ALPtraum.

Searching for dark matter and pseudoscalar mediators at the intensity frontier

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Challenges in the Dark Sector
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Laboratori Nazionali di Frascati

Based on
arXiv:1412.5174 with Matthew Dolan, Christopher McCabe and Kai Schmidt-Hoberg
arXiv:1512.03069 with Babette Döbrich, Joerg Jaeckel, Andreas Ringwald and KSH

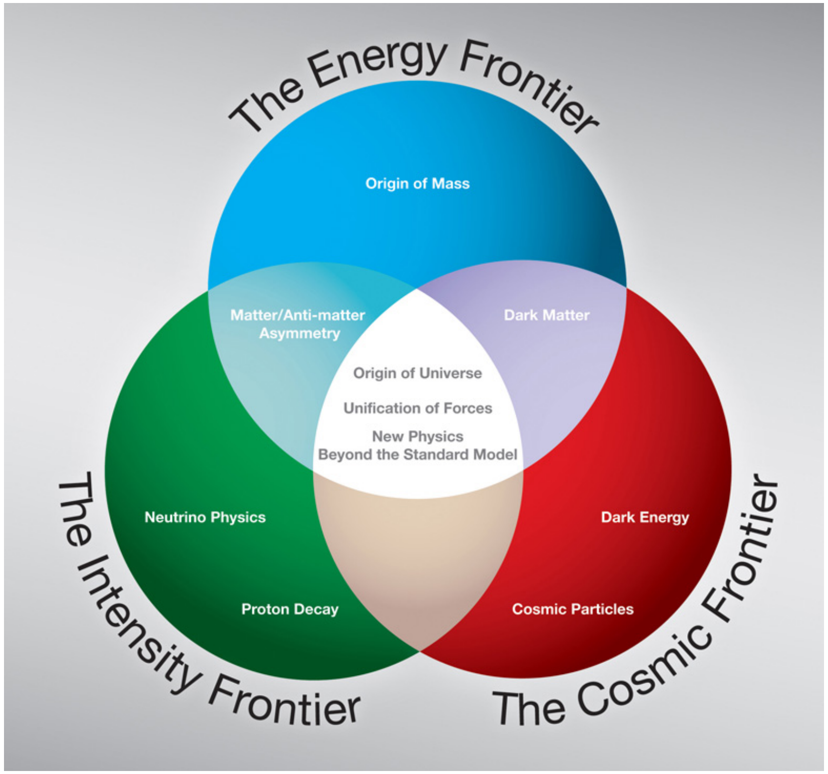
Why study the intensity frontier?

- Progress in particle physics has been guided by the paradigm of renormalizable interactions with O(1) dimensionless couplings, suggesting that any new particle to be discovered should be heavy.
- To search for such particles, we either need high-energy colliders or precision measurements of the effects of higher-dimension operators (e.g. in muon $g - 2$ or flavour physics).
- In spite of significant improvements of the sensitivity in both directions, Nature has not yet revealed any (conclusive) evidence for physics beyond the Standard Model.
- Maybe it's time to carefully examine our search strategy and look for potential places we have missed (as well as for new opportunities).
- For example, even light particles could still remain to be discovered, provided they have sufficiently small interactions with Standard Model (SM) particles, and therefore with our experiments.

Why study the intensity frontier?

> To search for new light particles, it is not always necessary to turn to ambitious future projects, many interesting searches can be performed using technologies and apparatuses that are already at our disposal.

- Experimental searches for rare meson decays resulting from flavour-changing processes such as $K \to \pi X$ or $B \to K X$.
- Fixed target experiments with a far detector searching for long-lived weakly-coupled states.
- Comparison with cosmological constraints (for example from Big Bang Nucleosynthesis).



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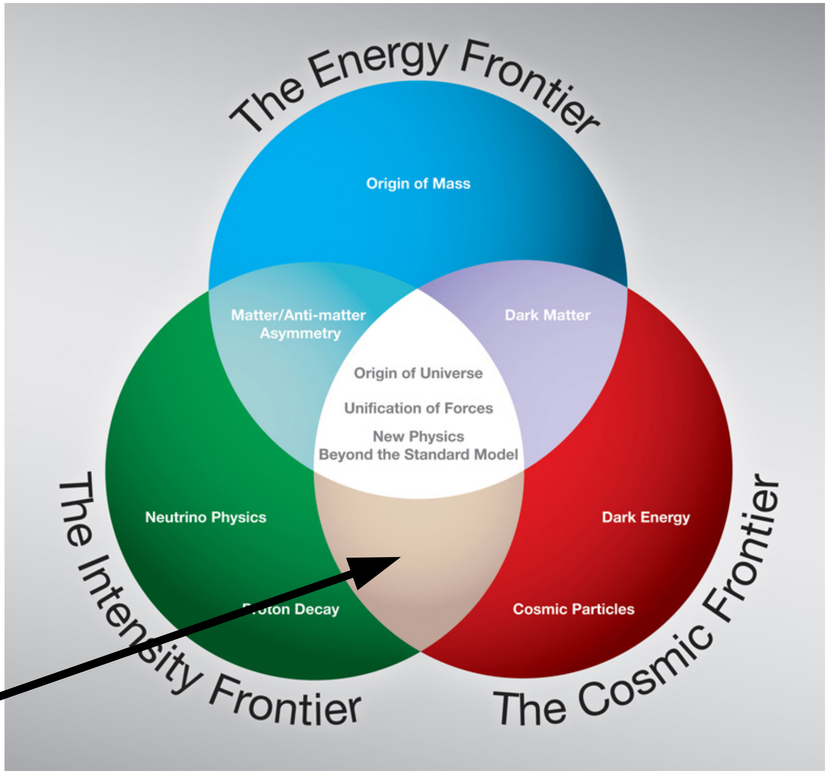


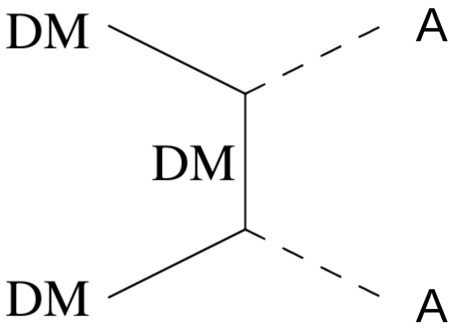
???

Why consider weakly-coupled light particles?

- Example 1: The Higgs portal with small mixing
  - A gauge singlet scalar can couple to the SM via the Higgs portal $\lambda_p |\varphi|^2 |H|^2$.
  - If the mass of the scalar singlet results only from the SM Higgs vacuum expectation value v, we obtain $m_\varphi \sim \lambda_p v$.
  - If the coupling λ_p is small (e.g. suppressed by a loop factor), we obtain a weakly-coupled light (pseudo-)scalar that can inherit couplings to other SM particles from mixing with the SM Higgs boson.
- Example 2: The axion portal with large suppression scale
  - Pseudo-Goldstone bosons can arise from spontaneously broken approximate global symmetries.
  - The underlying symmetry protects their mass from receiving large corrections, while interactions with SM particles are typically suppressed by the potentially large scale of spontaneous symmetry breaking.
- Common motivation for small mass and weak coupling!

Why consider weakly-coupled light particles?

- New weakly-coupled light particles may have interesting implications for the phenomenology of Dark Matter (DM).
- While these particles are typically unstable and therefore not a viable DM candidate themselves, they may act as the mediator for the interactions between SM particles and the dark sector (as well as for interactions within the dark sector).
- In particular, if the new state 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.



- Moreover, a light mediator offers the possibility to obtain large self-interactions in the dark sector, which may explain the discrepancies between N-body simulations and the observations of small-scale structures.

Axion-like particles (ALPs)

- Axion-like particles are defined in analogy to the QCD axion as pseudoscalar particles coupling to the SM via derivative interactions to fermions
$$\sum_{f=q,\ell} \frac{C_{Af}}{2\, f_A} \bar{f} \gamma^\mu \gamma^5 f\, \partial_\mu A$$
and dimension-5 couplings to gauge bosons
$$-\frac{1}{4} g_{\phi\gamma} \phi F^{\mu\nu} \tilde{F}_{\mu\nu}$$
where the effective photon coupling from the electromagnetic anomaly is expected to be of order
$$g_{\phi\gamma} \sim \frac{\alpha}{2\pi f_A}$$
- In contrast to the QCD axion, the ALP mass is taken to be a free parameter, unrelated to the scale f_A.
- Similarly, C_{Af} is a free parameter (and can in principle vanish).

Outline

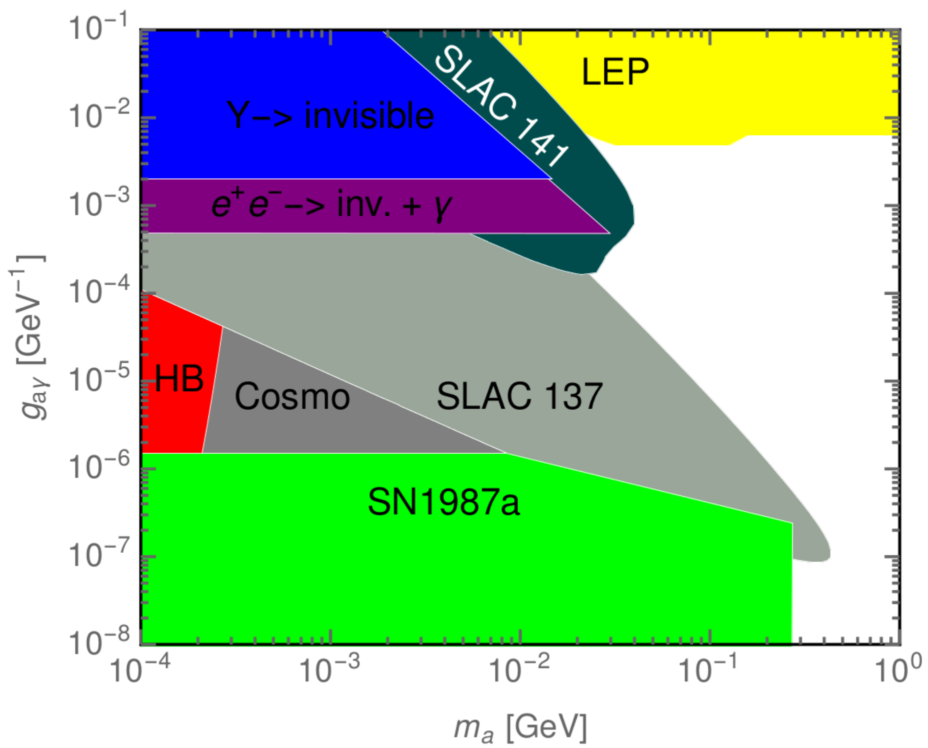
- Part 1: Probing the photon coupling
- Part 2: Probing the quark couplings
- Part 3: Implications for dark matter signals

Part 1: Probing the photon coupling

Existing constraints

> We first consider ALPs that couple dominantly to photons:

$$-\frac{1}{4}\, g_{a\gamma}\, a\, F^{\mu\nu}\, \tilde{F}_{\mu\nu}$$



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Large unexplored parameter region, which is potentially testable with beam-dump experiments.

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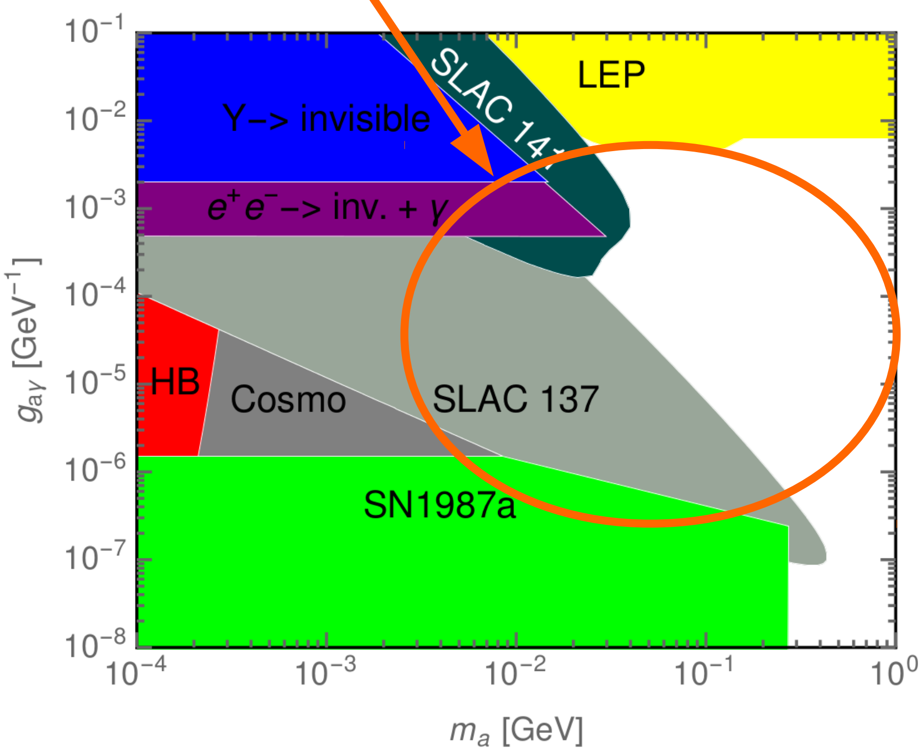

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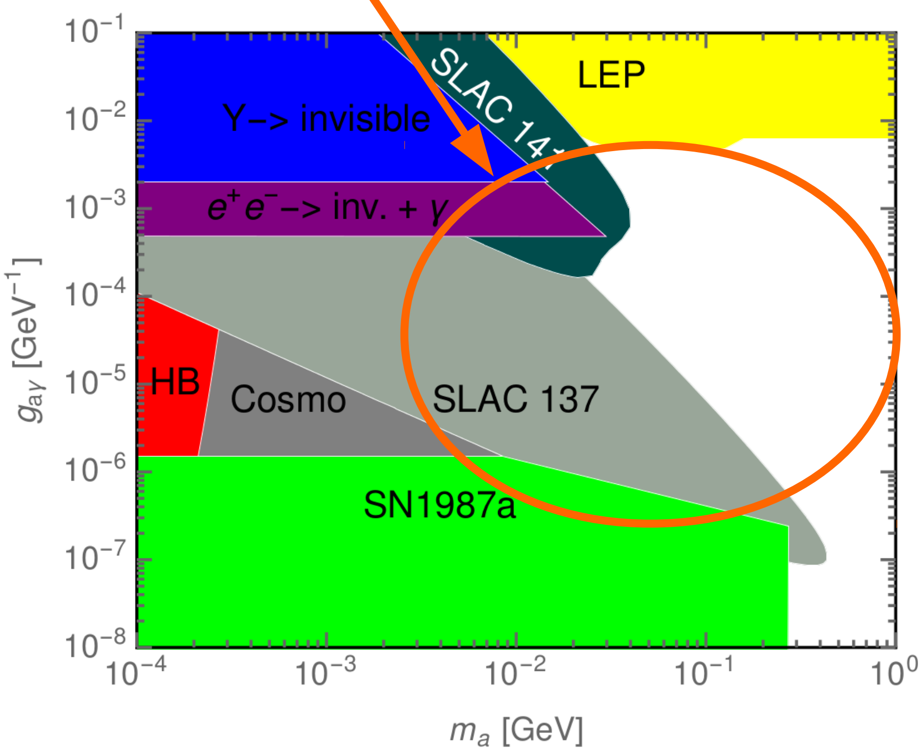

The sensitivity of a given beam-dump experiment depends on:

- The production cross section for ALPs in the target.
- The probability for ALPs to travel through the absorber without decaying and then decay within the detector / decay volume. This probability depends on the ALP decay length in the laboratory frame

$$l_a = \beta \, \gamma \, \tau \approx \frac{64\pi \, E_a}{g_{a\gamma}^2 \, m_a^4}$$

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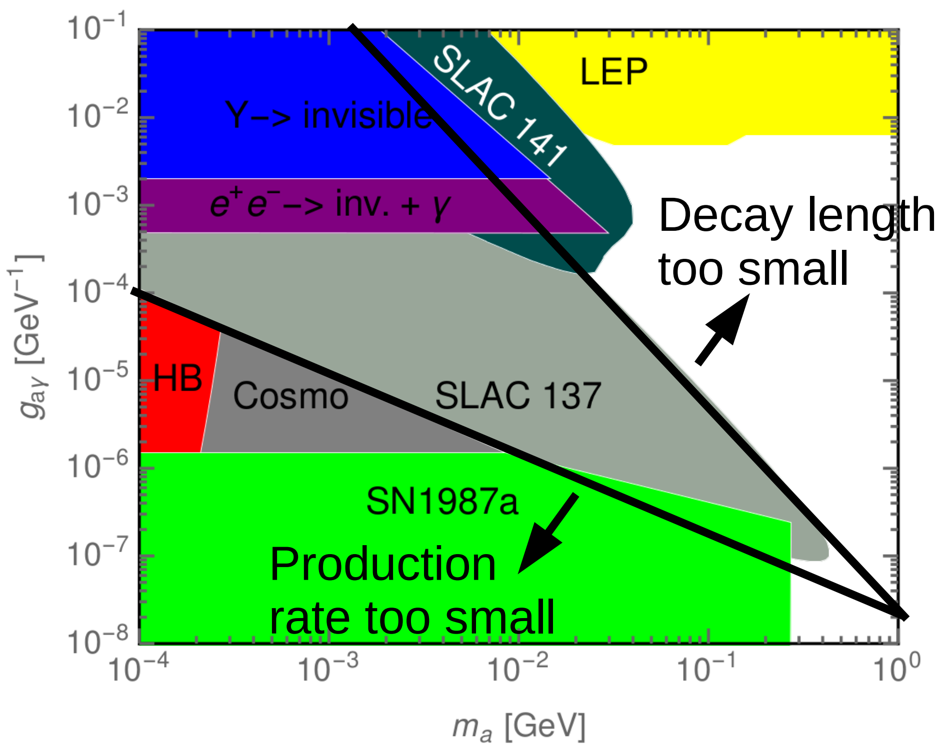

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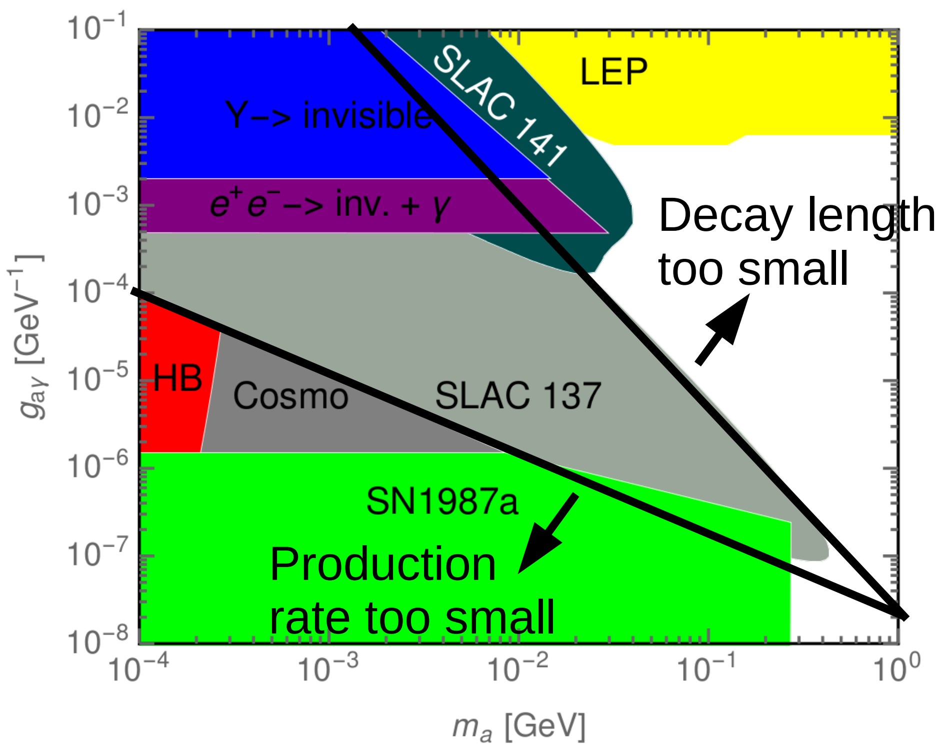
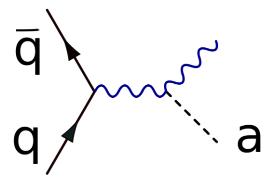


For large couplings $g_{A\gamma}$ the ALP production cross section is very large, but the ALP decay length is much smaller than the length of the absorber (l_a << L), so the number of observable ALP decays is exponentially suppressed.

→ Significant improvements possible with larger beam energy, leading to larger ALP decay lengths!

Proton beam-dump experiments

- Proton beam-dump experiments combine a very high reaction rate with a relatively high centre-of-mass energy.
- However, proton beam-dumps are also complicated: In order to calculate experimental predictions, we have to deal with the composite nature of both the proton and the nucleus.
- For example, it is very difficult to reliably calculate the simple ALP-strahlung process

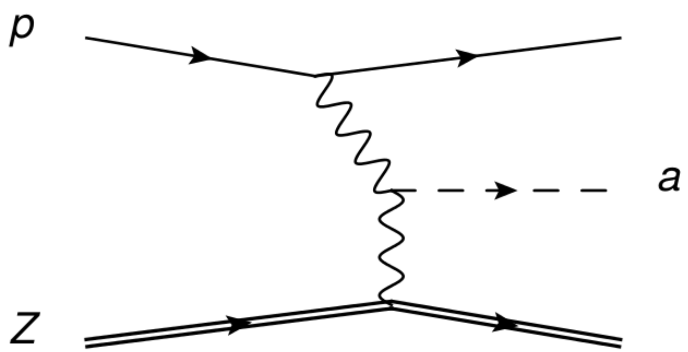


for ALP masses below 1 GeV.

- For a perturbative calculation to make sense (and for factorisation to work), we have to require rather large photon pT, which implies that the ALP in such a process will not be emitted in the forward direction.

Primakoff production

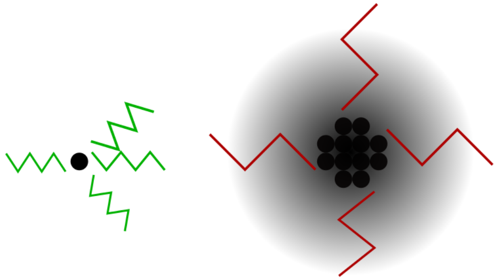
- Crucial observation: It is possible for GeV-scale ALPs to be produced from the fusion of two coherently emitted photons (Primakoff production).



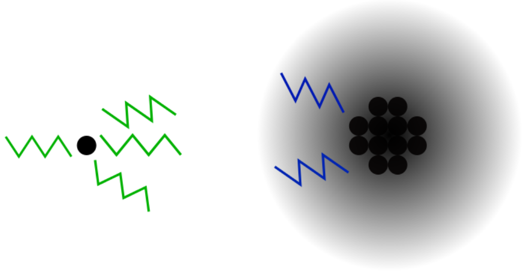
- Both the proton and the nucleus scatter elastically, so the interaction can be described using simple atomic form factors.
- Moreover, since the photon couples to the entire target nucleus, the ALP production cross section is enhanced proportional to Z^2.
- Transverse momenta are very small, so cross sections are very strongly peaked in the forward direction.

How is this possible?

- Both the proton and the ALP are surrounded by the virtual photons that make up the usual electric field of a charged particle.
- In the respective rest frames, these photons are soft, i.e. they do not resolve the sub-structure of the proton/nucleus.



- However, in the rest frame of the one particle, the photons emitted from the other particle are significantly blue-shifted.



- These photons provide enough energy to produce rather heavy ALPs.

Hasn't this been done already?

- Our basic approach is the well-known Weizsaecker-Williams approximation, which basically derives an equivalent photon spectrum γ(x) that replaces the charged particle(s) in the initial state.
- However, we are interested in fixed-target experiments, where the detector is very far away from the interaction point. Typical angular acceptances are of order 10 mrad.
- It is therefore crucial to accurately determine not only the ALP production rate, but also angular distributions.
- We therefore need to consider two-dimensional photon spectra:

$$\gamma(x, q_t^2) = \frac{\alpha}{2\pi} \frac{1+(1-x)^2}{x} \left[\frac{q_t^2}{(q_t^2 + x^2\, m^2)^2} D(q^2) + \frac{x^2}{2} C(q^2) \right]$$

Electromagnetic form factors

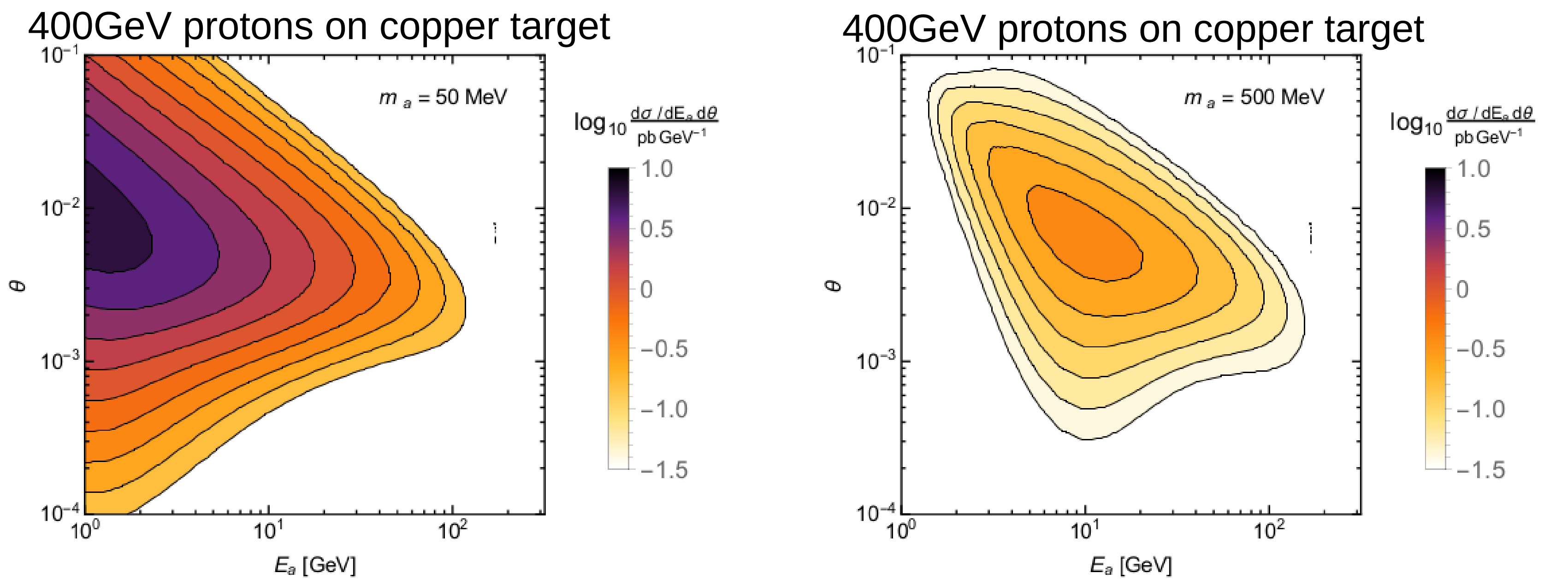
ALP production cross section

> We then find

$$\sigma_{pN} = \int \mathrm{d}x_1\, \mathrm{d}x_2\, \mathrm{d}q_{t,1}^2\, \mathrm{d}q_{t,2}^2\, \gamma_p(q_{t,1}^2, x_1)\, \gamma_N(q_{t,2}^2, x_2)\, \sigma(\gamma\gamma \to a)$$

with

$$\sigma(\gamma\gamma \to a) = \frac{\pi\, g_{a\gamma}^2\, m_a}{16} \delta(m_{\gamma\gamma} - m_a) \quad \text{and} \quad m_{\gamma\gamma} = 2\sqrt{x_1\, x_2}\sqrt{E_p^{\text{cms}}\, E_N^{\text{cms}}}$$



ALP production cross section

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$$\sigma_{pN} = \int \mathrm{d}x_1\,\mathrm{d}x_2\,\mathrm{d}q_{t,1}^2\,\mathrm{d}q_{t,2}^2\,\gamma_p(q_{t,1}^2, x_1)\,\gamma_N(q_{t,2}^2, x_2)\,\sigma(\gamma\gamma \to a)$$

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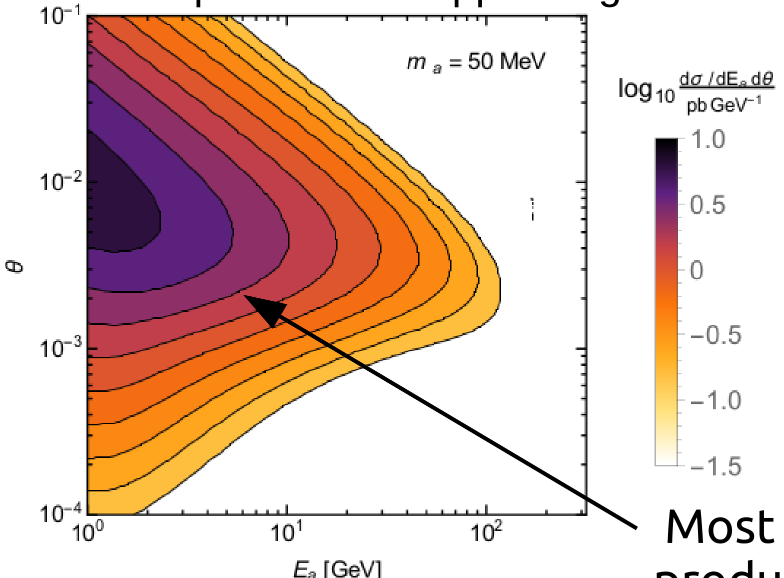
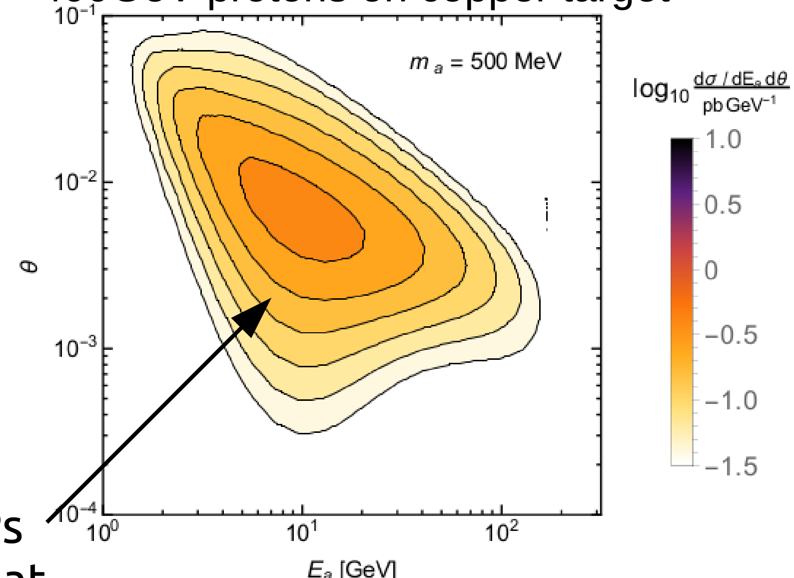
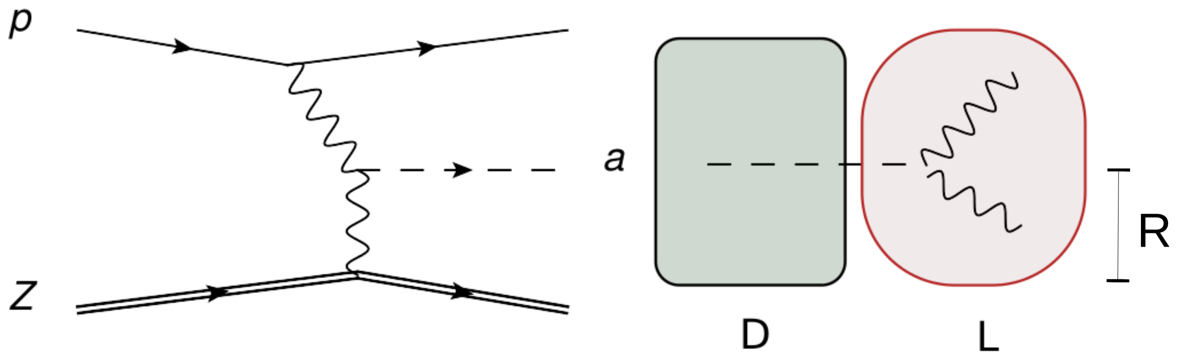




Most ALPs produced at ~ 20 mrad

Typical experimental set-up

- We assume that the target is immediately followed by an absorber of length D and a decay volume of length L:



- For a cylindrically symmetric detector with radius R, the probability to observe an ALP decay is given by

$$p(l_a) = \exp\left(-\frac{D}{l_a}\right) - \exp\left(-\frac{D+L}{l_a}\right) \quad \text{for } \theta < R\,/\,(D+L)$$

$$p(l_a) = 0 \quad \text{for } \theta > R\,/\,(D+L)$$

Existing constraints from past experiments

- Defining the fiducial cross section $\frac{\mathrm{d}\sigma_f}{\mathrm{d}E_a\,\mathrm{d}\theta} = p(l_a, \theta, \gamma) \cdot \frac{\mathrm{d}\sigma}{\mathrm{d}E_a\,\mathrm{d}\theta}$

  we then obtain $N = \frac{N_{\mathrm{pot}}}{\sigma_{pN}} \int \frac{\mathrm{d}\sigma_f}{\mathrm{d}E_a\,\mathrm{d}\theta}\,\mathrm{d}E_a\,\mathrm{d}\theta$

  with $\sigma_{pN} = 53\,\mathrm{mb} \times A^{0.77}$.

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N ~ Z^2 / $A^{0.77}$
N ~ 30 for iron
N ~ 100 for tungsten

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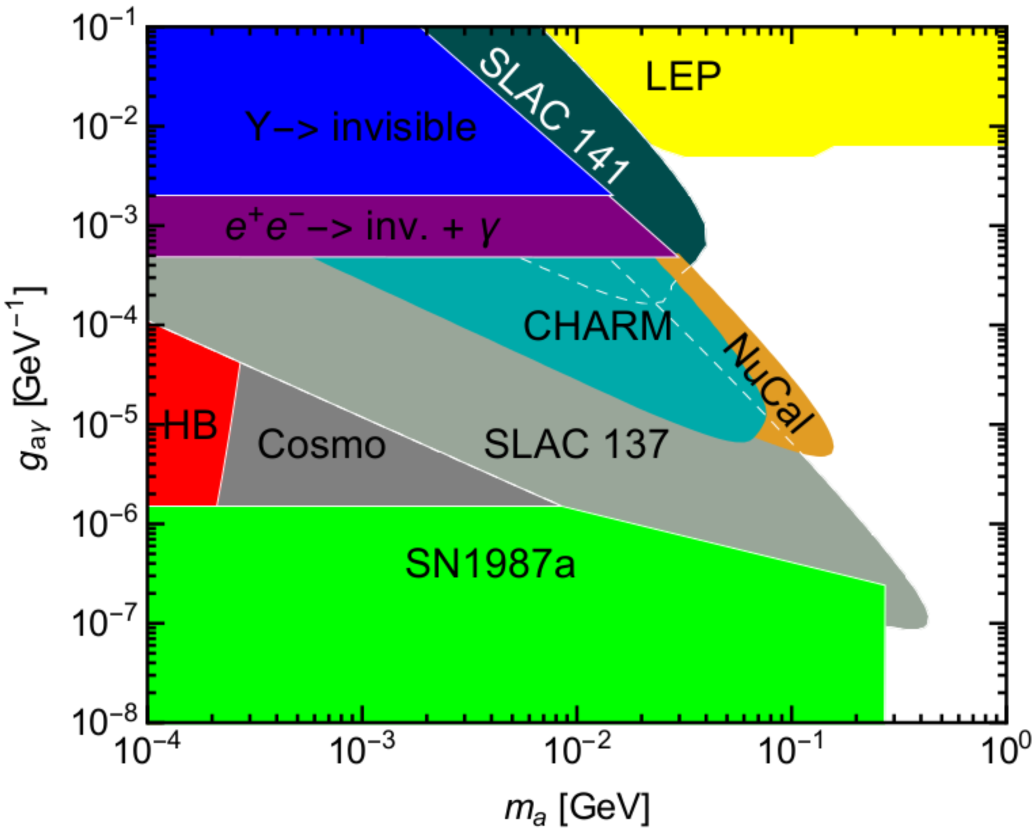


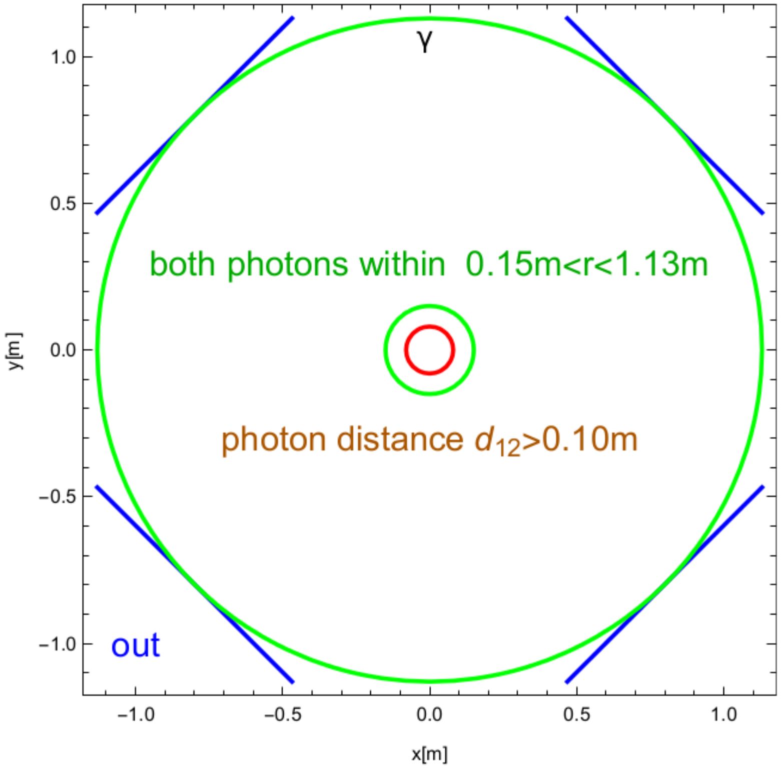
	CHARM	NuCal
E_{beam}	400 GeV	70 GeV
D	480 m	64 m
L	35 m	23 m
N_{pot}	2.4e18	1.7e18
Target	Copper	Iron
θ_{min}	7 mrad	0 mrad
θ_{max}	12 mrad	15 mrad

Probing further

- To extend the sensitivity further, we need new experiments
  - Higher beam energy (difficult)
  - Higher integrated intensity
  - Shorter absorber, longer decay volume
- All these modifications may lead to larger backgrounds, so we need to think about more refined analysis strategies.
- For this purpose, we require that both photons produced in the ALP decay are detected, i.e. we require two electromagnetic showers in the calorimeter coincident in time.
- For this purpose we need to know
  - the probability that both photons produced in the ALP decay reach the detector located at the far end of the decay volume;
  - the probability that the separation between the two photons is large enough to identify two separate showers

Realistic detector acceptance

- We can determine these probabilities from a toy Monte Carlo
- Example: NA62 in beam-dump mode
  - 400 GeV protons on copper target
- Excellent sensitivity to photons in Liquid Krypton Calorimeter (LKr)
  - D = 81 m, L = 135 m
- We approximate the octagonal shape of the LKr by a cylinder with a central hole for the vacuum tube containing the beam
  - $\theta_{min} = 0.7$ mrad, $\theta_{max} = 5.2$ mrad



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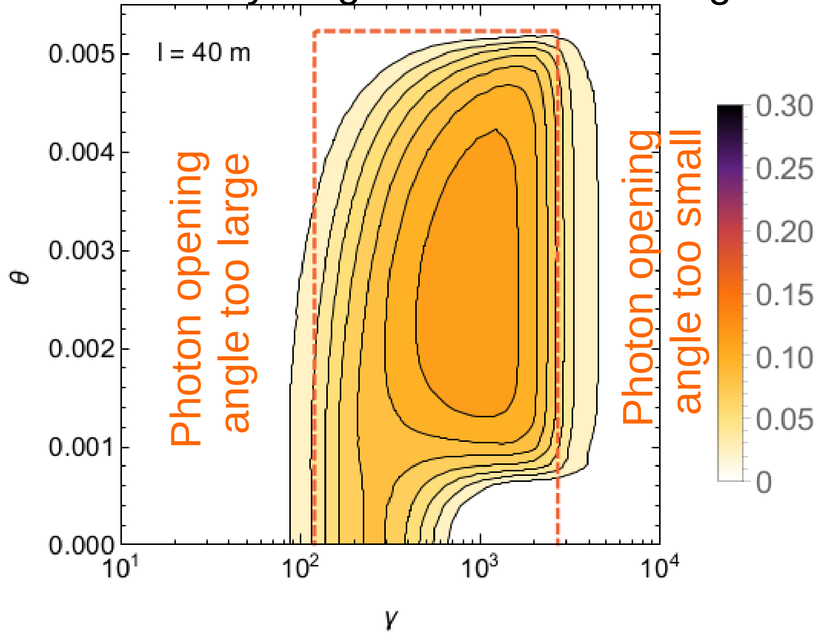
ALP decay length << Absorber length



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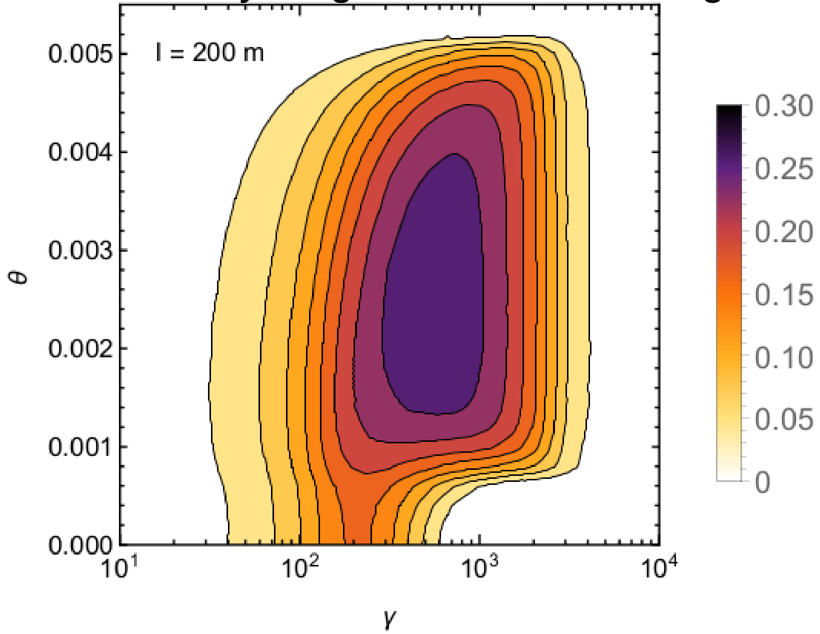
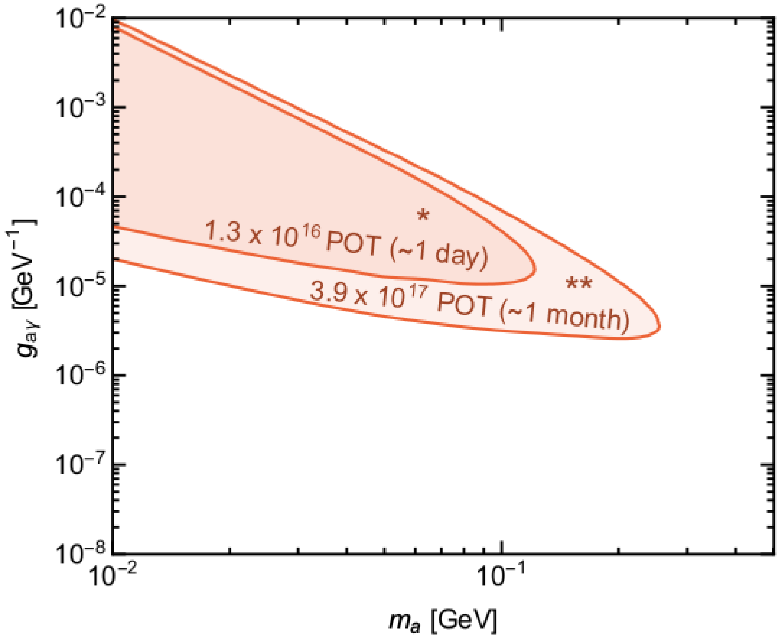
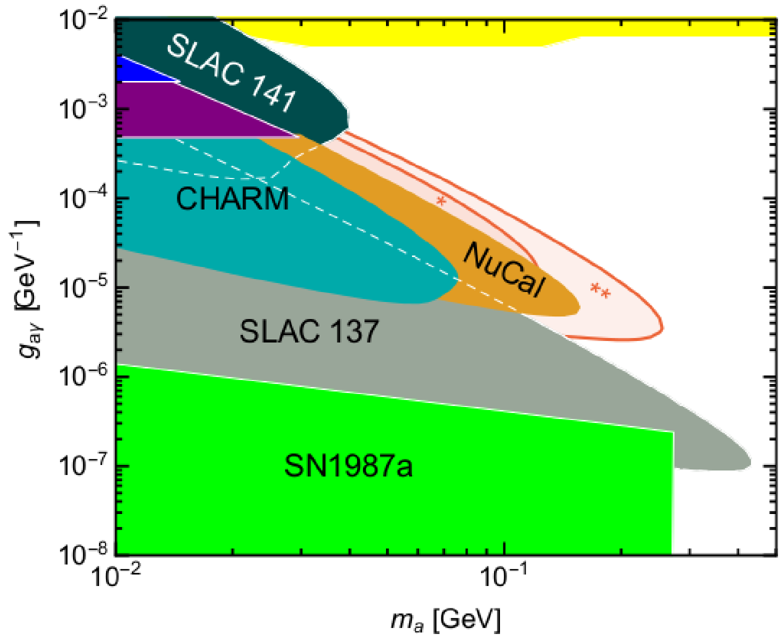


NA62

- NA62 can have about 1.3e16 protons on target per day.
- This data-taking period would already be enough to probe new parameter regions!

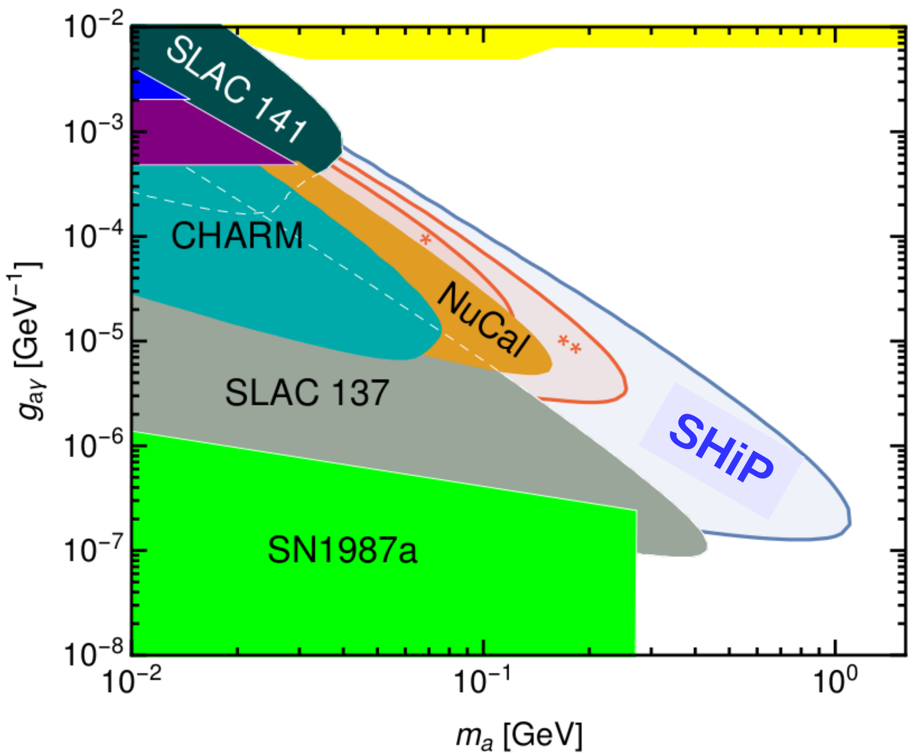




- There is significant discovery potential in a month of data-taking.

SHiP

> The proposed SHiP facility is optimised to search for hidden particles.
  - Up to 2e20 protons with energy 400 GeV on a molybdenum target
  - D = 70 m, L = 50 m
  - θ_{max} = 20 mrad (covers the peak of the ALP distribution)



Part 2: Probing the quark couplings

The general set-up

- Starting from derivative interactions to SM fermions

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

  we can integrate by parts to obtain

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

- The same coupling structure (proportional to the SM Yukawa couplings) is expected for pseudoscalars arising from extended Higgs sectors:

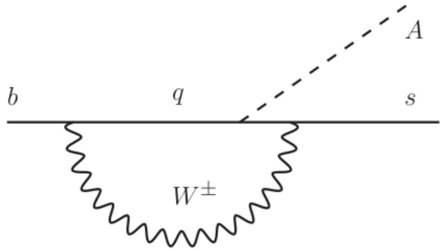
$$\mathcal{L}_{\mathrm{SM}}^{(Y)} = i\, g_Y \sum_{f=q,\ell} \frac{\sqrt{2}\, m_f}{v} A\, \bar{f} \gamma^5 f$$

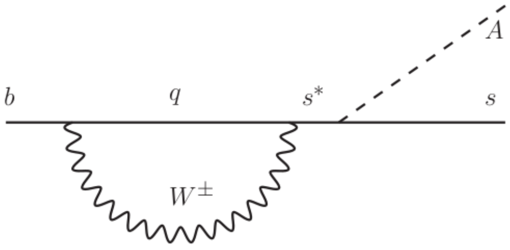
- Note that this coupling structure is consistent with the assumption of Minimal Flavour Violation and therefore rather weakly constrained.

- 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 decays from loop-induced FCNCs.





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

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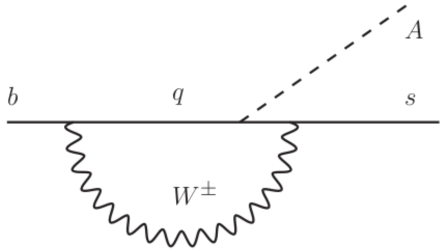

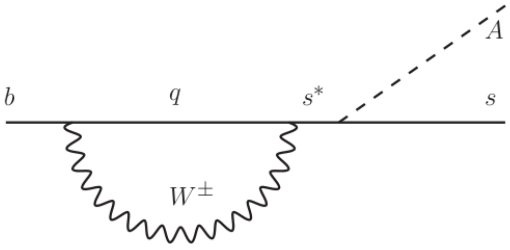

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Step 1: Determine the amplitude h_{ds} for the flavour-changing transition $s \to d\, A$.

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

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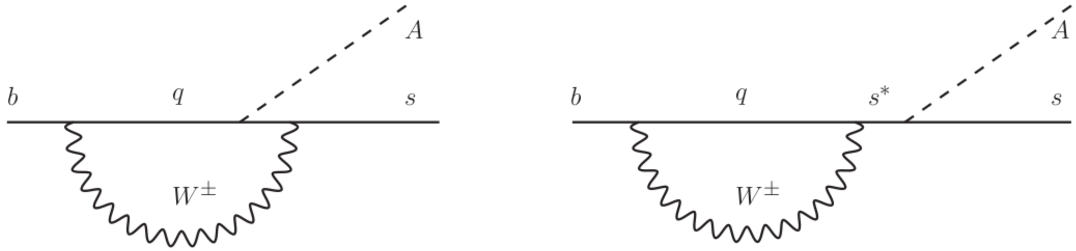

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Step 1: Determine the partial decay width for loop-induced decays into photons.

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

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

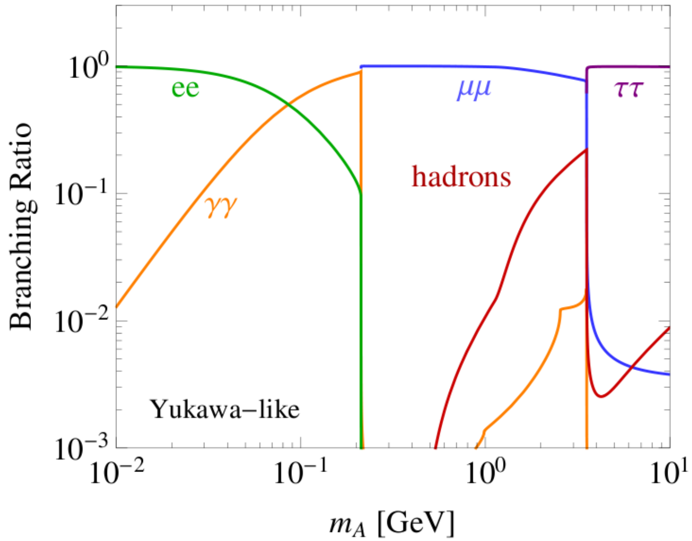
- It is well-known how to calculate the partial kaon decay width in terms of these effective couplings:

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

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

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.

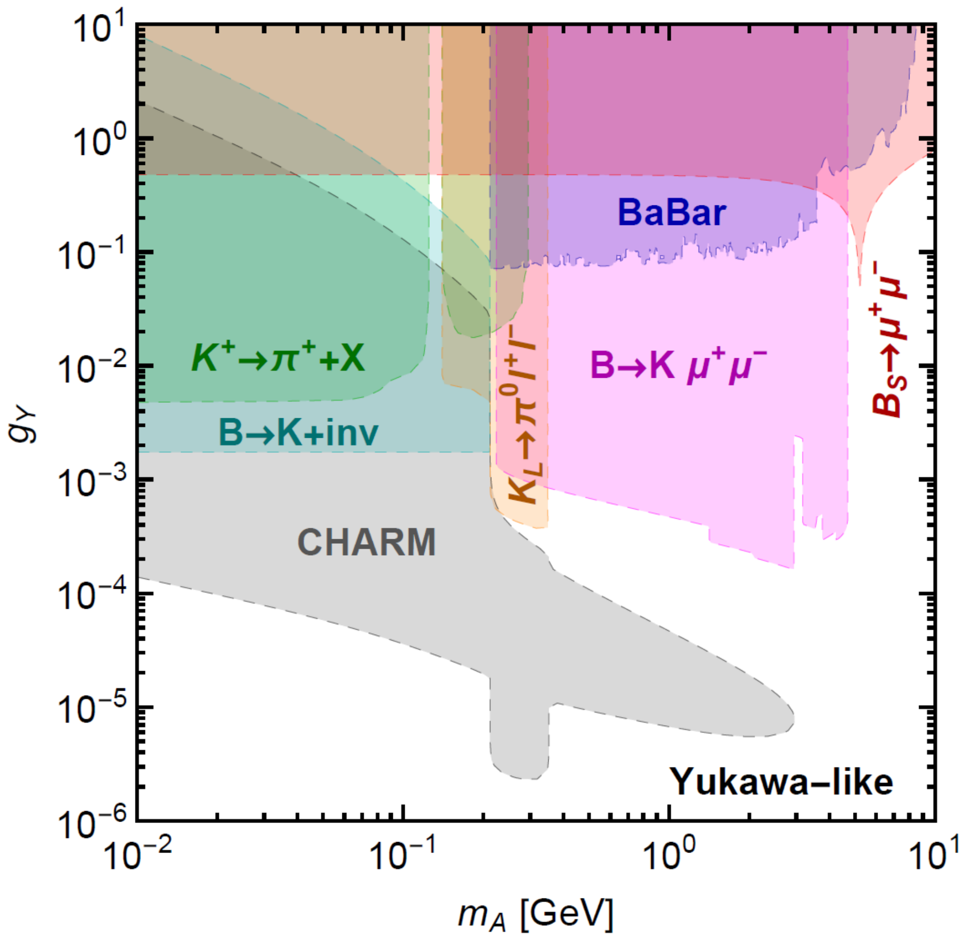


$$\Gamma(A \to \ell^+\ell^-) = \frac{g_f^2}{8\pi}\, m_A \sqrt{1 - \frac{1}{\tau_\ell}}\,,$$

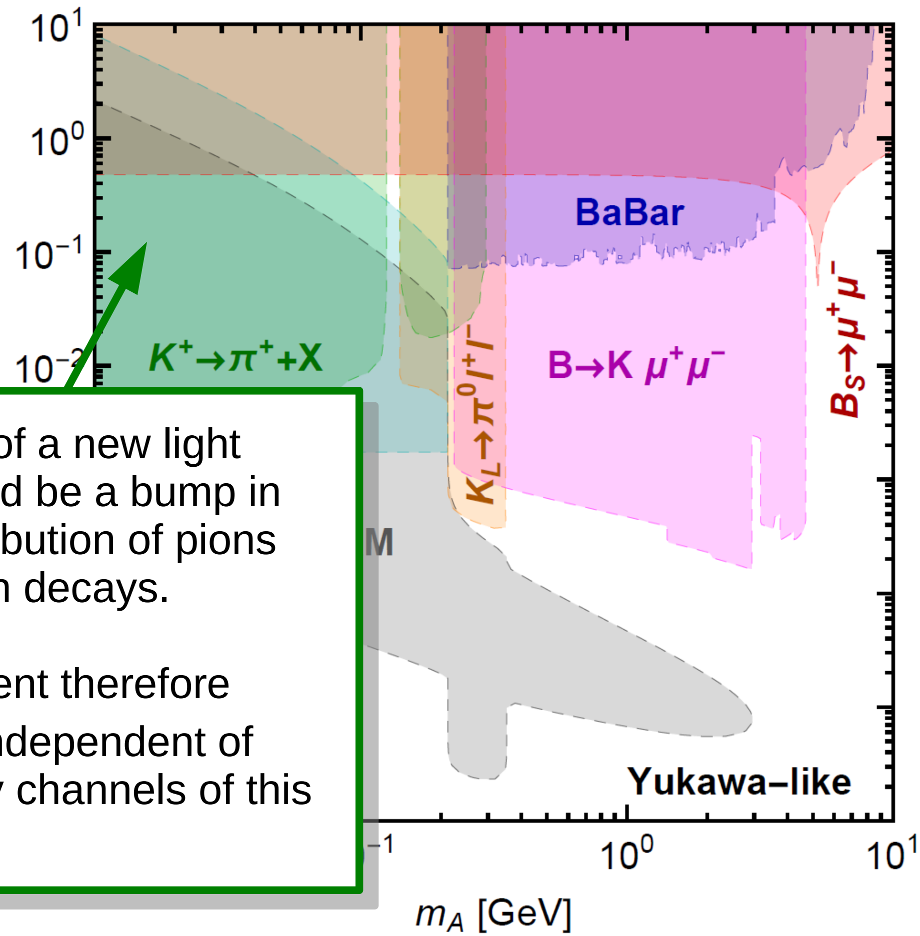
$$\Gamma(A \to \gamma\gamma) = \frac{\alpha^2\, m_A^3}{256\pi^3} \left| \sum_f \frac{N_c\, Q_f^2\, g_f}{m_f} F_A(\tau_f) \right|^2$$

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

Experimental results

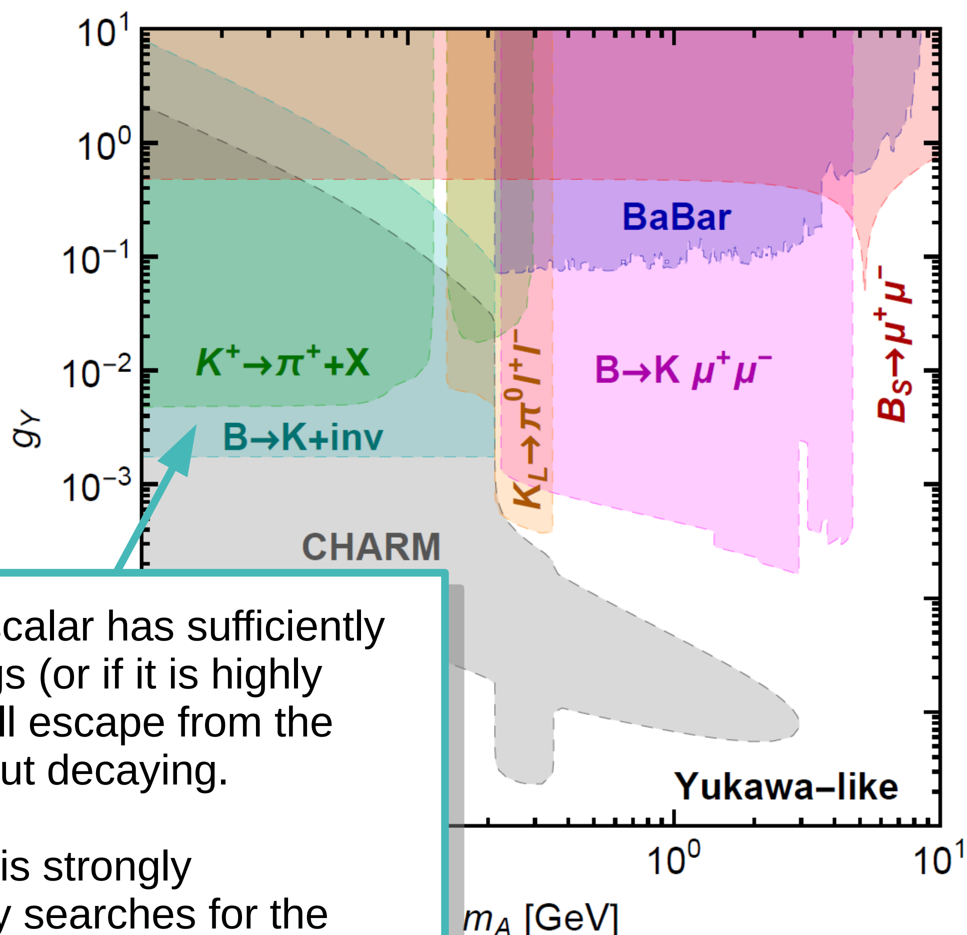


Experimental results



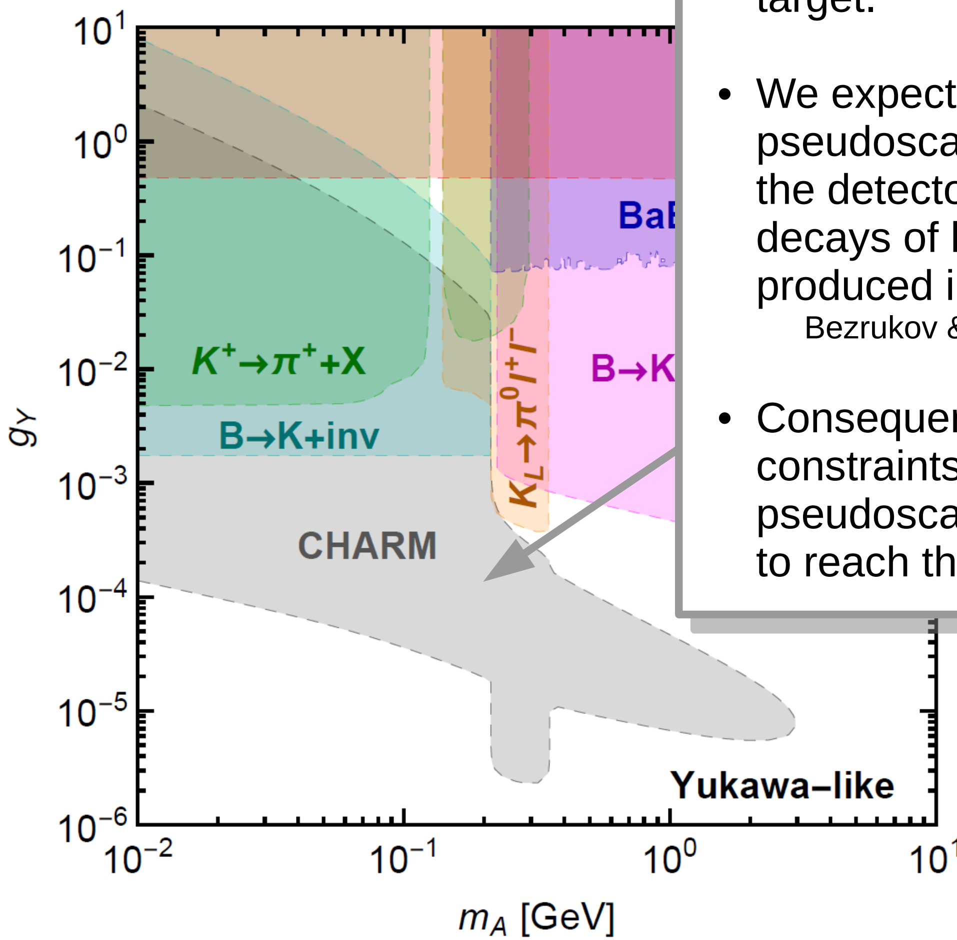
- In the presence of a new light state there should be a bump in momentum distribution of pions produced in kaon decays.
- The $K_{\mu 2}$ experiment therefore places bounds independent of the further decay channels of this new state.

Experimental results



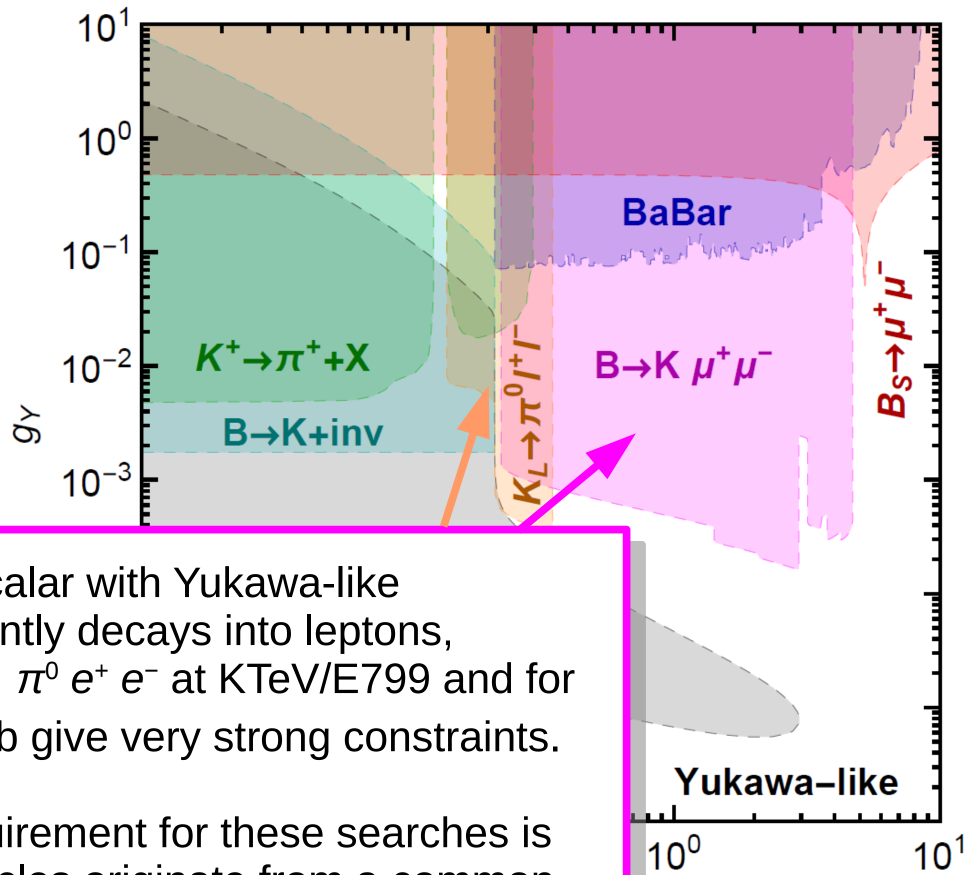
- If the pseudoscalar has sufficiently small couplings (or if it is highly boosted), it will escape from the detector without decaying.
- This scenario is strongly constrained by searches for the rare decay $B^0 \to K_S$ + inv at CLEO.

Experimental results



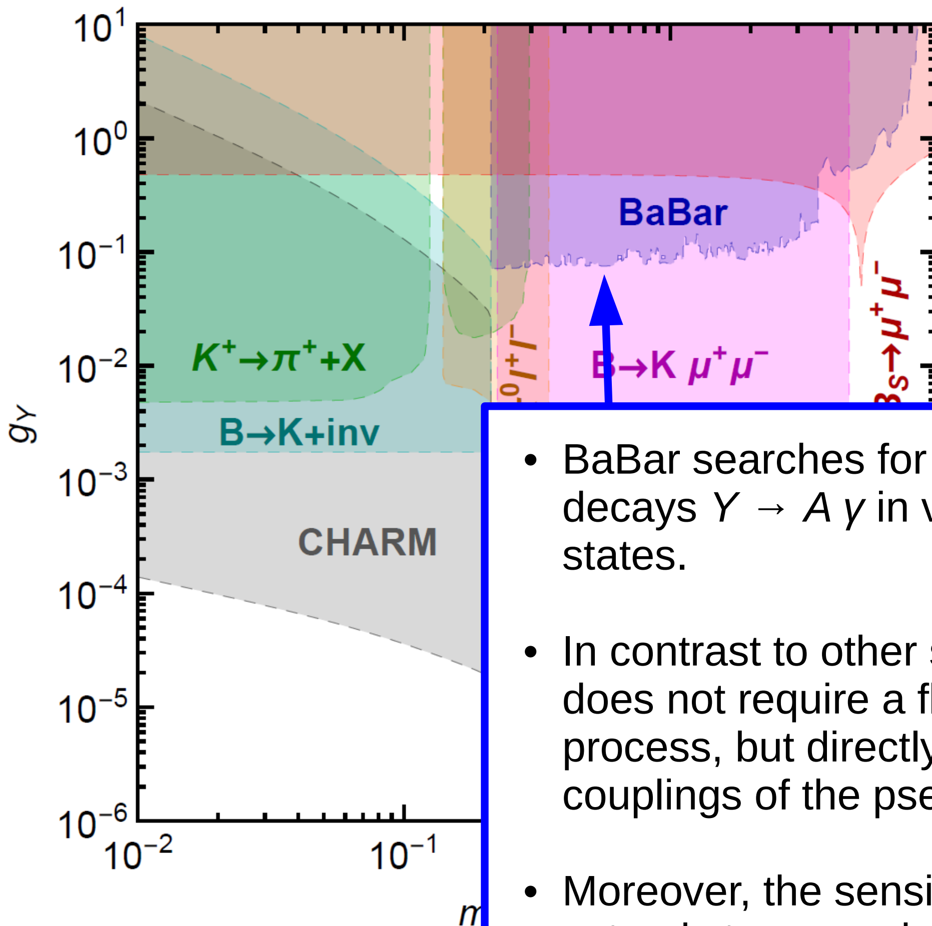
- CHARM is a proton beam-dump experiment with a detector placed 500m away from the target.
- We expect a large flux of pseudoscalars in the direction of the detector resulting from the decays of kaons and B-mesons produced in the target.
  Bezrukov & Gorbunov, arXiv:0912.0390
- Consequently we obtain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

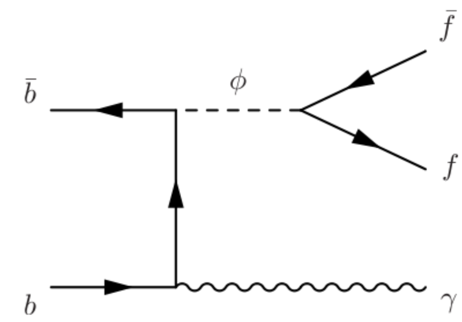
Experimental results



- 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





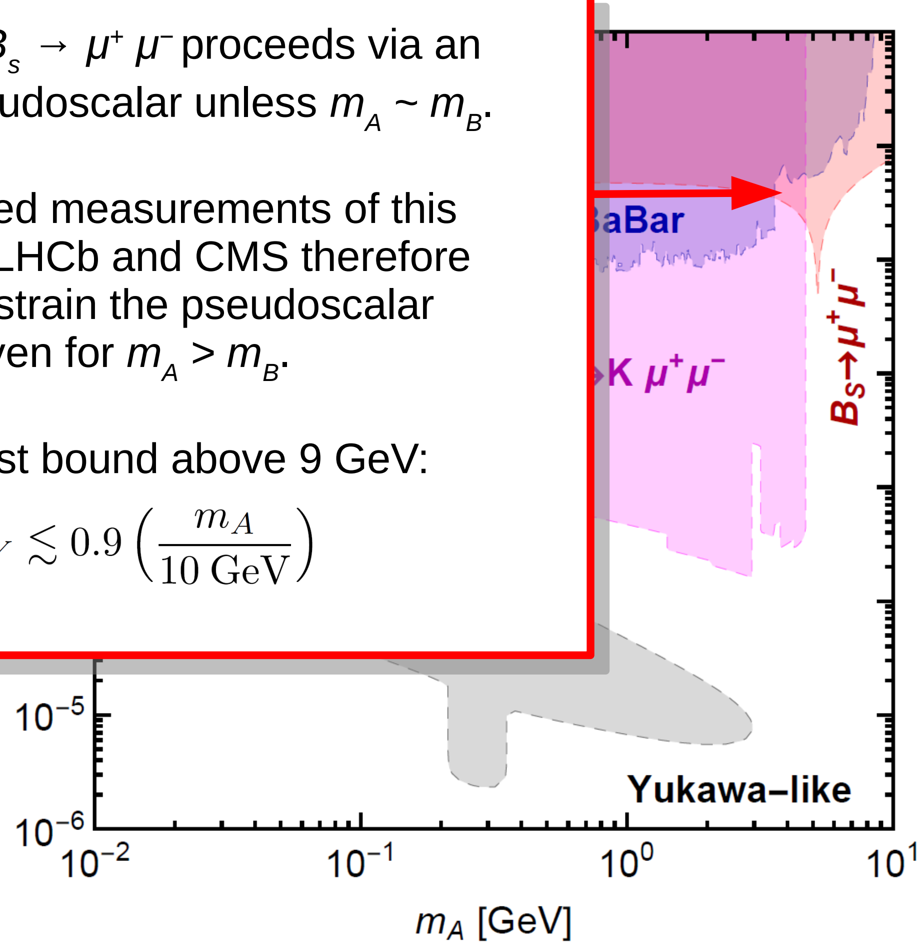
- BaBar searches for radiative Upsilon decays $Y \to A\,\gamma$ in various different final states.
- In contrast to other searches, this decay does not require a flavour-changing process, but directly probes the tree-level couplings of the pseudoscalar.
- Moreover, the sensitivity of this search extends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

Experimental results

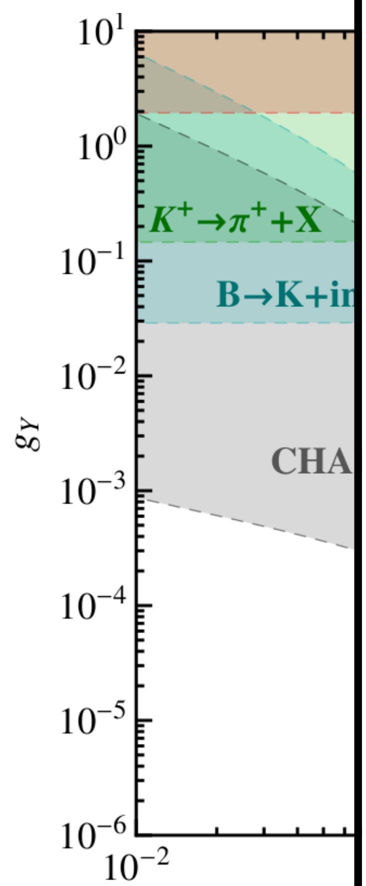
- The decay $B_s \rightarrow \mu^+ \mu^-$ proceeds via an off-shell pseudoscalar unless $m_A \sim m_B$.
- The combined measurements of this decay from LHCb and CMS therefore allow to constrain the pseudoscalar couplings even for $m_A > m_B$.

→ The strongest bound above 9 GeV:

$$g_Y \lesssim 0.9 \left(\frac{m_A}{10\ \mathrm{GeV}}\right)$$



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.

Part 3: Implications for the dark sector

Why pseudoscalars?

- Pseudoscalar mediators with $\mathcal{L}_{\rm DM} = i\, g_\chi\, A\, \bar{\chi}\gamma^5\chi$ are 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:

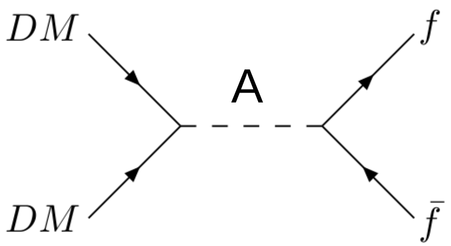
$$-0.4 \lesssim g_n/g_p \lesssim 0$$

Freytsis & Ligeti, arXiv:1012.5317

DESY

Why pseudoscalars?

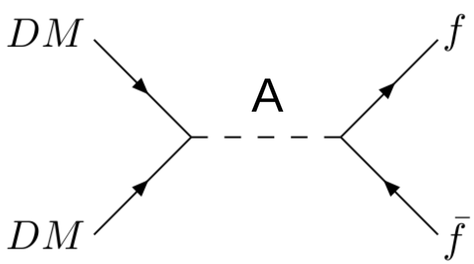
- Since constraints from direct detection experiments are largely absent, pseudoscalars can potentially give rise to a range of interesting signals:

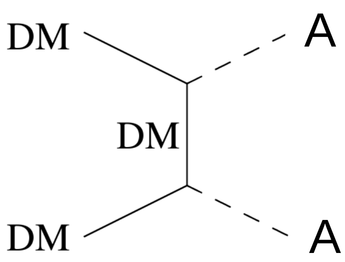


  - It is possible to obtain observable indirect detection signals and for example explain the Fermi-LAT Galactic Centre gamma-ray excess.
    - Coy Dark Matter (Boehm et al., arXiv:1401.6458)
  - A light pseudoscalar mediator offers the possibility to obtain large self-interactions in the dark sector 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)

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_x

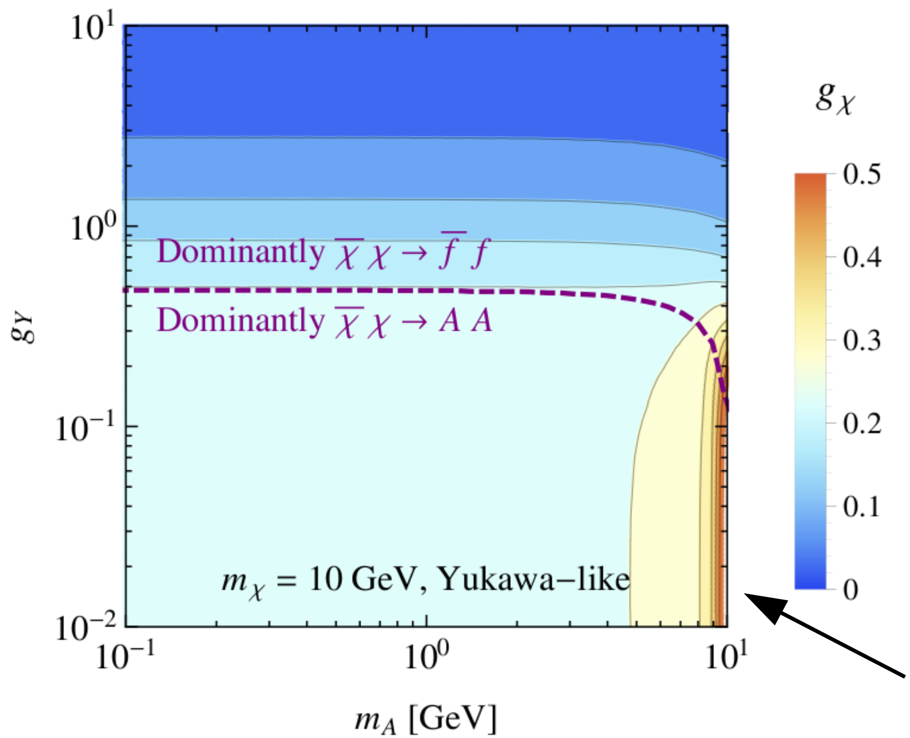
$$\langle \sigma v \rangle_{\bar{\chi}\chi \to AA} \simeq \frac{g_\chi^4}{24\pi} \frac{m_\chi (m_\chi^2 - m_A^2)^{5/2}}{(m_A^2 - 2\, m_\chi^2)^4} \frac{6}{x}$$

→ p-wave annihilation
→ depends only on g_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.

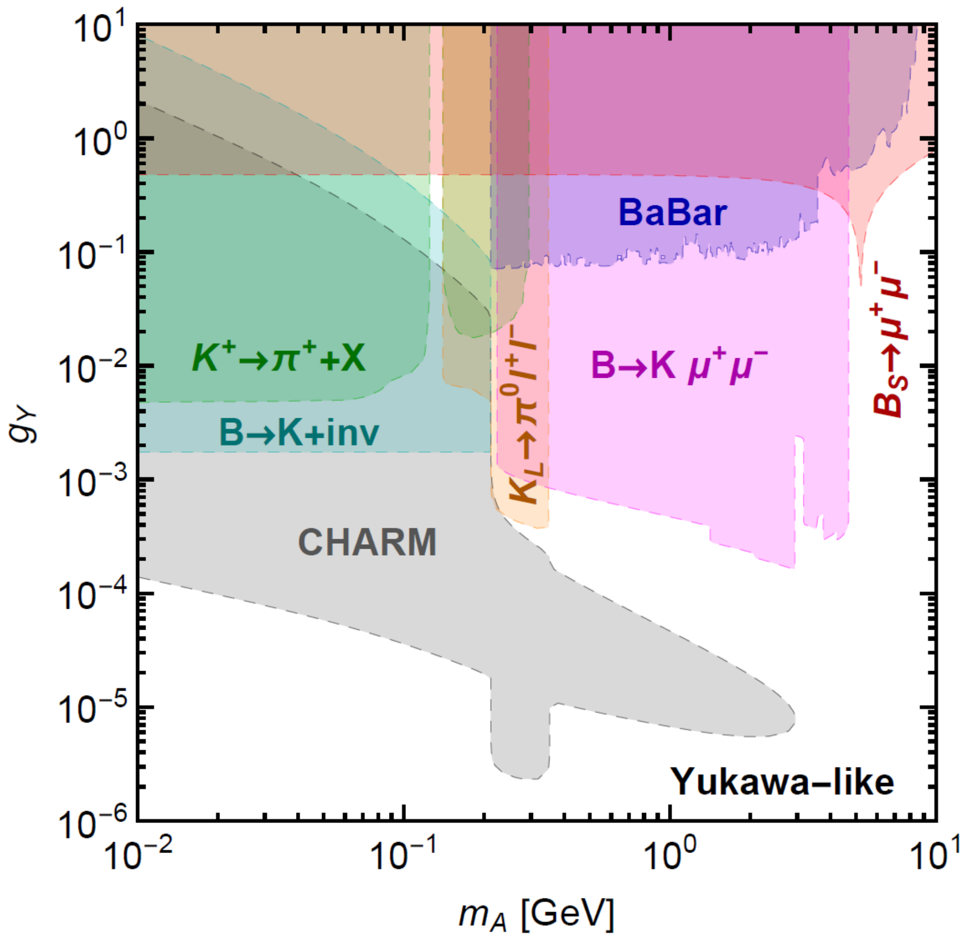
Relic density calculation

- 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.

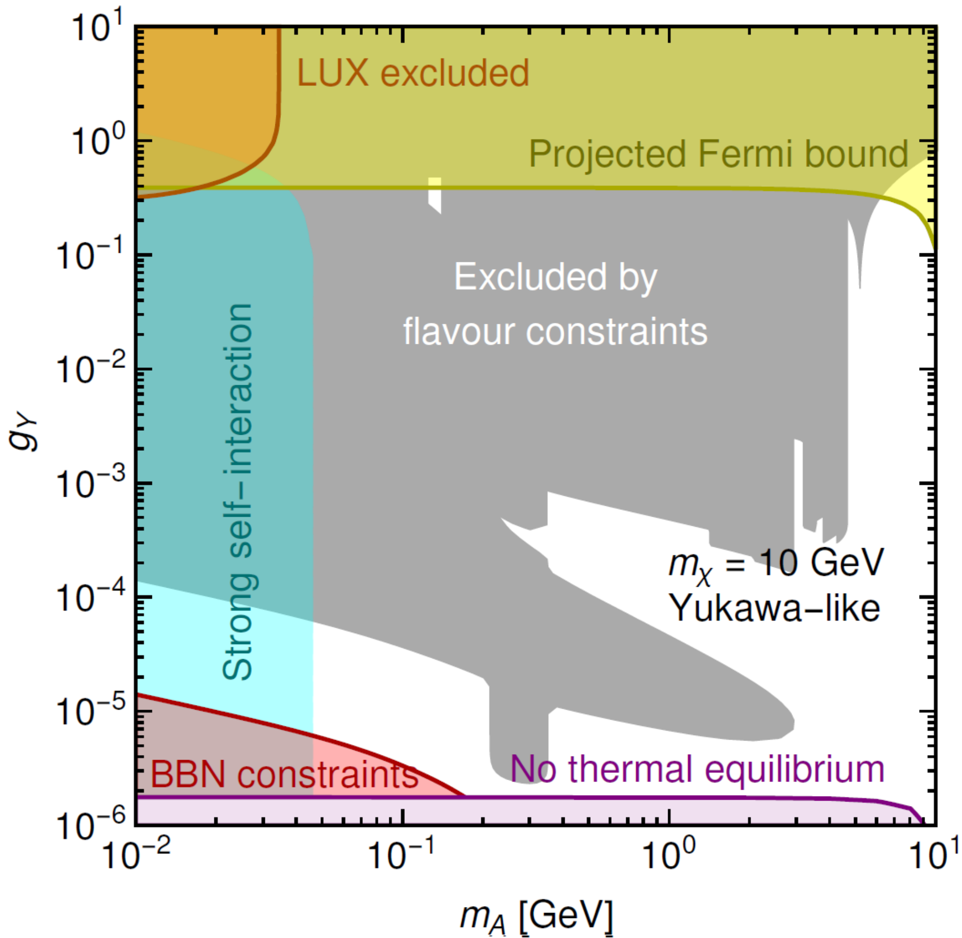


Phase-space suppression of annihilation into pseudoscalars for $m_A \sim m_\chi$.

Dark matter constraints

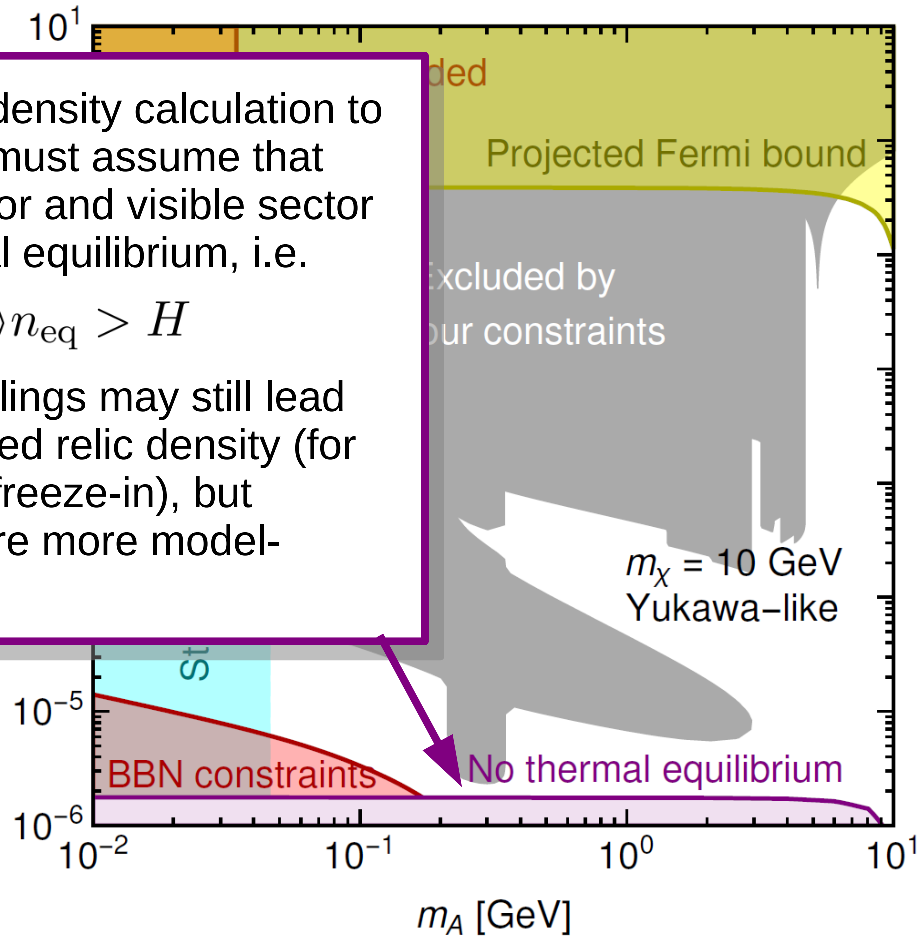


Dark matter constraints



g_χ fixed by relic density requirement!

Dark matter constraints

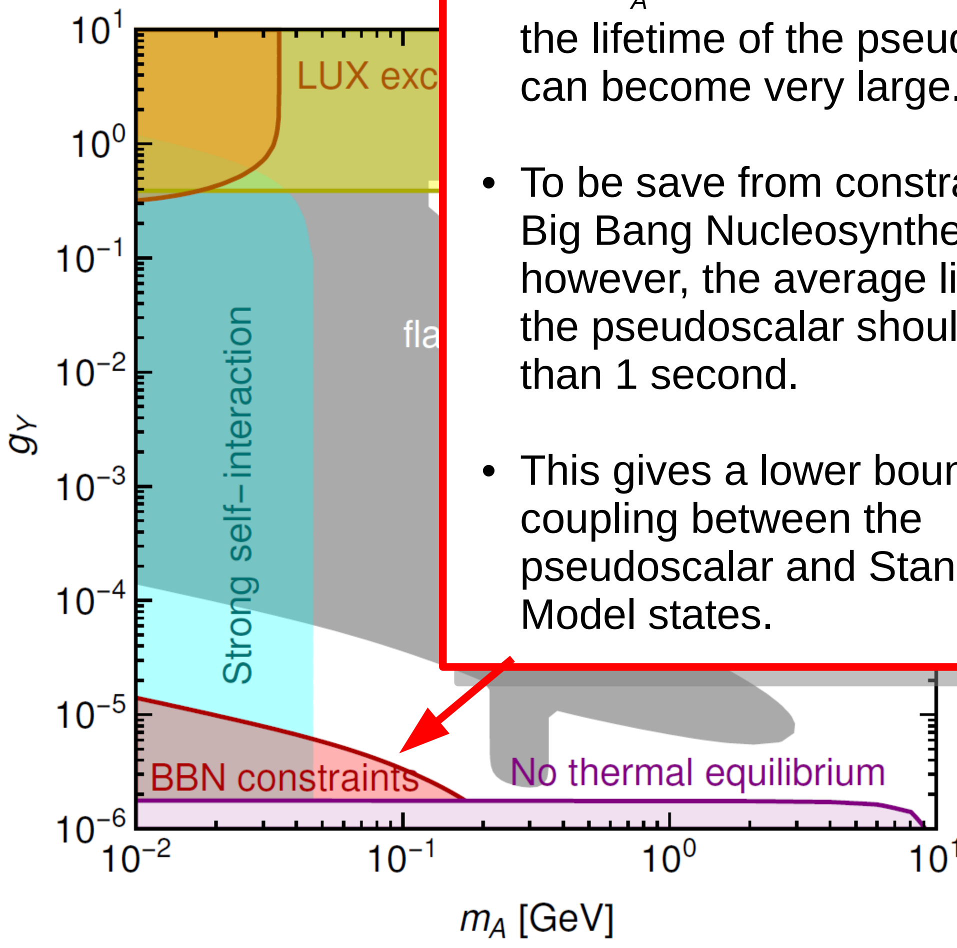


- For the relic density calculation to be valid, we must assume that the dark sector and visible sector reach thermal equilibrium, i.e.

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

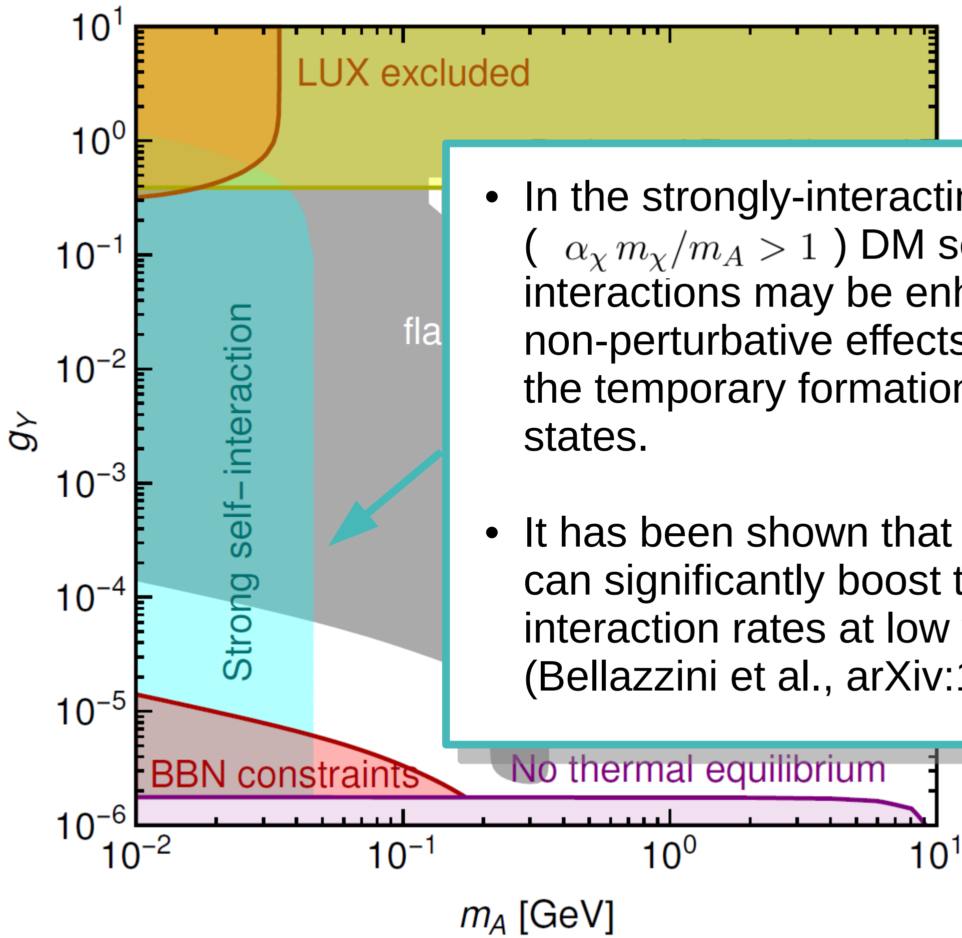
- Smaller couplings may still lead to the observed relic density (for example via freeze-in), but predictions are more model-dependent.

Dark matter constraints



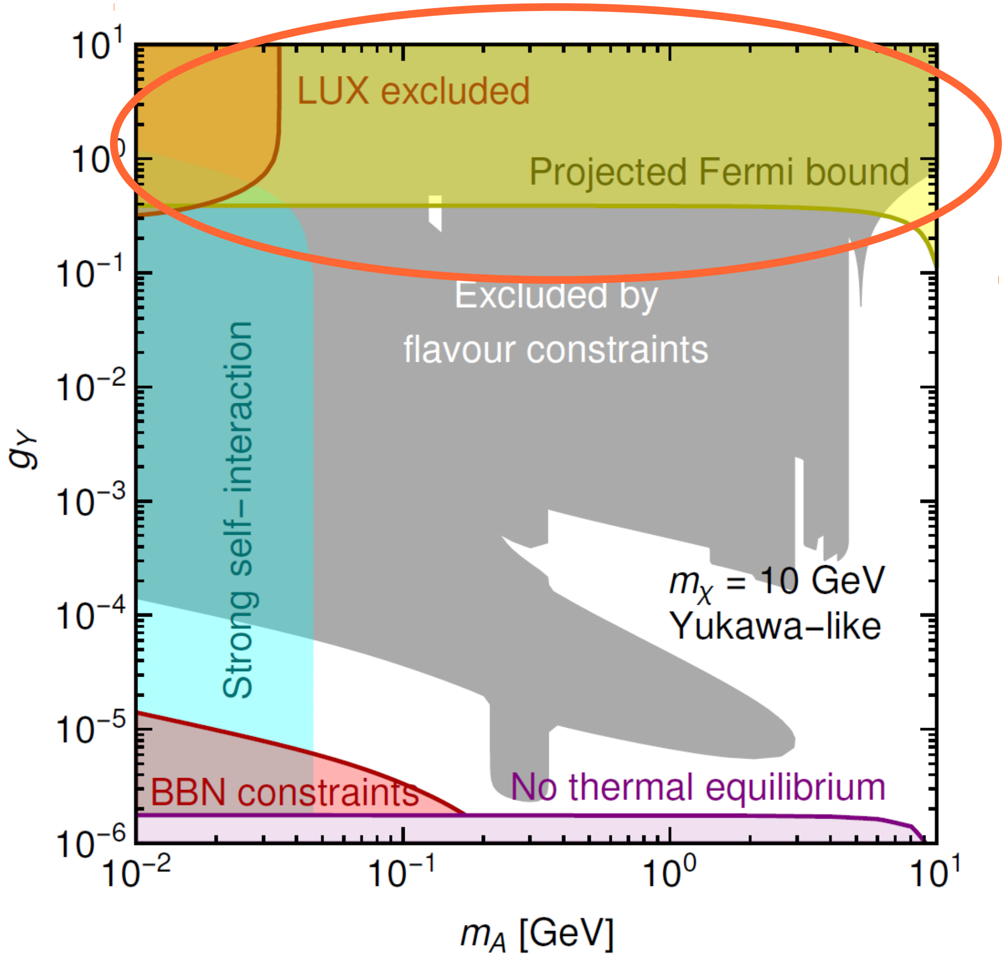
- For m_A below the muon mass, the lifetime of the pseudoscalar can become very large.
- To be save from constraints from Big Bang Nucleosynthesis, however, the average lifetime of the pseudoscalar should be less than 1 second.
- This gives a lower bound on the coupling between the pseudoscalar and Standard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

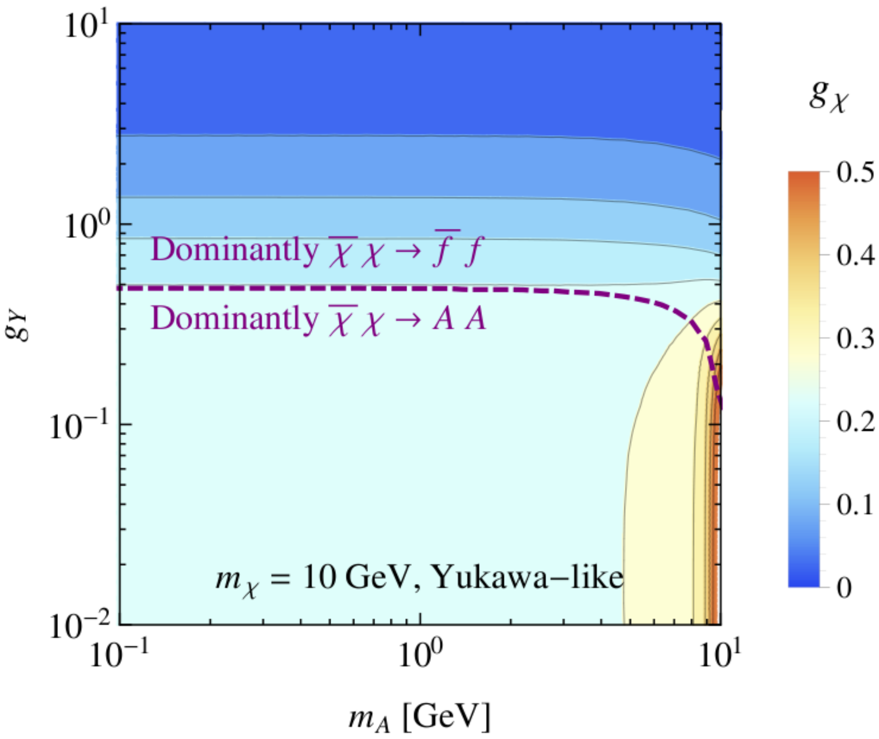
Dark matter constraints



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

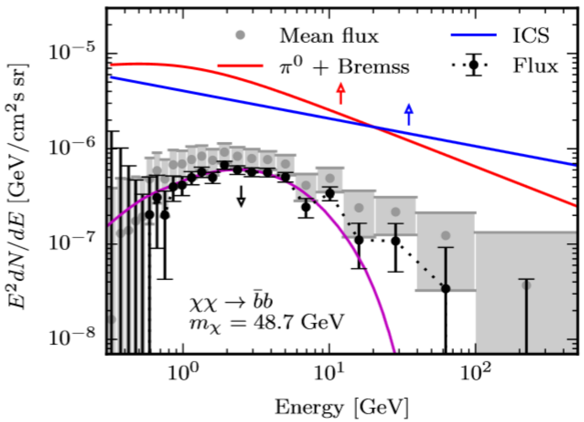
Indirect detection

- If dark matter freeze-out is dominated by *p*-wave annihilation into pseudoscalars, 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.

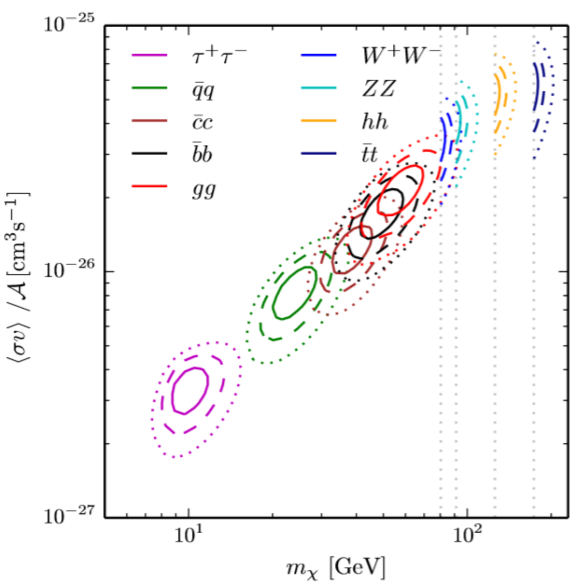


- If both annihilation channels contribute in the early universe, we expect to see an annihilation signal slightly below the standard expectation for a thermal relic.
  - Perfect for explaining the Galactic Centre Excess

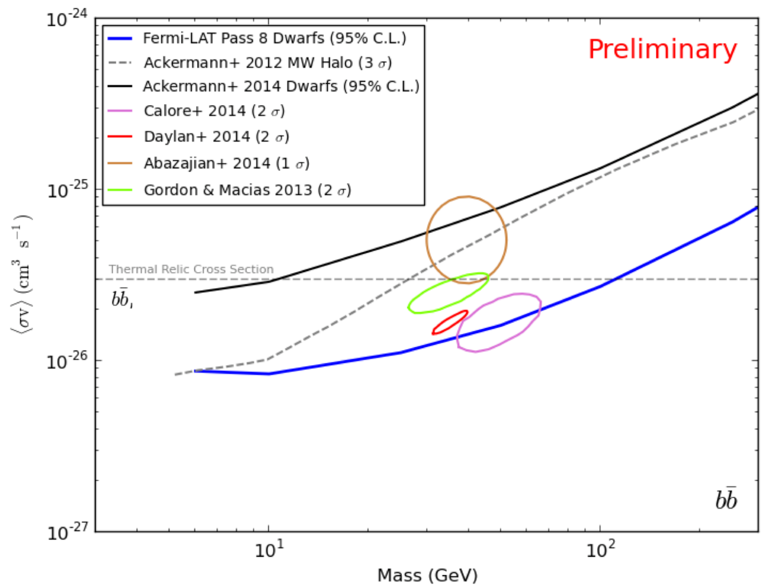
The Galactic Centre Excess



- 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.



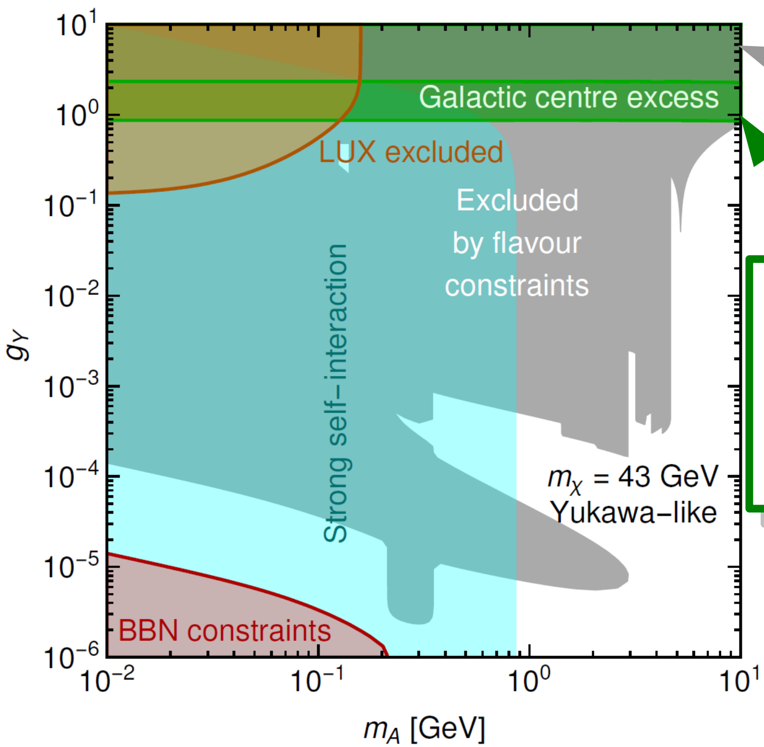
Calore et al., arXiv:1411.4647



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.

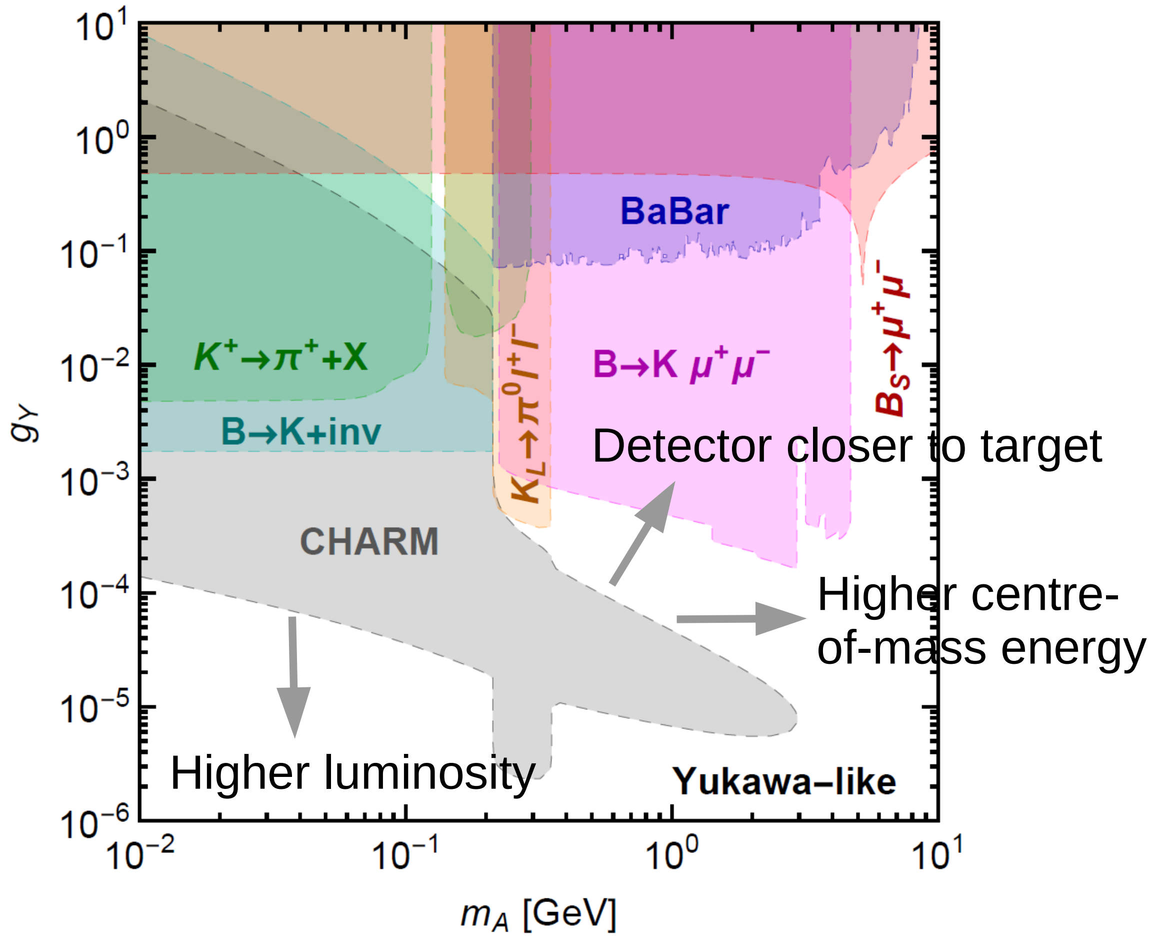
- Potential explanation of the Galactic centre excess within astrophysical uncertainties while at the same time being save from dwarf spheroidal constraints.

> For m_A > 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.

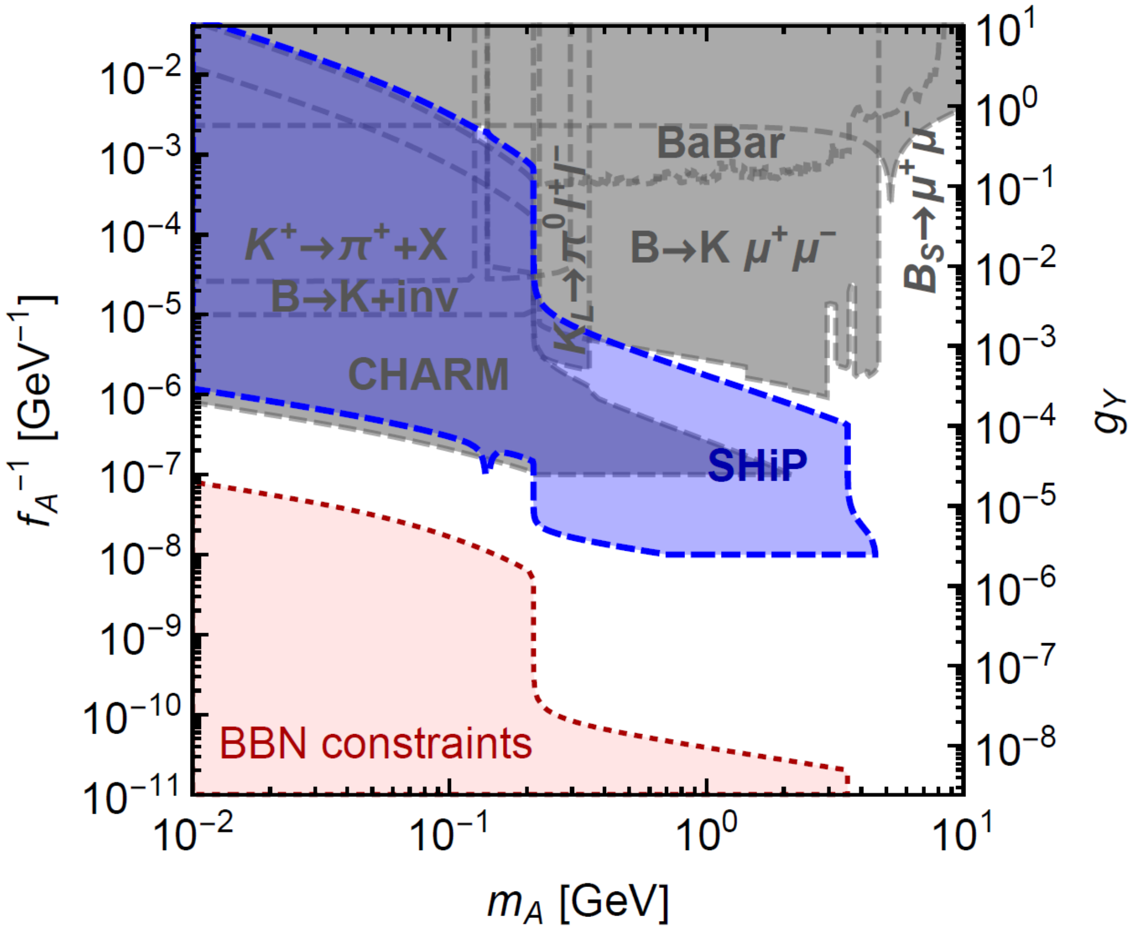
Future prospects

- 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.



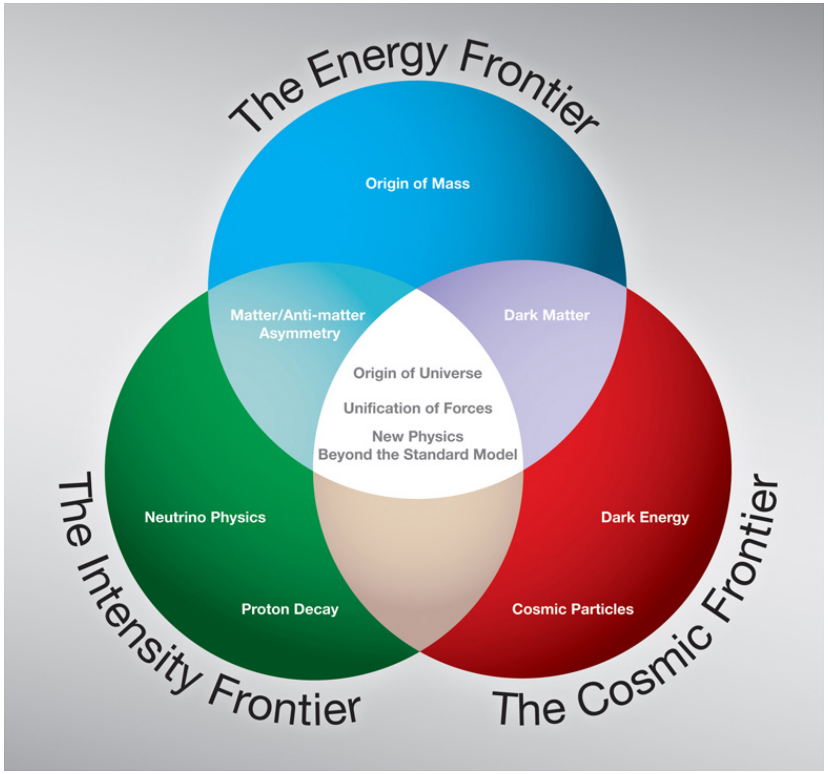
Future prospects

- 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.

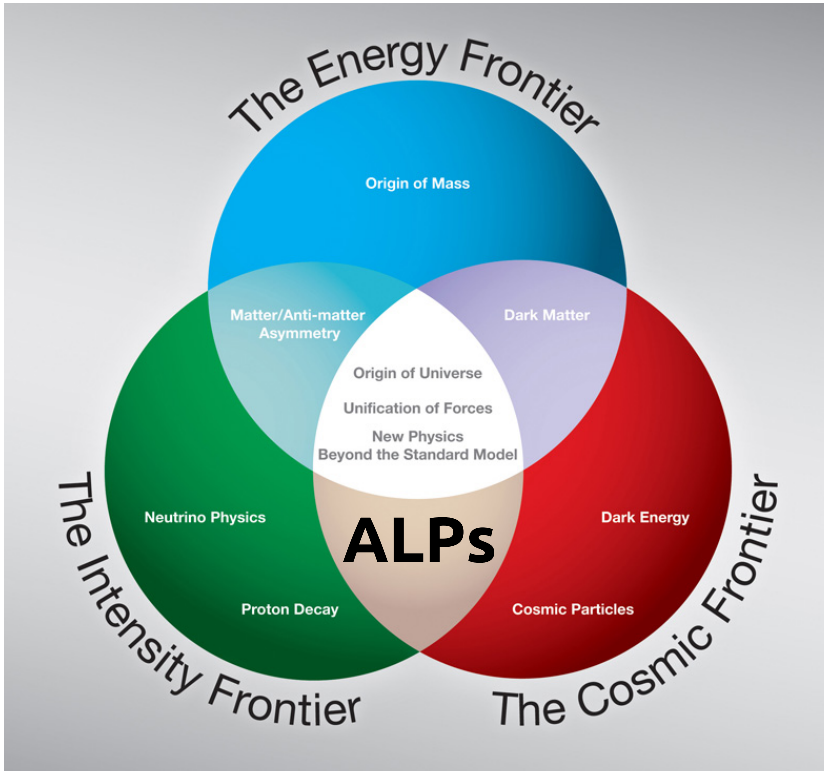


Alekhin, FK et al., arXiv:1504.04855

Conclusion


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

Conclusion



The Energy Frontier
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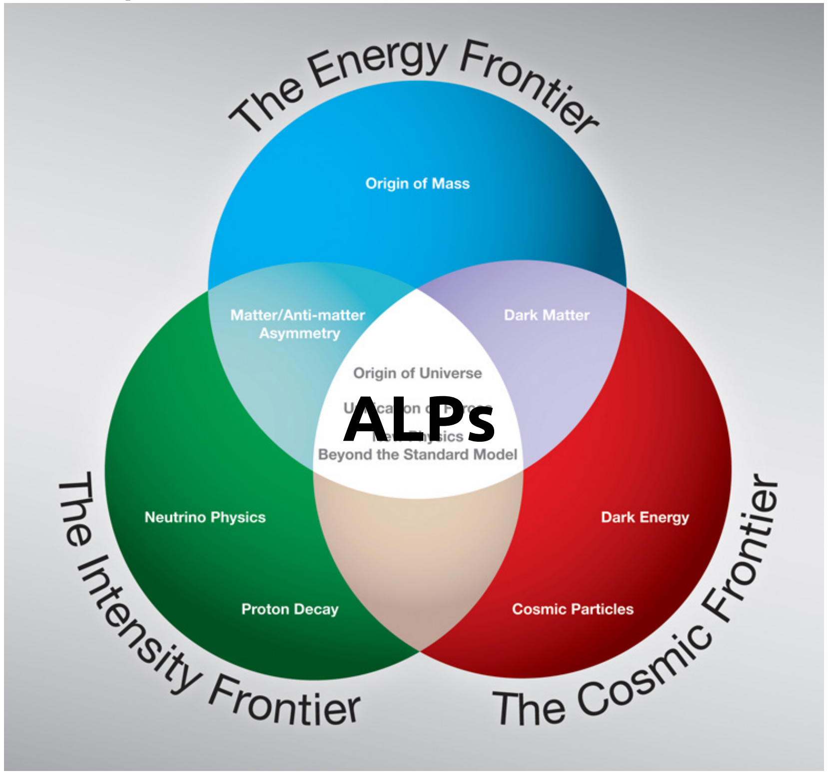
Updated 15 December 2015



Conclusions

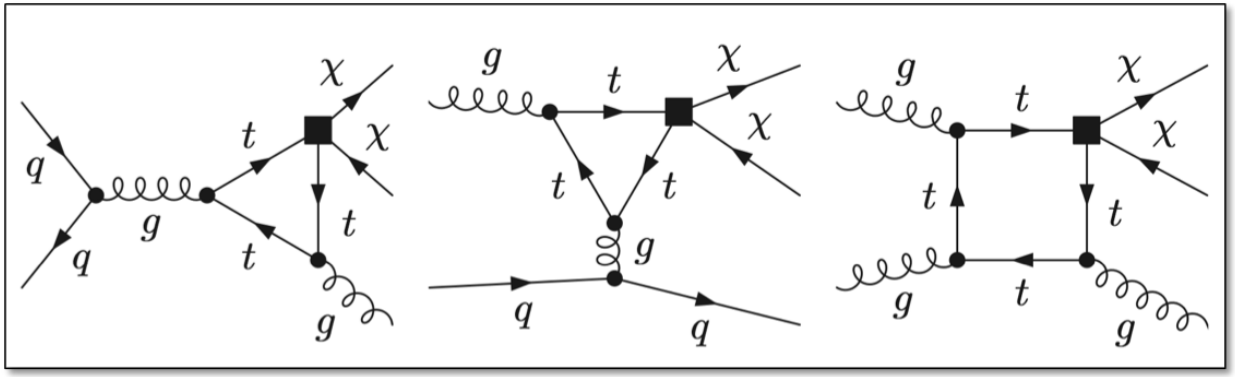
- Low-mass BSM physics can potentially be probed with existing and near-future experiments with comparably low effort, providing a complementary window to what is covered by high-energy accelerators.
- ALPs (i.e. pseudoscalar mediators) coupling the visible and dark sectors are interesting from model-building and phenomenological perspectives.
- The intensity frontier is a promising and rarely studied way to constrain these types of models and yields relevant and highly complementary information.
- 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.
  - An ALP mediator with 10 GeV < m_A < m_χ 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 ($\sqrt{s}$, 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)

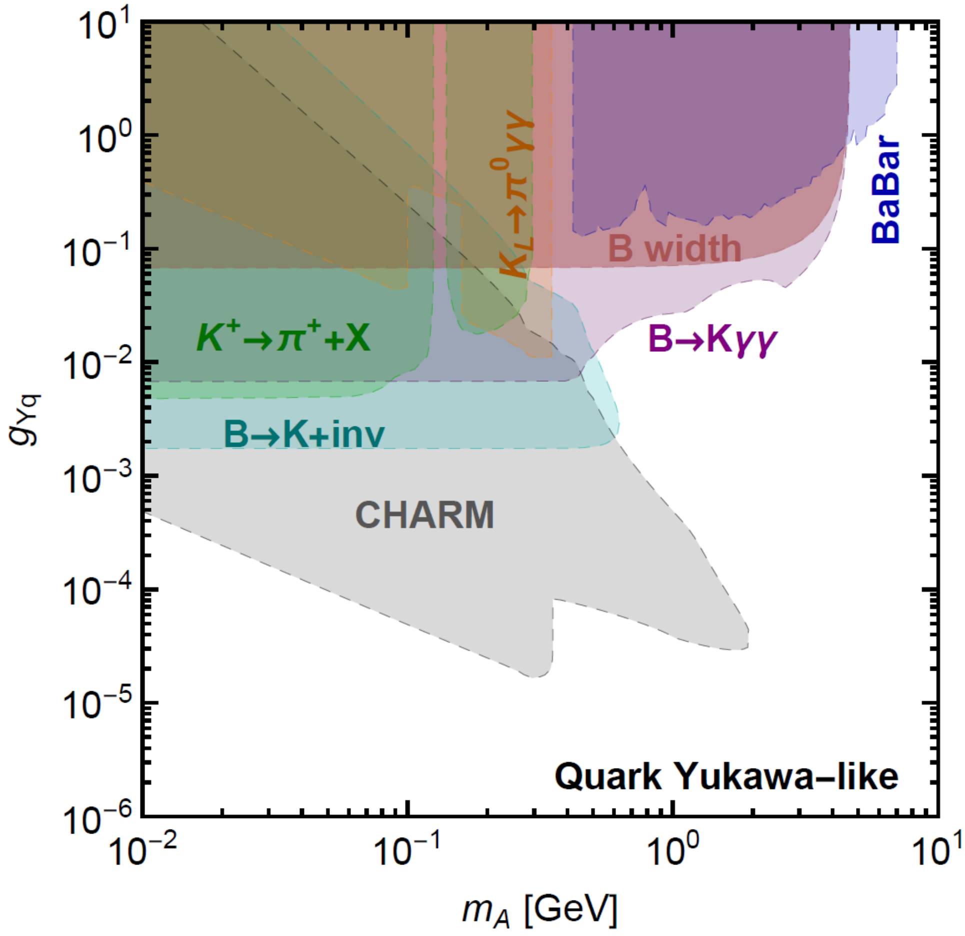
Haisch, FK, Unwin: arXiv:1208.4605



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

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.



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

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

- 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:

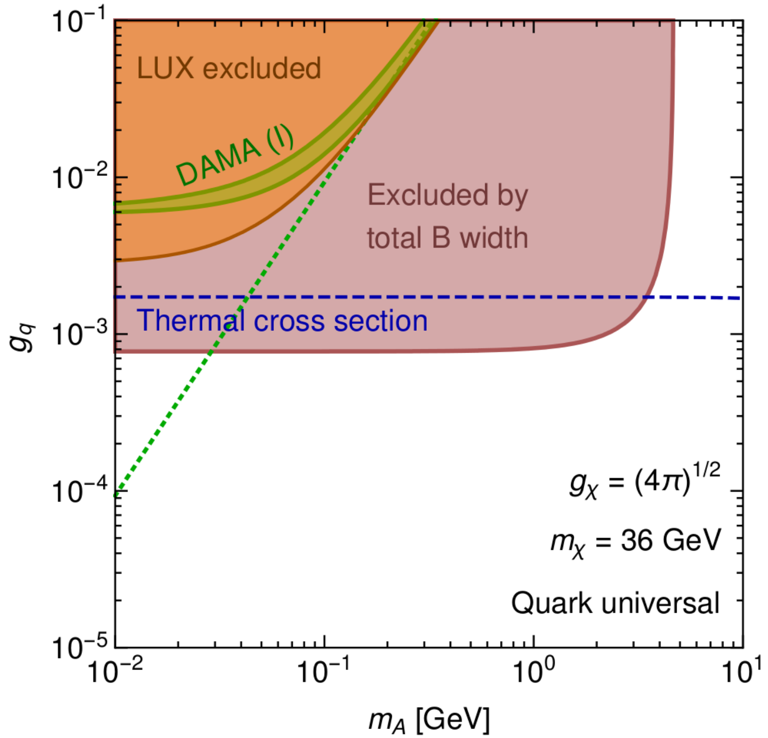
$$\mathcal{L}_{\mathrm{mixing}} = \lambda \frac{f_\pi}{\Lambda} \frac{m_\pi^2}{m_\pi^2 - m_A^2} \pi\, A \qquad \lambda = \frac{1}{2}\frac{m_u - m_d}{(m_u + m_d)} \approx -0.18$$

- 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.

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.

Implications for dark matter signals

> Differential event rate for direct detection experiments:

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

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.

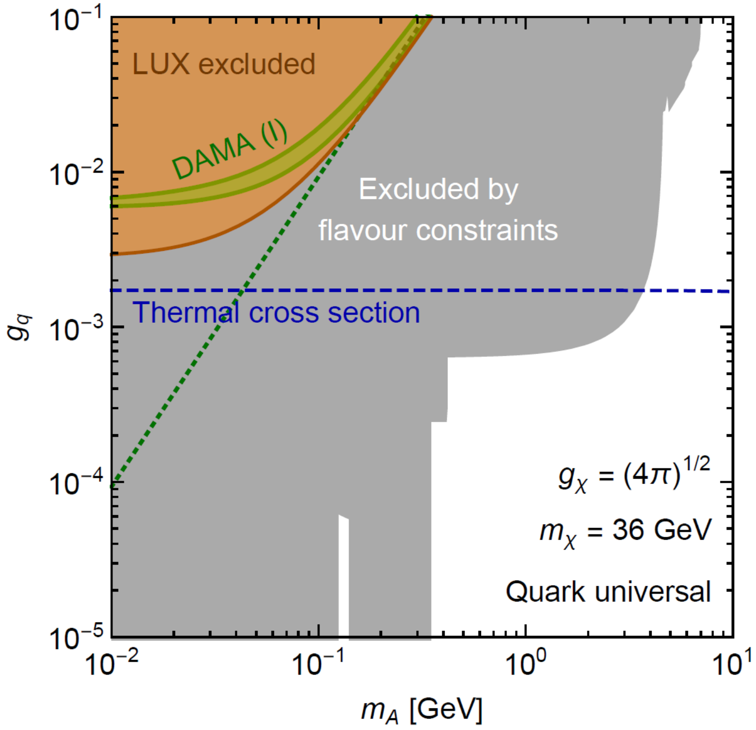
> Moreover, since pseudoscalars couple dominantly to the proton spin, constraints from LUX are much less severe than for standard interactions and it might be possible to reconcile LUX and DAMA.

Arina et al., arXiv:1406.5542

DAMA and LUX

- The ratio $g_p / g_n \sim -4$ 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

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



- Even in the most optimistic case that we make the DM coupling g_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.

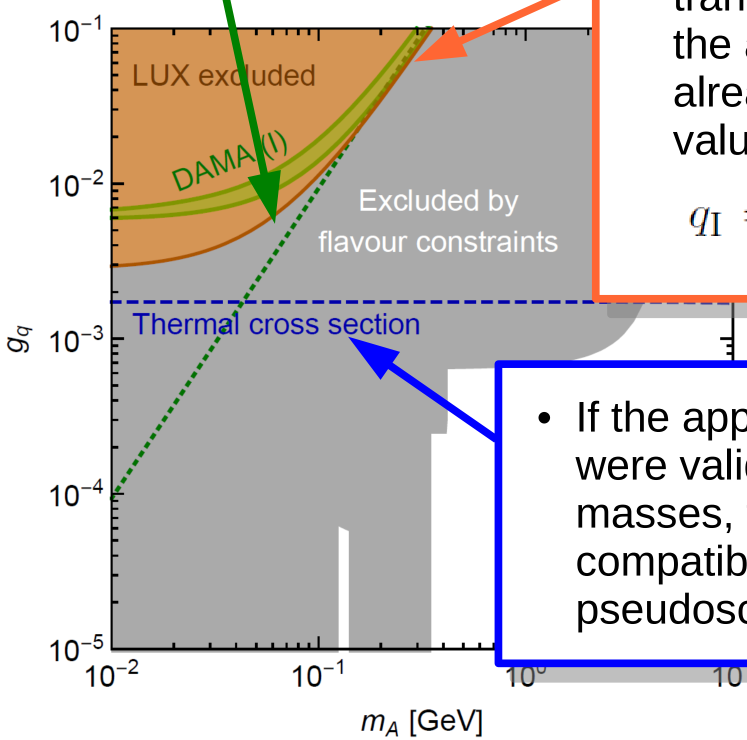
DAMA and LUX: Some additional observations

- 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.