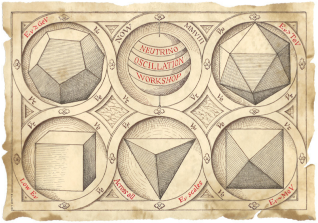


Unparticles and Solar Neutrinos

Renata Zukanovich Funchal

Universidade de São Paulo, Brazil

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

NOW 2008, Conca Specchiulla, Otranto, Italy
Sept. 11, 2008

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:

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

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

So below Λ_u unparticles emerge

$$\mathcal{O}_{UV} \to \mathcal{O}_{\rm U} \qquad \mathcal{L} \to \mathcal{L}_{\rm eff} = C_u \frac{\Lambda_u^{d_{\rm UV}-d}}{M^{d_{\rm UV}+d_{\rm SM}-4}} \, \mathcal{O}_{\rm SM} \, \mathcal{O}_{\rm U}$$

Unparticle Propagators

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

Scalar Unparticles ($d > 1$)

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

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)]

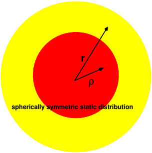
General Form satisfying the SM gauge symmetry

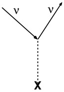
$$\mathcal{L}_f = -\frac{\lambda_S^f}{\Lambda_u^{d-1}}\,\bar{f}f\mathcal{O} - \frac{\lambda_V^f}{\Lambda_u^{d-1}}\,\bar{f}\gamma_\mu f\mathcal{O}^\mu - \frac{\lambda_T^f}{2\Lambda_u^d}\,\imath\,[\bar{f}\gamma_\mu\partial_\nu f - \partial_\mu\bar{f}\gamma_\nu f]\mathcal{O}^{\mu\nu}$$

where

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

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

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

Universal Long-Range Potential

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

n_f = number density of fermion f

R = radius of the distribution

Standard Neutrino Oscillation Explains Data Very Well

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}}$$

$c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

$\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2 **(MINOS)**

$\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2 **(KamLAND)**

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

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

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

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

flavor diagonal new couplings do not change hierarchy → 2ν factorization still holds as long as θ_{13} is small

Modified Neutrino Evolution in Matter

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

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

$$\nu_a = \cos\theta_{23}\ \nu_\mu + \sin\theta_{23}\ \nu_\tau \qquad V_{\rm CC}(r) = \sqrt{2}G_F n_e(r)$$

$$\mathbf{U}_{\theta_{12}} = \begin{pmatrix} \cos\theta_{21} & \sin\theta_{12}\\ -\sin\theta_{12} & \cos\theta_{12}\end{pmatrix}$$

Modified Neutrino Evolution in Matter

Scalar Unparticles

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

$$m_1 = 0 \qquad m_2 = \sqrt{\Delta m^2_{21}}$$

$$C^{\nu_a}_{S,V,T} = c^2_{23}\, C^{\nu_\mu}_{S,V,T} + s^2_{23}\, C^{\nu_\tau}_{S,V,T}$$

$$n_f(r) = n_e(r)\left[1 + \frac{C^p_{S,V,T}}{C^e_{S,V,T}} + \frac{C^n_{S,V,T}}{C^e_{S,V,T}}\frac{Y_n(r)}{Y_e(r)}\right]$$

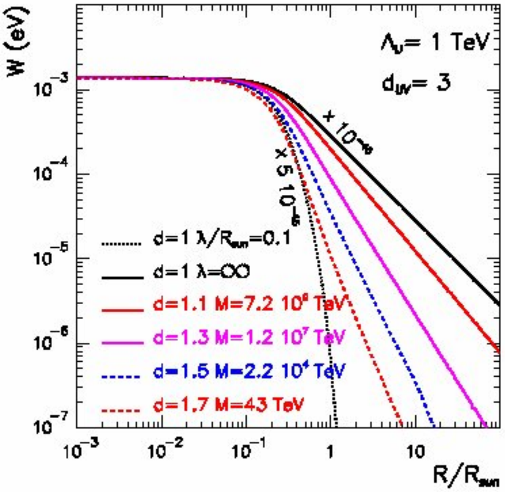
Effective Couplings

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

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

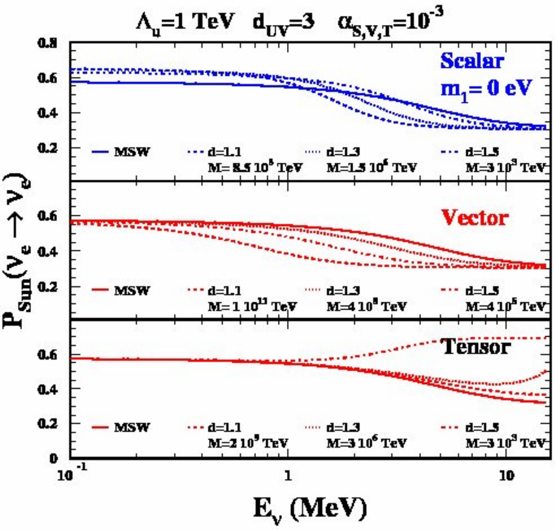
$\langle\frac{Y_n(r)}{Y_e(r)}\rangle =$ average of the relative number densities along the neutrino trajectory

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 $\Lambda_u = 1$ 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

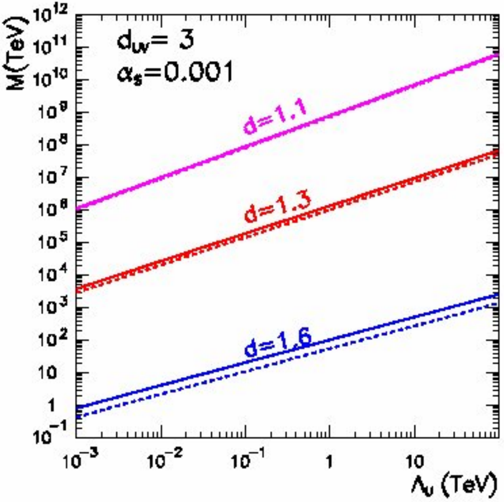


Survival probability of ν_e in the Sun as a E_ν for scalar (upper panel), vector (middle panel) and tensor (lower panel) unparticle force. We have used: $\tan^2\theta_{12} = 0.44$ $\Delta m^2_{21} = 7.9 \times 10^{-5}$ eV^2.

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 $\sim 3/\sqrt{\Lambda_u/\mathrm{TeV}}$ 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 $\Lambda_u \sim$ TeV, one cannot provide very significant constraints on vector ($d > 3$) and tensor ($d > 4$) unparticles

Final Conclusions

- **For a scalar unparticle, assuming *i.e.* $\alpha_s = 10^{-3}$, and $d_{\rm UV} = 3$, $M > 8 \times 10^8$ 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	$M >$ (TeV)			
Λ_u	1 TeV		10 TeV	
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 $d_{\rm UV} = 3$ was used in deriving all bounds and $\alpha_s = 10^{-3}$ was used for our work

Final Conclusions

- **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**

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

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

Thank you!