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

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In collaboration with Nicole Bell and Yi Cai

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ARC Centre of Excellence for Particle Physics at the Terascale

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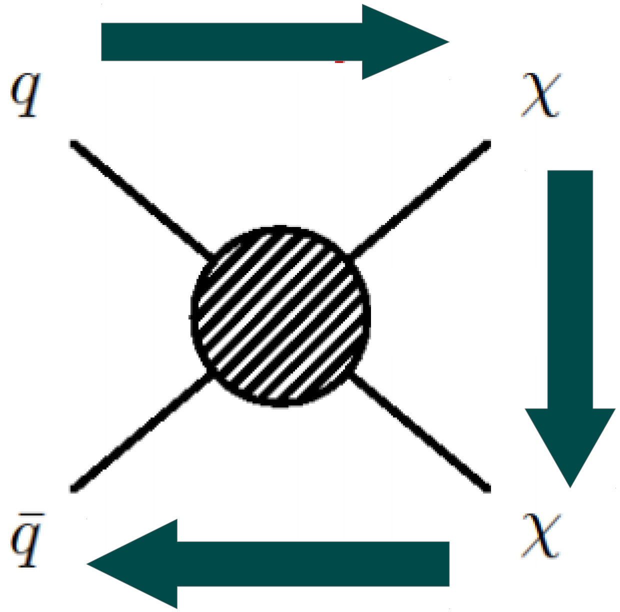
What is dark matter?

- Still no idea about fundamental nature
- WIMP dark matter well motivated
- Realistic detection prospects

Collider searches

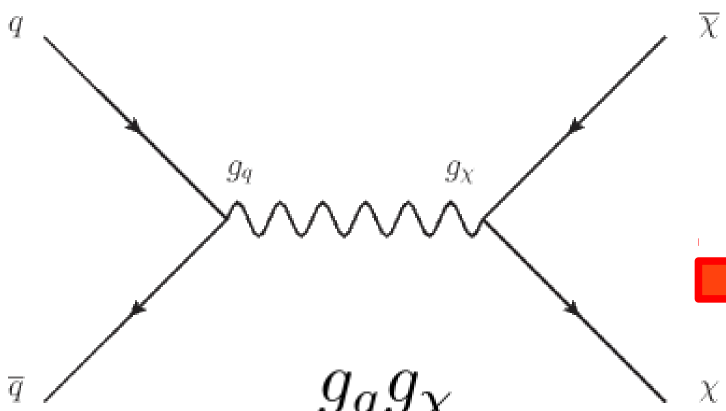


Direct detection

Indirect detection

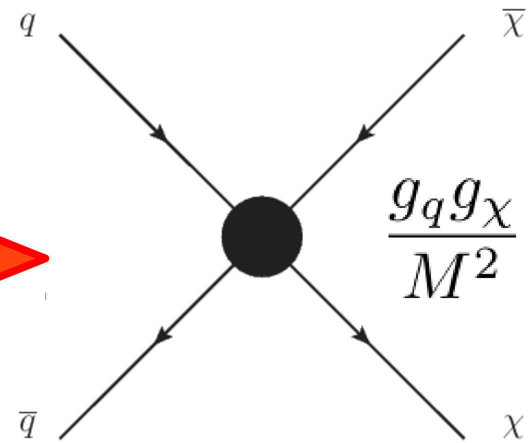
Searches provide complementary information

Simplified Models vs. EFTs



$$\frac{g_q g_\chi}{p^2 - M^2}$$

$$M^2 \gg p^2$$

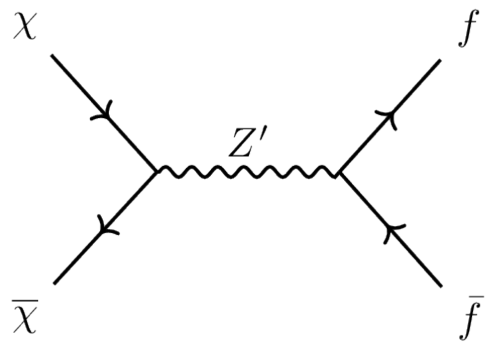


$$\frac{g_q g_\chi}{M^2} = -\frac{1}{\Lambda^2}$$

$$\frac{1}{\Lambda^2}\left(\overline{\chi}\Gamma_\chi \chi\right)\left(\overline{f}\Gamma_f f\right)$$

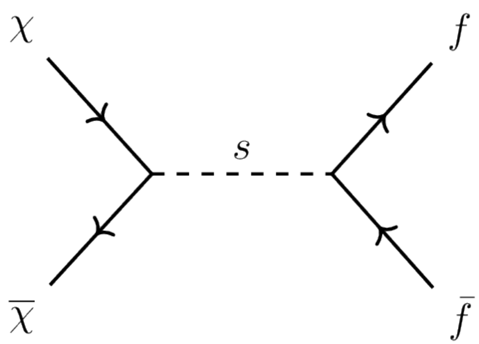
- Both fairly model independent
- EFTs useful at low energies only, SMs ok for a larger range
- Simplified models are becoming the norm for DM searches

Standard Simplified Models

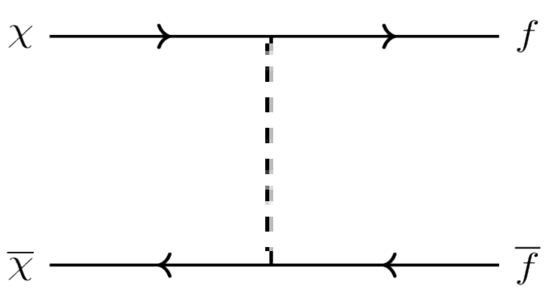


$$\mathcal{L}_{\mathrm{vector}} = g_{\mathrm{q}} \sum_{q=u,d,s,c,b,t} Z'_{\mu}\bar{q}\gamma^{\mu}q + g_{\chi}Z'_{\mu}\bar{\chi}\gamma^{\mu}\chi$$

$$\mathcal{L}_{\mathrm{axial-vector}} = g_{\mathrm{q}} \sum_{q=u,d,s,c,b,t} Z'_{\mu}\bar{q}\gamma^{\mu}\gamma^{5}q + g_{\chi}Z'_{\mu}\bar{\chi}\gamma^{\mu}\gamma^{5}\chi.$$



$$\begin{aligned}
\mathcal{L}_{\phi} &= g_{\chi}\phi\bar{\chi}\chi + \frac{\phi}{\sqrt{2}}\sum_{i}\left(g_{u}y_{i}^{u}\bar{u}_{i}u_{i} + g_{d}y_{i}^{d}\bar{d}_{i}d_{i} + g_{\ell}y_{i}^{\ell}\bar{\ell}_{i}\ell_{i}\right), \\
\mathcal{L}_{a} &= ig_{\chi}a\bar{\chi}\gamma_{5}\chi + \frac{ia}{\sqrt{2}}\sum_{i}\left(g_{u}y_{i}^{u}\bar{u}_{i}\gamma_{5}u_{i} + g_{d}y_{i}^{d}\bar{d}_{i}\gamma_{5}d_{i} + \right. \\
&\left. g_{\ell}y_{i}^{\ell}\bar{\ell}_{i}\gamma_{5}\ell_{i}\right).
\end{aligned}$$

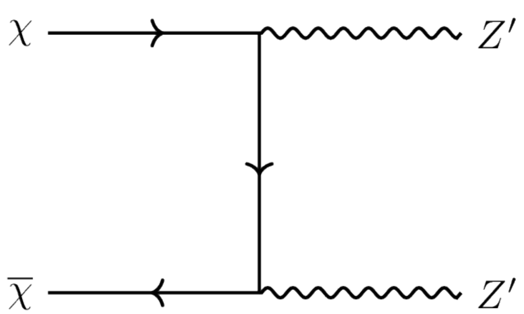


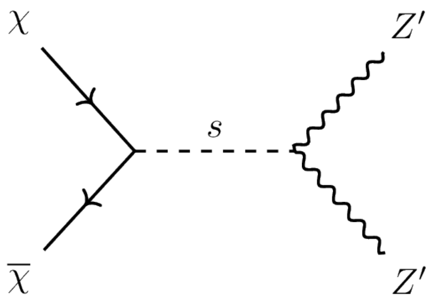
$$\mathcal{L}_{\mathrm{int}} = g \sum_{i=1,2} (\phi_{(i),L}\bar{Q}_{(i),L} + \phi_{(i),u,R}\bar{u}_{(i),R} + \phi_{(i),d,R}\bar{d}_{(i),R})\chi$$

...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:

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

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?

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$$+ \left[(\partial^\mu + ig_\chi Z'^\mu)S\right]^\dagger\left[(\partial_\mu + ig_\chi Z'_\mu)S\right] + \mu_s^2 S^\dagger S + \lambda_s(S^\dagger S)^2 + \lambda_{hs}(S^\dagger S)(H^\dagger H)$$

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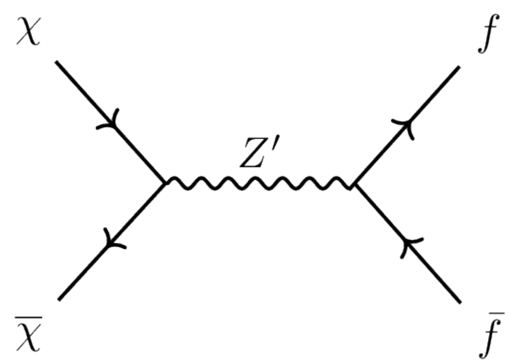
$$- g_\chi^2 w Z'^\mu Z'_\mu s + \lambda_s w s^3 + 2\lambda_{hs}(hvs^2 + swh^2) + g_f\sum_f Z'^\mu\overline{f}\Gamma_\mu f,$$

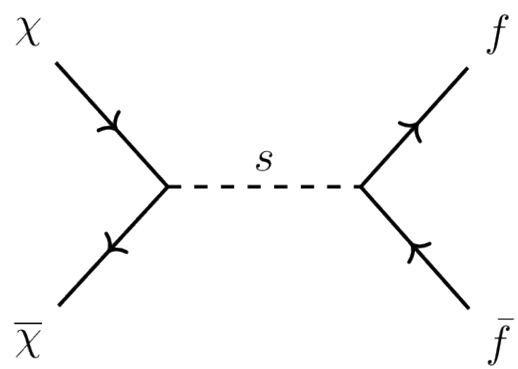
$$m_{Z'} = g_\chi w,$$
$$m_\chi = \frac{1}{\sqrt{2}}wy_\chi, \qquad y_\chi = \frac{\sqrt{2}g_\chi m_\chi}{m_{Z'}}.$$

Indirect Detection with Simplified Models

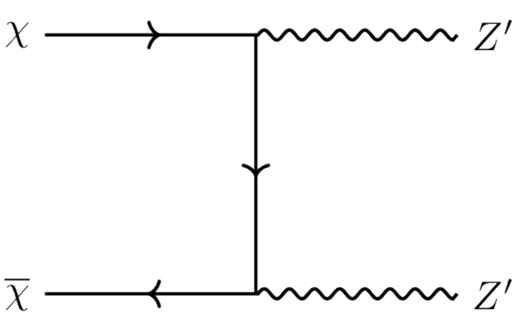
In universe today, only s-wave contributions to the annihilation cross section are relevant. P-wave contributions are negligible, suppressed as DM velocity ~10^-6. Hidden on-shell models popular.

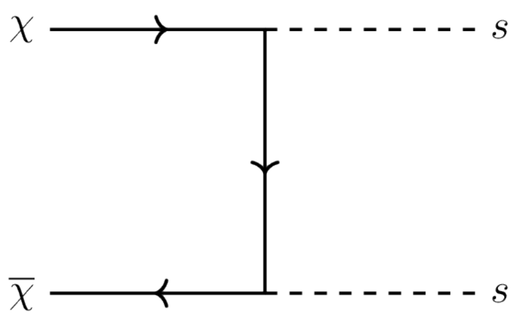
The following have been considered in the past for fermionic DM:

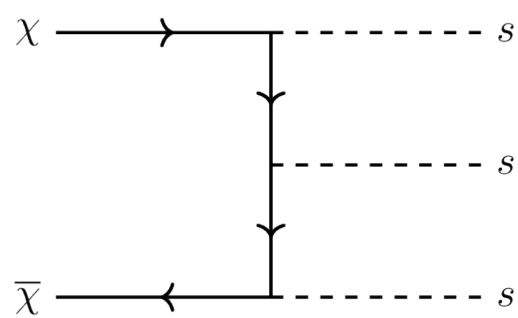




$$\sigma v = a + b v^2 + \cdots$$

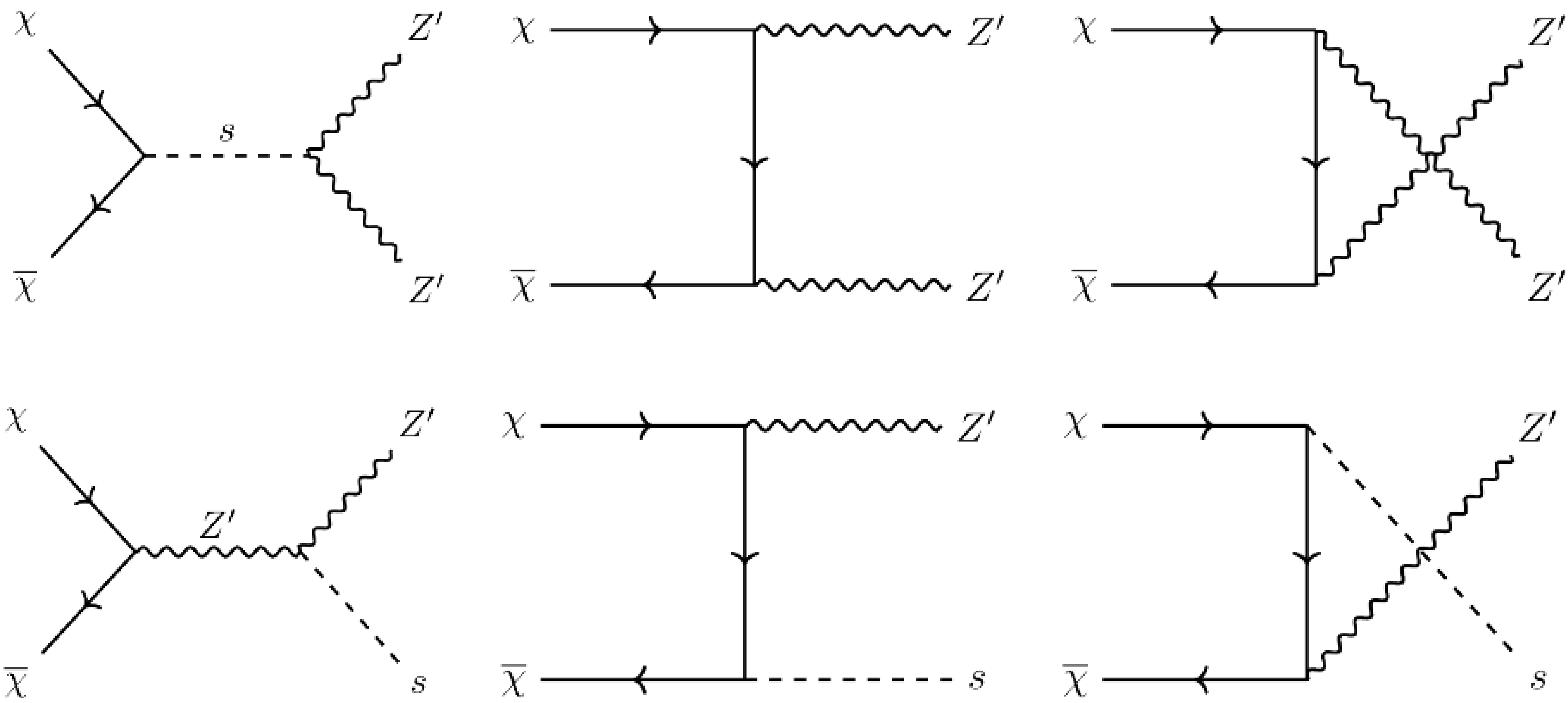






What happens when we consider the self-consistent dark sector?

Annihilation Processes

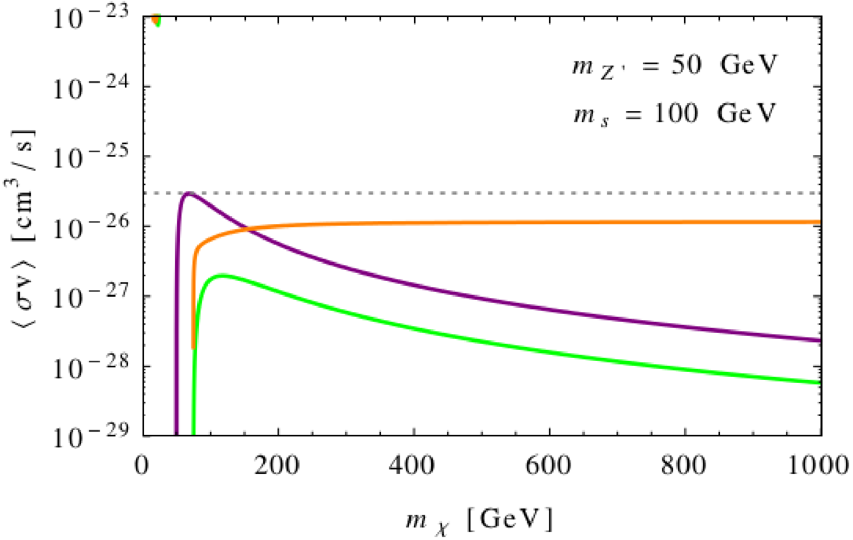


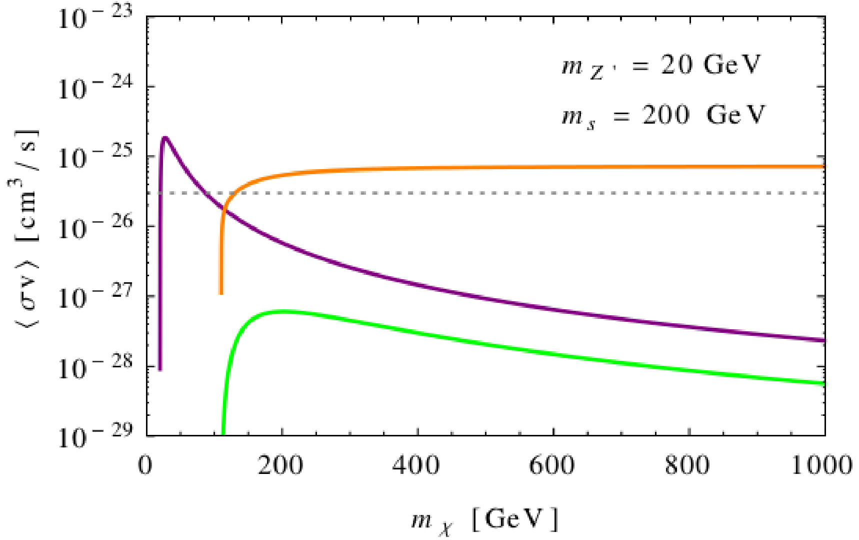
This opens up a new s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z', that is not ruled out by other exps.

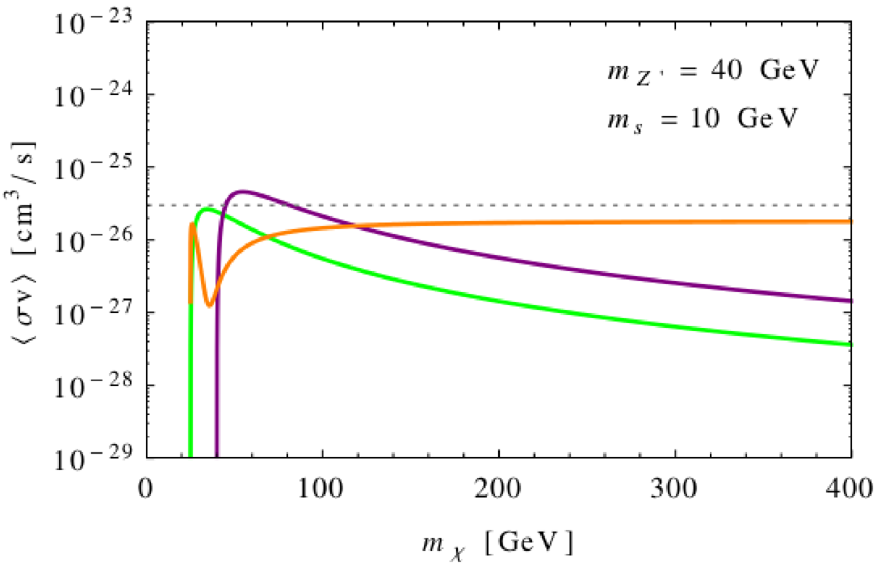
So we know we have a new s-wave process….

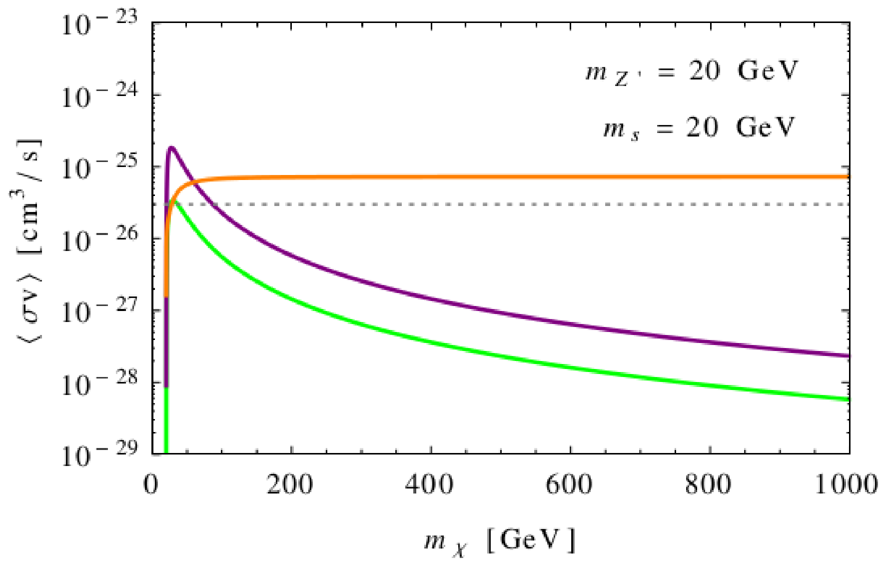
but how large is its annihilation rate?

Annihilation cross sections

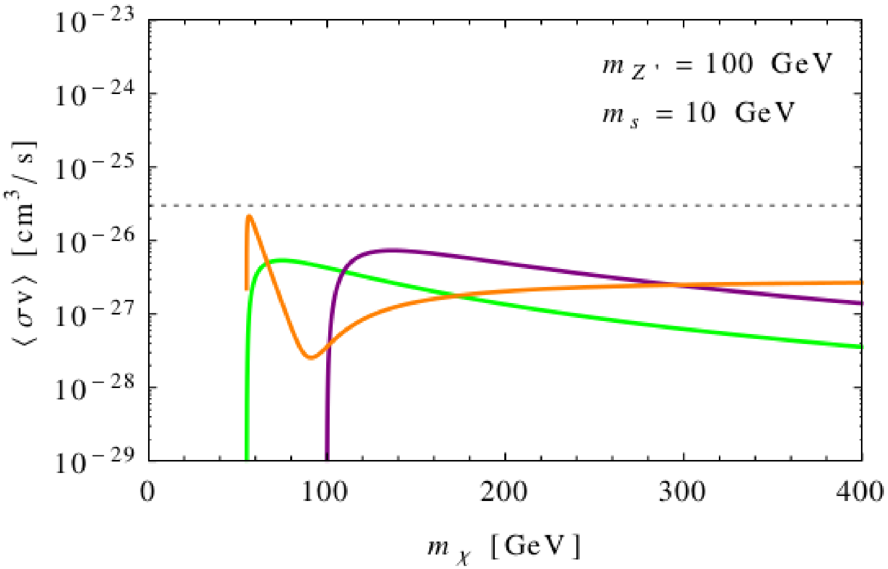


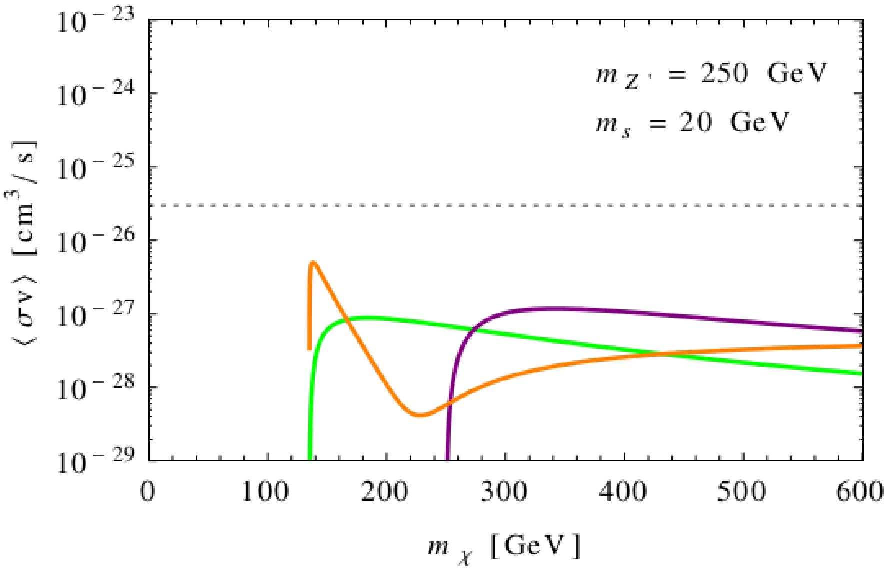


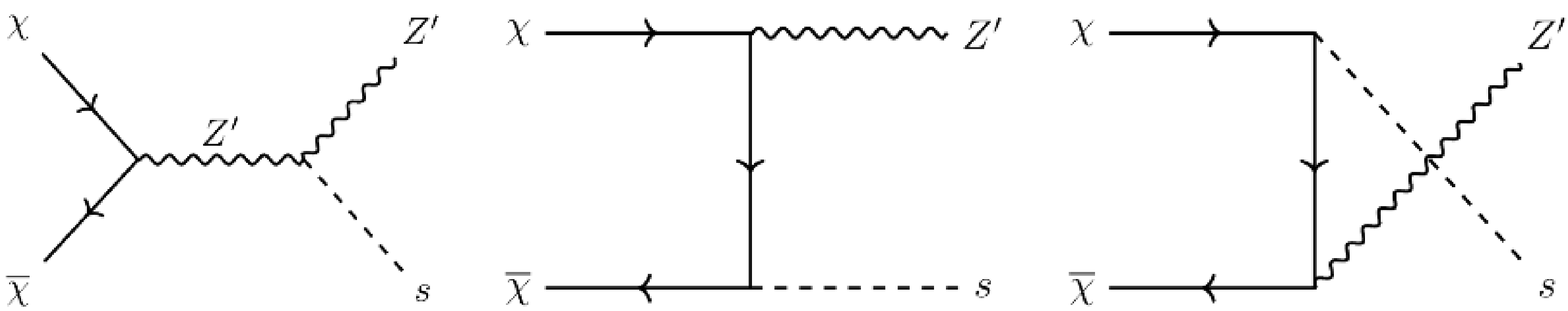




Annihilation cross sections







Indirect Detection Limits

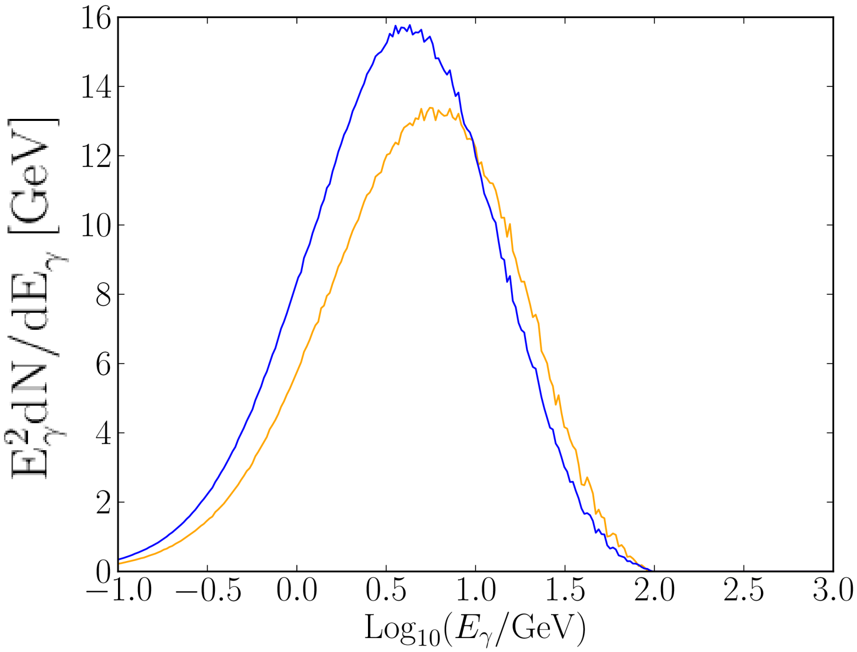
- Dwarf Spheriodal Galaxies, most DM dense objects in our sky.
- Can't just take existing limits on the cross section due to different final states, generate spectra ourselves, compare to Fermi data and find limits.

- AMS-02 limits for electron final states very strong. Only dominates in low DM mass region and is approximately flat here, so we take the cascade limits previously found.

The Energy Spectra

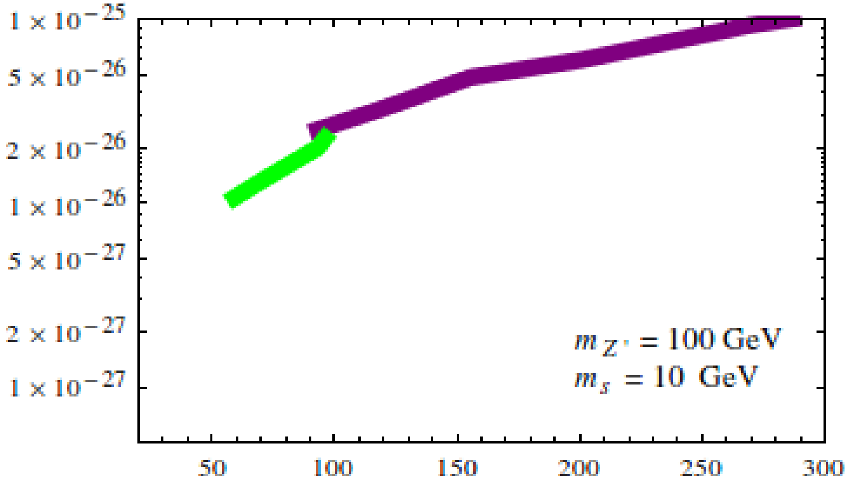
Generate in Pythia, make effective resonance in particle CoM frame, then average the separate spectra.

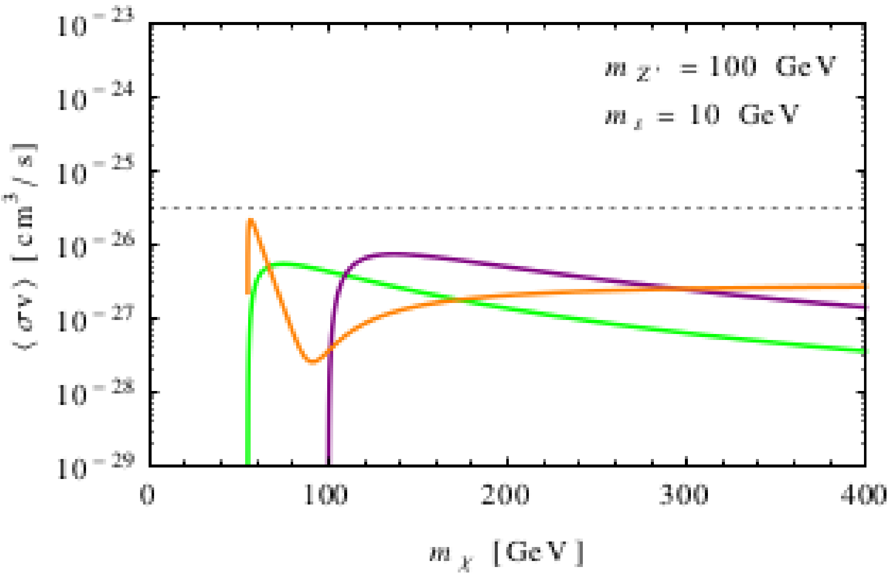
Right: Mixed final states blue, pure Z'Z' in orange.



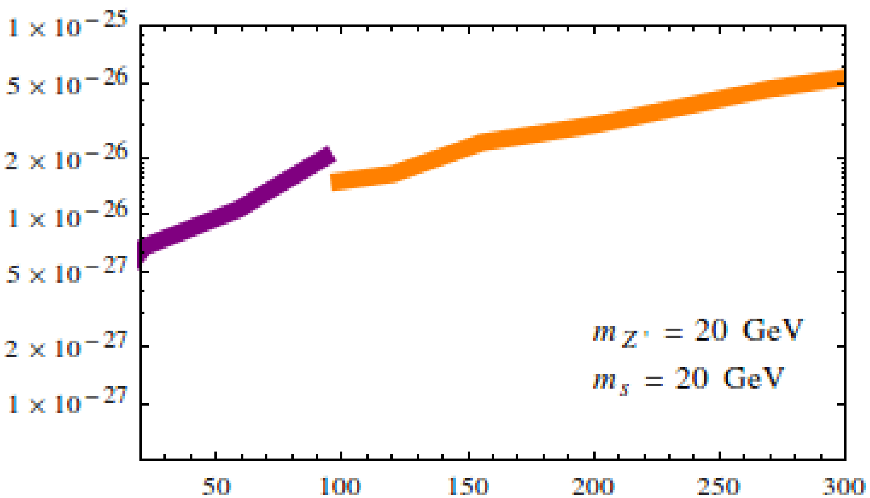
$$E_{1\mathrm{cm}} = \frac{s + m_1^2 - m_2^2}{2\sqrt{s}}, \qquad E_{2\mathrm{cm}} = \frac{s + m_2^2 - m_1^2}{2\sqrt{s}}$$

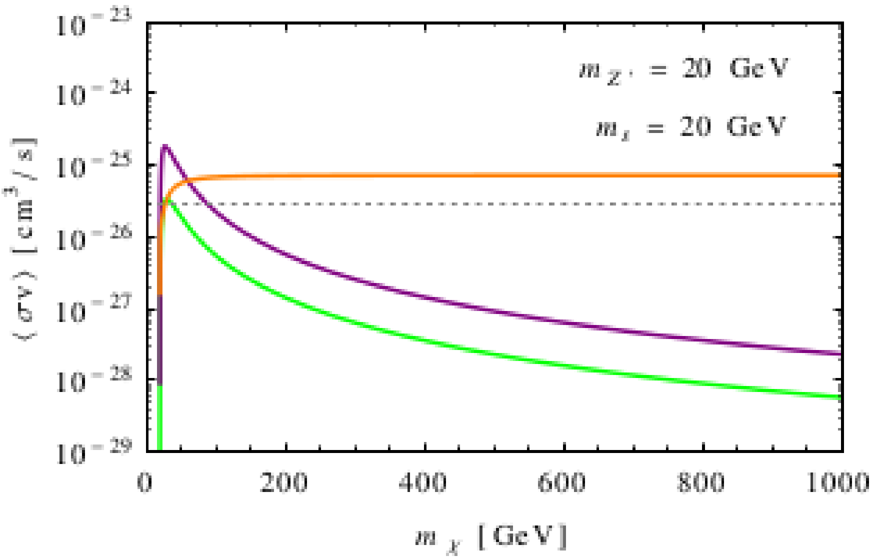
Majorana DM Limits





Dirac DM 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 within the lifetime of the galaxy, also needs 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. Different shaped spectra can also lead to stronger cross section limits.
- Also allows the properties of the scalar to be probed in this context with comparable strength to the vector!