BBN, variation of G and constraints on unparticle long range forces

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Phys. Rev. D 79, 127702 (2009), arxiv: 0905.1852 [hep-ph]

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Outline

- Introduction to unparticles
- Long range forces from unparticles
- Variation of G and BBN
- Bounds on unparticles from gravity ISL violation
- Conclusions

Introduction

❖ Beyond the SM physics: introduced to solve some problems of the SM (SUSY, extra dimensions,...);

❖ LHC era: looking for clues for that new physics. But we can have surprises...

❖ Can we have any other viable (testable) alternative that we could look for?

Unparticles

Georgi, PRL 2007, PLB 2007

❖ Unparticles represent a new possibility for the physics of a **hidden sector** which couples to the SM only through higher dimensional operators;

❖ They are based on the idea of a sector which becomes **scale invariant** at low energies.

Un-particles ⟷ **Un-conventinal particles** associated with this sector

Introduction

❖The SM does is not scale invariant, but we know theories which are: N=4 Super Yang Mills theory, Conformal Field Theory,...

❖ Moreover, Banks-Zaks theory for the N massless vector quarks exhibits non-trivial scale invariance in the infrared for suitable combinations of flavors and colors. Banks & Zaks, NPB 1982

❖ There might exist several other candidates in a gauge theory as in the SUSY QCD. Fox et al, PRD 2007

❖ Can such a hidden sector have any effects on the low energy phenomena?

Unparticles

Georgi, PRL 2007, PLB 2007

❖ The very high-energy theory contains fields of the SM and the fields of a theory with a nontrivial IR fixed point (eg. ZB fields);

❖ Below the scale M_U there are nonrenormalizable couplings involving both SM and ZB fields supressed by powers of M_U

$$\frac{1}{M_U^{d_{UV}+n-4}} O_{UV}\, O_{SM}$$

Unparticles

Georgi, PRL 2007, PLB 2007

Effective field theory

SM particles ⟷ (heavy particle, M_U) ⟷ Hidden Sector BZ field

nontrivial IR fixed point

Integrating out the heavy particle, below the scale M_U

$$\frac{1}{M_U^{d_{UV}+n-4}} O_{UV}\, O_{SM}$$

It becomes scale invariant at low energy

Unparticle

M_{Pl}

M_U

Λ_U

SM

Λ_U is usually assumed to be of TeV scale.

Unparticles

❖ Below Λ_U, the hidden sector becomes scale invariant and the operator O_{UV} mutates into an unparticle operator O_U with noninteger scaling dimension d_u. The coupling of field operators can be generically written as

$$\frac{\Lambda_U^{d_{UV}-d_u}}{M_U^{d_{UV}+n-4}} O_U \, O_{SM}$$

❖ The operator O_U can be a scalar, a vector, a tensor or even a spinor.

❖ It was shown that phase space $d\Phi(d_u)$ for an unparticle operator of dimension d_u is the same as the phase space for $n=d_u$ massless invisible particles. Thus $d\Phi(d_u)$ is proportional to

$$A_{d_u} = \frac{16\pi^{5/2}}{(2\pi)^{2d_u}} \frac{\Gamma(d_u+1/2)}{\Gamma(d_u-1)\,\Gamma(2d_u)}$$

Unparticle with scale dimension d_u looks like d_u invisible massless particles.

Georgi, PRL 2007, PLB 2007

Unparticles

❖ Collider signatures and other phenomenological aspects have been investigated. Also astrophysical and cosmological constraints have been studied.

Cheung et al, PRL2007, PRD2007; Luo & Zhu, PLB 2008; Chen & Geng, PRD 2007; Ding & Yan, PRD 2007; Liao, PRD 2007; Aliev et al, PLB 2007, Li & Wei, PLB 2007, Lu et al, PRD 2007, Fox et al, PRD 2007; Greiner, PLB 2007, Chen & He, PRD 2007, Kikuchi and Okada, PLB 2008, Delgado et al, JHEP 2007, Anchordoqui & Goldberg, PLB 2008, Davoudiasl, PRL 2007, MCDonald, JCAP 2009, Hannestad et al, PRD 2007, Das, PRD 2007, Freitas & Wyler, JHEP 2007,...

❖ The exchange of unparticles

$$\frac{\Lambda_U^{d_{UV}-d_u}}{M_U^{d_{UV}+n-4}} O_U \, O_{SM}$$

Liao & Liu, PRL 2007;
Deshpande et al, PLB 2008;
Goldberg & Nath, PRL 2008

can give rise to **long range forces**, which deviate from the usual inverse square law due to the anomalous scaling dimension of the unparticle propagator

❖ Here we will investigate the deviations from the ISL due to **tensor** and **vector** particle exchange.

Long range forces from tensor unparticles

❖ If O_U is a **rank-two tensor** it could couple to the **stress-energy tensor** $T^{\mu\nu}$

$$\frac{1}{M_\star \Lambda_U^{d_u-1}} \sqrt{g}\, T_{\mu\nu} O_U^{\mu\nu}$$

$$M_\star = \Lambda_U \left(\frac{M_U}{\Lambda_U}\right)^{d_{UV}}$$

$$G_N = 6.7\times 10^{-39}\ GeV$$

$$M_{Pl} = 1.22\times 10^{19}\ GeV$$

❖ This interaction generates the **potential**

$$V_u(r) = -G_N \frac{m_1 m_2}{r}\left(\frac{R_G}{r}\right)^{2d_u-2}$$

Goldberg & Nath, PRL 2008

where the characteristic length scale for which the "ungravity" interactions become significant is defined to be

$$R_G = \frac{1}{\Lambda_U}\left(\frac{M_{Pl}}{M_\star}\right)^{\frac{1}{d_u-1}} C(d_u)^{\frac{1}{2d_u-2}}$$

$$C(d_u) = \frac{2}{\pi^{2d_u-1}} \frac{\Gamma(d_u+\frac{1}{2})\Gamma(d_u-\frac{1}{2})}{\Gamma(2d_u)}$$

Long range forces from tensor unparticles

The **"ungravitational" potential** is, as usual, obtained by taking the Fourier transform of the propagator in the static limit ($P^0=0$)

$$V_u = \frac{1}{M_\star^2 \Lambda_U^{2d_U-2}} \int \frac{d^3P}{(2\pi)^3} T_{\mu\nu}\, \Delta^{\mu\nu\alpha\beta}\left(P^0=0\right) T_{\alpha\beta}\, e^{iP.x}$$

The ungraviton propagator is

$$\Delta^{\mu\nu\alpha\beta}(P) = \int d^4x\, e^{iP.x} \langle 0 | T\left(O_U^{\mu\nu}(x) O_U^{\alpha\beta}(0)\right) | 0 \rangle$$

$$= \frac{A_{d_u}}{\sin(\pi d_u)} P^{\mu\nu\alpha\beta}\left(-P^2\right)^{d_u-2}$$

$$A_{d_u} = \frac{16\pi^{5/2}}{(2\pi)^{2d_u}} \frac{\Gamma\left(d_u+1/2\right)}{\Gamma\left(d_u-1\right)\Gamma\left(2d_u\right)}$$

with a projection operator of the form

$$P^{\mu\nu\alpha\beta}(P) \equiv \frac{1}{2}\left(P^{\mu\alpha}P^{\nu\beta} + P^{\mu\beta}P^{\nu\alpha} - P^{\mu\nu}P^{\alpha\beta}\right)$$

$$P^{\mu\nu} = -\eta^{\mu\nu} + \frac{P^\mu P^\nu}{P^2}$$

Goldberg & Nath, PRL 2008

Long range forces from vector unparticles

❖ Let us know consider a coupling between a vector unparticle and a baryonic (or leptonic) current

$$\frac{\lambda}{\Lambda_U^{d_u-1}} J_\mu O_U^\mu$$

❖ This gives

$$V_u(r) = \frac{\lambda^2 N_1 N_2 \tilde{C}(d_u)}{\Lambda_U^{2d_u-2}} \frac{1}{r^{2d_u-1}}$$

Deshpande et al, PLB 2008;

where $N_{1,2}$ are the total number of baryons of the two interacting objects and

$$\tilde{C}(d_u) = \frac{1}{2\pi^{2d_u}} \frac{\Gamma(d_u + \frac{1}{2})\Gamma(d_u - \frac{1}{2})}{\Gamma(2d_u)}$$

Long range forces from vector unparticles

❖ Combined with the gravitational potential we can write

$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 - \left(\frac{\tilde{R}_G}{r}\right)^{2d_u - 2}\right]$$

with

$$\tilde{R}_G = \frac{1}{\Lambda_U}\left(\frac{\lambda M_{Pl}}{u}\right)^{\frac{1}{d_u - 1}} \tilde{C}(d_u)^{\frac{1}{2d_u - 2}}$$

❖ In both cases we have a **potential** of the same form, the **vector** one being **repulsive** and the **tensor attractive**.

$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 \pm \left(\frac{R_G}{r}\right)^{2d_u - 2}\right]$$

Varying G

The modification of the gravitational potential can be seen as **a dependence of the gravitational coupling on *r***.

The force associated with the unparticle potential

$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 \pm \left(\frac{R_G}{r}\right)^{2d_u-2}\right]$$

is

$$\mathbf{F}(r) = -\nabla V(r) = -G(r)\frac{m_1 m_2}{r^2}\hat{\mathbf{r}}$$

with an **effective gravitational** coupling given by

$$G(r) = G_N\left[1 \pm (2d_u - 1)\left(\frac{R_G}{r}\right)^{2d_u-2}\right]$$

Varying G and BBN

❖ The production of light elements (^2H, ^3He, ^4He and ^7Li) in BBN is the result of the efficiency of the week reactions ($p + e \leftrightarrow n + \nu$ and related processes) and nuclear reactions (which build light nuclei from neutrons and protons) in the expanding Universe;

❖The value of the gravitational coupling determines the expansion rate of the Universe and thus the relevant time scales for the production of light elements;

❖ As a consequence, if we assume that the gravitational coupling at the time of BBN is different from its value today, this means that the light element abundances will be different with respect to the standard BBN predictions;

❖ BBN is a good probe of a possible variation of G, since is the earliest event in the history of the Universe for which we obtain solid and well established predictions.

Varying G and BBN

❖ Although the measurements are in agreement with the standard BBN scenario, there is still some room for the variation in the effective number of neutrinos or in the gravitational coupling ;

❖Given the large statistical and systematic errors of the measurements, the typical **constraints** on the variation of G are of the **order of a few percent**

$$-0.036 \leq \frac{\Delta G}{G} \equiv \left| \frac{G(r) - G_N}{G_N} \right| \leq 0.086$$

at 95% C.L.

Iocco et al, Phys. Rep. 2009

Varying G, BBN and unparticles

❖ We will investigate the possible **limits on the different energy** scales that can be derived using **the bounds on the variation of the gravitational coupling *G***

$$V(r) = -G_N \frac{m_1 m_2}{r}\left[1 \pm \left(\frac{R_G}{r}\right)^{2d_u-2}\right] \quad \Rightarrow \quad \left|\frac{\Delta G}{G}\right| = (2d_u - 1)\left(\frac{R_G}{r}\right)^{2d_u-2}$$

❖ First we need to estimate a typical **distance r** between **particles interacting** through this new force at the time of **BBN**

❖ The typical distance between the interacting particles should be smaller or of the same order of magnitude as their **mean free paths** λ_p and λ_n.

❖ It turns out that during this epoch neutrons and protons have mean free paths of the same order of magnitude

Bertolami & Nunes, PLB 1999
Applegate et al, PRD 1987

$$\boxed{\lambda_p \sim \lambda_n \sim \lambda = 1\,m}$$

Varying G, BBN and unparticles

❖ This can be easily estimated if we take into account the relevant stopping cross sections and the densities of the stopping particles

$$\lambda = \frac{m}{\rho\, \sigma}$$

$$\sigma_{pe} = 2\pi \int_{\theta_0}^{\pi} d\theta\,(1-\cos\theta)\,\frac{2\pi\alpha^2 m_e^2}{4k^4 \sin^4\left(\frac{\theta}{2}\right)}\left(1+\frac{k^2}{m_e^2}\cos^2\left(\frac{\theta}{2}\right)\right) \simeq 1.5\times 10^{-24}\, cm^2$$

$$\sigma_{np}(E) = \frac{\pi a_s^2}{(a_s k)^2 + (1-05 r_s a_s k^2)^2} + \frac{3\pi a_t^2}{(a_t k)^2 + (1-05 r_t a_t k^2)^2} \simeq 1.9\times 10^{-24}\, cm^2$$

$$\sigma_{ne} = 3\pi\left(\frac{\alpha\, K_{mag}}{m_n}\right)^2 = 8\times 10^{-31}\ \mathrm{cm}^2$$

$$\rho_p = 0.9\times 10^{-2}\, g\, cm^{-3}$$

$$\rho_n = 0.3\times 10^{-2}\, g\, cm^{-3}$$

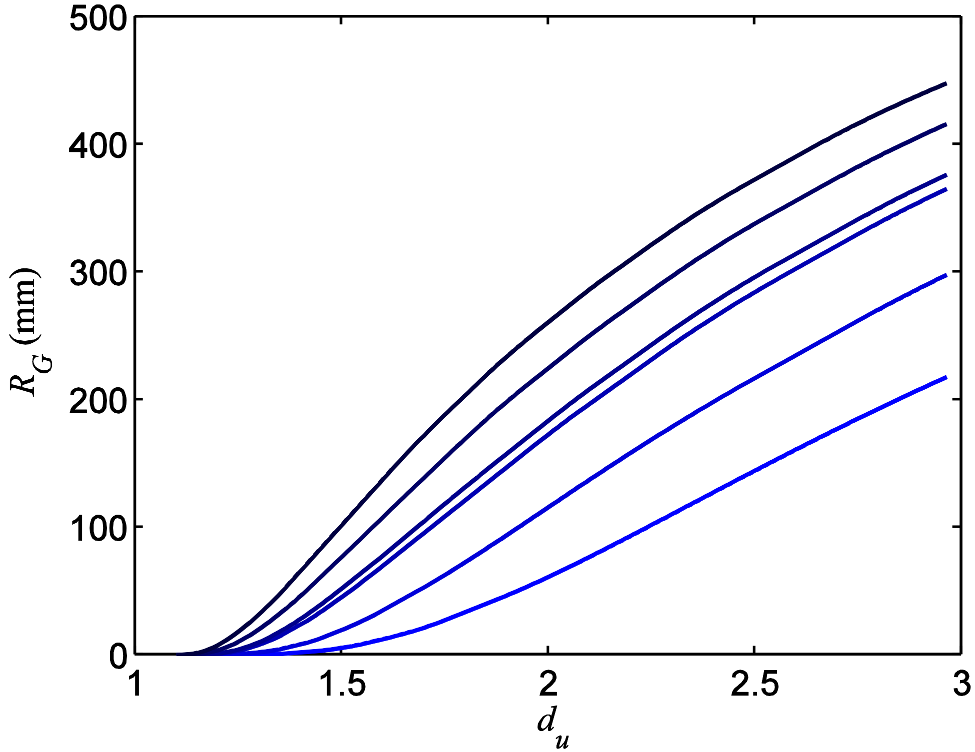
$$\rho_e = 0.5\times 10^{-5}\, g\, cm^{-3}$$

$$\lambda_p \sim \lambda_n \sim 1\, m$$

Bertolami & Nunes, PLB 1999
Applegate et al, PRD 1987
Wagoner et al, AJ 1967

Varying G, BBN and unparticles

Upper bound on R_G as function of d_u



$$\left|\frac{\Delta G}{G}\right| \leq 0.2,\ 0.15,\ 0.1,\ 0.086,\ 0.036,\ 0.01$$

(from top to bottom)

$$\left|\frac{\Delta G}{G}\right| = (2d_u - 1)\left(\frac{R_G}{r}\right)^{2d_u - 2}$$

$d_u, \Lambda_U, M_\star$ $\qquad$ d_u, Λ_U, λ

Gravity ISL violation laboratory searches

❖ Short distance modifications to the gravity ISL are constrained by **precision submilimiter tests**;

❖ The current experiments probe short distances up to around 0.05 mm and no significant deviation from the ISL is seen;

❖ **Torsion-balance searches** were used to constrain the **power-law modifications** of the form

Adelberger et al, PRL 2007

$$V_{12}(r) = -G_N \frac{m_1 m_2}{r}\left[1 + \beta_k \left(\frac{1\text{mm}}{r}\right)^{k-1}\right]$$

$$d_u = \frac{k+1}{2}$$

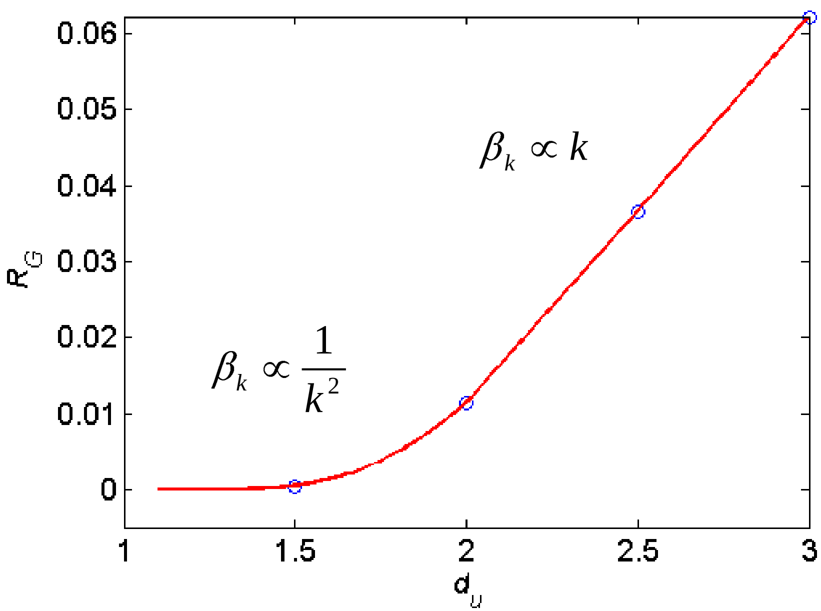
$$R_G = \beta_k^{1/(k-1)}$$

k	β_k
2	4.5×10^{-4}
3	1.3×10^{-4}
4	4.9×10^{-5}
5	1.5×10^{-5}

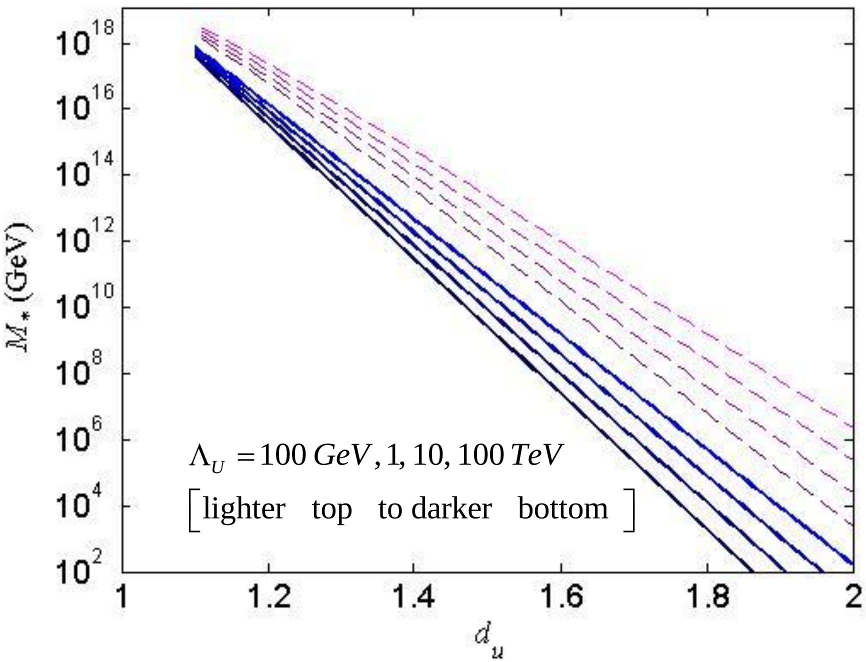
Gravity ISL violation laboratory searches

k	d_u	β_k	R_G
	1.1		3.7×10^{-10}
	1.25		4.3×10^{-6}
2	1.5	**4.5×10^{-4}**	**5.2×10^{-4}**
	1.75		3.8×10^{-3}
3	2	**1.3×10^{-4}**	**1.1×10^{-2}**
	2.25		2.4×10^{-2}
4	2.5	**4.9×10^{-5}**	**3.7×10^{-2}**
	2.75		5.4×10^{-2}
5	3	**1.5×10^{-5}**	**6.2×10^{-2}**

Interpolation

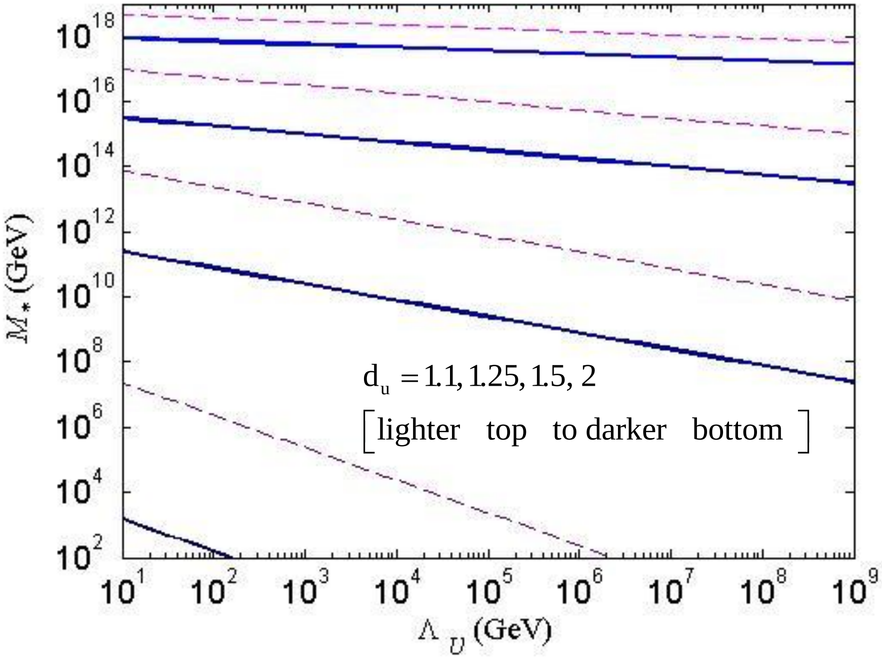


Constraints on tensor unparticles



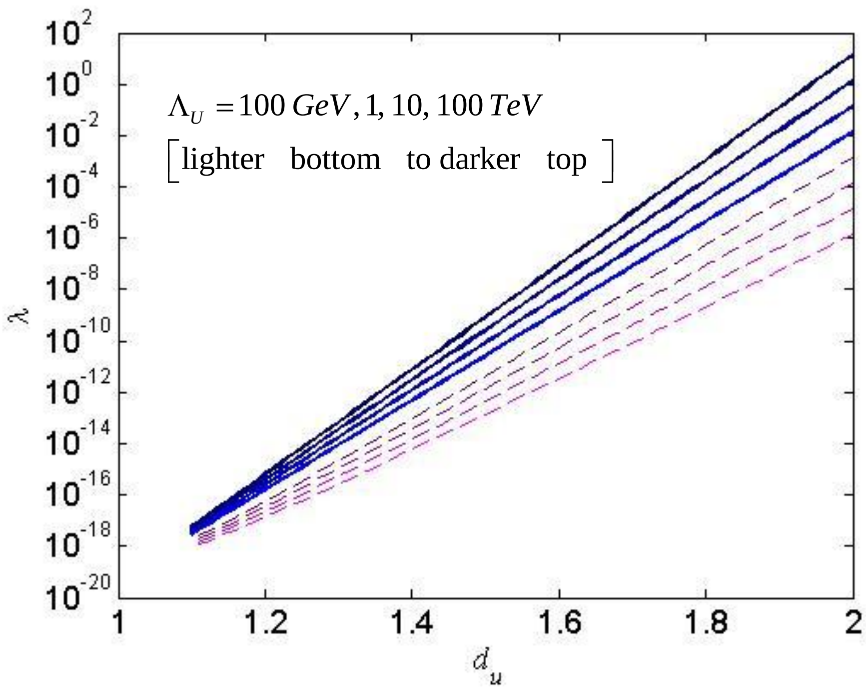
$$\frac{\Delta G}{G} = (2d_u - 1)\left(\frac{R_G}{r}\right)^{2d_u - 2} \leq 0.086$$

$$R_G = \frac{1}{\Lambda_U}\left(\frac{M_{Pl}}{M_\star}\right)^{\frac{1}{d_u - 1}} C(d_u)^{\frac{1}{2d_u - 2}}$$



Allowed region (above the curves) from
-- BBN bounds (solid lines)
-- ISL violation data (dashed lines).

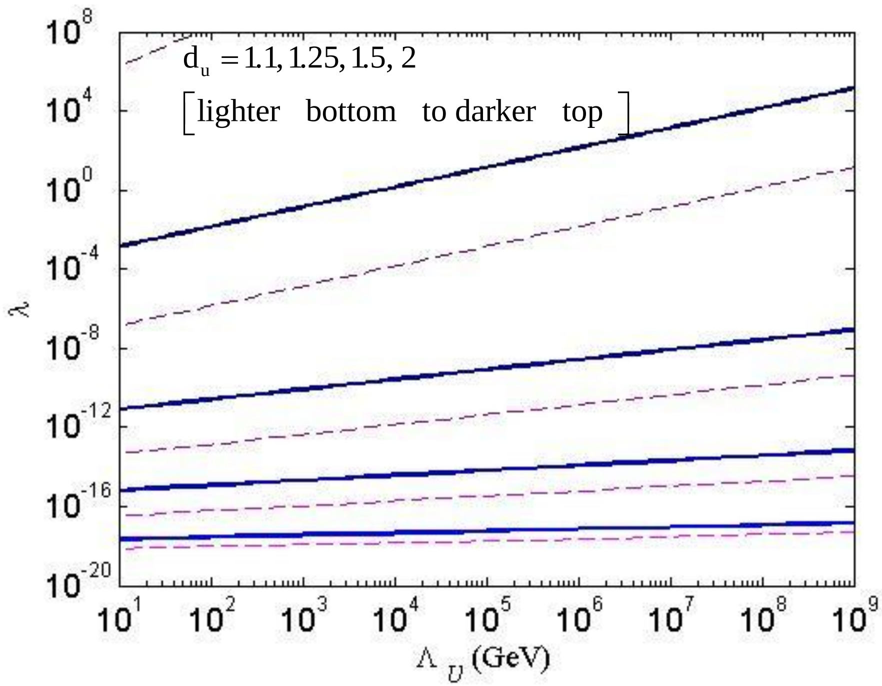
Constraints on vector unparticles



$$\frac{\Delta G}{G} = -(2d_u - 1)\left(\frac{\tilde{R}_G}{r}\right)^{2d_u-2} \geq -0.036$$

$$\tilde{R}_G = \frac{1}{\Lambda_U}\left(\frac{\lambda M_{Pl}}{u}\right)^{\frac{1}{d_u-1}} \tilde{C}(d_u)^{\frac{1}{2d_u-2}}$$

Allowed region (below the curves) from
-- BBN bounds (solid lines)
-- ISL violation data (dashed lines).



Constraints on unparticles

❖ We find that in both cases the BBN bounds are less stringent than the laboratory ones searching for violations of the ISL.

❖ For d_u close to unity, the bounds are comparable. The difference between BBN and laboratory bounds becomes more visible for larger values of d_u .

	d_u	1.1	2
BBN	M_* (GeV)	$\geq 6.04 \times 10^{17}$	≥ 15.9
	λ	$\leq 3.54 \times 10^{-18}$	$\leq 1.34 \times 10^{-1}$
Lab	M_* (GeV)	$\geq 2.83 \times 10^{18}$	$\geq 2.36 \times 10^{5}$
	λ	$\leq 1.17 \times 10^{-18}$	$\leq 1.40 \times 10^{-5}$

Bounds for $\Lambda_U = 1$ TeV

Conclusions

❖ Unparticle is a hiden (scale invariant) sector which couples to the SM particles only through higher dimensional operators;

❖Unparticle contains some peculiar properties which cause new effects in phenomenology.

❖ We have examined the importance of the existence of unparticles on BBN through the modification they introduce in the gravitatonal ISL.

❖ We found that in both cases the BBN bounds are less stringent than the laboratory ones searching for violations of the ISL. We remark however that our bounds concern unparticle effects on the early universe and, given the methodological differences, should be regarded as complementary to the laboratory ones.