

A possible title?

THE ANOMALY STRUCTURE OF  
REGULARIZED SUPERGRAVITY

D. Butter and MKG, Phys. Rev. D91 (2015) 2, 025015, arXiv:1410.6192 [hep-th]

or

HOW TO CANCEL THE ANOMALIES

In (slow) progress

or

BRST INVARIANT PV REGULARIZATION OF  
SUSY YANG-MILLS AND SUGRA

MKG, Pramana 78 (2012) 875-890, arXiv:1109.3221 [hep-th]

BZ: “Everybody said you gave a good talk, but they didn’t understand it.”

BETTER

ADVENTURES IN PHYSICS WITH BRUNO



LAPP-TH-15  
Ref. TH-2841-CERN  
April 1, 1980

ATTEMPTS AT SUPERUNIFICATION\*)

John Ellis,  
CERN, Geneva, Switzerland,

Mary K. Gaillard,  
LAPP, Annecy-le-Vieux, France,

Luciano Maiani,  
CERN, Geneva, Switzerland, and University of Rome,

Bruno Zumino,  
CERN, Geneva, Switzerland.

$N = 8$  SUGRA = T.O.E.? finite?

Gauged version:  $O(8)$  gauge symmetry  $\not\cong SU(3) \otimes SU(2) \otimes U(1)$

56 spin- $\frac{1}{2}$  states  $\not\cong$  all SM quarks & leptons

$\implies$  Some SM particles are composite

Murray Gell-Mann, 1979

Ungauged version:  $E(7, 7) \ni SU(8)$  global symmetry:

conjecture:  $SU(8)$  gauge symmetry dynamically generated

E. Cremmer & B. Julia, 1978, 1979

Example:  $CP^{n-1} \ni U(1)$  global symmetry in 2-d:

dynamically realized  $U(1)$  gauge symmetry with composite gauge boson

A. d'Adda, P. Di Vecchia, M. Lüscher, 1979

EGMZ: ALL SM particles composite

Using “Veltman’s theorem”: (lunch in Annecy)

Effective low energy theory must be renormalizable (anomaly free), found

★  $SU(5)$  unique GUT group

★ 3 generations of quarks and leptons

+ real reps  $\ni$  Higgs for breaking  $SU(5) \rightarrow SM \rightarrow SU_c(3) \otimes U(1)$

J. R. Ellis, MKG and B. Zumino, “A Grand Unified Theory Obtained from Broken Supergravity,” Phys. Lett. B **94**, 343 (1980). (Dedicated to Jaques Prentki on 60th birthday)

JRE, MKG and BZ, “Superunification,” Acta Phys. Polon. B **13**, 253 (1982).

Symmetry completion EGMZ: Particle spectrum represents SUSY &  $SU(8)$ .  
Need reps of full symmetry of SUGRA.

MKG, “Bound State Spectra In Extended Supergravity Theories,” in Proceedings of the 1982 Summer Seminar on Applications of Group Theory in Physics and Mathematical Physics, Lectures in Applied Mathematics **21**, 95 (1985).

Particular (reducible) rep of  $E(7, 7)$

2nd Shelter Island Conference, 1983

BZ: “expansion” vs “decontraction” of group (MKG vs MG-M & Y. Ne’eman)

+ CBA onslaught

General treatment of  $U(1, 1) \ni U(1)$  of  $N = 4$  SUGRA

JRE, MKG, M. Günaydin and BZ, Nucl. Phys. B **224**, 427 (1983).

Some unintended consequences

# 1. 1980 Harvard Loeb lectures: 4th on EGMZ

Howard Georgi had two students:

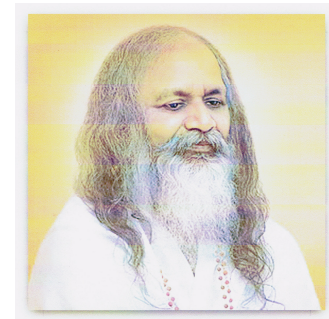
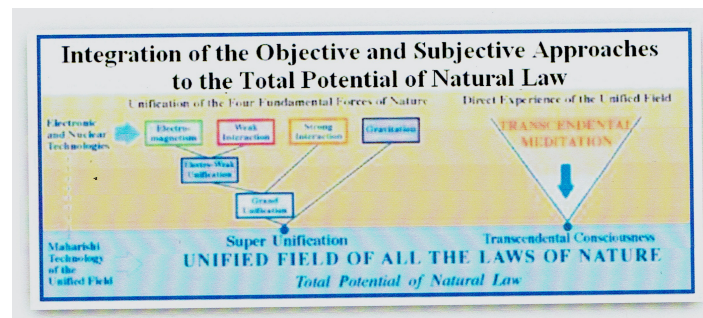
Lawrence Hall & John Hagelin (dating my cousin)

Dinner with JH and Holly TM & TP

JH xeroxed all my transparencies

Shortly thereafter **POSTER APPEARS**

## QUALITIES OF THE UNIFIED FIELD LOCATED IN THE LAGRANGIAN OF THE UNIFIED FIELD



Original **swallowed by strings?** had full  $N = 8$  Lagrangian + spectrum (not JH)

#2. 1996 White House council: 3 questions (that I remember)  
so as not to embarrass President Clinton ?!

★ Did I have a nanny problem?

“no” became “yes”

★ In 1993 I had written a letter to newspapers in support of SSC (125 women particle physicists; originally sent to women members of Congress (Year of the Woman) + Energy Secretary Hazel O’Leary).

Stand by my letter. SSC should have been built

★ Haim Harari wrote in a Scientific American article on composite models: described EGMZ as “ambitious”, but “like other composite models... has serious flaws”

We no longer believe in the model ourselves

### # 3. An important result for physics!

MKG and BZ, “Duality Rotations for Interacting Fields,” Nucl. Phys. B **193**, 221 (1981).

“On the occasion of his 60th birthday, we wish to dedicate this paper to Andrei Sakharov, whose work in gravitational and particle physics has been a great inspiration to us.

MKG & BZ, “Self-duality in nonlinear electromagnetism,” Lect. Notes Phys. **509**, 121 (1998)  
[hep-th/9705226]

MKG (typist) & BZ, “Nonlinear electromagnetic self-duality and Legendre transformations,” in Duality and Supersymmetric Theories, D. Olive and P. West, Eds, (Cambridge University Press, 1999), p. 33. [hep-th/9712103].

Applications in string theory and black holes; c.f. Sergio Ferrara, BZ, their postdocs and students.

Renata Kallosh: “Noether-Gaillard-Zumino current” used in her attempt to prove N=8 SUGRA finite. Come full swing?

Original motivation: Can  $SU(8)$  gauge symmetry be dynamically generated?  
 or Can there be massless vectors  $\sim SU(8)$  adjoint?

Not if corresponding conserved current invariant under all local symmetries

S. Weinberg & E. Witten, 1980

To address this: constructed most general (linear in  $F^2$ ) Lagrangian with electromagnetic duality:  $E \leftrightarrow H \quad F \leftrightarrow \tilde{F}$

Symmetry of EOM's, not Lagrangian

E.g. Free em field:  $L = \frac{1}{2}(E^2 - H^2) = -\frac{1}{4}F^2 = +\frac{1}{4}\tilde{F}^2$  not invariant

But  $F_{\mu\nu}^a = \partial_\mu \mathcal{A}_\nu^a - \partial_\nu \mathcal{A}_\mu^a \implies \partial^\mu \tilde{F}_{\mu\nu}^a = 0$ , and, defining  $G_{\mu\nu}^a$  by

$\tilde{G}_{\mu\nu}^a = 2\partial L/\partial F^{a\mu\nu}$  ( $\rightarrow -F_{\mu\nu}^a$  for free fields)  $\implies \partial^\mu \tilde{G}_{\mu\nu}^a = 0$  from EOM for  $A_\mu^a$

Invariance under EOM's (including matter) requires

$$\delta \begin{pmatrix} F \\ G \end{pmatrix} = X \begin{pmatrix} F \\ G \end{pmatrix}, \quad X = X^*$$

$$X = \begin{pmatrix} A & B \\ C & D \end{pmatrix}, \quad C = C^T, \quad B = B^T, \quad D = -A^T$$

$X$  rep of  $Sp(2n, R)$  for  $n$  fields  $F^a$ ,  $a = 1, \dots, n$



- ★ Found form of  $\delta\mathcal{L}$  under duality transformation
- ★ Found general form of Lagrangian
- ★ Scalars valued on coset space  $Sp(2n, R)/[U(n) = \text{maximal compact subgroup}]$ , or subgroup thereof, e.g.  $E(7, 7)/SU(8)$  in  $N = 8$  SUGRA
- ★ Found conserved currents (NGZ current).

Not invariant under local transformations:

$$\mathcal{A} \rightarrow \mathcal{A} + \partial\lambda, \quad \mathcal{B} \rightarrow \mathcal{B} + \partial\lambda' \quad \text{where } G_{\mu\nu} = \partial_\mu\mathcal{B}_\nu - \partial_\nu\mathcal{B}_\mu$$

evades Weinberg-Witten

But  $Q = \int d^3x J_0 =$  generator of  $E(7, 7)$  is invariant

Lot's of other applications

Viewpoint of EGMZ at time:

no evidence of SUSY partners; scale of SUSY breaking high

^

Still

Maybe rethink?

MKG, L. J. Hall, BZ, F. del Aguila, J. Polchinski and G. G. Ross, “Light Scalars in  $N = 1$  Locally Supersymmetric Theories,” Phys. Lett. B **122**, 355 (1983). Or

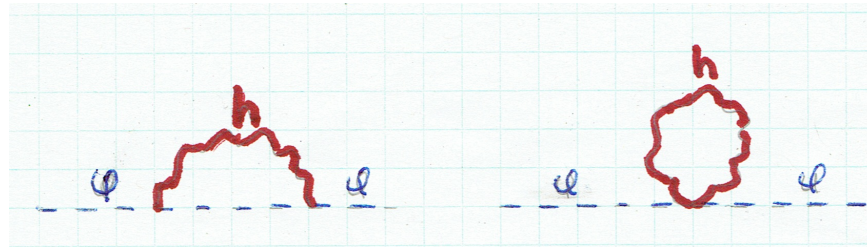
Mary K and the seven dwarfs

P. Binétruy

JP to MKG, LBL theory common room: Minimal gravity coupling to scalars

$$\mathcal{L}(h, \phi) = \frac{1}{2} \sum_{i=1}^n g^{\mu\nu} \partial_\mu \phi^i \partial_\nu \phi^i \implies$$

$\implies m_0 \rightarrow \infty \quad \forall$  scalars, e.g. GWS Higgs

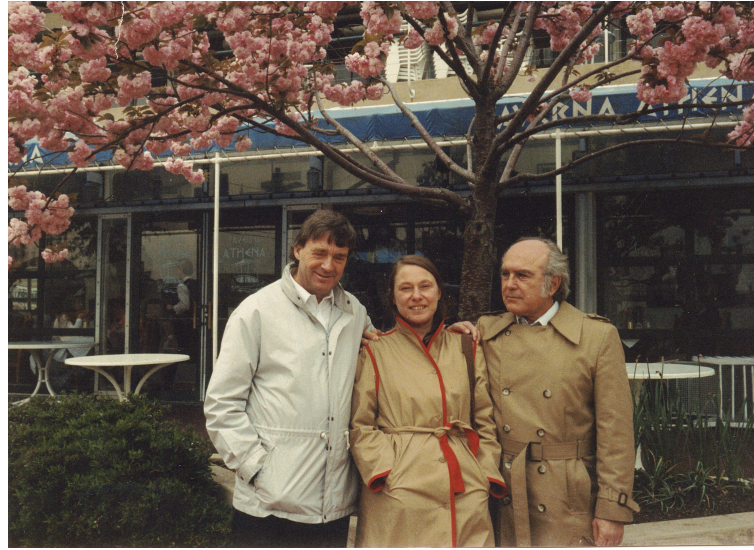


ANS:  $\mathcal{L}(h, \phi)$  invariant under  $SO(n)$  up to other couplings

Let  $\langle \phi_1 \rangle \neq 0$ :  $SO(n) \rightarrow SO(n - 1)$  left with  $n - 1$  Goldstone bosons.

An office in Aspen: “Dwarfs” generalized to SUGRA: in general  $m_0 \sim m_{\frac{3}{2}}$ .

Can suppress masses of scalars that are GB’s of SUSY-breaking sector  $\implies$   
much larger  $m_{\frac{3}{2}}$  allowed



Baltimore, April 1988

January 10-11 2005 Symposium in Honor of Julius Wess  
on the Occasion of his 70th Birthday

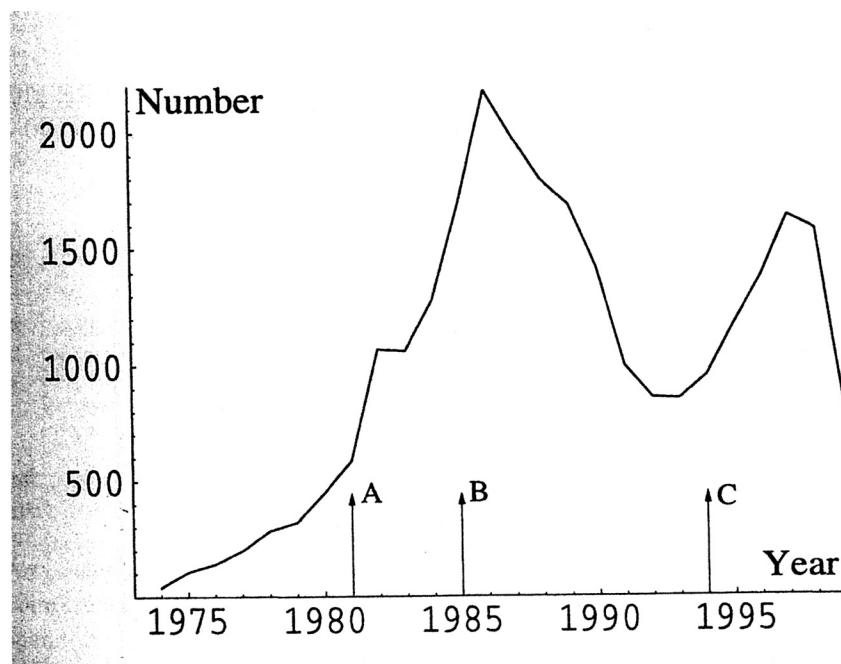
November 6-7 2008 Memorial Conference in Honor of Julius Wess

Supersymmetry and superstring phenomenology

MKG & BZ, The European Physics Journal C (2009) 59: 313–221, arXiv:0805.3726

Memorial volume in honor of Julius Wess

★ Early history of SUSY in physics and math



		↑	↑	↑		↑			↑
Golfand	Volkov								Seiberg
&	&			WZ	Witten	Candelas et al.			&
Likhtman	Akulov								Witten

# of papers found in Spires under “topic supersymmetry”

“prehistory” (including 2-d SUSY) = pre WZ 1974: M. Shifman, Golfand Memorial Volume

- ★ ABC's of SM & MSSM:  $f \rightarrow \tilde{f}, g \rightarrow \tilde{g}, H \rightarrow \tilde{H} \times 2$
- ★ Rudiments of string landscape heterotic  $E_8^2$  example with CY compactification à la Candelas et al. orbifolds
- ★ SUSY and dark matter
- ★ Hidden sector needed for SSB: no  $m_{\tilde{q}} < m_u$  Dimopoulos & Georgi
- ★ SUSY breaking example: gaugino condensation with Kähler stabilization of dilaton P. Binétruy, MKG & Y-Y Wu + students
- ★ Measured soft parameters (at LHC??) + RGE probe high scale physics e.g. M. Peskin review

Ended on optimistic note re SUSY at LHC Enthusiastically shared by Julius

But hedged our bets!



Lawrence Hall of Science, September, 2013



Graduation, May 23, 2014

Winter & Spring 1982: Bruno lectures on SUSY & SUGRA

Attended by grad students, UCB faculty, LBNL staff

Lecture notes preliminary version available at

<http://www-theory.lbl.gov/ZuminoSUSYnotes.pdf>

<http://www-theory.lbl.gov/ZuminoSUGRAnotes.pdf>