Three-forms, and Axions: String and Particle Physics Applications

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Fayet Fest

ENS, Paris, December 2016

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Of course:

One of the fathers
of supersymmetry

Many crucial insights...

Spontaneous symmetry breaking in SUSY....

Supersymmetry breaking......

R-parity

N=2

Fayet-Iliopoulos terms......

SUSY phenomenology......

Light dark matter

ultra light U(1)’s.....

What some of us had to study by 1980...

PHYSICS REPORT (Section C of Physics Letters) 32, No. 5 (1977) 249–334. NORTH-HOLLAND PUBLISHING COMPANY

SUPERSYMMETRY

P. FAYET* and S. FERRARA**

Laboratoire de Physique Théorique de l'Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France

Received 2 July 1976

Contents:

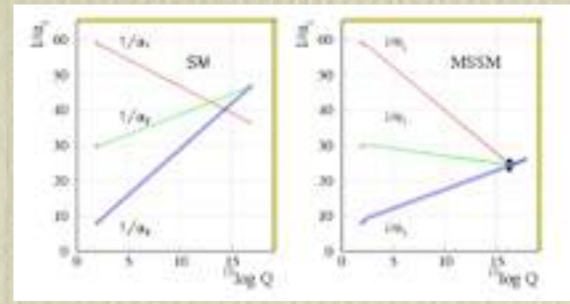
Abstract:

Supersymmetry transformations turn bosons into fermions and conversely. We discuss the algebraic aspects of the new structure, its role in relativistic quantum field theory and its possible applications to particle physics.

Suddenly 1981-1984 SUSY becomes popular !!

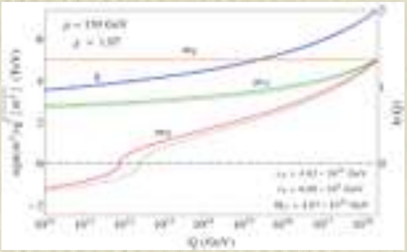
Emphasis on hierarchy problem

Gauge coupling unification



Coupling to supergravity induces soft terms: mSUGRA, CMSSM

Radiative SU(2)xU(1) breaking



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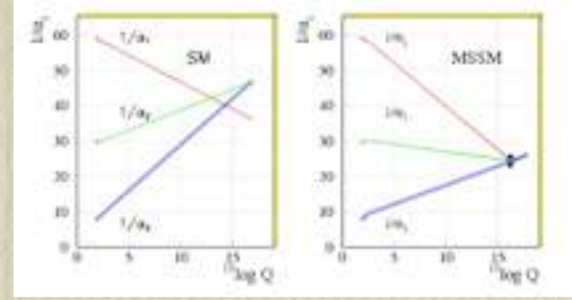

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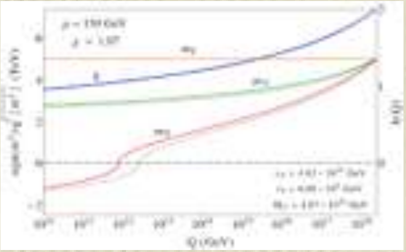


Still Pierre remains the father of the SUSY SM!

Later on, working in string theory, the inspiration of Pierre's work has been constant:

Two examples:

- Fayet-Iliopoulos terms in string-theory: important role in string compactification and D-brane physics and geometry

- R-parity appearing as a discrete gauge symmetry in string compactifications

I am going to talk about discrete shift symmetries:

$$\phi \rightarrow \phi + f$$

.....apparently unrelated to SUSY....

...we will see are related to SUSY auxiliary fields from the point of view of string theory ....

Three-forms, and Axions: String and Particle Physics Applications

Nima's argument for SUSY:

Poincaré in 4 dimensions:

$$Spin : 0, \ \boxed{1/2, \ 1}, \ 3/2, \ 2$$

Fermions and Gauge bosons

Nima's argument for SUSY:

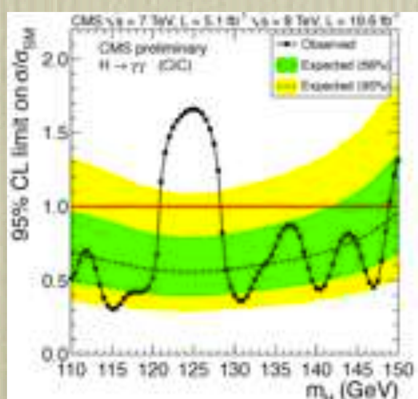
$$Spin: 0,\ \boxed{1/2,\ 1},\ 3/2,\ \boxed{2}$$

Gravity is there

Nima's argument for SUSY:

$$Spin:\ \boxed{0,}\ \boxed{1/2,\ \ 1},\ 3/2,\ \boxed{2}$$

Higgs found!!



Nima's argument for SUSY:

$$Spin : 0,\ 1/2,\ 1,\ 3/2,\ 2$$

SUSY must exist!!

Somewhat analogous:

Bosons:

$$Parity(+)\ \ :\ \ \phi\ ,\ \ g_{\mu\nu}$$

Higgs Gravity

$$Parity(-)\ \ :\ \ C_0\ ,\ C^{\mu},\ C^{\mu\nu}$$

Axions Gauge Axions

Somewhat analogous:

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Axions Gauge Axions

Usually ignored because it does not propagate but:

Gives shift invariant masses to axions

$$F_4 \ = \ dC_3$$

Contributes to c.c.:

Somewhat analogous:

Bosons:

$$Parity(+) \ : \ \phi \ , \ g_{\mu\nu}$$

Higgs Gravity

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Axions Gauge Axions

Usually ignored because it does not propagate but:

Gives shift invariant masses to axions

$$F_4 = dC_3$$

Contributes to c.c.: $\longrightarrow$ Landscape must exist !!

Summary

- The physics of Minkowski 3-forms

- Minkowski 3-forms in String Theory

- Applications:
    - String Inflation
    - Relaxion
    - Higgs mass landscape

The physics of Minkowski 3-forms

Bosonic action of a 3-form field in 4d:

$$S = -\int d^4x \sqrt{-g} \frac{1}{48} F_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma}$$

Eqs. of motion: $F_{\mu\nu\rho\sigma} = f_0 \epsilon_{\mu\nu\rho\sigma}$ f_0 is constant

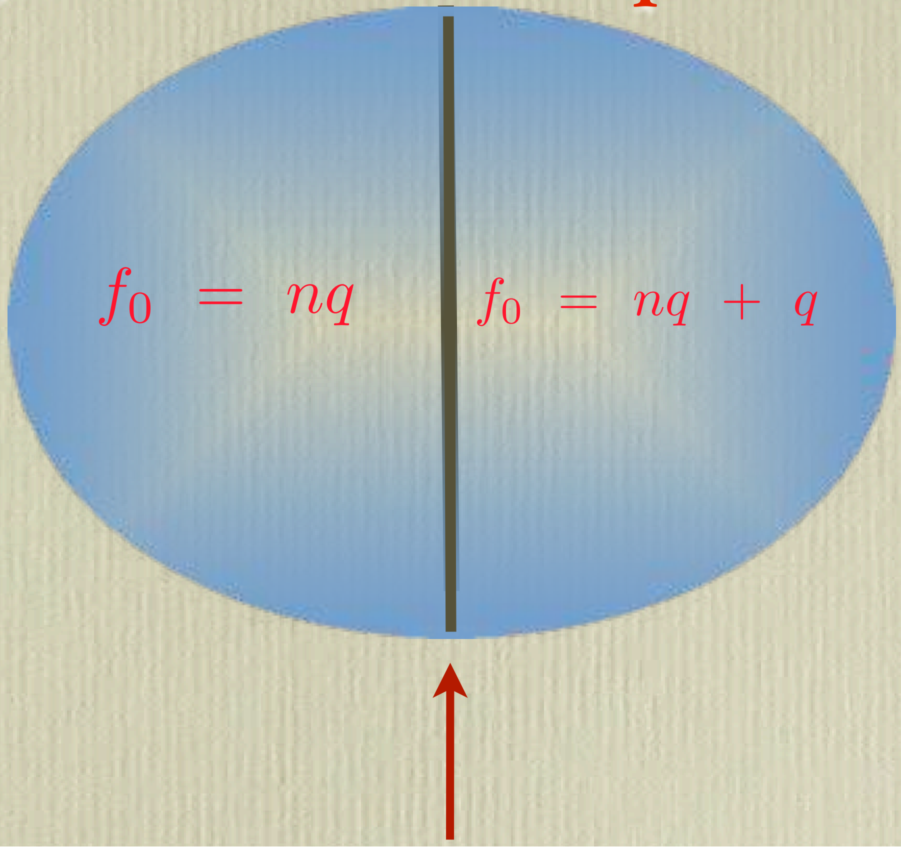
no propagation...

...but contributes to the c.c... $\delta\Lambda_{cc} = \sum_i |F_4^i|^2$

If embedded in string theory: Bousso, Polchinski '00

$f_0 = nq \ , \quad n \in \mathbf{Z}$ quantized in units of the membrane charge

But 3-forms also couple to membranes:



Brown, Teitelboim 1987

$$S_{mem} = q \int_{D_3} d^3\xi \epsilon^{abc} C_{\mu\nu\rho} \left(\frac{\partial X^\mu}{\partial \xi^a} \frac{\partial X^\nu}{\partial \xi^b} \frac{\partial X^\rho}{\partial \xi^c} \right)$$

membranes induce jumps in F_4 value

$\Delta F_4 = q,$ *when crossing the membrane wall*

Axions:

1) Pseudoscalars invariant under shifts

$$\phi \rightarrow \phi + f$$

2) Perturbatively massless

3) Mass from non-perturbative instanton effects

Coupling axions to 3-forms

$$\mathcal{L} = -F_4^2 + \mu\phi F_4 + \ldots$$

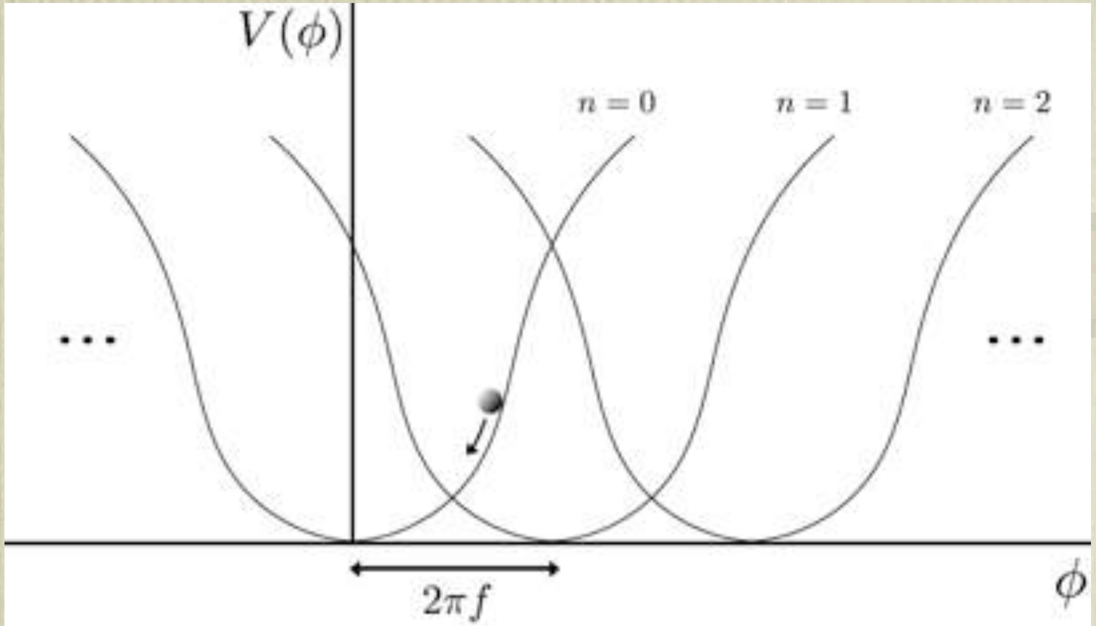
$$F_4 = \epsilon_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}$$

Dvali 05

Kaloper, Sorbo 08;

Eqs. of Motion yield:

$$V_0 = \frac{1}{2}(q + \mu\phi)^2$$



Discrete gauge shift symmetry:

$$\phi \to \phi + \phi_0\,,\; q \to q - \mu\phi_0$$

It is a family (landscape) of potentials parametrized by q, μ

Coupling axions to 3-forms

$$\mathcal{L} = -F_4^2 + \mu\phi F_4 + \ldots$$

$$F_4 = \epsilon_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}$$

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Axion mass consistent with shift symmetry !

Discrete gauge shift symmetry:

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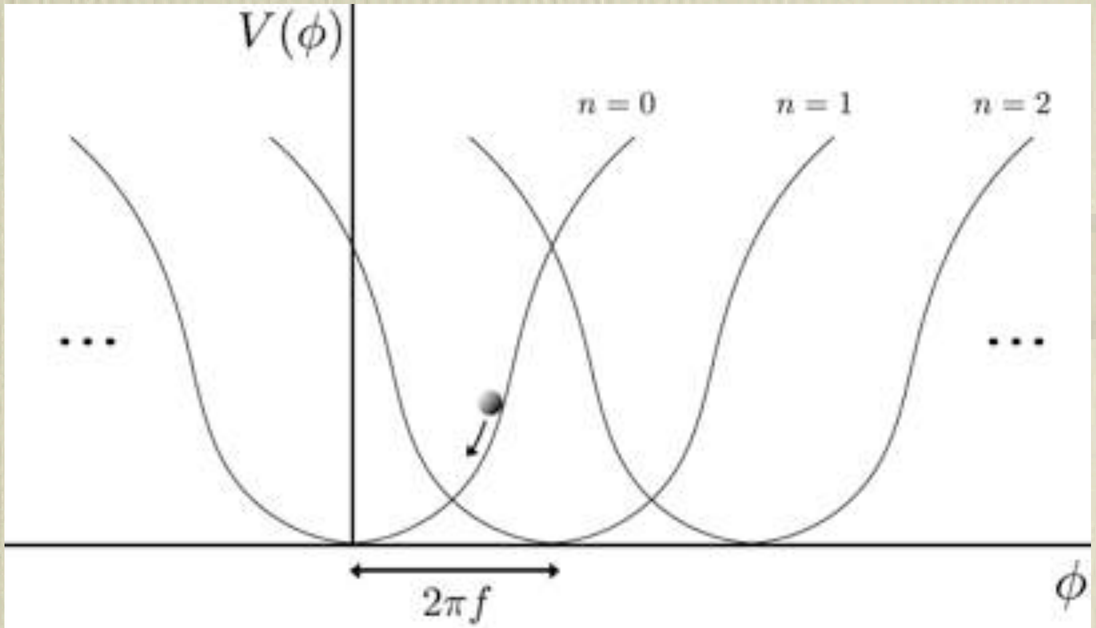

It is a family (landscape) of potentials parametrized by q, μ

One can formulate the same system in terms of a 2-form $B_{\mu\nu}$

$$\mathcal{L} = -F_4^2 - \frac{\mu^2}{2}|dB_2 - C_3|^2 + \ldots$$

$${}^*dB_2 = d\phi$$

C_3 *eats* B_2 *and becomes massive*

Quevedo, Trugenberger 96

Dudas 14

Invariant under the gauge transformation:

$$B_2 \to B_2 + \Lambda_2 \quad , \quad C_3 \to C_3 + d\Lambda_2$$

These gauge invariances protect potential from uncontrolled corrections

$$\cancel{\delta V = c_n \frac{\phi^n}{M_{UV}^{n-4}}}$$

$$\boxed{\delta V = V_0 \left(\frac{V_0}{M_{UV}^4}\right)^n}$$

Kaloper, Sorbo 08;

Minkowski 3-forms in String Theory

Type IIA Orientifolds:

Grimm et al, Louis et al, Villadoro et al, DeWolf et al,...

$$S_{RR} = -\frac{1}{8k_{10}^2}\int_{R^{1,3}\times Y}\sum_{p=0,2,4,6,8,10} G_p \wedge *_{10} G_p + \ldots\ , \quad S_{NS} = -\frac{1}{4k_{10}^2}\int_{R^{1,3}\times Y} e^{-2\phi} H_3 \wedge *_{10} H_3$$

democratic formulation Bergshoeff et al $(later\ Poincare\ duality\ impossed)$

Gauge invariant field strengths:

$$G_p = dC_{p-1} - H_3 \wedge C_{p-3} + \mathcal{F}e^B$$

$$H_3 = dB_2,\ F_p = dC_{p-1}$$

4-forms come from dimensionally reducing higher dimensional RR and NS p-forms: $F_p = F_4 \wedge \omega_{p-4} + \langle F \rangle\, \omega_p$

Minkowski 4-form

Internal flux

$(2h^{-}_{11}+2)\ \ F_4's\ \ from\ RR\ sector:$

$$F_0=-m\ ,\quad F_2=\sum_i q_i\omega_i\ ,\quad F_4=\underline{F_4^0}+\sum_i e_i\tilde{\omega}_i$$

$$F_6=\sum_i \underline{F_4^i}\omega_i+e_0 dvol_6\ ,\quad F_8=\sum_a \underline{F_4^a}\tilde{\omega}_a\ ,\quad F_{10}=\underline{F_4^m}dvol_6$$

$e_0, e_i, q_i, m\ RR\ quantized\ fluxes$

$(h^{+}_{21}+1)\ \ H_4's\ \ from\ NS\ sector:$

$$H_7=\sum_I \underline{H_4^I}\wedge\alpha_I \qquad H_3=\sum_{I=0}^{h^{-}_{2,1}} h_I\beta_I$$

$h_I\ NS\ quantized\ fluxes$

$Axions:$ $B_2=\sum_i b_i\omega_i\ ,\quad C_3=\sum_I c_3^I\alpha_I$

NS $\qquad$ RR

$$\int_Y \omega_\alpha\wedge\tilde{\omega}^\beta=\delta_\alpha^\beta\ ,\qquad \alpha,\beta\in\{1\ldots h_+^{(1,1)}\}$$
$$\int_Y \omega_a\wedge\tilde{\omega}^b=\delta_a^b\ ,\qquad a,b\in\{1\ldots h_-^{(1,1)}\}$$
$$\int_Y \alpha_K\wedge\beta^L=\delta_K^L\ ,\qquad K,L\in\{1\ldots h^{(2,1)}+1\}$$

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$NS\qquad\qquad RR$

$$\int_Y \omega_\alpha\wedge\tilde{\omega}^\beta=\delta_\alpha^\beta\ ,\qquad \alpha,\beta\in\{1\dots h_+^{(1,1)}\}$$

$$\int_Y \omega_a\wedge\tilde{\omega}^b=\delta_a^b\ ,\qquad a,b\in\{1\dots h_-^{(1,1)}\}$$

$$\int_Y \alpha_K\wedge\beta^L=\delta_K^L\ ,\qquad K,L\in\{1\dots h^{(2,1)}+1\}$$

Bieleman, L.I., Valenzuela 15;

Full scalar potential in terms of 4-forms+local terms:

$$V = \frac{k}{2}|F_4^0|^2 + 2k\sum_{ij} g_{ij} F_4^i F_4^j + \frac{1}{8k}\sum_{ab} g_{ab} F_4^a F_4^b + k|F_4^m|^2 + \frac{1}{2s^2}\sum_{IJ} c_{IJ} H_4^I H_4^J + V_{loc}$$

Sort of generalized Kaloper-Sorbo structure:

$$V_{loc} = \sum_a \int_\Sigma T_a \sqrt{-g}\, e^{-\phi}$$

$$\begin{aligned}
*_4F_4^0 &= \frac{1}{k}(e_0 + e_i b^i + \frac{1}{2}k_{ijk}q^i b^j b^k - \frac{m}{3!}k_{ijk}b^i b^j b^k - h_0 c_3^0 - h_i c_3^i) \\
*_4F_4^i &= \frac{g^{ij}}{4k}(e_j + k_{ijk}b^j q^k - \frac{m}{2}k_{ijk}b^j b^k) \\
*_4F_4^a &= 4kg^{ab}(q_b - mb_b) \\
*_4F_4^m &= -m \\
*_4H_4^I &= h^I
\end{aligned}$$

All axion dependence goes through 3-forms
4-forms act as auxiliary fields

Generalized shift symmetries

Axion shifts...

$NS: \quad b_i \rightarrow b_i + n_i \qquad RR: c_3^I \rightarrow c_3^I + n^I$

$$
\begin{aligned}
m &\rightarrow m \\
q_i &\rightarrow q_i + n_i m \\
e_i &\rightarrow e_i - k_{ijk} q^j n^k \\
e_0 &\rightarrow e_0 - e_i n_i
\end{aligned}
$$

$$e_0 \rightarrow e_0 + h_I n_I$$

...compensated by flux shifts...

$$transformations\ leave\ all\ 4-forms$$
$$invariant\ for\ any\ IIA\ CY\ orientifold$$

$$V_{RR} + V_{NS}\ invariant$$

Some lessons:

The flux-induced scalar potential of Type IIA and IIB can be written as

$$V = \sum_i Z_{ij}(ReM_a)\, F_4^i F_4^j + \sum_i F_4^i\, \Theta_i(ImM_a) + V_{local}(ReM_a)$$

where all the dependence on axionic fields comes through couplings to Minkowski 3-form fields.

Ecs. motion: $*_4 F_4^i = Z^{ij}\Theta^j(ReM_a, ImM_a)$

Bieleman, L. I., Valenzuela 15;

$$V_{4-forms} = \sum_{ij} Z_{ij}\, F_4^i F_4^j + V_{local}$$

Shift symmetries force potential axion dependence only through 4-forms

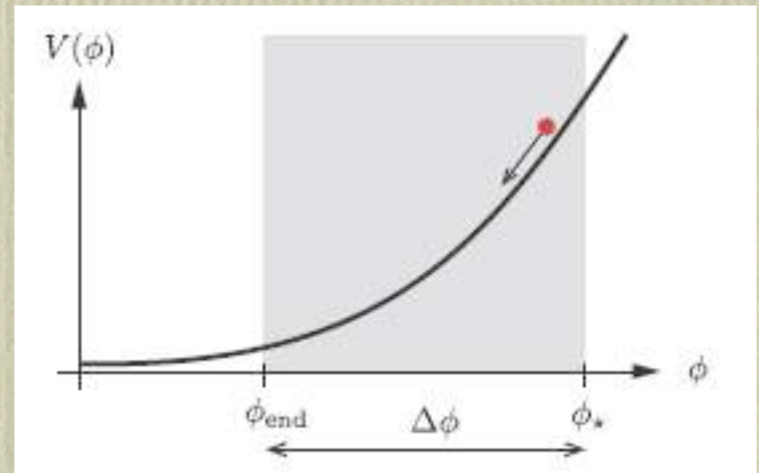
A N=1sugra formulation where auxiliary fields are 4-forms seems appropriate...not much studied....

Gates et al. '81
Ovrut et al. '97
Louis et al. '13

Applications

1) Application to large field inflation

Chaotic Inflation   Linde 88



$$V(\phi) \;=\; \mu^{4-p}\phi^p$$

$$N_* \simeq \frac{1}{2p}\left(\frac{\phi_*}{M_p}\right)^2 \to trans - Planckian$$

Is there a consistent string embeding?

Silverstein, Westphal 08;
McAllister, Silverstein, Westphal
Kaloper, Sorbo 08
Marchesano, Shiu, Uranga , 14

Monodromy inflation

Simplest:

$$V_0 = \frac{1}{2}(q + \mu\phi)^2$$

Chaotic

$$\delta V \simeq \cancel{\frac{\phi^n}{M_p^{n-4}}}$$

$$\delta V \simeq V_0 \left(\frac{V_0}{M_p^4}\right)^n \ll V_0$$

Simplest:

$$V_0 = \frac{1}{2}(q + \mu\phi)^2$$

Chaotic

$$\delta V \simeq \cancel{\frac{\phi^n}{M_p^{n-4}}} \qquad \delta V \simeq V_0 \left(\frac{V_0}{M_p^4}\right)^n \ll V_0$$

Quadratic potential is probably ruled out by Planck+BICEP !!

There are however in general flattening effects:

Silverstein, Westphal 08; McAllister, Silverstein, Westphal

$$E.g.\ if\ inflaton\ is\ a D-brane\ modulus:$$

$$\mathcal{L}_{DBI} = -[1 + aV(\phi)]\partial_\mu\phi\partial^\mu\bar{\phi} - V(\phi)$$

$$V \simeq \phi^n \longrightarrow V' \simeq (\phi')^{2n/(n+2)}$$

OK with Planck-BICEP!

Gur-Ari, 13

L.I., Marchesano, Valenzuela

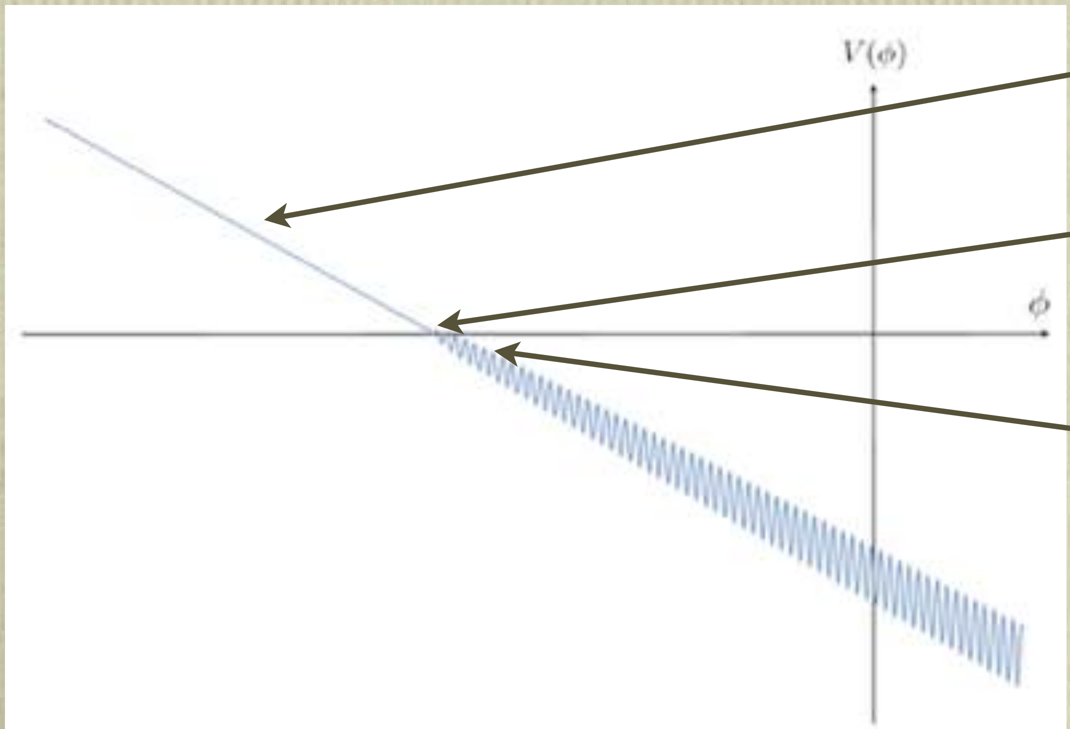
Bieleman, L.I., Pedro, Valenzuela, Wieck 16;

2) Cosmological Relaxation

$$V = V(\mu\phi) + (-M^2 + \mu\phi)|h|^2 + \Lambda^4(h)\cos\left(\frac{\phi}{f}\right).$$

$$V(\mu\phi) = \mu M^2\phi + \mu^2\phi^2 + \ldots$$

M=cut-off



Slow roll dictated by $V(\mu\phi)$

Higgs becomes massless

Higgs stopped by $\Lambda(h)^4\cos\left(\frac{\phi}{f}\right).$

$$\mu f M^2 \simeq \Lambda^4(h = v)$$

$$\mu \simeq \frac{\Lambda^4}{fM^2} \simeq 10^{-18}\left(\frac{10^{10}GeV}{f}\right)\left(\frac{M_W}{M}\right)^2 GeV$$

tiny!!

Consistency problems for relaxation

$$Hierarchy\ traded\ for\ a\ tiny\ value\ of\ \mu$$

$$Technically\ natural\ due\ to\ axion\ \phi\ shift\ symmetry$$

- Enormous trans-Planckian excursions of the axion: is the potential stable? A global shift symmetry not immune to gravitational corrections.

- If it is gauged, a non-vanishing axion potential $V(\mu\phi)$ explicitly breaks the gauge shift symmetry, which is inconsistent. [Gupta,Komargodski,Perez,Ubaldi'15]

Problems analogous to those of large field inflation:

Can one build a consistent monodromy-like relaxion model?

A minimal 3-form relaxion model

L.I., Montero, Uranga, Valenzuela, 15

(no string theory needed here)

$$V = V_{SM} + V_{KS} - \eta F_4 |H|^2 + V_{cos}$$

$$V_{SM} = -m^2|H|^2 + \lambda |H|^4 \qquad V_{KS} = F_4^2 - \mu\phi F_4$$

$$V = \tilde{\lambda}|H|^4 + \underbrace{(q + \mu\phi)^2}_{V(\mu\phi)} + 2\eta(-M^2 + \underbrace{\mu\phi}_{relaxion - Higgs\ coupling})|H|^2 + V_{cos}$$

$$Cut-off: \; M^2 = \frac{m^2}{2\eta} - q$$

Features of relaxion monodromy

L.I., Montero, Uranga, Valenzuela, 15

- Shift gauge symmetry is respected by the relaxion potential.

- Potential protected against Planck-supressed and loop corrections:

$$\delta V \simeq V_0 \left(\frac{V_0}{M^4}\right)^n \simeq V_0 \left(\frac{\Lambda^4}{M^4}\right)^n \ll V_0$$

- Scales:

$$F_4 = n\Lambda_k^2 \quad ; \quad \mu \simeq \frac{\Lambda_k^2}{2\pi f}$$

$$\mu \simeq 10^{-34}\ GeV \quad \longrightarrow \quad \Lambda_k \simeq 10^{-3} eV$$

Anything to do with the c.c.?

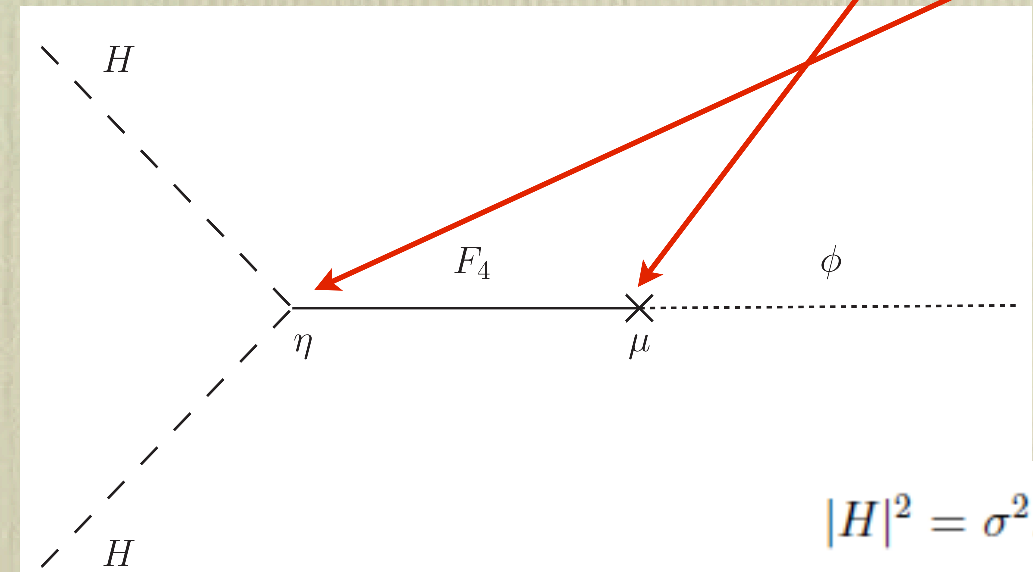
3) A Higgs landscape

A. Herraez, L.I, 16

Use 4-forms to construct a landscape of Higgss masses

$$\mathcal{L} = -\frac{1}{2}(F_a)^2 - \frac{1}{2}(F_h)^2 + \phi(\mu_a F_a + \mu_h F_h) + \eta F_h |H|^2$$

(no string theory assumed here)



$$|H|^2 = \sigma^2.$$

$$V = \frac{1}{2}|f_0^a + \mu\phi|^2 + \frac{1}{2}|f_0^h + \mu^h\phi + \eta\sigma^2|^2 - m^2\sigma^2 + \lambda\sigma^4$$

Different from Relaxion: NO cosmological rolling of the axion here!

Can fine-tune the Higgs vev in steps:

$$m_h, m_a \in \mathbf{Z}$$

$$q_a = \mu f$$

$$q_h = \mu^h f$$

$$cos^2\theta = \frac{(\mu)^2}{\mu^2 + (\mu^h)^2}$$

$$\delta(\sigma^2) = \frac{\eta \mu f}{(2\lambda + \eta^2 cos^2\theta)} \frac{q_a q_h}{q_a^2 + q_h^2} (m_a - m_h)$$

$$\delta(\sigma^2) \simeq \eta \mu f = \eta q_a \leq m_H^2$$

EW fine-tuning connected to 4-form quanta and coupling η

Large family of SM vacua with different Higgs masses and vevs

Antropic selection of correct EW vacua

Prediction: a Hierarxion

Pseudoscalar with a mass:

$$4.7\,\eta^{-3/2}\,10^{-3}eV\left(\frac{10^{10}GeV}{f}\right)\left(\frac{m}{10^{10}GeV}\right)^{3/2}\lesssim m_{axion}\lesssim\eta^{-1}\,10^{3}eV\,\left(\frac{10^{10}GeV}{f}\right) \tag{3.29}$$

For $\eta\simeq 1$ and $f\simeq m\simeq 10^{10}$ GeV one has $10^{-3}eV\lesssim m_{axion}\lesssim 10^{3}eV$

one can have ultralight axions with $m_{axion}\simeq 10^{-17}$ eV

Difficult to identify with QCD axion though...

Couplings to photons model dependent...

Possible to construct SUSY versions: the 4-forms are now part of the SUSY auxiliary fields

Conclusions

• 3-forms appear naturaly as new degrees of freedom in field theory. The field-strength is a 4-form which contributes to vacuum energy.

• 3-forms couple to membranes. Values of 4-forms change discretely while going through a membrane in units of the membrane charge.

• 3-forms can couple to axions and can give them a mass while mantaining the axion discrete shift symmetry. The scalar potential is necesarily a power expansion in 4-forms. Makes the axion potential stable.

• The field strength 4-forms appear naturally in String Theory from reduction of RR and NS higher dimensional antisymmetric tensors. The 4-forms are in bijection with internal fluxes and are quantized in units of membrane charges.

• The full NS and RR axion potential can be written in terms of 4-forms that act as auxiliary fields. In SUSY compactifications the 4-forms behave like SUSY auxiliary fields of Kahler and c.s. chiral multiplets. $F_{aux}^{SUSY} \rightarrow \epsilon_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma}$

• Axions in string theory are 'monodromy axions' with associated 3-forms. This makes the scalar potentials for axions stable even upon trans-Planckian trips. And makes string axions to be promising inflatons in large field.

• One can construct consistent 'relaxion models' involving 3-forms. They address some of the problems....
First attempts to embed in string theory, challenging.

One can also
construct a Higgs mass landscape from quantized 4-forms.

Thank you for your great physics!!


S SUSY ALIVE AND WELL
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Madrid, 28-30 September 2016
https://workshops.ift.uam-csic.es/susyaaw
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. Baer (Oklahoma U.)
. Bélanger (LAPTH-Annecy)
. Buchmüller (Imperial Coll.)
. Carena (Fermilab)
. Cicoli (ICTP & Bologna U.)
. Dreiner (Bonn U.)
J. Ellis (CERN & King's Coll.)
L. J. Hall (Berkeley)
A. Katz (CERN & Geneva U.)
J. Lykken (Fermilab)
J. March-Russell (Oxford U.)
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