$p$-wave Annihilating Dark Matter and the Galactic Center Excess

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Based on arXiv: 1604.01039 in collaboration with Jeremie Choquette and Jim Cline
The Galactic Center
Gamma-Ray Excess

Two classes of explanations:

1. *Astrophysical* — Millisecond pulsars, burst events

2. *Dark matter annihilation!*

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Figure 7: Plain GCE energy spectrum as extracted from our baseline ROI, assuming a generalized NFW profile with an inner slope $\rho = 1.2$, for all of the 60 GDE models (yellow lines). We highlight the model that provides the best overall fit to the data (model F, green points) and our reference model from the discussion in section 3 (model A, red points), together with $\pm 1$ statistical errors.

For all 60 GDE models, we find a pronounced excess that peaks at around 1–3 GeV, and follows a falling power-law at higher energies.

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Figure 8: Energy spectra of different components (dotted lines) from a template fit to the data (black points), compared to the predicted GDE model fluxes (solid lines). The reference model A is shown in the left panel, while the GDE model that provides the best-fit to the data, model F, is shown in the right panel.
The Galactic Center vs. Dwarf Spheroidal Galaxies

• The best fit s-wave cross section and DM mass to the galactic center excess are in tension with limits from dwarf galaxies

• A solution: p-wave annihilating DM — velocity dispersion is low in dwarfs relative to the GC.
Scalar Mediator Model

- Velocity dependent annihilation cross section to on-shell mediators.

- By putting mediator on-shell, coupling to SM does not matter for annihilation rate, so constraints from direct detection and LHC can be avoided. Abdullah, et. al. (2014)

- In calculation of gamma-ray spectrum, we include *prompt photon emission* as well as secondary *inverse Compton scattering* and *bremsstrahlung* from $b$-quark shower products.
Fitting calculated spectra to the excess:

\[ \langle \sigma v \rangle = C_\sigma (\sigma_v / c)^2 \]

velocity dispersion

\( m_\phi = 12 \text{ GeV} \)

\( m_\phi = 50 \text{ GeV} \)
• We avoid constraints from dwarf spheroidals entirely.

• However, galaxy clusters, with their large velocity dispersions, could possibly constrain this scenario.
The Relic Density

\[ \frac{dn_\chi}{dt} = -3H n_\chi - \frac{\langle \sigma v \rangle}{2} \left( n_\chi^2 - n_{\chi\text{EQ}}^2 \right) \]

For p-wave annihilating DM with parameters that fit GC excess,

\[ m_\chi \sim 90 \text{ GeV}, \quad C_\sigma \sim 10^{-20} \text{ cm}^3 \text{s}^{-1} \]

\[ \Omega_\chi = 3.6 \times 10^{-5} \]

Much too small!
The Relic Density

\[
\frac{dn_x}{dt} = -3H n_x - \frac{\langle \sigma v \rangle}{2} \left( n_x^2 - n_{\chi}^{\text{EQ}} \right)
\]

**Solution:** A heavier state \( \psi \) that freezes out earlier than \( \chi \) and then decays to \( \chi \)
3 Possible Decay Channels

Photon \quad e^+/e^- \quad \text{Hadronic}

\begin{align*}
\frac{1}{\Lambda_\gamma} \bar{\chi} \sigma_{\mu\nu} \psi F_{\mu\nu}, & \quad \frac{(\bar{\chi} \gamma^\mu \psi)(\bar{e} \gamma_\mu e)}{\Lambda_e^2}, & \quad \frac{(\bar{\chi} \gamma^\mu \psi)(\bar{b} \gamma_\mu b)}{\Lambda_b^2}
\end{align*}

Lead to a more complicated Boltzmann equation:

\[
\frac{dn_\chi}{dt} = -3Hn_\chi - \frac{\langle \sigma_{\chi \bar{\chi}} \rangle}{2} (n_\chi^2 - n_{\chi \text{EQ}}^2) - \frac{\langle \sigma_{\chi \psi} \rangle}{2} (n_\chi n_\psi - n_{\chi \text{EQ}} n_{\psi \text{EQ}})
\]

- \left( \langle \sigma'_{\chi f} \rangle n_\chi n_f - \langle \sigma'_{\psi f} \rangle n_\psi n_f \right)
- \Gamma (n_\chi - n_{\chi \text{EQ}})

Anti-particle annihilation

Co-annihilation

Inelastic scattering

Decay
Conditions needed to get correct relic density:

- **Decays:** Lifetime of $\psi$ should be longer than freeze-out time of $\chi$: $\Gamma < H(t_f)$

- **Co-annihilations:** Should not deplete number density below measured relic density

- **Inelastic scatters:** Should occur at a smaller rate than $\bar{\psi}\psi$ annihilations:
  \[
  (n_e + n_{\bar{e}})\langle \sigma v \rangle_{\psi e \rightarrow \chi e} < n_\psi \langle \sigma v \rangle_{\bar{\psi} \bar{\psi} \rightarrow f f}
  \]
Late time decays can also cause problems:

- **Big Bang Nucleosynthesis:** Photo-disassociation as well as hadronic processes lead to incorrect element abundances (particularly constrained by ratios of $^3\text{He}/^2\text{H}$ and $^6\text{Li}/^7\text{Li}$).
  
  Jedamzik (2006)

- **Cosmic Microwave Background:** Injection of energy at recombination causes CMB distortion.
  
  Slatyer (2013)
Conclusions

• p-wave annihilating DM is an avenue to alleviate the tension between the possible signal of DM annihilation to gamma-rays in the galactic center and a lack of corresponding observations in dwarf spheroidal galaxies.

• Such a DM candidate can be produced with the correct abundance by a decaying progenitor particle.

• This model predicts a large gamma-ray signal from nearby galaxy clusters.