Constraints on astro-unparticle physics from SN 1987A

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Abstract. SN 1987A observations have been used to place constraints on the interactions between standard model particles and unparticles. In this study we calculate the energy loss from the supernovae core through scalar, pseudo-scalar, vector, and pseudo-vector unparticle emission from nuclear bremsstrahlung for degenerate nuclear matter interacting through one pion exchange. In order to examine the constraints on $d_{\mathcal{U}} = 1$ we considered the emission of scalars, pseudo-scalars, vectors, pseudo-vectors and tensors through the pair annihilation process $e^+e^- \rightarrow \mathcal{U} \gamma$. In addition we have re-examined other pair annihilation processes. The most stringent bounds on the dimensionless coupling constants for $d_{\mathcal{U}} = 1$ and $\Lambda_{\mathcal{U}} = m_Z$ are obtained from the nuclear bremsstrahlung process for the pseudo-scalar and pseudo-vector couplings $|\lambda_{P_i}^0| \leq 4 \times 10^{-11}$, and for tensor interaction, the best limit on dimensionless coupling is obtained from $e^+e^- \rightarrow \mathcal{U} \gamma$ and we get $|\lambda_T^T| \leq 6 \times 10^{-6}$.

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1. Introduction

Recently Georgi [1,2] has considered the interesting possibility of the existence of new physics above the TeV scale through the introduction of unparticles. In this scheme, at high energies there is a hidden sector with a non-trivial IR fixed point $\Lambda_U$, below which there is scale invariance. At energies above $\Lambda_U$, there is a hidden sector operator $O_{UV}$ of dimension $d_{UV}$ that couples to the SM operator $O_{SM}$ of dimension $n$ through the exchange of high mass $M_U$ particles

$$L_{d_{UV}} = \frac{O_{SM} O_{UV}}{M_{d_{UV}+n-4}}.$$ (1)

Below $\Lambda_U$, the hidden sector becomes scale invariant and the operator $O_{UV}$ goes over to $O_U$, an unparticle operator of dimension $d_U$.

$$L_U = C_U \frac{\Lambda_{d_{UV}-d_U}}{M_{d_{UV}+n-4}} O_{SM} O_{UV}$$ (2)

where $C_U$ is the dimensionless coupling constant and the phase space of $O_U$ is the same as the phase space of massless particles, and $d_U$ is free to take non-integer values. The unparticle phase space for $d_U$ dimensions is then given by

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

which reduces to the standard value for $d_U = 1$. Since the unparticle sector appears at low energy as massless fields coupled to SM particles very weakly, their emission from the stellar matter will result in energy loss and thus the cooling of these objects. This can be used for putting constraints on the parameters of the theory. Recently Davoudiasl [3], Hannestad et al [4] and Freitas and Wyler [5] have used astrophysical limits to constrain the unparticle physics. Davoudiasl [3] and Hannestad et al [4] essentially used dimensional analysis considerations to put constraints on vector unparticles from supernova SN 1987 A. Freitas and Wyler [5] extended the analysis to include scalar, pseudo-scalar and axial unparticle operators. They, however, did not consider the scalar and pseudo-scalar couplings like $\bar{f} f O^{S}_{U}$ and $\bar{f} \gamma_5 f O^{P}_{U}$. These authors considered the dominant nucleon bremsstrahlung, namely $NN \rightarrow NN U$, process for the emission of unparticles from the...
supernova core. They have estimated the energy loss due to nucleon bremsstrahlung by factorizing the process into a ‘hard’ $NN$ collision process and ‘soft’ unparticle emission from one of the external nucleons. They then calculated the rates in the non-relativistic limit.

In addition, the authors of [4] also considered the vector unparticle production through electron neutrino–anti-neutrino annihilation. Recently Lewis [6] extended these calculations to include energy loss rates for tensor particle production from photon–photon ($\gamma\gamma \rightarrow U$) and electron–positron ($e^+e^- \rightarrow U$) annihilation. It is obvious that pair annihilation will not give any constraints for $d = 1$ simply because energy–momentum conservation forbids pair annihilation to a single massless particle. The most restrictive bounds from these studies have been obtained for vector unparticles [4] and the constraints on scalar unparticles [5] are much weaker.

The unparticles can arise as stated in [1] from the hidden sector or from the strongly interacting magnetic phase of a specific class of supersymmetric theories [7] or from the hidden valleys model [8]. However, we also note that under a specific conformal invariance [9] the propagators for vectors and tensors are modified. Fox et al [7] from a study of supersymmetric QCD in the conformal regime have shown that the interaction of dimension $d_U < 2$ unparticles with the SM Higgs particles break conformal invariance once the Higgs particles acquire non-zero VEV. The theory becomes non-conformal below that scale and unparticle physics loses its relevance. In this study we assume that the conformal invariance continues to remain valid down to the energy relevant in supernovae processes and that astrophysical constraints would remain in the unfolding issues in unparticle physics. This is also in conformity with the view taken in [3]–[6].

Recently there has been a lot of interest in phenomenological studies of unparticles [10]–[63]. The astrophysical studies were performed in [64], [65]–[67] where it is assumed that conformal invariance holds down to the low energy regime relevant for the processes in the supernova. Studies were also carried out on the impact of unparticles in the cosmology in [3], [68]–[70]. In this paper we revisit the rate of energy loss from the emission of unparticles from the supernova core for the dominant nucleon bremsstrahlung and subdominant pair annihilation processes. For that purpose we take vector, axial vector, scalar and pseudo-scalar unparticles. The rate of energy loss due to emission of unparticles from the supernova core through the nucleon bremsstrahlung and subdominant pair annihilation processes. For that purpose we take vector, axial vector, scalar and pseudo-scalar unparticles. The rate of energy loss due to emission of unparticles from the supernova core through the nucleon bremsstrahlung and subdominant pair annihilation processes. For that purpose we take vector, axial vector, scalar and pseudo-scalar unparticles. The rate of energy loss due to emission of unparticles from the supernova core through the nucleon bremsstrahlung and subdominant pair annihilation processes.

We also calculate the energy loss rate due to unparticle production through pair annihilation processes for the couplings mentioned above. In order to obtain a bound for the $d_U = 1$ case, we consider the pair annihilation of charged leptons through $e^+e^- \rightarrow U\gamma$. This process was mentioned by the author of [4] as a possible competitive process for obtaining constraints for $d_U = 1$. In section 2, we list the effective interactions between...
scalar, pseudo-scalar, vector, axial vector and tensor unparticles and the SM fields, and calculate the rate of energy loss from the nucleon bremsstrahlung process. In section 3 we perform calculations for the pair annihilation to unparticles and the resulting energy loss. In section 4 we numerically evaluate the energy loss from the supernova core and put constraints from SN 1987A on unparticle couplings with SM particles, and discuss the results. We also provide the comparison table for the constraints on the unparticle couplings from earlier work.

2. Unparticle emission from the nucleon bremsstrahlung process

The effective scalar and pseudo-scalar unparticle interactions with SM particles in the present study are

\[ \frac{\lambda_0^S}{\Lambda_{d_1}^{d_1-1}} \bar{f} f \mathcal{O}_u; \quad \frac{\lambda_0^P}{\Lambda_{d_1}^{d_1-1}} \bar{f} \gamma_5 f \mathcal{O}_u; \quad \frac{\lambda_0^{S_1}}{\Lambda_{d_1}^{d_1}} \bar{f} \gamma^\mu \left( \partial_\mu \mathcal{O}_u \right); \]

\[ \frac{\lambda_0^{P_1}}{\Lambda_{d_1}^{d_1}} \bar{f} \gamma_\mu \gamma_5 \left( \partial_\mu \mathcal{O}_u \right) \quad \text{and} \quad \frac{\lambda_0}{\Lambda_{d_1}^{d_1}} \mathcal{F}_{\mu\nu} \mathcal{F}_{\mu\nu} \mathcal{O}_u. \]  

(5)

For the vector and axial vector unparticle operators, we have

\[ \frac{\lambda_1^V}{\Lambda_{d_1}^{d_1-1}} \bar{f} \gamma_\mu f \mathcal{O}_u^\mu; \quad \frac{\lambda_1^A}{\Lambda_{d_1}^{d_1-1}} \bar{f} \gamma_\mu \gamma_5 f \mathcal{O}_u^\mu \]

and for tensor unparticles the interactions are

\[ \frac{-i}{4} \frac{\lambda_T}{\Lambda_{d_1}^{d_1}} \bar{f} \left( \gamma_\mu \not{D}_\nu + \gamma_\nu \not{D}_\mu \right) f \mathcal{O}_u^{\mu\nu}, \quad \text{and} \quad \frac{\lambda_T}{\Lambda_{d_1}^{d_1}} \mathcal{F}_{\mu\alpha} \mathcal{F}_{\nu}^{\alpha} \mathcal{O}_u^{\mu\nu}. \]

(6)

Here the dimensionless coupling constants \( \lambda_i \) are related to the coupling constant \( C_u \) and the mass scale \( M_u \) through

\[ \frac{\lambda_1^{V,A}}{\Lambda_{d_1}^{d_1-1}} = \frac{\lambda_0^{S,P}}{\Lambda_{d_1}^{d_1-1}} = C_u^{S,P,V,A} \Lambda_{u}^{3-d_1} \frac{M_u^2}{M_u^2} \quad \text{and} \quad \frac{\lambda_0^{S_1,P_1,T}}{\Lambda_{d_1}^{d_1}} = C_u^{S_1,P_1,T} \Lambda_{u}^{2-d_1} \frac{M_u^2}{M_u^2}. \]

(8)

We now calculate the rate of energy loss due to neutron bremsstrahlung:

\[ N(p_1) + N(p_2) \rightarrow N(p_3) + N(p_4) + \mathcal{U}(P) \]

(9)

for the interaction considered above. The energy loss rate is given by

\[ \dot{\epsilon}_{ul} = A_{ul} \int \left[ \prod_{i=1}^{4} \frac{d^3p_i}{2E_i(2\pi)^3} \right] \Theta(P_0)\Theta(P^2)(P^2)^{d_1-2}P_0^1 \frac{\Lambda^2}{4} \sum |\mathcal{M}|^2 f_1 f_2 (1 - f_3) (1 - f_4) \]

(10)

where \( \sum |\mathcal{M}|^2 \) is the matrix element squared summed over spins and \( (1/4) \) is the statistical factor for identical neutrons, and the \( f_i \) are the Fermi–Dirac distribution functions. Introducing

\[ 1 = \int d^4P \delta^4(p_1 + p_2 - p_3 - p_4 - P) \]

(11)
and integrating over \( d|\vec{P}| \), we get
\[
\dot{\epsilon}_U = \frac{\pi^{5/2}}{(2\pi)^{2d_U}} \frac{\Gamma(1/2)}{\Gamma(2d_U)} \left[ \int \prod_{i=1}^{4} \frac{d^3p_i}{2E_i(2\pi)^3} \right] \left( \frac{p^0}{E_U} \right)^{2d_U} dP_0 d\Omega_P \frac{1}{4} \sum_i |\mathcal{M}_i|^2 f_1 f_2 (1 - f_3)(1 - f_4).
\] (12)

Since the supernovae temperature \( \approx 30 \) MeV is small compared to the nucleon mass, the non-relativistic treatment of nucleons is adequate. In the limit of treating the nucleon propagator non-relativistically and keeping only the leading term, namely
\[
\frac{i}{(p + g)^2 - m_N^2} = \pm 2m_N \omega
\]
where \( \omega \) is the energy of the emitted unparticle, the leading contributions from the diagrams when the scalar and vector unparticles are emitted from the outgoing and incoming nucleon legs, respectively, cancel in pairs. This has also been emphasized by the author of [4], who then used the next to leading order term, namely, the quadrupole contribution for the vector case.

The matrix element squared for the scalar, pseudo-scalar (axion) and neutrino emission has been calculated in [71]–[75]. For the vector and the axial vector cases, the squared matrix element can be calculated by a slight modification of their result. The angular integrations can be done by neglecting pion mass in comparison with the nucleon Fermi momentum which is typically of the order of 356 MeV. This results in not more than 10–15% change in the energy loss. By using the standard techniques of replacing the neutron momenta by their Fermi momenta wherever possible, we get
\[
\dot{\epsilon}_U (\mathcal{P}) \approx \frac{64}{(2\pi)^{2d_U+5}} \frac{1}{\Gamma(2d_U)} T^{(2d_U+4)} m_n^2 \left( \frac{f}{m_\pi} \right)^4 \mathcal{J}(1)
\] (13)
where \( \mathcal{J}(n) = \pi^2 \int_0^\infty \frac{y^2 dy}{e^y - 1} \left( \frac{2}{3} + \frac{y^2}{6 \pi^2} \right) dy.\) (14)

For \( d_U = 1 \), this reduces to the well known axion case, namely
\[
\dot{\epsilon}_U (\mathcal{P}) \bigg|_{(d_U=1)} \approx \frac{31}{1890 \pi} |\lambda_{0,1}^P|^2 \left( \frac{f}{m_\pi} \right)^4 m_n^2 p_F T^6.
\] (15)

For the scalar and vector cases we get
\[
\dot{\epsilon}_U (\mathcal{S}, \mathcal{V}) \approx \frac{256}{75 (2\pi)^{2d_U+5}} \frac{1}{\Gamma(2d_U)} \left( \frac{|\lambda_{0,1}^{S,V}|}{\Lambda_{d_U-1}^{d_U}} \right)^2 \left( \frac{f}{m_\pi} \right)^4 p_F^5 T^{(2d_U+2)} \mathcal{J}(-1).
\] (16)

For \( d_U = 1 \), we recover the Ishizuka and Yoshimura [75] result for the scalar dilaton emission. For the other two cases, we get
\[
\dot{\epsilon}_U (\mathcal{P}_1) \approx \frac{64}{(2\pi)^{2d_U+5}} \frac{1}{\Gamma(2d_U)} m_n^2 \left( \frac{|\lambda_{0,1}^P|}{\Lambda_{d_U}^{d_U}} \right)^2 \left( \frac{f}{m_\pi} \right)^4 p_F T^{(2d_U+6)} \mathcal{J}(3) \quad \text{and} \quad (17)
\]
\[
\dot{\epsilon}_U (\mathcal{S}_1) \approx \frac{256}{75 (2\pi)^{2d_U+5}} \frac{1}{\Gamma(2d_U)} \left( \frac{|\lambda_{0,1}^S|}{\Lambda_{d_U}^{d_U}} \right)^2 \left( \frac{f}{m_\pi} \right)^4 p_F^5 T^{(2d_U+4)} \mathcal{J}(1).
\] (18)
3. Unparticle emission from pair annihilation

The possible pair annihilation processes in the supernova core responsible for energy loss through the emission of unparticles are \( \gamma \gamma \rightarrow \mathcal{U}, \ e^+e^- \rightarrow \mathcal{U} \) and \( \nu \bar{\nu} \rightarrow \mathcal{U} \). In the supernova core the electrons and electron neutrinos are degenerate, with chemical potential typically of the order of 150–200 MeV, whereas muon and tau neutrinos are essentially non-degenerate. Further, for \( d_\mathcal{U} = 1 \) as mentioned in section 1, the rate vanishes because of energy–momentum conservation. Using the photon coupling to the scalar unparticles given in equation (5), the pair annihilation cross-section is given by

\[
\sigma_{av}(\gamma \gamma \rightarrow \mathcal{U}) = \frac{1}{8} \left( \frac{\lambda_0^2}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}}} \right)^2 A_{d_\mathcal{U}} \ s^{d_\mathcal{U}-1}
\]

and the energy loss is calculated to be

\[
\epsilon_{\gamma} = \frac{2(2^{d_\mathcal{U}+1})}{d_\mathcal{U} + 1} A_{d_\mathcal{U}} \left( \frac{\lambda_0^2}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}}} \right)^2 \frac{T^{(2d_\mathcal{U}+5)}}{(2 \pi)^4} \zeta(d_\mathcal{U} + 3) \Gamma(d_\mathcal{U} + 3) \Gamma(d_\mathcal{U} + 2) \zeta(d_\mathcal{U} + 2).
\]

For \( e^+e^- \rightarrow \mathcal{U} \), we have the contribution from the vector unparticle operator

\[
\sigma_{av}(e^+e^- \rightarrow \mathcal{U}) = \frac{1}{2} \left( \frac{\lambda_0^2}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}}} \right)^2 A_{d_\mathcal{U}} \left( \frac{s}{\Lambda_{\mathcal{U}}} \right) \ s^{d_\mathcal{U}-2}
\]

and for \( \nu \bar{\nu} \rightarrow \mathcal{U} \) we have

\[
\sigma_{av}(\nu \bar{\nu} \rightarrow \mathcal{U}) = 2 \sigma_{av}(e^+e^- \rightarrow \mathcal{U}).
\]

The energy loss rate is given by

\[
\epsilon_{\nu e} = \frac{2(2^{d_\mathcal{U}-2})}{(2 \pi)^4} A_{d_\mathcal{U}} \left( \frac{\lambda_0^2}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}-1}} \right)^2 T^{(2d_\mathcal{U}+3)} \prod_{i=1}^2 \int \frac{x_i^{d_\mathcal{U}}}{e^{x_i}+1} (x_1 + x_2)
\]

where \( y = \mu F / T \). For \( \nu_\mu \) and \( \nu_\tau \) we can take \( y \) to be zero and hence the energy loss rate becomes

\[
\epsilon_{\nu e} = \frac{2(2^{d_\mathcal{U}+1})}{(2 \pi)^4} A_{d_\mathcal{U}} \left( \frac{\lambda_0^2}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}-1}} \right)^2 T^{(2d_\mathcal{U}+3)} \zeta(d_\mathcal{U} + 2) \Gamma(d_\mathcal{U} + 2) \zeta(d_\mathcal{U} + 1) \Gamma(d_\mathcal{U} + 1)
\]

\[
\times \left[ 1 - \frac{1}{2(d_\mathcal{U}+1)} \right]^{-1} \left[ 1 - \frac{1}{2d_\mathcal{U}} \right]^{-1} \left( \frac{\lambda_0^2}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}-1}} \right) \frac{1}{4} \frac{1}{d_\mathcal{U}+2} \frac{1}{d_\mathcal{U}} \left( \frac{T}{\Lambda_{\mathcal{U}}} \right)^2 \zeta(d_\mathcal{U}+1) \zeta(d_\mathcal{U}+3) \left[ 1 - \frac{1}{2(d_\mathcal{U}+1)} \right] \left[ 1 - \frac{1}{2d_\mathcal{U}} \right] \epsilon_{\gamma}.
\]

For the processes induced by the tensor unparticle operators, the corresponding energy loss rate for pair annihilation has been calculated in [6].

As discussed above, the limits on the \( d_\mathcal{U} = 1 \) case can be obtained by considering the pair annihilation process through \( e^+e^- \rightarrow \mathcal{U} \gamma \). We first consider the emission of the vector unparticle

\[
\frac{\lambda_0^2}{\Lambda_{\mathcal{U}}^{d_\mathcal{U}-1}} \tilde{f} \gamma_\mu \mathcal{O}_{\mu}^\nu.
\]
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There are two Feynman diagrams for the $u$ and $t$ channels. The matrix element squared is given by

$$|M|^2 = 2 \left( \frac{4 \pi \alpha_{em}}{\Lambda_{u,t}^4} \right)^2 \frac{2s P^2 + u^2 + t^2}{u t}$$  \hspace{1cm} (26)$$

and the cross-section is given as

$$\sigma_{av} = \frac{1}{2s} \frac{A_{dt}}{16 \pi^3} \int |M|^2 (P^2)^{d_{u,t} - 2} E_\gamma dE_\gamma d\Omega \Theta(P^2) \Theta(P_0).$$  \hspace{1cm} (27)$$

In the limit $d_{u,t} = 1$

$$\lim_{d_{u,t} \to 1} A_{dt} (P^2)^{d_{u,t} - 2} \Theta(P^2) = 2 \pi \delta(P^2) = \frac{\pi}{\sqrt{s}} \delta \left( E_\gamma - \frac{\sqrt{s}}{2} \right).$$  \hspace{1cm} (28)$$

Therefore the cross-section becomes

$$\sigma_{av} = \alpha_{em} |\lambda^V|^2 \frac{1}{8 \pi} \int \frac{1}{s} \left( \frac{u}{t} + \frac{t}{u} \right) d\Omega_\gamma$$

$$= \alpha_{em} |\lambda^V|^2 \frac{1}{4} \frac{1}{s} \left( 1 + \ln \frac{s}{m_e^2} \right).$$  \hspace{1cm} (29)$$

The emissivity is given as

$$\epsilon^V = \frac{2 \alpha_{em} |\lambda^V|^2}{4(2\pi)^4} T^5 \left[ \prod_{i=1}^2 \int_0^\infty \frac{dx_i}{e^{x_i + (-1)^i y} + 1} \right] \int_0^\beta \left( x_1 + x_2 - \frac{\sqrt{Z}}{2} \right) \left( 1 + \ln \frac{Z}{\alpha} \right) dZ$$

where $Z = \frac{s}{T^2}$; $\beta = 4 x_1 x_2$; and $\alpha = \left( \frac{m_e}{T} \right)^2$

$$= \frac{2 \alpha_{em} |\lambda^V|^2}{4(2\pi)^4} T^5 \left[ \prod_{i=1}^2 \int_0^\infty \frac{dx_i}{e^{x_i + (-1)^i y} + 1} \right] \times \left[ \ln \alpha^{-\beta(x_1 + x_2)} + \frac{\beta^2}{9} (\ln \alpha^3 - 1) + \left\{ x_1 + x_2 - \frac{\sqrt{\beta}}{3} \right\} \ln \beta \right].$$  \hspace{1cm} (30)$$

The leading terms in the cross-sections for scalar, pseudo-scalar and axial vector couplings have the same behaviour, namely

$$\sigma_{av} \approx \frac{1}{s} \ln \frac{s}{m_e^2}$$  \hspace{1cm} (31)$$

and the magnitude is roughly half that for the vector case. The energy loss is, therefore, given by equation (30) within a factor of 2. For the tensor unparticle operator given in equation (7), the cross-section for the process $e^+ e^- \to U \gamma$ is given by

$$\sigma_{av}^T = \frac{1}{9} \alpha_{em} \left( \frac{|\lambda^T|}{\Lambda_U} \right)^2$$  \hspace{1cm} (32)$$
and the emissivity calculated in the limit $d\Upsilon \to 1$ is given as

$$
\dot{\epsilon}^T (d\Upsilon = 1) = \frac{2 \alpha_{\text{em}}}{9 (2 \pi)^4} \left( \frac{|\lambda^7|}{\Lambda\Upsilon} \right)^2 T^7 \left[ \prod_{i=1}^{2} \int_0^\infty \frac{dx_i}{\omega^{x_i} + (\omega^{x_i})^v + 1} \right] \times \left[ 8 (x_1 + x_2) x_1^2 x_2^2 - \frac{(4 x_1 x_2)^{5/2}}{5} \right].
$$

(33)

4. Numerical estimation and discussion

Observation of neutrino flux from IMB and Kamiokande established that most of the energy released during supernovae explosions was carried away by neutrinos. This observation has been used to place constraints on new sources of energy loss by demanding that the energy loss per unit volume per second does not exceed $\dot{\epsilon}_{\text{SN}} \approx 3 \times 10^{33}$ ergs cm$^{-3}$ s$^{-1} = 9.45 \times 10^{-15}$ MeV$^5$. Using this upper bound on the energy loss rate, we put bounds on the parameters involved in the unparticle theories.

For calculating the energy loss rate due to nucleon bremsstrahlung and pair annihilation processes from the supernova core, we take the core temperature $T$ to be 30 MeV, effective nucleon mass $m^*_n \approx 0.8 m_n$ where $m_n$ is mass of the nucleon, and neutron Fermi momentum $p_F \approx 515 \rho^{1/3}$ MeV. We have used $p_F = 345$ MeV for $\rho \approx 3 \times 10^{14}$ g cm$^{-3}$. In figure 1 we have provided the contours on the $d\Upsilon$ and $|\lambda|$ plane by restricting the energy loss rate due to unparticle emissivity to be $3 \times 10^{33}$ ergs cm$^{-3}$ s$^{-1}$, induced by scalar, pseudo-scalar, vector and axial vector unparticle operators. In these calculations the energy scale $\Lambda\Upsilon$ has been normalized to $m_Z$.

The bounds on pseudo-scalar and pseudo-vector interactions, as can be seen from figure 1, are most restrictive and we obtain $|\lambda^P_{0,1}| \leq 4 \times 10^{-11}$ for $d\Upsilon = 1$. The corresponding bounds on scalar and vector couplings are $|\lambda^{S,V}_{0,1}| \leq 7 \times 10^{-11}$.
Figure 2. Contours on the $d_U$ and coupling $|\lambda_i|$ plane for $\Lambda_U = m_Z$ for the unparticle emitting pair annihilation processes.

For the purpose of calculating the rate of energy loss from pair annihilation processes, the electron chemical potential in the supernova core is taken to be $\mu_e \approx 345$ MeV. On the basis of a similar procedure, as mentioned above, we give the corresponding contours from pair annihilation processes in figure 2. We find that the contribution to the emissivity from the $\gamma\gamma$ annihilation process from the scalar unparticles is identical to that of the tensor unparticle as given in [6].

In table 1, the bounds on the unparticle couplings with SM particles from supernovae cooling obtained by us are compared with the previous work.

As discussed in the text, we utilize the pair annihilation processes $e^+ e^- \rightarrow U\gamma$ for constraining the dimensionless coupling for $d_U = 1$. Following equation (30) we find

$$\dot{\epsilon} \approx 15.4 |\lambda^V|^2 \text{ MeV}^5.$$  (34)

Therefore SN 1987A constraints the vector dimensionless coupling, $|\lambda^V| \leq 2.5 \times 10^{-8}$. The dimensionless coupling $|\lambda^T|$ is constrained from SN 1987A as

$$|\lambda^T| \leq 7.26 \times 10^{-4} \left[ \frac{\Lambda_U}{1 \text{ TeV}} \right]^2.$$  (35)

For $\Lambda_U = m_Z$ we find for $d_U = 1$, $|\lambda^T| \leq 6 \times 10^{-6}$. Another interesting feature worth mentioning is that the cross-section and hence the energy loss rate for the vector unparticle interaction as shown in equations (29) and (30) are independent of the energy scale $\Lambda_U$. 
Table 1. Comparison of the upper limits on the dimensionless couplings of the scalar, vector, pseudo-scalar, pseudo-vector and tensor unparticles with standard model particles obtained from the calculations based on SN 1987 A. We have assumed $\Lambda_U = m_Z$ for all the cases mentioned.

| Couplings                                                                 | $d_U$          |
|---------------------------------------------------------------------------|----------------|
|                                                                           | 1              | 4/3 | 3/2 | 5/3 | 2    | Ref. |
| **Fermions–scalar unparticles:**                                          | $7.66 \times 10^{-11}$ | $2.2 \times 10^{-9}$ | $1.41 \times 10^{-8}$ | $6 \times 10^{-8}$ | $1.5 \times 10^{-6}$ | Present |
| $(\lambda^S_0 / \Lambda^d_{U}) f f \xi U$                                | $8 \times 10^{-8}$ | $2.4 \times 10^{-6}$ | — | $6.6 \times 10^{-5}$ | $2 \times 10^{-3}$ | [5] |
| $(\lambda^S_1 / \Lambda^d_{U}) f \gamma^\mu f (\partial_\mu U)$         | $9.96 \times 10^{-8}$ | $2 \times 10^{-6}$ | $9.2 \times 10^{-6}$ | $4 \times 10^{-5}$ | $9.1 \times 10^{-4}$ | Present |
| **Fermions–pseudo-scalar unparticles:**                                   | $4.3 \times 10^{-11}$ | $8.7 \times 10^{-10}$ | $3.9 \times 10^{-9}$ | $1.8 \times 10^{-8}$ | $3.9 \times 10^{-7}$ | Present |
| $(\lambda^P_0 / \Lambda^d_{U}) f \gamma_5 f U$                          | — | $1.7 \times 10^{-5}$ | — | $3.8 \times 10^{-4}$ | $9 \times 10^{-2}$ | [5] |
| $(\lambda^P_1 / \Lambda^d_{U}) f \gamma^\mu f (\partial_\mu U)$         | $2.5 \times 10^{-8}$ | $4.3 \times 10^{-7}$ | $1.88 \times 10^{-6}$ | $8.2 \times 10^{-6}$ | $1.5 \times 10^{-4}$ | Present |
| **Fermions–vector unparticles:**                                          | $7.66 \times 10^{-11}$ | $2.2 \times 10^{-9}$ | $1.41 \times 10^{-8}$ | $6 \times 10^{-8}$ | $1.5 \times 10^{-6}$ | Present |
| $(\lambda^V_1 / \Lambda^d_{U}) f \gamma^\mu f \xi_5 U$                  | $1 \times 10^{-9}$ | $3.5 \times 10^{-8}$ | — | $1 \times 10^{-6}$ | $3 \times 10^{-5}$ | [5] |
|                                                                               | — | $4.3 \times 10^{-10}$ | $1.7 \times 10^{-9}$ | $6.3 \times 10^{-9}$ | $9.1 \times 10^{-8}$ | [4] |
| **Fermions–pseudo-vector unparticles:**                                   | $4.3 \times 10^{-11}$ | $8.7 \times 10^{-10}$ | $3.9 \times 10^{-9}$ | $1.8 \times 10^{-8}$ | $3.9 \times 10^{-7}$ | Present |
| $(\lambda^P_2 / \Lambda^d_{U}) f \gamma^\mu f \xi_5 U$                  | — | $1.5 \times 10^{-8}$ | — | $4 \times 10^{-7}$ | $1 \times 10^{-5}$ | [5] |
| **Photons–tensor unparticles:**                                           | $6 \times 10^{-6}$ | — | — | — | — | Present |
| $(\lambda^T / \Lambda^d_{U}) f F_{\mu \nu} F^{\mu \nu} U$              | $3.8 \times 10^{-6}$ | $1.4 \times 10^{-5}$ | $5.2 \times 10^{-5}$ | $8.7 \times 10^{-4}$ | [6] |
| **Fermions–tensor unparticles:**                                          | $6.6 \times 10^{-5}$ | $2.2 \times 10^{-4}$ | $7.6 \times 10^{-4}$ | $1.1 \times 10^{-2}$ | [6] |
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References

[1] Georgi H, 2007 Phys. Rev. Lett. 98 221601 [SPIRES] [hep-ph/0703260]
[2] Georgi H, 2007 Phys. Lett. B 650 275 [SPIRES] [0704.2457] [hep-ph]
[3] Davoudiasl H, 2007 Phys. Rev. Lett. 99 141301 [SPIRES]
[4] Hannestad S, Raffelt G and Wong Y Y Y, 2007 Preprint 0708.1404 [hep-ph]
[5] Freitas A and Wyler D, 2007 Preprint 0708.4339 [hep-ph]
[6] Lewis I, 2007 Preprint 0710.4147 [hep-ph]
[7] Fox P J, Rajaraman A and Shirman Y, 2007 Preprint 0705.3091 [hep-ph]
[8] Hannestad S, Raffelt G and Wong Y Y Y, 2007 Preprint 0708.1404 [hep-ph]
[9] Grinstein B, Intriligator K and Rothstein I Z, 2007 Preprint 0708.1140 [hep-ph]
[10] Huitu K and Rai S K, 2007 Preprint 0711.4754 [hep-ph]
[11] Cakir O and Ozansoy K O, 2007 Preprint 0710.5773 [hep-ph]
[12] Alan A T, Pak N K and Senol A, 2007 Preprint 0710.4239 [hep-ph]
[13] Cheung K, Keung W-Y and Yuan T-C, 2007 Phys. Rev. Lett. 99 051803 [SPIRES]
[14] Bander M, Feng J L, Rajaraman A and Shirman Y, 2007 Preprint 0706.2677 [hep-ph]
[15] Luo M and Zhu G, 2007 Preprint 0704.3518 [hep-ph]
[16] Chen C-H and Geng C-Q, 2007 Preprint 0705.0689 [hep-ph]
[17] Ding G-J and Yan M-L, 2007 Preprint 0705.0794 [hep-ph]
[18] Liao Y, 2007 Phys. Rev. D 76 056006 [SPIRES] [0705.0837] [hep-ph]
[19] Aliev T M, Cornell A S and Gaur N, 2007 Preprint 0705.1326 [hep-ph]
[20] Li X-Q and Wei Z-T, 2007 Phys. Lett. B 651 380 [SPIRES] [0705.1821] [hep-ph]
[21] Duraisamy M, 2007 Preprint 0705.2622 [hep-ph]
[22] Lu C-D, Wang W and Wang Y-M, 2007 Preprint 0705.2909 [hep-ph]
[23] Greiner N, 2007 Phys. Lett. B 653 141 [SPIRES] [0705.3518] [hep-ph]
[24] Choudhury D, Ghosh D K and Mamta, 2007 Preprint 0705.3637 [hep-ph]
[25] Chen S-L and He X-G, 2007 Preprint 0705.3946 [hep-ph]
[26] Aliev T M, Cornell A S and Gaur N, 2007 J. High Energy Phys. JHEP07(2007)072 [SPIRES] [0705.4542] [hep-ph]
[27] Mathews P and Ravindran V, 2007 Preprint 0705.4599 [hep-ph]
[28] Zhou S, 2007 Preprint 0706.0302 [hep-ph]
[29] Ding G-J and Yan M-L, 2007 Preprint 0706.0325 [hep-ph]
[30] Chen C-H and Geng C-Q, 2007 Phys. Rev. D 76 036007 [SPIRES] [0706.0850] [hep-ph]
[31] Rizzo T G, 2007 Phys. Rev. D 76 057701 [SPIRES] [0707.0925] [hep-ph]
[32] Deshpande N G, He X-G and Jiang J, 2007 Preprint 0707.2959 [hep-ph]
[33] Mohanta R and Giri A K, 2007 Phys. Rev. D 76 057701 [SPIRES] [0707.3308] [hep-ph]
[34] Huang C-S and Wu X-H, 2007 Preprint 0707.0187 [hep-ph]
[35] Zwicky R, 2007 Preprint 0707.0677 [hep-ph]
[36] Lenz A, 2007 Phys. Rev. D 76 055003 [SPIRES] [0707.3308] [hep-ph]
[37] Bhattacharyya G, Choudhury D and Ghosh D K, 2007 Preprint 0707.2835 [hep-ph]
[38] Majumdar D, 2007 Preprint 0708.3485 [hep-ph]
[39] Chen C-H and Geng C-Q, 2007 Preprint 0709.0235 [hep-ph]
[40] Hur T-i, Ko P and Wu X-H, 2007 Preprint 0709.0629 [hep-ph]
Constraints on astro-unparticle physics from SN 1987A

[52] Anchordoqui L and Goldberg H, 2007 Preprint 0709.0678 [hep-ph]
[53] Balantekin A B and Ozansoy K O, 2007 Preprint 0710.0028 [hep-ph]
[54] Aliev T M and Savci M, 2007 Preprint 0710.1505 [hep-ph]
[55] Itan E O, 2007 Preprint 0710.2677 [hep-ph]
[56] Chen S L, He X G, Li H-C and Wei Z-T, 2007 Preprint 0710.3663 [hep-ph]
    Liao Y, 2007 Preprint 0710.5129 [hep-ph]
[57] Balantekin A B and Ozansoy K O, 2007 Preprint 0710.0028 [hep-ph]
[58] Ibrahim A, Espinosa J R and Quiros M, 2007 Preprint 0709.4309 [hep-ph]
[59] Sahin I and Sahin B, 2007 Preprint 0711.1665 [hep-ph]
[60] Majhi S, 2007 Preprint 0709.1960 [hep-ph]
[61] Kumar M C, Mathews P, Ravindran V and Tripathi A, 2007 Preprint 0709.2478 [hep-ph]
[62] Ding G-J and Yan M-L, 2007 Preprint 0709.3435 [hep-ph]
[63] Kobakhidze A, 2007 Preprint 0709.3782 [hep-ph]
[64] Das P K, 2007 Preprint 0708.2812 [hep-ph]
[65] Liao Y and Liu J-Y, 2007 Preprint 0706.1284 [hep-ph]
[66] Deshpande N G, Hsu S D H and Jiang J, 2007 Preprint 0708.2735 [hep-ph]
[67] Das S, Mohanty S and Rao K, 2007 Preprint 0709.2583 [hep-ph]
[68] Kikuchi T and Okada N, 2007 Preprint 0711.1506 [hep-ph]
[69] Alberghi G L, Kamenshchik A Y, Tronconi A, Vacca G P and Venturi G, 2007 Preprint 0710.4275 [hep-th]
[70] McDonald J, 2007 Preprint 0709.2350 [hep-ph]
[71] Frieman B L and Maxwell O V, 1979 Astrophys. J. 282 541 [SPIRES]
[72] Brinkman R P and Turner M S, 1988 Phys. Rev. D 38 2338 [SPIRES]
[73] Iwamoto N, 1984 Phys. Rev. Lett. 53 1198 [SPIRES]
[74] Iwamoto N, 1989 Phys. Rev. D 39 2120 [SPIRES]
[75] Ishizuka N and Yoshimura M, 1990 Prog. Theor. Phys. 84 233 [SPIRES]