





GRAVITINOS IN HIGH-SCALE SUPERSYMMETRIC MODELS

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Outline

Spin 3/2, potential problems
Gravitino sound speed in supergravity
Causality and positivity bounds
Alternative minimal models of inflation
Perspectives







1) Spin 3/2, potential problems

- In supergravity, the gravitino Ψ_{μ} becomes massive by absorbing the goldstino ~G

$$\Psi_{\mu} \begin{pmatrix} 3/2 \\ - \\ - \\ - \\ -3/2 \end{pmatrix} + G \begin{pmatrix} - \\ 1/2 \\ -1/2 \\ - \end{pmatrix} = \Psi_{\mu} \begin{pmatrix} 3/2 \\ 1/2 \\ -1/2 \\ -3/2 \end{pmatrix}$$



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The consistency of low-energy actions for the spin 3/2 Rarita-Schwinger field has a long history :

- 1941: Rarita-Schwinger action
- 1969: Velo-Zwanziger pointed out potential acausal propagation for a charged gravitino in an e.m. background
- 1977: Deser-Zumino proved that gravitino propagation in minimal supergravity is causal
- 2001: Deser-Waldron proved that gravitino propagation in gauged supergravities is causal
- 2021 Gravitino swampland conjecture, gravitino mass conjecture (Cribiori,Lust,Scalisi; Castellano,Font, Herraez,Ibanez, 2021)





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History strongly suggest that usual supergravities have no problems with gravitino propagation.

SUSY/SUGRA (linearly realized): nb. bosons = nb. fermions Nonlinear SUSY/SUGRA: nb. bosons \neq nb. fermions

Inflation models in standard SUGRA's have at least one complex scalar field (often several). Recently, simple nonlinear SUGRA models were constructed. More minimal inflationary models, fewer fields. (Antoniadis,E.D.,Ferrara&Sagnotti; Kallosh,Linde & coll, 2014)

Possible to construct minimal models with only: graviton, massive gravitino and inflaton (real scalar)







Simplest nonlinear SUSY's: constrained superfields (talk F. Quevedo).

Why non-linear SUSY? Anti D3 brane in KKLT, strings with broken/nonlinear SUSY, split SUSY...

(Rocek,78) introduced a constrained, nilpotent superfield

$$S^{2} = 0$$

whose solution is

no fundamental scalar

Superspace fermionic coordinate

$$S = \frac{GG}{2F_S} + \sqrt{2}\theta G + \theta^2 F_S$$

auxiliary field

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2) Gravitino sound speed in supergravity (SUGRA)

The talk deals with the « speed of sound » c_s of gravitino in SUGRA, in inflation and more general time-dependent sols Normally $0 < c_s \leq 1$

Recently, two potential problematic behaviours were discussed:

- $c_s = 0$ at particular points on the inflationary trajectory **Large (catastrophic) production of gravitinos** (Hasegawa, Terada et al, 2017; Kolb, Long, McDonough, 2021).
- . $c_s > 1$ acausal behaviour at particular points on the inflationary trajectory in specific SUGRA models







The sound speed C_s is defined from the dispersion relation

$$\omega^2 = c_s^2 \mathbf{k}^2 + a^2 m^2$$

The transverse spin 3/2 component in a FRW background has a standard dispersion relation with $c_s=1$

For the longitudinal component:









A general expression for longitudinal gravitino sound speed is







The explicit formula in SUGRA is

$$c_s^2 = 1 - \frac{4}{\left(|\dot{\varphi}|^2 + |F|^2\right)^2} \left\{ |\dot{\varphi}|^2 |F|^2 - |\dot{\varphi} \cdot F^*|^2 \right\}$$

where $F^i \equiv e^{K/2} K^{ij^*} D_{j^*} W^*$ in <u>standard</u> SUGRA,

and we used the compact notation $|\dot{\varphi}|^2 = \dot{\varphi}^i K_{ij^*} \dot{\varphi}^{j*}$, etc Obs: Cauchy-Schwarz inequality causality $c_s < 1$

respected in standard SUGRA's





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For the (large) majority of SUGRA models we investigated , we found no problems : $0 < c_s^i \leq 1$

Few models with problems: ex. « orthogonal constraint » for the inflaton multiplet Φ (Ferrara,Kallosh,Thaler)

$$S(\Phi - \overline{\Phi}) = 0$$

Only $Re \phi$ =inflaton is a dynamical degree of freedom. $Im \phi$, the inflatino ψ_{ϕ} and the auxiliary field F_{ϕ} are determined by the constraint.

In particular F_{ϕ} is a bilinear in fermions and does not appear in the scalar potential : $F^{\Phi} \neq e^{K/2} K^{\Phi i} D_{i^*} W^*$







Consequences:

- No inflatino \implies gravitino sound speed problem $c_s = 0$ can arise (model-dependent)
- Cauchy-Schwarz argument for $c_s \leq 1$ not valid. Examples (orthogonal constraint) with $c_s > 1$!

However, the UV origin of the orthogonal constraint is not clear (Dall'Agata, E.D., Farakos, 2006; Bonnefoy, Casagrande, E.D)

Potential pathological behaviour reminiscent of the swampland program ! (Vafa,Ooguri)







3) Causality and positivity bounds

(Q.Bonnefoy,G. Casagrande & E.D., [arXiv:2206.13451 [hep-th]])

- The potential acausal behaviour concerns the longitudinal component of the gravitino.
- Gravitino equivalence theorem: at high-energy, gravitino longitudinal component described by the goldstino, enhanced couplings to matter.







General lagrangian orthogonal constraint

$$K = h(\mathcal{A})\mathcal{B}^2 + S\bar{S}$$
$$W = f(\Phi)S + g(\Phi)$$

where $\Phi = \mathcal{A} + i\mathcal{B}$

Is the acausality found in SUGRA captured by the low-energy lagrangian of the goldstino coupled to matter, in the decoupling limit $M_P \rightarrow \infty$?







Yes ! Ex: The goldstino lagrangian contains a higherderivative operator of the form

$$\frac{1}{f(\varphi)^2} \left(h(\varphi) - \frac{2g'(\varphi)^2}{f(\varphi)^2} \right) \left(\bar{G}i\gamma^m \partial^n G \right) \, \partial_m \varphi \, \partial_n \varphi$$

Operator subject to **positivity constraints** from dispersion relation arguments, enforce

$$\frac{h(\varphi)}{2}f(\varphi)^2 \ge g'(\varphi)^2 \quad \Longleftrightarrow \quad c_s \le 1$$

The issue arises due to the « elimination » of the auxiliary field by the orthogonal constraint, no simple physical interpretation.







 Obs: SUGRA/inflation subluminality condition valid throughout the inflationary trajectory, positivity constraints valid only in the ground state

SUGRA condition is stronger.

 Causality condition of goldstino propagation in timedependent solutions of the goldstino action seems equivalent to the SUGRA constraint.





4) Alternative minimal models of inflation

Orthogonal constraint is « reducible » « irreducible » constraints (dall'Agata





(dall'Agata, E.D, Farakos, 2016)

 $S\bar{S}(\Phi-\bar{\Phi})=0,$ eliminates a scalar $S\bar{S}D_{lpha}\Phi=0,$ eliminates the fermion $S\bar{S}D^2\Phi=0,$ eliminates the auxiliary field







Simplest alternative with no potential acausality problems: use only

$$S\bar{S}\left(\Phi - \bar{\Phi}\right) = 0$$
$$S\bar{S}D_{\alpha}\Phi = 0$$

(Same) minimal spectrum for inflation : Graviton, massive gravitino, inflaton

Equivalent alternative (Bonnefoy,Casagrande,E.D): orthogonal constraint, but higher-derivative UV action







 $V = e^{K} \{ |D_{S}W|^{2} - 3|W|^{2} \} \qquad V = e^{K} \{ |D_{S}W|^{2} + |D_{\Phi}W|^{2} - 3|W|^{2} \}$

Ex: SUGRA inflation model, alternative constraints

 $V(\varphi) = M^4 [1 - e^{-a\varphi}]^2$ is the Starobinsky model





- Important to check and impose sound speed
- $0 < c_s \leq 1 \implies \text{gravitino swampland conjecture}$
- Most SUGRA models satisfy it, except peculiar models with orthogonal constraint (or similar).
- Subluminality constraints captured by goldstino SUSY lagrangians in $M_P \to \infty$ limit and positivity constraints, but SUGRA condition is stronger.
- Alternative minimal inflation models, no causality issues
- General interest: consistency constraints on nonlinear SUSY/SUGRA, strings with broken SUSY







THANK YOU !

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