STRING THEORY AND INFLATION

with:

Burgess, Blanco-Pillado, Cline, Escoda, Gómez-Reino, Stoica, Kallosh Linde, . . .

Strings and Physics?

Challenges:

*Phenomenology:

$G \supset SU_3 \times SU_2 \times U_1$; 3-families ; Stable Proton; Yukawa couplings; Higgs; ...

*Cosmology:

Singularity

→ Inflation (or alternatives)

Dark Energy

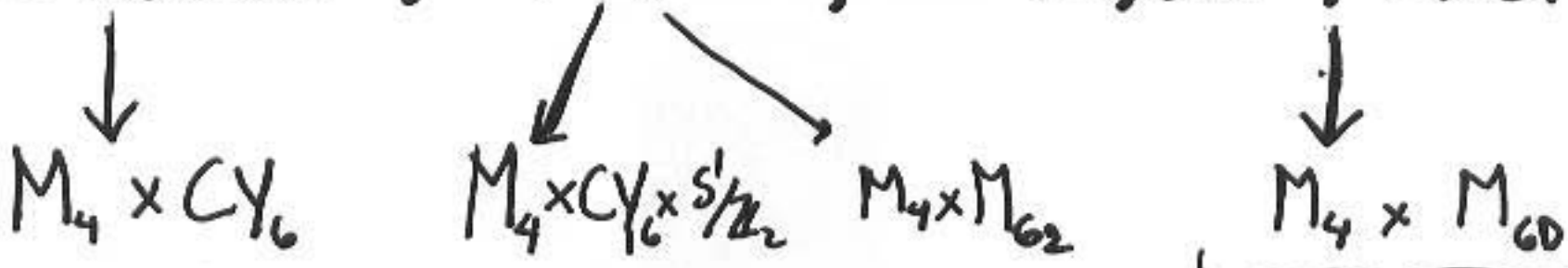
Dark Matter

Baryogenesis ...

"Realistic" String Models

Many Realisations:

Heterotic, M, I, IIA, IIB.



→ • D-branes at Singularit
• Intersecting D-bran

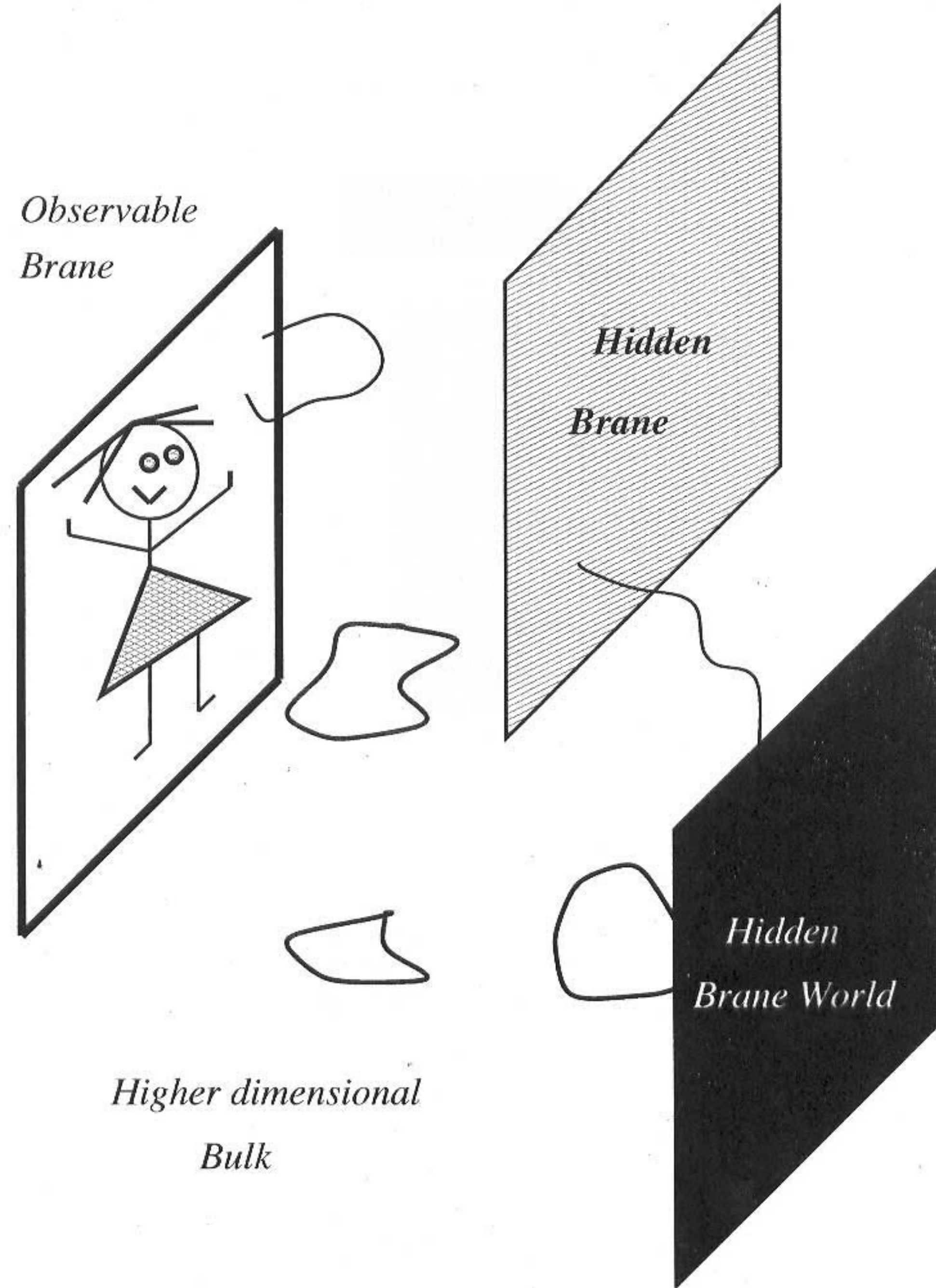
Realistic properties:

G 2 $SU_3 \times SU_2 \times U_1$; 3 families of quarks + leptons, Stable proton, ...

General Problems:

* SUSY Breaking
* Moduli Stabilisation

The Brane World



Strings + Inflation

1980's-1990's: Inflaton condidates:

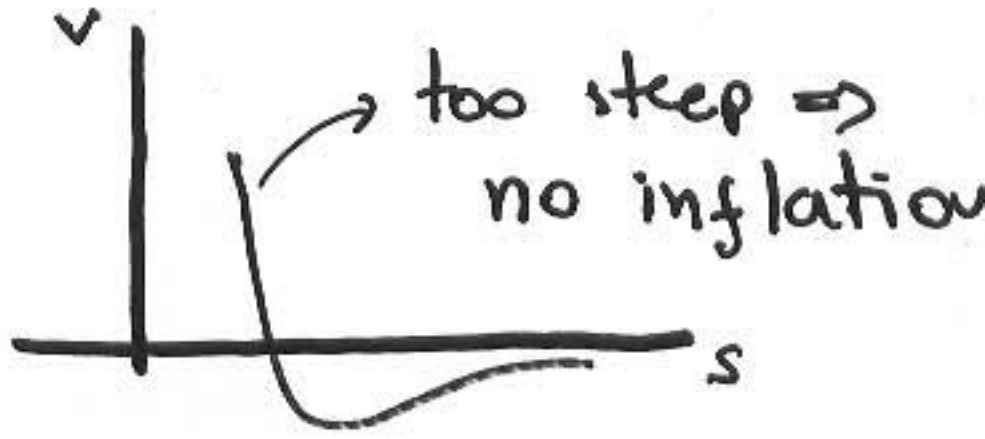
* Dilaton $S = e^{\phi} + ia$
* Moduli:

Size T_i

Shape U_a

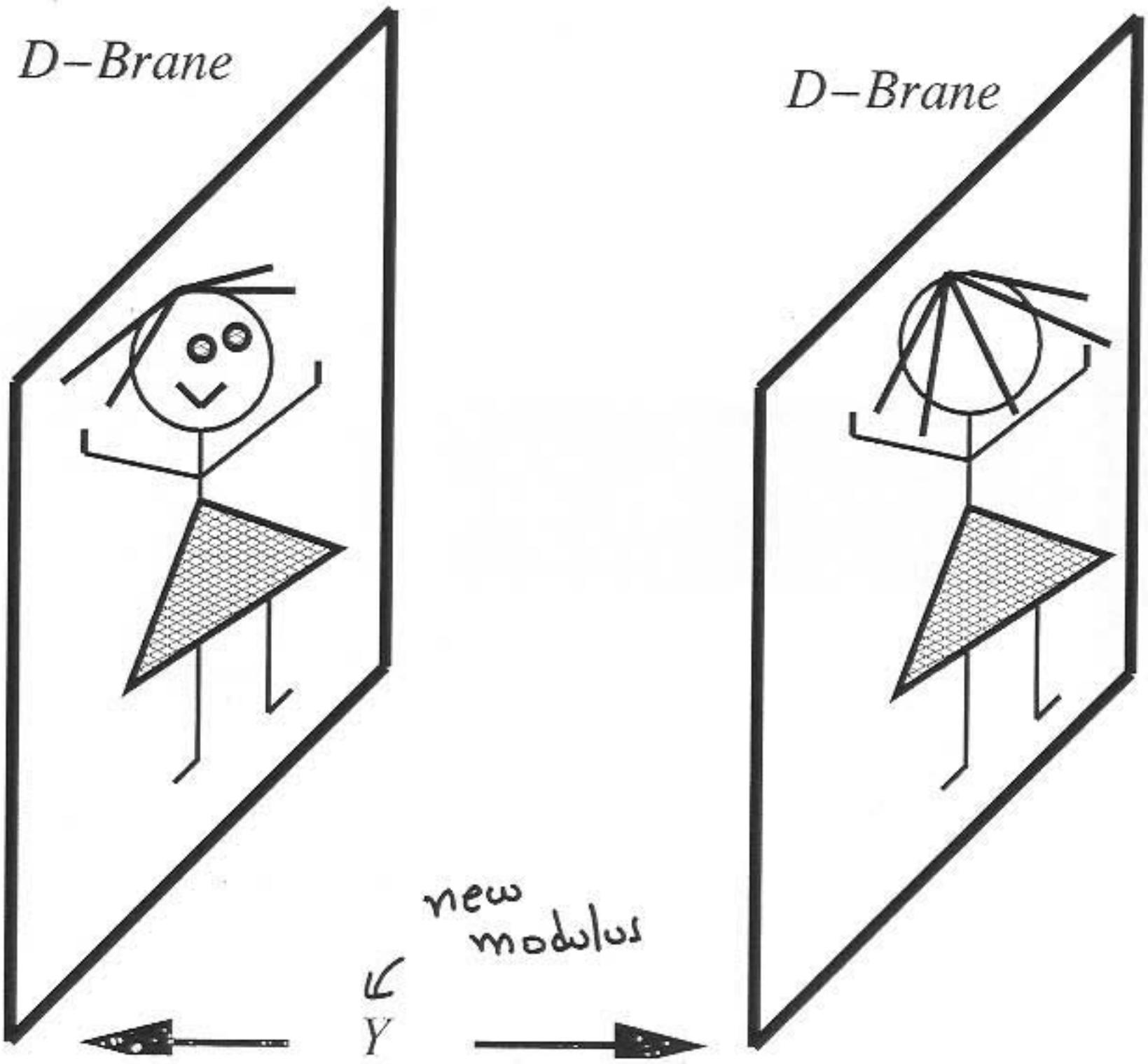
But: Potential $V(T_i, U_a) = 0$

Nonperturbative:



D-Brane Inflation

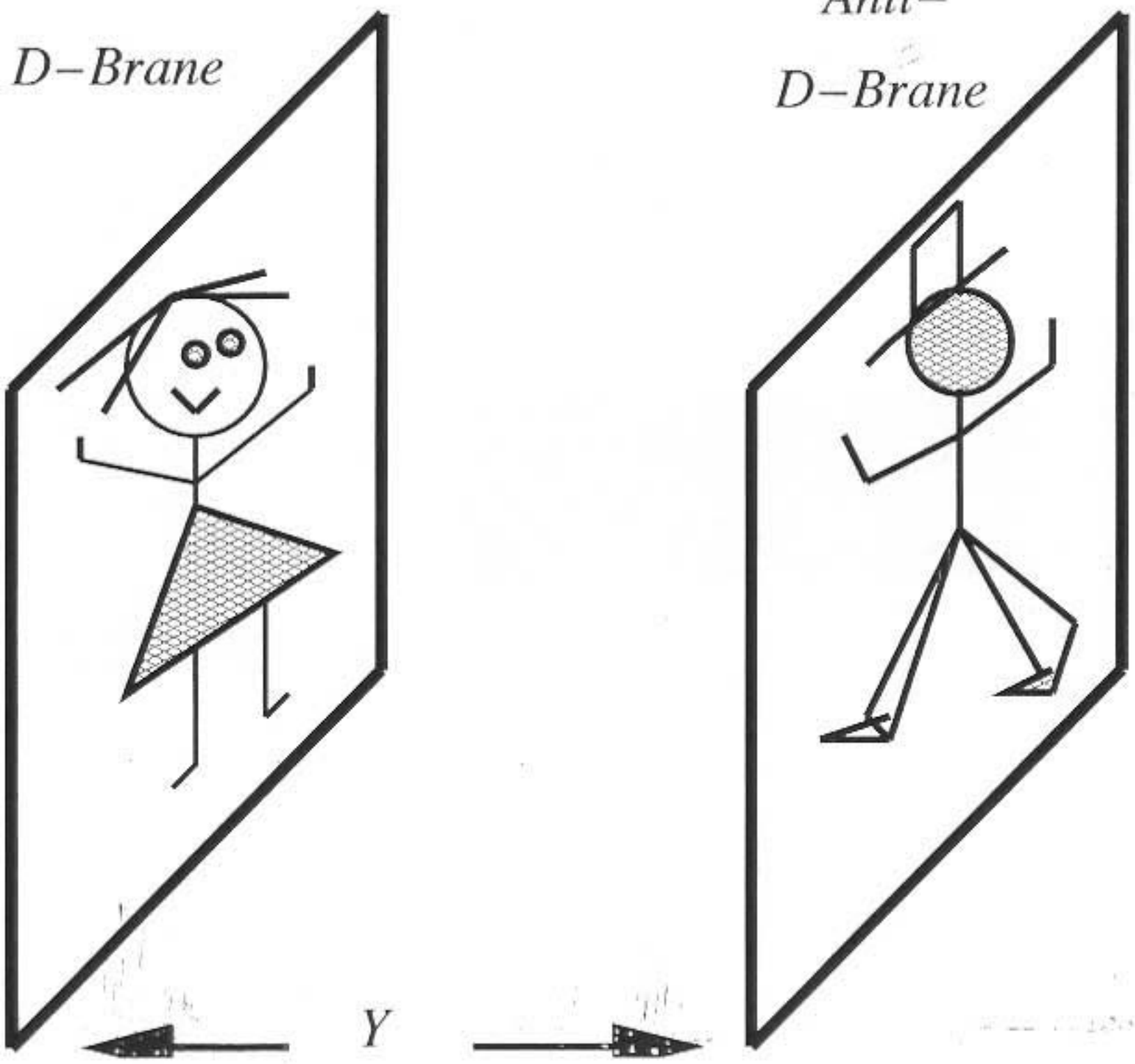
Dvali+Tye 1998



Potential not calculable.

D-Brane Antibrane Inflation

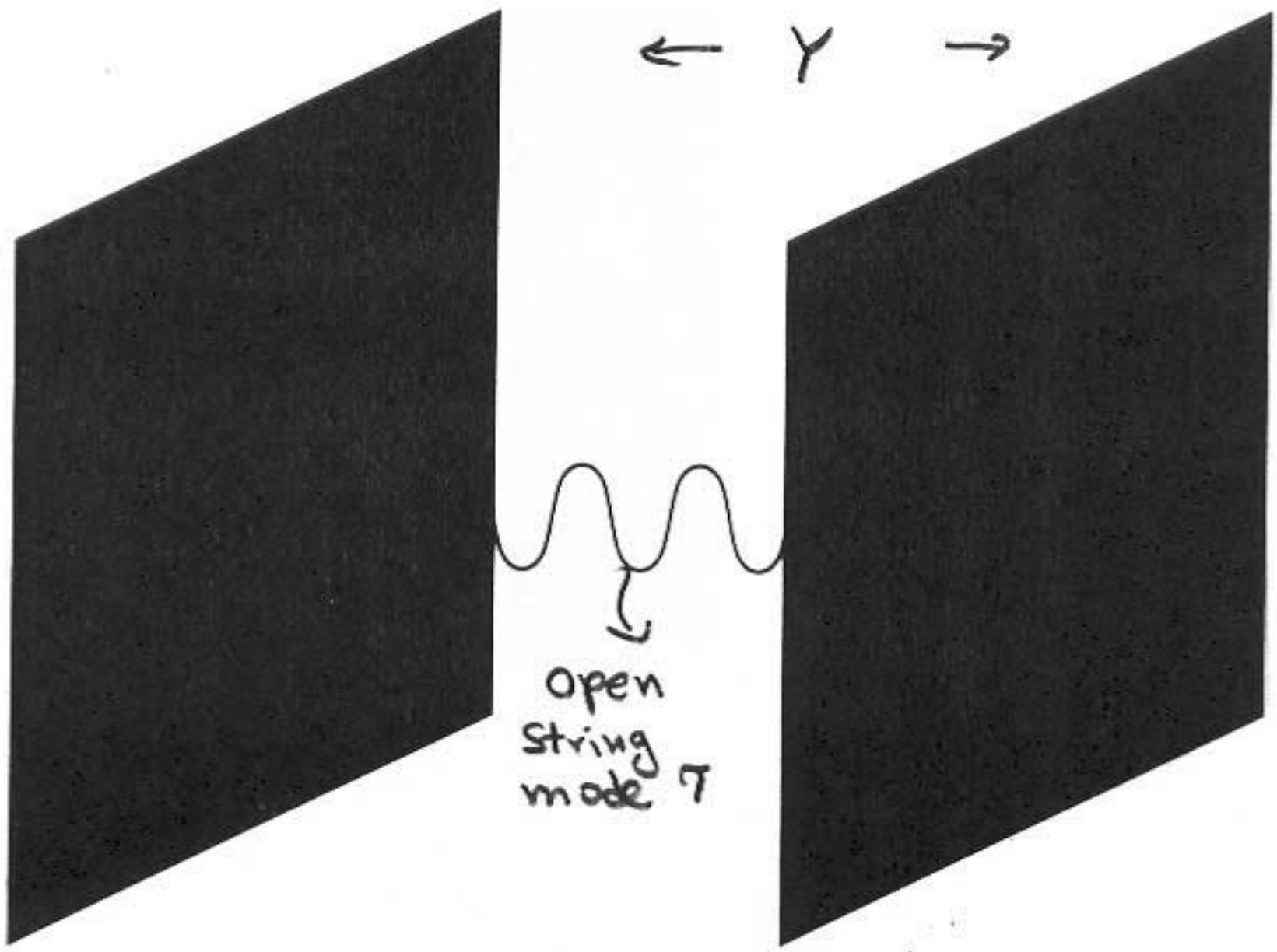
BMQRZ 2001
DSS



$$V(Y) = A - B/Y^{7-p} + \cdots$$

Inflation not generic but possible?

New Phenomenom : BMQRT

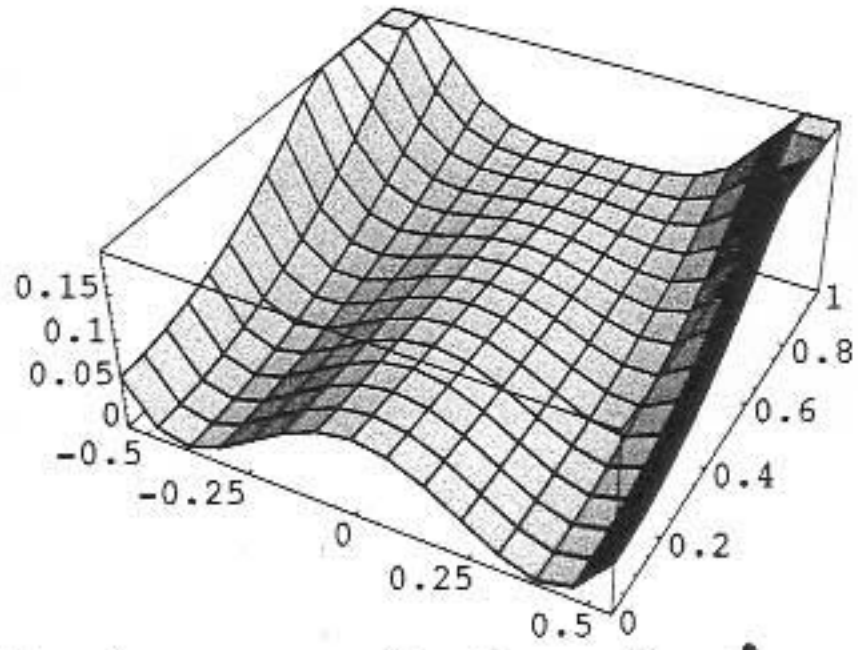


$$V(T,Y) \approx (Y-Y_c)T^2 + aT^4 + \cdots$$

$$\Rightarrow Y < Y_c \rightarrow T: \text{Tachyon !}$$

Tachyon ⇒

* Hybrid Inflation



* Tachyon Potential ⇒
Topological defects D(p-2) branes !

⇒ Cascades $D9-\bar{D}9 \to D7, D\bar{5}, D3, D1$ (gas ?)

Other Approaches:

* Intersecting branes
  García-Bellido et al

* D3 / D7
  Herdeiro, Hirano, Kallosh

⇓

Similar tachyon dynamics

General result: Tye et al

In 4D: no domain walls
no monopoles
only cosmic strings !

$G\mu < 10^{-7}$

Main Problem:

Moduli (T_i, U_a, S) fixing. ?!

Moduli Stabilisation:

Recent Progress

..... GKP, KKLT, ...

Type IIB :

g_{MN}, $\underbrace{\phi, C_0}_{S}$, B_{MN}, C_{MN} ; A_{MNPQ}

B_{MN} → $H_3 = dB$; C_{MN} → $F_3 = dC$; A_{MNPQ} → $F_5 = dA + \cdots$

$$G_3 \equiv F_3 - iS H_3$$

Ingredients:

* C-Y/O compactification $\mathcal{N}=1$
* Fluxes of F_3, H_3 (Fix Complex Structure Moduli)
* Nonperturbative W (Fix Kähler Moduli)

$$\boxed{W = W_0 + A e^{-aT}}$$

* Anti D3 branes (lift to dS space).

(or Magnetic fluxes, BKQ)

⇓

Fix all moduli ! But:

Not-realistic Models (where is the Standard Model ?)

Fluxes:

$$\frac{1}{4\pi^2\alpha'}\int_A F_3 = M \in \mathbb{Z}$$

$$\frac{1}{4\pi^2\alpha'}\int_B H_3 = -K \in \mathbb{Z}$$

A, B: 3-cycles.

Superpotential: (Gukov, Vafa, Witten)

$$W_0 = \int_M G_3 \wedge \underbrace{\Omega_3}$$

depends on shape moduli and dilaton S

Kahler:

$$K = -3\log(T+T^*) + K(\text{rest})$$

$$\Rightarrow \quad V = e^K \left\{ \sum_{ij} K^{-1}_{ij} D_i W D_j W^* - 3|W|^2 \right\}$$

$$\rightarrow \quad e^K \sum_{ij}{}' K^{-1}_{ij} D_i W D_j W^* \geq 0$$

$\Sigma' \Rightarrow$ not over T.

$\Rightarrow$ Minima $D_i W = 0$ $\Rightarrow$ fix all moduli except for T.

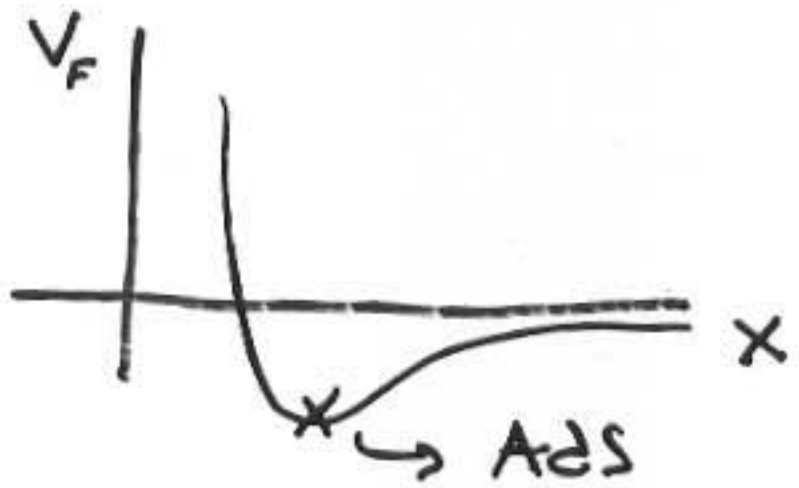
Fixing T:

D7 field theory gauge coupling: $\frac{1}{g^2} = Re\,T \equiv X$

Non perturbative effects: $(\sim e^{-1/g^2})$

$$W = W_0 + A e^{-aT}$$

$\Rightarrow$



$\Rightarrow$ All moduli fixed !

Lifting Minimum:

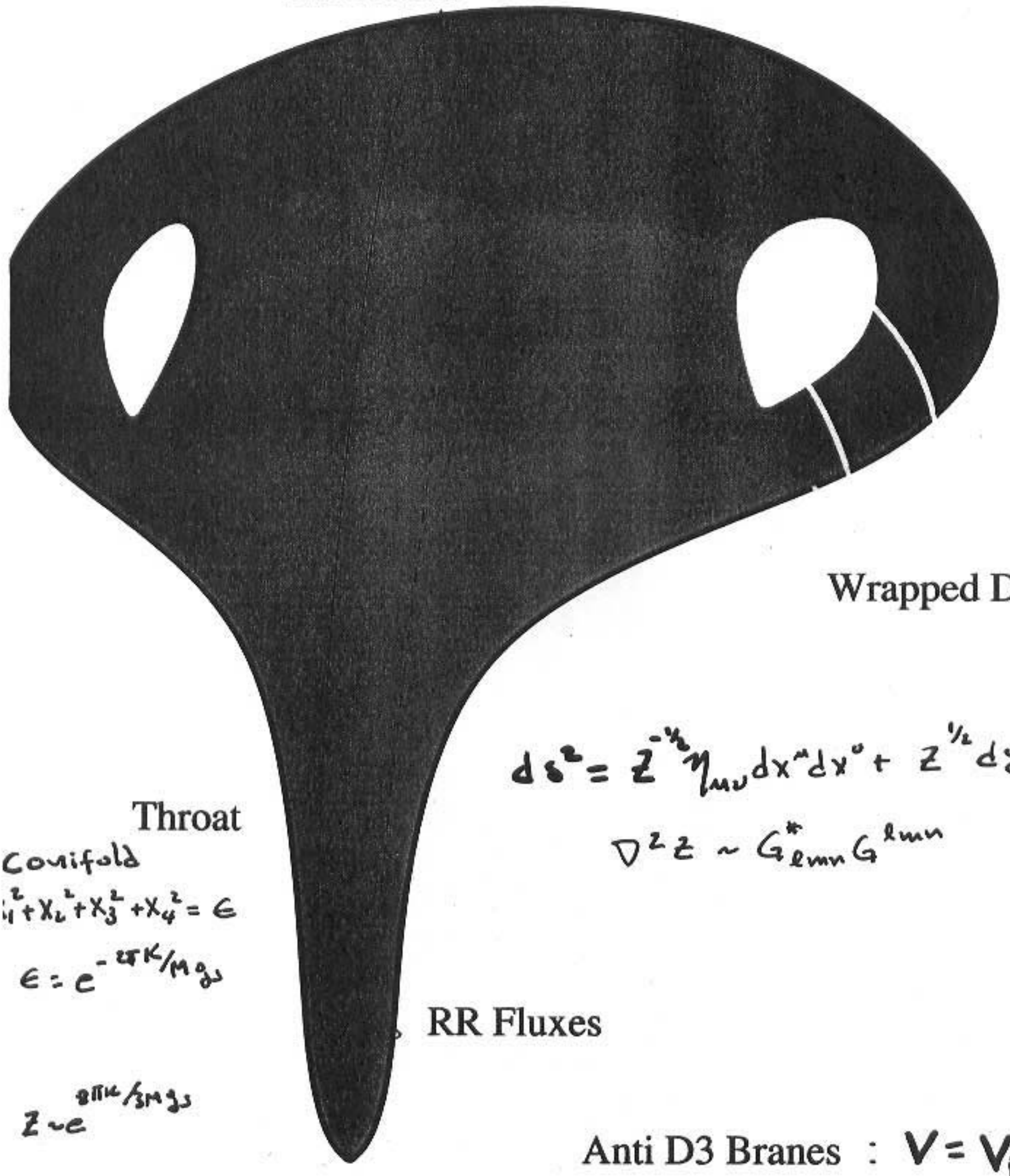
Add anti D3-branes $\Rightarrow V = V_F + \frac{E}{X^2}$ ($E \sim e^{-1/M}$)

$\Rightarrow$

de Sitter ! (current acceleration)

Many choices of fluxes K, M $\Rightarrow$ Landscape ! $(\sim 10^{100})$.

NS Fluxes



Wrapped D7 Bran

$$ds^2 = Z^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + Z^{1/2}dy^2_{CY}$$

$$\nabla^2 Z \sim G^*_{lmn}G^{lmn}$$

Throat

Conifold

$X_1^2+X_2^2+X_3^2+X_4^2=\epsilon$

$\epsilon = e^{-2\pi K/Mg_s}$

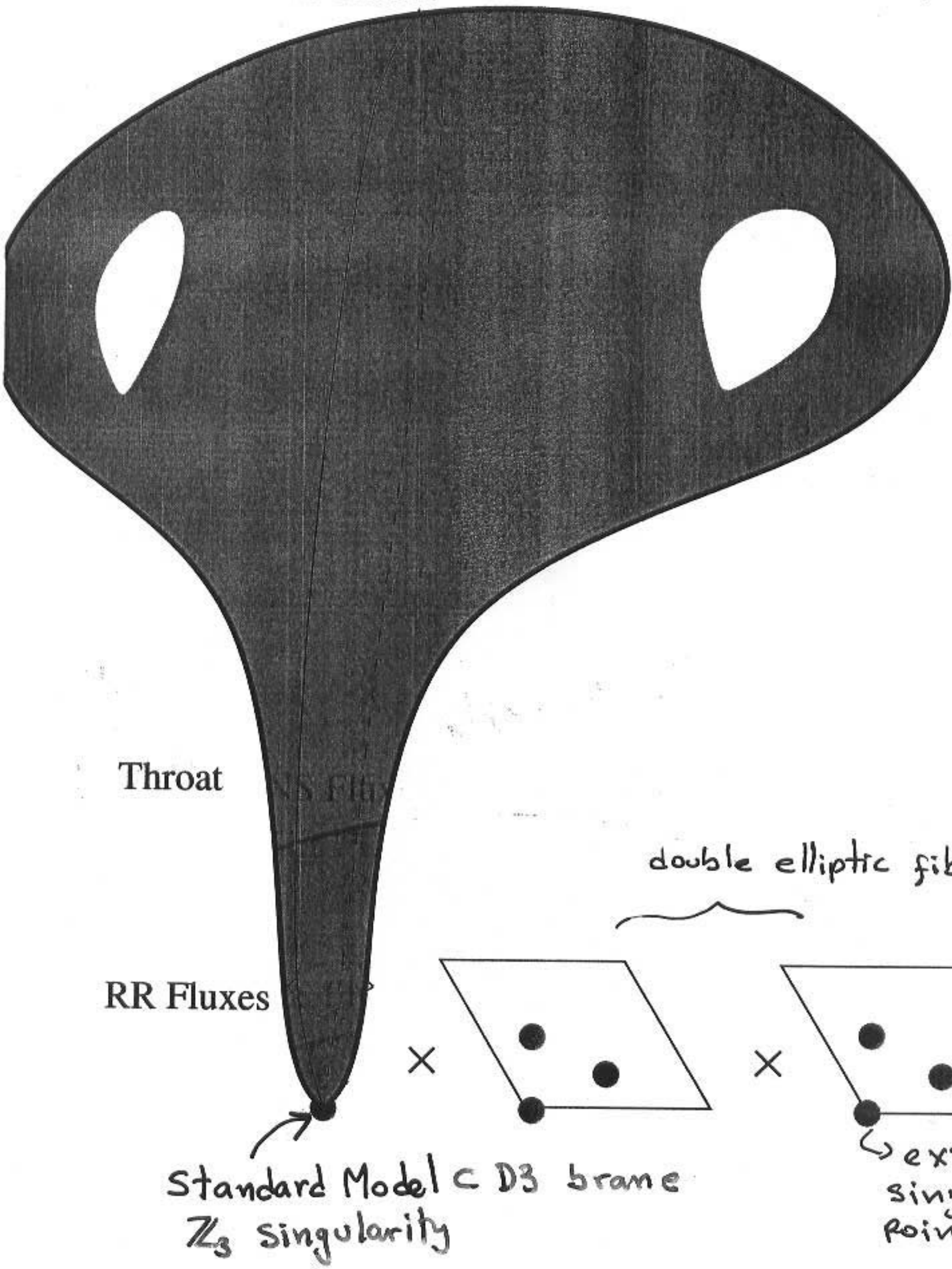
RR Fluxes

$Z \sim e^{8\pi K/3Mg_s}$

Anti D3 Branes : $V = V_F + \delta V$

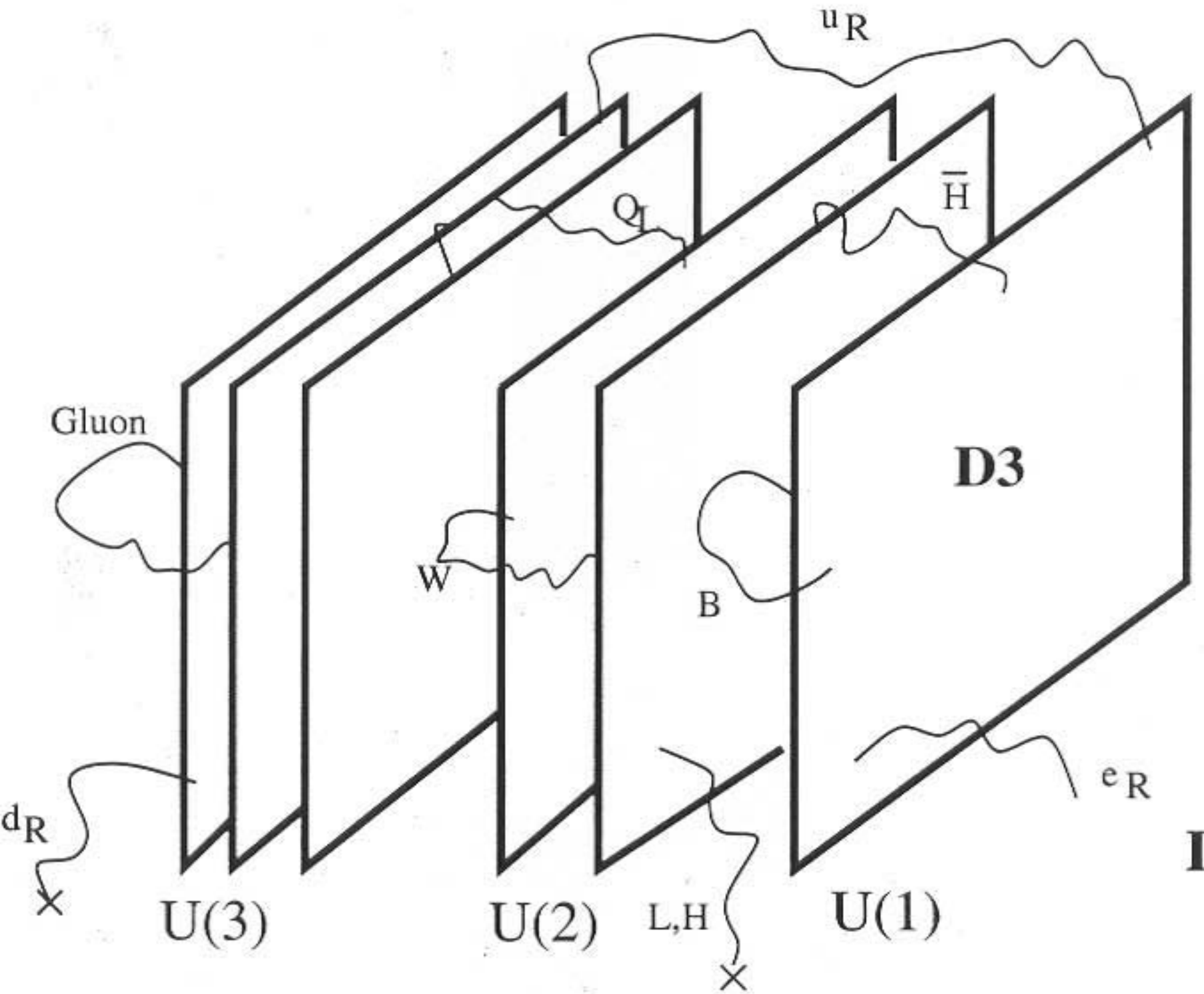
Realistic Models
(Orbifold within a Conifold)

Cascales, García, FQ
Uranga
hep-th/0312051
JHEP

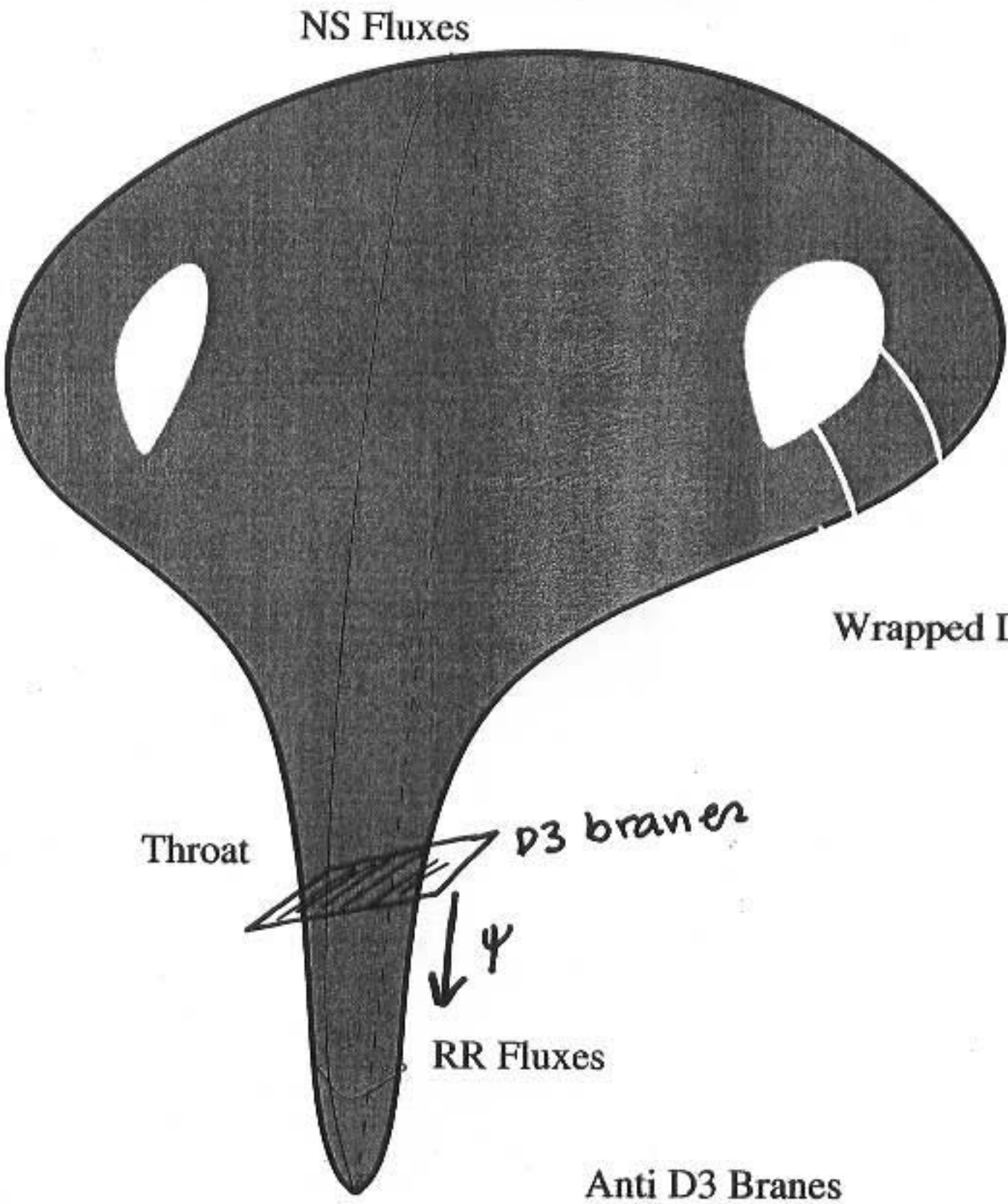


Matter fields	Q_3	Q_L	Q_R	Q_{D7}	Q_{D3^i}	$B-L$
$\bar{3}\bar{3}$ $=1$ Ch. Mults.						
$3(3,2,1;1)$	1	-1	0	0	0	1/3
$3(\bar{3},1,2;1)$	-1	0	1	0	0	-1/3
$3(1,2,2;1)$	0	1	-1	0	0	0
$\bar{3}7$ Ch. Fermions						
$(1,2,1;\bar{3})$	0	1	0	-1	0	-1
$(1,1,2;3)$	0	0	-1	1	0	1
$\bar{3}7$ Cmplx.Scalars						
$(3,1,1;\bar{3})$	1	0	0	-1	0	-2/3
$(\bar{3},1,1;3)$	-1	0	0	1	0	2/3
$\bar{3}_i7$ Cmplx.Scalars						
$(1,1,1;\bar{3})$	0	0	0	-1	$\mathbf{1}_i$	0
$(1,1,1;3)$	0	0	0	1	$-\mathbf{1}_i$	0

Table 1: Spectrum of $SU(3) \times SU(2)_L \times SU(2)_R$ model. We present the quantum numbers under the $U(1)$ groups. The first three $U(1)$'s arise from the D3-brane sector at the origin. The next two come from the D7- and additional D3-brane sectors, and are written as a single column, distinguished with a label i.


u_R
Q_L
$\overline{H}$
Gluon
W
B
D3
e_R
d_R
D7
U(3)
U(2)
L,H
U(1)

Brane - Anti brane Inflation?



BUT: $K = -3\log(T+T^* - \psi^*\psi)$

$\Rightarrow V = e^K \{\} \Rightarrow \eta \sim V''/V \sim 1$ (not $\ll 1$)

η- Problem (need fine tuning)

KKLMMT

"Realistic" Models Numerical Analysis

BCSG hep-th/0402119

* Parameters:

$\omega, f_0, A, a, C, c, \kappa, \kappa', \psi_0$

(values $\sim 10^{-3} - \mathcal{O}(1)$). (Setting $M_p = 1$)

* $V(\psi, \sigma)$ (other fields relax to their minimum value fast).

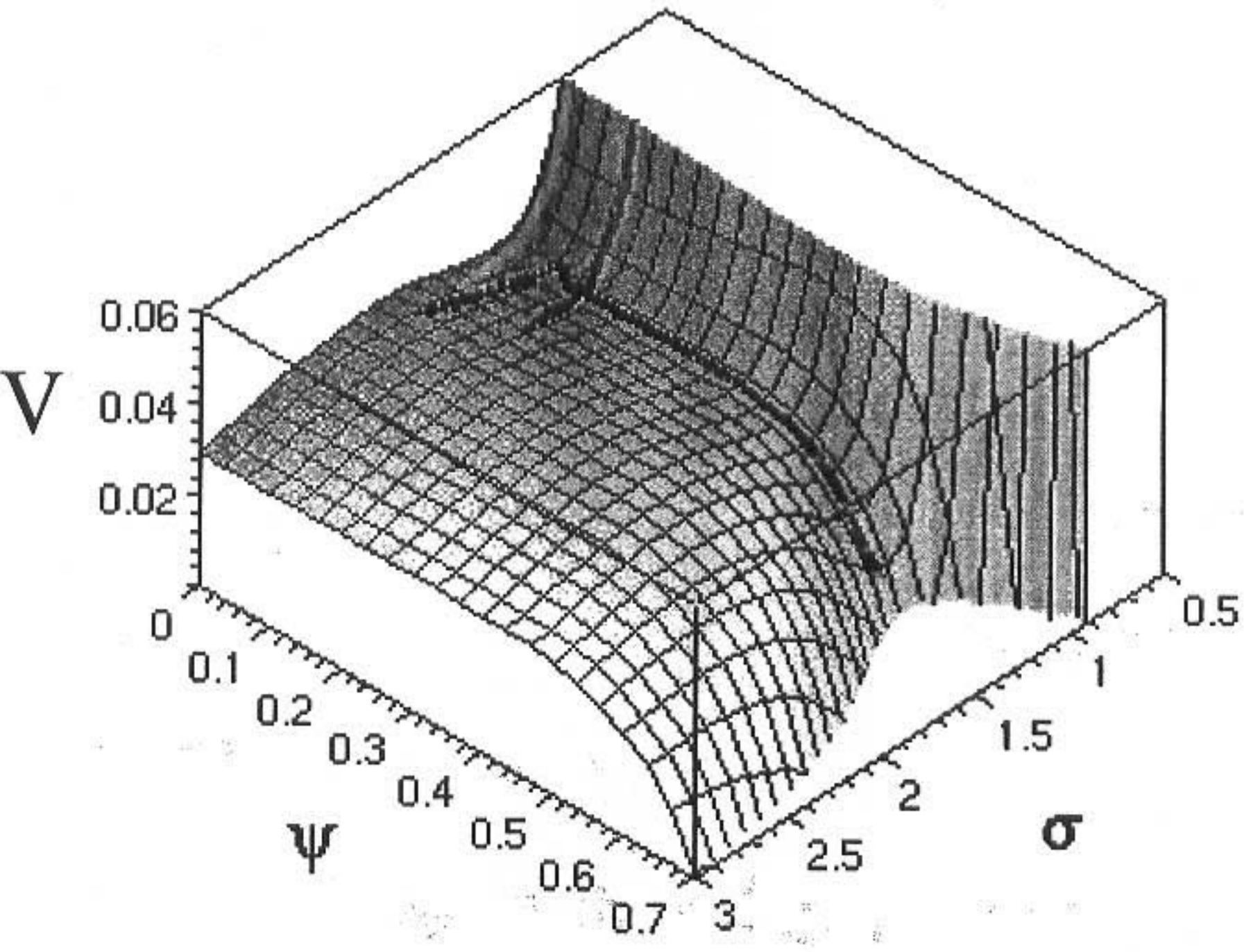
* $V(\psi, \sigma)$: flat trough or local minimum.

fine tuning: $1/1000 \rightarrow$ 60 - efoldings

$1/100 \rightarrow$ 30 e-foldings

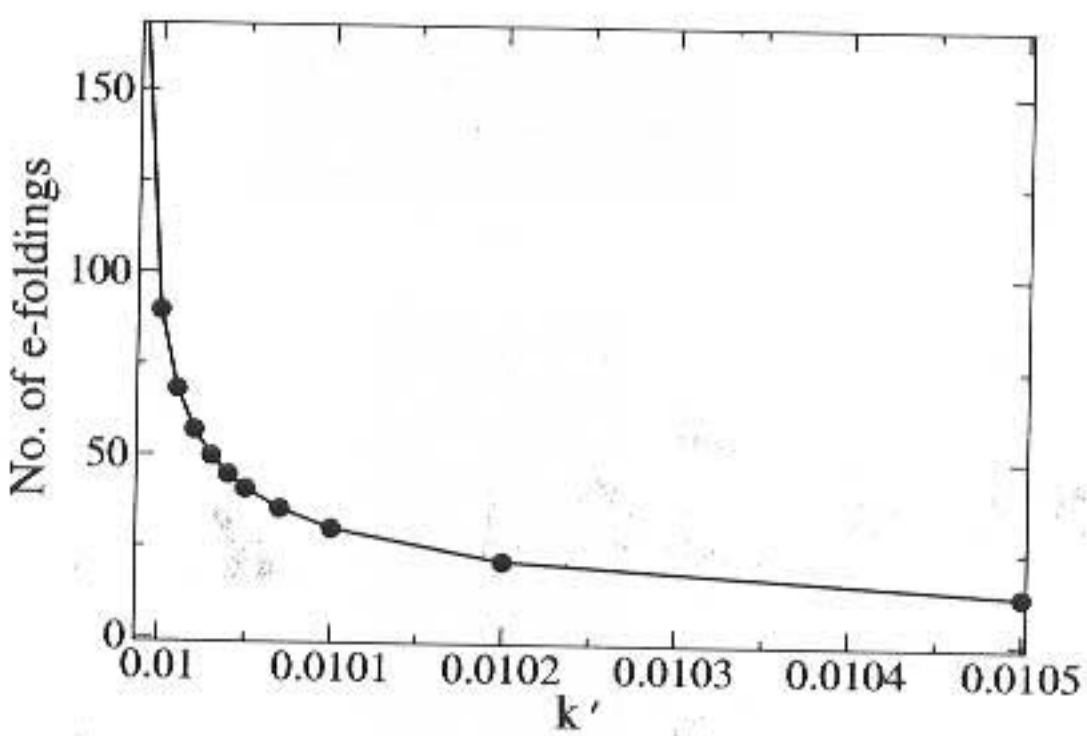
* Two- field inflation.

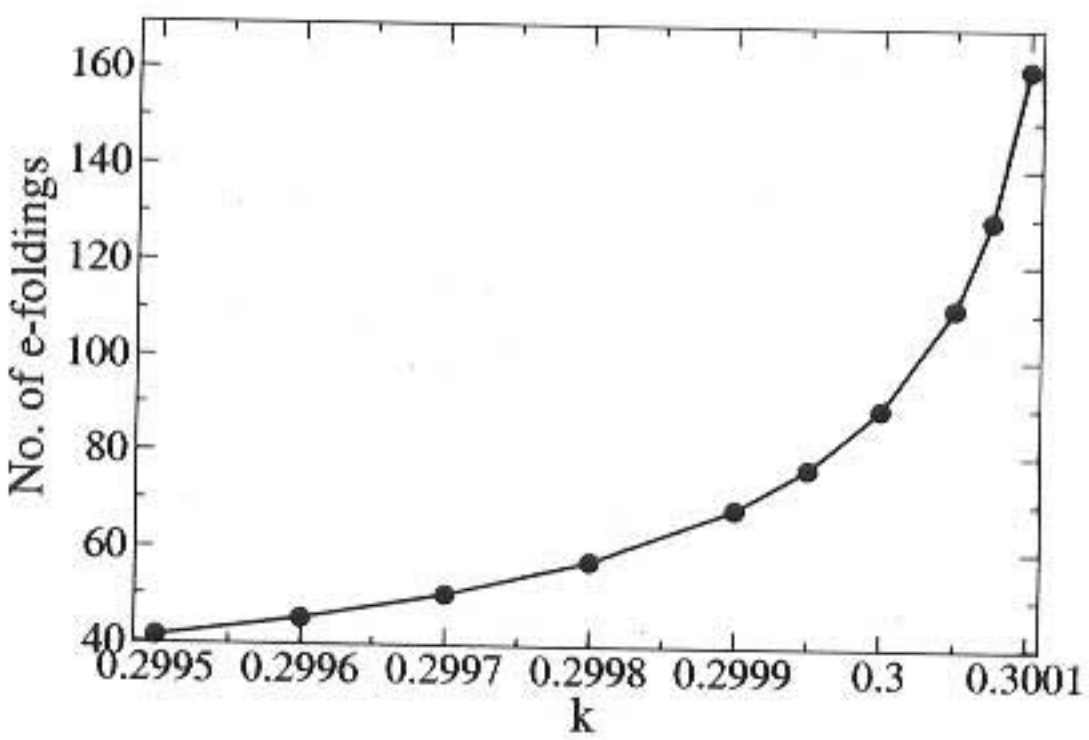
(no σ by itself)


flat trough
V
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ψ
3
2.5
2
1.5
1
0.5
σ

Fine tuning : 1/1000

(But generic initial conditions)





Density perturbations:

$$P(k) = \delta_H^2 = \frac{8\pi G V}{75\pi^2} g^{ij} \frac{\partial N}{\partial \phi^i} \frac{\partial N}{\partial \phi^j}$$

$$\sim \frac{3}{75\pi^2} \frac{H^4}{g_{ij}\dot{\phi}^i \dot{\phi}^j}$$

Cobe:

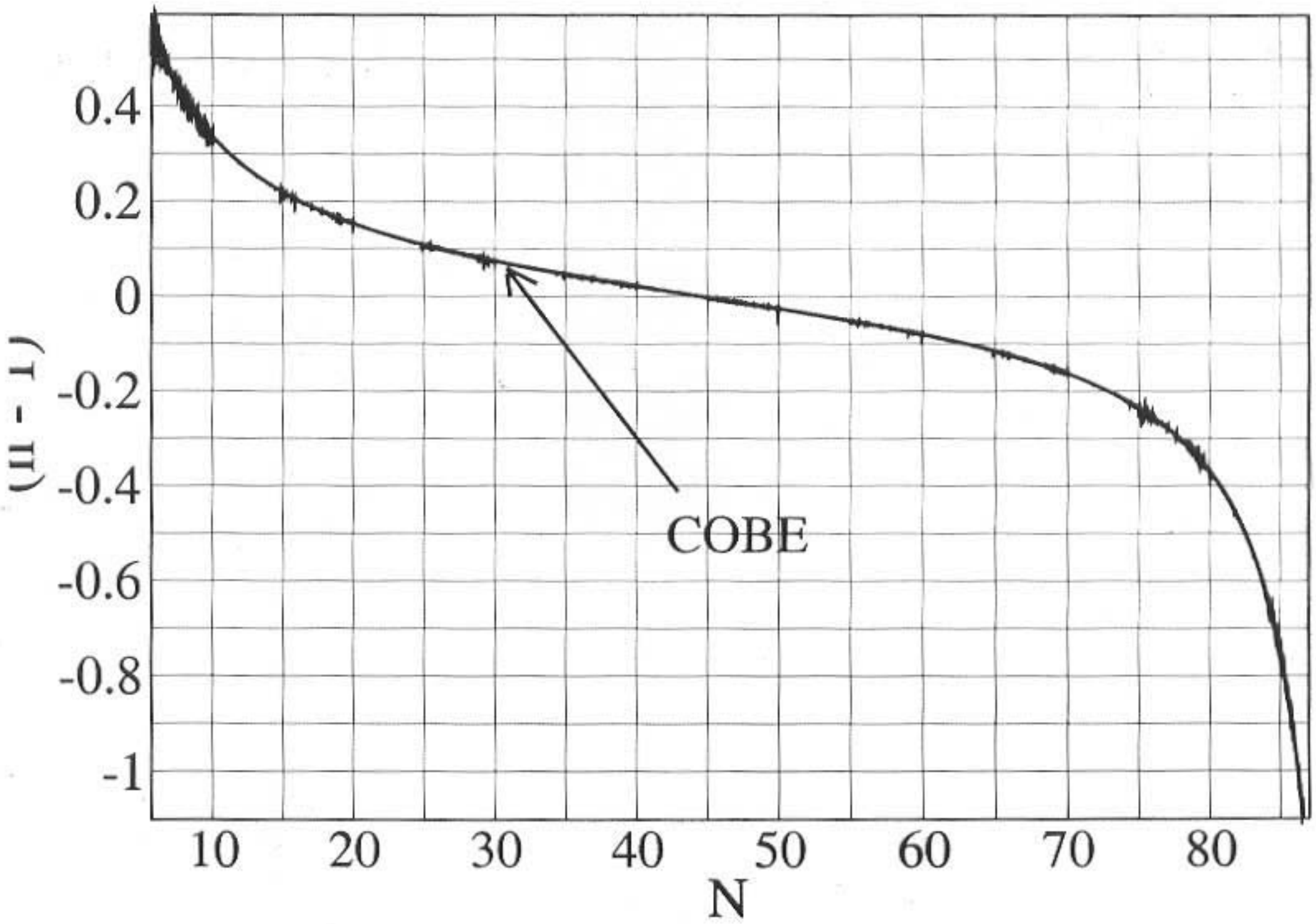
$$\delta_H = \sqrt{P(k_0)} \sim 2 \times 10^{-5}$$

$$\Rightarrow M_s \simeq 10^{-11/4} M_p \sim 4 \times 10^{15} \text{GeV}$$

Spectral index:

$$n = 1 + \frac{d \ln P}{d \ln k} \sim 1.03 - 1.08$$

↳ blue


0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
(Γ - Π)
COBE
10
20
30
40
50
60
70
80
N

* $D3-\overline{D3}$ inflation possible :

* $\frac{1}{1000}$ fine tuning

Two step inflation ?

- 20-30 e-foldings at M_{GUT}
- rest at $E \sim M_{EW}$

(Cosmological moduli problem)

* Concrete realisation

$n_s \sim 1.03 - 1.08$ $(dn/d\ln k \neq 0)$

$M_s \sim M_{GUT} \sim 10^{15}$ GeV

↳ small warping

But S.M. $\Rightarrow M \gtrsim 10^{10}$ GeV ; 1 Tev

↳ big warping

$\Rightarrow$ Multi throat.

* Reheating ?

* End of inflation : Tachyon

$\Rightarrow$ Cosmic Strings (unstable ?)

Generalizations of KKLT

* More general W_{np}

$$W_{np} = \sum_{i=1}^{N} A_i e^{a_i T} + W_0$$

(Escoda, Gomez-Reino, FQ.)

$\Rightarrow$ Many de Sitter minima.

* Magnetic Fluxes on D7:

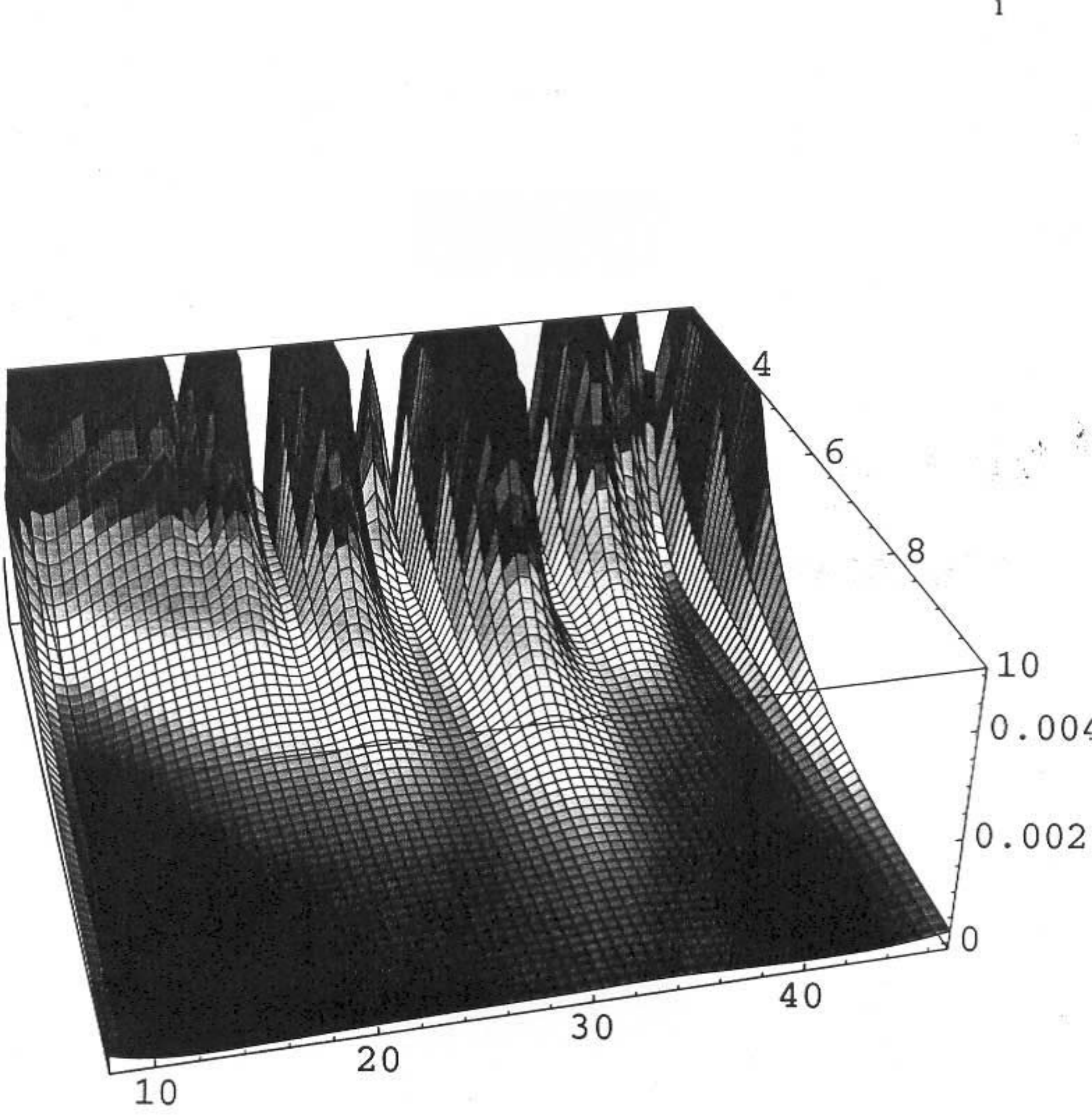
Burgess, Kallosh, FQ

$$F_{mn} F^{mn} \longrightarrow \frac{E}{X^3}$$

Identical to Antibrane tension

$\equiv$ Fayet-Iliopoulos D-term.

- Supersymmetric
- Generalizable to Heterotic


4
6
8
10
0.004
0.002
0
40
30
20
10

Racetrack Inflation

Blanco-Pillado, Burgess, Cline
Escoda, Gomez-Reino, Kallosh
Linde, PQ. hep-th/0406230

$$W = A e^{-aT} + B e^{-bT} + W_0$$

$$K = -3 \log(T + T^*) \qquad T \equiv X + iY$$

$$V = e^K \left[K^{i\bar{j}} D_i W D_{\bar{j}} W^* - 3|W|^2 \right] + E/X^2$$

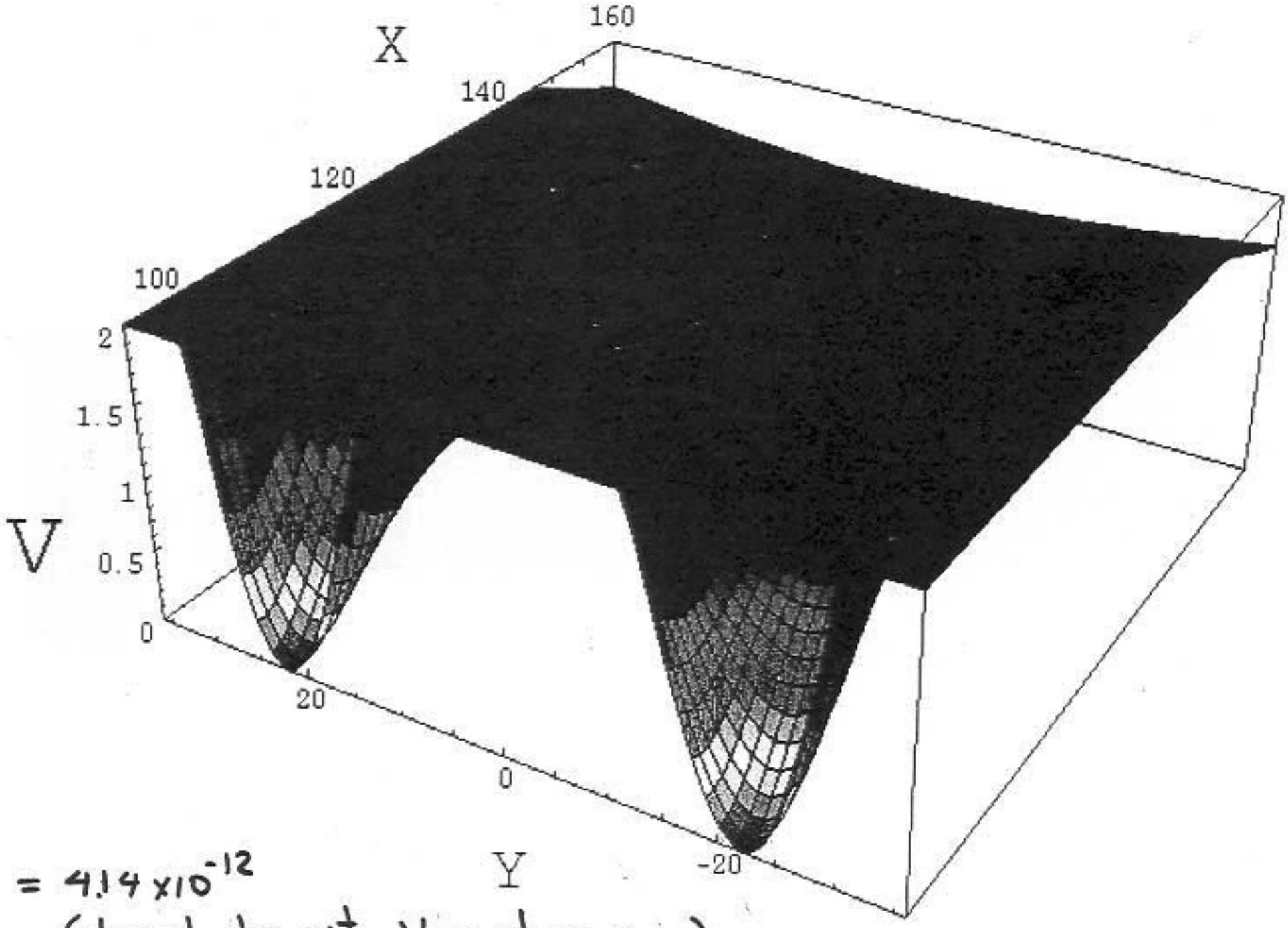
$$D_i W \equiv W_i + K_i W$$

$$= \frac{e^{-aX}}{6X^2} \left[a A^2 (aX+3) e^{-aX} + 3 W_0 a A \cos aY \right] +$$

$$\frac{e^{-bX}}{6X^2} \left[b B^2 (bX+3) e^{-bX} + 3 W_0 b B \cos bY \right] +$$

$$\frac{e^{-(a+b)X}}{6X^2} \left[AB (2ab X + 3a + 3b) \cos (a-b) Y \right] + \frac{E}{X^2}$$

$A = \frac{1}{50}$ $B = -\frac{35}{1000}$ $a = \frac{2\pi}{100}$ $b = \frac{2\pi}{90}$ $W_0 = -\frac{1}{25000}$



$E = 4.14 \times 10^{-12}$
(tuned to get V=0 at minima)

Saddle point: $X = 123.22$

$Y = 0$

Slow-roll: $\epsilon_{saddle} = 0$ $\eta_{saddle} = -0.006$

$\Rightarrow$ Topological Eternal Inflation!
(Linde + Vilenkin)

(Domain wall thickness $\delta > 1/H$).

Spectral index:

$n_s \sim 0.95$

$dn/d\ln k \sim -0.001$

Inflation Scale: $V^{1/4} \sim 10^{14}$ GeV

($\ll 3\times10^{16}$ GeV $\Rightarrow$ no tensor contribution)

Fine tuning of 0.1% (ok in landscape picture).

Warning: Explicit $W \neq 0$ for 1 size modulus?
(2 or more ok).

Douglas et al
Sethi et al.

Conclusions

Encouraging progress in

* Moduli Fixing
* $D\bar{D}$ inflation
  (also D3-D7 Kallosh et al)
* Modular (Racetrack) Inflation

Many Open questions

* Establish + Understand Landscape
* Explicit Models (Realistic)
* Reheating
* Cosmic Strings.

⋮