Light Fields and Flat Directions from Nonlinear Sigma Models in Supergravity

John Kehayias

(In collaboration with Simeon Hellerman & Tsutomu Yanagida)

arXiv:1411.3720

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    - What about other light fields?
- **Inflation** may be at a high scale (*chaotic inflation*): how are higher dimensional operators suppressed?
    - There are also fundamental questions, like the *origin* of the inflaton potential and the large field values

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A NONLINEAR SIGMA MODEL COUPLED TO SUPERGRAVITY

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For our earlier work on sigma models for charge quantization and quantum number relations in nonlinear sigma models see arXiv:1309.0692, 1312.6889

TURN THAT PAPER SIDEWAYS

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- The structure of the supergravity potential is why it is difficult to construct models of chaotic inflation: the potential has an exponential factor of e^{K/M_p^2}
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  - Thus fields *cannot* have field values larger than M_p
- The solution from KYY [1] is to use a shift symmetry:

$$\Phi \to \Phi + iCM_p \qquad \Rightarrow \qquad K(\Phi + \Phi^*)$$

  - Then the exponential factor does not contain the imaginary part of the field and the potential is exactly flat

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- Kugo-Yanagida (KY [4]): we need to break any U(1) factors

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A MODEL CITIZEN

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- We use the non-compact model $U(3)/SU(2) \times U(1) \cong SU(3)/SU(2)$ [5]
  - The unbroken subgroup is gauged as the electroweak group of the SM
  - There is an SU(2) NGB doublet with the quantum numbers of **the Higgs**
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- There is an equivalence between this model and the previous Kähler potential [for $SU(3)/SU(2) \times U(1)$], and an explicit connection between the different ways of understanding NLSMs in supergravity

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    - This allows one to connect to a *linear* sigma model

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EAT YOUR VEGGIES

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- One known model is the Witten-Bagger [2] $\mathbb{CP}^1$ models (or other manifold)
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- Can there be a relation between these different ways of coupling a NLSM to supergravity?

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- One branch has a quantized radius, a U(1), and free field, while the other is non-compact/broken U(1) and a field which transforms under Kähler transformations

$$K = f_\phi^2 \left[\log\left(1 + \frac{\phi\phi^*}{f_\phi^2}\right) + \frac{1}{f_\phi}(Z + Z^*) \right] + \frac{a^2}{2} f_\phi^2 \left[\log\left(1 + \frac{\phi\phi^*}{f_\phi^2}\right) + \frac{1}{f_\phi}(Z + Z^*) \right]^2 + \frac{b}{2}(Z + Z^*)^2 + XX^*.$$

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- One branch explains the large field values, while the other explains the shift symmetry and extra field

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- Along the way we have understood and connected different proposals for coupling to supergravity: extra fields/extended supergravity multiplet, broken U(1)s, quasi-NGBs

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- We have a general model-building framework which simultaneously gives light fields and chaotic inflation
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- The *structure* of NLSMs and supergravity was crucial and with no additional ad hoc ingredients
- Along the way we have understood and connected different proposals for coupling to supergravity: extra fields/extended supergravity multiplet, broken U(1)s, quasi-NGBs
- Finally, we have conjectured a link to Witten-Bagger models and an origin for large field values (string theory realization?)

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Our work:

S. Hellerman, J. Kehayias, and T.T. Yanagida, "Charge quantization in the CP(1) non-linear σ-model," Phys. Lett. B728, 358–362 (2014), arXiv:1309.0692 [hep-th];

"Charge Quantization and the Standard Model from the CP^2 and CP^3 Nonlinear σ-Models," Phys. Lett. B731, 148–153 (2014), arXiv:1312.6889 [hep-th];

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THANK YOU!

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"Chaotic Inflation from Nonlinear Sigma Models in Supergravity," Phys. Lett. B742, 390-393 (2015), arXiv: 1411.3720 [hep-ph].

[1] M. Kawasaki, M. Yamaguchi, and T. Yanagida, "Natural chaotic inflation in supergravity," Phys. Rev. Lett. 85, 3572–3575 (2000), arXiv:hep-ph/0004243 [hep-ph]; "Natural chaotic inflation in supergravity and leptogenesis," Phys. Rev. D63, 103514 (2001), arXiv:hep-ph/0011104 [hep-ph].

[2] E. Witten and J. Bagger, "Quantization of Newton's Constant in Certain Supergravity Theories," Phys.Lett. B115, 202 (1982).

[3] Z. Komargodski and N. Seiberg, "Comments on Supercurrent Multiplets, Supersymmetric Field Theories and Supergravity," JHEP 1007, 017 (2010), arXiv:1002.2228 [hep-th].

[4] T. Kugo and T.T. Yanagida, "Coupling Supersymmetric Nonlinear Sigma Models to Supergravity," Prog.Theor.Phys. 124, 555–565 (2010), arXiv:1003.5985 [hep-th].

[5] T. Kugo, S. Uehara, and T. Yanagida, "Weak Bosons as Composite Gauge Fields of Hidden Symmetries," Phys.Lett. B147, 321 (1984); T. Goto and T. Yanagida, "Nonlinear Sigma Model Coupled to a Broken Supergravity," Prog.Theor. Phys. 83, 1076–1081 (1990).

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- With the matrix $\xi \equiv \begin{bmatrix} e^{\kappa Z} & 0 \\ 0 & e^{\kappa Z} \\ \phi_1 & \phi_2 \end{bmatrix}$, we can construct a

  U(3) invariant Kähler potential $K = -F(\det \xi^\dagger \xi)$

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- This is a function of $e^{2\kappa(Z+Z^\dagger)} + e^{\kappa(Z+Z^\dagger)}\left(|\phi_1|^2 + |\phi_2|^2\right)$
  or (after a field redefinition) $x = e^{2\kappa(Z+Z^\dagger)}\left(1 + \phi_i' \phi_i'^\dagger\right)$

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- Once we define $y \equiv \log x = \log\left(1 + \phi_i' \phi_i'^{\dagger}\right) + 2\kappa\left(Z + Z^{\dagger}\right)$ we see we reproduce the form of the Kähler potential in KS [3] for a $\mathbb{CP}^2 \cong SU(3)/SU(2) \times U(1)$ model

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- This is exactly the condition given in Kugo-Yanagida [4]

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- m must be small ($\sim 10^{-5} M_p$), but is technically natural
- What about the allowed term cX? Unless this is small, inflation will not end
- In this model this is not a problem, it is simply a *scaling* in ξ or ϕ

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