The two-mediator dark matter (2MDM) model.

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based on **arXiv:1606.07609** in collaboration with
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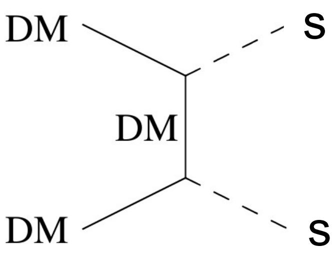
Introduction

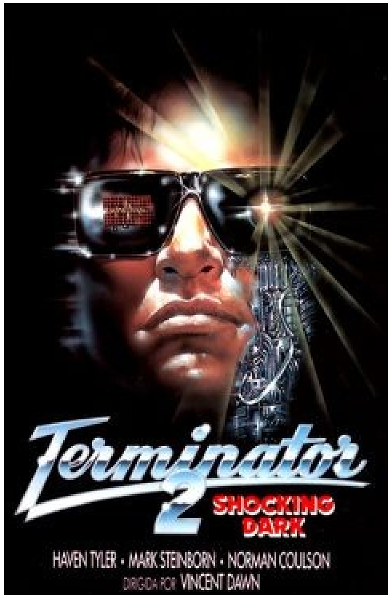
- Simplified models with a spin-1 mediator typically do not address the way in which the mass of the mediator is generated.
- For a spin-1 mediator with vector couplings, this can be achieved without adding new degrees of freedom (e.g. via a Stueckelberg mechanism).
- For a spin-1 mediator with axial couplings, however, new degrees of freedom are necessary to restore perturbative unitarity at high energies.
- The simplest way to generate the mediator mass and restore perturbative unitarity is to introduce a dark Higgs.
- It is only natural that such a dark Higgs would mix with the SM Higgs, so that it can also couple to SM fermions.
- This chain of arguments automatically leads to simplified models with two mediators.

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.

A specific example

- To be specific, we focus on the following set-up:
  - 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 and assume coupling to leptons to be negligible. This relaxes strong constraints from EWPT and dilepton searches.
- We thus consider the following interactions:

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

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

$$\frac{y_\chi}{m_\chi} = 2\sqrt{2}\,\frac{g_\chi}{m_{Z'}}$$

- The model is fully 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)

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:

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

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

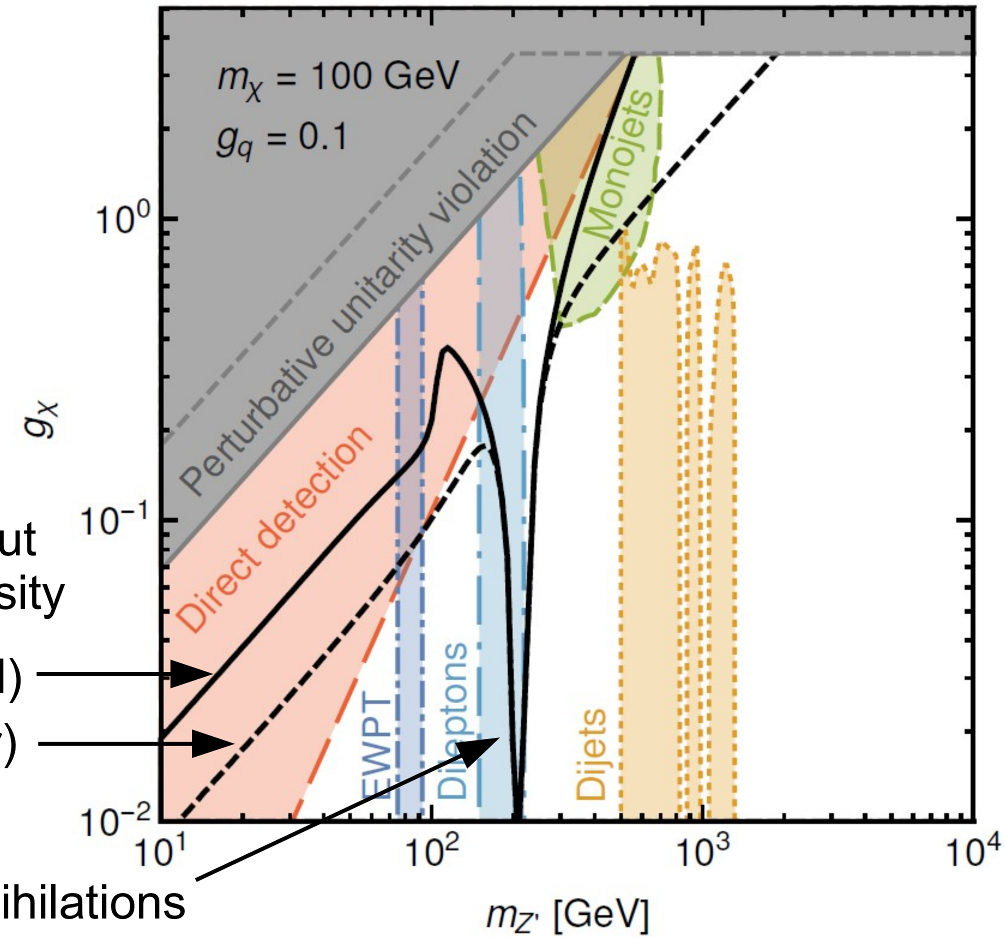
- All these effects should be taken into account in a global analysis of the model.

Why is this of interest for the LHC DM Working Group

- Reason 1: It is possible to interpret a large number of collider searches in this framework and present the experimental results in joint summary plots:
  - LHC DM searches (mono-X, invisible Higgs decays)
  - Heavy resonance searches (di-jets, di-leptons, heavy Higgs)
  - SM precision measurements (Higgs signal strength, EWPT)
- Reason 2: The extended parameter space allows to better explore the complementarity of different probes of DM.
  - For example, the additional degrees of freedom open up new possibilities to relax the relic density constraint
- Reason 3: The phenomenology of the model may point towards new searches presently not considered:
  - An extra (dark) Higgs in association with a Z'
  - The SM Higgs decaying into a pair of dark Higgs bosons or a pair of Z' bosons
  - Final state radiation of dark Higgs bosons

Spin-1 mediation: Some phenomenological aspects

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



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

micrOMEGAs 4, Belanger et al., arXiv:1407.6129

Spin-1 mediation: Some phenomenological aspects

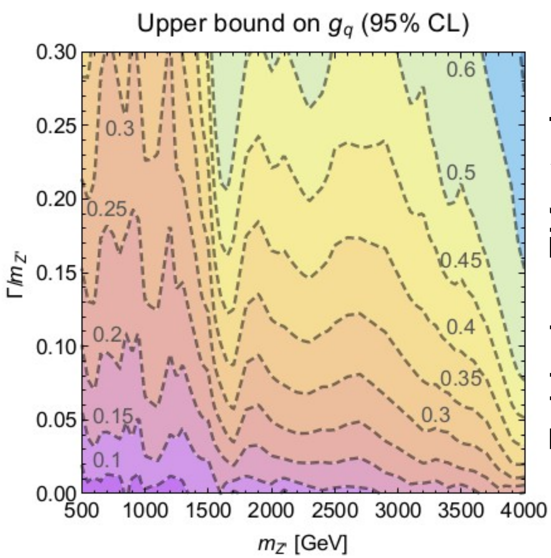
- **Direct detection:** $\bar{\chi}\gamma^{\mu}\gamma^{5}\chi\,\bar{q}\gamma_{\mu}q \quad \rightarrow \quad 2\vec{v}^{\perp}\cdot\vec{S}_{\chi} + 2i\vec{S}_{\chi}\cdot\left(\vec{S}_N \times \frac{\vec{q}}{m_N}\right)$

- Perturbative unitarity:

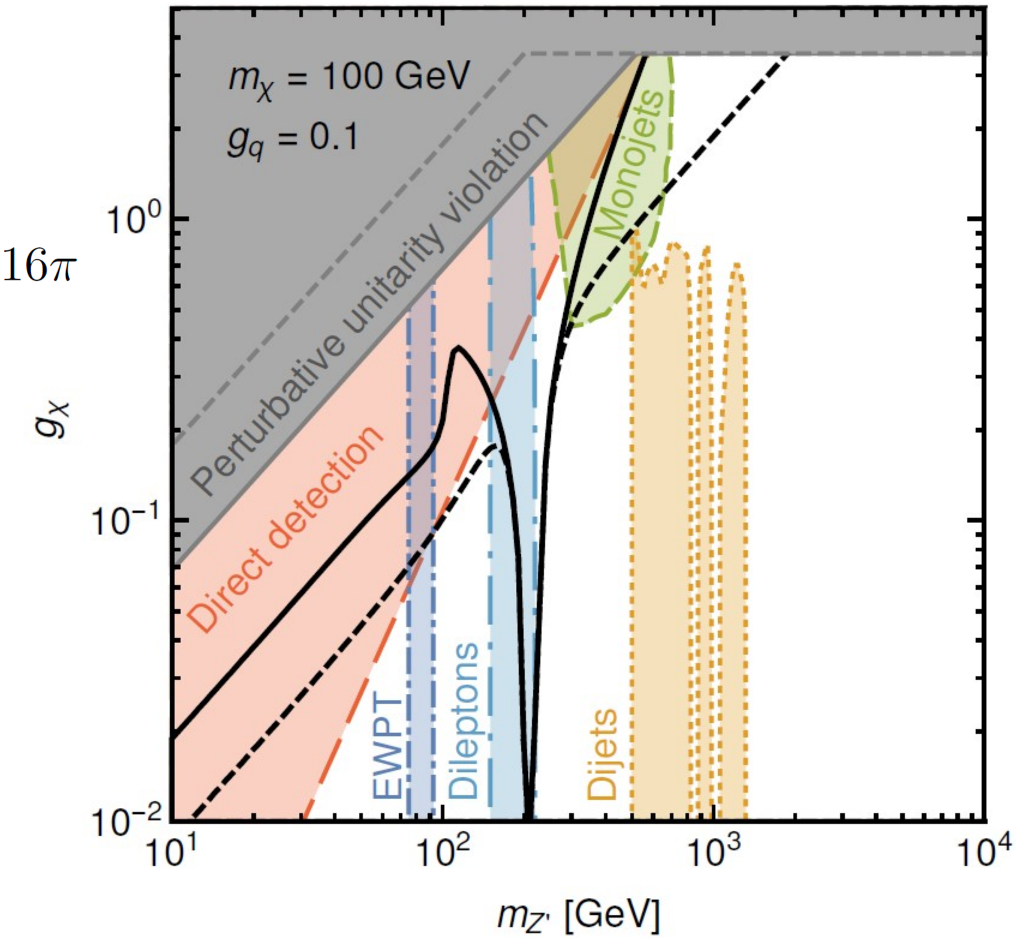
$$g_\chi < \sqrt{4\pi}\,, \qquad y_\chi < \sqrt{8\pi}$$

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

- Dijets:
  - Combination of ATLAS & CMS

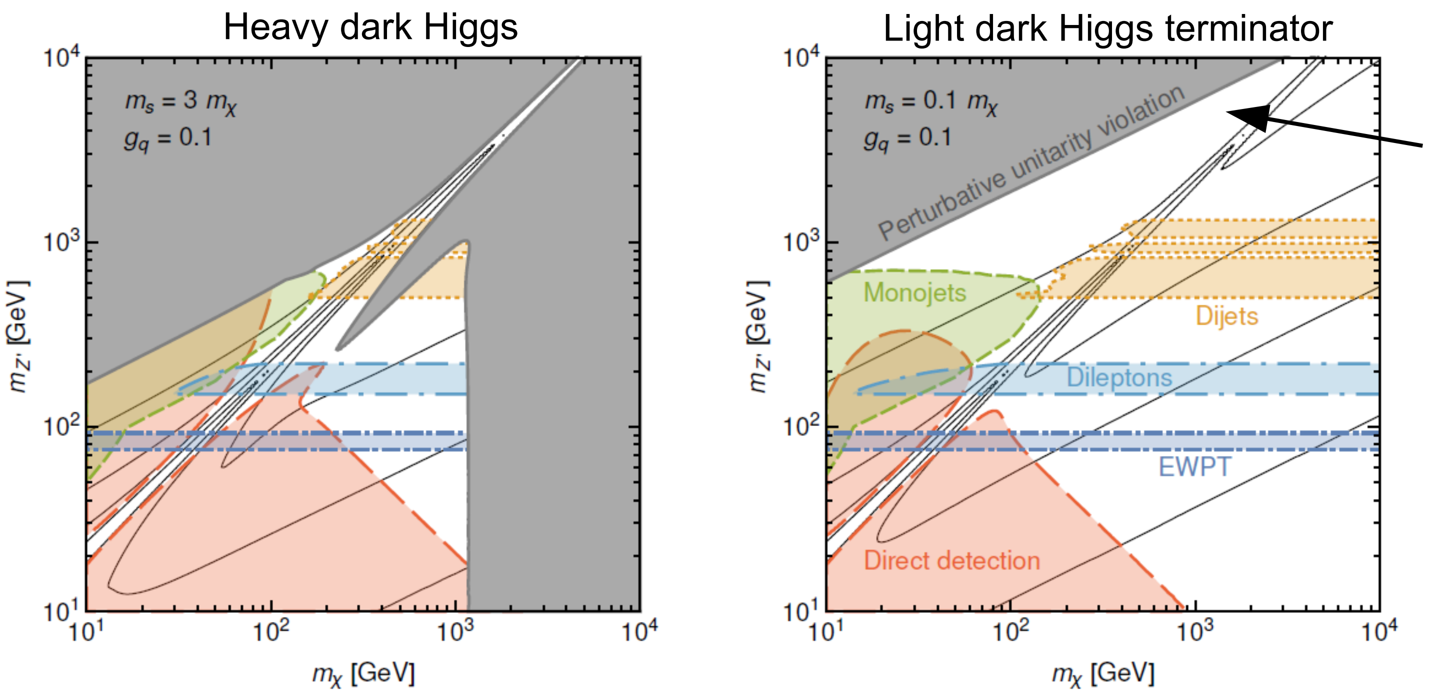


Fairbairn, FK et al., arXiv:1605.07940



Imposing the relic density constraint

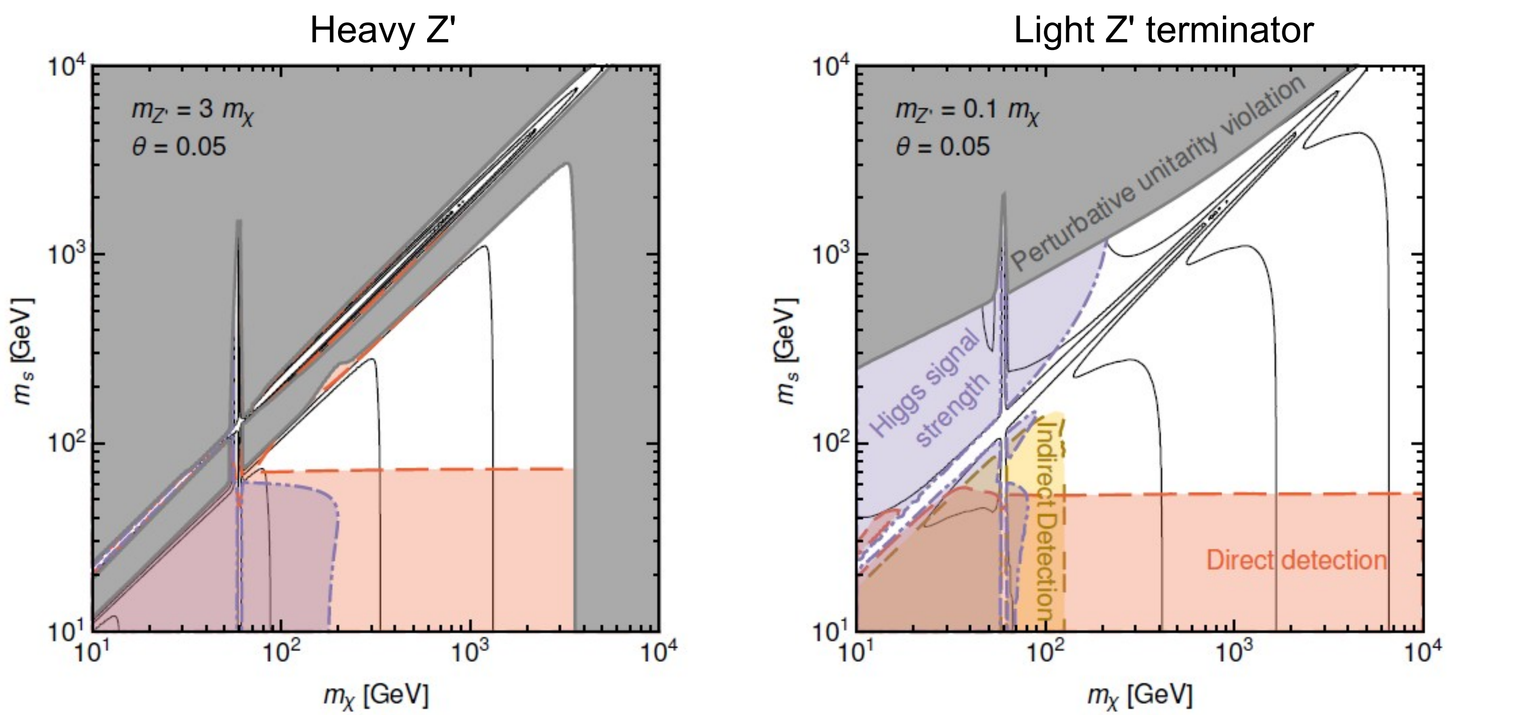
- From now on, we assume that our model captures all relevant DM annihilation channels.
- This allows us to fix g_χ by the requirement to reproduce the observed DM relic abundance and study the constraints as a function of the two masses.



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

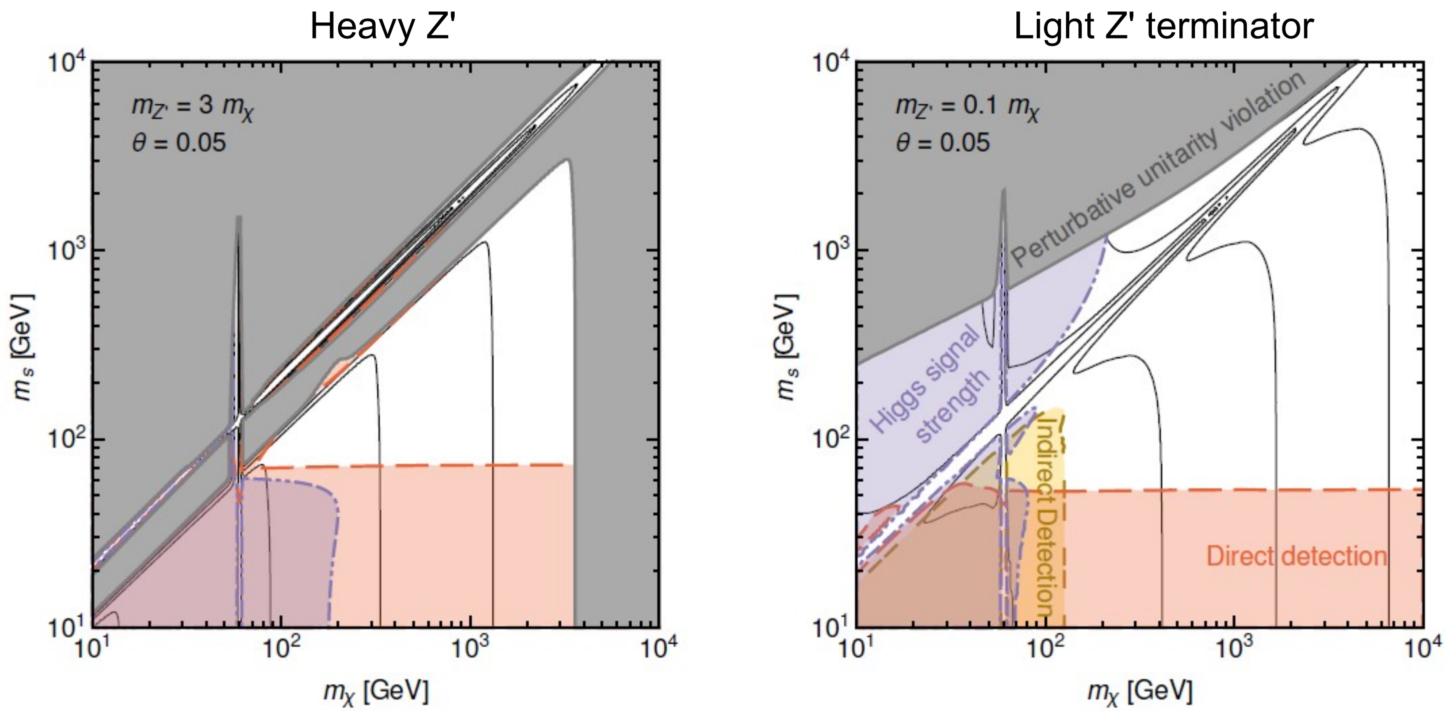
Spin-0 mediation: Some phenomenological aspects

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



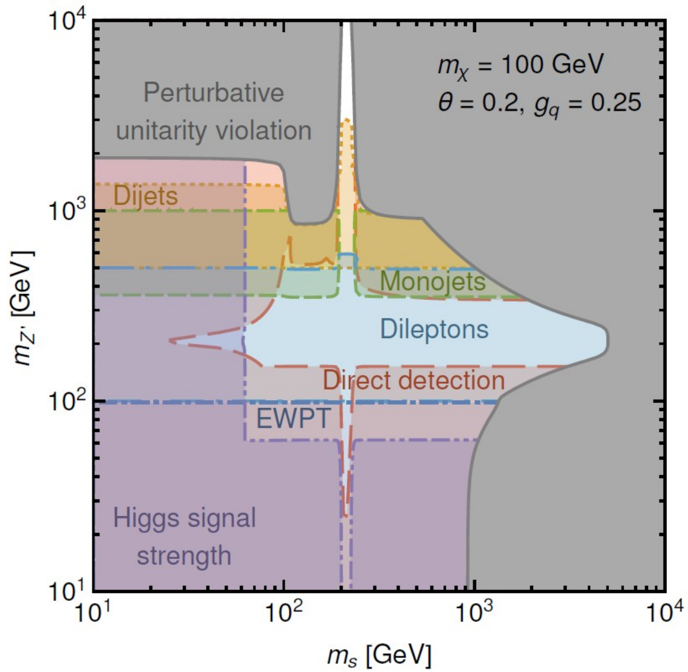
Spin-0 mediation: Some phenomenological aspects

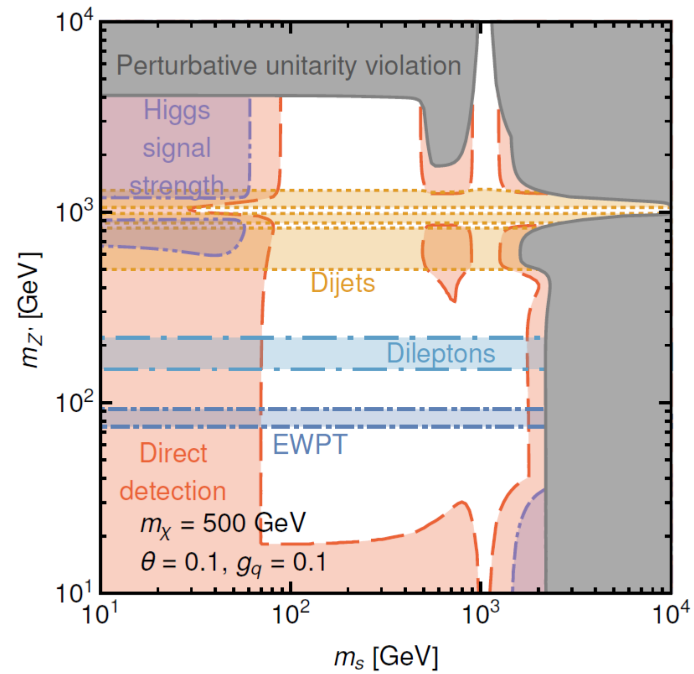
- Direct detection constraints arise from (spin-independent) Higgs mediation
- The Higgs signal strength is reduced by mixing, by invisible decays and my unobserved non-standard decays ($h \to 4b$, $h \to 4j$)



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 $m_{Z'}$.

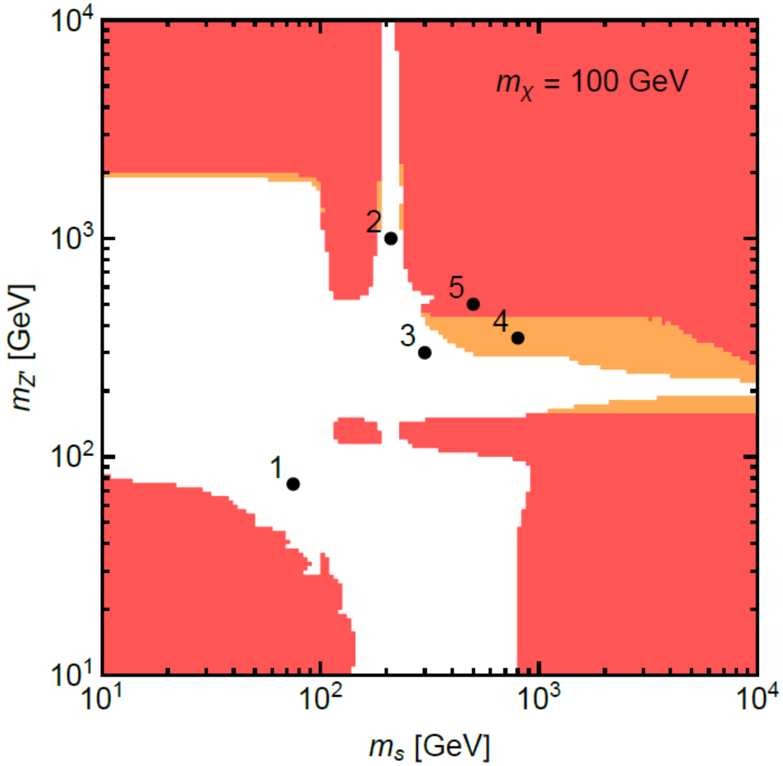




- For sizeable couplings and small DM mass, essentially all mediator masses are excluded.
- For smaller couplings and larger DM masses, allowed parameter regions open up.

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.

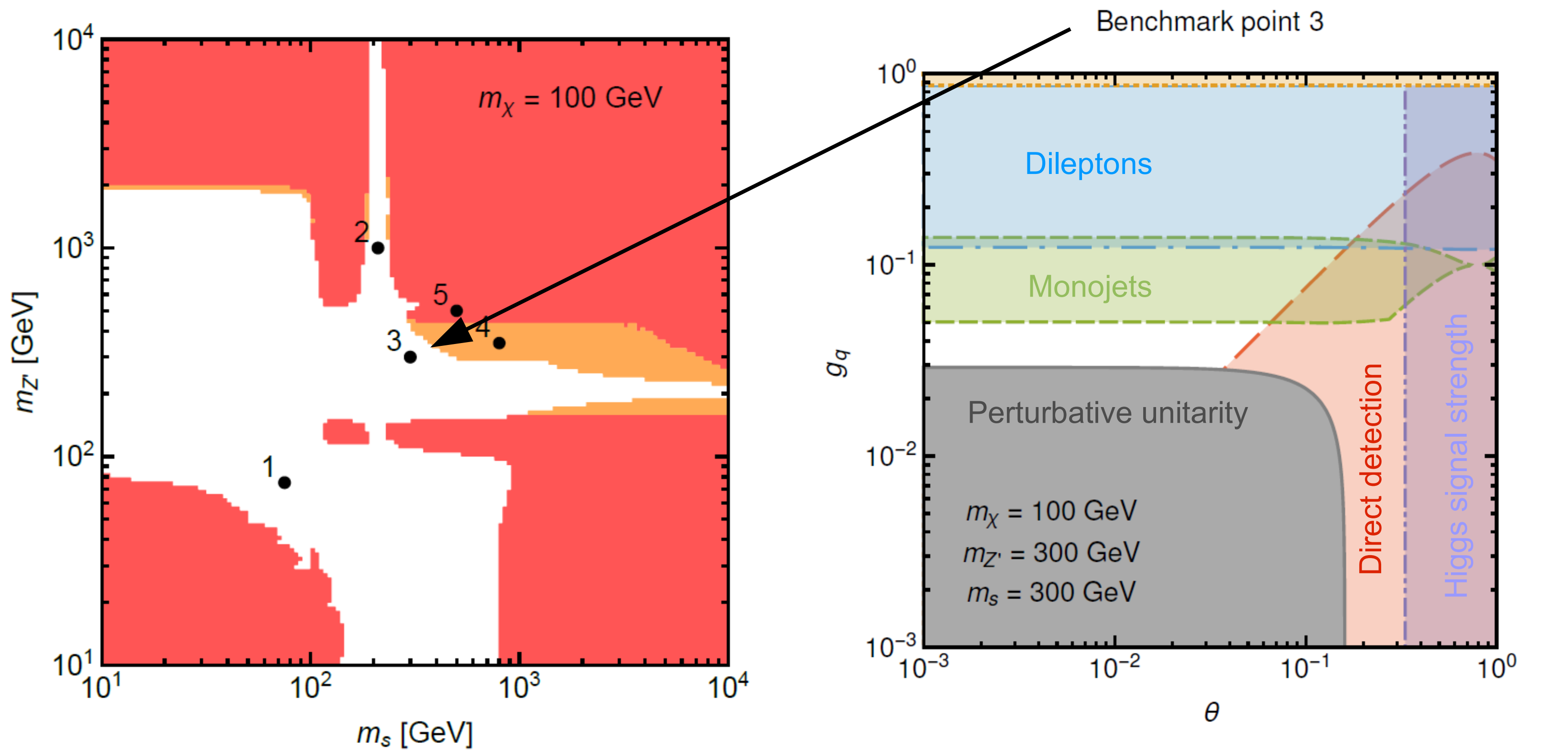


Red: All coupling combinations are excluded by at least one constraint.

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

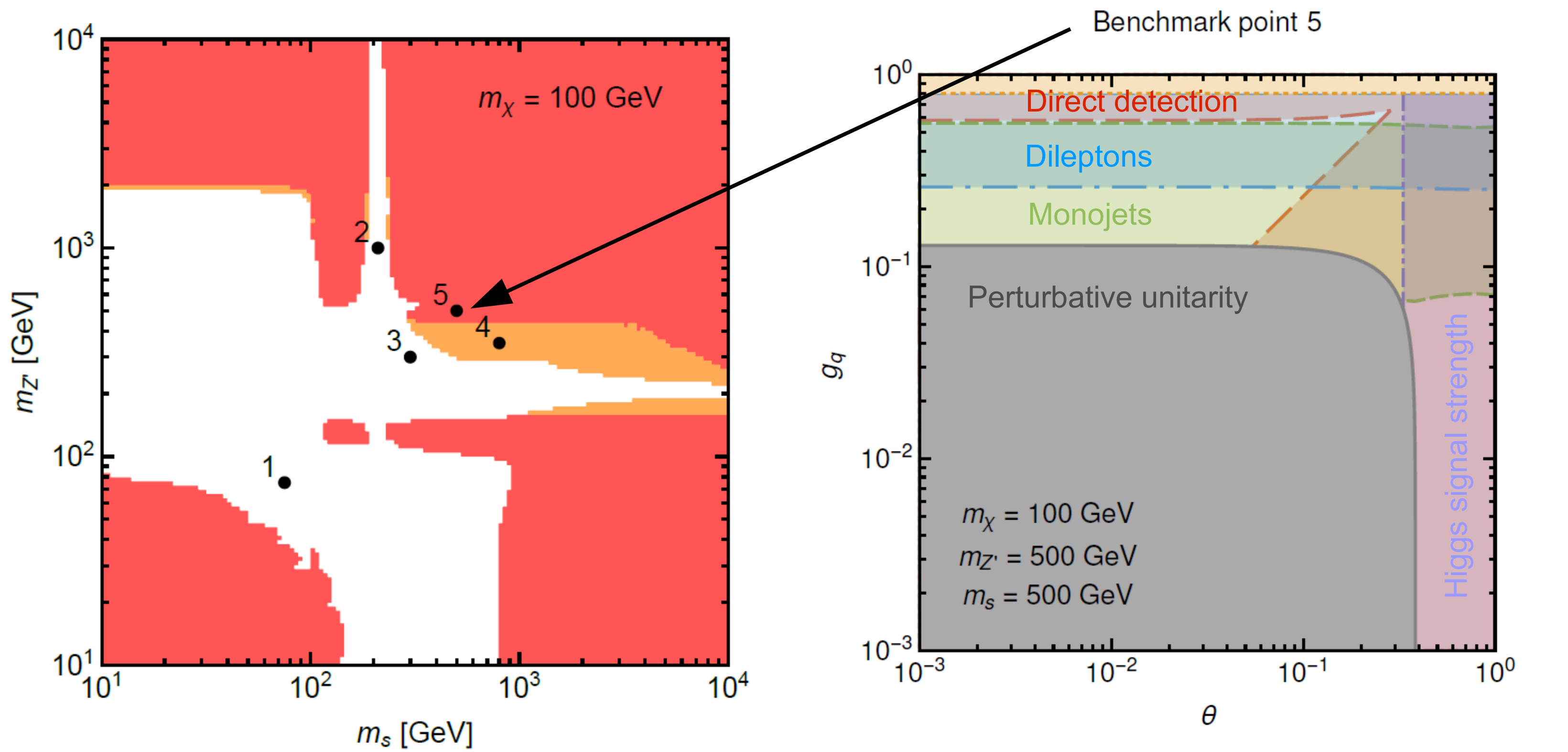
Orange: Large values of g_q cannot reliably be excluded due to the mediator width becoming large ($\Gamma/m_{Z'} > 0.3$).

A closer look at two benchmark cases



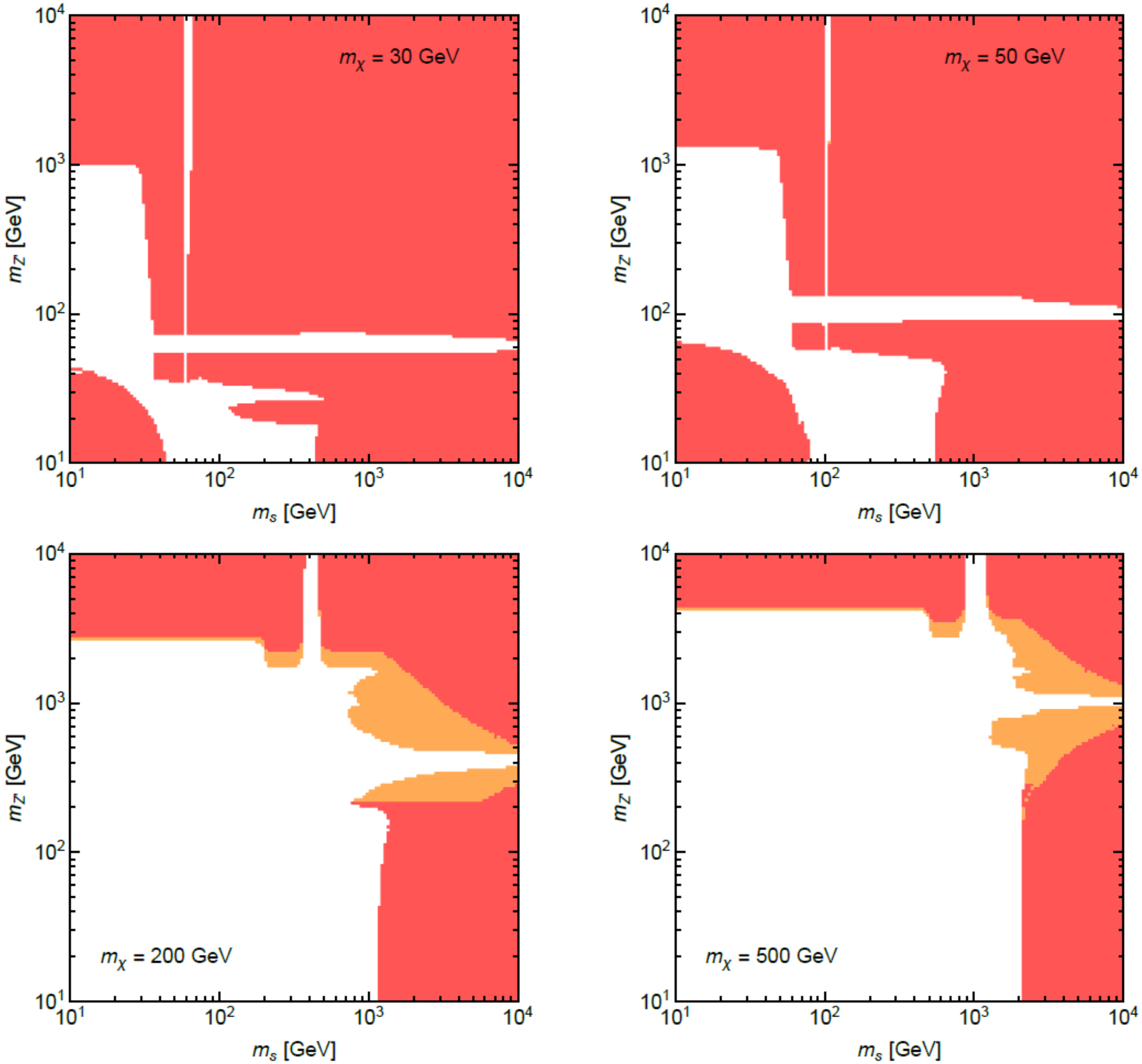
- Allowed parameter space for $g_q \sim 0.04$ and $\theta < 0.06$.

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.

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.
- We have performed a global analysis showing that the WIMP hypothesis is under severe pressure and that “classic” WIMP scenarios with heavy mediators are heavily constrained.
- Future LHC DM searches will play a crucial role in pushing further into the allowed parameter space.