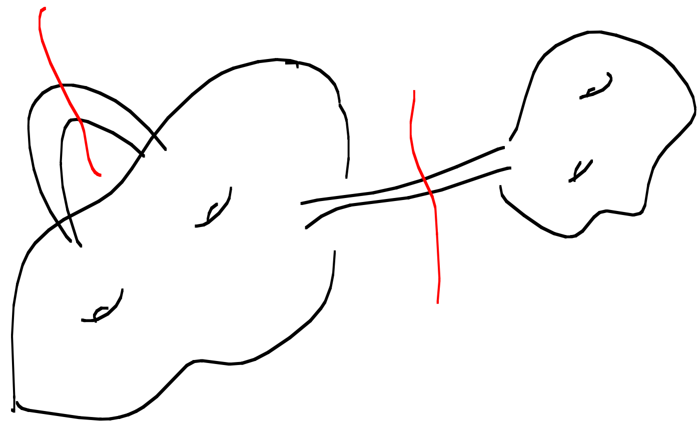


Things Fall Apart:

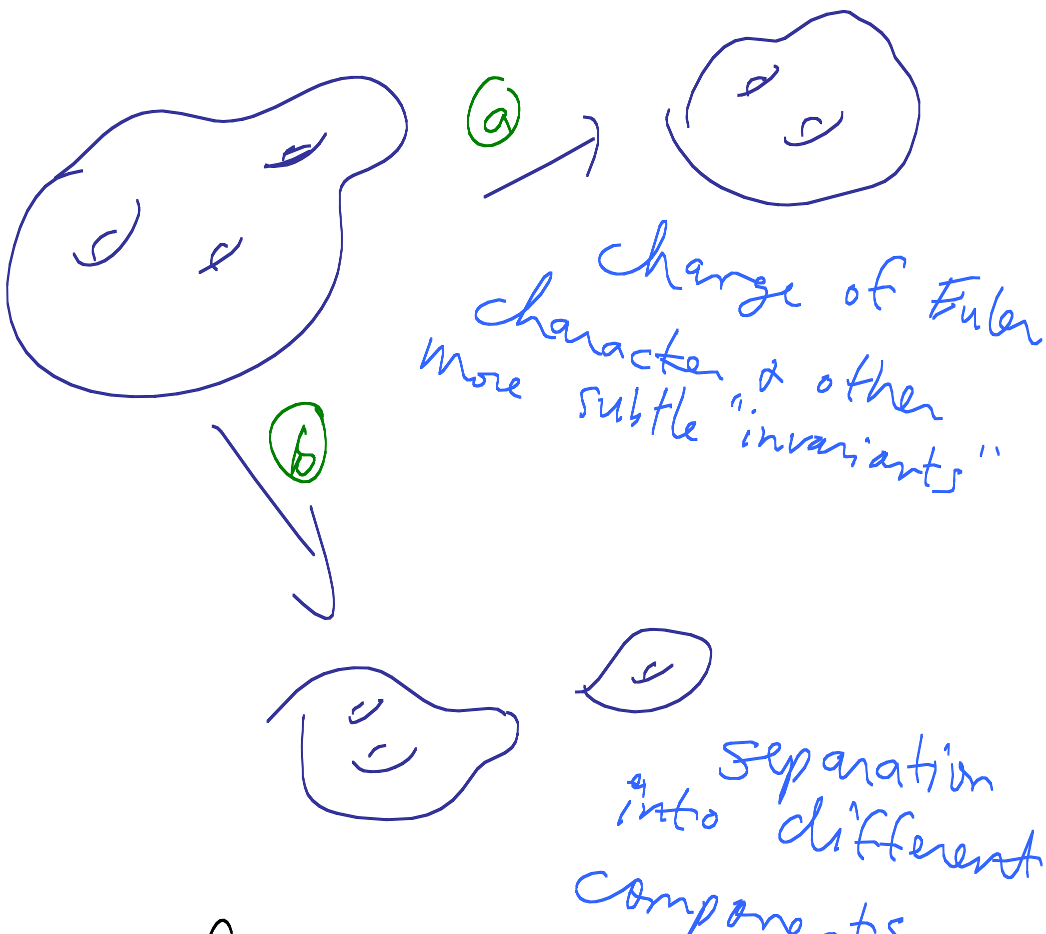
Topology Change from Winding Tachyon Condensation

with Adams, Liu, McGreevy
& Saltman

cf early work of Yeats
Sen, Adams Polchinski, ES

A basic question about gravity is whether spacetime topology can change dynamically

e.g.



In <u>Classical</u> GR, this would be singular (rip space)

In quantum or even classical stringy $\frac{L}{l_s} \lesssim 1$ regimes,

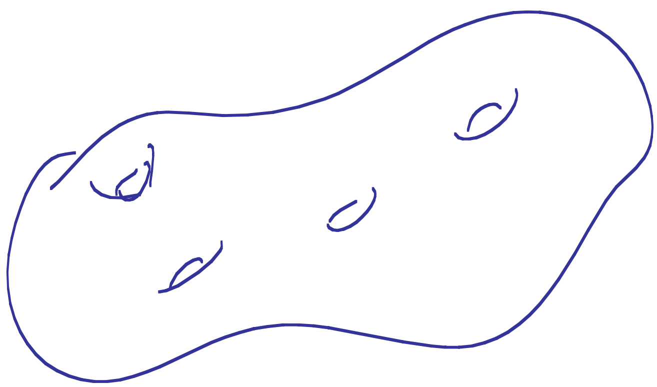
GR and ordinary geometry break down $\rightarrow$ room for topology change to happen in a physically non-singular way.

Some previous examples:

- flops Aspinwall, Greene, Morrison, Witten
- ΔX in $(0,2)$ models Distler & Kachru
- Conifold transitions * Strominger; + Greene, Morrison
- chirality-changing transitions Kachru & E.S.
- $\mathbb{C}^d/\mathbb{Z}_N$ "flips" and $D<10$ components (APS), Morrison et al, Harvey et al
- Euclidean Q. suggestions of baby universe Hartle Hawking Coleman Gross Giddings Strominger Susskind Fischler ... Polchinski ...

We find a very simple case of Δ (Euler character) as well as baby universe formation perturbatively

Consider Compactification of $D=10$ superstring theory on a Riemann Surface of genus h (h handles)



Its topology is characterized by

- # of components
- genus h
- spin structure of fermions

Its geometry (in the regime where all length scales are $\gg l_s$ so the notion makes sense)

is characterized by

$$g_{\mu\nu} = e^{\phi}\, \hat{g}_{\mu\nu}(\tau)$$

- conformal factor $\phi(X_1, X_2)$ including overall volume $V_\Sigma \sim e^{\phi}$
  in string units
- $3h-3$ complex structure deformations τ
  ↳ determines ratios of sizes of cycles & how far we are from factorization limits

with 1 component (to start with) the 8d effective potential energy descending from the 10d Einstein term is

$$U_{8d,\text{ Einstein frame}} \sim + \frac{1}{l_8^{\,8}} \left(\frac{g_s^2}{V_\Sigma}\right)^{4/3} \frac{1}{g_s^2} (2h-2)$$

(indep. of complex structure moduli)

Its dynamics (in the absence of other sources) is:

- evolves toward constant negative ($h>1$) curvature metric

  (regions of + curvature contract, & regions of − curvature expand)

- Expands toward flat space, weak coupling

- If can reduce h, energetically preferred

In other work, Saltman & I showed that additional ingredients (fluxes, triply intersecting 7-branes on $\Sigma_1 \times \Sigma_2 \times \Sigma_3$) suffice to perturbatively metastabilize the complex structure moduli of the Riemann surfaces their volumes, and g_s, leading to a large class of controlled 4d dS models cf KKLT, MSS

Here, we will study another regime, without such stabilizing ingredients, and will argue for simple stringy topology changing dynamics.

realizing $h \to h-1$; factorization

Brief summary of dS from Riemann Surfaces:

IIB)

$$\Sigma_1 \times \Sigma_2 \times \Sigma_3$$

$$H^{(3)}_{123}\,,\quad F^{(3)}_{123}\quad F^{(5)}_{11,22,3}$$

+cyclic

① Flux

$$U_{flux} = \oint F \wedge * F = f(V,g) \sum_{I=1}^{N_F} Q^{iI} A_{ij}(\tau)\, Q^{Ij}$$

allowed here for multiple 1-form fluxes

where

$$A_{ij}(\tau) = i \begin{pmatrix} 2\tau(\tau-\bar{\tau})^{-1}\bar{\tau} & -(\tau+\bar{\tau})(\tau-\bar{\tau})^{-1} \\ -(\tau-\bar{\tau})^{-1}(\tau+\bar{\tau}) & 2(\tau-\bar{\tau})^{-1} \end{pmatrix}$$

Fixes complex moduli τ

② Intersecting 7-branes & (separated) $\overline{7}$-branes

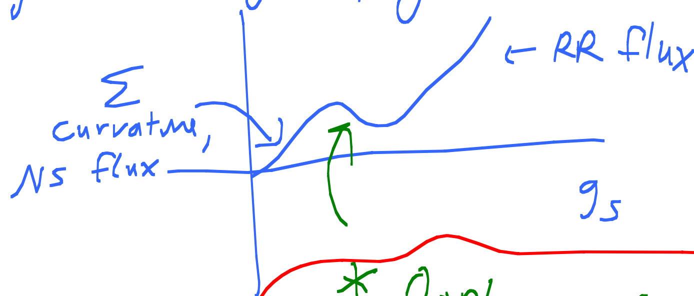
Triple intersections make anomalous **negative** contribution to potential energy, scaling like n_7^3 * $\ast\, T_{03\text{-}\overline{03}}$

(GKP)

as well as positive tension contribution.

Basic strategy: need at least 3 terms for each g, $\frac{1}{V_\Sigma}$ in expansion about weak coupling & large volume

e.g. for string coupling



* O-planes (& more general intersecting 7-branes)

$7-\bar{7}$ don't annihilate

Altogether, get:

$$U = \frac{g_s^2}{(V_1 V_2 V_3)^2 \ell_4^4} \sum_{a \neq b \neq c} \Big\{ \underbrace{[2(h_a + n_7 - 1) V_b V_c}_{\text{curvature, } 7Bs,\ \bar{7}Bs} + \underbrace{N^{i_a i_b i_c} A(\gamma_{i_a})_{i_a j_a} A(\gamma_{i_b})_{i_b j_b} A(\gamma_{i_c})_{i_c j_c} N^{j_a j_b j_c}]}_{\text{NS flux}}$$

$$- g_s \underbrace{[N_7]}_{\text{anomalous 3-brane tension}}$$

$$+ g_s^2 \Big[\underbrace{Q_3^{i_a i_b i_c} A(\gamma_{i_a})_{i_a j_a} A(\gamma_{i_b})_{i_b j_b} A(\gamma_{i_c})_{i_c j_c} Q_3^{j_a j_b j_c}}_{\text{RR 3-form flux}} + \underbrace{\frac{Q_5^{i_a} A(\gamma)_{i_a j_a} Q_5^{j_a}}{V_b V_c}}_{\text{RR 5-form flux}} \Big] \Big\}$$

($\frac{1}{g_s^2}$ × Einstein frame conversion)

This perturbatively stabilizes

τ, V_{Σ_i}, g_s

at values such that all α' and quantum corrections are small: $F\alpha' \ll 1$

$\alpha' R \ll 1$ $\quad g_s N_{light} \ll 1$

These work for the above model so long as we tune

$N_7 \gg h + n_7 - 1$ $\quad \left(\frac{N_7}{h+n_7-1}\right)^{\frac{3}{2}} \gg n_3^{\frac{1}{2}} q_3^{\frac{1}{2}}$

$q_5^2 \gg N_7$ where $N_7 \sim (24)^2 n_7^3$ is coefficient of negative term

$q_3^2 \sim Q_3 A Q_3$ $\quad n_3^2 \sim N_3 A N_3$

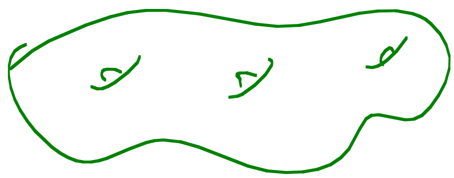
Remark:

People often consider Calabi-Yau compactifications or their SUSY cousins.

This is not required for consistency, control, or phenomenology (even low energy SUSY in the matter sector) and it's not generic.

In early days, people imposed the condition that all tadpoles cancel classically $\Rightarrow$ nice toy models, but bad for moduli fixing and very non-generic

Back to topology change: consider one Σ factor, no extra fluxes

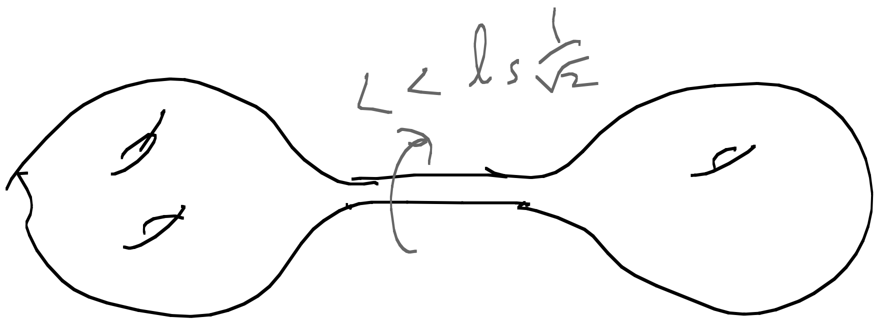


When all length scales are $\gg l_s$, then classical geometry (GR) applies, and h does not change at least perturbatively

(cf Witten bubble)

However, it may be possible to go through a string-scale regime where these notions break down, and come out to large radius in a new phase with different topology.

In particular,



$R l_s^2 \ll 1$

We can go to a regime where

- $l_s^2 R \ll 1$ everywhere
  $\Rightarrow$ control
- $L < l_s \frac{1}{\sqrt{2}}$ small tube locally

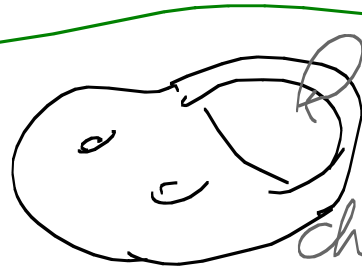
In both cases, winding modes around the thin tube can become light and condense.

* Given antiperiodic boundary conditions for spacetime Fermions:

$$m^2 l_s^2 = -\frac{1}{2} + \frac{L^2}{l_s^2} w^2$$

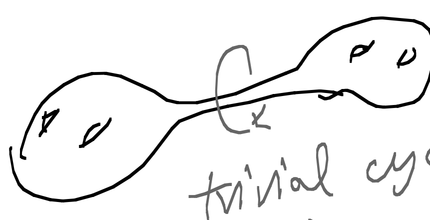
tachyonic for $L^2 < \frac{1}{2} l_s^2$ $\quad w \in \mathbb{Z}$

① small Handle:



Fermion b.c. depend on choice of spin structure

② near-factorization



trivial cycle: antiperiodic boundary conditions

Generally, tachyon condensation has been argued to reduce the # of degrees of freedom:

- $V_T = e^{\kappa X^0} \underbrace{\tilde{V}_T}_{\text{relevant operator in worldsheet matter sector}}$

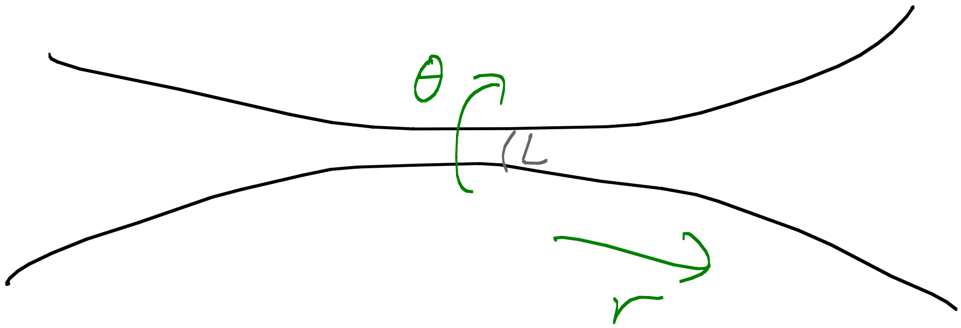
  suggests C_{matter} decreases in the process

- Several well-studied examples exist where this is borne out in detail (open string B-$\bar{B}$ tachyons; $\mathbb{C}^8/\Gamma$ tachyons ...)

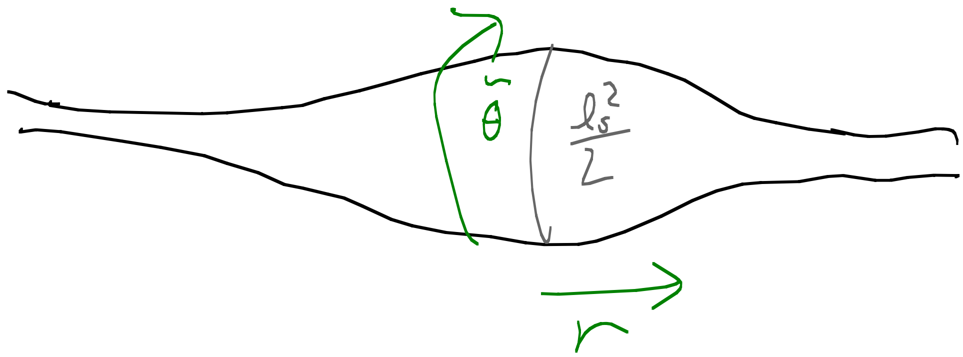
  Sen ... Adams Polchinski E.S. ⋮

In our case, there is very strong evidence that this occurs, which we will review, develop, and apply to top. charge

Let us coordinatize the tube as follows:



$\cong$ (T-duality)



The tachyon vertex operator is

$$\int d\theta^+ d\theta^- \, T(X) \quad \text{in } (1,1) \text{ Superspace}$$

$$T = \underbrace{e^{KX^0} \hat{T}(R)}_{\text{mildly varying ftn of } r,\, X^0} \cos(\tilde{\Theta}\, wL)$$

winding mode around Θ circle

where

$$R = r + \theta^+ \psi_+ + \theta^- \psi_-$$

$$\tilde{\Theta} = \tilde{\theta} + \theta^+ \chi_+ + \theta^- \chi_-$$

→ When we condense the Tachyon, the worldsheet theory becomes (the IR limit of)

$$\mathcal{L}_{ws} = \mathcal{L}_{kin} - U(X)$$

$$U(X) = \partial_\mu T \partial^\mu T$$

negative piece from ws supergravity

$$= \left(-\kappa^2 + k_r^2\right) \hat{T}(r)^2 \cos^2 w \check{\theta}\, e^{\kappa X^0}$$

$$+ w^2 L^2 \sin^2 w L \check{\theta}\, e^{\kappa X^0} \hat{T}(r)^2$$

dominant contribution in regime $\kappa^2 < k_r^2 \ll w^2 L^2$

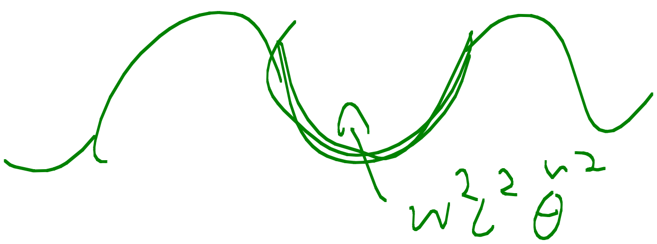
The interactions vary slowly with X^0 and r. Let us first therefore study the IR limit (RG flow) of the Ⓗ sector, treating X^0 & r as couplings. (We will then add back in r & then also X^0.)

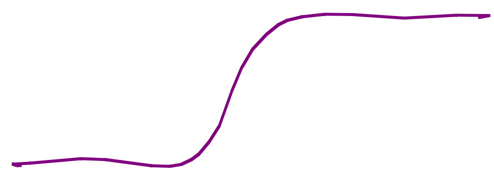
- This is a good approximation for energies $E \ll$ Mass in Ⓗ sector

- The RG flow in the matter sector (ignoring X^0) may well reflect off-shell string confiuration space (de Alwis, Schimmrigk, Polchinski, Myers, Kachru, Kiman, ES, APS, Vafa, Harvey et al)

The leading (H) Lagrangian is the well-studied Supersymmetric Sine-Gordon model.

Classically: massive in both the elementary and solitonic





Sectors.

Quantum Mechanically: $\exists$ strong arguments for mass Gap:

SSG Mass Gap:

1) physically - condensing vortices, expect them to destroy long-range order as in the bosonic SG's Kostelitz-Thouless transition

2) Integrable: proposed exact S-matrix has no massless poles or cuts (Shankar-Witten, Ahn)

$$m \propto T$$

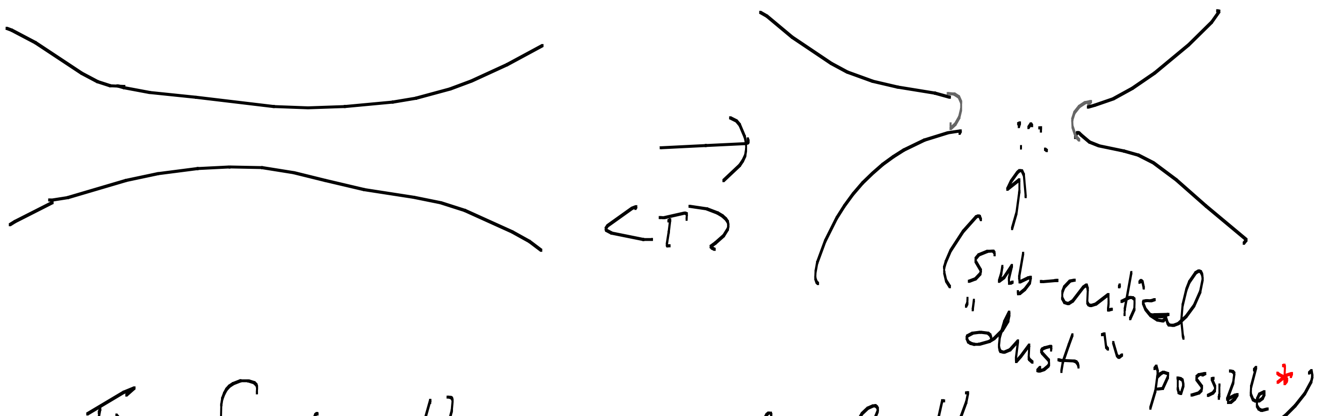
3) Flow below $c = \frac{3}{2}$ highly constrained by classification of $c < \frac{3}{2}$ CFT content. (Friedan, Qui, Shenker..)
No known realization of $c < \frac{3}{2}$ minimal models in which all relevant ops projected out.

Given the SSG mass gap

$$0 < m < T$$

we see that the RG flow removes the Θ direction, in the region of r where the tube was thin and the tachyon operator was relevant.

Once Θ is gone, the theory is sub-critical, and contains further tachyons which condense & remove degrees of freedom from the r sector, again generically removing r, Θ :



In fact, the removal of the middle region is evident more directly in the ws action, once Ⓗ frozen in its vacuum by its mass gap: For $E_{ws} < (M_{gap} \sim T)$

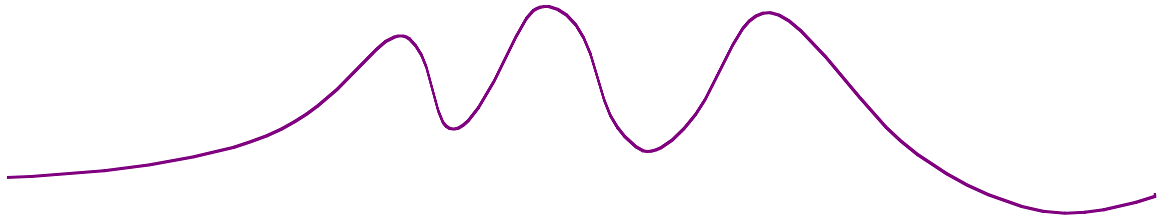
$$U = \left(-K^2 + k_r^2\right)\cos^2 w\check{\theta}\, e^{Kx^0}\, \hat{T}^2(r)$$

$$+ W^2 L^2 \sin^2 wL\check{\theta}\, e^{Kx^0}\, \tilde{T}^2(r)$$

$wL\check{\theta} \simeq 0$

$$= \left(\frac{(\partial_r \hat{T})^2}{\hat{T}^2(r)} - K^2\right)\hat{T}(r)^2 e^{Kx^0}$$

<u>potential barrier</u> for string: repelled from <T> region

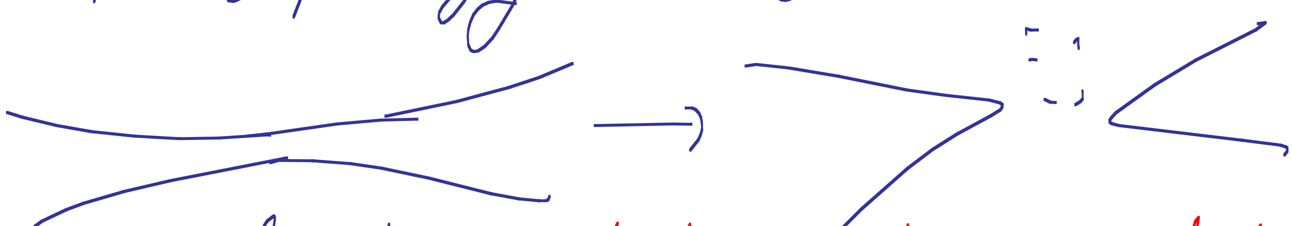


This potential barrier grows with $T \propto e^{\kappa X^0}$, as does the window of energies

$$E < m_{ssG} < T$$

to which our controlled analysis applies. All indications $\longrightarrow$ space in $\langle T \rangle$ region disappears

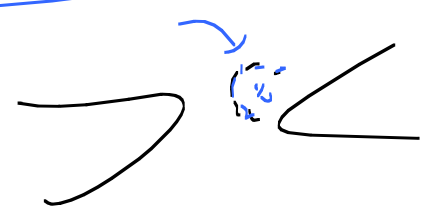
$\Rightarrow$ topology change!



including baby universe production

A few more remarks on the details:

① Classically, the Witten index $\mathrm{tr}(-1)^F$ is preserved $\Rightarrow$ the "subcritical dust" must carry this away



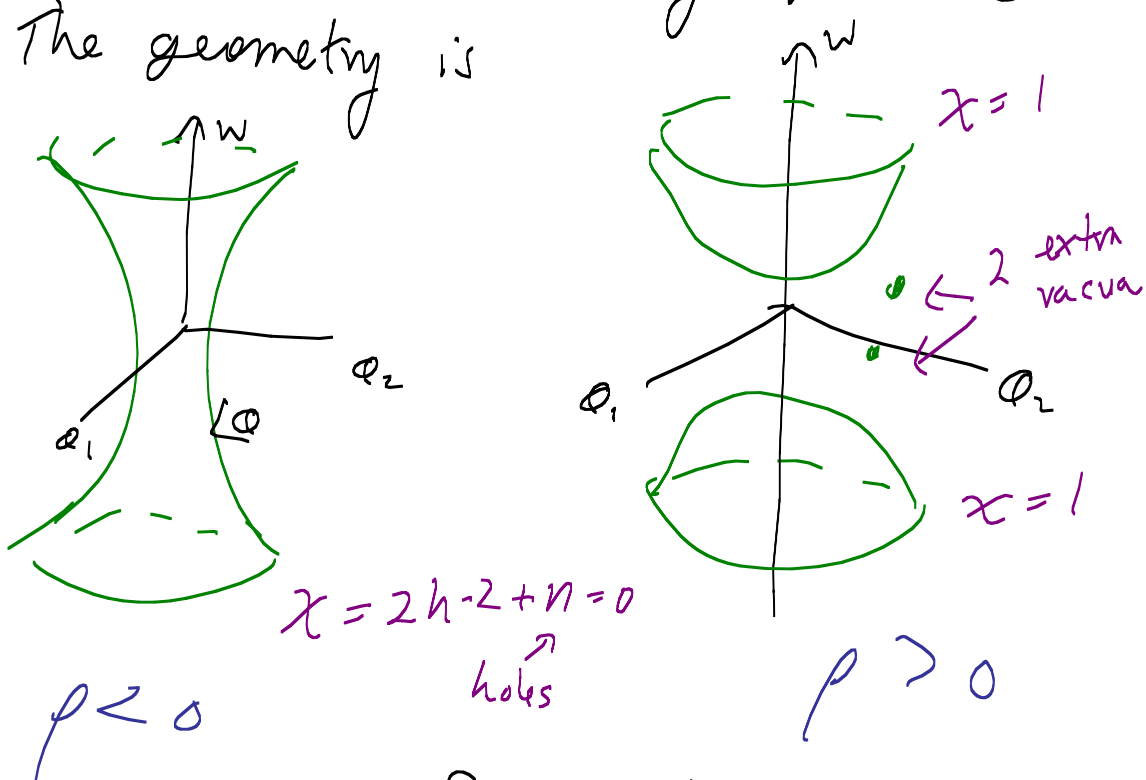
We see this explicitly in a gauged linear sigma model description of the flow:

Consider the geometry determined by the equation $\left(w^2 - |\phi|^2 - \rho\right)^2 = 0$ (w real, ϕ complex)

from a superpotential $\int d^2\theta\, \Sigma\left(w^2 - |\phi|^2 - \rho\right)$

in a $\simeq$ flat embedding space w, ϕ

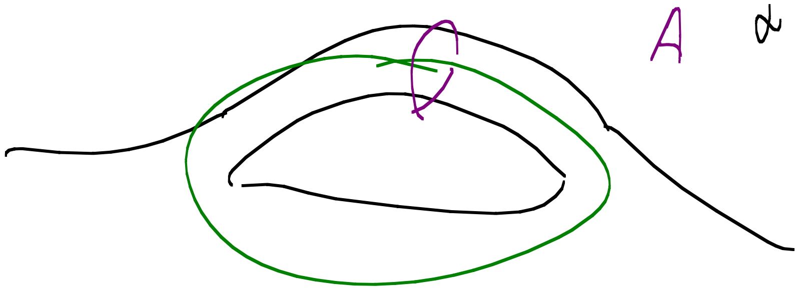
The geometry is



We obtained this from a larger super-renormalizable Gauged linear sigma model, for which ρ indeed flows positive as we go to the IR and the extra vacua are evident.

② **Spacetime changes:** In handle decay, we lose winding charges

A & B



F_A is Higgsed by the condensate of winding tachyon.

F_B appears to be confined in the process ($\frac{1}{g_B^2} < 1$ in the regime of τ where $\langle T \rangle$ can condense)

$$\mathcal{L}_F = \int d^8x\sqrt{g}\,(F_A\ \ F_B)\begin{pmatrix} 2\tau\,(\mathrm{Im}\,\tau)^{-1}\,\bar{\tau} & -(\mathrm{Re}\,\tau)(\mathrm{Im}\,\tau)^{-1} \\ -(\mathrm{Im}\,\tau)^{-1}\,\mathrm{Re}\,\tau & 2\,(\mathrm{Im}\,\tau)^{-1} \end{pmatrix}\begin{pmatrix} F_A \\ F_B \end{pmatrix}$$

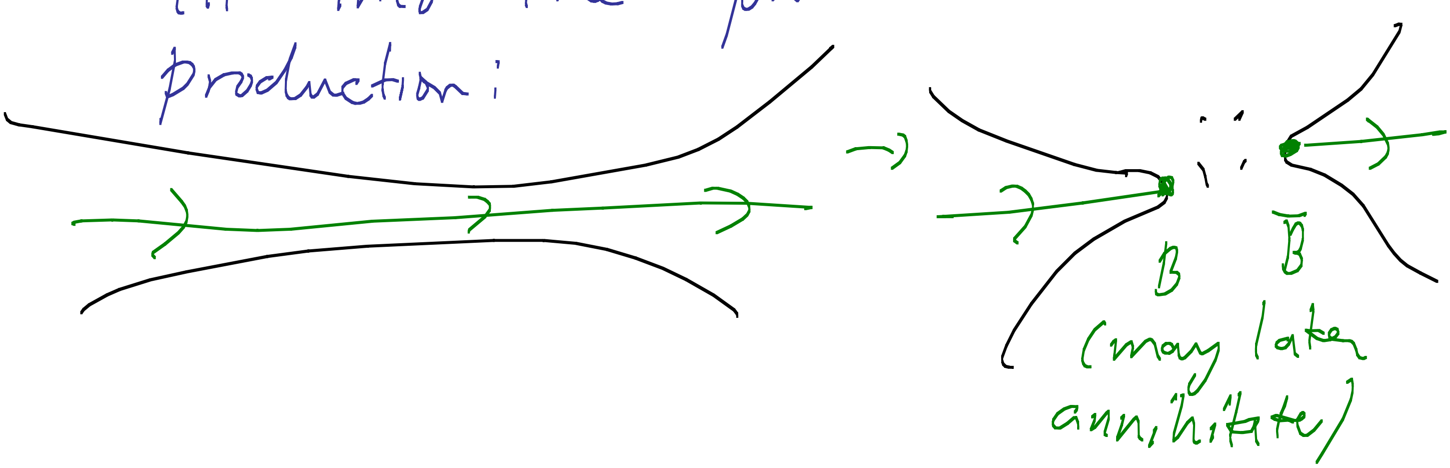
$$\to \int d^8x\sqrt{g}\;\frac{1}{\tau_2}\left| F_A + \tau F_B \right|^2$$

for isolated handle τ_2 small $\Rightarrow$ F_A weakly coupled, F_B strongly coupled

③ Fluxes:

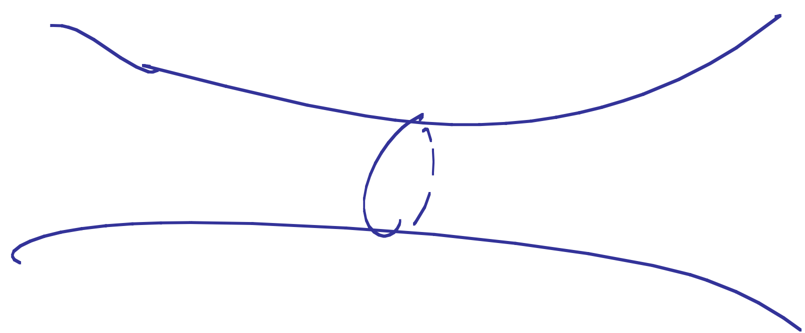
- Large flux contributions can stabilize the T moduli far from the topology change regime (Saltman-E.S.), as do periodic b.c. for fermions.

- Mild fluxes which still allow T to go tachyonic fit into the process via B-$\bar{B}$ production:



Generalizations: (discussions w/ Matt Headrick)

If we considered higher-dimensional tubes with S^q cross-section $q > 1$

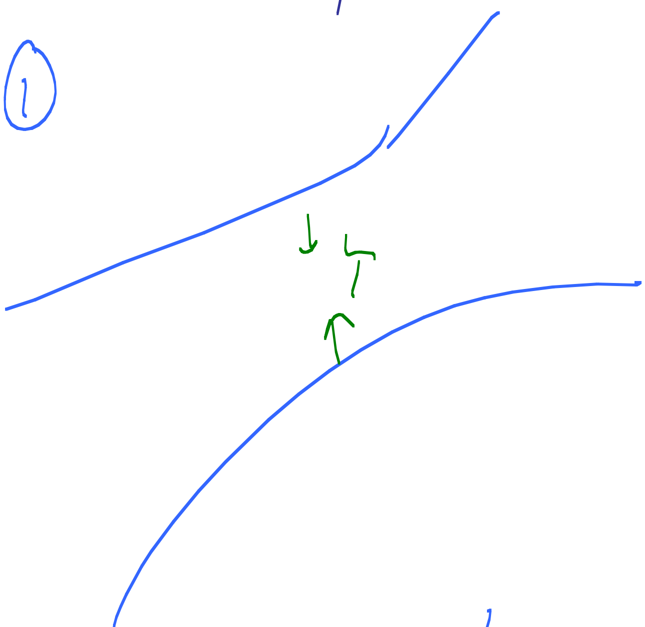


Similar remarks apply to the RG problem: NLSM on S^q target develops mass gap in IR...

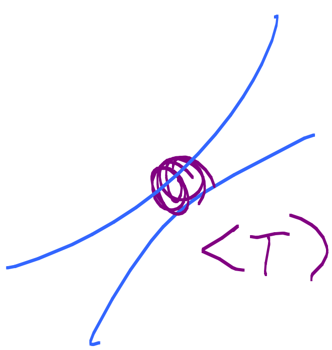
The S^1 case is just a special example of a more general phenomenon...

④ Time-Dependent Process:

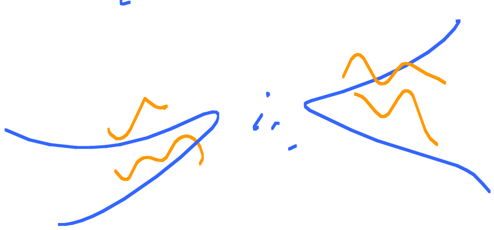
The dynamical realization of this process involves:

① 

rolling in T toward thin tube region

② 

condensation of T

③ 

decay of liberated potential energy into ...

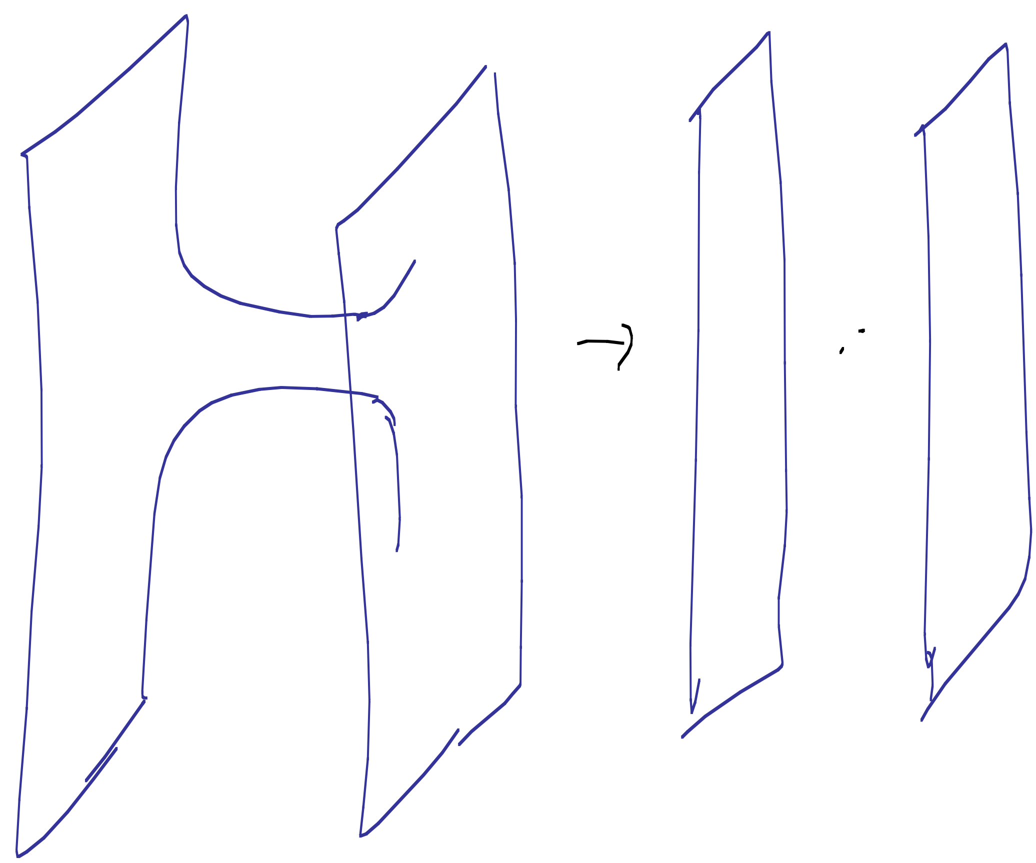
cf hybrid inflation, (p)reheating

Steps 1 – 2 can occur much more efficiently here than in say conifold transitions, which are thwarted by moduli trapping. As in every other tachyon process ($B-\bar{B}$, $\mathbb{C}/\mathbb{Z}_N$, ...) step 3 is difficult to follow explicitly in detail. Basic picture: the energy density goes into everything it can ($D-\bar{D}$, strings, gravitons, ... cf Spacebrane work)

The case of complete disconnection is particularly striking:

can be applied in several qualitatively different settings:

1

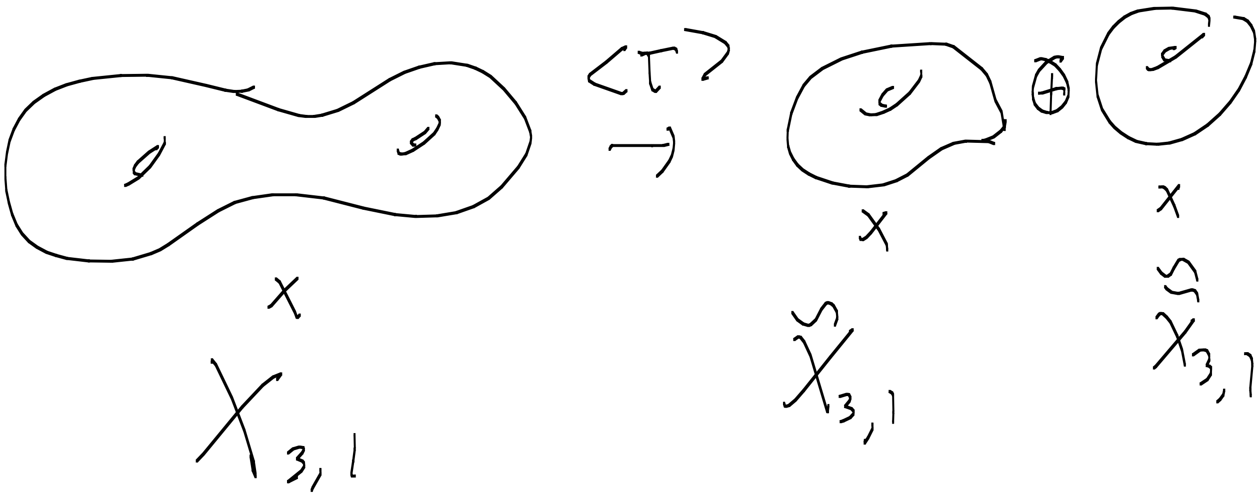


$\Psi_{pure} \rightarrow \rho_{mixed}$

cf Hawking

2

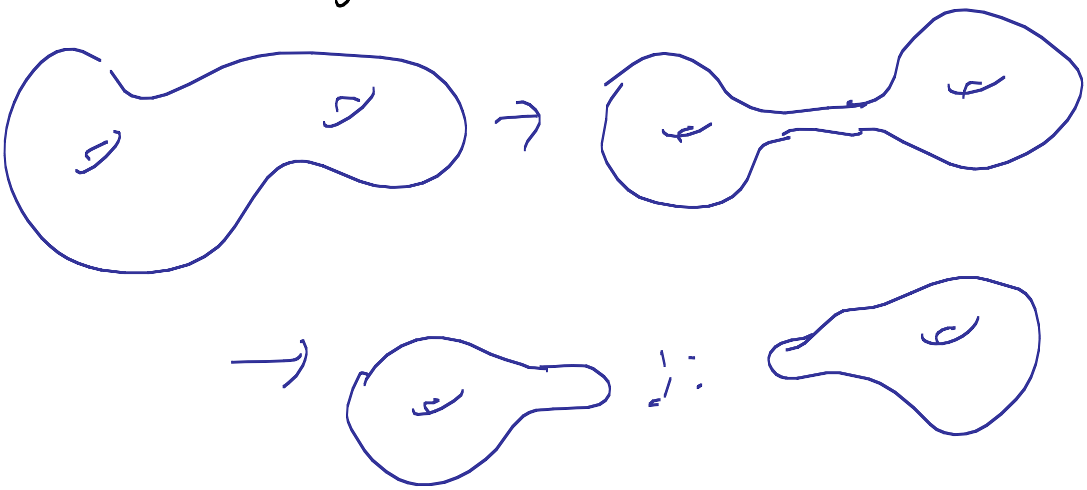
Inside the compactification:



- simplify the discretuum/landscape?

- New meaning to unification at high energies

The "baby universe" case



is also intriguing – happens perturbatively, without need for subtle Euclidean quantum gravity computations

Coleman, Giddings-Strominger, ... argued that, given a nonzero amplitude to break off a "baby universe", there is ultimately no loss of coherence but one is forced to integrate over couplings

Coleman's EFT model:

$$\mathcal{H} = \sum \mathcal{O}_i \, A_i$$

Standard model operator

$a_i^\dagger + a_i$

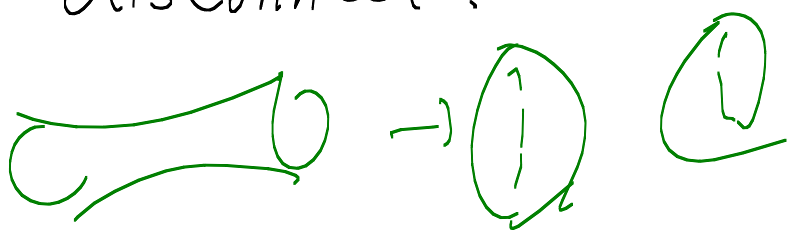
Creation & annihilation ops for B. Universes

$$[A_i, A_j] = 0$$

$\Rightarrow$ measuring S.M. couplings projects onto A_i eigenstates (as opposed to eigenstates of

$$N_{\text{components}} = \sum a_i^\dagger a_i$$

A priori we did not know whether in string theory, the target spacetime can disconnect. (cf Giddings-Strominger)

The process 

provides an explicit realization of Coleman's "a^+" and forces us to make sense of third quantization, apparently.

Outs? Conceivable, not likely!

(1) No mass gap in SSG?
would contradict every study, including
integrable S-matrices etc.

If there were some other
endpoint of the RG, the process
could have aborted.

(2) We did not establish explicitly
that the process occurs in finite time
according to appropriate observer.
However – this aspect no different
from brane-antibrane or $\mathbb{C}^2/\mathbb{Z}_N$
tachyons; no evident slowdown
mechanism, lots of fast particle
production

A priori, both cases are likely to appear in the early universe: at times with energy density of order

$$U_{4d,E} \sim (2h-2)\left(\frac{g_s^2}{V_E}\right)^4 \frac{1}{g_s}$$

handles should be generic.

→ can they survive and decay late enough to produce signature?

· collider signatures in RS / large dims?
· topological topological defects