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Reflections on Supergravity

celebrating Pietro Fré

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A common thread

- Geometry, Symmetries and Supergravity
- First encounter in Erice (1981): highlighting the 'Torino approach' to supergravity !

Our only joint work

Class. Quantum Grav. **2** (1985) 133–145. Printed in Great Britain

Multiplet structure and spectra of $N = 2$ supersymmetric compactifications

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Abstract. We use properties of the Osp(2, 4) algebra to determine the spectra of $N = 2$ supersymmetric compactifications. The correspondence with the results obtained by harmonic expansions is established.

Supergravity

When supergravity was discovered in 1976
[Ferrara,Freedman,van Nieuwenhuizen(1976);Deser,Zumino(1976)]
it came with great expectations:

- **Perturbatively finite quantum gravity ?**
- **Unification of fundamental interactions ?**

How have these expectations worked out after 46 years?
→ enormous progress on many fronts but still no hint from experiment or observation whether and how Nature might make use of this theoretical framework.

In this talk: a personal (and perhaps unconventional) perspective on the present state of the art.

$N = 8$ supergravity: to be or not to be?

Goroff-Sagnotti counterterm (for pure gravity) does not admit superextension, but supersymmetric counterterm exists at three loops $\rightarrow$ no hope for an 'easy' proof of finiteness! Nevertheless:

We now know that $N = 8$ supergravity is more finite than expected: behaves like $N = 4$ super-Yang-Mills up to four loops [Bern,Carrasco,Dixon,Johansson, Roiban, PRL103(2009)081301]

- **However: recent computation at five loops shows divergence at $D = \frac{24}{5} = 2 + \frac{14}{L} < \frac{26}{5} = 4 + \frac{6}{L}$ (for $L = 5$)** [Bern,Carrasco,Chen,Edison,Johansson,Parra-Martinez,Roiban,PRD98(2018)086021]

Although no fully supersymmetric and fully $E_{7(7)}$ invariant counterterm known, finiteness would probably still require novel (so far hidden) symmetries...

Thus: question of finiteness is still up in the air !

Superstring Finiteness?

Superstring: $N=1(\frac{1}{2})$ conformal supergravity in $D=2$!

The string magic: quantum gravity path integral reduces to (sum over) *finite*-dimensional integrals:

$$\textbf{amplitude} = \sum_{g\geq 0} g_s^{2-2g} \int_{(\mathcal{S})\mathcal{M}_{g,n}} d\mu_{g,n} \left\langle V_1(P_1)\cdots V_n(P_n)\right\rangle_{\Sigma_g}$$

where

- $\langle\cdots\rangle$ = **CFT correlator on Riemann surface** Σ_g **of genus** g
- $(\mathcal{S})\mathcal{M}_{g,n}$ = **moduli or supermoduli space of** n**-punctured Riemann surface of genus** g **with suitable measure** $d\mu_{g,n}$**.**

No UV divergences, but in presence of tachyons there are IR divergences ≡ integral over $\mathcal{M}_{g,n}$ does not converge at cusp(s) ⇔ *supersymmetry is essential!*

Depending on your point of view question of finiteness remains unsettled, especially noting that supersymmetry must be broken.

Phenomenology: early (failed) attempts

1. **Focus on vector-like SU(3) $\times$ U(1) $\subset$ SO(8), with identifications SU(3) $\equiv$ SU(3)$_c$ and U(1) $\equiv$ U(1)$_{em}$** [Gell-Mann(1978)]
   $\rightarrow$ does not work: color sextets and octets

2. **Following a suggestion by Cremmer and Julia: elevate (chiral) R symmetry SU(8) to a *dynamical* symmetry $\rightarrow$ 3 $\times (\bar{\mathbf{5}} \oplus \mathbf{10})$ fermions of SU(5) GUT + much more** [Ellis,Gaillard,Zumino(1981)]

Prevailing view (since about 1982): $N=8$ supergravity is *obviously not* a good candidate for quantum gravity and the unification of all interactions!

Alternatively ($\rightarrow$ Pietro's work!)

- **Compactification of $D = 11$ SUGRA** [Freund,Rubin(1982)]
- **$\mathcal{M}_{pqr}$ spaces and $SU(3) \times SU(2) \times U(1)$ symmetry**
  [Castellani, D'Auria,Fré, NPB239(1984)610]
- **But: chiral fermions? Huge negative cosmological constant?**

$\rightarrow$ no obvious path to Standard Model physics !

The Heterotic String (1985)

"... Although much work remains to be done there seem to be no insuperable obstacles to deriving all of known physics from the $E_8 \times E_8$ heterotic string."

[Gross,Harvey,Martinec,Rohm, Nucl.Phys.B256(1985)253]

"We study candidate vacuum configurations in ten-dimensional O(32) and $E_8 \times E_8$ supergravity and superstring theory that have unbroken $N = 1$ supersymmetry in four dimensions. This condition *permits only a few possibilities*, all of which have vanishing cosmological constant..."

[Candelas,Horowitz,Strominger,Witten, NPB258(1985)46]

So the hope for an (almost) *unique* path from the $E_8 \times E_8$ heterotic string to the Standard Models of particle physics and cosmology, and thus to our four-dimensional real world, was clearly there....

A huge step away from uniqueness

Following [Narain(1985)]**:** ***Chiral Four-Dimensional Heterotic Strings from Selfdual Lattices*** [Lerche,Lüst,Schellekens, NPB287(1987)477]

$\rightarrow$ Proliferation of string vacua via lattice compactifications!

... all of which lead to different physics (gauge groups, particle multiplets, *etc.*) in 4D low energy world.

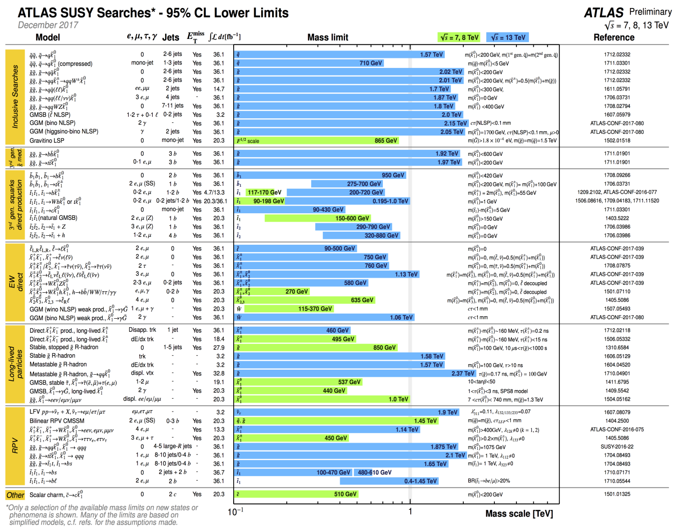
Meanwhile this number has gotten even larger: flux compactifications, orbi- and orientifolds, brane constructions, F theory,...

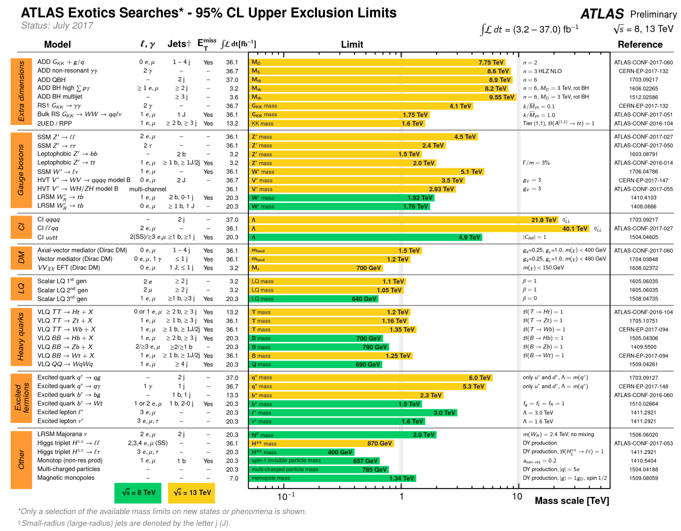
- ***Big Numbers in String Theory*** [A.Schellekens,1601.02462 [hep-th]]
- ***Scanning the skeleton of the 4D F-theory landscape*** [W.Taylor,Y.N.Wang, JHEP 01 (2018) 111] $\rightarrow 10^{272000}$ **vacua? Or even more?**

Current strategy: try to recover SM physics with some extension of MSSM, with $N = 1$ low energy supersymmetry motivated by hierarchy problem. But problems remain, in particular:

- **Extra ingredients (superpartners, additional multiplets,...).**
- **No fully satisfactory mechanism to break supersymmetry.**

(No) News from LHC





Exclusion limits, nothing but exclusion limits, ...

- No hints whatsoever of new physics
- RG Evolution of (slightly amended) SM couplings: no Landau poles, no instabilities of effective potential up to Planck scale

Conclusion (so far, at least): Standard Model could survive more or less *as is* all the way to Planck scale !

A strange coincidence?

$SO(8) \to SU(3)\times U(1)$ **breaking and 'family-color locking'**

$$
\begin{array}{rlll}
(u\,,\,c\,,\,t)_L & : & \mathbf{3}_c \times \bar{\mathbf{3}}_f \to \mathbf{8} \oplus \mathbf{1}\,, & +\frac{1}{2} = \frac{2}{3} - q \\
(\bar{u}\,,\,\bar{c}\,,\,\bar{t})_L & : & \bar{\mathbf{3}}_c \times \mathbf{3}_f \to \mathbf{8} \oplus \mathbf{1}\,, & -\frac{1}{2} = -\frac{2}{3} + q \\
(d\,,\,s\,,\,b)_L & : & \mathbf{3}_c \times \mathbf{3}_f \to \mathbf{6} \oplus \bar{\mathbf{3}}\,, & -\frac{1}{6} = -\frac{1}{3} + q \\
(\bar{d}\,,\,\bar{s}\,,\,\bar{b})_L & : & \bar{\mathbf{3}}_c \times \bar{\mathbf{3}}_f \to \bar{\mathbf{6}} \oplus \mathbf{3}\,, & +\frac{1}{6} = \frac{1}{3} - q \\
(e^-,\mu^-,\tau^-)_L & : & \mathbf{1}_c \times \mathbf{3}_f \to \mathbf{3}\,, & -\frac{5}{6} = -1 + q \\
(e^+,\mu^+,\tau^+)_L & : & \mathbf{1}_c \times \bar{\mathbf{3}}_f \to \bar{\mathbf{3}}\,, & +\frac{5}{6} = 1 - q \\
(\nu_e\,,\,\nu_\mu\,,\,\nu_\tau)_L & : & \mathbf{1}_c \times \bar{\mathbf{3}}_f \to \bar{\mathbf{3}}\,, & -\frac{1}{6} = 0 - q \\
(\bar{\nu}_e\,,\,\bar{\nu}_\mu\,,\,\bar{\nu}_\tau)_L & : & \mathbf{1}_c \times \mathbf{3}_f \to \mathbf{3}\,, & +\frac{1}{6} = 0 + q
\end{array}
$$

Realized at $SU(3)\times U(1)$ **stationary point with residual unbroken** $N=2$ **supersymmetry** [Warner,HN, NPB259(1985)412]

Supergravity and Standard Model assignments agree if spurion charge is chosen as $q = \frac{1}{6}$ [Gell-Mann (1983)]

Fixing the U(1) mismatch

[Meissner,HN: Phys.Rev.D91(2015)065029]

Spurion charge shift can be realised as $\exp(\frac{1}{6}\omega\mathcal{I})$ **with**

$$\mathcal{I} = \frac{1}{2}\big(T\wedge\mathbf{1}\wedge\mathbf{1} + \mathbf{1}\wedge T\wedge\mathbf{1} + \mathbf{1}\wedge\mathbf{1}\wedge T + T\wedge T\wedge T\big) \;\Rightarrow\; \mathcal{I}^2 = -\mathbf{1}$$

acting on 56 fermions χ^{ijk} **in** $\mathbf{8}\wedge\mathbf{8}\wedge\mathbf{8}$ **of SU(8), with**

$$T = \begin{pmatrix} 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} , \qquad T^2 = -\mathbf{1}$$

However: $\mathcal{I}$ ***not*** **in SU(8)** $\equiv K(\mathrm{E}_7)$ $\Rightarrow$ **mismatch can *not* be fixed *within*** $N=8$ **supergravity** $\rightarrow$ **requires going all the way to** $\mathrm{K}(\mathrm{E}_{10})$ **(and thus** E_{10} **!)** [Kleinschmidt,HN: PLB747(2015)]

Idea: $N=8$ **supergravity not quite but 'almost' right...**

Curious Gravitinos

Gravitinos are the telltale signature of supergravity!

Under $\mathbf{SU(3)}_c \times \mathbf{U(1)}_{em}$ gravitinos transform as

$$\left(\mathbf{3}_c\,,\,\frac{1}{3}\right) \oplus \left(\bar{\mathbf{3}}_c\,,\,-\frac{1}{3}\right) \oplus \left(\mathbf{1}_c\,,\,\frac{2}{3}\right) \oplus \left(\mathbf{1}_c\,,\,-\frac{2}{3}\right)$$

Unusual features: [K.Meissner,HN:PRD100(2019)035001]

- **Spurion shift of electric charges must be included**
- **strong and electromagnetic interactions**
  $\rightarrow$ very different from $N=1$ MSSM gravitinos!
- **stable against decay into SM matter because of peculiar quantum numbers $\Rightarrow$ (superheavy) Dark Matter candidates?**
- **Possibly interesting (real physics!) applications: UHECRs and seeds for primordial black holes?**

Explaining UHECRs?

[K.Meissner, HN: JCAP1909(2019)041]

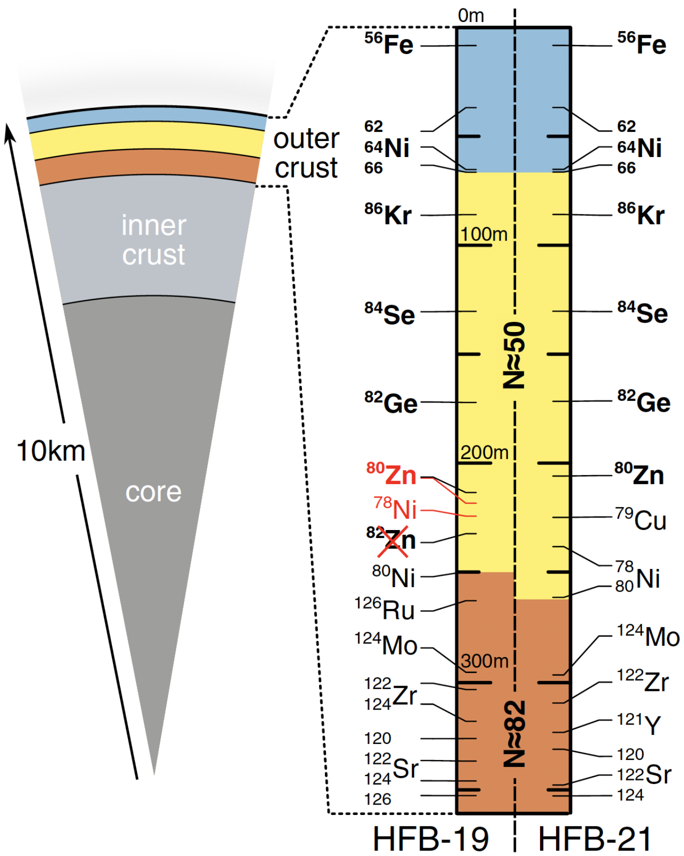
New mechanism: **color triplet gravitinos could explain observed UHECR events via gravitino-antigravitino annihilation in the 'skin' of neutron stars, provided**

- **Gravitinos (or 'gravimesons') get absorbed into stars ...**
- **... and get 'compressed' in neutron stars so as to enable them to annihilate in appreciable rates**

New features:

- **Annihilation of Planck mass particles into 10^6 (mostly hadronic) particles $\rightarrow 10^{-6} \times 10^{18}$ GeV $\sim 10^{21}$ eV per ejectum**
- **Ejection from 'skin' of neutron star could explain observed dominant appearance of ions towards very highest energies**
- **with some 'reasonable' assumptions calculated event rates come close to the ones observed at Pierre Auger Observatory (in Argentina) $\sim$ one UHECR event per month and per 3000 km^2.**

Hints of supergravity from neutron stars?



[Diagram from: R.N.Wolf et al., PRL110(2013)041101]

Outlook

- Supergravity is a beautiful theoretical framework – it is hard to believe that Nature would not make use of it (cf. Yang-Mills theory in the 50ies.)
- But ultimate framework not clear: IIA, IIB and heterotic superstrings not the most symmetric (maximally extended) worldsheet theories
  $\rightarrow$ is supermembrane theory a better ansatz?

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- Supergravity is a beautiful theoretical framework – it is hard to believe that Nature would not make use of it (cf. Yang-Mills theory in the 50ies.)
- But ultimate framework not clear: IIA, IIB and heterotic superstrings not the most symmetric (maximally extended) worldsheet theories
  $\rightarrow$ is supermembrane theory a better ansatz?

Caro Pietro: grazie per i tanti anni di amicizia e di inspirazione – ti auguro ogni bene per il futuro!