STRUCTURE FORMATION, CMB AND LSS IN A MIRROR DARK MATTER SCENARIO

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Abstract

In the mirror world hypothesis the mirror baryonic component emerges as a possible dark matter candidate. Here we study the behaviour of the mirror dark matter and the differences from the more familiar CDM candidate for structure formation, cosmic microwave background and large scale structure. We show mirror models for CMB and LSS power spectra and compare them with observations, obtaining bounds on the mirror parameter space.
1 Introduction

The idea that there may exist a hidden mirror sector of particles and interactions with exactly the same properties as our visible world was suggested long time ago by Lee and Yang [1], and the model with exact parity symmetry interchanging corresponding fields of two sectors was proposed many years later by Foot at al. [1]. The two sectors communicate with each other only via gravity\(^1\). A discrete symmetry \(G \leftrightarrow G'\) interchanging corresponding fields of \(G\) and \(G'\), so called mirror parity, guarantees that two particle sectors are described by identical Lagrangians, with all coupling constants (gauge, Yukawa, Higgs) having the same pattern. As a consequence the two sectors should have the same microphysics\(^2\). After its first applications to non-baryonic dark matter [4], the mirror matter hypothesis has been invoked in many physical and astrophysical questions: large scale structure of the Universe [5, 6], galactic halo [7], MACHOs [8], gamma ray bursts [9], orthopositronium lifetime [10, 11], neutrino physics [12], interpretation of dark matter detection experiments [13], meteoritic event anomalies [14, 15], close-in extrasolar planets [16], Pioneer spacecraft anomalies [17].

If the mirror (M) sector exists, then the Universe along with the ordinary (O) particles should contain their mirror partners, but their densities are not the same in both sectors. In fact, Berezhiani et al. [18] showed that the BBN bound on the effective number of extra light neutrinos implies that the M sector has a temperature lower than the O one, that can be naturally achieved in certain inflationary models [19]. Then, two sectors have different initial conditions, they do not come into thermal equilibrium at later epoch and they evolve independently, maintaining approximately constant the ratio among their temperatures.

All the differences with respect to the ordinary world can be described in terms of only two free parameters in the model, \(x \equiv T'/T\) and \(\beta \equiv \Omega'_b/\Omega_b\), where \(T\) (\(T'\)) and \(\Omega_b\) (\(\Omega'_b\)) are respectively the ordinary (mirror) photon temperature and the ordinary (mirror) baryon density. The bounds on the mirror parameters are \(x < 0.64\) [18] and \(\beta > 1\), the first one coming from the BBN limit and the second one from the hypothesis that a relevant fraction of dark matter is made of mirror baryons.

In fact, if \(\Omega'_b \geq \Omega_b\), mirror baryons emerge as a possible dark matter candidate (MBDM) [20]; the peculiar properties of mirror dark matter were discussed in ref. [1].

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\(^1\)There could be other interactions, as for example the kinetic mixing between O and M photons [21], but they are negligible for the present study.

\(^2\)Here we do not consider the possibility that the mirror parity is spontaneously broken, leading to somewhat different particle physics in the mirror sector [3].
2 Relevant length scales

The important moments for the structure formation are related to the matter-radiation equality (MRE) and to the matter-radiation decoupling (MRD) epochs. The MRE occurs at the redshift

\[ 1 + z_{\text{eq}} = \frac{\Omega_m}{\Omega_r} \approx 2.4 \cdot 10^4 \frac{\Omega_m h^2}{1 + x^4}. \]

Therefore, for \( x \ll 1 \) it is not altered by the additional relativistic component of the M sector. The mirror MRD temperature \( T'_\text{dec} \) can be calculated following the same lines as in the O one \[18\], and hence

\[ 1 + z'_\text{dec} \simeq x^{-1} (1 + z_{\text{dec}}) \simeq 1100 x^{-1}, \]

so that the MRD in the M sector occurs earlier than in the O one. Moreover, for values \( x < x_{\text{eq}} \simeq 0.046 (\Omega_m h^2)^{-1} \), the mirror photons would decouple yet during the radiation dominated period. This critical value plays an important role in our further considerations, where we distinguish between two cases: \( x > x_{\text{eq}} \) and \( x < x_{\text{eq}} \).

The relevant scale for gravitational instabilities is the mirror Jeans mass, defined as the minimum scale at which, in the matter dominated epoch, subhorizon sized perturbations start to grow. In the case \( x > x_{\text{eq}} \) (where the mirror decoupling happens after the matter-radiation equality) its maximum value is reached just before the mirror decoupling, and is expressed in terms of the O one as

\[ M'_{\text{J, max}} \approx \beta^{-1/2} \left( \frac{x^4}{1 + x^4} \right)^{3/2} M_{\text{J, max}}, \]

which, for \( \beta \geq 1 \) and \( x < 1 \), means that the Jeans mass for the M baryons is lower than for the O ones, with implications for the structure formation process. If, e.g., \( x = 0.6 \) and \( \beta = 2 \), then \( M'_J \sim 0.03 M_J \). We can also express the same quantity in terms of \( \Omega_b, x \) and \( \beta \), in the case that all the dark matter is in the form of mirror baryons, as

\[ M'_J(a'_\text{dec}) \approx 3.2 \cdot 10^{14} M_\odot \beta^{-1/2} (1 + \beta)^{-3/2} \left( \frac{x^4}{1 + x^4} \right)^{3/2} \left( \Omega_b h^2 \right)^{-2}. \]

For the case \( x < x_{\text{eq}} \), the mirror decoupling happens before the matter-radiation equality. In this case we obtain for the highest value of the Jeans mass just before decoupling the expression

\[ M'_J(a'_\text{dec}) \approx 3.2 \cdot 10^{14} M_\odot \beta^{-1/2} (1 + \beta)^{-3/2} \left( \frac{x}{x_{\text{eq}}} \right)^{3/2} \left( \frac{x_{\text{eq}}}{1 + x^4} \right)^{3/2} \left( \Omega_b h^2 \right)^{-2}. \]
In case $x = x_{eq}$, the expressions (4) and (5), respectively valid for $x \geq x_{eq}$ and $x \leq x_{eq}$, are coincident, as we expect. If we consider the differences between the highest mirror Jeans mass for the particular values $x = x_{eq}/2$, $x = x_{eq}$ and $x = 2x_{eq}$, we obtain the following relations:

$$M'_{J,\text{max}}(x_{eq}/2) \approx 0.005 M'_{J,\text{max}}(x_{eq}),$$

$$M'_{J,\text{max}}(2x_{eq}) \approx 64 M'_{J,\text{max}}(x_{eq}).$$

Density perturbations in MBDM on scales $M \geq M'_{J,\text{max}}$ which enter the horizon at $z \sim z_{eq}$ undergo uninterrupted linear growth. Perturbations on scales $M \leq M'_{J,\text{max}}$ start instead to oscillate after they enter the horizon, thus delaying their growth till the epoch of $M$ photon decoupling.

As occurs for perturbations in the $O$ baryonic sector, also the $M$ baryon density fluctuations should undergo the strong collisional Silk damping around the time of $M$ recombination, so that the smallest perturbations that survive the dissipation will have the mass

$$M'_{S} \sim \left[f(x)/2\right]^{3} (\beta \Omega_{b} h^{2})^{-5/4} 10^{12} \, M_{\odot},$$

where $f(x) = x^{5/4}$ for $x > x_{eq}$, and $f(x) = (x/x_{eq})^{3/2} x_{eq}^{5/4}$ for $x < x_{eq}$. For $x \sim x_{eq}$ we obtain $M'_{S} \sim 10^{10} \, M_{\odot}$, a typical galaxy mass.

3 CMB and LSS spectra

In order to obtain quantitative predictions we computed numerically the evolution of scalar adiabatic perturbations in a flat Universe in which is present a significant fraction of mirror dark matter at the expenses of diminishing the CDM contribution and maintaining constant $\Omega_{m}$. We have chosen a “reference cosmological model” with the following set of parameters [21]: $\omega_{b} = 0.023$, $\Omega_{m} = 0.25$, $\Omega_{\Lambda} = 0.75$, $n_{s} = 0.97$, $h = 0.73$.

The dependence of the CMB and LSS power spectra on the parameters $x$ and $\beta$ is shown in fig. 1. The predicted CMB spectrum is quite strongly dependent on the value of $x$, and it becomes practically indistinguishable from the CDM case for $x < x_{eq} \approx 0.3$. However, the effects on the CMB spectrum rather weakly depend on the fraction of mirror baryons. As a result of the oscillations in MBDM perturbation evolution, one observes oscillations in the LSS power spectrum; their position clearly depends on $x$, while their depth depends on the mirror baryonic density. Superimposed to oscillations one can see the cut-off in the power spectrum due to the aforementioned Silk damping.

In the same figure our predictions can be compared with the observational data in order to obtain some general bound on the mirror parameters space.
Figure 1: CMB (left) and LSS (right) power spectra for different values of $x$ and $\omega_b$, as compared with a reference standard model (solid line) and with observations (WMAP [21], ACBAR [22] and 2dF binned data [23]). Models where dark matter is entirely due to MBDM (no CDM) are plotted in top panels for $x = 0.3, 0.5, 0.7$, while models with mixed CDM+MBDM ($\beta = 1, 2, 3, 4; x = 0.7$) in bottom panels.

- The present LSS data are not compatible with a scenario where all the dark matter is made of mirror baryons, unless we consider enough small values of $x$: $x \leq 0.3 \approx x_{eq}$.

- High values of $x$, $x > 0.5$, can be excluded even for a relatively small amount of mirror baryons. In fact, we observe relevant effects on LSS and CMB power spectra down to values of M baryon density of the order $\Omega_b^\prime \sim \Omega_b$.

- Intermediate values of $x$, $0.3 < x < 0.5$, can be allowed if the MBDM is a subdominant component of dark matter, $\Omega_b^\prime \leq \Omega_b \leq \Omega_{CDM}$.

- For small values of $x$, $x < 0.3$, the MBDM and the CDM scenarios are indistinguishable as concerns the CMB and the linear LSS power spectra. In this case, in fact, the mirror Jeans and Silk lengths, which mark region of the spectrum where the effects of mirror baryons are visible, decrease to very low values, which undergo non linear growth
from relatively large redshift.

Thus, with the current experimental accuracy, we can exclude only models with high $x$ and high $\Omega_0^\prime$; however, there can be many possibilities to disentangle the cosmological scenario of two parallel worlds with the future high precision data concerning the large scale structure, CMB anisotropy, structure of the galaxy halos, gravitational microlensing, oscillation of observable particles into their mirror partners, etc.

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