

Probing Unparticle Stuff with Neutrinos

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[M.C. Gonzalez-Garcia, P.C. de Holanda, RZF, arXiv:0803.1180]

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What are Unparticles?

Georgi (07)

Fields of a **Hidden Sector (HS)** couple to SM particles at very high energies by the exchange of a particle of mass M

In the UV:

$$\mathcal{L} = \frac{1}{M^{d_{UV}+d_{SM}-4}} \mathcal{O}_{UV} \mathcal{O}_{SM}$$

Scale Invariance emerges at scale Λ_u as **HS** \implies **IR fixed point**

So below Λ_u unparticles emerge

$$\mathcal{O}_{UV} \rightarrow \mathcal{O}_U \quad \mathcal{L} \rightarrow \mathcal{L}_{\text{eff}} = C_u \frac{\Lambda_u^{d_{UV}-d}}{M^{d_{UV}+d_{SM}-4}} \mathcal{O}_{SM} \mathcal{O}_U$$



Unparticle Propagators

Scale Invariance determines the propagation properties of **unparticle operators** (up to normalization) [Georgi (07), Grinstein *et al.* (08)]

Scalar Unparticles ($d > 1$)

$$\Delta(P^2) = \frac{A_d}{2 \sin(d\pi)} (-P^2)^{d-2} \quad A_d = \frac{16\pi^2 \sqrt{\pi}}{(2\pi)^{2d}} \frac{\Gamma(d + \frac{1}{2})}{\Gamma(d-1)\Gamma(2d)}$$

Vector Unparticles ($d > 3$)

$$[\Delta(P^2)]_{\mu\nu} = \Delta(P^2) \pi_{\mu\nu} \quad \pi_{\mu\nu} = -g_{\mu\nu} + 2 \frac{(d-2)}{d-1} \frac{P_\mu P_\nu}{P^2}$$



Unparticle Phenomenological Consequences

- *QED bounds*: Liao (07), Luo and Zhu (07),...
- *Signals in past and future colliders*: Cheung, Keung and Yuan (07), Chen, He and Tsai (07), Greiner (07),...
- *CP-violation*: Chen and Geng (07), Bashiry (08),...
- *DIS*: Ding and Yan (07)
- *Lepton Flavor Violating Processes*: Aliev, Cornell and Gaur (07), Lu, Wang and Wang (07),...
- *Hadron mixing and Decays*: Li and Wei (07), Aliev, Cornell and Gaur (07),...
- *Nucleon Decay*: He and Pakvasa (08)
- *Neutrino Interactions*: Zhou (07), Anchordoqui and Goldberg (07), Montanino, Picariello and Pulido (08)
- *Cosmological and Astrophysical bounds*: Hannestad, Raffelt and Wong (07), Das (07), Freitas and Wyler (07),...



Spin-off: Macroscopic Long-range Forces

If unparticles couple to fermions they may give rise to **long-range forces operating at macroscopic distances** and governed by a **non-integral power law**

These can affect neutrino trajectories in matter similar to forces

coupled to lepton flavor number [M.C. Gonzalez-Garcia, P.C. de Holanda, RZF, JCAP 0701, 005 (2007)]

General Form satisfying the SM gauge symmetry

$$\mathcal{L}_f = -\frac{\lambda_S^f}{\Lambda_u^{d-1}} \bar{f} f \mathcal{O} - \frac{\lambda_V^f}{\Lambda_u^{d-1}} \bar{f} \gamma_\mu f \mathcal{O}^\mu - \frac{\lambda_T^f}{2\Lambda_u^d} i [\bar{f} \gamma_\mu \partial_\nu f - \partial_\mu \bar{f} \gamma_\nu f] \mathcal{O}^{\mu\nu}$$

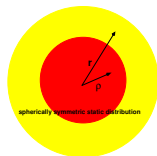
where

$$\lambda_{S,V,T}^f = C_{S,V,T}^f \left(\frac{\Lambda_u}{M} \right)^{d_{UV}-1}$$



Universal Long-Range Potential

Effective low-energy Lagrangian describing long-range force generated by a static, spherically symmetric distribution of fermions f (in the Sun) on ν



Effective Form

$$\mathcal{L}_\nu^{\text{eff}} = \left[\frac{C_S^f C_S^\nu}{4\pi} \bar{\nu} \nu - \frac{C_V^f C_V^\nu}{4\pi} \bar{\nu} \gamma^0 \nu + \frac{C_T^f C_T^\nu}{4\pi} \frac{m_f E_\nu}{\Lambda_U^2} B \bar{\nu} \gamma^0 \nu \right] W_f(r)$$

Universal Long-Range Potential

$$W_f(r) = \left(\frac{\Lambda_U}{M}\right)^{2(d_{UV}-1)} \frac{2}{\pi^{2(d-1)}} \frac{\Gamma[d + \frac{1}{2}]\Gamma[d - \frac{1}{2}]}{\Gamma[2d]} R^3 \frac{1}{(R\Lambda_U)^{2(d-1)}} \\ \times \frac{2}{r} \begin{cases} \frac{1}{3-2d} \int_0^1 y n_f(y) [(x+y)^{3-2d} - |x-y|^{3-2d}] dy & d \neq \frac{3}{2} \\ \frac{1}{2} \int_0^1 y n_f(y) \ln \left[\frac{(x+y)^2}{(x-y)^2} \right] dy & d = \frac{3}{2} \end{cases}$$

n_f = number density of fermion f

R = radius of the distribution



Standard Neutrino Oscillation Explains Data Very Well

$$\mathbf{U} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathbf{c}_{23} & \mathbf{s}_{23} \\ 0 & -\mathbf{s}_{23} & \mathbf{c}_{23} \end{pmatrix}}^{\text{Atmospheric}} \begin{pmatrix} \mathbf{c}_{13} & 0 & \mathbf{s}_{13} \\ 0 & 1 & 0 \\ -\mathbf{s}_{13} & 0 & \mathbf{c}_{13} \end{pmatrix} \overbrace{\begin{pmatrix} \mathbf{c}_{12} & \mathbf{s}_{12} & 0 \\ -\mathbf{s}_{12} & \mathbf{c}_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{Solar}}$$

$$\mathbf{c}_{ij} \equiv \cos \theta_{ij} \text{ and } \mathbf{s}_{ij} \equiv \sin \theta_{ij}$$

$$\Delta m_{23}^2 \sim 2.4 \times 10^{-3} \text{ eV}^2 \text{ (MINOS)}$$

$$\Delta m_{21}^2 \sim 7.6 \times 10^{-5} \text{ eV}^2 \text{ (KamLAND)}$$

$$\Delta m_{21}^2 / |\Delta m_{23}^2| \approx 0.03$$

$$\sin^2 \theta_{13} \leq 0.04 \text{ (CHOOZ)}$$

$$\sin^2 \theta_{12} \approx 0.3 \text{ (Solar)}$$

$$\sin^2 \theta_{23} \approx 0.5 \text{ (Atmospheric)}$$

flavor diagonal new couplings do not change hierarchy $\rightarrow 2\nu$ factorization still holds as long as θ_{13} is small



in the limit where the sub-systems 12 and 23 decouple

$$i \frac{d}{dr} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = \left\{ \frac{1}{2E_\nu} \left[\mathbf{U}_{\theta_{12}} \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix} \mathbf{U}_{\theta_{12}}^\dagger - \begin{pmatrix} M_{\text{UNP}}(r) & 0 \\ 0 & 0 \end{pmatrix} \right] \right\}^2 + \begin{pmatrix} V_{\text{CC}}(r) + V_{\text{UNP}}(r) & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix}$$

$$\nu_a = \cos \theta_{23} \nu_\mu + \sin \theta_{23} \nu_\tau$$

$$V_{\text{CC}}(r) = \sqrt{2} G_F n_e(r)$$

$$\mathbf{U}_{\theta_{12}} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} \\ -\sin \theta_{12} & \cos \theta_{12} \end{pmatrix}$$



Modified Neutrino Evolution in Matter

Scalar Unparticles

$$M_{\text{UNP}} \equiv M_S(r) = \frac{C_S^e (C_S^{\nu_e} - C_S^{\nu_a})}{4\pi} W(r) \simeq \alpha_S W(r), \quad V_{\text{UNP}}(r) = 0$$

$$m_1 = 0 \quad m_2 = \sqrt{\Delta m_{21}^2}$$

Vector Unparticles

$$V_{\text{UNP}}(r) \equiv V_V(r) = \frac{C_V^e (C_V^{\nu_e} - C_V^{\nu_a})}{4\pi} W(r) \simeq \alpha_V W(r), \quad M_{\text{UNP}} = 0$$



Tensor Unparticles

$$V_{\text{UNP}}(r) \equiv -V_T(r) = -\frac{C_T^e(C_T^{\nu_e} - C_T^{\nu_a})}{4\pi} \frac{m_e E_\nu}{\Lambda_U^2} B W(r)$$

$$V_{\text{UNP}}(r) \simeq -\alpha_T \frac{m_e E_\nu}{\Lambda_U^2} W(r), \quad M_{\text{UNP}} = 0$$

$$C_{S,V,T}^{\nu_a} = c_{23}^2 C_{S,V,T}^{\nu_\mu} + s_{23}^2 C_{S,V,T}^{\nu_\tau}$$

$$n_f(r) = n_e(r) \left[1 + \frac{C_{S,V,T}^p}{C_{S,V,T}^e} R_p + \frac{C_{S,V,T}^n}{C_{S,V,T}^e} \frac{Y_n(r)}{Y_e(r)} R_n \right]$$

$R_{p,n} = 1$ (scalar and vector)

$R_{p,n} = m_{p,n}/m_e$ (tensor)



Effective Couplings

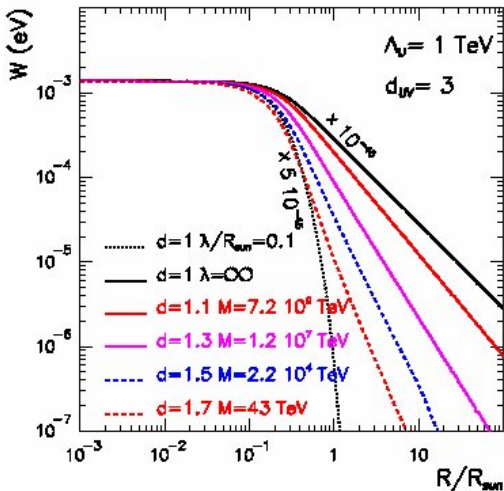
We neglect small unparticle effect in the profile of the potential and absorbed it in the definition of effective r average couplings:

$$\alpha_{S,V,T} = \frac{C_{S,V,T}^e (C_{S,V,T}^{\nu_e} - C_{S,V,T}^{\nu_a})}{4\pi} \left[1 + \frac{C_{S,V,T}^p}{C_{S,V,T}^e} R_p + \frac{C_{S,V,T}^n}{C_{S,V,T}^e} \left\langle \frac{Y_n(r)}{Y_e(r)} \right\rangle R_n \right]$$

$\left\langle \frac{Y_n(r)}{Y_e(r)} \right\rangle$ = average of the relative number densities along the neutrino trajectory



Potential Function $W(r)$



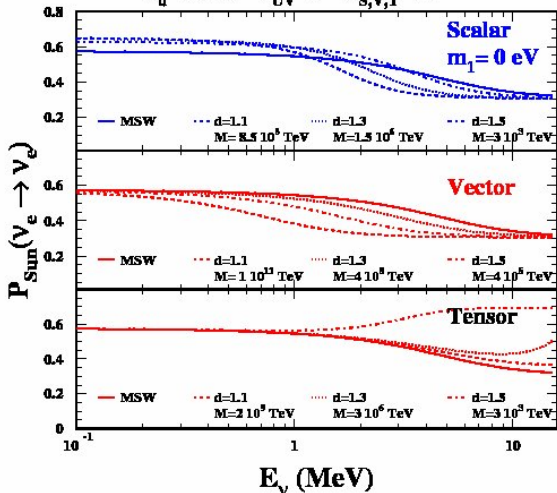
Function $W(r)$ due to the density of protons (or electrons) in the Sun as a function of the distance from the solar center in units of the solar radius, R_{\odot} , for various values of the dimension d and the mass scale M . We take $\Lambda_U = 1 \text{ TeV}$ and $d_{UV} = 3$. For comparison, we show the value of the $W(r)$ function for a Coulomb-type ($d = 1$) long-range force with range $\lambda = 0.1 R_{\odot}$ and with the same strength at the center of the Sun.

d acts like a kind of range of the potential



Survival Probability of Solar ν_e

$$\Lambda_u = 1 \text{ TeV} \quad d_{UV} = 3 \quad \alpha_{S,V,T} = 10^{-3}$$



Survival probability of ν_e in the Sun as a E_ν for scalar (upper panel), vector (middle panel) and tensor (lower panel) unparticle force. We have used: $\tan^2 \theta_{12} = 0.44$
 $\Delta m_{21}^2 = 7.9 \times 10^{-5} \text{ eV}^2$.

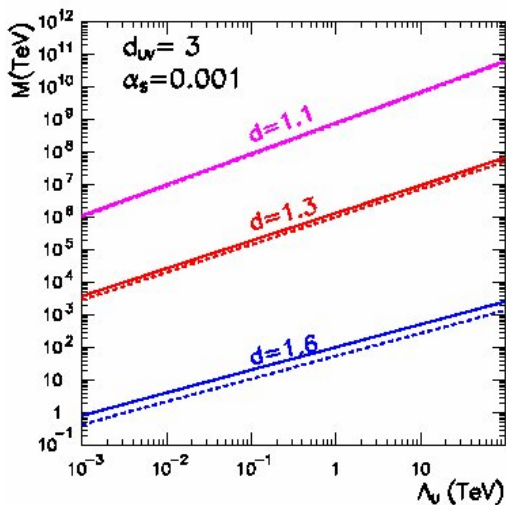


Analysis: Solar + KamLAND Data

- **Gallium Expts. (SAGE+GALLEX/GNO) - 2 points (rates)**
- **Chlorine Experiment - 1 point (rates)**
- **Super-Kamiokande - 44 points (zenith spectrum)**
- **SNO - 34 points (day-night spectrum)**
- **SNO - 38 points (rates+spectrum salt phase)**
- **KamLAND - 13 points (spectrum)**



Limits on Scalar Unparticle Forces



Bounds from the analysis of solar and KamLAND data on the fundamental parameters (Λ_U, M) for a scalar unparticle for $d = 1.1, 1.3, 1.6$ and $d_{UV} = 3$. The region below the curves is excluded. We have fixed $\alpha_S = 10^{-3}$.



Limits on Vector and Tensor Unparticle Forces

- For a given value of Λ_U at the same scale dimension d , bounds on M are ~ 100 times more stringent for vector unparticles
- For tensor unparticles the bounds on M will be $\sim 3/\sqrt{\Lambda_U/\text{TeV}}$ times those for the scalar case
- The bounds tend to get substantially relaxed as d increases
- So, if the low energy scale is of the other $\Lambda_U \sim \text{TeV}$, one cannot provide very significant constraints on vector ($d > 3$) and tensor ($d > 4$) unparticles



- **For a scalar unparticle, assuming *i.e.* $\alpha_s = 10^{-3}$, and $d_{UV} = 3$, $M > 8 \times 10^8$ TeV ($M > 7 \times 10^9$ TeV), for $d = 1.1$, if $\Lambda_u = 1$ TeV (10 TeV)**
- **Our bounds are stronger than the reach of present and future colliders**
- **Bounds are comparable to cosmological and astrophysical bounds**



Final Conclusions

Scalar Unparticle	$M > (\text{TeV})$			
	1 TeV		10 TeV	
Λ_U				
d	1.3	1.6	1.3	1.6
This work	1.3×10^6	100	9×10^6	500
BBN	3.2×10^5	5.8×10^3	4.7×10^6	1.2×10^6
Eötvös-type	1.9×10^6	3.5×10^3	1.3×10^7	1.6×10^4
Energy loss from stars	800	26	5.5×10^3	120
SN 1987A	430	55	3×10^3	260

Table: Limits on M from various sources testing for signals from scalar unparticle couplings to fermions. Here $d_{UV} = 3$ was used in deriving all bounds and $\alpha_s = 10^{-3}$ was used for our work



- Our bounds can be converted into constraints on universality violation of neutrino couplings to unparticles accessible in future colliders. For $M = \Lambda_u = 1$ TeV and $C_S^f = \mathcal{O}(1)$, they imply

$$\frac{C_S^{\nu_e} - C_S^{\nu_a}}{C_S^{\nu_e}} \leq 4.5 \times 10^{-38} - 1.5 \times 10^{-9} \quad d = 1.1 - 1.6$$

- It is more likely fermion couplings to unparticles that will be tested in future colliders will be flavor blind



Thank you!

