Dark Forces in the Sky: Signals from Z' and the Dark Higgs

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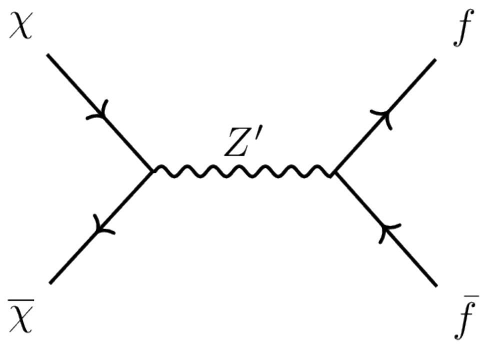
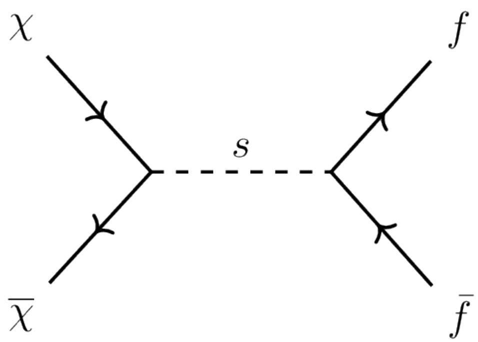
Simplified Models for Dark Matter

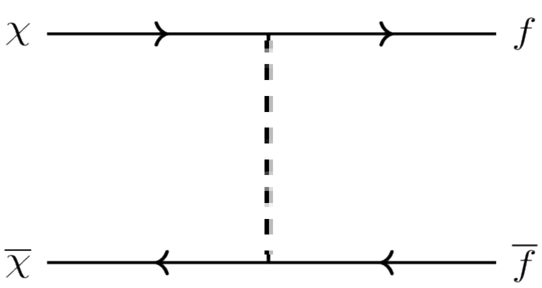
- Still no idea about fundamental nature of DM, model independent framework desirable where possible
- EFTs → issues at high momentum transfer, not generically applicable
- Simplified models: only lightest mediator is retained, set limits on couplings and mediators. Allow for richer phenomenology.

<u>Benchmark simplified models:</u>

s-channel spin-1 s-channel spin-0 t-channel spin-0.



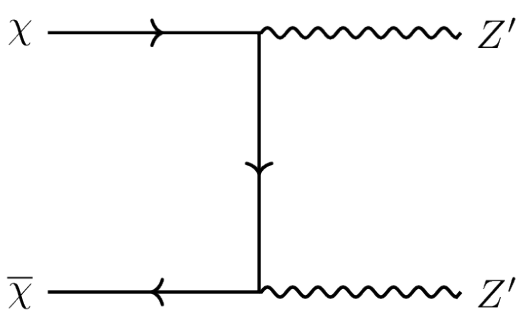


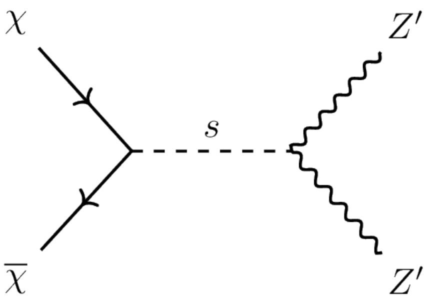


...this can run into problems!

The vector and scalar should generally be included together in the theory.

For Majorana DM, can't write down a mass term which is gauge invariant. Need spontaneous symmetry breaking, leads to constraints on the relation of mass scale and couplings. As a consequence, the Z'Z' cross section:





violates unitarity at high energies, unless the Higgs exchange diagram is included.

For Dirac DM, scalar is not imperative, but its presence is still well motivated as it provides a mass generation mechanism.

Simple renormalizable theory

Model lagrangian is:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{i}{2}\overline{\chi}\partial\!\!\!/\chi - \frac{1}{2}g_\chi Z'_\mu\overline{\chi}\Gamma^\mu\chi - \frac{1}{2}y_\chi\overline{\chi}(P_L S + P_R S^*)\chi - \frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu}$$
$$+ \left[(\partial^\mu + ig_\chi Z'^\mu)S\right]^\dagger\left[(\partial_\mu + ig_\chi Z'_\mu)S\right] + \mu_s^2 S^\dagger S + \lambda_s(S^\dagger S)^2 + \lambda_{hs}(S^\dagger S)(H^\dagger H)$$

After symmetry breaking and mixing, relevant terms are:

$$\mathcal{L} \supset \frac{1}{2}m_s^2 s^2 + \frac{1}{2}m_{Z'}^2 Z'^\mu Z'_\mu - \frac{1}{2}m_\chi\overline{\chi}\chi - \frac{1}{2}g_\chi Z'_\mu\overline{\chi}\Gamma^\mu\chi - \frac{y_\chi}{2\sqrt{2}}s\overline{\chi}\chi + h.c.$$
$$- g_\chi^2 w Z'^\mu Z'_\mu s + \lambda_s w s^3 + 2\lambda_{hs}(hvs^2 + swh^2) + g_f\sum_f Z'^\mu\overline{f}\Gamma_\mu f,$$

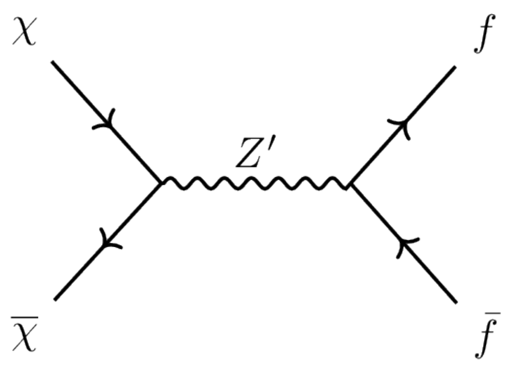
- New field content: Z', dark Higgs, DM candidate.
- Interactions with visible sector via Higgs portal or hypercharge portal
- Mass generation achieved with the dark Higgs.
- Well behaved at high energies.

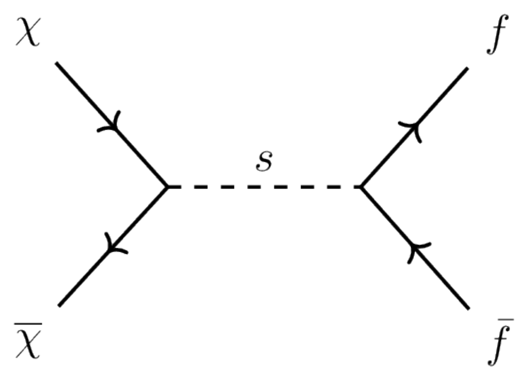
How does this compare to the simplified model benchmarks?

Indirect Detection with Simplified Models

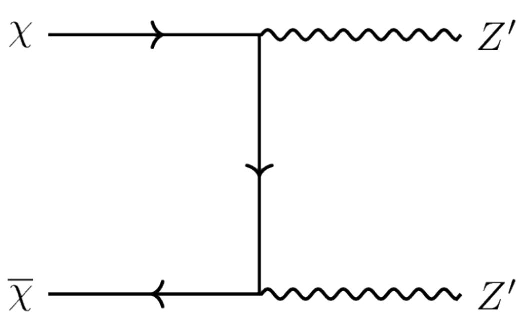
In universe today, only s-wave contributions to the annihilation cross section are relevant. P-wave contributions are negligible, suppressed as DM velocity $v_\chi^2 \approx 10^{-6}$.

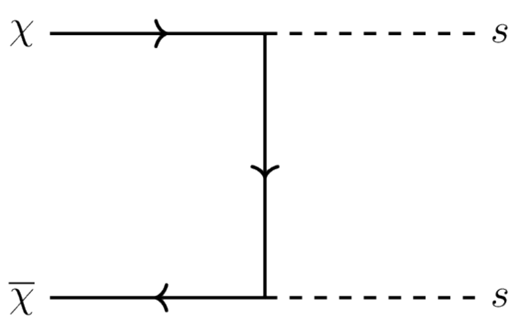
The following have been considered in the past for fermionic DM:

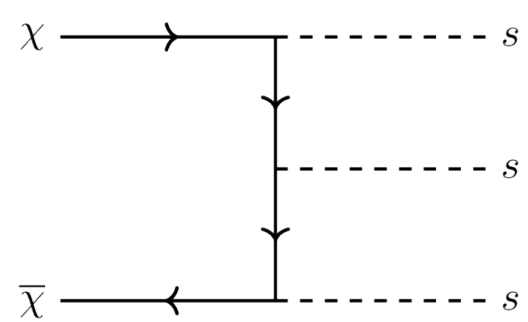




$$\sigma v = a + b v^2 + \cdots$$

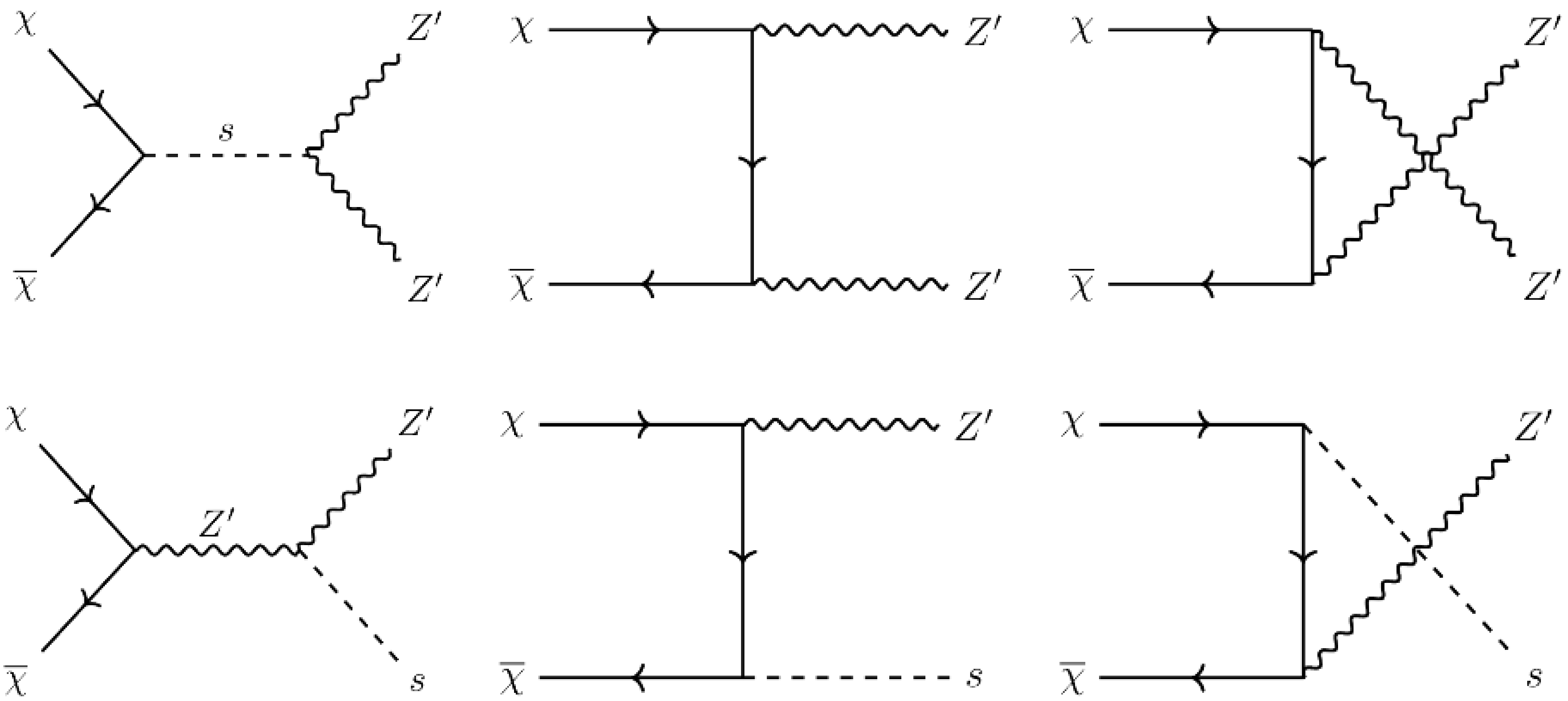






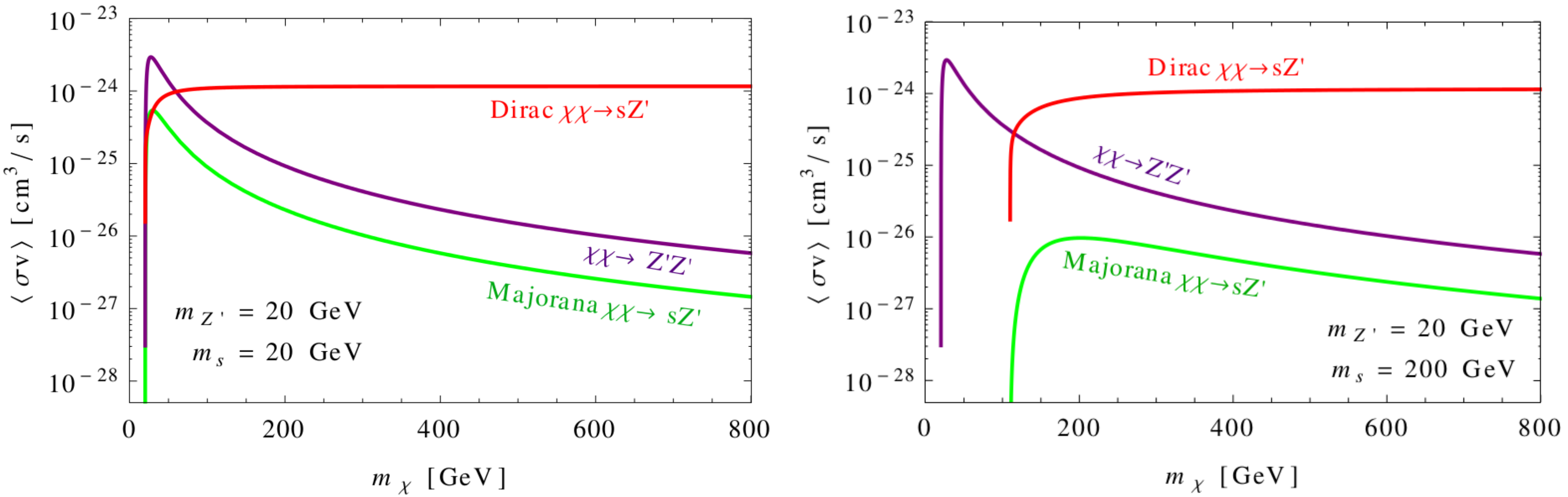
What happens when we consider the self-consistent dark sector?

Annihilation Processes

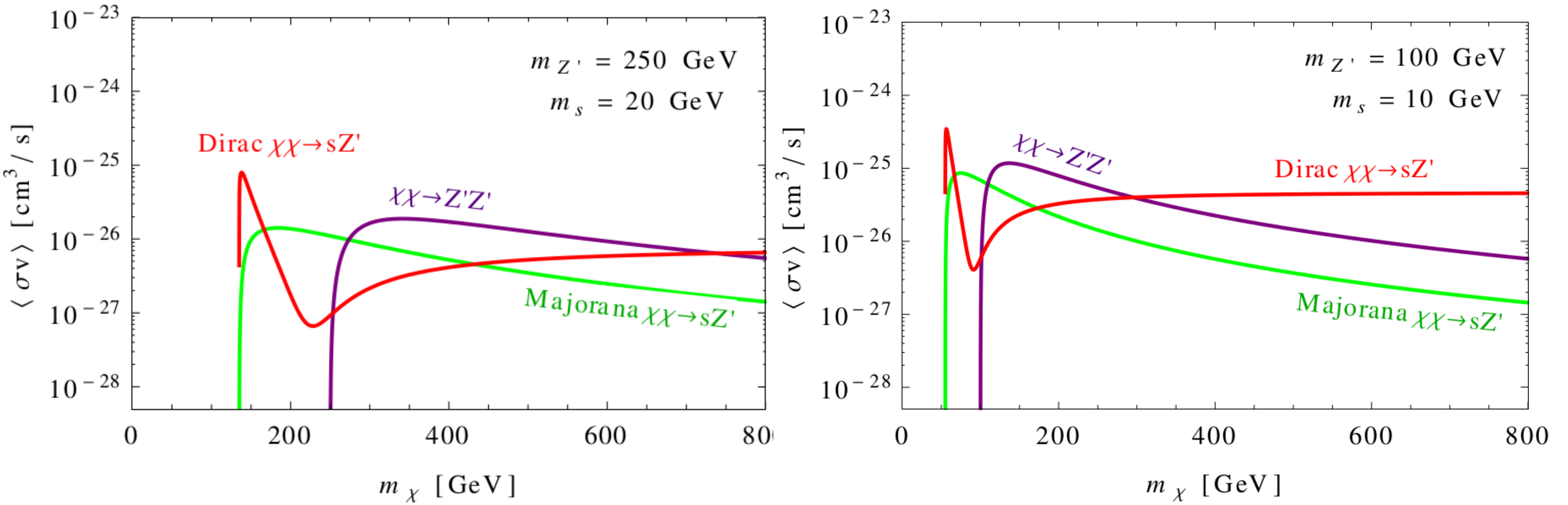


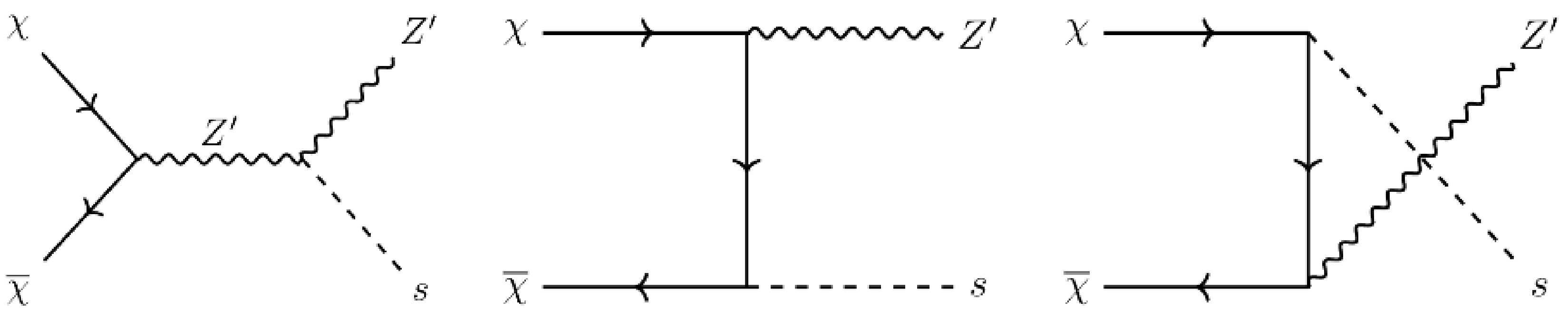
This opens up a new s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z', that is not ruled out by other exps.

Annihilation cross sections



Annihilation cross sections

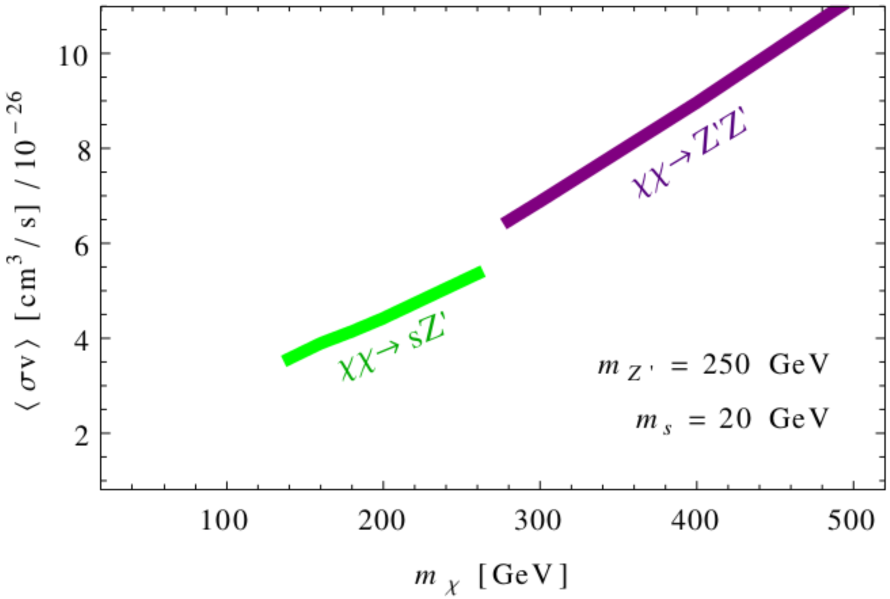


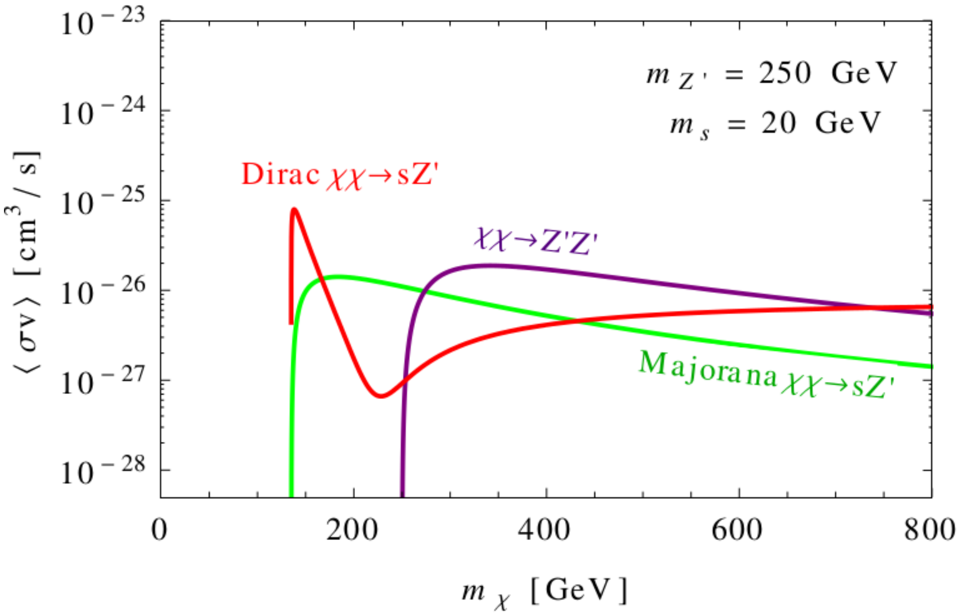


Indirect Detection Limits

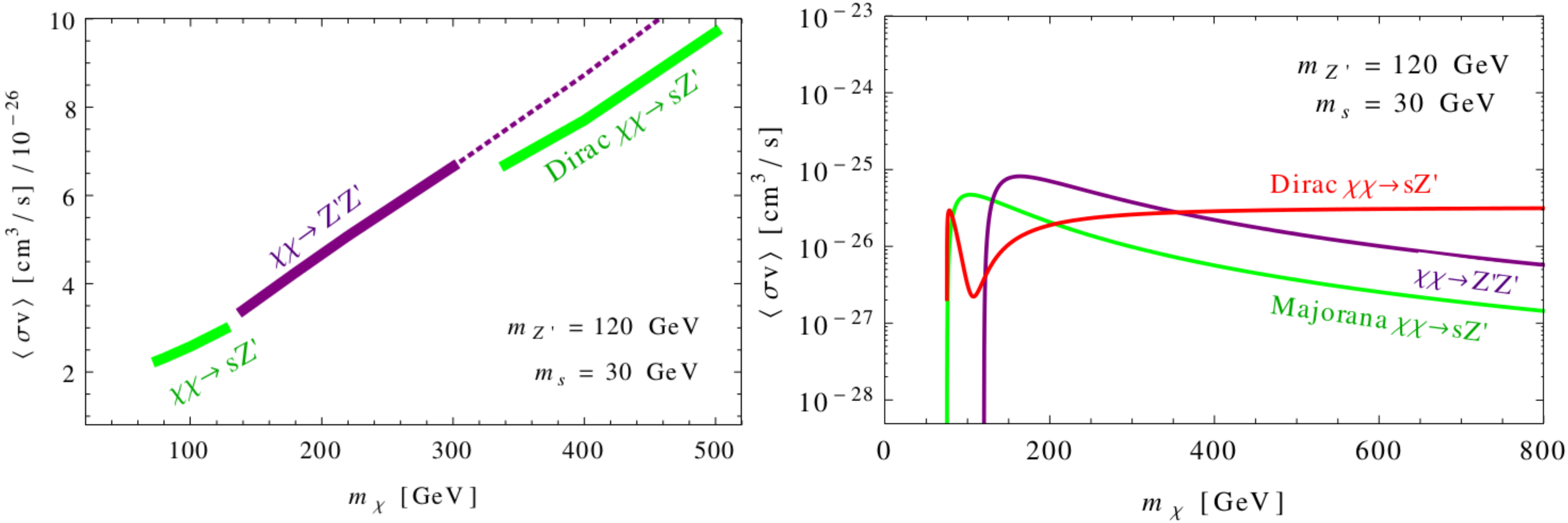
- For most of parameter space, strongest limits come from Fermi measurements of Dwarf Spheriodal Galaxies, most DM dense objects in our sky.
- At lower DM masses, and for electron positron final states, AMS-02 can provide stronger limits.

Indirect Detection Limits





Indirect Detection Limits



Other Limits?

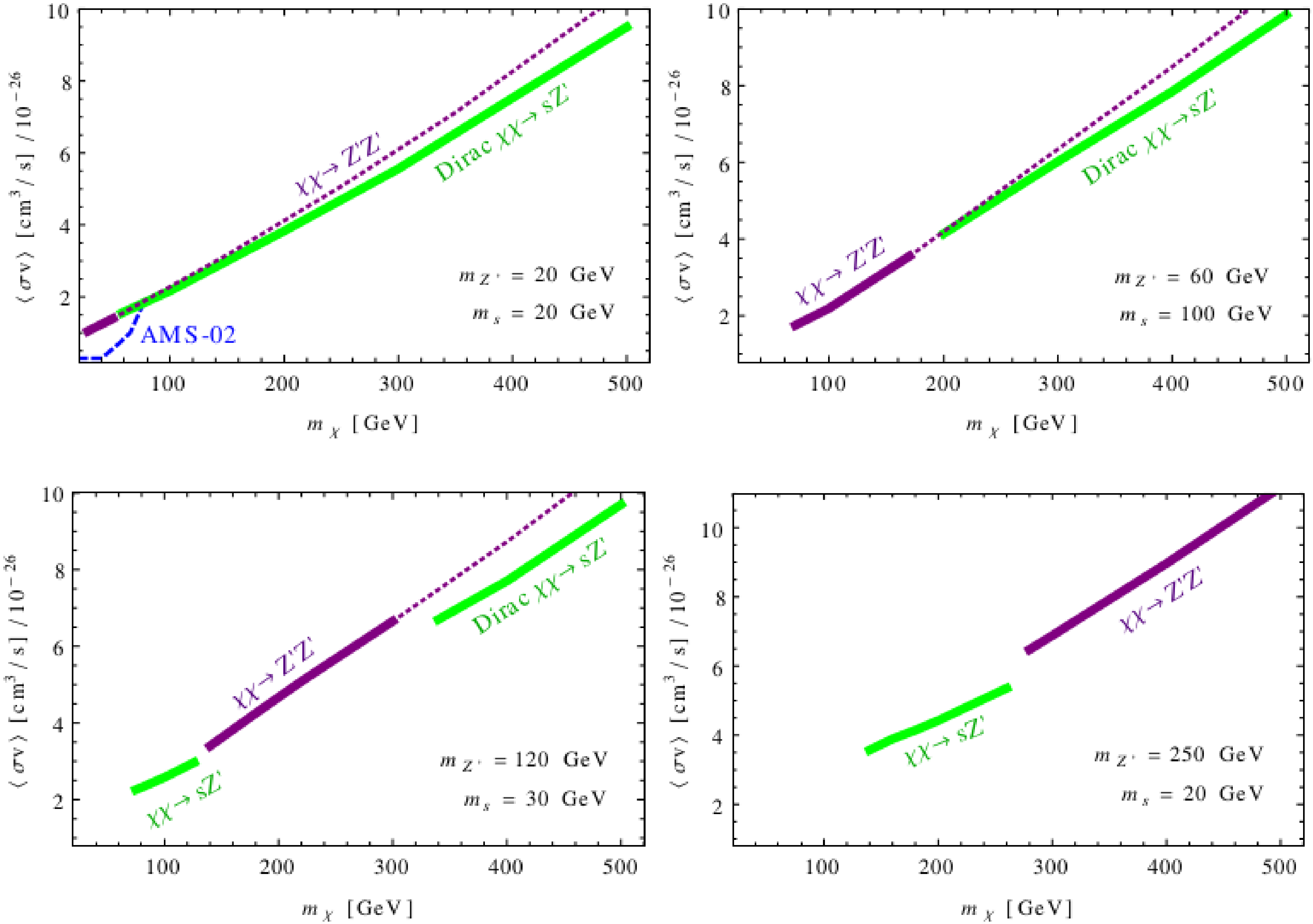
- Small couplings between the dark and visible sector… almost vanishing!
- Can effectively remove direct detection and collider bounds.
  - Given WIMP DM is becoming increasingly constrained, this is also nicely motivated.
- Can't have arbitrarily small couplings, as need the mediator to decay quickly enough to avoid BBN bounds.

Summary

- Simplified models are a popular framework for setting limits on the properties of DM.
- However, they are not intrinsically capable of capturing the full phenomenology of UV complete theories.
- In fact, it can be inconsistent to consider benchmarks separately, and Majorana DM it is necessary to include the scalar in the theory.
- Leads to interesting phenomenology: previously unconsidered s-wave process, which for some couplings can dominate the annihilation rate.
- Also allows the properties of the scalar to be probed in this context with comparable strength to the vector.

Back up slides

Indirect Detection Limits



Unitarity Bounds

$$\sqrt{s} < \frac{\pi m_{Z'}^2}{g_\chi^2 m_\chi}$$

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

Parameters in the theory are all related to each other. Need to ensure sensible choices are made to avoid unitarity problems, i.e. Yukawas:

$$m_{Z'} = g_\chi w,$$
$$m_\chi = \frac{1}{\sqrt{2}} w y_\chi, \qquad y_\chi = \frac{\sqrt{2} g_\chi m_\chi}{m_{Z'}}.$$