Is dark matter made of mirror matter? Evidence from cosmological data.

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We present new fast numerical simulations of cosmic microwave background and large scale structure in the case in which the cosmological dark matter is made entirely or partly of mirror matter. We consider scalar adiabatic primordial perturbations at linear scales in a flat Universe. The speed of the simulations allows us for the first time to use Markov Chain Monte Carlo analyses to constrain the mirror parameters. A Universe with pure mirror matter can fit very well the observations, equivalently to the case of an admixture with cold dark matter. In both cases, the analyses show a clear indication of the presence of a consistent amount of mirror dark matter, $0.05 \lesssim \Omega_{\rm mirror} h^2 \lesssim 0.12$.

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The existence of dark matter in the Universe seems to be an unavoidable evidence, as confirmed by all the currently available astrophysical observations at scales ranging from cosmological to galactic. At the same time, its nature is still completely unknown, and is limited to its qualitative behaviour for the process of structure formation. Together with Big Bang nucleosynthesis (BBN), the most powerful cosmological tests for dark matter candidates are the cosmic microwave background (CMB) and large scale structure (LSS) power spectra, with their increasing precisions due to the huge observational efforts of several groups.

Previous analytical and numerical studies on CMB and LSS power spectra [1–6] have only limited the parameter space of mirror dark matter, without providing a definitive cosmological answer to its existence. Here we finally address this question.

As suggested many years ago by Lee and Yang [7], to suppose the existence of mirror matter is the simplest way to restore the parity symmetry of the laws of nature. Their idea was later developed by other authors [8–11], and a lot of studies were devoted to it, showing its compatibility with all the available experimental and observational constraints (for reviews, see Refs. [3, 12–14]). In some cases, as the results of direct detection experiments [15, 16] or the observations of neutron stars [17, 18], there are interesting suggestions of the existence of mirror matter.

The original idea was to have a parallel hidden (mirror) sector of particles which is an exact duplicate of the observable sector. In the modern context of gauge theories this implies the existence of an exact parity (mirror) symmetry between two particle sectors, that are described by the same Lagrangian and coupling constants, and consequently have the same microphysics, but where ordinary particles have left-handed interactions, mirror particles have right-handed interactions [11]. Thus, they are stable exactly as their ordinary counterparts.

The ordinary and mirror particles have the same masses and obey to the same physical laws, but the three non-gravitational interactions act on ordinary and mirror sectors completely separately, the only link between all of them being the gravity. Since mirror baryons do not interact with photons, or interact only very weakly, the presence of mirror matter is felt mainly by its gravitational effects, which is exactly the definition of "dark matter".

Hence mirror matter is a stable self-interacting[1] dark matter candidate that emerges if one, instead of (or in addition to) assuming a symmetry between bosons and fermions (supersymmetry), assumes that nature is parity symmetric.

Besides being a viable and powerful candidate for dark matter, the increasing interest on mirror matter is due to the fact that it provides one of the few potential explanations for the recent DAMA annual modulation signal [15], together with the results of other direct detection experiments (CDMS, CoGeNT, CRESST, XENON) [16]. The compatibility of this scenario with BBN constraints has already been studied [19, 20].

Given its consistency with experiments and observations, and the unfruitful attempts to prove the existence of the other dark matter candidates, scientific community is facing an emergent question: "is mirror matter the dark matter of the Universe (or at least a significant part of it)?" One possibility to answer this question is to look at the cosmological signatures of mirror particles.

It is worthwhile to note that the presence of the mirror

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[1] Astrophysical constraints on self interactions of dark matter present in literature are valid only for homogeneous distributions of dark matter particles, and are therefore not directly applicable to the mirror matter case.

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sector does not introduce any new parameters in particle physics (if we neglect the possible weak non-gravitational interactions between visible and hidden sectors). But the fact that microphysics is the same in ordinary and mirror sectors does not mean that also macroscopic realizations should be the same. The different macrophysics is usually parametrized in terms of only two "cosmological" free parameters: the ratio x of temperatures of the two sectors, in terms of temperatures of the ordinary and mirror photons in the cosmic background radiation; the relative amount β of mirror baryons compared to the ordinary ones.

$$x \equiv \left(\frac{S'}{S}\right)^{1/3} \simeq \frac{T'}{T} \qquad \text{and} \qquad \beta \equiv \frac{\Omega'_{\rm b}}{\Omega_{\rm b}} \ , \tag{1}$$

where T (T'), $\Omega_{\rm b}$ ($\Omega'_{\rm b}$), and S (S') are respectively the ordinary (mirror) photon temperature, cosmological baryon density (normalized, as usual, to the critical density of the Universe), and entropy per comoving volume [12].

The present energy density contains relativistic (radiation) component $\Omega_{\rm r}$, non-relativistic (matter) component $\Omega_{\rm m}$ and the vacuum energy (cosmological term or dark energy) density Ω_Λ. According to the inflationary paradigm the Universe should be almost flat, $\Omega_{\rm tot} = \Omega_{\rm m} + \Omega_{\rm r} + \Omega_\Lambda \approx 1$, which agrees well with the results on the CMB anisotropy. Now both radiation and matter components contain the mirror components[2], and the matter composition of the Universe is expressed in general by

$$\Omega_{\rm m} = \Omega_{\rm b} + \Omega'_{\rm b} + \Omega_{\rm DM} = \Omega_{\rm b}(1+\beta) + \Omega_{\rm DM} \ , \tag{2}$$

where the term $\Omega_{\rm DM}$ includes the contributions of any other possible dark matter particles but mirror baryons.

At the time of BBN the mirror photons γ', electrons $e^{\pm\prime}$ and neutrinos $\nu'_{e,\mu,\tau}$ would give a contribution to the energetic degrees of freedom equivalent to an effective number of extra neutrino families $\Delta N_\nu \simeq 6.14\, x^4$. Current estimates of ΔN_ν [21] correspond to an upper bound $x \lesssim 0.7$, and hence at the nucleosynthesis epoch the temperature of the mirror sector should be smaller than that of the ordinary one, $T' < T$.

Due to the temperature difference between the two sectors, the cosmological key epochs take place at different redshifts, and in particular they happen in the mirror sector before than in the ordinary one [2, 12]. The relevant epochs for the cosmic structure formation are related to the matter-radiation equality (MRE) $z_{\rm eq}$, the matter-radiation decouplings (MRD) $z_{\rm dec}$ and $z'_{\rm dec}$ due to the plasma recombinations in both sectors, and the photon-baryon equipartitions $z_{{\rm b}\gamma}$ and $z'_{{\rm b}\gamma}$. The MRE occurs at the redshift

$$1 + z_{\rm eq} = \frac{\Omega_{\rm m}}{\Omega_{\rm r}} \approx 2.4 \cdot 10^4 \frac{\Omega_{\rm m} h^2}{1+x^4} \ , \tag{3}$$

which is always smaller than the value obtained for an ordinary Universe. The MRD takes place in every sector only after most electrons and protons recombine into neutral hydrogen and the free electron number density diminishes, so that the interaction rate of the photons drops below the Hubble expansion rate. Since $T'_{\rm dec} \simeq T_{\rm dec}$ up to small corrections, we obtain

$$1 + z'_{\rm dec} \simeq x^{-1}(1 + z_{\rm dec}) \ , \tag{4}$$

so that the MRD in the mirror sector occurs earlier than in the ordinary one. It has been shown [2, 12] that, comparing Eqs. (3) and (4), for x smaller than a typical value $x_{\rm eq}$ the mirror photons would decouple yet during the radiation dominated period, and the evolution of primordial perturbations in the linear regime is practically identical to the standard cold dark matter (CDM) case. Also the photon-baryon equipartition happens in the mirror sector earlier than in the ordinary one, according to the relation

$$1 + z'_{{\rm b}\gamma} = \frac{\Omega'_{\rm b}}{\Omega'_\gamma} \simeq \frac{\Omega_{\rm b}\,\beta}{\Omega_\gamma\, x^4} = (1 + z_{{\rm b}\gamma}) \frac{\beta}{x^4} > 1 + z_{{\rm b}\gamma} \ . \tag{5}$$

Previous analytical and numerical studies on CMB and LSS power spectra [1–6, 22] have only shown, using a qualitative comparison with observations, that: (i) for low values of mirror temperatures ($x \lesssim 0.3$) all the dark matter can be made of mirror baryons; (ii) for high values ($x \gtrsim 0.3$) mirror baryons can be present as an admixture with CDM.

Now we are finally able to fit the cosmological parameters and obtain their quantitative estimates.

TABLE I. Adopted flat priors for the parameters.

parameter	lower limit	upper limit
$\Omega_{\rm b} h^2$	0.01	0.1
$\Omega_{\rm cdm} h^2$	0.01	0.8
x	0.05	0.7
β	0.5	9.0
$100\ \theta_{\rm s}$	0.1	10
τ	0.01	0.8
$n_{\rm s}$	0.7	1.3
$\ln(10^{10} A_{\rm s})$	2.7	4

We have modified the publicly available cosmological simulation tools CAMB [23] and CosmoMC [24] in order to include the effects of mirror matter. Since the physics of the mirror particles is the same as our particles, we have doubled the equations separately in each sector, and considered all the particles when describing the gravitational interactions. The recombinations are computed separately for each sector. The computational

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[2] Since mirror parity doubles *all* the ordinary particles, even if they are "dark" (i.e., we are not able to detect them now), whatever the form of dark matter made by some exotic ordinary particles, there will exist a mirror counterpart.

TABLE II. 1-σ constraints on the parameters obtained using different dark matter compositions and cosmological tests.

	parameter	standard	mirror	mirror	mirror+CDM	mirror+CDM
			CMB	CMB+LSS	CMB	CMB+LSS
primary	$\Omega_{\rm b}h^2$	0.02218 ± 0.00053	0.02184 ± 0.00069	0.02188 ± 0.00045	0.02226 ± 0.00058	0.02184 ± 0.00053
	$\Omega_{\rm cdm}h^2$	0.1157 ± 0.0036	0	0	0.055 ± 0.016	0.0661 ± 0.0062
	$n_{\rm s}$	0.961 ± 0.013	0.952 ± 0.019	0.950 ± 0.011	0.969 ± 0.015	0.951 ± 0.013
	$\ln(10^{10}A_{\rm s})$	3.088 ± 0.032	3.105 ± 0.035	3.099 ± 0.032	3.114 ± 0.044	3.099 ± 0.031
	$100\,\theta_{\rm s}$	1.0382 ± 0.0026	1.0376 ± 0.0036	1.0363 ± 0.0026	1.0403 ± 0.0035	1.0366 ± 0.0028
	τ	0.084 ± 0.014	0.080 ± 0.014	0.079 ± 0.013	0.086 ± 0.014	0.079 ± 0.013
mirror	x	–	0.29 ± 0.10	0.180 ± 0.030	0.39 ± 0.11	0.170 ± 0.034
	β	–	5.75 ± 0.33	5.62 ± 0.11	3.14 ± 0.71	2.61 ± 0.15
derived	$\Omega_{\rm m}$	0.295 ± 0.020	0.345 ± 0.041	0.343 ± 0.016	0.312 ± 0.042	0.344 ± 0.034
	Ω_Λ	0.705 ± 0.020	0.655 ± 0.041	0.657 ± 0.016	0.688 ± 0.042	0.656 ± 0.034
	$z_{\rm re}$	10.4 ± 1.2	10.3 ± 1.3	10.3 ± 1.2	10.8 ± 1.2	10.2 ± 1.2
	h	0.685 ± 0.016	0.656 ± 0.032	0.650 ± 0.011	0.690 ± 0.025	0.651 ± 0.023
	age [Gyr]	13.84 ± 0.12	13.84 ± 0.25	13.95 ± 0.11	13.56 ± 0.25	13.95 ± 0.13
	σ_8	0.827 ± 0.022	–	0.830 ± 0.028	–	0.834 ± 0.034

times of this modified version of CAMB are considerably increased, but still fast enough to compute the many models needed for a Monte Carlo fit in reasonable times.

Compared with previous numerical simulations [1–5], we have used an updated estimate of the primordial chemical composition of mirror particles present in Refs. [12, 25–28], and a more accurate treatment of the recombinations of ordinary and mirror particles using the numerical code RECFAST [29]. The new models based on CAMB and the more accurate treatment of mirror BBN are consistent with the previous ones, but there is a strong improvement of the computational time, allowing us now to constrain the parameters.

We use a Markov Chain Monte Carlo (MCMC) sampling of the multi-dimensional likelihood as a function of model parameters, based on the computations of CMB and LSS power spectra obtained with our modified version of CAMB.

We sample the following eight-dimensional set of cosmological parameters, adopting flat priors on them with broad distributions, as shown in Table I: the baryon and cold dark matter densities $\Omega_{\rm b}h^2$ and $\Omega_{\rm cdm}h^2$, the relative mirror photon temperature x, the relative mirror baryon density β, the ratio of the sound horizon to the angular diameter distance at decoupling $\theta_{\rm s}$, the reionization optical depth τ, the scalar spectral index n_s and the scalar fluctuation amplitude A_s. The upper limit on x is set by the aforementioned BBN limit. In addition, we obtain constraints on derived parameters: the matter and dark energy densities normalized to the critical density $\Omega_{\rm m}$ and Ω_λ, the reionization redshift $z_{\rm re}$, the Hubble parameter h, the age of the Universe in Gyr, the density fluctuation amplitude σ_8 at $8h^{-1}$Mpc. The runs also include weak priors on the Hubble parameter, $0.4 \leq h \leq 1.0$, and on the age of the universe, $10 \leq \text{age(Gyr)} \leq 20$. In all the computations we assume scalar adiabatic initial conditions in a flat Universe ($\Omega_{\rm tot} = 1$), a dark energy equation of state with $w = -1$, massless neutrinos, and the number of neutrino families of the standard model $N_{\rm eff} = 3.046$.

We consider two different chemical compositions of dark matter: the case pure mirror and the case mixed mirror-CDM. In addition, we perform analyses using two different configurations: the CMB only and the CMB combined with the LSS. The CMB dataset is provided by the WMAP7 team [30], which measured the acoustic oscillations of the primordial plasma on degree scales with cosmic-variance-limited precision. For the LSS, instead, we include the power spectrum extracted from the SDSS-DR7 luminous red galaxy sample [31] limited to the length scales larger than $k \sim 0.2h\,\text{Mpc}^{-1}$ to avoid non-linear clustering and scale-dependent galaxy biasing effects. For comparison, we run also a MCMC chain for a standard ΛCDM cosmology, with the same assumptions and priors, to use as a reference model. The results of the runs are shown in Table II, where the estimates of the parameters and the 1-σ confidence intervals are obtained by marginalizing the multi-dimensional likelihoods down to one dimension. The corresponding best-fit models are shown in Figs. 1 and 2.

Looking at Table II, we see that the values of the primary cosmological parameters, except obviously for the CDM density, do not vary significantly between the standard model and both the pure and mixed mirror compositions, for both kinds of analysis (CMB and CMB+LSS). Going to the derived parameters, there is an increase of the matter content of the Universe at the expenses of the dark energy. This is partly due to a bigger matter density, and partly to the decrease of the Hubble parameter, that is anyway compatible with the current estimates. For all the models, the non-baryonic matter density is between 5 and 6 times the baryonic density, in accordance with common cosmological analyses. But the most interesting result is concentrated in the lines constraining the mirror parameters. Concerning x, the CMB only analysis estimates a pure mirror model with $x \simeq 0.3$, around the preferred values able to explain the dark matter direct detection experiments [15, 16], while for mixed mirror

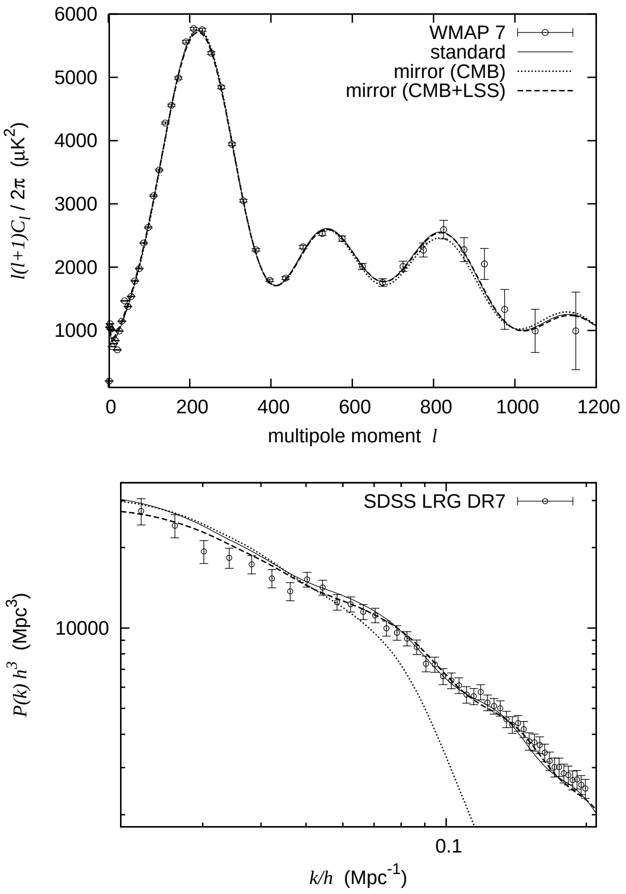

FIG. 1. CMB and LSS power spectra for best-fit models with baryons and mirror matter obtained using CMB only (dotted line) or both CMB and LSS (dashed line). For comparison we show also the standard model fit (solid line).

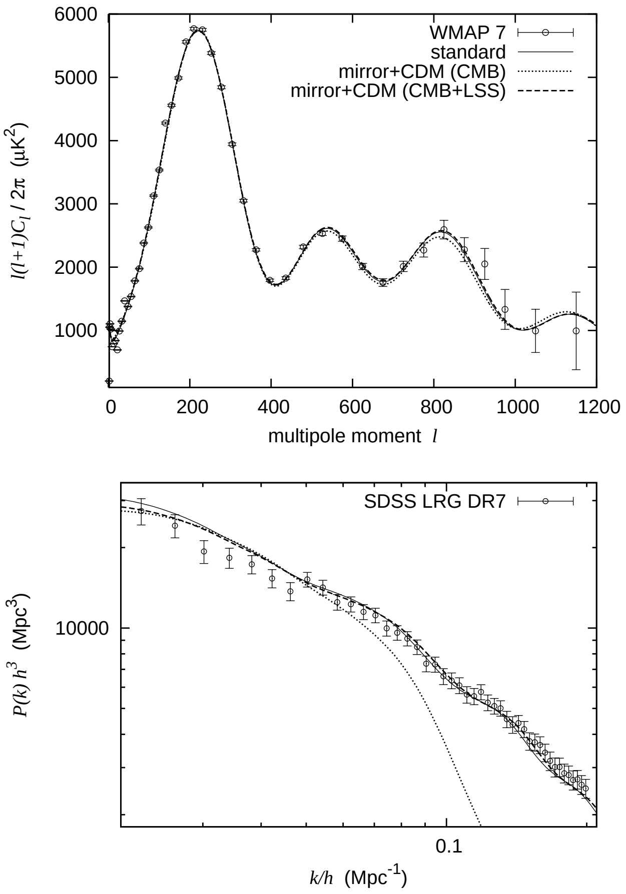

FIG. 2. As in Fig. 1, but for models with baryons, mirror matter, and cold dark matter.

this value is even bigger, around $x \simeq 0.4$. The inclusion of the LSS lowers significantly these values at $x \simeq 0.18$ for both pure and mixed mirror, confirming the higher sensitivity of the LSS on x already evidenced in previous works [1, 12]. We finally look at the most significant parameter, β, which expresses how much, if any, mirror matter is present in the Universe. In this case the results obtained using CMB alone or combined with the LSS are similar. For pure mirror this value is between 5.5 and 6, clearly showing that cosmology requires a strong presence of mirror matter in order to interpret its observables. In case of mirror mixed with CDM, the results show similar densities of mirror matter and CDM. This is a very interesting result, since it means that, when it can freely choose between mirror dark matter or collisionless massive WIMPs, cosmology unequivocally requires the presence of a consistent fraction of mirror matter.

In Figs. 1 and 2 the agreement of the best fits with the data is shown, together with the comparison with the reference standard model. For the CMB the models obtained fitting both CMB and LSS data are almost indistinguishable, and few differences are present in the LSS power spectra. The exceptions are the models computed using CMB only, for which the high values obtained for x compromise, as expected, their compatibility with the matter power spectrum.

To summarize, in this work we have obtained two main results. First of all, for the first time the two parameters describing the mirror matter are constrained. Considering the most stringent analyses performed using both the CMB and LSS, we obtained $x = 0.180 \pm 0.030$ and $\beta = 5.62 \pm 0.11$ for pure mirror, $x = 0.170 \pm 0.034$ and $\beta = 2.61 \pm 0.15$ for mixed mirror-CDM. These values lie in the range required for interesting consequences on observations and experiments. Secondly, but even more important, the analyses show a clear indication of the presence of consistent amounts of mirror dark matter in the Universe.

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