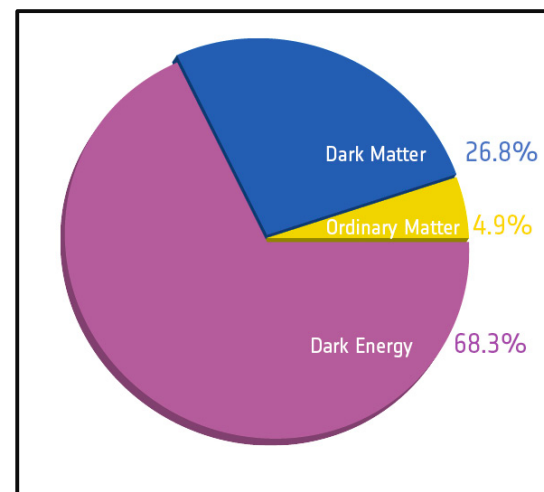
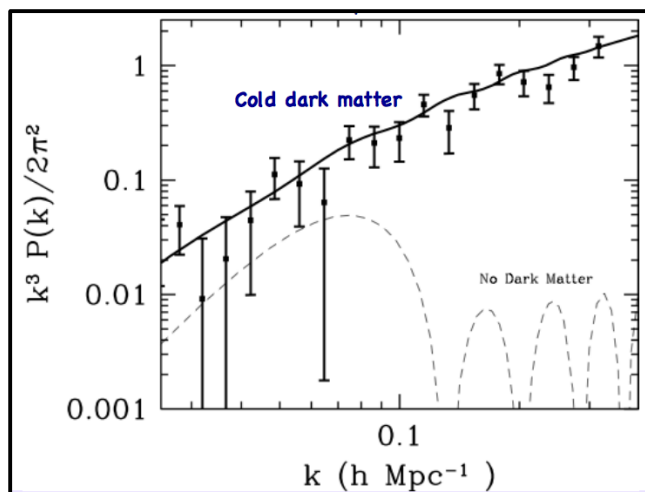
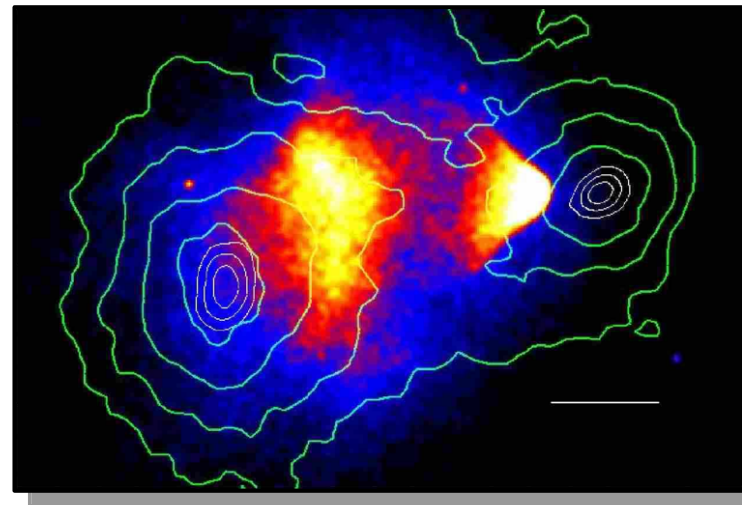
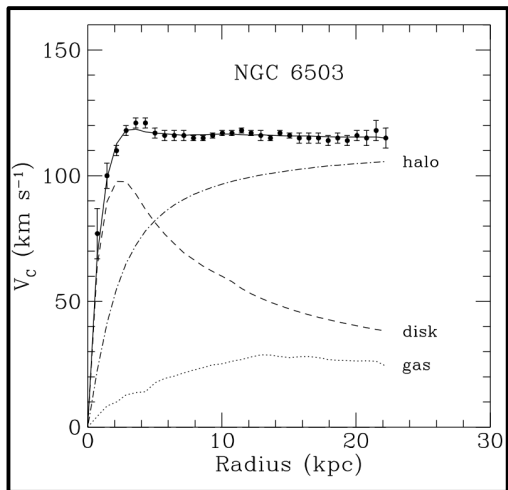


How (not) to use simplified models to search for dark matter at the LHC

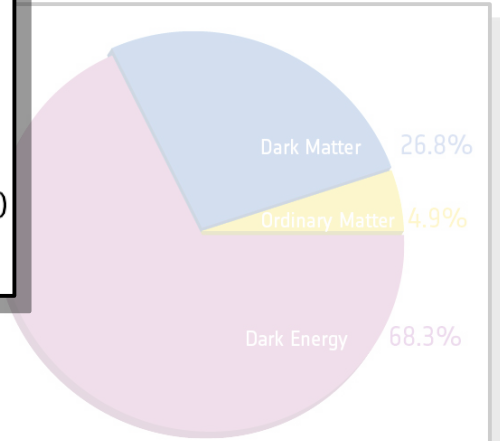
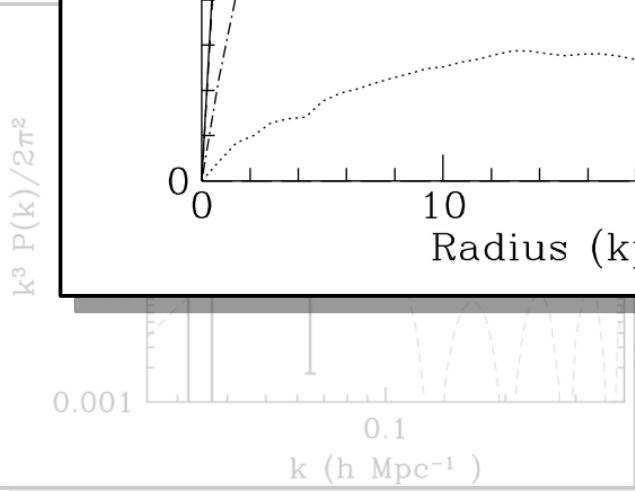
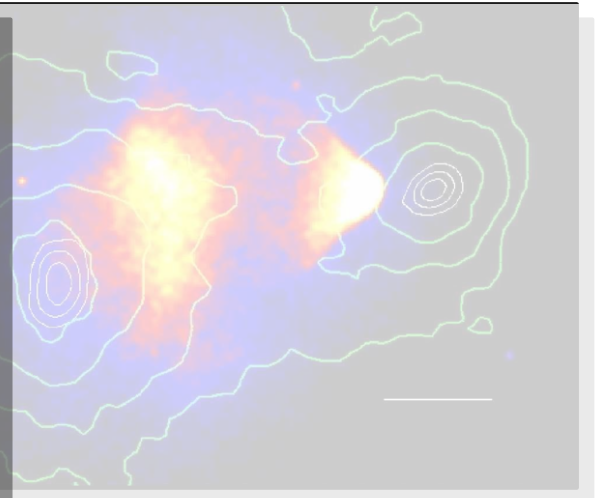
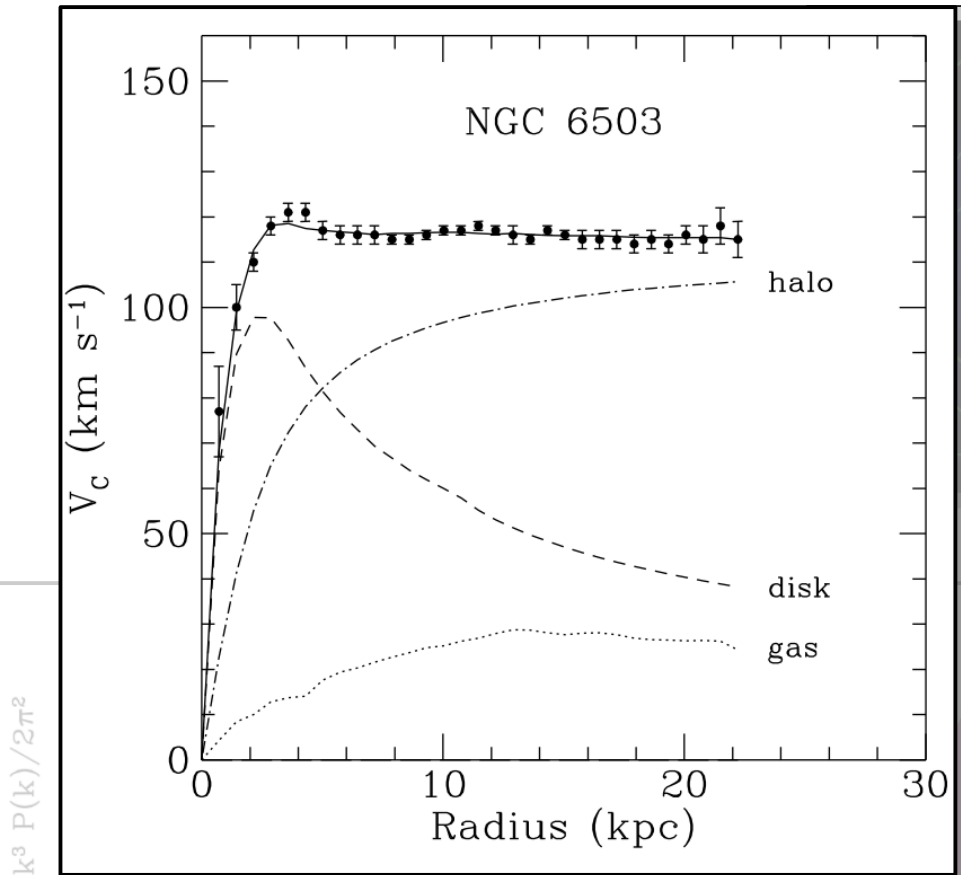
Felix Kahlhoefer
University of Oslo
27 April 2016

based on **arXiv:1510.02110**, **arXiv:1603.01267**
and **work in preparation** in collaboration with
Michael Duerr, Ulrich Haisch, Kai Schmidt-Hoberg,
Thomas Schwetz, Tim Tait and Stefan Vogl

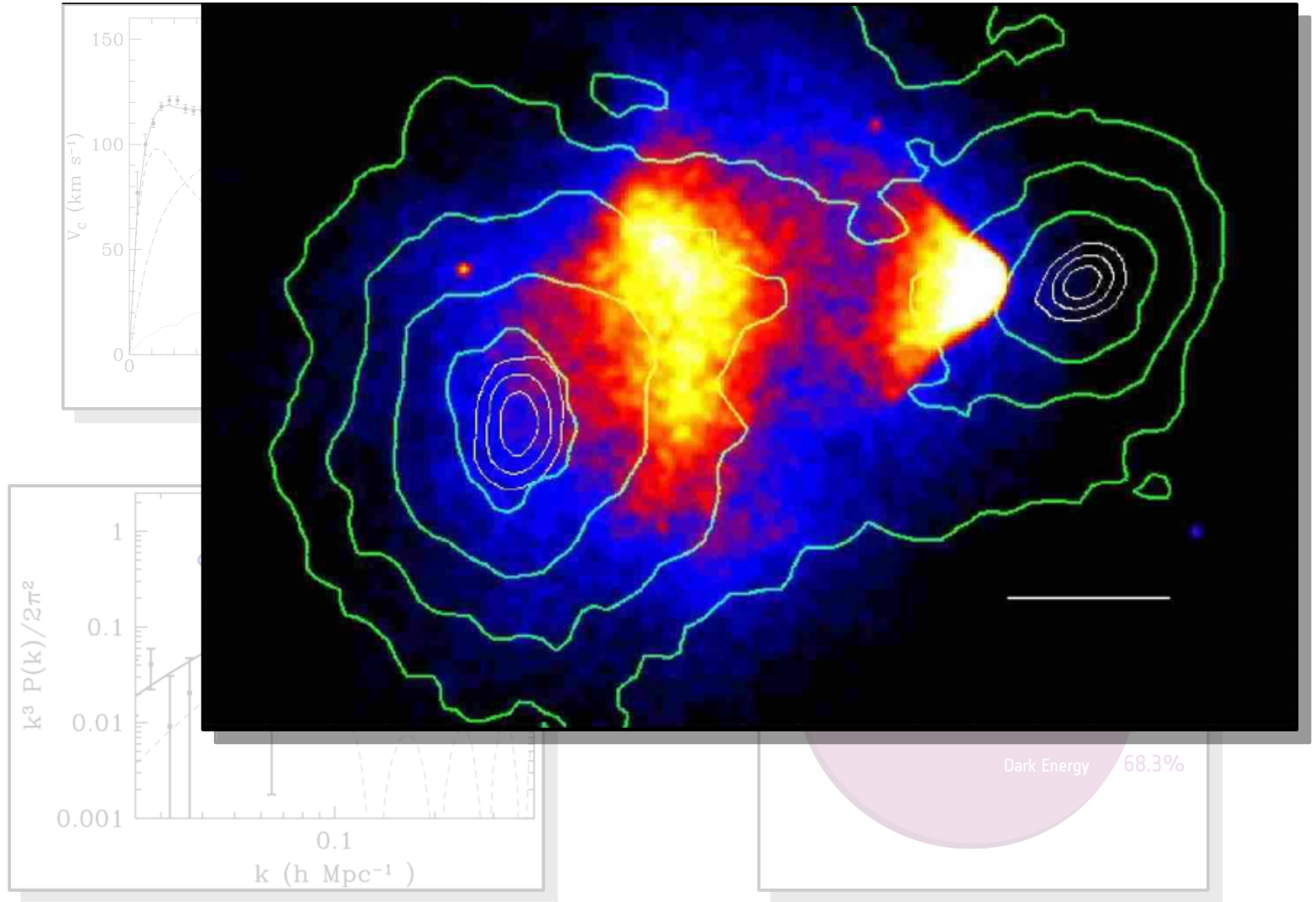
Evidence for Dark Matter



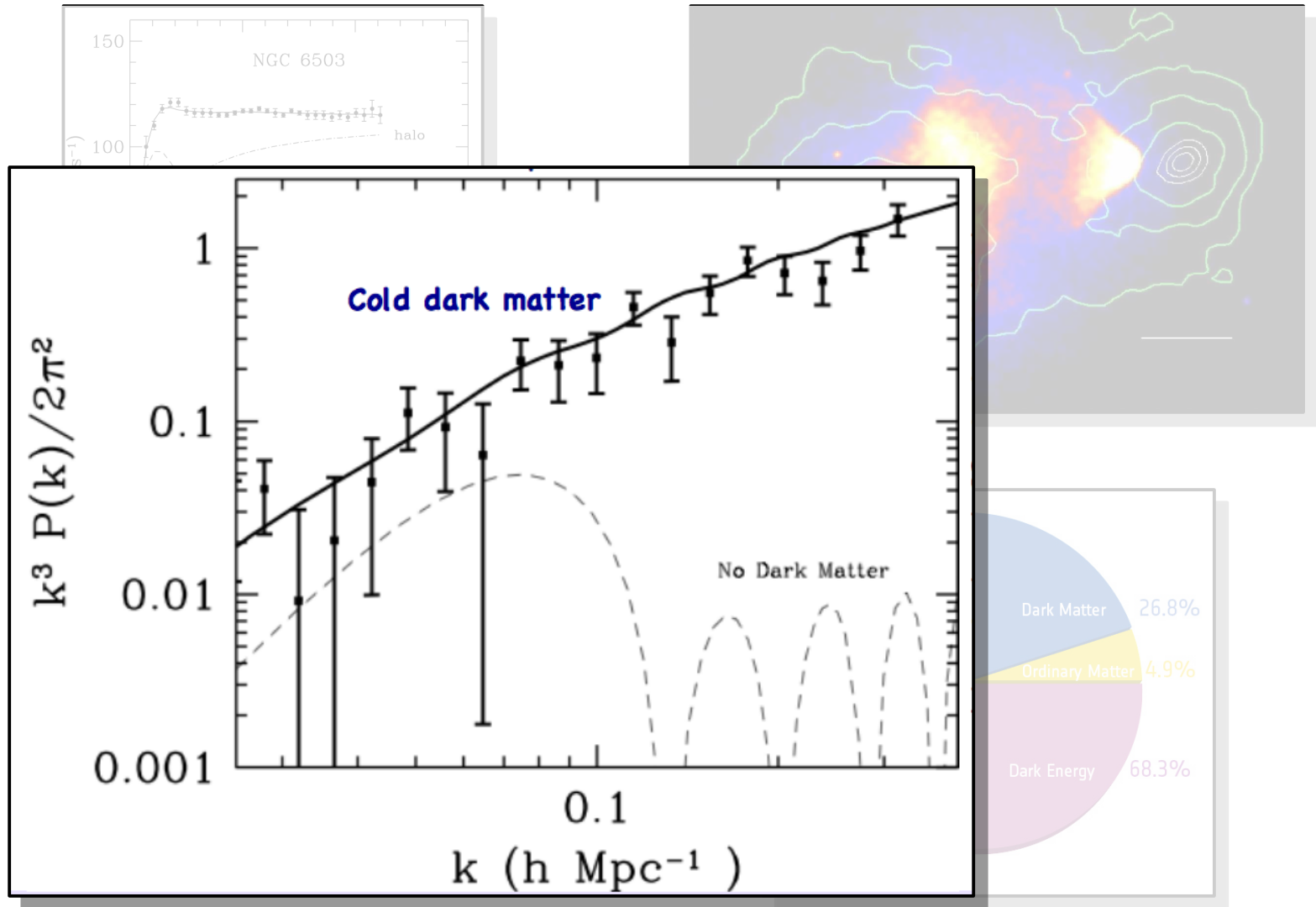
Evidence for Dark Matter: Galactic rotation curves



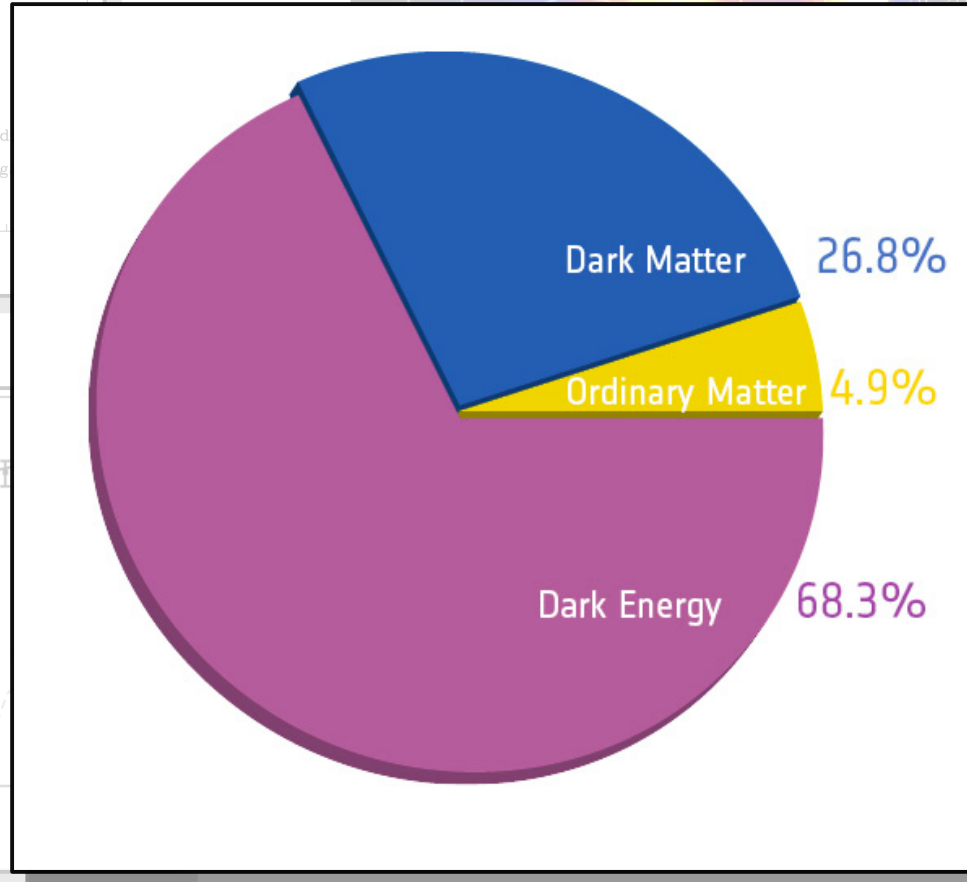
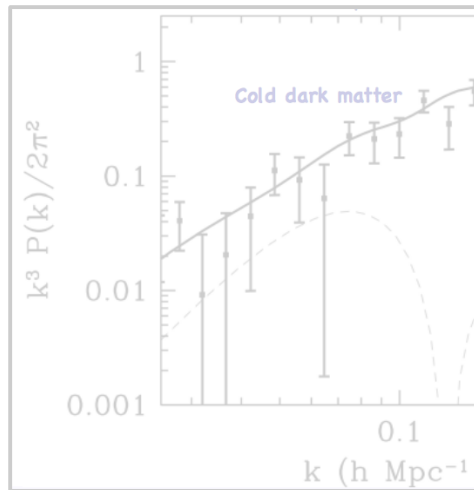
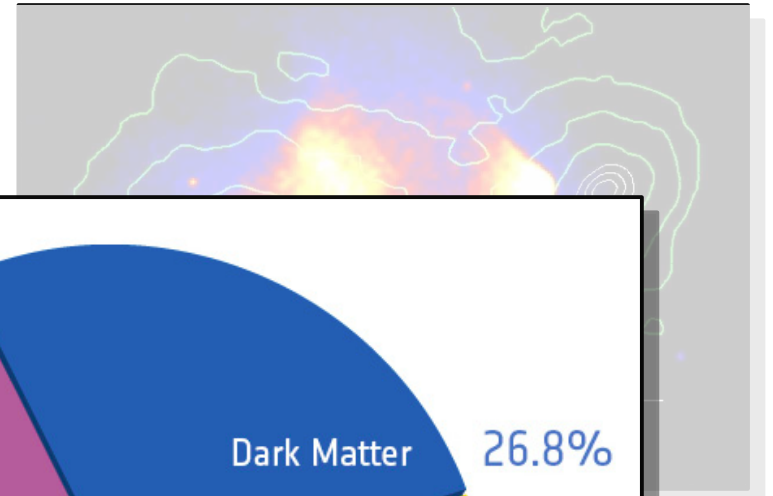
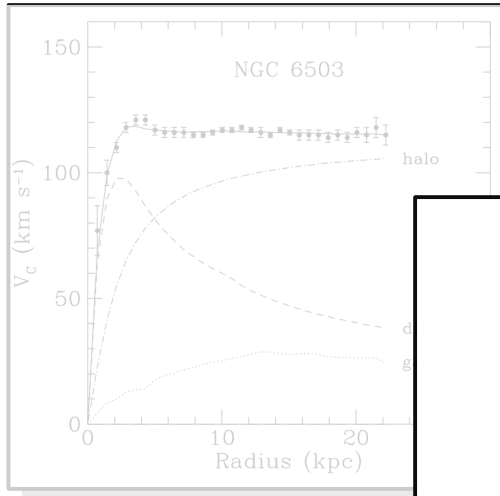
Evidence for Dark Matter: Weak lensing



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



Properties of dark matter

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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 $\sigma/m_{\text{DM}} \sim 1 \text{ barn/GeV}$



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

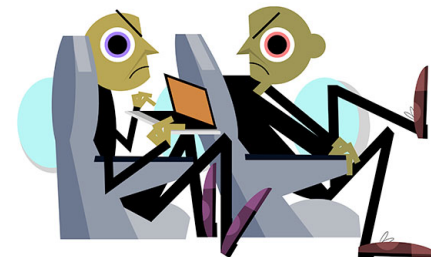
- > The opposite strategy is to focus entirely on explaining the observed dark matter abundance. The simplest possibilities are so-called portal models, which include just a single new particle with tiny couplings to Standard Model states, such as
 - Sterile neutrinos
 - Hidden photons
 - Scalar singlets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



Dark matter candidates: The bottom-up approach

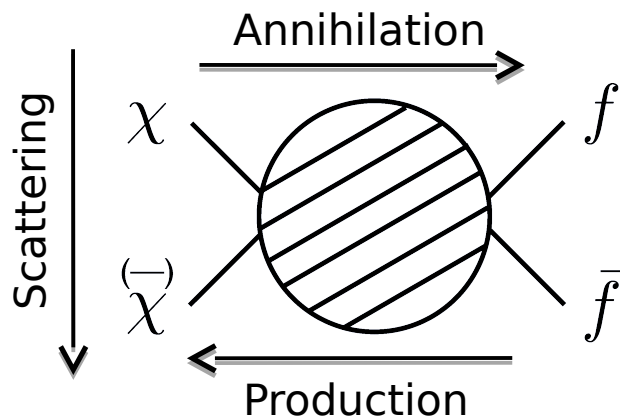
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Too little legroom!



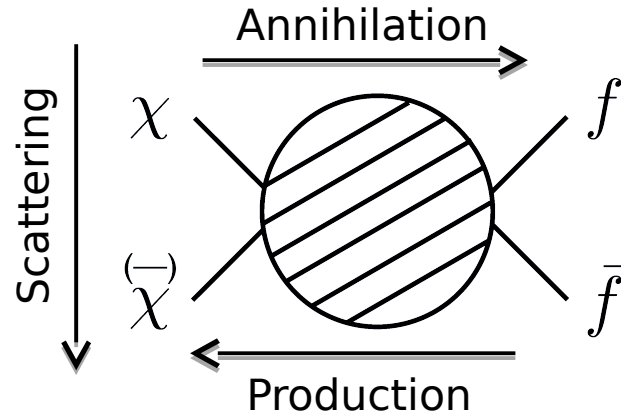
Dark matter phenomenology: The middle ground

- > 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.



$\Delta\mathcal{L}$	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	v^2
	SD	q^2
$\hat{\mathcal{O}}_s^\phi : \frac{m_q}{\Lambda^2} \phi^\dagger \phi \bar{f} f$	SI	1
$\hat{\mathcal{O}}_s^\psi : \frac{m_q}{\Lambda^2} \bar{\psi} \psi \bar{f} f$	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



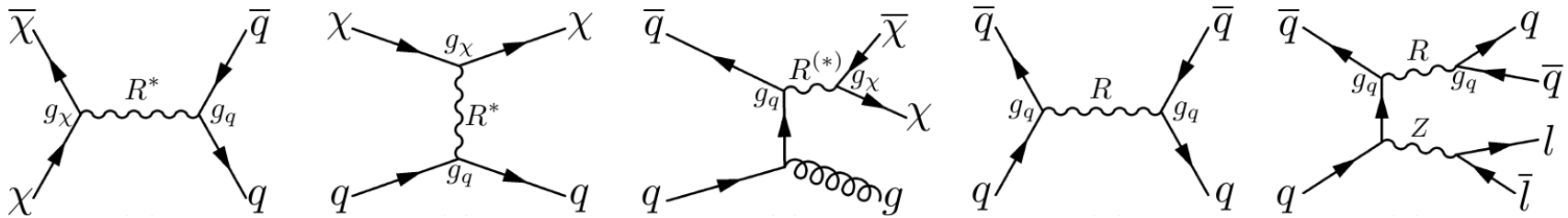
- > In the effective operator approach, all DM searches constrain the same new-physics scale Λ , so we can directly compare bounds from different search strategies.
- > However, the resulting bounds are often rather weak compared to LHC energies ($\Lambda \sim 1$ TeV still allowed), so it may be inconsistent 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.

Buchmueller et al., arXiv:1308.6799; Harris et al., arXiv:1411.0535

- > 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.

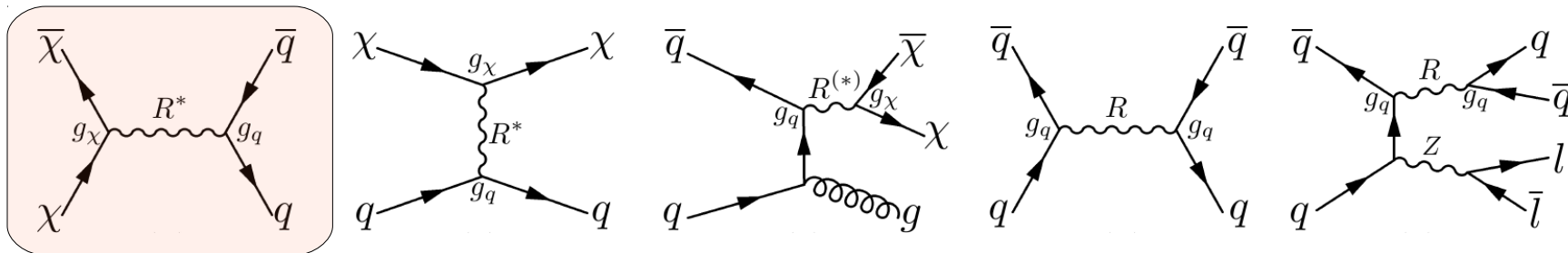
What is a simplified dark matter model?

- > 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 consistent – it only needs to parameterize the properties of the invisible particles in an efficient way.
- > Better name: Simplified missing energy models

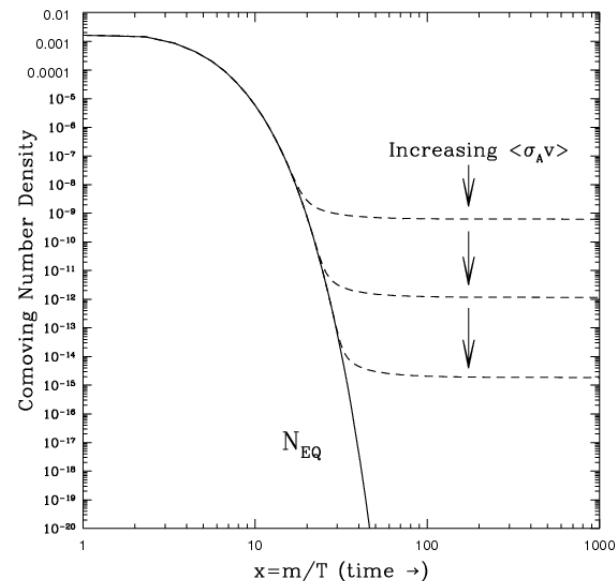
- > For the DM community, a simplified DM model serves to connect LHC physics to other aspects of DM phenomenology.
- > The fundamental assumption is that the invisible particles produced at the LHC are stable and therefore contribute to the observed DM abundance.
- > Predicting LHC signatures is only one aspect of this more ambitious approach.
- > Better name: Dark mediator models



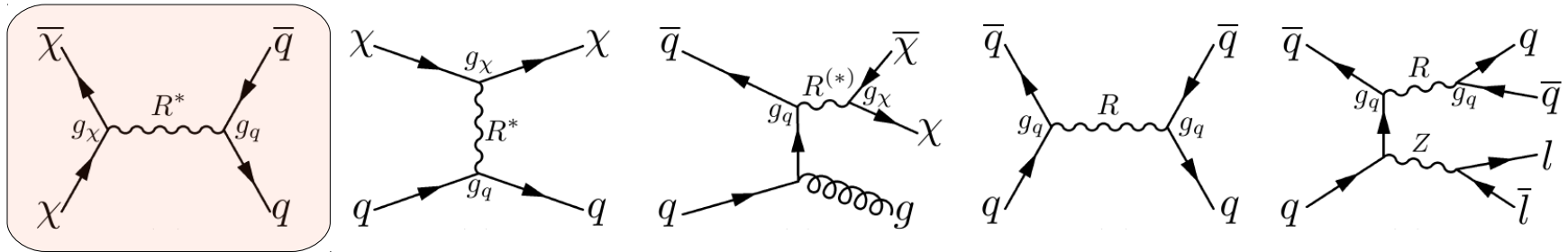
Dark mediator models: Relic density



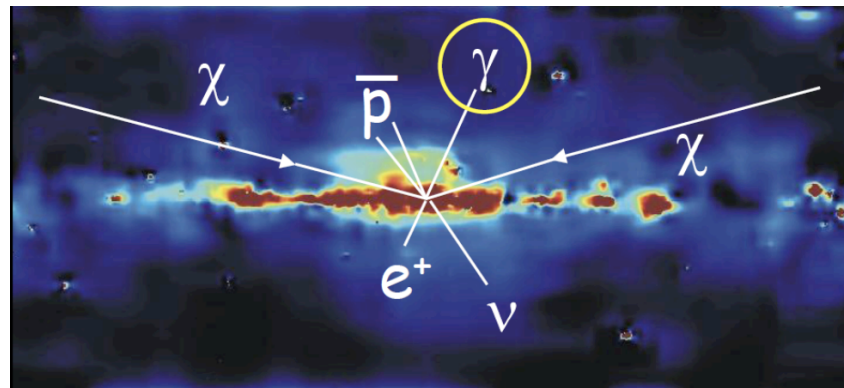
- In the early Universe, DM annihilation and DM production happen frequently and keep DM in thermal equilibrium with SM states.
- As the temperature drops below the DM mass, its number density is suppressed, and DM interactions become less frequent.
- Once the interaction rate is smaller than the expansion rate of the Universe, DM interactions freeze out and the comoving number density becomes constant.
- Larger annihilation cross sections lead to smaller relic abundances.



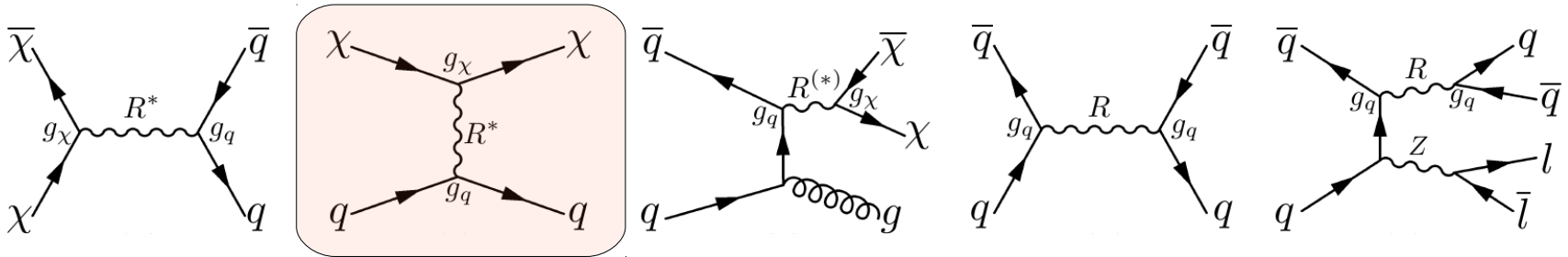
Dark mediator models: Annihilation



- > 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.



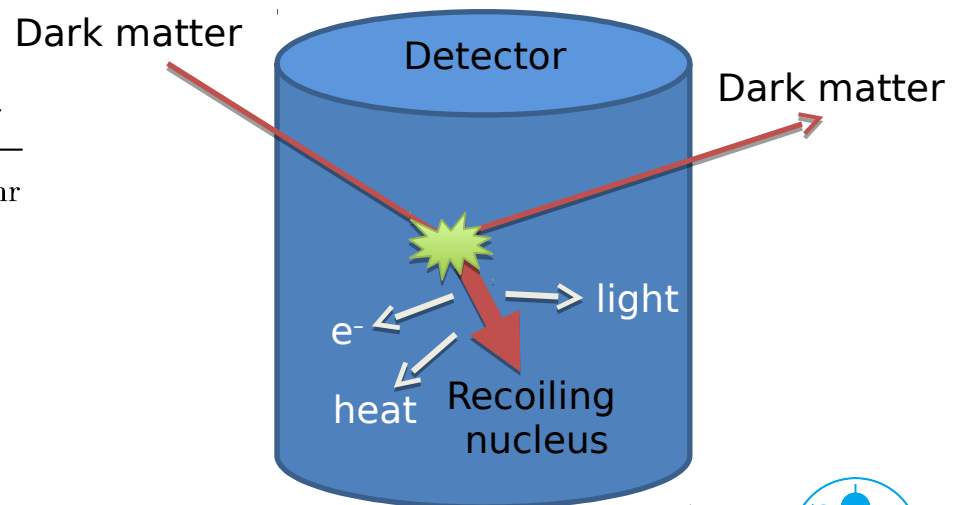
Dark mediator models: Direct detection



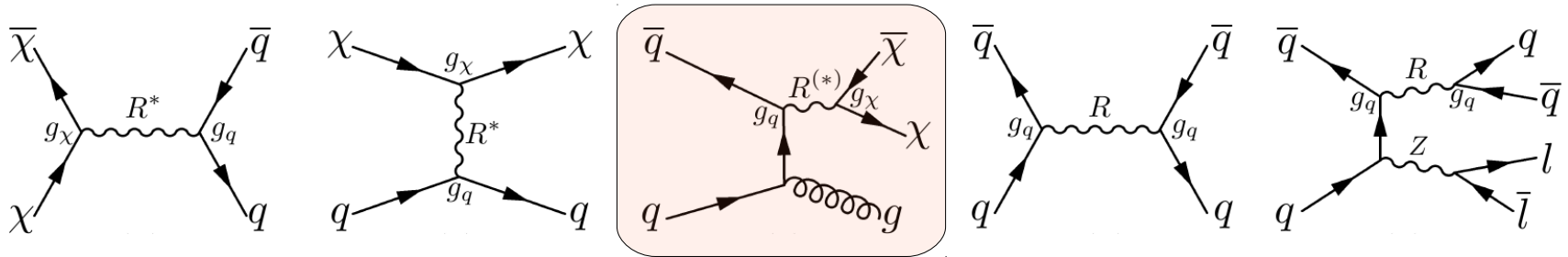
- > Dark matter particles from the Galactic halo that pass through the Earth will occasionally **scatter off nuclei**.
- > The resulting **recoil energy** of the nucleus can be measured in **dedicated low background detectors**.

$$\frac{dR}{dE_{nr}} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{\infty} dv v f(v, v_E) \frac{d\sigma}{dE_{nr}}$$

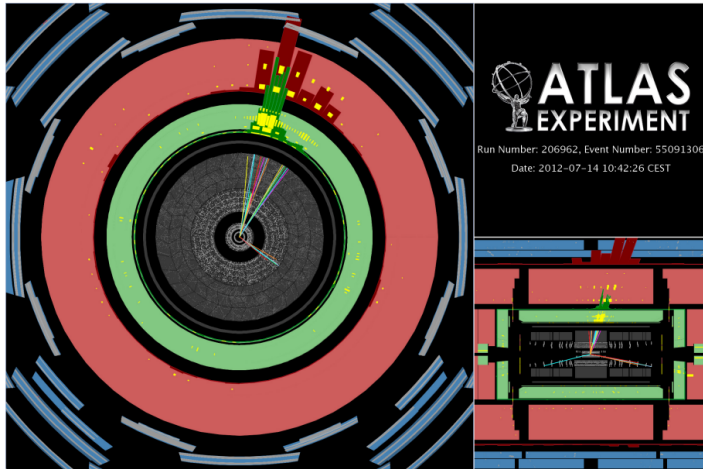
Typical event rates are less than
1 event per kg per year
 A great experimental challenge!



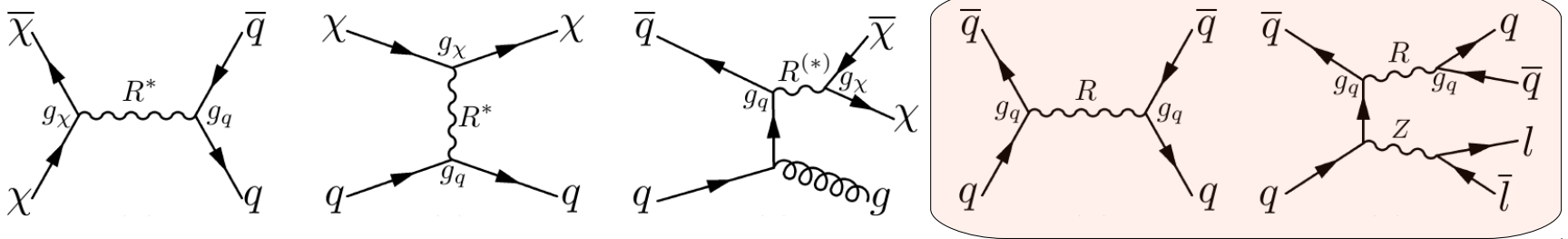
Dark mediator models: Colliders



- > 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.

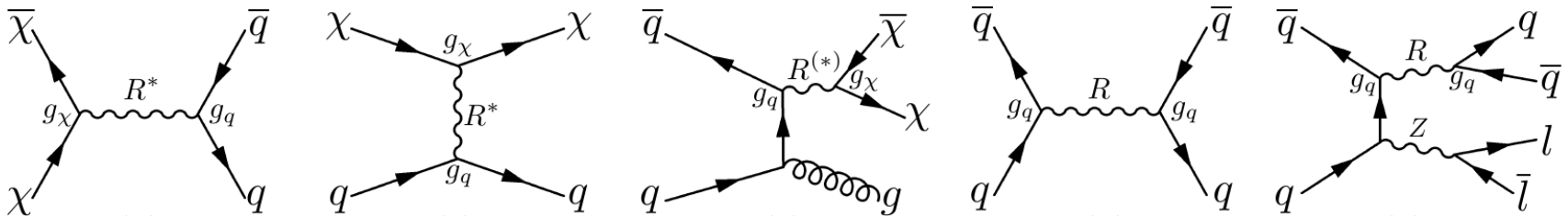


Searching for dark mediator



- > 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.

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:

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

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 $0 \leq \text{Im}(\mathcal{M}_{ii}^J) \leq 1$, $|\text{Re}(\mathcal{M}_{ii}^J)| \leq \frac{1}{2}$, where

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

Kinematical factor

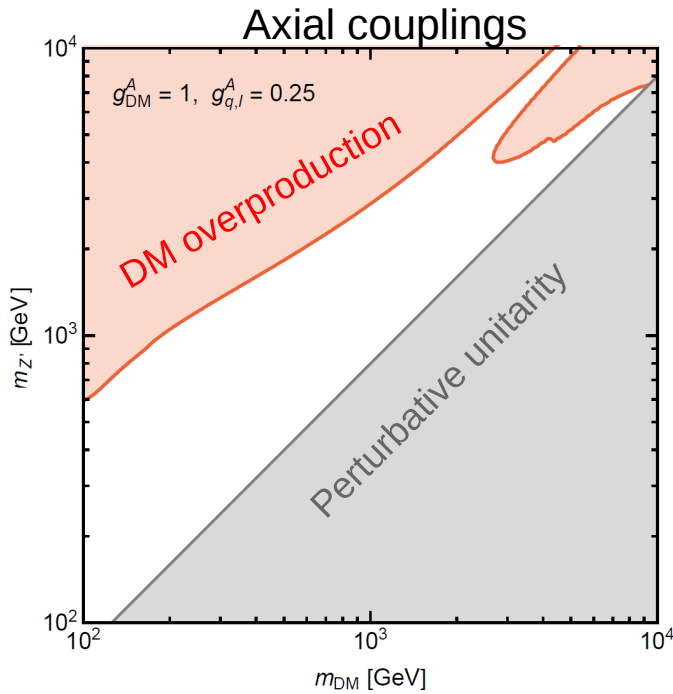
Wigner d-function

- > Unitarity can be violated in two ways:
 - Large couplings: If the theory becomes non-perturbative, tree-level matrix elements will no longer satisfy the unitarity conditions from above (but the all-order matrix element is still unitary).
 - Large energies: If the theory is incomplete (i.e. only an effective low-energy description), matrix elements may grow with the centre-of-mass energy, leading to unphysical predictions at large energies.



How large is the allowed parameter space?

- > If we impose the unitarity requirement on the tree-level matrix elements, this will yield upper bounds on the various couplings of the model in order to ensure that the theory remains perturbative.
- > If couplings cannot be arbitrarily large, the requirement that DM is not overproduced then implies an upper bound on the particle masses.



- > In the red parameter region additional interactions are required in order to achieve sufficiently large annihilation rates.
- > For axial couplings, there is another non-trivial implication of perturbative unitarity:

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

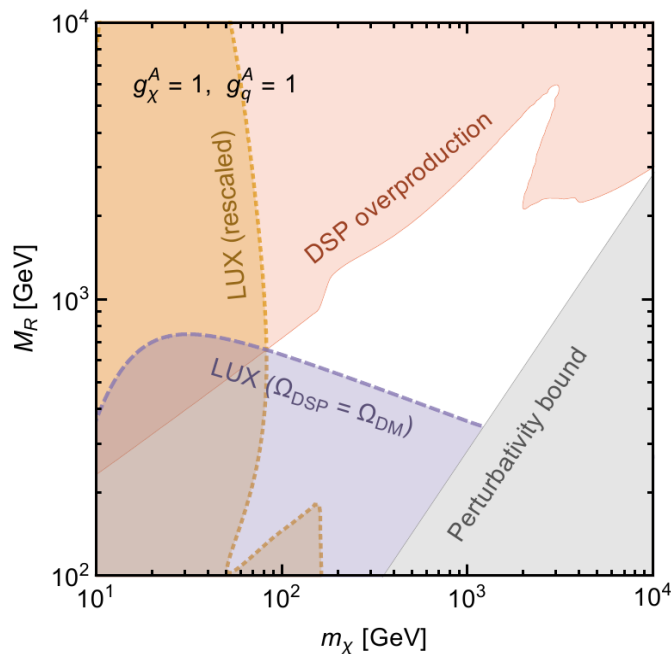
- > Reason: For axial couplings, DM couples to the longitudinal component of the mediator with coupling strength $2 g_f^A m_f / m_{Z'}$.

Chala, FK et al., arXiv:1503.05916



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).

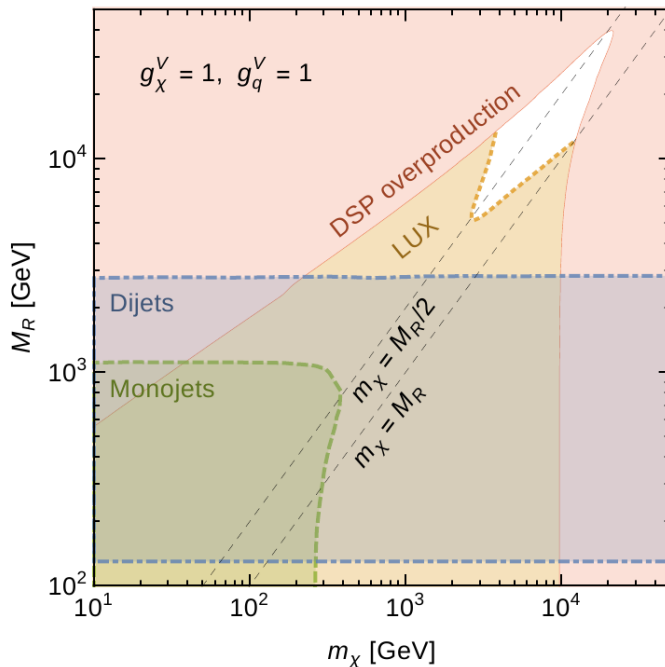


- > If the dark sector is composed of several sub-components, the sensitivity of direct and indirect detection experiments is strongly suppressed.
- > The LHC may be uniquely suited for probing such dark sectors.



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 from now on assume that the DM particle is a Majorana fermion, such that the DM vector current vanishes and tension with direct detection is reduced.

Axial couplings: Another look at perturbative unitarity

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

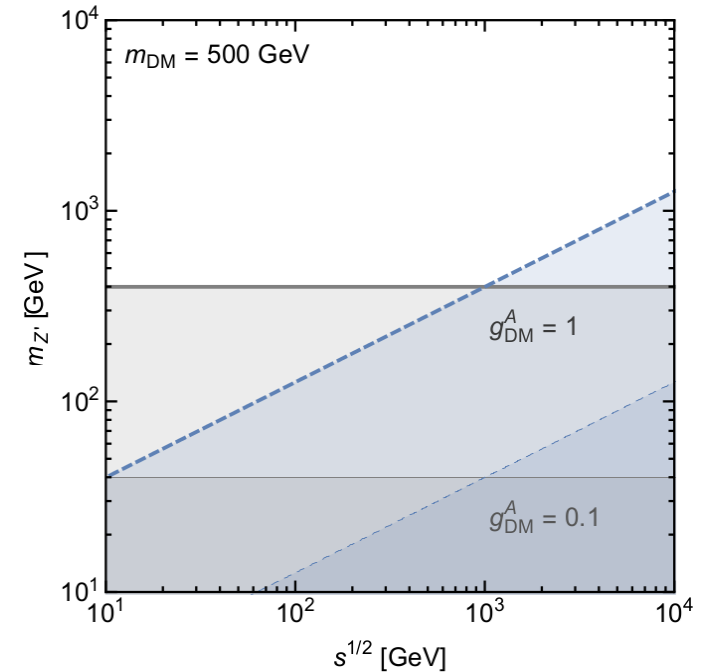
> For axial couplings, the matrix element for this process grows with energy proportional to

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

> Perturbative unitarity then implies

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

> 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

$$\mathcal{L}_{\text{DM}} = \frac{i}{2} \bar{\psi} \not{\partial} \psi - \frac{1}{2} g_{\text{DM}}^A Z'^{\mu} \bar{\psi} \gamma^5 \gamma_{\mu} \psi - \frac{1}{2} y_{\text{DM}} \bar{\psi} (P_L S + P_R S^*) \psi ,$$

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

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

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



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

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

we immediately obtain the requirements

$$q_H = q_{qL} - q_{uR} = q_{dR} - q_{qL} = q_{eR} - q_{\ell L}$$

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



Axial couplings to Standard Model fermions

> The consistency conditions

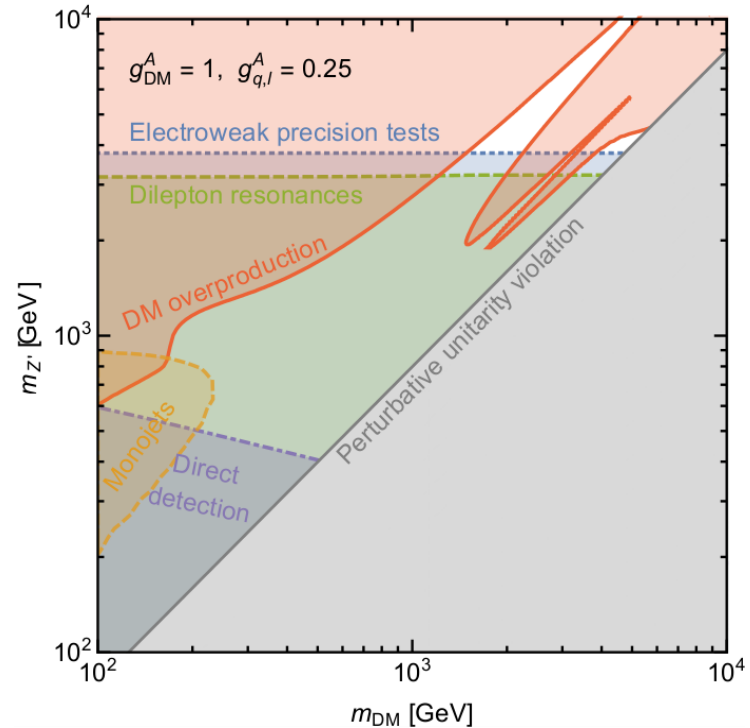
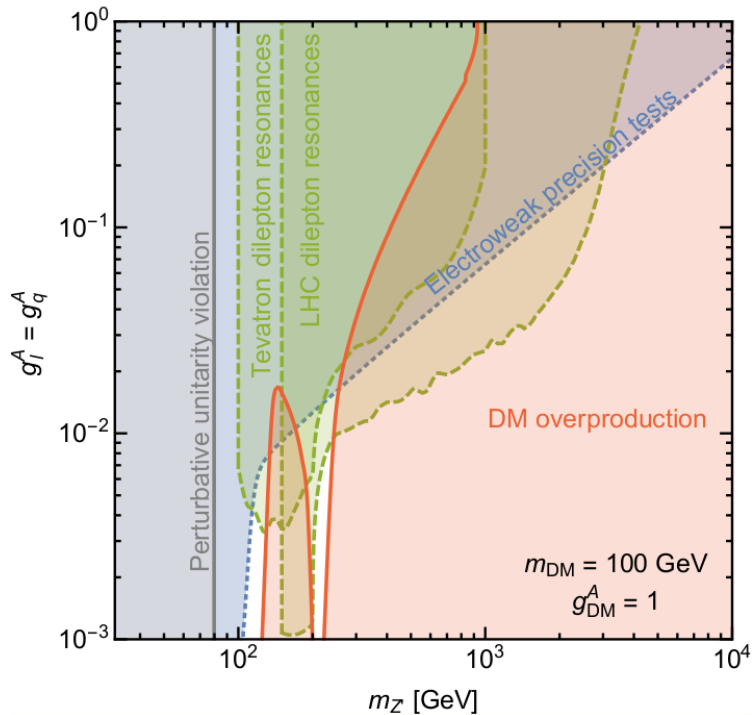
$$q_H = q_{q_L} - q_{u_R} = q_{d_R} - q_{q_L} = q_{e_R} - q_{\ell_L}$$

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, 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.

FK et al., arXiv:1510.02110



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 :

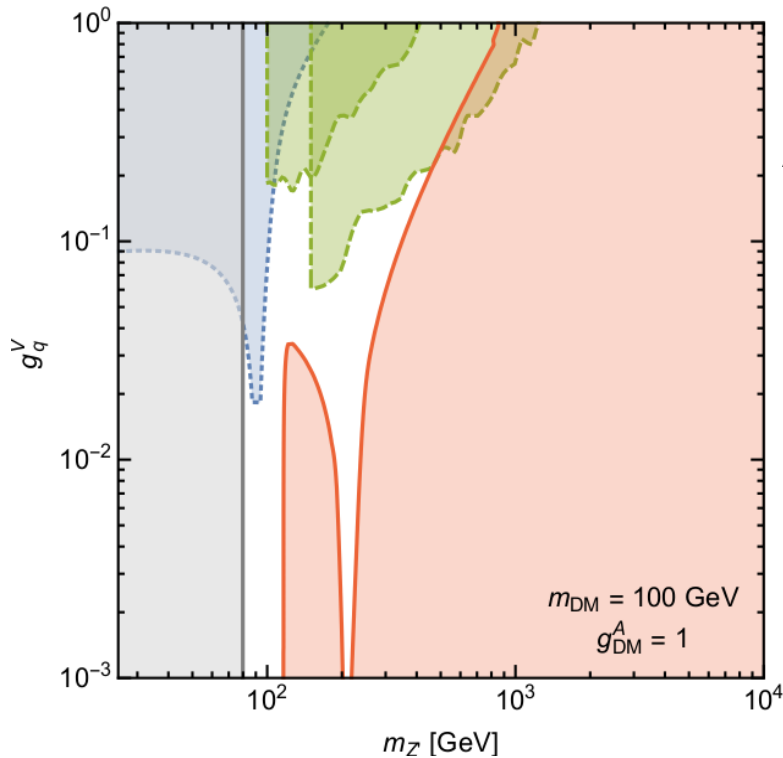
$$\mathcal{L} \supset -\frac{1}{2} \sin \epsilon F'^{\mu\nu} B_{\mu\nu}$$

- > 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:

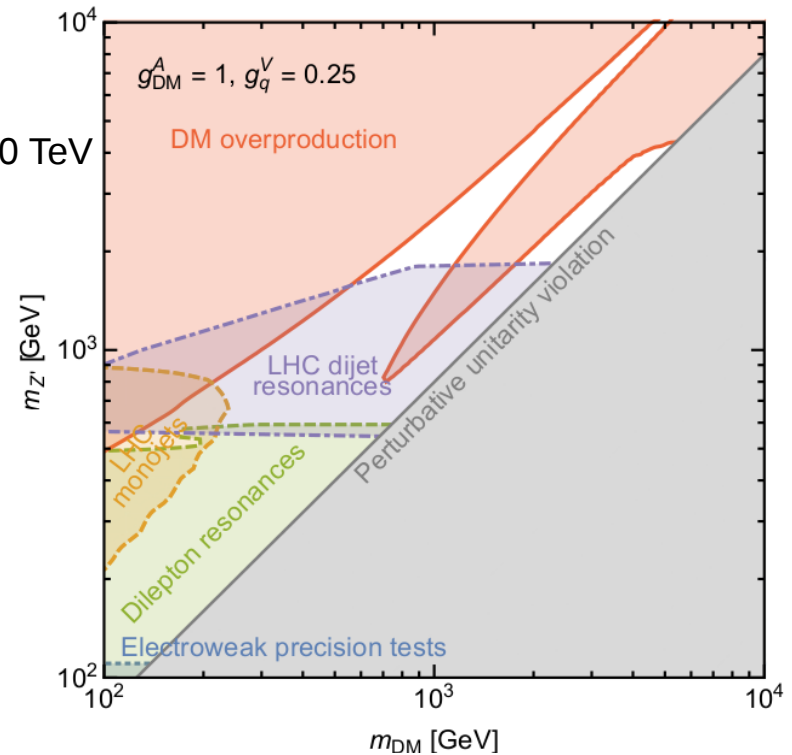
$$\epsilon(\mu) = \frac{e g_q^V}{2\pi^2 \cos \theta_W} \log \frac{\Lambda}{\mu} \simeq 0.02 g_q^V \log \frac{\Lambda}{\mu}$$



Vector couplings to Standard Model fermions: Constraints



$\Lambda = 10$ TeV

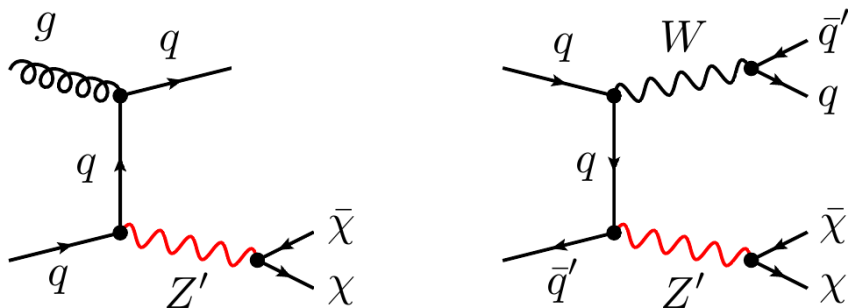


- > There is a compelling interplay of the constraints due to loop-induced kinetic mixing and bounds from conventional LHC DM searches.
- > The combined constraints leave only a small region in parameter space (close to the Z resonance), where DM overabundance is avoided.

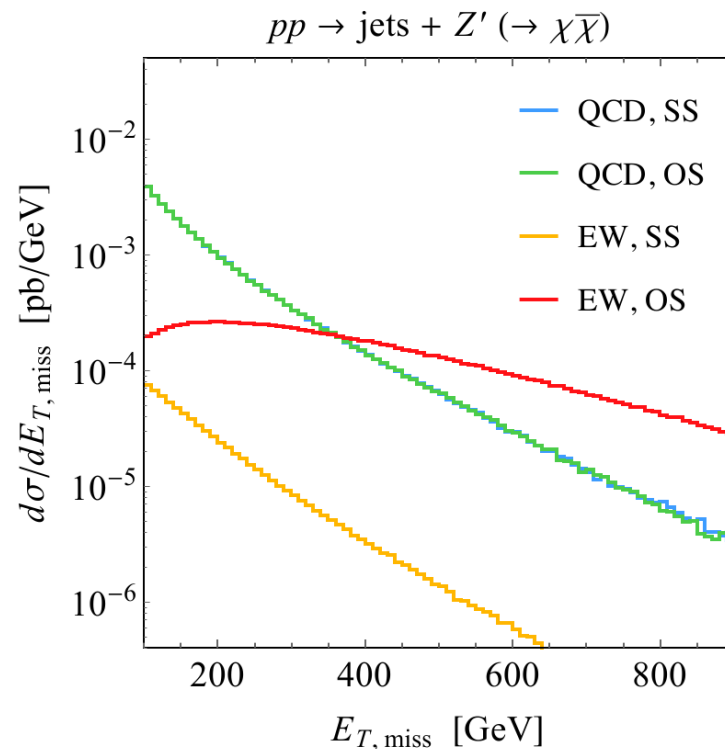


How dangerous is unitarity violation really?

- > How do these theoretical consistency requirements impact LHC DM searches?
- > Consider the hadronic mono-W process, which contributes to LHC “mono”jet searches:



- > For same-sign (SS) couplings to up-type quarks and down-type quarks, the mono-W process gives a subleading contribution.
- > For opposite-sign (OS) couplings, the mono-W process seems to dominate over QCD processes at large energies.

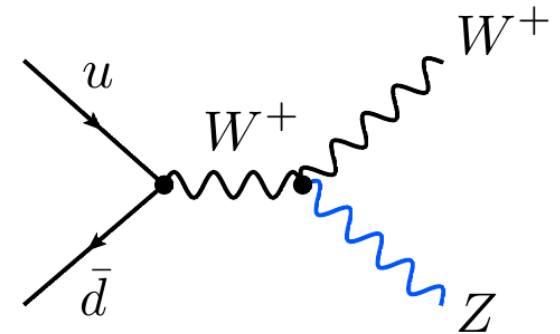


The mono-W problem

- > Indeed, one finds that the J=1 partial wave of the amplitude grows proportional to

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

- > This leads to violation of unitarity at large energies unless the couplings satisfy the conditions derived above (to conform to the $SU(2)_L$ symmetry of the SM).
- > Note: The SM Z does not actually satisfy the coupling structure discussed above due to the effects of electroweak symmetry breaking.
- > A mono-W problem in the SM is however absent, due to the presence of an additional diagram, which cancels the unitarity-violating behaviour.
- > It may be an interesting possibility to copy this structure into the simplified model.



Bell et al., arXiv:1503.07874; Bell et al., arXiv:1512.00476; Haisch, FK, Tait, arXiv:1603.01267

Unitarity bounds on the dark Higgs

- > In order to restore perturbative unitarity in the process $\psi\bar{\psi} \rightarrow Z'_L Z'_L$, the mass of the dark Higgs must satisfy 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

$$m_s \leq \frac{\sqrt{\pi} m_{Z'}}{g_{\text{DM}}^A} = \sqrt{4\pi} w$$

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

Take-home message:

Consistent simplified models may require additional degrees of freedom that cannot be made arbitrarily heavy.



Dark Higgs mixing

- > Indeed, the presence of the dark Higgs can significantly change the phenomenology of the model if it mixes with the SM Higgs:

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

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

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

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

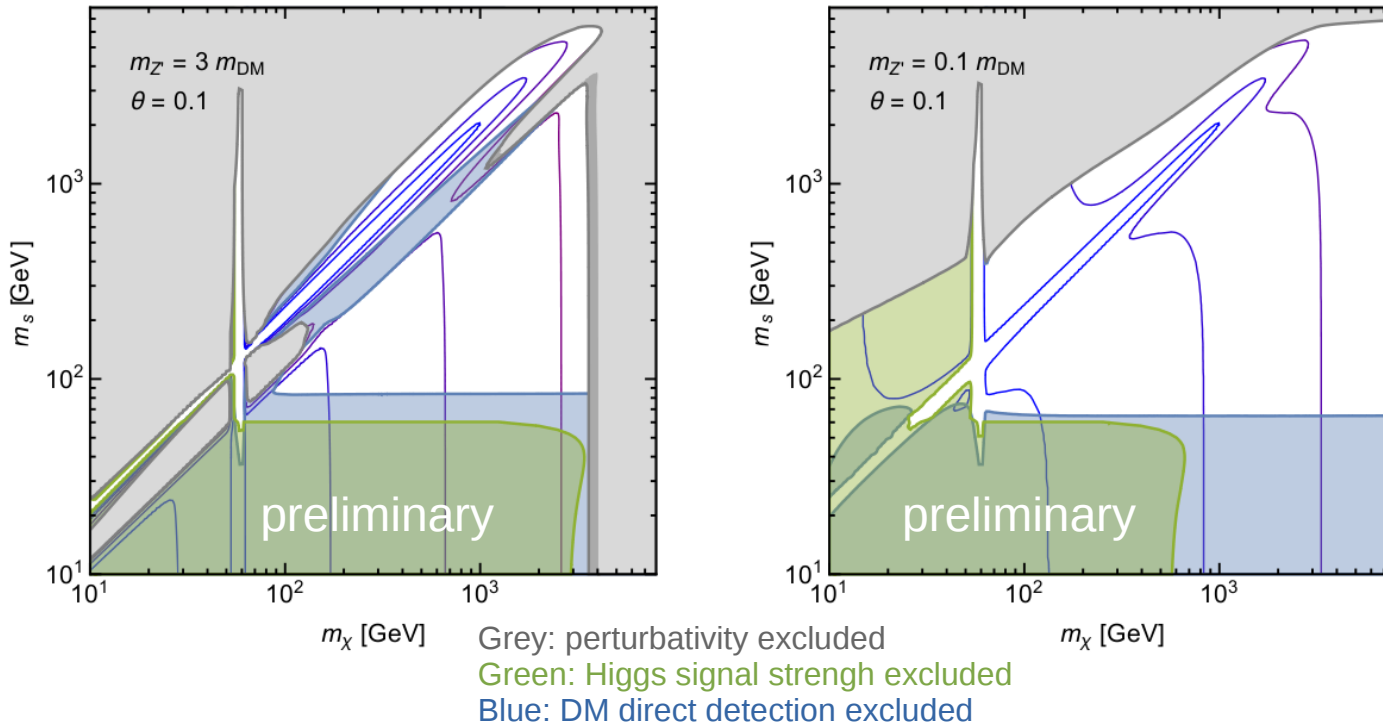
- > Such a mixing can lead to a number of observable effects:
 - Modification of the SM Higgs signal strength μ and electroweak observables
 - New decay modes of the SM Higgs (such as $h \rightarrow \text{inv}$)
 - New resonances at heavy masses (such as $S \rightarrow ZZ \rightarrow 4l$)
 - Spin-independent scattering in DM direct detection experiments



The return of the dark Higgs

- > But mixing between the dark Higgs and the SM Higgs does not only lead to additional constraints. The presence of an additional mediator between the dark sector and the visible sector may help avoid DM overproduction.

Duerr, FK, Schmidt-Hoberg, Schwetz, Vogl, in preparation

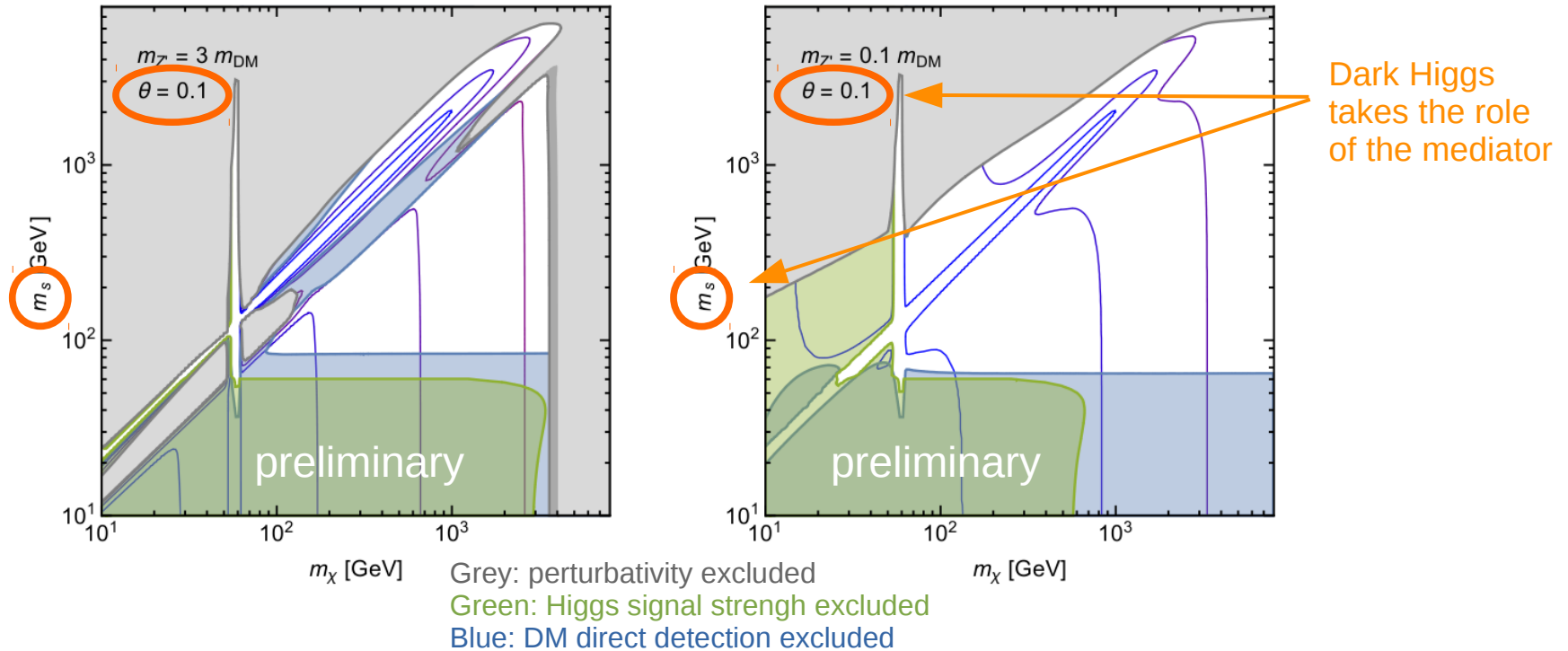


- > Interesting interplay between the two mediators

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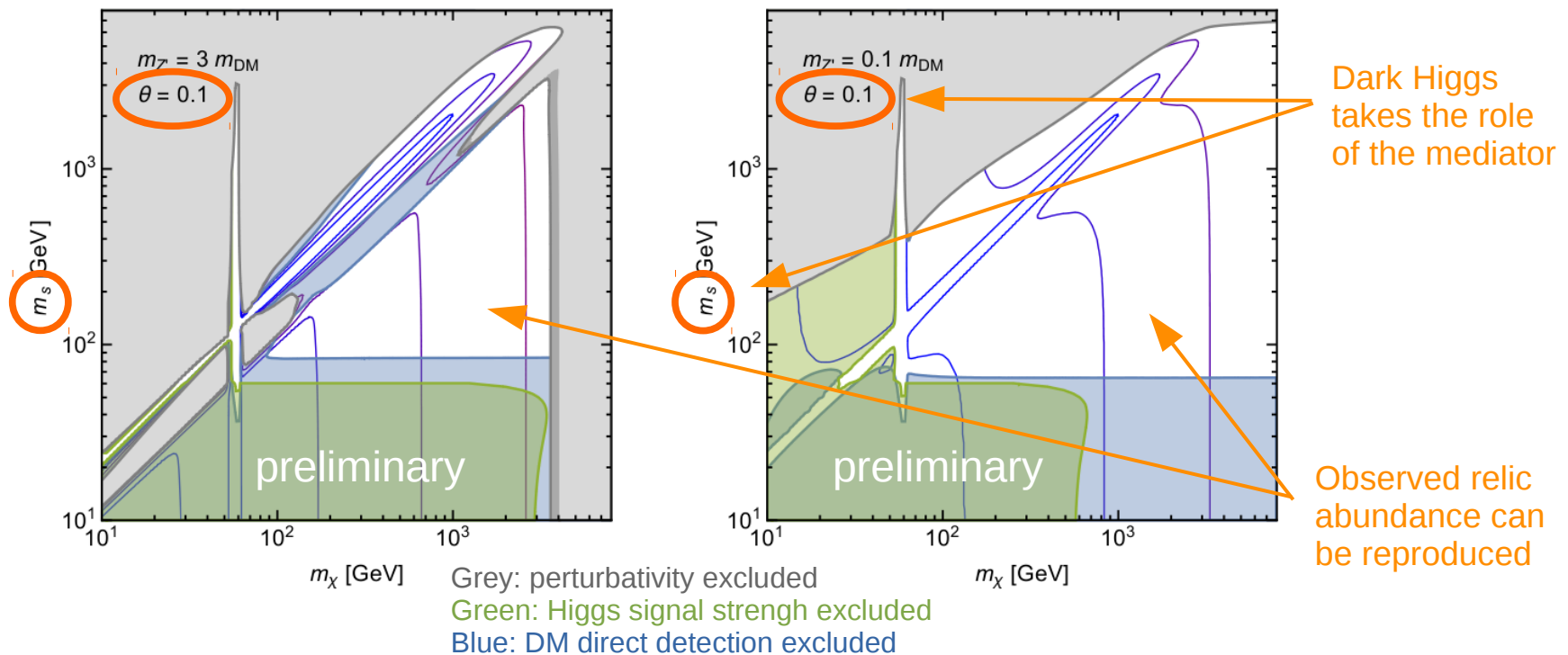


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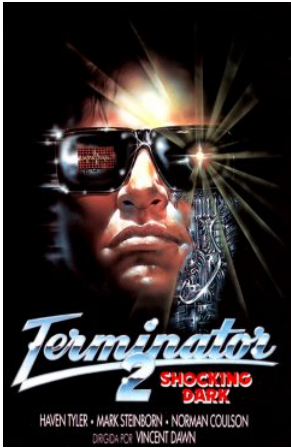
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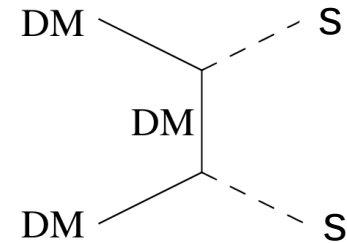
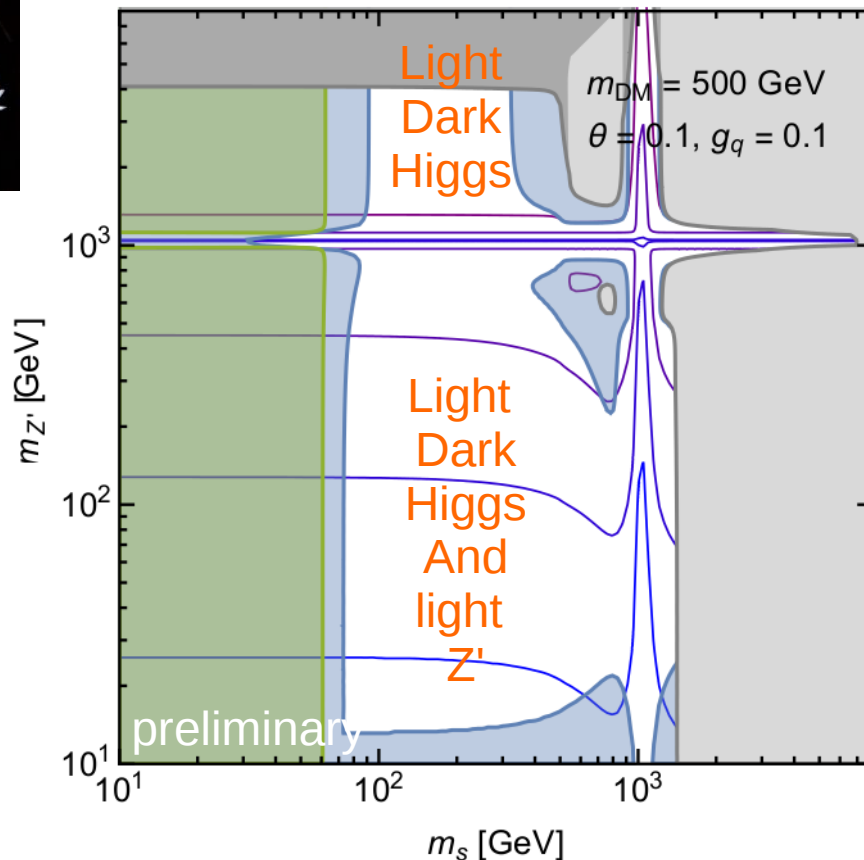


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Dark terminators



- > A particularly interesting situation occurs if either (or both) the Z' and the dark Higgs are light compared to the DM particle. In this case, they can appear in the final state of DM annihilations, i.e. they *terminate* rather than *mediate* the interactions of DM.



- > Much weaker constraints from direct detection and LHC searches, but potentially interesting signatures in indirect detection.



Conclusions

- > Dark mediator (simplified?) models are a useful tool for describing the phenomenology of DM at the LHC and compare the sensitivity with other kinds of DM searches.
- > The requirement of perturbative unitarity provides a guideline to determine the most interesting parameter regions in such models and at the same time allows to determine where the validity of the simplified description breaks down.
- > In many situations, consistent simplified models require additional degrees of freedom that cannot be arbitrarily heavy (such as an additional dark Higgs) or additional interactions (such as couplings to leptons and gauge bosons).
- > Moreover, it is important that even such simple models are constructed in a way that is consistent with the gauge structure of the SM. This requirement often implies certain non-trivial relations between the different couplings not normally imposed on a simplified model.
- > It is often insufficient to only consider the interactions of the mediator with DM and quarks in order to correctly address these issues. Relevant constraints may arise from other signatures like EWPT, Higgs physics or searches for dilepton resonances.

