Gamma-ray from Dark Matter Annihilation in Three-loop Radiative Neutrino Mass Generation Models

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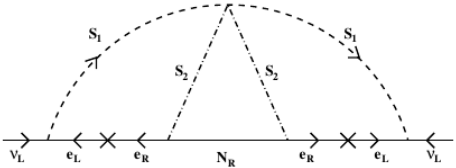
Based on PLB (2018) **782**, 215 and 1912.xxxxx

TeV Particle Astrophysics 2019
2 - 6 December, 2019, Sydney, Australia

Motivation

- Astrophysical and cosmological observations have strongly supported Dark Matter (DM) as an essential component of the Universe.
- Still, we don't know the particle nature of the DM.
- On the other hand, we know that Neutrino has the mass but only at the eV range compared to the other Standard Model (SM) particles.
- Again, the origin and the smallness of the Neutrino mass don't have any conclusive physics of the Beyond Standard Model (BSM) yet.
- The Krauss-Nasri-Trodden (KNT) model, which is in the class of Radiative Neutrino Mass Generation Models (RνMass Models), explains these two issues in a coherent manner. arXiv:hep-ph/0210389

The KNT Model



- The KNT model contains two single charged scalars, S_1^+, S_2^+ and three fermionic singlets, N_{R_i} as the BSM field contents.
- Neutrino mass is generated at three loops.
- The DM candidate of the model is N_{R_1} that has the lowest mass.
- Neutrino mass is generated radiatively if the Dirac term, $y_\nu \overline{l_L} N_R H$ is absent. So one requires to impose a Z_2 symmetry on S_2^+ and N_{R_i}.
- That Z_2 symmetry can also stabilize N_{R_1}.

KNT model with Large Electroweak Multiplets

- Subsequently, for 3-loop KNT model the replacements $S_2^+ \to \mathbf{\Phi}$ with $(J = n, Y = 1)$ and $N_{R_i} \to \mathbf{F_i}$ with $(J = n, Y = 0)$ leave the neutrino generation topology invariant. arXiv:1404.2696; 1404.5917; 1504.05755
- There is no symmetry reason to forbid replacing minimal field content with larger electroweak (EW) multiplets in the KNT model.
- If $J = 2$ (5-plet), there is no SM invariant Dirac term at the renormalizable level of the Lagrangian.
- Still, one has terms in the Lagrangian which induce 4-body and 5-body decays for DM but the couplings associated with them can be set small and setting them to zero leads to Z_2 symmetry again.

  arXiv:1404.5917
- But when $J = 3$ (7-plet), even those terms are absent and the model has the accidental Z_2 symmetry. arXiv:1504.05755

Viability of Models with large EW Multiplets

- What is the possible upper bound on the size of the EW multiplets?
- One possible bound can be derived from Tree-unitarity of high energy scattering. Annals Phys. **7**, 404 (1959); PRL, **38**, 883 (1977)
- At unbroken SM gauge symmetry, we have looked into $F_i^{(Q)} F_j^{(-Q)} \to W^+ W^-, W^3 W^3$, $F_i^{(Q+1)} F_j^{(-Q)} \to W^+ W^3$ and $F_i^{(Q+2)} F_j^{(Q)} \to W^+ W^+$ scattering to set $J \leq 6-8$ for $N=1$ and $J \leq 3-5$ for $N=3$.
- Another bound can be derived from appearance of low scale Landau pole in $SU(2)$ gauge coupling. arXiv:1310.8152; 1504.00359; 1505.01721
- For $J=1$, $\Lambda_{\text{Landau}} = 10^{11}$ GeV, for $J=2$, $\Lambda_{\text{Landau}} = 10^4$ GeV and finally for $J=3$, $\Lambda_{\text{Landau}} = 650$ GeV.
- Therefore, larger EW multiplets, $J \geq 2$ are disfavored by as there is no strong $SU(2)$ coupling at the LHC accessible energy.

Electroweak Multiplets as DM Candidates

- In KNT model, the DM candidate is the neutral component, F_1^0 of lightest fermionic multiplet, $\mathbf{F_1}$ where $M_{F_1} \ll M_{F_{2,3}}$.
- We can use DM phenomenology to constrain the size of EW multiplets.
- our region of parameter space is TeV mass-ranged DM (Heavy WIMP or Electroweak DM).
- At TeV, annihilation cross-section of non-relativistic EW DM increases due to the Sommerfeld enhancement (SE) in SM gauge bosons channels. hep-ph/0212022, hep-ph/0307216, hep-ph/0412403, arXiv:0706.4071, arXiv:0810.0713
- SE also increases with the size of multiplet.
- So, one can expect enhanced gamma-ray signature from such heavy non-relativistic DM annihilation at the Galactic center (GC). Diffuse spectrum for WW, ZZ, and line-like spectrum for $\gamma\gamma$ and γZ.

TeV Gamma-ray and Cherenkov Telescopes

TeV Gamma-ray coming from the DM annihilation at the GC can be detected by Imaging Atmospheric Cherenkov Telescopes (IACTs).

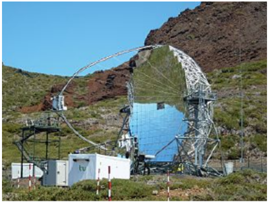


Figure: (Upper left) Major Atmospheric Gamma Imaging Cherenkov Telescope (MAGIC), (Upper right) Very energetic Radiation Imaging Telescope Array System (VERITAS), (lower) High Energy Stereoscopic System (H.E.S.S.)

The Cherenkov Telescope Array (CTA)

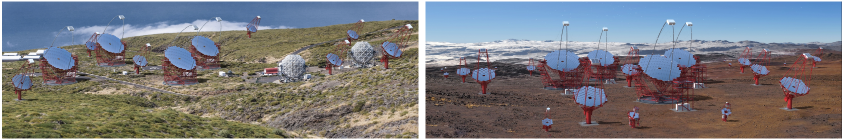


Figure: (left) CTA northern site (La Palma, Spain) and (right) CTA southern site (Atacama, Chile) http://www.cta-observatory.org

- CTA has the plan to install about 19 and 99 telescopes in its northern and southern sites, respectively.
- This will allow for CTA to have large effective area $\sim O(10^6)\,\mathrm{m}^2$.
- Also, CTA has the wide field of view, $\sim 10\,\mathrm{deg}$.
- CTA can also probe gamma-ray with energy ranging from 20 GeV - 300 TeV.
- Moreover, it has better rejection of Cosmic ray (CR) background.
- Therefore, CTA will have at least $O(10)$ improvement in sensitivities compared to currently operating IACTS. arXiv:1709.07997

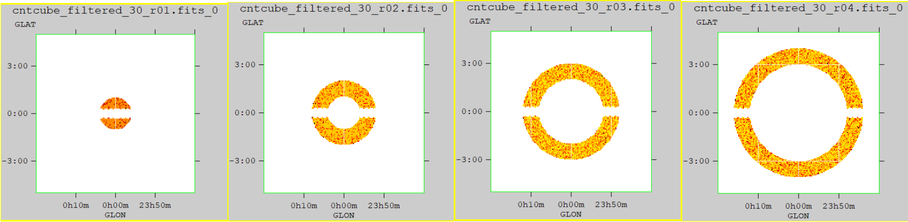
TeV gamma-ray from DM in KNT: Singlet vs Triplet

- At TeV, the triplet DM is expected to have large cross-section due to SE in gauge bosons annihilation channels.
- In contrast, the SM singlet DM of the minimal KNT model has 2-body annihilation: $N_1 N_1 \to e\bar{e}$ which is p-wave suppressed.
- Still, $N_1 N_1 \to e\bar{e}\gamma$ via virtual internal Bremsstrahlung (VIB) can result large gamma-ray flux for $m_{\rm DM} \lesssim 1$ TeV.
- For $m_{\rm DM} \gtrsim 10$ TeV, gamma-ray flux for VIB induced annihilation channel is highly suppressed compared to WW channel. So one expects the triplet DM of the KNT model to be within the reach of CTA.

KNT model at the CTA

- We've used ctools 1.6.2 to determine expected count for DM in KNT model and the relevant backgrounds. cta.irap.com.eu/ctools.
- Our analysis methodology is based on arXiv:1408.4131; 1502.05064; 1706.01505
- We've considered five co-centric annuli centered at the Galactic center and ranging from 0 to 5 degrees to be our region of interest (ROI).
- We've determined the expected counts from DM signal for NFW profile and two main backgrounds: Cosmic ray (CR) and Galactic Diffusion Emission (GDE) for each ROI and energy bin (20 logarithmically spaced energy bins from 30 GeV to $E_\gamma^{max} = m_{\rm DM}$).
- Expected CR background count is determined by incorporating CTA prod3b-v2 Instrument response function (IRF) South_z20_50h into ctools. www.cta-observatory.org/science/cta-performance
- Expected GDE count is determined using a power law extrapolated from Fermi-LAT P7V6 backgroud model. fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

KNT model at the CTA



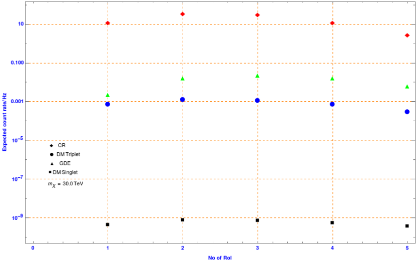


Figure: (upper) Expected CR counts from first four ROIs where energy range is 30 GeV - 30 TeV. (lower) Expected count rates from DM, CR and GDE for $m_{\rm DM} = 30$ TeV.

Limits on Triplet DM in KNT

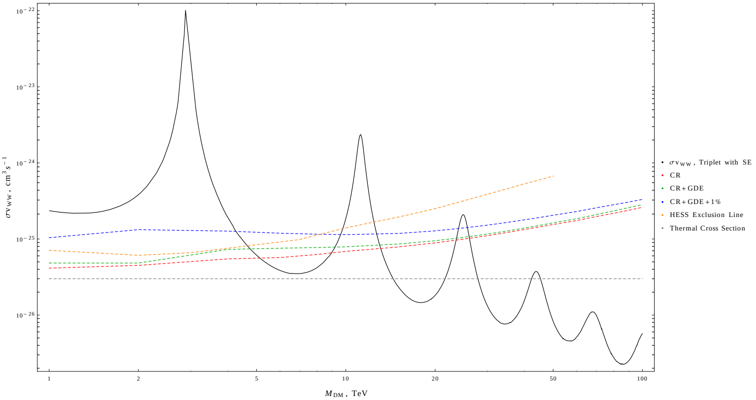


Figure: Limits on SE annihilation cross-sections to WW for triplet DM (NFW profile). H.E.S.S. limit (arXiv:1607.08142)

Limits on larger EW multiplet DM in KNT

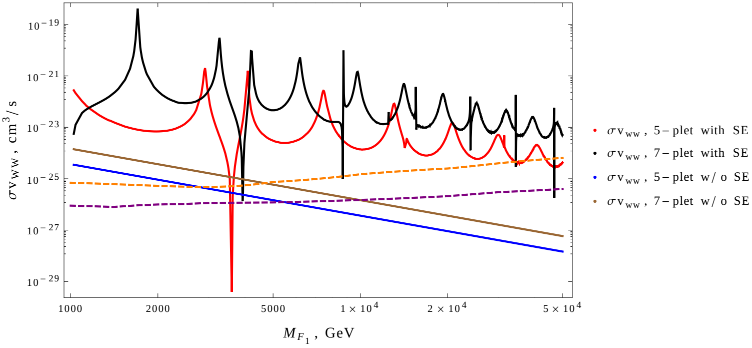


Figure: Limits on SE annihilation cross-sections to WW for 5-plet (red) and 7-plet (black) (Einasto profile). Orange dashed line: H.E.S.S. limit (arXiv:1607.08142) and Purple dashed line: CTA limit (arXiv:1709.07997)

Conclusion

- Theoretical limits on the size of the EW multiplets in KNT model set $J \leq 1$.
- Sensitivity of detecting TeV gamma-ray from DM annihilation in KNT model also put complementary limit on the size of the EW multiplet.
- DM in 5-plet and 7-plet of the KNT model can be entirely probed by CTA for $m_{\rm DM} = 1 - 50$ TeV.
- In case of Triplet DM, CTA can probe DM up to 20 TeV.
- The minimal KNT model with singlet DM is favored with respect to TeV gamma-ray detection aspects from DM annihilation.

Thank you very much for your attention.