Probing the Dark Matter of the Three-loop Radiative Neutrino Mass Generation Model with the Cherenkov Telescope Array

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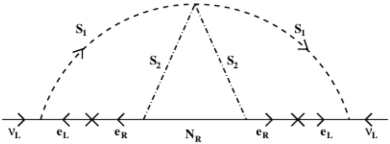
Based on PRD, **103**, 035002 (2021)

17th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2021)
26 August - 3 September, 2021, Valencia, Spain (Online Conference)

Motivation

- The upcoming Cherenkov Telescope Array (CTA) will offer a unique opportunity to probe the nature of the Dark Matter (DM) in the Universe.
- The CTA is expected to have 10 times more sensitive detection capability of very high-energy gamma rays, specially of $\mathcal{O}(\mathrm{TeV})$ energy compared to the currently operating Imaging Atmospheric Cherenkov Telescopes (IACTs).
- Therefore, we study the detection sensitivity of the possible TeV gamma rays produced from heavy DM annihilation with mass also in the multi-TeV range.
- We focus on the DM candidate in the large electroweak multiplet and its realization in the three-loop radiative neutrino mass generation model: The Krauss-Nasri-Trodden (KNT) model. arXiv:hep-ph/0210389
- So that we can say more about the DM, the large electroweak multiplet and the KNT model itself.

The minimal KNT Model



BSM Field(s)	Spin	$SU(2)_L$	$U(1)_Y$	Z_2
S_1^+	0	0	1	1
S_2^+	0	0	1	-1
$N_{R_{1,2,3}}$	1/2	0	0	-1

- Neutrino mass is generated radiatively at three loops.
- The minimal KNT model has a Z_2 symmetry imposed on S_2^+ and N_{R_i}.
- The DM candidate of this model is the lightest majorana fermion, N_{R_1}.
- The Z_2 symmetry also stabilizes N_{R_1}.

KNT model with Large Electroweak Multiplets

- We introduce large electroweak multiplets with $SU(2)_L$ isospin, J and hypercharge, Y in the KNT model as follows,

$$S_2^+ \quad \to \mathbf{\Phi} = \left(\phi^{(n+1)}, .., \phi^+, \phi^0, \phi'^-, .., \phi'^{(-n+1)}\right)^T, \ (J = n,\ Y = 1)$$

$$N_{R_i} \quad \to \mathbf{F_i} = \left(F_i^{(n)}, ..., F_i^+, F_i^0, F_i^-, .., F_i^{(-n)}\right)^T, \ (J = n,\ Y = 0)$$

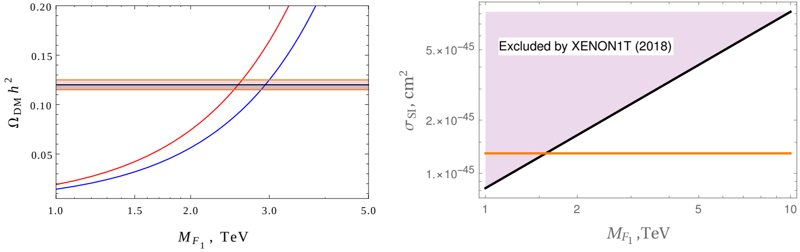
- The replacements leave the neutrino generation topology invariant. arXiv:1404.2696; 1404.5917; 1504.05755

- There is no symmetry to forbid such replacements in the KNT model.

- One advantage of such large electroweak multiplet is to have accidental Z_2 symmetry in the model, e. g. the KNT model with $J = 3$ multiplets (7-plet). arXiv:1504.05755

DM Candidates in Electroweak Multiplets

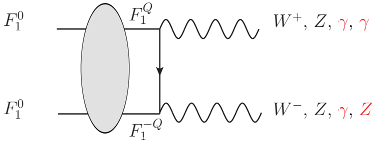
- In the generalized KNT model, the DM candidate is the neutral component, F_1^0 of the lightest fermionic multiplet.
- We can use the DM phenomenology to constrain the size of EW multiplets.
- We focus on the immediate extension of the minimal KNT model, which is the model with $J = 1$ electroweak multiplets (Triplet KNT model).
- We explore the region of parameter space where the DM has $O(\mathrm{TeV})$ mass.



- One can even go beyond the unitarity bound on the DM mass ($\gtrsim$ 100 TeV) for thermal freeze-out by considering various Non-thermal production mechanism.

Why TeV mass range for the DM?

- When $(m_W/m_{DM})/\alpha_W \ll 1$ & $(v_{DM}/c)/\alpha_W \ll 1$, the annihilation cross-sections of such non-relativistic heavy DM to SM gauge bosons increase due to the Sommerfeld enhancement (SE). hep-ph/0212022, hep-ph/0307216, hep-ph/0412403, arXiv:0706.4071, arXiv:0810.0713

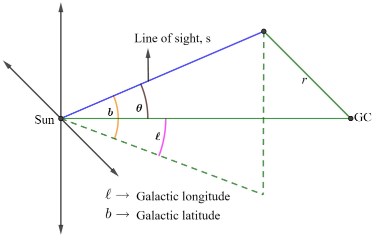


- The Sommerfeld Enhancement also increases with the size of electroweak multiplet as more of its component fields coherently contribute to the enhancement.
- So, enhanced gamma-ray signature from such heavy non-relativistic DM annihilation is expected.
- We have considered the DM rich Galactic Center for which the CTA also has an extensive observational plan.
- We expect diffuse gamma ray spectra for WW, ZZ final states and line-like spectra for $\gamma\gamma$ and γZ.

Gamma-ray flux from DM annihilation at Galactic center

- Gamma rays, unlike charged particles, are not scrambled by interstellar magnetic field and travel directly to the observer from the source.
- The gamma-ray flux (for Majorana DM):

$$\frac{d\Phi_\gamma}{dE_\gamma} = \underbrace{\frac{\langle \sigma v \rangle_{\text{ann}}}{8\pi m_{DM}^2} \sum_f B_f \frac{dN_f}{dE_\gamma}}_{\text{Particle Physics}} \underbrace{\int_{\Delta\Omega} \int_{l.o.s} ds \, d\Omega \, \rho_{DM}^2(r(s,\theta))}_{\text{Astrophysical J-factor}}$$



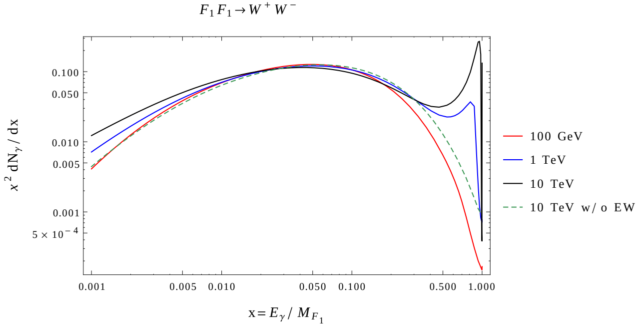
Gamma-ray flux from DM annihilation at Galactic center

- Two DM density profiles: Navarro-Frenk-White (NFW) profile and Einasto profile,

$$\rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}, \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

- J-factor still contains large uncertainties. Affects the final sensitivity.
- The photon spectrum, $\frac{dN_f}{dE_\gamma}$ can be determined by PPPC 4 DM ID or PYTHIA8.2.

1012.4515; 1410.3012



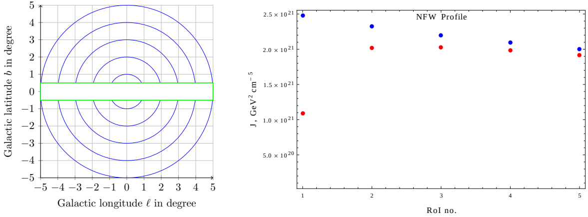
From DM annihilation at GC to the CTA

- Two main backgrounds: Cosmic-ray (CR) and Galactic Diffusion Emission (GDE).
- CR initiated air shower is wider than γ shower. Can be rejected by shower image and arrival time of shower front. Still residual contamination.
- Expected CR background at CTA has been derived by extensive Monte Carlo simulations and incorporated in CTA prod3b-v2 Instrument Response Function (IRF). www.cta-observatory.org/science/cta-performance
- GDE originates from CR interacting with interstellar dust and radiation fields. Large GDE has been detected from Galactic ridge of latitude, $|b| < 0.3^\circ$ with E_γ up to 20 TeV. 1202.4039; astro-ph/0603021

From DM annihilation at GC to the CTA

Observational Strategy

- Our observational method is based on the Multi-RoI morphological analysis. 1408.4131, 1502.05064, 1706.01505.
- The Region of Interest (RoI) is divided into five concentric circles, each with width 1° such that the outermost circle has radius 5°.



- The central part of the GC, populated with several astrophysical sources including Sagittarius A* (SgrA*), has large gamma-ray background. So, we discard that part with a rectangular patch of $0.3^\circ < b < -0.3^\circ$ and $-5^\circ < \ell < 5^\circ$ within each RoI.
- The expected number of photon counts for **signal** (DM) and **backgrounds** (CR, GDE) in each circular RoI have been computed simultaneously.

The expected differential and total photon count for each RoI i and energy bin j from the source $X =$ DM, CR and GDE, are calculated using the relations,

$$\frac{d\Gamma^X_{\gamma,i}}{dE'_\gamma} = \int_{\Omega'_i} d\hat{p}' \int dE_\gamma \int d\hat{p}\, \underbrace{A_{\rm eff}(E_\gamma, \hat{p})}_{\text{Effective Area}} \overbrace{PSF(\hat{p}, \hat{p}')}^{\text{Point Spread Function}} \underbrace{E_{\rm disp}(E'_\gamma, E_\gamma, \hat{p})}_{\text{Energy Dispersion}} \overbrace{\frac{d\phi^X_\gamma}{dE_\gamma d\Omega}(E_\gamma, \hat{p})}^{\text{Differential photon flux}}$$

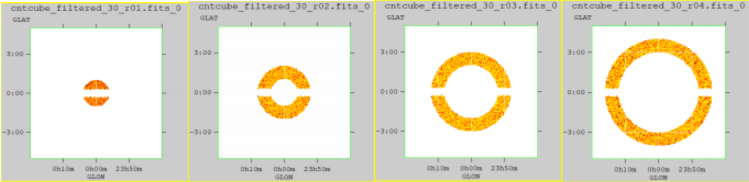
And the total photon count,

$$\mu^X_{ij} = T_{\rm obs} \int_{\Delta E_j} \mathrm{d}E_\gamma \frac{\mathrm{d}\Gamma^X_{\gamma,i}}{\mathrm{d}E_\gamma}$$

- We focus on the DM annihilating into the W^+W^- final state that would lead to the diffuse gamma ray spectrum.
- We divide our photon counts into twenty logarithmic spaced energy bins from 30 GeV to m_{DM}, and five RoIs. Also, the observation time is set to $T_{\rm obs} = 100$ hr.

Analysis

- For analysis, we specifically make use of **South_z20_50h** in the 'CTA-Performance-prod3b-v2-FITS.tar.gz' IRF (southern site with zenith angle 20° and exposure time 50 hours) throughout our entire study.
- Because, our focus is to probe DM signal from the GC, and the CTA southern site is favorable for surveying the γ sources in the GC with energy ranges from 20 GeV to 300 TeV.
- The expected gamma-ray count associated with the CR is evaluated using `ctools` version 1.6.2. 1606.00393.

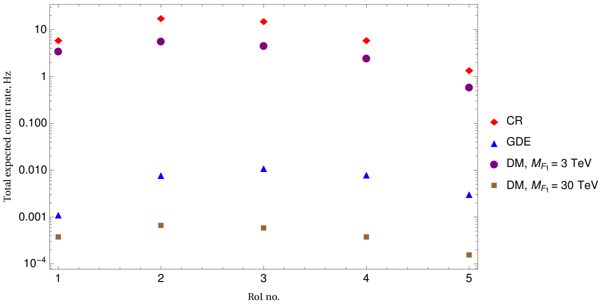


- We compute the expected photon count for the GDE using the following simplified flux which is a power-law extrapolation up to 100 TeV from the Fermi P7V6 model,

$$\frac{\mathrm{d}\phi^{\mathrm{GDE}}}{\mathrm{d}E_\gamma} = 1.0064 \times 10^{-6} \left(\frac{E_\gamma}{\mathrm{GeV}}\right)^{-2.333} \quad \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

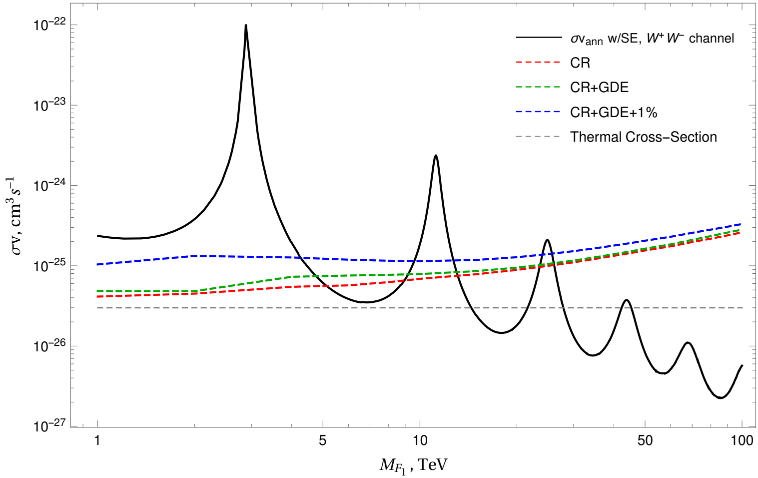
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

KNT model at the CTA



- Total expected count rates from DM, CR and GDE at *i*-th RoI which is given by $\sum_j \mu_{ij}/T_{\text{obs}}$.
- Here, the total expected count rates for 3 TeV DM are comparable to CR counts because of its large SE annihilation cross-section $\sigma v = 2.6 \times 10^{-23}\text{cm}^3\text{s}^{-1}$ compared to 30 TeV DM which has $\sigma v = 1.3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$.

Limits on Triplet DM in KNT



The projected upper limit on the annihilation cross-section for the triplet dark matter into W^+W^- final state for the NFW profile and 100 hour of observation at the CTA.

Conclusion

- The DM of an electroweak multiplet, being charged under the SM gauge group, can have large Sommerfeld enhanced annihilation when it's non-relativistic and $m_{DM} \gg m_W$. This is the case for the triplet extension of the KNT model.

- We have seen that the CTA can probe large portion of the KNT model's parameter space where the DM mass is $O(\mathrm{TeV})$.

- We show that the DM of the triplet KNT model annihilating into W^+W^- at the GC can be probed up to 25.7 TeV by the CTA experiment considering NFW profile and 100 hours of observation.

- Sensitivity of detecting TeV gamma-ray from DM annihilation in KNT model also put complementary limit on the size of the EW multiplet.

- The CTA can also probe such heavy DM annihilation signatures in other Beyond the Standard Model (BSM) scenarios with large electroweak multiplets.

Thank you very much for your attention.