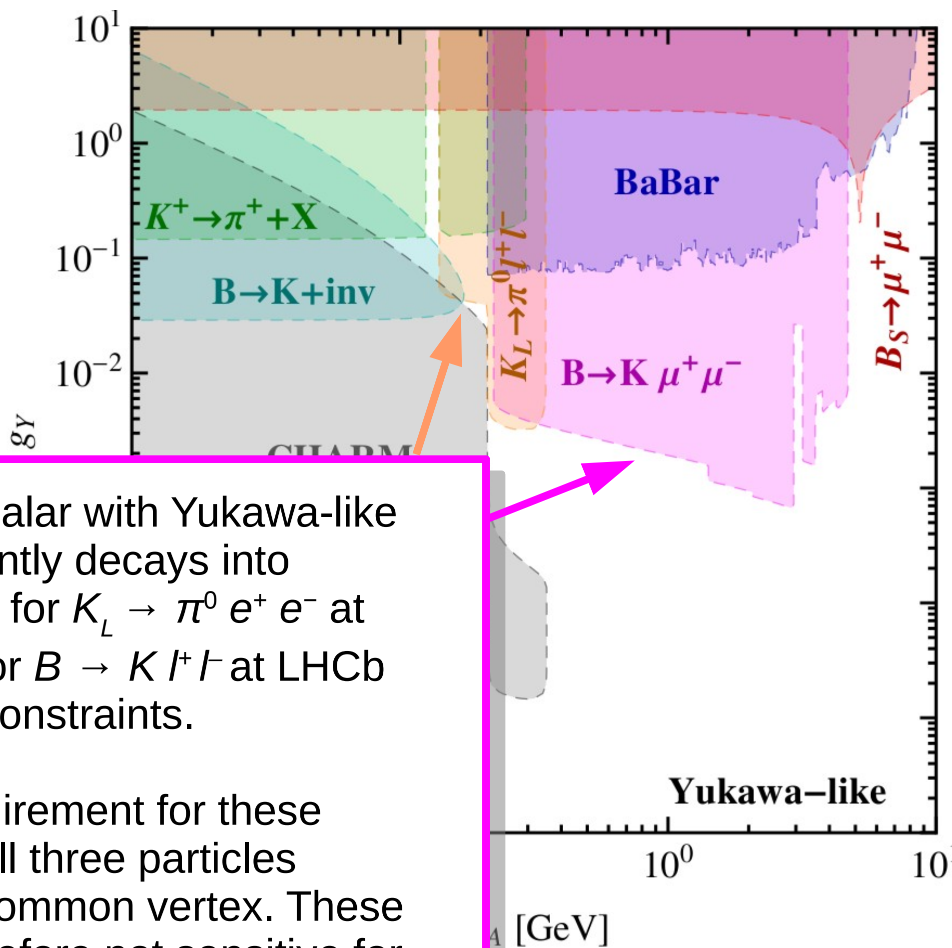
- If the pseudoscalar has sufficiently small couplings (or if it is highly boosted), it will escape from the detector without decaying.
- This scenario is strongly constrained by searches for the rare decay $B^0 \to K_S$ + inv at CLEO.

Experimental results



- CHARM is a proton beam-dump experiment with a detector placed 500m away from the target.
- We expect a large flux of pseudoscalars in the direction of the detector resulting from the decays of kaons and B-mesons produced in the target.
  Bezrukov & Gorbunov, arXiv:0912.0390
- Consequently we obtain strong constraints in the case that the pseudoscalar lives long enough to reach the detector.

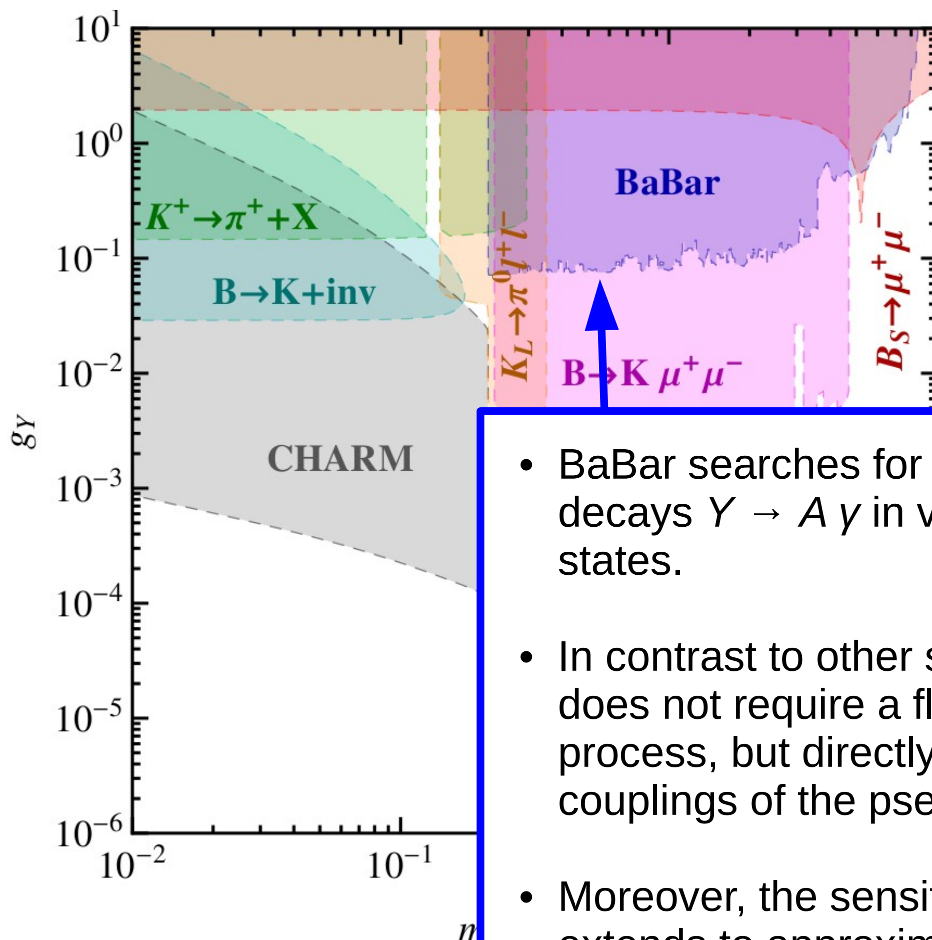
Experimental results

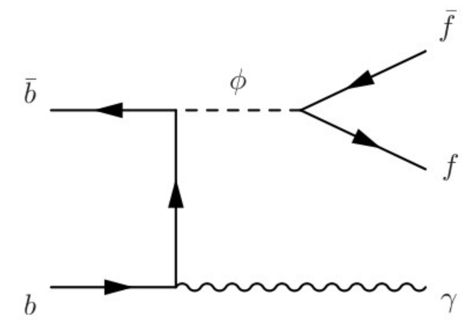


- Since a pseudoscalar with Yukawa-like couplings dominantly decays into leptons, searches for $K_L \to \pi^0 e^+ e^-$ at KTeV/E799 and for $B \to K\, l^+ l^-$ at LHCb give very strong constraints.

- An important requirement for these searches is that all three particles originate from a common vertex. These searches are therefore not sensitive for the case that the pseudoscalar decays from a displaced vertex.

Experimental results





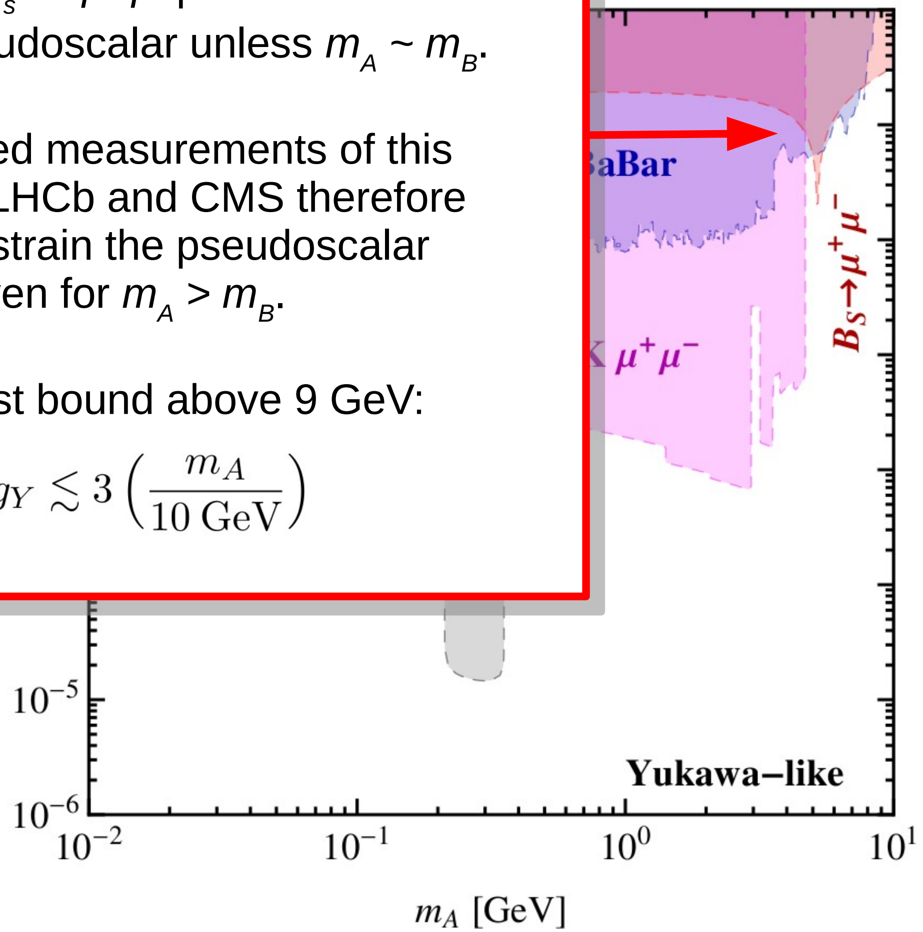
- BaBar searches for radiative Upsilon decays $Y \to A\, \gamma$ in various different final states.
- In contrast to other searches, this decay does not require a flavour-changing process, but directly probes the tree-level couplings of the pseudoscalar.
- Moreover, the sensitivity of this search extends to approximately 9 GeV.

Experimental results

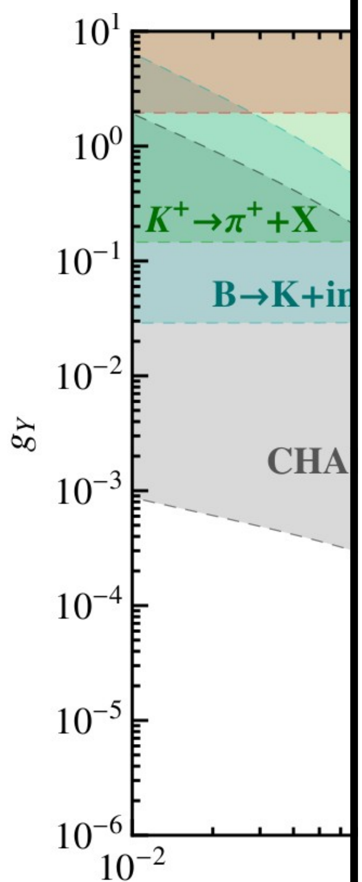
- The decay $B_s \rightarrow \mu^+ \mu^-$ proceeds via an off-shell pseudoscalar unless $m_A \sim m_B$.
- The combined measurements of this decay from LHCb and CMS therefore allow to constrain the pseudoscalar couplings even for $m_A > m_B$.

→ The strongest bound above 9 GeV:

$$g_Y \lesssim 3 \left(\frac{m_A}{10 \text{ GeV}} \right)$$



Experimental results

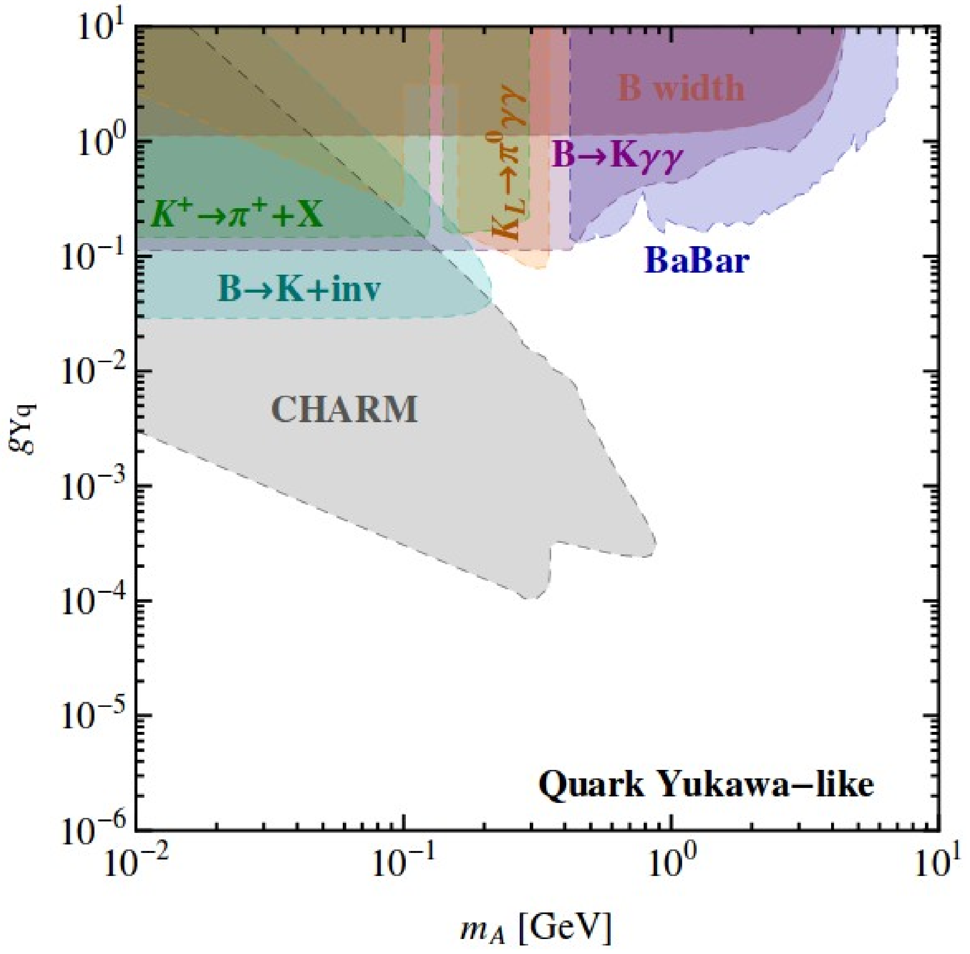


Channel	Experiment	Mass range [MeV]	Ref.	Relevant for
$K^+ \to \pi^+ + \text{inv}$	E949	0–110	[70]	Long lifetime*
		150–260	[71]	Long lifetime*
	E787	0–110 & 150–260	[72]	Long lifetime
$K^+ \to \pi^+\pi^0 \to \pi^+\nu\bar{\nu}$	E949	130–140	[73]	Long lifetime*
$K^+ \to \pi^+ e^+ e^-$	NA48/2	140–350	[74]	Leptonic decays
$K_L \to \pi^0 e^+ e^-$	KTeV/E799	140–350	[75]	Leptonic decays*
$K^+ \to \pi^+ \mu^+\mu^-$	NA48/2	210–350	[76]	Leptonic decays
$K_L \to \pi^0 \mu^+\mu^-$	KTeV/E799	210–350	[77]	Leptonic decays*
$K_L \to \pi^0 \gamma\gamma$	KTeV	40–100 & 160–350	[78]	Photonic decays*
$K_L \to \pi^0\pi^0 \to 4\gamma$	KTeV	130–140	[79]	Photonic decays*
$K^+ \to \pi^+ A$	$K_{\mu 2}$	10–130 & 140–300	[80]	All decay modes*
$B^0 \to K_S^0 + \text{inv}$	CLEO	0–1100	[81]	Long lifetime*
$B \to K \ell^+\ell^-$	BaBar	30–3000	[82]	Leptonic decays
	BELLE	140–3000	[83]	Leptonic decays
	LHCb	220–4690	[84]	Leptonic decays*
$B \to X_s \mu^+\mu^-$	BELLE	210–3000	[85]	Leptonic decays
$b \to s\, g$	CLEO	$m_A < m_B - m_K$	[86]	Hadronic decays*
$B_s \to \mu^+\mu^-$	LHCb/CMS	all masses	[87, 88]	Lepton couplings*
$\Upsilon \to \gamma\, \tau^+\tau^-$	BaBar	3500–9200	[89]	Leptonic decays*
$\Upsilon \to \gamma\, \mu^+\mu^-$	BaBar	212–9200	[90]	Leptonic decays*
$\Upsilon \to \gamma + \text{hadrons}$	BaBar	300–7000	[91]	Hadronic decays*
$K,\ B \to A + X$	CHARM	0–4000	[92]	Leptonic and photonic decays*

Many other searches considered.
Focus on the most constraining here.

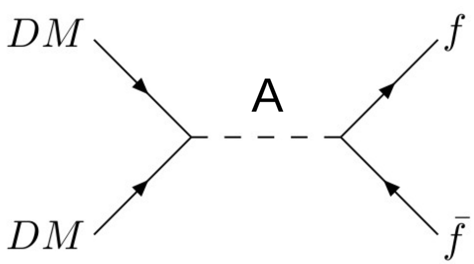
Yukawa-like couplings only to quarks

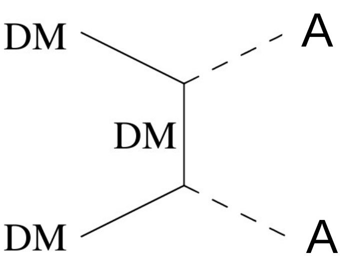
- Bounds are generally weaker, since there are no constraints from pseudoscalar decays into leptons.
- However, escaping particles and loop-induced decays into photons still give relevant constraints.
- Bounds from CHARM even get stronger because of the longer pseudoscalar lifetime.
- A promising search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



The dark matter connection

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





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

→ s-wave annihilation
→ depends on g_f and g_χ

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

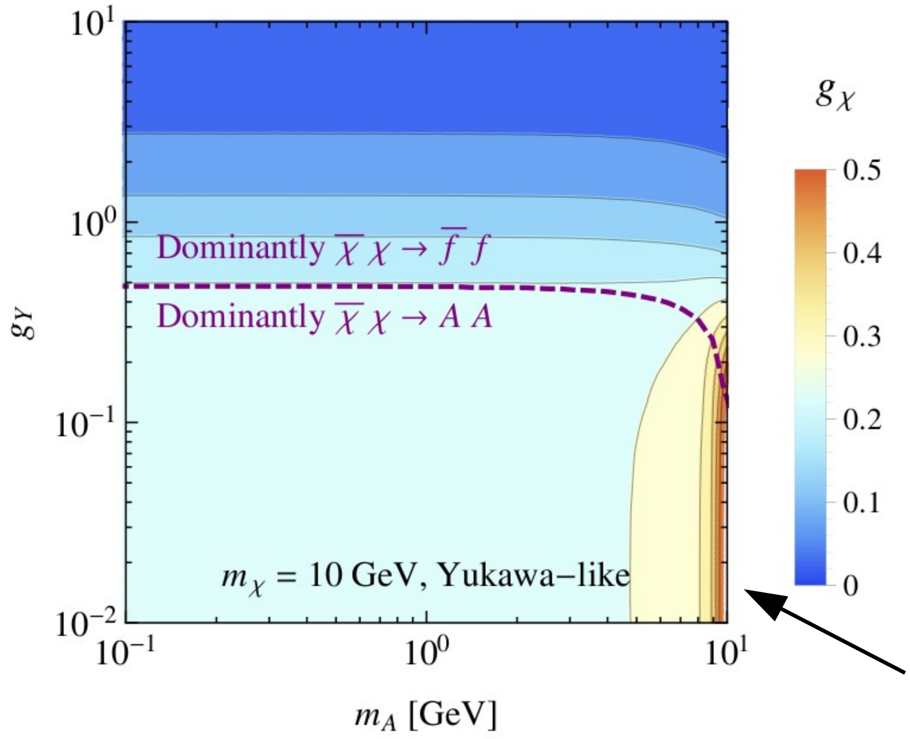
→ p-wave annihilation
→ depends only on g_χ

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

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

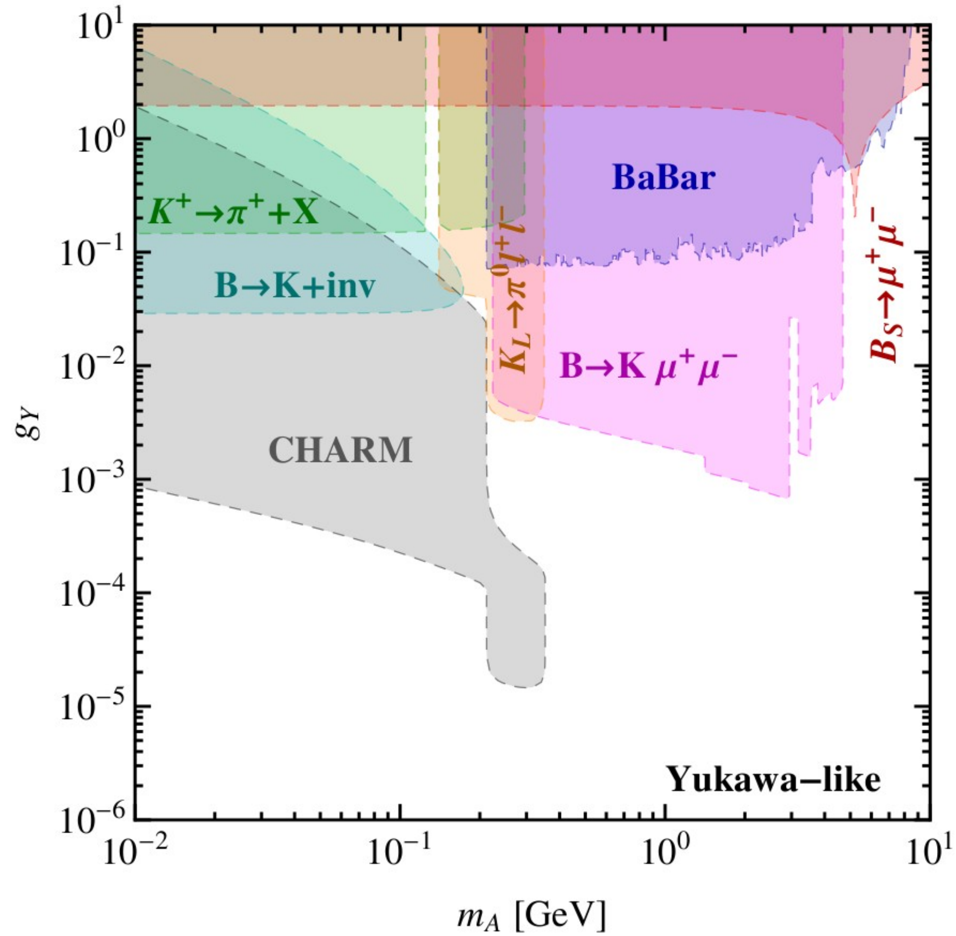
Relic density calculation

> 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.

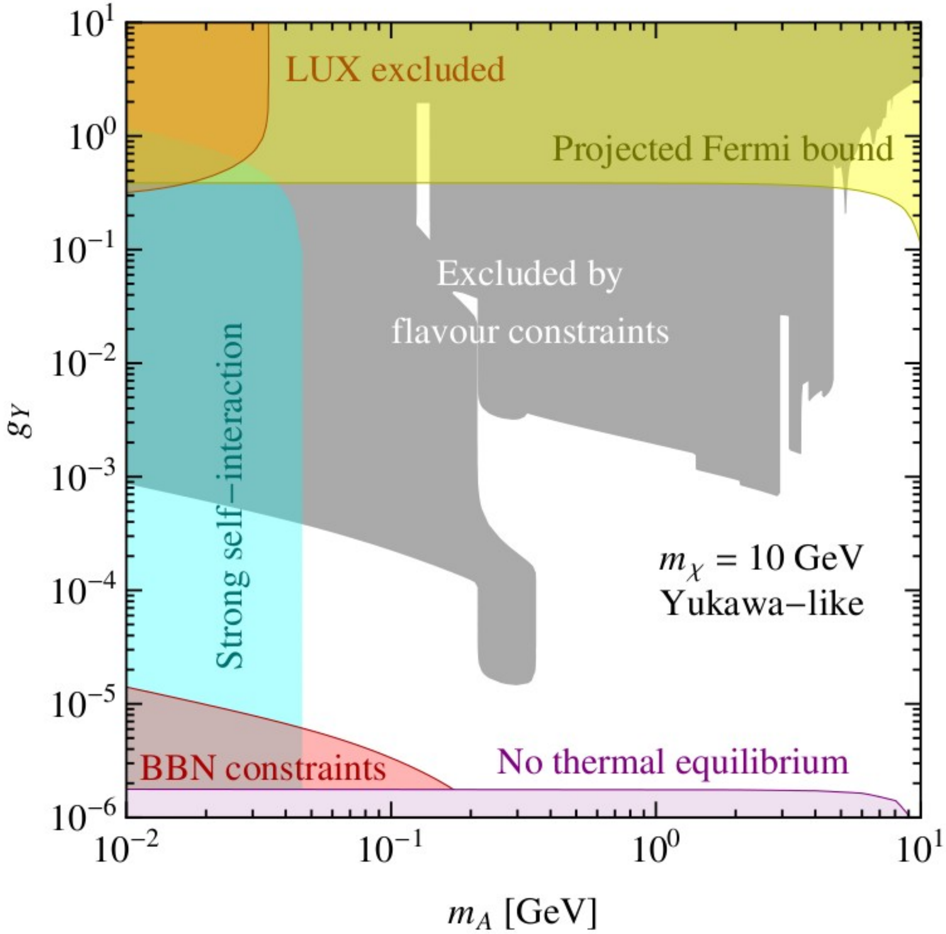


Phase-space suppression of annihilation into pseudoscalars for $m_A \sim m_\chi$.

Dark matter constraints



Dark matter constraints



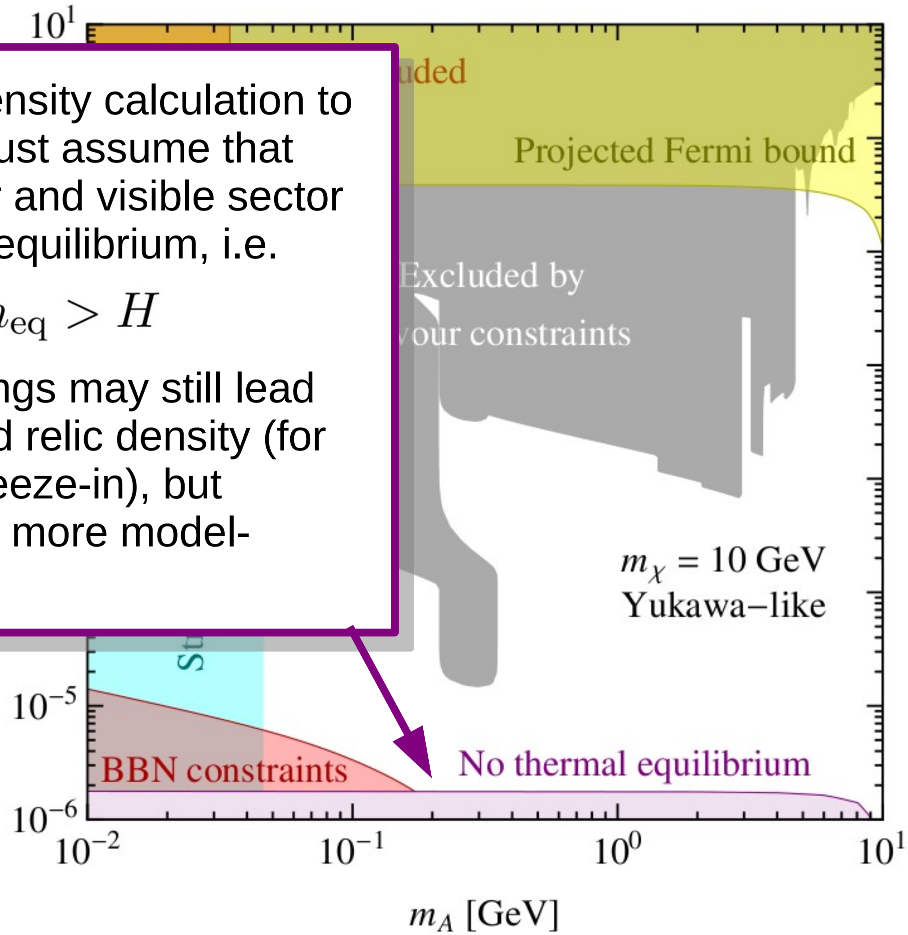
g_χ fixed by relic density requirement!

Dark matter constraints

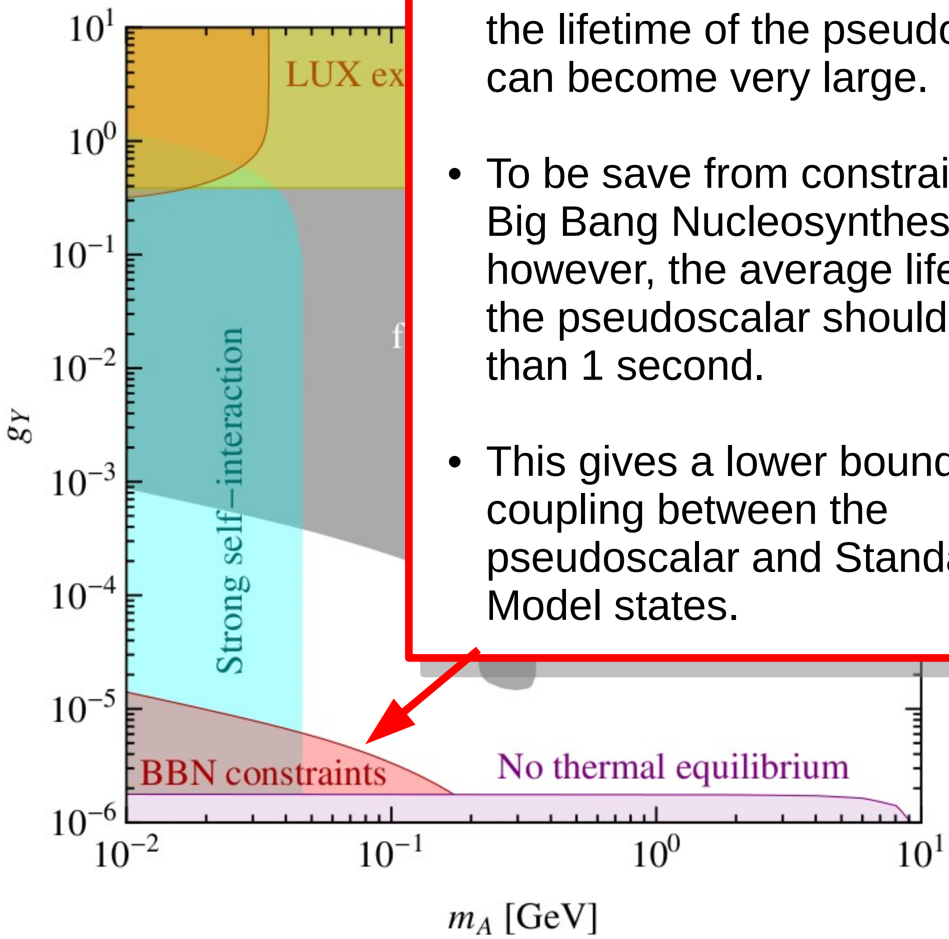
- For the relic density calculation to be valid, we must assume that the dark sector and visible sector reach thermal equilibrium, i.e.

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

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

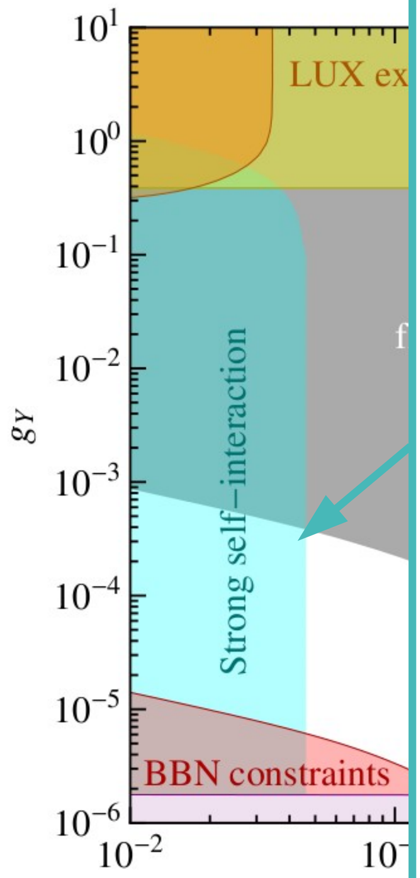


Dark matter constraints



- 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

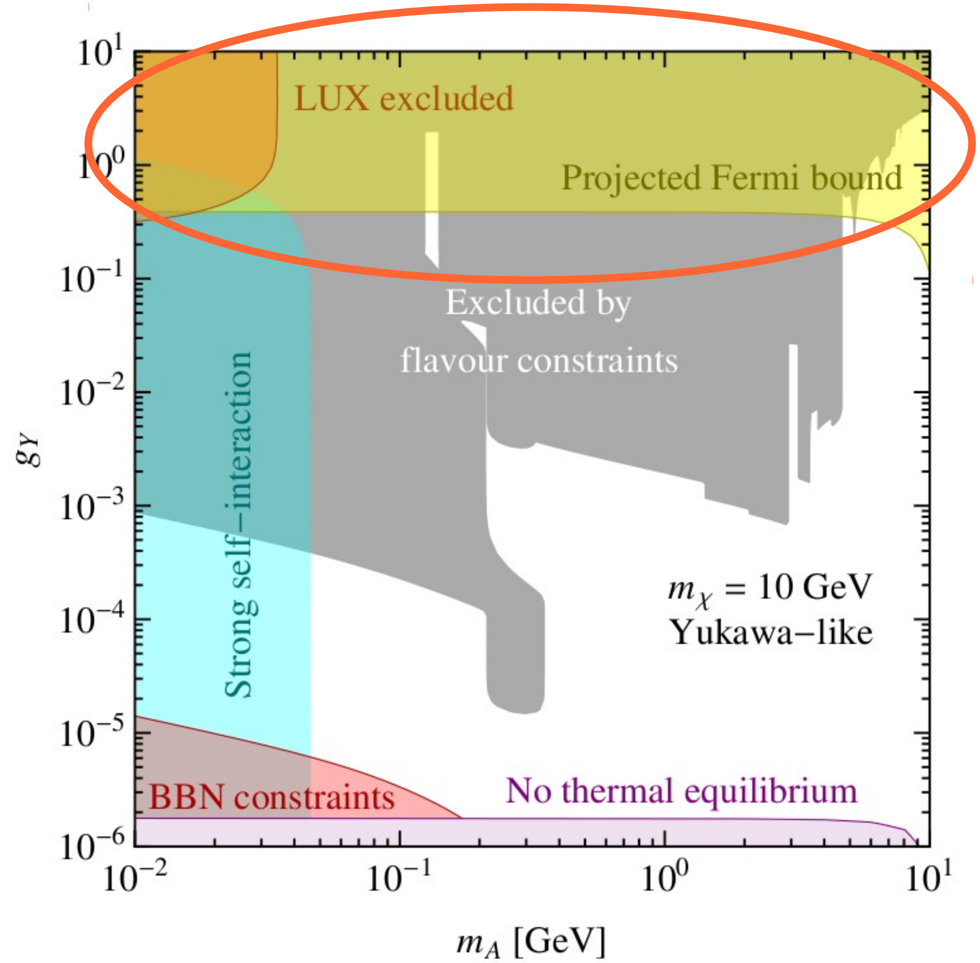


- In the weakly-coupled regime ($\alpha_\chi \, m_\chi / m_A < 1$), scattering via pseudoscalar exchange does not lead to observable DM self-interactions.
- In particular, there is no enhancement of the momentum transfer cross section for small velocities (in contrast to scalar exchange).
- In the strongly-interacting regime, we need to solve the Schroedinger equation for the singular one-pion-exchange potential

$$V(\mathbf{r}) = \frac{\alpha_\chi}{3} \left[\frac{e^{-m_A r}}{r} - \frac{4\pi}{m_A^2} \delta^3(\mathbf{r}) \right] \sigma_1 \cdot \sigma_2 + \frac{\alpha_\chi}{3} \left(1 + \frac{3}{m_A r} + \frac{3}{m_A^2 r^2} \right) \frac{e^{-m_A r}}{r} S_{12}(\hat{\mathbf{r}})$$

- It has been shown that resonances can significantly boost the interaction rates at low velocities (Bellazzini et al., arXiv:1307.1129).
- The shaded region in the plot indicates the strongly-interacting regime ($\alpha_\chi \, m_\chi / m_A > 1$).

Dark matter constraints



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

Implications for dark matter signals

- Differential event rate for direct detection experiments:

$$\frac{d\sigma}{dE} = \frac{m_T}{32\pi} \frac{1}{v^2} \frac{g_\chi^2}{(q^2 + m_A^2)^2} \frac{q^4}{m_N^2\, m_\chi^2} \sum_{N,N'=p,n} g_N\, g_{N'}\, F_{\Sigma''}^{N,N'}$$

Momentum suppression proportional to q^4 for pseudoscalar mediators

Enhancement proportional to q^{-4} for mediators with $m_A < q$ (long-range interactions)

- For very light mediators, the momentum suppression can be cancelled and event rates in direct detection experiments may become observable.

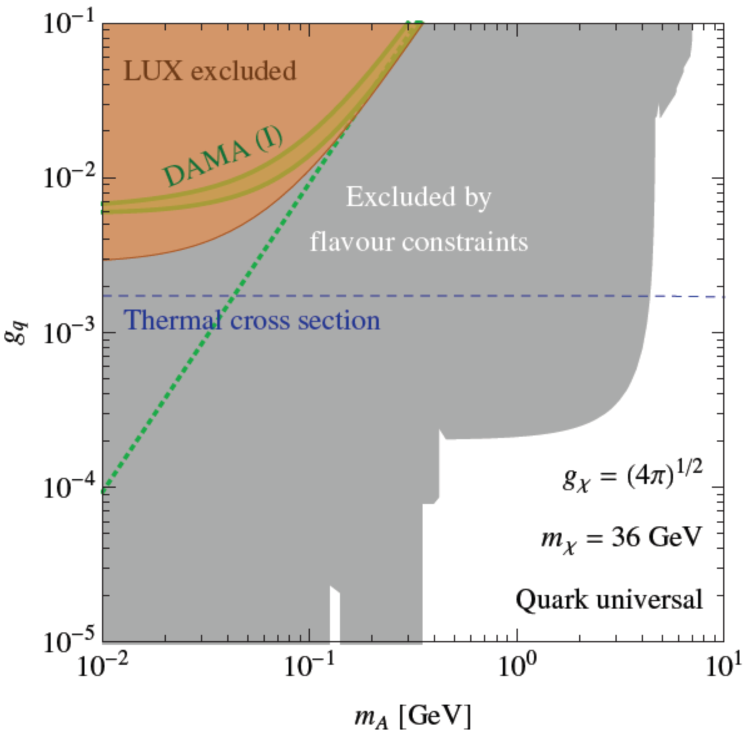
- Moreover, since pseudoscalars couple dominantly to the proton spin, constraints from LUX are much less severe than for standard interactions and it might be possible to reconcile LUX and DAMA.

Arina et al., arXiv:1406.5542

DAMA and LUX

- The ratio g_p / g_n ~ –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 ~ –16 for couplings of the form

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



- Even in the most optimistic case that we make the DM coupling g_x as large as possible (e.g. $g_x = (4\pi)^{1/2}$), 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.

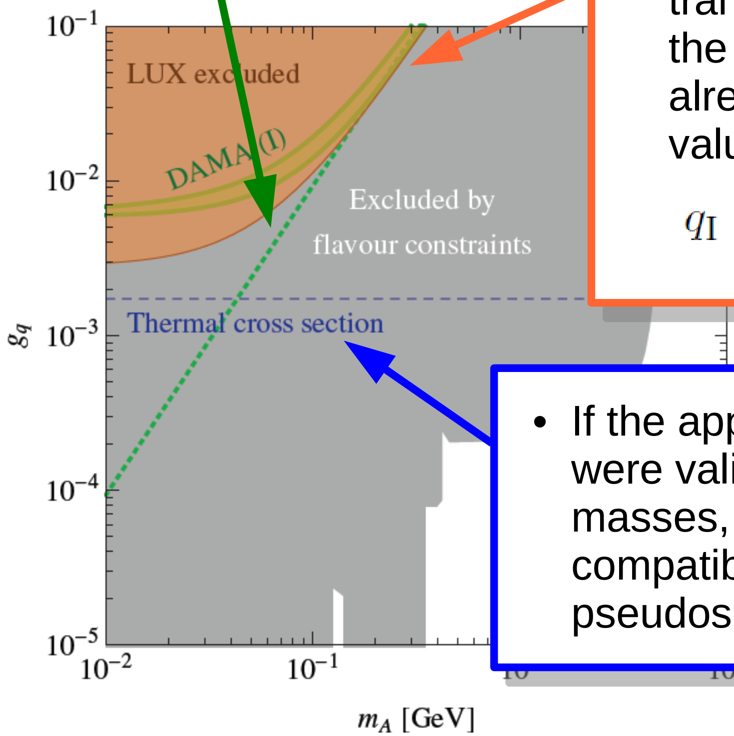
DAMA and LUX: Some additional observations

- 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 >> 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:

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

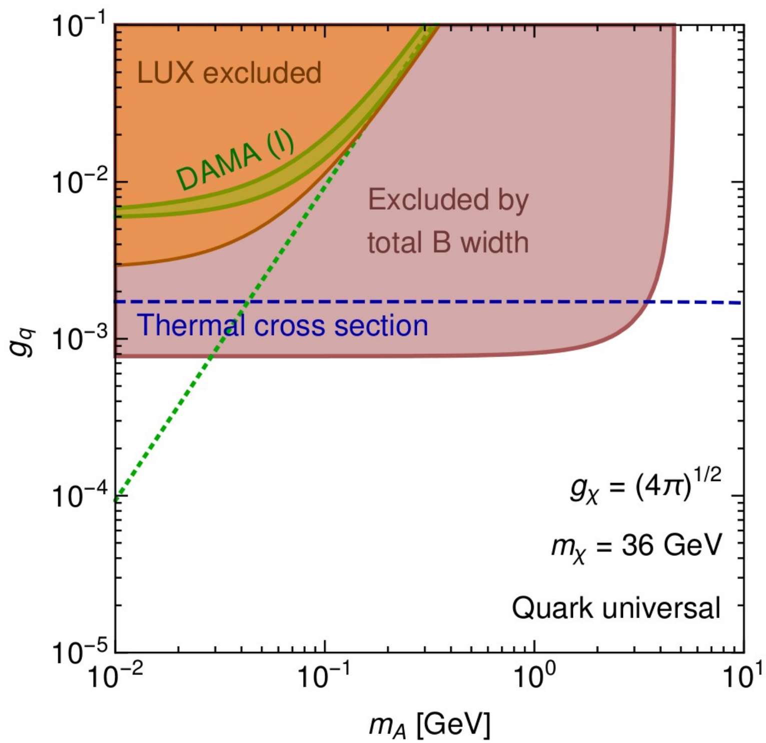


- If the approximation of contact interactions were valid down to small pseudoscalar masses, the DAMA modulation could be compatible with thermal freeze-out for pseudoscalar masses around 30-40 MeV.

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

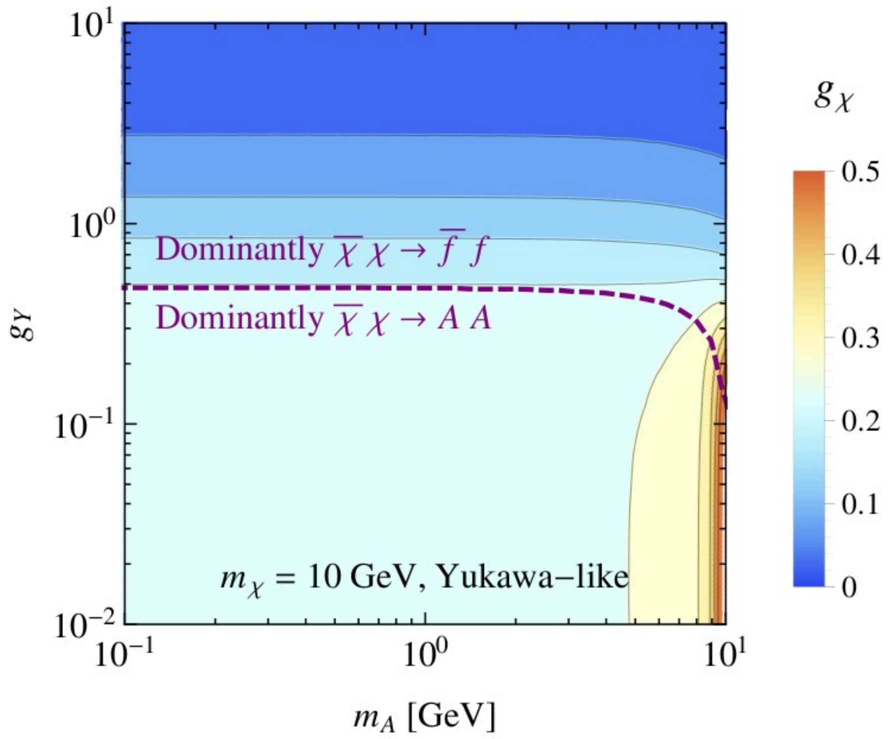
$$\mathrm{BR}(B \to X_s A) < 1.$$



- 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.

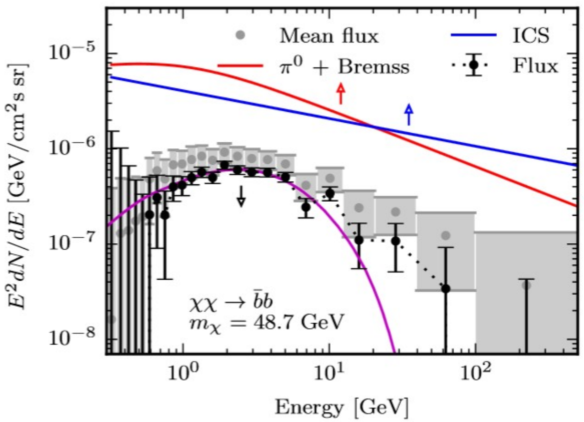
Indirect detection

- 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.

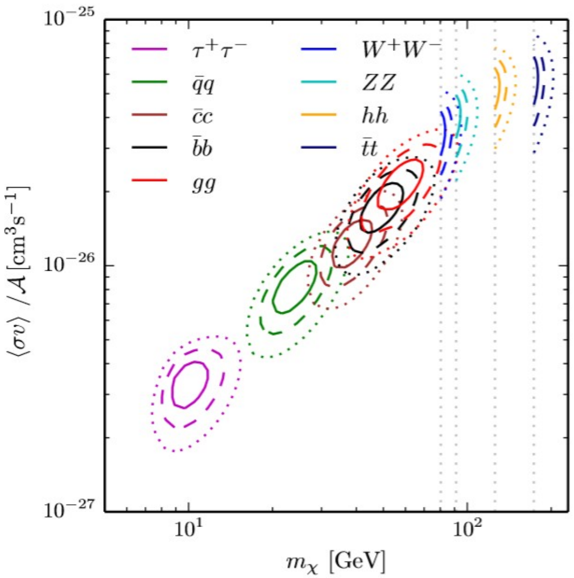


- If both annihilation channels contribute in the early universe, we expect to see an annihilation signal slightly below the standard expectation for a thermal relic.
  - Perfect for explaining the Galactic Centre Excess

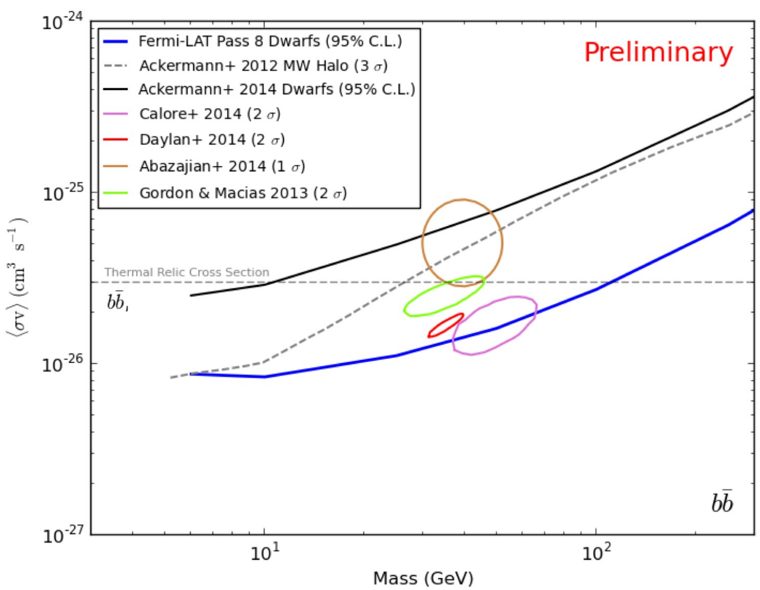
The Galactic Centre Excess



- Explaining the Galactic Centre Excess in terms of a pseudoscalar mediator with Yukawa-like couplings (i.e. annihilation dominantly into b-quarks) requires a dark matter mass mx ~ 40-50 GeV.
- To evade constraints from recent Fermi-LAT observations of dwarf spheroidals, the annihilation cross section must be well below the thermal one.



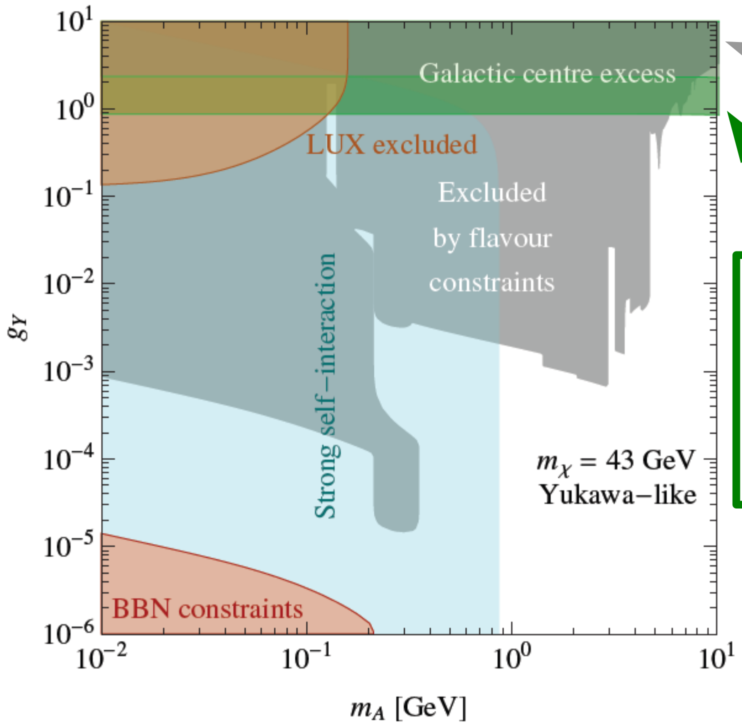
Calore et al., arXiv:1411.4647



Fermi-LAT collaboration

- Difficult to achieve if $m_A > m_\chi$, but very natural for $m_A < m_\chi$.

The Galactic Centre Excess from pseudoscalars



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

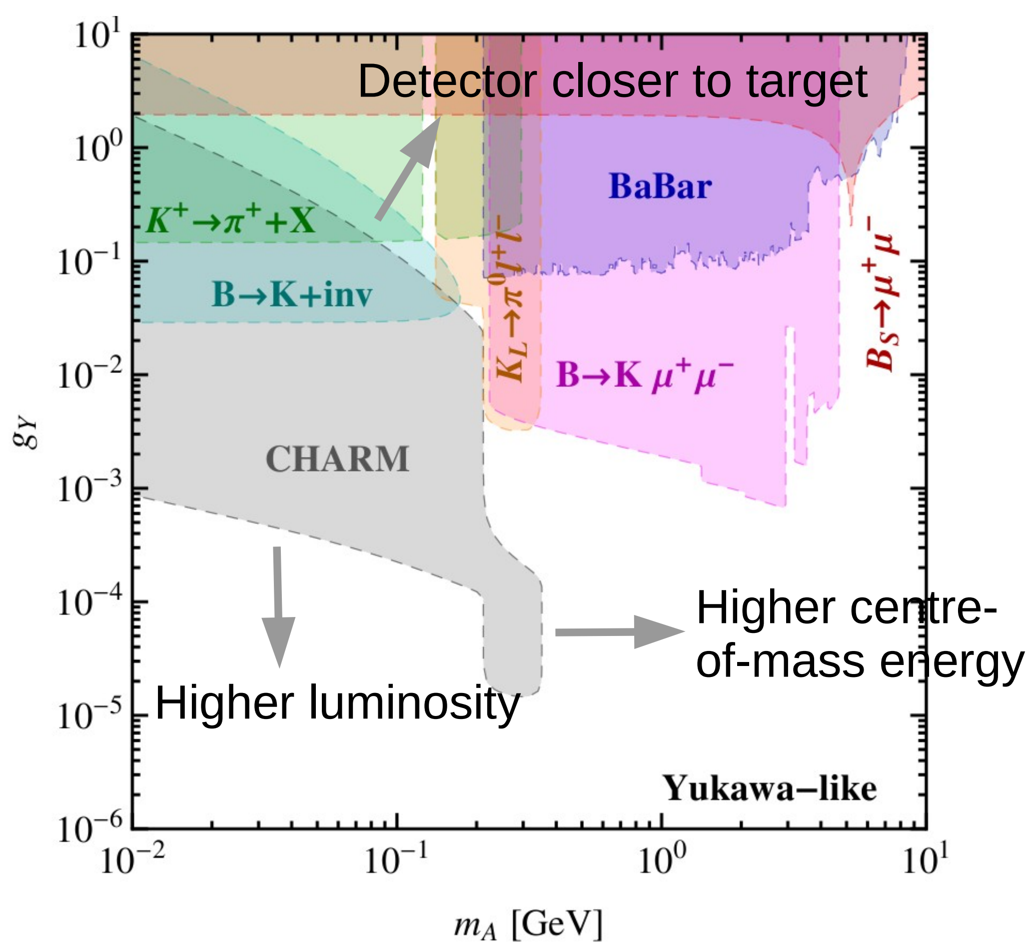
- Potential explanation of the Galactic centre excess within astrophysical uncertainties while at the same time being save from dwarf spheroidal constraints.

> For m_A > 5 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.

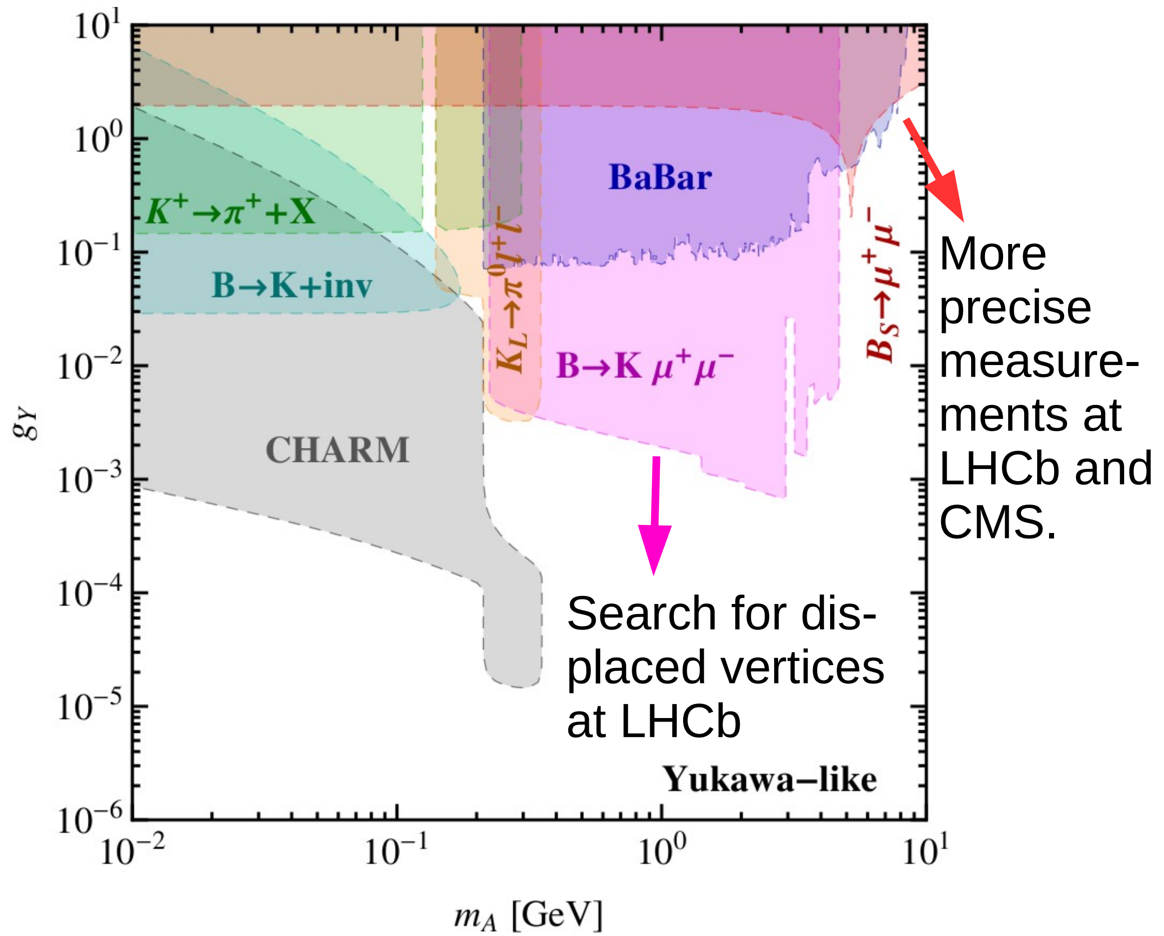
Future prospects

- For low pseudoscalar masses (m_A < 1 GeV), future proton beam-dump experiments (e.g. SHiP) have great potential to improve existing constraints and explore new regions of parameter space.



Future prospects

- For low pseudoscalar masses (m_A < 1 GeV), future proton beam-dump experiments (e.g. SHiP) have great potential to improve existing constraints and explore new regions of parameter space.
- For larger masses, new and improved searches at the LHC are particularly promising.



Application to other kinds of models

- Flavour constraints are not only relevant for pseudoscalar mediators. Very similar constraints are obtained for almost any sub-GeV mediator (see e.g. Fayet, hep-ph/0607318 for constraints on light vector mediators).
- Nevertheless, they are often not considered in the literature, in particular in the context of self-interacting dark matter.
- For example, in “Galactic Center Excess in Gamma Rays from Annihilation of Self-Interacting Dark Matter” (Kaplinghat et al., arXiv:1501.03507) the authors propose a vector mediator with $m_V < 100$ MeV to explain the Galactic Centre Excess while stating that “this model is compatible with all current constraints”.
- Take-home message: Light mediators are not always a solution – if they are too light they tend to create more problems than they solve.

Conclusions

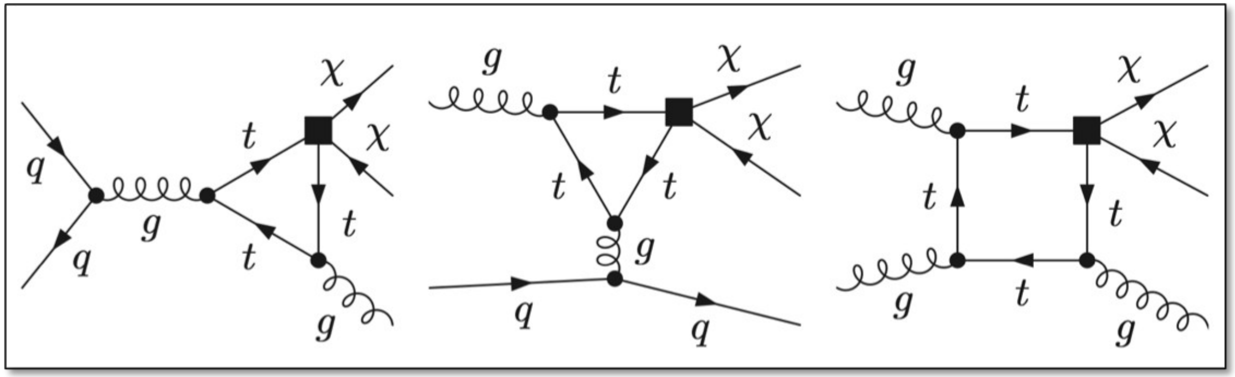
- Pseudoscalar mediators coupling the visible and dark sectors are interesting from both the model-building and phenomenological perspectives.
- Flavour physics is an interesting and rarely studied tool to constrain these types of models and yields relevant and highly complementary information.
- There are many interesting ways to further constrain the parameter space, e.g. $B_s \to \mu^+ \mu^-$, 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 5 GeV < $m_A < m_\chi$ remains one of the most attractive explanations for the Galactic centre gamma-ray excess.

Backup

What about LHC monojet searches?

- Typically, for light particles high-luminosity experiments such as B-factories win over high-energy colliders.
- Moreover, the tree-level cross section for monojet events is very small, since there are no heavy quarks in the initial state.
- At the same time, we cannot use effective DM-gluon interactions, because the typical energies (√s, p_T, …) are large compared to m_t, so one has to perform a full calculation including the finite top-quark mass (e.g. using FormCalc & LoopTools or MCFM)

Haisch, FK, Unwin: arXiv:1208.4605



Weak constraints if the mediator is forced to be off-shell ($m_A < 2\ m_\chi$).

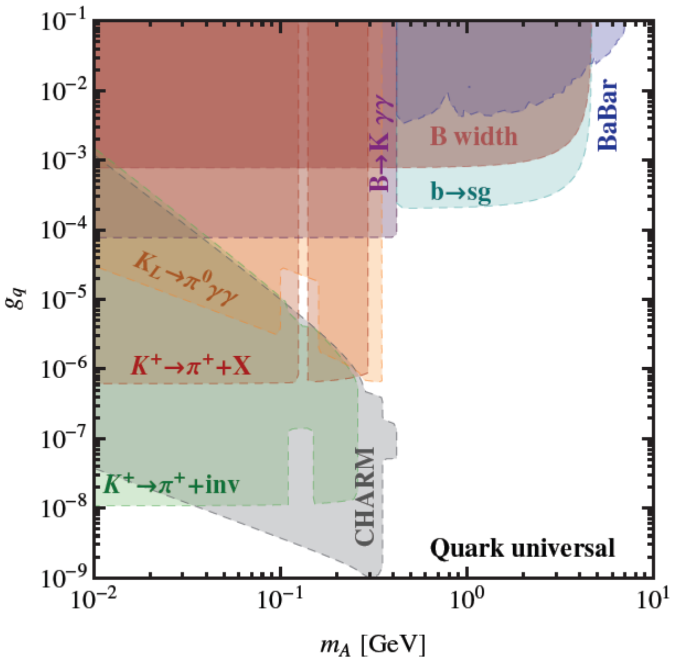
Universal quark couplings

> Universal quark couplings violate the assumption of minimal flavour violation.

> As a result, one-loop divergences do not cancel and the theory is no longer renormalisable

$$h^R_{sb} \propto -\alpha\, x_t \frac{(m_s^2 + 2\, m_b^2)\, g_b - 3\, m_s\, m_b\, g_s + 2\, \frac{m_b\, g_t}{m_t} (m_s^2 - m_b^2)}{16\pi\ \sin(\theta_W)^2\, (m_s^2 - m_b^2)} V_{tb} V_{ts}^* \times \frac{1}{\epsilon}$$

$$h^L_{sb} \propto -\alpha\, x_t \frac{(2\, m_s^2 + m_b^2)\, g_s - 3\, m_s\, m_b\, g_b + 2 \frac{m_s\, g_t}{m_t} (m_b^2 - m_s^2)}{16\pi\ \sin(\theta_W)^2\, (m_s^2 - m_b^2)} V_{tb} V_{ts}^* \times \frac{1}{\epsilon}$$



> If we consider universal couplings to be an effective theory below some scale Λ, we can approximately calculate the flavour-changing couplings and obtain very strong experimental constraints.

Coupling directly to gluons

- Let us assume that the pseudoscalar does not couple to quarks at all, but only to some new heavy coloured state, so that at low energies, we obtain the effective coupling

$$\mathcal{L}_{\text{SM}}^{(G)} = i\,\frac{\alpha_S}{8\pi\,\Lambda} A\, G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

-

- This case is well-studied in the axion literature (hadronic or KSVZ axions). The crucial observation is that matching to chiral perturbation theory leads to an effective pseudoscalar-pion (and pseudoscalar-eta) mixing:

$$\mathcal{L}_{\text{mixing}} = \lambda \frac{f_\pi}{\Lambda} \frac{m_\pi^2}{m_\pi^2 - m_A^2} \pi\, A \qquad \lambda = \frac{1}{2}\frac{m_u - m_d}{(m_u + m_d)} \approx -0.18$$

- This mixing leads to *A* being produced in kaon decays and in proton-proton collisions (e.g. in beam-dump experiments) and its subsequent decay into photons with a very long lifetime.

- Again there are very strong constraints from CHARM and searches for rare kaon decays.