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Cosmic Bose dark matter

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It is known that cold and hot dark matter imprint opposed effects on the cosmological observables; naturally, it is often thought that they should be made of different kinds of particles. We point out, however, that a Bose-Einstein condensate could be the source of both components. In this framework, the mass and temperature constraints on hot dark matter contain fundamental information of cold dark matter. We discuss two scenarios: a gas made of bosons and a gas made of boson-antiboson pairs. We obtain constraints on the bosonic dark matter parameters from cosmological data and test the idea by probing the condition on the critical temperature of condensation, including a forecast for the Planck mission. We find that the bosonic dark matter picture is consistent with data in the boson scenario, while the boson-antiboson scenario might be increasingly interesting for future data surveys.

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One of the most intriguing questions in modern cosmology comprises the nature of the so far unidentified one-quarter part of the Universe's content, known as *dark matter* (DM). Cosmological observations indicate that DM is mostly composed of some kind of nonbaryonic perfect fluid with no pressure. Many efforts to elucidate this issue have been made over the last decade, mainly motivated by the idea that the answer to the riddle will very likely change our current understanding of matter and its interactions. One favorite possibility is that DM could be sourced by a Bose-Einstein (BE) condensate made of light particles. Several noteworthy candidates have been addressed in this category, e.g., axions and axionlike particles [1], scalar fields [2], and perhaps more exotic species such as bosonic neutrinos and massive photons [3]. The landscape of bosonic DM appears attractive enough for a deliberate study. Our pursuit is not to analyze one specific candidate, but instead outline generic properties of a BE condensate as the source of the whole DM in the Universe, and test the validity extents of this idea by performing analyses of cosmological data.

At the very early stages of the Universe, DM is thought to be in thermal contact, either with itself or other species, composing a *primeval fireball*. DM candidates can be classified according to their particle velocity dispersion, for our purposes: (1) Particles with vanishing velocity dispersion are termed *cold dark matter* (CDM). (2) *Hot dark matter* (HDM) is particles that, being ultrarelativistic at early stages, become nonrelativistic at recent epochs. During the expansion of the Universe, CDM tends to cluster gravitationally while HDM *free streams* without forming structures until it becomes nonrelativistic. A universe dominated by HDM is ruled out by cosmological observations (although a small abundance of HDM is yet allowed) and CDM is favored to form the overall structures and compose most of the DM in the Universe. A popular family of CDM candidates includes weakly interacting massive particles (WIMPs), predicted by extensions to the standard model of particles. WIMPs predict cuspy density profiles, apparently in disagreement with observational data on galactic scales [4], while BE condensates predict flat density profiles in galaxies, in good agreement with data [5]. On cosmological scales, however, there is no distinction between WIMPs and BE condensates in their description of CDM [1,2]. Consequently, cosmological observations give no direct information on the mass of CDM. Neutrinos are, on the other hand, the standard candidate of HDM [6], and cosmological data are very useful to bound their masses with high accuracy. Thus, given that CDM and HDM cause very different (even opposed) effects, it would be natural to think that they are made of rather unrelated particle families. Nevertheless, the DM paradigm does not preclude scenarios where the key would be an intrinsic relation between CDM and HDM particles; specific examples have been discussed for bosonic neutrinos, axions, and Majorons [3,7,8].

Let us now introduce the *bosonic DM picture*, our assumptions framework: DM is made of bosonic particles—a large fraction is composed of *condensed bosons* acting as CDM, but a small fraction of *thermal bosons* resides in excited states as HDM. At decoupling, thermal bosons are still relativistic, but condensed bosons already possess a small velocity dispersion and are nonrelativistic. As the Universe expands, the temperature decreases, and thermal bosons might pass through a nonrelativistic transition, being present today as bosonic HDM. Following this idea, we describe the full bosonic system in equilibrium as the sum of two momentum distributions: thermal bosons obey the standard BE momentum distribution, while the condensed bosons momentum distribution exhibits a *deltalike* shape. Accordingly, we evolve thermal bosons in phase space and condensed bosons as a nonrelativistic fluid. Bosonic DM evolves along with baryons, photons, and other species, coupled only gravitationally, whose dynamics determine the observed distribution of galaxies and the cosmic microwave background (CMB) pattern, which can be compared to cosmological data today. We discuss two scenarios likely to yield relativistic BE condensation: a gas made of bosons only [9] and a gas of boson-antiboson pairs [10,11]. This picture must necessarily be consistent with the condition that the boson temperature must be smaller than the critical temperature of condensation, and thus, we are interested to test such a condition.

Let us begin to outline the BE condensation in the primeval fireball, at *zero* order in perturbation theory. The process of condensation should be driven by self-interactions of high-energy bosonic particles [12]. Accordingly, bosons obey the BE momentum distribution $f^{(0)}_{\rm BE}(\mathbf{p}) = g_\phi/(e^{(E-\mu)/T_\phi} - 1)$ in the relativistic limit $m \ll T_\phi$, where m is the mass of bosons, T_ϕ their temperature, μ the chemical potential, and g_ϕ is the number of internal degrees of freedom. $f_{\rm BE}$ defines the critical temperature of condensation T_c. In the relativistic regime, if bosons ϕ are their own antiparticle, then $T_c^\phi = (\pi^2 n^{(0)}/g_\phi \zeta(3))^{1/3}$ [9], where $\zeta(3) \approx 1.202$; but, in the case of abundant boson-antiboson $\phi\bar{\phi}$ pairs production, $T_c^{\phi\bar{\phi}} = (3\Delta n^{(0)}/g_\phi m)^{1/2}$ [10]. Here, $n^{(0)}$ is the total number density, and $\Delta n^{(0)}$ the excess of boson over antiboson number density. In either case, at temperatures below the critical temperature and the limit $\mu \to m$, a large number of bosons flows from the excited to the lowest-energy states, the momentum distribution *blows up* forming a corelike coherent state, and it continues until local thermodynamic equilibrium is reached.

The evolution of bosonic DM after decoupling is as follows. Provided that local thermodynamic equilibrium has been reached between condensed and thermal bosons, both abundances evolve independently, affected only by the expansion of the Universe. We also take the diluteness approximation, provided that the self-interaction scale is small compared to the cosmological scales of interest. Accordingly, both condensed and thermal bosons interact with other matter species only through primordial small gravitational instabilities. These instabilities are expressed as linear perturbations to the space-time geometry. In the conformal Newtonian gauge, the metric reads $ds^2 = a(\tau)^2[-(1+2\psi)d\tau^2 + (1-2\varphi)dx^i dx_i]$. Here a is the scale factor of the Universe, τ the proper time, and ψ along with φ are perturbation scalar modes. For thermal bosons, we describe their dynamics by the usual approach to HDM [13]. The momentum distribution is perturbed to first order as $f_T(\mathbf{x}, \mathbf{p}, \tau) = f^{(0)}(p)[1 + \Psi(\mathbf{x}, \mathbf{p}, \tau)]$, with $f^{(0)}(p) = g_\phi/(e^{p/T_\phi} - 1)$. Then, Ψ is expanded in a Legendre series to obtain a hierarchical system of coupled Vlasov equations. For condensed bosons, their zero-order momentum distribution is as well perturbed to first order due to gravitational instabilities, inducing small matter overdensities and a small bulk flow speed. From condensed matter physics, we introduce the momentum distribution of condensed bosons as a narrow Maxwell-like function [14,15],

$$f_c(\mathbf{p}) = (2\pi)^{3/2}\frac{n_c(a)}{\sigma(a)^3}\exp\left(-\frac{(\mathbf{p} - m\mathbf{v})^2}{2\sigma(a)^2}\right), \qquad (1)$$

where n_c is the number density of condensed bosons. The spatial overdensities are defined in terms of $n_c = n_c^{(0)}(1+\delta)$, while $v = |\mathbf{v}|$ is a small bulk flow speed. The distribution width σ determines the velocity dispersion of condensed bosons; it is certainly small, manifesting the distinctive blowup of BE condensation. Notice the formal analogy between the Maxwell-like momentum distribution of condensed bosons and the Maxwell-Boltzmann momentum distribution of superheavy DM candidates [6]. In contrast, bosonic candidates are expected to be very light, but BE condensation yields a corelike coherent state of particles with small velocity dispersion; i.e., condensed bosons behave in bulk as a nonrelativistic or CDM fluid. From the Vlasov equation of f_c, two fluid equations are obtained for δ and v; in Fourier space they read $\dot{\delta}_k + ikv_k = 3\varphi_k$, and $\dot{v}_k + \frac{\dot{a}}{a}v_k = ik\psi_k$ [6], where $k = |\mathbf{k}|$ is the Fourier wave-vector magnitude. These are formally the dynamic equations of CDM.

Thermal bosons should induce distinctive signatures in the cosmological observables. First, thermal bosons may undergo a nonrelativistic transition, giving us information of the boson mass. Notice that the temperature can be affected only by the expansion rate of the Universe and the total number density of bosons is conserved in a comoving reference frame. That is, the number density of bosons evolves like a^{-3} and the temperature, as well as the critical temperature, like a^{-1}. The temperature may drop below the mass $m \gtrsim T_\phi$, causing the bosonic system to be made of two nonrelativistic components at late times. Cosmological data allow us to estimate simultaneously the abundances of CDM Ω_c and HDM Ω_H. Assuming that both CDM and HDM are sourced by the same bosonic particles, most of them residing in the condensate and a little fraction in thermal states, we may constrain the mass of bosonic DM by means of

$$m = \frac{\Omega_c \rho_{cr}}{n_c^{(0)}} = \frac{\Omega_H \rho_{cr}}{n_T^{(0)}} \qquad (2)$$

(nonzero mass), with ρ_{cr} the critical density of the Universe as measured today in terms of the Hubble constant H_0 [16] and $n_T \sim T_\phi^3$ the number density of thermal bosons. Second, the BE momentum distribution of thermal bosons allocates more bosons in the low-energy states; it should imprint distinctive CMB and galaxy distribution patterns from those due to a fermionic distribution. Third, the free-streaming scale of HDM may be influenced by the boson temperature T_ϕ, which can be estimated as deviations from the standard HDM prediction. Recall that thermal bosons decouple being still relativistic; consequently, their temperature should be proportional to the CMB photon temperature. This proportion depends on the number of relativistic degrees of freedom of the thermal bath from which thermal bosons decouple [6,11]. In the particular case of neutrinos, which are the standard candidate for HDM, the proportion factor is given by $T_{\nu,0} = (4/11)^{1/3}T_{\rm cmb}$, where $T_{\rm cmb} = 2.725$ K. Hence, we measure generic departures from the standard HDM temperature prediction by means of

$$T_{\phi,0} = \left(\frac{11}{4} + g_{\rm x}\right)^{-1/3} T_{\rm cmb}, \tag{3}$$

where the free-parameter $g_{\rm x}$ is positive/negative if bosons decouple before/after neutrinos. Provided some specific model of bosonic particles, $g_{\rm x}$ might be used to study the interaction couplings; the case of axions could be studied as in Ref. [17]. Notice that the number of extra relativistic species $N = N_{\rm eff} - 3$ may be written in terms of g_x. The free-streaming scale depends on the thermal velocity T_ϕ/m, so that an increase of $g_{\rm x}$ reduces free streaming, causing a less severe depletion of small scale structures.

As an additional remark, we address a bound on the strength of boson self-interactions. It comes from the fact that our study relies on the range of validity of the diluteness approximation [14], which can be written for condensed bosons in terms of the scattering cross section, $\sigma_{\rm scatt} \ll (n_c^{(0)})^{-2/3}$. Besides, as a minimal condition, the content of Ω_c should be at least larger than baryonic; we find $\sigma_{\rm scatt} \ll 8\pi(m/\rho_{cr}\Omega_b)^{2/3}$, which is more restrictive for ultralight-mass models. Conversely, it may be written for Ω_H as $\sigma_{\rm scatt} \ll 3/4[(11/4 + g_{\rm x})\Omega_H/(g_\phi\Omega_b)]^{2/3}$ cm^2.

In the generic study of bosonic DM we present here, the free parameters are the mass m and the factor $g_{\rm x}$; bounds on their values can be obtained from a statistical analysis on cosmological data. To this end, we perform a simultaneous χ^2 analysis [18] of data provided by the seven-year WMAP, ACBAR, and QUaD surveys for the CMB [19], together with the SDSS large redshift galaxy survey [20]. We call this set W + AQS. The input model fit to data is obtained from an adapted version of the public code CAMB [21], which includes our bosonic DM component through the BE statistics in $f_{\rm BE}^{(0)}$ and the g_x parameter. We study two models of scalars ($g_\phi = 1$) given by the case of a gas of bosons ϕ and boson-antiboson $\phi\bar{\phi}$ pairs; in the relativistic limit, they differ only by a factor of 2 in the momentum distribution of thermal bosons. For simplicity, we consider a flat geometry with cosmological constant and choose to vary the following set of cosmological parameters: the content of baryons Ω_b, the content of CDM Ω_c, the scalar initial amplitude A_s, the spectral index n_s, the optical depth of reionization τ_r, and one free bias parameter for the SDSS data. We make use of flat priors with starting points

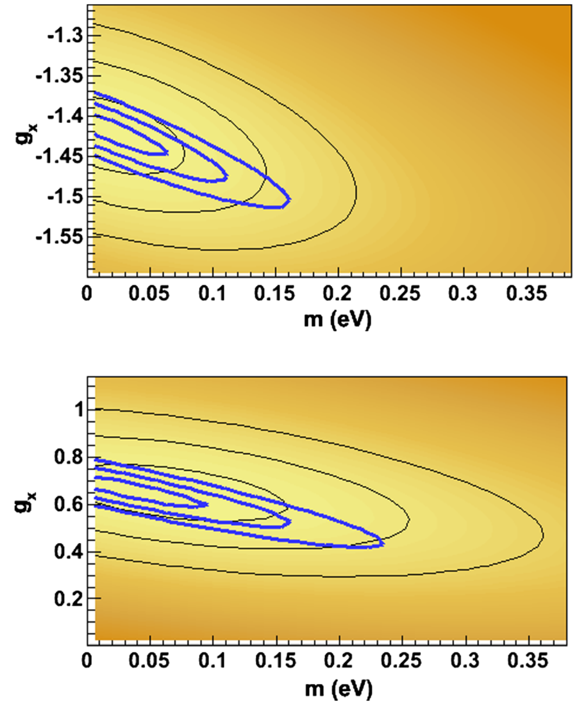

FIG. 1 (color online). 1-, 2-, 3-σ probability contours from WMAP + AQS for the bosonic HDM parameters in the case of bosons (up) and boson-antiboson pairs (down) models. Thicker (blue) contours refer to Planck + AQS.

at $g_{\rm x} = 0$, $m = 0$, and the best-fit values found by the WMAP team [22] for the rest of the parameters.

The posterior probabilities of bosonic DM parameters with conditional errors are plotted in Fig. 1 and listed in Table I, The preferred mass region extends to zero as a consequence of the bounds on the bosonic HDM free-streaming scale. From these outcomes it follows constraints in the temperature of bosons $T_0^\phi = 2.14 \pm 0.02$ K, and boson-antiboson gas $T_0^{\phi\bar{\phi}} = 1.91 \pm 0.05$ K (95%). The bound on the cross section of self-interaction becomes $\sigma_{\rm scatt} \ll 0.18$ cm^2. From Eq. (2), we may set lower limits on the critical temperature of condensation (evaluated today): $T_{c,0}^\phi \gtrsim 9.53$ K and $T_{c,0}^{\phi\bar{\phi}} \gtrsim 1.91$ K, for the two scenarios. From g_x in Table I we also infer $N = 2.18 \pm 0.22$ and 0.85 ± 0.1 for the cases of bosons and boson-antiboson, respectively. It is interesting to explore the constraints that the Planck mission will achieve on our

TABLE I. Posterior probabilities of bosonic DM parameters from the two data sets considered, for the case of bosons ϕ and boson-antiboson $\phi\bar{\phi}$.

(95%)		$g_{\rm x}$	m (eV)	$\Omega_c \times 10^{-1}$
ϕ	W + AQS	-1.42 ± 0.11	$\lesssim 0.14$	2.1 ± 0.025
	P + AQS	-1.42 ± 0.05	$\lesssim 0.11$	2.1 ± 0.010
$\phi\bar{\phi}$	W + AQS	0.67 ± 0.26	$\lesssim 0.26$	2.5 ± 0.030
	P + AQS	0.67 ± 0.16	$\lesssim 0.16$	2.5 ± 0.012

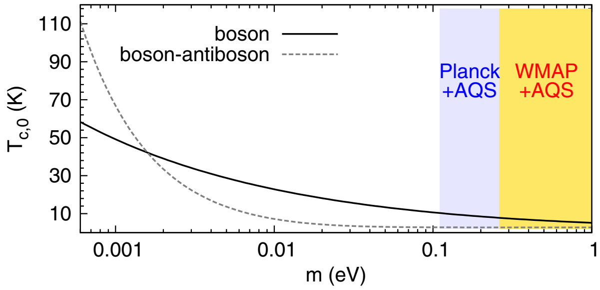

FIG. 2 (color online). Critical temperatures of condensation (evaluated today) as a function of the mass for each model. For bosons, the lower limit $T^{\phi}_{c,0} \gtrsim 10.33$ K is higher than our best fit of $T^{\phi}_{0} = 2.14$ K. For boson-antiboson, the limiting-critical temperature is comparable with the bosonic temperature.

model parameters. We take a fiducial power amplitude given by the best fit to the WMAP data, we neglect systematic effects, and we assume a sky coverage of 65%. The data forecast is based on the contributions from cosmic variance and noise specifications of the first three channels of the high frequency instrument [23]; we label this set of data as P + AQS. As appreciated in Fig. 1 and Table I, our Planck forecast reduces considerably the probability parameter space. Subsequently, we find $T^{\phi}_{0} = 2.14 \pm 0.009$ K, $T^{\phi}_{c,0} \gtrsim 10.33$ K, $N = 2.18 \pm 0.1$ for bosons, and $T^{\phi\bar{\phi}}_{0} = 1.91 \pm 0.009$ K, $T^{\phi\bar{\phi}}_{c,0} \gtrsim 1.92$ K, $N = 0.85 \pm 0.05$ for boson-antiboson. The bound on the self-interaction cross section becomes $\sigma_{\rm scatt} \ll 0.15\ {\rm cm}^2$ (95%). Our result $T^{\phi}_{0} \lesssim 0.22 T^{\phi}_{c,0}$ indicates consistency with the assumptions of the bosonic DM picture. Even if the case of boson-antiboson is not conclusive in this respect, note however, that the critical temperature depends mainly on the mass constraints. We show this dependence in Fig. 2 with the temperature fixed to our best fit. A boson-antiboson gas exhibits a huge critical temperature if its particles are ultralight. Therefore, better constraints on the mass of bosons by larger surveys could yield upper bounds on the critical temperature, perhaps in consistency with the hypothesis of BE condensation.

Finally, from a similar analysis for fermionic HDM we find bounds in the sum of neutrino masses and the number of extra relativistic species, $\sum m_\nu \lesssim 0.45$ eV, $N = 1.10 \pm 0.18$ (95%), in concordance with some previous reports [24]. When we compare the fermionic and bosonic HDM spectra, differences are roughly apparent at the 10 percent level; however, our χ^2 study shows no significant difference between their respective ability to fit the presented data. This should be considered as a source of systematic uncertainty in cosmic neutrino parameter estimations [24].

In summary, we present a generic study of DM based on BE condensation, where CDM and HDM are intrinsically related. From our statistical analysis, we provide conditional uncertainties on the mass of bosonic DM (which in our framework is the same for both CDM and HDM), the temperature, the critical temperature of condensation, and the self-interaction cross section; from Monte Carlo integration in parameter space, the corresponding marginal uncertainties may be obtained. We find that the requirement for condensation on the critical temperature is satisfied at cosmological scales for a gas of bosons. Our forecast of Planck data predicts important improvements in the parameter estimation. We observe that bosonic and fermionic HDM are both compatible with the presented data; this systematic could be further studied in the future. We also discuss how future surveys would yield much better parameter bounds, particularly interesting for the boson-antiboson critical temperature.

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