Enhancing Dark Matter Annihilation with Dark Bremsstrahlung

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arXiv:1705.01105 (PRD 2017)

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Dark Matter Annihilation

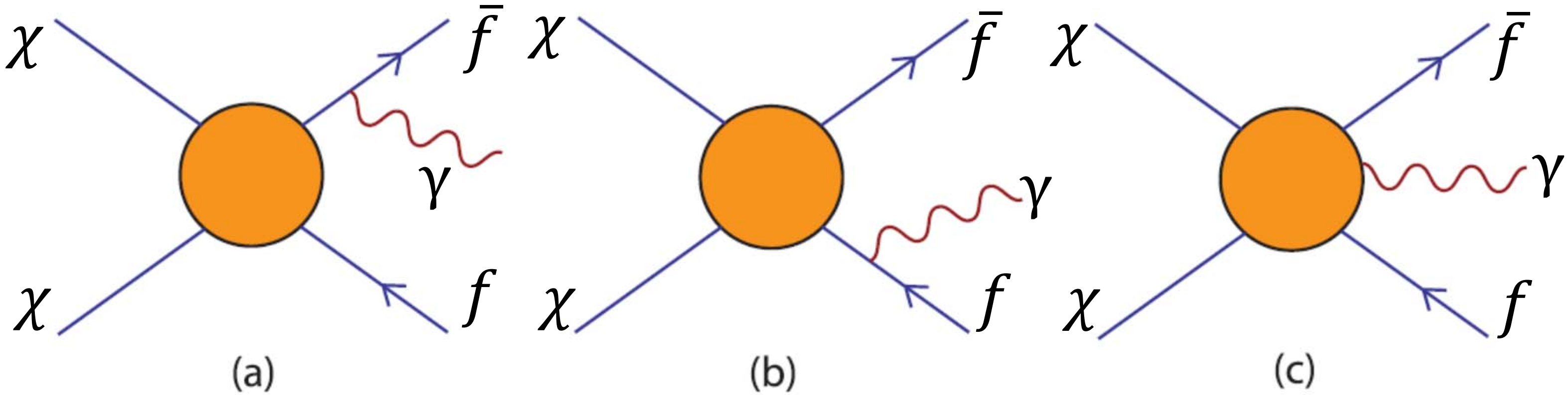
- Large indirect detection signals typically require an un-suppressed s-wave annihilation mode (in absence of Sommerfeld enhancements)

- In many interesting models, s-wave is absent or suppressed
  - p-wave → $v^2 \sim 10^{-6}$ suppressed indirect-detection (*e.g. scalar mediators)*
  - helicity suppressed s-wave → $(m_f/m_{DM})^2$ suppression *(e.g. axial vector mediators)*

- Thus, the dominant annihilation channel may be a higher order process

Lifting the suppression

Bremsstrahlung can open an s-wave → *radiation of photon/W/Z from final state or internal propagator has been well studied*



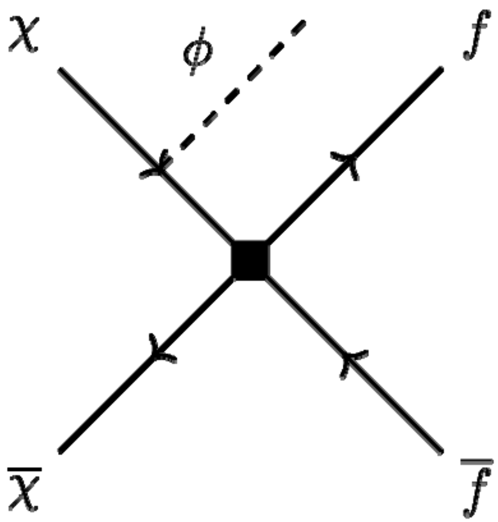
Bringmann, Bergstrom, Edsjo, 2008

FSR (Final state radiation)

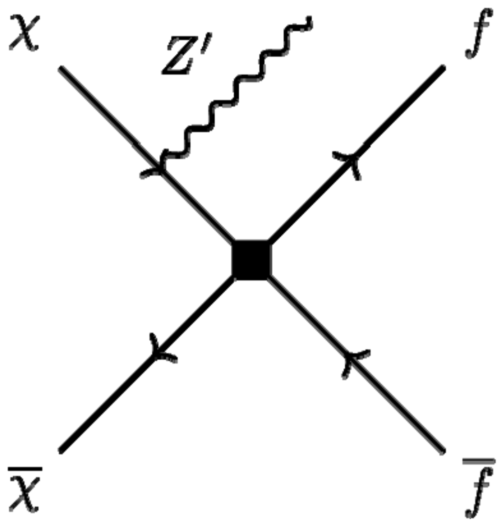
VIB (Virtual internal bremsstrahlung)

- $\chi\chi \rightarrow \bar{f} f \gamma$ (s-wave) can dominate over $\chi\chi \rightarrow \bar{f} f$ (p-wave) for indirect detection
- Large effect if DM and mediator are nearly degenerate (e.g. coannihilation region)

Dark *initial state radiation*



Dark scalar ISR



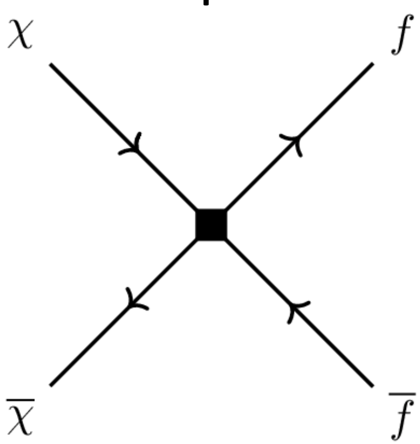
Dark gauge boson ISR

- Requires an additional dark-sector particle, which is natural in many models
- Scalar can decay to SM states via small Higgs portal coupling; Z' can decay to SM via small kinetic mixing portal.

Comparing Dark-ISR with visible-FSR/VIB

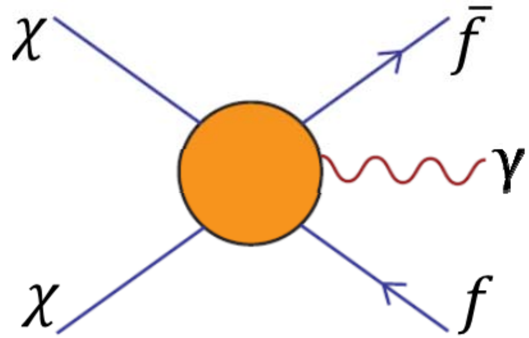
$$\mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\Gamma\chi)(\bar{f}\Gamma f)$$

$2 \rightarrow 2$ process



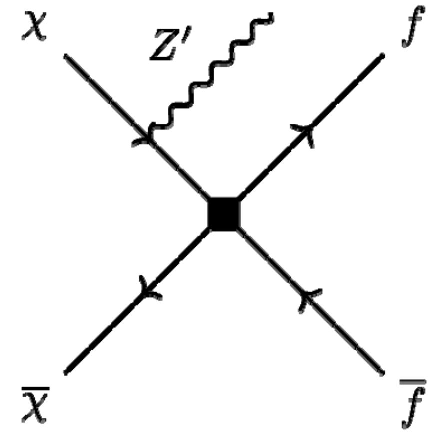
$$\sigma v \sim \frac{1}{\Lambda^4} \times \text{suppression factor}$$

Photon VIB/FIB



$$\sigma v \sim \frac{1}{\Lambda^8}$$

Dark ISR



$$\sigma v \sim \frac{1}{\Lambda^4}$$

Dark ISR opens an unsuppressed s-wave annihilation mode at lower order in $1/\Lambda$ than FSR/VIB. (i.e. no longer need near degenerate DM and mediator)

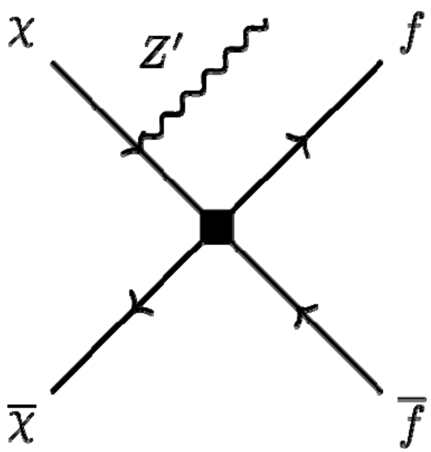
Suppression factors

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

$\Gamma_\chi \otimes \Gamma_f$	$\bar{\chi}\chi \to \bar{f}f$	$\bar{\chi}\chi \to \bar{f}fZ'$		$\bar{\chi}\chi \to \bar{f}f\phi$	
		Vector radiation	Axialvector radiation	Scalar radiation	Pseudoscalar radiation
$V \otimes V$	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

Complementarity:

Indirect detection: $\bar{\chi}\chi \to \bar{f} f Z'$



Collider mono-Z' production: $\bar{f} f \to \bar{\chi}\chi Z'$

Large collider cross-sections possible, particularly for light masses.

(Also collider mono-dark Higgs process)

Lifting p-wave suppression of scalar interactions

Assume scalar EFT interaction: $\mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{f}f)$

Lowest order cross section p-wave: $\sigma v(\bar{\chi}\chi \rightarrow \bar{f}f) \sim \frac{m_\chi^2}{8\pi\Lambda^4} v^2$

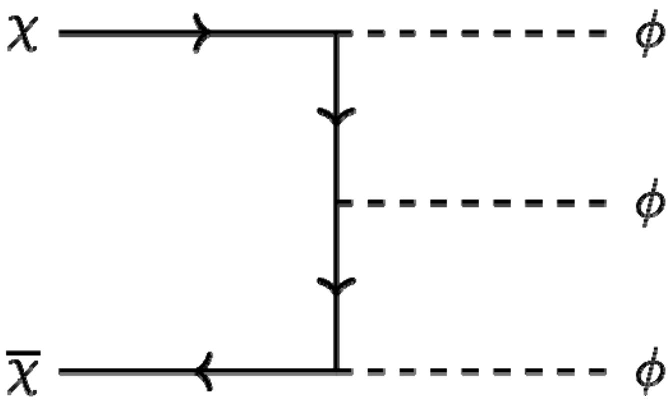
Add a DM coupling to a new pseudoscalar ϕ:

$$\mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{f}f) + i g_\phi \bar{\chi}\gamma_5\chi\phi$$

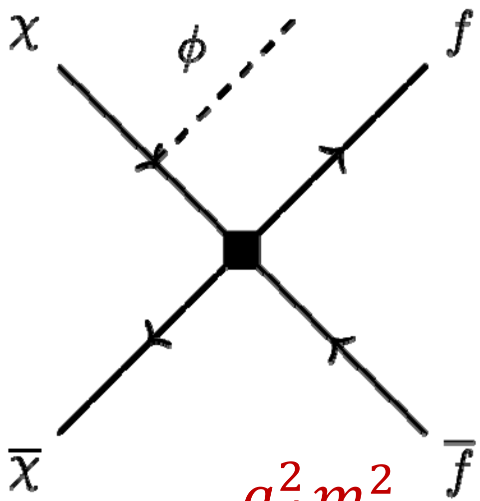
ISR process opens an unsuppressed s-wave:

$$\sigma v(\bar{\chi}\chi \rightarrow \bar{f}f\phi) \sim \frac{g_\phi^2 m_\chi^2}{48\pi^3\Lambda^4}$$

Competing s-wave processes



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

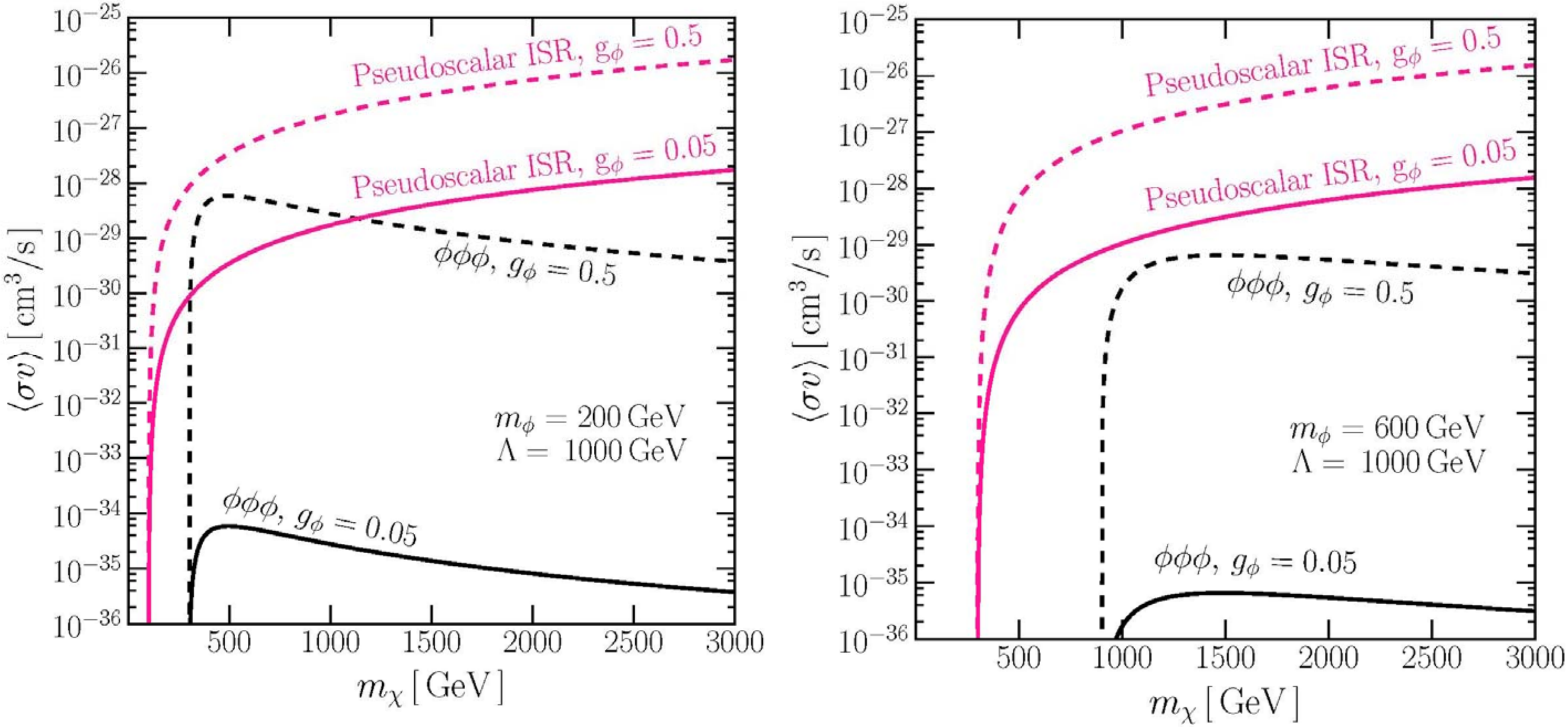


$$\sigma v \sim \frac{g_\phi^2 m_\chi^2}{48\pi^3\Lambda^4}$$

- $\bar{\chi}\chi \to \phi\phi$ is p-wave (neglect for indirect detection)

- $\bar{\chi}\chi \to \phi\phi\phi$ is s-wave for *pseudoscalar* ϕ (there is no s-wave annihilation to a pure scalar final state)

Pseudoscalar ISR vs $\phi\phi\phi$ process



$\bar{f} f \phi$ ISR process easily dominates over $\phi\phi\phi$

Lifting helicity suppression of axial interactions

Assume axialvector EFT interaction: $\mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\gamma^\mu\gamma^5\chi)(\bar{f}\gamma^\mu\gamma^5 f)$

Lowest order cross section is helicity suppressed: $\sigma v(\bar{\chi}\chi \to \bar{f}f) \sim \left(\frac{m_f}{m_\chi}\right)^2 \frac{m_\chi^2}{2\pi\Lambda^4}$

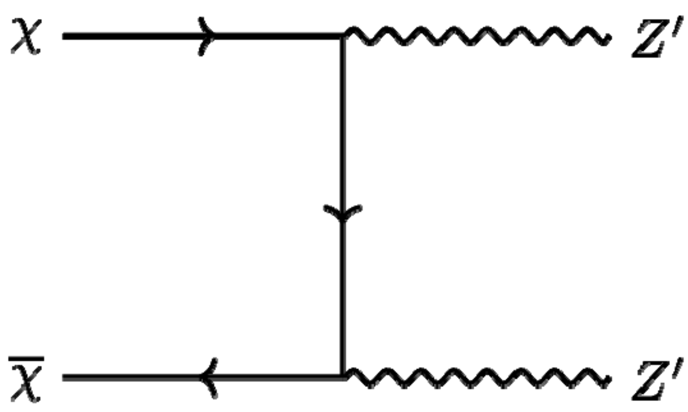
Add a DM coupling to a new dark vector Z':

$$\mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{f}f) + i g_{Z'}\bar{\chi}\gamma^\mu\chi Z'_\mu$$

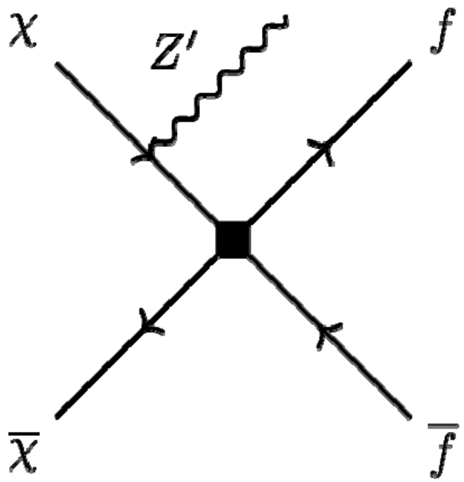
ISR process opens an unsuppressed s-wave:

$$\sigma v(\bar{\chi}\chi \to \bar{f}fZ') \sim \frac{g_{Z'}^2 m_\chi^2}{36\pi^3\Lambda^4}$$

Competing s-wave processes



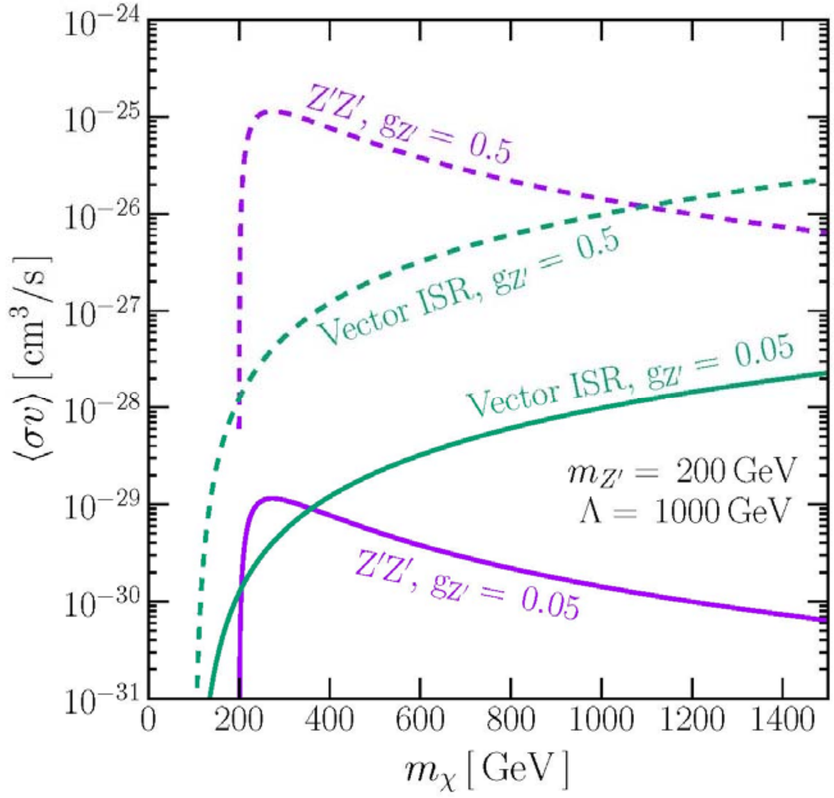
$$\sigma v \sim \frac{g_{Z'}^4}{16\pi m_\chi^2}$$

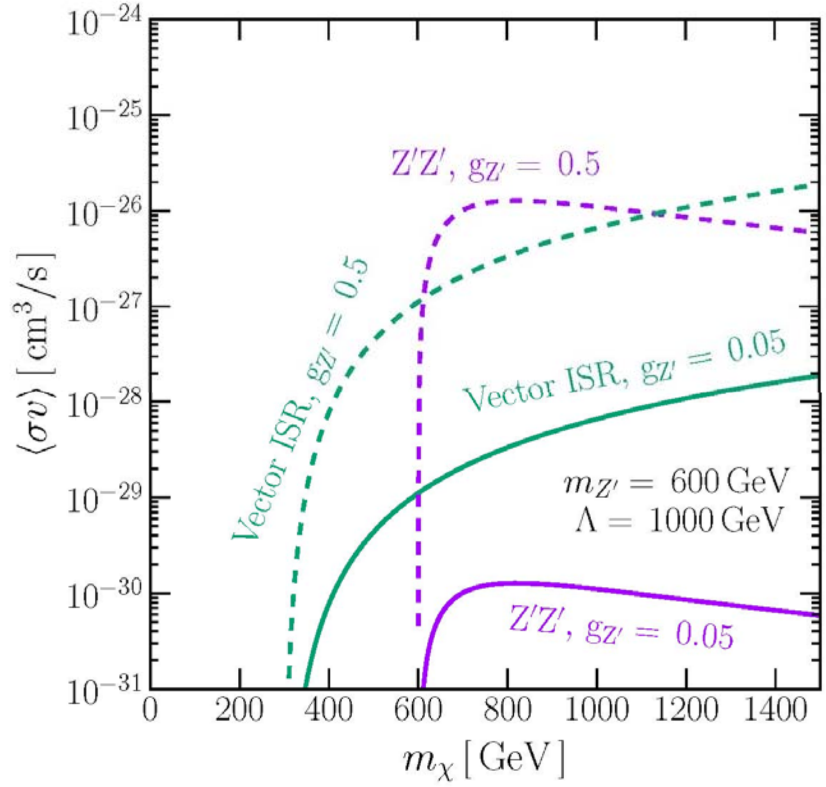


$$\sigma v \sim \frac{g_{Z'}^2 m_\chi^2}{36\pi^3\Lambda^4}$$

- $\bar{\chi}\chi \to Z'Z'$ is always s-wave (irrespective of whether the Z' coupling is axial or vector) and can compete with the (phase space suppressed) ISR process.

Vector ISR vs $Z'Z'$ process





$\bar{f} f Z'$ ISR process dominates over $Z'Z'$ for some parameters (small Z' and large DM mass).

Summary

- Many DM-SM interaction types feature velocity or helicity suppressed $\bar{\chi}\chi \rightarrow \bar{f}f$ annihilations (axial vector or scalar dark matter vertex) that prevent indirect detection.

- Dark initial state radiation can open an unsuppressed s-wave annihilation channel, thus allowing indirect detection.

- $(\sigma v)_{dark-ISR}^{s-wave} \sim 1/\Lambda^4$ compared to $(\sigma v)_{SM-FSR,VIB}^{s-wave} \sim 1/\Lambda^8$

- Competing $\bar{\chi}\chi \rightarrow Z'Z'$ or $\bar{\chi}\chi \rightarrow \phi\phi\phi$ annihilations can be subdominant to the dark-ISR processes