Searching for Dark Mediators.

Collider and flavour constraints for dark matter

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12 May 2015

based on **arXiv:1412.5174** with Matthew Dolan, Christopher McCabe and Kai Schmidt-Hoberg and **arXiv:1503.05916** with Mikael Chala, Matthew McCullough, Germano Nardini and Kai Schmidt-Hoberg

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Outline

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  - Evidence for dark matter
  - Modelling dark matter
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- Part 2: GeV-scale (pseudoscalar) mediators
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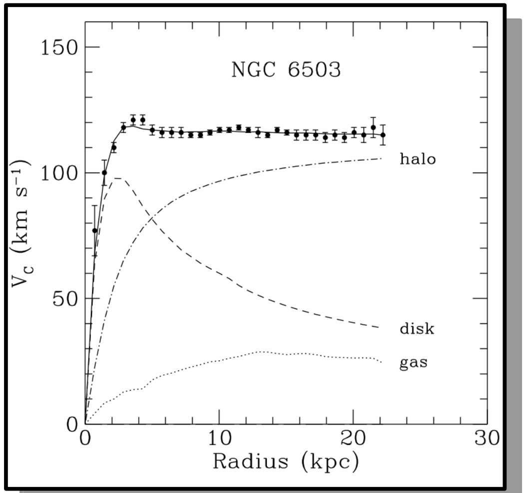
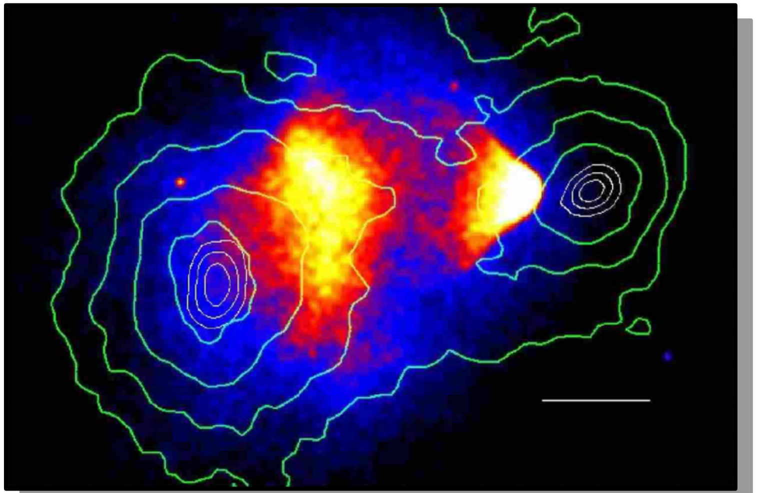
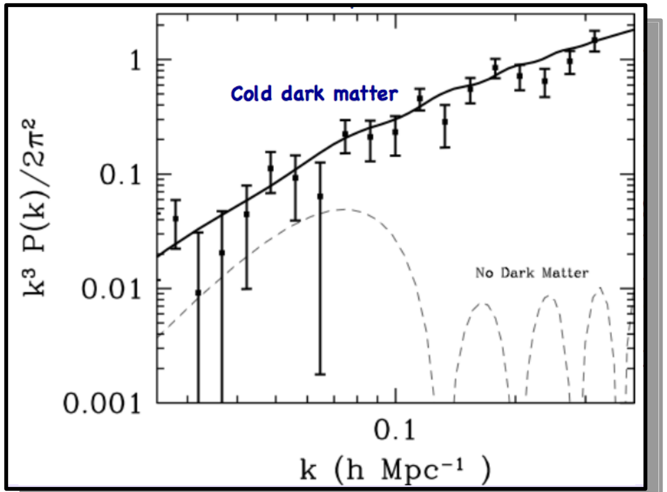
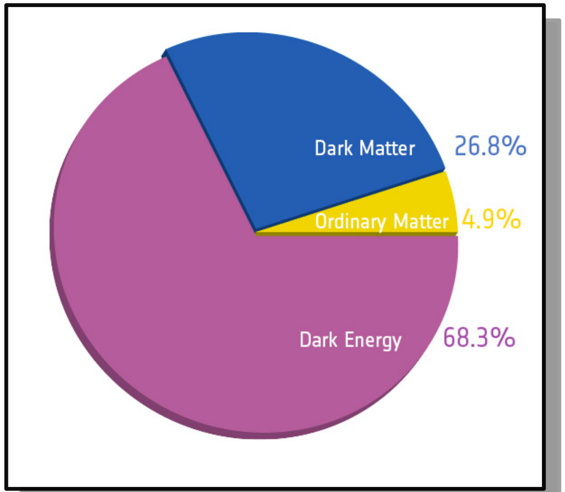
  - Implications for dark matter signals
- Part 3: TeV-scale (axial-vector) mediators
  - Non-collider constraints
  - Monojet and dijet searches
- Conclusions

Evidence for Dark Matter

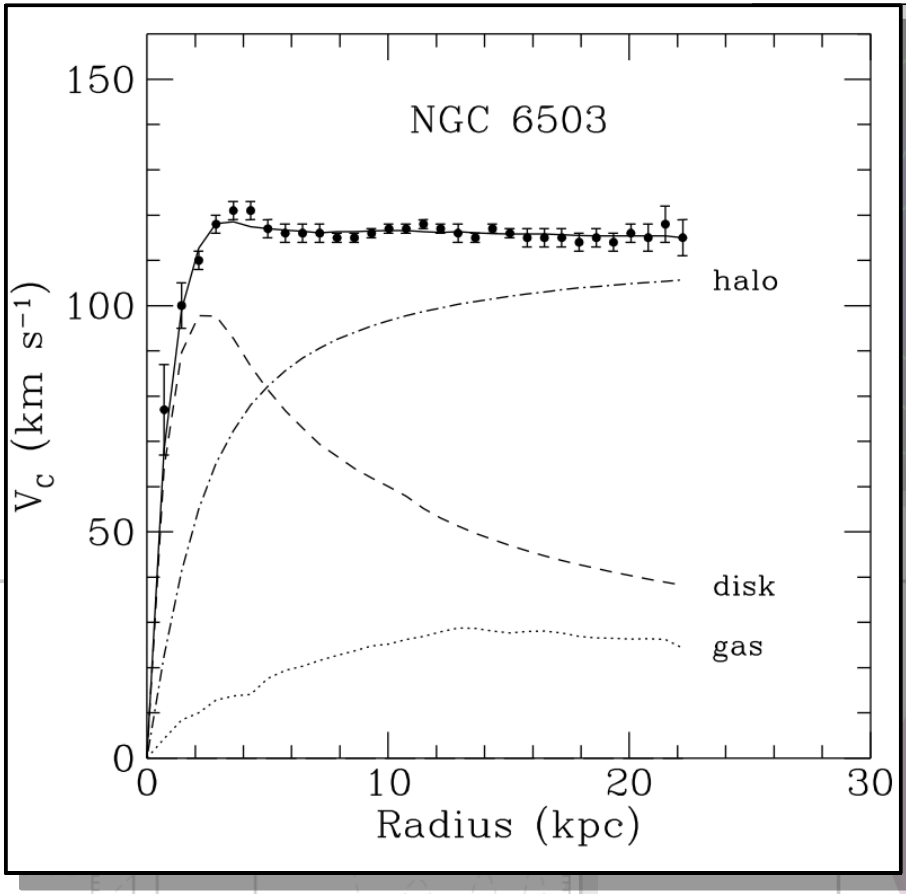


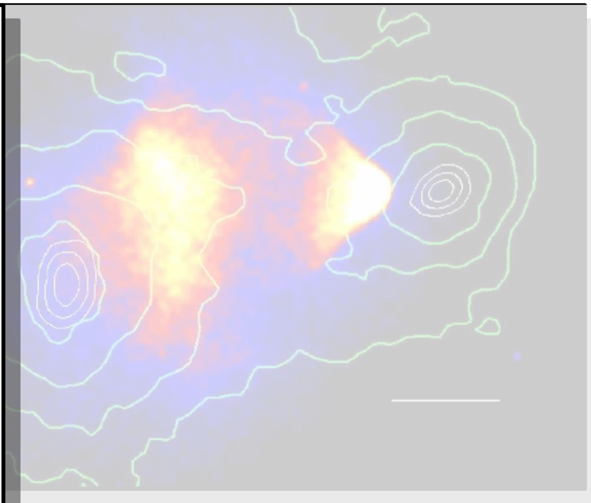


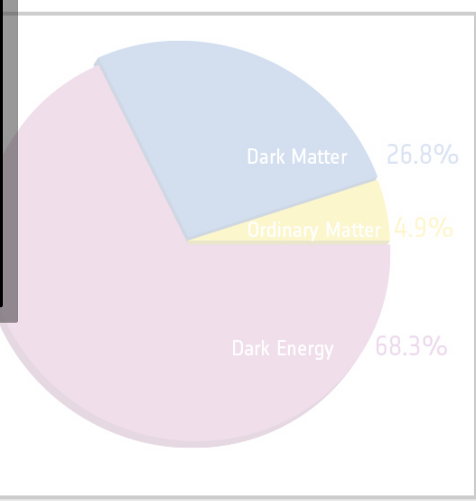




Evidence for Dark Matter: Galactic rotation curves







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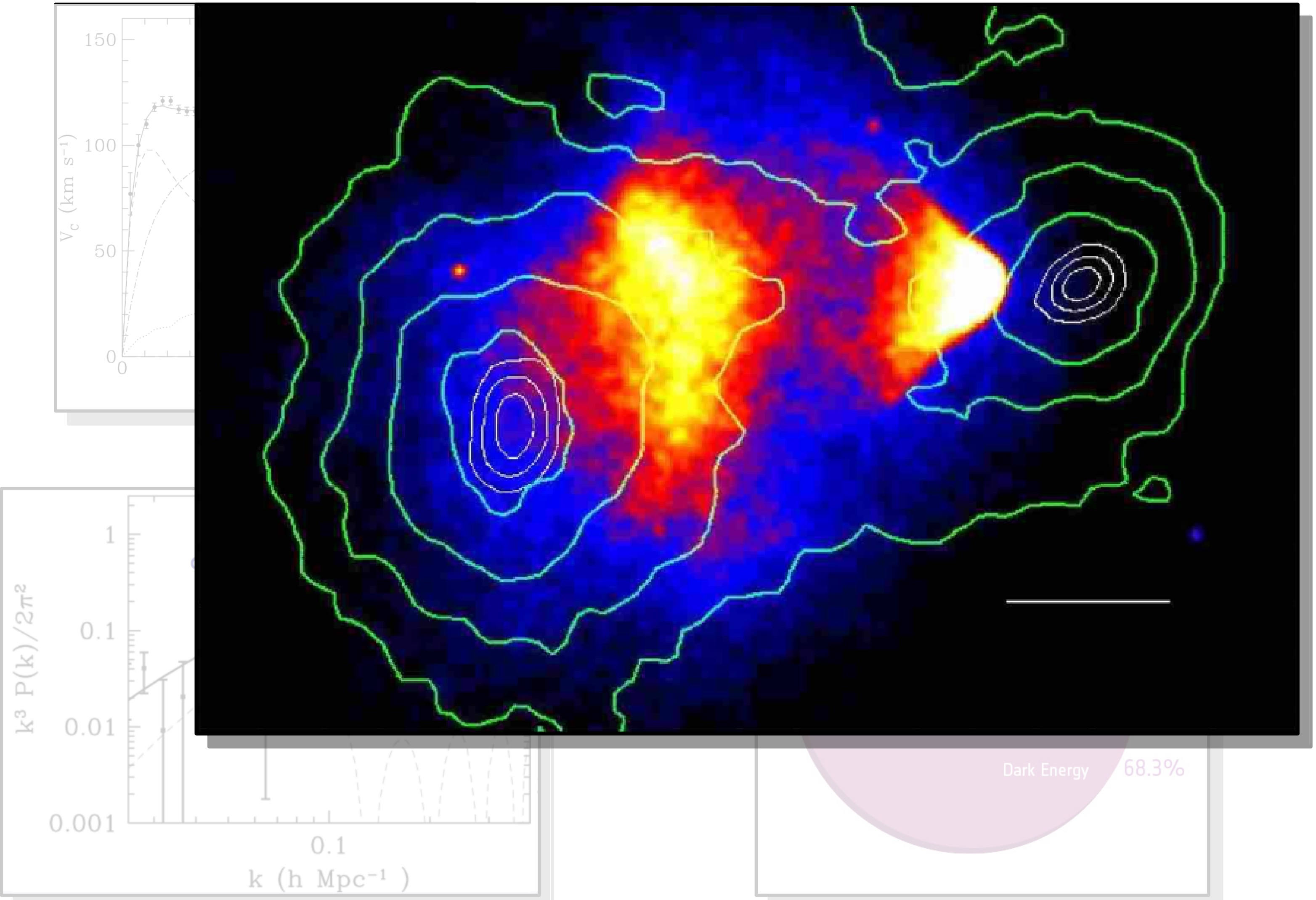
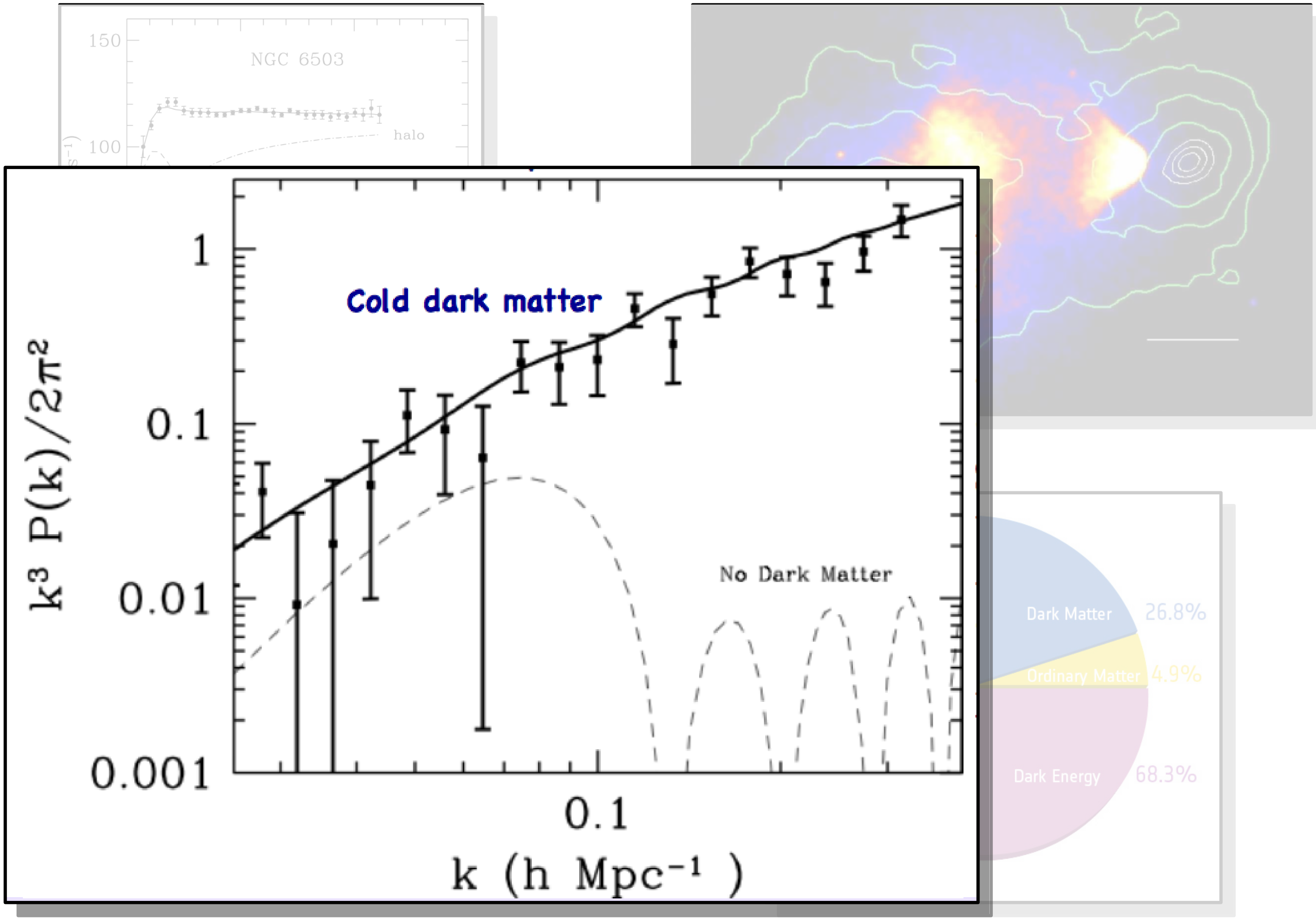
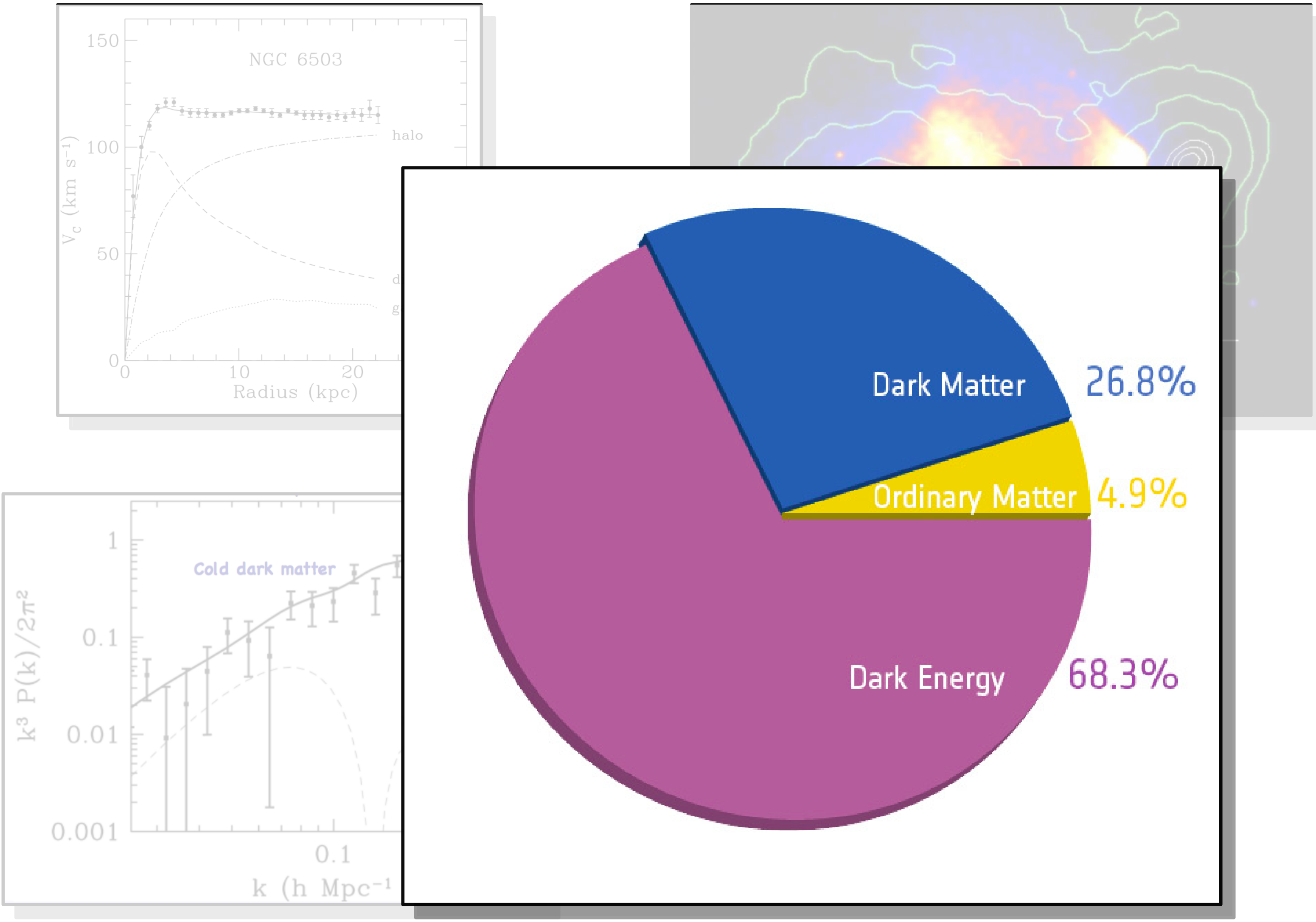
Evidence for Dark Matter: Weak lensing



Evidence for Dark Matter: Large-scale structure



Evidence for Dark Matter: Summary



Properties of dark matter

- By definition: Electromagnetically neutral[1] and stable[2]
- Structure formation: Dark matter must be cold[3]
- Primordial nucleosynthesis: Dark matter must be non-baryonic[4]
- Cluster collisions: Dark matter must be collisionless[5]

1 Dark matter millicharges of order $q_{DM} < 10^{-6}$ are still allowed.

2 Dark matter could also be unstable with a lifetime large compared to the age of the Universe.

3 Dark matter can be warm, i.e. relativistic at creation, as long as it is non-relativistic during structure formation.

4 A sizeable fraction of dark matter may be in the form of MACHOs or diffuse baryons.

5 The self-interaction cross sections can be as large as $\sigma_{DM}/m_{DM} \sim 1$ barn/GeV.

Dark matter candidates: The top-down approach

> Remarkably, many theories of physics beyond the Standard Model developed for completely different reasons predict new particles that have the required properties to be dark matter.

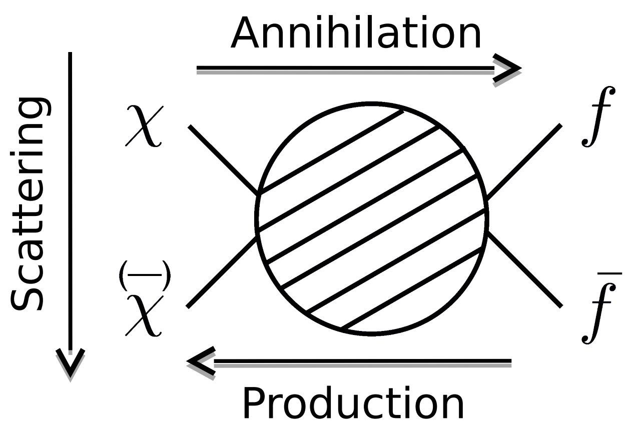
- WIMPs: Most solutions to the hierarchy problem postulate the existence of new states at the electroweak scale. The lightest new state is typically stable and can naturally be produced in the early Universe with the required relic abundance.
- Axions: The Peccei-Quinn solution to the strong CP problem naturally predicts a new light particle, which – in spite of its very small mass – could act as cold dark matter.
- Asymmetric dark matter: If additional particles participate in the generation of baryons, they could inherit the same asymmetry and therefore obtain a comparable relic abundance.

Dark matter candidates: The bottom-up approach

- If we just want to explain the observed dark matter abundance, it is often sufficient to add only one new particle to the Standard Model.
  - Sterile neutrinos: Can act as warm dark matter and suppress the formation of small-scale structures
  - Hidden photons: Gauge bosons of an additional broken U(1), coupling to Standard Model particles via kinetic mixing
  - Scalar singlets: Interacting with Standard Model particles via the exchange of Higgs particles (Higgs portal dark matter)
  - Minimal dark matter and hypercharged dark matter: A new fermionic multiplet charged under either SU(2) or $U(1)_Y$.
- These models have very few free parameters and are therefore highly predictive – but also strongly constrained.
- Although testable, these models do not provide a useful guideline for devising experimental strategies to search for dark matter (e.g. all the candidates above would be unobservable at the LHC).

Dark matter phenomenology

- To obtain a more interesting phenomenology (and evade experimental constraints), we can relax the assumption that DM couples directly to Standard Model states and instead consider the case that interactions between DM and the Standard Model are mediated by additional new particles.
- If these particles are sufficiently heavy, we can describe the interactions between DM and the Standard Model using effective interactions involving higher-dimensional operators.



	$\Delta\mathscr{L}$	Int.	Suppression
$\mathcal{O}_s^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}f$	SI	1
$\mathcal{O}_v^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_{va}^\phi$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2
$\mathcal{O}_p^\phi$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_s^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}f$	SI	1
$\mathcal{O}_v^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}_a^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	1
$\mathcal{O}_t^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\sigma^{\mu\nu}\psi\bar{f}\sigma_{\mu\nu}f$	SD	1
$\mathcal{O}_p^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4
$\mathcal{O}_{va}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2, q^2
$\mathcal{O}_{pt}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\sigma^{\mu\nu}\gamma^5\psi\bar{f}\sigma_{\mu\nu}f$	SI	q^2
$\mathcal{O}_{ps}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}i\gamma^5\psi\bar{f}f$	SI	q^2
$\mathcal{O}_{sp}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}_{av}^\psi$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu f$	SI SD	v^2 q^2
$\hat{\mathcal{O}}_s^\phi$:	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_s^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\psi\bar{f}f$	SI	1
$\hat{\mathcal{O}}_p^\psi$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4

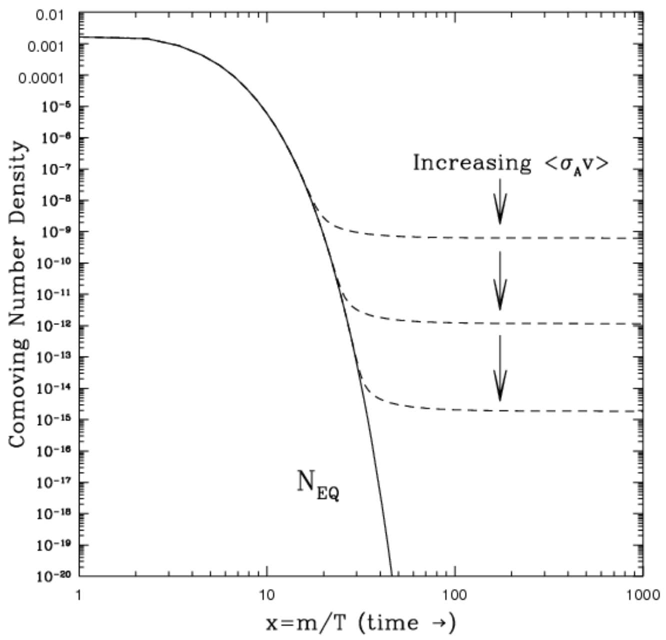
Thermal freeze-out

> In the early Universe, the density and temperature is so high that DM annihilation and DM production happen frequently and keep the DM particle in thermal equilibrium with the thermal bath of SM states.

> As the temperature drops below the DM mass, its number density becomes Boltzmann-suppressed, so that the rate of DM interactions decrease rapidly.

> Once the interaction rate drops below the expansion rate of the Universe, DM drops out of thermal equilibrium (its interactions "freeze out") and the (comoving) number density becomes constant.

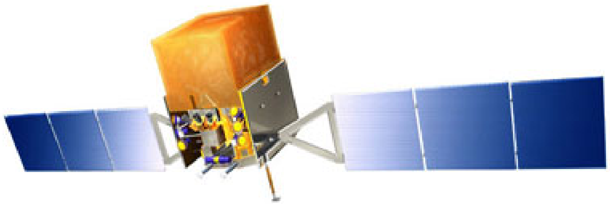
> Larger annihilation cross sections lead to smaller relic abundances.

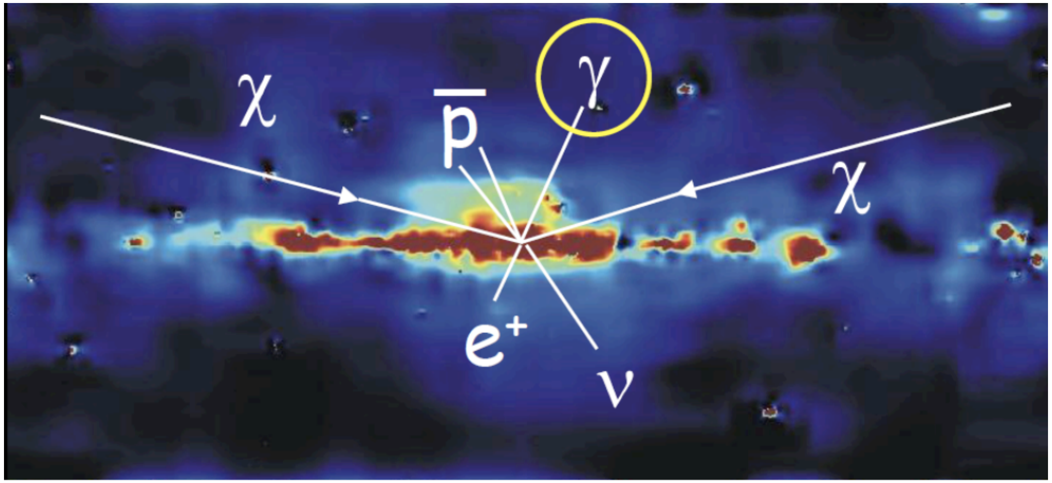


Dark matter indirect detection

In regions of high DM density (e.g. the galactic center), DM annihilation may still continue today.

Indirect detection experiments look for the annihilation products with satellites, balloons and ground based telescopes.



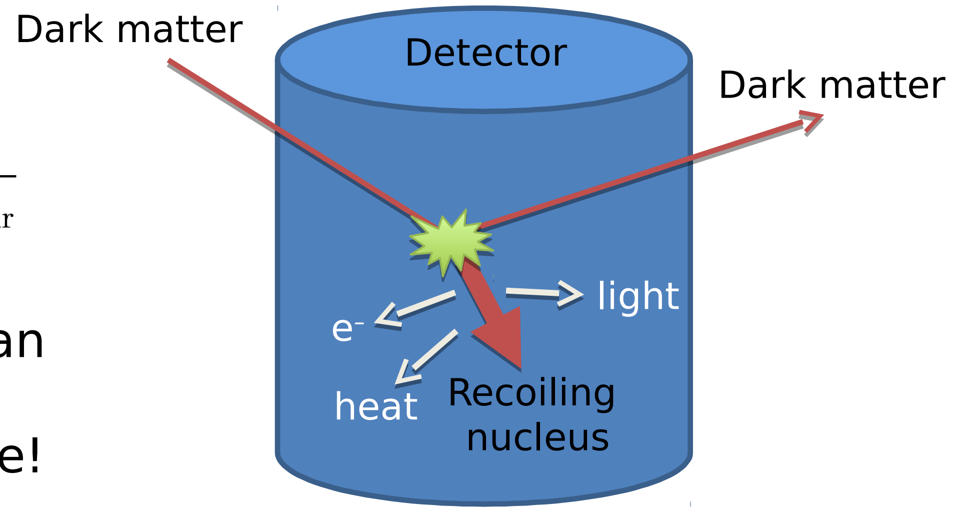


Difficulties arise from astrophysical backgrounds and the unknown DM density profile.

Dark matter direct detection

Dark matter particles from the Galactic halo that pass through the Earth will occasionally scatter off nuclei.
The resulting recoil energy of the nucleus can be measured in dedicated low background detectors.

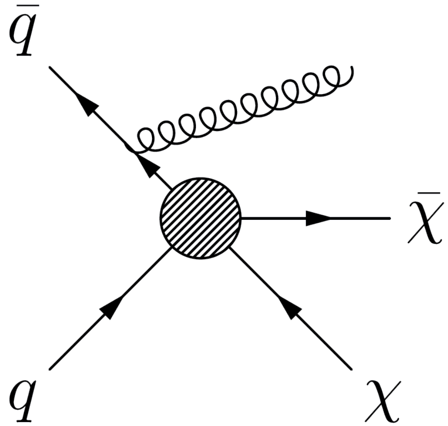
$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{nr}}} = \frac{\rho_0}{m_\chi m_{\mathrm{N}}} \int_{v_{\mathrm{min}}}^{\infty} \mathrm{d}v \, v f(v, v_{\mathrm{E}}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{nr}}}$$



Typical event rates are less than
1 event per kg per year
A great experimental challenge!

Collider searches for dark matter

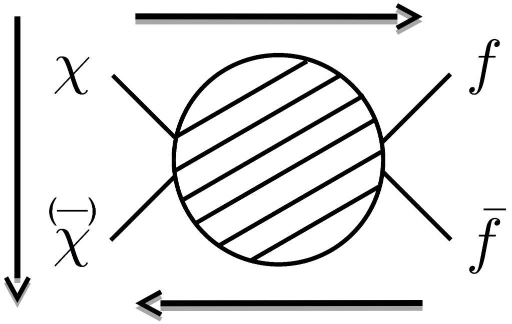
Any DM particles produced at colliders will escape from the detector unnoticed. But if other particles (such as jets) are produced in association with a pair of DM particles, we may observe large amounts of missing transverse energy .



Detecting dark matter particles

- In the effective operator approach, all DM searches constrain the same new-physics scale Λ, so we can directly compare bounds from different search strategies.

- However, the resulting bounds are often rather weak compared to LHC energies (Λ ~ 1 TeV still allowed), so it may be inconsistent to use this approach to interpret DM searches at the LHC.



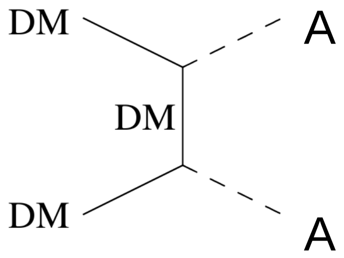
- Moreover, if the mediator is very heavy compared to the DM particle, it is typically very difficult to achieve a sufficiently large annihilation rate in the early Universe to avoid overproduction of DM.

Dark mediators

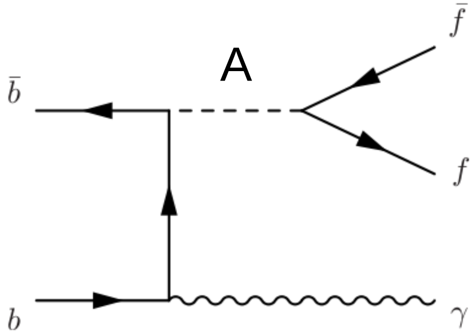
> If the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting:

- For mediator masses below a few TeV, the mediator may be produced on-shell at the LHC, leading to a resonant enhancement of the DM production cross section as well as other observable processes.

- If the mediator mass is smaller than the DM mass, DM can directly annihilate into pairs of mediators, which subsequently decay into SM states.



- The mediator will also lead to new interactions between Standard Model states, so there may be observable signals from processes involving no dark matter particles at all.



Part II.

GeV-scale pseudoscalar mediators

Motivation: pseudoscalars

- 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:

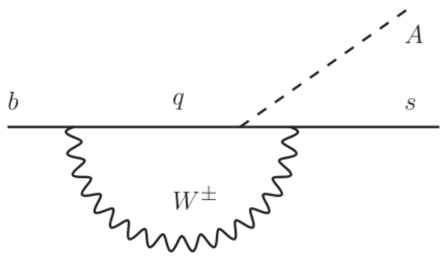
$$\sum_{f=q,\ell} \frac{C_{Af}}{2\, f_A} \bar{f} \gamma^\mu \gamma^5 f \, \partial_\mu A$$

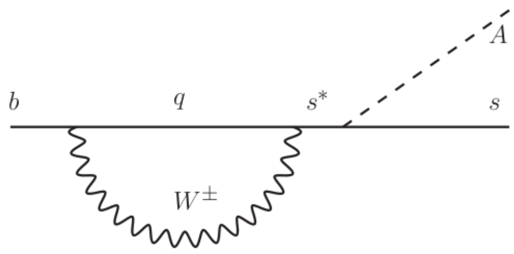
- Integrating by parts and using the equations of motion, this can be written as

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

Why 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 $K \rightarrow \pi A$ or $B \rightarrow K A$.
  - 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

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

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

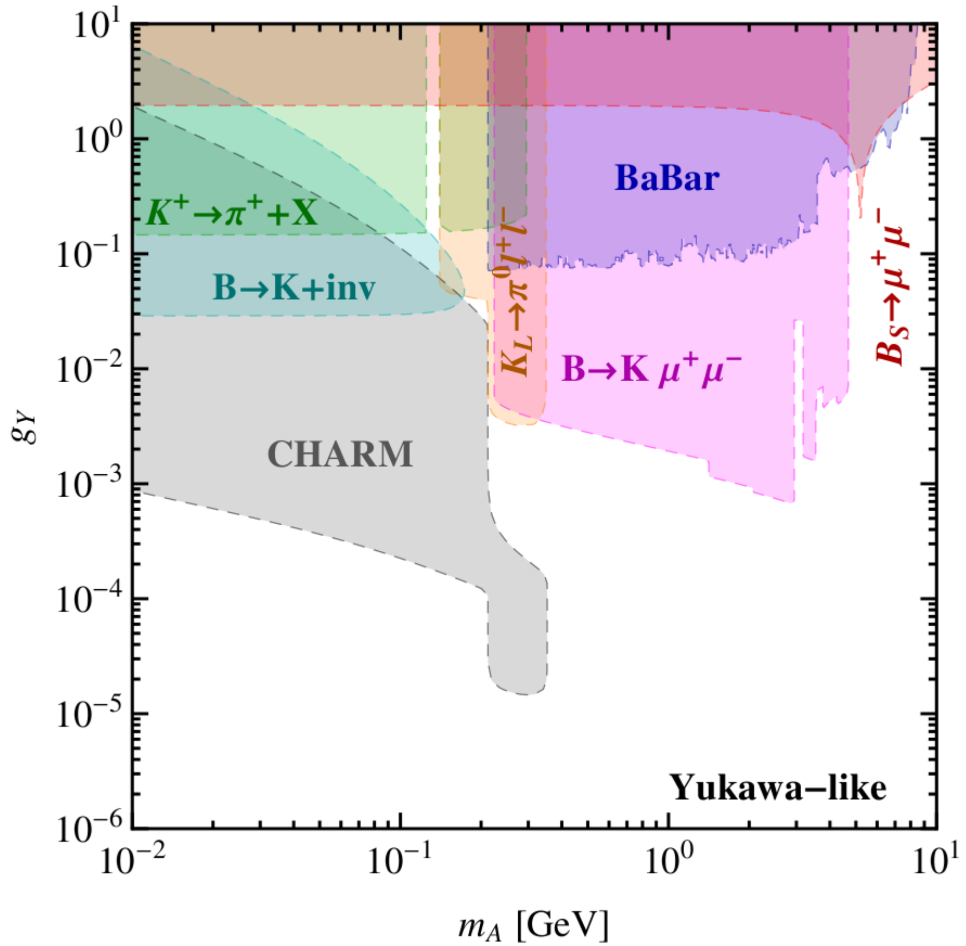
Step 1: Determine the amplitude h_{ds} for the flavour-changing transition $s \to d\, A$.

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

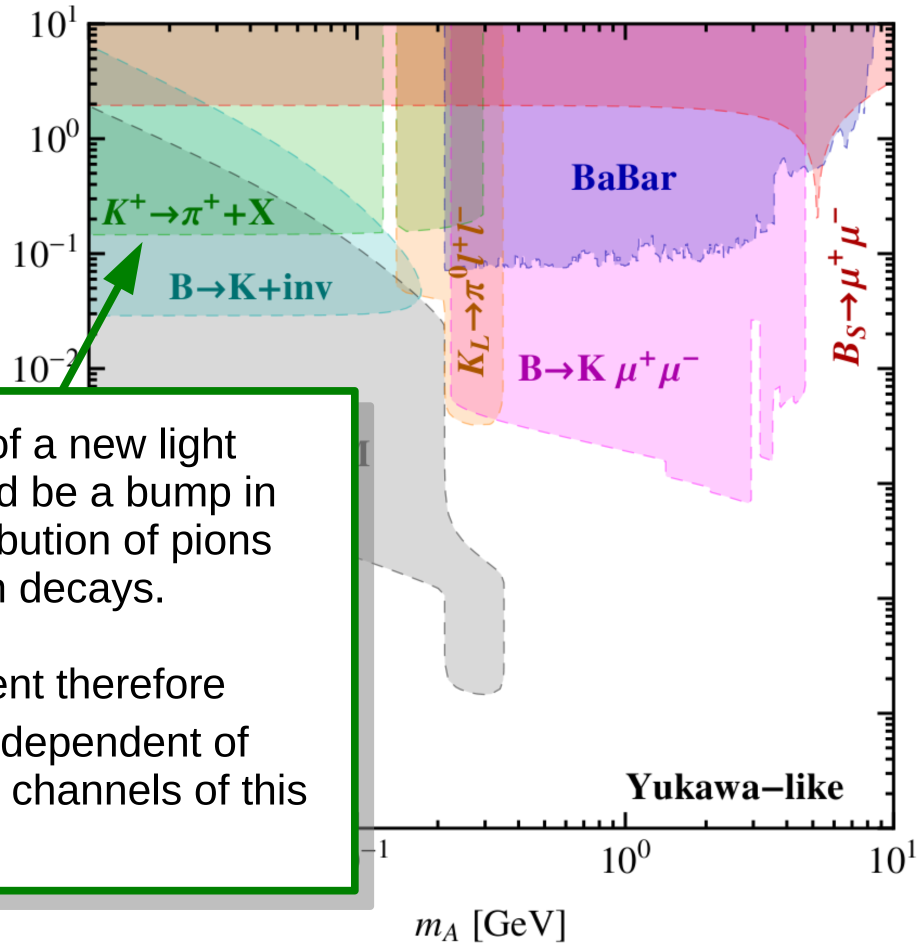
Step 1: Determine the partial decay width for loop-induced decays into photons.

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

Experimental results

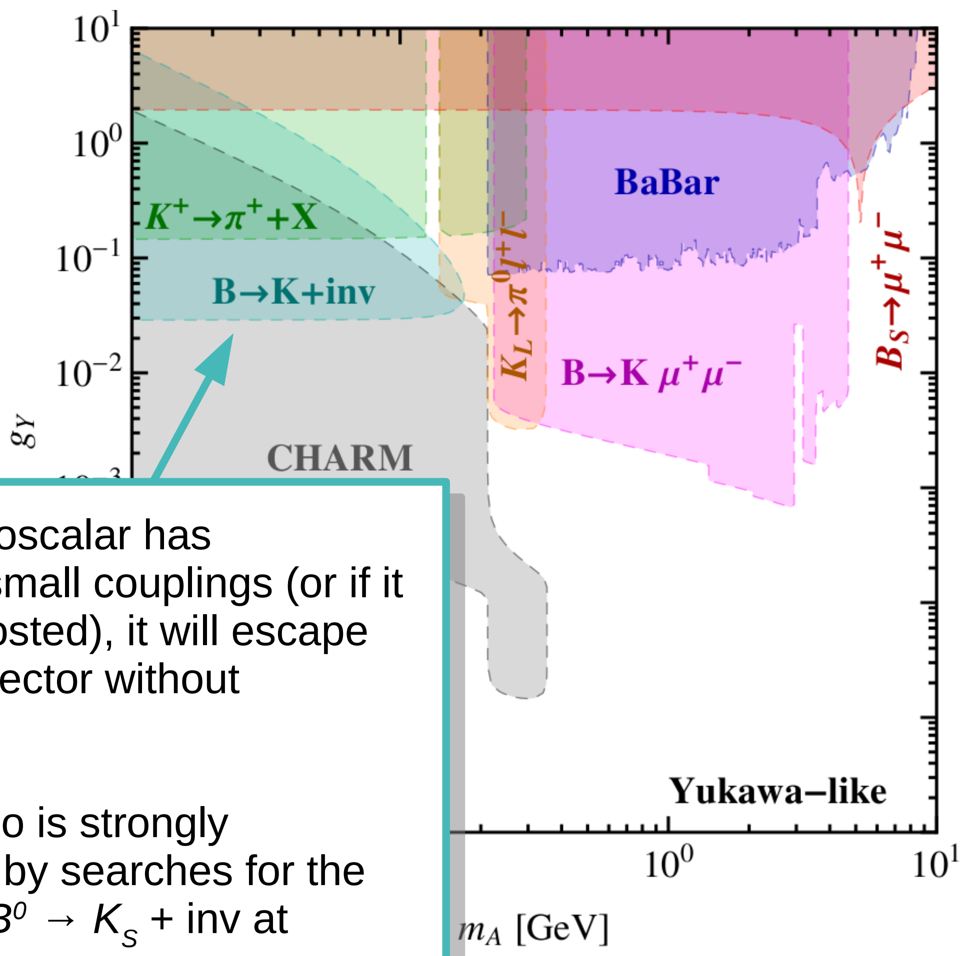


Experimental results



- 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.

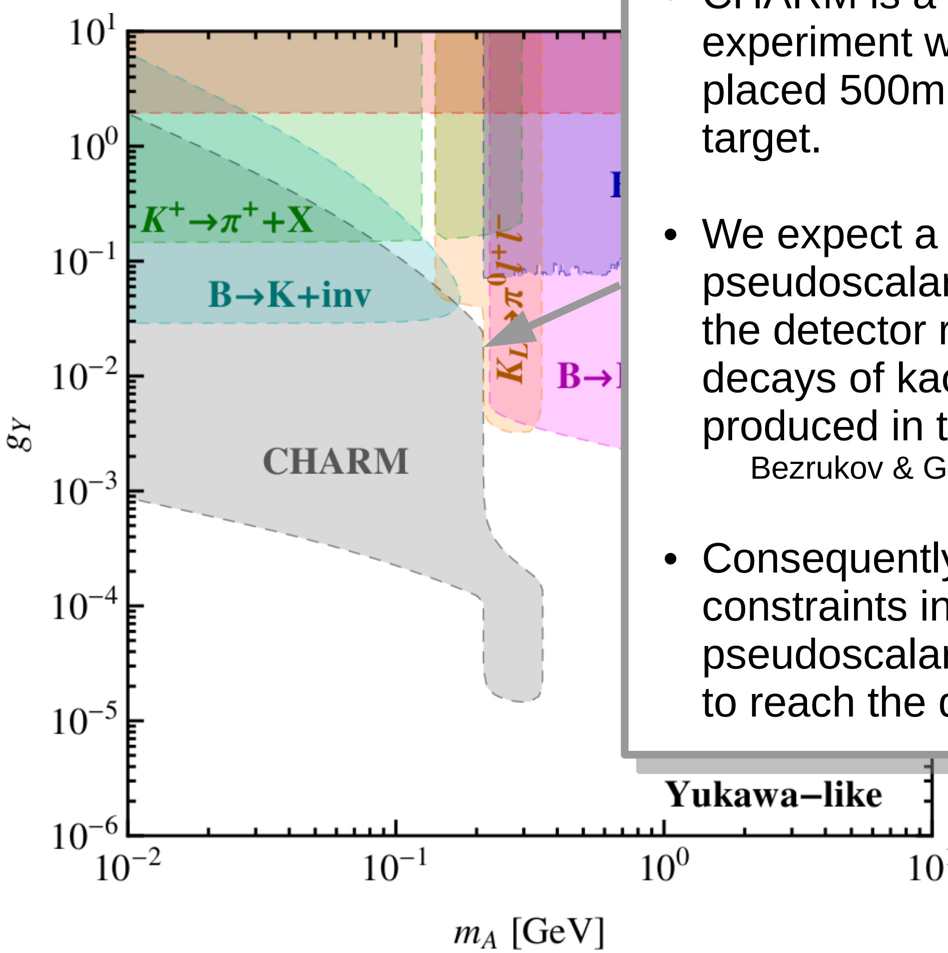
Experimental results



- 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.

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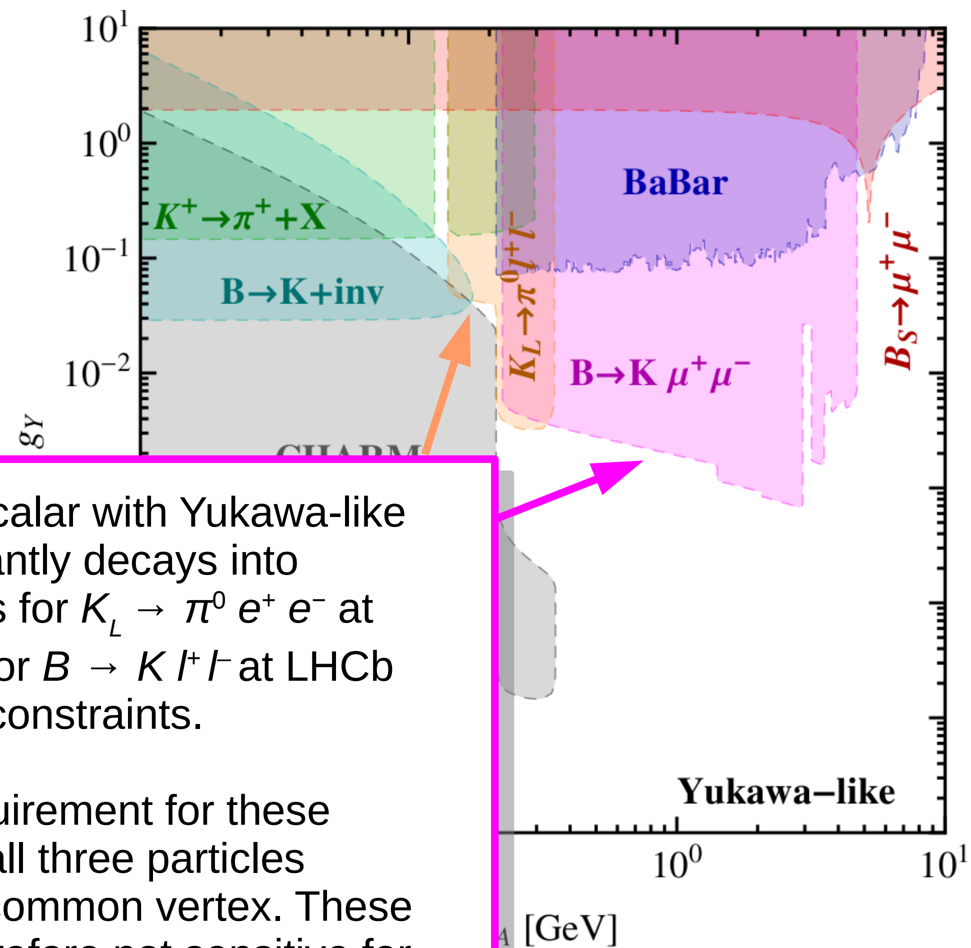
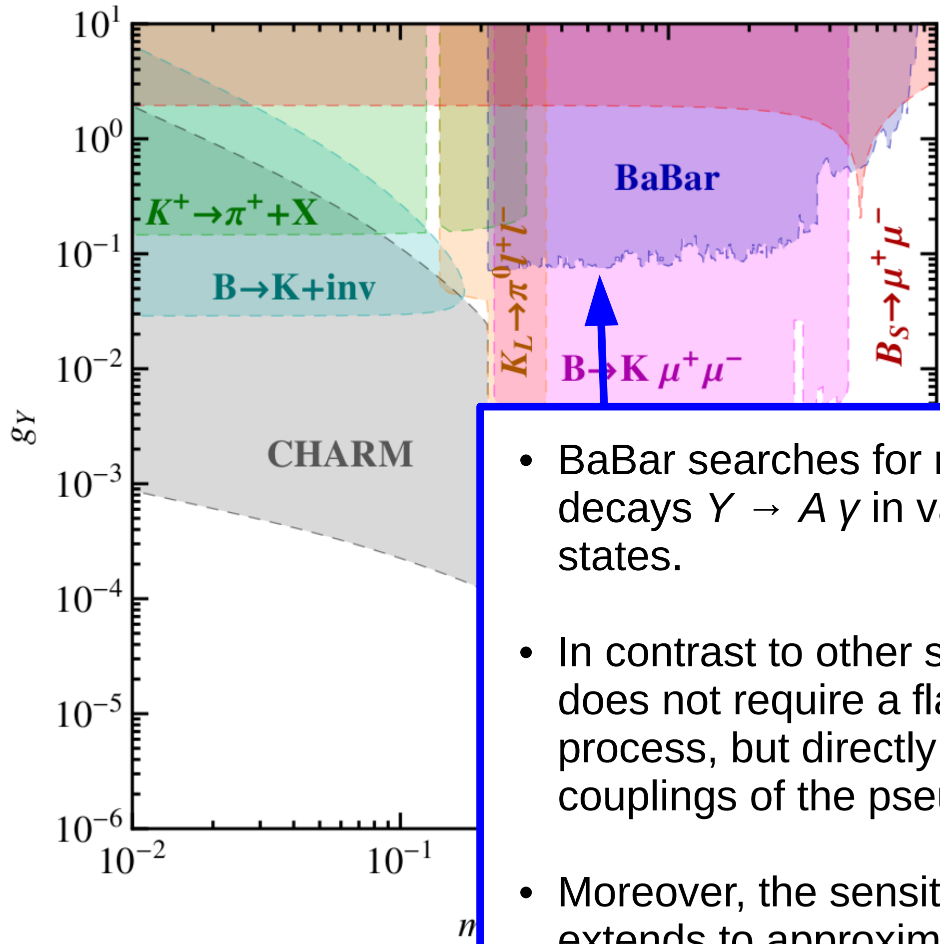
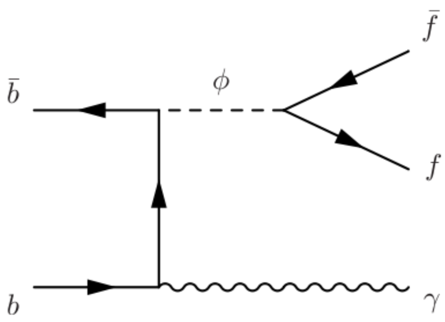
Experimental results



- 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.

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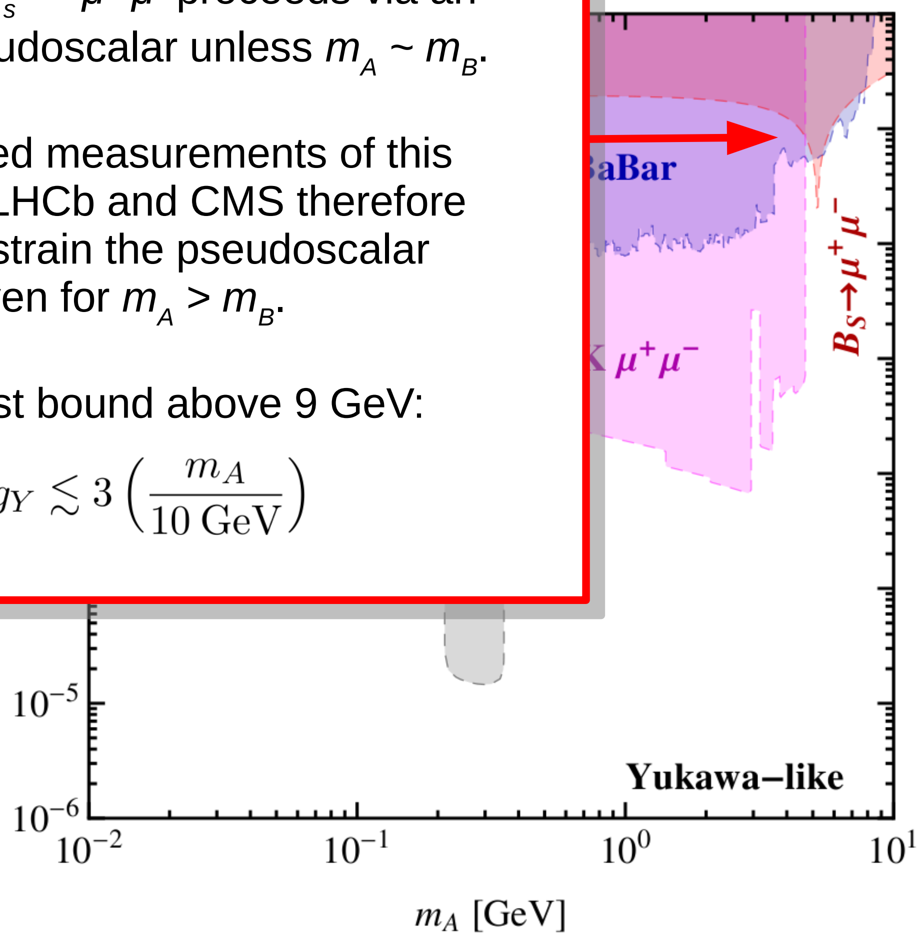
Experimental results

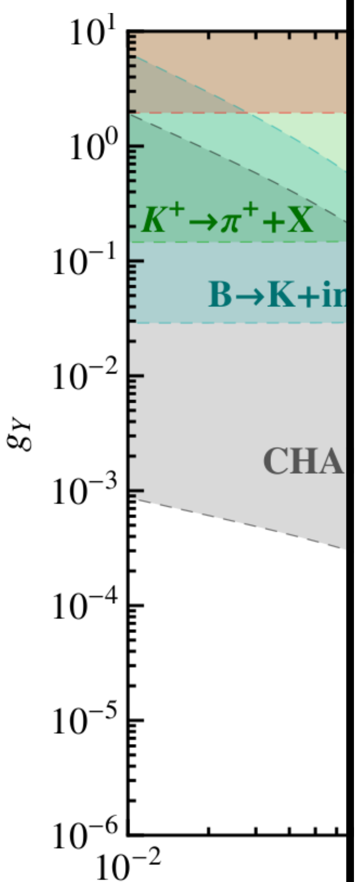
- The decay $B_s \to \mu^+ \mu^-$ proceeds via an off-shell pseudoscalar unless $m_A \sim m_B$.
- The combined measurements of this decay from LHCb and CMS therefore allow to constrain the pseudoscalar couplings even for $m_A > m_B$.

→ The strongest bound above 9 GeV:

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



Experimental results

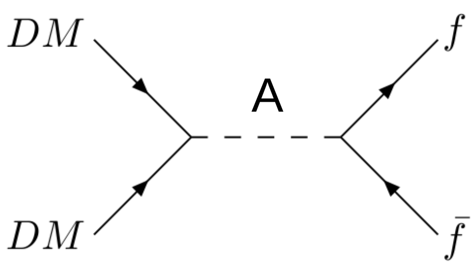


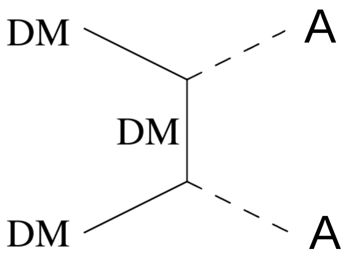
Channel	Experiment	Mass range [MeV]	Ref.	Relevant for
$K^+ \to \pi^+ + \text{inv}$	E949	0–110	[70]	Long lifetime*
		150–260	[71]	Long lifetime*
	E787	0–110 & 150–260	[72]	Long lifetime
$K^+ \to \pi^+\pi^0 \to \pi^+\nu\bar{\nu}$	E949	130–140	[73]	Long lifetime*
$K^+ \to \pi^+ e^+e^-$	NA48/2	140–350	[74]	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*
$B^0 \to K^0_S + \text{inv}$	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.

The dark matter connection

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





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

→ s-wave annihilation
→ depends on g_f and g_x

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

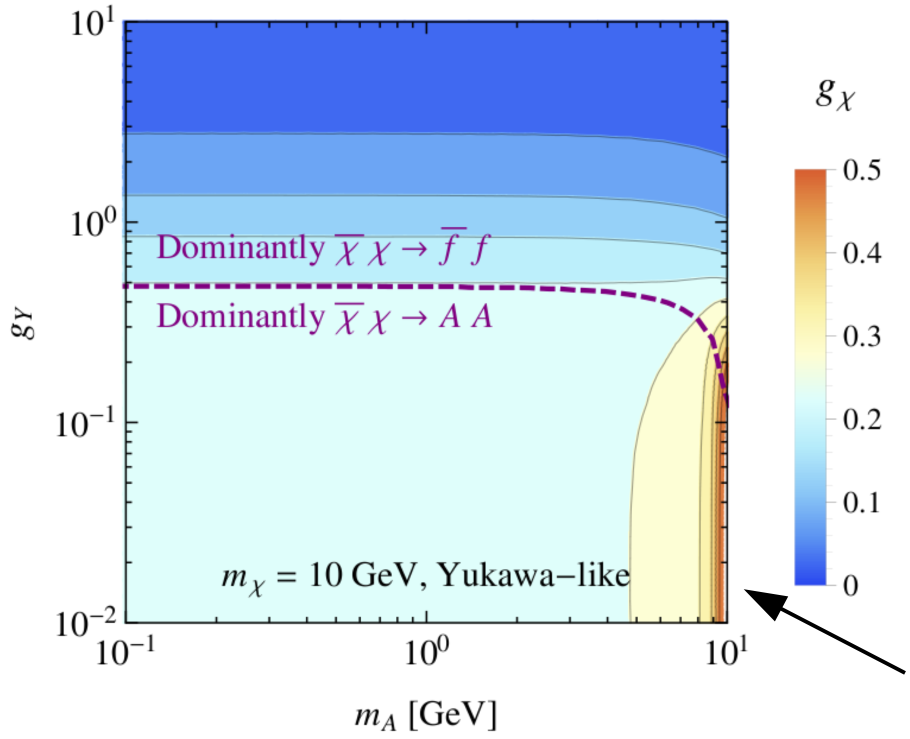
→ p-wave annihilation
→ depends only on g_x

- 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.

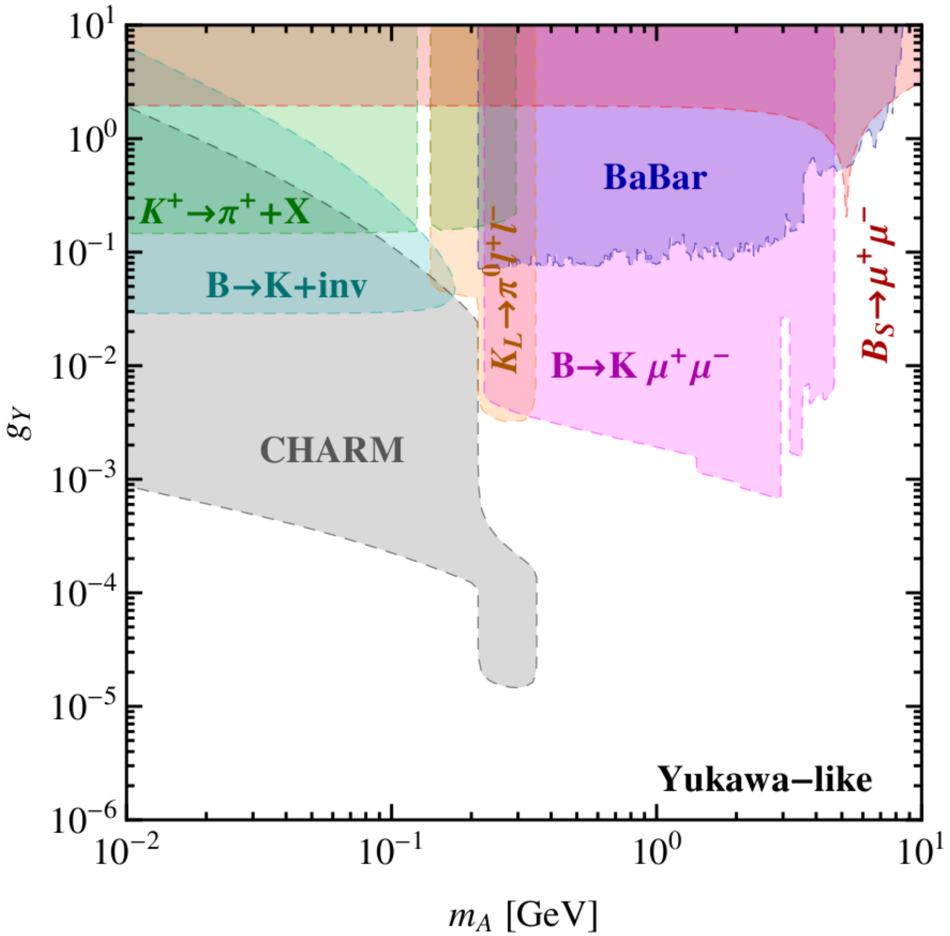
Relic density calculation

- 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.

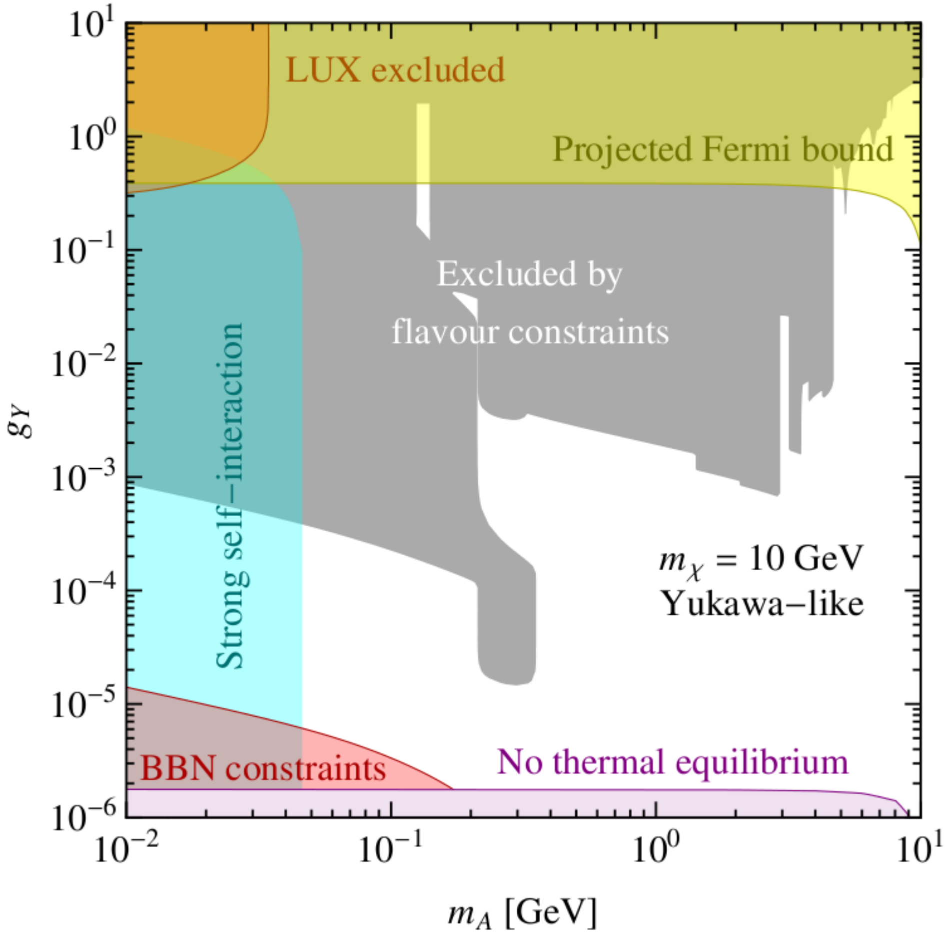


Phase-space suppression of annihilation into pseudoscalars for $m_A \sim m_\chi$.

Dark matter constraints

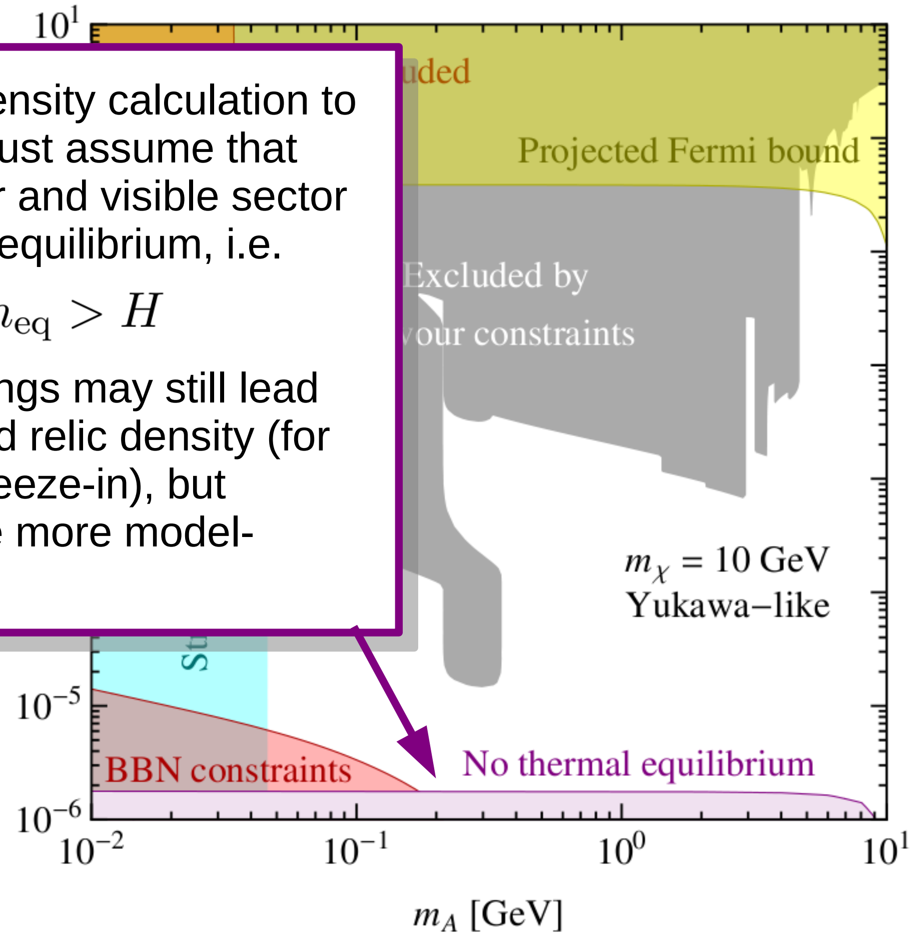


Dark matter constraints



g_x fixed by relic density requirement!

Dark matter constraints

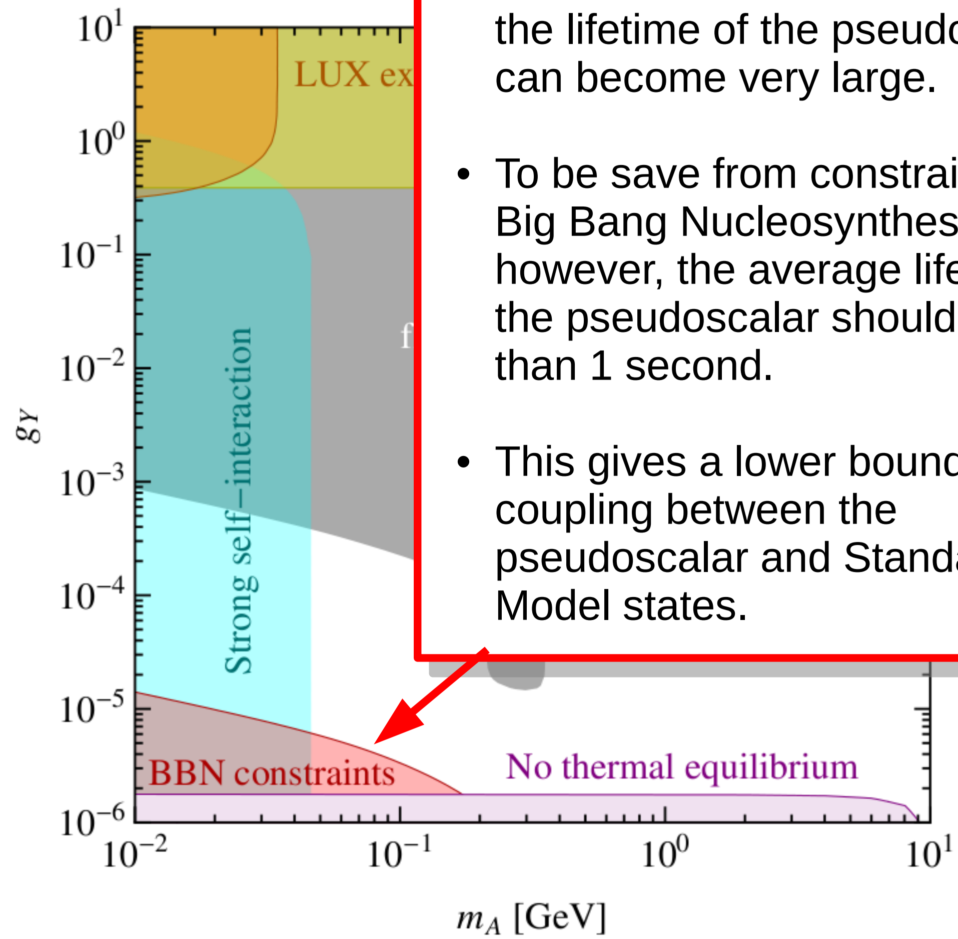


- For the relic density calculation to be valid, we must assume that the dark sector and visible sector reach thermal equilibrium, i.e.

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

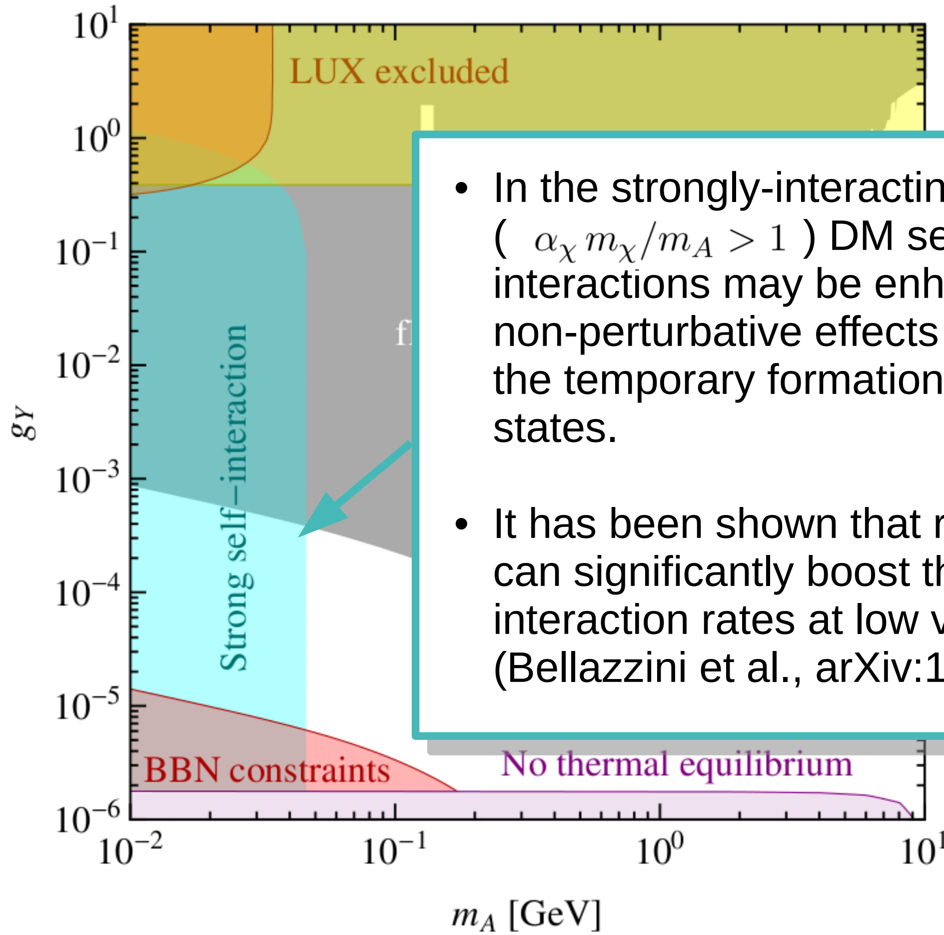
- Smaller couplings may still lead to the observed relic density (for example via freeze-in), but predictions are more model-dependent.

Dark matter constraints



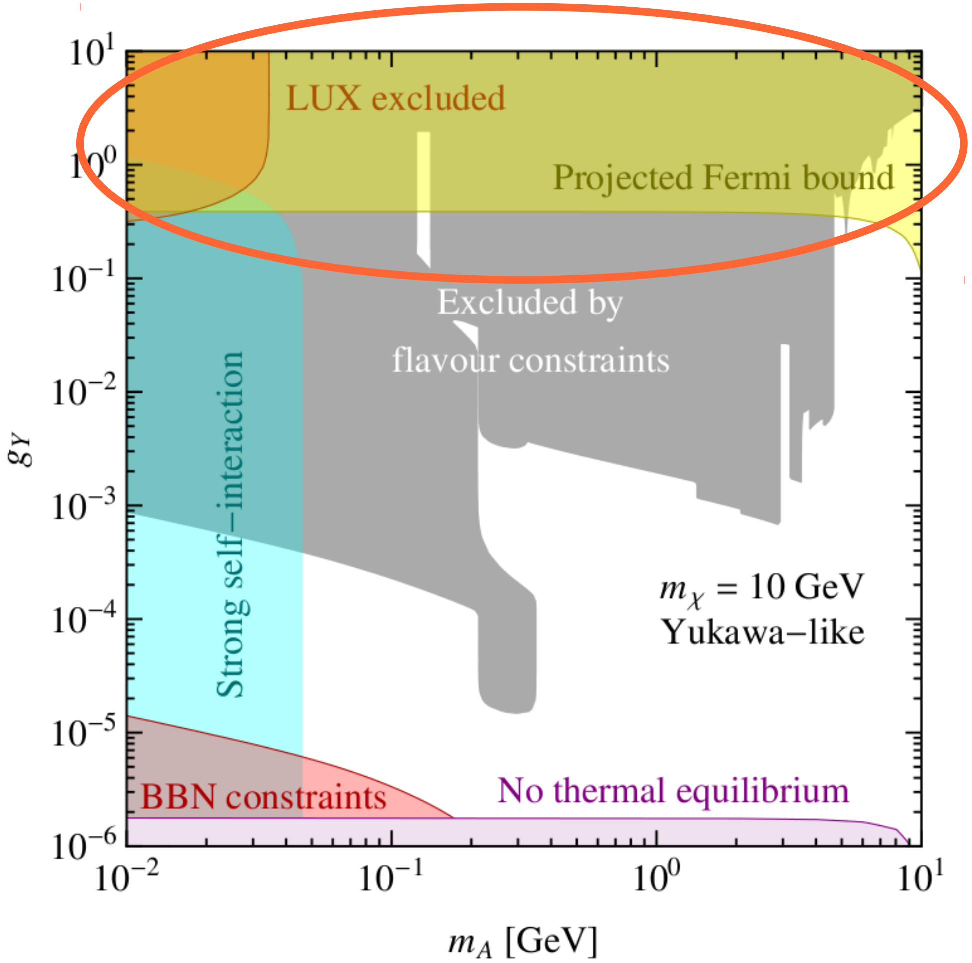
- For m_A below the muon mass, the lifetime of the pseudoscalar can become very large.
- To be save from constraints from Big Bang Nucleosynthesis, however, the average lifetime of the pseudoscalar should be less than 1 second.
- This gives a lower bound on the coupling between the pseudoscalar and Standard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

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:

$$q \sim \mu\, v \qquad v \simeq 10^{-3} c$$

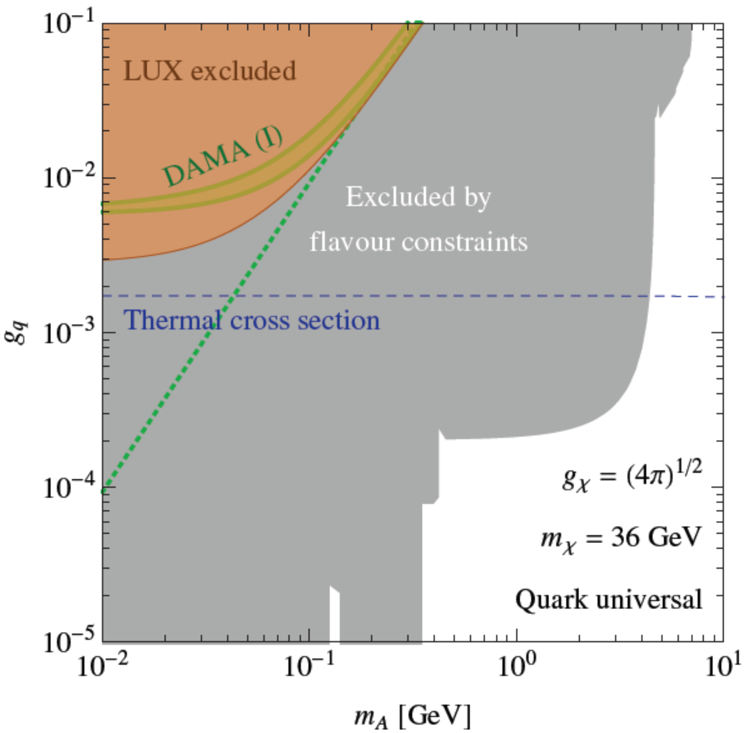
- For very light mediators ($m_A^2 < q^2$), the momentum suppression can be cancelled by the propagator and event rates in direct detection experiments may become observable.
- Interestingly, pseudoscalars couple dominantly to the proton spin, so constraints from Xe-based experiments (like LUX) are much less severe than for standard interactions. It might therefore be possible to reconcile LUX with the DAMA modulation.

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

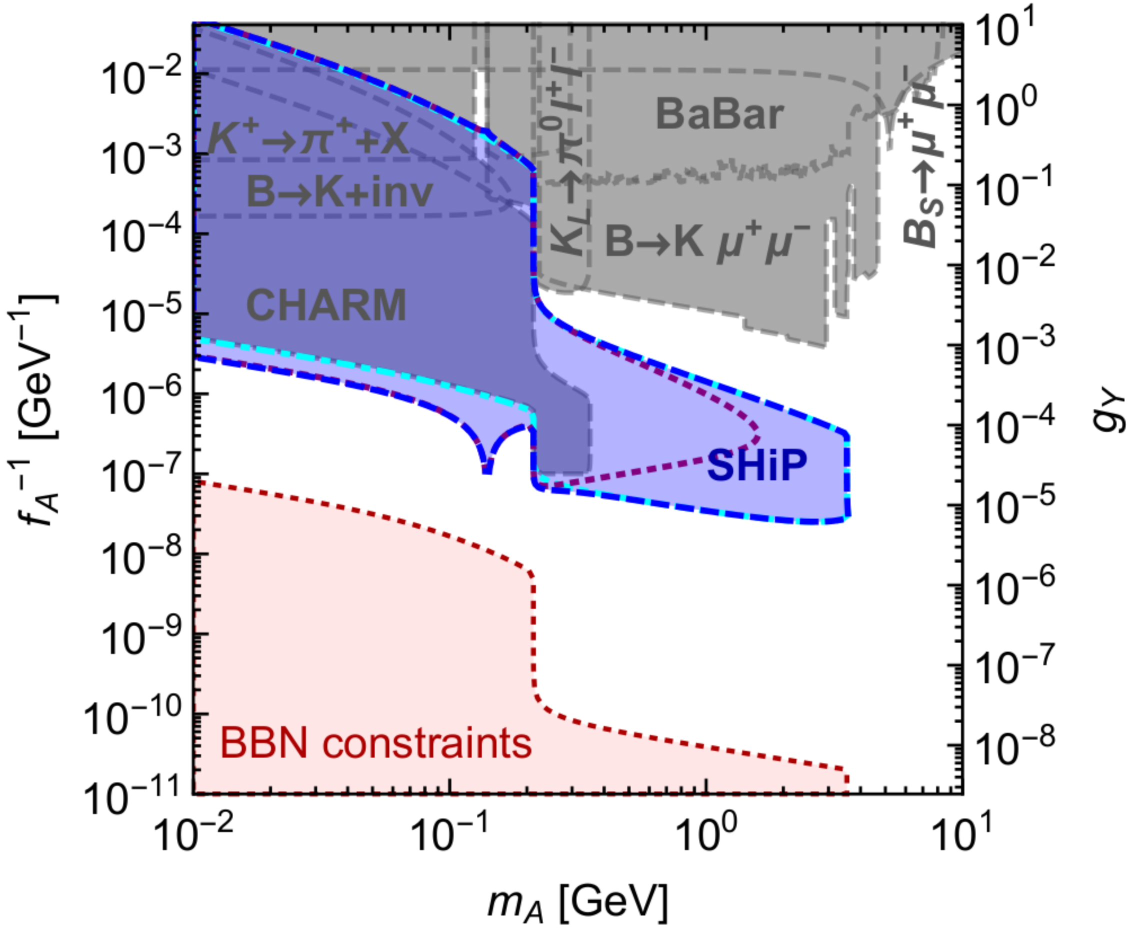
$$\mathcal{L}_{\rm SM}^{(q)} = i\, g_q \sum A\, \bar{q}\gamma^5 q$$



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

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 (e.g. for displaced vertices) are particularly promising.



Alekhin, FK et al., arXiv:1504.04855

Part III.

TeV-scale axial-vector mediators

Motivation: Axial-vector mediators

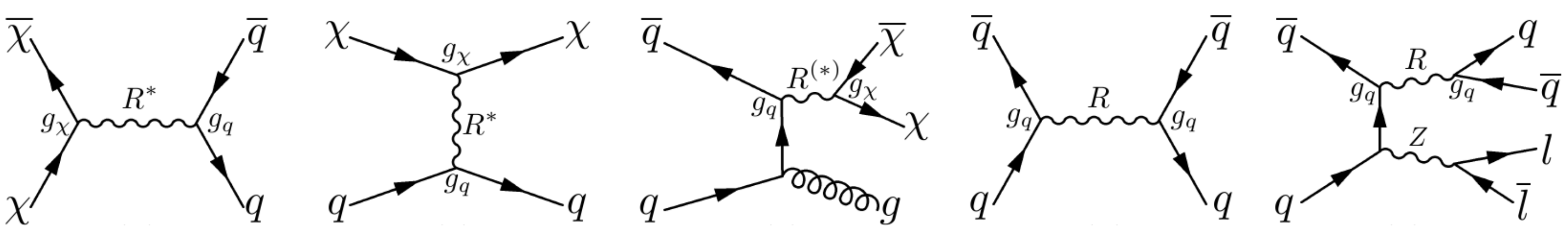
- For mediators with a mass between 100 GeV and a few TeV, the strongest constraints are expected to come from LHC searches.
- We study these constraints by considering the case of an axial-vector mediator, which could for example be a massive *Z'* arising from a new broken *U(1)'* gauge symmetry:

$$\mathcal{L} \supset g_\chi^A \, \bar{\chi}\gamma^\mu\gamma^5\chi \, R_\mu + \sum_q g_q^A \, \bar{q}\gamma^\mu\gamma^5 q \, R_\mu$$

Dudas et al., arXiv:0904.1745; Arcadi et al., arXiv:1401.0221; Lebedev & Mambrini, arXiv:1403.4837; Frandsen, FK et al., arXiv:1107.2118; An et al., arXiv:1202.2894, arXiv:1212.2221; Alves et al., arXiv:1312.5281, arXiv:1501.03490

- This set-up is particularly well suited for demonstrating the complementarity between different experimental probes.

Frandsen, FK et al., arXiv:1204.3839; Buchmueller et al., arXiv:1308.6799; Buchmueller et al., arXiv:1407.8257; Harris et al., arXiv:1411.0535



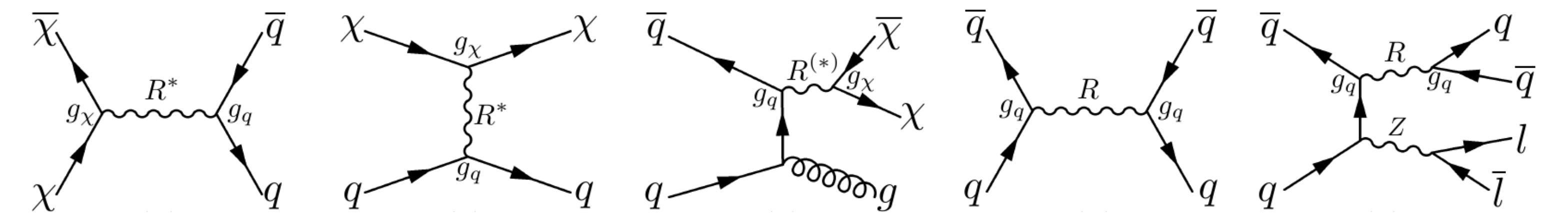
Motivation: Phenomenology

- Any cross section involving interactions between the visible sector and DM via an off-shell mediator will scale as $\sigma \propto g^4$, where $g = \sqrt{g_q\, g_\chi}$.
- However, the local dark sector particle (DSP) density ρ_{DSP} is proportional to the relic abundance Ω_{DSP}, which scales according to

$$\Omega_{\text{DSP}} \propto \frac{1}{\langle \sigma v \rangle} \propto g^{-4}$$

where we allow for the possibility that the DSP is underproduced in the early Universe and hence constitutes only a fraction of the DM.

Process:



Rate:	$(\sigma \times \rho^2) \propto g^{-4}$	$(\sigma \times \rho) \propto g^0$	$\sigma \propto g^4$	$\sigma_R \propto g_q^2$	$\sigma_R \propto g_q^2$

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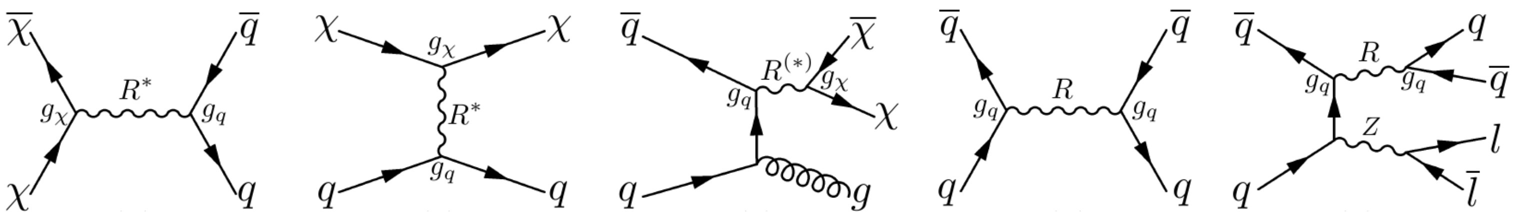

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$(\sigma \times \rho^2) \propto g^{-4}$	$(\sigma \times \rho) \propto g^0$	$\sigma \propto g^4$	$\sigma_R \propto g_q^2$	$\sigma_R \propto g_q^2$

The different DM searches are parametrically complementary

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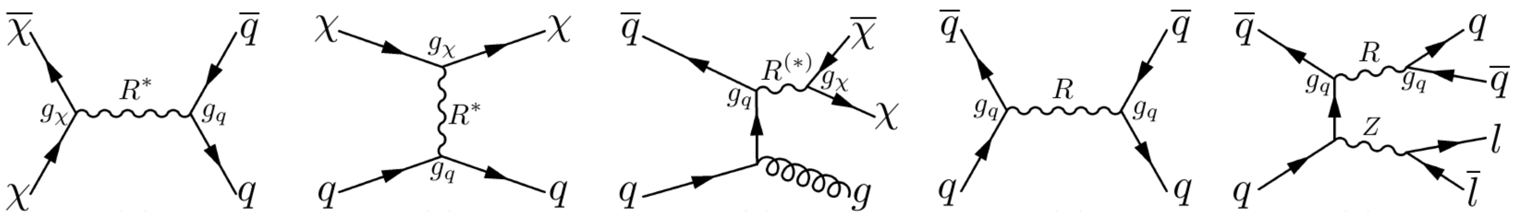


Rate:

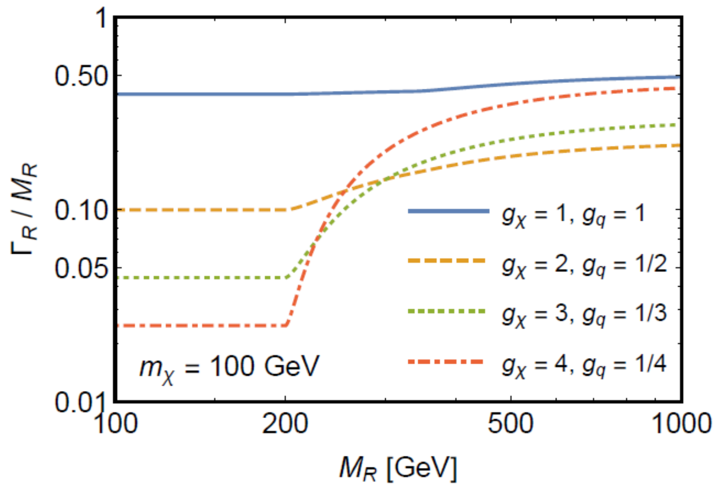
$(\sigma \times \rho^2) \propto g^{-4}$	$(\sigma \times \rho) \propto g^0$	$\sigma \propto g^4$	$\sigma_R \propto g_q^2$	$\sigma_R \propto g_q^2$

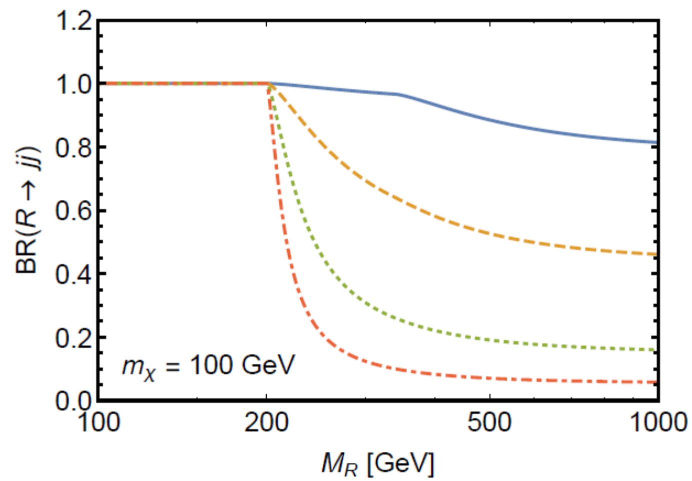
The different DM searches are parametrically complementary

Resonance searches break the degeneracy between g_χ and g_q.

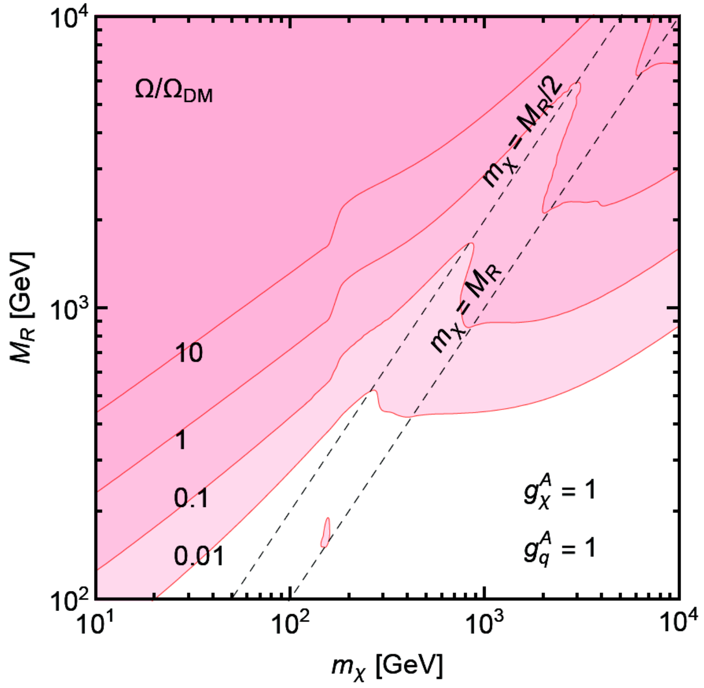
Motivation: Axial-vector mediators

- In reality, cross sections exhibit a somewhat more complicated dependence on the ratio m_χ/M_R.
- This ratio determines whether certain processes are kinematically allowed and whether there can be resonant enhancements.
- If the mediator can be produced on-shell, the branching ratios of the relevant decay channels will depend sensitively on the coupling ratio g_χ^A/g_q^A .
  - For $g_\chi^A/g_q^A \lesssim 4$ the mediator decays dominantly into quarks.
  - For $g_\chi^A/g_q^A \gtrsim 4$ the mediator decays dominantly into DSPs as soon as the phase space for this decay channel opens up.



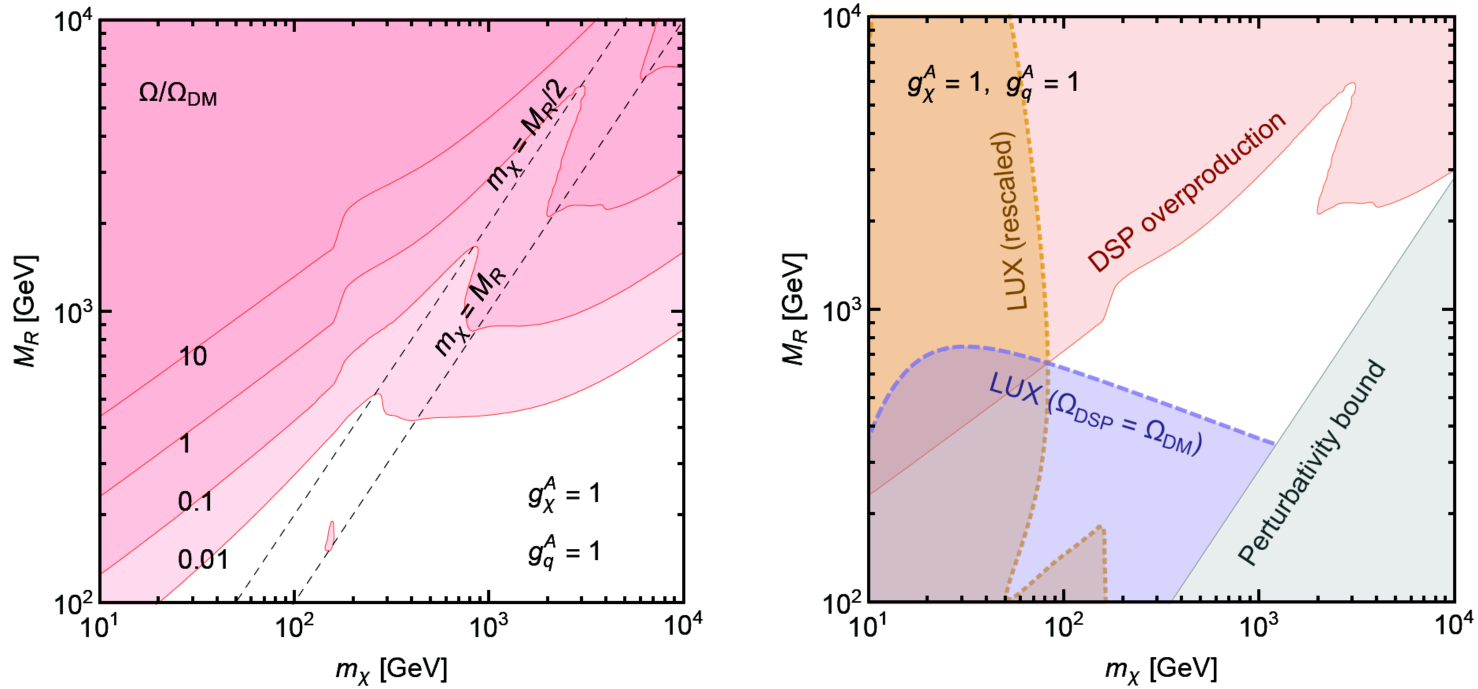


Relic density constraints



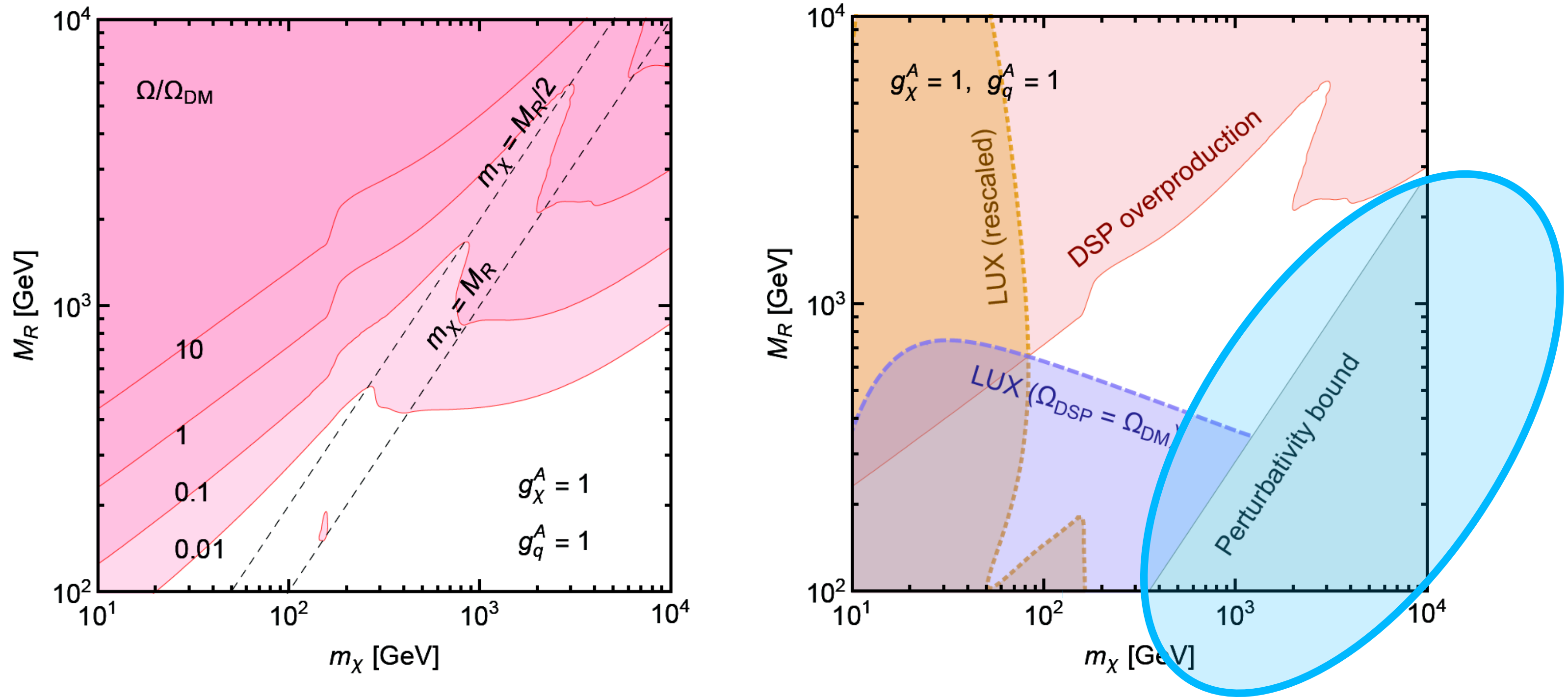
- The *s*-wave contribution to the annihilation cross section is helicity suppressed, so higher-order terms in the velocity expansion must be considered.
- Close to the resonance, the velocity expansion breaks down entirely, so we use micrOMEGAs to take into account the full expression.

Relic density constraints



- The DSP-nucleus interactions are spin-dependent, so we re-analyse the published LUX results (for spin-independent interactions) in this context.
- We can then rescale the conventional bound (assuming $\Omega_{DSP} = \Omega_{DM}$) using the results from the relic density calculation. This rescaling weakens the bound from direct detection in the parameter region where the DSP is underproduced.

Relic density constraints



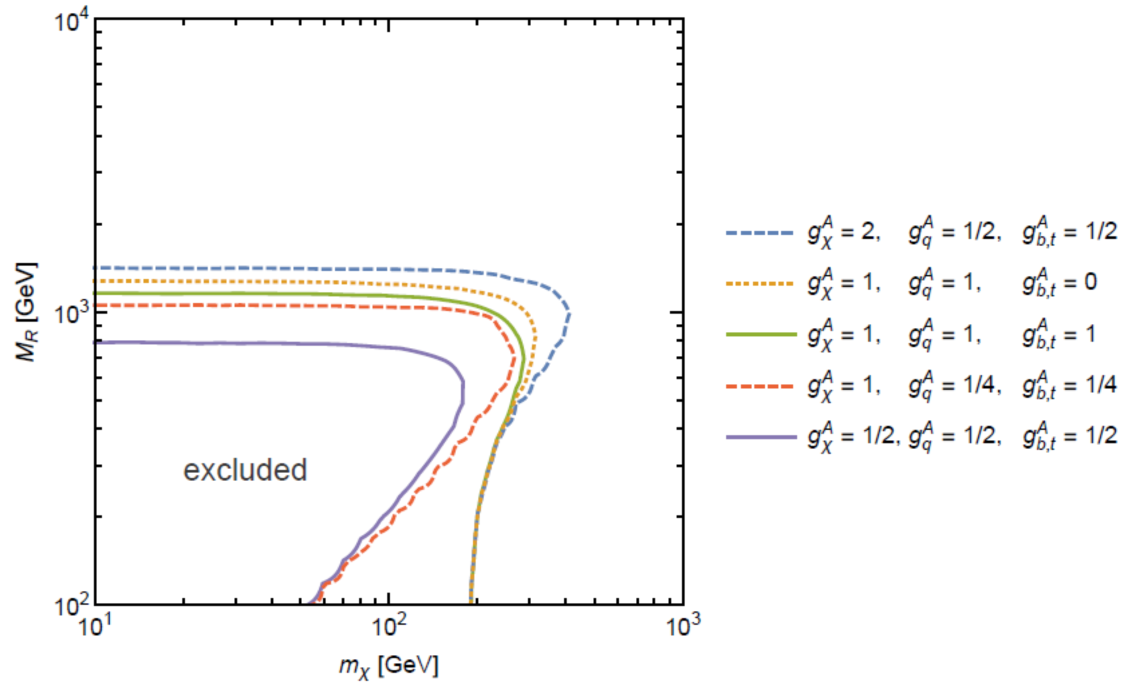
- Another important bound comes from the fact that the DSP mass cannot be raised arbitrarily above the mediator mass, if both masses are generated by the same mechanism in a perturbative UV-completion.
- Indeed, we must impose $M_R > g_\chi^A \, m_\chi / \sqrt{4\pi}$ to ensure that DSP scattering and annihilation via the longitudinal component of *R* do not violate perturbative unitarity. Shoemaker & Vecchi, arXiv:1112.5457; Busoni et al., arXiv:1307.2253, arXiv:1402.1275

Collider constraints: Monojets

- MET > 450 GeV
- $p_T(j_1)$ > 110 GeV
- No tertiary jets
- Event simulation in the Powheg-Box

Haisch, FK, Re, arXiv:1310.4491

- Showering with Pythia 6.



> Monojet searches are most sensitive for $m_\chi < M_R/2$, such that the mediator can be on-shell and there is a resonant enhancement.

For small DSP masses, current searches (here from CMS arXiv:1408.3583) probe mediator masses up to 1–1.5 TeV.

> Even for rather large couplings there is yet insufficient energy to produce DSPs with masses above 300–400 GeV.

Collider constraints: Dijets

- Searches for dijet resonances give the strongest constraints when the invisible branching ratio of the mediator is small, either because g_χ^A / g_q^A is small or because the invisible decay channel is kinematically closed.
- There are, however, two important complications limiting the sensitivity of dijet searches in the context of our model:

Dobrescu & Yu, arXiv:1306.2629

1. For small mediator masses (MR < 1 TeV) the QCD background (from two gluons in the initial state) becomes so large, that the LHC cannot record and process all of these events.

2. For large couplings the width of the mediator becomes so large that the usual searches for narrow resonances no longer apply.

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   Solution: Consider dijet searches from UA2 and Tevatron, as well as LHC searches with smaller backgrounds, such as searches for dijet resonances produced in association with Z and W bosons.

   ATLAS-CONF-2013-074

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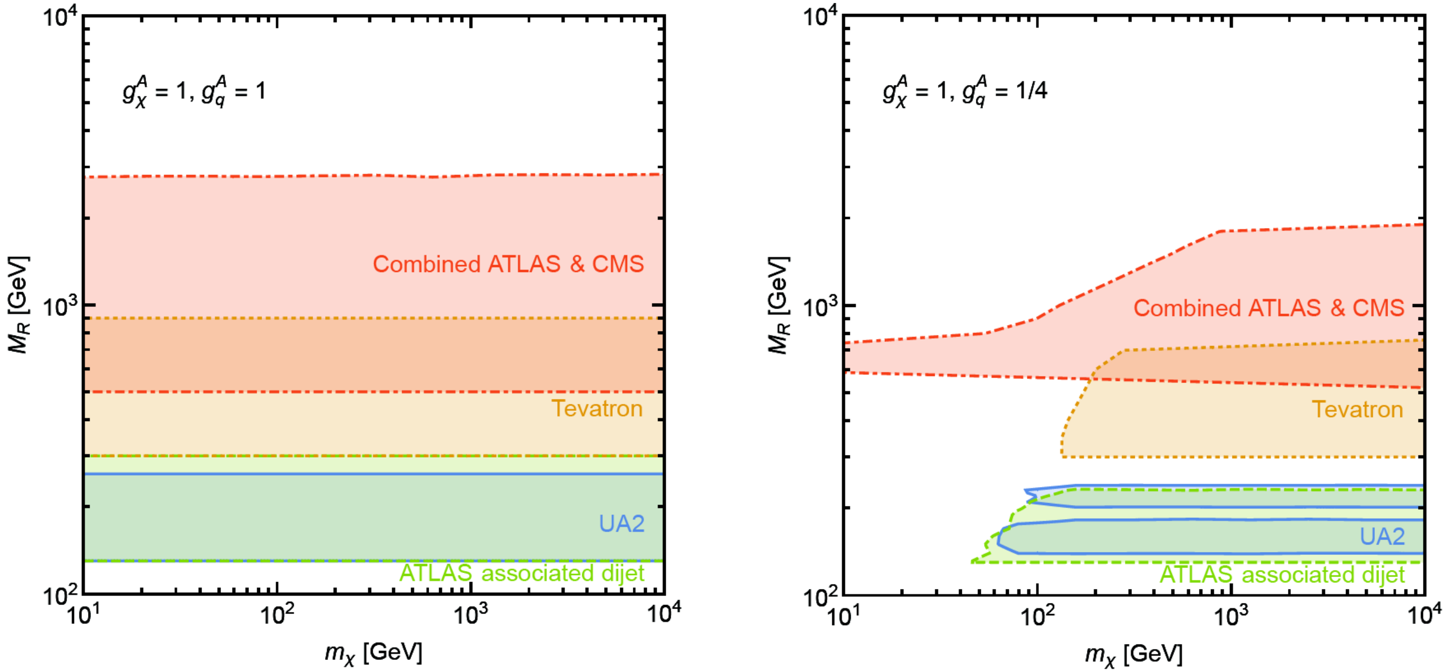
   ATLAS-CONF-2013-074

2. For large couplings the width of the mediator becomes so large that the usual searches for narrow resonances no longer apply.

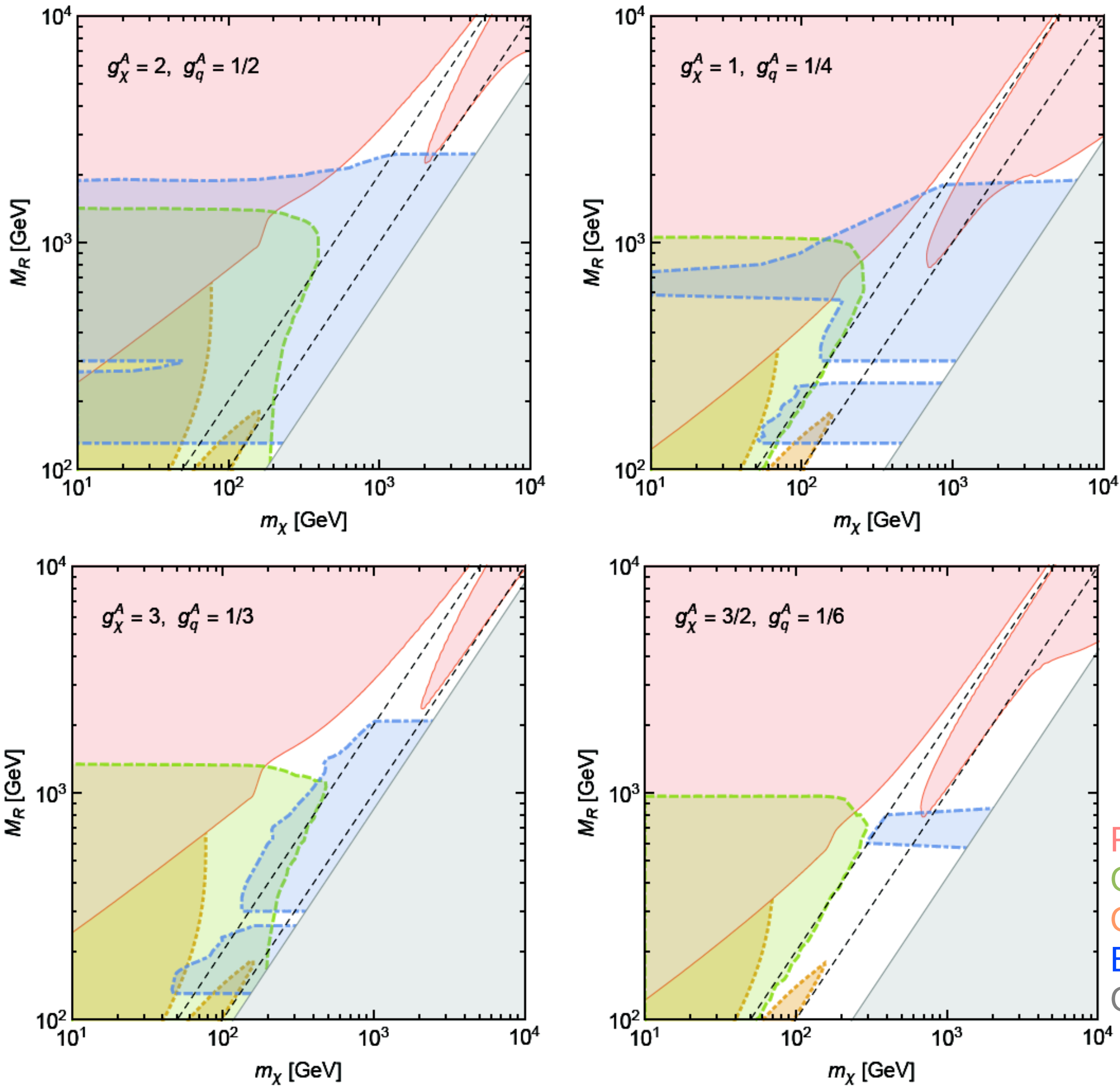
   Solution: Reinterpret existing searches in terms of broad resonances using MadGraph+Pythia6+Delphes for the signal generation and FastJet+MadAnalysis+MCLimit for the analysis.

Dijets: Results



- We find that (at least as long as $g_q < 1$), we obtain stronger bounds for larger couplings, i.e. the enhancement of the production cross section overcompensates the reduction of the efficiency due to the broadening of the resonance.
- For $g_q = g_\chi = 1$, we exclude all mediator masses with 130 GeV < M_R < 2.8 TeV.
- For smaller quark couplings, dijet searches are most sensitive to $M_R > 2\, m_\chi$.

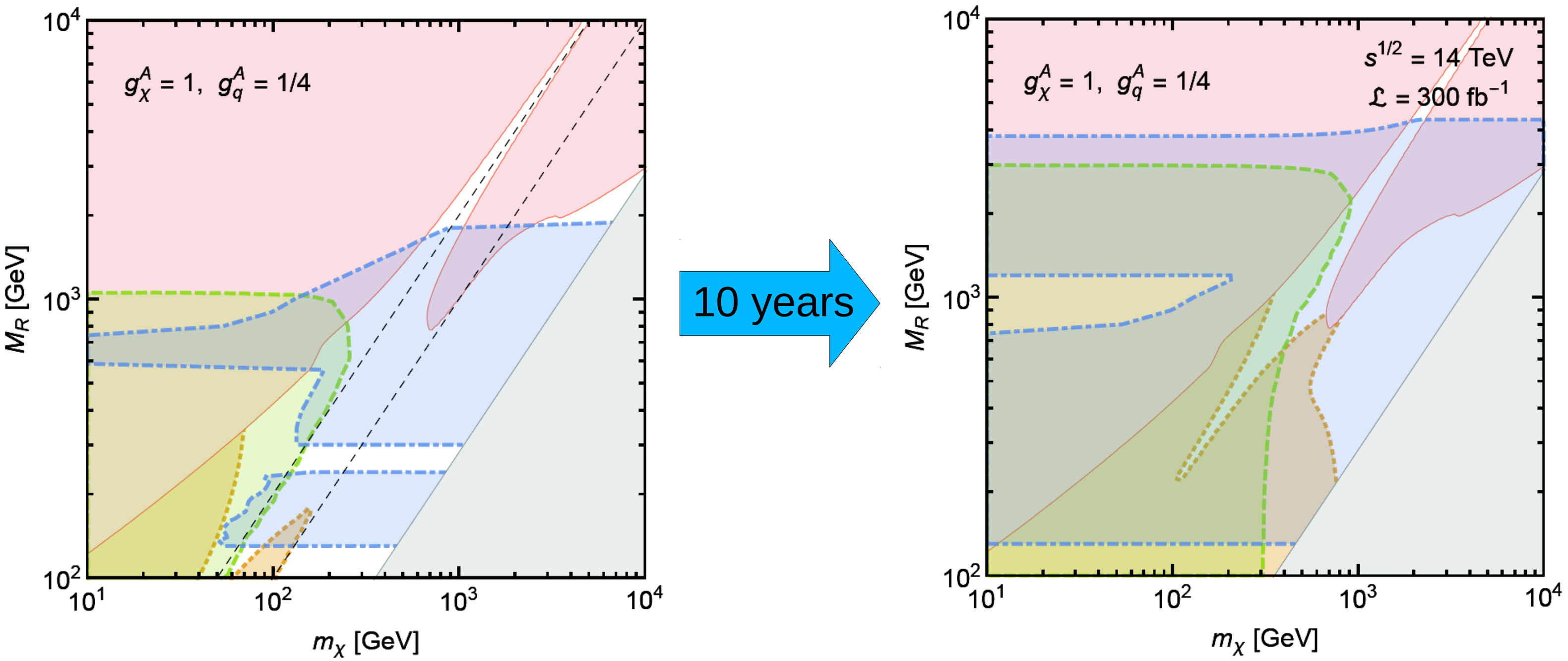
Combined constraints



- Almost no constraints from direct detection in the parameter region where the DSP is underproduced.
- Strong complementarity between monojet searches and dijet searches
- For g > 0.5, only small mass ranges remain viable.
- Presently very limited sensitivity for g < 0.2.

Red (solid line): Relic density
Green (dashed line): Monojets
Orange (dotted line): Direct detection
Blue (dot-dashed line): Dijets
Grey (solid line): Perturbativity

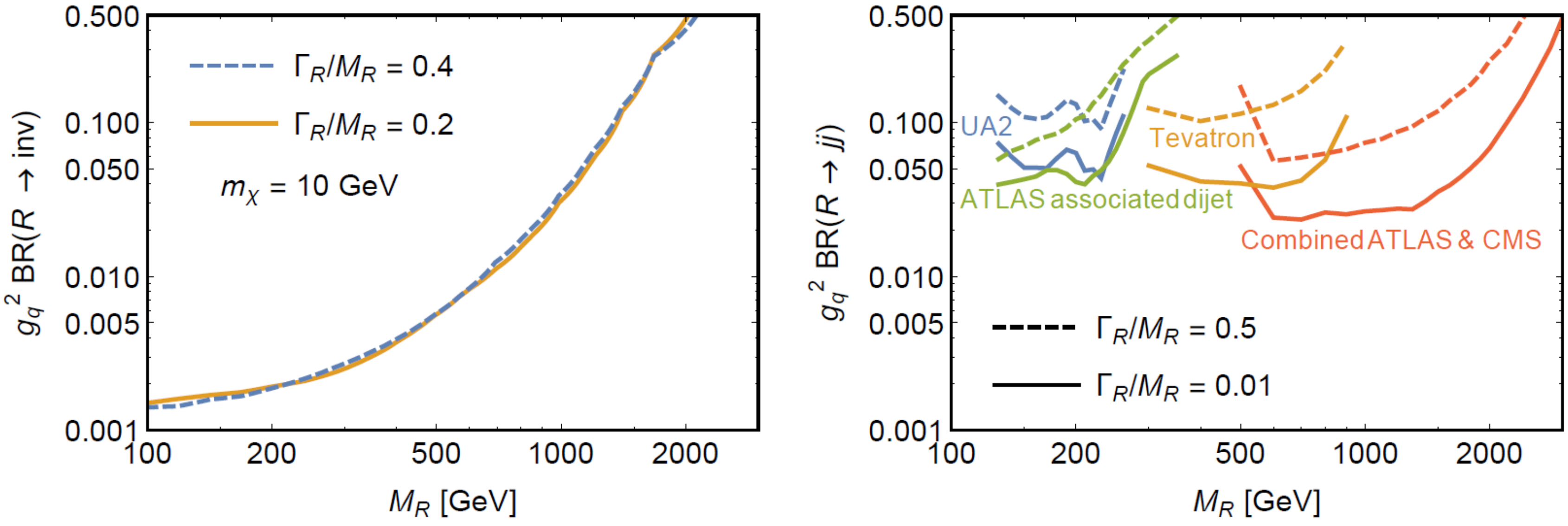
Future prospects



> Large improvements expected in the near future:

- LHC@14TeV will probe mediator masses up to 4 TeV and DSP masses up to 1 TeV.
- Searches for dijet resonances in association with SM gauge bosons will significantly gain in sensitivity. Chiang et al., arXiv:1502.00855; Xiang et al, arXiv:1503.02931
- The upcoming direct detection experiments XENON1T and LZ will be highly competitive with LHC searches.

Discussion



- We can also use our analysis to construct more model-independent bounds on the mediator production cross section times its branching ratios.
- These bounds apply to cases where additional decay channels contribute to the total width of the mediator.
- Additional constraints for such models could come from dijet angular correlations and searches for ttbar resonances.

Plenty of opportunities for future work!

Conclusions

- There are many different candidate theories for the DM particle, but fortunately we have a broad range of experimental strategies to shed light on its nature.
- An interesting possibility both from both model-building and phenomenological perspective are dark mediators coupling the visible and dark sectors.
- For mediator masses below a few GeV, one can obtain highly relevant constraints on the interactions of DM from flavour physics.
- For example, these constraints rule out an interpretation of DAMA (and indeed of any direct detection signal observed in the foreseeable future) in terms of pseudoscalar exchange.
- For TeV-scale mediators, there is an important complementarity between monojet searches and dijet searches in constraining both visible and invisible decays of the mediator.
- Searches for dijet resonances remain sensitive even for very broad resonances. A combination of different searches allows to probe mediator masses in the range 130 GeV < M_R < 3 TeV and rule out couplings larger than about $g_q \sim 0.2$.

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

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

- For Yukawa-like couplings to quarks, we find

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

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

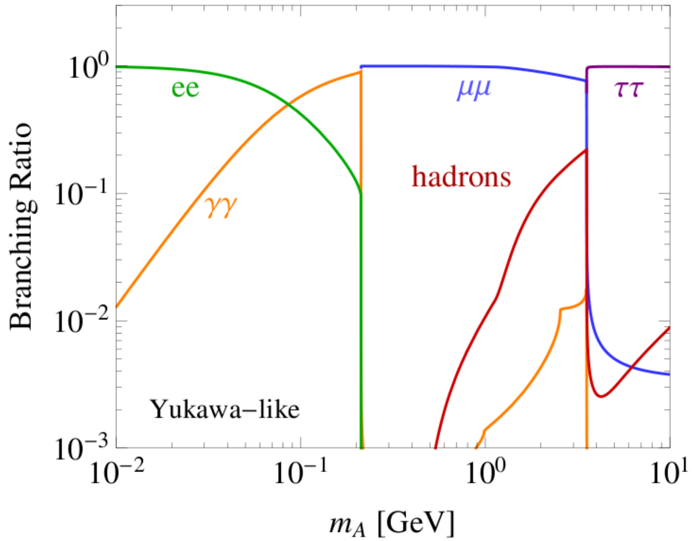
- It is well-known how to calculate the partial kaon decay width in terms of these effective couplings:

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

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

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.



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

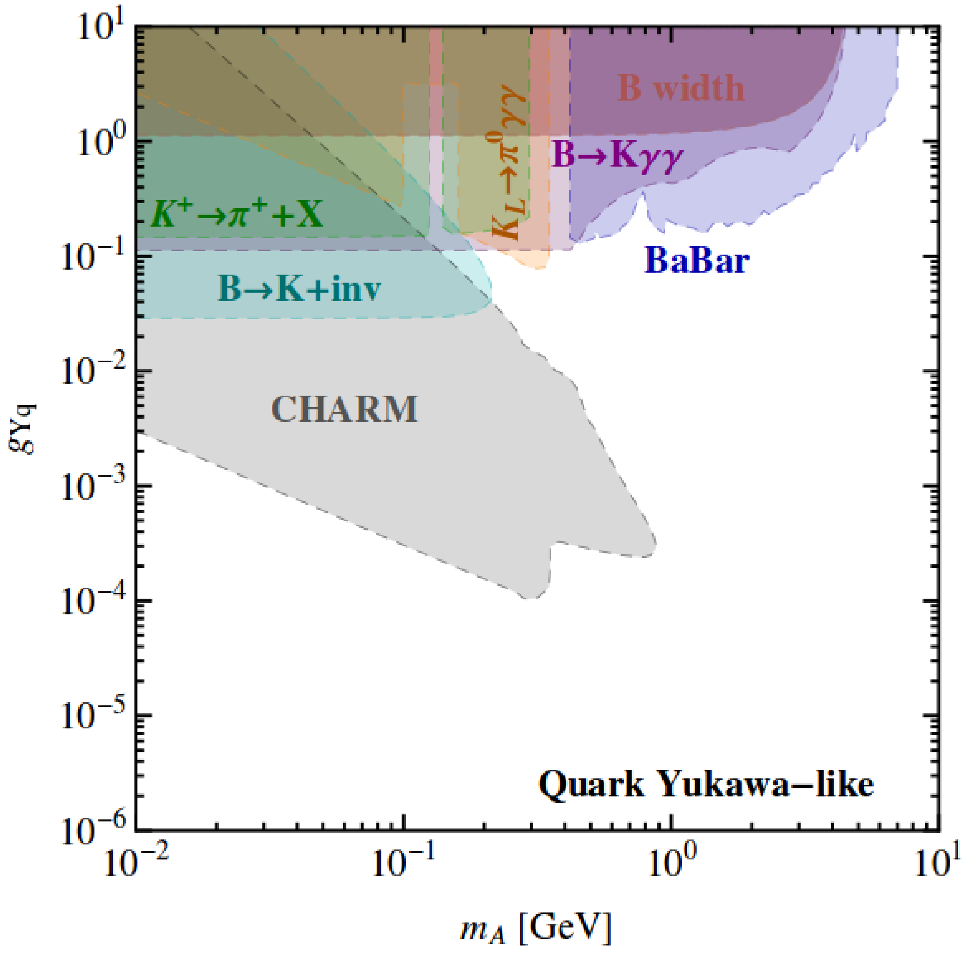
$$\Gamma(A \to \gamma\gamma) = \frac{\alpha^2\, m_A^3}{256\pi^3} \left| \sum_f \frac{N_c\, Q_f^2\, g_f}{m_f} F_A(\tau_f) \right|^2$$

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

DESY

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.



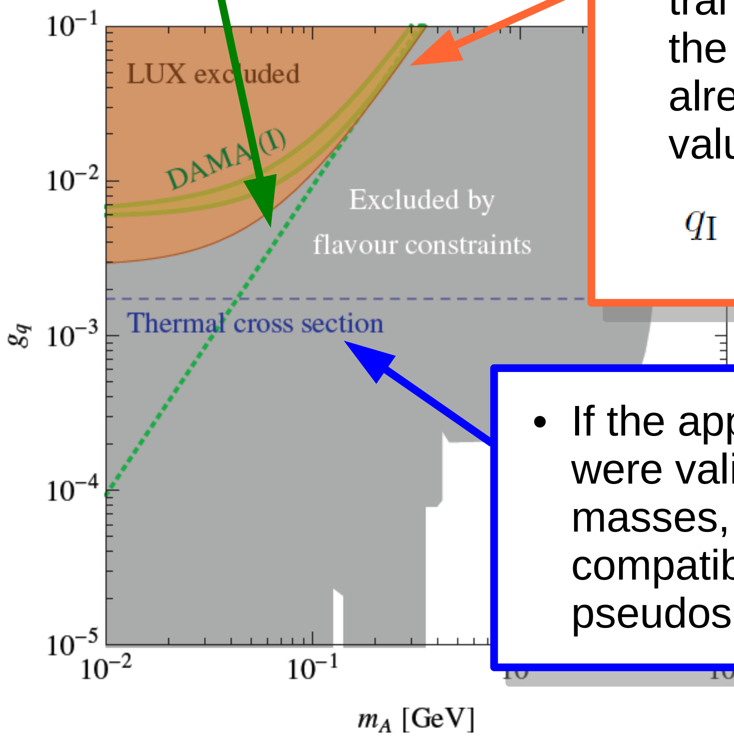
DAMA and LUX: Some additional observations

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

- 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:

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

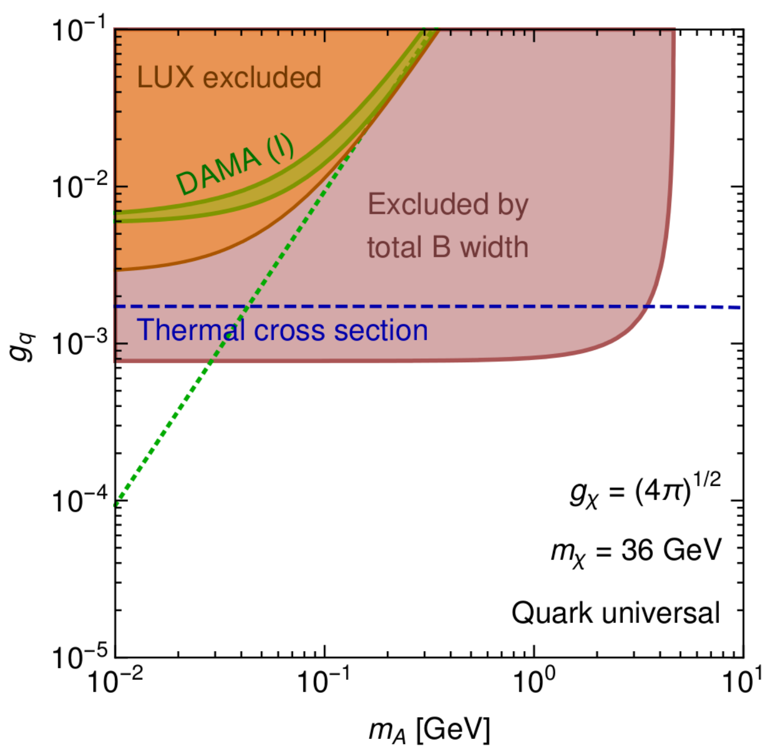


- If the approximation of contact interactions were valid down to small pseudoscalar masses, the DAMA modulation could be compatible with thermal freeze-out for pseudoscalar masses around 30-40 MeV.

DAMA and LUX: Some additional observations

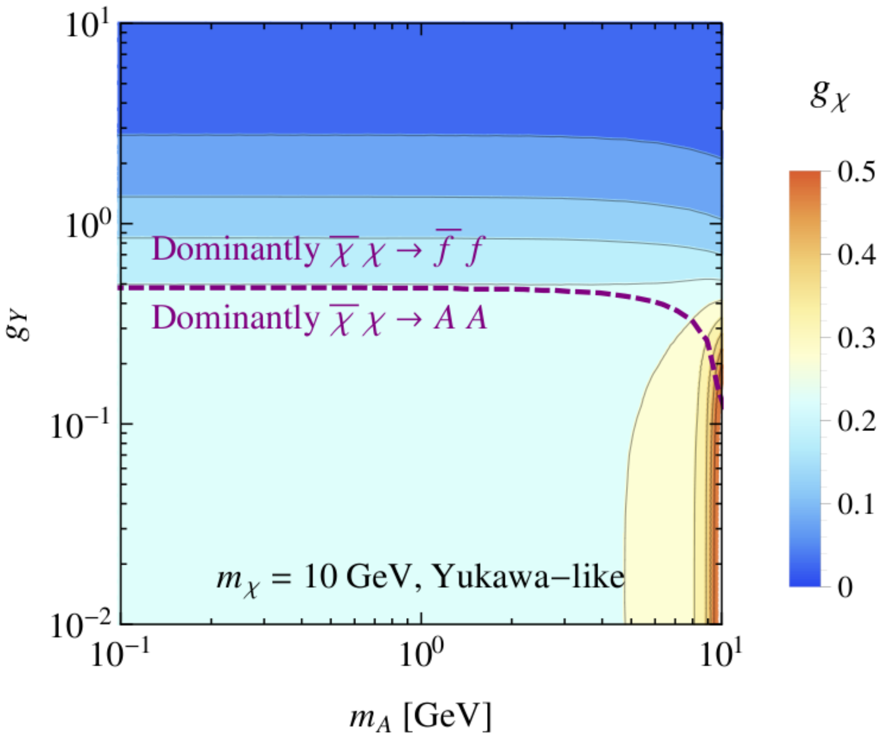
- In fact, an interpretation of DAMA in terms of pseudoscalar exchange with universal quark couplings is solidly excluded even my the simplest and most conservative bound, namely the requirement that

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



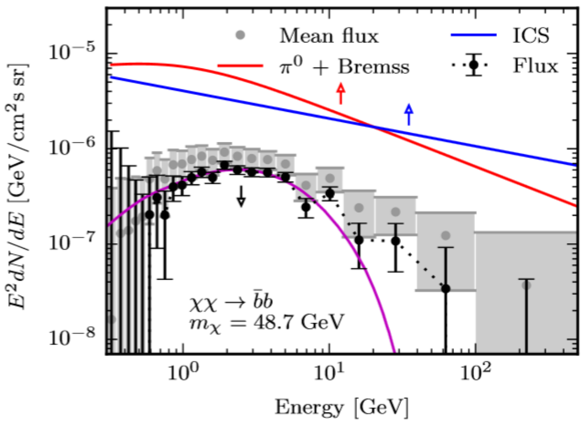
- This constraint is completely independent of the mass of A (as long as $m_A << m_B$) and its subsequent decays and it does not require any matching to chiral perturbation theory.
- Taking into account that B mesons are observed to decay almost exclusively into c-quarks, this constraint could be improved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

- 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.

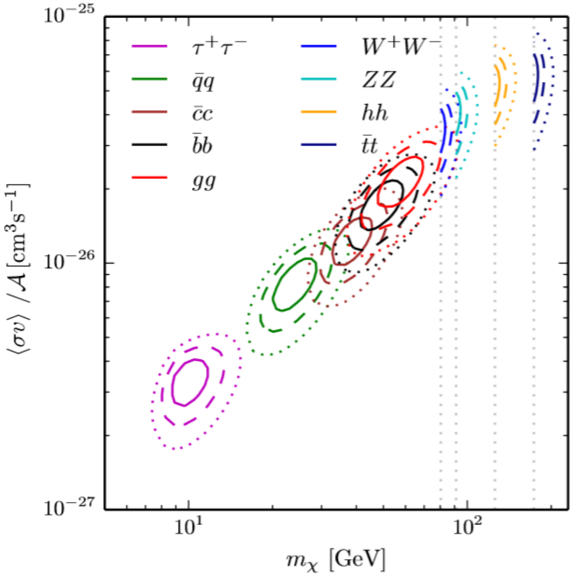


- If both annihilation channels contribute in the early universe, we expect to see an annihilation signal slightly below the standard expectation for a thermal relic.
  - Perfect for explaining the Galactic Centre Excess

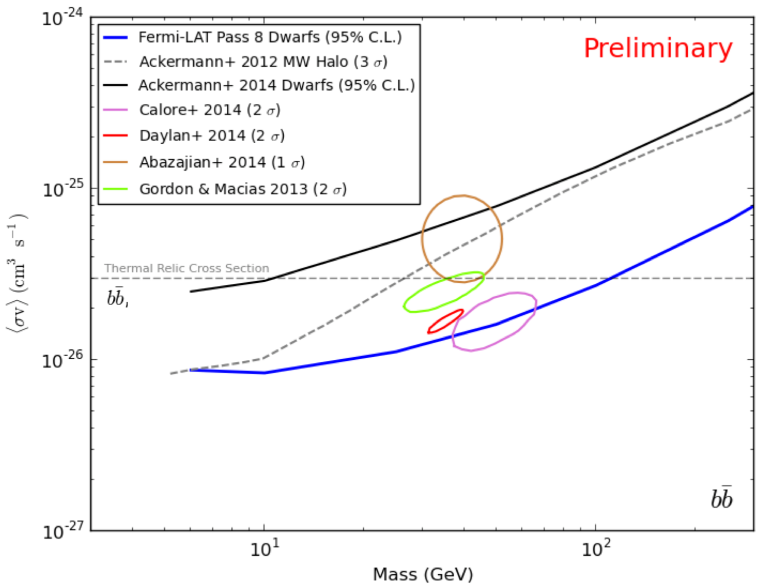
The Galactic Centre Excess



- 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.



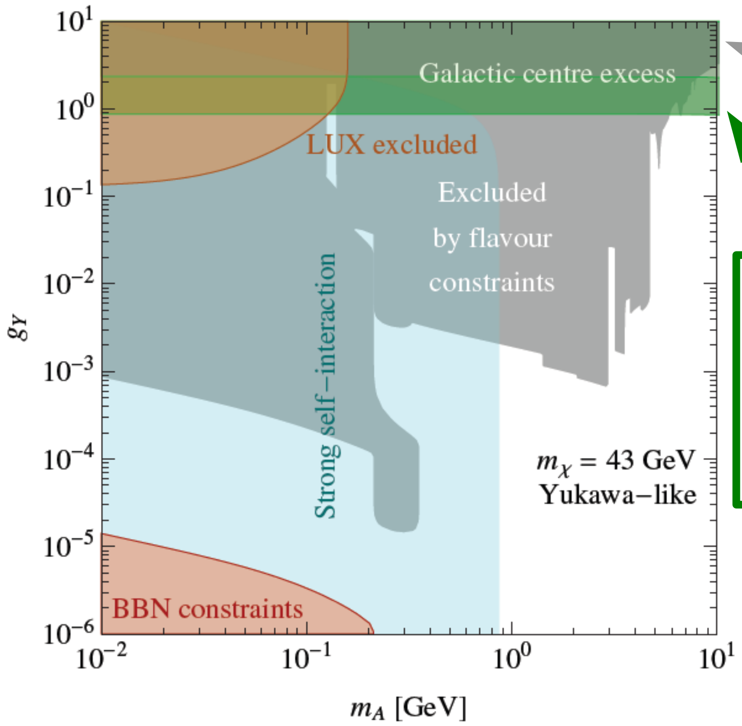
Calore et al., arXiv:1411.4647



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



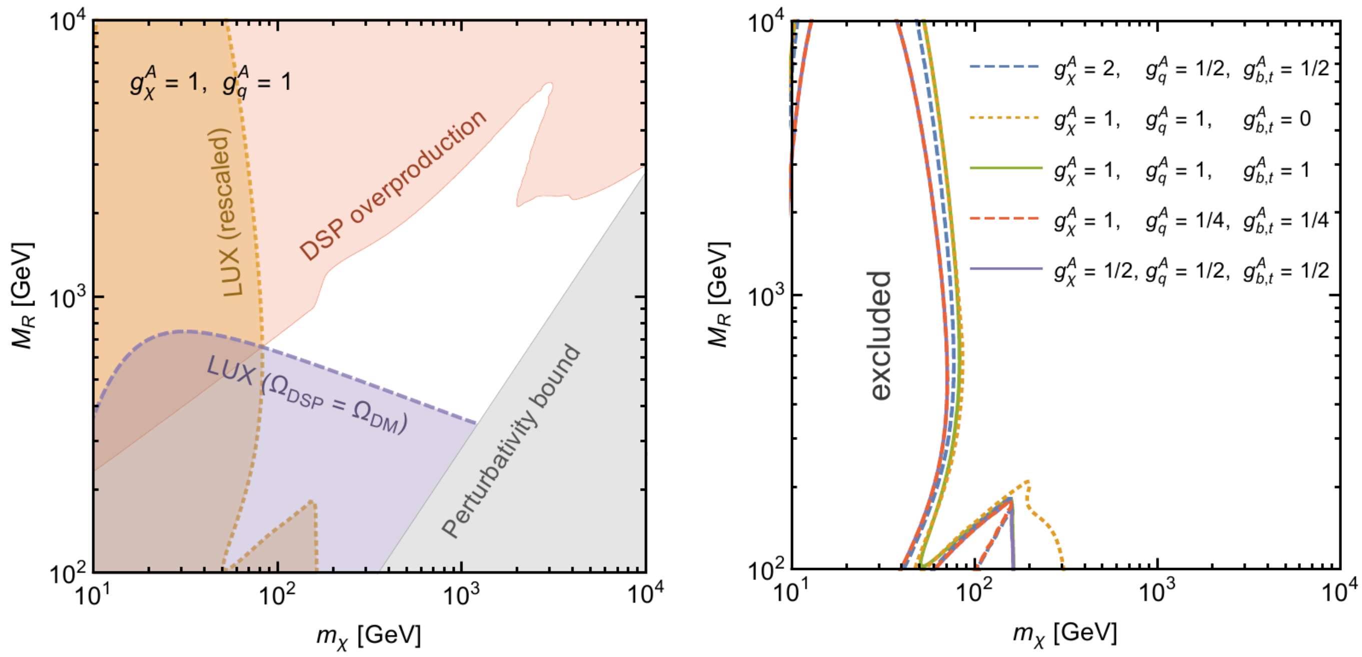
- Conventional explanation of the Galactic centre excess, but strong constraints from dwarf spheroidals.

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

> For m_A > 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.

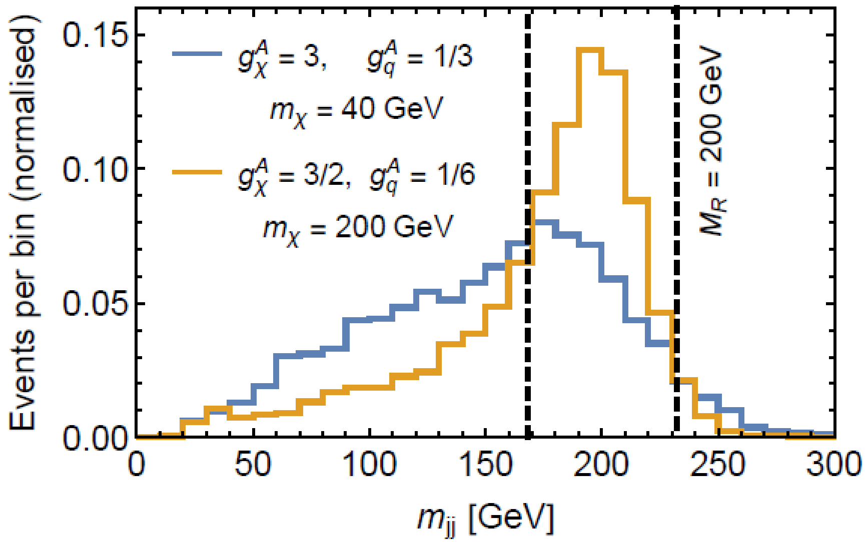
Details on direct detection



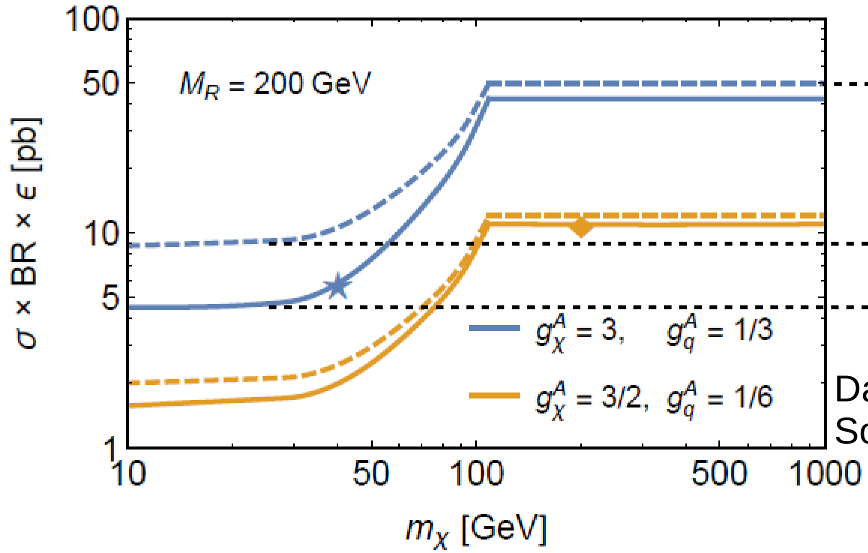
> Direct detection bounds are not entirely independent of couplings, due to a combination of three different reasons:

- Variations in the freeze-out temperature
- Variations in the mediator width
- Relevant contributions from direct annihilation of DSPs into mediators.

Example: Dijets at UA2



- Typical distribution of the dijet invariant mass for a narrow resonance with $\Gamma_R/M_R \sim 0.01$ (orange) and a broad resonance with $\Gamma_R/M_R \sim 0.1$ (blue).
- For the broad resonance the cut efficiency is reduced from about 70% to about 40%.



Reduction of cross section due to suppressed branching into dijet final states

Reduced efficiency for broad resonances

Dashed: nominal efficiency for narrow resonances
Solid: actual efficiency for broad resonances

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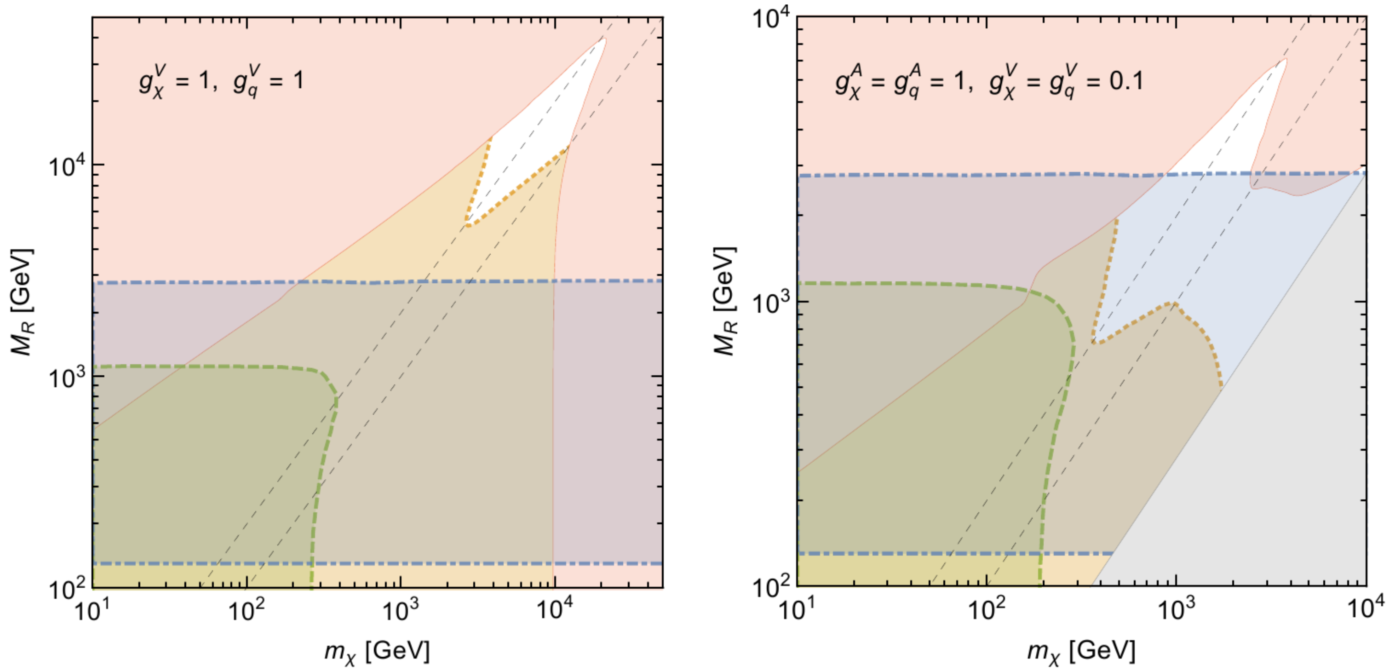
Vector couplings



- > The presence of non-zero vector couplings enhances both the DSP annihilation rate and the DSP-nucleus scattering cross section.
- > If vector couplings dominate, bounds from LHC searches are significantly less constraining than direct detection experiments.
- > An interesting interplay of different searches is possible if the vector couplings are small compared to the axial couplings.

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