Novel Signatures of Dark Matter in the Sky

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Based on 1605.09382*, 1610.03063*, 1612.xxxxx†

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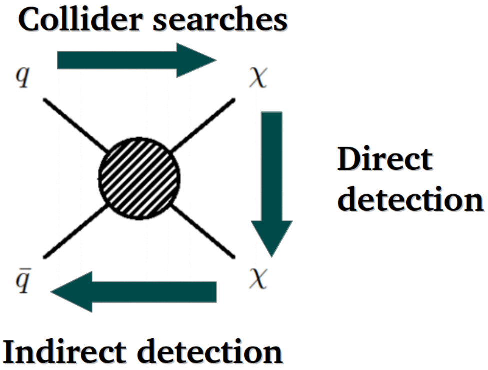
CoEPP

Probing the nature of dark matter

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

Searches provide complementary information



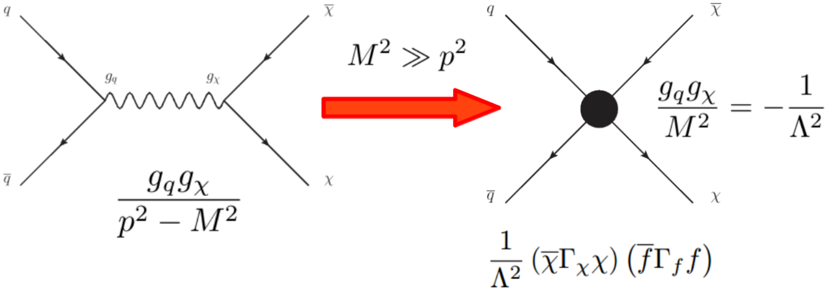
Past and present work

New physics at colliders:

- Mono-W Dark Matter Signals at the LHC: Simplified Model Analysis, JCAP, 1512.00476
- Dark matter at the LHC: Effective field theories and gauge invariance, PRD, 1503.07874
- Leptophilic dark matter with Z' interactions, PRD, 1407.3001

Astrophysical searches for new physics:

- Dark Bremsstrahlung as the Dominant Dark Matter Annihilation Channel, 1612.xxxxx
- Powerful Solar Signatures of Long-Lived Dark Mediators, 1612.xxxxx
- Impact of Mass Generation for Simplified Dark Matter Models, Submitted to JCAP, 1610.03063
- Dark Forces in the Sky: Signals from Z' and the Dark Higgs, JCAP, 1605.09382



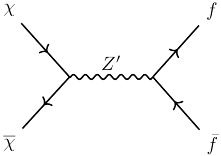
- Model independent
- Useful at low energies, i.e. direct detection
- Colliders? Need to be careful...

Simplified Models for Dark Matter

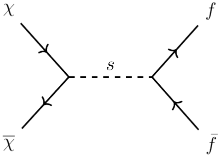
- Only lightest mediator is retained, set limits on couplings and mediators
- Allows for richer phenomenology

Benchmark Simplified Models:

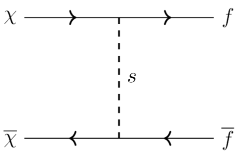
s-channel spin-1



s-channel spin-0



t-channel spin-0

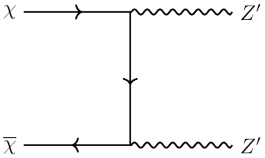


...this can run into problems!

- Not intrinsically capable of capturing full phenomenology of UV complete theories
- Separate consideration of these benchmarks can lead physical problems and inconsistencies
  - Results may not map to any viable model!
- To avoid this, important to consider minimal ingredients of gauge invariant models, ensuring valid interpretation of experimental data

Issues with Spin-1 Simplified Models

Consider the high energy production of longitudinal Z' bosons:



$$\epsilon_L^\mu(k) = k^\mu / m_{Z'}$$

violates unitarity at high energies, for axial-vector Z'-DM couplings.

Kahlhoefer et al, 1510.02110

Issues with Spin-1 Simplified Models

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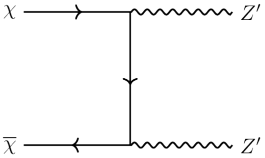

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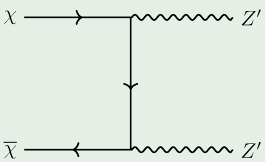
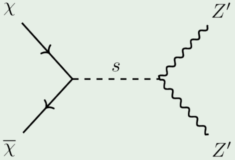




Bad high energy behaviour cancelled by additional scalar!

Issues with Spin-1 Simplified Models

Consequences for both Majorana and Dirac DM.

For Majorana DM, vector current is vanishing, leaving pure axial-vector interactions.

** Inclusion of the dark Higgs is unavoidable! **

Furthermore, can't write down Majorana mass term without breaking the $U(1)_\chi$ symmetry.

Minimal Simplified Setup

New fields: Majorana DM candidate, χ, Spin-1 dark gauge boson, Z', Dark Higgs field S.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dark} + \mathcal{L}_{\rm mix}$$

$$\mathcal{L}_{\rm dark} = \frac{i}{2}\overline{\chi}\partial\!\!\!/\chi - \frac{1}{4}g_\chi Z'^\mu\overline{\chi}\gamma_5\gamma_\mu\chi - \frac{1}{2}y_\chi\left(\overline{\chi}_L^C\chi_L S + h.c.\right) + \left(D^\mu S\right)^\dagger\left(D_\mu S\right) - \mu_s^2 S^\dagger S - \lambda_s(S^\dagger S)^2$$

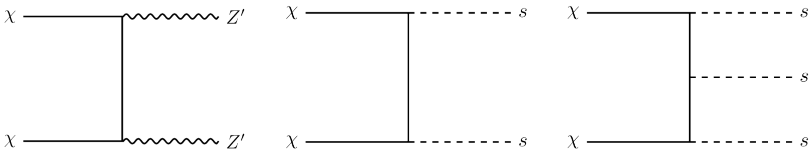
- S obtains a vev to give mass to χ and Z'
- $U(1)$ charges of χ and S related by gauge invariance: $Q_S = 2Q_\chi$
- Parameters tied together: $y_\chi/g_\chi = \sqrt{2}m_\chi/m_{Z'}$

$$\mathcal{L}_{\rm mix} = -\frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu} - \lambda_{hs}(S^\dagger S)(H^\dagger H)$$

Small mixing between dark and visible sectors allows mediators to decay.

Annihilation Processes: Standard Simplified Models

- To investigate phenomenology, focus on hidden sector models, where couplings to SM are small
- In universe today, only s-wave contributions to the annihilation cross section are relevant. P-wave contributions are negligible, suppressed as DM velocity $v_\chi^2 \approx 10^{-6}$



s-wave | p-wave | p-wave / phase space suppressed

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

Annihilation Processes: Self-Consistent Scenario

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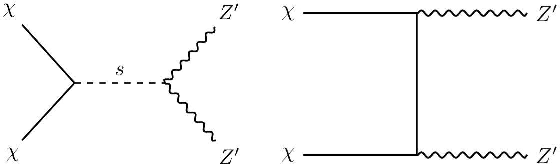
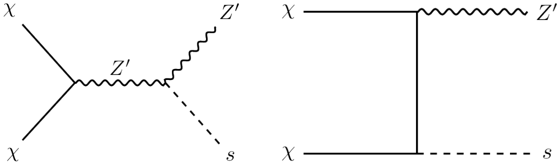
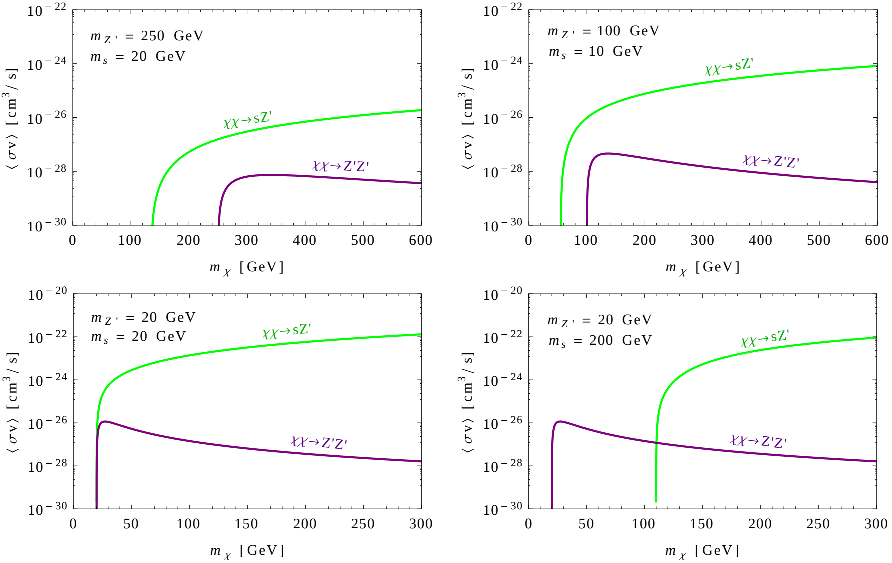


New addition to $\chi\chi \to Z'Z'$ process.



New s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z'.

Annihilation Processes: Comparison



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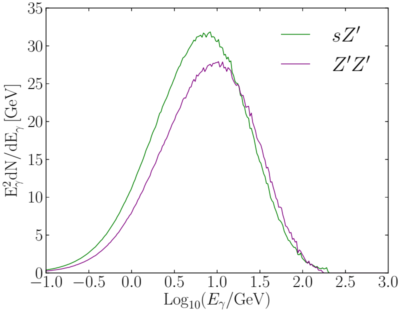
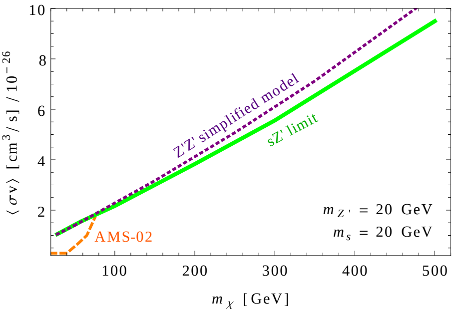
Indirect Detection Limits

- Best limits from Dwarf Spheriodal Galaxies, most DM dense objects in our sky
- Use PYTHIA to generate gamma-ray spectra, compare to Fermi Pass 8 data and find limits





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Linked to Dark Sector Mass Generation

Majorana DM:

- Pure axial-vector couplings to Z'
- Both DM and Z' masses arise from dark Higgs mechanism

Dirac DM:

- Both vector and axial-vector couplings possible
- If Z' has pure vector couplings:
  - Z' mass: either Higgs or Stueckelberg mechanism
  - DM mass: bare mass or Higgs mechanism
  - Mass generation mechanisms not necessarily connected
- If Z' has non-zero axial couplings:
  - Dark Higgs gives mass to both Z' and DM (like Majorana)

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Other Ingredients for DM Discovery?

- Correctly enforcing gauge invariance is key for DM models, leads to important phenomenology missed in "over-simplified" model approach
- Another important avenue is finding distinctive new signatures, exploiting strengths of different experiments

Complementary probe of the DM scattering cross section

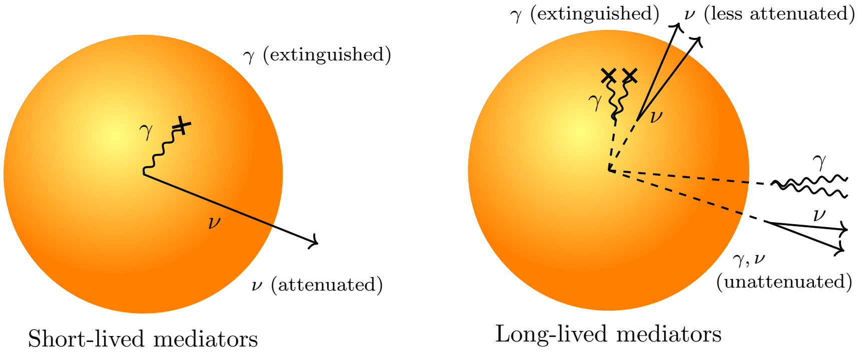
DM can be captured in the Sun by scattering with solar nuclei.

- Of possible DM annihilation modes, only neutrinos weakly interacting enough to escape
- These neutrinos are measured at SuperK and IceCube, provide probe of DM scattering cross section
- What if DM annihilates to long-lived mediators instead?

Solar Signatures of Long-lived Dark Mediators

If annihilation proceeds via long-lived dark mediators:

1. Neutrinos will be less attenuated
2. Other particles such as gamma-rays can escape



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Measuring gamma-rays with new Fermi-LAT data

Standard annihilation fluxes of DM to gamma-rays are enormous.
For example, if 100 GeV DM with scattering $\sigma_{\chi P}^{SD} \sim 10^{-40}\,\mathrm{cm}^2$ annihilates directly to gamma-rays, the energy flux is

$$\sim 10^{-2}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}.$$

In this region, the sensitivity of Fermi-LAT is

$$\sim 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}.$$

The annihilation flux is in excess of sensitivity by a factor of $\mathbf{10^6}$!

$\rightarrow$ Long-lived mediators open a window to otherwise lost DM signals, potentially large rates!

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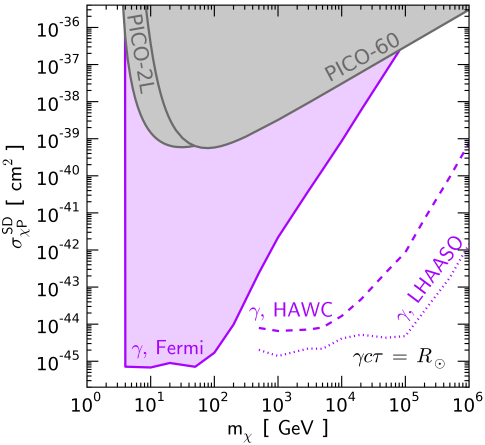
Can outperform direct detection exps by several orders of magnitude!



$$\chi\chi \to YY \to 2\gamma + 2\gamma$$

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Summary

Understanding the nature of DM is one of the foremost goals of the physics community. Important steps forward for discovery include:

Theoretically consistent models:

- Single mediator Simplified Models not always self-consistent
- Two mediators can be required by gauge invariance
  - Leads to different phenomenology
  - New s-wave process, which dominates the annihilation rate
  - Allows the scalar to be probed with comparable strength to the vector

New ways of exploiting complementarity of DM searches:

- DM annihilation to long-lived mediators in the Sun provides probe of DM scattering cross section
- Can outperform direct detection exps by several orders of magnitude

Backup slides

Long-lived dark mediator flux

$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\rm ann}}{4\pi D_\oplus^2} \times E^2 \frac{dN}{dE} \times {\rm Br}({\rm Y} \to {\rm SM}) \times P_{\rm surv}, \quad (1)$$

where

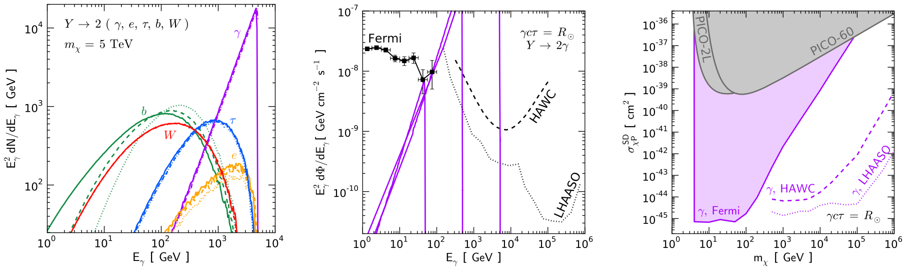
- $D_\oplus = 1$ A.U. is the distance between the Sun and the Earth
- $E^2 dN/dE$ is the particle energy spectrum per DM annihilation
- ${\rm Br}({\rm Y} \to {\rm SM})$ is the branching fraction of the mediator Y to SM particles
- $P_{\rm surv}$ is the probability of the signal surviving to reach the detector, given by

$$P_{\rm surv} = e^{-R_\odot/\gamma c\tau} - e^{-D_\oplus/\gamma c\tau}. \quad (2)$$

Need mediator Y to have sufficiently long lifetime τ or boost factor $\gamma = m_\chi/m_Y$, leading to a decay length L that exceeds the radius of the Sun, $R_\odot$, as

$$L = \gamma c\tau > R_\odot. \quad (3)$$

Gamma-ray limit procedure



$$\chi\chi \to YY \to 2\,(\,\mathrm{SM}+\mathrm{SM}\,) \to \ldots\gamma\ldots$$

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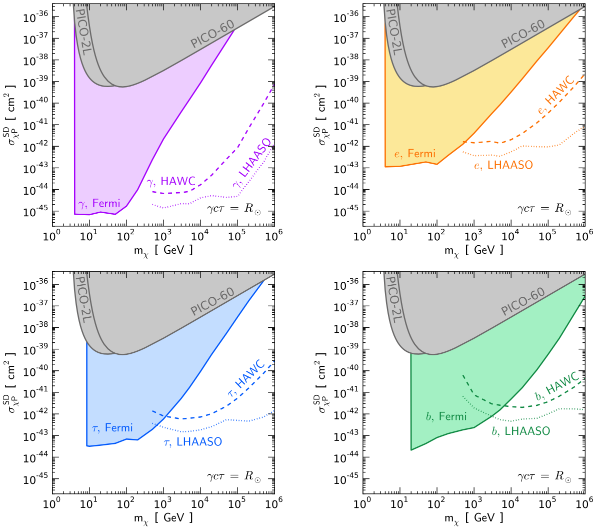
Gamma-ray limits



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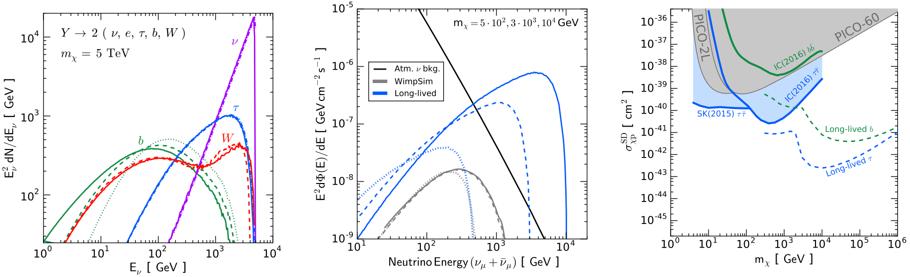
Neutrino limit procedure



$$\chi\chi \to YY \to 2\,(\,\mathrm{SM}+\mathrm{SM}\,) \to \ldots\nu\ldots$$

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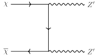
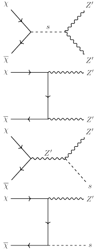
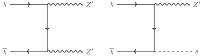
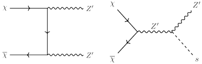
Long-lived dark mediator constraints

- **BBN:** The observed relic abundance of SM particles by BBN implies any new mediator must have lifetime τ which satisfies $\tau < 1$s.
- **CMB:** DM annihilation to SM products in the early universe is constrained by the CMB.
- **Supernovae:** Particularly for low mass mediators ($<$GeV), from mediator decay and supernova cooling.
- **Colliders:** If the dark sector is secluded, may be negligible. Otherwise, Belle, BaBar, ATLAS and CMS
- **Beam Dump/Fixed Target experiments:** Most relevant when the mediator has $\sim$sub-GeV mass. E137, LSND and CHARM
- **Other indirect detection signals:** Fermi-LAT and DES measurements of dSphs at low DM mass, and large positron signals can be constrained by AMS-02
- **Thermalization and Unitarity:** Issues with thermalization for > 10 TeV DM, and unitarity issues over $\mathcal{O}(100)$ TeV DM mass. Furthermore bound state effects at high DM mass.

Impact of Specifying Mass Generation

Scenario	χ mass	Z' mass	Required $\chi - Z'$ coupling type	Annihilation processes	Z' pol
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.		Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector		Z'_T
IV	Bare mass term	Dark Higgs mechanism	Vector		Z'_T

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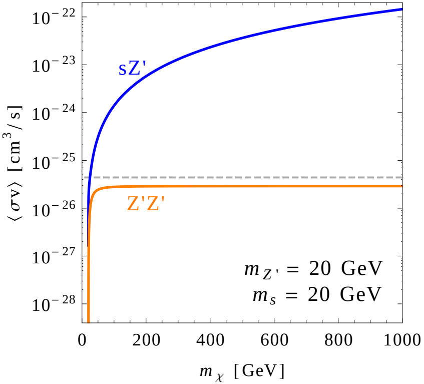
DM and Z' Mass from Dark Higgs



- Couplings related: $y_\chi/g_\chi = \sqrt{2}m_\chi/m_{Z'}$
- sZ' dominates over Z'Z' when kinematically allowed
- Cross sections enhanced by longitudinal Z' (for Z'Z' this only occurs when both vector and axial couplings are non-zero)

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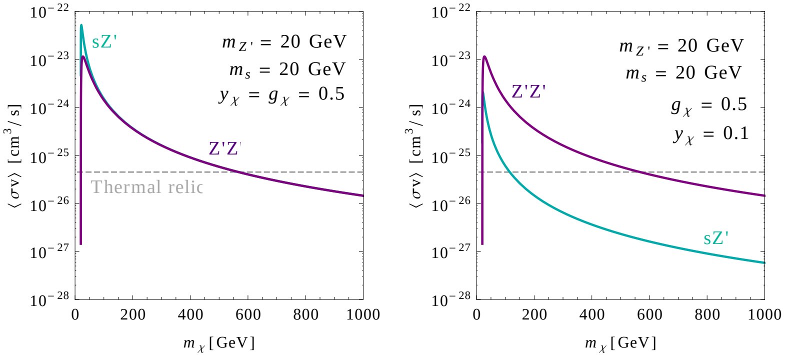
DM mass from Dark Higgs, Z' mass from Stueckelberg

- Gauge and Yukawa couplings no longer related, freedom in processes
- Z' is only transversely polarized



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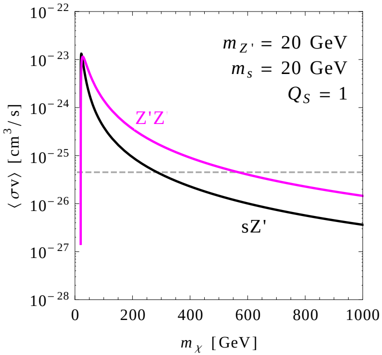
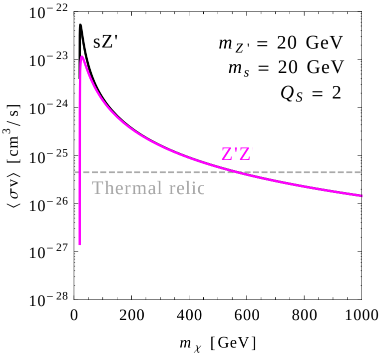
Bare DM Mass, Z' Mass from Stueckelberg

- Gauge and Yukawa couplings no longer related, $U(1)$ charges of Z' and dark Higgs unrelated
- Z' is only transversely polarized





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Two-Mediator Scenario: Charge Assignments

Yukawa term is

$$\mathcal{L}_{\text{Yukawa}} = -\left(y_\chi \overline{\chi}_R \chi_L S + h.c.\right), \tag{4}$$

and so the charges of the dark sector field must be chosen to satisfy

$$Q_{\chi_R} - Q_{\chi_L} = Q_S \ . \tag{5}$$

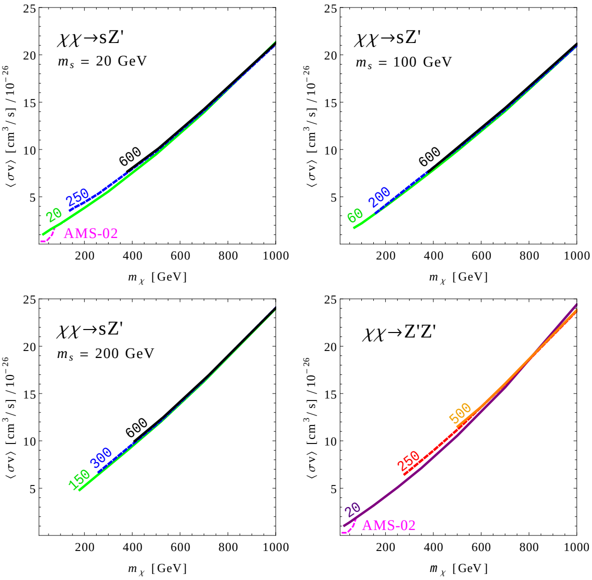
Set the dark Higgs charge to $Q_S = 1$. The χ charges therefore satisfy

$$Q_A \equiv \frac{1}{2}(Q_{\chi_R} - Q_{\chi_L}) = \frac{1}{2}, \tag{6}$$

$$Q_V \equiv \frac{1}{2}(Q_{\chi_R} + Q_{\chi_L}) = \frac{1}{2} + Q_{\chi_L}. \tag{7}$$

These charges determine the vector and axial-vector couplings of the Z' to the χ. Q_A is completely determined, while there is freedom to adjust Q_V by choosing $Q_{\chi_{L,R}}$ appropriately.

Two-Mediator Scenario: Indirect Detection Constraints



Lagrangian: Scenario I

In all scenarios, the gauge group is: $SM \otimes U(1)_\chi$, and so the the covariant derivative is $D_\mu = D_\mu^{SM} + iQg_\chi Z'_\mu$, where Q denotes the $U(1)_\chi$ charge.

Bare DM Mass, Z' Mass from Stueckelberg

This is the most minimal spin-1 setup, and no additional fields are introduced, as Z' obtains mass via Stueckelberg and DM is vectorlike so a bare mass term is allowed. The lagrangian is

$$\mathcal{L} = \mathcal{L}_{SM} + i\,\overline{\chi}(\partial_\mu + ig_\chi Q_V Z'_\mu)\gamma^\mu \chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} - m_\chi \overline{\chi}\chi + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu. \tag{8}$$

Lagrangian: Scenario II

In this scenario, the vev of the dark Higgs field provides a mass generation mechanism for the dark sector fields Z' and χ. Before electroweak and $U(1)_\chi$ symmetry breaking, the most general Lagrangian is

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{\chi}_L \not{D}\chi_L + i\overline{\chi}_R \not{D}\chi_R - (y_\chi \overline{\chi}_R \chi_L S + h.c.) - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} + (D^\mu S)^\dagger (D_\mu S) - \mu_s^2 S^\dagger S - \lambda_s (S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H). \quad (9)$$

After symmetry breaking, this becomes

$$\mathcal{L} \supset -\frac{1}{2} m_s^2 s^2 + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu - m_\chi \overline{\chi}\chi + g_\chi^2 w Z'^\mu Z'_\mu s - \lambda_s w s^3 - 2\lambda_{hs} h\, s(v\, s + w\, h) + g_f \sum_f Z'_\mu \overline{f} \Gamma_f^\mu f - g_\chi Q_V Z'_\mu \overline{\chi}\gamma^\mu \chi - g_\chi Q_A Z'_\mu \overline{\chi}\gamma^\mu \gamma_5 \chi - \frac{y_\chi}{\sqrt{2}} s \overline{\chi}\chi\,. \quad (10)$$

DM Mass from Dark Higgs, Z' Mass from Stueckelberg

The most minimal Lagrangian for this scenario is

$$\mathcal{L} = \mathcal{L}_{SM} \quad + \quad i\,\overline{\chi}\left(\partial\!\!\!/ + ig_\chi Q_V Z\!\!\!/'\right)\chi - \frac{y_\chi}{\sqrt{2}}\overline{\chi}\chi\phi - \frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu} \quad + \quad \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu_s^2\phi^2 - \frac{1}{4}\lambda_s\phi^4 - \frac{1}{2}\lambda_{hs}\phi^2(H^\dagger H), \tag{11}$$

with the real scalar $\phi = w + s$, where w is the vev of ϕ and s is the dark Higgs. The vectorlike charge Q_V can be chosen freely.

Lagrangian: Scenario IV

Bare DM Mass, Z' Mass from Dark Higgs

The most minimal gauge invariant Lagrangian is

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} + i\,\overline{\chi}\left(\not{\partial} + ig_\chi Q_V \not{Z}'\right)\chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} - m_\chi \overline{\chi}\chi \qquad (12)\\ &+ \left[(\partial^\mu + ig_\chi Q_S Z'^\mu)S\right]^\dagger \left[(\partial_\mu + ig_\chi Q_S Z'_\mu)S\right] - \mu_s^2 S^\dagger S\\ &- \lambda_s (S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H).\end{aligned}$$

The vectorlike charge Q_V and dark Higgs charge Q_S under the dark $U(1)_\chi$ can be chosen freely.

Unitarity bounds

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

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

Parameters related, sensible choices required to avoid unitarity problems:

$$m_{Z'} = g_\chi w$$

$$m_\chi = \frac{1}{\sqrt{2}} y_\chi w$$

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