

Constraining Unparticle Physics with Cosmology and Astrophysics

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It has recently been suggested that a scale-invariant “unparticle” sector with a nontrivial infrared fixed point may couple to the standard model (SM) via higher-dimensional operators. The weakness of such interactions hides the unparticle phenomena at low energies. We demonstrate how cosmology and astrophysics can place significant bounds on the strength of unparticle-SM interactions. We also discuss the possibility of a having a non-negligible unparticle relic density today.

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In a recent Letter [1], Georgi suggested that a scale-invariant sector with a nontrivial infrared fixed point may couple to the standard model (SM) via higher-dimensional operators cut off by a large scale. Because of its scale-invariance, this sector is not described in terms of particles. Thus, the corresponding phenomenology would be different from all other extensions of the SM, like supersymmetry and extra dimensions, which are based on a particle interpretation. Following Ref. [1], we will refer to this sector collectively as “the unparticle.” Subsequent works in Ref. [2] and in Refs. [3–11] have presented some of the interesting collider and flavor phenomenology of the unparticle that may appear above the TeV scale or in precision measurements. Refs. [12,13] elucidate some of the more theoretic aspects of unparticle physics, in the context of AdS₅ deconstruction and supersymmetry, respectively.

In this Letter, we will examine possible effects of the unparticle sector on cosmology and astrophysics. We will use considerations based on preserving the success of big bang nucleosynthesis (BBN) and stellar evolution to place constraints on this new physics. Similar cosmological and astrophysical constraints have been considered in Ref. [14], in the specific context of anti de Sitter/conformal field theory (AdS/CFT) correspondence [15]. Here, we also discuss a possible mechanism for generating a significant relic unparticle density that could survive until today and contribute to the cosmic dark density (we cannot call this “dark matter”). Before presenting our analysis, we will first review the basic framework outlined in Ref. [1].

The main assumption here is that, at high energy, the SM and the fields of a Banks-Zaks (BZ) theory [16], with a nontrivial infrared fixed point, interact via the exchange of particles of mass M_U :

$$\mathcal{L}_{\text{BZ}} = \frac{O_{\text{SM}} O_{\text{BZ}}}{M_U^k}, \quad (1)$$

where O_{SM} is a SM operator of mass dimension d_{SM} and O_{BZ} is a BZ operator of mass dimension d_{BZ} . In Eq. (1), we have taken the coefficient of the operator to be unity. Upon the onset of scale invariance, the interactions of the BZ fields give rise to dimensional transmutation at a scale Λ_U ,

below which $\mathcal{L}_{\text{BZ}} \rightarrow \mathcal{L}_U$, where

$$\mathcal{L}_U = C_U \frac{\Lambda_U^{d_{\text{BZ}}-d_U}}{M_U^k} O_{\text{SM}} O_U. \quad (2)$$

Here, C_U is a coefficient in the low energy effective theory and O_U is an unparticle operator of dimension d_U . Generally speaking, each unparticle operator has a different coefficient. To avoid complicating the notation, we will use C_U to denote all such coefficients, with the understanding that they are not assumed to be universal.

It was shown in Ref. [1] that the phase space $d\Phi$ for an unparticle operator of dimension d_U is the same as the phase space for $n = d_U$ massless *invisible* particles. This is an interesting and exotic feature of this sector, since d_U is not necessarily integral. Thus, $d\Phi(d_U)$ is proportional to the coefficient function

$$A_{d_U} = \frac{16\pi^{5/2}}{(2\pi)^{2d_U}} \frac{\Gamma(d_U + 1/2)}{\Gamma(d_U - 1)\Gamma(2d_U)}. \quad (3)$$

In what follows, we will not present exact expressions, as they would be rather unwarranted at the level cosmological and astrophysical effects are treated here. The A_{d_U} phase space factors for $d_U \sim 1$ will not change our conclusions significantly, and are hence ignored.

Unparticle cosmology.—In order to have a handle on unparticle cosmology, we begin with the unparticle equation of state. The type of substance that makes up the unparticle sector can only be described by a massless equation of state. In fact, it is well known that pure radiation is classically scale invariant, $T_\mu^{(\text{Rad})\mu} = 0$, and only develops scale dependence through quantum mechanical interactions. In the case of the unparticle, the scale invariance persists even at the quantum level and hence we adopt the trivial equation of state $p_U = \rho_U/3$ for this sector [14], where ρ_U is the energy density and p_U is the pressure of the unparticle.

Given the success of BBN in predicting light element abundances, we are compelled to make sure the unparticle will not significantly change the physics of this epoch. For a general scale-invariant sector $\rho_U \sim T_U^4$ [14], up to an

unknown coefficient that we take to be $\mathcal{O}(1)$, where T_U is the unparticle temperature. Hence, one way to ensure that ρ_U does not interfere with BBN, is to require $T_U \ll T$, where $T \sim 1$ MeV is the temperature of the SM radiation during this epoch. To end up with a cold unparticle sector, we may assume that O_U decoupled from the SM at an earlier time and did not get reheated in the subsequent evolution of the radiation dominated Universe. However, we will see that, for certain ranges of parameters, the unparticle recouples at lower temperatures. For such cases, we must demand that the unparticle stays decoupled throughout BBN.

In order to get a quantitative estimate, we consider the case $O_{\text{SM}} = \bar{\psi}\gamma^\mu\psi$, with ψ an SM fermion. Since we will mostly rely on dimensional analysis for our estimates, this case well represents other dimension-3 SM operators. We note that the lowest dimension gauge-invariant SM operator we can write down is $\phi^\dagger\phi$, where ϕ is the *elementary* Higgs field [13]; an interesting analysis of this coupling has been provided in Ref. [13]. Here, we will study the consequences of the scenario in Ref. [1], with scale invariance. We thus ignore Higgs effects which could be suppressed due to, say, compositeness, above the electroweak scale. Then, SM dimension-3 operators are the most important ones for our analysis and we will focus on them.

To study how the unparticle decouples, we consider

$$\mathcal{L}_\psi = C_U \frac{\Lambda_U^{d_{\text{BZ}}-d_U}}{M_U^k} \bar{\psi}\gamma_\mu\psi O_U^\mu, \quad (4)$$

with $d_{\text{BZ}} = k + 1$. The unparticle-SM interactions will drop out of equilibrium once the rate Γ_ψ falls below H , the relevant Hubble constant. At temperature T , we have

$$\Gamma_\psi \sim \left| \frac{C_U \Lambda_U^{k+1-d_U}}{M_U^k} \right|^2 T^{2d_U-1}. \quad (5)$$

During the radiation domination era, $H \sim T^2/M_P$, where $M_P \sim 10^{19}$ GeV is the Planck scale. Requiring $\Gamma_\psi \lesssim H$ then gives

$$\left| \frac{C_U \Lambda_U^{k+1-d_U}}{M_U^k} \right| T^{d_U-1} \lesssim (T/M_P)^{1/2}. \quad (6)$$

It is reasonable to assume $k = 2$, if massive bosons in the ultraviolet couple the BZ and SM sectors. These particles must be heavier than ~ 1 TeV, since we have no evidence for them. In fact, they are likely much heavier if one considers precision data, leading to $M_U \sim 10^3$ TeV as the cutoff scale. We will present most of our results for cases $d_U = 1, 3/2, 2$. Here, we only consider a new scale-invariant sector. Without the assumption of full conformal symmetry, our analysis is not subject to spin-dependent constraints which would otherwise apply to d_U [17]. Reference [2] only considers noninteger d_U to avoid possible pathologies. Since most of our numerical results are given as orders of magnitude, we may take our results for

integer d_U to be also the relevant estimates for sufficiently close noninteger values.

Equation (6), implies that for $1 \leq d_U \leq 3/2$, the unparticle rate of thermal interactions redshifts more slowly than H . For this range of values, we must then ensure that the unparticle sector remains decoupled throughout BBN. We hence demand $\Gamma_\psi \lesssim H$ for $T \sim 1$ MeV. With $M_U \sim 10^3$ TeV, we find $\tilde{\Lambda} \lesssim 3, 100$ GeV, for $d_U = 1, 3/2$, respectively, where $\tilde{\Lambda} \equiv C_U^{1/(k+1-d_U)} \Lambda_U$.

For $d_U > 3/2$, the rate Γ_ψ redshifts faster than H and we have a decoupling behavior. In this case, we require that the unparticle decouple before BBN, but not get reheated after SM phase transitions. A minimal assumption is that this decoupling happened before the quantum chromodynamics (QCD) phase transition at $T \sim 1$ GeV. The released latent heat after the transition only heats up the SM radiation. This leaves the unparticle colder, resulting in $\rho_U \ll \rho_{\text{SM}}$ during BBN. We note that this conclusion holds, as long as the unparticle sector does not have a very large number of degrees of freedom [14]. For $T \sim 1$ GeV and $M_U \sim 10^3$ TeV, we find $\tilde{\Lambda} \lesssim 100$ GeV with $d_U = 2$. We have plotted the above BBN bounds on $\tilde{\Lambda}$ for a range of M_U values and $d_U = 1, 3/2, 2$ in Fig. 1. Stronger constraints apply if QCD phase transition does not heat up the visible sector enough to marginalize the unparticle contribution.

Having a decoupled or colder unparticle gas is not necessarily enough to ensure that our standard picture of cosmology is intact. In fact, we will have to consider the possibility that the SM plasma can lose energy into the unparticle and undergo evaporative cooling. This constraint has been previously studied in the context of models with large extra dimensions [18] and AdS/CFT correspondence [14]. By dimensional analysis, ensuring that evaporative cooling is subdominant to the one from the expansion of the Universe yields the minimal condition $\rho_{\text{SM}} H \gtrsim \Gamma_\psi T^4$, where the left-hand side is the cooling rate due to the expansion and the right-hand side is given by evaporation into the unparticle. To be specific, we will take

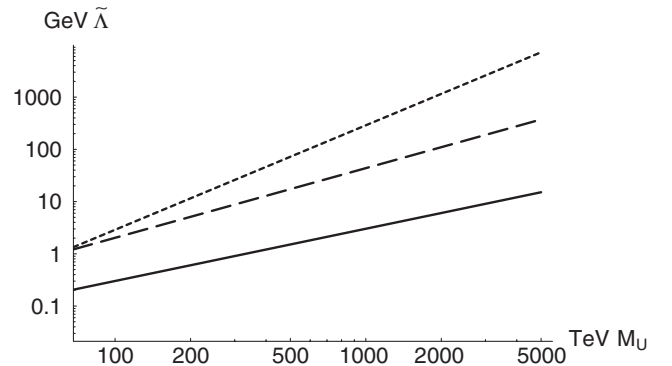


FIG. 1. BBN constraints on the unparticle sector from decoupling requirements. We have used Eq. (6), with $k = 2$. From bottom to top, the lines are for $d_U = 1, 3/2, 2$, respectively. The excluded region lies above the lines.

the BBN era with $T \sim 1$ MeV and require that the cooling during this period is dominantly from cosmological expansion. We find that this does not yield stronger bounds than decoupling; with $M_U \sim 10^3$ TeV we get $\tilde{\Lambda} \lesssim 3, 100, 10^4$ GeV for $d_U = 1, 3/2, 2$, respectively. For $d_U = 3/2$ the bound becomes T -independent. We have assumed that BBN is characterized by one temperature of $\mathcal{O}(\text{MeV})$. This is a simplification, however changing T by factors of order unity does not change our conclusions significantly. For $d_U = 2$, cooling sets a weaker upper bound on Λ_U than before.

Here, we note that if the unparticle recouples after BBN, as in the above discussion for $1 \leq d_U \leq 3/2$, it could come into equilibrium with neutrinos, with $\psi = \nu$ in Eq. (4). In this case, neutrinos will cease to free stream and a ν - U fluid gets established. This can lead to nonstandard shifts in the location of the acoustic peaks of the cosmic microwave background [19]. The cosmic evolution of the ν - U fluid can have interesting signatures that merit more consideration. However, these will be outside the scope of the present work.

Given the above discussion, thermally produced unparticles will not be a significant component of the “invisible” energy density today. To see this, note that the unparticle redshifts like radiation and that it is likely no hotter than the relic photon temperature of order 10^{-4} eV. However, this conclusion can change if the unparticle is produced nonthermally. This can happen if the unparticle sector is coupled to “dark matter operators.” If the dark matter produced in the early Universe is unstable and can decay into other dark matter plus the unparticle U , then we can expect to have a more sizable U -density today. Let us consider the following interaction between dark matter and the unparticle

$$\mathcal{L}_{\text{DM}} = C_U \frac{\Lambda_U^{d_{\text{BZ}} - d_U}}{M_U^k} O_{\text{DM}} O_U, \quad (7)$$

where O_{DM} is made out of dark matter fields. Assuming a dimension-3 fermionic dark matter operator $\bar{\chi}_1 \gamma^\mu \chi_2$, with $m_{\chi_1} \gtrsim m_{\chi_2} \sim 10^2$ GeV, as expected for weakly interacting massive particle (WIMP) dark matter, the decay rate Γ_χ for $\chi_1 \rightarrow \chi_2 U$ is given by

$$\Gamma_\chi \sim \left| \frac{C_U \Lambda_U^{k+1-d_U}}{M_U^k} \right|^2 m_{\chi_1}^{2d_U-1}. \quad (8)$$

Let us first consider $k = 2, d_U = 2$; we find $\Gamma_\chi \sim 10^{-15} |C_U \Lambda_U|^2 \text{TeV}^{-1}$. For the above decay to take place in the recent cosmological epoch, to avoid redshifting the unparticle away, we require $\Gamma \lesssim H_0$, where $H_0 \sim 10^{-33}$ eV. We then find $|C_U \Lambda_U| \lesssim 10^{-3}$ eV. However, a value of Λ_U close to this limit is rather inconsistent with our assumption that dimensional transmutation in the BZ sector takes place above the energy scales we are considering. Another motivated mass scale above the weak scale

is $M_{\text{GUT}} \sim 10^{15}$ GeV. If we choose $M_U \sim M_{\text{GUT}}$, we get $|C_U \Lambda_U| \lesssim 10^3$ TeV.

Current precision for the measured cosmological parameters [20] allow one dark matter component, comprising roughly 5%–10% of the original WIMP population, to decay into the unparticle. We may then expect that today the energy densities in baryonic matter and the unparticle are roughly of the same order. If the unparticle thermalizes by the present time, we may expect it to have a temperature T_0^U roughly given by

$$x \Omega_{\text{DM}} \sim (T_0^U)^4, \quad (9)$$

where x is the small fraction of today’s dark matter density $\Omega_{\text{DM}} \sim (1.5 \times 10^{-3} \text{eV}^4)$ that decayed recently. In Eq. (9), we have ignored effects coming from different redshifts of matter and radiation. We may then expect an unparticle gas of temperature $T_0^U \sim 10^{-3}$ eV for $x \sim 0.1$.

For this substance to be a viable component of cosmic energy density today, we must consider whether it can decay back into the SM. A reasonable assumption is that such a cold scale-invariant gas can return back into the visible sector only by transferring its energy into massless photons. We then consider the interaction

$$\mathcal{L}_\gamma = C_U \frac{\Lambda_U^{k-d_U}}{M_U^k} F_{\mu\nu} F^{\mu\nu} O_U, \quad (10)$$

where $F_{\mu\nu}$ is the photon field strength tensor. We estimate the rate Γ_γ of energy leakage from the unparticle into photons by

$$\Gamma_\gamma \sim |C_U|^2 \left(\frac{\Lambda_U}{M_U} \right)^{2k} \left(\frac{T_0^U}{\Lambda_U} \right)^{2d_U} T_0^U. \quad (11)$$

If this leakage occurs on time scales that are short compared to Hubble time it can distort the cosmic background radiation. We thus require $\Gamma_\gamma \ll H_0$. Choosing $k = 2$ and $M_U \sim 10^3$ TeV again, yields $\Lambda_U \ll |C_U|^{-1} 10^6$ TeV for $d_U = 1$, implying that we do not have a constraint. For $d_U = 2$ the bound is also well satisfied.

Unparticle astrophysics.—New physics that includes very light degrees of freedom can be strongly constrained by astrophysical processes. Examples of such physics are axions [21] and light graviton Kaluza-Klein modes [18,22]. It is then interesting to inquire how the unparticle interactions can be constrained by these processes. One such bound can be obtained by considering the SN 1987A. The observation of this supernova constrains the emission of non-neutrino species from its hot core, with $T_{\text{SN}} \sim 30$ MeV. The bound on the axion coupling constant $f_a \gtrsim 10^9$ GeV [21] can be translated into a bound on unparticle-nucleon interactions as follows.

Let us consider the interaction

$$\mathcal{L}_N = C_U \frac{\Lambda_U^{k+1-d_U}}{M_U^k} \bar{N} \gamma_\mu N O_U^\mu, \quad (12)$$

where N is a nucleon. The coupling of the axion to the

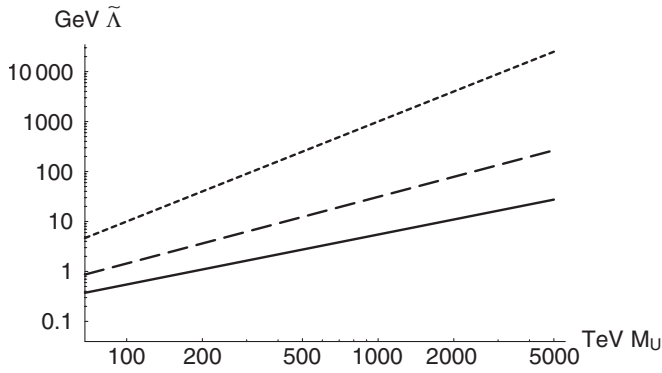


FIG. 2. Supernova overcooling constraints on the unparticle-nucleon interactions, from Eq. (14). Other conventions are as in Fig. 1.

nucleon tends to zero in the nonrelativistic limit. Therefore, the relevant dimensionless effective coupling for the axion is given by

$$g_a^{\text{SN}} \sim (T_{\text{SN}}/f_a) \sim 3 \times 10^{-11}. \quad (13)$$

To avoid over-cooling the supernova via unparticle emission, we then require, for $k = 2$,

$$\left| \frac{C_U \Lambda^{3-d_U}}{M_U^2} \right| T_{\text{SN}}^{d_U-1} \lesssim g_a^{\text{SN}}. \quad (14)$$

For $M_U \sim 10^3$ TeV, $\tilde{\Lambda} \lesssim 5, 30, 10^3$ GeV with $d_U = 1, 3/2, 2$. Bounds on $\tilde{\Lambda}$ for a range of M_U and $d_U = 1, 3/2, 2$ are presented in Fig. 2. There is also a very stringent bound on axion-photon coupling from the evolution of globular clusters: $g_a^{\text{GB}} \lesssim 10^{-10}$ GeV $^{-1}$ [21]. The relevant temperature here is $T_{\text{GB}} \sim 10$ keV and hence $g_a^{\text{GB}} T_{\text{GB}} \lesssim 10^{-15}$. Using the interaction in Eq. (10), with $k = 2$, $d_U = 1$, and $M \sim 10^3$ TeV, we get $\Lambda_U \lesssim |C_U|^{-1} 100$ GeV, whereas for $d_U = 3/2$ we get $\Lambda_U \lesssim |C_U|^{-1} 10^7$ TeV. The case with $d_U = 2$ does not yield a new limit.

Before closing, it is interesting to see how the above considerations can affect the collider and precision phenomenology of unparticle physics. For example, let us take the results of Ref. [3] for Drell-Yan processes and $(g-2)_\ell$. A typical range of d_U in Ref. [3] is $3/2 \leq d_U \leq 2$ and $\Lambda_U = 1$ TeV has been assumed for the above processes. To make contact with their notation, we define $\lambda_1 \equiv C_U (\Lambda_U/M_U)^k$. Then, our Eq. (6) becomes $\lambda_1 (T/\Lambda_U)^{d_U-1} \lesssim (T/M_p)^{1/2}$. For $d_U = 3/2$ we get $\lambda_1 \lesssim 10^{-16}$, whereas for $d_U = 2$ and $T \sim 1$ MeV we get $\lambda_1 \lesssim 10^{-5}$, whereas in Ref. [3], $\lambda_1 \geq 10^{-3}$. Hence, cosmological constraints severely affect the viable parameter space relevant for these processes.

In summary, we considered how current standard cosmology and astrophysics place bounds on unparticle inter-

actions. The suppression power of the cutoff M_U scale was taken to be $k = 2$, as would often be the case for higher-dimensional operators. The strongest bounds we obtained are for $d_U = 1$, imposed by the success of BBN and agreement with the SN 1987A data. We also considered a scenario in which couplings of a WIMP-type dark matter to the unparticle lead to a present ‘‘dark-unparticle’’ energy density at a level near that of baryons. The bounds in our work can be useful guides for unparticle model building and phenomenology, as demonstrated for some of the hitherto studied collider and precision phenomenology of unparticle physics.

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- [1] H. Georgi, Phys. Rev. Lett. **98**, 221601 (2007).
- [2] H. Georgi, Phys. Lett. B **650**, 275 (2007).
- [3] K. Cheung, W. Y. Keung, and T. C. Yuan, Phys. Rev. Lett. **99**, 051803 (2007).
- [4] M. Luo and G. Zhu, arXiv:0704.3532.
- [5] C. H. Chen and C. Q. Geng, arXiv:0705.0689.
- [6] G. J. Ding and M. L. Yan, arXiv:0705.0794 [Phys. Rev. D (to be published)].
- [7] Y. Liao, arXiv:hep-ph/0705.0837 [Phys. Rev. D (to be published)].
- [8] T. M. Aliev, A. S. Cornell, and N. Gaur, arXiv:0705.1326.
- [9] X. Q. Li and Z. T. Wei, Phys. Lett. B **651**, 380 (2007).
- [10] M. Duraismy, arXiv:hep-ph/0705.2622.
- [11] C. D. Lu, W. Wang, and Y. M. Wang, arXiv:0705.2909 [Phys. Rev. D (to be published)].
- [12] M. A. Stephanov, Phys. Rev. D **76**, 035008 (2007).
- [13] P. J. Fox, A. Rajaraman, and Y. Shirman, arXiv:0705.3092 [Phys. Rev. D (to be published)].
- [14] S. S. Gubser, Phys. Rev. D **63**, 084017 (2001).
- [15] J. M. Maldacena, Adv. Theor. Math. Phys. **2**, 231 (1998); Int. J. Theor. Phys. **38**, 1113 (1999).
- [16] T. Banks and A. Zaks, Nucl. Phys. B **196**, 189 (1982).
- [17] G. Mack, Commun. Math. Phys. **55**, 1 (1977).
- [18] N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Lett. B **429**, 263 (1998); N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, Phys. Rev. D **59**, 086004 (1999). For earlier work with TeV-scale compactification see Ref. [23].
- [19] Z. Chacko, L. J. Hall, T. Okui, and S. J. Oliver, Phys. Rev. D **70**, 085008 (2004).
- [20] D. N. Spergel *et al.* (WMAP Collaboration), Astrophys. J. Suppl. Ser. **170**, 377 (2007).
- [21] W. M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006).
- [22] S. Cullen and M. Perelstein, Phys. Rev. Lett. **83**, 268 (1999).
- [23] I. Antoniadis, Phys. Lett. B **246**, 377 (1990).