“Non-Local” Effects from Boosted Dark Matter in Indirect Detection

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Based Upon:

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Detection of dark matter interactions coming from large dark matter densities is one indirect approach.

The flux can be written as follows.

\[
\frac{d\Phi}{dE_\gamma} = \frac{dN}{dE_\gamma} \left\{ \frac{\langle \sigma_{\text{ann}} v \rangle_0}{8\pi m_\chi^2} \times J_{\text{ann}} \right\} \quad \text{(annihilation)}
\]

\[
\frac{d\Phi}{dE_\gamma} = \frac{dN}{dE_\gamma} \left\{ \frac{1}{4\pi m_\chi \tau_{\chi,0}} \times J_{\text{decay}} \right\} \quad \text{(decay)}
\]

The equations are separated into a particle physics portion and an astrophysical part, the $J$-factor.

\[
J_{\text{ann}} = \int_{\text{ROI}} \int_{\text{los}} \rho^2(r) \, d\ell \, d\Omega
\]

\[
J_{\text{decay}} = \int_{\text{ROI}} \int_{\text{los}} \rho(r) \, d\ell \, d\Omega
\]
The $J$-factor contains all astrophysical information.
Non-Local Scheme

\[ \chi \chi \rightarrow \chi^c_{\text{boost}} + \ldots \]

\[ \chi^c_{\text{boost}} + \chi \rightarrow \gamma + \ldots \]

DM halo

extragalactic

S. J. Clark (steven_j_clark@brown.edu)  Non-Local Dark Matter Annihilation  May 5, 2020
Non-Local Interaction

Features of the Non-Local Mechanism:

- Dark matter particles undergo an interaction event (just like the canonical scenario).
- The products are boosted and transported away from the original interaction sight.
- After traveling a non-negligible distance, the products interact with the local environment.

Some models that naturally incorporate these properties include:

- Semi-annihilation
- Asymmetric
- Forbidden
At low secondary annihilation rates, smaller galaxies experience a larger reduction in their overall rate.
Recall the canonical $J$-factor ratios.
Non-local $J$-factor is non-trivially dependent on the second interaction.
Naturally predicts a variation between GCE and dSph signals

\[ 10^1 \quad 10^2 \quad 10^3 \]

DM mass [GeV]

\[ 10^{-26} \quad 10^{-25} \quad 10^{-24} \]

\( \sigma v \) [cm\(^3\)/s]

- prof. J & B (this work)
- prof. J (this work)
- Fermi-LAT, measured J-factors (2016)
- Mazziotta et al. (combined)
- Calore et al. 2015 (2\( \sigma \))

Thermal Relic cross section
Steigman et al. 2012

*Calore, Serpico, and Zaldivar – arXiv:1803.05508
Summary

- Canonical $J$-factors are solely astrophysical
- The non-local mechanism introduces non-trivial scale dependencies
- The non-local mechanism includes multiple scales and reduces to the canonical framework for limiting cases
- One possible consequence of the non-local mechanism is to alleviate GCE/dSph discrepancies
Thank You!
The $J$-factor of the gamma-ray signal from a galaxy is derived as

$$J_{\text{NL}} = \int_{\text{ROI}} \int_{\text{los}} d\ell \, d\Omega_{\ell} \rho_{1,0}^2 \times \mathcal{P}_{\chi_2^c \chi_2}(|\vec{r}|) \times \frac{dN}{d\Omega}(\vec{r}, \Omega_{\ell}). \quad (3)$$

$\mathcal{P}_{\chi_2^c \chi_2}$ is the probability of $\chi_2^b$ annihilating after traveling a displacement $\vec{s}$ from the $\chi_1$ annihilation point

$$\mathcal{P}_{\chi_2^c \chi_2}(r) = \frac{\Lambda \eta_2(r)}{4\pi} \int dq \, d\Omega_q \left[ \eta_1(q) \right]^2 \left( \frac{q}{s} \right)^2 \exp \left[ -\Lambda \int_0^s ds' \, \eta_2(s') \right] \quad (4)$$

$\frac{dN}{d\Omega}(\vec{r}, \Omega_{\ell})$ accounts for the directional dependence in the signal, a result of the boosted reference frame.
Non-Local Annihilation $J$-Factor: Limiting $d \gg r_s$ Behavior

In the far away approximation with distance $d$, the $J$-factor becomes

$$J_{NL} \approx d^{-2} \int dV \rho_{1,0}^2 \times P_{\chi^c_2\chi_2}(\vec{r}).$$  \hspace{1cm} (5)

$\frac{dN}{d\Omega}(\vec{r}, \Omega_\ell)$ no longer appears in the large $d$ approximation as interior annihilation angles are averaged out over the entire galaxy resulting in spherical symmetry.

In the limit $d \gg r_s$, the canonical $J$-factors can also be reduced.

$$J_{\text{ann}} \approx d^{-2} \int dV \rho^2(r) \quad J_{\text{decay}} \approx d^{-2} \int dV \rho(r)$$  \hspace{1cm} (6)
Recall Eq. (4),

\[ \mathcal{P}_{\chi_2^c\chi_2}(r) = \frac{\Lambda \eta_2(r)}{4\pi} \int dq \, d\Omega_q \, [\eta_1(q)]^2 \left(\frac{q}{s}\right)^2 \exp \left[-\Lambda \int_0^s ds' \, \eta_2(s')\right] \]

At \( \Lambda \gg 1 \), we recover canonical annihilation as \( \chi_2^c \) is unable to travel far.

\[ \mathcal{P}_{\chi_2^c\chi_2}(r) \approx [\eta_1(r)]^2 \quad J_{NL} \approx d^{-2} \int dV \, [\rho_1(r)]^2 \quad (7) \]

At \( \Lambda \ll 1 \), \( \chi_2^c \) have a very low chance of annihilation within the galaxy.

\[ \mathcal{P}_{\chi_2^c\chi_2}(r) \approx \frac{\Lambda \eta_2(r)}{4\pi} \int dq \, d\Omega_q \, [\eta_1(q)]^2 \left(\frac{q}{s}\right)^2 \quad (8) \]

Furthermore, if most \( \chi_1 \) annihilation occurs in a central core, then \( q \ll r \) for relevant regions, and \( s \to r \)

\[ J_{NL} = c_1 \, d^{-2} \Lambda \int dr \, \eta_2(r) \int q^2 dq \, d\Omega \, \rho_1^2(q) = c_2 \Lambda \, d^{-2} \int dV \, \rho_1^2(q) \quad (9) \]