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# SLOW AND SAFE GRAVITINOS

Based on :

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# Outline

1) Gravitino sound speed in supergravity
2) Complete eq. for the longitudinal gravitino
3) Specific models
   - models with orthogonal nilpotent superfields
4) Conclusions

# 1) Gravitino sound speed in supergravity

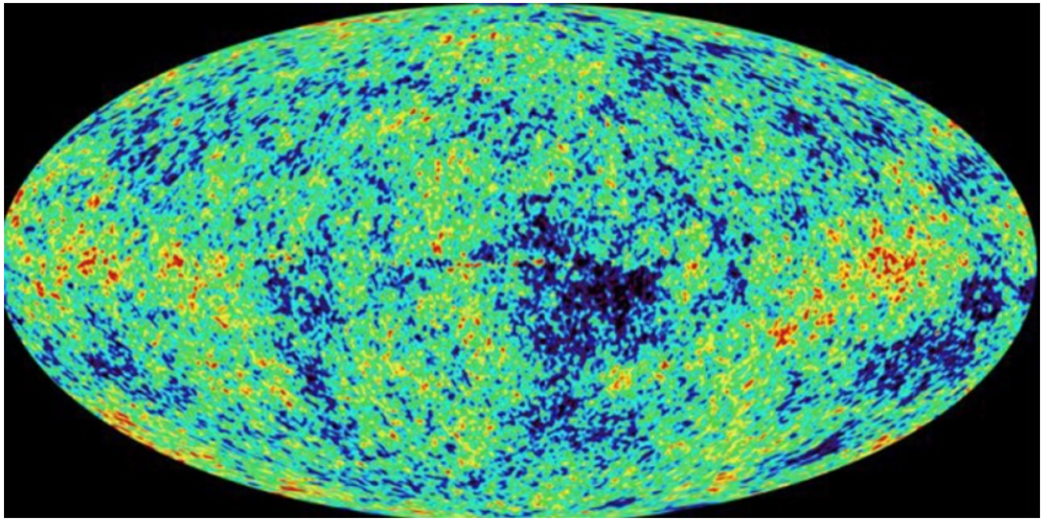
Supergravity = Supersymmetry + Gravity

It contains :

- gravity multiplet: Graviton $g_{\mu\nu}$ , gravitino $\psi_\mu$

- « matter » fields: chiral superfields $\Phi_i$ (complex) Scalars $\phi_i$ , Weyl Fermions $\psi_i$

# Why Supergravity for early cosmology ?



- Inflation with super-Planckian field variations needs an UV completion → String Theory
- Supersymmetry crucial ingredient in String Theory, supergravity its low-energy effective action

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- In supergravity, the gravitino $\Psi_\mu$ becomes massive by absorbing the goldstino G

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

and its mass is $$m_{3/2} = e^{\frac{K}{2}} |W|$$

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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 $c_S = 1$

$$(\gamma^0 \partial_0 + i \gamma^i k_i + a m_{3/2}) \Psi_{3/2, \mathbf{k}} = 0$$

scale factor

Obs: Supergravity solves potential pathological behaviour of Rarita-Schwinger spin 3/2 fields pointed out by Velo-Zwanziger in 1969.

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The longitudinal (goldstino) component satisfies a more involved equation

$$(\gamma^0\partial_0 - i\gamma^i k_i \frac{\alpha_1+\gamma^0\alpha_2}{\alpha} + a m_{3/2})\Psi_{1/2,\mathbf{k}} = 0$$

with $\alpha_1, \alpha_2, \alpha$ specific functions of scalar fields in SUGRA, with the sound speed depending generically on time

$$c_s^2 = \frac{|\alpha_1|^2+|\alpha_2|^2}{\alpha^2}$$

$c_s < 1$ ⟹ Slow gravitino (Benakli,Darmé, Oz, 2014)

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A general expression for longitudinal gravitino speed sound is

pressure — time-derivative

$$c_s^2 = \frac{\left(p - 3m_{3/2}^2\right)^2}{\left(\rho + 3m_{3/2}^2\right)^2} + \frac{4\dot{m}_{3/2}^2}{\left(\rho + 3m_{3/2}^2\right)^2}$$

energy density

$c_s = 0$ is possible if $m_{3/2}$ is const. and $p = 3m_{3/2}^2$

In this case, there would be a catastrophic production of gravitinos during inflation

(Hasegawa et al, 2017; Kolb, Long, McDonough, 2021).

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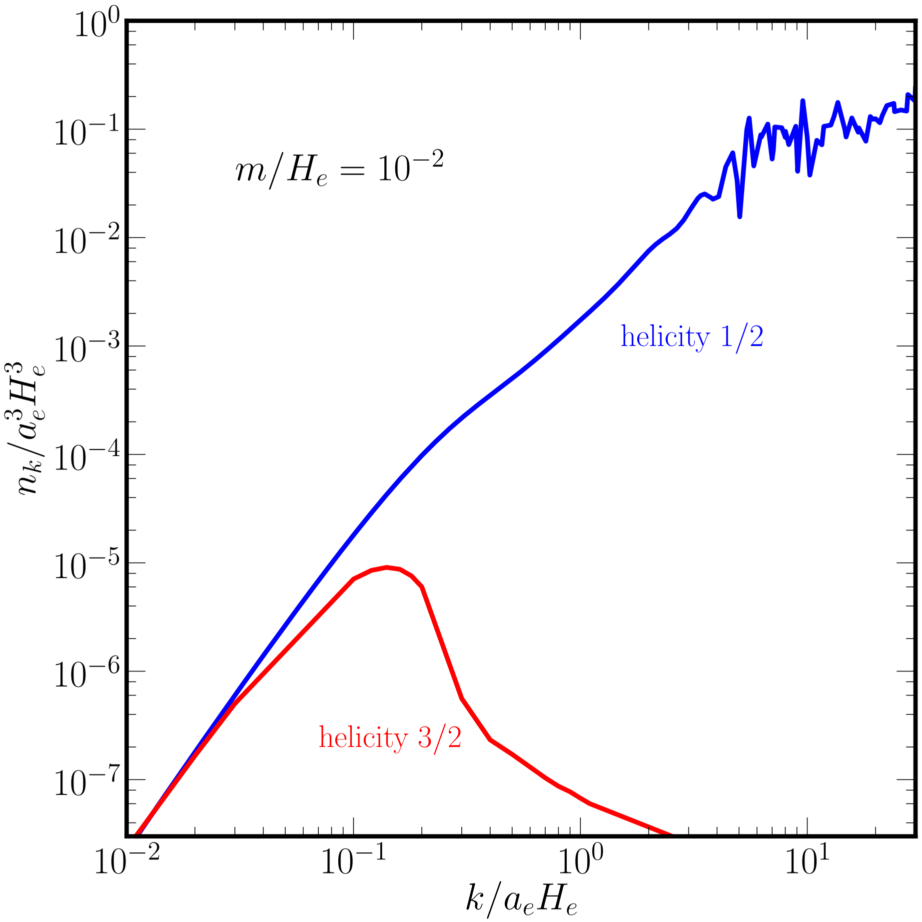
The problem was argued to arise for $m_{3/2} < H$ . If the problem is generic ⟹ potential issue for low-energy SUSY models.




(taken from Kolb et al, 2021)

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The explicit formula in SUGRA is (Kolb et al, 2021)

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

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

$$D_i W \equiv \frac{\partial W}{\partial \varphi^i} + \frac{\partial K}{\partial \varphi^i} W$$

and we used the compact notation $|\dot{\varphi}|^2 = \dot{\varphi}^i K_{ij^*} \dot{\varphi}^{j*}$ ,etc

Obs: Cauchy-Schwarz inequality → causality $c_s \leq 1$
respected in all standard SUGRA's

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## 2) Complete eqs. for the longitudinal gravitino

In an expanding background, the longitudinal gravitino $\theta$ is coupled to another fermion, the inflatino

$$\Upsilon = K_{ij^*} \left( \chi^i \partial_0 \varphi^{j^*} + \chi^{j^*} \partial_0 \varphi^i \right)$$

(Kallosh,Kofman,Linde, Van Proeyen,2000; Nilles,Peloso,Sorbo, 2001)

$\theta$ and $\Upsilon$ are coupled via

$$\left( \gamma^0 \partial_0 + i \gamma^i k_i N + M \right) X = 0 \quad , \quad X = \begin{pmatrix} \tilde{\theta} \\ \tilde{\Upsilon} \end{pmatrix}$$

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where the « sound speed matrix »

$$N = \begin{pmatrix} -\frac{\alpha_1}{\alpha} - \gamma^0 \frac{\alpha_2}{\alpha} & -\gamma^0 \Delta \\ -\gamma^0 \Delta & -\frac{\alpha_1}{\alpha} + \gamma^0 \frac{\alpha_2}{\alpha} \end{pmatrix}$$

with $\Delta = \sqrt{1 - c_s^2}$ , is now the key to the « slow gravitino » problem.

When $c_s = 0$ , then $N = \begin{pmatrix} 0 & -\gamma^0 \\ -\gamma^0 & 0 \end{pmatrix}$

is nonsingular, leading to a nonvanishing sound speed for the physical eigenstates.

(DGMOPV,2021; see also Antoniadis,Benakli, Ke, 2021 for a more general analysis)

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# 3) Specific models

For the (large) majority of SUGRA models we investigated , we found no problems, $c_s \neq 0$ :

- standard SUGRA models with two chiral superfields (inflaton+SUSY breaking): general statement

- SUGRA models with nilpotent SUSY breaking field

$$S^2 = 0$$

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The only models with problems we found is with the « orthogonal constraint » for the inflaton multiplet $\Phi$

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

Only $Re\ \phi$ is a dynamical degree of freedom.
$Im\ \phi$ , the inflatino $\psi_\phi$ and the auxiliary field $F_\phi$ are determined by the constraint.

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

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Consequences:

- There is no inflatino ⟹ $\Upsilon = 0$ , the gravitino sound speed problem can reappear (model-dependent)

- The Cauchy-Schwarz argument for $c_s \leq 1$ not valid ! We found examples with $c_s > 1$ !

On the other hand, the UV origin of the orthogonal constraint is not clear (dall'Agata,E.D.,Farakos, 2006)

⟹ Pathological behaviour reminiscent of the swampland program ! (Vafa 2005,Ooguri & Vafa…)

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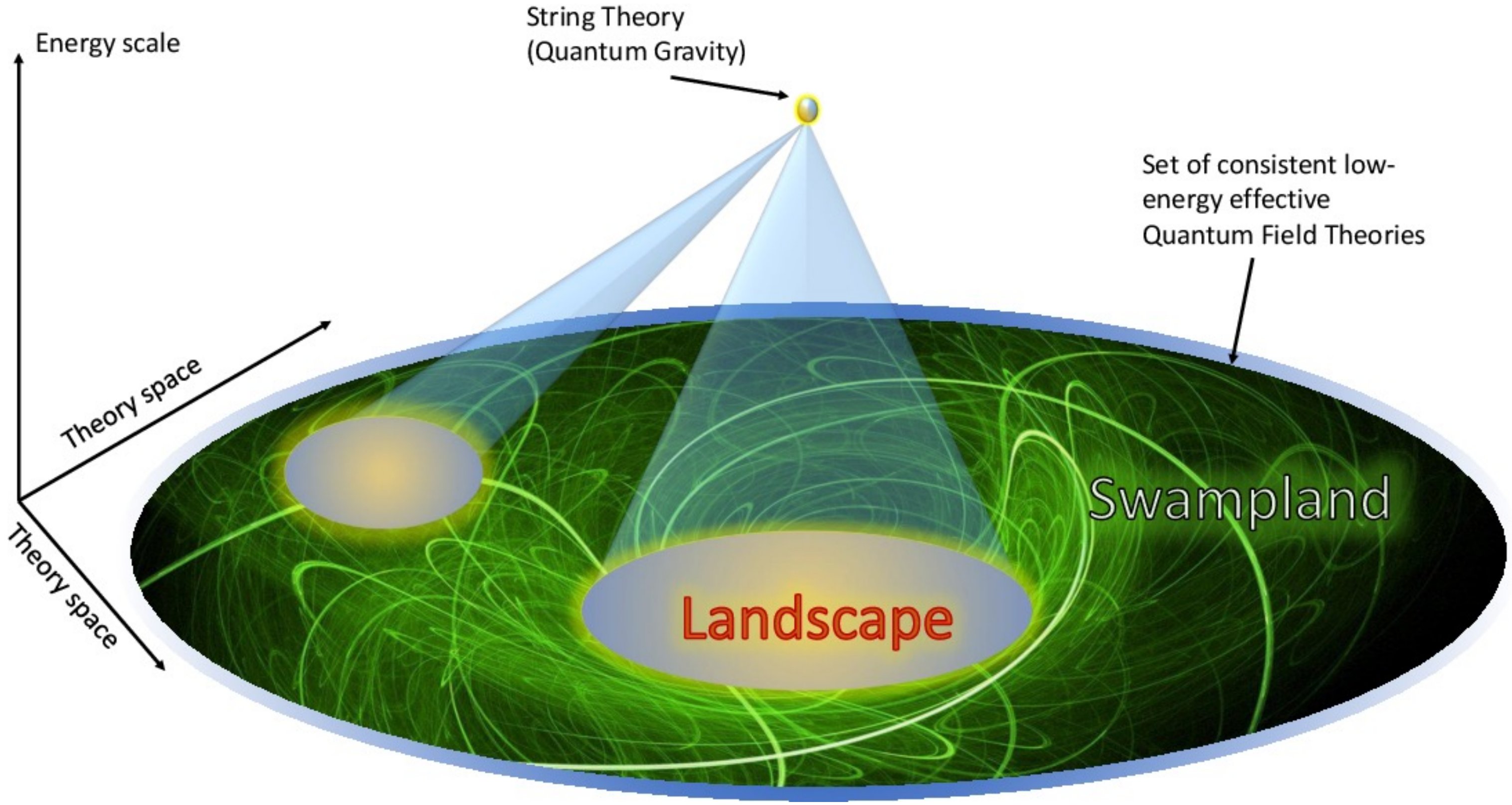


(taken from E. Palti, « The Swampland: Introduction and Review », Fortsch. Phys. **67**, no.6, 1900037 (2019) [arXiv:1903.06239 [hep-th]])

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Interesting to contemplate a « gravitino swampland conjecture »

« In all 4d effective field theories that are low-energy limits of quantum gravity, at all points
in moduli space and for all initial conditions, the sound speed of the gravitino(s) must be non-vanishing $c_s > 0$ »
(Kolb,Long,McDonough)

our refined version

« In all 4d effective field theories that are low- energy limits of quantum gravity, at all points
in moduli space and for all initial conditions, all eigenvalues of the sound speed matrix for fermions must be non-vanishing and subluminal $0 < c_s^i \leq 1$ »

# Conclusions

- Gravitino production constraints important for viability of SUGRA models.

- Very often, the inflatino is produced, alleviating the gravitino problem.

- Important to check and impose sound speed

$$0 < c_s \leq 1 \Longrightarrow$$ gravitino swampland conjecture

- We believe that most SUGRA models do satisfy it, except peculiar models with nonlinear supersymmetry (orthogonal constraint). Interesting to test other models.