Snowmass2021 - Letter of Interest

Probing Dark Matter Dynamics with An Ensemble of Gamma-Ray Signals from Different Galaxies

Thematic Areas: (check all that apply □/■)
■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Theory Frontier: Astro-Particle Physics and Cosmology

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Abstract:
The search of dark matter (DM) annihilation or decay in experiments designed primarily to detect cosmic-ray particles and gamma-rays, despite being called *indirect* detection of DM, can provide direct information on many properties of DM particles inside galactic halos. For different types of DM models, the rate of the indirect detection signals produced from different DM interactions can have different dependence on halo properties, such as the halo mass, size, and the velocity distribution of DM particles. As a result, a comparison of signals from different DM halos, especially from the comparison of signals from the dSphs, may allow us to identify additional details of the generating process. Our proposal is to study the possibility of distinguishing DM models based on the gamma-ray observations from the existing and near future experiments.

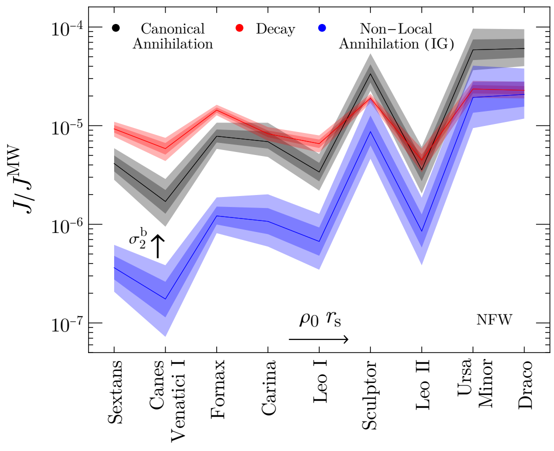

Figure 1: An illustration of the ratio of dSph J-factors to the MW's for various dark matter models assuming an NFW DM profile. We connect the results between dSph in order to better visualize the trend of galaxy-dependence. The width of the colored-bands at each galaxy represents the 1 and 2σ uncertainties from the NFW fit. Please see [1] for more details. Our proposal is to study the possibility of disentangle different scenarios of DM annihilation using an ensemble of gamma-ray signals from different galaxies.

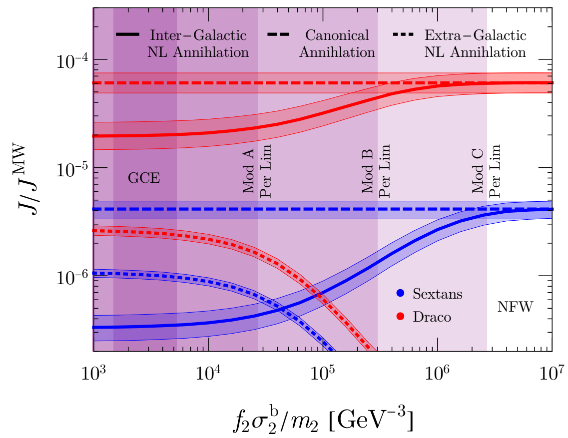

Figure 2: An illustration of the additional galaxy dependence in J-factors associated with the "non-local" DM model for select dSph. The ratio of J transitions between different characteristics as model parameters vary. These transitions occur at different values depending on DM halo properties. Please see [1] for more details. Bands represent 1σ uncertainties on halo NFW properties. Shaded vertical regions are permitted paramter space for various models discussed in [1].

Motivation: Over the past few years, several anomalies in astrophysical signatures have provided strong motivations to study such signals from DM models. Among the different searches, the Fermi-LAT experiment [2] produced a gamma-ray survey of the sky for 100 MeV $-$ 100 GeV scale photons for both the Milky Way (MW) and dwarf spheroidal galaxies (dSph). The experiment also observed an intriguing excess of gamma-rays from the MW center [3] (thus called the galactic center excess or GCE) that has the right morphology to be explained by DM physics [4]. As future experiments like e-ASTROGAM [5], Gamma-400 [6], and DAMPE [7] have been proposed to extend the energy coverage of the gamma-ray signal, we expect significant improvements in the observations of MW and dSph. We will therefore use the DM production of gamma-ray signal as an example to discuss how we can probe the dynamics of DM from an ensemble of such detections from different objects.

Galaxy-dependent signal from different DM models: The differential photon flux $\mathrm{d}\Phi/\mathrm{d}E_\gamma$ arising from DM annihilation or decay in any astrophysical target for indirect DM detection contains the so-called J-factor that encodes all the astrophysical contributions. Since these J-factors are galaxy-dependent, once the gamma-ray signals from different galaxies are measured, we can fit the power of DM densities and determine the production mechanism of the signal. As is illustrated in Fig. 1, the two scenarios of canonical DM annihilation (black) and decay (red) can be distinguished by their ratio of J-factors with a reference galaxy after taking into account the uncertainty of the NFW fit used in the figure. Our plan is to study more DM models that have non-trivial galaxy-dependent J-factors and determine if differences in their J-factors will be visible after taking into account uncertainties in halo profiles and the sensitivity of the experiments.

Many DM models can generate different galaxy-dependent J-factors than the canonical DM annihilation and decay. For example, if the annihilation of DM particles is velocity-dependent, the J-factors will also depend on the velocity distribution of DM particles [8, 9, 10]. In models that DM produces gamma-rays through more than one step annihilation processes, such as $\chi_1\chi_1 \to \chi_1^{\rm boost} + X$, $\chi_1^{\rm boost} + \chi_1 \to$ SM in the so-called "non-local" annihilation scenarios [1], the J-factor will further depend on the density and the core size of DM halos. The non-local annihilation signal is also shown in Fig. 1 (blue) and is distinguishable from both canonical annihilation and decay. In scenarios where DM first decay into boosted mediator particles that later decay into gamma-rays [11, 12], the signal will also depend on the choice of the "region of interest" in the gamma-ray observation. Each of these DM scenarios can predict a distinct fingerprint of the J-factors in an ensemble of dSph observations, and we plan to study how robust the distinction is even after considering the uncertainty of halo properties.

An interesting property of some DM models is a galaxy-dependent degeneracy with the canonical DM models. This degeneracy results in some (typically larger) galaxies possessing signals similar to canonical models, while other (smaller) galaxies will have J-factors with different dependencies on galactic parameters. This degeneracy is observed in Fig. 2 for the non-local annihilation model discussed in [1]. As the annihilation cross-section for the second interaction increases, the J-factor compared to a reference galaxy merges with the canonical model. This merger between the two models also occurs for different model parameters in different galaxies as seen in Fig. 2. This transition based on galactic halo size presents an additional signature to distinguish the two models. We plan to study the magnitude of such a transition in various models and its significance with experimental uncertainties.

References

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