Testing merging of Dark Exotic Stars from Gravitational Waves in the Multi-messanger approach.

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Abstract

We discuss possible implications of the recent detection by the LIGO and VIRGO collaboration of the gravitational-wave event GW170817, the signal of which is consistent with predictions in general relativity on the merging of neutron stars. A near-simultaneous and spatially correlated observation of gamma-ray burst, the GRB 170817A signal, was achieved independently by the Fermi Gamma-ray Burst Monitor, and by the Anti-coincidence Shield for the Spectrometer for the International Gamma-Ray Astrophysics Laboratory. Motivated by this near temporal and spatial concomitance of events, which can occur by chance only with the probability $5.0 \times 10^{-8}$, we speculate on the possibility that new dark stars signals could be detected from LIGO/VIRGO detectors. This proposal, which aims at providing a test for some models of dark matter, relies on this recent achievement of detecting for visible ordinary matter the merging of neutron stars both in the gravitational and the electromagnetic channel. A lack of correlation between the two expected signals would then suggest a deviation from properties of ordinary matter. Specifically, we focus on models of invisible dark matter, and in particular we study the case of mirror dark matter, in the framework of which a large amount of mirror neutron stars are naturally envisaged in our dark matter halo.

1 Introduction

The recent discovery of the gravitational-wave event GW170817 by the LIGO and VIRGO collaboration was the first observation of a gravitational wave to be combined with gamma rays signal. The latter was detected thanks to the FERMI and INTEGRAL collaborations, and to other constraints from multi-messengers observations. This concomitance of signals opens a clear pathway to the development of a new era of observations in astrophysics and cosmology [1, 2, 3]. At the level of the knowledge of the Universe’s microphysics, data are compatible with the signal expected in general relativity (GR) from the merging of neutron stars, thus confirming predictions of the Einsteinian theory of gravitation at an high accuracy level.

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Following a line of thoughts that hinges on the current availability of data sets in both the gravitational and the electromagnetic channel, at least for a class of phenomena such as neutron stars merging we may envisage the intriguing possibility to test dark exotic stars merging scenarios. The underlying idea is based on focusing on the multi-messenger approach in order to distinguish the observation of ordinary matter stars — predicted from General Relativity and the Standard Model — from the observation of new exotic stars that are predicted by extensions of the Standard Model with *new dark gauge sectors* and dark matter particles.

Contrary to standard WIMP candidates of dark matter, there are many possible extensions of the Standard Model that explain dark matter while predicting a richer astrophysical complexity than WIMP candidates that is hidden in the dark halo. The paradigm that the Standard Model could be extended with a hidden gauge sector, namely $G'$, as $SU(3) \times SU(2) \times U(1) \times G'$ is old-standing idea and it was explored accounting for several different choices of $G'$. Within this scenario, standard model particles are assumed to be sterile with respect to the dark gauge group.

The first proposal of hidden sector that was ever considered in the literature is the
Figure 2: The energy-density evolution (related to the gravitational wave strain $\rho h_{22}^+$) as a function of time is displayed. We consider the case in which the Neutron stars have the same mass and with an initial realistic inter-distance between the two Mirror neutron stars (we sets 40 km). The different signal predicted from the various EoS models, displayed in Fig.1, the APR4 [63] (blue), SLy [64] (green), H4 [62] (red) and MS1 (light blue) [65] models.

Mirror Dark Matter (MDM) model, suggested by T.D. Lee and C.N. Yang in their Noble prize paper Ref. [4]. The phenomenological implications of the Mirror World were first analyzed by Kobzarev, Okun and Pomeranchuk in Ref. [5], and then hitherto elaborated in Refs. [6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. After these seminal papers, many astrophysical and phenomenological aspects were investigated, independently by Z. Berezhiani et al [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28] and by R. Foot et al [31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41] — see also Ref. [42] for a review by L.B. Okun on this topic.

The Mirror world is a hidden replica of the Standard Model gauge group $G'_{SM} = SU'(3) \times SU'(2) \times U'(1)$ that restores the left-right symmetry violated in the Standard Model by the weak interactions. In other words, the Mirror World is a parity completion of the Standard Model as a $G_{SM} \times G'_{SM}$ gauge theory. The complete theory $G_{SM} \times G'_{SM}$ is invariant under Mirror discrete transformations as $G_{SM} \leftrightarrow G'_{SM}$. If Mirror parity is an exact discrete symmetry, then it must relate every ordinary particles, including the electron $e$, the proton $p$, the neutron $n$, the photon $\gamma$, the neutrinos $\nu$ etc. with their mirror twins $e'$, $p'$, $\gamma'$, $\nu'$ etc. Mirror partners are sterile to ordinary
strong, weak and electromagnetic interactions, but in turn undergo their own hidden
gauge interactions, belonging to the $SU'(3) \times SU'(2) \times U'(1)$ hidden sector, with exactly
the same Ordinary Standard Model couplings. Thus, no new extra coupling parameters describing the Mirror physics are introduced. Ordinary and Mirror twin particles
have the same mass and the same microphysics rules, from high energy particle physics
to atomic and nuclei physics.

Minimal version of MDM have been also considered in the literature, especially in
light of their cosmological applications. These models usually double a subgroup of the
Standard Model gauge group — see e.g. Ref. [43, 44, 45, 46, 47], and do not necessarily
preserve the dark visible symmetry at the level of the coupling constants of the theory.
This might then allow for a resolution of both the dark energy problem and the dark
matter problem, at the same time, by allowing for an imbalance between the energy
scales of the dark matter and quintessence fields. We are not anyway biased in propos-
ing this working direction. Within this analysis we take a minimalistic approach, so
to be as much as possible general about our assumptions and encode the most generic
cases.

The plan of the paper is the following. In Sec. 2 we address the cosmological con-
straints of MDM models, extending the analysis on minimal models making use only
of subgroups of the Standard Model of particle physics. In Sec. 3 we review structure
formation within the framework of MDM models, and illustrate the complexity of the
dark matter scenario and its constraints for MDM models. In Sec. 4 we review theoret-
cal predictions from General Relativity on the gravitational waves signal. Finally, in
Sec. 5 we spell out conclusions and specify future outlooks for research in this direction.

2 Mirror Cosmology

We start reviewing the peculiar cosmological features that must be fulfilled by MDM
models, in order to become valid models of dark matter. We then generalize the dis-
cussion so to encode minimal and partial scenarios of MDM.

Although the Ordinary and the Mirror Sectors share the same microphysics, a reli-
able dark matter model must posses a specific cosmological evolution consistent with
experimental constraints. For instance, if we naively assume that $\Omega'_B = \Omega_B$, in which $\Omega_B$ and $\Omega'_B$ are the relative amounts of Ordinary and Mirror Baryons, then the Mirror Matter cannot provide for all the amount of Cold Dark Matter $\Omega_{DM} \approx 5\Omega_B$. On the other hand $T' = T$, i.e. an equal temperature between the two sectors, would be in inconsistent with limits from Big Bang Nucleosynthesis (BBN) on the amount of relativistic degrees of freedom. Extra Mirror neutrinos must contribute as $\Delta N_{\nu}^{eff} = 6.15$, which is inconsistent with the experimental bound on it — close to $\Delta N_{\nu}^{exp} \approx 0.5$.

To avoid encountering this kind of shortcomings, we must assume that:

1. after the inflationary epoch, the two sectors were re-heated with different temperatures;

2. the Ordinary and Mirror Worlds – with different mediators from gravity — are very weakly interacting, in such a way that both the systems evolve adiabatically, without undergoing into thermal equilibrium.

Under these two hypotheses, the Mirror matter becomes a viable candidate of collisional and dissipative cold dark matter.

Furthermore, BBN in the Mirror World will happen in a cosmological time antecedent to the time of BBN in the Ordinary World. The condition $T' << T - T'$ and $T$ are respectively the Mirror and the Ordinary temperatures — implies that a larger amount of baryon asymmetry is produced in the Mirror sector, i.e. $\eta'_B > \eta_B \approx (2 \div 6) \times 10^{-10}$ [18]. As shown in Ref. [18], as a consequence of temperature asymmetry between the two sectors, the produced He-4 mass fraction is considerably larger then in the ordinary sector, since $Y'_4 \approx 0.4 \div 0.8$ against $Y_4 \approx 0.24$. Thus He-4 constitutes the largest amount of MDM during recombination epoch.

We emphasize that the aforementioned issue of recovering extra relativistic degrees of freedom is solved when $T' \ll T$. Basically, the number of degrees of freedom $g_*$ gets a contribution from the Mirror sector ($e', \nu', \gamma'_{e, \mu, \tau}$) that is suppressed with a ratio $(T'/T)^4$ [18]. Consequently, since the extra degrees of freedom are found to be

$$\Delta g_* = g_*(1 + x^4) - 10.75 = 1.75 \Delta N_{\nu},$$

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we recover the bound
\[ \Delta N_e = 6.14 \times x^4 \rightarrow x < 0.64, \]
which is highly compatible with the “Mirror Matter=Dark Matter” bound, i.e.
\[ \Omega_{B'}/\Omega_B \simeq 5. \]
This opens the pathway to the possibility of reconciling neutrinos flux anomalies in short baseline, understandable in terms of extra sterile neutrinos, with BBN bounds \cite{16,31}.

Minimal dark models that double subgroups of the Standard Model gauge group may be taken into account in stead, and finally encoded into this proposal on correlated GW and BRB detection, making more general our discussion. For instance, discrete symmetries are present in some extensions of the Standard Model, in which we encounter vector-like couplings of the electroweak SU(2) subgroup to an “hidden” fermionic sector undergoing confinement by strong forces. This was for instance considered in Ref. \cite{45}, in which the hidden fermionic sector is shown to lead to the formation of isotriplet.

On the other hand, doubling directly the QCD sector as in \cite{46,47} without taking into account any discrete symmetry that involves the coupling constants of the visible and invisible sectors, can lead to scenarios in which the resolution of the dark energy paradigm entails an usual path toward the explanation of dark matter. For instance, fixing the pion decay constant to be \( f_D \simeq \text{meV} \) in order to reproduce constraints on the current accelerated expansion of the universe, induces to set up a scale for invisible dark matter that predicts a halo composed of very compact dark neutron stars, strange/quark stars and black holes, the masses of which are \( M_{\text{MACHO}} < 10^{-7} M_\odot \).

We will not further refer to this scenario here, and leave the reader to the relevant references.

3 Structure Formation and Dark Halo

We focus in this section on dark matter structure formation, specifying how dark halo densities can be reproduced in MDM models.
As we mentioned above, a dark astrophysical complexity can be envisaged: nothing prevents the formation of galaxy structures and stars in both the extended and minimalistic Mirror sectors. Though, the dark stars formation will be radically different than the ordinary one, being highly affected from the initial nuclei composition arising from BBN. The problem of mirror stars formation was studied in Ref. [28], in which using numerical methods for stars evolution and explosion time, the evolution of stars with large helium abundances \((Y = 0.30 - 0.80)\) and a range of masses \(0.5 \div 10 \, M_\odot\) was analyzed. The authors of Ref. [28] found that Helium dominated mirror stars have a much faster evolutionary time than ordinary stars with same masses. Since the abundance of Helium is higher in the Mirror sector, Mirror stars evolve faster as compared to ordinary ones. This means that they will explode earlier (as type II Supernovae) injecting Mirror nuclei in the Mirror interstellar medium. In turn, this will change the second generation stars formation processes, as well as the abundance of neutron stars, black holes, white and brown dwarfs.

The dynamical evolution of the dark halos emerging from this picture is highly complicated and unpredictable, since much more complicated that in the WIMP-like case. The problem of Mirror neutron stars distributions in the Milky Way dark halo as well as in other galaxies and clusters is affected from huge astrophysical uncertainties. Further more considerations and remarks on Mirror structure formation problem are more extensively discussed in Appendix.

4 Gravitational waves signals

In this section we show gravitational waves signals as expected from Mirror Neutron stars merging processes. The Equivalence Principle at the basis of General Relativity entails for Mirror twin objects exactly the same features as for the (exhaustively studied) Ordinary twin systems. Our task then trivializes into a simple review of results widely known in the literature.

Being more specific, we may model Mirror Neutron Stars equations as for the case of ordinary Neutron Stars. We then consider four realistic EoS models, \textit{i.e.} the APR4 [63], SLy [64], H4 [62] and MS1 [65] models. In Fig.1, we show the emitted energy-density in gravitational waves, on the right side, in order to allow a comparison of
results with the EoS displayed on the left side. In such a demonstrative case, we have assumed the mass of the two Neutron Stars to be equal to each other\footnote{Our results can be reproduced using open sources codes. In particular, we used The Einstein Toolkit in order to simulate the numerical evolution of the Hydrodynamical Equations in General Relativity \cite{66}. We also consider the LORENE library \cite{67,68} for tabulated EoS.} Our numerical results are in agreement with the large numerical GR literature dedicated on Neutron Stars Merging — see e.g. \cite{69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,97}.

We may ask how many events for LIGO/VIRGO we should expect according to Mirror Dark Matter predictions, and where these should take place in or outside the galaxy. Unfortunately Mirror Dark Matter cannot provide a sharp answer to these questions, because of the aforementioned Mirror astrophysical complexity. Indicatively, if the Mirror Dark halo is distributed as a Silk Disk, then most of the galactic events are expected to be localized on the MW Disk. On the other hand, in the case of MW Elliptical Mirror halo, some events are also expected outside the Disk, where the gravitational waves noise is also much less present than in the Disk. Finally, most part of the events are expected to point toward the Galactic Bulge, since the Dark Matter halo has an over-density distribution in the center. Other events are expected outside our galaxy, in the proximity of Dark Matter halos, \textit{i.e.} close to spirals, elliptical and irregular galaxies, clusters and so forth.

5 Conclusions and remarks

We discussed the intriguing possibility that the merging of exotic Dark Stars, not predicted by the Standard Model of particle physics and General Relativity, can be tested thanks to the detection of gravitational waves signals that show no correlation with electromagnetic signals. This is a strategy that is enabled now days by the recent experimental observations of correlated gravitational and electromagnetic signals arisen out of the LIGO/VIRGO and FERMI/INTEGRAL collaborations.

We discussed such a possibility examining signals consistently produced by “invisible” candidates of Dark Matter, \textit{i.e.} non interacting with the electromagnetic sector. Specifically, we focused on the framework of Mirror Dark Matter, a long-standing candidate for Dark Matter that predicts similar microphysics laws than the ordinary Standard Model of particle physics, while doubling entirely the gauge sector of the
latter.

Specifically, to claim detection of Mirror Dark Matter via tests of Mirror Stars Merging we must observe gravitational waves signals with \textit{exactly} the same main features than the ones predicted by ordinary matter, and at the same time correlation to electromagnetic signals proper of ordinary Stars Merging must be rejected as hypothesis. Indeed the equations of state of Mirror Neutron Stars are exactly the same as in the ordinary sector. This is a sharp prediction arising from Mirror Symmetry and constitutes a fundamental principle of Nature within the Mirror paradigm.

Thanks to this, despite of the astrophysical complexity of the Mirror Dark Halos and their highly unpredictable hidden structure formation, numerical investigations already carried out for Ordinary Neutron Stars can be deployed in the search for Mirror Neutron Stars merging, in the gravitational channel. In this scenario, there a fundamental \textit{caveat} to take care of. Mirror systems must be totally invisible in the electromagnetic channel, \textit{i.e.} the hypothesis of correlations to electromagnetic signals that are proper of ordinary stars merging must be rejected. This highly motivates a multi-messenger approach in order to discriminate signals arising from the merging of \textit{Exotic} Stars from signals predicted by the microphysics (Standard Model of particle physics and General Relativity) of ordinary systems.

We focused on the case of Mirror Neutron stars, but of course \textit{Mirror Supernovae} would also represent valid candidates to test signals of gravitational waves originated by the Mirror sector. Remarkably, a third channel would be present in this latter case to corroborate detection of the event. This further channel is represented by the detection of neutrinos signals, to be combined now with gravitational waves signals. Correlations between the gravitational waves signals and the neutrinos signals allows to identify the class of objects that are merging. The presence of neutrinos channel in Mirror Supernovae is due to the fact that Mirror Dark Matter is compatible with large — enough to be observed at cosmological distances — mixing among Mirror neutrinos and ordinary neutrinos [16, 31].

Another interesting possibility is that Mirror Dark Matter coexists with axion dark matter. The axion field can be introduced as a common Peccei-Quinn shift symmetry
among the Ordinary and the Mirror sector. In such a picture, the Milky Way Mirror halo can be distributed as a Silk Disk, i.e. a Double Disk Dark Matter scenario can be envisaged. On the other hand, axion dark matter can be mostly distributed outside the Milky way disk, organized as an elliptical halo. In this case, it is also conceivable the existence of exotic axion stars from overdensity instabilities of the axion condensate. In such a scenario, merging of boson stars can predict a peculiarly interesting gravitational wave signal (see Refs. [98, 99] for recent numerical analysis on Boson Stars merging). According to this hypothesis, observations of GW signal from Mirror neutron stars merging are predicted in the Milky Way plane, while axion stars merging are expected from the sky regions outside the Milky Way plane.

To conclude, we emphasize that the strategy discussed in this paper, which mainly pertains the theoretical framework of Mirror Dark Matter, can be opportunely generalized so encode several other dark gauge sectors, as for instance:

- Minimal instantiation of Mirror Dark Matter (discrete symmetries scenarios, IQCD, extra SU(2), etc...);
- Dark Silk Disk;
- Technicolor.

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Appendix: more about the structure formation problem

In this section, we will add further more considerations and remarks on the insidious problem regarding the structure formation in Mirror dark matter halos.

The main open problem is how MDM can form an extended dark halo, which is dissipative. One might expect indeed that Mirror Matter forms Galactic Silk Disks despite of extended halos. The Milky Way (MW) disk predicted by the Mirror sector
must have different radius and thickness. In principle, this is not incompatible with local dark matter halo constraints. As it is well known, the total matter surface density at the Sun radius is \((68 \pm 4) \ M_\odot/pc^2\) (see Ref.[48]). Since, the amount of visible energy density contributes to the total amount as \((38 \pm 4) \ M_\odot/pc^2\) [48], the surface density of the Mirror matter density should account for the remaining part, compatible with the presence of a Mirror Silk Disk. A Dark Matter Silk Disk cannot explain the MW galaxy rotational curves without considering other dark matter components, such as axions or other parallel asymmetric Mirror sectors. Such a multi-component dark matter scenario seems to lie into the class of models that are dubbed *Double Disk Dark Matter* and were recently analyzed in Refs. [49, 50, 51, 52, 53].

Nonetheless these considerations cannot be claimed to be definitive, since any numerical N-body simulations within the framework of MDM have been yet performed. For example, it is still possible that the high rate of supernovae explosions in the Mirror halo core could cause a back-reaction effect that is able to reheat Mirror nuclei and can compete with dissipative contraction.

Another possibility that is still open, also suggested in Ref. [30], is that the Mirror stars formation is so rapid — generally, it is faster than stars formation in the Ordinary World — that stars arise faster than the Silk Disk would originate from dissipative cooling. In this latter case, the Mirror halo that emerges from the dissipative process is similar to an elliptical galaxy rather than a Silk Disk. Such a possibility may be suggested also following Jeans criteria [54]. The Jeans mass is indeed smaller within the Mirror matter framework. Mirror matter is cooler and helium dominated, i.e. the star formation is more efficient. Let us remind that, from present data, the most accreditate mechanism for the formation of the Elliptical galaxies in our Ordinary Matter sector is imagined to be the merging of galactic spiral galaxies. Nonetheless, our galactic dark halo may be formed too from the merging of two Silk Disks, generating an elliptical halo [55]. It is not clear though how in this case the MW ordinary disk would be preserved from such a collision. Still, it is possible that our MW Dark halo is formed from the merging of an almost totally dominated elliptical Mirror galaxy and a Double Disk system.
From these considerations, we may argue that the internal structure of the MW Dark halo is the least predictable issue of MDM, as it deserves sophisticated numerical N-body simulations. However current astrophysical observations, e.g. micro-lensing constraints from Massive Compact Astrophysical Halo objects and Gravitational Waves emissions, allow to limit a posteriori available theoretical scenarios. For example, MA-CHO and EROS collaborations set sever limits on the ratio of Massive Compact Astrophysical Halo Objects (MACHOs). For instance, they exclude that the halo has more then the 0.1% of MACHOs or so, within a mass spectrum of approximately $10^{-6} \div 10^{-3} M_\odot$. The hypothesis that the Mirror MW halo could be an elliptical galaxy seems to be disfavored at a first sight. Conversely, the Double Dark Disks hypothesis can be subtly compatible with MACHO/EROS analysis, since the measure is performed pointing toward the Large Magellanic Cloud, outside the direction of the galactic plane. In this case, the presence of MACHOs on the Dark Silk Disk is still unconstrained and the hypothesis cannot be excluded.

It is worth noting that even this conclusion might not be completely correct. This is because limits arisen from the MACHO and EROS collaborations are highly model dependent, relying on the choice of the Dark Halo models. The latter are assumed by the MACHO and EROS collaborations to be deformations of isothermal-like halos. Nonetheless, constraints from MACHO/EROS can be further relaxed, if one assumes a co-rotating or counter-rotating Mirror halo. The optical depth factor, from which the average MACHO masses and ratio are related, is quadratically dependent on the relative velocity among the Earth and the MACHO objects. Then, a co-rotating halo will change the relative velocity, making the MACHOs detection more elusive. Since Elliptical galaxies are observed to have a rotation of almost $50 \div 100$ km/s, this can radically change the analysis. For instance, comparing the assumptions for the Mirror MW halo with the ones for the MACHO/EROS halo models, it is straightforward to note that the estimate of the ratio may change by a factor 2 or even more.

Analogue comments concern constraints on the Mirror Dark halo that arise from the Bullet Cluster observations. The Bullet Cluster imposes strong limits on the Dark Matter self-collisional cross section $\sigma_{s.c.}$ over the dark matter particle mass $m$. The bound on the ratio, which is approximately $\sigma_{s.c.}/m < 10^{-23}$ cm$^2$/GeV, seems to be
a gravestone for Mirror matter appearing in the form of a plasma of collisional nuclei. Nonetheless, if Mirror Dark halos of Bullet Clusters are mostly organized in mirror stars, the Mirror star-star collision probability over the star mass is highly suppressed, and again Mirror Dark Matter can be subtly compatible with Clusters data. Indeed, contrary to the WIMP paradigm, Mirror Halo can be organized in several different structures, including plasma like forms, very similarly to what observed in the ordinary sector. Such a rich cosmological picture offers also the possibility to explain possible future hints of dark matter self-collisionality from specific clusters.

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