Dark mediators and dark terminators.

How to save the WIMP

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DESY

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- Part I: Simple and less simple models for DM
  - From effective field theories to simplified models
  - Simplified models and theoretical consistency requirements
- Part II: The two-mediator dark matter model
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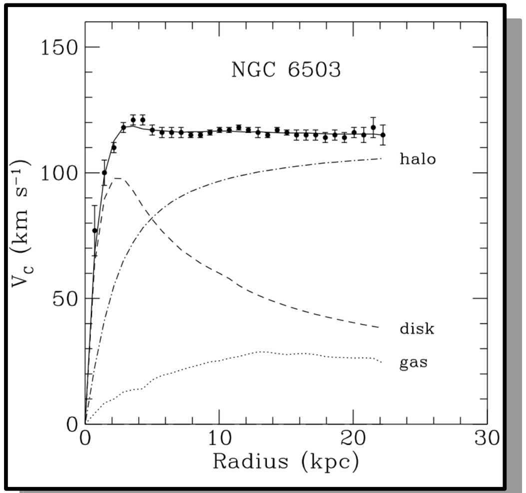
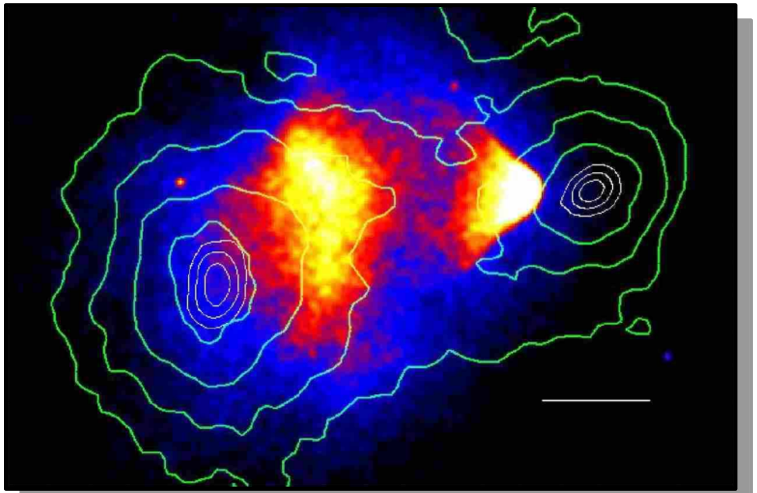
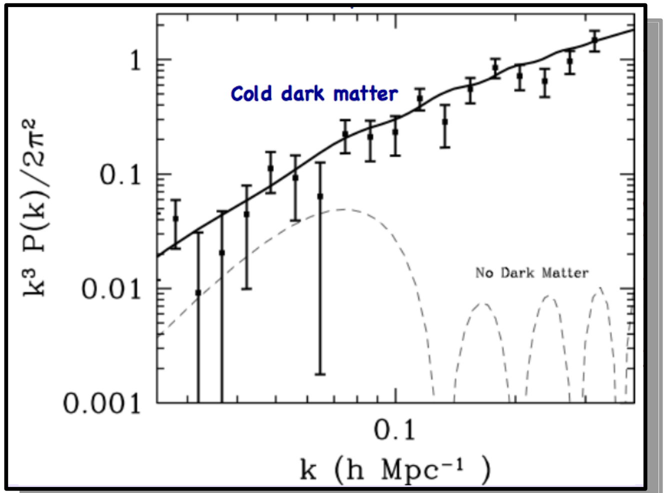
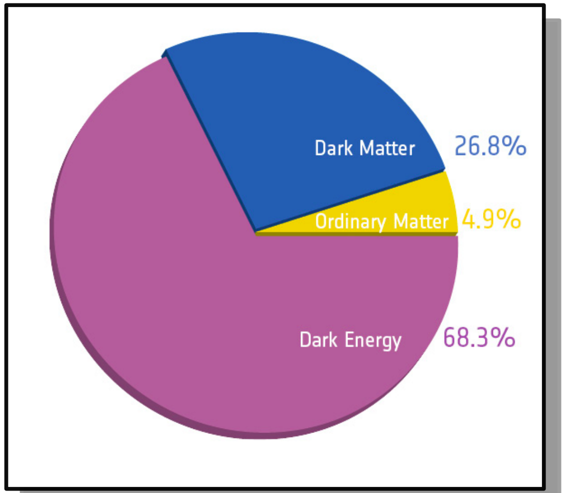
  - Phenomenology of two mediators
  - Results from global scans
- Conclusions

Evidence for Dark Matter



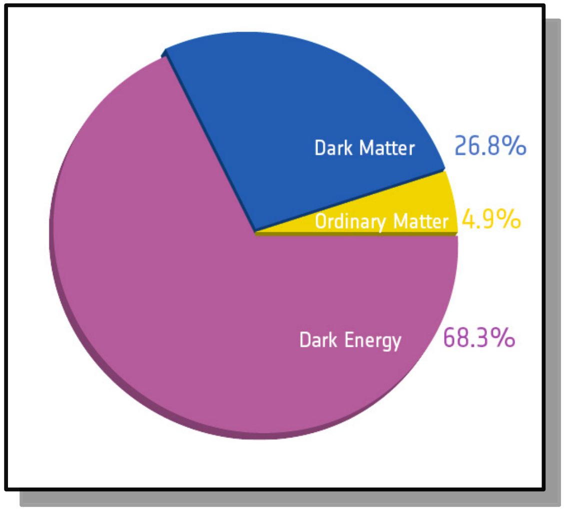






Dark matter particles

- Although astrophysical observations clearly confirm the existence of dark matter (DM) in the Universe, they give almost no indications concerning its particle nature.
- In particular, the mass of the DM particles and their couplings to Standard Model (SM) states are completely unknown and can vary over many orders of magnitude.



- In order to devise experimental search strategies it is necessary to construct specific models for dark matter as a guidance.
- The top-down approach to this problem aims to obtain a well-motivated candidate for DM from theoretical considerations (concerning for example the hierarchy problem or the strong CP problem).
- In the bottom-up approach, on the other hand, the foremost aim is to explain the observed DM relic abundance by adding the minimal necessary amount of additional structure to the SM.

Thermal freeze-out

- The most widely studied paradigm for DM production in the early Universe is thermal freeze-out.

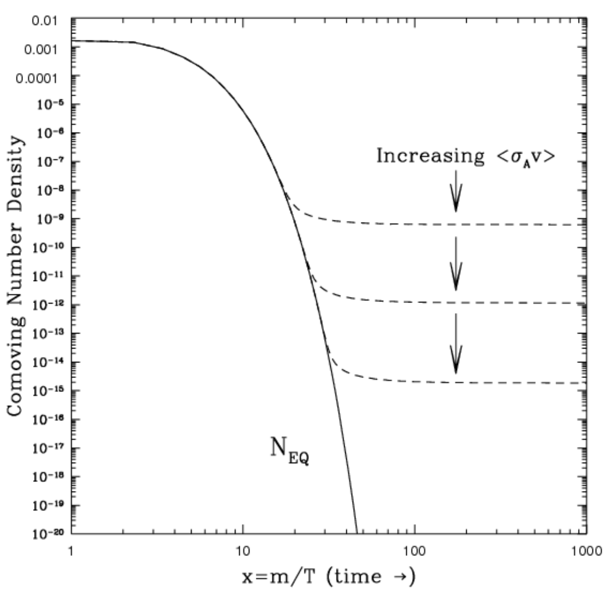
  Lee & Weinberg, 1977

- This idea is based on the assumption that DM was in thermal equilibrium with SM states at high temperatures and that DM annihilation and production processes happened frequently.

- As the temperature drops below the DM mass, its number density is suppressed, and DM interactions become less frequent.

- Once the interaction rate is smaller than the expansion rate of the Universe, DM interactions freeze out and the co-moving number density becomes constant.

- Larger annihilation cross sections lead to smaller relic abundances.



Weakly-interacting massive particles

- If the DM particles are non-relativistic during freeze-out, they become cold DM and can form the observed large-scale structure.

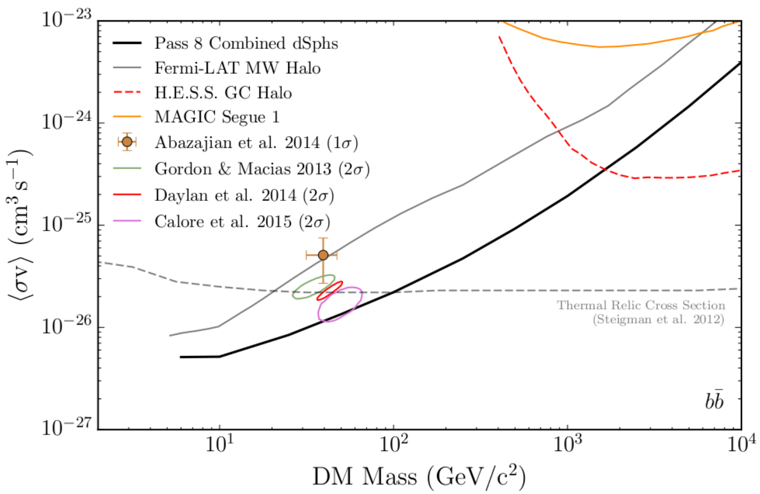
- Such particles are often referred to as weakly-interacting massive particles (WIMPs), because the typical interaction strength required to reproduce the observed DM abundance is comparable to weak interactions (for a particle with weak-scale mass).

- WIMPs are also the most promising DM candidate from an experimental point of view
  - Interactions with SM particles have to be sizeable and can therefore potentially be observed with particle detectors.
  - Perturbative unitarity implies that the DM particle cannot be arbitrarily heavy (typically m_χ < 100 TeV). Griest & Kamionkowski, 1990
  - Some prototypical WIMPs (e.g. a heavy Dirac neutrino) have already been excluded.

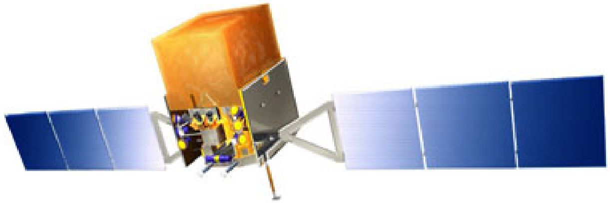
- Can we comprehensively test the WIMP paradigm?

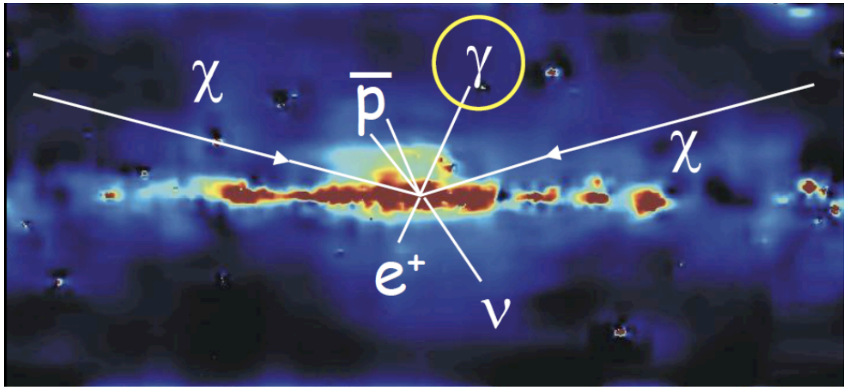
WIMPs in indirect detection

- In regions of high DM density (e.g. the galactic center), DM annihilation may still continue today.
- The same processes can therefore be probed by indirect detection experiments, which look for the annihilation products with satellites, balloons and ground based telescopes.



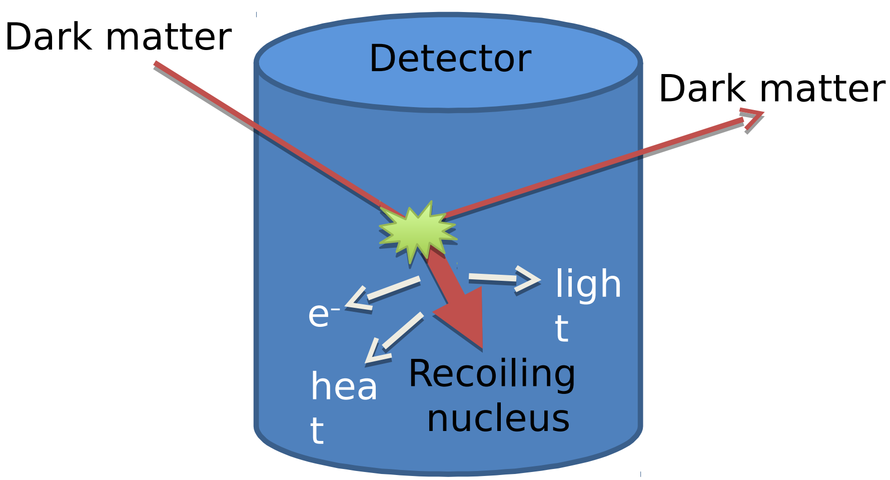
Fermi-LAT, arXiv:1503.02641



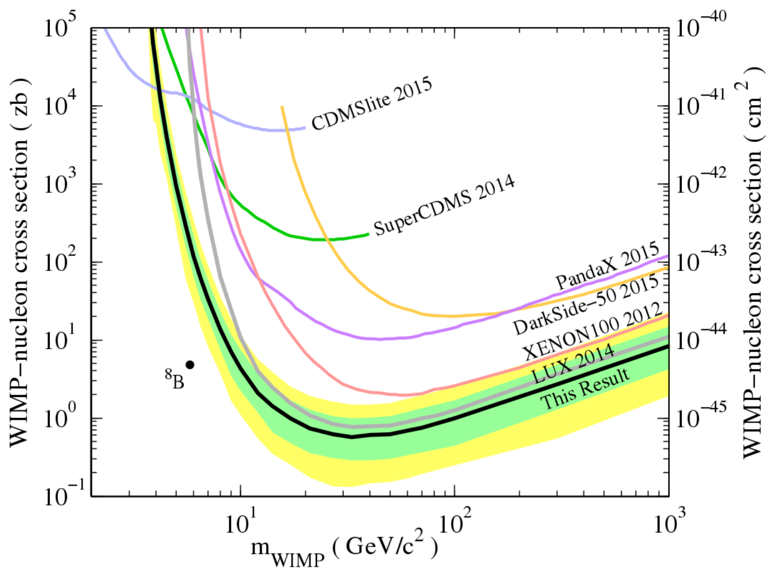


WIMPs in direct detection

- 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.
- Typical event rates are less than 1 event per kg per year - a great experimental challenge!



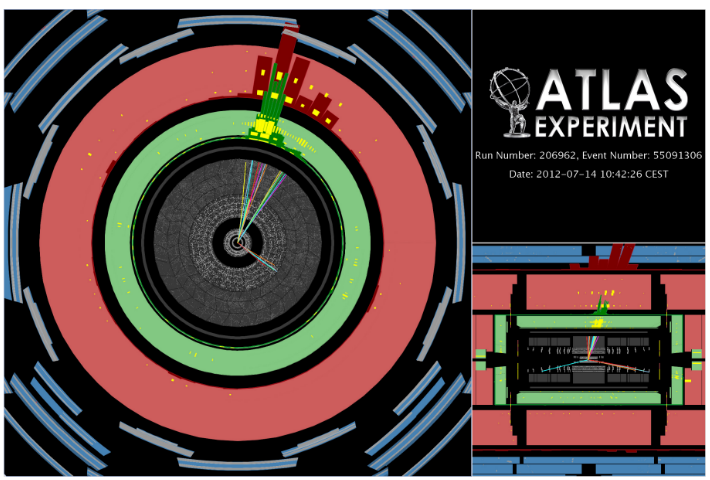
$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{nr}}} = \frac{\rho_0}{m_\chi m_{\mathrm{N}}} \int_{v_{\min}}^{\infty} \mathrm{d}v\, v f(v, v_{\mathrm{E}}) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{nr}}}$$

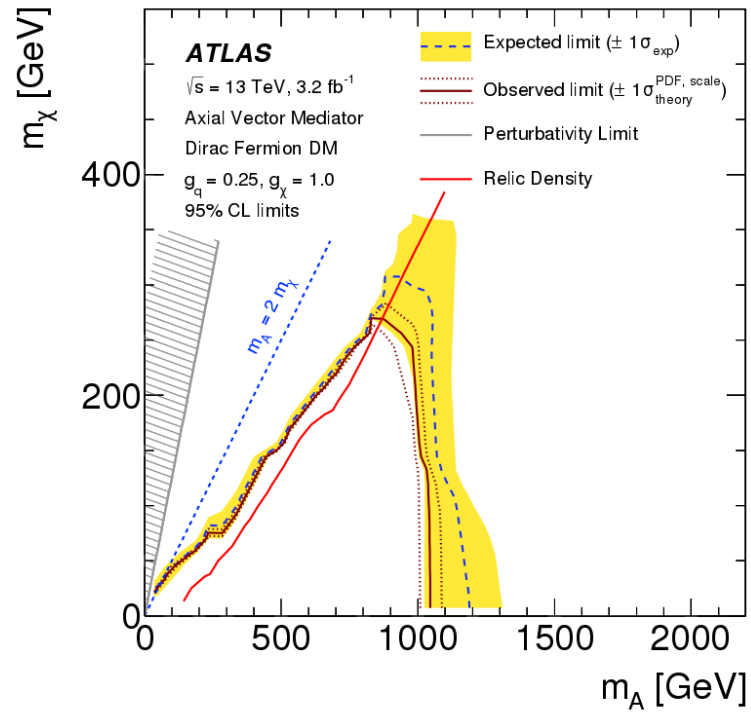


LUX, arXiv:1512.03506

WIMPs at colliders

- 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.





ATLAS, arXiv:1604.07773

The complementarity of different DM searches

- It is crucial for the search for DM to understand the interplay of different kinds of experiments.
  - We want to compare the sensitivity of different experimental strategies in order to identify which ones are the most promising to make a discovery.
  - Once a DM signal is seen, we need to understand how to best confirm it with complementary measurements.

- The LHC by itself can never establish the (cosmological) stability of an invisible particle that escapes from the detector.
  - It will be essential to identify the presence of a particle with compatible properties in the Milky Way or beyond non-collider experiments.
  - We would like to understand whether the interactions of the potential DM candidate probed at the LHC can provide a viable mechanism for the production of DM in the early Universe and thus explain the observed relic abundance.

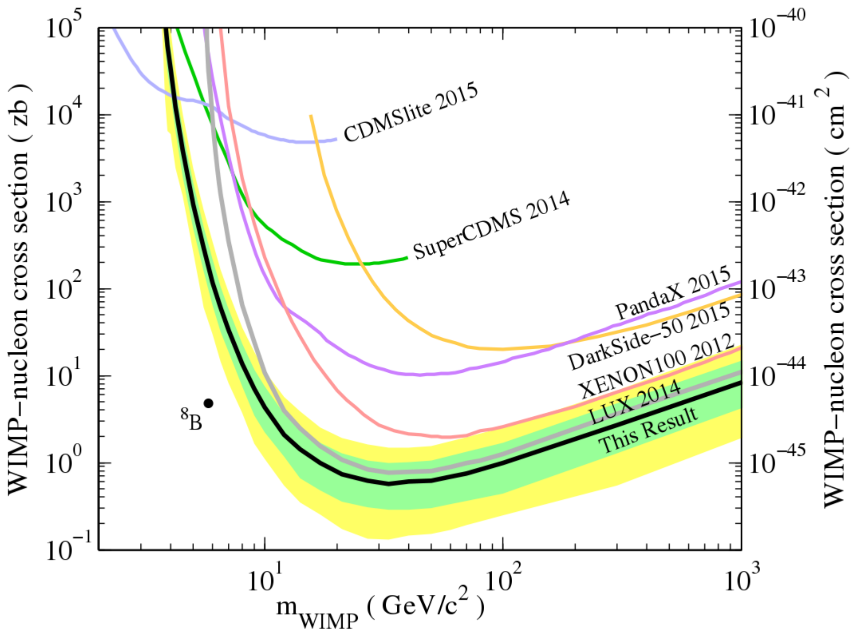
see e.g. Chala, FK et al., arXiv:1503.05916

The easiest case: Direct detection experiments

- Direct detection experiments probe the interactions of DM in the non-relativistic limit

- It is thus often sufficient to specify just two properties of the DM particle: its mass and its scattering cross section with nucleons.

- A comparison between different direct detection experiments can therefore be performed without specifying a complete model of DM.



LUX, arXiv:1512.03506

- As always, things can be more complicated:
  - DM-nucleon interactions may have a non-trivial momentum- and velocity-dependence
  - Nuclear response functions can depend on the details of the DM-quark couplings
  - Long-range interactions may make it impossible to integrate out the mediator of the interaction

How about the LHC?

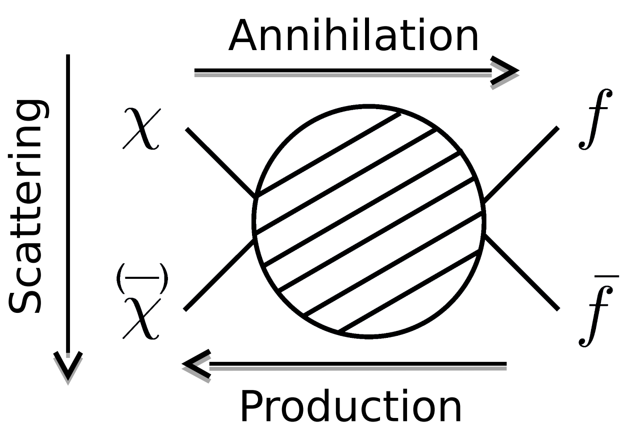
- It is tempting to try and parametrise LHC searches for DM in a similar way and describe the interactions between DM and quarks in terms of effective operators.

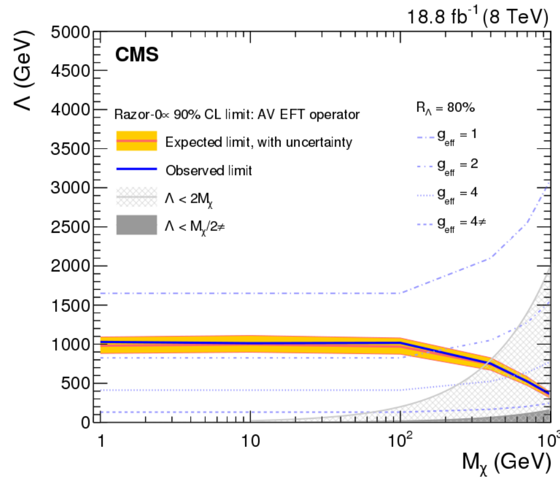
- This approach promises a straight-forward and widely applicable interpretation of LHC searches.

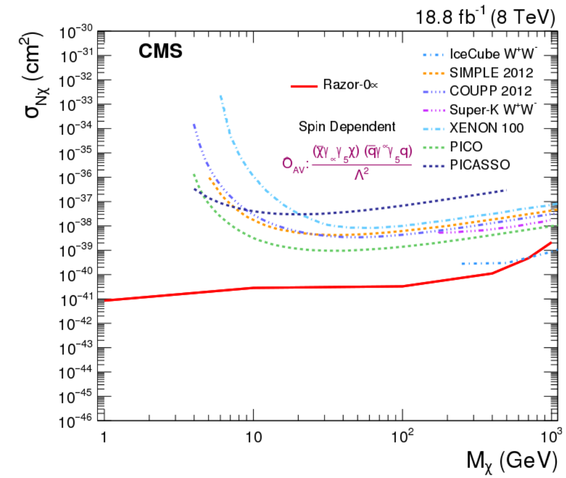
- In the EFT approach, all DM searches constrain the same new-physics scale Λ, so we can directly compare bounds from different search strategies.

$\Delta\mathscr{L}$		Int.	Suppression
$\mathcal{O}^\phi_s$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}f$	SI	1
$\mathcal{O}^\phi_v$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}^\phi_{va}$:	$\frac{1}{\Lambda^2}\phi^\dagger\partial^\mu\phi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2
$\mathcal{O}^\phi_p$:	$\frac{1}{\Lambda}\phi^\dagger\phi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}^\psi_s$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}f$	SI	1
$\mathcal{O}^\psi_v$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu f$	SI	1
$\mathcal{O}^\psi_a$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	1
$\mathcal{O}^\psi_t$:	$\frac{1}{\Lambda^2}\bar{\psi}\sigma^{\mu\nu}\psi\bar{f}\sigma_{\mu\nu} f$	SD	1
$\mathcal{O}^\psi_p$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4
$\mathcal{O}^\psi_{va}$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\psi\bar{f}\gamma_\mu\gamma^5 f$	SD	v^2, q^2
$\mathcal{O}^\psi_{pt}$:	$\frac{1}{\Lambda^2}\bar{\psi}i\sigma^{\mu\nu}\gamma^5\psi\bar{f}\sigma_{\mu\nu} f$	SI	q^2
$\mathcal{O}^\psi_{ps}$:	$\frac{1}{\Lambda^2}\bar{\psi}i\gamma^5\psi\bar{f}f$	SI	q^2
$\mathcal{O}^\psi_{sp}$:	$\frac{1}{\Lambda^2}\bar{\psi}\psi\bar{f}i\gamma^5 f$	SD	q^2
$\mathcal{O}^\psi_{av}$:	$\frac{1}{\Lambda^2}\bar{\psi}\gamma^\mu\gamma^5\psi\bar{f}\gamma_\mu f$	SI SD	v^2 q^2
$\hat{\mathcal{O}}^\phi_s$:	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{f}f$	SI	1
$\hat{\mathcal{O}}^\psi_s$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\psi\bar{f}f$	SI	1
$\hat{\mathcal{O}}^\psi_p$:	$\frac{m_q}{\Lambda^3}\bar{\psi}\gamma^5\psi\bar{f}\gamma^5 f$	SD	q^4

March-Russel et al., arXiv:1203.4854







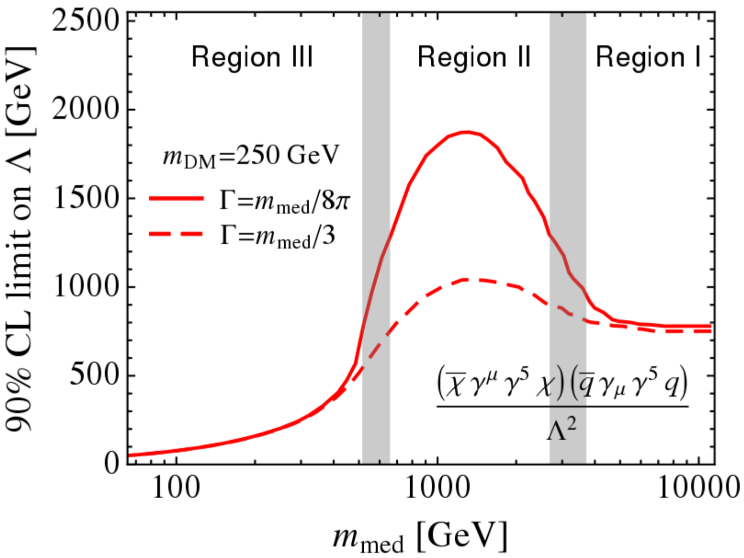
CMS, arXiv:1603.08914

How about the LHC?

- It is well understood by now that the original EFT approach to DM searches at the LHC has been too naïve.

- First of all, it turns out to be necessary to apply a self-consistent truncation procedure to avoid extrapolating the EFT beyond its range of validity.

- More importantly, many DM models simply cannot be reduced to an EFT at LHC energies and predict very different kinematic distributions.



Buchmueller et al., arXiv:1308.6799

- For these models a larger number of parameters is required to characterise the LHC phenomenology.

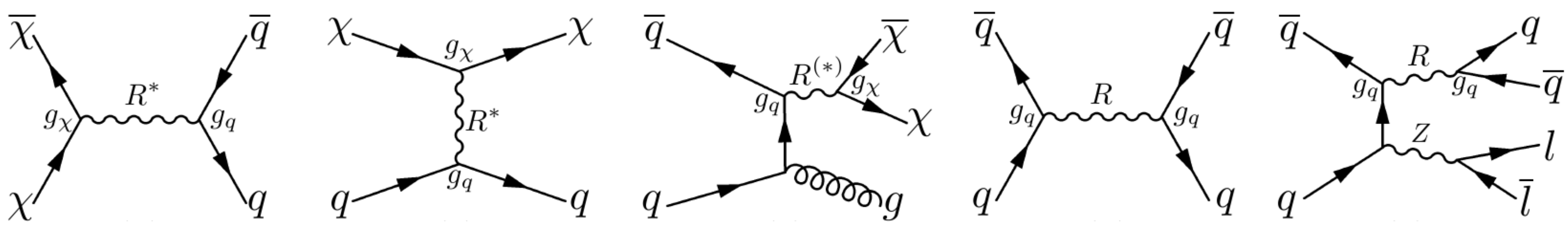
- The comparison with direct detection experiments then turns out to be a lot less straight-forward.

Are simplified models the solution?

- The obvious solution is to extend the DM parameter space in such a way that the kinematic distributions for a wider range of DM models can be captured.
- A first step in this direction is to assume that the mediator of the DM interactions is comparable to LHC energies and then specify its couplings to DM and SM fermions.
- The ATLAS/CMS DM Forum and the LHC DM Working Group have now compiled a list of simplified models with an s-channel mediator coupling to quarks and DM.

Abdallah, FK et al., arXiv:1506.03116
Abercrombie, FK et al., arXiv:1507.00966
Boveia, FK et al., arXiv:1603.04156

- These models also allow for a well-defined comparison of LHC searches and direct detection experiments.



Are simplified models too simplified?

- For the LHC community, the main purpose of simplified DM models is to generate events with missing energy and to study the kinematic distributions.
- To be useful, a simplified model does not need to be theoretically consistent – it only needs to parametrize the properties of the invisible particles in an efficient way.
- As soon as one is interested in comparing results from the LHC with other experimental or observational probes of DM, however, a more ambitious approach is required.

FK et al., arXiv:1510.02110

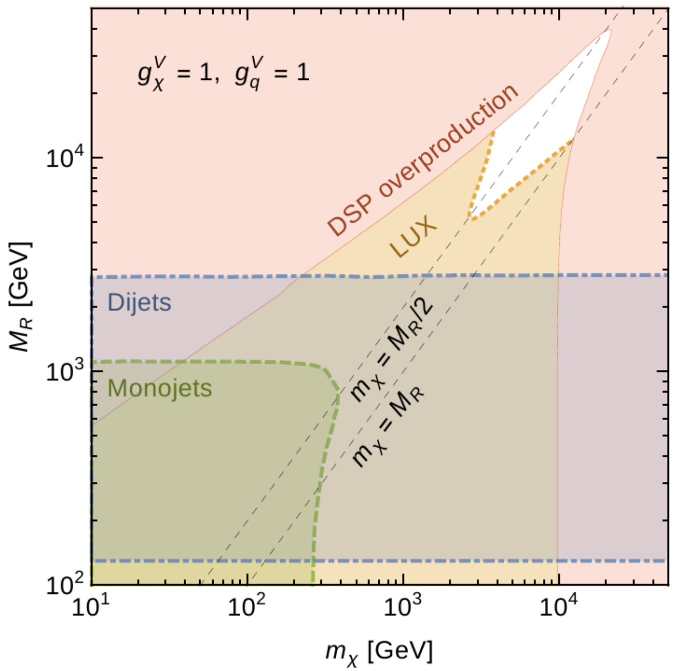
- It then becomes essential that the models under consideration full certain basic requirements, such as gauge invariance and perturbative unitarity.

Example: Spin-1 mediator with vector couplings

- A good example for a consistent simplified model is a spin-1 mediator with vector couplings to quarks and DM (arising for example from a Stueckelberg mechanism).

$$\mathcal{L} = - \sum_{f=q,l,\nu} Z'^{\mu}\, \bar{f}\, [g_f^V \gamma_\mu + g_f^A \gamma_\mu \gamma^5]\, f - Z'^{\mu}\, \bar{\psi}\, [g_{\mathrm{DM}}^V \gamma_\mu + g_{\mathrm{DM}}^A \gamma_\mu \gamma^5]\, \psi$$

- This model is gauge-invariant, satisfies the assumption of minimal flavour violation and has no issues with unitarity at high energies.



Chala, FK et al., arXiv:1503.05916

- For this simplified model scattering in direct detection experiments receives a coherent enhancement proportional to the square of the target nucleus mass.

- As a result, direct detection is much more sensitive to vector couplings than LHC searches and thermal cross sections are largely excluded.

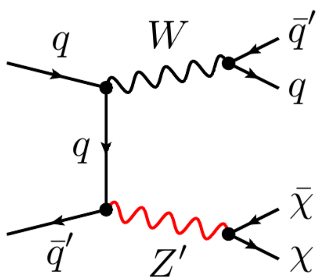
Problems with other simplified models

- A number of simplified models have been proposed that only respect the symmetries of the broken gauge group SU(3) x U(1), but are not gauge invariant under SU(3) x SU(2) x U(1)

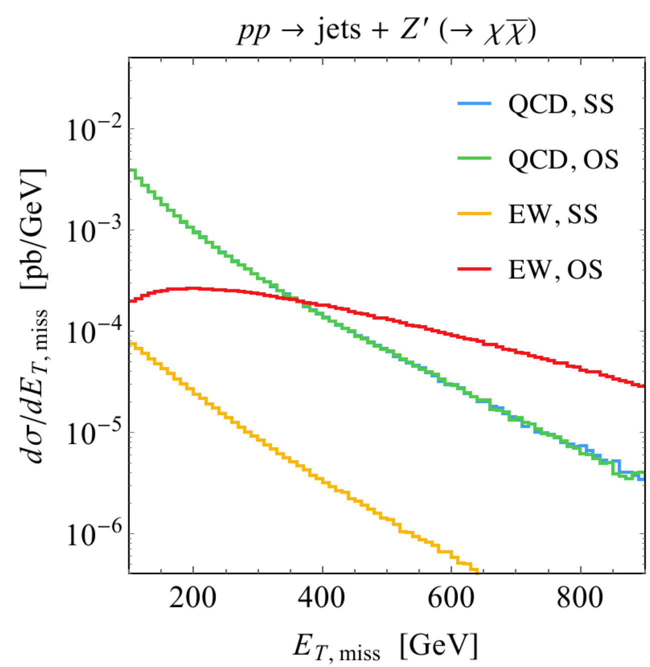
Bell et al., arXiv:1512.00476

  - Spin-0 s-channel mediators
  - Spin-1 s-channel mediators with different couplings to up- and down-quarks.

- Such structures not only make it more difficult to find a viable UV-completion, but they may also lead to unphysical predictions, such as the violation of perturbative unitarity in LHC DM searches.



$$\mathcal{M}^1 = \frac{g\,s}{96\pi\, M_W\, M_{Z'}} \left(g_u^A - g_d^A - g_u^V + g_d^V\right)$$



Haisch, FK & Tait, arXiv:1603.01267

Problems with other simplified models

- A more subtle issue arises for spin-1 s-channel mediators with axial couplings.
- In this case, the longitudinal component of the mediator couples to fermions with coupling strength $2\, g_f^A\, m_f / m_{Z'}$.
- The requirement that this coupling does not violate perturbative unitarity yields an upper bound on the fermion masses:

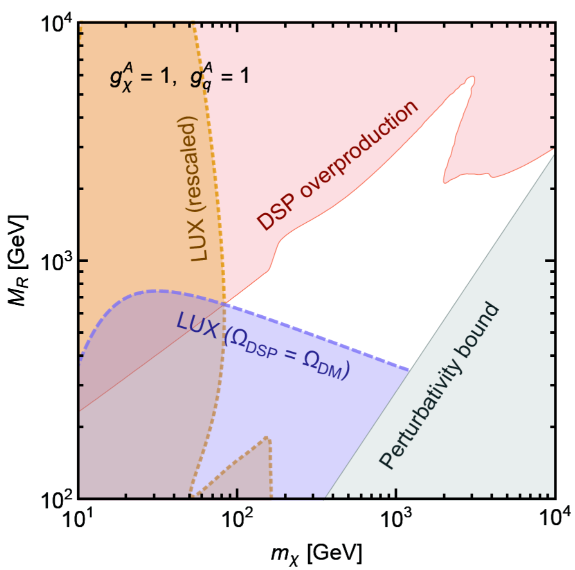
$$m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$$

FK et al., arXiv:1510.02110

- This is not an issue for LHC searches, since only very light fermions contribute in the initial state.

Englert et al., arXiv:1604.07975

- It does however become important for the calculation of the relic density, which depends on the annihilation cross section of DM into top-quarks.



Chala, FK et al., arXiv:1503.05916

Axial couplings: A closer look at perturbative unitarity

- We could also consider the process $\psi\bar{\psi} \to Z'_L Z'_L$.   FK et al., arXiv:1510.02110

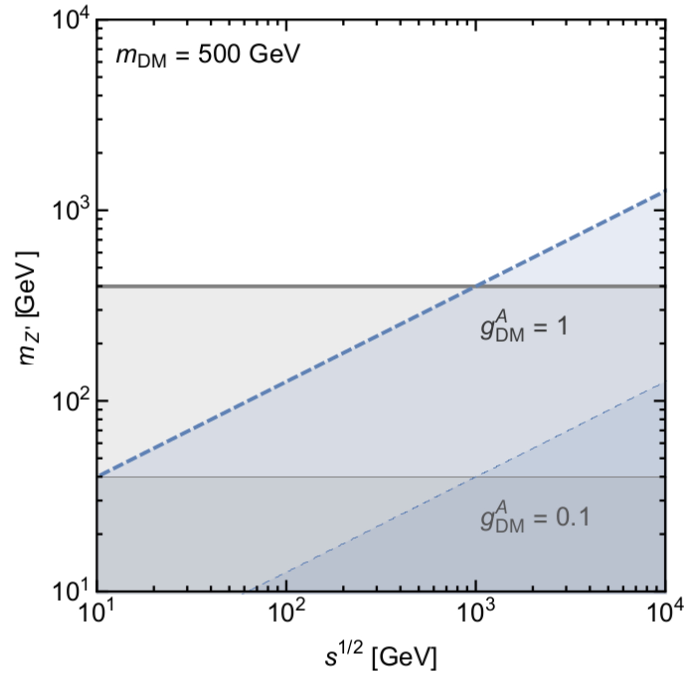
- For axial couplings, the matrix element for this process grows with energy proportional to

$$(g_{\mathrm{DM}}^A)^2 \sqrt{s}\, m_{\mathrm{DM}} / m_{Z'}^2$$

- Perturbative unitarity then implies

$$\sqrt{s} < \frac{\pi\, m_{Z'}^2}{(g_{\mathrm{DM}}^A)^2\, m_{\mathrm{DM}}}$$

- New physics must appear below this scale to restore unitarity.



Take-home message:

The problem of unitarity violation present in effective theories is not simply solved by reducing the mass of the mediator. The issue remains relevant even for simplified models.

Including a dark Higgs

- The simplest way to restore perturbative unitarity is to generate the mass of the mediator from an additional Higgs mechanism.

- The mediator is then assumed to be the gauge boson of a new *U(1)'* gauge group, which is broken by the vev of a SM singlet *S*.

- The Lagrangian of the dark sector is then given by

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\bar{\psi}\partial\!\!\!/\psi - \frac{1}{2}g_{\rm DM}^{A}Z'^{\mu}\bar{\psi}\gamma^5\gamma_\mu\psi - \frac{1}{2}y_{\rm DM}\bar{\psi}(P_L S + P_R S^*)\psi\,,$$

$$\mathcal{L}_S = \left[(\partial^\mu + i\,g_S\,Z'^\mu)S\right]^\dagger\left[(\partial_\mu + i\,g_S\,Z'_\mu)S\right] + \mu_s^2\,S^\dagger S - \lambda_s\left(S^\dagger S\right)^2$$

- The Higgs singlet vev therefore generates both the *Z'* mass and the DM mass.

$$m_{\rm DM} = \frac{1}{\sqrt{2}}\,y_{\rm DM}\,w\,, \quad m_{Z'} \approx 2g_{\rm DM}^{A}\,w$$

Implications for the visible sector

- Including a dark Higgs to restore perturbative unitarity only works if the coupling structure of all interactions respects gauge invariance of the full gauge group before EWSB (which is not normally imposed on simplified models).

- Writing the interactions between the Z' and the visible sector as

$$\mathcal{L}'_{\rm SM} = \frac{1}{2}\left[(D^\mu H)^\dagger(-i\, g'\, q_H\, Z'_\mu\, H) + \text{h.c.}\right] + \frac{g'^2\, q_H^2}{2} Z'^\mu Z'_\mu H^\dagger H$$
$$- \sum_{f=q,\ell,\nu} g'\, Z'^\mu \left[q_{f_L}\, \bar{f}_L \gamma_\mu f_L + q_{f_R}\, \bar{f}_R \gamma_\mu f_R\right] \;,$$

we immediately obtain the requirements

$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

which furthermore ensures that no new coloured states are needed to cancel anomalies.

Axial couplings to Standard Model fermions

- The consistency conditions

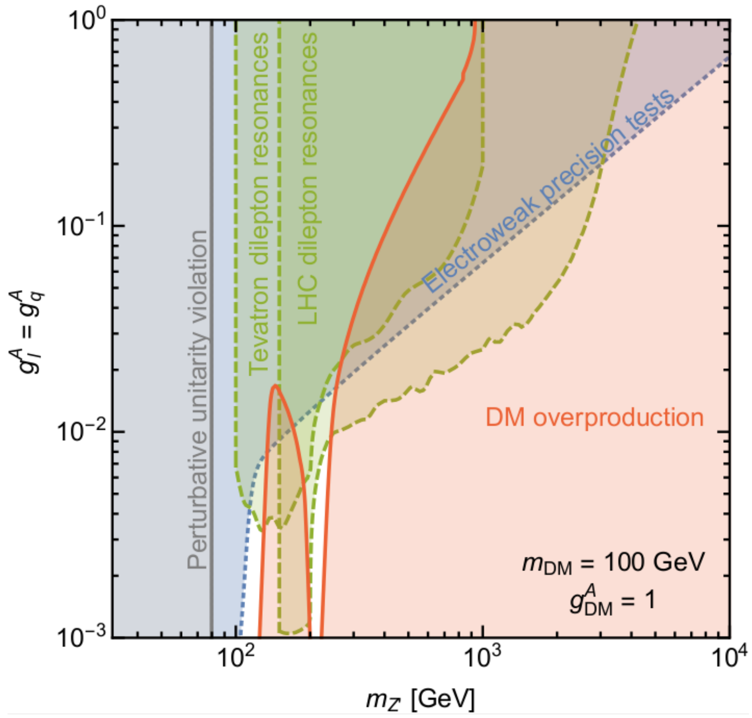
$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

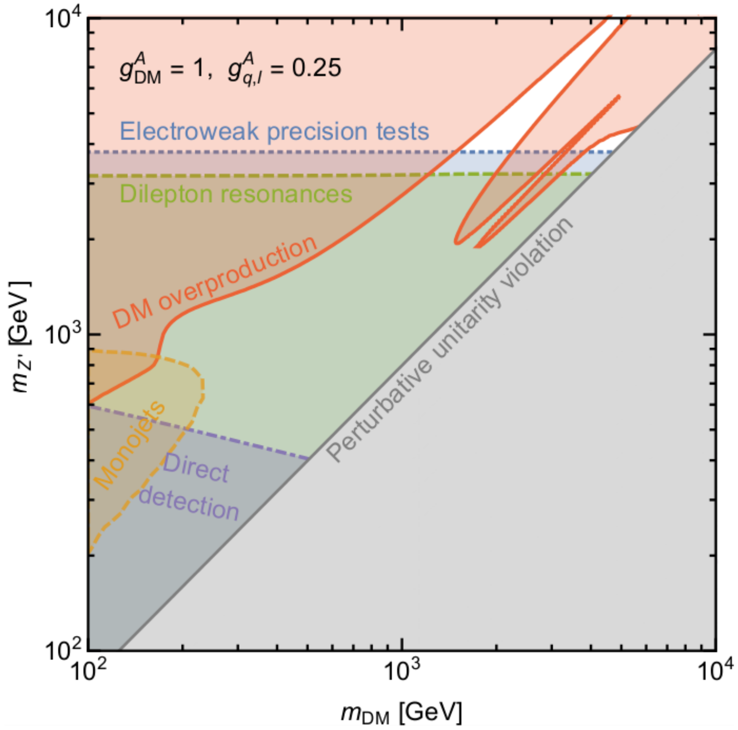
imply that for non-zero axial couplings to SM fermions, the SM Higgs must be charged under the new *U(1)'*. This has two important consequences:

1. The *Z'* must couple with the same strength to all generations of quarks and to leptons (assuming a single Higgs doublet), such that we can expect strong constraints from searches for dilepton resonances.

2. The vev of the SM Higgs induces a non-diagonal mass term of the form $\delta m^2 \, Z^\mu Z'_\mu$, which leads to mixing between the *Z'* and the SM *Z* boson and hence strong constraints from electroweak precision tests (EWPT).

Axial couplings to Standard Model fermions: Constraints





- The case with non-vanishing axial couplings on the SM side is strongly constrained by dilepton searches as well as EWPT.
- Monojet and dijet searches as well as direct detection experiments are typically not competitive in this case.

FK et al., arXiv:1510.02110

Part I: Summary

- Simplified models are a useful tool for performing and interpreting LHC DM searches.
- The (essential) comparison with other probes of DM may however require additional consistency conditions.
- Spin-1 s-channel mediator with vector couplings
  - No theoretical problems, easy to embed in a consistent UV-completion
  - Highly constrained by direct detection, difficult to avoid DM overproduction
- Spin-0 s-channel mediator; spin-1 mediator with opposite-sign couplings
  - Violation of SU(2) gauge invariance may lead to unphysical predictions and additional constraints
- Spin-1 s-channel mediator with axial couplings
  - Issues with violation of perturbative unitarity
  - Requires additional new physics (e.g. a dark Higgs)
  - Strong constraints from EWPT and dilepton resonance searches

Part 2: The two-mediator dark matter (2MDM) model

- We take the model with a Z' and a dark Higgs and make three modifications:
  - We limit ourselves to Majorana DM, so that the DM vector current vanishes and constraints from direct detection experiments are significantly reduced.
  - We focus on vector couplings of the Z' to quarks (such that the SM Higgs is uncharged under the *U(1)'*) and assume coupling to leptons to be negligible.
  - We allow for mixing between the dark Higgs and the SM Higgs, so that the dark Higgs obtains couplings to SM fermions.
- We then obtain two dark mediators with the following interactions:

$$\mathcal{L}_\chi \supset -\frac{g_\chi}{2}\bar{\chi}\gamma^\mu\gamma^5\chi Z'_\mu - \frac{y_\chi}{2\sqrt{2}}\bar{\chi}\chi s \, , \qquad \frac{y_\chi}{m_\chi} = 2\sqrt{2}\,\frac{g_\chi}{m_{Z'}}$$

$$\mathcal{L}_q \supset -\sum_q \left(g_q \bar{q}\gamma^\mu q Z'_\mu + \sin\theta \frac{m_q}{v}\bar{q}qs \right)$$

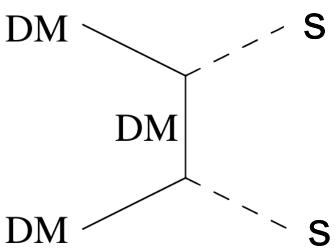
- The model is thus described by 6 independent parameters (three masses and three couplings).

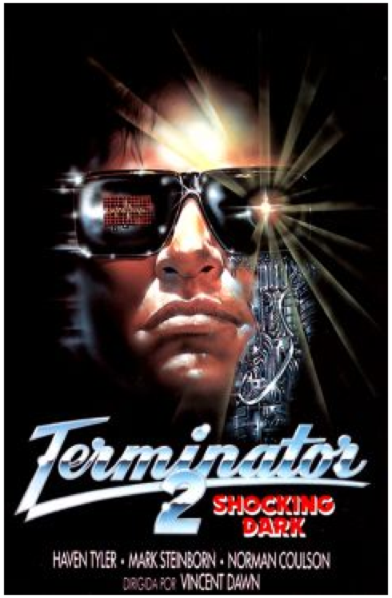
Similar to DM models with gauged baryon number
(Fileviez & Wise, arXiv:1002.1754, Duerr et al., arXiv:1304.0576)

The two-mediator dark matter (2MDM) model

- If one of the mediators is heavy and weakly-coupled, it will play no role in the phenomenology and one recovers a simpler model with only one mediator.

- If one of the two mediators is *light* and weakly coupled, it can provide a new final state for DM annihilation.





- We call such a light state a dark terminator, because it *terminates* rather than *mediates* the interactions of DM.

- Such a dark terminator can relax the relic density constraints on the interactions of the second mediator and thus extended viable parameter space.

The two-mediator dark matter (2MDM) model

- The 2MDM model can be thought of as a combination of several simplified models:

	$g_q \gg \sin\theta$	$g_q \sim \sin\theta$	$\sin\theta \gg g_q$
$m_s \gg m_{Z'}$	Spin-1 mediator simplified model		Spin-0 mediator with spin-1 terminator
$m_{Z'} \sim m_s$		Two-mediator model	
$m_{Z'} \gg m_s$	Spin-1 mediator with spin-0 terminator		Spin-0 mediator simplified model

- By construction, the 2MDM model is renormalisable and gauge invariant, and there are no issues with unitarity at large energies.
- This provides an overarching framework for theoretically consistent simplified models.

Implications of theoretical consistency

- The origin of the the two mediators from a spontaneously broken U(1)' imply a number of additional effects that are important for the phenomenology of 2MDM:
  - The two mediators can interact with each other, for example a dark Higgs can decay into two Z'.
  - The mixing between the two Higgs bosons implies that DM can also interact with SM bosons. In particular, the SM Higgs can decay into a pair of DM particles.
  - The fact that SM quarks are charged under both $U(1)_Y$ and the U(1)' will induce kinetic mixing at loop level:

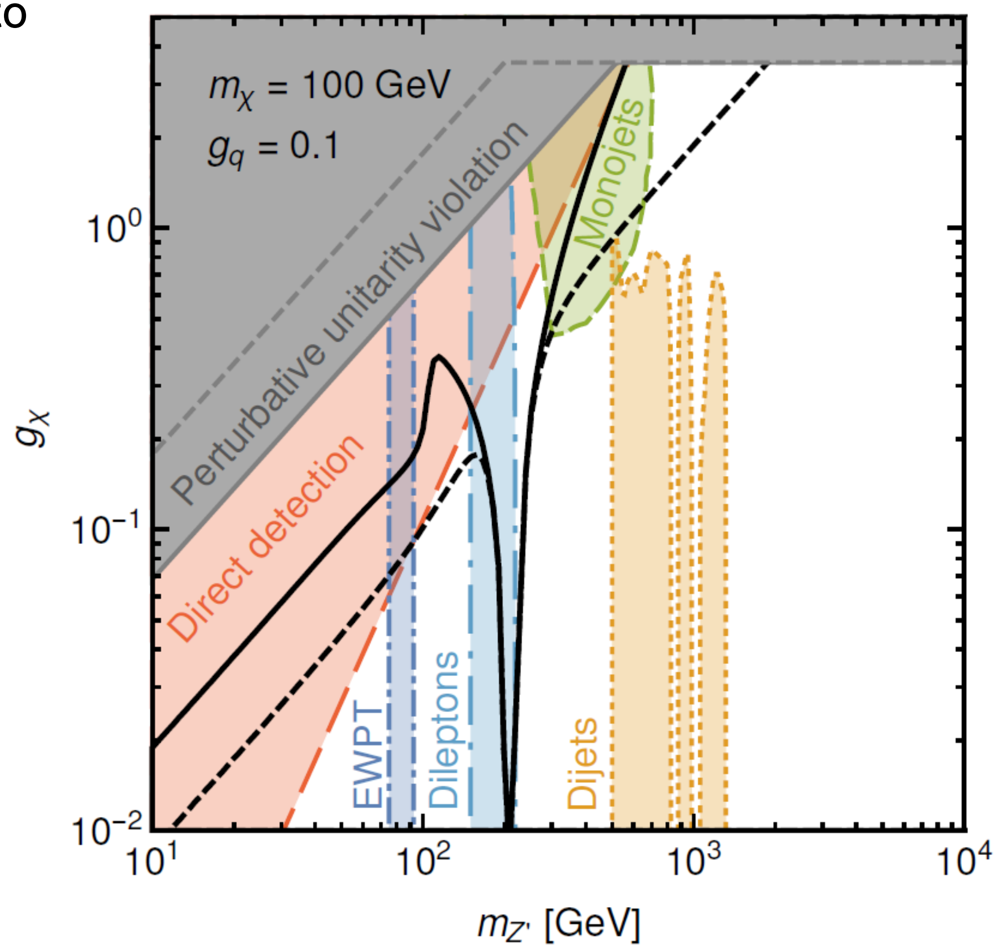
$$\mathcal{L} \supset -\frac{1}{2} \sin \epsilon \, F'^{\mu\nu} B_{\mu\nu}$$

$$\epsilon(\mu) = \frac{e \, g_q^V}{2\pi^2 \, \cos\theta_W} \log \frac{\Lambda}{\mu} \simeq 0.02 \, g_q^V \, \log \frac{\Lambda}{\mu}$$

- All these effects should be taken into account in a global analysis of the model.

Spin-1 mediation: Some phenomenological aspects

- Let us first consider the case that the dark Higgs has negligible couplings to the SM ($\theta \sim 0$).



Spin-1 mediation: Some phenomenological aspects

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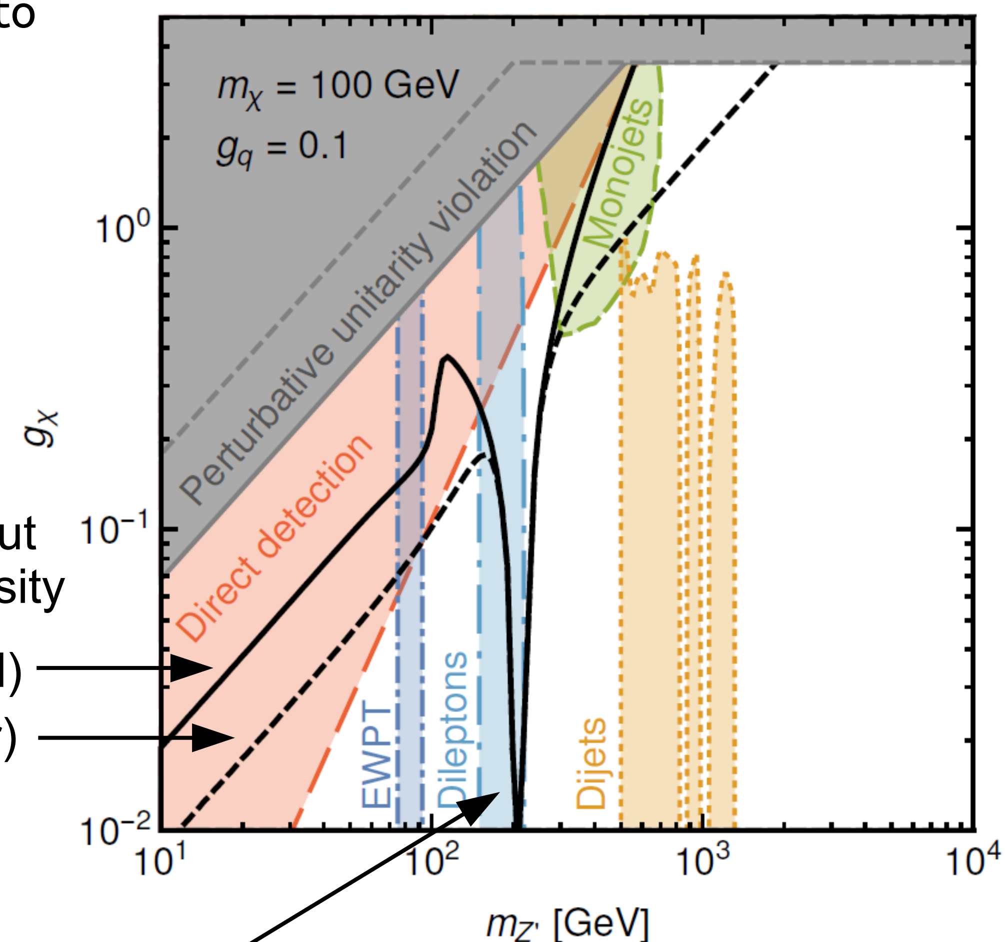


For the black line thermal freeze-out reproduces the observed relic density

$m_s = 3\, m_\chi$ (dark Higgs decoupled)

$m_s = 0.1\, m_\chi$ (dark Higgs terminator)

Resonant enhancement of DM annihilations

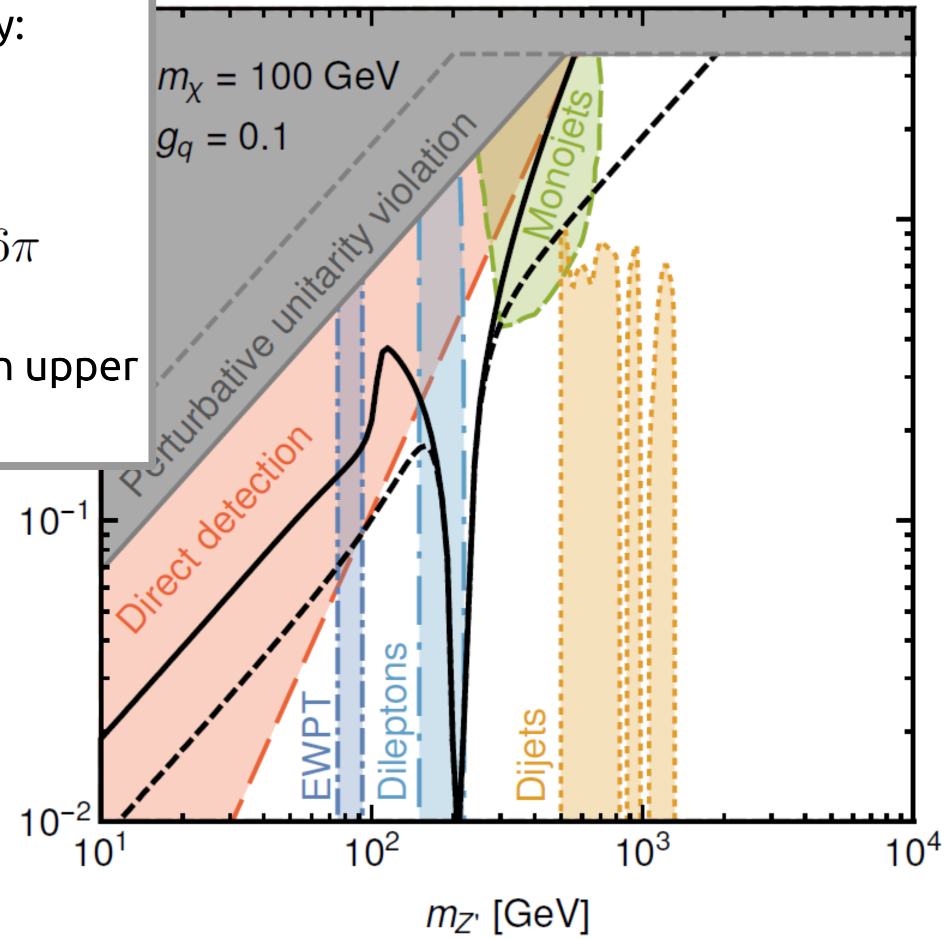
Spin-1 mediation: Some phenomenological aspects

- The requirement of partial wave perturbative unitarity leads to three independent inequalities that the couplings of the model must satisfy:

$$g_\chi < \sqrt{4\pi}\,, \qquad y_\chi < \sqrt{8\pi}$$

$$3(\lambda_h + \lambda_s) \pm \sqrt{9(\lambda_h - \lambda_s)^2 + \lambda_{hs}^2} < 16\pi$$

- The third inequality can be interpreted as an upper bound on the Higgs boson mixing.



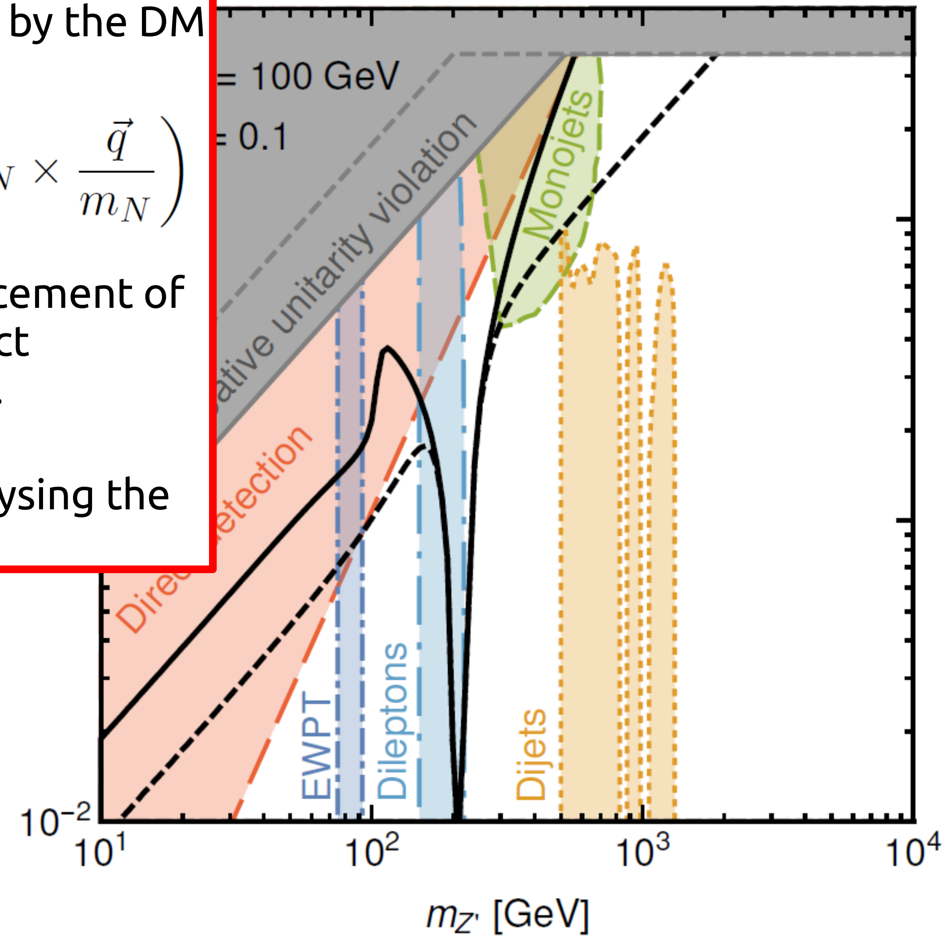
Spin-1 mediation: Some phenomenological aspects

- For the coupling structure of the model, scattering in the non-relativistic limit is suppressed by the DM velocity and the momentum transfer:

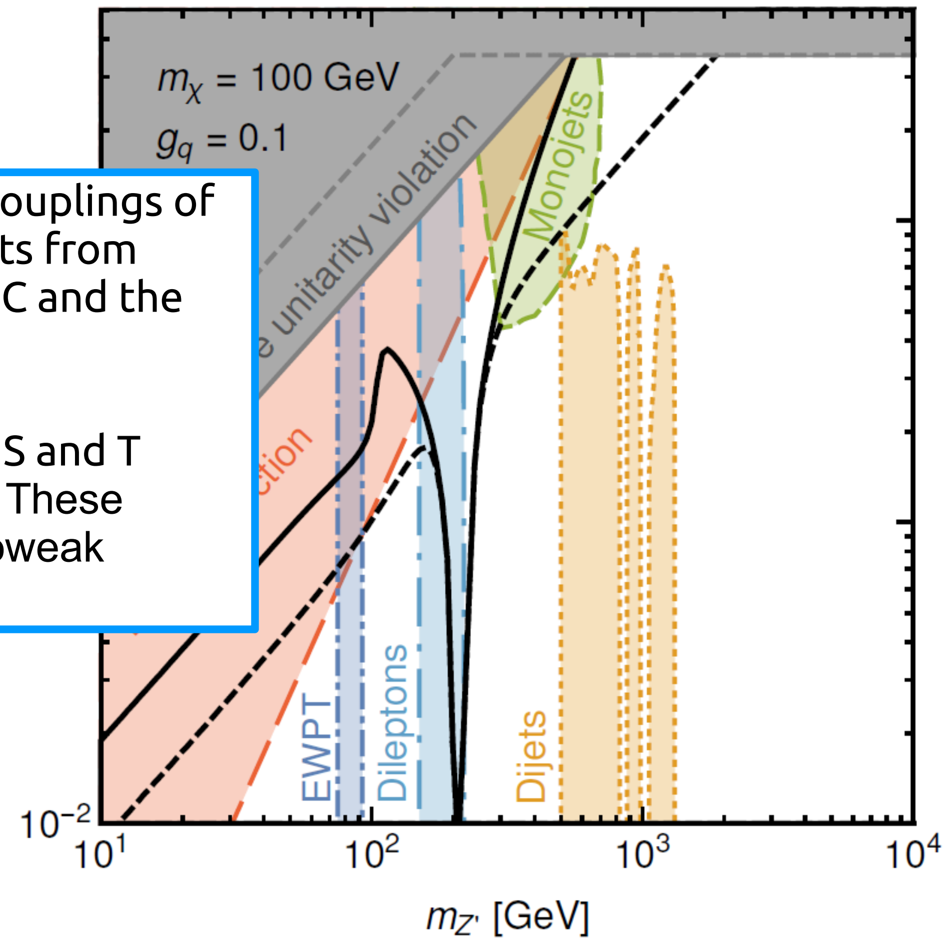
$$\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\,\bar{q}\gamma_{\mu}q \quad \rightarrow \quad 2\vec{v}^{\perp}\cdot\vec{S}_{\chi} + 2i\vec{S}_{\chi}\cdot\left(\vec{S}_{N}\times\frac{\vec{q}}{m_{N}}\right)$$

- Nevertheless, there is a coherent enhancement of the scattering cross section, so that direct detection still gives relevant constraints.

- We calculate these constraints by reanalysing the recent bounds from LUX.



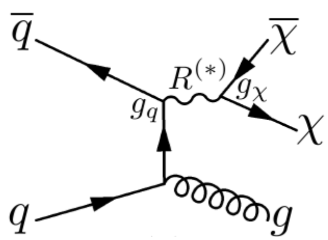
Spin-1 mediation: Some phenomenological aspects

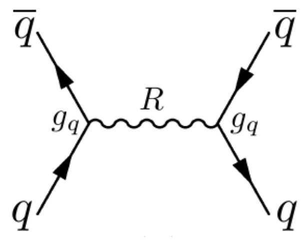


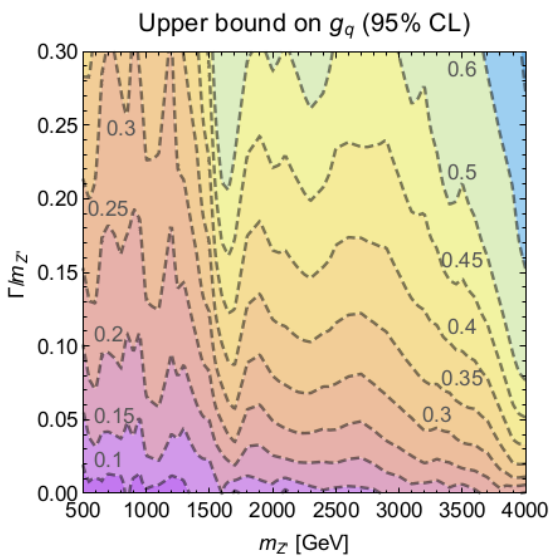
- Loop-induced kinetic mixing leads to couplings of the Z' to leptons and thus to constraints from dilepton resonance searches at the LHC and the Tevatron.
- Moreover, kinetic mixing modifies the S and T parameter, as well as the ρ parameter. These modifications are constraints by electroweak precision tests.

Spin-1 mediation: Some phenomenological aspects

- Finally, the LHC constraints both invisible decays of the Z' (via searches for monojets in association with missing energy) and visible decays (via searches for dijet resonances).

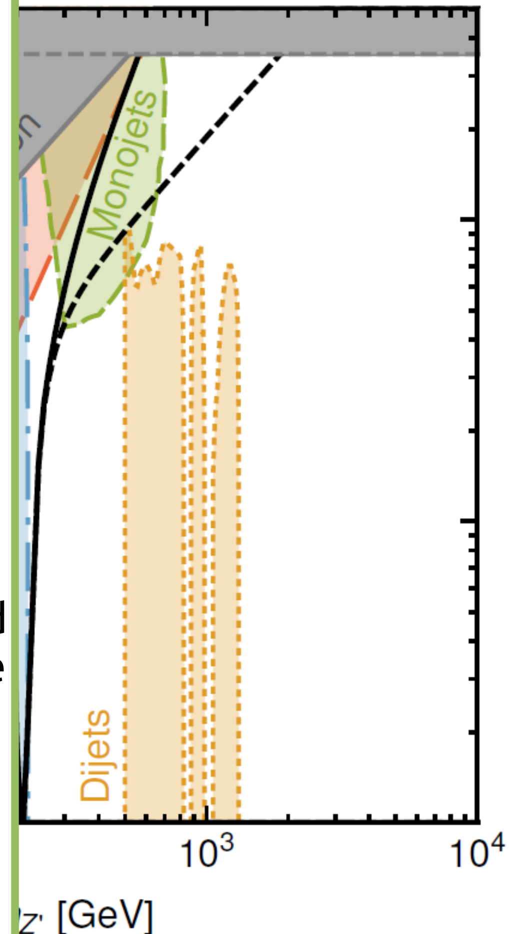






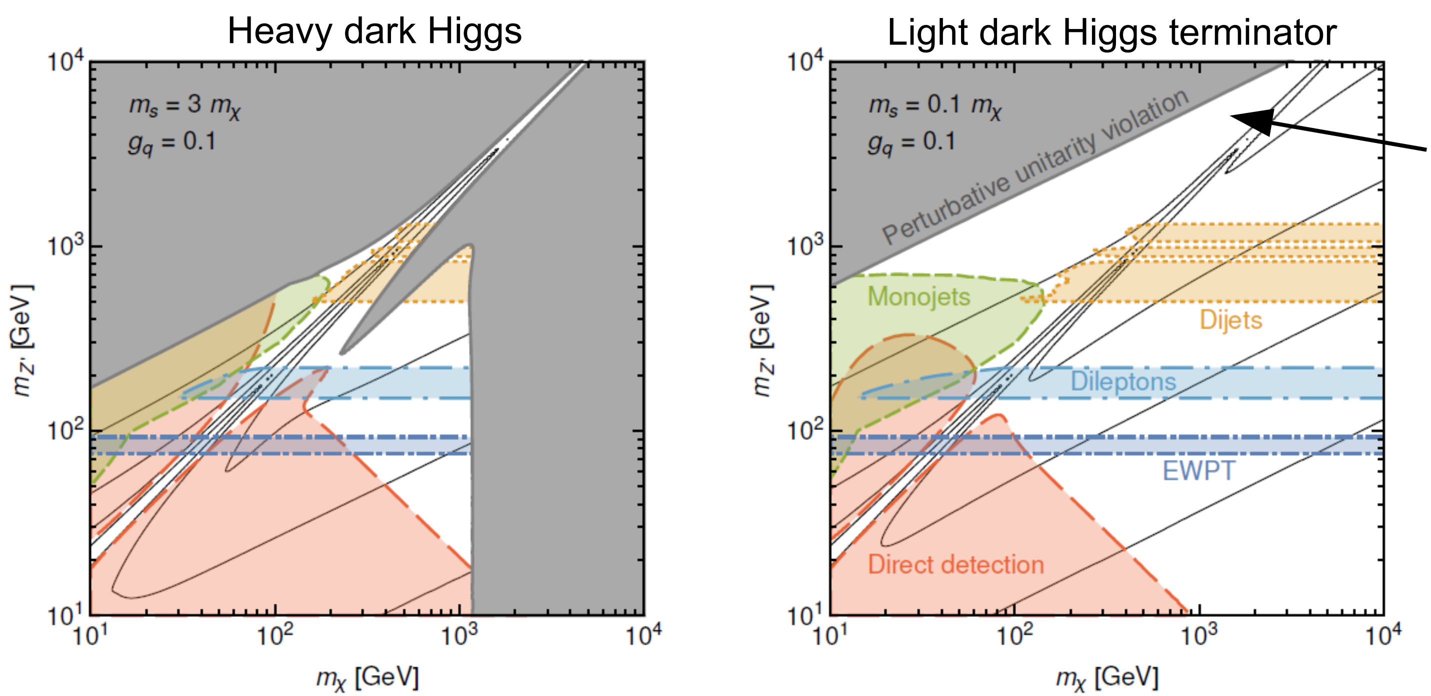
For the latter constraint, we implement a combined analysis of dijet resonance searches from ATLAS and CMS at 8 TeV and 13 TeV.

Fairbairn, FK et al., arXiv:1605.07940



Imposing the relic density constraint

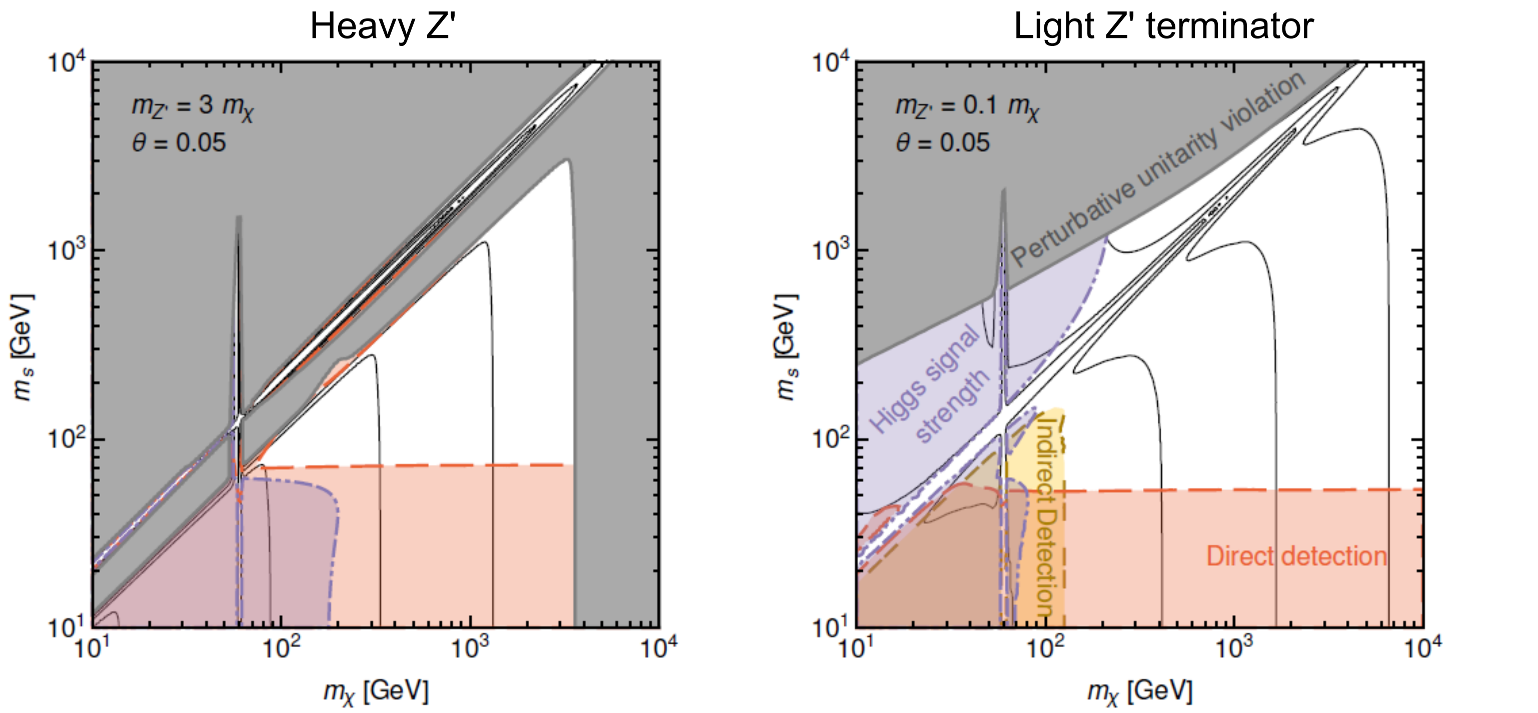
- From now on, we assume that our model captures all relevant DM annihilation channels.
- This allows us to fix g_χ by the requirement to reproduce the observed DM relic abundance and study the constraints as a function of the two masses.



The presence of a light terminator opens up large regions of parameter space

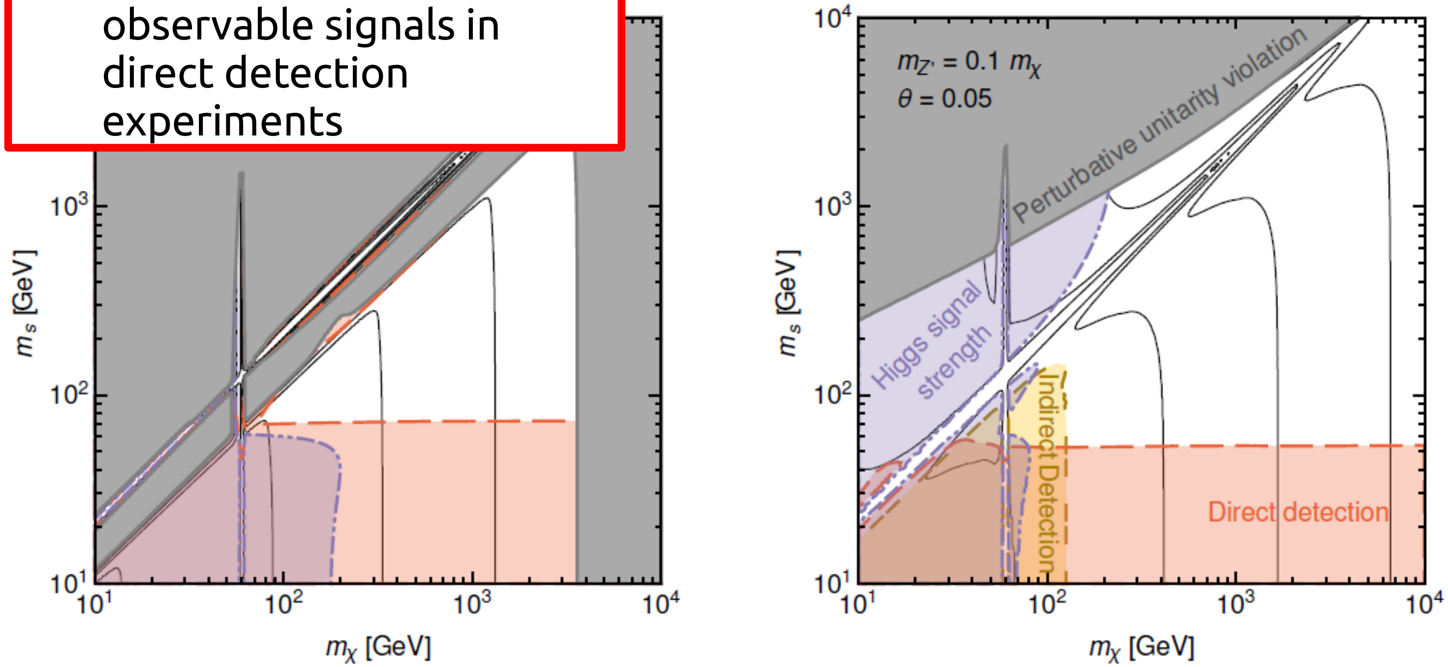
Spin-0 mediation: Some phenomenological aspects

- Similarly, we can look at the case that the dark Higgs plays the dominant role and the Z' is largely decoupled ($g_q \sim 0$).



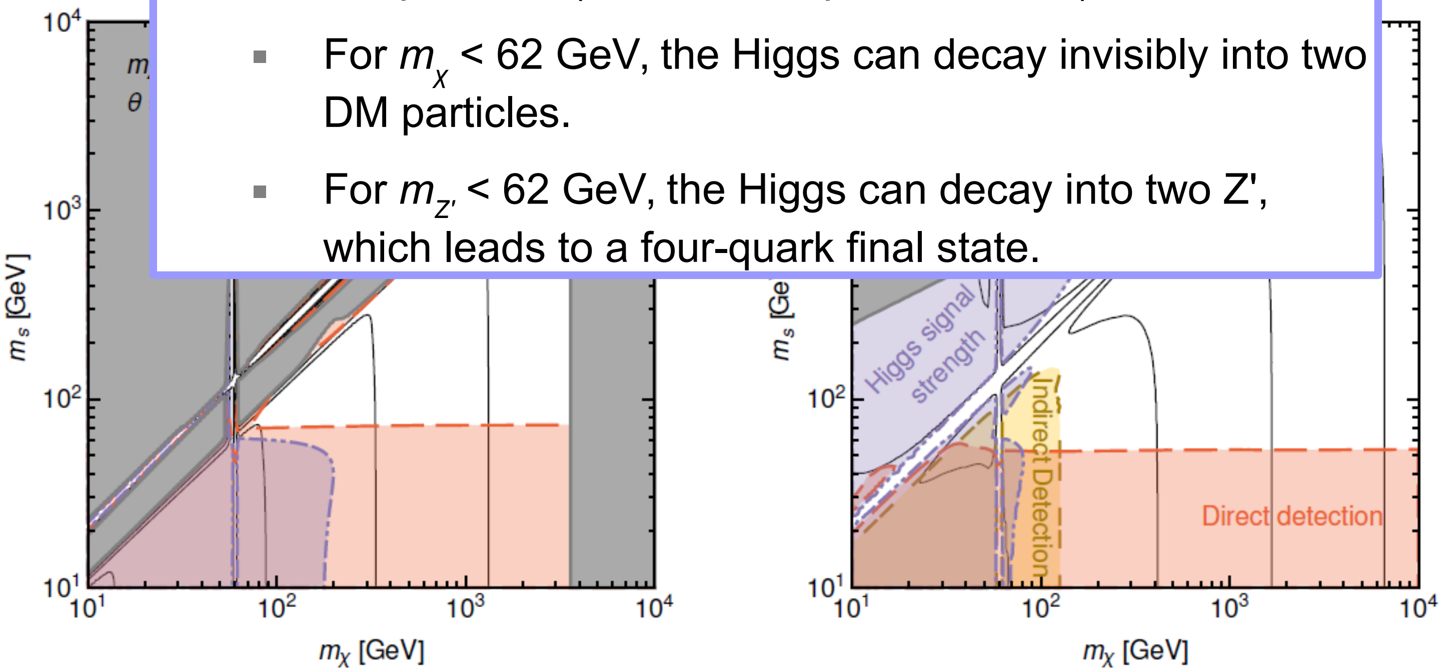
Spin-0 mediation: Some phenomenological aspects

- In the presence of Higgs mixing, both the dark Higgs and the SM Higgs can mediate DM-nucleon scattering and lead to observable signals in direct detection experiments

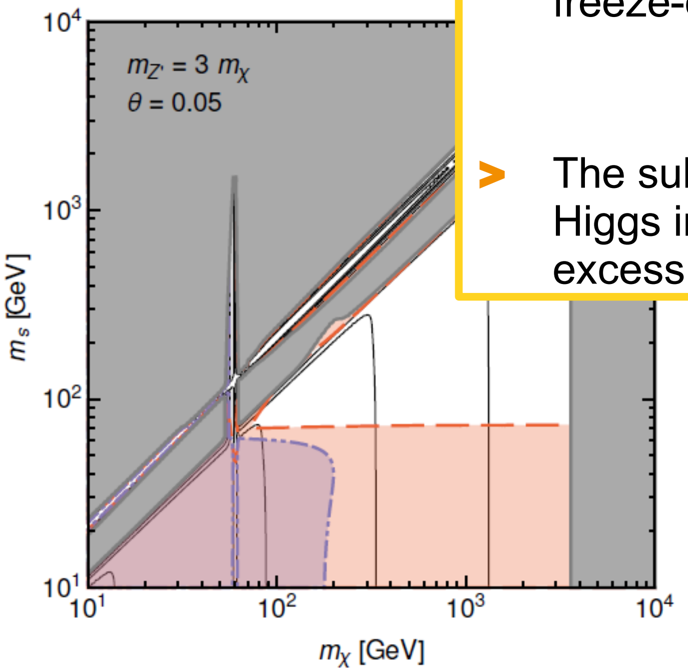


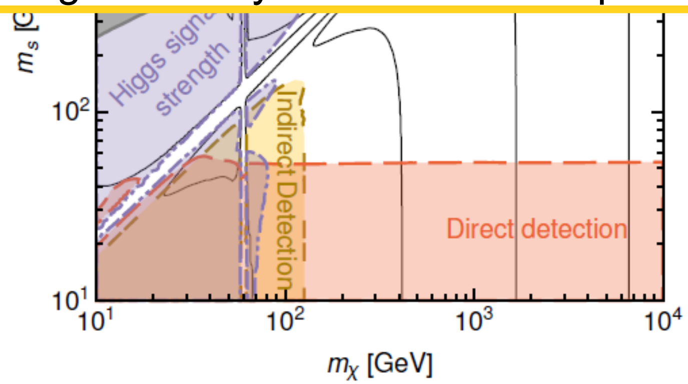
Spin-0 mediation: Some phenomenological aspects

- The total Higgs signal strength is experimentally constrained to satisfy $\mu > 0.89$.
- In this model, there are three effects that may reduce μ:
  - Mixing reduces the couplings of the SM Higgs to other SM particles (this alone implies $\theta < 0.34$).
  - For $m_\chi < 62$ GeV, the Higgs can decay invisibly into two DM particles.
  - For $m_{Z'} < 62$ GeV, the Higgs can decay into two Z', which leads to a four-quark final state.



Spin-0 mediation: Some phenomenological aspects





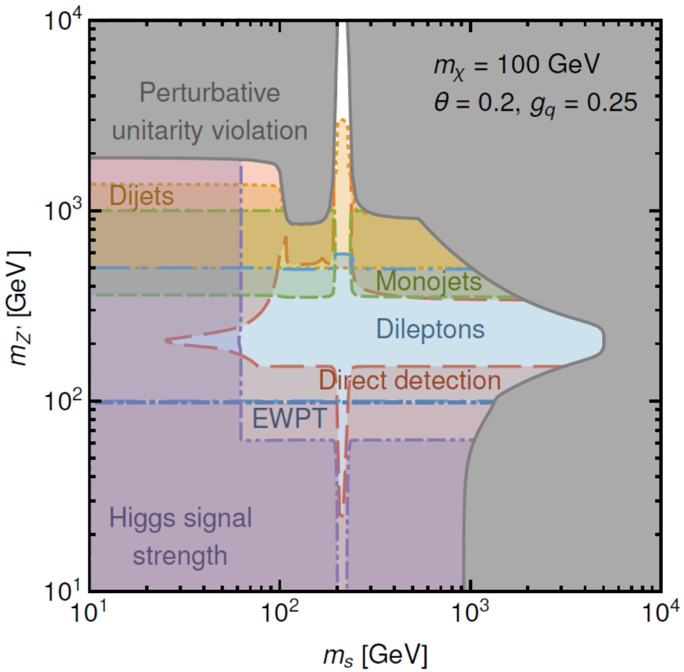
- For Majorana DM annihilation into two identical particles can only proceed at p-wave and is thus unobservable in the present Universe.
- However, if the process $\chi\chi \to Z's$ is kinematically allowed, it will proceed at s-wave and thus dominate both freeze-out and present-day annihilation signals.

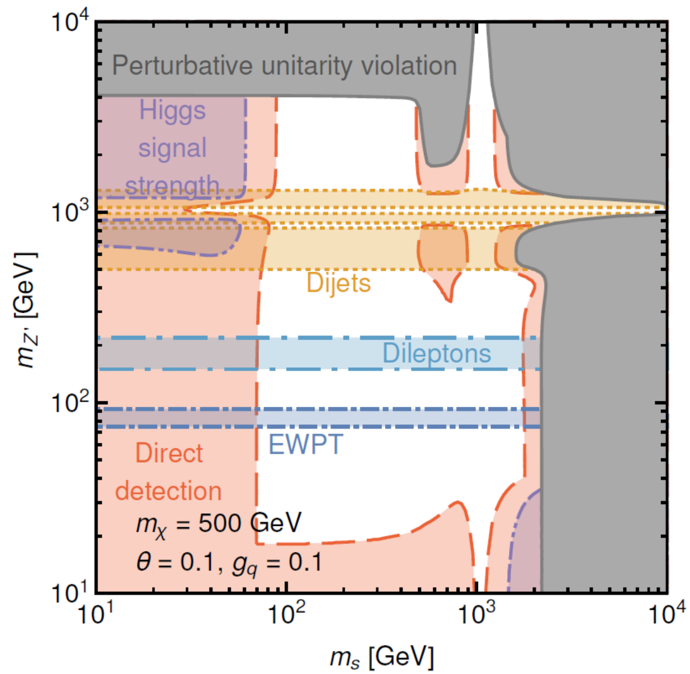
Bell et al., arXiv:1605.09382

- The subsequent cascade decays of the Z' and the dark Higgs into SM fermions may then lead to an observable excess in the gamma-ray flux from dwarf spheroidals.

Two mediators: Putting everything together

- Let us now study the constraints for non-zero θ and g_q. The most convenient way to proceed is to fix the DM mass and vary m_s and $m_{Z'}$.

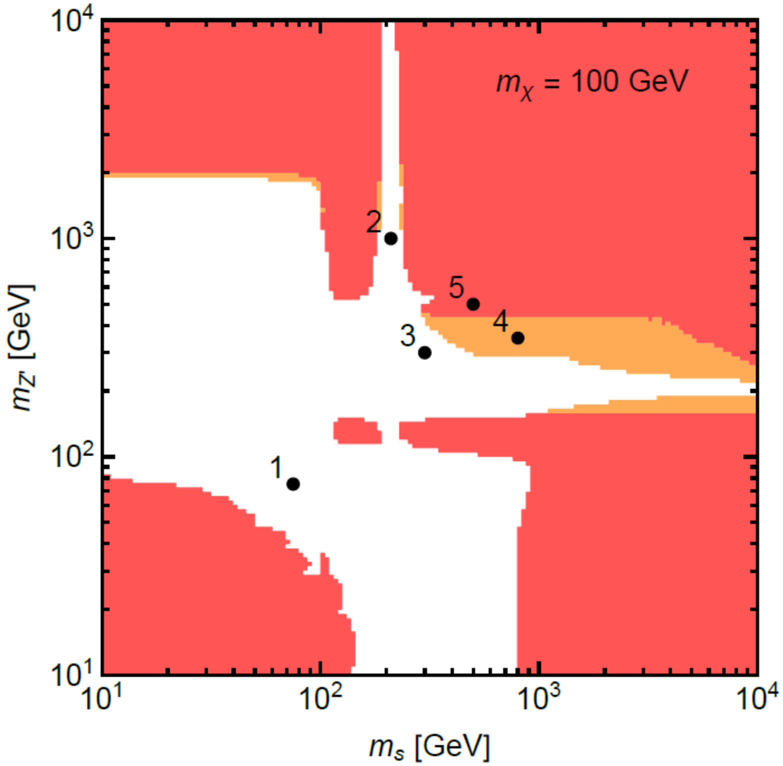




- For sizeable couplings and small DM mass, essentially all mediator masses are excluded.
- For smaller couplings and larger DM masses, allowed parameter regions open up.

Global scans

- It is impractical to reproduce such plots for all interesting combinations of DM masses and mediator couplings.
- This requires a global analysis: For fixed masses we scan over g_q and θ and determine for each choice of those parameters the dark sector coupling by the relic abundance.

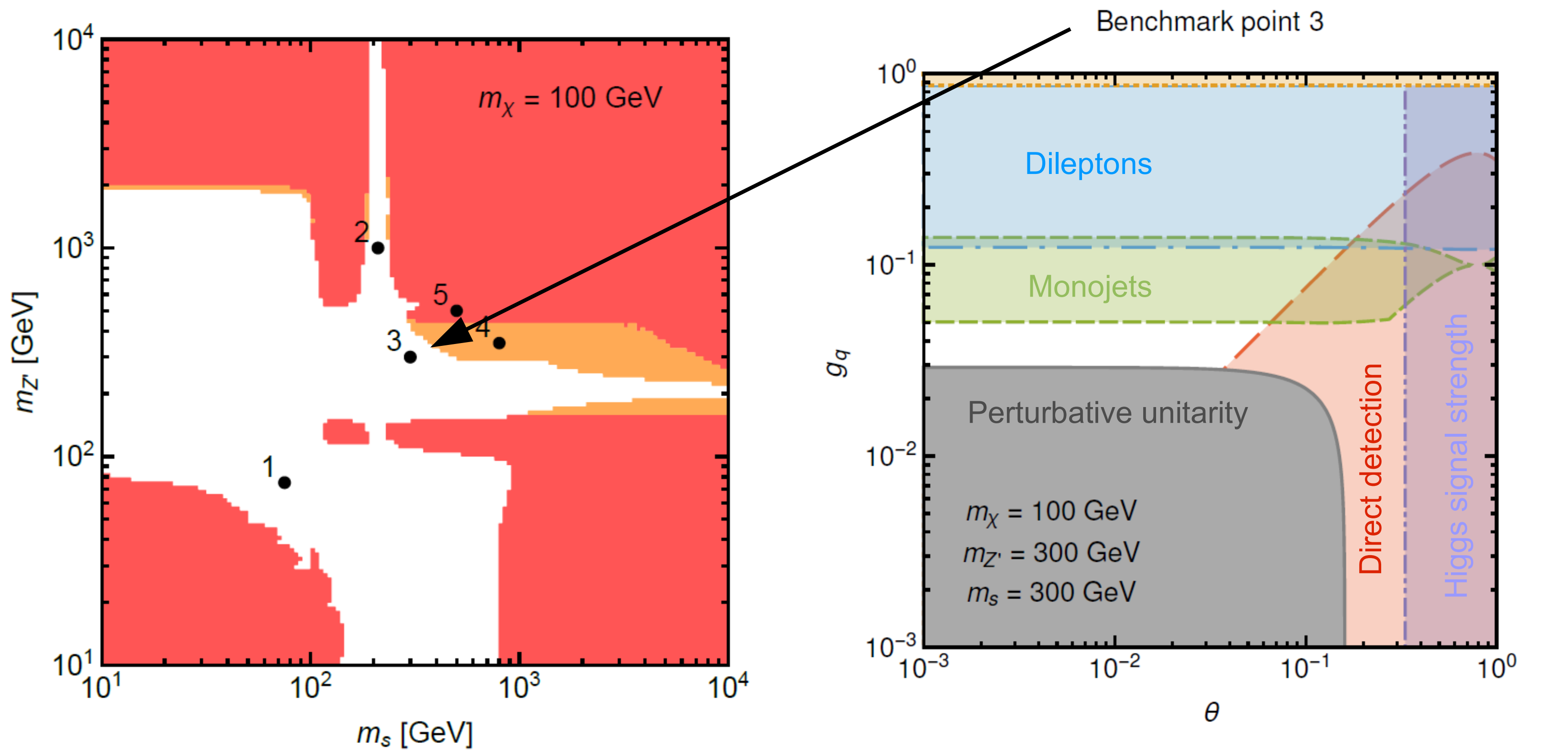


Red: All coupling combinations are excluded by at least one constraint.

White: At least one coupling combination is compatible with all constraints.

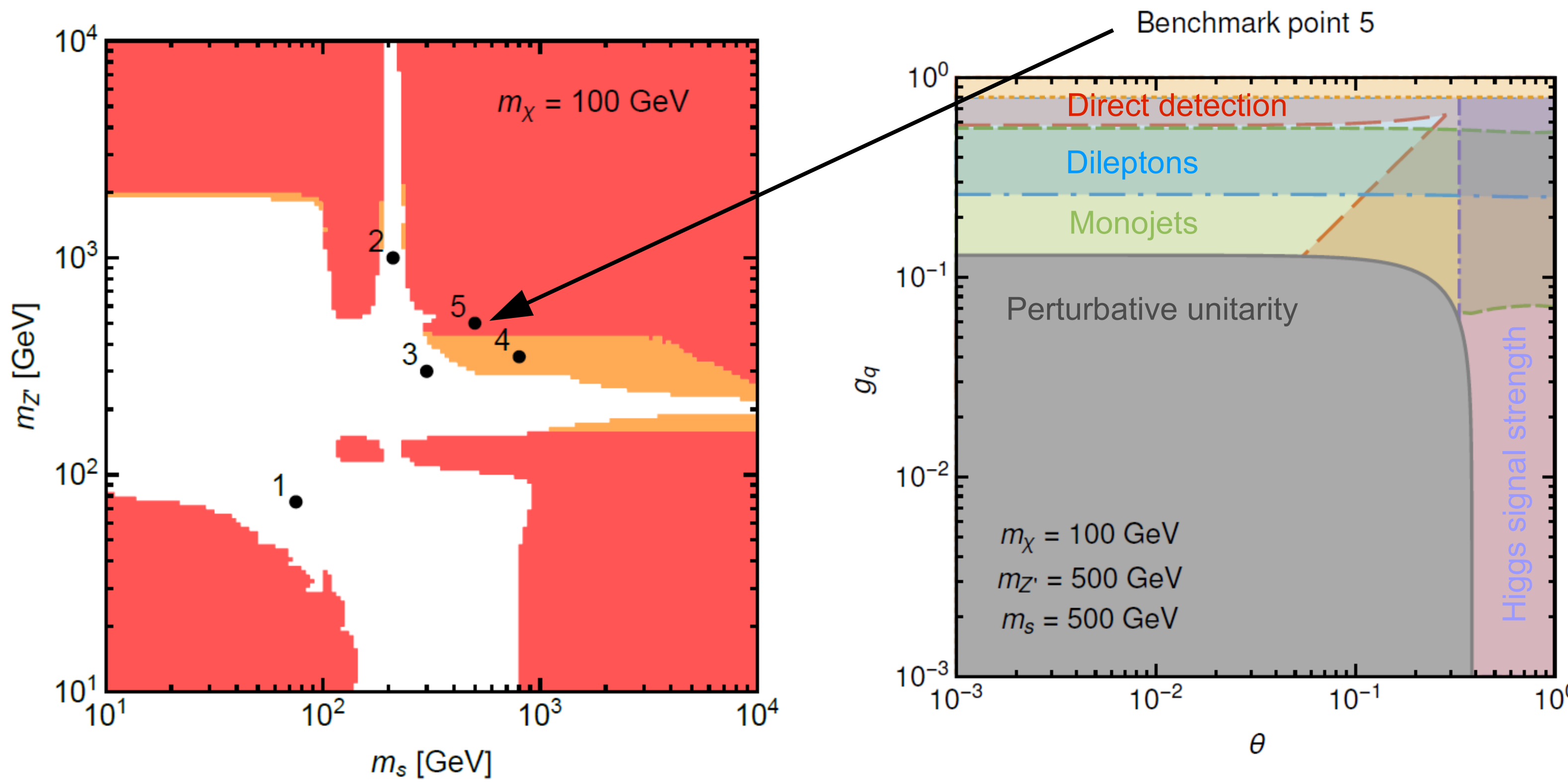
Orange: Large values of g_q cannot reliably be excluded due to the mediator width becoming large ($\Gamma/m_{Z'} > 0.3$).

A closer look at two benchmark cases



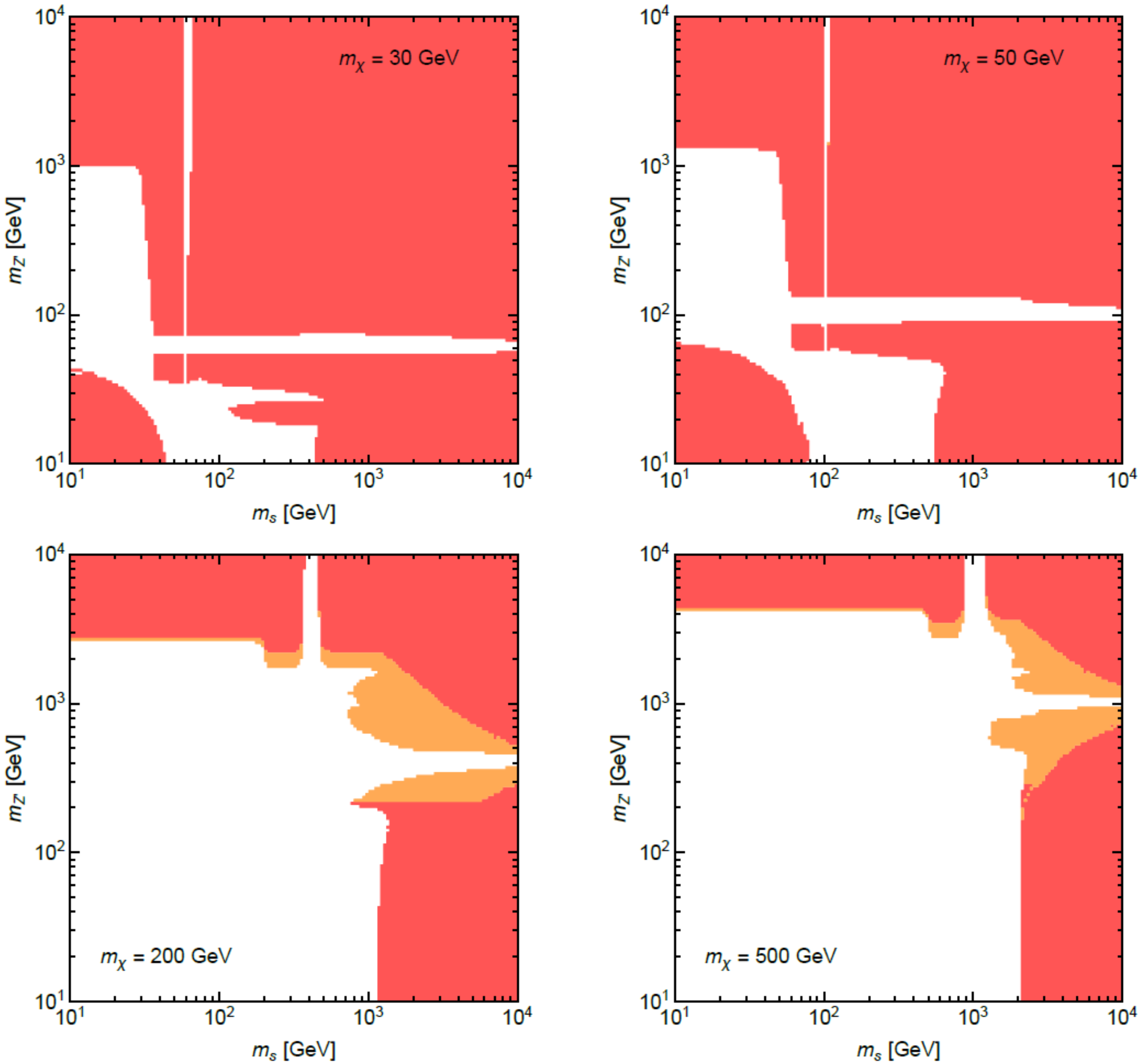
- Allowed parameter space for $g_q \sim 0.04$ and $\theta < 0.06$.

A closer look at two benchmark cases



- It takes a combination of several different constraints to rule out the given set of DM and mediator masses.

Global scans: Final results



- Repeating the global scan for different DM masses, we find that small DM masses are indeed tightly constrained by the data and require the presence of at least one dark terminator.
- In fact, the presence of two dark terminators is excluded by indirect detection constraints for $m_\chi < 100$ GeV.
- The conguration with one or two dark terminators remains viable up to $m_\chi < 50$ TeV.

Outlook

- While dark terminators are very difficult to probe experimentally, we have been able to identify a few promising search channels:
  - Non-standard Higgs decays involving either four *b*-quarks (for $h \to s\, s$) or four light quarks (for $h \to Z' Z'$) in the final state.
  - Mono-dark-Higgs searches arising from either dark Higgs Strahlung

    $$pp \to Z'^* \to Z's \to \chi\chi s$$

    or from final state radiation of a dark Higgs

    $$pp \to Z' \to \chi\chi \to \chi\chi s$$

  - Indirect detection of DM cascade annihilations. Indeed, the 2MDM model can provide a viable explanation for the Galactic Centre Excess and also accommodation annihilation cross sections slightly below the thermal cross section.

Part II: Conclusions

- The 2MDM model provides a flexible framework to combine several simplified models in a theoretically consistent way.
- This approach enables us to study typical constraints on WIMP DM in a very general way.
- Our global scans show that the WIMP hypothesis is under severe pressure and that “classic” WIMP scenarios with heavy mediators are largely excluded.
- There are basically only two possibilities to obtain the correct relic abundance:
  - The DM and mediator masses are tuned close to an s-channel resonance
  - One or both mediators are lighter than the DM (a dark terminator), such that DM annihilations into the dark sector control the relic abundance, while the coupling to the SM can be quite small.
- If DM is indeed a WIMP then the dark sector is likely more complicated than just a weak-scale DM particle with effective interactions with the SM.