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String Vacua : Implications to Cosmology/Astrophysics

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arXiv: 1803.08941 ; 1809.05060 ; 1901.05075 ; 1909.10525

S.F. King(Southampton) G.G. Ross (Oxford), Q. Shafi(Delaware),

arXiv: 1005.1025 ; 1009.6000 ; 1706.08372 ; 1608.04746

Outline of the Talk

- Introductory remarks
- de Sitter vacua in String Theory?
- Inflation
- $\mathcal{F}$-Theory GUTs and low energy Phenomenology
- Concluding Remarks

A few facts about Cosmology and de Sitter Vacua

▲ *Major Observational Discovery* ~ 20 *years ago:*

$\exists$ ongoing **Accelarating Expansion of the Universe**

▲ *Standard Interpretation:*

Universe dominated by **Dark Energy** permeating all of space

▲ *in G.R. framework:*

... expressed in Einstein's equs with a positive cosmological constant *(see review by Peebles, Ratra: astro-ph/0207347)*:

$\Lambda \approx 10^{-120}$ *(in 4-d Planck units)*

or equivalently,

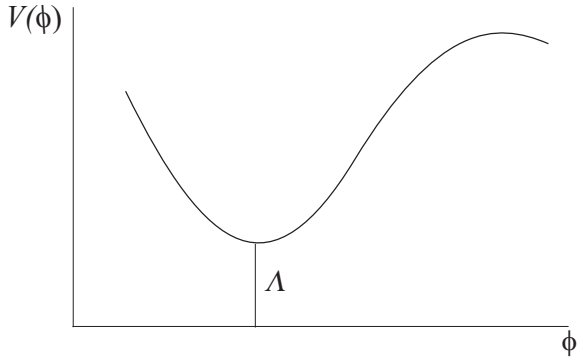
positive vacuum energy

▲ *Simple Effective Field Theory description:*

with a scalar field, ϕ acquiring

Potential Energy $V(\phi)$

with positive vacuum energy:



▲ de Sitter vacua ▲

...with some additional requirements: $\phi \rightarrow$ inflaton

suitable for slow roll inflation

(*see works of Linde, Albrecht, Steinhart, Shafi, Lazarides...*)

However!

▲Finding de Sitter vacua in String Theory is a real challenge ▲

▲ In *String Theory* one starts with 10-d spacetime

$$R^{(3,1)} \times \mathcal{M}^{(6)}$$

▲ $\mathcal{M}^{(6)} \rightarrow$ (compact) Calabi-Yau manifold of radius r_c.

▲ Classical SUGRA Equs invariant under *rescalings* of $r_c \rightarrow$.

$\Rightarrow \forall$ *solution* determining low energy Effective Theory (e.g. SM) ...changing r_c, $\exists$ family of solutions

▲ In 4-dimensions r_c corresponds to a massless scalar field ▲

A more general phenomenon:

▲ Deformations of compactification correspond to

$\Rightarrow$ **massless scalars** (moduli) in 4-dimensions

▲ *Some common classes of moduli*

1. ▲ Dilaton $e^{\phi} = \frac{1}{g_s}$, $(g_s :$ *string coupling*$)$
   Controls the worldsheet perturbative expansion of the theory

2. ▲ Axions
   Harmonic forms -associated with p-form potentials (C_p)- which do not affect the field strengths:

$$F_{p+1} = dC_p$$

   ▲ Scalars C_0, $\phi \rightarrow$ *combined to* **axion-dilaton** *modulus:*

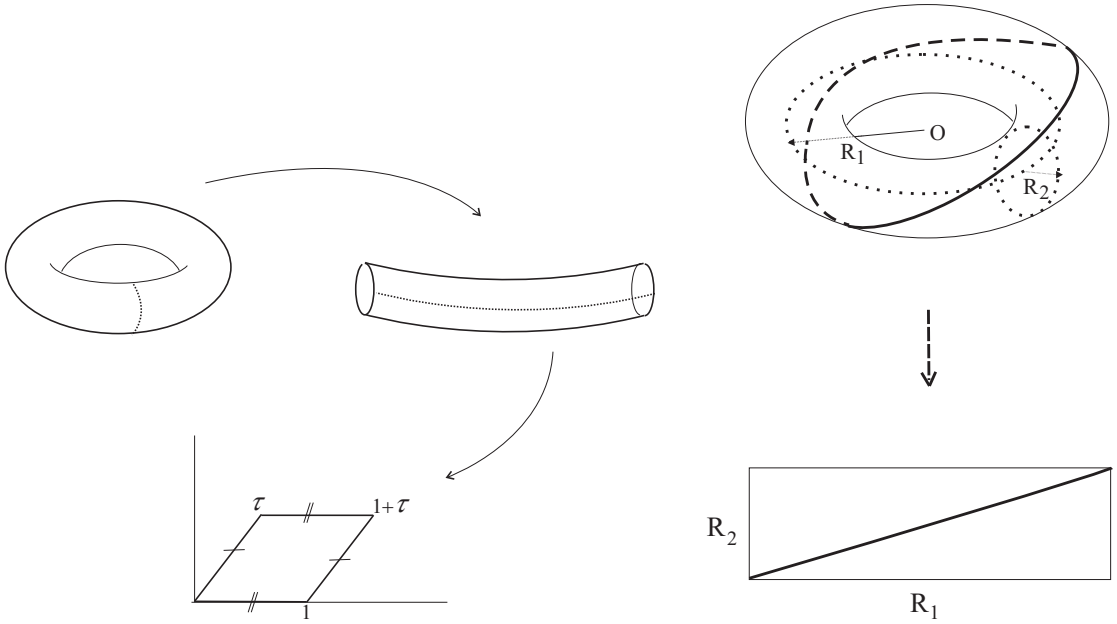
$$S = C_0 + i\, e^{\phi} \rightarrow C_0 + i g_s{}^{-1}$$

3. z_a : *Complex Structure (CS)* moduli$\cdots$*related to shape* $\rightarrow$

... analogous to the complex structure τ of the 2-torus $\mathcal{T}^2$

4. T_i : Kähler (*size*) moduli analogous to the overall size of $\mathcal{T}^2$.

5. Brane deformations (non-perturbative objects)



Left: A 2-torus described by CS structure modulus τ.

Right: A non-perturbative "object" called D-brane is wrapped around a 2-torus ($\mathcal{M}^{(6)}$ usually taken $\mathcal{T}^2 \times \mathcal{T}^2 \times \mathcal{T}^2$)

$\Rightarrow$ *Moduli fields ubiquitous in CY compactifications*

They are characterised by vanishing classical potential $V_{cl.} \equiv 0$

This raises several cosmo/astro issues, associated with:

- Implications on cosmological evolutions
- *Problems in Big-Bang nucleosynthesis*
- If coupled gravitationally to matter $\Rightarrow$ *long range* forces

  ... and a few interesting features:

  ▲ Possible dark matter component

  ▲ Inflaton candidates

▲ Arduous, however Important Task: ▲

to generate a potential (*including quantum corrections*) and assure positive mass-squared for all moduli fields. This is called:

$\Rightarrow$ *Moduli Stabilisation* $\Leftarrow$

Zeitgeist

▲ $\exists$ enormous number of String Vacua forming the so called:
String Landscape ($\mathcal{L}$)

Ongoing debate on the existence of dS vacua $\in \mathcal{L}$

Reason: Some discouraging no-go theorems and conjectures

▲ *Maldacena-Nunez no-go theorem (hep-th/0007018)*:
No stable dS compactifications of 10-d SUGRA

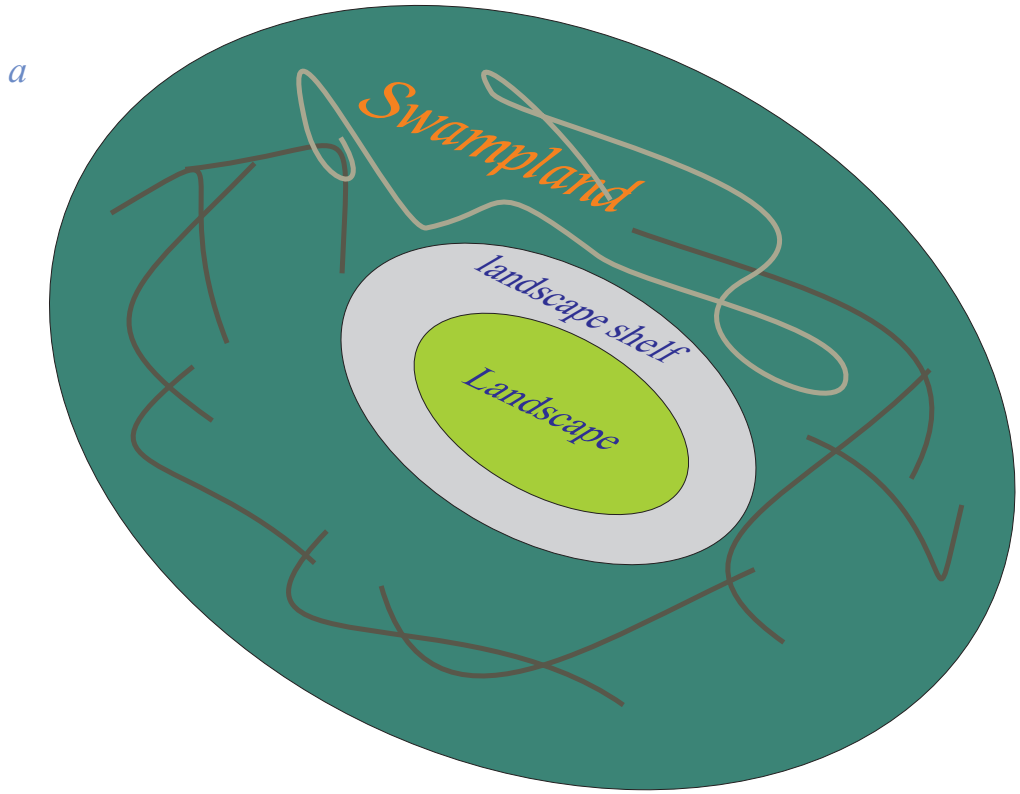
▲ *Vafa et al conjecture (hep-th/1806.08362)*:

The scalar field potential $V(\phi)$ of a consistent field theory (in the sense that $\exists$ UV completion) satisfies constraints such as:

$$\frac{|\nabla V|}{V} \geq \frac{c}{M_{Pl.}} \quad ; \quad \frac{\min(\nabla_i V \nabla_j V)}{V} \leq -\frac{c'}{M_{Pl.}^2}, \; c, c' > 0$$

i.e., according to the spirit of time ... all dS vacua fall into the:

SWAMPLAND!



String landscape is surrounded by a vast swampland of inconsistent field theories of dS vacua... (according to recent conjectures...)

Grayzone populated by 'stringy' dS vacua not unanimously adopted

$\mathcal{A}$

$\mathcal{F}$ist part of this $\mathcal{T}$alk

- Propose a solution to the Moduli Stabilisation problem
- Examine whether a dS vacuum exists in String Theory

($\cdots$ based on **perturbative** quantum corrections only!)

- If yes,

examine if slow roll inflation can be accommodated.

(*Working in the context of* Type II-B effective Supergravity)

Basic 'ingredients':

- Superpotential $\mathcal{W}$ and,
- Kähler potential $\mathcal{K}$ *used to compute the scalar potential of the effective field theory*

▲ Supersymmetric conditions ($\mathcal{W}_0 = f(z_a, S)$ but not of T_i)

$$D_{z_a}\mathcal{W}_0 = 0$$

fix the values of the CS moduli z_a.

▲ Kähler moduli $\notin \mathcal{W}_0 \Rightarrow$ remain unfixed! ▲

▲ The Kähler potential depends on all types of Moduli:

$$\mathcal{K}_0 = -\sum_{i=1}^{3} \ln(-i(T_i - \bar{T}_i)) - \ln(-i(S - \bar{S})) - \ln(i \int \Omega \wedge \bar{\Omega}) \cdot$$

▲ **However**, at the classical level the scalar potential is **identically** zero

$$V \quad = \quad e^{\mathcal{K}} (\sum_{I,J} \mathcal{D}_I \mathcal{W}_0 \mathcal{K}_0^{I\bar{J}} \mathcal{D}_{\bar{J}} \mathcal{W}_0 - 3|\mathcal{W}_0|^2) \equiv 0$$

$\Rightarrow$ ...due to **no scale** structure of the Kähler potential, the Kähler moduli remain completely **undetermined** !

$\Rightarrow$ ...need to include **Quantum corrections** ...

"breaking" no-scale structure:

two types:

1. α'-corrections (*Beckers, Haack, Louis, hep-th:0204254*)

$$\xi = -\frac{\zeta(3)}{4(2\pi)^3}\chi$$

2. Perturbative string loop-corrections

   important in the presence of D-branes

   (*Antoniadis, Chen, G.K.L.: hep-th/1803.08941, 1909.10525*)

$$\delta = \sum_{i=1}^{3} \gamma_i \log(\tau_i)$$

▲▲ Then, Kähler potential takes the form:

$$\mathcal{K} \quad = \quad -\ln[-i(S-\bar{S})] - 2\ln\left(\hat{\mathcal{V}} + \hat{\xi} + \hat{\delta}\right)$$

where the compactification 6-d volume $\mathcal{V}$ is a function of the Kähler moduli, taken here to be

$$\mathcal{V}(\tau_i) = \sqrt{\tau_1\tau_2\tau_3}$$

▲▼ ξ and δ break **no-scale** structure of Kähler potential.

Minimisation of $V_{\rm eff}$ implies a positive minimum

$$V_{\rm eff} \propto \gamma\frac{\ln\mathcal{V} - 4}{\mathcal{V}^3} + \frac{d}{\mathcal{V}^2} > 0$$

for suitable parameter space $\gamma,\ d$

INFLATION

I. Antoniadis, Y. Chen, GKL

(*hep-th/1809.05060*)

Although a dS minimum exists, allowed region too restrictive.
Additional requirements for slow-roll inflation hard to be met.

way out of this impasse ?

introducing a nilpotent field X, $X^2 = 0$, it uplifts the scalar potential

$$V_{up} = \frac{f^2}{\mathcal{V}^{2-2n}}$$

▲ Total scalar potential

$$V_{total} = V + V_{up}$$

Slow-roll inflation occurs when a scalar field ϕ starting from top of the potential $V(\phi)$, rolls down slowly compared to Universe's expansion $H = \frac{\dot{a}}{a}$.
Then, equation of motion can be approximated:

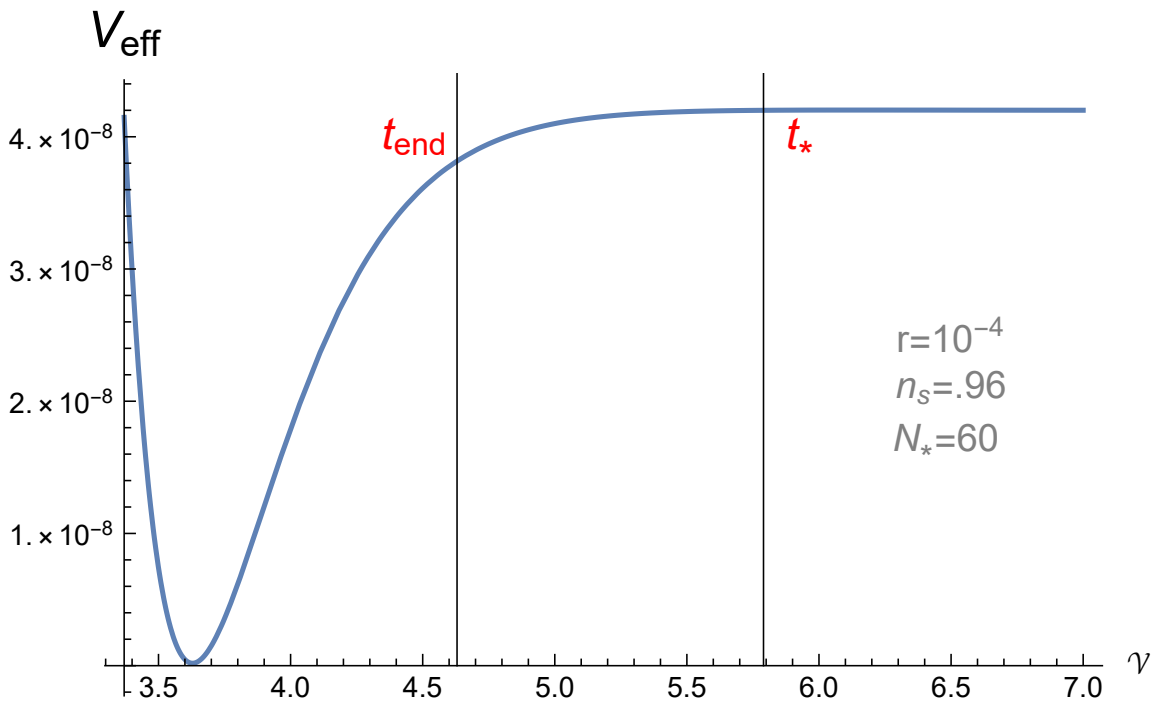
$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) \approx 3H\dot{\phi} + V'(\phi) = 0$$

• Then, slow-roll conditions follow and are satisfied in this model.
In particular:
Number of e-folds:

$$N_* = \int_{t_{end}}^{t_*} \frac{V}{V_t} dt \sim 50 - 60$$

Spectral index (*variation of density perturbations w.r.t. scale*):

$$n_s = 1 - 3\left(\frac{V_t}{V}\right)^2 + 2\frac{V_{tt}}{V}\bigg|_{t_*} \approx 0.96$$



Plot of $V_{\rm eff}$ *vs* $\mathcal{V}$. *Inflation occurs between* t_* *and* t_{end}

Part $\mathcal{B}$

GUTs *from a Geometric perspective of String Theory*

a.k.a.

F-theory

(*C. Vafa 1996*)

Ordinary GUTs vs F-GUTs

★ interesting features

▲ Gauge coupling unification

▲ Assembling of SM fermions in a few irreps. ($\in \bar{5}$, 10.)

▲ Charge Quantisation

★ deficiencies

▲ fermion mass hierarchy and mixing not predicted

▲ Yukawa Lagrangian poorly constrained

▲ Baryon number non-conservation

... Solution requires new insights ... such as:
Discrete and $U(1)$ symmetry extensions

▲ These appear naturally in F-Theory constructions ▲

New Ingredients from F-theory

★ Discrete and $U(1)$ symmetries:

• necessary tools to suppress or eliminate undesired superpotential terms

★ Fluxes :

• ... truncate GUT irreps, eliminate coloured Higgs triplets, induce chirality...

★ "Internal" Geometry :

• ... determines SM arbitrary parameters from a handful of topological properties

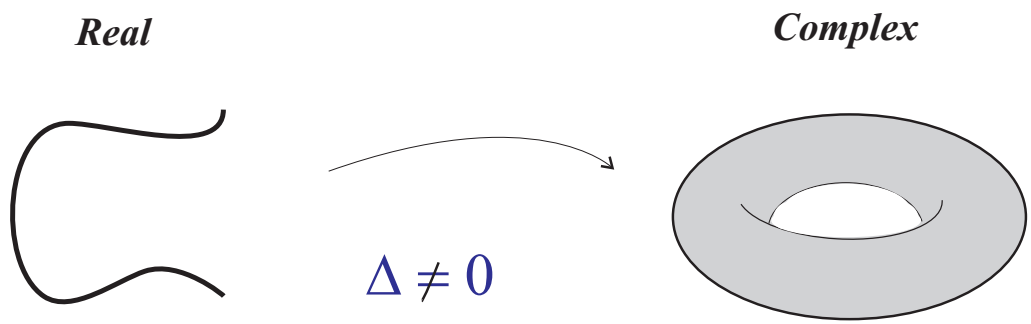
F-theory and Elliptic Fibration

(explaining with a few pictures ...)

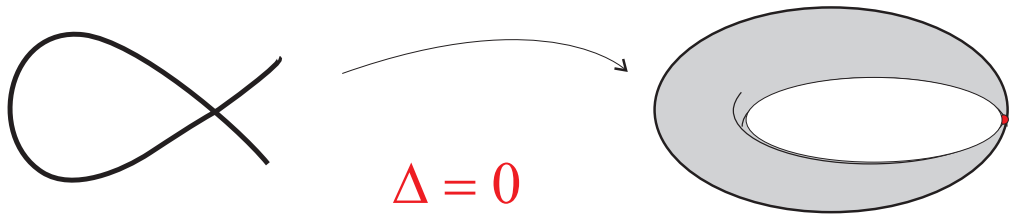
...let's first recall some mathematical facts...

★ **Weierstrass** equation (complex coefficients → torus)

$$y^2 = x^3 + fx + g$$



non-singular elliptic curve



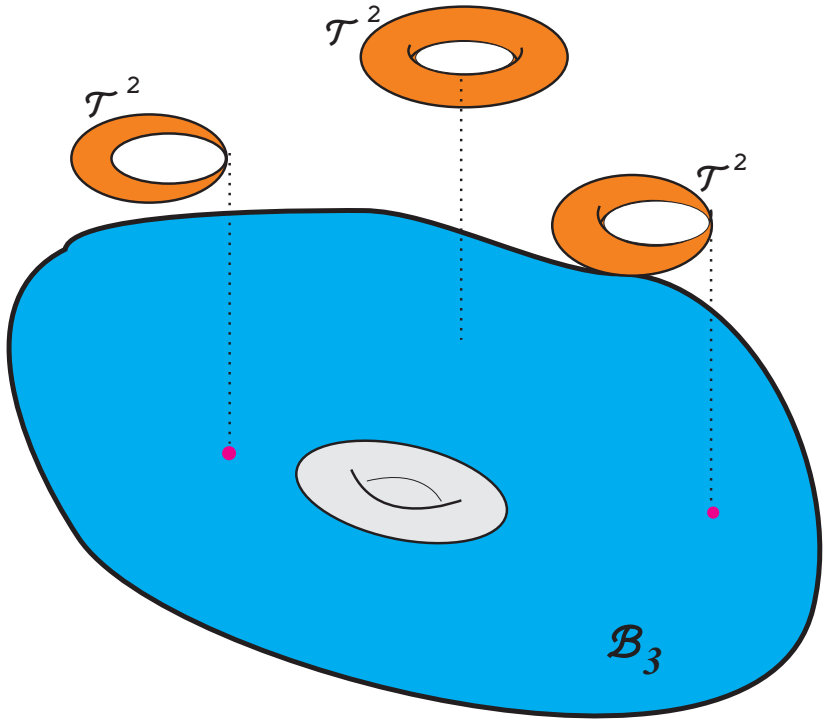
singular elliptic curve

Non-singular curve "upgrades" to normal torus

Singular curve corresponds to torus with a pinched radius.

In F-theory the internal space is "*enhanced*" by two extra "*dimensions*" of a torus $S = C_0 + ie^{-\phi}$ (recall $C_0, e^{\phi} \to$ moduli) and it is described by the $\mathcal{W}$eierstraß $\mathcal{E}$quation

This is called $\to$ *elliptic fibration*



$\exists$ singularities of fibration (red points: pinched torus)

Interpretation: $\exists$ non-perturbative 'objects', a.k.a. 7-branes $\perp B_3$

These geometric singularities have been classified by mathematicians (Kodaira '60s) and it was found that they belong to one of the Lie group structures $\mathcal{A}, \mathcal{D}, \mathcal{E}$.

Interpretation of geometric singularities

$$\Downarrow$$

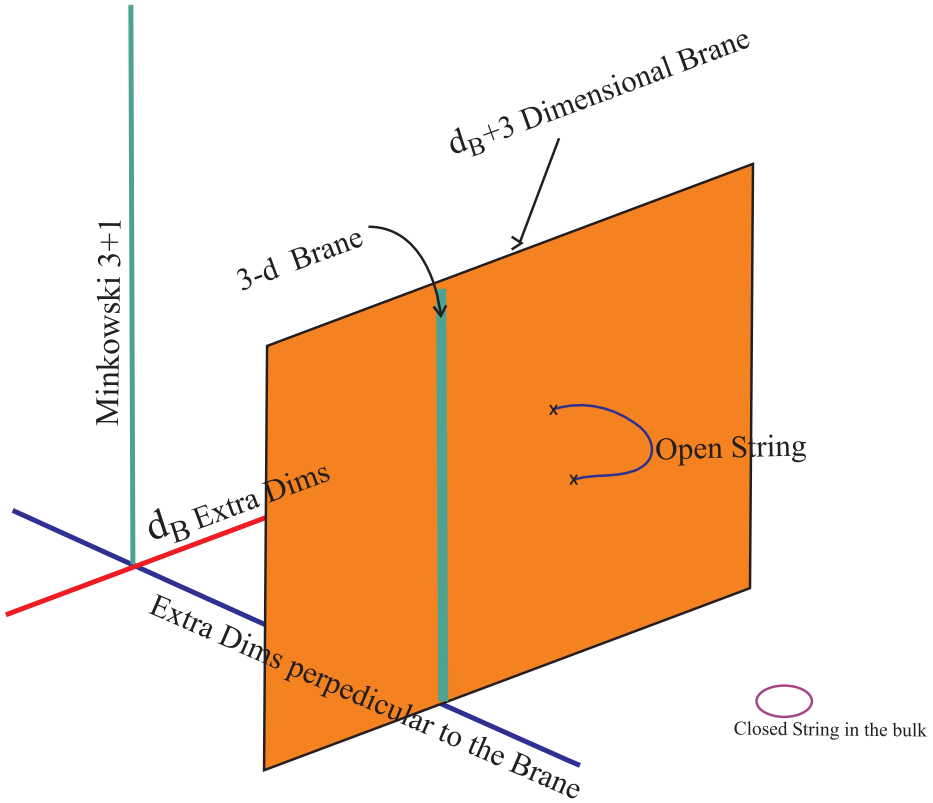
$$\boxed{CY_4\text{-}\textbf{Singularities} \rightleftarrows \textbf{gauge symmetries}}$$

$$\textbf{Groups} \quad \rightarrow \quad \begin{cases} \mathcal{A} \rightarrow SU(n) \\ \mathcal{D} \rightarrow SO(m) \\ \mathcal{E}_n \ (exceptional\, \mathcal{E}_{8,7,6,\ldots}) \end{cases}$$

The Kodaira classification: w.r.t. vanishing order of the polynomials f, g and the discriminant $\Delta = 4f^3 + 27g^2$.
(see Morrison, Vafa hep-th/9603161)

ord(f)	ord(g)	ord(Δ)	fiber type	Singularity
0	0	n	I_n	A_{n-1}
≥ 1	1	2	II	none
1	≥ 2	3	III	A_1
≥ 2	2	4	IV	A_2
2	≥ 3	$n+6$	I_n^*	D_{n+4}
≥ 2	3	$n+6$	I_n^*	D_{n+4}
≥ 3	4	8	IV^*	$\mathcal{E}_6$
3	≥ 5	9	III^*	$\mathcal{E}_7$
≥ 4	5	10	II^*	$\mathcal{E}_8$

Basic ingredient in F-theory: 7 - brane



Example of a brane immersed in the higher dimensional space.

▲ GUTs are associated with 7-branes wrapping certain classes of *'internal'* **2-complex dim.** surface: **S** $\subset B_3$.

▲ Other 7-branes in transverse dimensions, intersect **S**.

▲ MSSM particles reside on these Riemann Surfaces.

▲ $\lambda_{t,b}$-Yukawas localised at triple intersections

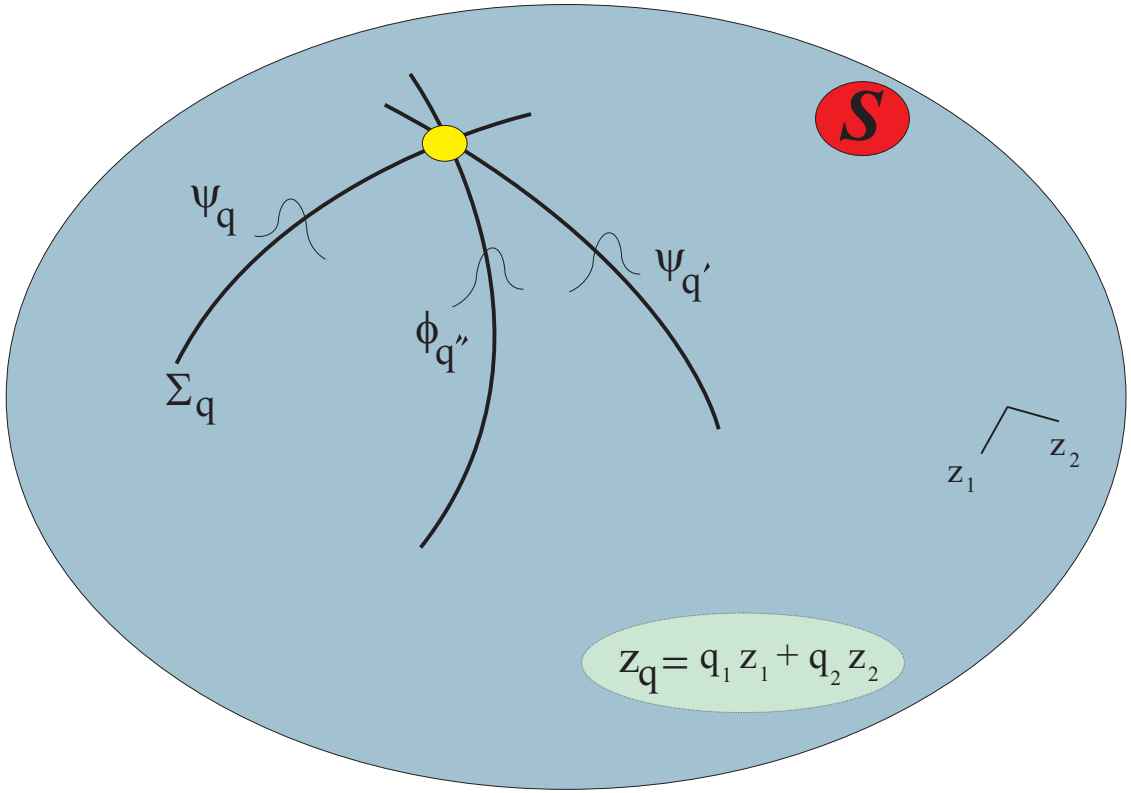
▲ Solving a system of EoM one finds that:

▲ Matter and Higgs Particles characterised by Wavefunctions with Gaussian profile:

$$\psi \sim f(z_i) e^{-M|z_i|^2}$$

Strength of Yukawa coupling $\propto$ integral of overlapping ψ's

$$\lambda_{ij} \propto \int \psi_i(z_1, z_2)\psi_j(z_1, z_2)\psi_H(z_1, z_2)dz_1 \wedge dz_2$$



Phenomenology

Using stringy mechanisms (e.g. fluxes, Wilson lines...), original Exceptional group $\mathcal{E}_8$ breaks down to

$$\mathcal{E}_8 \supset SU(5) \times SU(5)_\perp \supset SU(5) \times U(1)^n,\ 1 \leq n < 4$$

▲ $U(1)$'s act as family symmetries

▲ Note that $SU(5)_\perp \to U(1)^4$

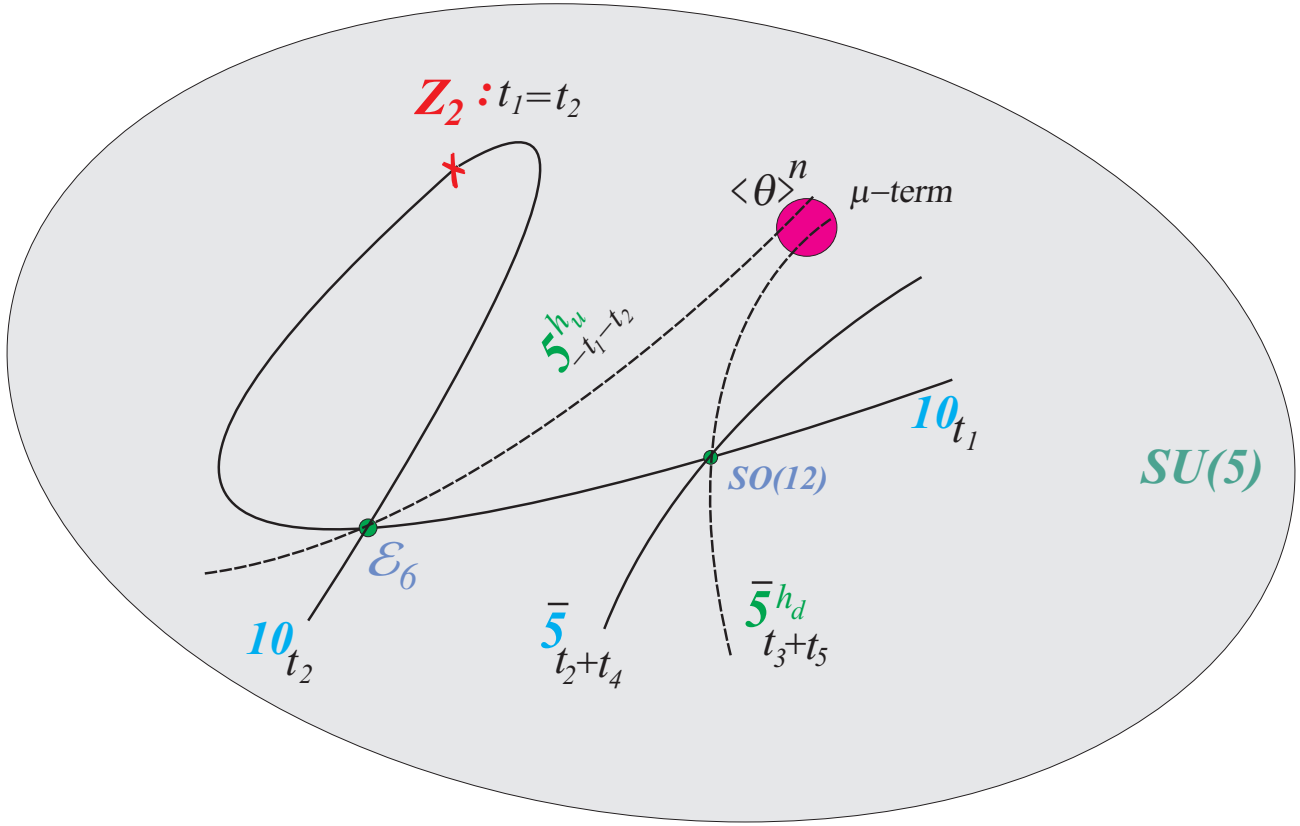
but... monodromies ($=Z_k$), identify some of the $U(1)$'s

Example of a Z_2-monodromy model (GKL & GG Ross 1009.6000)

$SU(5), U(1)_i$	SM spectrum	Exotics	R-parity
$10_i, t_i$	Q_i, u_i^c, e_i^c	–	–
$\bar{5}_1, t_3 + t_4$	d_1^c, ℓ_1	–	–
$\bar{5}_2, t_1 + t_3$	d_2^c, ℓ_2	–	–
$\bar{5}_3, t_1 + t_4$	d_3^c, ℓ_3	–	–
$5_{H_u}, -2t_1$	H_u	D	+
$\bar{5}_{H_d}, t_3 + t_5$	H_d	–	+
$5_x, -(t_1 + t_5)$	–	$(H_{u_i}, D_i)_{i=1,\ldots,n}$	+
$\bar{5}_{\bar{x}}, t_4 + t_5$	–	$D^c + (H_{d_i}, D_i^c)_{i=1,\ldots,n}$	+
$\theta_{12,21}, \theta_0$		S (singlets)	–

(for phenomenological aspects see GKL and Q. Shafi: 1706.08372)

Geometric picture of a generic $SU(5)$ model with Z_2 monodromy



Resulting quark mass matrices of Froggatt-Nielsen type,
for example:

$$M_u = \begin{pmatrix} 0.09\,\theta_{14}^2\theta_{43}^2 & 0.22\,\theta_{14}^2\theta_{43} & 0.16\,\theta_{14}\theta_{43} \\ 0.22\,\theta_{14}^2\theta_{43} & 0.18\,\theta_{14}^2 & 0.22\,\theta_{14} \\ 0.16\,\theta_{14}\theta_{43} & 0.22\,\theta_{14} & 0.35 \end{pmatrix}$$

where θ_{ij} singlets with VEVs $\sim 10^{-1}$.

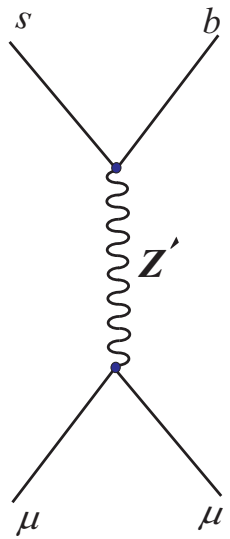
In general, F-models predict
i) Heavy Quark/LeptoQuark states in vector-like pairs

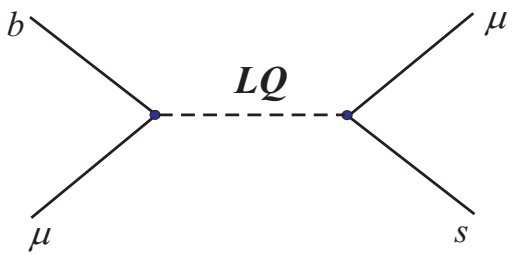
$$Q + \bar{Q},\ D + \bar{D}, \cdots$$

(*In some cases their masses can be in the few TeV range.*)
ii) neutral gauge bosons Z', which couple differently to families,
violating:

Lepton Flavour Universality

Graphs: Z' boson and Leptoquark contributions to $b \to s\mu^+\mu^-$





focusing on B-meson anomalies...

Z' contribution to $B^+ \to K^+\mu^+\mu^-$ (*see 1710.02349*)

★ Conclusions ★

Interesting Predictions of Effective String Theory Models

Plenty of scalars (moduli) with implications:

- Cosmological Evolution, Inflation
- Localised, long-lived, non-linear excitations (Astrophysics)

BSM Physics:

- Heavy Quark states (usually vector-like $Q + \bar{Q}$, $D + \bar{D}$)
- Novel neutrino states ("sterile?") and,

KK-excitations→ heavy N^c's.

Z' bosons non-universaly coupled to families, possibly related to (B-meson anomalies, cosmic rays...)

THANK YOU