Abstract

We argue in favor of the existence of the LIPs, the least interacting particles, which would only interact with ordinary matter through gravitational field and could account for (at least) part of the dark matter. The detectability of LIP matter is addressed at the end.
The last fifty years have witnessed continuous efforts towards the solution of what can be fairly considered the most important puzzle in Cosmology, namely, most matter of the Universe resists to show up except through its gravitational effects. This is the so–called dark–matter problem. In fact, as we scrutinize the Universe at larger and larger scales, we conclude that 95% (or even more) of its total mass is hidden from direct observation.

This missing amount of matter could be expected under theoretical grounds as follows: present observations show that the energy density \( \rho \) in the form of luminous matter is about 1% of \( \rho_c \), the critical energy density just necessary to close the Universe. Now, if most matter in the Universe was in this form, and we traced back in time \( \rho(t) \), we would find that near the Big Bang the energy density of the Universe would be \textit{extremely} close to the critical value. Such a fine tuning seems unnatural, and it is a current prejudice to assume that \( \rho = \rho_c \). In such a case, the Universe would be flat along its whole history, and an enormous amount of non–luminous matter should presently exist in the Universe in order to account for the missing mass \cite{1}.

The fact that we would be living today in a Universe with energy density \textit{extremely} close to the critical value is also predicted by Inflation. The inflationary theory became very popular recently because of giving a natural explanation for several cosmological problems – like the horizon and monopole problems – and for providing a nice explanation for the inhomogeneities observed by COBE in the primordial cosmic radiation \cite{2}. Notwithstanding, some points are still open, as for example, the necessary scalar field to drive inflation \cite{3} finds no room in the elementary particle standard model.

It is known that some dark matter should be in baryonic form, but this cannot account for all of it. The energy density due to baryons cannot exceed about 10% of \( \rho_c \) in order that nucleosynthesis calculations in the primordial fireball fit the current abundance of light elements. So, according to measurements taken over length scales above 1 Mpc, there must exist at least as much non–baryonic dark matter as baryonic matter. But what could non–baryonic dark matter be?

Maybe the most widespread conjecture is provided by supersymmetry, which predicts
a number of weakly interacting massive particles – WIMPs [4]. Attempts to detect these particles are being made without conclusive results up to now. Many experiments are currently under investigation, and more precise results are being expected, but how to proceed if all attempts to detect WIMPs eventually fail?

We would like to suggest the possibility that the failure in detecting WIMPs, and other dark-matter candidates [3] at Earth laboratories might indicate that non-baryonic dark matter could be constituted of particles that do not interact with ordinary matter by any means, except gravitationally. Let us call them the “least interacting particles” (LIPs). Although exotic at a first glance, particular realizations of this conjecture have already appeared in the literature – like some kinds of mirror matter, introduced to restore the parity symmetry [4], and the shadow matter which comes from the superstring–inspired $E^8 \times E^8'$ effective gauge theory [5], but in these cases the LIP universe would be restricted to be a perfect copy of our Universe. Here, we would like to argue in favor of the LIPs, and possible ways of their detection, in a model–independent manner in order not to contaminate the discussion with bias which in general are more related with the underlying theories which give rise to LIP matter than with the “LIP conjecture” itself. Indeed, we aim to show that the existence of the LIPs would be a quite natural and attractive possibility in its own right.

In order to introduce the LIPs in a model–independent framework, let us assume that after all symmetry breakings – which are expected to happen in the very first second – of an yet unknown all-embracing grand unification theory, the relevant world action would be

$$S = \int d^4x\sqrt{-g} (\mathcal{R} + \mathcal{L}_0 + \mathcal{L}_{\text{LIP}}),$$

where $g = \det(g_{\mu\nu})$, $\mathcal{R}$ is the curvature scalar, $\mathcal{L}_0$ is the ordinary–matter Lagrangian density, and $\mathcal{L}_{\text{LIP}}$ is some Lagrangian density associated with the LIPs. The only restrictions that $\mathcal{L}_0$ and $\mathcal{L}_{\text{LIP}}$ must satisfy is that they are scalar functions under general coordinate transformations, they do not have any fields in common, and $\mathcal{L}_0$ reduces to the usual standard model in flat spacetimes. It is clear from the action that the coupling between LIP and ordinary matter is indirect through the metric, i.e. they only interact gravitationally.
through the spacetime curvature. The spacetime curvature is determined by the energy content associated with the fields as ruled by Einstein equations.

Now we address the problem of how likely is the detection of LIP matter. It is very difficult to observe the LIPs on Earth–based laboratory experiments. It is clear from the action above that the annihilation of an ordinary–matter pair into a LIP pair through graviton exchange could be observable by looking for missing–energy events. However, since gravitons couple to any kind of matter very faintly and with the same strength (because of the equivalence principle), this kind of process would not be observed in practice. Thus, it is desirable that we discuss the detectability issue through cosmological and astrophysical observations.

Under some assumptions it is possible to fix constraints on LIP matter by using primordial nucleosynthesis and baryogenesis [8]. This is because LIP matter would increase the degrees of freedom of the primordial plasma modifying (i) the energy content of the Universe and thus (ii) its expansion rate which is crucial for nucleosynthesis and baryogenesis.

The extra degrees of freedom introduced in form of LIP matter would be relevant not only cosmologically but also astrophysically. Hawking has shown that black holes must radiate particles in a thermal spectrum [9] and might completely evaporate. A static black hole of mass $M$ has an area $A = 16\pi M^2$, and a temperature $T = 1/8\pi M$ as measured by asymptotic observers. In good approximation, a black hole radiates as a black body. Using the Stephan-Boltzman law, $dE/dt = a(M)AT^4$, for the black hole, we obtain that the black–hole mass evaporates as

$$\frac{dM}{dt} = -\frac{a(M)}{M^2},$$

where $a(M)$ accounts for the degrees of freedom of the emitted particles. The more particles a black hole can radiate the faster the black hole will evaporate. Thus, if we observed a black hole to evaporate faster than what is predicted by using the standard model of particles, it could be indicating that part of the emitted energy is in LIP form. (Because of the no-hair theorems, a black hole would evaporate by the emission of LIP matter as well as ordinary
matter, no mind whether it was originally formed by the collapse of ordinary or LIP matter.)

A nicer scenario would be provided if $\mathcal{L}_{\text{LIP}}$ gave rise to structures, and eventually solved the dark–matter problem. Assuming the hypothesis that most mass of the Universe hidden as dark matter is in LIP form, and since the most important interaction in large–scale for structure formation is gravity, we should expect that most of the inhomogeneity of the observable ordinary matter would be determined by the inhomogeneity of LIP matter itself. In this vein, it would be natural to expect that large–scale ordinary–matter structures like observable galaxies, galaxy clusters, etc, would be located in regions with high LIP–matter concentrations. Indeed, roughly speaking, the larger the scale the more dark matter is gravitationally “observed”. It is possible to speculate in this context that the so–called great–attractor could be constituted of LIP matter. Clearly, short–scale structures, like solar systems are formed by local processes like supernovae, and because of the low density of the Universe the probability of finding LIP– and ordinary–matter structures overlapping at short scales is very small.

Furthermore LIP stellar objects could be observed through the lensing effect. Typically, gravitational lensing events are associated with extra–galactic sources where, for example, the radiation emitted by quasars is bent by the gravitational field of a foreground galaxy. For our purposes, however, it is useful to consider events associated with the lensing of galactic compact objects. In fact, the MACHO program \cite{MACHO} is searching for galactic dark matter in the form of massive compact halo objects. Let us suppose a sufficiently massive object, like a neutron star, lying almost collinear between some emitting source and Earth in such a way that a double image of the emitting source is observed. If the massive object was made of LIP matter we should also expect an extra luminous point between those two images because of the light ray that would pass through it. Thus the detection of three clone images in the sky with same $z$ via lensing effect of a galactic massive object would be a very stimulating feature for the search of LIP matter.

Up to here, we have suggested that the LIPs can be a reasonable solution to the dark–matter problem. Now, we would like to argue in favor of their existence in their own
right: Quarks interact through strong, electromagnetic, weak and gravitational (as far as we know) interaction; charged leptons, e.g. electrons, interact through electromagnetic, weak and gravitational interaction; neutrinos interact through weak and gravitational interaction. Why should not we expect to exist a class of matter particles that would only interact through gravitational interaction with ordinary matter? If this is true that nature follows the motto that everything that is not forbidden is mandatory, it is hard to believe that at least part of the energy content of the Universe is not in LIP form. If this reasoning was used fifty years ago to conjecture the existence of the LIPs, dark matter would be its most outstanding prediction. Moreover the LIPs can give us clues for the solution of other problems. For example, the LIP sector of the Lagrangian provides natural room for particles like scalars which not only are important for Inflation (to cite just an example), but also are expected to exist under “naturality” grounds.

In summary, we think that even if experiments rule out the existence of the LIPs, the fact that Nature has chosen not to realize particles that interact only gravitationally must be indicating some very deep fact. Using Bohr’s words: “The opposite of a deep statement is another deep statement”. It seems to us that it is more natural to hold that the LIPs exist, than the opposite.

ACKNOWLEDGMENTS

This research was supported in part by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (GM, JM and VP), and in part by Fundação de Amparo à Pesquisa do Estado de São Paulo (DV).
REFERENCES

[1] P. J. E. Peebles, *Large Structure of the Universe* (Princeton University Press, Princeton, 1980).

[2] G. F. Smoot *et al.*, Astrophys. J. Lett. 396, L1 (1992); E. L. Wright, Nucl. Phys. (Proc. Suppl.) 51B, 54 (1996).

[3] A. Linde, *Particle Physics and Inflationary Cosmology* (Harwood, Chur, 1990); S. Plan and A. Guth in *300 Years of Gravitation*, ed. by S. W. Hawking and W. Israel (Cambridge University Press, Cambridge, 1987); K. Olive, Phys. Rep. 190, 307 (1990); R. H. Brandenberger, Particle Physics Aspects of Modern Cosmology, [hep-ph/9701276](https://arxiv.org/abs/hep-ph/9701276).

[4] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267, 195 (1996).

[5] M. S. Turner, Phys. Rep. 197, 67 (1990).

[6] T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956); I. Yu. Kobzarev, L. B. Okun and I. Ya. Pomeranchuk, Yad. Fiz. 3, 1154 (1966) [Sov. J. Nucl. Phys. 3, 837 (1966)].

[7] M. B. Green and J. H. Schwarz, Phys. Lett. 148B, 117 (1984); D. J. Gross, J. A. Harvey and E. Martinec, Phys. Rev. Lett. 54, 503 (1985).

[8] E. W. Kolb, D. Seckel and M. S. Turner, Nature 314, 415 (1985); H. M. Hodge, Phys. Rev. D 45, 1113 (1992); *ibid* 47, 456 (1993).

[9] S. W. Hawking, Nature 248, 30 (1974); Commun. Math. Phys. 43, 199 (1975).

[10] M. R. Pratt *et al.*, Nucl. Phys. B (Proc. Suppl.) 51B, 131 (1996) and references therein.