Expanding the Search for Dark Matter to Models with Strong Self-interactions
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Abstract
The In our search for dark matter, we aim to test models with strong self-interactions. For this, we estimate the expected signal on the Super-Kamiokande (SK) telescope and test models that expand the “Cold Dark Matter” (CDM) include these self-interactions (Self-interacting dark matter-SIDM). The inclusion of these interactions can resolve CDM inconsistencies on galactic scales. We tested SIDM models, comparing our result with the results obtained from the SK experiment, that is, comparing our estimated number of upward muon events in the detector with those of the SK collaboration. Given the self-interaction of dark matter, the number of neutrons from the Sun will be greater than for CDM without collisions. We analyzed the neutrons from the annihilation channels in W⁺W⁻ and BB. The signal obtained in this analysis is consistent with the background of atmospheric muons, therefore, no significant excess of ascending muons induced by neutrons from the Sun was found. Thus, our results excluded a significant region of SIDM models. The channels of annihilation considered, include more energetic neutrons coming from the channel W⁺W⁻ and BB, less energetic of the channel BB. Given the low energy threshold of SK, when compared to the IceCube telescope, we obtained more stringent results for the channel BB.

INTRODUCTION
It is known that dark matter whose nature is not yet revealed, interacts gravitationally with known matter and does not present electromagnetic interaction, therefore, it does not emit light. We know of its presence through cosmological measurements such as rotation curves, among others.

RESULTS
\[ N_{\mu} = \Gamma_{\text{ann}} \int \frac{dE}{E} A_{\text{eff}}(\theta) dE \] (2)
The number of muons estimated on the detector SK, dependent on the annihilation rate, the data collection time (3109.6 days for SKI-III), the flux of upward muons into the detector, the threshold energy and the effective area of the detector, being theta zenith angle.

CONCLUSIONS
1) We simulate DM with strong self-interactions, being captured in the Sun and annihilating itself in the nucleus. We determine and compare the estimated number of muon events with the upper limit of Super-K Collaboration Events. 2) We exclude 90% C.L. several SIDM models, considered as potential solutions to CDM problems on small scales. 3) We established the new interval, \( 0.7 \text{cm}^2/\text{g} \leq \sigma \leq 1.3 \times 10^{-40} \text{cm}^2/\text{g} \), for the \( \sigma \) / \( m_\chi \) ratio if the DM annihilates in \( W^+W^- \) with \( \sigma \leq 3 \times 10^{-27} \text{cm}^3/\text{s} \). 4) We established the strictest upper limit of exclusion, at 90% C.L., for \( \sigma \), for \( m_\chi = 100 \text{GeV/c}^2 \), with \( 1.3 \times 10^{-40} \text{cm}^2/\text{g} \) all values of the cross-section of self-interaction.

REFERENCES
In the absence of a clear hint of dark matter (DM) signals in the GeV regime so far, TeV DM candidates are gradually earning more attention within the community. Among others, extra-dimensional braneworld models may produce thermal DM candidates with masses up to 100 TeV, which could be detected with the next generation of very-high-energy gamma-ray observatories such as the Cherenkov Telescope Array (CTA). In this work, we study the sensitivity of CTA-North and CTA-South to branon annihilations using the latest publicly available instrument response functions and most recent analysis tools. We computed annihilation cross section values needed to reach a 5σ detection as a function of the branon mass. Additionally, in the absence of a predicted DM signal, we obtained 2σ upper limits on the annihilation cross section. These limits lie 1.5-2 orders of magnitude above the thermal relic cross section value, depending on the considered branon mass. Yet, CTA will allow to exclude a significant portion of the branon tension-mass parameter space in the 0.1-60 TeV branon mass range, and up to tensions of ~10 TeV. More importantly, CTA will significantly enlarge the region already excluded by AMS and CMS, and will provide valuable complementary information to future SKA radio observations. We conclude that CTA will possess potential to constrain braneworld models and, more in general, TeV dark matter models.

**Branchons**

A particular class of WIMPs are branchons [1], i.e. DM candidates that annihilate in several SM channels at once, depending on their mass. More specifically, they are WIMPs that annihilate into e.g. a pair of quarks, of leptons, of gauge bosons, or even of photons, but the ratio for the latter to occur is extremely low. The branching ratio of annihilation into each channel depends on parameters of the branon. If branchons were thermal relics, the tension of the brane would be a function of the branon mass, and we are thus left with only one free parameter; see Fig. 1.

The differential annihilation flux yielded by branchons will be

$$dN/ddt = \int \frac{d\sigma}{dt}\rho(p)\mathcal{L} \sum B_i\frac{dN_i}{dt}\left[\text{ph cm}^{-2}\text{s}^{-1}\text{GeV}^{-1}\right]$$

(1)

Here, $\rho(p)$ is the averaged annihilation cross section of the DM particle times the velocity, $m_i$ is the branon mass, $B_i$ are the branching ratios of Fig. 1 and $\mathcal{L}$ is the luminosity of the source. In Fig. 2, the annihilation spectra for different branon masses are shown. The photon yield is shown on the left panel and the annihilation flux on the right panel.

**Cherenkov Telescope Array (CTA)**

CTA [3] is an international project whose main goal is to build a new generation of ground-based gamma-ray telescopes. The energy range will cover from dozens of GeV up to 300 TeV. CTA will actually consist of two arrays. One of them will be located in the Northern Hemisphere, namely La Palma (Canary Islands, Spain), and the Southern array will be situated in the Atacama desert (Chile).

**Analysis pipeline**

We have used the ctools software package [4] to simulate the CTA gamma-ray observations and make analyses. ctools operates with reconstructed event lists, supressing most of the background based on Cherenkov showers properties. We also have made use of the public CTA instrument response functions (IRFs).

- First, in our simulations we generate source events assuming a DM annihilation spectrum for the source.
- After that, a maximum likelihood analysis is applied to those data to look for a DM signal.
- In the absence of a signal, we compute 2σ upper limits to the annihilation cross section. We also compute the annihilation cross section values that are needed for detection.

**Results**

We have performed several realizations with 50 hours of observation time, using the full CTA energy range and reaching both TS-25 for detection and TS-2.71 for 95% confidence level upper limits. In the latter case, as seen in Fig. 3, our limits are around 1.5 orders of magnitude above the estimates of the thermal relic cross section. We are assuming a NFW profile for the selected dwarfs, Draco and Sculptor, and the J-factors listed in Table 1 of our paper.

We have also set constraints in the mass-tension parameter space, our results expanding the excluded region for TeV masses with respect to the limits from current experiments such as AMS and CMS, as shown in Fig. 4.

**Conclusions and future**

In this work, we have studied the branon detection prospects for the future CTA. We chose two dSphs as DM targets, Draco and Sculptor. In the absence of a detection signal, we have computed expected 2σ exclusion limits for branon DM. Finally, we have set a large exclusion region in the tension-mass parameter space, enlarging the current one.
A number of gravitational microlensing surveys have been conducted to search for primordial black holes (PBHs) in nearby dark matter halos (Nikishin et al, Nat. Astron. 2018). In many DM models, spatially extended structures are predicted in the form of exotic compact objects (Croon et al, PRD 2020). Establishing microlensing limits on these extended DM structures requires us to use the existing microlensing limits on PBHs. One essential step is to investigate the microlensing signal produced by a non-pointlike lens (Croon et al, PRD 2020).

An important scale in gravitational lensing is the Einstein radius $R_E = \sqrt{\frac{4G}{c^2} \frac{M}{D} (1 - \frac{x}{L})}$, where $M$ is the lens mass and $x = D_s / D_l$ with $D_l$ and $D_s$ the lens-observer and source-observer distance. We shall express physical length scales by upper case letters and dimensionless scales in unit of $R_E$ by lower case letters. On the lens plane, the lens size and source size are $r_L$ and $r_s$, respectively, where

$$r_L = 2x \frac{R_s}{R_E} \text{ and } r_s = \frac{2\pi r_L}{x}$$

The geometry of the setup is depicted in the figure below, with $u$ being the lens-source distance, $u(\varphi) = \sqrt{r^2 + 2ur_0 \cos \varphi}$ being the distance from a point on the edge of the source to lens.

For every infinitesimal point on the edge of the source, the lensing equation which relates the true position of the point and the image can be written as $u(\varphi) = r(\varphi) = m(t(\varphi))/t(\varphi)$, where $m(t)$ is the projected lens mass enclosed within $t$. The magnification of each image is:

$$\mu = \frac{1}{(2\pi)^2} \int_{-\infty}^{\infty} \frac{1}{2\pi} \left| \frac{f(y)}{y} \right|^2 dy,$$

where $f = \text{sign}(d^2u/dy^2)|_{y=y_0}$ is the “parity” of the image. The total magnification $\mu_{tot}$ is the sum of individual $\mu_i$. In typical microlensing surveys, an event is called if the magnification exceeds 1.34. By numerically solving these equations, we find the impact parameter $u_{1.34}$ corresponding to $\mu_{tot} = 1.34$. For NFW subhalos and boson stars, we obtain $u_{1.34}$ as a function of $R_s$ and $r_L$ in the figure below.

If the mass fraction of lenses in the DM halo is $f_{DM}$ and all the lenses have an identical mass $M$ and size $R_s$, the lensing rate of a particular background star with size $R_s$ is given by (Griest, APJ 1990)

$$\frac{dN}{dR_s} = f_{DM}(R_{s}, \frac{R_s}{R_L}) \frac{dD_s}{dD_L} \frac{d\rho(x)}{R_s^2} \frac{vx_e}{2} \left( 1 - \frac{x}{L} \right)^{1/2},$$

where $\rho(x)$ is the local DM density projected along the line of sight, $v_e$ is the detector efficiency, $\gamma_{DM}(x) = 2\gamma_{DM}(R_{s})(x)/v_e$ and $v_e$ is the DM circular velocity. The expected number of events is

$$N_{\text{events}} = N_{\text{obs}} \left( \frac{d\rho}{dR_s} \right) \left( \frac{d\Gamma}{dR_s} \right) \frac{d\mu}{dR_s} dx,$$

where $N_{\text{obs}}$ is the number of stars, $T_{\text{obs}}$ is the net observation time, and $d\mu/dR_s$ is the (normalized) stellar radius distribution of the source stars. The Subaru-HSC survey is towards M11, and we take $d\mu/dR_s$ derived in (Smyth et al, PRD 2019). At 95% CL, the survey finds $N_{\text{events}} \leq 4.74$ and we show the corresponding upper limits on $f_{DM}$ in the figure below. Deviations from PBHs limits become viable for lens sizes larger than $O(0.1R_L)$, and lenses up to $O(10^2R_L)$ can be probed by Subaru-HSC. Constraints from EROS-2 and OGLE-IV surveys are also shown.

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**Microlensing of an extended star by an extended lens**

**Results**

**Microlensing constraints on extended dark matter structures from Subara-HSC**

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INTRODUCTION

Several studies have been proposed to investigate the dark matter (DM), trying to uncover its origin and nature. Distinct approaches aim to understand how DM interacts and what are the possible mechanisms for detecting it. Theories beyond the Standard Model of the Elementary Particles (SM) investigate the possible couplings of DM with conventional matter in order to measure its interaction in the laboratory.

Our work aims to investigate the differential production cross section for dark matter (DM) particles in a process with a $Z'$ boson mediator in proton-proton collisions at a centre-of-mass energy of 14 TeV. The production of scalar, fermionic, and vector DM pairs via quark-antiquark annihilation into the new boson is investigated evaluating the differential cross section for on-shell production.

OBJECTIVES

The main goal of this study is to probe the limits and analyze parameters for the thermal production of DM, through a process that involves an interaction of the standard model with the dark sector mediated by a new massive boson mediator ($Z'_\mu$) as a Breit-Wigner resonance peak.

METHODS

In this work we investigate three possible DM candidates, i.e. scalar, fermion, and vector DM particles. Making use of the Feynman rules, we compute the total cross sections for the following diagrams and its respective Lagrangians [1]:

### SCALAR DM

\[
\mathcal{L}_{\text{sc}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}M^2 Z'_\mu Z'^\mu + \bar{\psi}_c \gamma^\mu (g_P \psi + g_P \bar{\psi}) \psi Z'_\mu + m_c \left( \chi \bar{\chi} - \bar{\chi} \chi \right) Z'^\mu
\]

### FERMION DM

\[
\mathcal{L}_{\text{fr}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}M^2 Z'_\mu Z'^\mu + \left[ \bar{\psi}_c \gamma^\mu (g_P \psi + g_P \bar{\psi}) \psi + \bar{\chi} \gamma^\mu (g_P \chi + g_P \bar{\chi}) \chi \right] Z'_\mu
\]

### VECTOR DM

\[
\mathcal{L}_{\text{ve}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}M^2 Z'_\mu Z'^\mu + \bar{\psi}_c \gamma^\mu (g_P \psi + g_P \bar{\psi}) \psi Z'_\mu - m_c \left( \chi \bar{\chi} - \bar{\chi} \chi \right) \gamma^\mu Z'_\mu + \bar{\psi}_c \gamma^\mu (g_P \psi + g_P \bar{\psi}) \psi Z'_\mu + m_c \left( \chi \bar{\chi} - \bar{\chi} \chi \right) \gamma^\mu Z'_\mu + m_c \left( \chi \bar{\chi} - \bar{\chi} \chi \right) \gamma^\mu Z'_\mu
\]

DISCUSSION AND CONCLUSION

Using a factorization as described in Ref. [2], we have developed a code to evaluate the differential cross section for DM ($m_\text{DM}$) and mediator ($M_{\text{med}}$) mass ranges as employed in the literature, using the LHAPDF package [4]. Using data from Refs. [5-6], we are able to estimate exclusion limits for the proposed models. For observed DM density, we assume a scenario with being the mass of the DM cold relic density.

As a result, we still seek to obtain the dependency of the coupling constants with the possible masses for the DM and the dark mediator for this simplified model, in addition to determining the observation limits in the LHC kinematic regime.

Additionally, we will be able to estimate the sensitivity of the experimental and phenomenological parameters, such as uncertainties in the partons distributions, favorable phase space regions towards the kinematics variables and detection uncertainties for production of initial- and/or final-state radiation.

SOME REFERENCES


Marcio de Sousa Mateus Junior (a) • Gustavo Gil da Silveira (b)
We have found magnetic monopole solutions (in GUTs) whose magnetic field is not in the direction of electromagnetism.

Dark Monopoles Construction

- We consider that the gauge group is $G = SU(n)$ and that it is broken down to $G_u = [SU(p) \times SU(n-p) \times U(1)] / Z$ by a Higgs field $\phi$ (adjoint representation) with a vacuum of the form $\phi_0 = v \frac{\lambda_p}{\sqrt{\mu}} \mathbf{1}$, where $\lambda_p$ is a fundamental weight of the Lie algebra $L(G)$.
- Our ansatz is constructed using an $SO(3)$ subgroup of $G$, whose generators are called the monopole generators, $M_i$ ($i = 1, 2, 3$), which are given by a linear combination of step operators of $L(G)$.
- Their mass possess lower and upper bounds (similar to the 't Hooft-Polyakov monopole).
- They have a purely non-abelian magnetic flux. The magnetic charge is conserved, quantized and it follows from an asymptotic symmetry of the field configuration.
- Regarding stability, we found unstable modes.

Conclusions

- We expect that our construction can be generalized to other gauge groups.
- These Dark Monopoles must exist in some GUTs and we analyzed the $SU(5)$ case in details.
- The cosmological implications of these monopoles are still an open question.

Some Technical Notes

- Ansatz:
  
  \[
  W_i(r) = - \frac{1 - u(r)}{er} e_{ijk} n^j M_k, \\
  \phi(r) = v S + \frac{2v}{\sqrt{6} |\mu|} \sqrt{\frac{4\pi}{f(r)}} \sum_{m=-2}^{2} y_{2m} Q_m, 
  \]

  where

  \[
  M_3 = 2T_2^{ij}, \quad M_1 = 2T_2^{ij}, \quad M_2 = 2T_2^{ij},
  \]

  with $2T_2^{ij} = -i(E_{ij} - E_{ji})$ while the $E_{ij}$ are the step operators associated with the root $\alpha_i$.
  Moreover, $Q_m$ form a quintuplet under the $su(2)$ algebra of $M_i$, while $S$ is a singlet. In addition, $n^i = \sqrt{f} \frac{v}{r}$.

- Asymptotic Magnetic Field:
  
  \[
  B_i(r \to \infty) = - \frac{n^i}{er} n^6 M_a.
  \]

  That is, the magnetic field only takes values in the direction of some step operators $s.t. \text{Tr}(B_i \phi) = 0$.

Numerical Solution for the radial equations $f(r)$ and $u(r)$ for the $SU(5)$ case:

- Monopole Mass:
  
  \[
  M = 4\pi v \frac{\bar{E}(\lambda/e^2)}{e},
  \]

  where $\bar{E}(\lambda/e^2)$ is a monotonically increasing function of $\lambda/e^2$. In the $SU(5)$ case, we obtained that:

  \[
  \bar{E}(0) = 1.294, \quad \bar{E}(\lambda \to \infty) = 3.262.
  \]

- Magnetic Charge: $Q_M = -8\pi/e$.

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Dark matter deficient galaxies have lost their dark matter halos due to interactions during their evolution. In particular, during their fusion history. The existence of these galaxies is a debated subject, both from the observational and theoretical points of view. In this work in progress, we study the population of dark matter deficient galaxies in the hydrodynamical simulation IllustrisTNG, which follows the evolution of dark matter and baryonic matter. We analyse the distribution of these galaxies within the host halo, and how this distribution changes with halo mass, and redshift. The aim of this study is to gather information about how these galaxies are formed, and how their population evolves.
Context and motivation

In the standard $\Lambda$CDM framework, cold dark matter is the dominant mass budget of the Universe, but it can be less important at small scales. Nevertheless, low-mass galaxies are expected to be dark-matter-dominated even within their central regions.

However, recent observations suggest that some of these low-mass galaxies may have very low dark matter fractions\textsuperscript{1,2}. This type of galaxies, which would be dark matter deficient according to what we have established above, is an unknown and debated subject, and their dark matter deficiency makes them a very interesting object of study.

There are some studies in the literature that address this problem using hydrodynamical simulations (EAGLE, ILLUSTRIS\textsuperscript{3}). In this poster, we present the preliminary results of our study using IllustrisTNG simulations, to analyze the population of dark matter deficient galaxies. Our aim is to study this population as a function of the mass of the host, as well as a function of redshift, and try to find out which is the mechanism by which those satellites lose most of their dark matter halo.

\textsuperscript{1} Oh S.H. et al., 2015, AJ, 149, 180.
\textsuperscript{3} Jing, Y. 2019, MNRAS 488, 3, 3298.
Project description

The IllustrisTNG project is a suite of state-of-the-art cosmological galaxy formation simulations. It consists of hydrodynamical simulations in which the evolution of different components (dark matter, gas, stellar mass, black holes) is studied. The set of simulations are of high resolution in mass, for all of the particle types.

Three physical simulation box sizes are employed: cubic volumes of roughly 50, 100, and 300Mpc side length. In this project, the TNG100 data at redshifts $z= 0, 0.4, 1$ and 2 were used to study dark matter deficient galaxies.

The dark matter fraction is measured using the formula $f_{DM} = \frac{M_{DM}}{M_{tot}}$. Dark matter deficient galaxies are defined as those with a dark matter fraction below 50%. We select the satellite galaxies of the most massive host halo’s central subhalo at each snapshot and obtain their dark matter fraction within two times of the half-stellar-mass radius ($2R_h$), as well as their halocentric distances.
We have computed the mass function at different redshifts, to account for the full population of DM halos. We also investigate which is the mass distribution of DMDGs for the most massive halo at $z=0$.
### Results

While dark matter dominates the total mass budget of the majority of the satellite galaxies within $2R_h$, we have found that a few percent of galaxies have a dark matter fraction below 50%.

This percentage of dark matter deficient galaxies over the total amount of satellite galaxies is higher at higher redshifts, for the most massive halo: we found that at $z=2$ there is a percentage of 0.53%, while at $z=0$ it decreases to 0.23%.

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Mass of the most massive host halo</th>
<th>Amount of satellite galaxies of the most massive host halo</th>
<th>Amount of dark matter deficient galaxies</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z = 0$</td>
<td>$38878 \times 10^{10} \text{M}_\odot$</td>
<td>17184</td>
<td>39</td>
</tr>
<tr>
<td>$z = 0.4$</td>
<td>$18533 \times 10^{10} \text{M}_\odot$</td>
<td>7718</td>
<td>32</td>
</tr>
<tr>
<td>$z = 1$</td>
<td>$10938.9 \times 10^{10} \text{M}_\odot$</td>
<td>4948</td>
<td>26</td>
</tr>
<tr>
<td>$z = 2$</td>
<td>$3053.65 \times 10^{10} \text{M}_\odot$</td>
<td>1501</td>
<td>8</td>
</tr>
</tbody>
</table>
Results

In these figures, we show the dark matter fraction $f_{\text{DM}}$ as a function of halo-centric distance, $r/R_{200}$, at the different redshifts in which the dark matter deficient galaxies were studied.

$z = 0$

$z = 0.4$

$z = 1$

$z = 2$
Preliminary conclusions and future goals

- Dark matter deficient galaxies are allowed in current galaxy formation models.
- In the future, we plan to track down the dark matter deficient galaxies found at $z=0$ in order to study their evolution and history, and also to see if they match the ones found at $z=0.4$, $z=1$ and $z=2$.
- We will also study the environment in which the group is located, and whether there is a dependence of the abundance of deficient dark matter subhalos on the properties of the environment.
- We will repeat this analysis for different mass ranges of the host halo, at different redshifts, to study if there is a dependence of the population of dark matter deficient galaxies with the mass of the host.

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It is generally accepted nowadays that the matter density of the Universe mainly consists of an unknown component, called Dark Matter (DM). It is also believed that DM is formed of a new neutral, stable and non-baryonic elementary particle. In high density environments of the Universe DM may self-annihilate and produce a strong gamma-ray signal. Among all possible targets, dwarf galaxies of the Local Group are among the most promising for discoveries due to their large DM content. This project aims at using the predicted increase of the number of known dwarf galaxies and estimate the improvement in the detection sensitivity to a dark matter signal that will be achieved by the future gamma-ray observatories.

**Objectives**

- Study new models of dark matter annihilation
- Calculate the gamma ray flux
- Estimate the sensitivity of CTA and other future gamma-ray experiments
- Implement analysis techniques to optimize the sensitivity to a Dark Matter signal.

**Methods**

**New models of dark matter annihilation**

This project start with a overview of dark matter annihilation process including secluded and scalar doublets. The idea is to have a list of potential model candidates to be tested by CTA.

**Calculate the gamma ray flux**

\[
\frac{d\Phi}{dE}(E, \phi, \theta) = \frac{1}{4\pi} \int \frac{dN_t}{dE} \sum_i \left( \sigma_{\text{ann}} v \right) \frac{dE}{dE} B_t \times \int_{\Delta\Omega(\phi, \theta)} d\Omega \left( \rho(\vec{r}, \phi, \theta) \right) d(\vec{r}, \phi) \]

**Estimate the sensitivity of CTA and other future gamma-ray experiments**

This is the challenging part of the project for which there is no recipe. The possibility to detect a Dark Matter signal depends on the measurement strategy and on the analysis techniques. Current experiments have developed strategies and techniques optimized for their telescope and array configurations. Such an optimization still has to be done for CTA and this project intends to contribute with these efforts.

The basic procedure consists in comparing the signal in different parts of the sky, subtracting the diffuse emission to keep on the Dark Matter signal. The analysis procedure used by the H.E.S.S. experiment, is going to be the starting point for the development of such optimization.

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On the role of rotation in galactic dynamics

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Abstract

Although the exisence of dark matter would allow good explanations for various cosmic phenomena, the nature of such matter is unknown and it still lacks direct detection. This limitation has stimulated the investigation of alternative gravity models to explain phenomena such as the galactic dynamics that yields rotation curves of galaxies. These models depart from general relativity in different ways, like in EPR theories or in brane-world approaches, or in the MOND framework, in which an acceleration is a fundamental constant. Other approaches propose that the dark matter phenomenon can be attributed to an elastic response of a dark energy medium permeating the universe, or that spacetime would consist of an anisotropic fluid. Several alternative models investigate scenarios where galaxies are described as static, spherically symmetric systems. However, galaxies are rotating systems and studies have signaled the possible relevance of this rotation in the explanation of the flat rotation curves of galaxies. In this work we apply general relativity to analyze the behavior of a mass probe moving in the gravitational field of a massive, rotating body. We focus on the motion far from the source, where the gravitational field is weak, looking for clues that might help understand the role of rotation in galactic dynamics.

Introduction

The existence of dark matter (DM) is a powerful assumption aimed at explaining the motion of stars in galaxies, among other cosmic phenomena [1, 13]. In this work we focus on the unexplained rotation curves of galaxies, where stars far from the center of spiral galaxies display nearly constant and relatively high rotational speeds in contrast to the theoretical ones expected in Newtonian gravity (NG), as sketched in Fig. 1. Normally, the DM content in galaxies is estimated using NG, under the assumption that star velocities are non-relativistic and the gravitational field is weak in the galactic interior. Calculations are then normally performed assuming a steady-state configuration and a spherically symmetric DM mass distribution.

In this work we argue that general relativity may be a good candidate to explain galactic RC.

This argument is based on the success of the theory in explaining other phenomena. Some works have been developed with this goal and we will briefly comment on them.

Galactic dynamics and Newtonian gravity

When NG is applied to galactic dynamics, the determination of DM mass distribution is guided by the virial theorem applied to a star (w) with mass m positioned at a galactocentric radius r with a speed v, that belongs in the flat part of the RC [13]:

\[ \sum_i m v_i^2 = - \sum_j F_{ij} \Rightarrow mv^2 = -G M(r) \]

where \( v \) denotes a time average and \( G \) is Newton's gravitational constant. In this context, the gravitational interaction between the star and the rest of the galaxy is mediated solely by the Newtonian potential. The DM mass distribution is obtained from a adequate fit that yields the function \( M(r) \) that best reproduces the respective rotation curve. This procedure obviously leads to variations of the DM content from galaxy to galaxy, hindering the development of a general theory that would explain galactic RC.

The application of Newtonian gravity to the rotation curve problem has been justified in view of the weak gravity throughout galaxies and the non-relativistic velocities of their stars. However, these conditions are also present in various important phenomena where GR has a role to play.

Stars in galaxies move exclusively under gravity (they are gravitationally bound), and it has been known for quite some time that this kind of system yields nonlinear equations of motion in GR, in contrast to the linear equations of NG. Two phenomena where GR is required are the precession of Mercury's perihelion and the Lense-Thirring effect, about which we comment below.

Galactic dynamics and general relativity

The explanation of the precession of Mercury's perihelion demanded the use of general relativity despite the fact that the motions of the planet and of the Sun are non-relativistic and that the gravitational fields involved are weak. The relativistic correction is very small yet essential, and NG is not able to supply it because this classical theory involves a flat space, while GR involves a curved space-time. It is the curved space in GR that contributes decisively to the correct precession [12].

Another phenomenon that results from GR is the Lense-Thirring effect, in which extra gravitational effect is created by the motion of the source, and felt only by moving test particles. In this case, a rotating object causes the surrounding space-time also to rotate, thus influencing the motion of the moving test particle. Orbiting satellite projects were designed to detect this GR prediction on the gravitational field of the Earth, as it should be manifested even under weak fields and non-relativistic speeds [7-11].

Recently this effect was reported under a new scenario, induced by a fast-rotating white dwarf in a binary pulsar system [8].

Such examples suggest that the rotation curve problem in galaxies could be solved with appropriate applications of general relativity.

Preliminary works in this direction have been reported, as we present next.

First relativistic models for galaxies

A galaxy is an extremely complex system and the application of general relativity to it is expected to be a difficult task.

The challenge to describe galaxies using general relativity started to be faced more than a decade ago, when a galaxy was described by dust rotating under axial symmetry.

That pioneering work, authored by Cooperstock and Tieu (CT) [4], was able to fit RC with amazing precision using the metric

\[ ds^2 = c^{-2} dt^2 - \frac{c^2 dr^2}{a - 2 \phi} - \frac{c^2 dr^2}{c z^2 - \omega z^2} - c^2 (d\theta^2 + d\phi^2), \]

where \( c \) and \( \omega \) is the symbols are explained in [5].

A striking aspect of this metric is that star velocities are proportional to \( N \), the velocity coefficient that describes rotation. Therefore, as in the Lense-Thirring effect, rotation may be key to the description of rotation curves, an ingredient that Newtonian gravity lacks.

The CT model was criticized by several theoreticians, especially because of a discontinuity in one derivative. This would, according to some critics, render the solution unphysical. This and other criticisms were answered by those authors in later papers [5]. Cooperstock was aware that dust is a crude model for a galaxy, but he envisioned it as a first approximation to the RC problem using GR [3].

The excellent fit given by the model allowed estimated of galactic masses, which suggested that no DM would be necessary to explain RC using GR.

Amidst that debate another relativistic dust model for spiral galaxies was proposed by Balasin and Grumiller (BG) [2], which had a singularity at the galactic center, hence being as unphysical as its precedent. Nevertheless, the authors were able to gain by the model the insight that the Newtonian approximation breaks down in an extended rotating region, as well as overestimates the amount of matter needed to explain RC.

Both relativistic dust models for spiral galaxies suggest that the use of Newtonian gravity to solve the rotation curve problem may overestimate the amount of matter necessary for the solution.

To date, CT and BG dust models seem to be the only ones that try to address the RC problem using GR. Their mathematical issues were investigated in detail by Neill [10], who also proposed ways to overcome them, concluding that one should attempt to solve the Einstein field equations for dust more generally than CT and BG did, setting physically appropriate boundary conditions and perhaps involving numerical integration. The resulting solution could yield not only a better picture of the DM distribution, but also boost our understanding of the current cosmological model.

Astrophysics from relativistic models of galaxies

Despite the limitations of the simplified CT and BG models, astrophysical investigations were pursued in search for information about any differences in behavior between GR and NG. Moreover, the predictive success of the CT model was yet to be tested, as pointed out by Neill. For example, one should use CT's expression for the mass density with the coefficients produced in the velocity fit and compare the calculated density profile with the observed density.

Such project was developed by this author and Cooperstock [9], where the CT model still fitted RC very well but was not able to fully explain the extra mass density to the observed one, which was interpreted as a general-relativistic distribution. However, the amount of extra mass has significantly smaller than the amount required using NG.

A recent work investigated similar issues using Milky Way data under the BG model[6], suggesting that GR could explain rotation curves without DM.

As pointed out before, in GR curved space is responsible for important physical contributions to gravitating systems. Therefore, more suited metrics are used to describe galaxies - as with many spatial details as possible - more contributions to rotation curves in the flat regime are expected to appear from spatial curvature, perhaps finally fulfilling the role that dark matter plays in Newtonian gravity.

It is possible that a relativistic galactic model, more accurate than CT and BG simple models, might explain galactic rotation curves and yield observed mass densities using only barionic matter. Such investigation could be carried on with, for example, the methodology proposed by Neill.

Concluding remarks

As pointed out before, in GR curved space is responsible for important physical contributions to gravitating systems.

As more suited metrics are used to describe galaxies - with as many spatial details as possible - more contributions to rotation curves in the flat regime are expected to appear from spatial curvature, perhaps finally fulfilling the role that dark matter plays in Newtonian gravity.

It is possible that a relativistic galactic model, more accurate than CT and BG simple models, might explain galactic rotation curves and yield observed mass densities using only barionic matter. Such investigation could be carried on with, for example, the methodology proposed by Neill.

References

A theory of Dark Matter particle

Light particles with feeble coupling with Standard Model, such as axion-like particle(ALP) or hidden photon (HP), are excellent candidates to solve the Dark Matter (DM) problem [1]. These candidates can be created in early times by means of a non-thermal process like misalignment mechanism or inflationary vectorial fluctuations and, in addition, have a very rich phenomenology to be tested. So far, the null result of the searches suggest that the experimental investigation and astrophysical observation need to be improved in order to examine smaller masses or weaken coupling. In this work we propose an alternative explanation. We suggest that the dark sector is more complex than usually thought. Concretely, in this model, the hidden photon (the DM particle in our model) interacts with the visible sector (photon) by means of an ALP that serves as a mediator between the two particles. Many variants of the model has been consider in the literature, see for example [2]. In order to establish our model we propose the following lagrangian

$$\mathcal{L} = \mathcal{L}_\gamma + \mathcal{L}_\phi + \mathcal{L}_\gamma \gamma = \frac{1}{4}g_{\phi\gamma\gamma} F_{\mu\nu} F^{\mu\nu}$$

We impose a $Z_2$-symmetry in the dark sectors that forbid any other interaction between the visible and invisible sectors, then all the effects come from the coupling $g_{\phi\gamma\gamma}$. The aim of the present work is to study the viability of this theory mainly through the cosmological stability and phenomenological effects in laboratories as well as astrophysical observations. For the sake of brevity we show the results assuming a massless ALP, however a broad range of masses has been considered in the original work [3] as well as other bounds not discussed here.

Cosmological stability

From the well-established $\Lambda$CDM paradigm the DM has been present from early times to nowadays. Then, a basic examination of the model is that the hidden photons DM must be long-lived to agree with the cosmological theory. The depletion of the DM background can be at least the age of the universe

$$\Gamma_{\gamma\gamma\phi} = \frac{g^{2}_{\gamma\gamma\phi}}{96\pi} \left(1 - \frac{m_{\phi}^2}{m_{\gamma}^2}\right)^2 < \frac{1}{t_{\text{uni}}}$$

This bound is showed in the orange region of the summary plot. On the other hand, the stimulated decay occurs because the HP DM background serves as an external "hidden" electric field that oscillates with frequency $m_{\gamma}$

$$\nabla = X_0 \cos(m_{\gamma} t),$$

then a parametric resonance regime is possible when a external photon with momentum

$$k = \frac{(m_{\gamma}^2 - m_{\phi}^2)}{2m_{\gamma}}$$

is coming. If this resonance is reached the DM is depleted quickly and the photon number grows exponentially. Furthermore the contribution of Bose-enhanced decay increase the depletion process. Imposing the condition for the energy densities $\rho < \rho_{\text{dm}}$, at every cosmological epoch we found that the exclusion area where this model is unstable and then is not a DM model. Additionally, we look CMB distortions including the annihilation process $\gamma' + \gamma' \rightarrow \phi$. By using FIRAS data we found the exclusion area CMB.

Stellar energy loss

The inner structure of a star can be modify due to non-standard interaction involving photons as our model incorporate. We focus on the plasmons decay process $\gamma' \rightarrow \gamma + \phi$ with decay rate

$$\Gamma_{\gamma'\gamma\phi} = \frac{g_{\gamma'\gamma\phi}^2}{96\pi} \omega^2 \omega^\phi,$$

where $\omega_{\phi}$ is the plasma mass that is a function of the star radius, then we have computed the anomalous energy loss rate

$$Q_{\gamma'\phi} = \frac{g_{\gamma'\gamma\phi}^4}{48\pi^3} \omega_{\phi}^2 \omega_{\gamma}^4 R^3,$$

The solar luminosity (volumetric integration of $Q_{\gamma'\phi}$) is currently constrained $L_{\phi} < 0.1 L_\odot$ while for HB stars is customary to consider that dark emission per unit mass at the core can account for $\varepsilon_{\gamma'\phi} < 10^{-9}$ erg s$^{-1}$ g$^{-1}$. We show these bounds in the blue region of the plot.

Exclusion plot

Extensive summary of several tests considering massless ALP. Extended version can be found in [3].

References

Abstract

In Newtonian gravity, we can model the observed rotation curves in the external regions of disk galaxies by assuming the presence of dark matter. This mass discrepancy can be neatly quantified by the RAR (McGaugh et al. 2016), which shows that the observed radial acceleration traced by the rotation curves ($g_{\text{obs}}(R)$) is tightly correlated with the Newtonian acceleration due to the baryonic matter distribution ($g_{\text{bar}}(R)$). The observed RAR is fitted by this relation (McGaugh et al. 2016):

$$g_{\text{obs}}(R) = \frac{g_{\text{bar}}(R)}{1 - \exp(-\sqrt[3]{g_{\text{bar}}(R)/a_0})}$$

with $a_0 = 1.20 \times 10^{-10} \text{m/s}^2$.

Newtonian gravity needs dark matter also to reproduce the velocity dispersions in the outermost regions of elliptical galaxies, probed by the detection of kinematic tracers, like globular clusters (GCs) or planetary nebulae. Specifically, the mass discrepancy in these systems might be positively correlated with their ellipticity (Deur 2014).

2. REFRAC TED GRAVITY

RG (Matsakos & Diaferio 2016) is a classic theory of gravity whose field equations yield the modified Poisson equation

$$\nabla \cdot \left[ \epsilon(\rho) \nabla \phi \right] = 4\pi G \rho_c,$$

where the permittivity $\epsilon(\rho)$ is an arbitrary monotonic function of the mass density $\rho$ with the asymptotic limits $\epsilon(\rho) = 1$ for $\rho \gg \rho_c$ and $\epsilon(\rho) = \epsilon_0$ for $\rho \ll \rho_c$. As a test case, we adopt the function

$$\epsilon(\rho) = \epsilon_0 + (1 - \epsilon_0) \frac{1}{2} \left[ \tanh \left( \frac{\rho}{\rho_c} \right)^Q + 1 \right],$$

with $\epsilon_0$, $Q$, and $\rho_c$ free universal parameters (Fig. 1). Fig. 2 compares the gravitational fields in Newtonian and Refracted gravities for flat and spherical systems. In RG the acceleration boost in flat systems is due to the focusing of force lines rather than to the presence of dark matter as in Newtonian gravity.

3. ROTATION CURVES AND VERTICAL VELOCITY DISPERSIONS IN DMS

We consider 30 disk galaxies from the DMS (Bershady et al. 2010a). We model the mass distribution with (1) a stellar disk, (2) a spherical stellar bulge, and (3) an atomic and molecular gas components. We solve the RG Poisson equation (Eq. (2)) with a Successive Over Relaxation numerical method and use a MCMC algorithm to estimate the mass-to-light ratio, $\gamma$, the disk scale height, $h$, and the 3 RG parameters, $\epsilon_0$, $Q$, and $\rho_c$, from the two kinematic profiles at the same time. Fig. 3 shows one example. Both profiles are well described and the flat trend in the outer region of the rotation curve is properly reproduced by RG.

4. RAR IN DMS

Fig. 4 shows the RAR for DMS galaxies. The points with error bars show the data of the DMS sample, the black curve is Eq. (1), and the blue lines are the RG models. $g_{\text{obs}}$ is the centripetal acceleration implied by the observed rotation curve $v_{\text{obs}}(R)$ and $g_{\text{bar}}$ is the baryonic radial acceleration $\frac{\partial \phi}{\partial R}$ obtained by solving the Newtonian Poisson equation, $\nabla^2 \phi = 4\pi G \rho$, where $\rho$ is the sum of the contributions (1), (2), and (3). The two asymptotic limits for large and small $g_{\text{bar}}$ of Eq. (1) are properly reproduced by RG.

5. RMS VELOCITY DISPERSIONS IN SLUGGS

We consider 3 E0 galaxies from the SLUGGS survey (Pota et al. 2013). We model at the same time, the rms velocity dispersions of the 3 kinematic tracers, stars, blue GCs, and red GCs, with spherical Jeans analysis:

$$V_{\text{rms}}^2(R) = \frac{2G}{l(R)} \int_0^\infty K \left( \frac{\beta_i r}{R} \right) \sqrt{M(r)} \frac{dV}{dR} \rho(r) dr,$$

where $M(r)$ is the mass profile and $l_i(R)$, $\rho_i(r)$, and $\beta_i$ are the surface brightness, the 3D luminosity density, and the anisotropy parameter of each tracer $t$. We estimate the mass-to-light ratio, $\gamma$, the 3 RG parameters and the 3 $\beta_i$ from the data with a MCMC. Fig. 5 shows one example: RG properly describes the dynamics of the three populations with a unique set of RG parameters.

References

Abstract
Among the questions at the center of multimessenger astronomy is the nature of dark matter. Various methods for indirect detection of dark matter have been employed, taking from phenomenological models that predict possible dark matter annihilation and decay channels into Standard Model particles. In the case of dark matter decay, measurements of gamma-rays by Fermi-LAT were combined with IceCube neutrino data to obtain constraints of dark matter mass and lifetime for various models and channels. However, tensions existing between these measurements suggest that gamma rays become heavily suppressed below energies of around 50 TeV. A reason for this could be that properties of the traversed medium, which consists of extragalactic background light (EBL), the cosmic microwave background (CMB), and the intergalactic magnetic field, significantly alter the final gamma-ray spectrum that reaches telescopes on Earth. The existence of competing models for the EBL, moreover, complicates estimates of these dark matter constraints. My research aims to address these questions and to improve measurement techniques in order to understand the impact that the EBL has on indirect measurements of dark matter decay. I present my predictions for gamma-ray spectra undergoing attenuation by different EBL models, and I show how optical depth varies across these models, as well as its dependence on injected energy and redshift.

Background
Gamma rays originating from dark matter decay can be expressed in terms of their Galactic and Extragalactic contributions:
\[ \phi_{\gamma} = \phi_{\gamma}^{G} + \phi_{\gamma}^{EG} \]  
(1)
As these photons propagate to Earth, a portion of them scatter off of intermediate photons and electrons, giving rise to attenuated spectra. This effect becomes significant particularly at low energies for the Extragalactic component as photons traverse through the CMB and EBL. In addition, secondary photons can get produced as a result of these collisions, resulting in cascades. The final spectrum perceived at redshift \( z \) can be written as
\[ \frac{d\phi_{\gamma}}{dE_{\gamma}} = \frac{1}{E_{\gamma}} \int_{z}^{\infty} dz' \frac{1}{H(z')(1+z')} \left( \frac{1}{1+z'} \right)^3 \times j_{\text{EG}}(E', z') e^{-\tau(E', z', z)}, \]  
(2)
where \( \tau \) is the optical depth for pair production in an isotropic radiation field:
\[ \tau_{\gamma}(E_{\gamma}) = \int \int d\sigma_{\gamma}(E_{\gamma}, \gamma) \frac{d\sigma_{\gamma}}{d\Omega}(\gamma, r), \]  
(3)
\( \epsilon \) standing for the energy of the target photon, and \( j_{\text{EG}} \) is the emissivity, which can be separated into two components:
- **Prompt**: Photons created at the source can be described using
  \[ j_{\text{EG}}(E_{\gamma}, z') = \frac{\rho_{\gamma}(1+z')^3}{m_{\text{DM}}} \sum_{f} \frac{dN_{\gamma}}{dE_{\gamma}}(E_{\gamma}'), \]  
  (4)
- **Secondary**: Lepton pairs produced from collisions of primary photons with background radiation inverse Compton Scatter (ICS) with radiation photons, producing secondary gamma rays. The final gamma ray spectrum depends on the radiated power loss \( P_{\text{IC}} \) and energy loss \( b_{\text{IC}} \), which depend on the electron distribution and number density of the radiation field:
  \[ j_{\text{EG}} = 2 \int_{m_{\text{DM}}}^{m_{\text{DM}}} dE_{\gamma} \frac{P_{\text{IC}}}{b_{\text{IC}}} \int_{m_{\text{DM}}}^{m_{\text{DM}}} dE_{\gamma} \]  
  (5)
Both \( P_{\text{IC}} \) and \( b_{\text{IC}} \) depend on the radiation field in question and so will differ with different EBL models.

Optical Depths
Below we show CMB and EBL optical depths, where we use the EBL model from [1]:

Spectra from CMB and EBL & Next Steps
We use GCascade [2] and CRPropa [3] to propagate photons and obtain final spectra for different initial energy distributions from a distance of 4 Mpc:

On the top right, we show the attenuation due to one EBL model [1], while directly to the right, we show the attenuation due to another, different EBL model [4]. Going forward, we will obtain fluxes for gamma ray spectra from decaying dark matter, propagated using different EBL models. From there, we plan to extract the uncertainty associated with EBL so that we could apply these uncertainties to current constraints on dark matter. These results, along with a paper, are in preparation.

References
1 Resumen.

Se han publicado varias discusiones sobre las posibles observaciones de los campos 4-vectores. Nuestro estudio tiene en cuenta la forma general de las ecuaciones de movimiento así como los invariantes dinámicos de base tal como el trabajo de Noether. Restauramos la teoría de los campos A'TS y de los potenciales 4-vectores y estudiamos los límites sin masas. Las movimientos teóricos serían las anteriores publicaciones de Ojeytvitych y Polubarinov así como las de Kalb y Ramond. Ojetivtych presenta el concepto del Notof, cuya propiedad se demostraría de una serie de complementariedades. Analizamos la teoría cuántica de campos tomando en cuenta la dimensión de masa del notof y del fotón. Es posible describir de los grados de libertad del notof y del fotón en base a las observaciones medidas de los físicos. Presentamos la teoría cuántica de campos para espacios simétricos de segundo rango. Después, procedemos a derivar las ecuaciones para el tensor simétrico de segundo rango en base al formalismo Bagmann-Wigner. El multispacer simétrico de cuatro rango es utilizado. Generalizamos, y obtenemos las ecuaciones relativistas para ejes, que son consistentes con la relatividad general.

2 Teorema de Noether.

A cada transformación continua de N variables y funciones de campo que deja invariante la acción expresada como integral en un volumen cuadrimensional le correspondería N invariantes dinámicos, por ejemplo, una corriente-conservada de forma que el campo de deformación

\[ \eta(x) = \psi(x) + \delta\eta(x), \quad \delta\psi = \delta x + \delta\eta. \]  

Comenzamos diciendo que la acción es invariante

\[ I = \int \left[ (\partial_x \psi)^1 (P_1 - P_2) + (\partial_x \psi)^2 (P_2 - P_1) \right] dx \]  

con respecto a cualquier variación de \( \eta \) que sea consistente con la ley de conservación.

3 Formalismo Bargmann-Wigner.

Repräsentando el procedimiento de Bargmann-Wigner para obtener las ecuaciones para bosones con espín 0 y 1. Las ecuaciones básicas son

\[ \left[ r^2 \delta_{ij} + m \delta_{ai} \right] A_{ij}(x) = 0 \]  

Expandiendo la función de campo en las partes antissimétricas y simétricas

\[ \Psi_{\mu}(\eta) = R_{a b c} \delta_{\mu a} + \frac{1}{2} \left( R_{a b c} + g_{a b c} \right) \eta A_{a b} \]  

y

\[ \Psi_{\nu}^{s}(\eta) = \frac{1}{2} \left( R_{a b c} - g_{a b c} \right) \eta A_{a b} \]  

donde R es CP. Las ecuaciones (9) llevan al juego de ecuaciones de Kemmer para \( s = 0 \):

\[ m = 0 \]  

y

\[ m = 2 \]  

las ecuaciones de Proca-Duffin-Kemper para el caso \( s = 1 \):

\[ K = \frac{\partial F_{\mu \nu}}{\partial F_{\mu \nu}} = \frac{1}{n} \frac{\partial F_{\mu \nu}}{\partial F_{\mu \nu}} \]  

y

\[ 2m F_{\mu \nu} = \partial \times F_{\mu \nu} \]  

El campo cuantizado de "potencial" es

\[ A^0(x) = \sum_{\alpha, \beta} \left\{ \frac{1}{(2\pi)^3} \epsilon_{\mu \nu} \rho(x) \phi(p) \frac{1}{2} \right\} \]  

Para obtener estados transversales hay que utilizar relaciones entre \( F_{\mu \nu} \) y el potencial

4 Lagrangiano, Tensor de energía-momento y Momento Angular.

Comenzando con el Lagrangiano, incluyendo, en general, el término de masa

\[ L = \frac{1}{2} (\partial_x A_{\mu}) (\partial^\mu A_{\alpha}) - \frac{1}{2} (\partial^\alpha A_{\mu}) (\partial_x A_{\mu}) - \frac{1}{2} \frac{4}{3} \eta \partial^\alpha A_{\mu} \]  

y la ecuación de movimiento resultante es

\[ \frac{1}{2} \left( \eta^2 + 4 \right) A_{\alpha} = \frac{1}{2} \delta_{\alpha \beta} A_{\mu} \]  

y obteniendo el tensor energético

\[ T_{\mu \nu} = \frac{1}{2} \left( \eta^2 + 4 \right) \eta A_{\mu} \eta A_{\nu} - \frac{1}{2} \delta_{\mu \nu} \eta \partial^\alpha A_{\alpha} \]  

Y para rotaciones, los generadores de transformaciones infinitesimales se definen como

\[ \left( \delta_{\mu \nu} \right) = \frac{1}{2} \left( \eta^2 + 4 \right) \eta A_{\mu} \eta A_{\nu} - \frac{1}{2} \delta_{\mu \nu} \eta \partial^\alpha A_{\alpha} \]  

obteniendo el tensor energético

\[ T_{\mu \nu} = \frac{1}{2} \left( \eta^2 + 4 \right) \eta A_{\mu} \eta A_{\nu} - \frac{1}{2} \delta_{\mu \nu} \eta \partial^\alpha A_{\alpha} \]  

Referencias


6 El Tensor Simétrico.

Se obtiene la ecuación de segundo orden para tensores simétricos de segundo rango

\[ \frac{\delta (\partial_x A_{\mu} + \partial^\mu A_{\alpha})}{\partial (\partial_x A_{\mu})} = - \frac{\partial^\alpha (\partial_x A_{\mu})}{\partial \partial^\alpha A_{\mu}} \]  

Después de la contracción en las indices y z la ecuación se reduce al conjunto de las ecuaciones

\[ \partial_\alpha C_{\alpha \beta} = \frac{2}{m} F_{\alpha \beta} = 0, \]  

las ecuaciones que controlan los análogos del tensor energéo momento y el k-vector potencial.

7 Bosones de Espin 2.

El Lagrangiano más general invariante relativo para el tensor simétrico de segundo rango es

\[ L = -\alpha_1 (\partial_\alpha A_{\beta}) (\partial_\beta A_{\alpha}) - \alpha_2 (\partial_\alpha A_{\beta}) (\partial_{\beta+1} A_{\alpha}) + \alpha_3 (\partial_\alpha A_{\beta}) (\partial_{\beta+1} A_{\alpha}) + \alpha_4 (\partial_\alpha A_{\beta}) (\partial_{\beta+1} A_{\alpha}) \]  

y

\[ A_{\alpha} = \frac{1}{2} \delta_{\alpha \beta} \eta \partial^\alpha A_{\alpha} \]  

Donde esto resulta en el siguiente campo

\[ \eta^2 + 4 \]  

El tensor \( \eta^2 + 4 \) desaparece debido a la restricción de la traza nula. También es interesante notar que gracias a los posibles términos

\[ V(F) = \frac{1}{2} \delta_{\mu \nu} F_{\mu \nu} + \frac{1}{2} F_{\mu \nu} F_{\mu \nu} \]  

podemos darle a la GGA componente del campo de spin 2. Esto es debido a la posibilidad de que la simetría espontánea del Higgs se rompa de la siguiente manera

\[ V(F) = \text{constante} \times v + c \left( \frac{1}{2} \delta_{\mu \nu} F_{\mu \nu} \right)^2 \]  

con \( v \) siendo el valor esperado del vacío, \( c \geq 0 \). Otras grados de libertad de 4-vector son removi dos debido a que son los bosones de Goldstinos. Como es usual, estos modos deben ser importantes para probar masas a los bosones de forma normal. Esta expresión no permite una base arbitraria para \( F_{\mu \nu} \), es lo que es posible solamente si el 4-vector sea de variable complejo.

8 Conclusiones.

Deducimos las ecuaciones gravitacionales del MCR. Las relaciones de esta teoría con la gravedad tensori-espectral han sido discutidas. Se le puso especial atención a las definiciones correctas del tensor energéo momento y a las corrientes de Noether en EM y TIRG. Estimando interacciones concluimos que pueden ser vistas prácticamente en experimentos.
ABSTRACT

Dark matter--anti-dark matter ($\chi - \bar{\chi}$) oscillations can cause the reactivation of DM annihilations during structure formation, eliminating cusps from galactic DM profiles while respecting constraints from BBN, CMB, and the observed DM relic density.

OSCILLATION FORMALISM: TWO MODELS

$$\mathcal{L}_m = \frac{1}{2} \delta m (\bar{\chi} \chi + \text{H.c.})$$

$$\mathcal{L}_1 \supset \frac{1}{2} m_1^2 V_\mu - g \bar{\chi} V \chi$$ (vector mediator)

$$\mathcal{L}_2 \supset \frac{1}{2} m_2^2 \phi^2 - \frac{1}{2} m_a^2 a^2 - g' \bar{\chi} (\phi + i a \gamma_5) \chi$$ (scalar mediator)

For annihilations to recouple during structure formation, the oscillations should start before $\sim 0.1$ Gyr, so

$$10^{-31} \text{eV} \lesssim \delta m \lesssim \sqrt{\frac{\eta_{\text{DM}}}{M_p}} \frac{m_1}{\sigma_T} \sim 10^{-14} \text{eV},$$

assuming $m_{\chi} \sim 100$ MeV. Annihilations could decouple in the early universe while still being important in overdense environments at late times.

EARLY COSMOLOGY

Following [1, 2], the quantum Boltzmann equations are

Model 1 (flavor-sensitive vector mediator)

$$Y' = -\frac{i}{xH} [H_0, Y] - \xi^3 \frac{(\sigma v)}{xH} s \begin{pmatrix} 0 & Y_{12} \cr Y_{21} & 0 \end{pmatrix} \text{Tr} Y$$

Model 2 (flavor-blind scalar mediator)

$$Y' = -\frac{i}{xH} [H_0, Y]$$

where $\text{det}' Y \equiv Y_{11} Y_{22} + Y_{12} Y_{21}$ and $\xi = T/\chi$.

Figure 1: Comoving density $Y \times 10^{10}$ vs. $x = m_{\chi}/T$.

STRUCTURE FORMATION & N-BODY SIMULATIONS

Figure 2: $\log_{10} \rho_\chi$ vs. $\log_{10} r$. Evolving $\rho_\chi$ for $\sim 10$ Gyr in a dwarf spheroidal galaxy and a cluster of galaxies.

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ACKNOWLEDGEMENTS

Figure 1: Comoving density $Y \times 10^{10}$ vs. $x = m_{\chi}/T$. 

Figure 2: $\log_{10} \rho_\chi$ vs. $\log_{10} r$. Evolving $\rho_\chi$ for $\sim 10$ Gyr in a dwarf spheroidal galaxy and a cluster of galaxies.
We study a dark matter production mechanism based on decays of a messenger WIMP-like state into a pair of DM particles that are self-interacting via exchange of a light mediator. Its distinctive thermal history allows the mediator to be stable and therefore avoid strong limits from the cosmic microwave background and indirect detection. A natural by-product of this mechanism is a possibility of a late time transition to a dominant dark radiation component which can help alleviate the $H_0$ tension. We provide a simple realization of the mechanism in a Higgs portal dark matter model. We find a significant region of the parameter space that leads to a mild relaxation of the Hubble tension while simultaneously having the potential of addressing small-scale structure problems of $\Lambda$CDM. In addition, the light mediator lying in cosmologically preferred region we considered was recently shown to provide one of most promising explanations of XENON1T electronic recoils excess.

**Shortcomings of $\Lambda$CDM model**

- small-scale problems
  - too big to fail
  - missing satellites
  - core-cusp problems
- early-late Universe tensions
  - $H_0$, $\sigma_8$ tension
  - $\Omega_0$ tension ($\Omega_0$ tension)

**Cosmological scan**

- We used public MCMC code MontePython with combined datasets from Planck, BAO data from the BOSS survey, the galaxy cluster counts from Planck catalogue and local measurement of the Hubble constant to constrain decaying DM model and compare with standard $\Lambda$CDM cosmology.

**Model**

- Consider a dark sector comprised of a Dirac fermion $\chi$ charged under new gauge $U(1)_X$ broken spontaneously at some higher scale resulting in massive vector $A^\mu$.
- The dark sector part of the Lagrangian after the $U(1)_X$ breaking reads:
  
  \[ L^\text{DM} = \frac{1}{2} \partial \mu \partial^\mu \chi + m_\chi^2 \chi^2 + \lambda_1 |\chi|^4 + \lambda_2 |\chi|^2 |
  
- Connect with the visible sector is given by the portal:

**Thermal history**

- The illustration of the thermal history of $S$ (blue), $\chi$ (black) and $A^\mu$ (orange) with example parameter choices leading to early (regime A), solid lines, late (regime B), dashed and very late (regime C, dotted) decays of $S$.
- Parametrizing the symmetry breaking by a small parameter $\epsilon$, one can distinguish four regimes:
  - $\epsilon < 0$: usual thermal self-interacting model subject to strong limits
    - regime A: $\epsilon < 0$: viable regime for self-interacting DM
    - regime B: $\epsilon < 0$: weak regime for self-interacting DM
    - regime C: $\epsilon > 0$: regime potentially addressing the $H_0$ tension and providing an uSIDM candidate.

**XENON1T electronic recoils excess**

- Light, very weakly interacting dark photon seems well suited to simultaneously explain the excess as well as provide extra cooling of stars, as favored by observations of horizontal branch stars.
- This scenario can be naturally accommodated for in our model.

**Takeaway**

- uSIDM production by late decays of WIMP-like messenger
- Mechanism exemplified in a Higgs portal DM model
- Well-motivated mechanism deserving further model building