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

European Research Council
SPLE Advanced Grant

Luis Ibáñez

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Quevedo Fest
ICTP, Trieste, May

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One of the greatest Particle Theorist of his generation worldwide

Many very important contributions:

String theory compactifications: Effective action, Orbifolds, Wilson Lines, CY's,

Dualities: T- and S-dualities, antisymmetric fields,...

Cosmology: moduli problem, Kahler inflation, brane worlds

D-brane models: Orientifolds, Branes at singularities,...

Moduli fixing: Fluxes, Large volume...

Cosmological Constant: D=6 KK,

Phenomenology at LHC, SUSY soft terms and more...

Many fruitful collaborations over the years !!

Citations summary

Generated on 2016-05-08

31 papers found, 30 of them citeable (published or arXiv)

Citation summary results	Citeable papers	Published only
Total number of papers analyzed:	30	27
Total number of citations:	4,698	4,692
Average citations per paper:	156.6	173.8
Breakdown of papers by citations:		
Renowned papers (500+)	0	0
Famous papers (250-499)	7	7
Very well-known papers (100-249)	11	11
Well-known papers (50-99)	4	4
Known papers (10-49)	5	5
Less known papers (1-9)	1	0
Unknown papers (0)	2	0
h_{HEP} index [?]	27	27

CERN , 1986

Our first paper together...

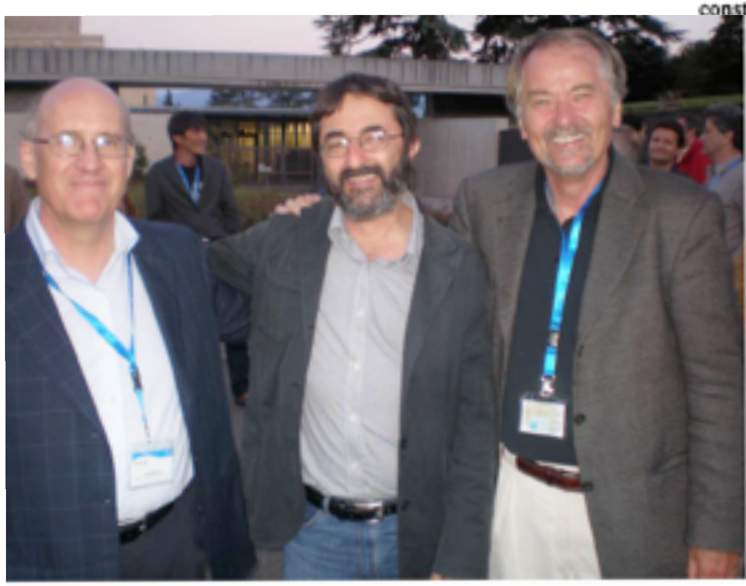
Volume 187, number 1,2 PHYSICS LETTERS B 19 March 1987

ORBIFOLDS AND WILSON LINES

L.E. IBÁÑEZ, H.P. NILLES and F. QUEVEDO
CERN, CH-1211 Geneva 23, Switzerland

Received 12 December 1986

We study the consequences of the presence of gauge background fields on the torus underlying orbifold compactification of the heterotic string. It is pointed out that such Wilson lines provide us with a mechanism for controlling the number of chiral matter states both from twisted and untwisted sectors, as well as breaking the symmetry group. Starting from the Z orbifold, we can construct a variety of four-dimensional string models with three families of quarks and leptons and different gauge groups such as $U(3)^3$, $SU(6)\times U(1)$ or $SU(5)\times[SU(2)\times U(1)]^2$.



First 3 generation orbifold models constructed....

Divonne, 1988

CERN TH-Division Circa 1987

CERN TH-Division Circa 1987

Strong–weak coupling duality and non-perturbative effects in string theory

S-DUALITY

A. Font [a], L.E. Ibáñez [b], D. Lüst [b] and F. Quevedo [c]
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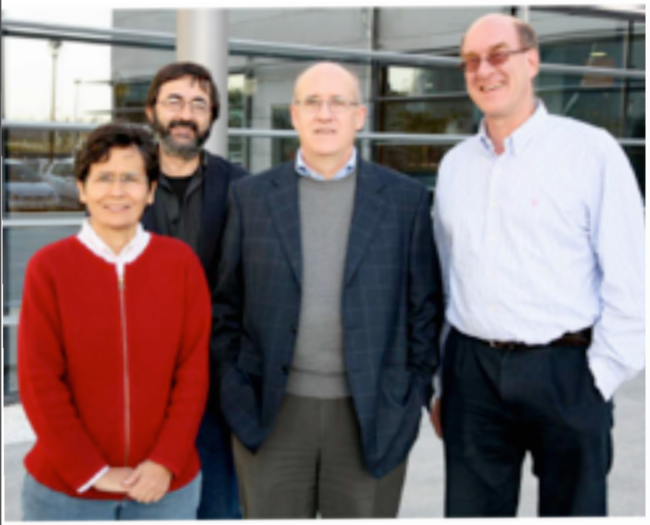
[c] Theoretical Division LANL, Los Alamos, NM 87545, USA

Received 13 July 1990

We conjecture the existence of a new discrete symmetry of the modular type relating weak and strong coupling in string theory. The existence of this symmetry would strongly constrain the non-perturbative behaviour in string partition functions and introduces the notion of a maximal (minimal) coupling cons
expectation value is dynamically fixed to be of order on
modular symmetry itself) is generically spontaneously br



and non-perturbative effects in string theory

A. Font [a], L.E. Ibáñez [b], D. Lüst [b] and F. Quevedo [c]
[a] Departamento de Fisica, Universita Central de Venezuela, Aptdo 20513, Caracas 1020-A, Venezuela
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Received 13 July 1990

We conjecture the existence of a new discrete symmetry of the modular type relating weak and strong coupling in string theory. The existence of this symmetry would strongly constrain the non-perturbative behaviour in string partition functions and introduces the notion of a maximal (minimal) coupling constant. An effective lagrangian analysis suggests that the dilaton vacuum expectation value is dynamically fixed to be of order one. In supersymmetric heterotic strings, supersymmetry (as well as this modular symmetry itself) is generically spontaneously broken.

Modular invariance appears in a variety of physical problems [1]. These symmetries involve an invariance under the inversion of coupling constants along with the discrete translations of a "theta term". The first example of this type of symmetry in field theory was discovered by Cardy [2] who showed that the phase structure of the abelian Higgs model on the

to the existence of the $B_{\mu\nu}$ antisymmetric tensor which acts as a θ-parameter. In more realistic six-dimensional compactifications (like e.g. orbifolds) the same structure (conveniently generalized) is also found. This target-space modular invariance strongly constrains the form of the low-energy effective action as a function of the compactification moduli [5]. It

. Then it is natural to conjecture
heory, the one which describes si-
entary and solitonic states, should
symmetry of the type described in
e conjecture that the Montonen–
of the heterotic strings will lead to
ice symmetry as in eq. (2).
rangian should be explicitly dual-
appens with the $R \to 1/R$ duality.
te complete. For small g (big R)
strings dominate and the "dual"
modes in T-duality are very mas-
opposite occurs. Thus a duality

the membrane include those of the string together
with a duality transformation for the dilaton field
(Type II A strings, however, are not selfdual bu
"dual" to type II B strings [22,23]). Of course, there
is at the moment no idea about how a ten-dimen
sional heterotic string could be obtained from any
eleven-dimensional extended structure, but that is
certainly an open possibility. If this was the case
duality in both T and S would be expected.

The S-duality we are discussing includes an invar
iance under the transformation of the string coupling
constant $g \to 1/g$. Montonen and Olive [24] conjec
tured some time ago that this type of duality invari
ance does in fact occur in field theory models of the

$g \to 1/g$ in the effective four-dimensional field theory should exist if the above arguments are correct. It follows that inequivalent theories are characterized by coupling constants g smaller (larger) than some critical value. [The notion of a maximal (minimal) coupling could possibly be understood in the sense that the coupling constant determines the "size" of the internal gauge group manifold which should not be "smaller" than the typical scale in string theory.] In analogy with T-duality, one also expects the continuous Peccei–Quinn symmetry $S \to S + ia$, $a \in \mathbb{R}$ not to be completely broken but a discrete subgroup ($a \in \mathbb{R}$)

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D-branes at singularities: a bottom-up approach to the string embedding of the standard model

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TeV-scale Z' bosons from D-branes

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...and so many more...

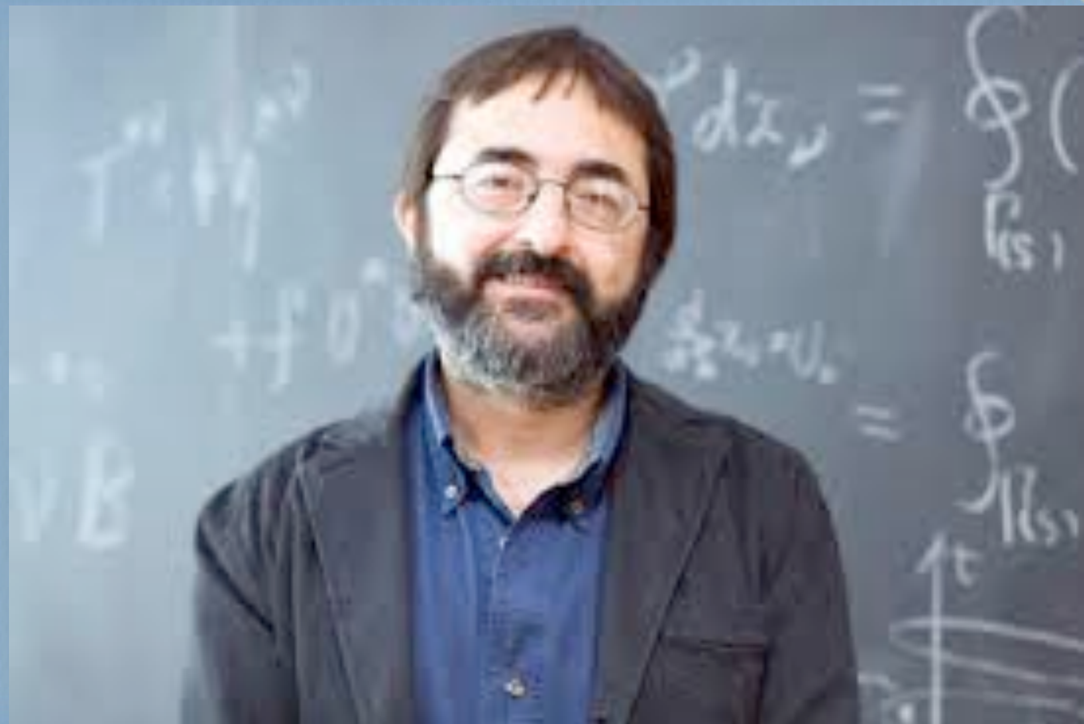
But, most important...

One of the best human beings I have ever met....

......and a real “Caballero”....

‘ That is more difficult than getting Fernando annoyed‘ (E. Ibáñez)

Founex
1991



Thank you Fernando !!

Your friendship is a privilege!!

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:

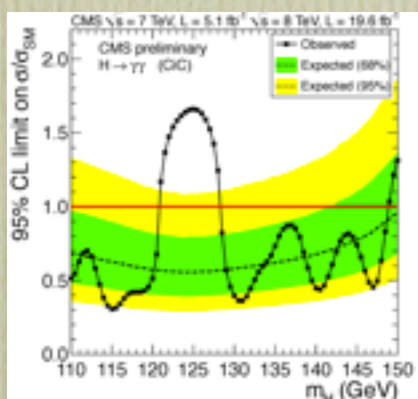
$$Spin : 0,\ \boxed{1/2,\ 1},\ 3/2,\ \boxed{2}$$

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

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Bosons:

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

Higgs Gravity

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

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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:

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

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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
  TeV axions (750 GeV?)

The physics of Minkowski 3-forms

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

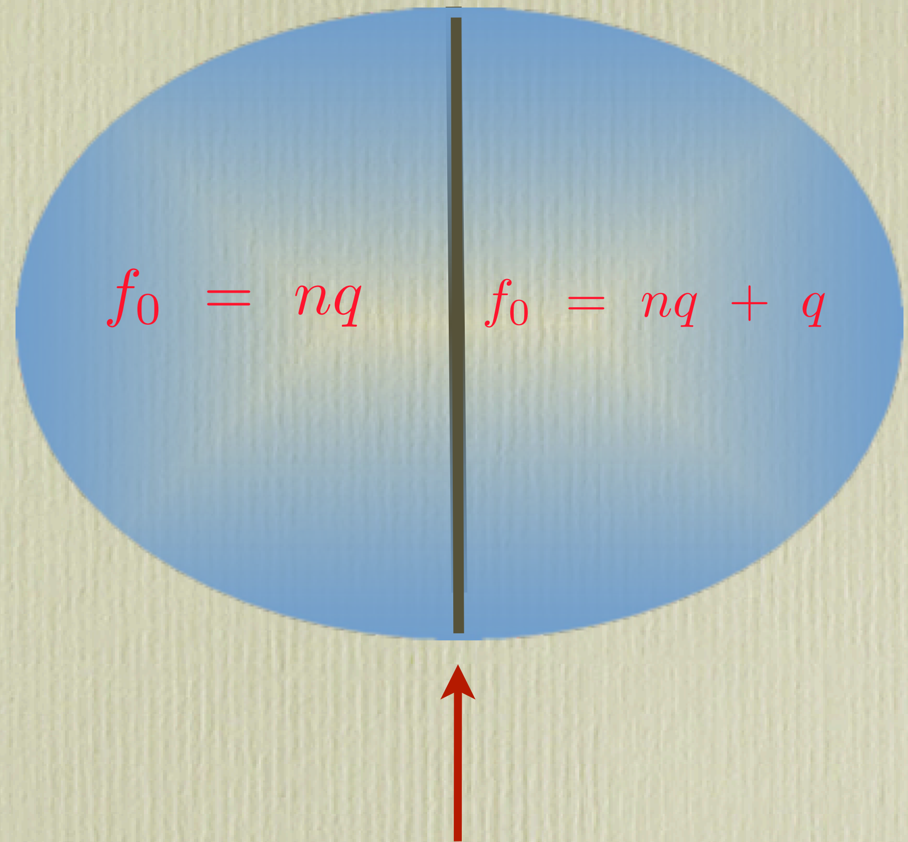
$$S = -\int d^4x\sqrt{-g}\frac{1}{48}F_{\mu\nu\rho\sigma}F^{\mu\nu\rho\sigma}$$

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

If embedded in string theory: Bousso, Polchinski '00

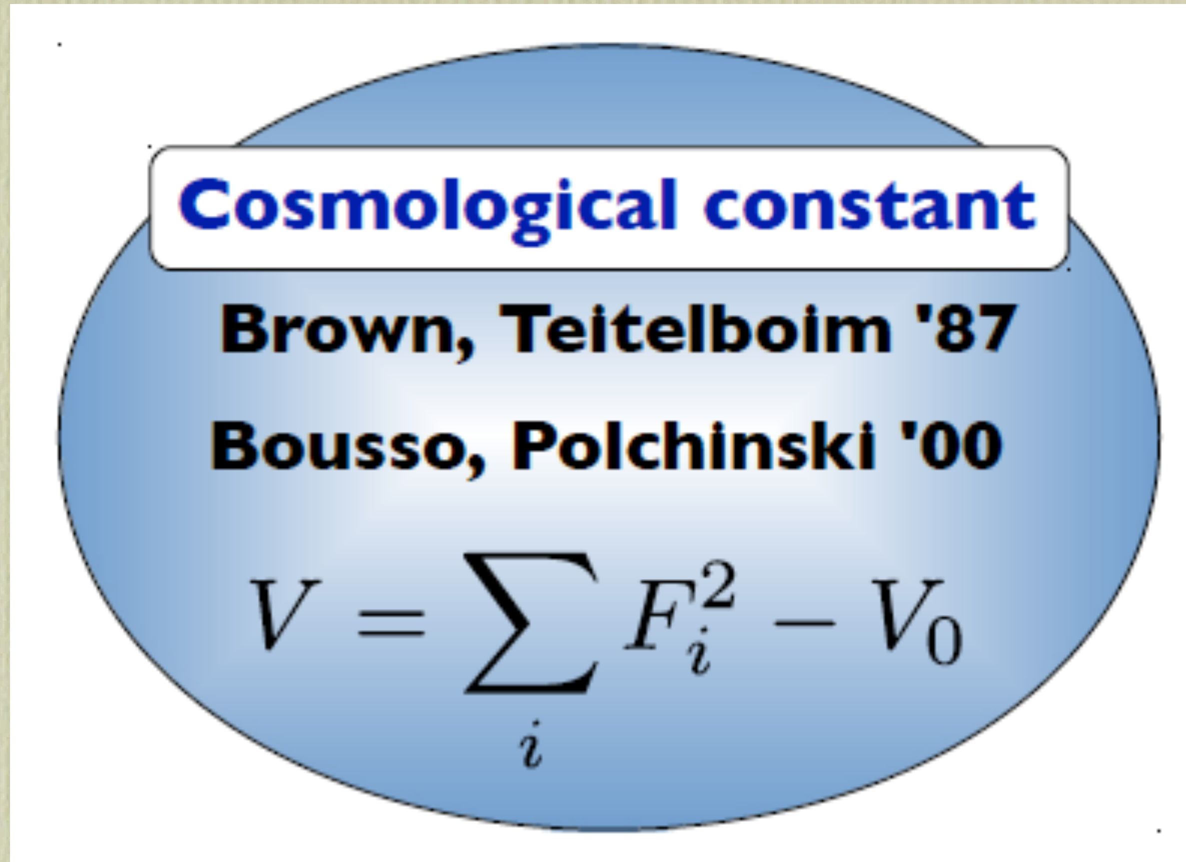
$f_0 = nq \quad , \quad n \in \mathbf{Z}$ quantized in units of the membrane charge

But 3-forms also couple to membranes:



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

$$\Delta f = q, \;\; when \; crossing \; the \; membrane \; wall$$



Large set of 4-form fluxes can cancel the c.c.

Life is slightly more complicated: charges q of 3-forms depend on the compact volumes. Also 4-forms couple to axions.Need first to understand moduli fixing (e.g. KKLT, LVS)

2003 2005

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

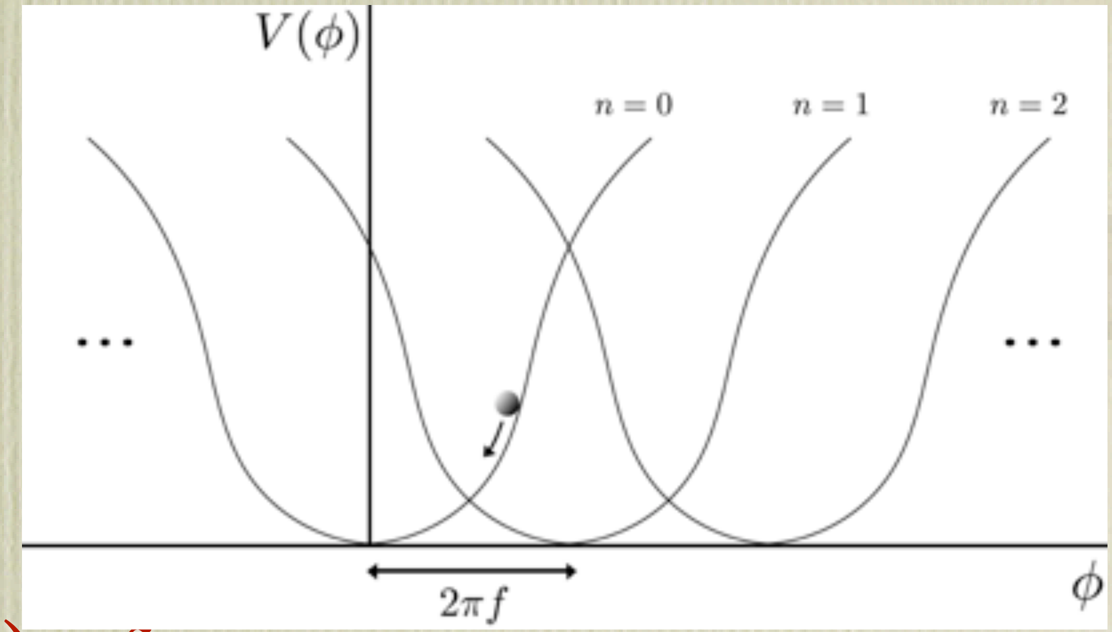
Kaloper, Sorbo 08;

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

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

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

Eqs. of Motion yield:

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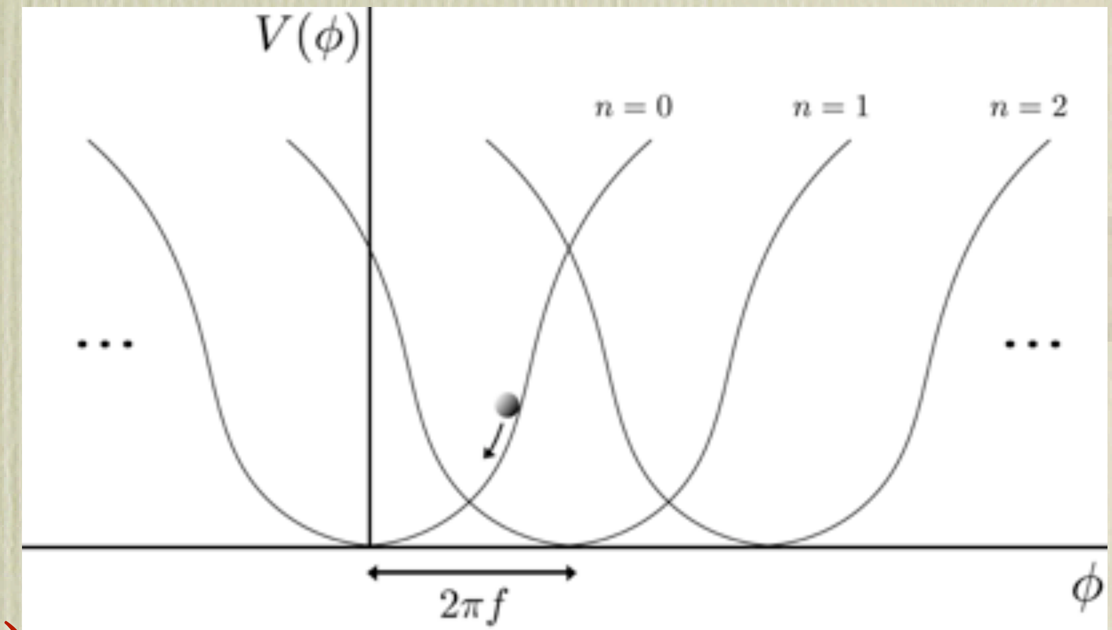
Axion is massive!



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

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

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

$$\cancel{\delta V = c_n \frac{\phi^n}{M_{UV}^{n-4}}} \qquad \boxed{\delta V = V_0 \left(\frac{V_0}{M_{UV}^4}\right)^n}$$

Minkowski 3-forms in String Theory

Type IIA Orientifolds:

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

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

Gauge invariant field strengths:

RR $G_p = dC_{p-1} - H_3\wedge C_{p-3} + \mathcal{F}e^B$ NS $H_3 = dB_2,\ F_p = dC_{p-1}$

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

$F_4's$ from RR sector :

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

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

e_0, e_i, q_i, m *RR quantized fluxes*

$H_4's$ from NS sector :

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

h_I *NS quantized fluxes*

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

$RR \qquad NS$

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

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

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

$(2h_{11}^{-}+2)\ \ F_4's\ \ from\ RR\ sector:$ $2(\#Kahler)\ F_4's$

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

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

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

$(h_{21}^{+}+1)\ \ H_4's\ \ from\ NS\ sector:$ $(\#c.s.)\ H_4's$

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

$h_I\ NS\ quantized\ fluxes$

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

NS RR

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

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

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

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:

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

$$\begin{aligned}
*_4 F_4^0 &= \frac{1}{k}\left(e_0 + e_i b^i + \frac{1}{2} k_{ijk} q^i b^j b^k - \frac{m}{3!} k_{ijk} b^i b^j b^k - h_0 c_3^0 - h_i c_3^i\right) \\
*_4 F_4^i &= \frac{g^{ij}}{4k}\left(e_j + k_{ijk} b^j q^k - \frac{m}{2} k_{ijk} b^j b^k\right) \\
*_4 F_4^a &= 4k g^{ab}(q_b - m b_b) \\
*_4 F_4^m &= -m \\
*_4 H_4^I &= h^I
\end{aligned}$$

All axion dependence goes through 3-forms!!

Generalized shift symmetries

Axion shifts...

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

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

$$e_0 \to e_0 + h_I n_I$$

...compensated by flux shifts...

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

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

4-forms in Type IIB orientifolds

$$S_{IIB} = -\frac{1}{2k_{10}^2}\int_{\mathbb{R}^{1,3}\times Y}\frac{1}{3!}\frac{1}{S+S^*}G_3\wedge^*\bar{G}_3$$

$$G_3 = F_3 - iSH_3$$

Allow for IASD fluxes and expand:

$$\overline{G}_7 = \overline{G}_4^0 \wedge \overline{\Omega} + \overline{G}_4^a \wedge \chi_a \ , \ a = 1,..,h_{21}$$

$(h_{21}+1)$ $complex\ 4-forms:$

$(\#c.s.)\ G_4's$

$$G_4^0 = F_4^0 - iSH_4^0 \ , \ G_4^a = F_4^a - iSH_4^a \ .$$

As many as complex structure scalars

$$V = \frac{1}{S+S^*}\left(\kappa\ (|G_4^0|^2\ -\ G_4^a\overline{G}_4^b G_{a\bar{b}})\ - \overline{G}_4^0\ (S+S^*)\overline{D_S W}_{GVW} + \sum_a \overline{G}_4^a\ D^a W_{GVW}\right)$$

$$W_{GVW} = \int_X G_3 \wedge \Omega \qquad \kappa = \int \Omega \wedge \overline{\Omega} \qquad G_{a\bar{b}} = -\frac{1}{\kappa}\int_X \chi_a \wedge \overline{\chi}_b$$

Applying G_4 eq. motion

$$G_4^{\bar{b}} \ = \ e^{K_{c.s.}} G^{a\bar{b}}\,(D_a W_{GVW}) \qquad = F^{\bar{b}}_{sugra-aux}$$

$$G_4^0 \ = \ e^{K_{c.s.}}(S+S^*)\,(\overline{D_S W}_{GVW}) \qquad = F^{0}_{sugra-aux}$$

$$4 - forms = sugra\ auxiliary\ fields\ of\ c.\ structure$$

Recover: $V = e^{K_S + K_{c.s.}}\left(|(S+S^*)\overline{D_S W} + \cancel{g_0}|^2 + K^{a\bar{b}}|D_a W - \cancel{g_a}|^2\right)$

Bieleman, L.I., Valenzuela 15;

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

4-forms from open strings

$e.g. D7's$ $$S_{DBI} = \mu_7 \sigma \int_{\mathbb{R}^{1,3}\times S_4} \frac{1}{2}(B_2 + \sigma F_2) \wedge *_8 (B_2 + \sigma F_2) + \dots$$

4-forms come from dimensionally reducing the magnetic dual of the brane gauge field: $F_6 = iF_4 \wedge \bar{\omega}_2 - i\bar{F}_4 \wedge \omega_2$

G_3 ISD fluxes induce a B-field: $B_2 = \frac{g_s \sigma}{2i}(G^* \phi - S\bar{\phi})\omega_2 + cc.$

$$V_4 = \mu_7 \sigma \rho \left| f - \frac{1}{2} g_s \sigma (G^* \phi - S\phi^*) \right|^2$$

L.I., Valenzuela 14;
Marchesano, L.I., Valenzuela 14
Bieleman, L.I., Valenzuela 15;

Axion stability in string vacua

- Gauge invariance under shift symmetries force action to depend only on 4-forms. Potential should admit an expansion on 4-forms.

Only one 4-form: Kaloper-Sorbo structure. $\delta V = (F_4^2/M_p^4)^n = (V_0/M_p^4)^n$

String Theory vacua a priori more complicated: $\delta V = \sum_n (\Pi_i (F_4^2)^i)^n$

- 4-forms typically transform into each other under geometric transformations. In this case the structure simplifies to

$$\boxed{V = \sum_n c_n V_0^n}$$

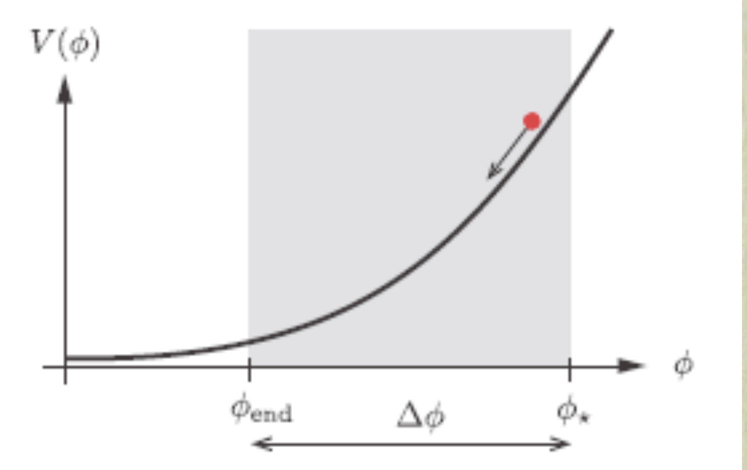
e.g DBI action, *Marchesano, ,L.I., Valenzuela 14;*

higher derivative sugra *Ciupke, Louis, Westphal 15*

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

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

Required Structure of Scales:

10^{13}	10^{14}	10^{16}	10^{18}	10^{19}
m_I	H_I	$V^{1/4}$	M_p	ϕ_*

$D = 4$ *field theory ok*

NEED:

1) $Stable\ m_I \ll M_p\ (m_I \ll H_I\ if\ SUSY) : \eta\ problem$

2) $Large\ \phi_* \gg M_p\ possible$

3) $Corrections\ under\ control\ for\ \phi_* \gg M_p$

$All\ this\ is\ possible\ for\ string\ axions!!$

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

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

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

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

OK with
Planck-BICEP!

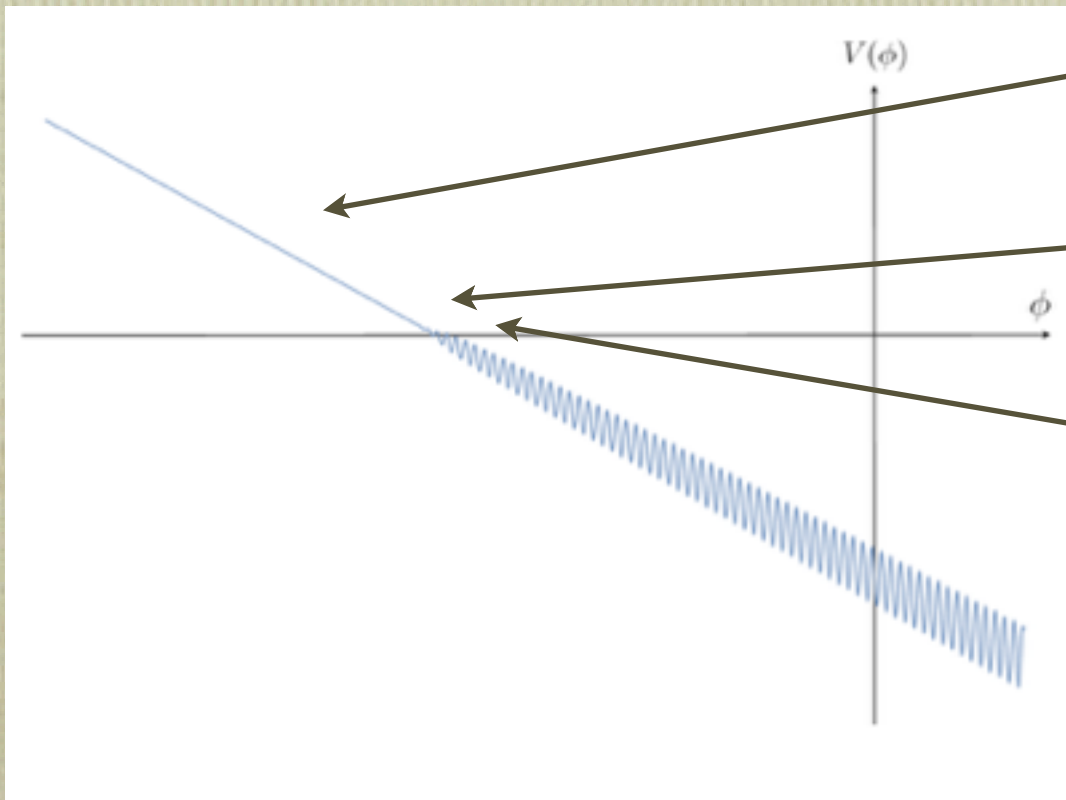
Gur-Ari, 13
L.I., Marchesano, Valenzuela
Bieleman, L.I., Pedro, Valenzuela, Wieck 16;

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

[Graham,Kaplan,Rajendran'15]



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!!

Additional conditions:

[Graham,Kaplan,Rajendran'15]

- Inflation lasts enough for axion to scan entire range of Higgs masses:

$$\frac{\Delta\phi}{f} \geq \frac{M^2}{f\mu} \simeq 10^{12}\left(\frac{M}{M_W}\right)^4 \quad : \quad trans - Planckian$$

- For the QCD barriers to form and the vacuum energy dominated by inflaton rather than the relaxion:

$$\Lambda > H > \frac{M^2}{M_p} \longrightarrow M \leq \sqrt{\Lambda M_p} \simeq 10^9 GeV$$

- Enormous number of efolds:

$$N_e \geq \frac{H^2}{\mu^2} \simeq 10^{37} - 10^{67}$$

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 inmune 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)

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

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

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

$V(\mu\phi)$ $\qquad$ $relaxion - Higgs\ coupling$

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

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:

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

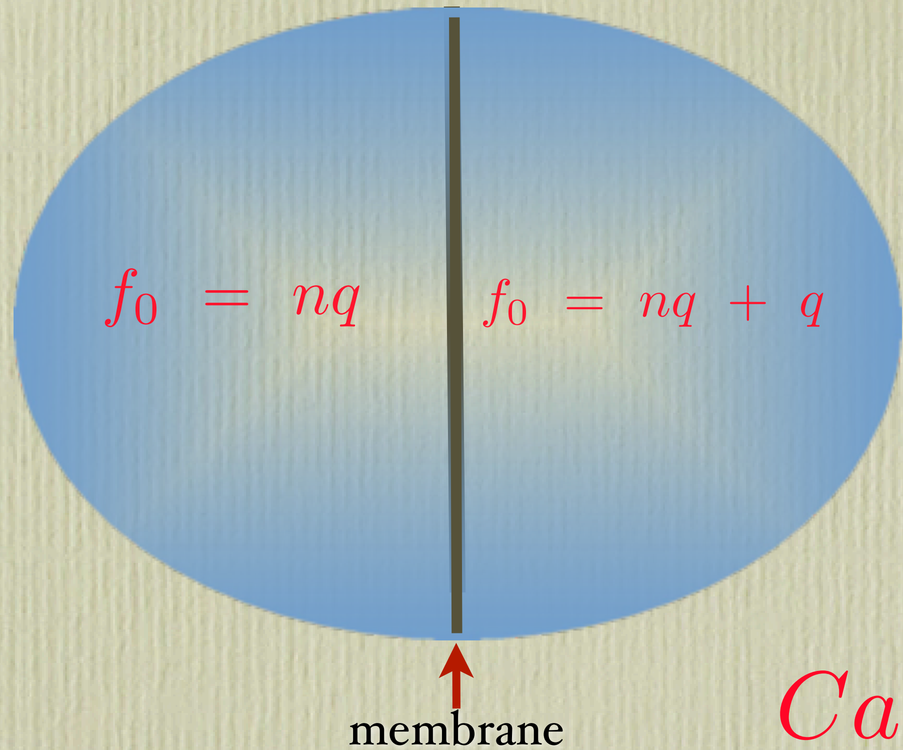
- Scales:

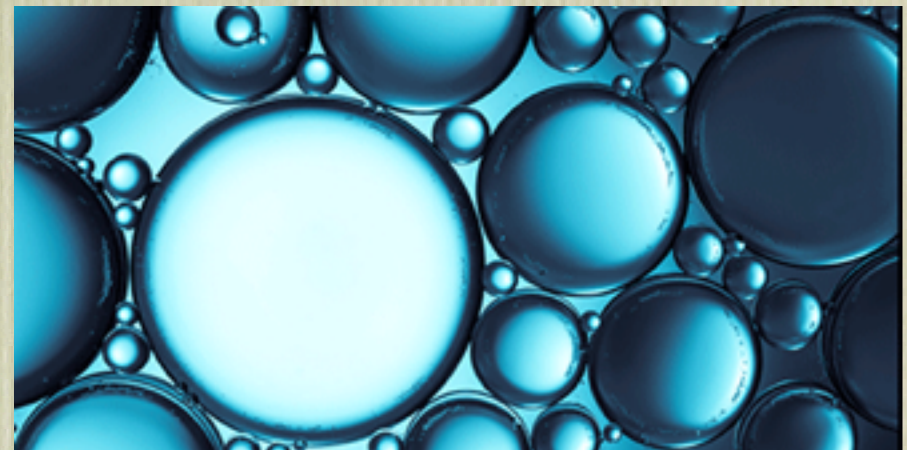
$$F_4 = n\Lambda_k^2 \quad ; \quad \mu \simeq \frac{\Lambda_k^2}{2\pi f}$$

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

Anything to do with the c.c.?

Constraints from nucleation





Bubbles with different f_0

Can spoil relaxion slow roll?

Need tunneling rate $P \simeq e^{-B} \ll 1$

Coleman, De Lucia 80

$$B \approx w(q) \frac{2\pi^2 T}{H^3}$$

$$q \equiv \frac{1}{rH} \sim \frac{\Delta V}{TH} < 1$$

r = bubble radius

Need to know the membrane tension T....

Evaluate B using the 'Weak Gravity Conjecture'

Weak Gravity Conjecture

[Arkani-Hamed et al.'06]

For an Abelian $p-form$ with coupling g_p there must exist a $p-dimensional$ charged object which is superextremal :

$$\frac{T}{M_p} \leq g_p Q$$

Brown, Cottrell, Shiu, Soler 15
Heidenreich, Reece, Rudelius 15
Hebecker, Rompineve, Westphal 15
L.I., Montero, Uranga, Valenzuela 15

3-forms: $$g_3 = \Lambda_k^2 \simeq 2\pi f \mu$$

$$\boxed{T \leq 2\pi f \mu M_p}$$

$$B \simeq \frac{4\pi^3 f \mu M_p}{H^3} \simeq \left(\frac{M_p \Lambda}{M^2}\right)^4$$

$$B > 1 \rightarrow M \leq \sqrt{M_p \Lambda} \simeq 10^9\ GeV$$

We already knew from other considerations..not strong cons.

L.I., Montero, Uranga, Valenzuela

Stronger constraints if one takes into account that inflation lasts very long:

$$N_e \;\geq\; \frac{H^2}{\mu^2} \;\simeq\; 10^{37} - 10^{67}$$

Average number of bubbles produced:

$$N_b \;\simeq\; Vol(\mathcal{R})e^{-B} \;\simeq\; e^{(3N_e - B)}$$

For bubble nucleation not to spoil relaxation need

$$B \gg N_e \;\rightarrow\; M \lesssim \hat{w}(q)\left(\frac{\Lambda_v^6 M_P^3}{f}\right)^{\frac{1}{8}} \simeq \hat{w}(q)\cdot 300\ \mathrm{TeV}$$

Essentially would rule out the generation of a large hierarchy....

L.I., Montero, Uranga, Valenzuela

Relaxation within string theory?

String theory has many required ingredients:

Monodromic axions, Axion potentials from fluxes...

We need though:

1) Axion-Higgs couplings

Toy Model: 2) Right mass scales

- D5-brane wrapping 2-cycle in IIB orientifold:
- Relaxion: NS axion from $B_2 = \phi\omega_2$
- Gauge group $U(3) \to U(2) \times U(1)$
- Higgs h from off-diagonal adjoint open string modulus
- 4-form: dual of gauge F_2

$$V_{DBI} = \mu_5 V_{\Sigma_2} g_s^{-1} \left(1 + 4\sigma^2 m^2 |h|^2\right) \left(1 + (q - \mu\phi)^2\right) .$$

upon Higgs kinetic redefinition and including loop contribution

$$V = \left(- \frac{m_h^2}{1 + (q - \mu\phi)^2} + 4M^4\sigma^2 m^2 \right) |h|^2 + M^4 (q - \mu\phi)^2$$

Axion-Higgs Coupling

Has relaxionic behavior

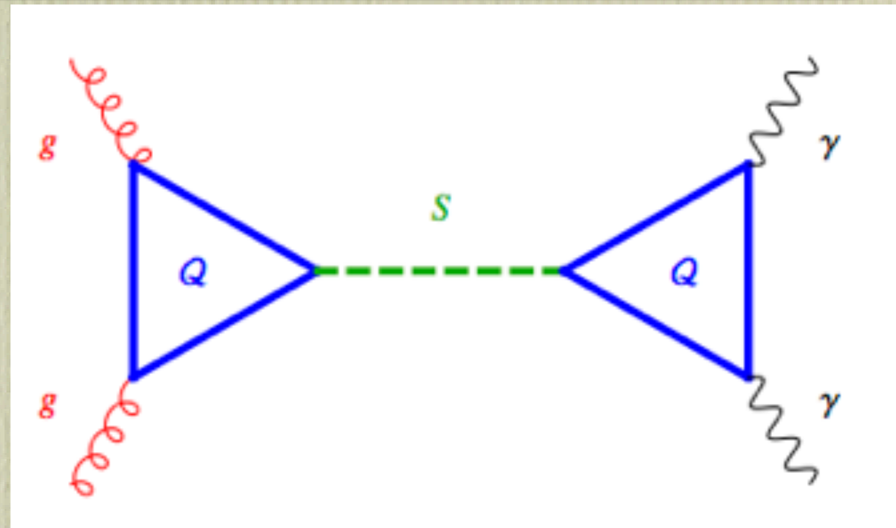
However:

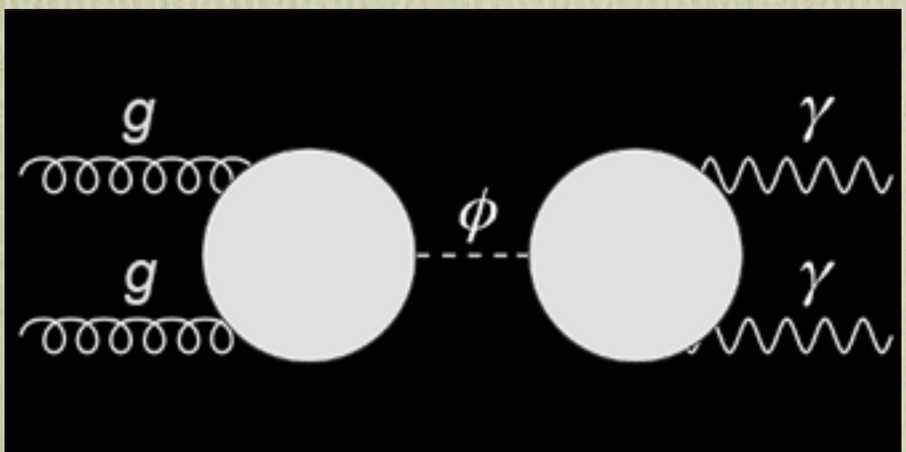
$$\Lambda_k^4 = \frac{4\pi^2\alpha'\sqrt{\pi}}{g_s V_{\Sigma_2} \kappa_{10}} =\sim \frac{M_s^2}{g_s V_{\Sigma_2}} .$$

$$Difficult\ to\ reconcile\ with\ \Lambda_k \simeq 10^{-3} eV\ !!$$

3) TeV axions (750?)

Boring interpretation:



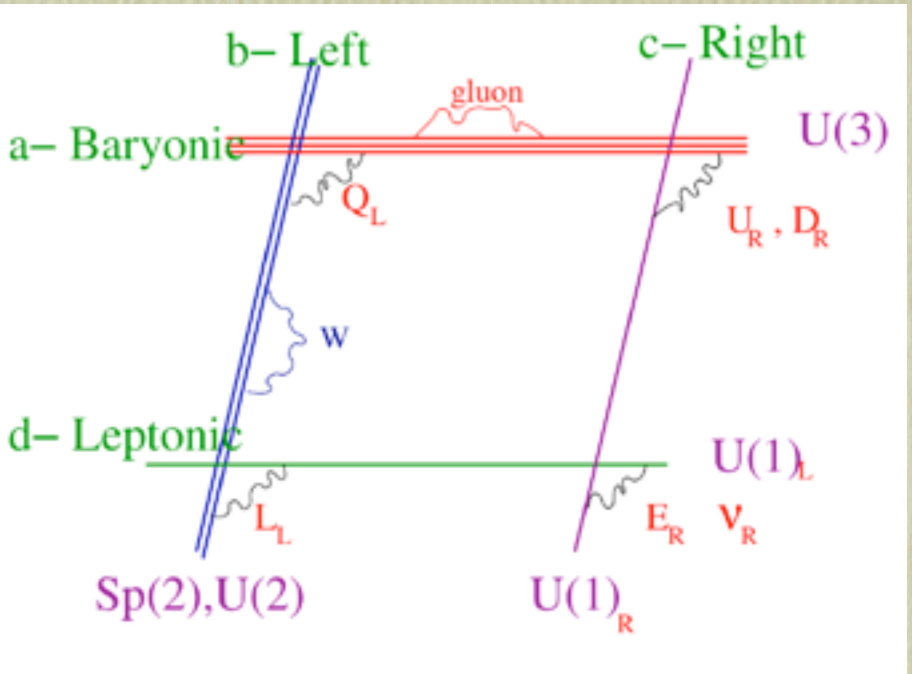


Direct couplings.....

$$\mathcal{L}_{a_0} = \frac{\alpha_s}{4\pi} g_g \frac{a_0}{f} G_{\mu\nu} \widetilde{G}^{\mu\nu} + \frac{\alpha_Y}{4\pi} g_Y \frac{a_0}{f} B_{\mu\nu} \widetilde{B}^{\mu\nu}$$

ϕ *a string axion??*

.....from 7-100 TeV String Theory?



Type IIA Orientifolds

SM at intersecting D6-branes

$axions$

Fluxes

$$H_3 = \sum_i H_i \beta^i \ , \ C_3 = \sum_j \eta_j \alpha_j \ , \ \int_{CY} \alpha_j \wedge \beta^i = \delta_j^i$$

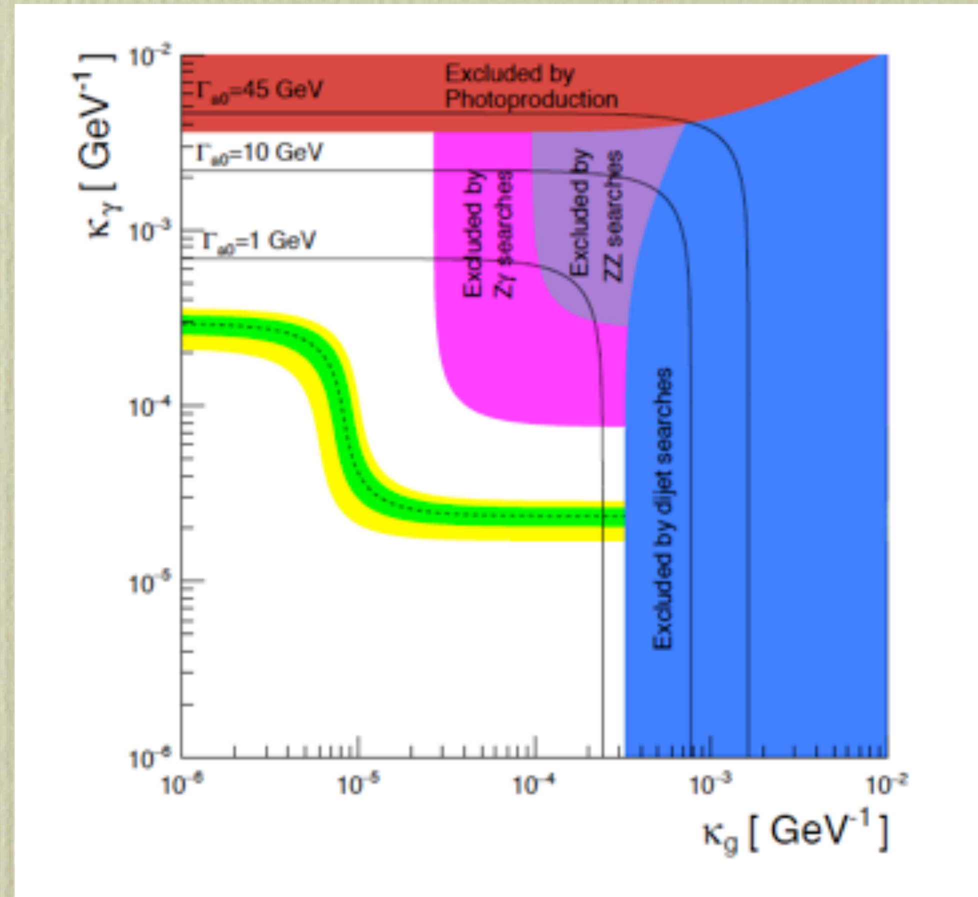
$$\eta_0 \left[d_0^a \ F^a \wedge F^a \ + \ d_0^b \ F^b \wedge F^b \ + \ d_0^d \ F^d \wedge F^d \right]$$

$$V \ = \ \sigma f^4 |n_0 - \sum_i h_i \eta_i|^2 \ , \ n_0, h_i \in \mathbf{Z} \ \longrightarrow \ m_{a_0}^2 \ = \ \sigma f^2 h_0^2 \ .$$

Kaloper Sorbo structure

MEGAXION

L.I.,Martin-Lozano 15



Consistent with CMS/ATLAS hints for e.g:

$$\frac{f}{g_g} \simeq 10^2 - 10^3 GeV$$

$$\frac{f}{g_\gamma} \simeq 30\ GeV$$

L.I.,Martin-Lozano 15

Anchordoqui et al 15

Aug 2002

TeV-Scale Z' Bosons from D-branes

D.M. Ghilencea[a], L.E. Ibáñez[b], N. Irges[c], F. Quevedo[a]

[a] DAMTP, CMS, University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, U.K.

Additional signatures:

$$Z's$$

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.

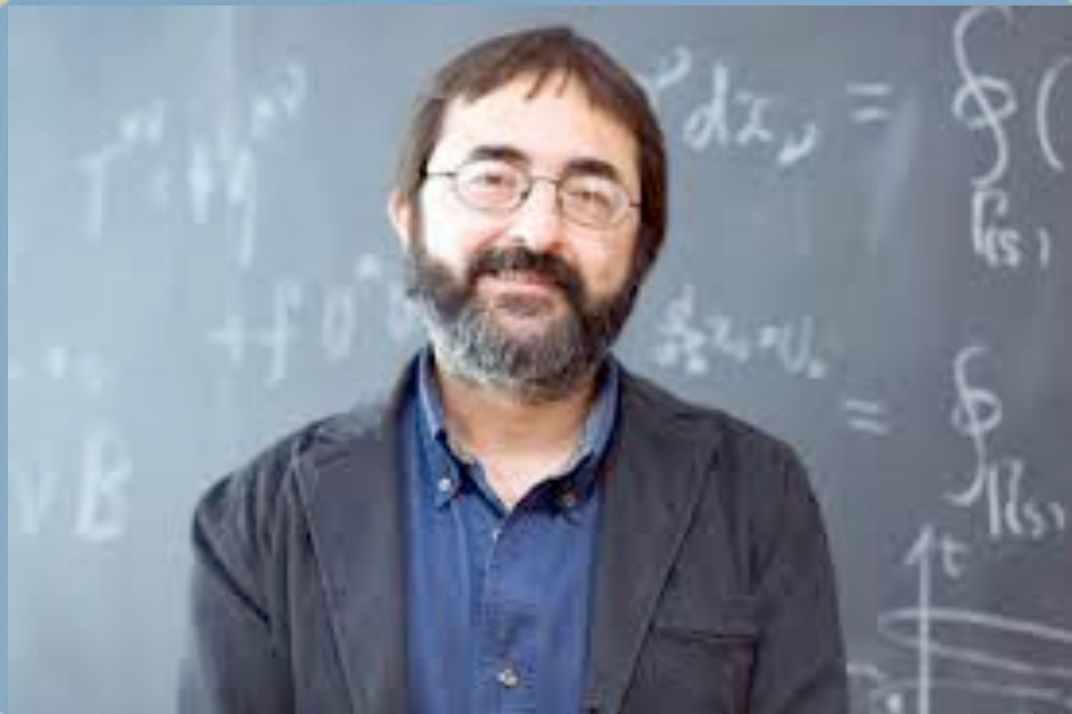
- The full NS and RR axion potential can be written in terms of 4-forms that act as auxiliary fields. In SUSY compactifications the 4-forms behave like SUSY auxiliary fields of Kahler and c.s. chiral multiplets. $F_{aux}^{SUSY} \rightarrow \epsilon_{\mu\nu\rho\sigma} F^{\mu\nu\rho\sigma}$

- All 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, but avoiding too much membrane nucleation makes the possible hierarchies not large. Difficult to embed in string theory.

- Axions coupled to 3-forms can have TeV masses in models with low string scale. The possible 750 GeV state could be such an axion

Thank you !!



Thanks again!!
We are all looking forward to your next seminal contributions !!

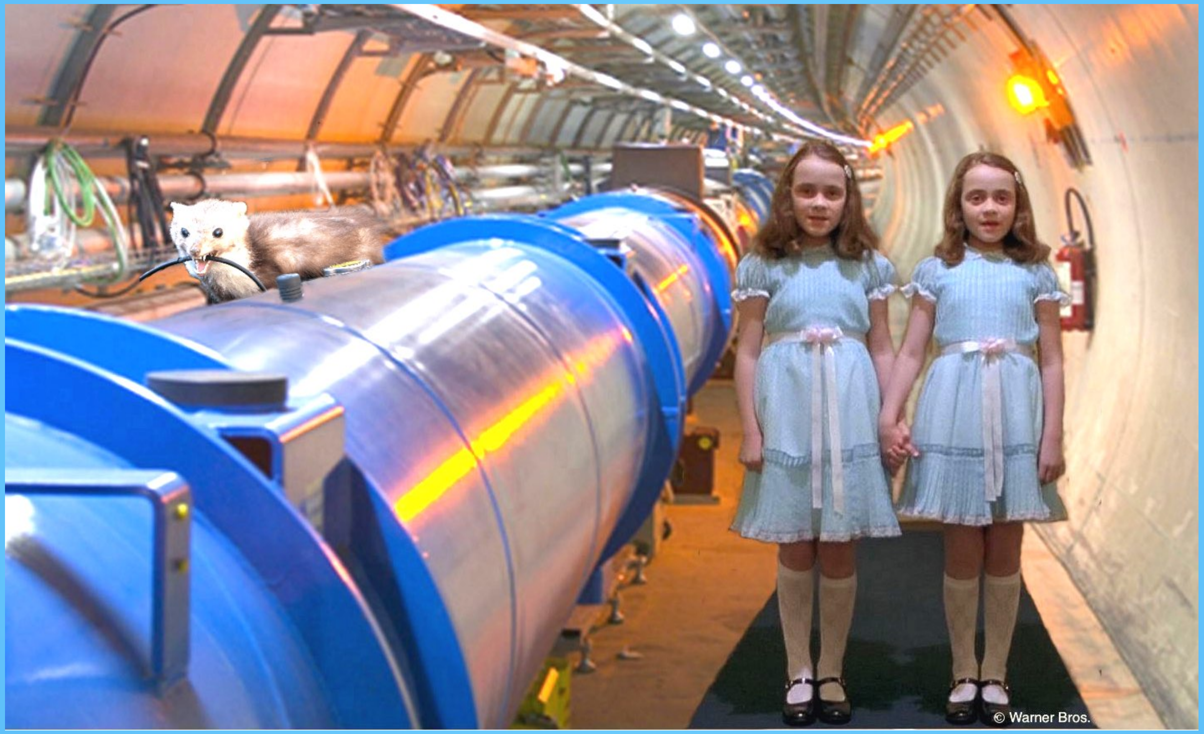
Satigny 2001

Planck 2015, Ioanina


At IFT
2013
the
PHOTO


IFT 2013

IS SUSY ALIVE AND WELL?



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J. Ellis (CERN & King's Coll.)
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