Issues in Type IIB Cosmology and Phenomenology

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Outline

- Moduli stabilization / cosm. constant / susy-breaking
- Throats – statistics
  – inflation and energy transfer
  – dark matter
- Model building – at singularities
  – brane-stacks at weak coupling / in F-theory
  – obstructions / D-brane motion vs. cycles

Why type IIB ?

→ Grana '05
Douglas, Kachru '06
Denef '08

- ideally: model building & tuning of cosm. constant in the same setting
  ("prove" existence of fully realistic string vacua)

- best "MSSM" models: heterotic CYs / heterotic orbifolds

  (→ Ovrut et al.)
  - few models
  - analysis "by hand"

  (→ Buchmüller et al.)
  - computarizable search in "mini landscape"
  - blow-up not understood

analogue of flux discretuum (and hence tuning of Λ) not understood.

type IIA toric orientifolds (intersecting D6-brane models)

(→ Ibanez ; Lüst ; Honecker ...)

Again: tuning of Λ not demonstrated (also: GUTs less natural)

type IIA CY-orientifolds

- technically challenging since D6-branes need to wrap special Lagrangian submanifolds
- fine-tuning of Λ may be doable: (→ De Wolfe et al. '05; Acharya et al. '06)
  - $M_{KK}/M_{Pl} \sim D_0(N)/\sqrt{N}$
    - F_4 flux number
    - size of space with unit volume
  - controlled uplift problematic

type IIB CY-orientifolds (→ GKP/KKLT)

- compl. structure stabilized by fluxes

  ⇒ no-scale model with unstabilized Kähler moduli ("T")

- D7-brane-gaugino-cond. / D3-brane-instanton → $W = W_0 + e^{-T}$

  ⇒ AdS-SUSY-vacuum with $M^2_{AdS} \sim W_0$;

  uplift by $\overline{D3}$-brane in throat with warp factor h :

  $$-|W_0|^2 + h^{-4} \sim 0$$

Crucial: uniform distribution of $|W_0|^2$ demonstrates existence of vacua with realistic cosm. const.

(→ Douglas ; Denef, Douglas '04)

The explicit SUSY-breaking by $\overline{D3}$ has been criticized and alternatives have been suggested:

- D-term-uplift (by D7-brane gauge fluxes)
  [Not very successful, mainly since it can not be viewed as a "simple extra feature"]
- ISS-uplift (effective F-term generated non-pert.-ly)
  [successful]

However, one may argue that the $\overline{D3}$ uplift is quite sufficient:

- Consider a sequestered O'Raifeartaigh sector as a model for the $\overline{D3}$:

$$e^{-K/3} = T + \bar{T} + h^{-2} f(x,\bar{x})$$
$$W = W_0 + e^{-T} + h^{-3} g(x)$$

It is easy to see that:
- $F_x \neq 0$ uplifts appropriately if $h^{-2} \sim W_0$
- $F_\varphi \neq 0$ & $F_\tau \neq 0$ follow as fcts. of M_{AdS} (completely independently of the O'Raifeartaigh sector)

$\Rightarrow$ viewing hard ~~susy~~ as a ("non-lin. σ-model-") limit of soft breaking, the above conclusions extend to the $\overline{D3}$-case.

(→ Choi, Nilles, ...
Choi, Jeong
Brümmer, A.H., Trapletti)

other issues:
- Mirage mediation
- Breaking of sequestering by throat-vector-fields
- Breaking of sequestering by tachyonic fields in throat ??

Alternatives:

Large-volume scenario

(→ Balasubramanian, Berglund, Conlon, Quevedo '05)

- balance α'-corrections & non-perl. corrections for two Kähler moduli

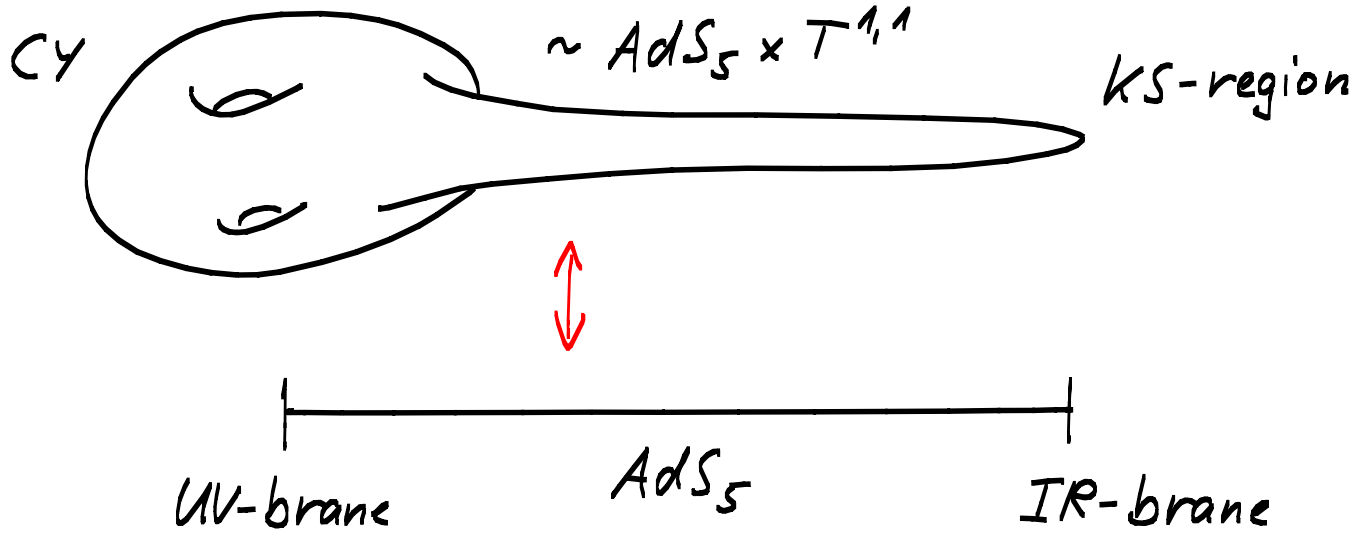
purely perturbative stabilization

(→ Silverstein; von Gehrsdorff, A.H.; Berg, Haack, Körs)

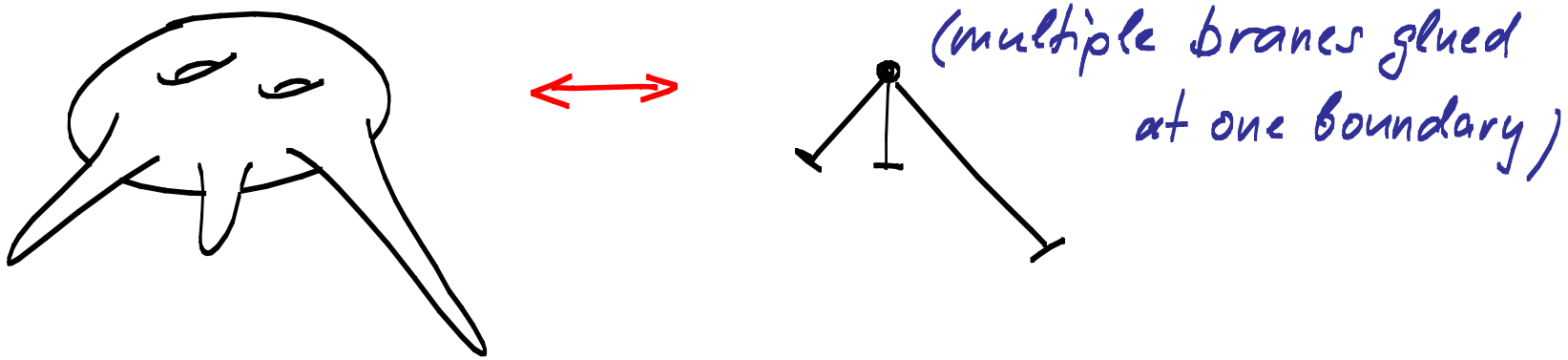
- balance α'-corrections & 1-loop Kähler corrections

Throats

very appealing as a stringy version of the RS model:



maybe even:



Throats can be argued to be ubiquitous in the type IIB landscape

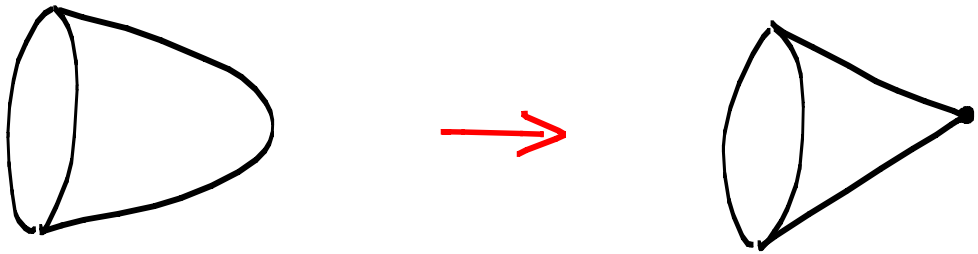
(→ A.H., March-Russell '06

building on

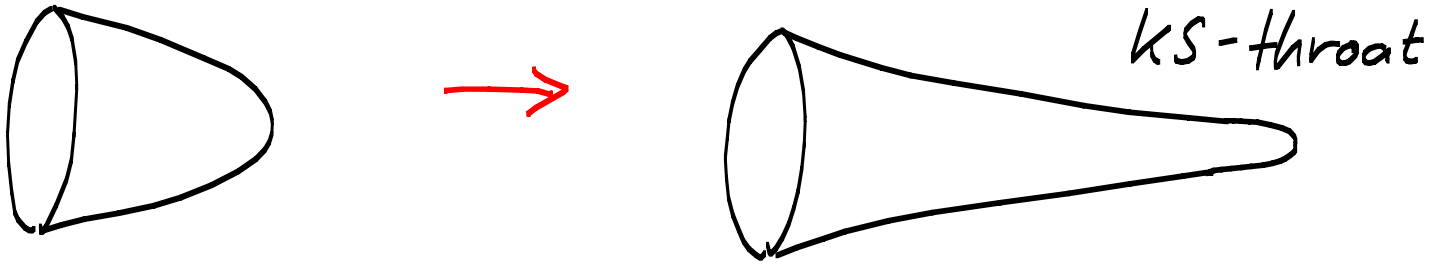
Denef, Douglas '04
Giryavets, Kachru, Tripathy '04
Conlon, Quevedo, '04
Eguchi, Tachikawa, '05)

- A throat appears when a generic 3-cycle shrinks in the presence of flux:

Without flux:



with flux:



warp factor : $h \sim \exp(K/M)$

K: flux on throat cycle

M: flux on dual cycle

very roughly : small Λ $\Rightarrow$ many 3-cycles $\Rightarrow$ some large ratios K/M $\Rightarrow$ some long throats

Results of detailed analysis :

Binomial distribution of throats:

$$p(n, h > h_* \mid K) = \binom{K}{n} p^n (1-p)^{K-n}$$

$$p \equiv \frac{1}{3c \log h_*}$$

c: $O(1)$-number parameterizing our ignorance of CY-moduli-space

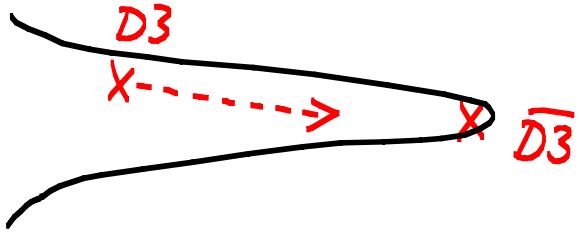
Consider two extreme cases:

- 60 cycles ; $c = 3$ $\Rightarrow$ warp factors down to 10^{-3}
- 200 cycles ; $c = 1/3$ $\Rightarrow$ warp factors down to 10^{-80}

  (+ many shorter throats)

$\Rightarrow$ Throats of various lengths can be considered a prediction of the type IIB landscape (the precise distribution remains an interesting open problem).

- As a particular physics application, brane inflation in throats has been considered by many authors:



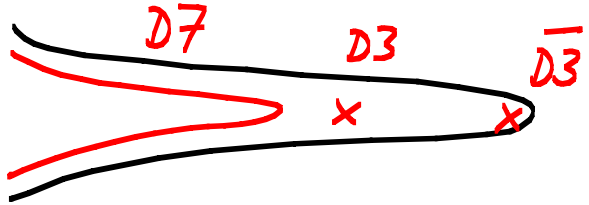
- KKLMMT (..., McAllister)

  flatness of $D3-\overline{D3}$ potential $\Rightarrow$ slow roll

  problem: other effects (gaugino condensation, α'^2-corrections) spoil flatness and fine tuning reemerges

- D3/D7-inflation

  fine-tuning realized using D7-brane in throat:



- DBI-inflation (Silverstein, Tong)

  brane-velocity limited by non-linearity of DBI-action

  but: very long throats needed (→ Mukohyama, ...)

- possible way out: wrapped DBI-inflation

  (D3 → wrapped D5)

  but: required throats are still too long

- other idea: conformal brane inflation

  (H^2-corrections absent because of hidden conformal symmetry)

an important issue in this context:

Energy transfer between throats

for: • reheating of SM after D3-$\overline{\text{D3}}$ annihilation
- absence of dangerous relics
- throat dark matter

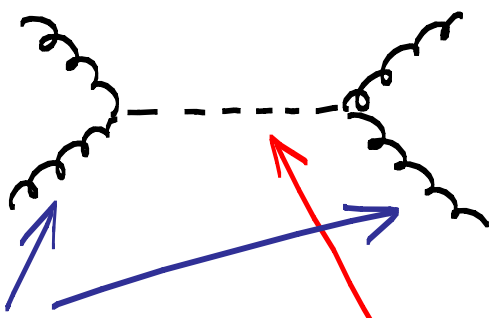
(→ Dimopoulos et al., '01
Kofman, Yi ; Langfelder ;
Chen, Tye '06 ; ...)

Our approach: Describe throat by large-N brane stack

(including coupling to bulk SUGRA fields)

(Harling, A.H., Noguchi, '07)

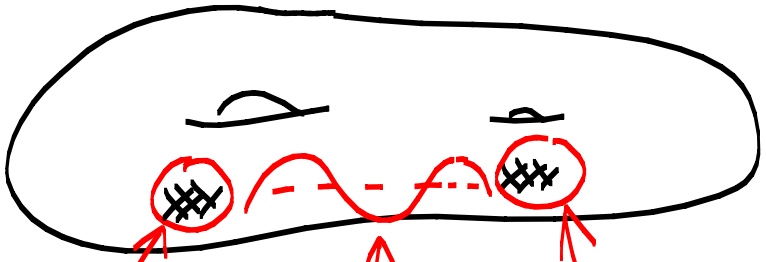
- Calculate energy transfer via



gauge fields on 2 brane stacks

dilaton

physical picture:



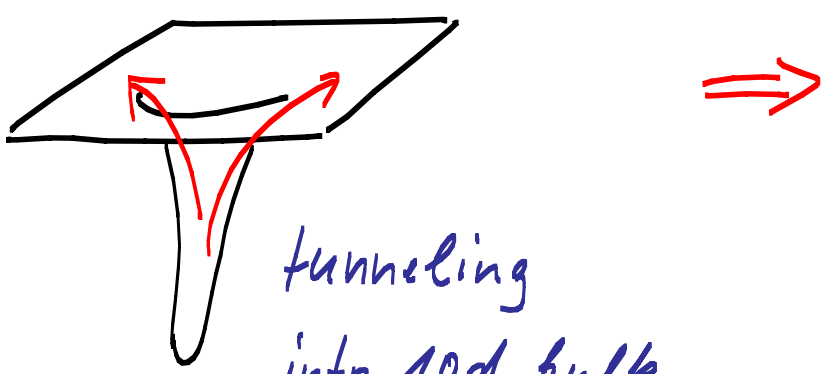
brane stack ≡ throat

bulk modes

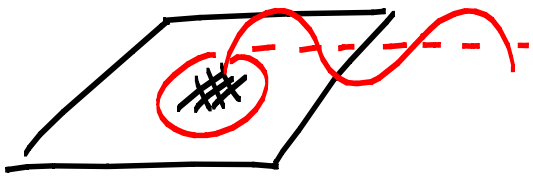
brane stack = throat

Comments:

- This approach is superior to older tunneling calculations, which are difficult to extend from 5d to 10d
- It can also be applied to the decay of light kk modes:



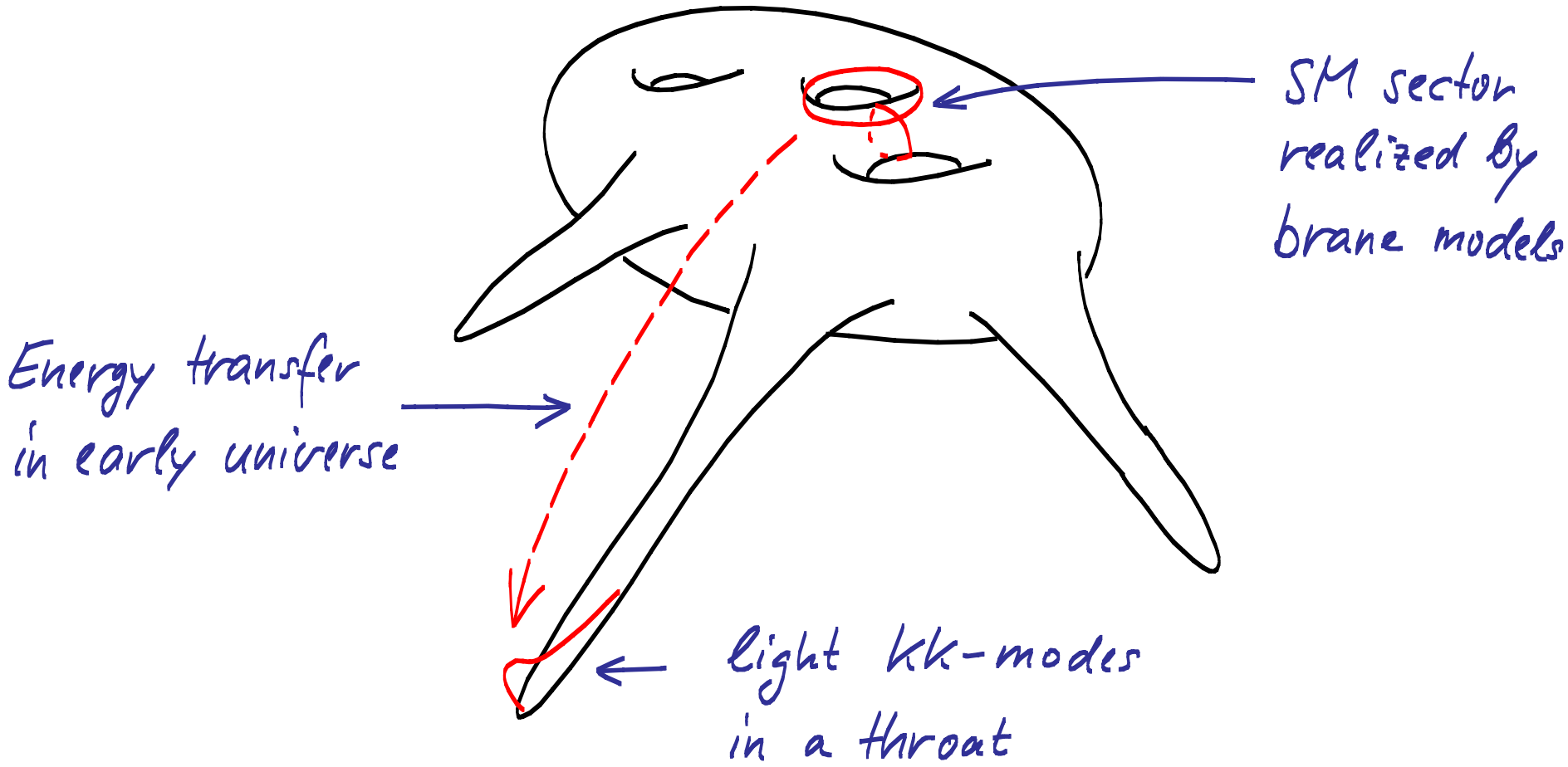
tunneling into 10d bulk



effective decay vertex for glueball

Sequestered Dark Matter (Harling, A.H., '08)

Based on the following "generic" situation:



- calculate evolution of energy density in throat
  (scaling depends on whether the equivalent gauge theory is below or above confinement transition)
- to get appropriate dark matter density, we need

$$T_{RH} \sim 10^{11}\ \text{GeV}$$

- the mass of the resulting dark matter candidate is between 10^5 GeV and 10^{11} GeV.

Observational consequences

- Dark matter decaying to gravitons on cosmol. time scales
- Dark matter decaying to 2γ (observation by HESS)
  or to Higgs + leptons (observation by GLAST)

[SUSY in throat essential!]

Comment

The previously discussed statistical analysis confirms the availability of the required throats

(see also recent papers by Barnaby et al. and Kofman et al.)

Type IIB / F-theory model building

- probably more critical than cosmology: building SM-sector
- one promising approach (Verlinde et al., Uranga et al.)

D3-branes at singularities

Advantage: Due to warping near singularity, this may lead to direct tests of string theory at future colliders

Problems:
- Stabilization of moduli (after SUSY-breaking)
- Global embedding

Comment: The global embedding issue may be universally solvable as follows:

- the toricaly constructed local geometry can always be extended to a compact Kähler manifold
- introducing an O7 plane on the Chern-class divisor, one can find an appropriate CY-orientifold

(→ Braun, A.H., Triendl. '08)

More canonical approach!

Models on intersecting 7-branes (D7 or strongly coupled)

Work on model building with 7-branes in CY's

- $SU_5 \times SU_5$ GUTs (→ Watari, Yanagida)
- exceptional branes, e.g. 7-branes in strongly coupled type IIB (with GUTs) with group E_6, E_7 ..., broken by gauge bundles to SM
  - geometrical analysis of matter content at intersections
  - Yukawa couplings from tiple-intersections (→ Donagi, Wijnholt '08 Beasley, Heckman, Vafa '08)

- F-theory obstructions to brane motion

  (→ Braun, A.H., Triendl '08
  Collinucci, Denef, Esole '08)

- Brane-motion from M-theory cycles

  (→ Görlich, Kachru, Tripathy, Trivedi '04
  Lüst, Mayr, Reffert, Stieberger, '05
  Aspinwall, Kallosh '05
  Braun, A.H., Triendl, '08)

Type IIB with D7 branes from M theory ("F theory")

M theory on S^1 with small radius

↓

type IIA in $d = 10$; compactify on another small S^1 and use T duality

↓

type IIB in $d = 9 \times$ (large S^1)

Thus: M theory on T^2 (with volume $\to 0$)

= type IIB in $d = 10$

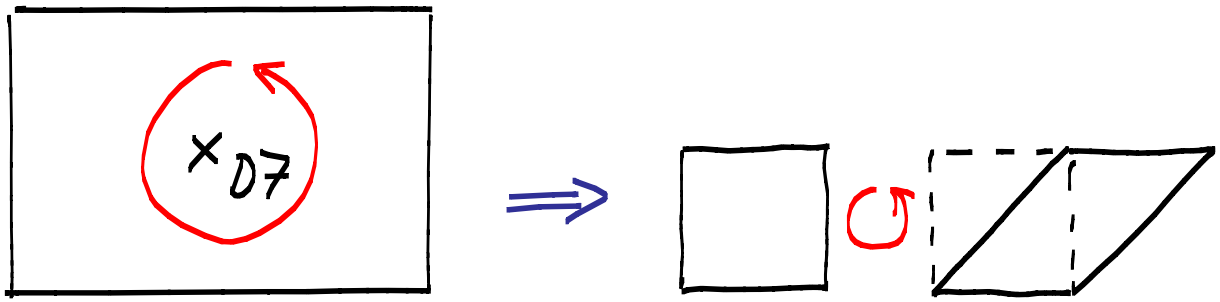
The only information left over from T^2 is its compl. structure

$\Rightarrow$ complex dilaton $\tau(x)$ of type IIB

D7 branes in F theory

Recall: $\tau = C_0 + ie^{-\phi}$

D7 branes source C_0 $\Rightarrow$ C_0 goes to C_0+1 if one "goes around" D7 brane



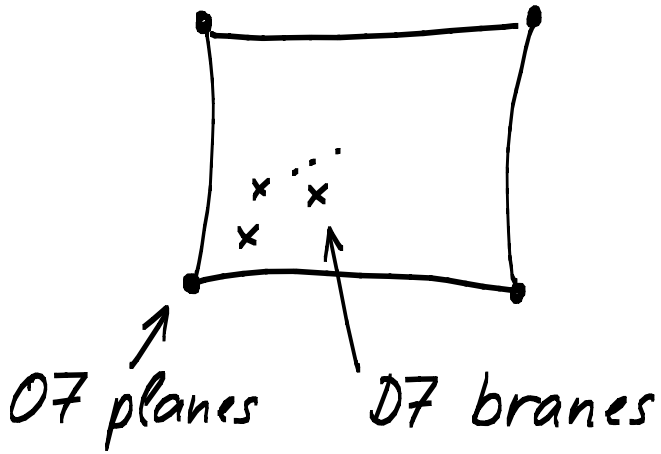
$\tau \to \tau+1$ for fibre torus

$\Rightarrow$ D7 branes are encoded in non-triviality of torus fibration

Note:
- We assume $\mathrm{Im}\,\tau \to \infty$ almost everywhere
- There are also monodromy points at which $T^2 \to "-T^2"$ (O7-planes)

Explicit analysis of simplest example

- F-theory on K3 corresponds to type IIB on T^2/Z_2 with 4 O7 planes & 16 D7 branes:



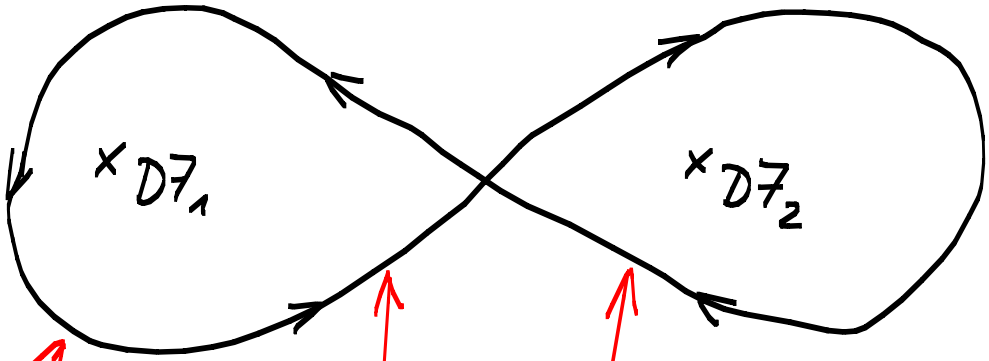
"pillow geometry"

- over every point of this $S^2 = \mathbb{C}P^1$ there is a T^2 with complex structure τ

(= K3 as elliptic fibration with base $\mathbb{C}P^1$)

We want to identify K3-cycles in "moving D-brane picture"

Basic building block:

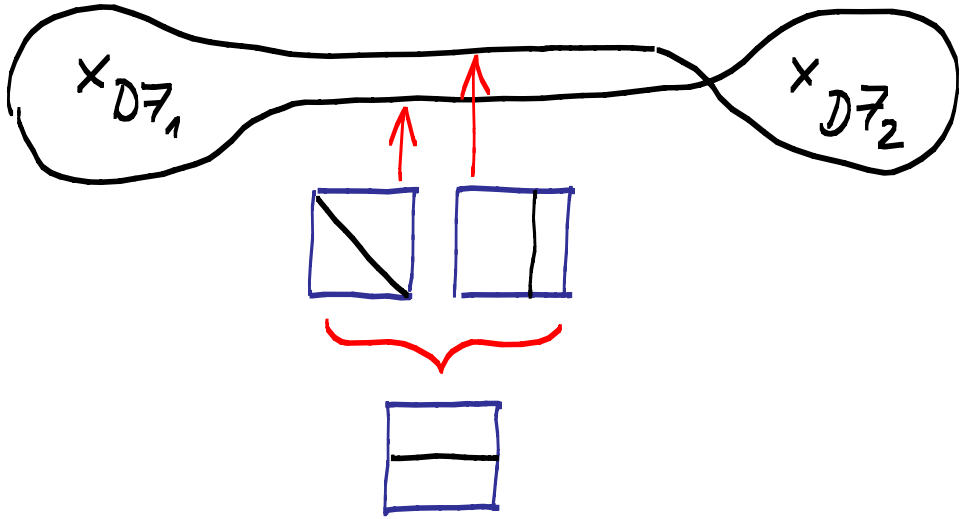


These are the two 1-dim. legs of a non-trivial 2-cycle of K3

fibre torus

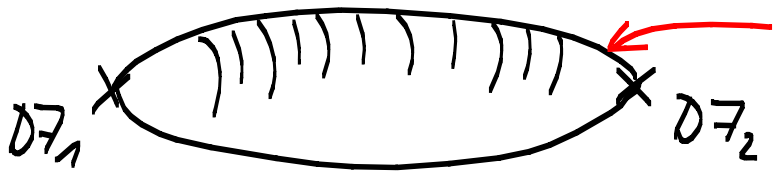
(we have redrawn the torus after the monodromy $\Rightarrow$ change of cycle)

Further deformation of this cycle:



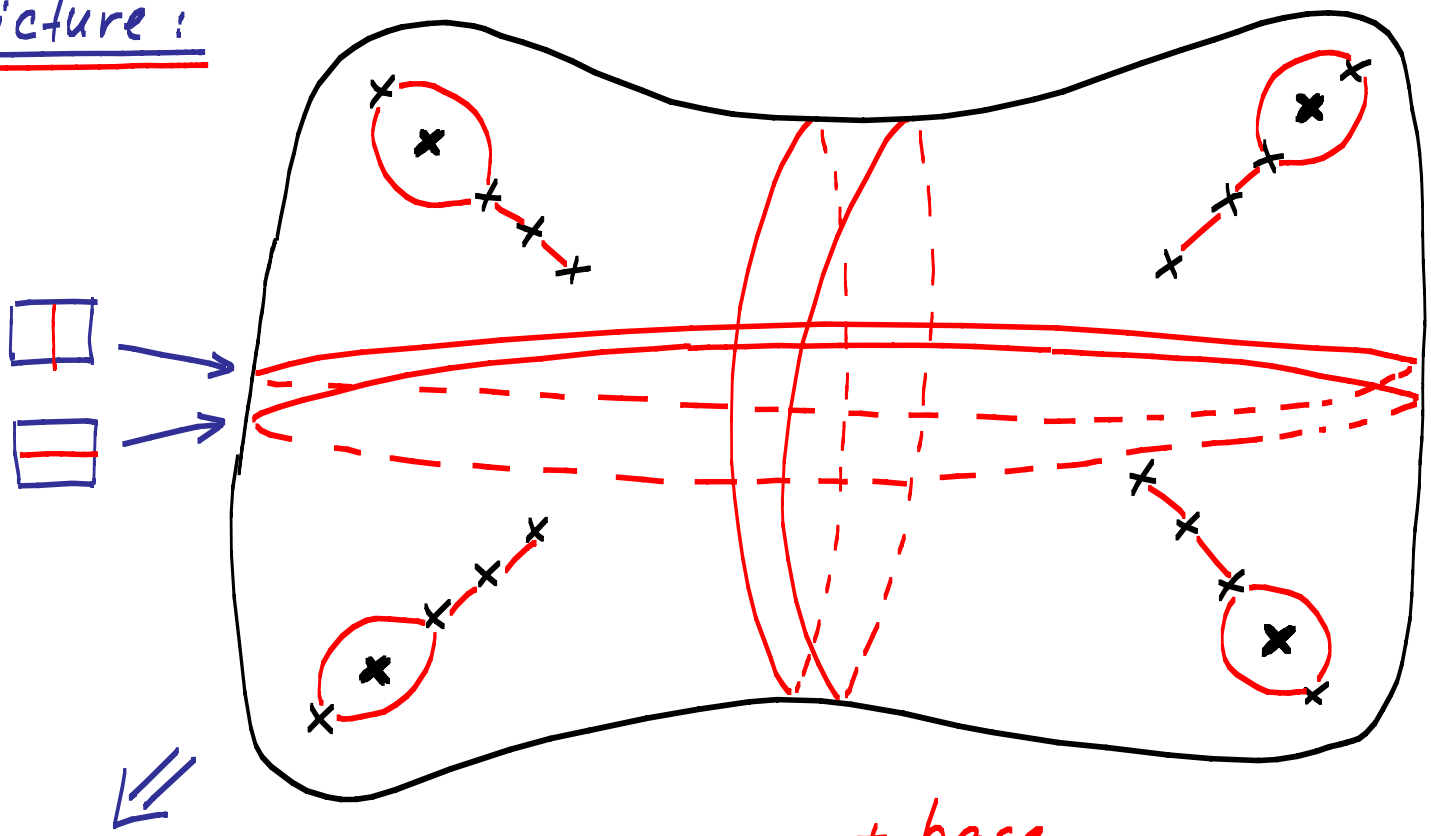
⇒ **natural expectation:**

The cycle is an S^2 wrapping the T^2 horizontally between the branes. At each brane, the horizontal extension of T^2 shrinks to zero & the cycle "ends":



S^2-cycle between two D7 branes

Final picture :



+ base
+ fibre

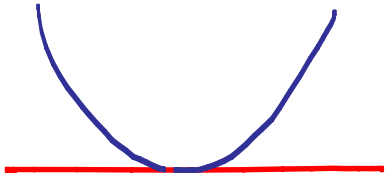
22 cycles of K3

We have explicitly translated the sizes (periods) of these cycles into Ω of K3 and into D-brane positions on the pillow.

Obstructions to D7-brane motion

- At the intersection with an O7-plane, the weak-coupling limit can not be maintained
- D7-branes can not be simply viewed as holomorphic submanifolds respecting the orientifold-$\mathbb{Z}_2$-symmetry (as discussed by Jockers and Louis)
- in more detail: The Weierstraß-description of the T^2-fibration in Sen's weak-coupling limit forces alle D7-O7 intersections to be double-intersection-points

Picture in fundamental space:



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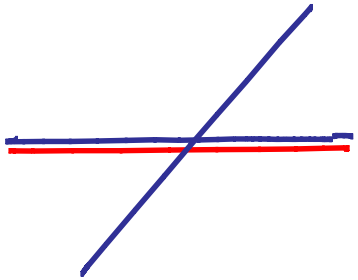

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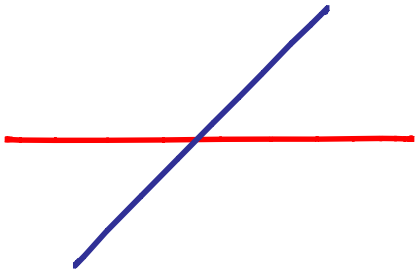

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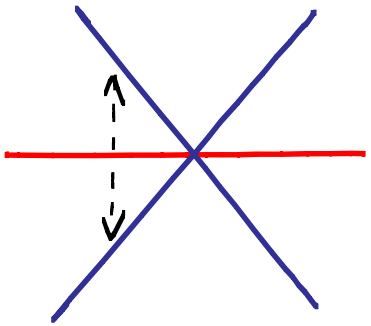
Picture in double-cover CY (reparameterization $z \to \sqrt{z}$)



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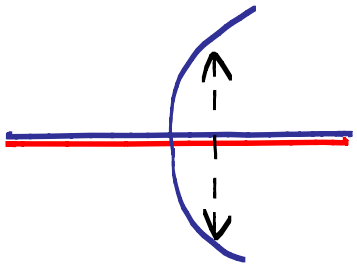

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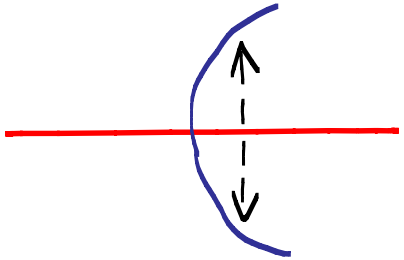

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