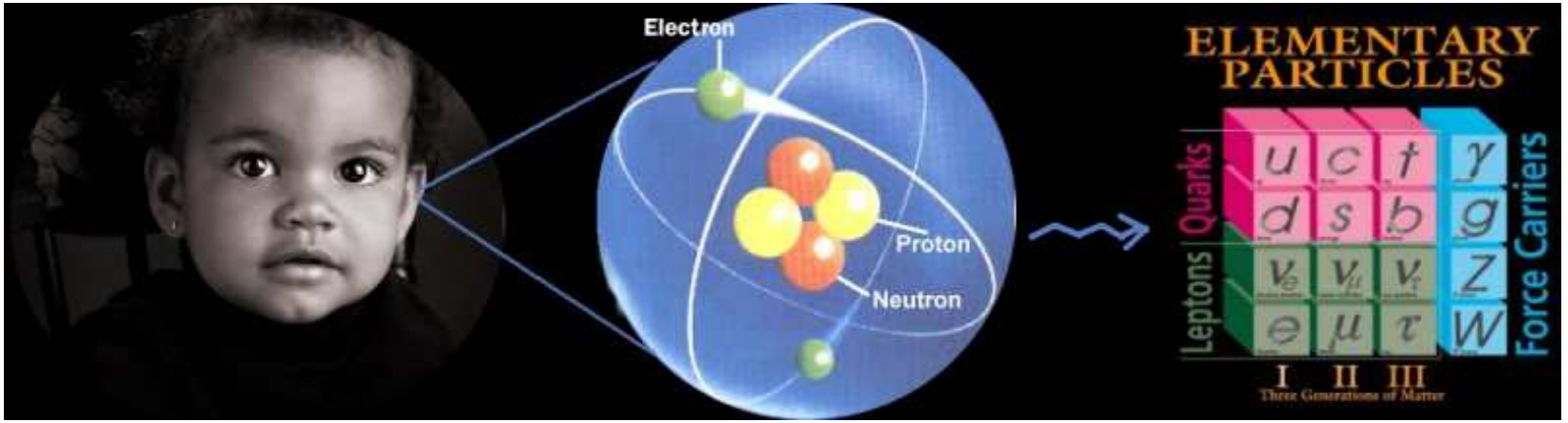
Challenges of string theory: particle physics and cosmology

Saúl Ramos-Sánchez

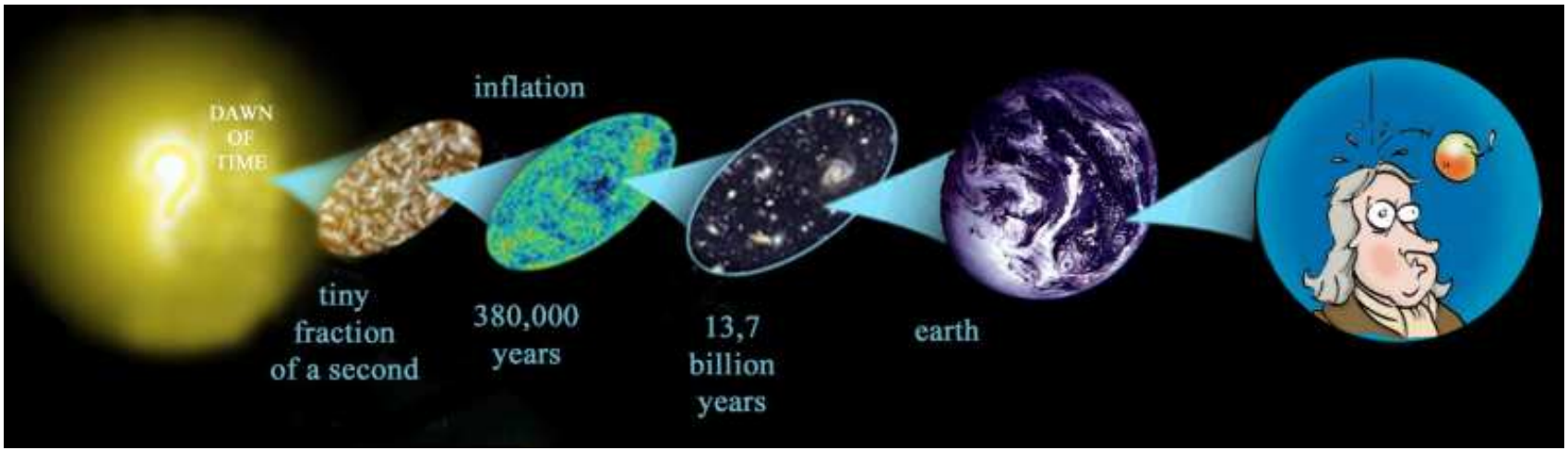
XIII Mexican Workshop on Particles and Fields

October 20, 2011

What do we know?



SM = QCD $(\mathrm{SU}(3))$ + EW $(\mathrm{SU}(2)\times\mathrm{U}(1)_Y)$ ☺

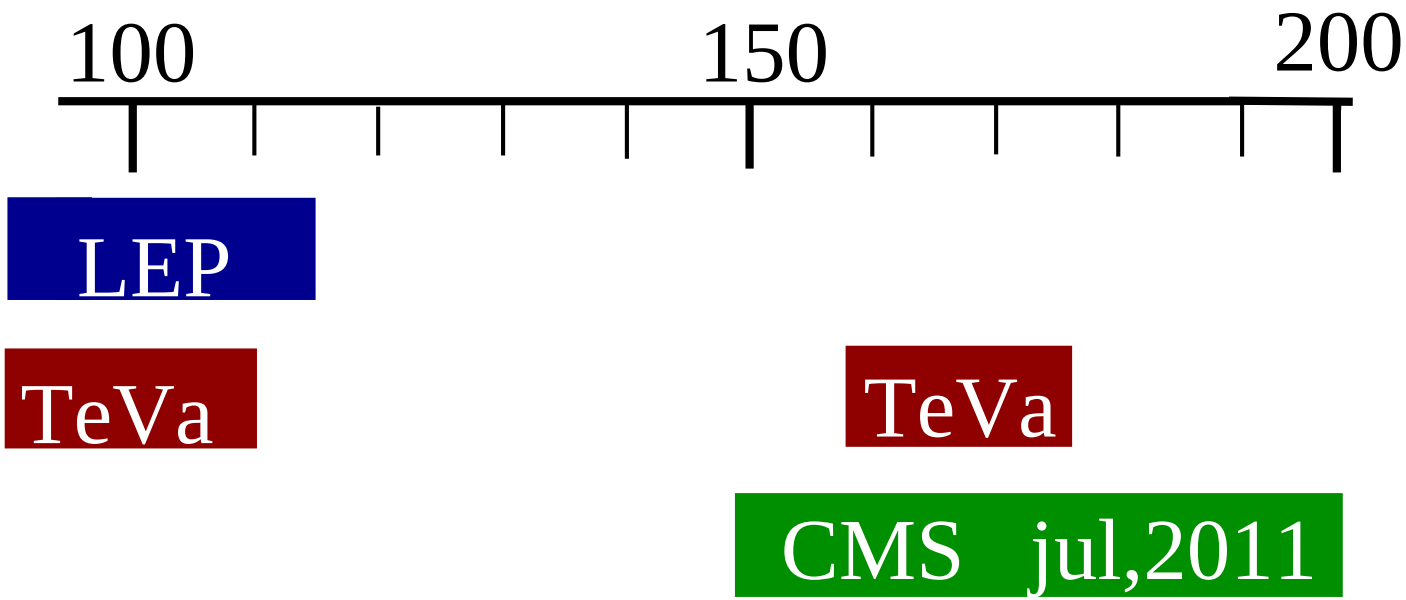


General relativity: Cosmology ☺

Urge to go beyond SM...

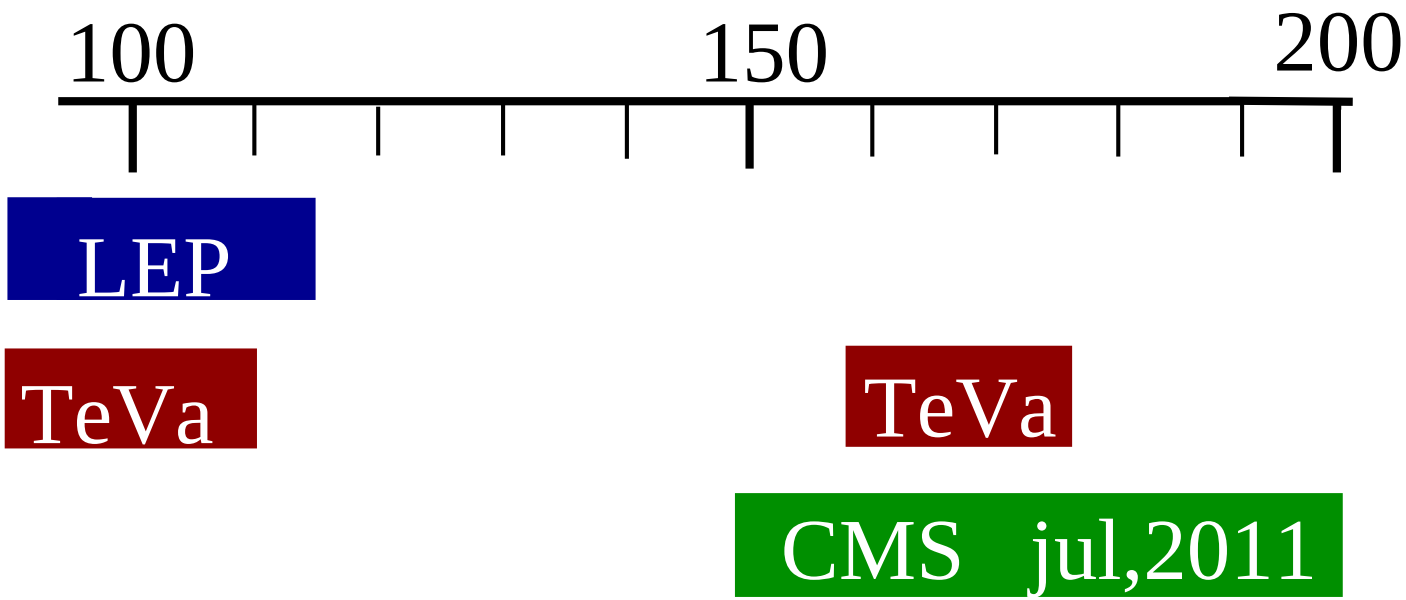
Urge to go beyond SM...

Urge to go beyond SM...



$$115 < m_H < 145 \text{ GeV}$$

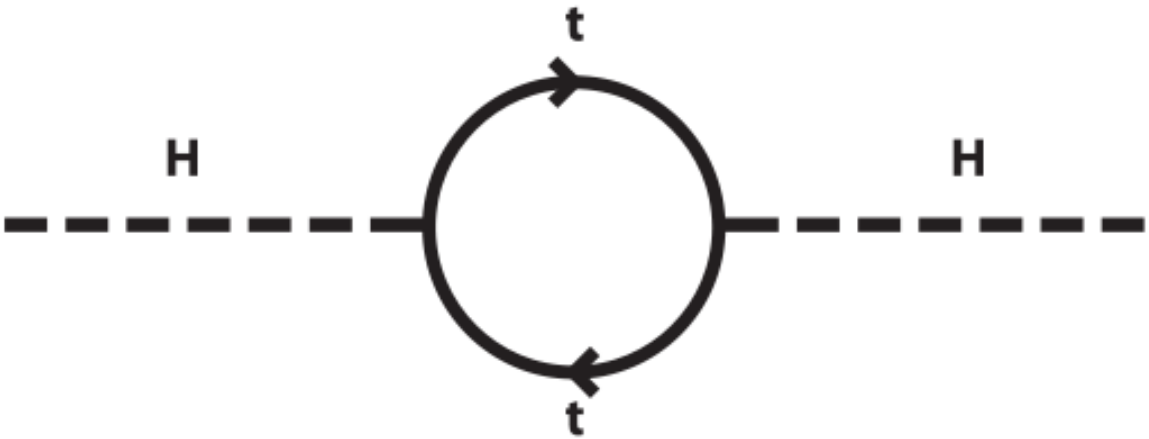
Urge to go beyond SM...



$$115 < m_H < 145 \text{ GeV}$$

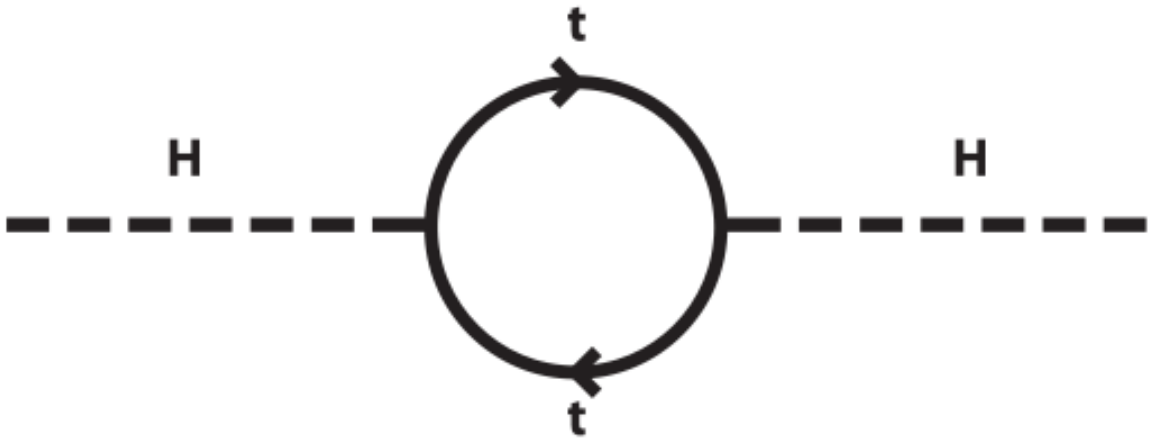
Why?

Urge to go beyond SM...



$$\Rightarrow \quad \Delta m_H^2 \sim \Lambda^2$$

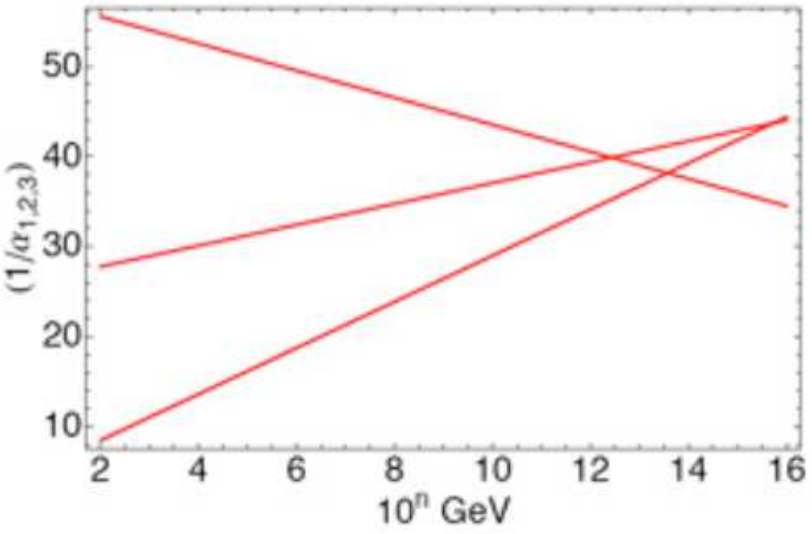
Urge to go beyond SM...

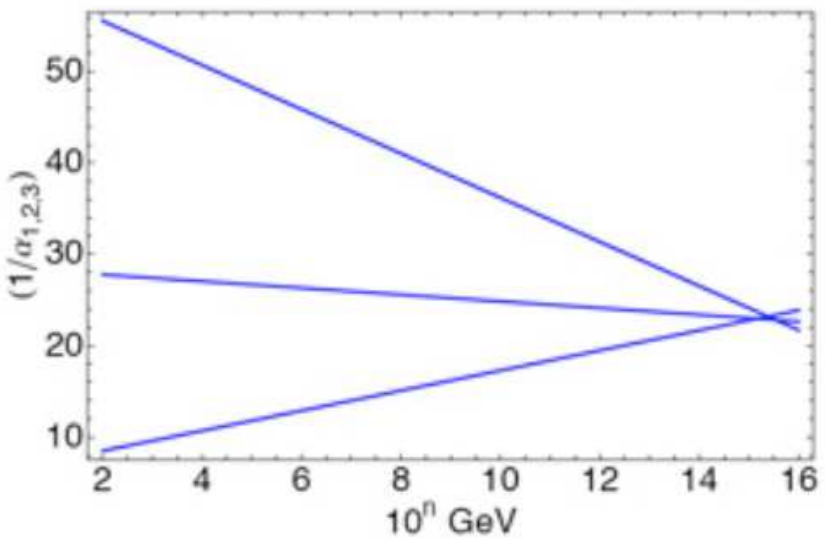


$+$ SUSY @ $E \sim$ TeV ?

$$\Rightarrow \quad \Delta m_H^2 \sim \Lambda^2 - \Lambda^2$$

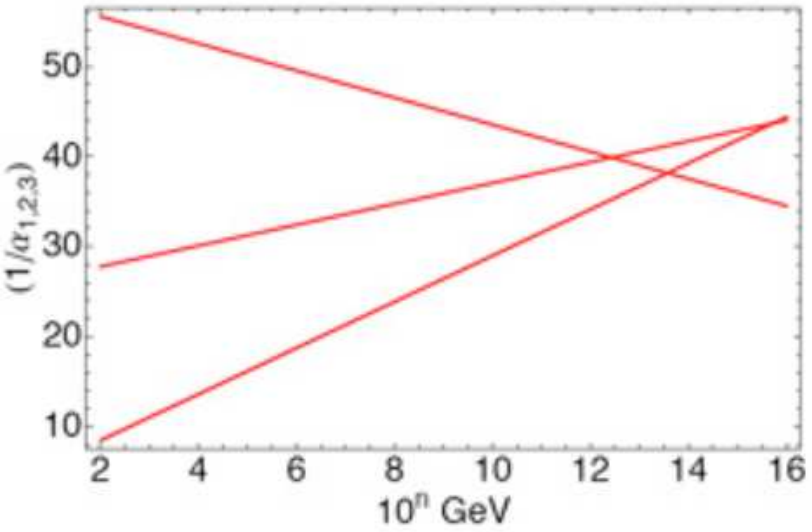
Urge to go beyond SM...

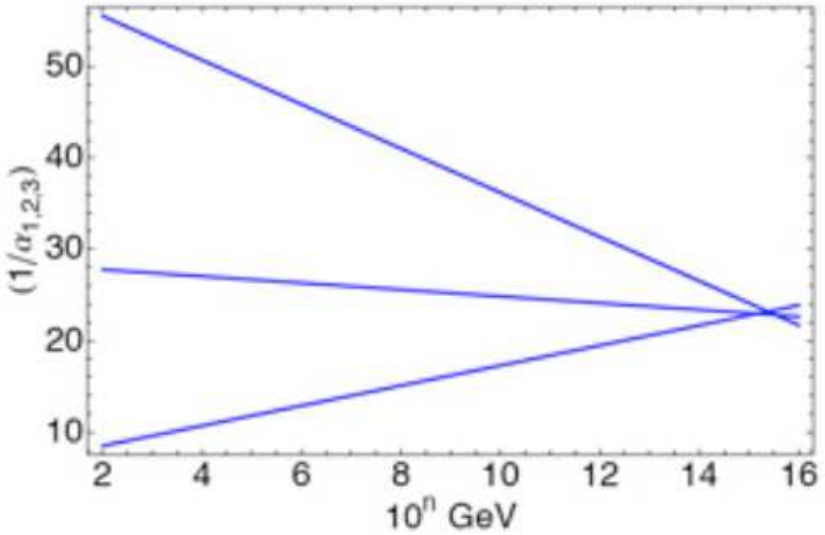




Why?

Urge to go beyond SM...

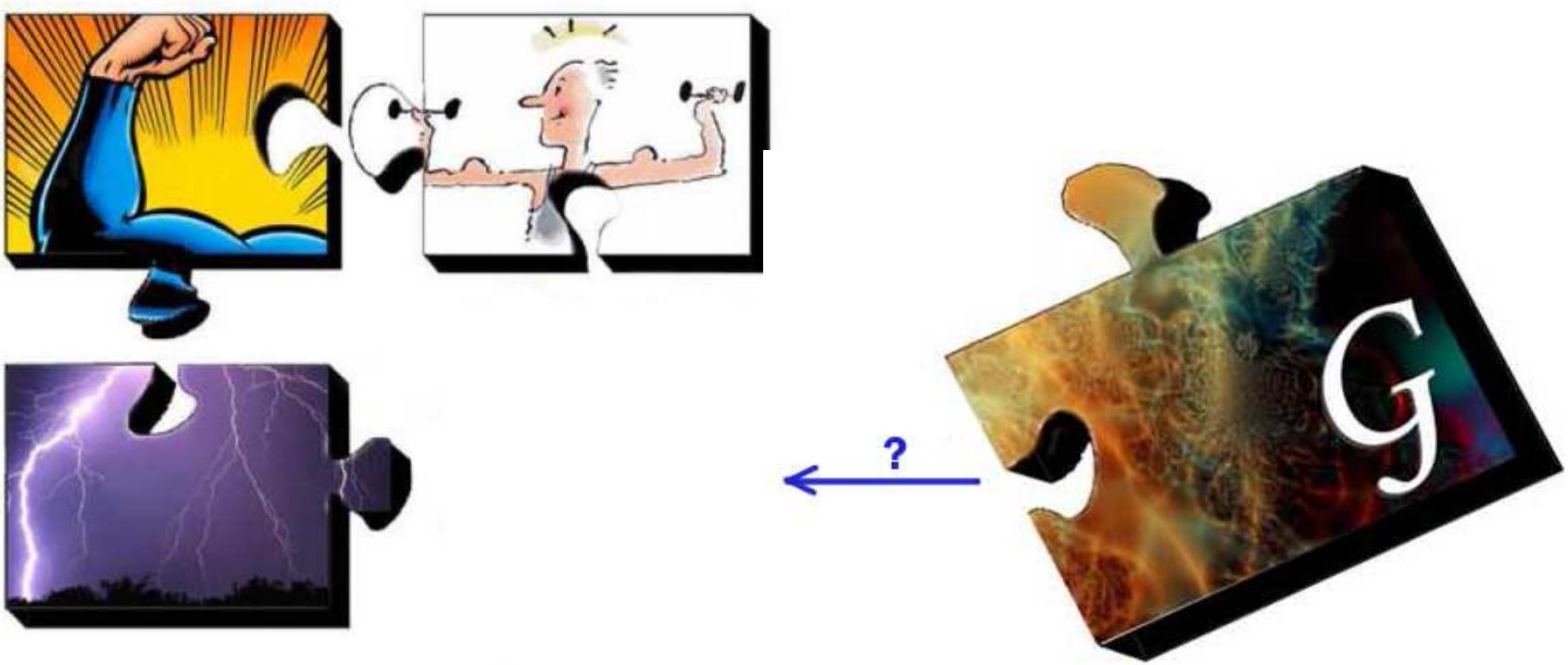




Why?

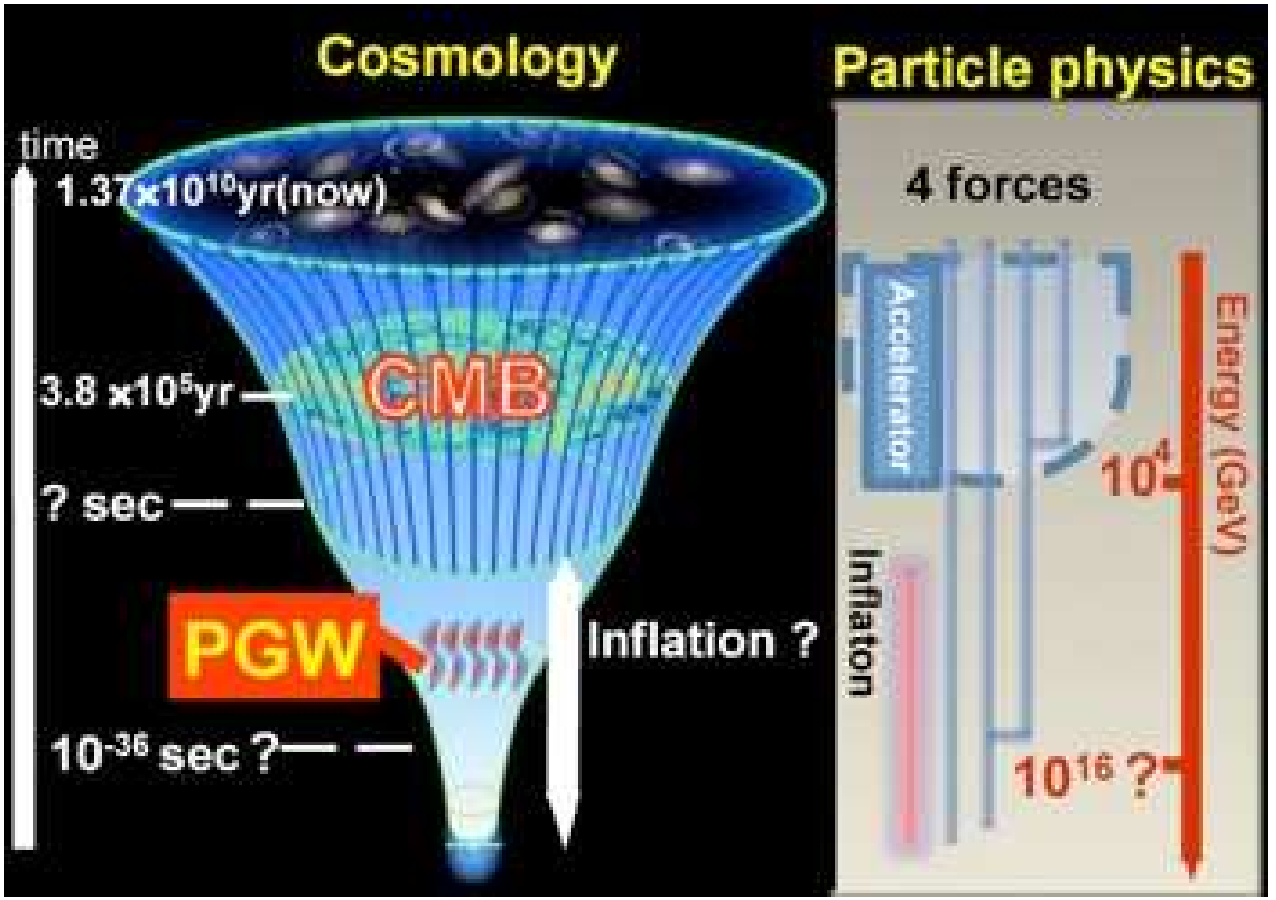
GUTs?

Urge to go beyond SM...



Quantum Gravity ?

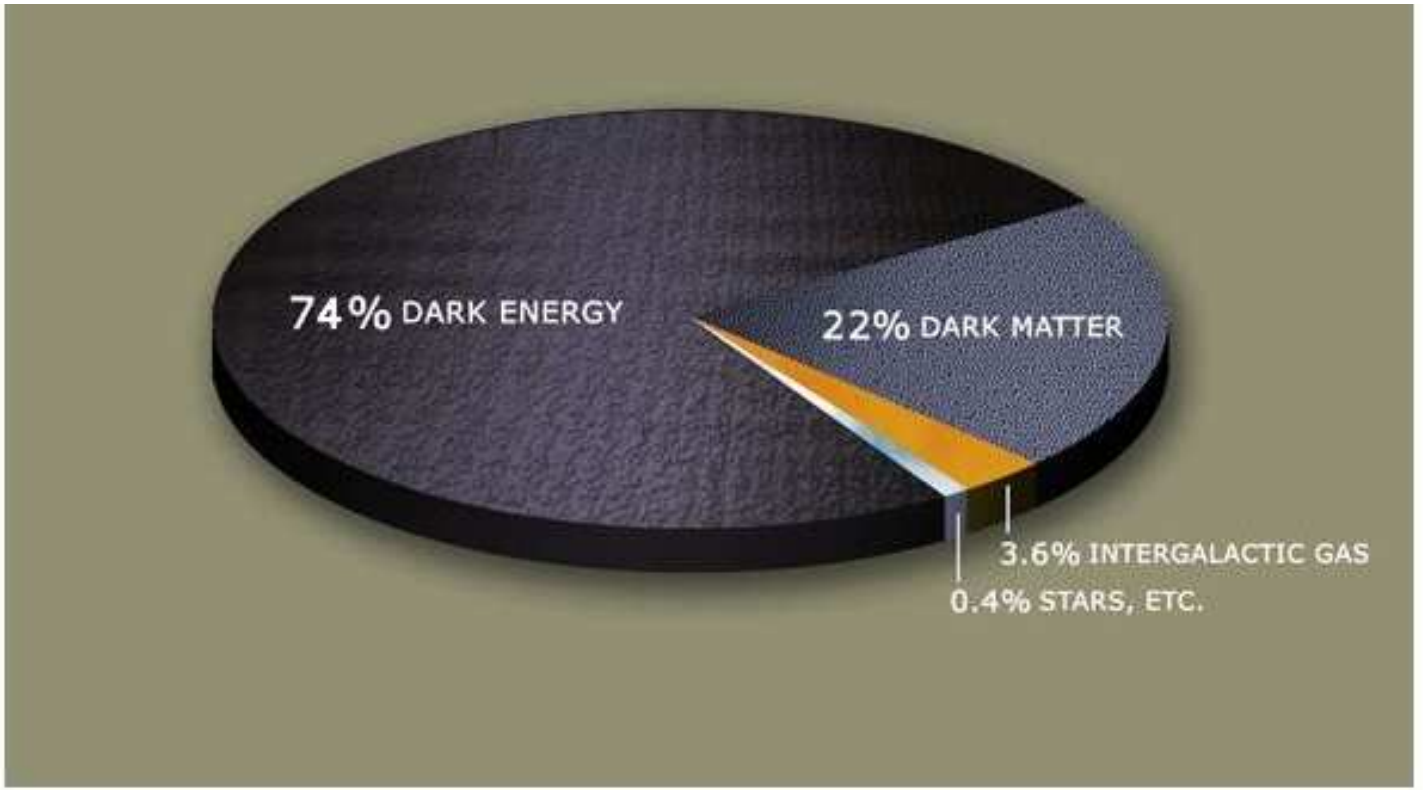
Urge to go beyond ΛCDM...



$$V(\varphi) \ = \ ?$$

What is φ ?

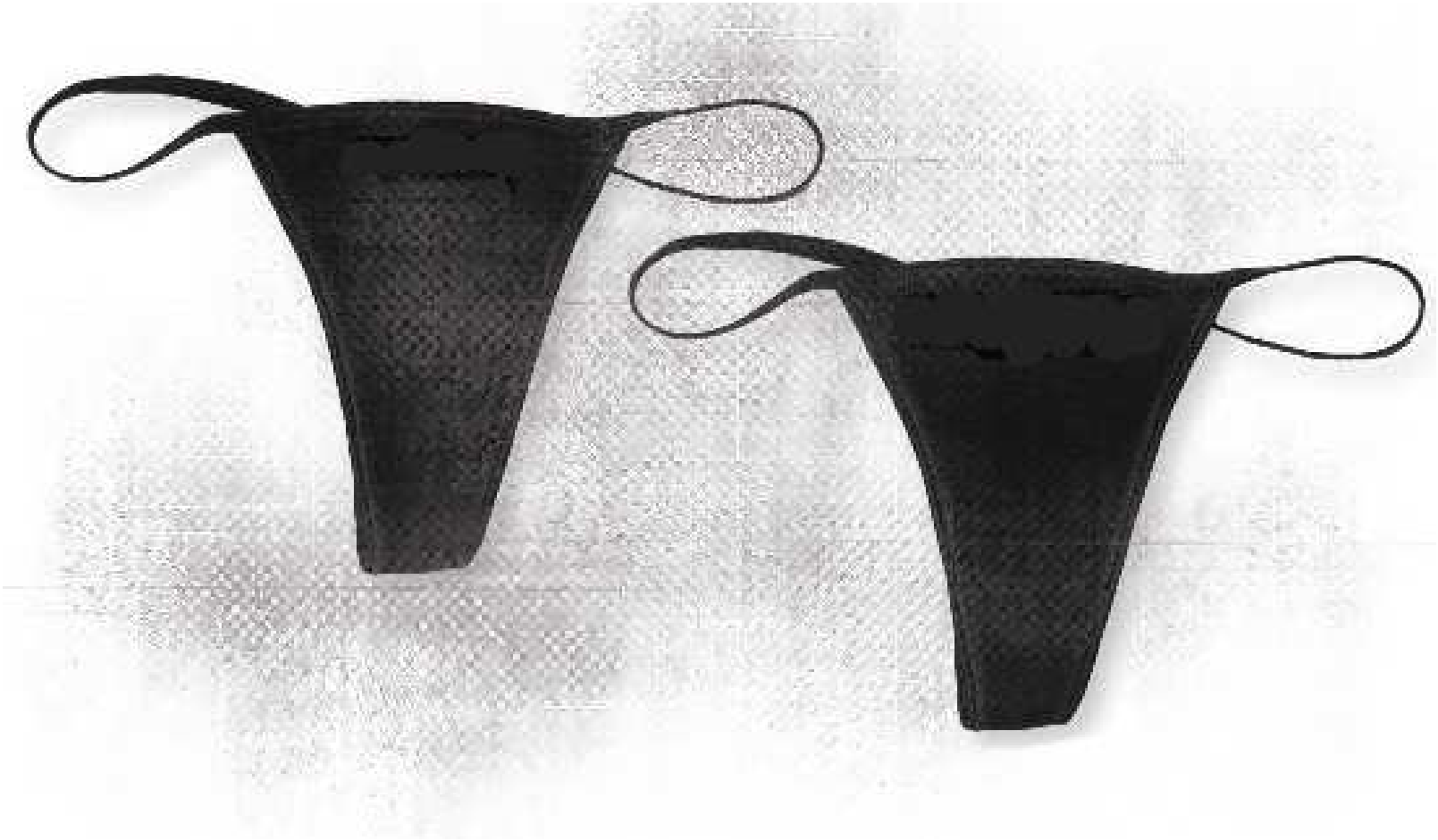
Urge to go beyond ΛCDM...



dark matter: neutralino, gravitino, ... ?

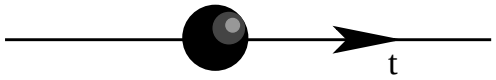
dark energy: $\Lambda \sim 10^{-120}$, chameleon, ... ?

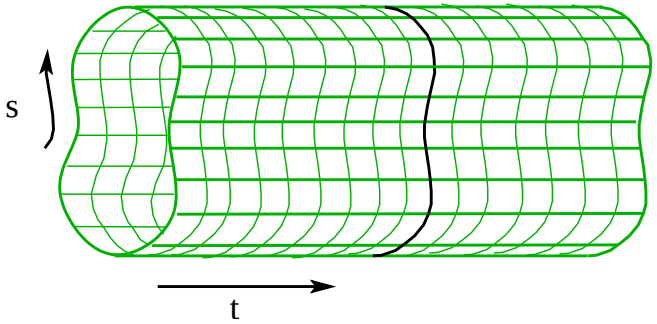
String Theory



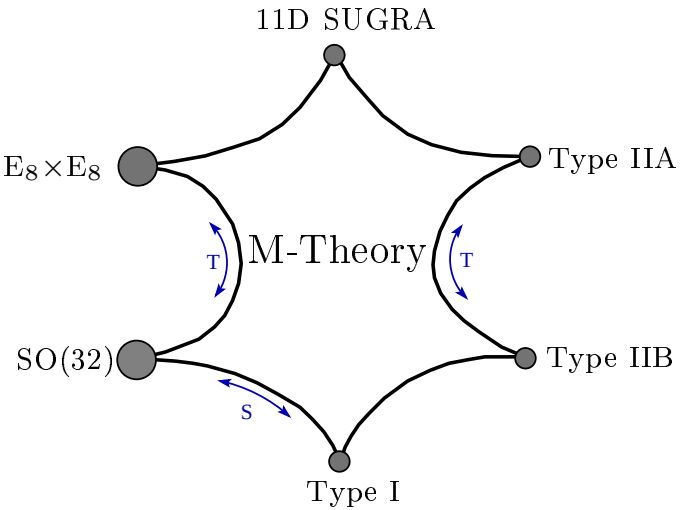
Cuerdas

1970's: particles $\rightarrow$ strings





80-90's: 5 theories of superstrings (+branes)



quantum consistency

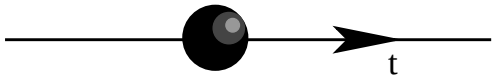
(no anomalies, "ghosts", tachyons):

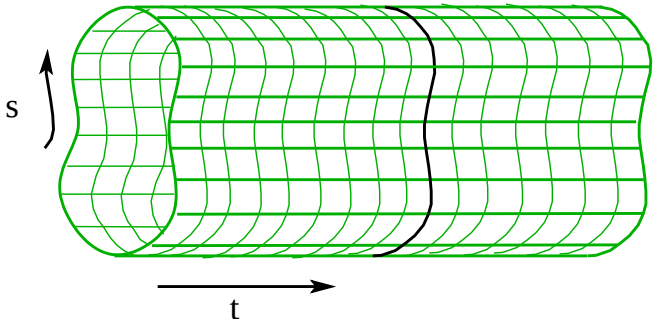
$\rightarrow$

* graviton included
* gauge bosons
* supersymmetry
* 10 dimensions

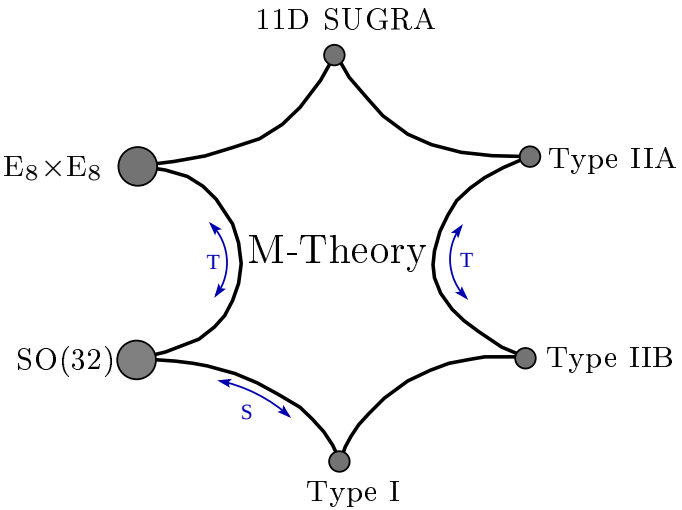
Cuerdas

1970's: particles $\rightarrow$ strings





80-90's: 5 theories of superstrings (+branes)



quantum consistency

(no anomalies, "ghosts", tachyons):

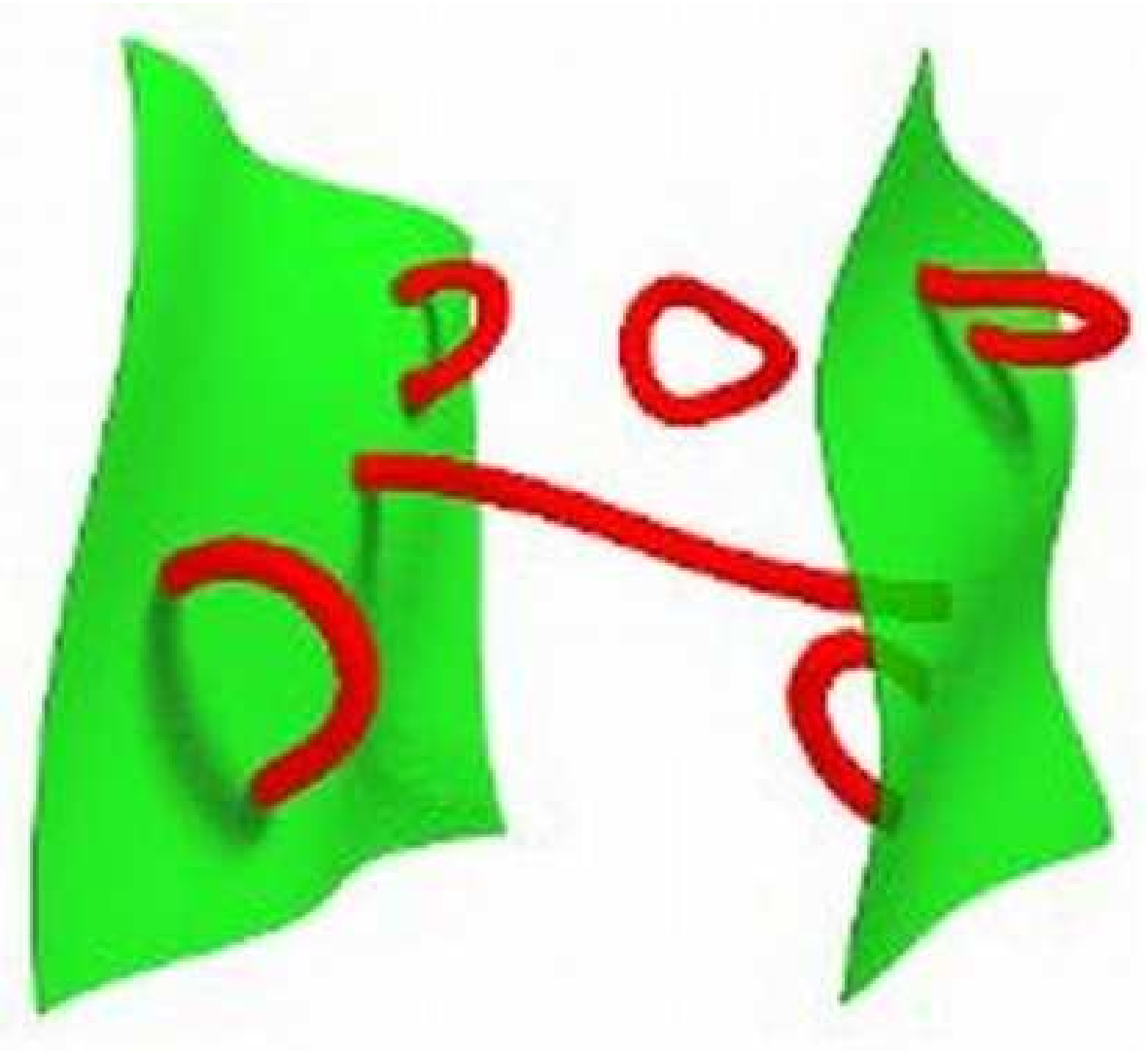
$\rightarrow$

* graviton included ☺
* gauge bosons ☺
* supersymmetry ☺ ☹
* 10 dimensions ☹

D-Branes in type I/II

Open strings $\rightarrow$ $\mathrm{U}(1)$ gauge symmetry (90's revolution!)

Stacks D-Branes in type I/II



Open strings $\rightarrow$ $\mathrm{U}(2) \simeq \mathrm{SU}(2) \times \mathrm{U}(1)$ gauge symmetry

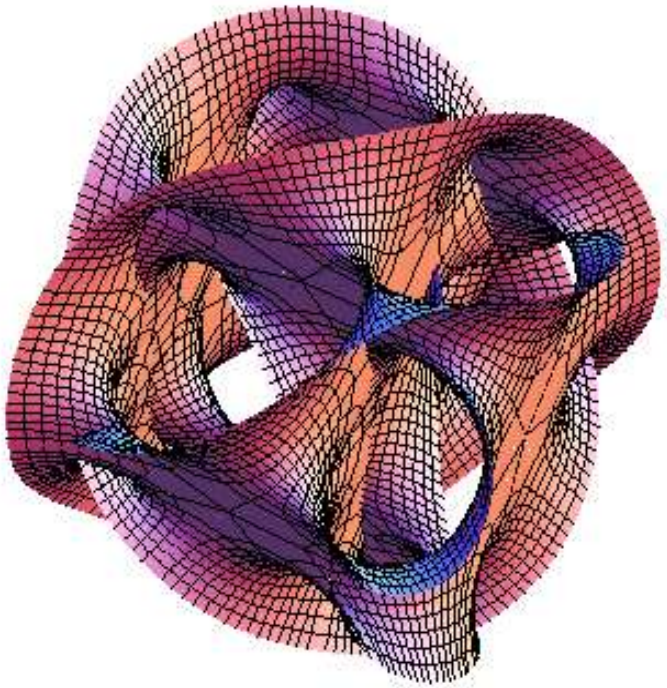
String Phenomenology Challenges

First challenge: $10 \neq 4$

- **Compactifications**

$$X_{10} = \mathbb{M}^4 \otimes X_6 \qquad \text{size}(X_6) \sim \ell_{Pl}^6, \quad \mathcal{N} = 1$$

1. X_6: Calabi-Yau (CY_3) manifolds Candelas,Horowitz,Strominger,Witten (1985)

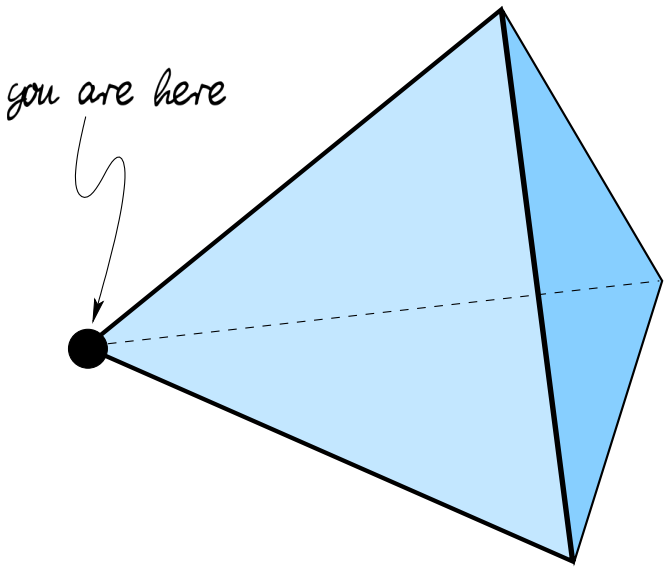


First challenge: $10 \neq 4$

- **Compactifications**

$$X_{10} = \mathbb{M}^4 \otimes X_6 \qquad \text{size}(X_6) \sim \ell_{Pl}^6, \quad \mathcal{N} = 1$$

1. X_6: Calabi-Yau (CY_3) manifolds — Candelas,Horowitz,Strominger,Witten (1985)
2. X_6 : Orbifolds — Dixon,Harvey,Vafa,Witten (1985)



First challenge: $10 \neq 4$

- **Compactifications**

$$X_{10} = \mathbb{M}^4 \otimes X_6 \qquad \text{size}(X_6) \sim \ell_{Pl}^6, \quad \mathcal{N} = 1$$

1. X_6: Calabi-Yau (CY_3) manifolds — Candelas,Horowitz,Strominger,Witten (1985)
2. X_6 : Orbifolds — Dixon,Harvey,Vafa,Witten (1985)
3. Generalized, half-flat, $\mathrm{SU}(3)\times\mathrm{SU}(3)$ manifolds, ... — Oscar Loaiza-Brito

Second challenge: some matter!

- Heterotic strings $\mathrm{E}_8 \times \mathrm{E}_8$ or $\mathrm{SO}(32)$

$$\begin{array}{rcl} \mathrm{E}_8 & \overset{\text{compact.}}{\to} & \mathrm{E}_6 \times \mathrm{SU}(3) \\ \mathbf{248} & \to & (\mathbf{78},\mathbf{1}) + (\mathbf{1},\mathbf{8}) + (\mathbf{27},\mathbf{3}) + (\overline{\mathbf{27}},\overline{\mathbf{3}}) \end{array}$$

E_6 GUTs ☺

Second challenge: some matter!

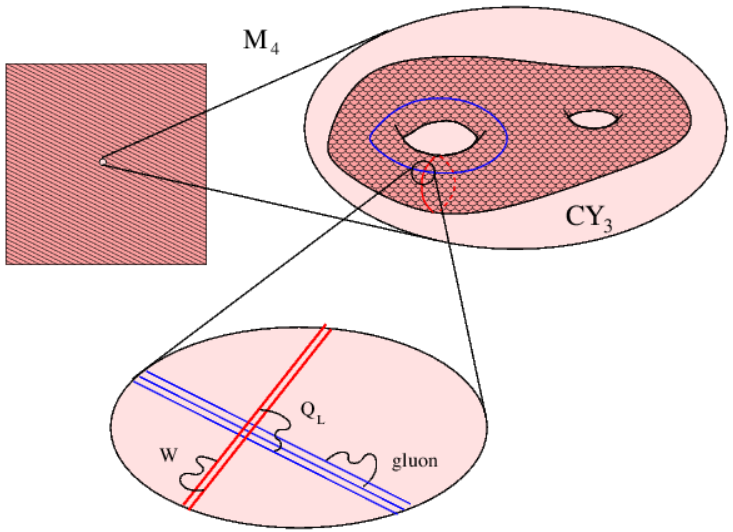
- Heterotic strings $\mathrm{E}_8 \times \mathrm{E}_8$ or $\mathrm{SO}(32)$

$$\begin{array}{ccc} \mathrm{E}_8 & \overset{\text{compact.}}{\rightarrow} & \mathrm{E}_6 \times \mathrm{SU}(3) \\ \mathbf{248} & \rightarrow & (\mathbf{78},\mathbf{1}) + (\mathbf{1},\mathbf{8}) + (\mathbf{27},\mathbf{3}) + (\overline{\mathbf{27}},\overline{\mathbf{3}}) \end{array}$$

E_6 GUTs ☺

- Type II A/B

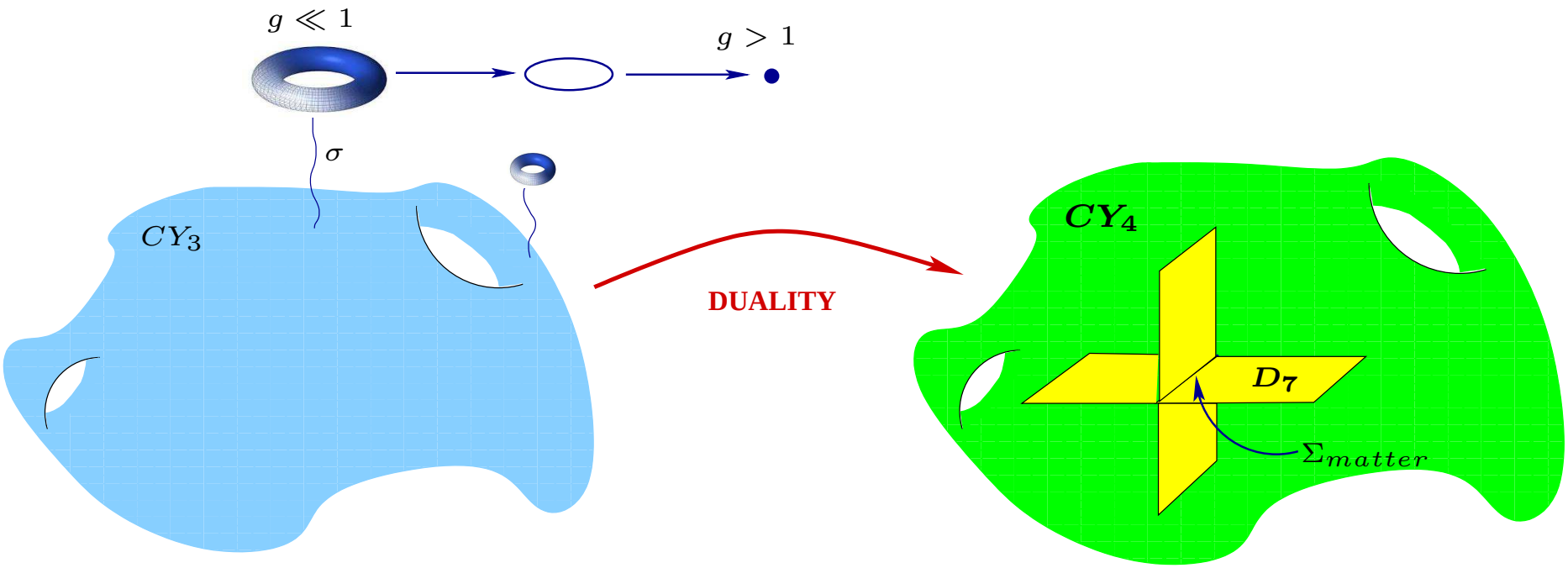
Berkooz et al. (1996)



Second challenge: some matter beyond traditional strings!

- F-theory

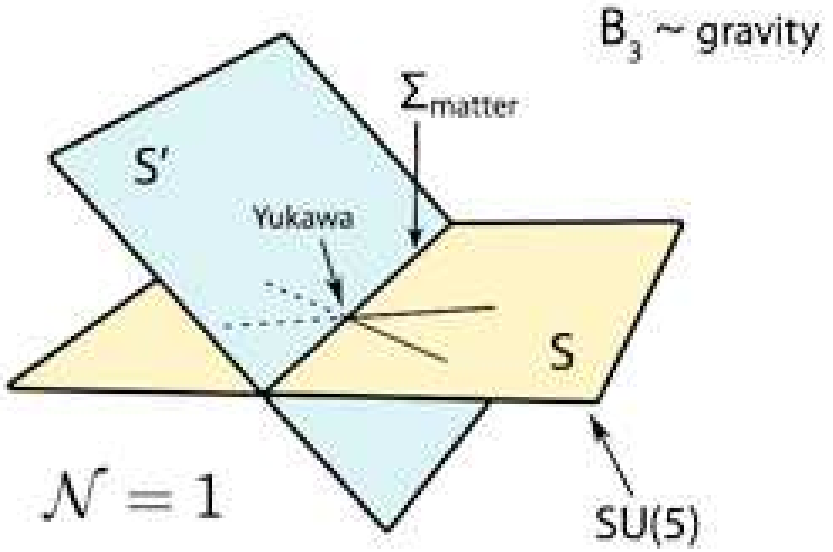
Beasly, Heckman, Vafa (2008-2010)



Second challenge: some matter beyond traditional strings!

- F-theory

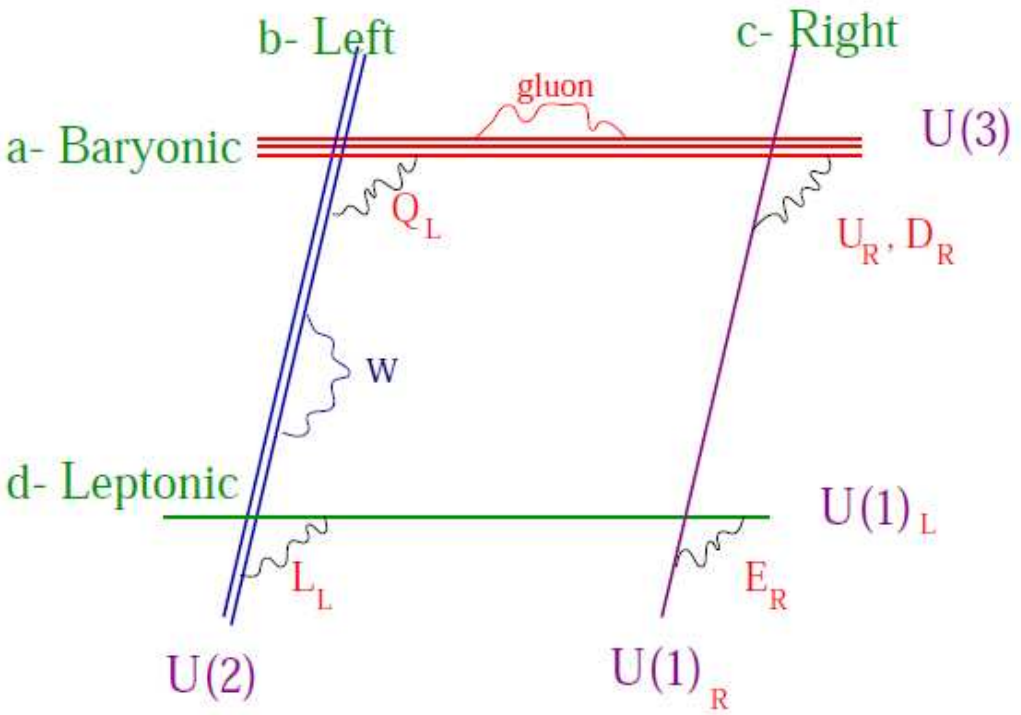
Beasly, Heckman, Vafa (2008-2010)



Third challenge: (MS)SM matter & interactions

- Type IIA : Madrid Model

Cremades, Ibáñez, Marchesano (2001-2003)



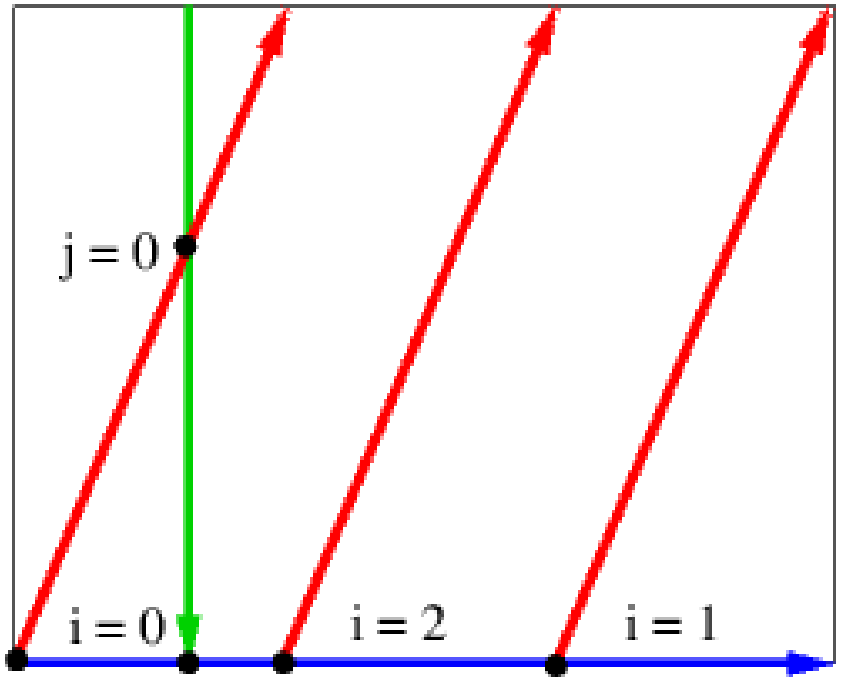
$$X_6 \;=\; T^2 \times T^2 \times T^2/\mathbb{Z}_2 \times \mathbb{Z}_2$$

with $D6$ branes $\quad\Rightarrow\quad$ $\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y\times\mathrm{U}(1)^4$

Third challenge: (MS)SM matter & interactions

- Type IIA : Madrid Model

Cremades,Ibáñez,Marchesano (2001-2003)

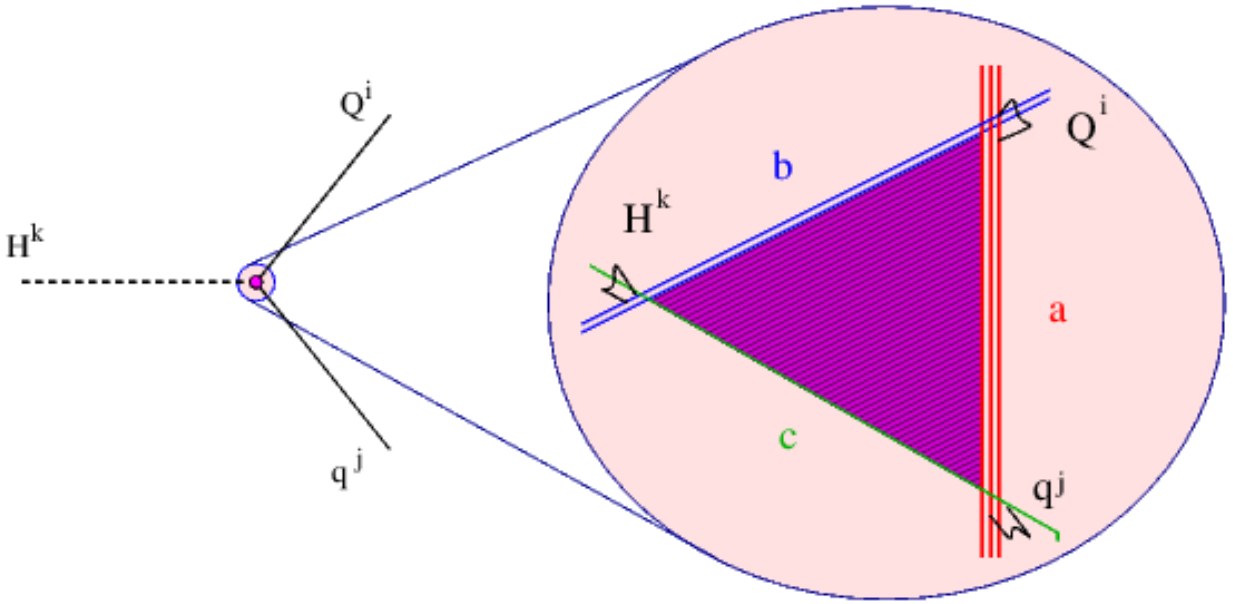


3 generations

Third challenge: (MS)SM matter & interactions

- Type IIA : Madrid Model

Cremades,Ibáñez,Marchesano (2001-2003)



Yukawa couplings from instantons

$Y_u^{33} \propto e^{-A} \neq 0, \qquad A \sim$ area triangle

Third challenge: (MS)SM matter & interactions

- Type IIA : Madrid Model hurdles and solutions

Cremades,Ibáñez,Marchesano (2001-2003)

  - Anomalies: tadpoles do not cancel
  - ~~SUSY~~ @ M_{str} $\Rightarrow$ hierarchy problem! ☹

Solution: $X_6 = CY_3$ or orbifold

Blumenhagen (2002), Honecke, Gmeiner (2004-2008)

  - Only $Y_{b,t} \neq 0$ non-perturbatively
    $\Rightarrow$ 4 quarks massless ☹
    $Y_t \ll 1$ ☹

Solution: different intersections
$\Rightarrow Y_{u,d,c,s} \neq 0$ perturbatively

  - Other issues: $Y_t < Y_u$, chiral exotics, ... ☹

Third challenge: (MS)SM matter & interactions

- Type IIA : An intersecting D-brane model

Gmeiner, Honecker (2008)

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times G_{hidden}$$

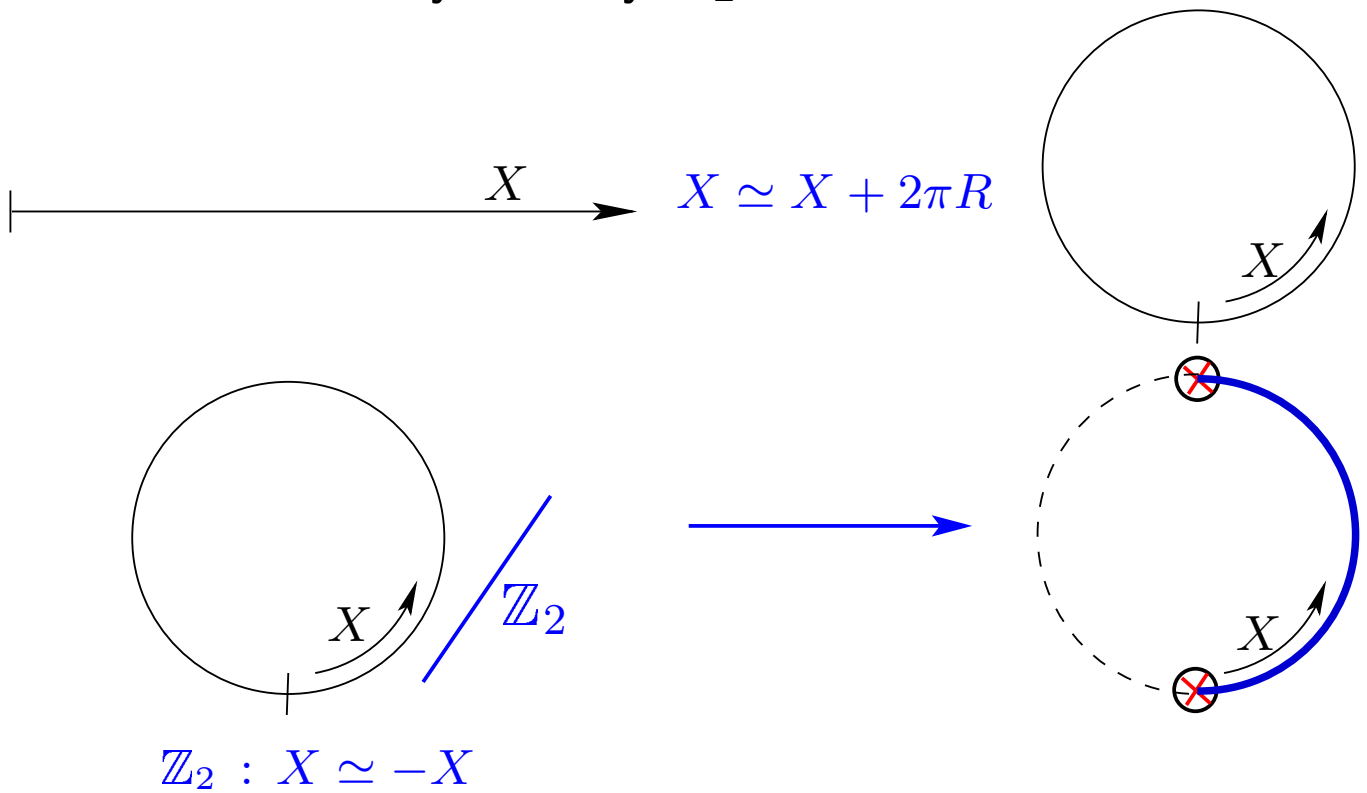
$$\begin{aligned}
[C] = 3 \times \Big[& (3,2)^{(0,0)}_{1/6,1/3} + (\overline{3},1)^{(1,0)}_{1/3,-1/3} + (\overline{3},1)^{(-1,0)}_{-2/3,-1/3} \\
& + (1,1)^{(1,1)}_{1,1} + (1,1)^{(-1,1)}_{0,1} + 2 \times (1,2)^{(0,-1)}_{-1/2,-1} \\
& + (1,2)^{(0,1)}_{1/2,1} + 3 \times (1,\overline{2})^{(-1,0)}_{-1/2,0} + 3 \times (1,\overline{2})^{(1,0)}_{1/2,0} \Big] \\
\equiv 3 \times & \Big[Q_L + d_R + u_R + e_R + \nu_R + 2 \times L + \overline{L} \Big] + 9 \times \Big[H_d + H_u \Big]
\end{aligned}$$

- plus ~ 100 vectorlike exotics
- Yukawa couplings for 2 generations allowed
- Majorar neutrino masses allowed

Third challenge: (MS)SM matter & interactions

- $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic orbifolds

  1D Orbifold with symmetry $\mathbb{Z}_2$ in 5D



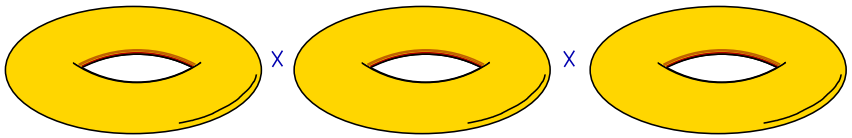
Very small singular space $R \ll 1mm \rightarrow$ we do not see it!!

Kaluza, Klein (1920s)

Third challenge: (MS)SM matter & interactions

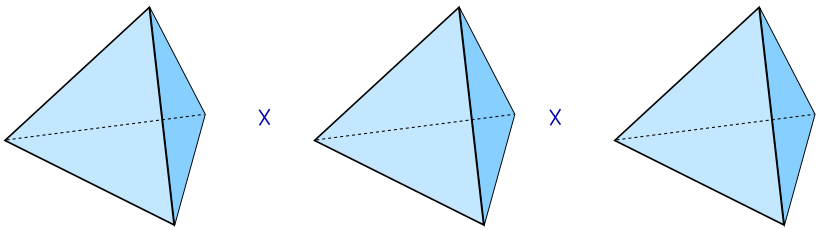
- $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic orbifolds

T^6:



$\mathbb{Z}_2 \times \mathbb{Z}_2$

$T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$:



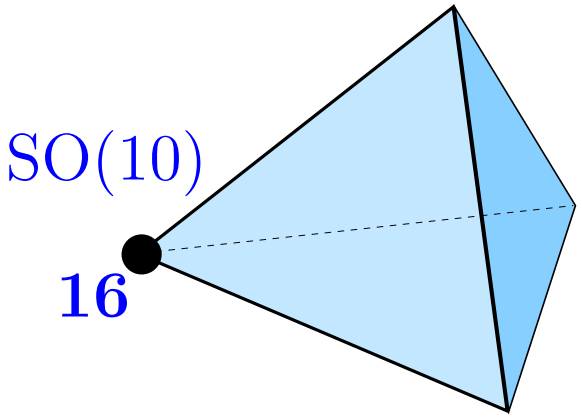
Strings in the 'bulk' : gravity and
$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times G_{hidden}$ ☺

Can we compute stuff?

Lebedev, Nilles, Ramos-Sanchez, Ratz, Vaudrevange (2006-2008)

Third challenge: (MS)SM matter & interactions

- $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic orbifolds



$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times G_{hidden}$ ☺

Strings @ 3 singularities (by construction):

$\mathbf{16}$ = complete family

- Many other appealing features: neutrino masses $m_\nu \sim 10^{-2}$eV, $M_{SUSY} \sim$ TeV, proton stability, no strong CP problem,...

Can we compute stuff?

Lebedev,Nilles,Ramos-Sanchez,Ratz,Vaudrevange (2006-2008)

Third challenge: (MS)SM matter & interactions

- $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic orbifolds. Quark sector

$$Y_u \sim \begin{pmatrix} 0.0316272 & 0.0316272 & 0.0085564 \\ 0.0316272 & 0.031 & 0.00841811 \\ 0.0183063 & 0.0183171 & 1.14437 \end{pmatrix},$$

$$Y_d \sim \begin{pmatrix} 0.000483779 & 0.000664073 & 6.158592 \times 10^{-7} \\ 0.000664073 & 0.000483779 & 1.026432 \times 10^{-7} \\ 0.0000867024 & 0.000036018 & 0.0357596 \end{pmatrix},$$

$$|Y_u^{\mathsf{diag}}| \sim \mathrm{diag}(0.00032,\, 0.06265,\, 1.14466)\,,$$
$$|Y_d^{\mathsf{diag}}| \sim \mathrm{diag}(0.00018,\, 0.00115,\, 0.03576)\,.$$

semirealistic quark masses!

Lebedev,Raby,Ramos-Sanchez

Fourth challenge: moduli stabilization (towards cosmology)

Potential problem: the geometry of space is not fixed!!

Allowed deformations: position of branes, size and shape of X_6

$$\Rightarrow \text{moduli: } \varphi_j$$

Perturbatively $V(\varphi_j) = 0$ ☹

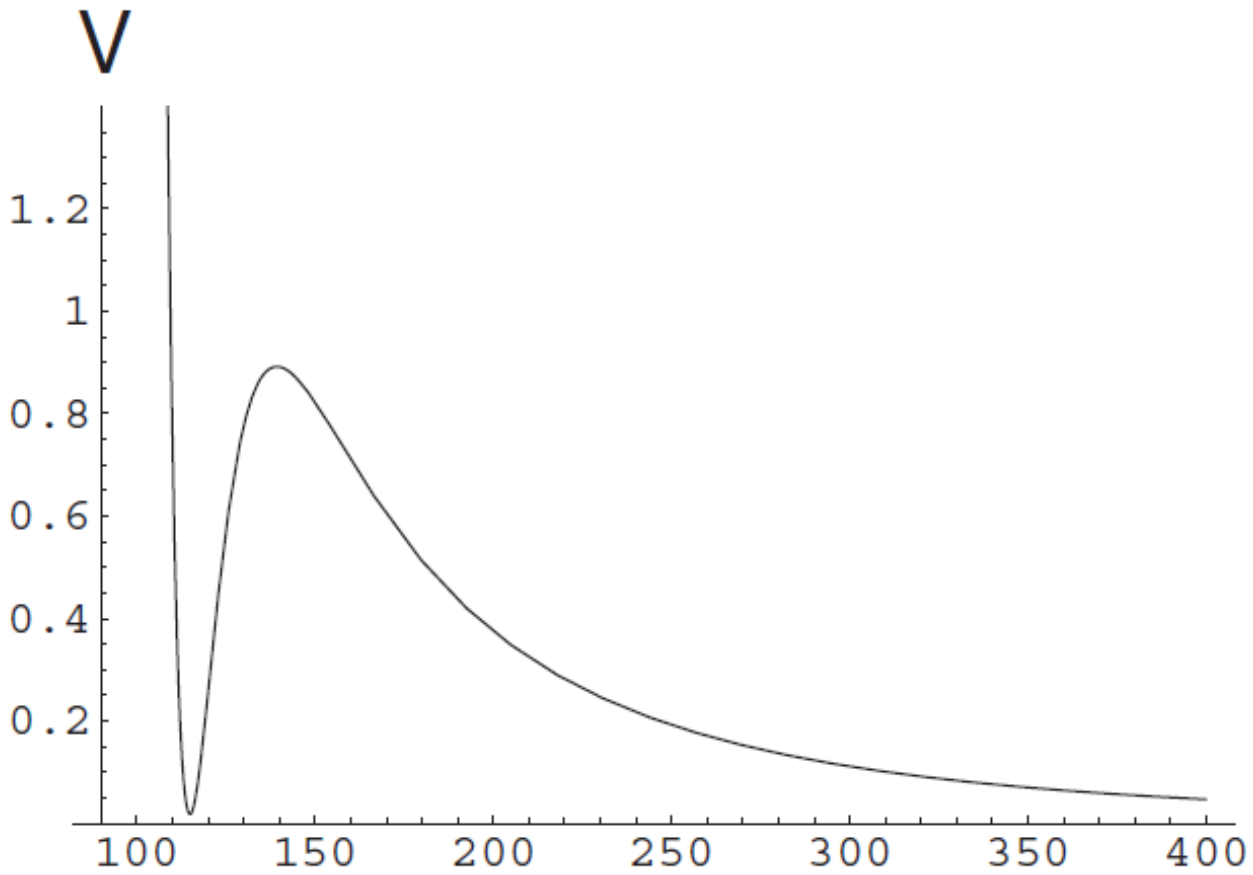
fifth forces, cosmological overclosure

BUT non-perturbative effects (instantons, gaugino condensation, fluxes...) and possible field-VEVs can induce

$$V(\varphi_j) \sim -\frac{1}{\varphi_j} + e^{-\alpha\varphi_j}$$

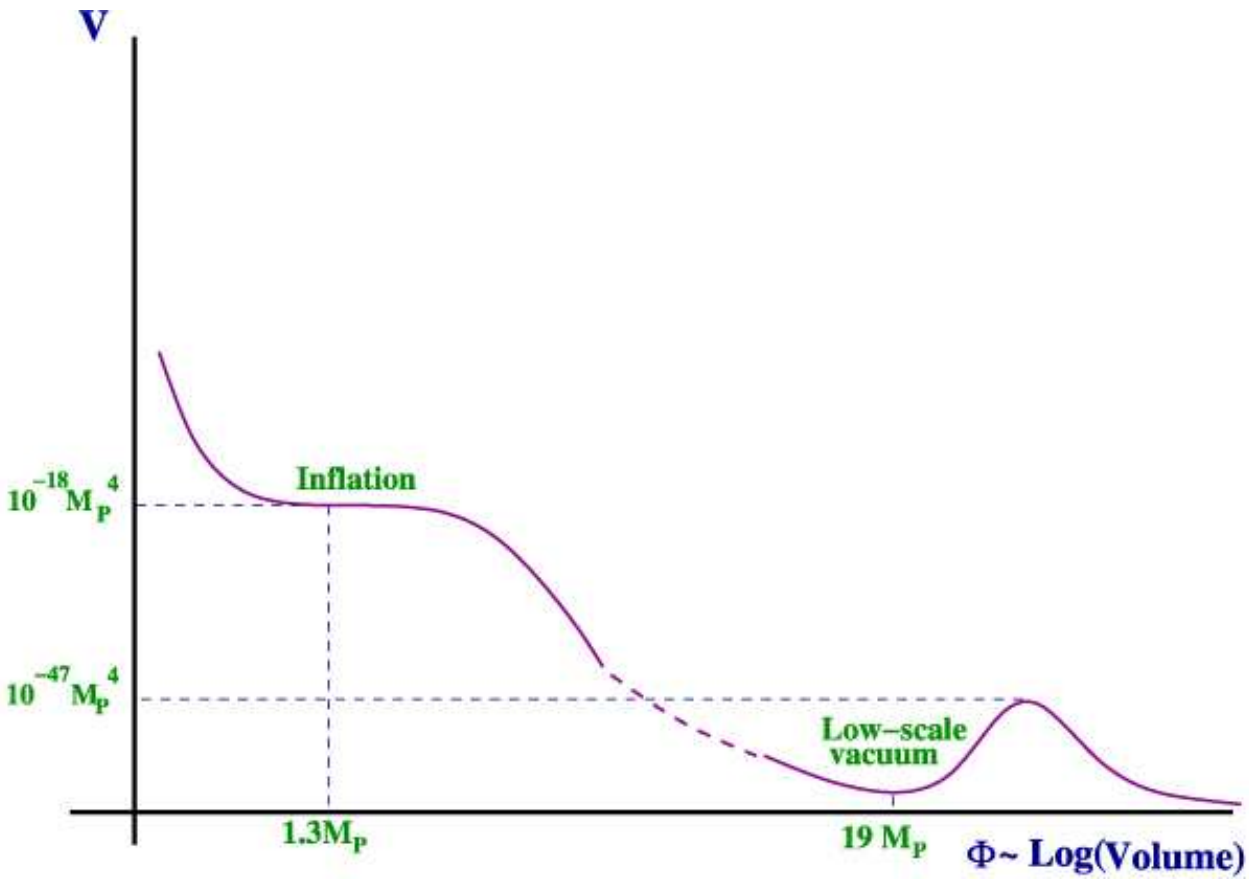
Kachru,Kallosh,Linde,Trivedi (2003)

Fourth challenge: moduli stabilization (towards cosmology)



Kachru, Kallosh, Linde, Trivedi (2003)

Fourth challenge: moduli stabilization and inflation



Conlon,Kallosh,Linde,Quevedo (2008s)

To take home...

- String phenomenology from all corners ✓
- Very close to the MSSM ✓
- In some scenarios, even computability available ✓
- Still much work to do for cosmology