Supergravity with broken Lorentz invariance: theory and phenomenological consequences

A. O. Marakulin

in collaboration with S. M. Sibiryakov

Institute for Nuclear Research of the Russian Academy of Sciences, 2018

Main sections

Main sections:

- Gravity with broken Lorentz invariance.
- Supersymmetry and broken Lorentz invariance.
- Linearized supergravity in terms of superfields.
- Lorentz violating supergravity theory.
- Results, phenomenology and outlook.

Motivation

Motivation for the Lorentz breaking:

- Extended models in theoretical physics
- New approaches to quantization of gravity (Horava, 2009; Blas, Pujolas, Sibiryakov, 2010)
- Phenomenology (Rubakov, 2006; Blas, Sibiryakov, 2011)

Motivation

Motivation for the supersymmetry in Lorentz breaking models (Bolokhov, Groot Nibbelink, Pospelov, 2005; Pujolas, Sibiryakov, 2011):

- Extended models in theoretical physics
- Phenomenology
- Mechanism for the emergent Lorentz invariance at low energies

Gravity with broken Lorentz invariance

Action for the Einstein-aether gravity (Jacobson, Mattingly, 2001):

$$S = S_{GR} + S_{æ},$$

Action for the aether:

$$S_{æ} = -\frac{1}{2}\int d^4x\sqrt{-g}\{c_1\left(\nabla_n u_m\right)^2 + c_2\left(\nabla_m u_m\right)^2 + \\ + c_3\nabla_n u_m \nabla^m u^n - c_4 u^r u^s \nabla_r u_m \nabla_s u^m\}$$

Aether norm:

$$u_m u^m = -1$$

Constraints on the theory parameters

PPN-parameters:

$$\alpha_1 = -8\frac{{c_3}^2 + c_1 c_4}{2c_1 - {c_1}^2 + {c_3}^2}$$

$$\alpha_2 = \frac{\alpha_1}{2} - \frac{(c_1 + 2c_3 - c_4)(2c_1 + 3c_2 + c_3 + c_4)}{(c_1 + c_2 + c_3)(2 - c_1 - c_4)}$$

Experimental constraints (observations in Solar System):

$$|\alpha_1| \lesssim 10^{-4}$$

$$|\alpha_2| \lesssim 4 \times 10^{-7}$$

From gravity to supergravity

- Ordinary gravity is compatible with Lorentz breaking, the formulation is parametrized by four constants.
- What about supergravity?
- The first step is to supersymmetrize aether.

Supersymmetry and broken Lorentz invariance

Supersymmetric aether (Pujolas, Sibiryakov, 2011):

$$U^m = u^m(x_L) + \sqrt{2}\theta\eta^m(x_L) + \theta^2 G^m(x_L)$$

Super-aether norm:

$$U_m U^m = -1$$

Super-aether action:

$$S = \int d^8 z f\left(U_m \bar{U}^m\right) + \int d^6 z \Lambda\left(U_m U^m + 1\right)$$

leads to the constraints:

$$c_2 = -c_3,$$

$$c_4 = 0.$$

Linearized supergravity in terms of superfields.

Non-minimal supergravity (e. g., Buchbinder, Kuzenko, 1998):

$$S_{SG} = \frac{1}{\varkappa^2}\int d^8z\Big[\frac{1}{4}\Big((\partial_k H_m)^2 - (\Delta_k H_m)^2\Big) + \frac{n+1}{2n}(\partial_m H^m)^2 + \\ + \frac{n+1}{2}(\Delta_m H^m)^2 - i\frac{3n+1}{2n}\partial_m H^m\left(\Gamma - \bar{\Gamma}\right) + \\ + \frac{3n+1}{2}\Delta_m H^m\left(\Gamma + \bar{\Gamma}\right) + \frac{9n^2-1}{8n}(\Gamma^2 + \bar{\Gamma}^2) + \frac{(3n+1)^2}{4n}\Gamma\bar{\Gamma}\Big].$$

Super-gauge transformations:

$$\delta H_{\alpha\dot{\alpha}} = \bar{D}_{\dot{\alpha}} L_\alpha - D_\alpha \bar{L}_{\dot{\alpha}}$$

$$\delta\Gamma = -\frac{n+1}{4(3n+1)}\bar{D}^2 D^\alpha L_\alpha + \frac{1}{4}\bar{D}^{\dot{\alpha}} D^2 \bar{L}_{\dot{\alpha}}$$

Super-aether transformations

$$U^a = w^a + V^a$$

Super-gauge transformations:

$$\delta V^a = w^b M_b{}^a$$

$$M_{ab} = \frac{1}{4}(\sigma_{ab})_\beta{}^\alpha D_\alpha \bar{D}^2 L^\beta + \frac{1}{4}(\bar{\sigma}_{ab})^{\dot{\alpha}}{}_{\dot{\beta}} \bar{D}^{\dot{\beta}} D^2 \bar{L}_{\dot{\alpha}}$$

Chirality constraint:

$$\bar{D}_{\dot{\alpha}} V^c = -w^b \Phi_{\dot{\alpha}b}{}^c \ .$$

Superconnection:

$$\Phi_{\dot{\alpha}bc} = -\frac{1}{4}(\sigma_{bc})_\alpha{}^\beta \bar{D}^2 D^\alpha H_{\beta\dot{\alpha}} - (\bar{\sigma}_{bc})^{\dot{\beta}}{}_{\dot{\alpha}} \bar{D}_{\dot{\beta}} \Gamma$$

Supergravity with broken Lorentz invariance

Lorentz-violating supergravity:

$$S = S_{SG} + \frac{C}{2\kappa^2} \int d^8 z \Big[V_a \bar{V}^a + i w^a w^b \partial_a H_b (\Gamma - \bar{\Gamma}) + w^a w^b \Delta_a H_b (\Gamma + \bar{\Gamma}) +$$
$$+ \frac{1}{4} (\Delta_k H_m \Delta^k H^m - \partial_k H_m \partial^k H^m - (\Delta_m H^m)^2 + (\partial_m H^m)^2) +$$
$$+ \frac{i}{4} \partial_m H^m (\Gamma - \bar{\Gamma}) + \frac{1}{4} \Delta_m H^m (\Gamma + \bar{\Gamma}) + \frac{3}{8} (\Gamma^2 + \bar{\Gamma}^2) \Big] ,$$

(Marakulin, Sibiryakov, 2016)

Super-aether expansion:

$$V_b|_{\text{bos}} = v_b(x_L) + \theta^2 G_b(x_L) + \theta\sigma^k\bar{\theta} f_{bk}(x_L)\,.$$

Bosonic part of the theory:

$$L_{bos} = \frac{1}{2\varkappa^2}\Big\{\frac{1}{4}h_{km}\Box h^{km} + \frac{1}{2}\partial^k h_{km}\partial_l h^{lm} - \frac{1}{2}\partial_k h^{km}\partial_m h +$$
$$+\frac{1}{4}\partial_m h\partial^m h - \partial_m\hat{v}^R_a\partial^m\hat{v}^{R,a} - \partial_m\hat{v}^I_a\partial^m\hat{v}^{I,a} + \sqrt{C}\,\hat{v}^{R,a}w^b\left(\partial_b\partial^k h_{ka} - \partial_a\partial^k h_{kb}\right) -$$
$$-\frac{C}{4}w^a w^b\left(\partial_a h_{mn} - \partial_m h_{na}\right)\left(\partial_b h^{mn} - \partial^m h^n{}_b\right) - \frac{C}{2}w^a w^b\partial_a\hat{v}^{I,m}\partial_b\hat{v}^I_m +$$
$$+\frac{C}{2}(\partial_a\hat{v}^{I,a})^2 - C w^b w^c\epsilon_{bkam}\partial^k\hat{v}^{R,a}\partial_c\hat{v}^{I,m} + O(C^{3/2})\Big\}\,.$$

(Marakulin, Sibiryakov, 2016)

Supergravity with broken Lorentz invariance

- Bosonic part of the theory is obtained. As a consequence, the number of free parameters is reduced from four down to one.
- Is there any alternative way to prove it?
- What about fermionic part?

Supercurrent supermultiplet

$$\mathcal{J}_m = \left(j_m^R, \Sigma_{m\alpha}, T_{mn}\right)$$

Supersymmetric transformations:

$$\delta_\xi \Sigma_{n\alpha} = 2\left(\sigma^n \bar{\xi}\right)_\alpha T_{mn} + \text{o. s. t.}$$

$$\delta_\xi T_{mn} = i\left(\xi \sigma_{mp} \partial^p \Sigma_n + \xi \sigma_{np} \partial^p \Sigma_m\right) + \text{h. c.}$$

First order interaction terms:

$$L_{int}^{(1)} = h^{mn} T_{mn} + \Psi^n \Sigma_n + \text{h. c.}$$

Supergravity with broken Lorentz invariance

$$T_{ab} = \frac{c_1 + c_3}{2} w_k \partial_k \partial_a v_b - \frac{c_1 + c_3}{2} w_a \Box v_b -$$
$$- \frac{c_1 - c_3}{2} w_a \partial_b \partial_k v_k - \frac{c_3}{2} g_{ab} w_k \partial_k \partial_p v_p + (a \leftrightarrow b) + \text{h. c.}$$

From the supercurrent supermultiplet:

$$c_1 = C; \; c_3 = 0$$

$$\Sigma_b = \frac{i}{2} C \left(w_b \partial_k \eta_k - w_k \partial_k \eta_b \right),$$

Fermionic part of the theory:

$$L_{ferm} \sim w_k \eta_b \Psi^{bk}$$

Results and outlook

- Lorentz violating linearized supergravity model is considered both in terms of superfields and at the component level.
- The theory parameters are:

$$c_1 = C; \; c_2 = c_3 = c_4 = 0.$$

- From the constraints on the PPN-parameters:

$$C \lesssim 10^{-7}. \tag{1}$$

- From the pulsar astronomy:

$$C < 1.6 \times 10^{-9}. \tag{2}$$

Results and outlook

- Dispersion relations for the small perturbations are obtained.
- Dispersion relation of the gravitational waves is

$$E^2 = (1 + C)\, p^2.$$

- From the GW astronomy:

$$C \lesssim 10^{-15}. \tag{3}$$

- The next step: non-linear extension (Grim, Müller, Wess, 1984).