Towards discovering dark matter at the LHC.

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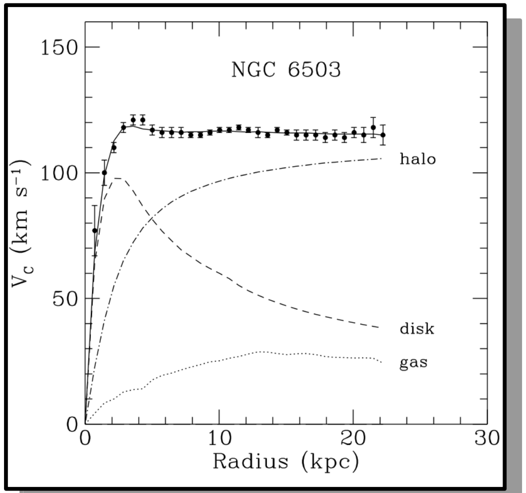
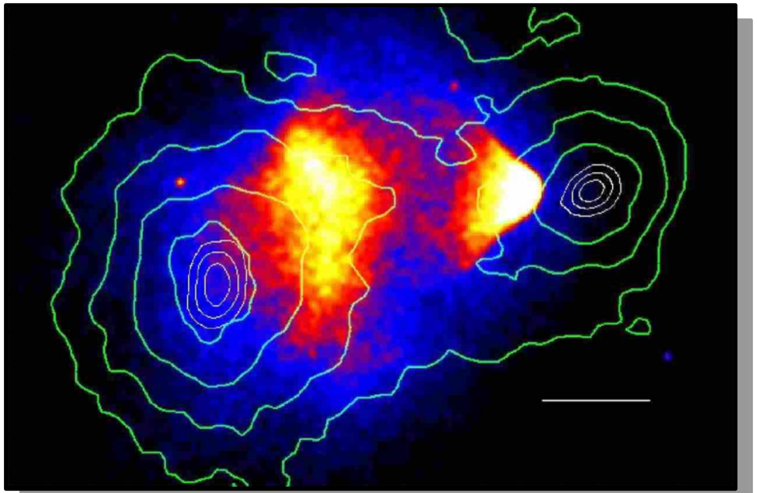
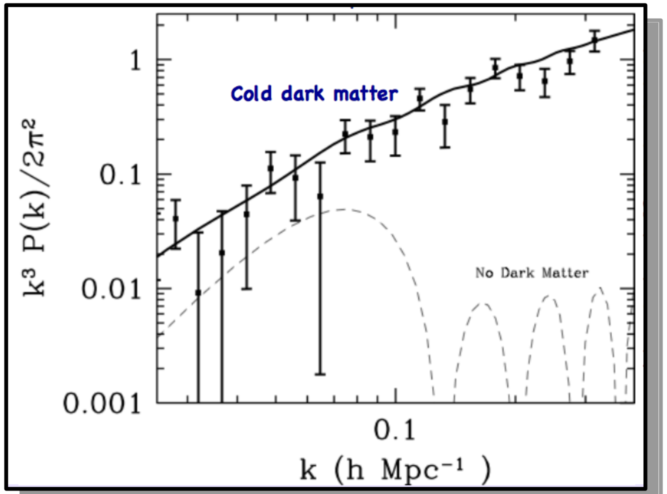
RWTH Aachen
21 January 2016

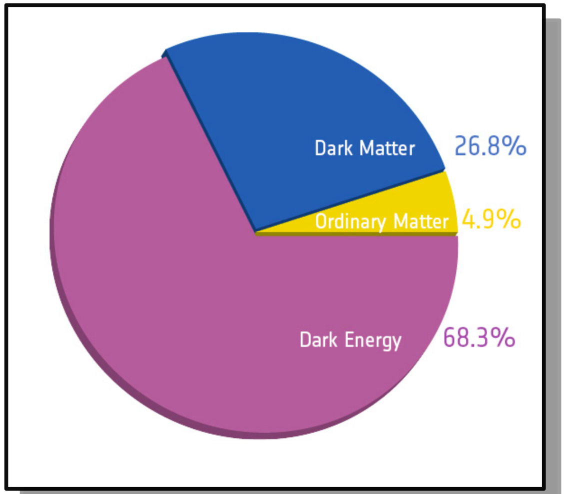
based on **arXiv:1503.05916** and **arXiv:1510.02110** in collaboration with Mikael Chala, Matthew McCullough, Germano Nardini, Kai Schmidt-Hoberg, Thomas Schwetz and Stefan Vogl

Evidence for Dark Matter

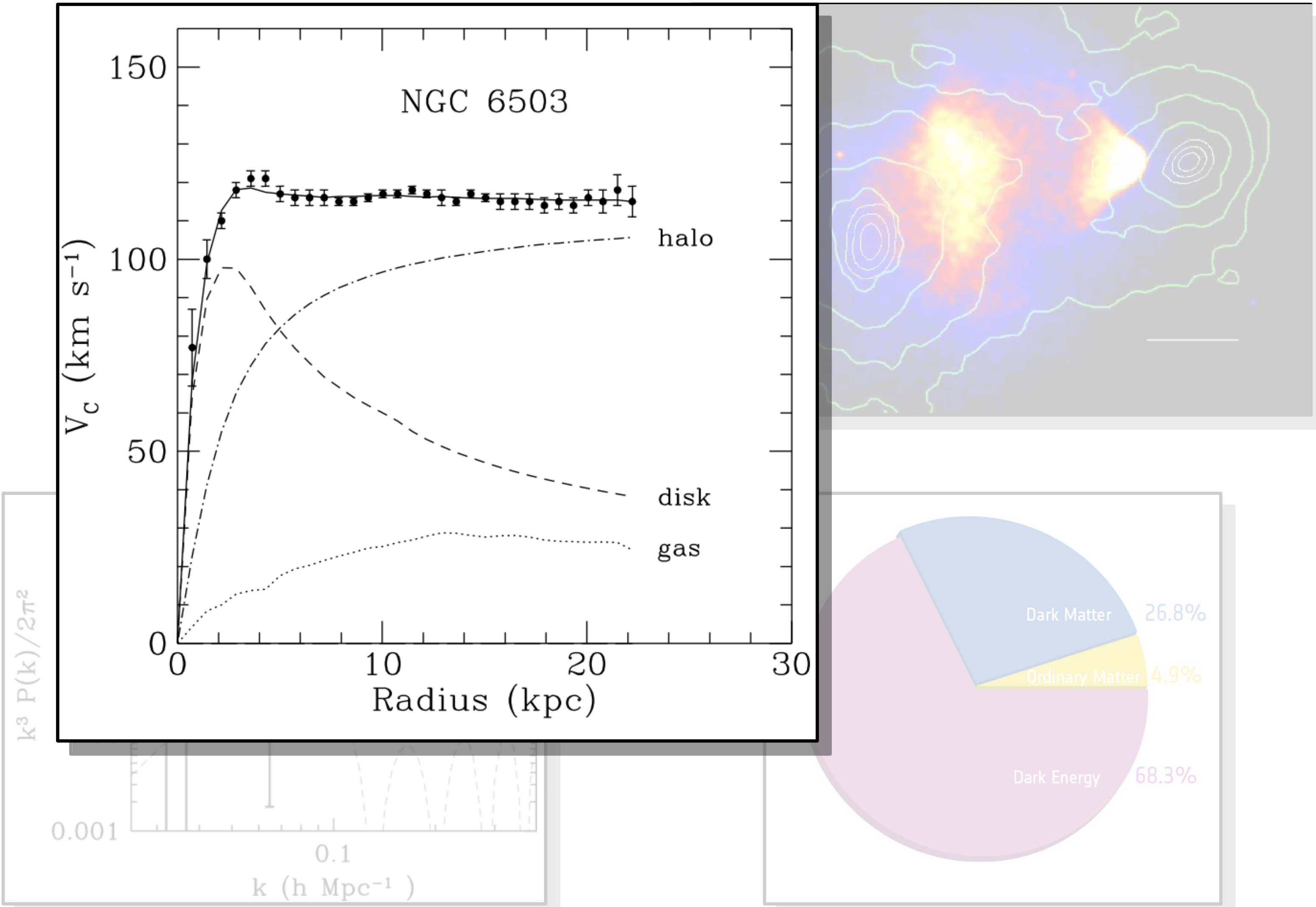




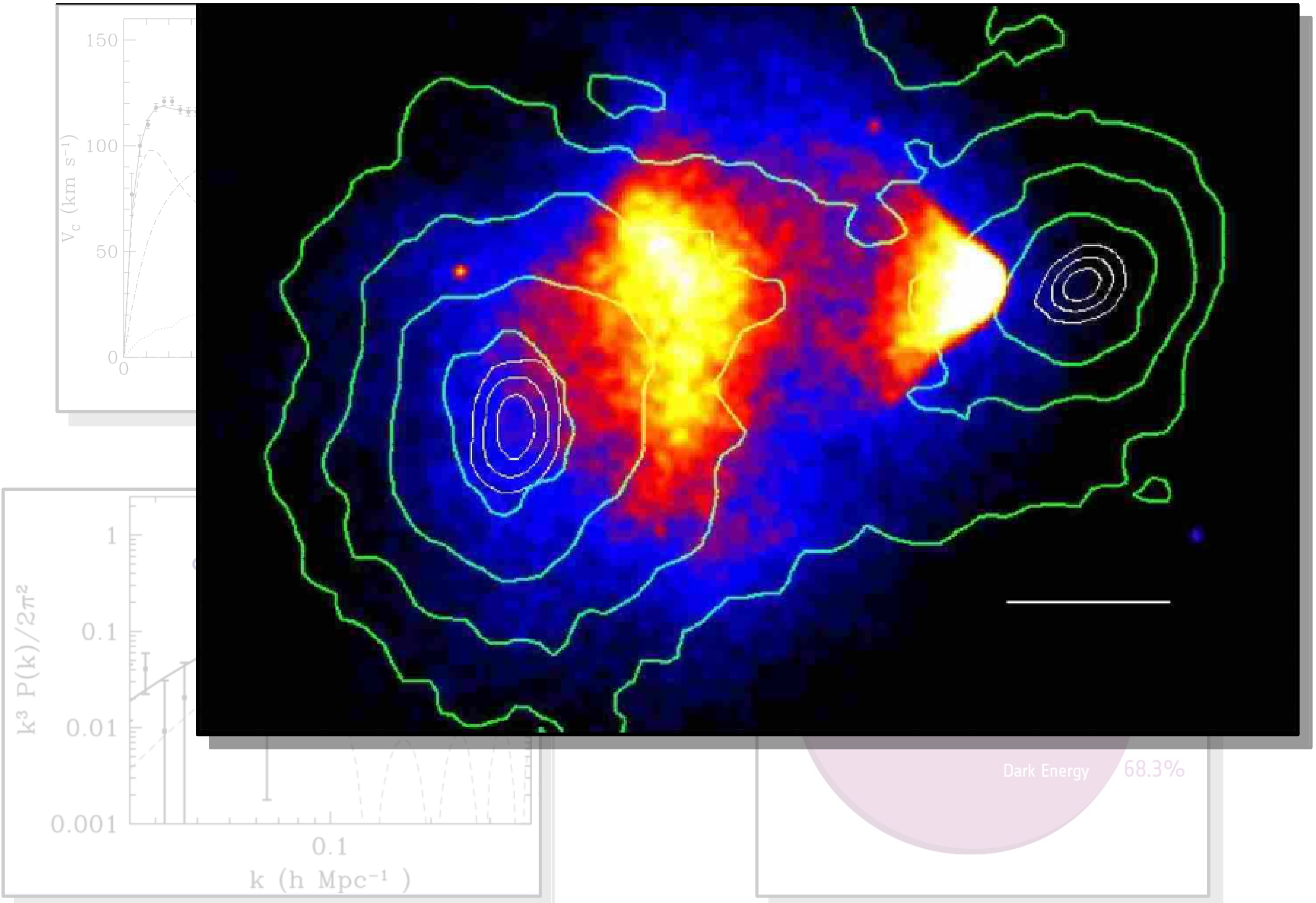




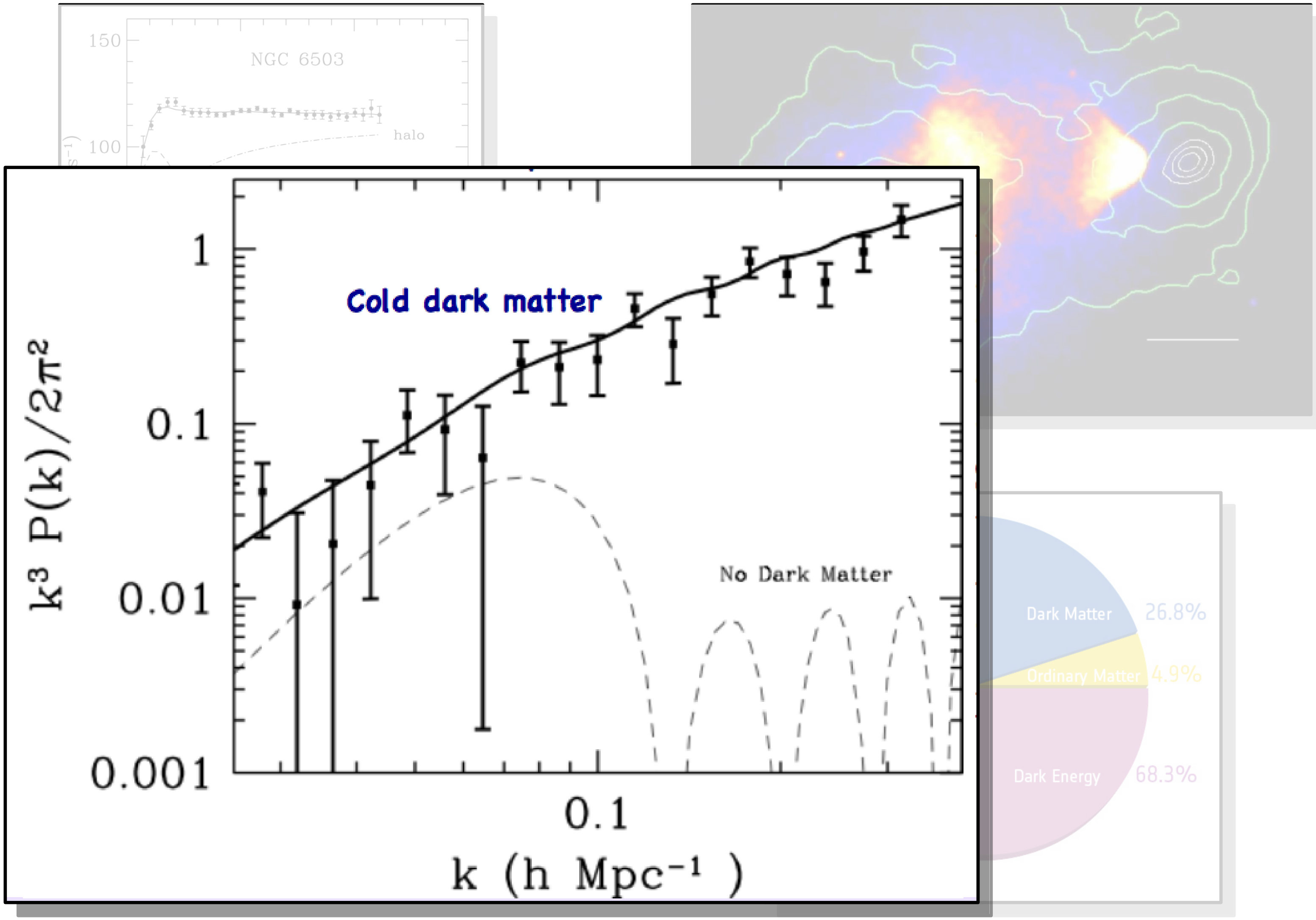
Evidence for Dark Matter: Galactic rotation curves



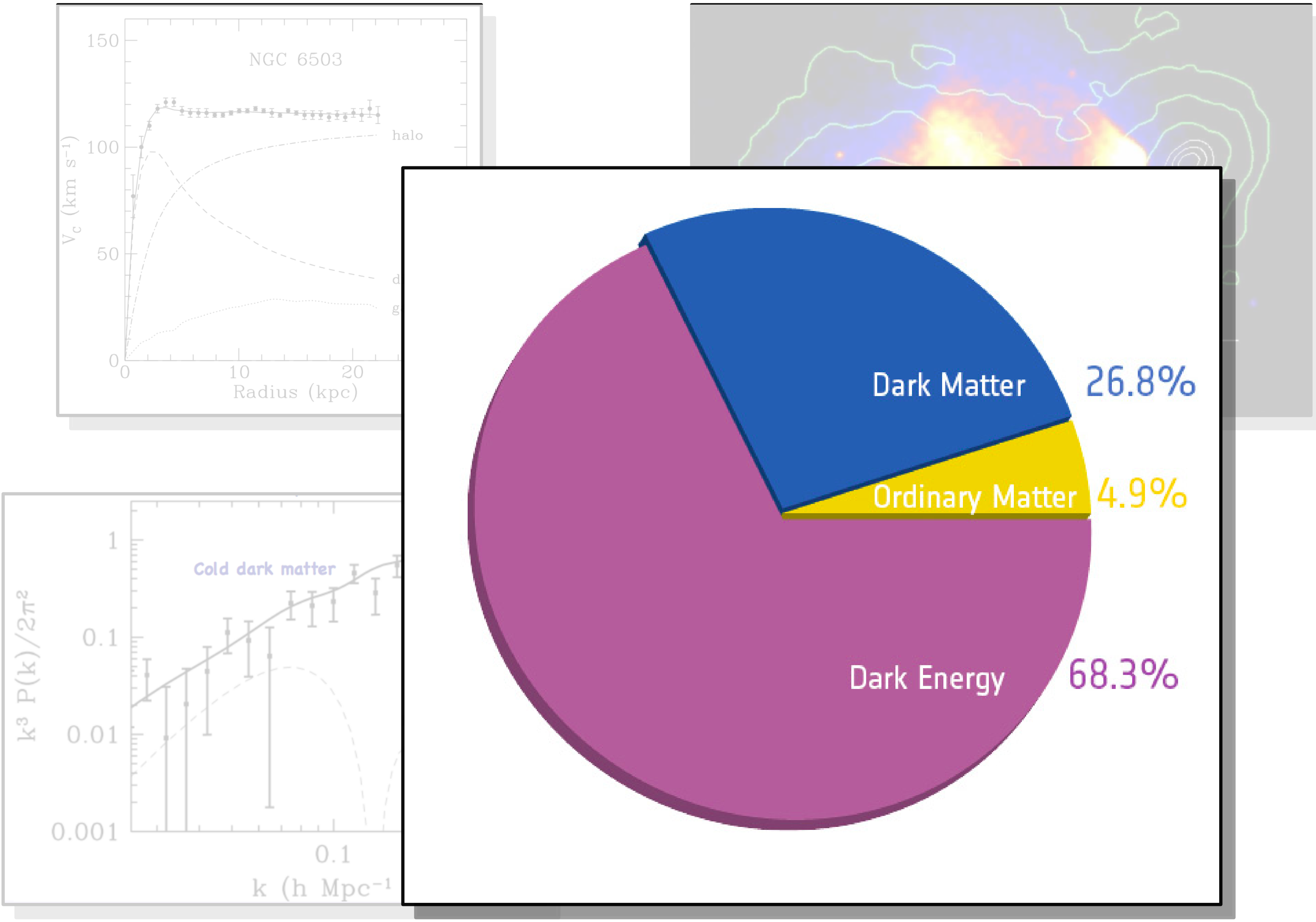
Evidence for Dark Matter: Weak lensing



Evidence for Dark Matter: Large-scale structure



Evidence for Dark Matter: Summary



Properties of dark matter

- By definition: Dark matter is electromagnetically neutral and stable
- Structure formation: Dark matter is cold
- Primordial nucleosynthesis: Dark matter is non-baryonic
- Cluster collisions: Dark matter is collisionless

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- Cluster collisions: Dark matter is mostly collisionless at present times, but the self-interaction cross section can still be as large as $\sigma/m_{\mathrm{DM}} \sim 1$ barn/GeV

Dark matter particles

- Astrophysical observations give almost no indications concerning the particle nature of dark matter.

- In particular, the mass of the dark matter particles and their couplings to Standard Model 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.

- Such models should not only be consistent with the known properties of dark matter, but they should be able to predict the amount of dark matter produced in the early Universe, so that we can compare with the observed dark matter abundance.

Dark matter candidates: The top-down approach

- Many theories of physics beyond the Standard Model, which have been developed for completely different reasons, predict new particles that have the required properties to be dark matter. Two famous examples:
  - 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.
- While these models provide well-motivated dark matter candidates, most of the experimental and theoretical constraints (and potential search strategies) are actually unrelated to the properties of the dark matter particle.

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Too much extra baggage!

Dark matter candidates: The bottom-up approach

> The opposite strategy is to focus entirely on explaining the observed dark matter abundance. The simplest possibility are so-called portal models, which include just a single new particle with tiny couplings to Standard Model states, such as

- Sterile neutrinos
- Hidden photons
- Scalar singlets

> These models have very few free parameters and are therefore highly predictive – but also strongly constrained.

> These models typically 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).

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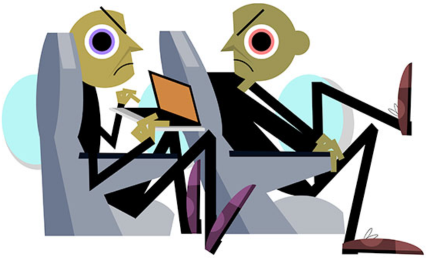
Too little legroom!

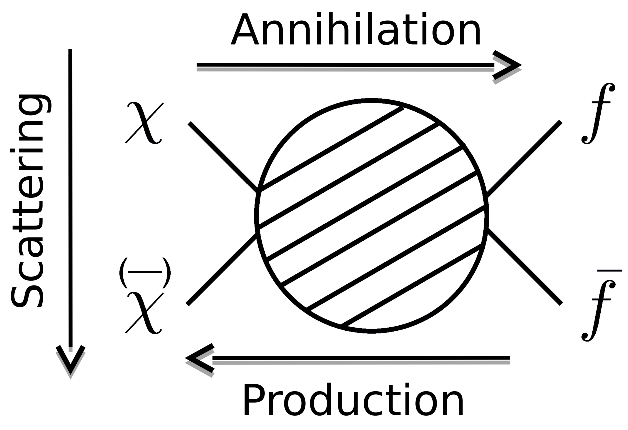


Dark matter phenomenology: The middle ground

- We want a framework that allows us to focus on the DM particle, while at the same time being flexible enough to offer a rich phenomenology.

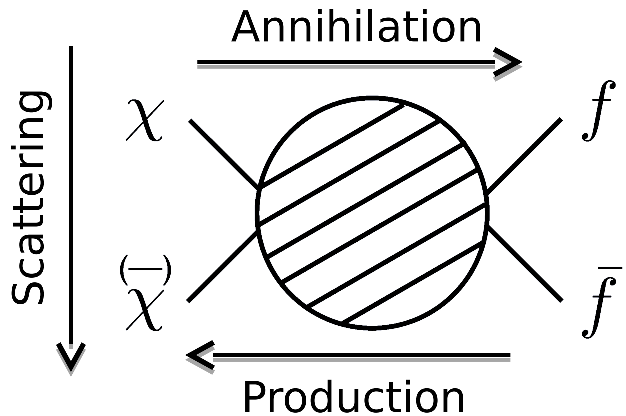
- We therefore relax the assumption that DM couples directly to Standard Model states and instead consider the case that interactions between DM and the Standard Model are mediated by additional new particles.

- 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

Detecting dark matter particles



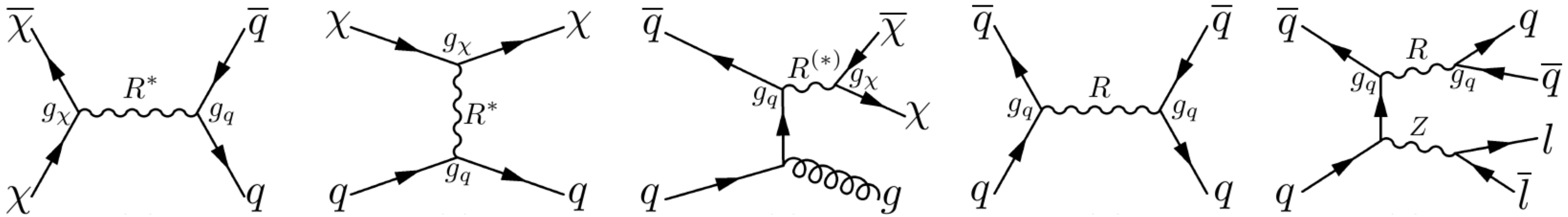
- In the effective operator approach, all DM searches constrain the same new-physics scale Λ, so we can directly compare bounds from different search strategies.

- 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 reproduce the observed DM relic abundance from thermal freeze-out.

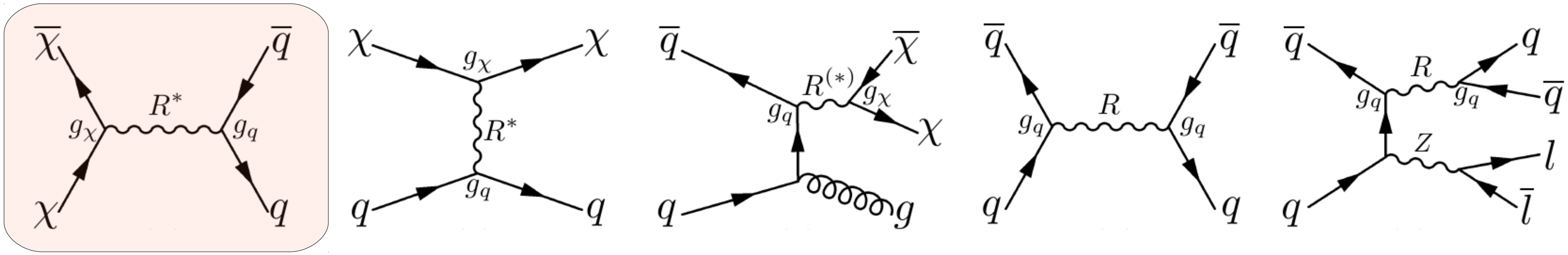
Motivation: New mediators

- We should therefore not limit ourselves to the assumption that the particles responsible for mediating DM interactions are very heavy.
- Indeed, if the DM particle and the mediator of the DM interactions are comparable in mass, the phenomenology can become much more interesting.



- There are two ways to think of such a model:
  - In the top-down approach, this model is a simplification of a UV-complete theory of dark matter, boiled down to capture the most relevant experimental signatures.
  - In the bottom-up approach, this model contains the minimal number of ingredients necessary to calculate predictions for a range of different experiments in a self-consistent way.

Motivation: New mediators

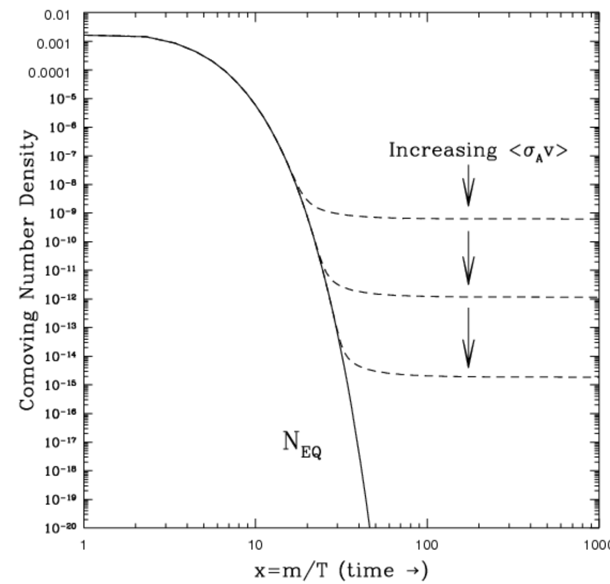


- In the early Universe, DM annihilation and DM production happen frequently and keep DM in thermal equilibrium with SM states.

- 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 comoving number density becomes constant.

- Larger annihilation cross sections lead to smaller relic abundances.



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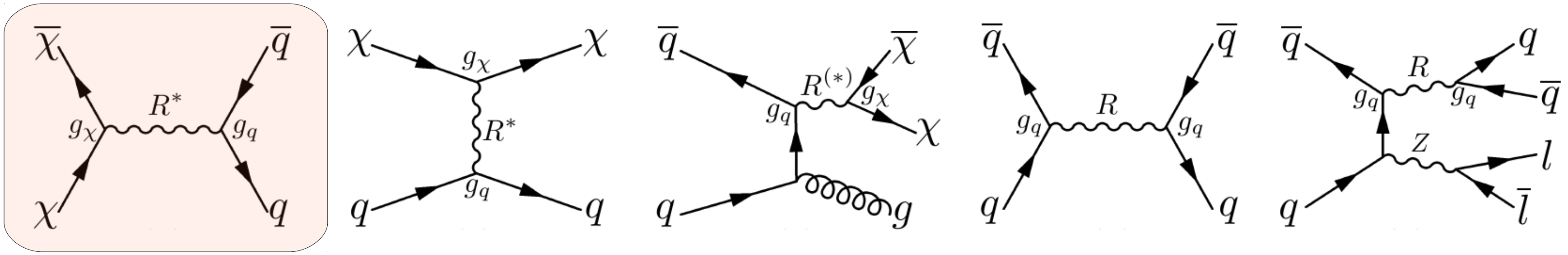
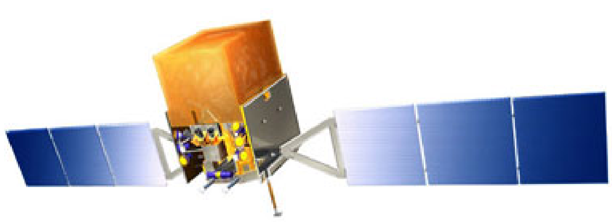
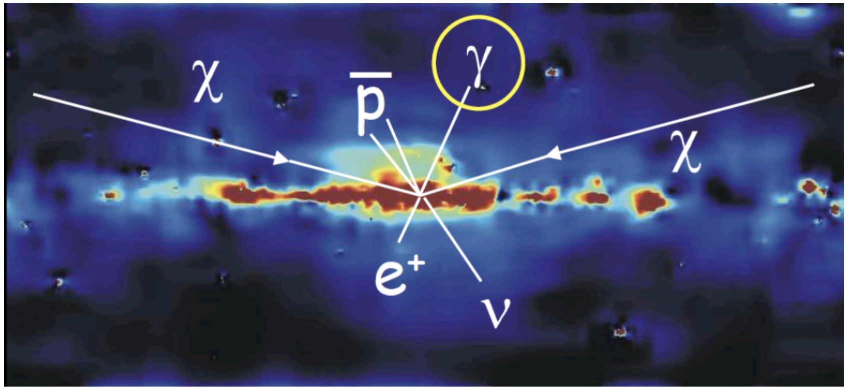


- In regions of high DM density (e.g. the galactic center), DM annihilation may still continue today.
- The same processes can therefore be probed by indirect detection experiments, which look for the annihilation products with satellites, balloons and ground based telescopes.





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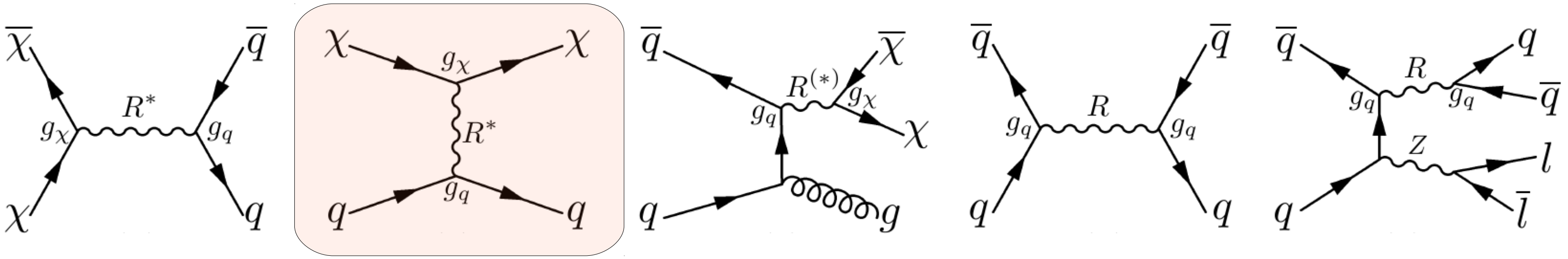
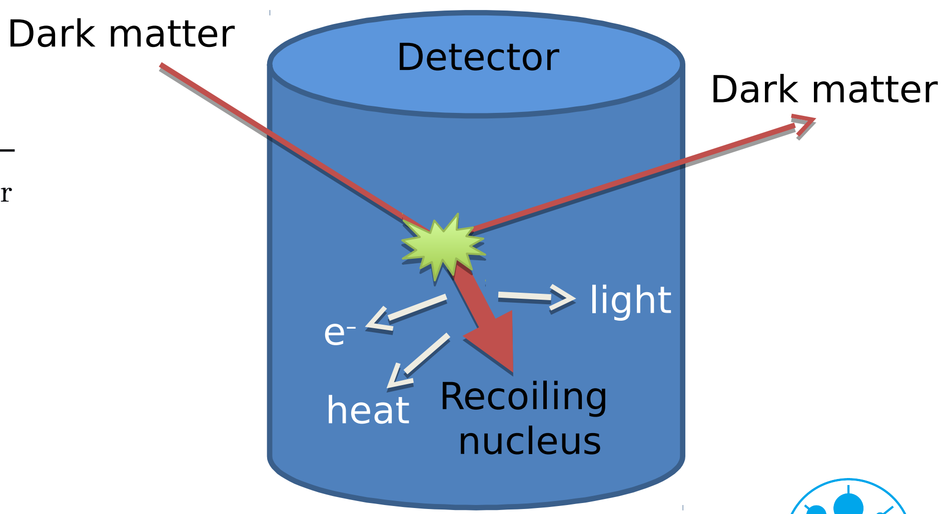


- Dark matter particles from the Galactic halo that pass through the Earth will occasionally scatter off nuclei.
- The resulting recoil energy of the nucleus can be measured in dedicated low background detectors.

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

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



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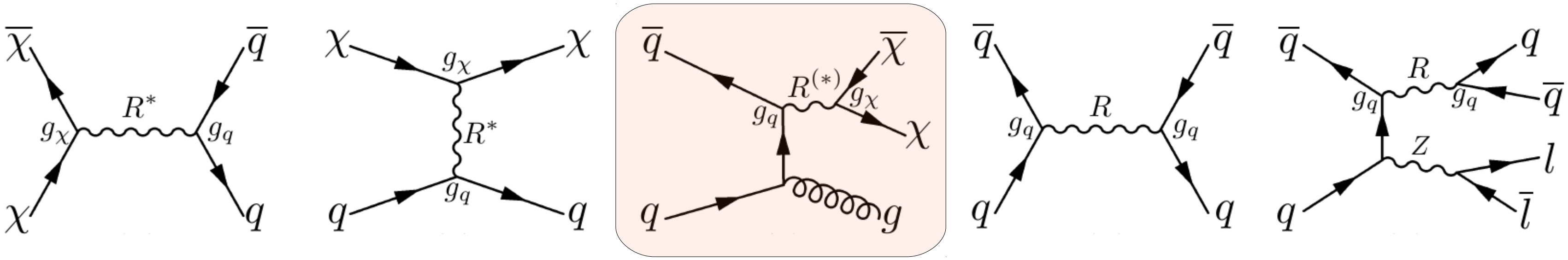
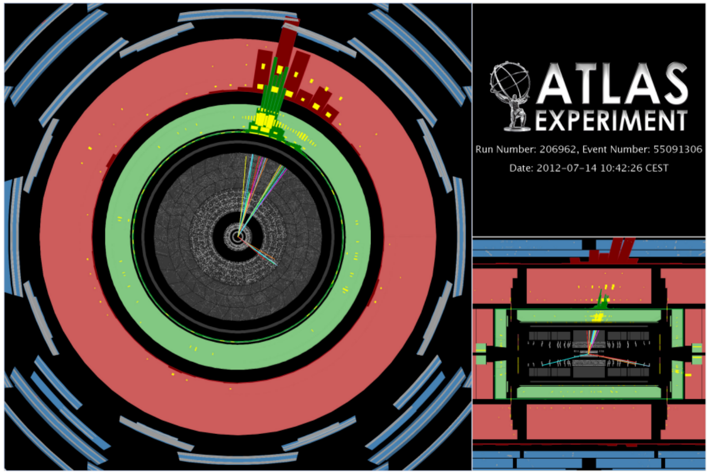


> Any DM particles produced at colliders will escape from the detector unnoticed. But if other particles (such as jets) are produced in association with a pair of DM particles, we may observe large amounts of missing transverse energy.



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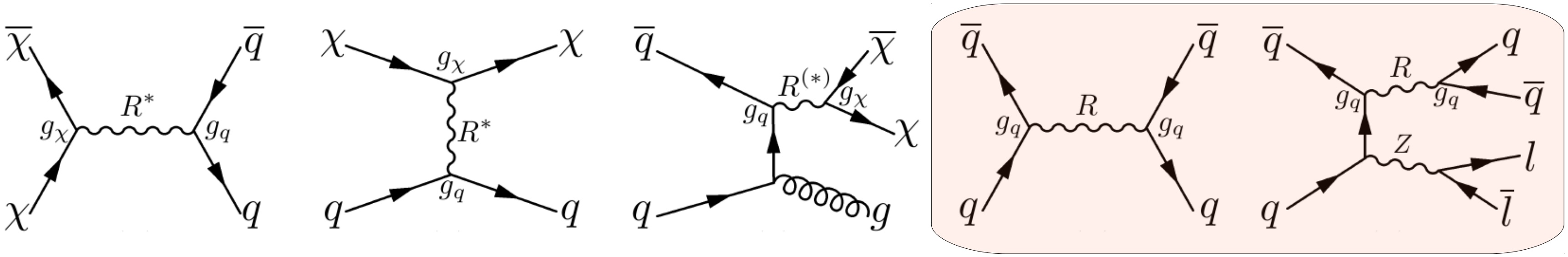


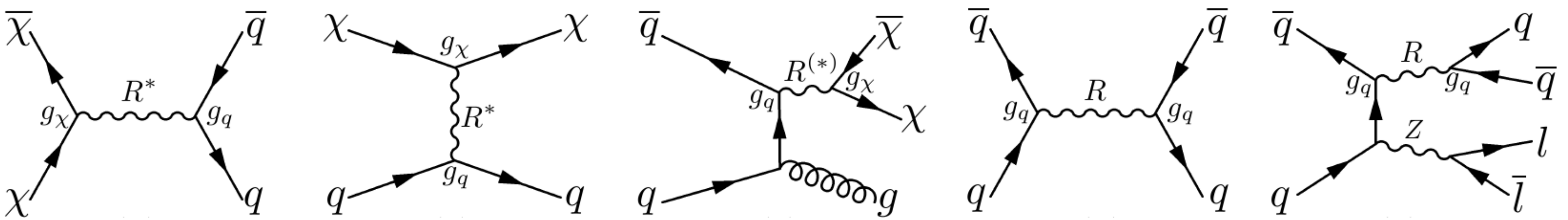
- The mediator will also lead to new interactions between Standard Model states, so there may be observable signals from processes involving no dark matter particles at all.

- For example, if the mediator can be produced at the LHC, it can also decay back into quarks. One should therefore consider dedicated searches for the mediator particles themselves, such as searches for dijet resonances.

- While it is difficult for the LHC to constrain dijet resonances below 1 TeV due to large QCD background, this background can be suppressed by searching for dijet resonances produced in association with leptonically decaying gauge bosons.

DESY

Outline (part 1)



> Given all these promising experimental searches, we would like to answer the following questions (outline, part 1):

- How large is the allowed parameter space? What sensitivity should we aim for? How do we know when to stop?
- Out of the various searches, which ones are the most promising? Where do we expect to see DM first?

Outline (part 2)

> It is difficult to answer these questions in full generality, so we need to focus on a specific example for the mediator.

> In this talk I will focus on a spin-1 mediator and Dirac fermion DM:

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

Dudas et al., arXiv:0904.1745; Arcadi et al., arXiv:1401.0221; Lebedev & Mambrini, arXiv:1403.4837; Frandsen, FK et al., arXiv:1107.2118, arXiv:1204.3839; An et al., arXiv:1202.2894, arXiv:1212.2221; Alves et al., arXiv:1312.5281, arXiv:1501.03490; Buchmueller et al., arXiv:1308.6799, arXiv:1407.8257; Fairbairn & Heal, arXiv:1406.3288; Harris et al., arXiv:1411.0535

> This leads to even more questions (outline, part 2):

- Where does such a (simplified) model come from?
- What are the relations between the different couplings?
- Is it justified to write down just these interactions and nothing else?

How large is the allowed parameter space?

- Guiding principle: Combination of relic density calculations and the requirement of perturbative unitarity.

Griest & Kamionkowski, 1990

- Unitarity implies that $0 \leq \mathrm{Im}(\mathcal{M}_{ii}^{J}) \leq 1\,, \quad \left|\mathrm{Re}(\mathcal{M}_{ii}^{J})\right| \leq \frac{1}{2}$, where

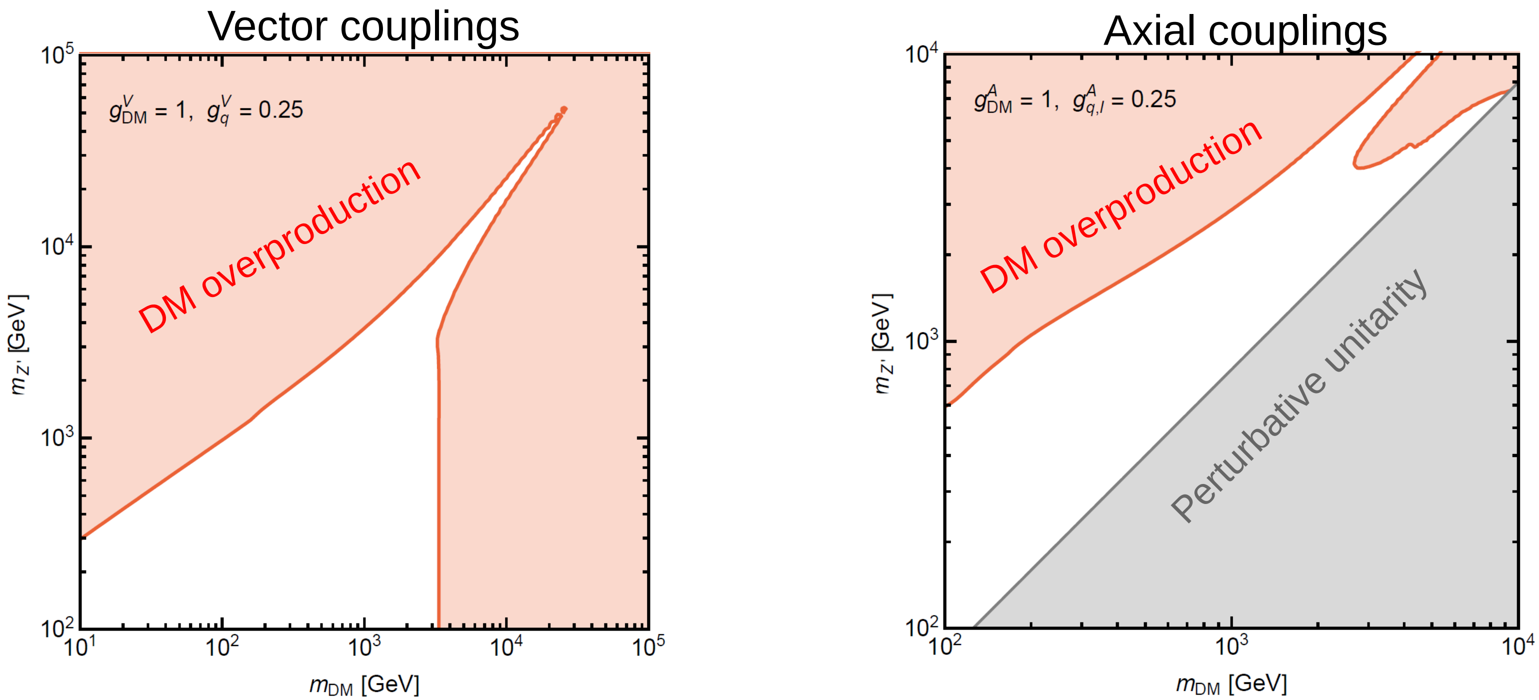
$$\mathcal{M}_{if}^{J}(s) = \frac{1}{32\pi}\beta_{if}\int_{-1}^{1} \mathrm{d}\cos\theta\, d_{\mu\mu'}^{J}(\theta)\, \mathcal{M}_{if}(s,\cos\theta)$$

Kinematical factor — Wigner d-function

- Imposing the same conditions on the tree-level matrix elements gives an upper bound on the various couplings of the model.

- The relic density requirement on the other hand typically gives an upper bound on the particle masses.

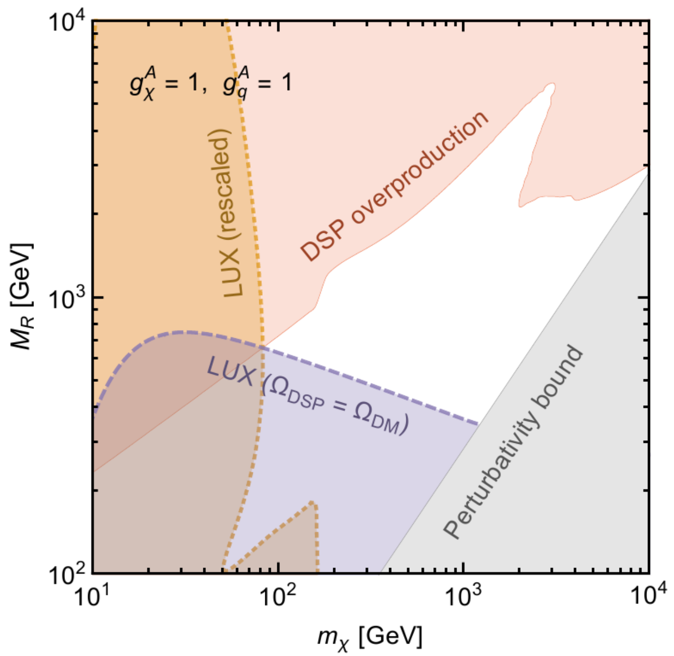
How large is the allowed parameter space?



- In the parameter region predicting DM overproduction (red), additional interactions are required in order to achieve sufficiently large annihilation rates.
- Moreover, for axial couplings the longitudinal component of the mediator couples to fermions with a coupling strength given by $2\, g_f^A\, m_f / m_{Z'}$.
- Perturbative unitarity thus bounds the DM mass: $m_f \lesssim \sqrt{\frac{\pi}{2}} \frac{m_{Z'}}{g_f^A}$

Where do we expect to see DM first?

- If DM is predicted to be underproduced, there are two possibilities:
  - Dark matter is asymmetric, i.e. only the symmetric component annihilates away and the relic abundance is set by the initial asymmetry.
  - Dark matter consists of several sub-components, each of which constitute only a fraction of the total DM abundance. The model under consideration hence describes only one out of several Dark Sector Particles (DSPs).

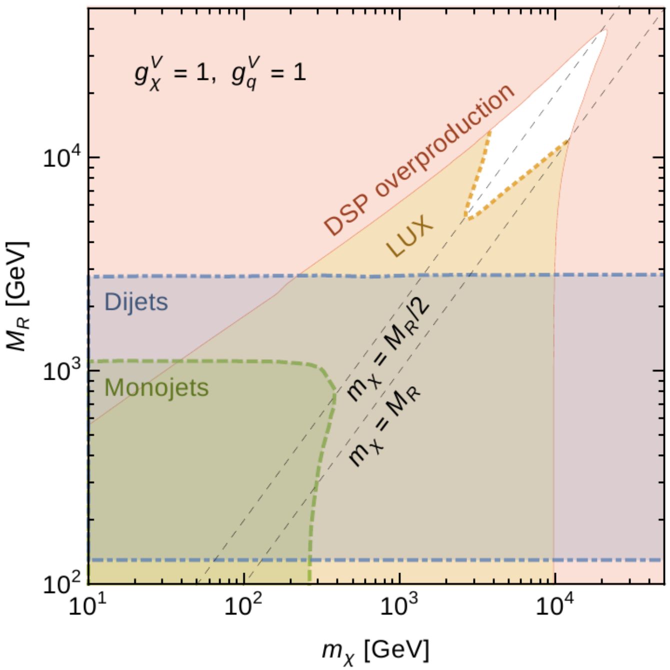


- If the dark sector is composed of several sub-components, the sensitivity of direct and indirect detection experiments is strongly suppressed.
- The LHC may be uniquely suited for probing such dark sectors.

Where do we expect to see DM first?

- Nevertheless, for vector couplings, scattering in direct detection experiments benefits from a coherent enhancement, proportional to the square of the mass number of the target nucleus.

- As a result, direct detection is much more sensitive to vector couplings than LHC searches, even when rescaling the event rate proportional to the predicted relic abundance.



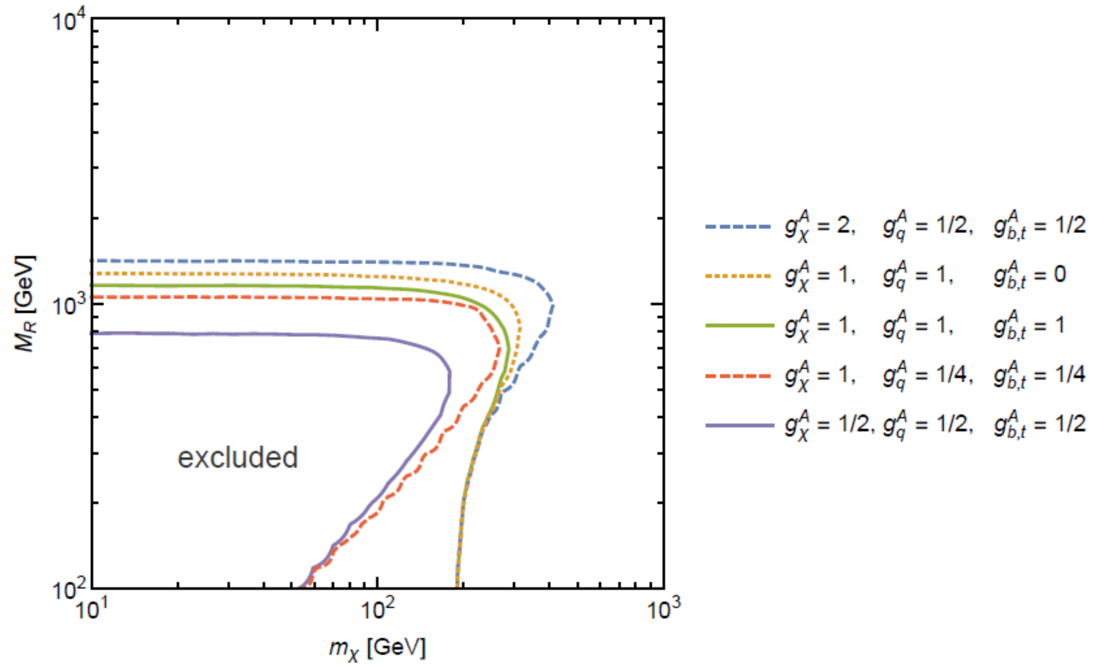
- Direct detection experiments are the obvious discovery channel for vector couplings.
- We will focus on axial couplings from now on, where the sensitivity of direct detection is much reduced.

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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   ATLAS-CONF-2013-074

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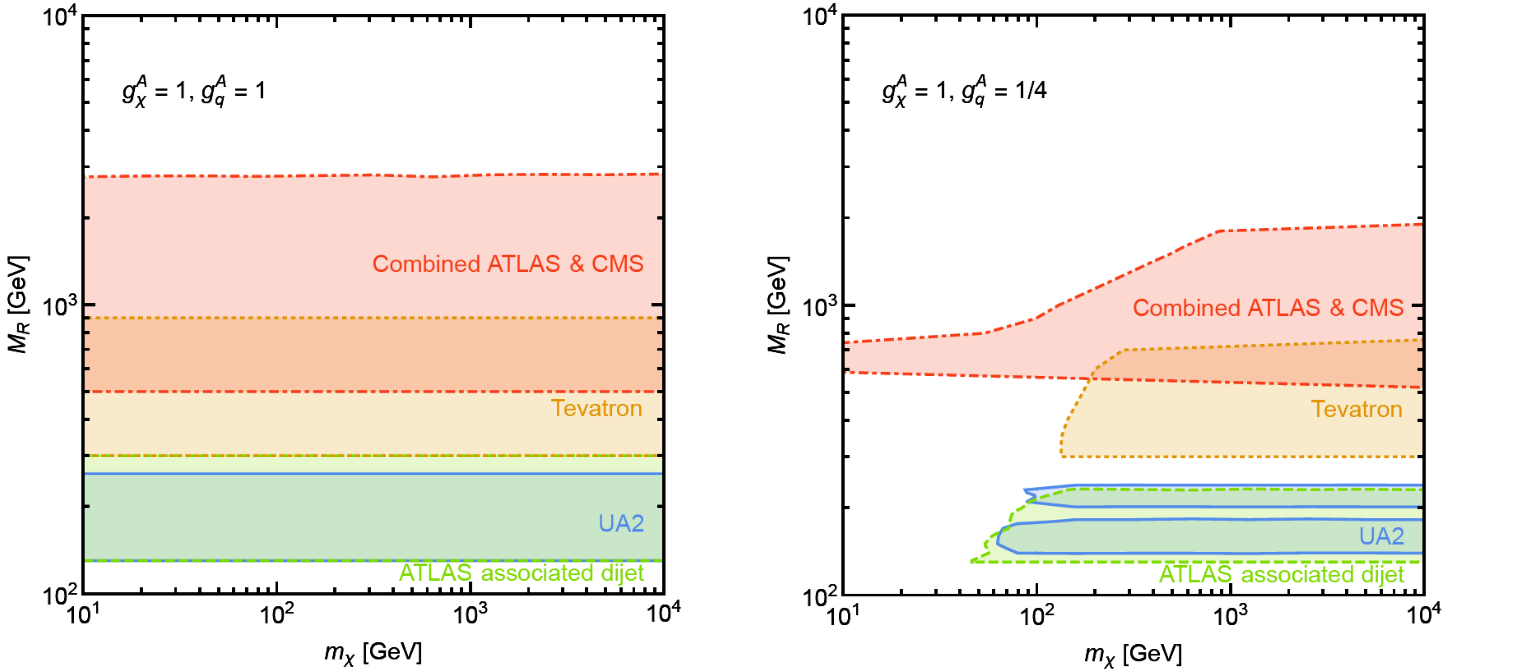
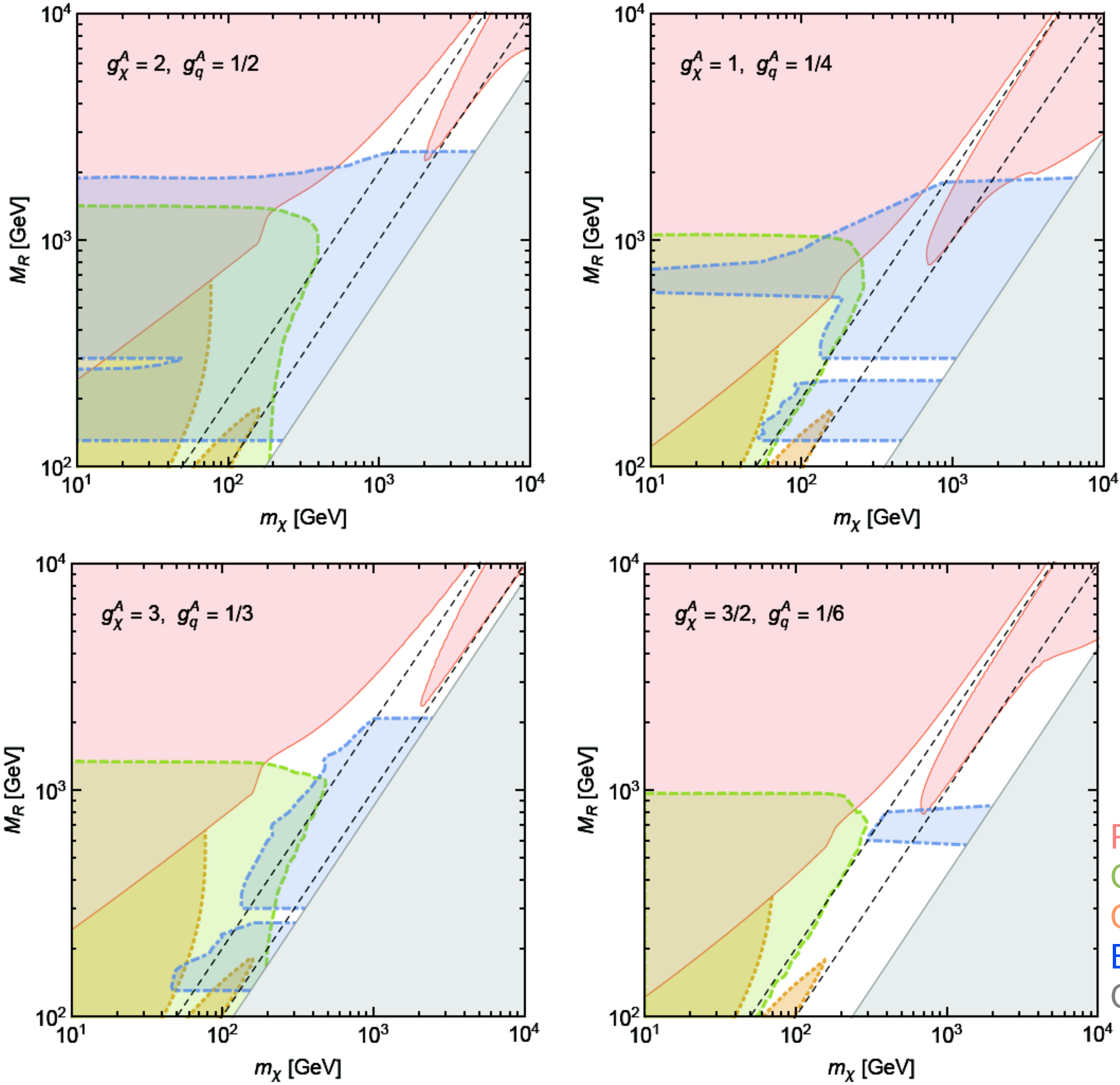
   Solution: Reinterpret existing searches in terms of broad resonances using MadGraph+Pythia6+Delphes for the signal generation and FastJet+MadAnalysis+MCLimit for the analysis.

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 $g_q = g_x = 1$, we exclude all mediator masses with 130 GeV < M_R < 2.8 TeV.
- For smaller quark couplings, dijet searches are most sensitive to $M_R > 2\ m_\chi$.

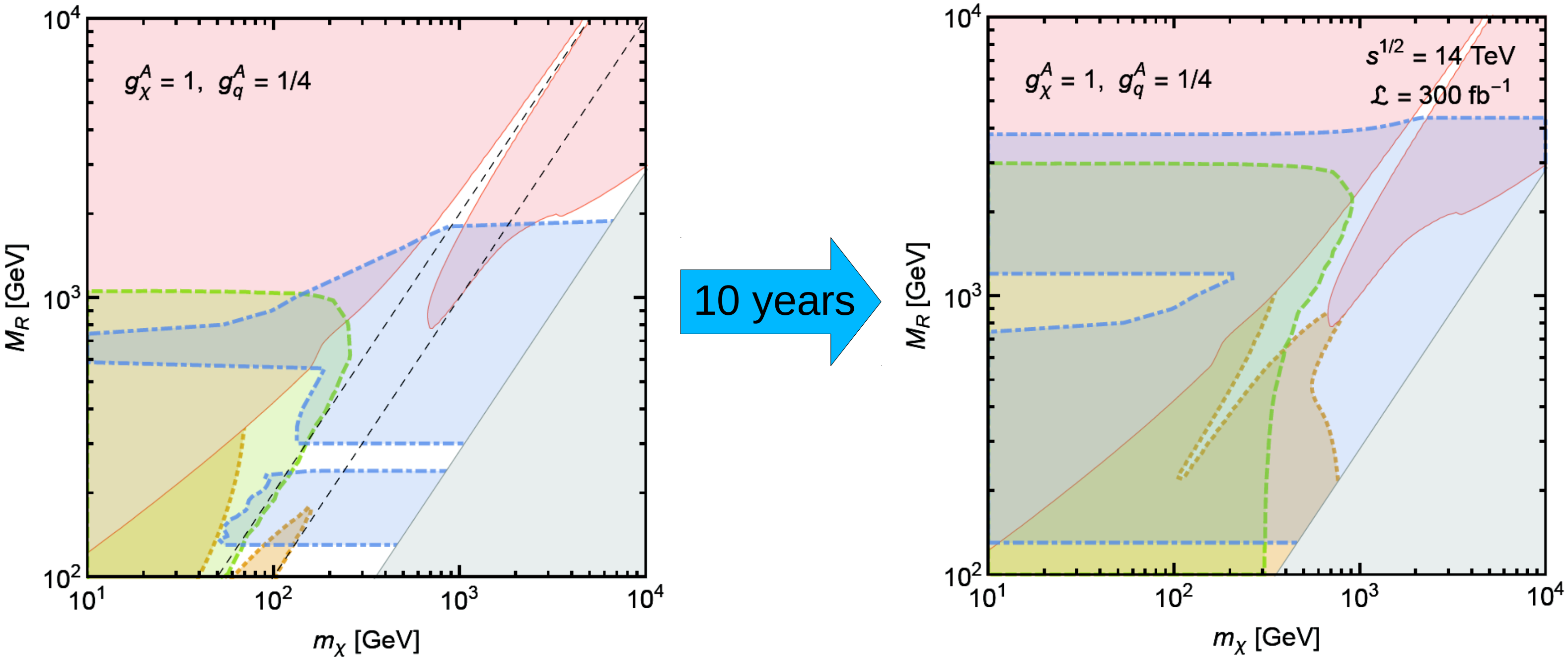
Combined constraints



- 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

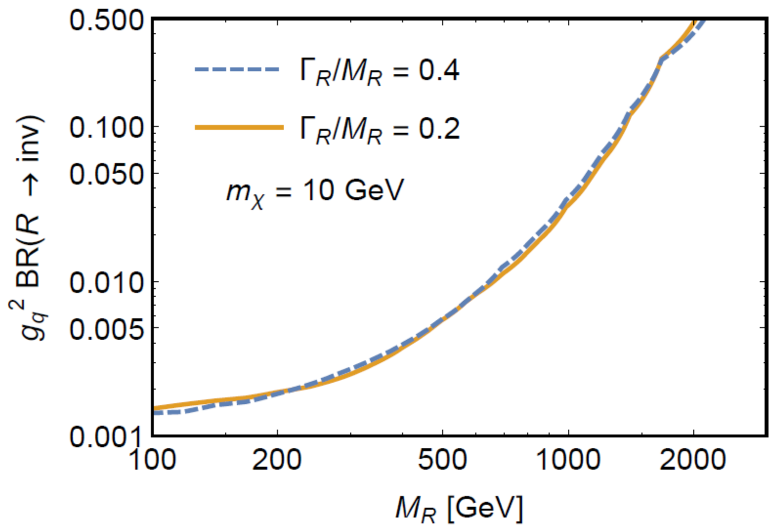


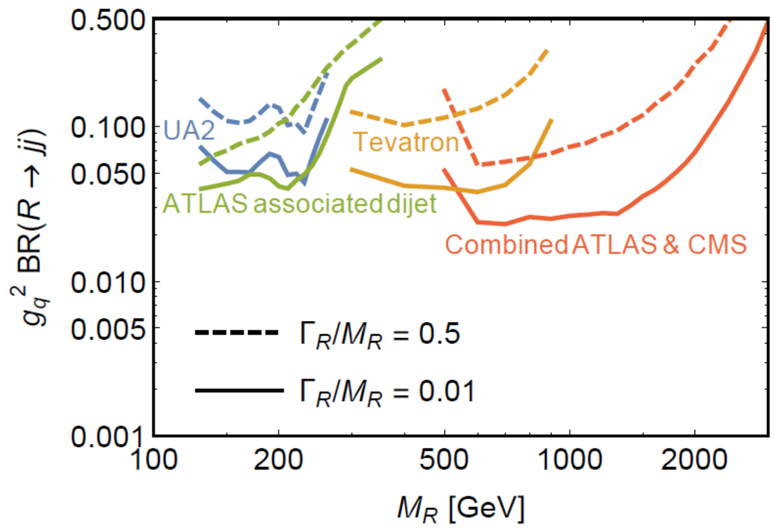
- Large improvements expected in the near future:
  - LHC will probe mediator masses up to 4 TeV and DSP masses up to 1 TeV.
  - Searches for dijet resonances in association with SM gauge bosons will significantly gain in sensitivity.

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!

More questions remain

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

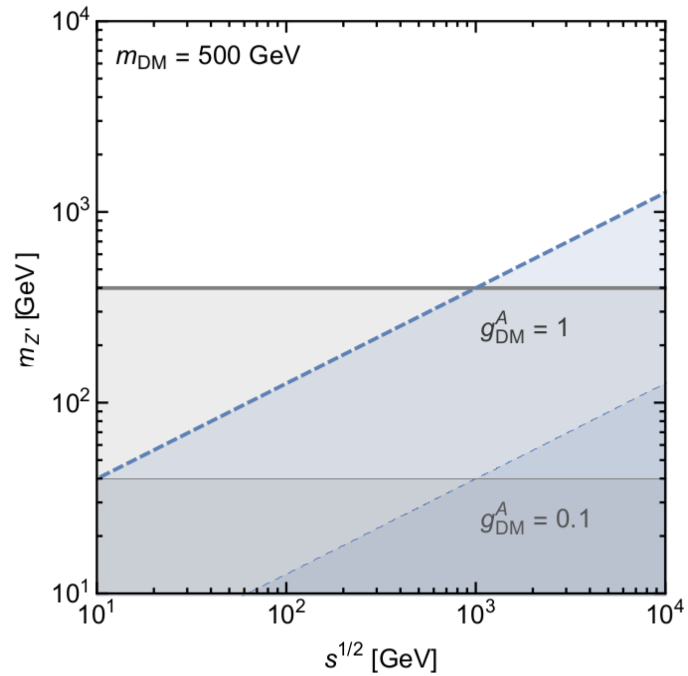
- Where does such a (simplified) model come from?
- What are the relations between the different couplings?
- Is it justified to write down just these interactions and nothing else?

More questions remain

- Let us take another look at perturbative unitarity.
- For axial couplings, the matrix element for the process $\psi\bar{\psi} \rightarrow Z'_L Z'_L$ grows with energy proportional to $(g^A_{\rm DM})^2 \sqrt{s}\, m_{\rm DM}/m^2_{Z'}$
- Perturbative unitarity then implies

$$\sqrt{s} < \frac{\pi\, m^2_{Z'}}{(g^A_{\rm DM})^2\, m_{\rm DM}}$$

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



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.
- We furthermore assume that the DM particle is a Majorana fermion, such that the DM vector current vanishes and tension with direct detection is reduced.
- The Lagrangian of the dark sector is then given by

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

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

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

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

Unitarity bounds on the dark Higgs

- The dark Higgs also gives an additional contribution to $\psi\bar{\psi} \rightarrow Z'_L Z'_L$, which restores perturbative unitarity, provided the mass of the dark Higgs satisfies the inequality

$$m_s < \frac{4\sqrt{2}\pi w}{y_{\text{DM}}}$$

- In fact, an even stronger bound is obtained from considering processes like $ss \rightarrow Z'_L Z'_L$. Considering all such processes, we recover the famous Lee-Quigg-Thacker bound

$$m_s \leq \frac{\sqrt{\pi}\, m_{Z'}}{g^A_{\text{DM}}} = \sqrt{4\pi} w$$

- Given this bound we can expect the dark Higgs to play a relevant role in the phenomenology of our model.

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

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

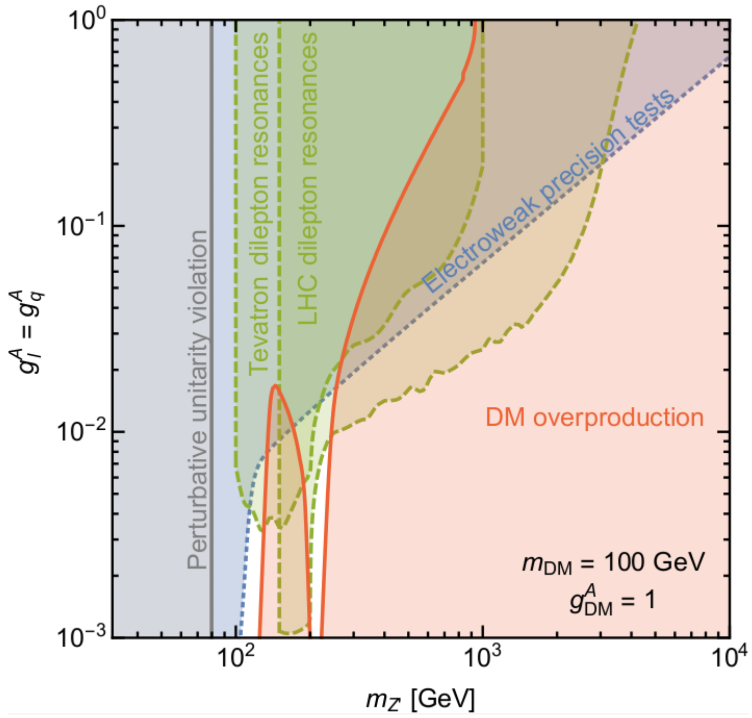
imply that for non-zero axial couplings to SM fermions, the SM Higgs must be charged under the new U(1)'. This has two important consequences:

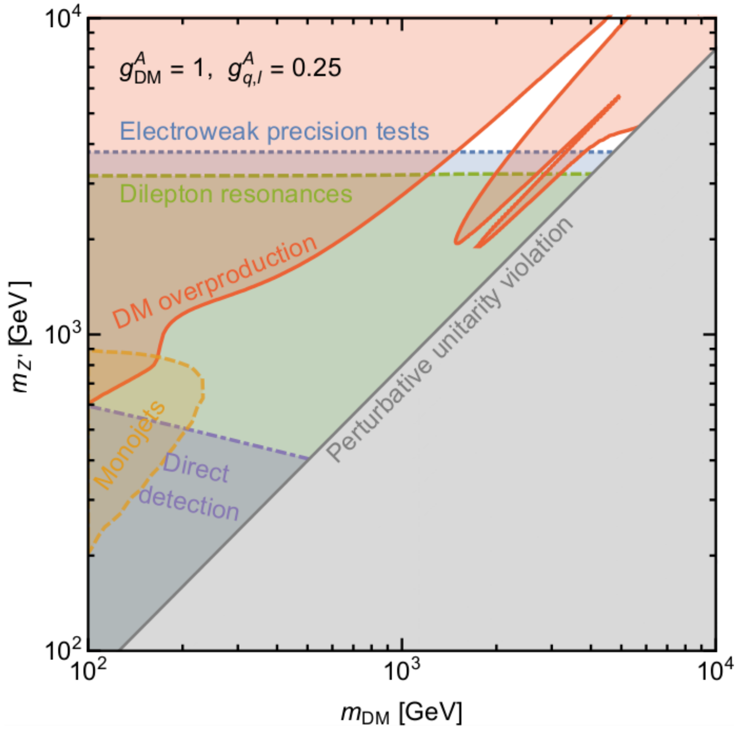
1. The Z' must couple with the same strength to all generations of quarks and to leptons (assuming a single Higgs doublet), such that we can expect strong constraints from searches for dilepton resonances.

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).

DESY

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, implying that in a UV complete model this is where a signal should first be seen.
- Monojet and dijet searches as well as direct detection experiments are typically not competitive in this case.

Vector couplings to Standard Model fermions

- The picture changes significantly if the couplings on the SM side are purely vectorial, such that the SM Higgs is uncharged under the *U*(1)', and if we furthermore assume that $g_q^V \gg g_\ell^V$.

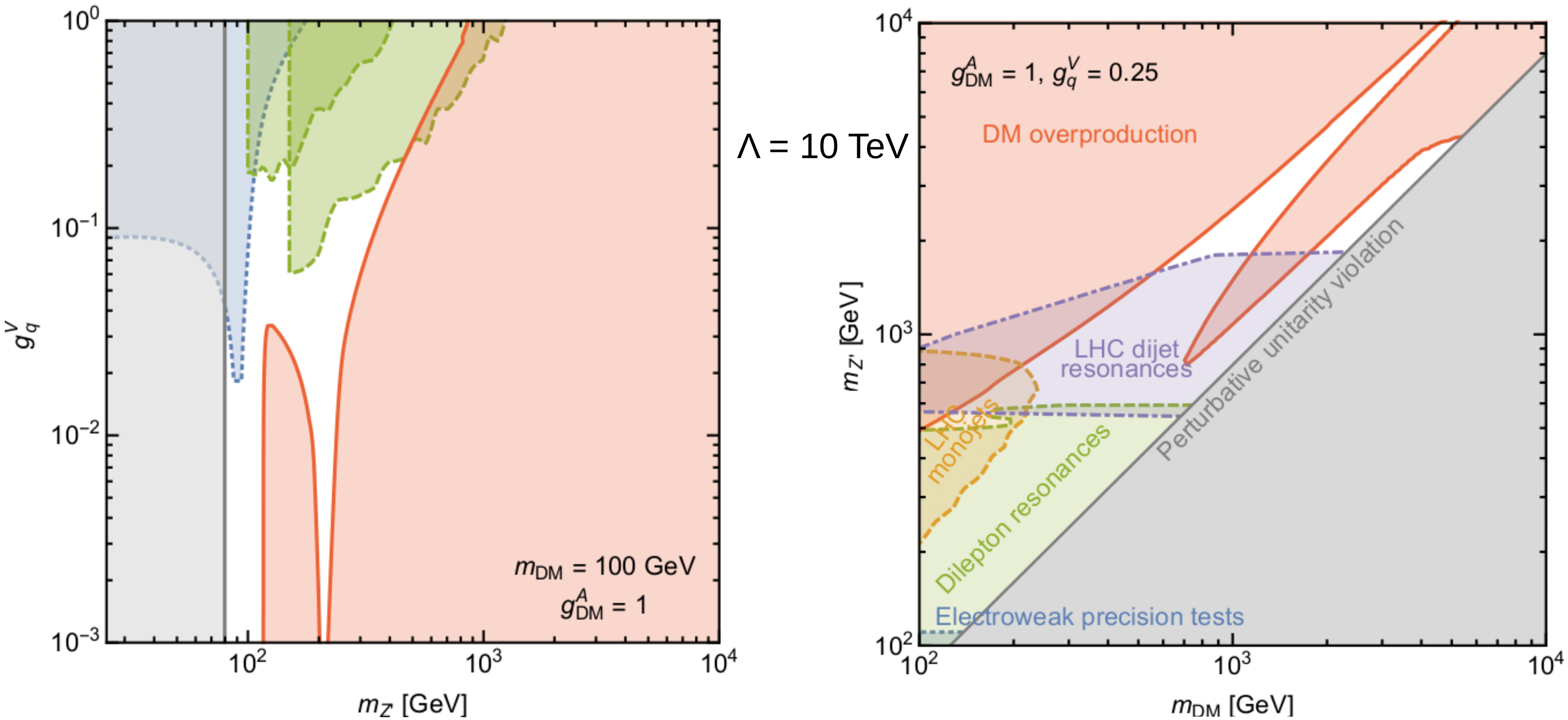
- Nevertheless, there will still be constraints from searches for dilepton resonances and EWPT due to kinetic mixing between the Z' and the Z:

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

- While it is reasonable to assume that the kinetic mixing vanishes at high scales, quark loops will always induce kinetic mixing at lower scales, since quarks are assumed to be charged under both *U*(1)s:

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

Vector couplings to Standard Model fermions: Constraints



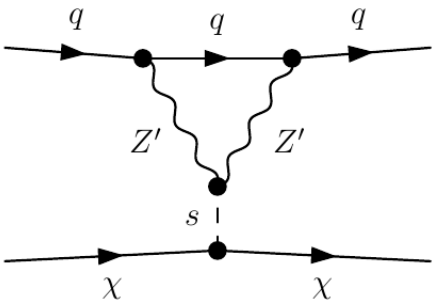
> There is a compelling interplay of the constraints due to loop-induced kinetic mixing and bounds from conventional LHC DM searches.

> The combined constraints leave only a small region in parameter space (close to the Z resonance), where DM overabundance is avoided.

The return of the dark Higgs

- So far, we have only discussed the indirect implications of having an additional dark Higgs to generate the mediator mass and the DM mass.

- However, the presence of the dark Higgs can change the phenomenology of the model in two important ways:
  - Loop-induced spin-independent couplings between DM and nucleons:



$$\mathcal{L}_{\text{eff}} \supset \frac{(g_{\text{DM}}^A)^2 \, (g_q^V)^2}{\pi^2} \frac{1}{m_s^2 \, m_{Z'}^2} \times m_{\text{DM}} \, f_N \, m_N \, \bar{N} N \, \bar{\psi}\psi$$

  - Mixing between the dark Higgs and the SM Higgs:

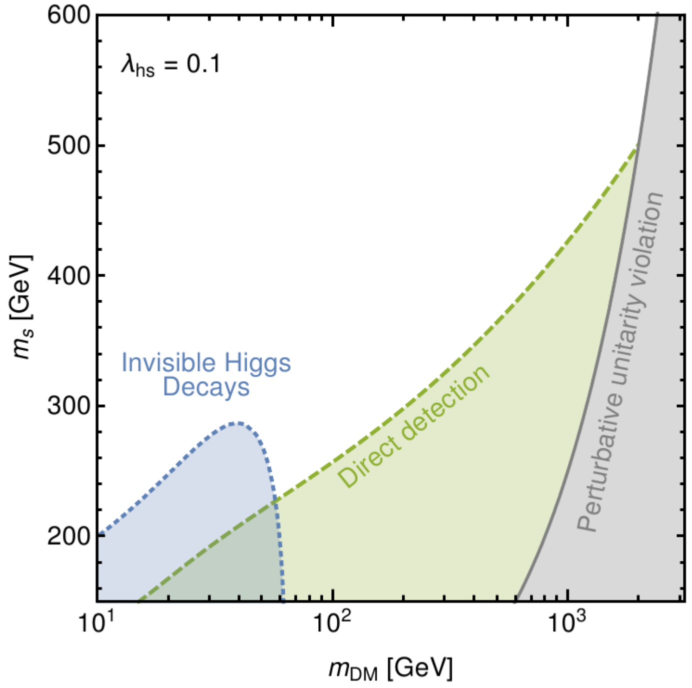
$$V(S,H) \supset \lambda_{hs}(S^* S)(H^\dagger H)$$

$$H_1 = s \sin\theta + h \cos\theta$$
$$H_2 = s \cos\theta - h \sin\theta$$

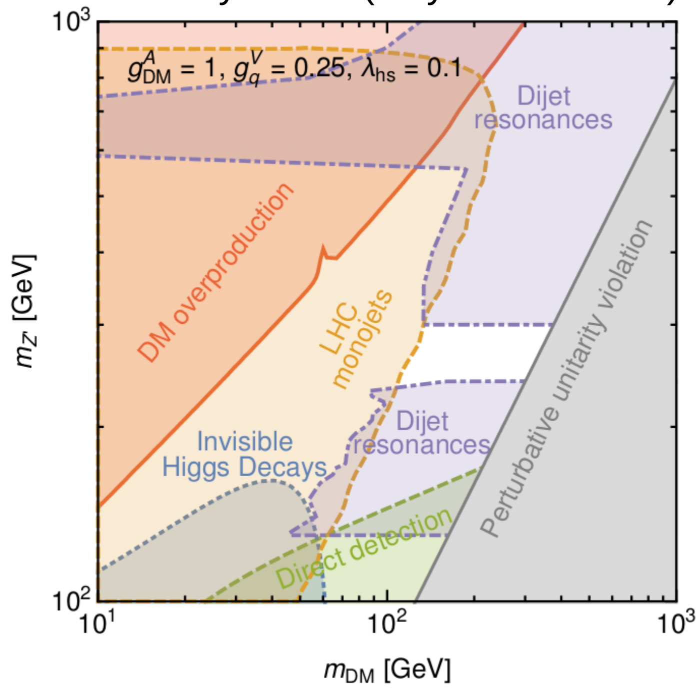
$$\mathcal{L} \supset -\frac{m_{\text{DM}} \, \sin\theta}{2\,w} h \, \bar{\psi}\psi \simeq -\frac{m_{\text{DM}} \, \lambda_{hs} \, v}{2(m_s^2 - m_h^2)} h \, \bar{\psi}\psi$$

The return of the dark Higgs

- If the dark Higgs is sufficiently light, we can hope to see the effects of the Higgs mixing in invisible Higgs decays (for small DM masses) or in direct detection (for heavy DM).



Dark Higgs mass taken to saturate the unitarity bound (very conservative)



- The additional constraints due to Higgs mixing provide valuable complementary information in the parameter region with small mZ and large mDM , which is difficult to probe with monojet or dijet searches.

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.
- Although these models are rather simplistic, they serve as a useful tool to combine and compare different DM search strategies.
- For example, there is an important complementarity between monojet and dijet searches in constraining both visible and invisible decays of the mediator.
- Nevertheless, it is important that such models fulfil basic requirements, such as gauge invariance and that perturbative unitarity is guaranteed in the regions of the parameter space where the model is used to describe data.
- These requirements imply certain relations between the different couplings and point towards the need to introduce additional states for a complete description.
- As a result, relevant experimental signatures are not captured by considering only the interactions of the mediator with DM and quarks.

Summary

- Our results depend on the coupling structure of the mediator:
- Vector(SM)-Vector(DM)
  - Highly constrained by direct detection
  - Difficult to avoid DM overproduction
  - LHC searches typically not competitive
- Axial(SM)-Axial(DM)
  - New physics (e.g. a dark Higgs) required to restore perturbative unitarity.
  - Strong constraints from EWPT and dilepton resonance searches.
  - Monojet searches and direct detection not competitive.
- Vector(SM)-Axial(DM)
  - Most weakly constrained scenario
  - Relevant constraints from kinetic mixing and Higgs mixing
  - Compelling interplay between traditional DM searches and new signatures