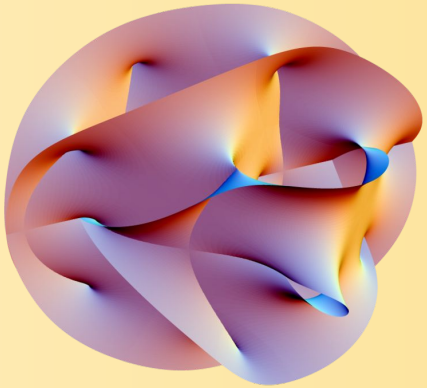
Dark energy from Dark bubbles in a Dark dimension

Ivano Basile | LMU

Strings & the real world



- *grocery list of string pheno/cosmology:*
  - *small (if any) extra dimensions*
  - *small (positive)* ***dark energy*** $\sim +10^{-120}\ M^4_{\text{Planck}}$
  - *"details" (gauge groups, (chiral) matter, etc.)*
  - ***SUSY breaking*** *tied to all these**

each is difficult! different approach?

**moduli stabilization, dS, light spectra...*

Guided by the swampland

- *recurring issues in stringy model building:*
  - *hard to* ***separate*** *(bulk) scales* ***(cf. N. Cribiori's talk)***
  - *hard to get (quasi)-****de Sitter*** ***(cf. A. Westphal's talk)***
  - *issues w/ soft* ***SUSY breaking*** ***(cf. M. Scalisi's talk)***

- *"****thread the needle****"... or* ***take the hint?***
  - ~~*SUSY*~~ *AdS w/o scale separation*
  - *embrace high-~~energy~~ SUSY*

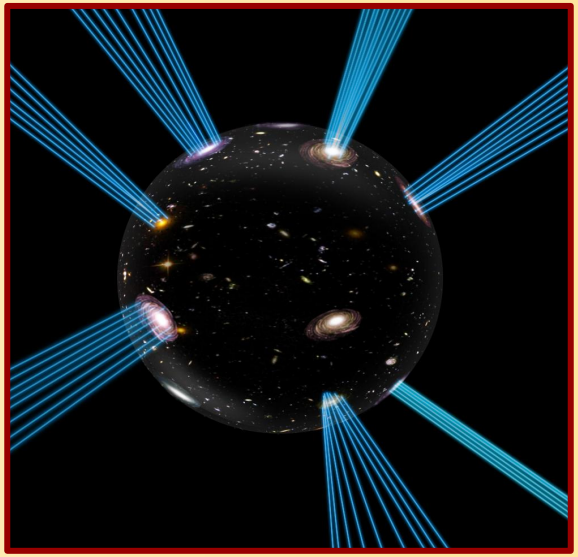
unstable AdS ⟶ *braneworld cosmology*

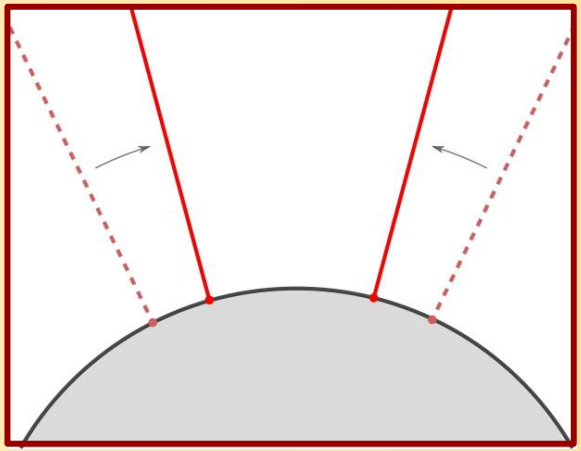
(Nahal Taninim, Israel)

Dark bubble cosmology

- ***unstable AdS*** *nucleates bubbles/branes*
  - *induced* ***dS braneworld*** *(not RS)*
  - *exploit instability (~~SUSY~~)*
- ***alternative*** *4d gravity mechanism*
  - *matter = stretched strings*
  - *"sandwich" construction*

(Banerjee, Danielsson, Dibitetto, Giri, Schillo, 2018-2022)
(Danielsson, Henriksson, Panizo, 2022)
(Danielsson, Van Hemelryck, Van Riet, 2022)
(Danielsson, Panizo, Tielemans, Van Riet, 2021)
credits to them for the relevant figures!





Life on the brane

$$R^{5d}_{abcd} = R^{4d}_{abcd} + K_{ad}K_{cb} - K_{cd}K_{ab}$$

extended strings

$$G^{4d}_{ab} = T^{\text{brane}}_{ab} + T^{\text{sources}}_{ab}$$

$$\Lambda_{\text{brane}} \propto \left(\frac{T_{\text{crit}}}{T}\right)^2 - 1$$

- *gravity on the brane:*
  - *graviton propagator*
  - *Gauss-Codazzi projection*
- *stuff on the brane*
  - *AdS* ***BHs*** → ***radiation***
  - *AdS* ***strings*** → ***matter***

this talk: stringy realization in ~~SUSY~~ models?

low | high

SUSY breaking

SUSY model

UV

many ingredients
(CY, fluxes, Dp/Op...)

IR

N=1 EFT

~~SUSY~~

harder constructions
(rotating branes, ...)

issues w/ gravitini
(Cribiori, Lüst, Scalisi, 2021)

N=0 EFT

THIS TALK

~~SUSY~~ model

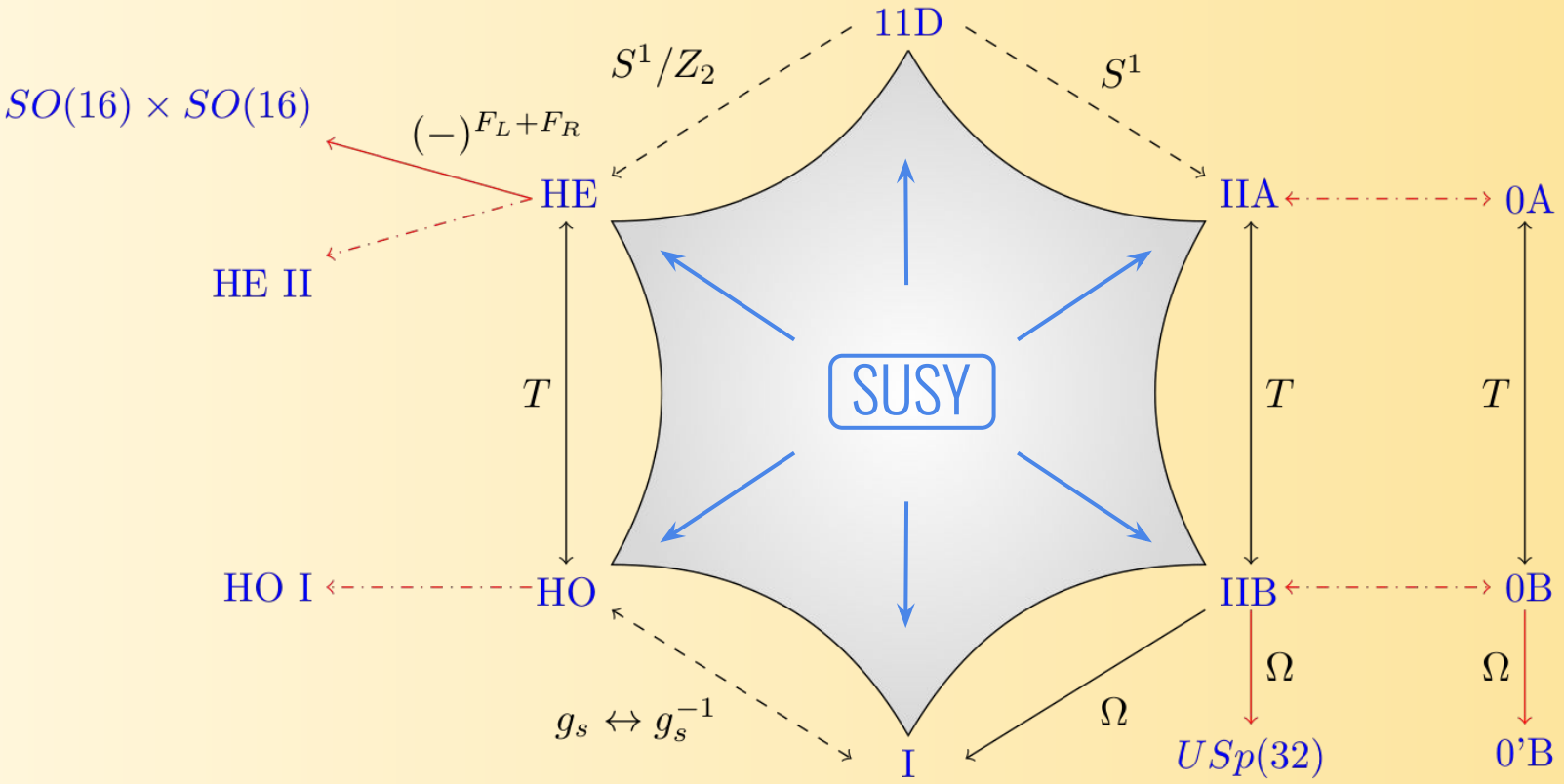
UV

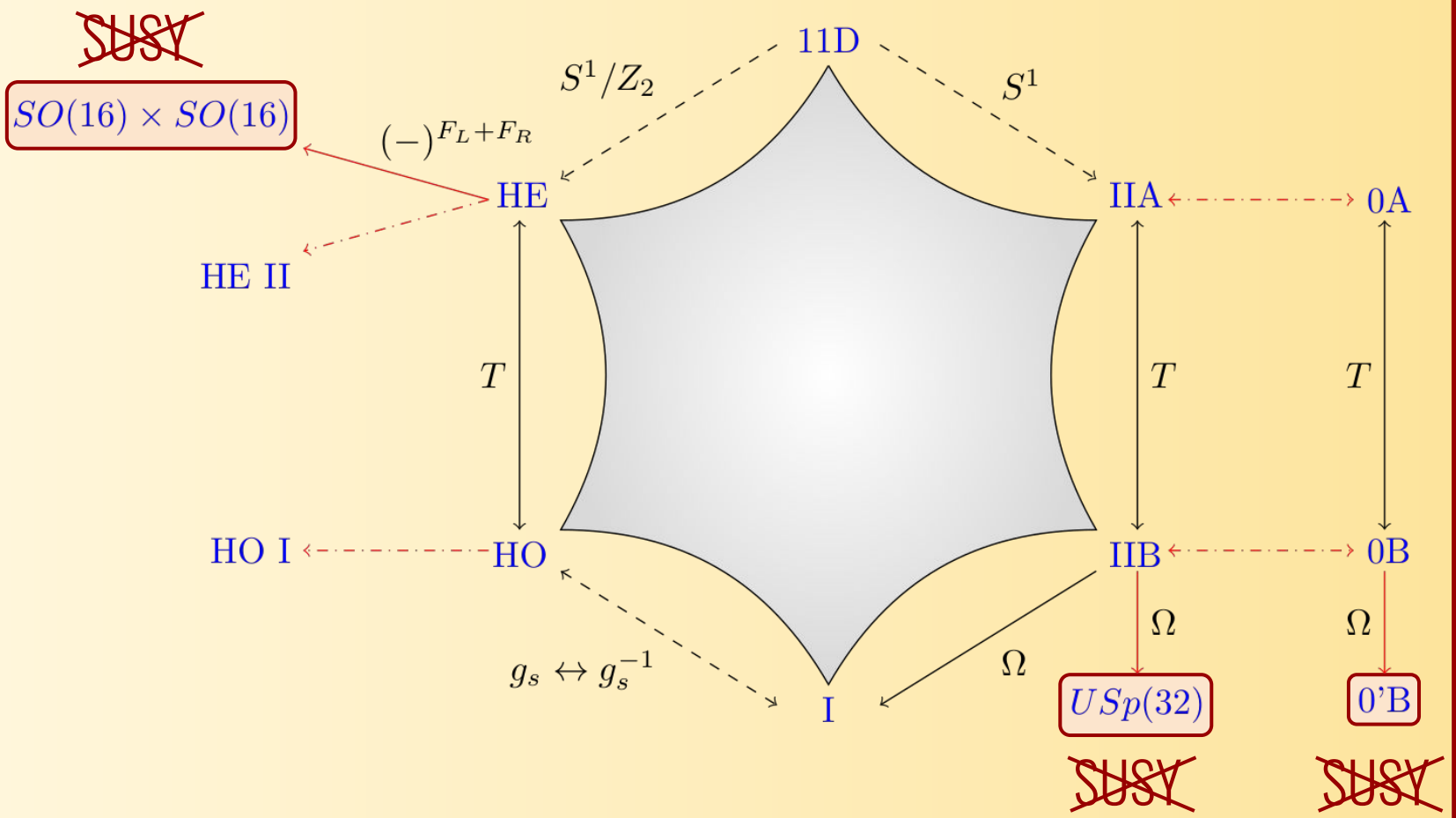
stringy natural:
broken @ M_{string}

simpler constructions
(parallel branes)

IR

N=0 EFT


11D
S^1/Z_2
S^1
$SO(16) \times SO(16)$
$(-)^{F_L+F_R}$
HE
IIA
0A
HE II
T
T
T
SUSY
HO I
HO
IIB
0B
Ω
Ω
Ω
$g_s \leftrightarrow g_s^{-1}$
I
$USp(32)$
0'B


SUSY
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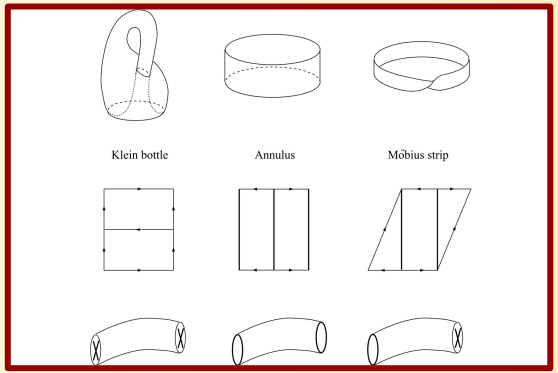
$USp(32)$
0'B
SUSY
SUSY

How I learned to stop worrying and love ~~SUSY~~

orientifold models:

- *IIB* → *Sugimoto* USp(32)
- *0B* → *Sagnotti 0'B* U(32)

O9 + 32 anti-D9 = ***residual tension***



heterotic models:

- $E_8 \times E_8$ → $SO(16) \times SO(16)$

(Alvarez-Gaume, Ginsparg, Moore, Vafa, 1986) (Dixon, Harvey, 1986)

quantum effects = ***vacuum energy***

$$V(\phi) = V_0 e^{\gamma\phi}$$

The 10d low-energy description

- *fields in the 10d game:*
  - *gravity (metric tensor)* $g_{\mu\nu}$
  - *B-field (2-form)* $B_{\mu\nu} \to H = dB$
  - *dilaton (scalar)* ϕ

1-branes & 5-branes

~~SUSY~~

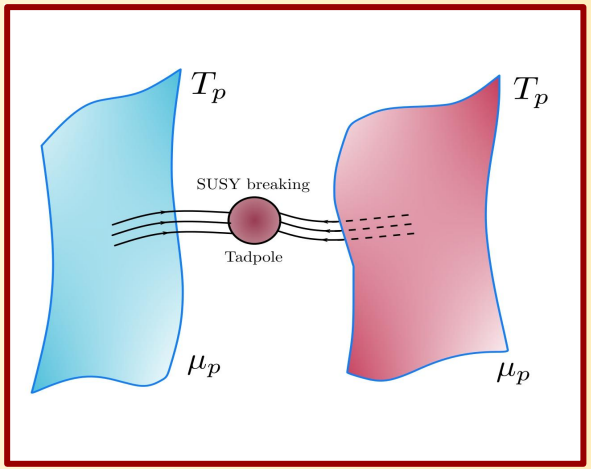
$$\mathcal{L} = R - (\partial\phi)^2 - e^{\alpha\phi} H^2 - V_0\, e^{\gamma\phi}$$

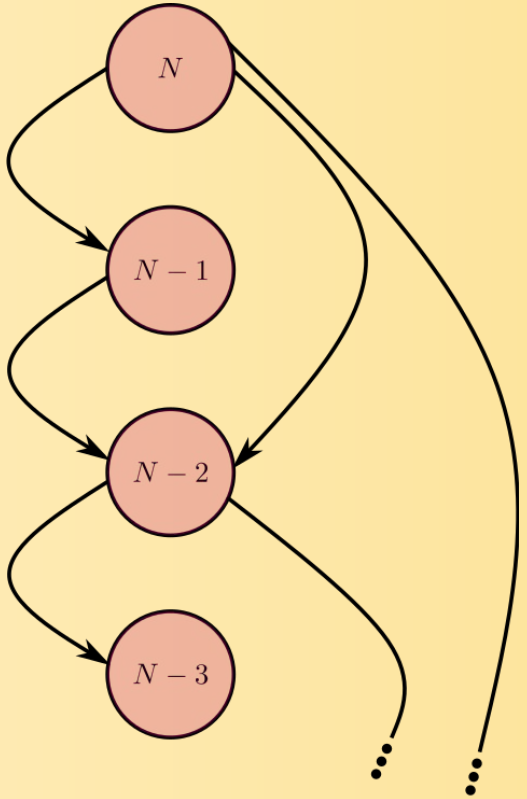
no flat space vacuum! :(

+ F_5 flux & D3-branes in 0'B

Getting down to business — AdS vacua

- *large flux (**many branes**) balances runaway*
  - ***no dS vacua** whatsoever (IB, Lanza, 2020)*
  - *Freund-Rubin **family of AdS***
  - ***slow decay** to lower flux (**WGC**) (Antonelli, IB, 2019)*





Near-horizon geometry: AdS x M

$$ds^2 = L^2 \frac{du^2}{u^2} + \frac{\alpha'^2 u^2}{L^2} dx^2_{1,p} + R^2 \, d\Omega^2_{8-p}$$

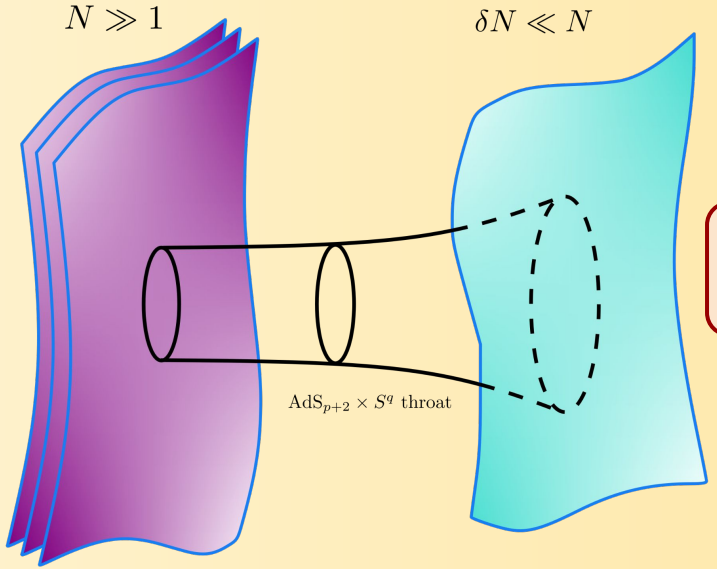
elec (p=1) *mag (p=5)*

- *small curvatures* $\mathcal{R} \propto N^{-\frac{3}{8}}$ *or* $N^{-\frac{5}{4}}$
- *small coupling* $g_{\text{string}} \propto N^{-\frac{1}{4}}$ *or* $N^{-\frac{1}{2}}$

only free parameter: N

exception: *D3-branes in 0'B...*

Unstable AdS = parallel branes repel (here D1 or NS5)



$$\frac{q}{T} > \left(\frac{q}{T}\right)_{\text{bare}} = 1$$

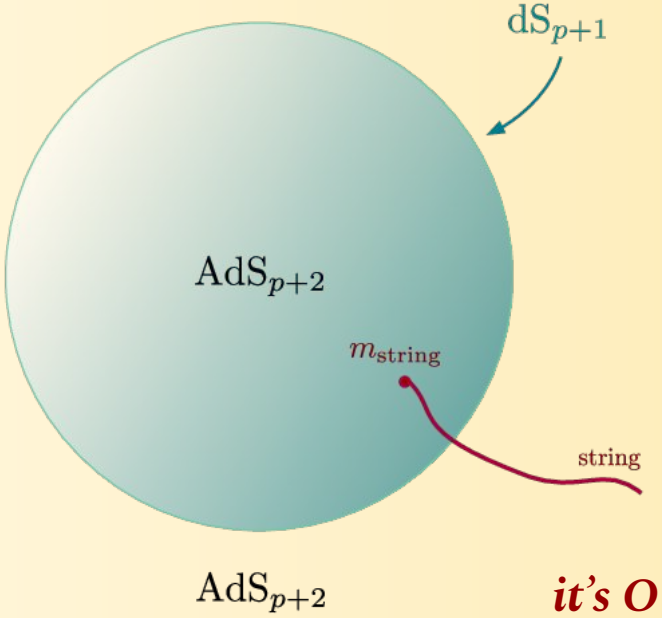
WGC works!

(Antonelli, IB, 2019) (IB, 2021)

$$V_{\text{probe}} = \left(\frac{L}{Z}\right)^{p+1} \left(1 \pm \frac{q}{T}\right)$$

Ride the bubble out of the swampland

(IB, Lanza, 2020)



- *observer **on bubble**: dS gravity!*
- *now with microscopic data*
  - *matter on the brane*
  - *gauge groups* U(n), Sp(n)
  - *wrong dimension (oops)*

it's O(1) :(
no scale sep.

$$\frac{\Lambda_{\rm dS}}{|\Lambda_{\rm AdS}|} \propto \left(\frac{q}{T}\right)^2 - 1$$

Next attempt: D3-branes in 0'B *(Angelantonj, Armoni, 1999-2000) (IB, 2021)*

$$ds^2 = L^2(u)\,\frac{du^2}{u^2} + \frac{\alpha'^2\,u^2}{L^2(u)}\,dx^2_{1,3} + R^2(u)\,d\Omega_5^2$$

$$L^2(u)\,,\; R^2(u)\,,\; g_s N \sim (\mathrm{SUSY}) + \frac{T}{N}\,\log u$$

quasi-extremal: parametric scale separation?

Scale separation, like all dark magic, comes at a price

$$\frac{\Lambda_{\rm dS}}{|\Lambda_{\rm AdS}|} \sim g_s^2 N \log a(\tau)$$

control on EFT > Hubble time: bounds on "dark dimension(s)"

$$\Lambda_{\rm dS}^{1/2} \lesssim \Lambda_{\rm AdS} \lesssim \Lambda_{\rm dS}^{1/6}$$

- ***small running*** *dark energy: generic (?)* ***feature*** *of these models*
- ***4d*** *world,* ***chiral*** *fermions,* **U(n)** *gauge groups,* ***no SUSY****...*
  - ➢ *coupling to 4d gravity from 10d open strings: work in progress*

Outlook

- *different "model-building pipeline"*
- *different pros & cons*
  - *vacuum (in)**stability vs** moduli **stabilization***
  - *(**quasi-**)**dS braneworlds** from (0'B) ~~SUSY~~ strings?*
  - *how does a **full EFT** (gravity + matter QFT) work?*

thank you!

low | high

pros

- *computational control*
- *vacuum stability*

cons

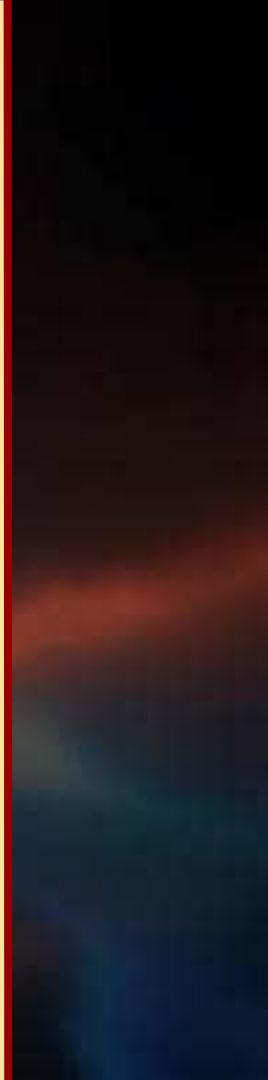
- *moduli stabilization*
- *scale* ***separation***

pros

- *no moduli (usually)*
- *no IR superparticles*

cons

- *much* ***less control***
- *vacuum* ***instabilities***



Breaking SUSY: heterotic

SUGRA SYM

$$\mathcal{T}_{E_8\times E_8} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^6}\frac{1}{|\eta(\tau)|^{16}}\Big[(V_8 - S_8)\,\overline{(O_{16}+S_{16})^2}\Big]$$

projection + modular invariance

$$\mathcal{T}_{SO(16)\times SO(16)} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^6}\frac{1}{|\eta(\tau)|^{16}}\Big[O_8\,\overline{(V_{16}\,C_{16}+C_{16}\,V_{16})}+$$

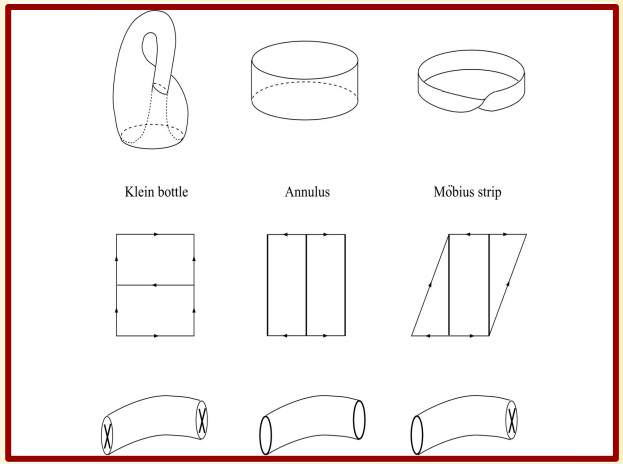
NS-NS (gravity) + gauge $V_8\,\overline{(O_{16}\,O_{16}+S_{16}\,S_{16})}-$

128_1+ 128_2 *left fermions* $\bar{S}_8\,\overline{(O_{16}\,S_{16}+S_{16}\,O_{16})}-$

(16,16) *right fermions* $C_8\,\overline{(V_{16}\,V_{16}+C_{16}\,C_{16})}\Big]$

Breaking SUSY: orientifolds (one example)

- *unoriented strings*
  - *Klein bottle*
  - *annulus*
  - *Möbius*



$$\mathcal{K} = \frac{1}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\,\frac{(V_8 - S_8)(2i\tau_2)}{\eta^8(2i\tau_2)}$$

Chan-Paton

$$\mathcal{A} = \frac{N^2}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\,\frac{(V_8 - S_8)\left(\frac{i\tau_2}{2}\right)}{\eta^8\left(\frac{i\tau_2}{2}\right)}$$

O9 tension

$$\mathcal{M} = \frac{\pm N}{2}\int_0^\infty \frac{d\tau_2}{\tau_2^6}\,\frac{\left(\widehat{V}_8 \pm \widehat{S}_8\right)\left(\frac{i\tau_2}{2} + \frac{1}{2}\right)}{\widehat{\eta}^8\left(\frac{i\tau_2}{2} + \frac{1}{2}\right)}$$

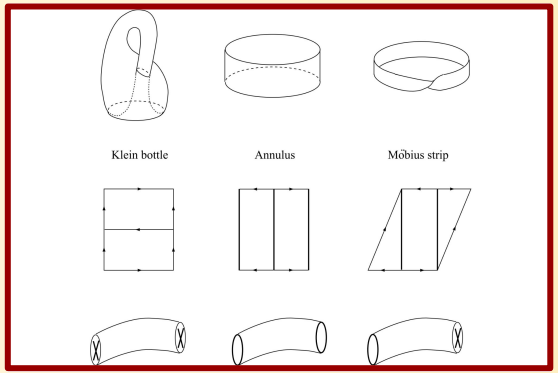
O9 charge

How I learned to stop worrying and love ~~SUSY~~

orientifold models:

O9 + 32 anti-D9 = ***residual tension***

$$(32T_{\mathrm{D9}} + T_{\mathrm{O9}})e^{-\phi}$$



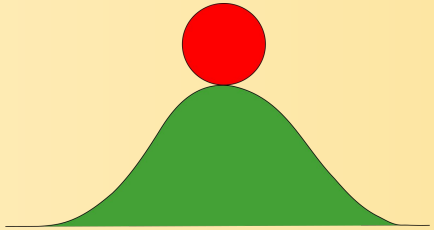
heterotic models:

quantum effects = ***vacuum energy***

$$\int_{\mathcal{F}} \frac{d^2\tau}{\mathrm{Im}(\tau)^2}\,(\dots)\,e^{-0\phi}$$

$$V(\phi) = V_0\, e^{\gamma\phi}$$

Perturbative stability: BF bounds



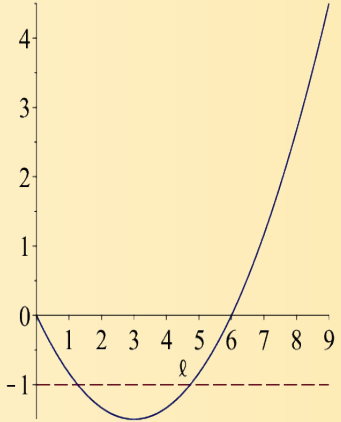
$g_{\mu\nu} + \delta g_{\mu\nu}$
$B_{\mu\nu} + \delta B_{\mu\nu}$
$\phi + \delta\phi$

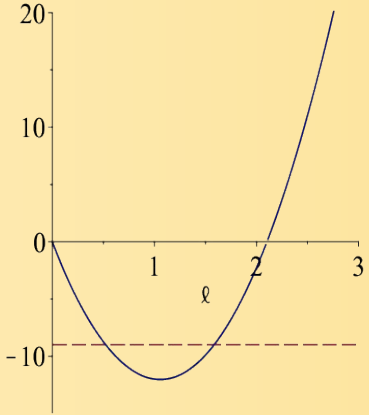
decompose in irreps

diagonalize masses

scalar KK modes

- *orientifolds* $\ell = 2\,,3\,,4$
- *heterotic* $\ell = 1$ *kill w/* Z_2





Perturbative stability: multitrace effects

explicit heterotic background: $\mathrm{AdS}_7 \times \mathrm{RP}^3$

- *multitrace-induced instability?* *(Aharony, Gur-Ari, Klinghofer, 2015)*
- *need single-trace conformal dimensions summing to 6**

$$m^2 L^2_{\mathrm{AdS}} = \Delta(\Delta - 6) \longrightarrow \Delta_{\mathrm{s.tr.}} \gtrsim 5.59$$

**thanks to A. Guarino, E. Malek, C. Sterckx!*

Nonperturbative instabilities: brane nucleation

$$\frac{\Gamma}{\mathrm{Vol}} \sim e^{-S_{\mathrm{inst}}}$$

elec: $e^{-\sqrt{N}}$

mag: e^{-N^4}

*explicit **metastable** vacuum?*

*charged **bubbles of nothing**?*

(Bomans, Cassani, Dibitetto, Petri, 2021)

see also:
(Giambrone, Guarino, Malek, Samtleben, Sterckx, 2020-2021)

*consistency **requires/predicts:***

- *WGC bound* q > T
- *correct tension of Dp or NS5!*

$$T_{\mathrm{dressed}} = \frac{T}{g_s^{\sigma=1,2,\ldots}}$$