Novel Signatures of Dark Matter in the Sky

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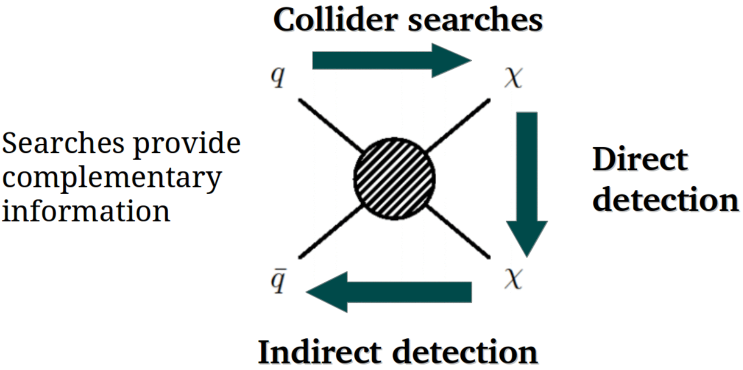
BSM Journal Club
September 15, 2017

Based on 1605.09382*, 1610.03063*, 1703.04629†, 1705.01105*⋆

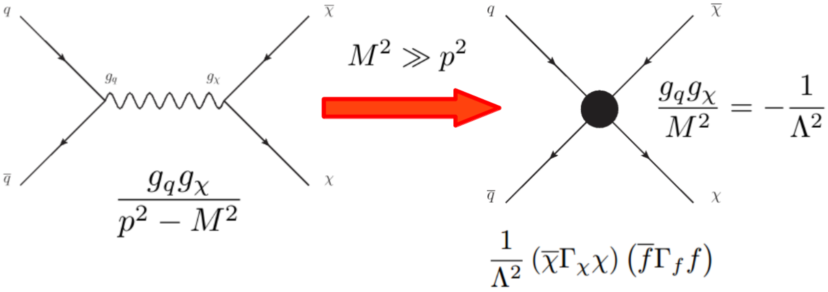
*with Nicole Bell and Yi Cai (⋆+ Dent and Weiler)
†with John Beacom and Kenny Ng

Probing the nature of dark matter

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



Effective Field Theories for Dark Matter



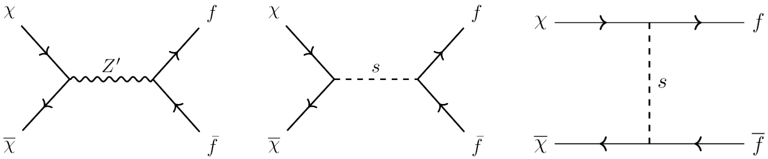
- Model independent
- Useful at low energies, i.e. direct detection
- Colliders? Need to be careful, cutoff at new physics scale. Violate perturbative unitarity, as $\sigma \sim E^2/\Lambda^4$

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

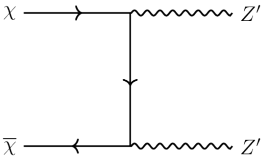


...this can run into problems!

- 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

Extend SM by additional $U(1)_\chi$.

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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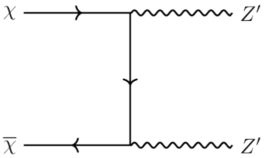

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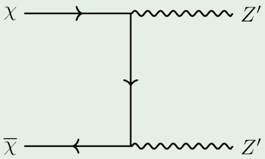

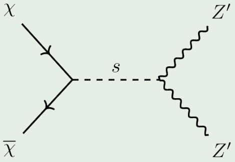

Bad high energy behavior canceled by additional scalar!

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.

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

For Dirac DM: axial-vector Z' interactions will yield same issues.

However, possible to have pure vector couplings to a Z'. Stueckelberg mechanism may give mass to the Z', and a bare mass term for the DM is possible.

Minimal Simplified Setup

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

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

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

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

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

- $U(1)_\chi$ charges of χ and S related by gauge invariance: $Q_S = 2Q_\chi$
- S obtains a vev, $\langle S\rangle = \frac{1}{\sqrt{2}}(\mathrm{w}+\mathrm{s}+i\mathrm{a})$, gives mass to χ and Z'
- Masses:

  $m_{Z'} = g_\chi \mathrm{w}$ $\quad m_\chi = \frac{1}{\sqrt{2}}y_\chi \mathrm{w}$ $\quad \rightarrow y_\chi/g_\chi = \sqrt{2}m_\chi/m_{Z'}$

How does this compare to simplified models?

Indirect Detection with Simplified Models

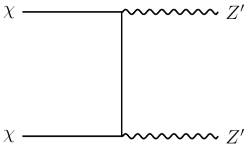
- In universe today, s-wave contributions to the annihilation cross section dominate where present. P-wave contributions usually negligible, suppressed as DM velocity $v_\chi^2 \approx 10^{-6}$

$$\sigma v = a + bv^2 + ...$$

- Collider and direct detection experiments $\rightarrow$ increasing tension between allowed DM parameters and the thermal WIMP paradigm

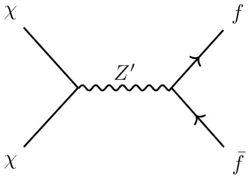
- Hidden on-shell models common approach to avoid such constraints.

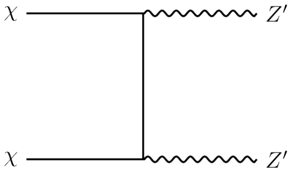
i.e. Abdullah et al, 1404.6528



Spin-1 mediator annihilation processes

For fermionic DM:



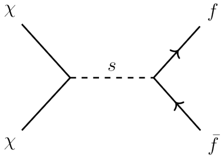


Vector: s-wave
Axial: s/p-wave

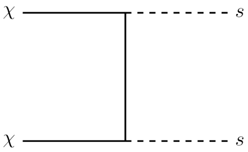
Always s-wave!

Spin-0 mediator annihilation processes

Analogous diagrams not quite the same.



Pseudoscalar: s-wave
Scalar: p-wave



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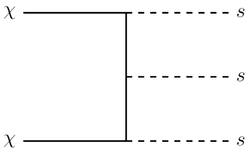
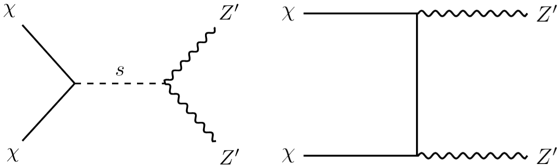


Pseudoscalar: s-wave
Scalar: p-wave

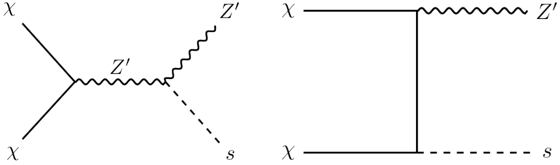
No s-wave diagram for scalars!

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

Annihilation Processes: Self-Consistent Scenario

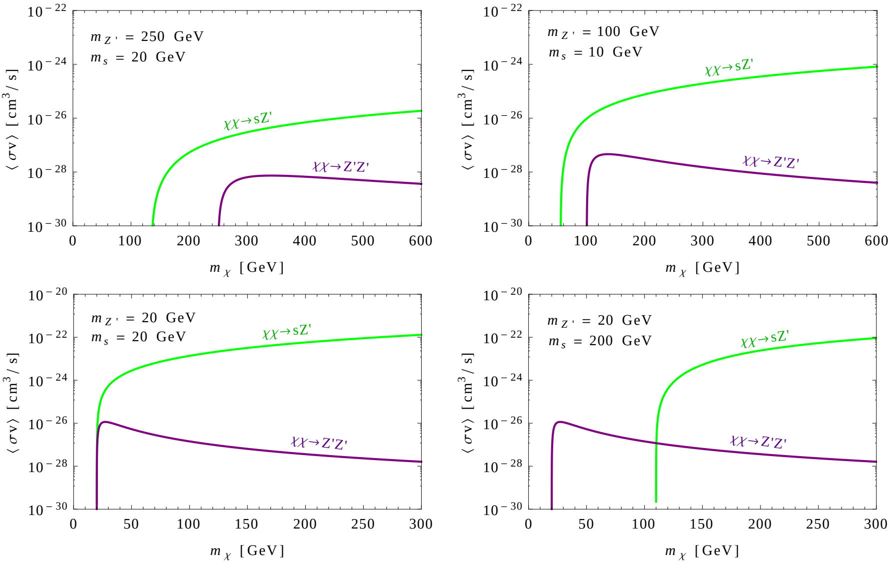


New addition to $\chi\chi \to Z'Z'$ process.



New s-wave annihilation process!
Further, this allows us to probe the nature of the scalar with comparable strength to the Z'. Bell, Cai, RKL, 1605.09382 (JCAP 2016)

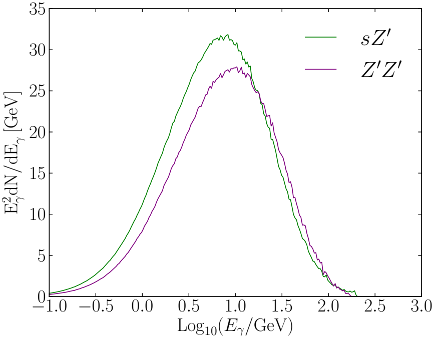
Annihilation Processes: Comparison



Bell, Cai, RKL, 1605.09382 (JCAP 2016)

Indirect Detection Limits

- Best limits from Dwarf Spheriodal Galaxies, most DM dense objects in our sky
- Mixed final states and different mediator masses
  - Use PYTHIA to generate gamma-ray spectra, compare to Fermi Pass 8 data and find annihilation limit



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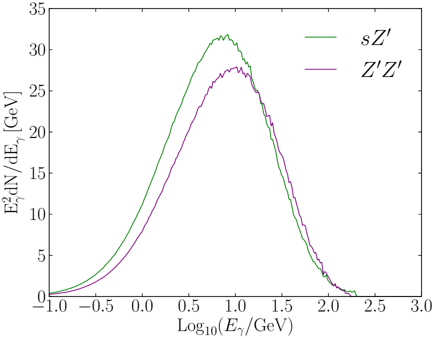
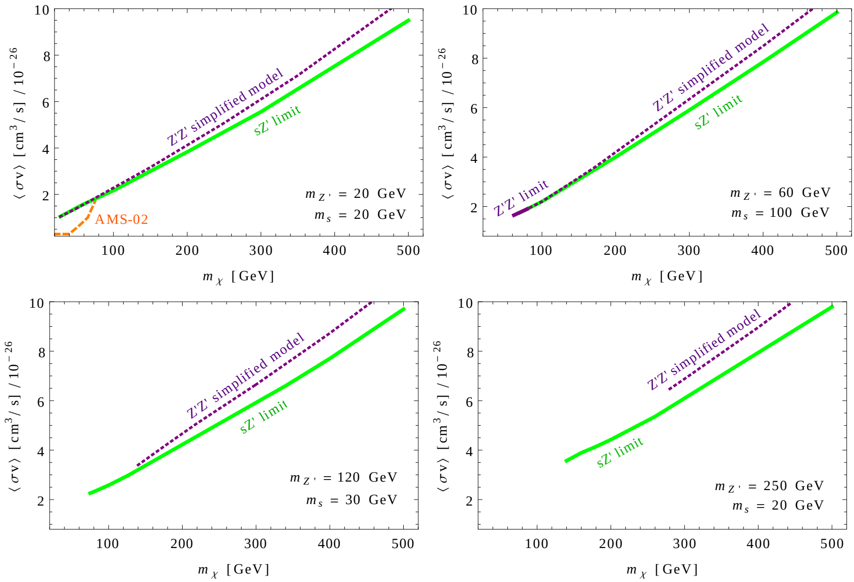


- AMS-02 limit: relevant for electron positron final states and lower DM masses, rough rescaled limit
- CMB: weaker than AMS-02 and dSphs

Indirect Detection Limits



Linked to Dark Sector Mass Generation

Majorana DM:

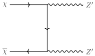
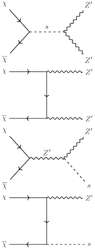
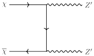
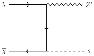
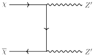
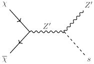
- Pure axial-vector couplings to Z'
- Both DM and Z' masses arise from dark Higgs mechanism

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)

Bell, Cai, RKL, 1610.03063 (JCAP 2017)

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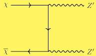
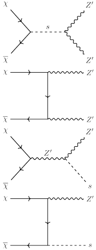
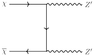
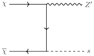
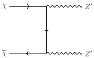
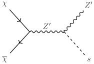
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.		Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism	Vector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

Scenario II

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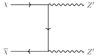
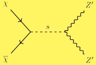
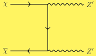
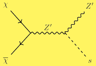
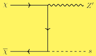
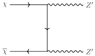
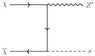
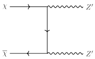
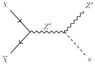
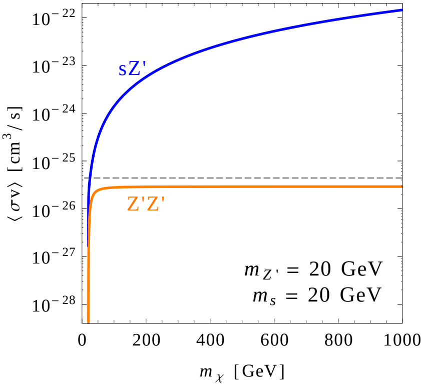
I	Bare mass term	Stueckelberg mechanism	Vector		Z'_T
II	Yukawa coupling to Dark Higgs	Dark Higgs mechanism	Non-zero axial-vector The $U(1)$ charge assignments of χ_L and χ_R determine the relative size of the V and A couplings.	   	Z'_T & Z'_L
III	Yukawa coupling to Dark Higgs	Stueckelberg mechanism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

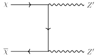
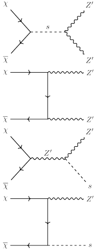
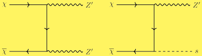
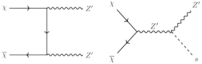
DM and Z' Mass from Dark Higgs



- 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)

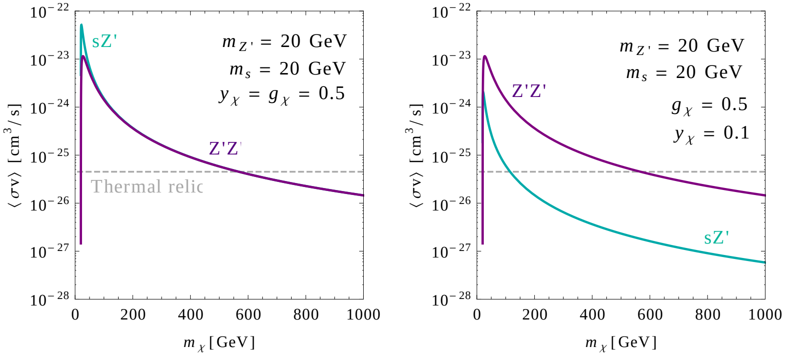
Bell, Cai, RKL, 1610.03063 (JCAP 2017)

Scenario III

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

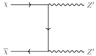
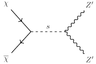
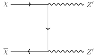
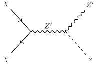
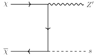
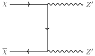
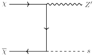
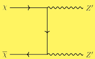
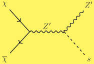
DM mass from Dark Higgs, Z' mass from Stueckelberg

- Gauge and Yukawa couplings no longer related, freedom in processes
- If $g_\chi \ll y_\chi$, p-wave processes such as $\chi\chi \to ss$ can be relevant
- Z' is only transversely polarized



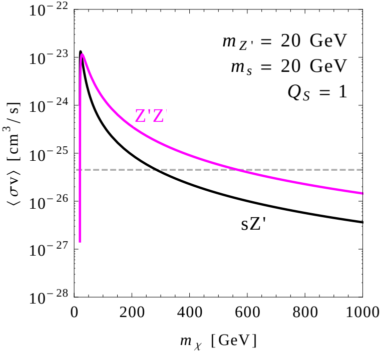
Bell, Cai, RKL, 1610.03063 (JCAP 2017)

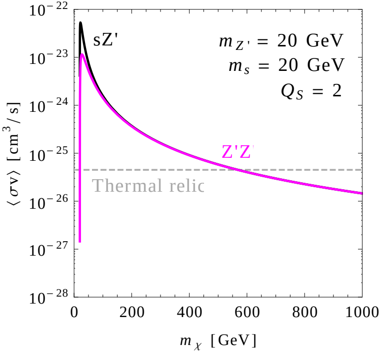
Scenario IV

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

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





Bell, Cai, RKL, 1610.03063 (JCAP 2017)

Two-mediator approach

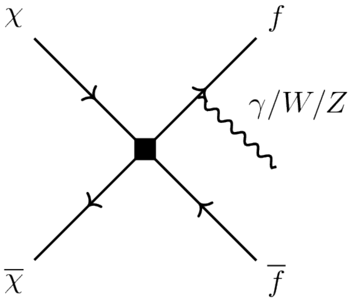
- Correctly enforcing gauge invariance is key for DM models, leads to important phenomenology missed in "over-simplified" model approach
- In general, can lead to interesting signatures for other models

Higher order processes for DM annihilation

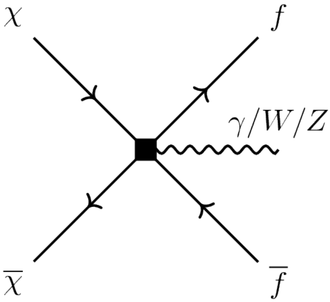
- To significally probe nature of DM, want unsuppressed annihilation mode
- In many interesting models, *s*-wave is absent or helicity suppressed
  - Indirect detection then unlikely, as p-wave suppression $\sim 10^{-6}$, helicity suppression $\sim (m_f/m_\chi)^2$
  - Dominant annihilation channel may be a higher order process

SM Bremsstrahlung Annihilation Processes

- Well known that helicity suppression in DM annihilation can be lifted with bremsstrahlung of a SM particle
- EM radiative corrections can give processes which dominate over lower level $\chi\overline{\chi} \rightarrow f\overline{f}$ *Bringmann et al, 0710.3169, 0808.3725*



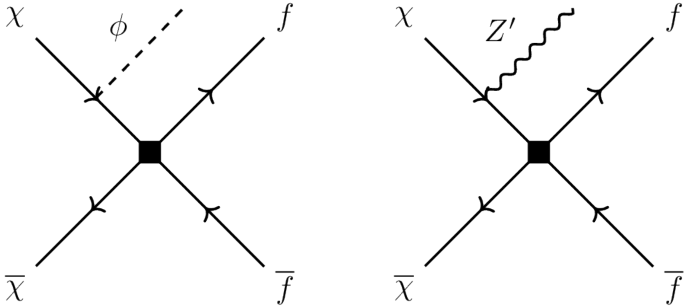
SM Final State Radiation (FSR)



SM Virtual Internal Bremsstrahlung (VIB)

Dark Initial State Radiation

- Dark radiative corrections from the inital state can lift helicity and *p*-wave suppression!
- Requires two dark mediators, common in renormalizable theories



Dark scalar ISR

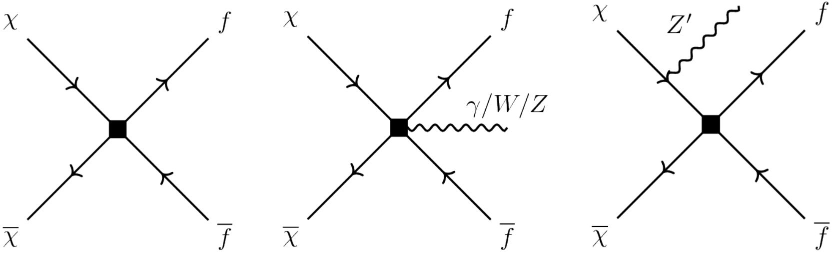
Dark vector ISR

Bell, Cai, Dent, RKL, Weiler, 1705.01105 (PRD 2017)

Dark ISR vs. SM VIB or FSR

Dark ISR lifts suppression at lower order than SM VIB or FSR processes!

$$\mathcal{L} \supset \frac{1}{\Lambda^2}(\chi\Gamma_\chi\overline{\chi})(f\Gamma_f\overline{f})$$



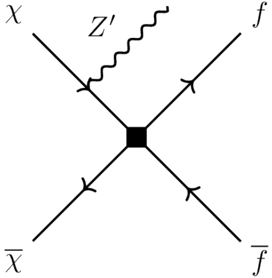
$2 \to 2$	SM FSR/VIB	Dark ISR
$\langle \sigma v \rangle \propto 1/\Lambda^4$	$\langle \sigma v \rangle \propto 1/\Lambda^8$	$\langle \sigma v \rangle \propto 1/\Lambda^4$

Bell, Cai, Dent, RKL, Weiler, 1705.01105 (PRD 2017)

Complementarity with collider searches

Dark ISR is complementary probe of a mono-Z' or mono dark Higgs collider search

$\rightarrow$ Indirect detection $\rightarrow$



$\leftarrow$ Collider $\leftarrow$

Lifts suppression in several cases

$\Gamma_\chi \otimes \Gamma_f$	$\overline{\chi}\chi \to \overline{f}f$	$\overline{\chi}\chi \to \overline{f}fZ'$		$\overline{\chi}\chi \to \overline{f}f\phi$	
		$\Gamma_{Z'} = V$	$\Gamma_{Z'} = A$	$\Gamma_\phi = S$	$\Gamma_\phi = P$
$V \otimes V$	1	1	1	1	1
$A \otimes V$	v^2	1	1	v^2	v^2
$V \otimes A$	1	1	1	1	1
$A \otimes A$	$(m_f/m_\chi)^2$	1	1	v^2	v^2
$S \otimes S$	v^2	1	v^2	v^2	1
$P \otimes S$	1	1	v^2	1^*	v^2
$S \otimes P$	v^2	1	v^2	v^2	1^*
$P \otimes P$	1	1	v^2	1	v^2

Bell, Cai, Dent, RKL, Weiler, 1705.01105 (PRD 2017)

Lifts suppression in several cases

$\Gamma_\chi \otimes \Gamma_f$	$\overline{\chi}\chi \to \overline{f}f$	$\overline{\chi}\chi \to \overline{f}fZ'$		$\overline{\chi}\chi \to \overline{f}f\phi$	
		$\Gamma_{Z'} = V$	$\Gamma_{Z'} = A$	$\Gamma_\phi = S$	$\Gamma_\phi = P$
$V \otimes V$	1	1	1	1	1
$A \otimes V$	v^2	1	1	v^2	v^2
$V \otimes A$	1	1	1	1	1
$A \otimes A$	$(m_f/m_\chi)^2$	1	1	v^2	v^2
$S \otimes S$	v^2	1	v^2	v^2	1
$P \otimes S$	1	1	v^2	1^*	v^2
$S \otimes P$	v^2	1	v^2	v^2	1^*
$P \otimes P$	1	1	v^2	1	v^2

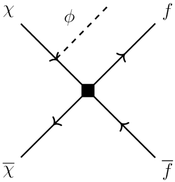
Bell, Cai, Dent, RKL, Weiler, 1705.01105 (PRD 2017)

Pseudoscalar ISR example

- Lowest order $S \otimes S$ DM annihilation is p-wave, suppressed as $\langle \sigma v \rangle_{\chi\chi \to ff} \sim \frac{m_\chi^2}{8\pi\Lambda^4} v^2$
- Introduce a pseudoscalar coupling to the DM,

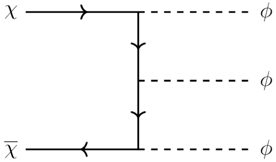
$$\mathcal{L}_{\rm int} \supset \frac{1}{\Lambda^2}(\overline{\chi}\chi)(\overline{f}f) + i\, g_\phi \phi \overline{\chi}\gamma_5\chi$$

- New ISR process is $s-$wave, competes with also induced $\chi\chi \to \phi\phi\phi$



Pseudoscalar ISR

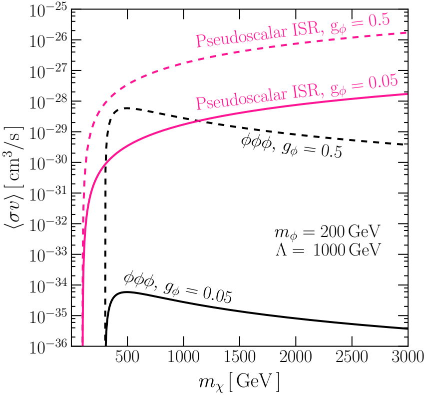
$\langle \sigma v \rangle \sim \frac{g_\phi^2 m_\chi^2}{48\pi^3\Lambda^4}$

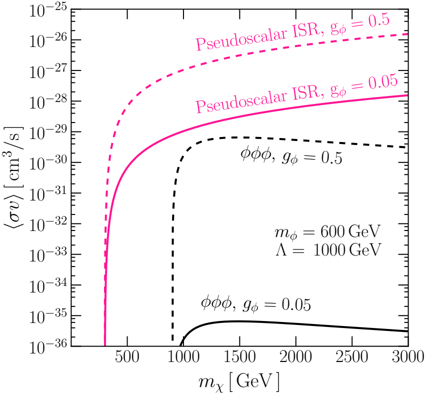


$\chi\chi \to \phi\phi\phi$

$\langle \sigma v \rangle \sim \frac{g_\phi^6}{1536\pi m_\chi^2}$

Pseudoscalar ISR example





Dark ISR easily dominates the parameter space.

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

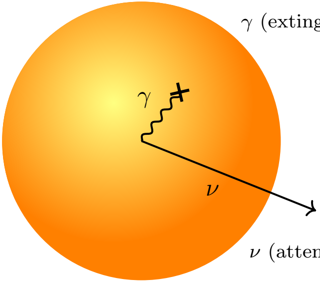
DM can be captured in the Sun by scattering with solar nuclei.

- 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?

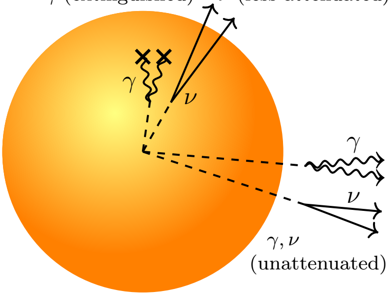
Solar signatures of long-lived dark mediators

If annihilation proceeds via long-lived dark mediators:

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



Short-lived mediators



Long-lived mediators

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

Measuring gamma rays with new Fermi-LAT data

Annihilation fluxes of DM to gamma rays in solar core 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

$$\sim 10^{-4}\,\mathrm{GeV}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}.$$

In this region, the sensitivity of Fermi-LAT is

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

The annihilation flux is in excess of sensitivity by a factor of $\mathbf{10^4}$!

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

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

Searches in gamma ray and neutrino channels

Gamma rays:

- Current limits use Fermi data on solar gamma rays
  - 2011 and 2015 analyses
- Future sensitivity with water cherenkov telescopes HAWC and LHAASO
  - HAWC has data, sensitive to very high-energy ($>$TeV) gamma rays
  - LHAASO upcoming, also extremely sensitive to very high-energy ($>$TeV) gamma rays

Searches in gamma ray and neutrino channels

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Neutrinos:

- Best gain for long-lived mediators is at higher ($>$TeV) energies
  - Less neutrino absorption by the solar matter
  - Less cooling of the secondaries (pions, muons etc)
- Use gigaton neutrino telescopes IceCube and KM3NeT

Long-lived dark mediator flux

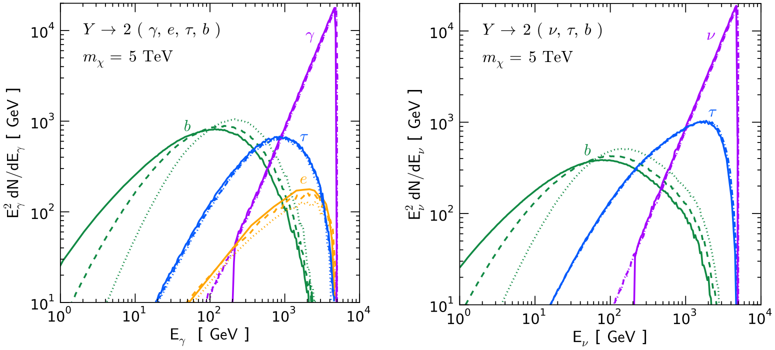
$$E^2 \frac{d\Phi}{dE} = \frac{\Gamma_{\rm ann}}{4\pi D_\oplus^2} \times E^2 \frac{dN}{dE} \times {\rm Br}({\rm Y} \to {\rm SM}) \times P_{\rm surv}, \tag{1}$$

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 signal survival probability

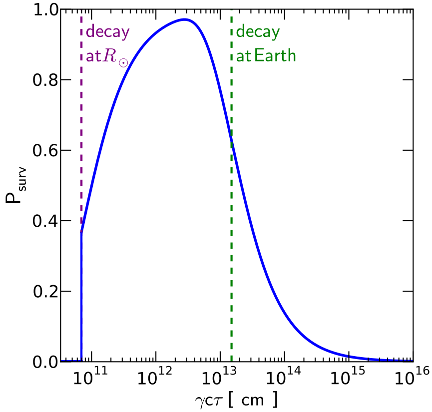
Energy spectra

- Process is $\chi\chi \to YY \to 2\,(\,\mathrm{SM} + \overline{\mathrm{SM}}\,) \to ...\gamma, \nu...$
- Generate energy spectra with Pythia
- Check variance for range of mediator masses, $m_Y = 20, 200, 2000$ GeV. Spectra are approx the same.



RKL, Ng, Beacom, 1703.04629 (PRD 2017)

Optimal Signal Conditions



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

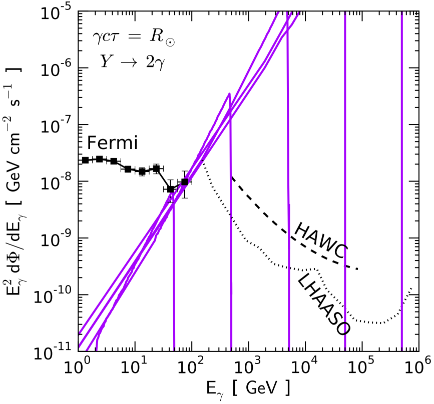
Need mediator Y to have sufficiently long lifetime τ or boost factor $\gamma = m_\chi/m_Y$, leading to a decay length L that exceeds the radius of the Sun, $R_\odot$, as

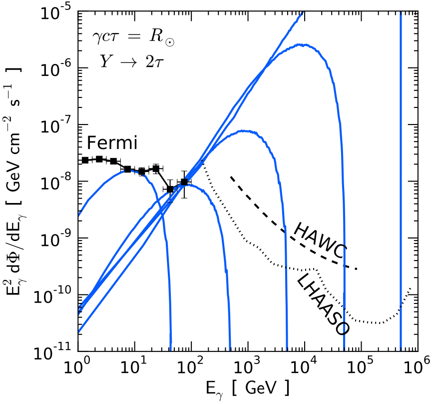
$$L = \gamma c\tau > R_\odot. \quad (3)$$

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

Determining sensitivity: Gamma rays

Scan over DM masses, once gamma-ray spectrum exceeds sensitivity, limit is set



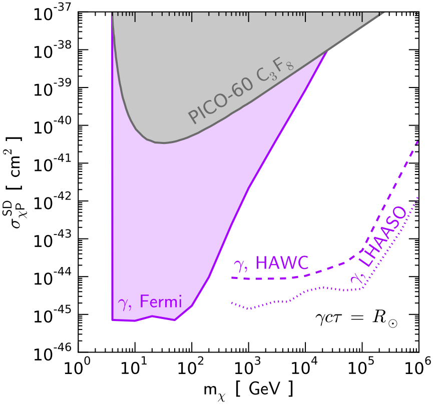


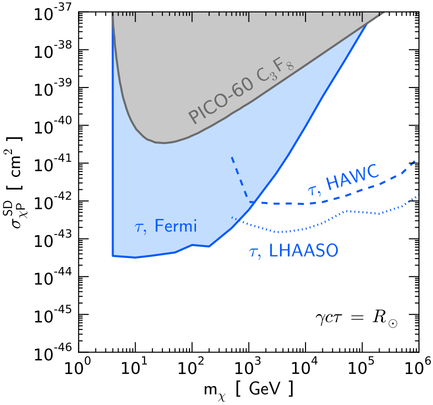
$$\chi\chi \to YY \to 2\,(\mathrm{SM}+\mathrm{SM}) \to ...\gamma...$$

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

DM scattering cross section limits: Gamma rays

Can outperform direct detection exps by several orders of magnitude!



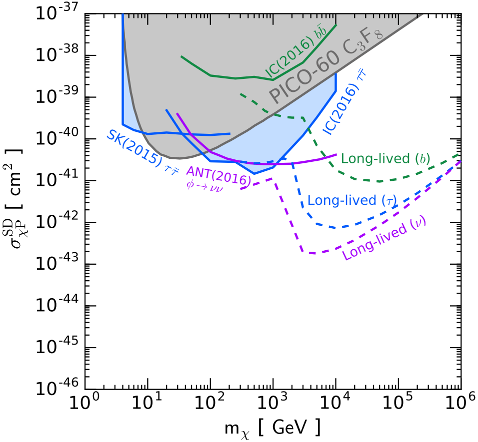


$$\chi\chi \rightarrow YY \rightarrow 2\,(\,\mathrm{SM} + \mathrm{SM}\,) \rightarrow ...\gamma...$$

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

DM scattering cross section limits: Neutrinos

Outperforms both direct detection exps and standard neutrino searches



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

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

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 processes, which can dominate 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 be tested at both direct and indirect detection exps
  - Bonus: cross-check between indirect det channels
- Can outperform direct detection exps by several orders of magnitude

Back up slides

Long-lived dark mediator flux

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

where

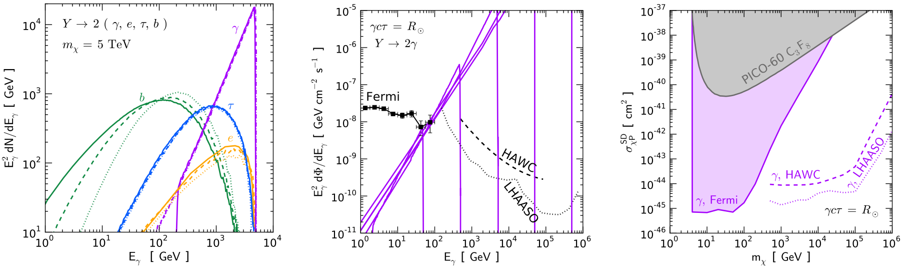
- $D_\oplus = 1$ A.U. is the distance between the Sun and the Earth
- $E^2 dN/dE$ is the particle energy spectrum per DM annihilation
- ${\rm Br(Y \to SM)}$ is the branching fraction of the mediator Y to SM particles
- $P_{\rm surv}$ is the probability of the signal surviving to reach the detector, given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

$$P_{\rm surv} = e^{-R_\odot/\gamma c\tau} - e^{-D_\oplus/\gamma c\tau}. \quad (5)$$

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

$$L = \gamma c\tau > R_\odot. \quad (6)$$

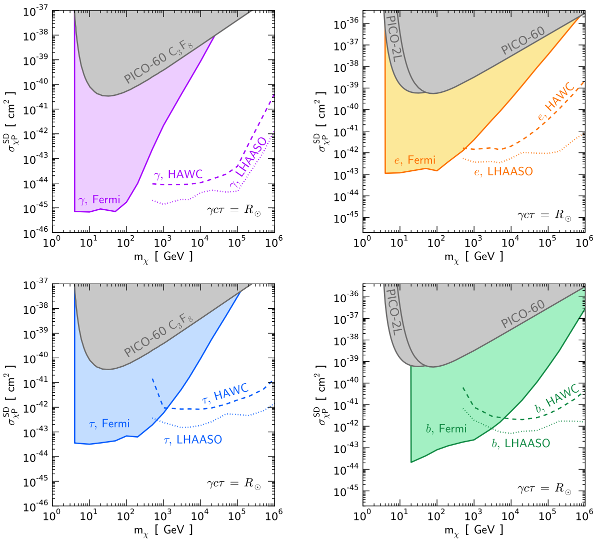
Gamma-ray limit procedure



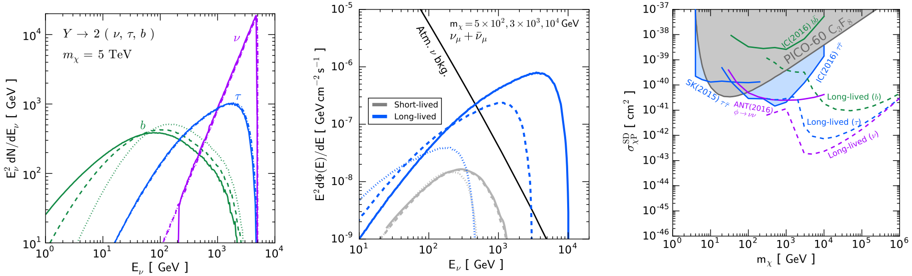
$$\chi\chi \to YY \to 2\,(\,\mathrm{SM} + \mathrm{SM}\,) \to \ldots\gamma\ldots$$

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

Gamma-ray limits



RKL, Ng, Beacom, 1703.04629 (PRD 2017)



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

RKL, Ng, Beacom, 1703.04629 (PRD 2017)

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.

Two-Mediator Scenario: Charge Assignments

Yukawa term is

$$\mathcal{L}_{\rm Yukawa} = -\left(y_\chi \overline{\chi}_R \chi_L S + h.c.\right), \tag{7}$$

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

$$Q_{\chi_R} - Q_{\chi_L} = Q_S \ . \tag{8}$$

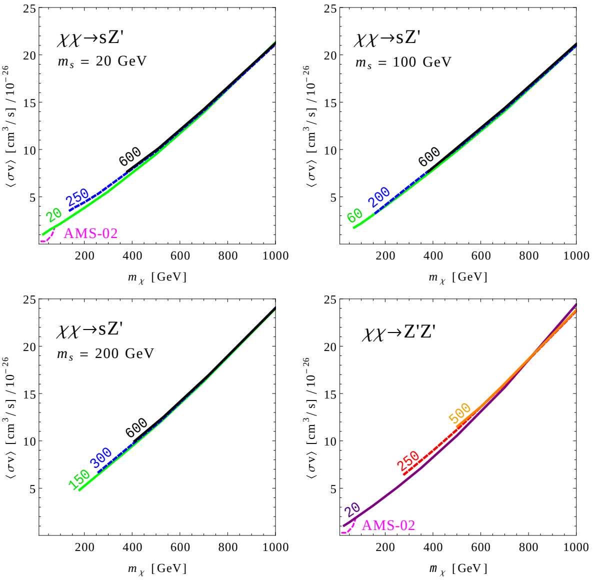
Set the dark Higgs charge to $Q_S = 1$. The χ charges therefore satisfy

$$Q_A \equiv \frac{1}{2}(Q_{\chi_R} - Q_{\chi_L}) = \frac{1}{2}, \tag{9}$$

$$Q_V \equiv \frac{1}{2}(Q_{\chi_R} + Q_{\chi_L}) = \frac{1}{2} + Q_{\chi_L}. \tag{10}$$

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.

<u>Bare DM Mass, Z' Mass from Stueckelberg</u>

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

$$\mathcal{L} = \mathcal{L}_{SM} + i\,\overline{\chi}(\partial_\mu + ig_\chi Q_V Z'_\mu)\gamma^\mu \chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} - m_\chi \overline{\chi}\chi + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu. \tag{11}$$

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

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\overline{\chi}_L \not{D}\chi_L + i\overline{\chi}_R \not{D}\chi_R - (y_\chi \overline{\chi}_R \chi_L S + h.c.) - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} \\ + (D^\mu S)^\dagger (D_\mu S) - \mu_s^2 S^\dagger S - \lambda_s (S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H). \quad (12)\end{aligned}$$

After symmetry breaking, this becomes

$$\begin{aligned}\mathcal{L} \supset & -\frac{1}{2} m_s^2 s^2 + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu - m_\chi \overline{\chi}\chi \\ & + g_\chi^2 w Z'^\mu Z'_\mu s - \lambda_s w s^3 - 2\lambda_{hs} h\, s(v\, s + w\, h) + g_f \sum_f Z'_\mu \overline{f} \Gamma_f^\mu f \quad (13) \\ & - g_\chi Q_V Z'_\mu \overline{\chi}\gamma^\mu \chi - g_\chi Q_A Z'_\mu \overline{\chi}\gamma^\mu \gamma_5 \chi - \frac{y_\chi}{\sqrt{2}} s \overline{\chi}\chi \,.\end{aligned}$$

Lagrangian: Scenario III

DM Mass from Dark Higgs, Z' Mass from Stueckelberg

The most minimal Lagrangian for this scenario is

$$\mathcal{L} = \mathcal{L}_{SM} \quad + \quad i\,\overline{\chi}\left(\partial\!\!\!/ + ig_\chi Q_V Z\!\!\!/'\right)\chi - \frac{y_\chi}{\sqrt{2}}\overline{\chi}\chi\phi - \frac{\sin\epsilon}{2}Z'^{\mu\nu}B_{\mu\nu} \quad + \quad \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\mu_s^2\phi^2 - \frac{1}{4}\lambda_s\phi^4 - \frac{1}{2}\lambda_{hs}\phi^2(H^\dagger H), \tag{14}$$

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

$$\begin{aligned} \mathcal{L} &= \mathcal{L}_{SM} + i\,\overline{\chi}\left(\partial\!\!\!/ + ig_\chi Q_V Z\!\!\!/'\right)\chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} - m_\chi \overline{\chi}\chi \\ &+ \left[(\partial^\mu + ig_\chi Q_S Z'^\mu)S\right]^\dagger \left[(\partial_\mu + ig_\chi Q_S Z'_\mu)S\right] - \mu_s^2 S^\dagger S \\ &- \lambda_s (S^\dagger S)^2 - \lambda_{hs}(S^\dagger S)(H^\dagger H). \end{aligned} \tag{15}$$

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

Charge assignments

Yukawa term is

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

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

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

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

$$Q_A \equiv \frac{1}{2}(Q_{\chi_R} - Q_{\chi_L}) = \frac{1}{2},$$
$$Q_V \equiv \frac{1}{2}(Q_{\chi_R} + Q_{\chi_L}) = \frac{1}{2} + Q_{\chi_L}.$$

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.

Scenario I: Full Lagrangian

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

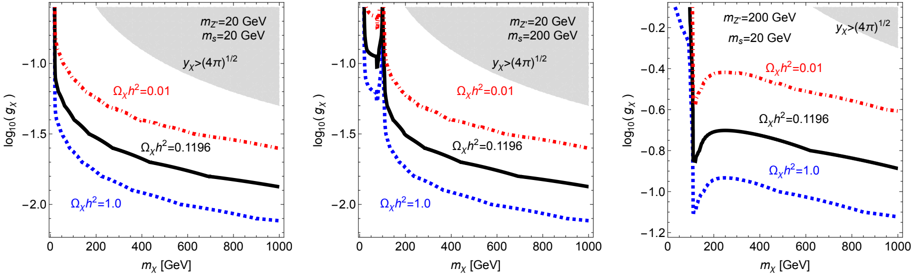
$$\mathcal{L} = \mathcal{L}_{SM} + i\,\overline{\chi}(\partial_\mu + ig_\chi Q_V Z'_\mu)\gamma^\mu\chi - \frac{\sin\epsilon}{2} Z'^{\mu\nu} B_{\mu\nu} \\ - m_\chi\overline{\chi}\chi + \frac{1}{2} m_{Z'}^2 Z'^\mu Z'_\mu.$$

Scenario II: Full Lagrangian

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

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

Scenario II: Relic Density



Scenario III: Full Lagrangian

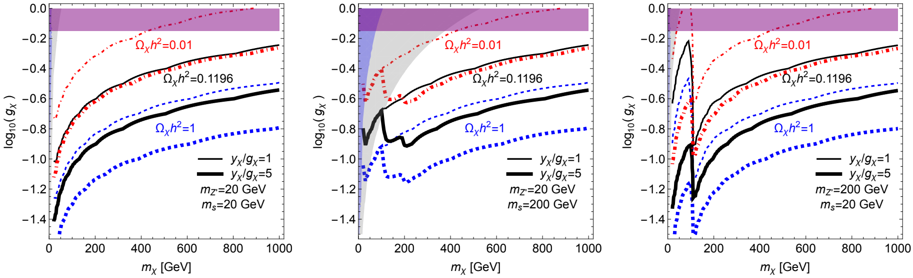
DM Mass from Dark Higgs, Z' Mass from Stueckelberg

The most minimal Lagrangian for this scenario is

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

with the real scalar $\phi = w + s$, where w is the vev of ϕ and s is the dark Higgs.

Scenario III: Relic density

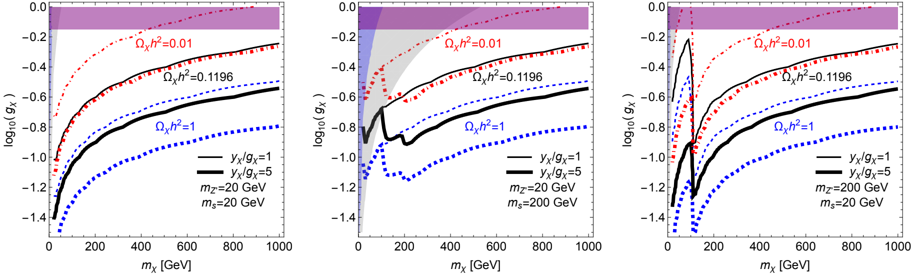


Bare DM Mass, Z' Mass from Dark Higgs

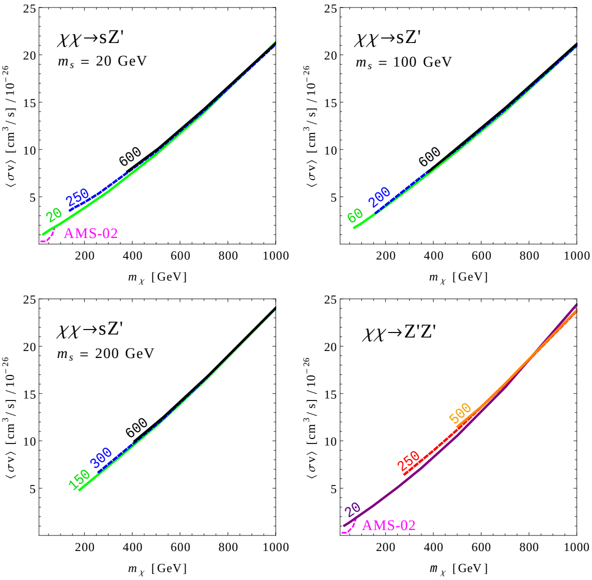
The most minimal gauge invariant Lagrangian is

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

Scenario IV: Relic Density



Indirect Detection Constraints



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:

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

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

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

Vector ISR example