Multi-messenger Observations of Ultra-faint Dwarf Galaxies as Probes of Dark Matter

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Abstract

Multi-messenger observations using next generation telescopes have great potential in understanding the nature of Dark Matter. DM indirect detection through observations with CTA and LHAASO (in the gamma ray domain) and KM3NeT (in the neutrino domain) can shed light upon the non-Gravitational properties of DM. The DM models under consideration in this work were proposed to explain the DAMPE excess flux detected by Wukong in late 2017 and all involve Weakly Interacting Massive Particles, with a mass on the TeV scale, coupled exclusively to Standard Model Leptons via a heavy mediator. We make use of simulations of the expected indirect emissions from the Annihilation and Decay of the WIMPs, in both gamma and neutrinos. We consider observations, in both domains, of two Dwarf Spheroidal galaxies in the Local Group. The target galaxies are chosen as Segue I and Tucana II – with four observations in total being proposed for the three telescopes under consideration. All target Dwarf Spheroidal galaxies are Ultra-faints with particularly high astrophysical J and D factors. Using conservative estimates of telescope sensitivities, we forecast non-detection upper bounds upon the free parameters - the WIMP Annihilation Cross Section and the Decay Rate respectively.

Existing Limits on WIMP Parameter Space

We focus only on constraints placed upon the WIMP Annihilation Cross-Section - $<\sigma v>$ - on account of the fact that the Decay channel is suppressed. The constraints upon the Decay Rate will be dealt with in the conference proceedings. Constraints have been imposed upon $<\sigma v>$ by a number of observations and experiments, including [1]:

- The relic density
- The Cosmic Microwave Background
- The Large Electron-Positron (LEP) Collider constraints on Z', the mediator particle
- The Dark Matter Direct Detection Constraints
- The DAMPE excess flux

The DAMPE Excess Flux and MLMPs

In late 2017, Wukong, the DArk Matter Particle Explorer, detected an excess e^-/e^+ flux at approximately 1.4 TeV [2]. A number of WIMP models, as detailed in [3], [4] and [1], were posited to explain the unexplained DAMPE flux. These posited WIMPs, ψ, all have the following features in common:

- They are Leptophilic and couple to SM leptons via a heavy mediator Z'
- Their masses are on the TeV scale
- They are self-annihilating Majorana fermions

These WIMPs are thus termed Massive Leptophilic Majorana Particles (MLMPs), which interact on the scale of the Weak force. Each of the three models under consideration have an MLMP mass between 1 TeV and 2 TeV. They differ primarily with respect to their annihilation channels (their coupling to SM leptons), with [4] looking at the e^-/e^+ channel only, while [1] considers both the e^-/e^+ and μ^-/μ^+ channel. [3] posits an MLMP coupling to e^-/e^+ only or all leptons equally (the 3l democratic case). The Annihilation spectra for the respective channels are produced by event generators, as presented in [5]. These MLMP models must now be tested in the context of new target objects.

Ultra-faint Dwarf Spheroidal Galaxies and the Search for Dark Matter

The ultra-faints under consideration, Segue I and Tucana II, have very high observed ratios of DM to Baryons, corresponding to high mass to luminosity ratios. Therefore, annihilation signals in gamma and neutrinos are uncontaminated by baryonic backgrounds. Both ultra-faints have high J and D factors [6], reflecting high concentrations of Dark Matter and their suitability as target objects in the search for DM. These Ultra-faints are not the sort of galaxies that evoke images of diamonds floating on an emerald ocean. They are, in the truest state, dark. And inside that darkness, there are secrets. DM indirect detection allows us to astrophysicslly probe one such secret - the non-Gravitational properties of Dark Matter. We focus here on Segue I and leave Tucana II to the proceedings, owing to the fact that the results are quite similar.

The Potential of Next-Generation Telescopes

Powerful upcoming telescopes like the Cherenkov Telescope Array (CTA) and the Cubic Kilometer Neutrino Telescope (KM3NeT) boast unprecedented sensitivities and thus allow for a strong multi-messenger astrophysical test of the MLMP models. The conservative sensitivity data is taken from the analysis in [7], with CTA having a minimum confidence level of 5σ and KM3NeT having a minimum confidence level of 3σ. We note that we focus only on muon neutrinos for KM3NeT, owing to the fact that only muon neutrinos were relevant to KM3NeT in 2018, when the analysis in [7] was conducted. We compare these sensitivites to the sensitivities of prior telescopes like the Large High Altitude Air Shower Observatory (LHAASO) and thus we compare the constraints imposed by the different telescopes. For LHAASO, we utilise the analysis of the sensitivity in [8], which is gathered from one year of exposure time.

Constraints upon Annihilation Cross-Section: CTA

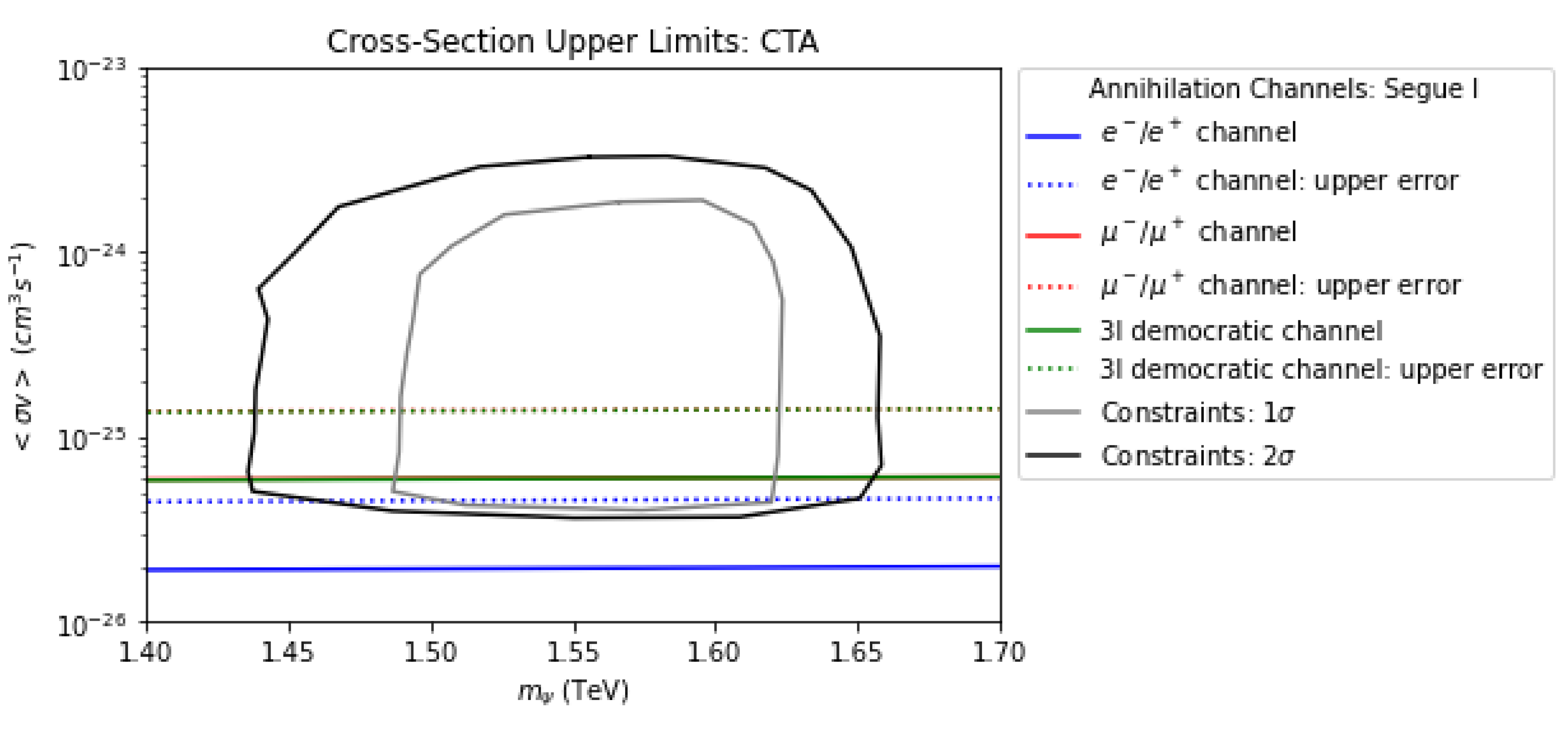

Figure 1: Novel constraints placed upon the MLMP annihilation cross section by gamma ray observations with CTA

Constraints upon Annihilation Cross-Section: LHAASO

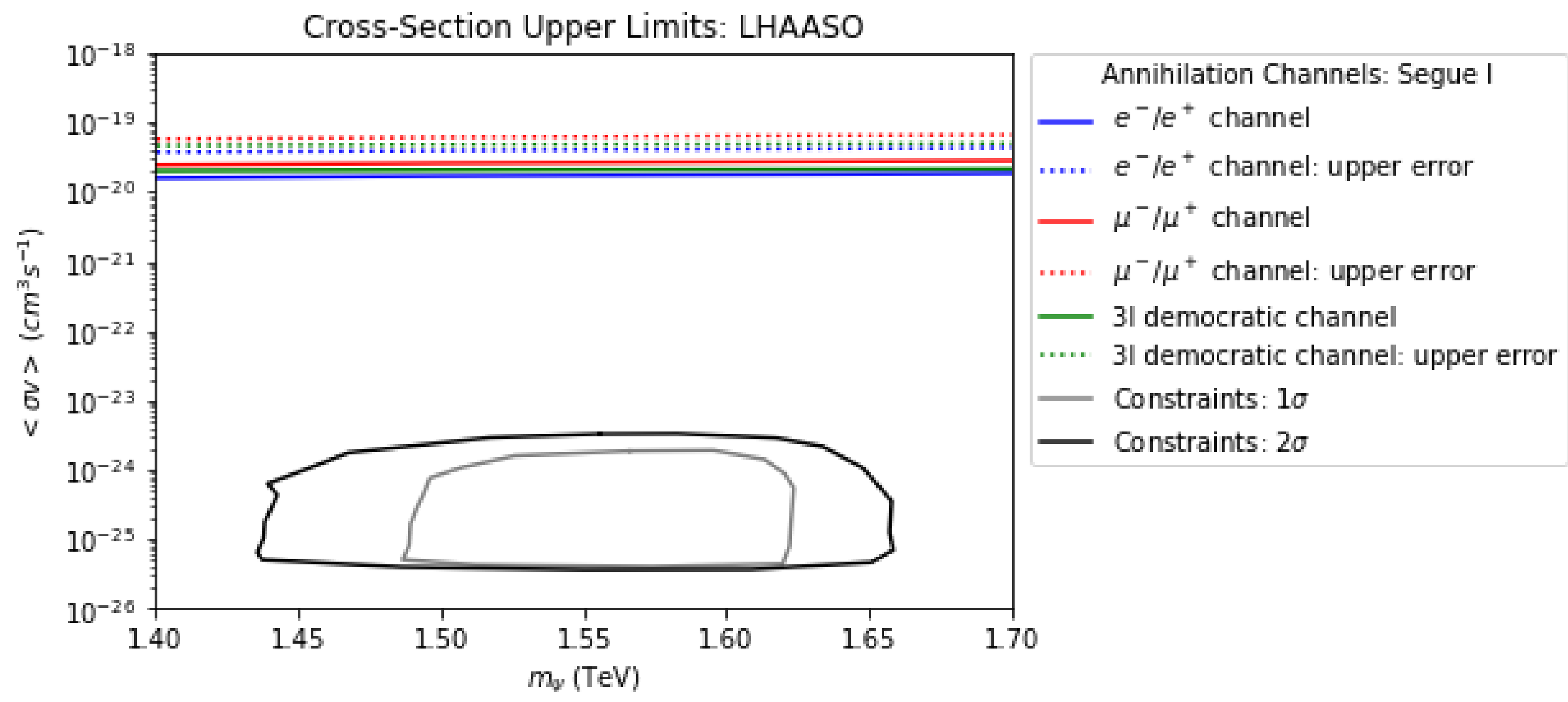

Figure 2: Novel constraints placed upon the MLMP annihilation cross section by gamma ray observations with LHAASO

Constraints upon Annihilation Cross-Section: KM3NeT

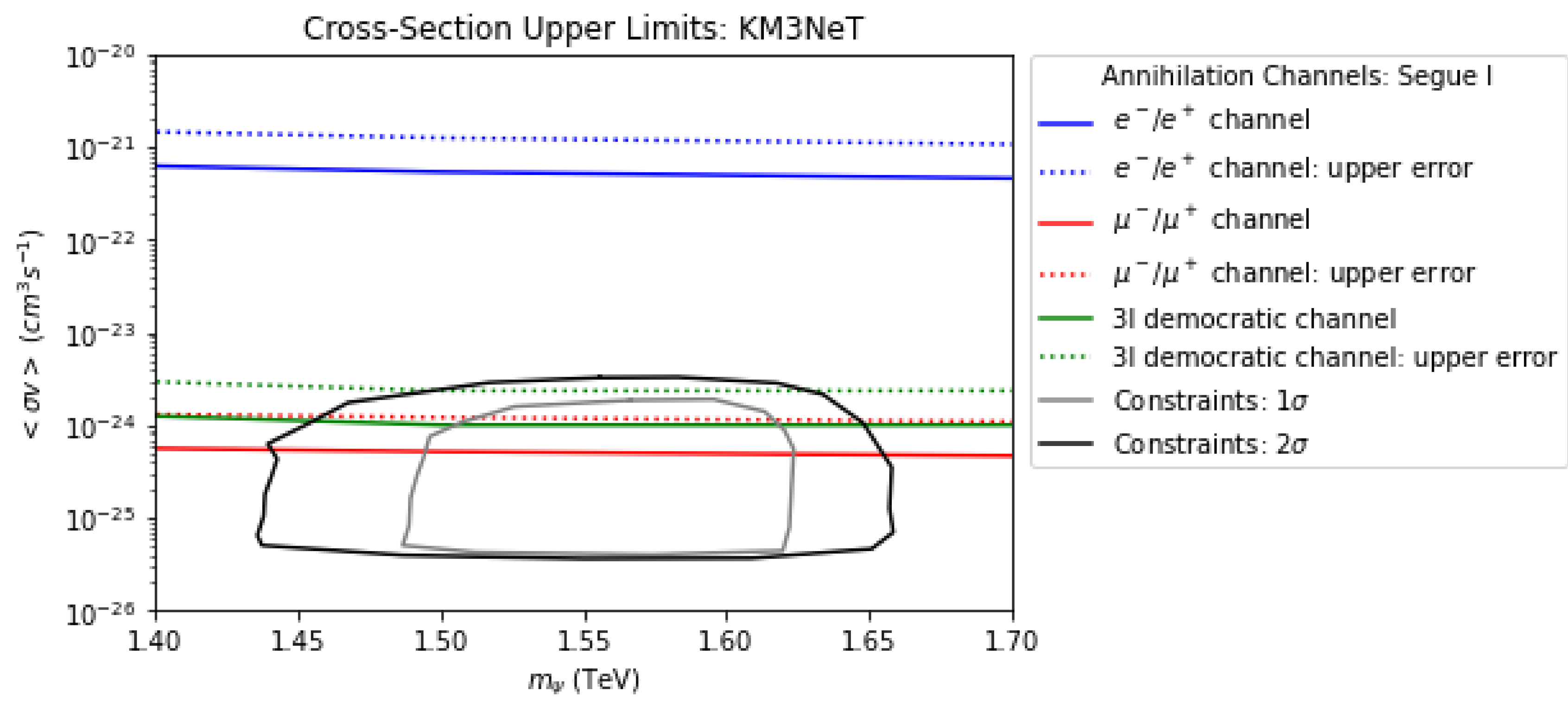

Figure 3: Novel constraints placed upon the MLMP annihilation cross section by muon neutrino observations with KM3NeT

Interpretation of Results

Gamma ray bservations of Segue I with CTA places significant constraints upon ¡σv¿, for all annihilation channels, even when error is accounted for. On the other hand, gamma ray observations with LHAASO fail to impose constraints upon the parameter space for all channels. This is unsurprising, given that CTA is the largest and most sensitive gamma ray observatory in history and thus better constraints are imposed when compared to prior telescopes like LHAASO. In the case of KM3NeT, neutrino observations will impose significant constraints upon the parameter space, except in the case of the e^-/e^+ channel.

Conclusions

We can thus significantly constrain the parameter space for the velocity averaged annihlation cross section of the MLMP models under consideration, imposing an upper bound on $<\sigma v>$. We do so by calculating the consequences of non-detection by powerful next generation telescopes like CTA and KM3NeT, along with contemporary telescopes like LHAASO, in gamma rays and neutrinos. This strategy will allow us to potentially eliminate MLMP models on the basis of future multi-messenger astrophysical observations. The annijhilation cross-section dealt with in this work can be physically conceptualised as inversely proportional to the mean free path of the MLMPs. This will be fleshed out in the conference proceedings.

Forthcoming Research

If the observations proposed do detect significant pairs of excess fluxes for the target Ultra-faints, the theoretical methodology employed in this research will allow us to process the data and determine intrinsic properties of DM beyond those of gravitation. Moreover, radio observations of the target Ultra-faint Dwarf Spheroidal Galaxies like Segue I and Tucana , using powerful radio telescopes like MeerKAT, will compliment the analysis conducted here in gamma rays and neutrinos. Thus, one more astronomical messenger willl be entrusted to whisper the secrets of Dark Matter into the listening ears of our world's most powerful telescopes.

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