Collider & Astrophysical Phenomenology of Massive Spin-2 Mediated WIMP Dark Matter (Preview!)

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May 7th, 2018

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The Standard Model? Dark Matter??

The Universe's Energy Budget

SM Content: $\sim 5\%$ $\leftarrow$ **Good at High** E
Dark Energy: $\sim 71\%$ $\leftarrow$ **Vacuum Energy?**
Dark Matter: $\sim 24\%$ $\leftarrow$ **???**

DM Guess: Non-baryonic thermally-cold neutral massive particle?

The theory DM density must be less than observed DM density ("**relic density/abundance**"), which equals[1]

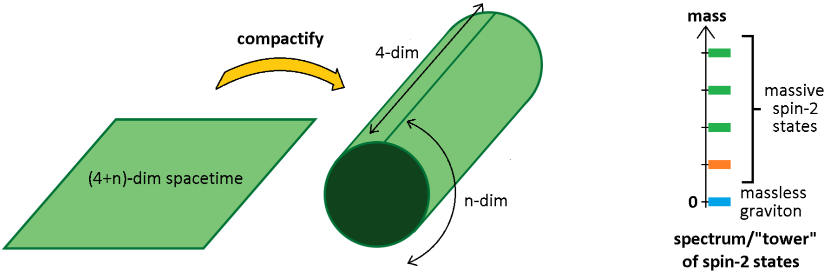
$$(\Omega h^2)_{theory} \leq (\Omega h^2)_{exp} = \left[\frac{\rho_{\text{DM}}}{\rho_{critical}}\right] h^2 = 0.11425 \pm 0.00311$$

* **What if DM only interacts gravitationally?** *

[1] P. A. R. Ade, et al., Planck 2015 results. XIII. Cosmological parameters, Astron. Astrophys. 594 (2016) A13.

Higher-Dimensional Consequences

Massive spin-2 particles naturally emerge when compactifying higher-dimensional gravity to 4-dimensions (such as in Randall-Sundrum models); **4D spectrum depends on model.**



Q: Can we make any general statements about the phenomenology of these models by focusing on the lowest massive state?

The Effective Massive Spin-2 Theory... and Dark Matter

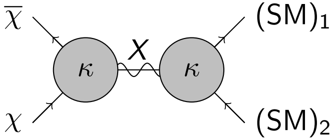
We may write the **simplified massive Spin-2 Lagrangian**,

$$\mathcal{L}_X = \underbrace{\sqrt{-\det g}\,\left[\frac{2}{\kappa^2}R(g) + \mathcal{L}_{matter}(g)\right]}_{\text{usual 4D gravity Lagrangian; expand in }\kappa} + \underbrace{m_X^2\left(X^{\mu\nu}X_{\mu\nu} - X^{\mu}{}_{\mu}X^{\nu}{}_{\nu}\right)}_{\text{spin-2 ``Fierz-Pauli'' mass term}}$$

where $g_{\mu\nu} \equiv \eta_{\mu\nu} + \kappa\, X_{\mu\nu}$, and $X_{\mu\nu}$ = massive spin-2 field.

Suppose we also throw in a **dark sector** w/ **WIMP-like** χ...

$$\mathcal{L}_{matter} = \mathcal{L}_{SM} + \mathcal{L}_{DM} \quad \Longrightarrow$$



Spin-2 mediated portal model of DM!

Key Points - The Project in Summary

Model Space: We test viability of this model for...

- We scan a wide range of masses m_χ, m_X, and coupling κ and **we include second-order interaction vertices**.
- **DM Nature:** $\chi = \overline{\chi}$ and $\chi \neq \overline{\chi}$
- **DM Spin:** $\chi =$ scalar, fermion, and vector

Constraints: ... where viability is measured against...

- **Collider Limits** (ATLAS & CMS diphoton, dilepton, ...)
- **Relic Density** (Planck)
- **Direct DM Searches** (XENON1T)
- **Indirect DM Searches** (H.E.S.S.-I & II, Fermi-LAT, DAMPE)
- **Tree-Level Partial Wave Unitarity** (b.c. tower is truncated)

Key Points - The Project in Summary

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Key Complications

Plenty of room for errors, so to ensure correct & confident results,

Guiding Principle: calculate from scratch, and only then cross-check with community tools

In the process, we've developed programs for...

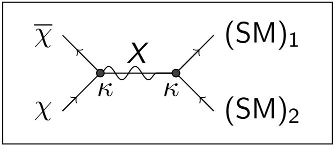
1. Computing **analytic** functions of **helicity amplitudes**
2. Calculating a model's **relic density** given the appropriate σ_{ann}

Furthermore, **we perform a complete** $\mathcal{O}(\kappa^2)$ **analysis, including multi-mediator vertices.**

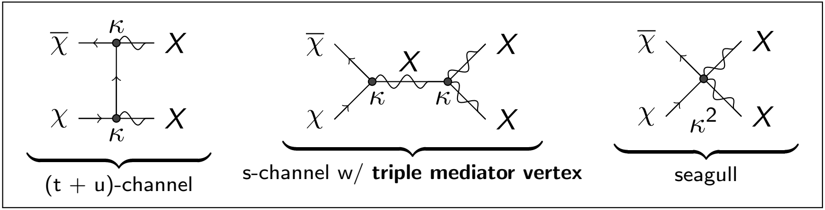
Example Diagrams: DM Annihilation

Many models only include $\mathcal{O}(\kappa)$ matter-mediator vertices:

$$\mathcal{L}_X \supseteq -\frac{\kappa}{2}(T^{\mu\nu}_{\chi} + T^{\mu\nu}_{SM})X_{\mu\nu} \implies$$



Our simplified model includes additional $\mathcal{O}(\kappa^2)$ diagrams, including **dark matter annihilation to final-state mediator pairs**



Triple Mediator Vertex

So we need the X^3 vertex, which comes from:

$$\mathcal{L}_X \supseteq \frac{\kappa}{8} X_{\mu\nu} \Big\{ \eta^{\mu\nu} \Big[-(\partial_\rho X)(\partial^\rho X) + 2(\partial_\rho X_{\sigma\tau})(\partial^\rho X^{\sigma\tau}) \Big] - 4(\partial^\mu X_{\rho\sigma})(\partial^\nu X^{\rho\sigma}) - 8(\partial_\sigma X^{\nu\rho})(\partial^\sigma X_\rho{}^\mu) + 4(\partial_\rho X^{\mu\nu})(\partial^\rho X) + 8(\partial^\mu X_{\rho\sigma})(\partial^\rho X^{\sigma\nu}) \Big\}$$

These terms result from expanding $\mathcal{L}_{EH}$, which naively generates $\sim$ **180 terms**. *Yikes.*

3. We developed a **diagrammatic method** for calculating the $\mathcal{O}(X^3)$ Lagrangian and with it ultimately **we derived the** X^3 **terms by hand!**

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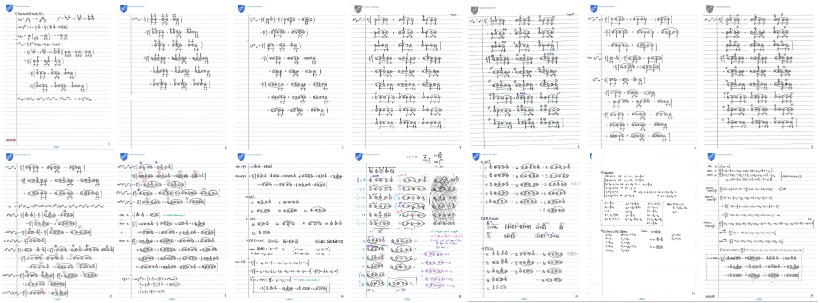
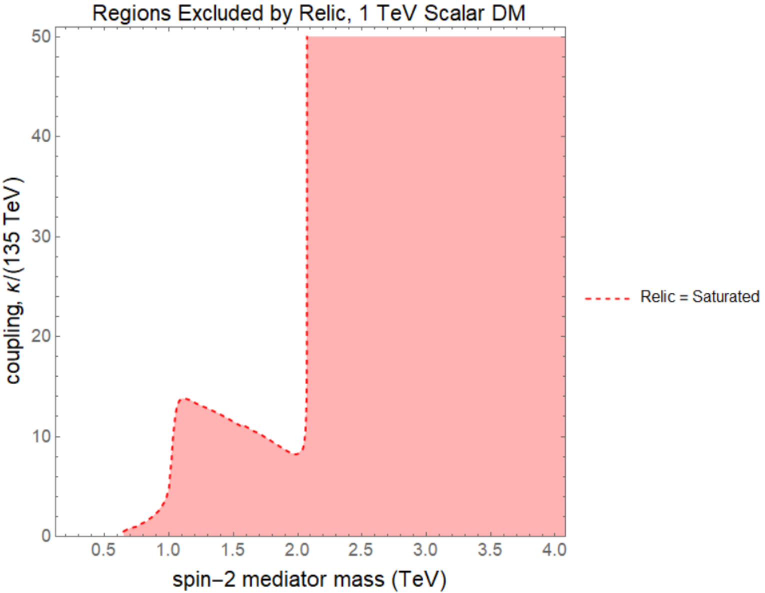
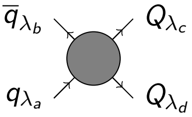


Example of Relic Density Constraint



Partial Wave Unitarity

$$i\mathcal{M}_{\lambda_a\lambda_b;\lambda_c\lambda_d} =$$



This matrix element decomposes into **partial wave amplitudes**:

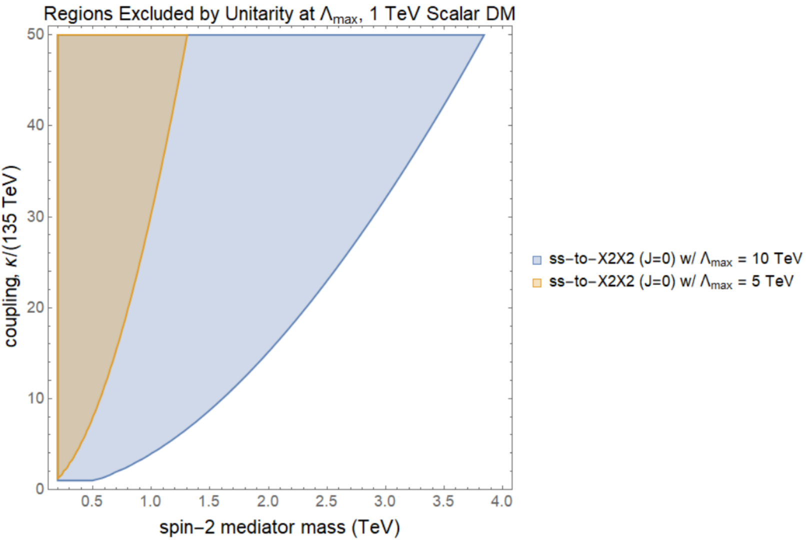
$$\mathcal{M}_{\lambda_a\lambda_b;\lambda_c\lambda_d} \equiv 32\pi^2 \sum_{J=\max\{\lambda_i,\lambda_f\}}^{+\infty} \frac{2J+1}{4\pi} \cdot a^J_{\lambda_a\lambda_b;\lambda_c\lambda_d}(s) \cdot D^{J*}_{\lambda_a-\lambda_b,\lambda_c-\lambda_d}(\theta,\phi)$$

where $D^J_{\lambda_i,\lambda_f}$ = Wigner D-function. The **optical theorem** implies,

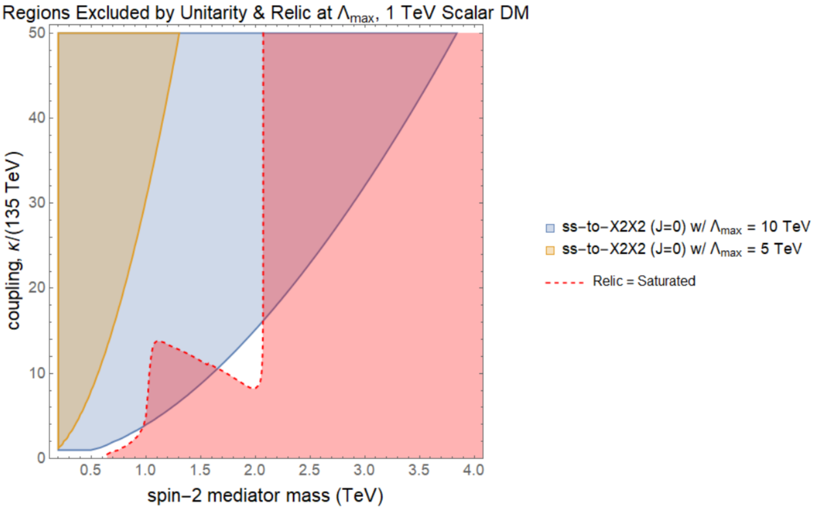
$$* \quad \boxed{\sqrt{1-\frac{4m_q^2}{s}} \cdot \left|\Re[a^J_{\lambda_a,\lambda_b;\lambda_c,\lambda_d}(s)]\right| \leq 1} \quad *$$

for *all* amplitudes. **We demand satisfaction of this inequality up to some appropriately-chosen scale Λ_{max}.**

Example of Unitarity Constraints



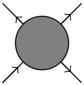
Example of Unitarity + Relic Density Constraints



How Apply Unitarity To Relic Density?

The relic density depends on the **DM annihilation cross-section**:

$$\sigma_{\text{ann}} = \sum_{\text{SM}} \sigma \left(\begin{array}{ccc} \overline{\chi} & & (\text{SM})_1 \text{ or } X \\ & \bullet & \\ \chi & & (\text{SM})_2 \text{ or } X \end{array} \right)$$



Namely, though the **thermally-averaged cross-section**,

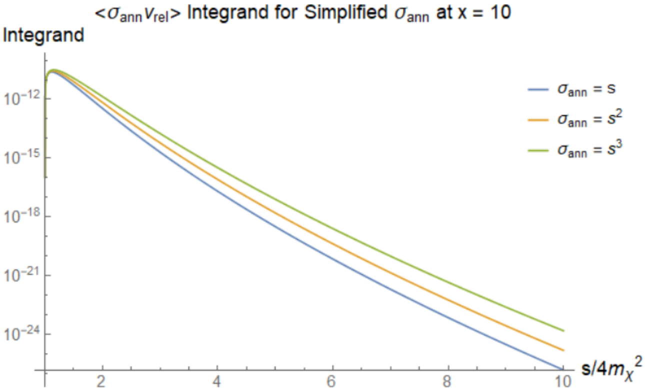
$$\langle \sigma_{ann} v_{rel} \rangle(x) = \frac{4x}{K_2(x)^2} \int_1^{+\infty} d\bar{s} \quad \sqrt{\bar{s}} \cdot (\bar{s} - 1) \cdot K_1(2x\sqrt{\bar{s}}) \cdot \sigma_{ann}$$

where $\bar{s} \equiv s/4{m_\chi}^2$ and evolution parameter $x = m_\chi/T$.

$\langle \sigma v_{rel} \rangle$ needs information about $s = +\infty$!?

Well...

Integrand of Thermally-Averaged Cross Section



Choose pre-freeze-out x-value, demand accuracy ϵ

$\implies$ Integrate over $[1, \bar{s}_{max}]$ so that $= (1 - \epsilon) \times$(full integral)

$\implies$ Partial-wave analysis w/ $\Lambda_{max} = 2m_\chi\sqrt{\bar{s}_{max}}$

Conclusions & Future of this Work

These are elements of a project exploring the viability of **simplified spin-2 mediated dark matter for $s_\chi = 0, \frac{1}{2}, 1$.** Generally...

- **Relic density and partial-wave unitarity** significantly constrain available parameter space in opposite ways.
- **Indirect detection** restricts models on threshold
- **Direct detection** limits are weak.
- **Collider** limits demand very weak coupling or heavy mediator.

$\ast$ **Expect to see something on the ArXiv soon!** $\ast$

Furthermore, following this project's completion, **we plan to optimize & rework our codes for public use.**

Thank you for your attendance and attention!