



# Dark energy & braneworlds

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~~supergravity~~ & cosmology

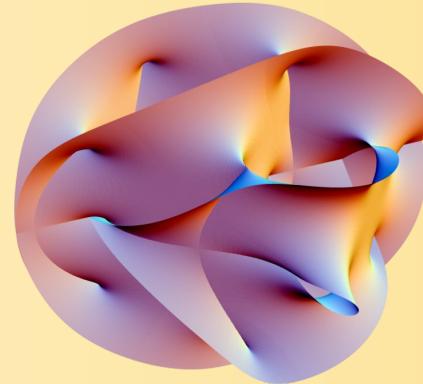


braneworld

*our universe on a 3d “bubble” inside bigger universe*

# Strings & the real world

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



each is difficult! different approach?

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

# 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

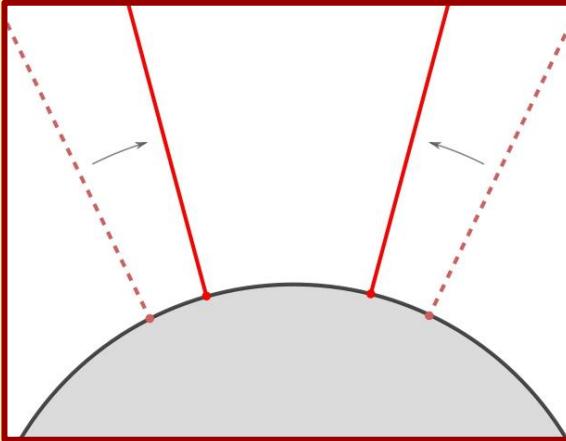
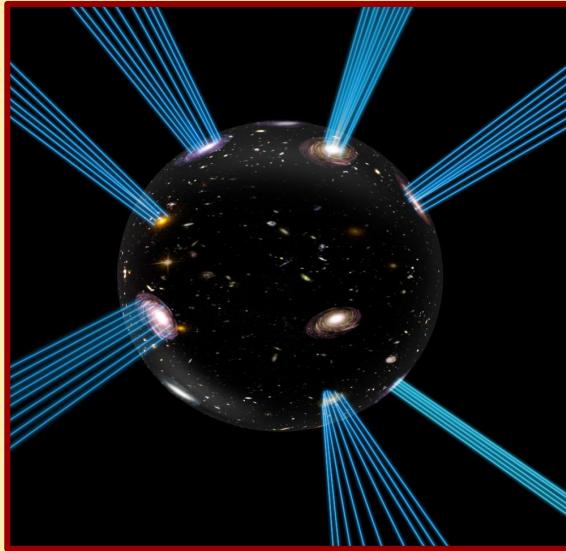
(Banerjee, Danielsson, Dibitetto, Giri, Schillo, 2018-2022)

(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

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

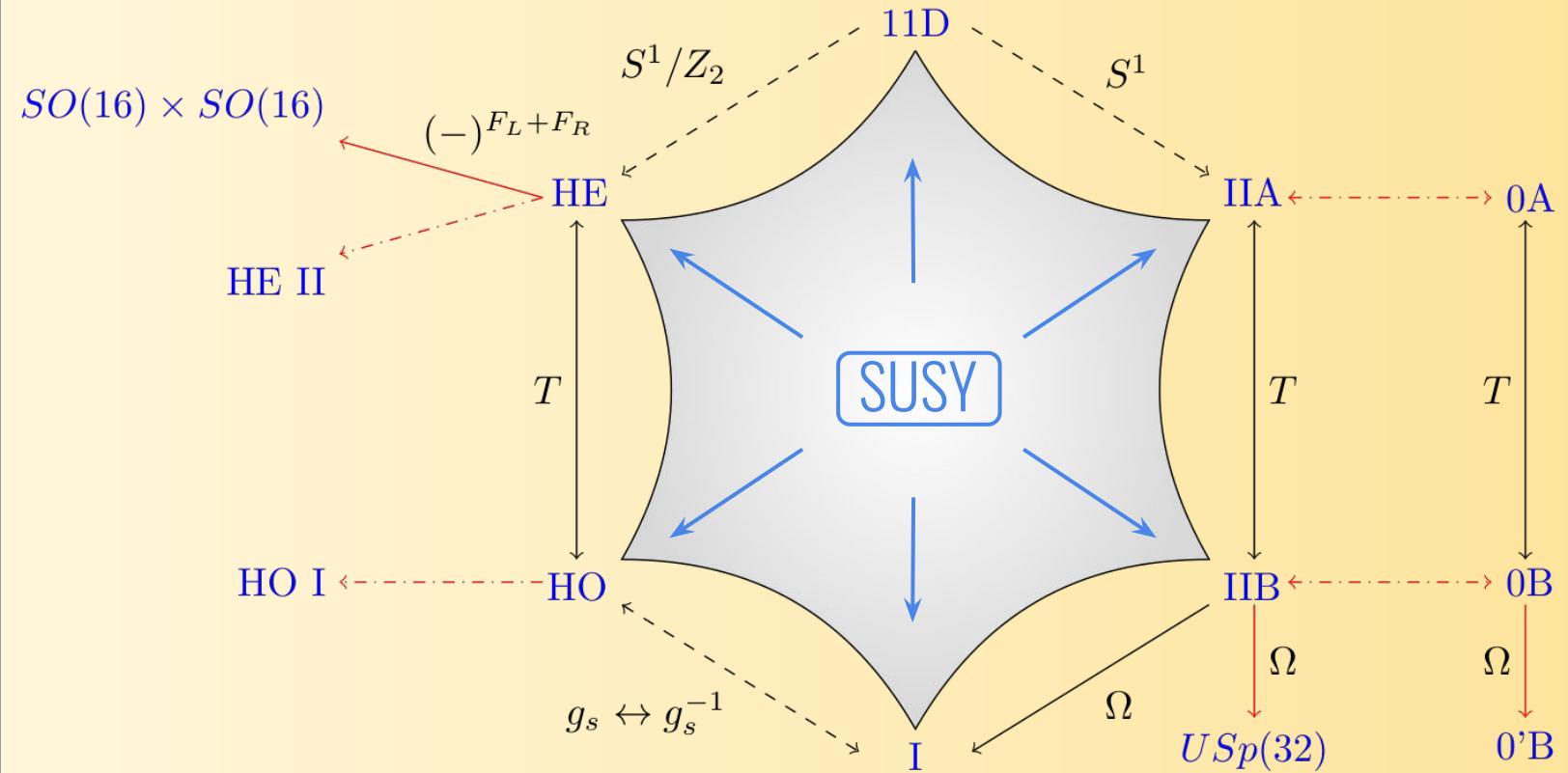
- ❖ gravity on the brane:
  - graviton propagator
  - Gauss-Codazzi projection
  
- ❖ stuff on the brane
  - *AdS BHs* → **radiation**
  - *AdS strings* → **matter**

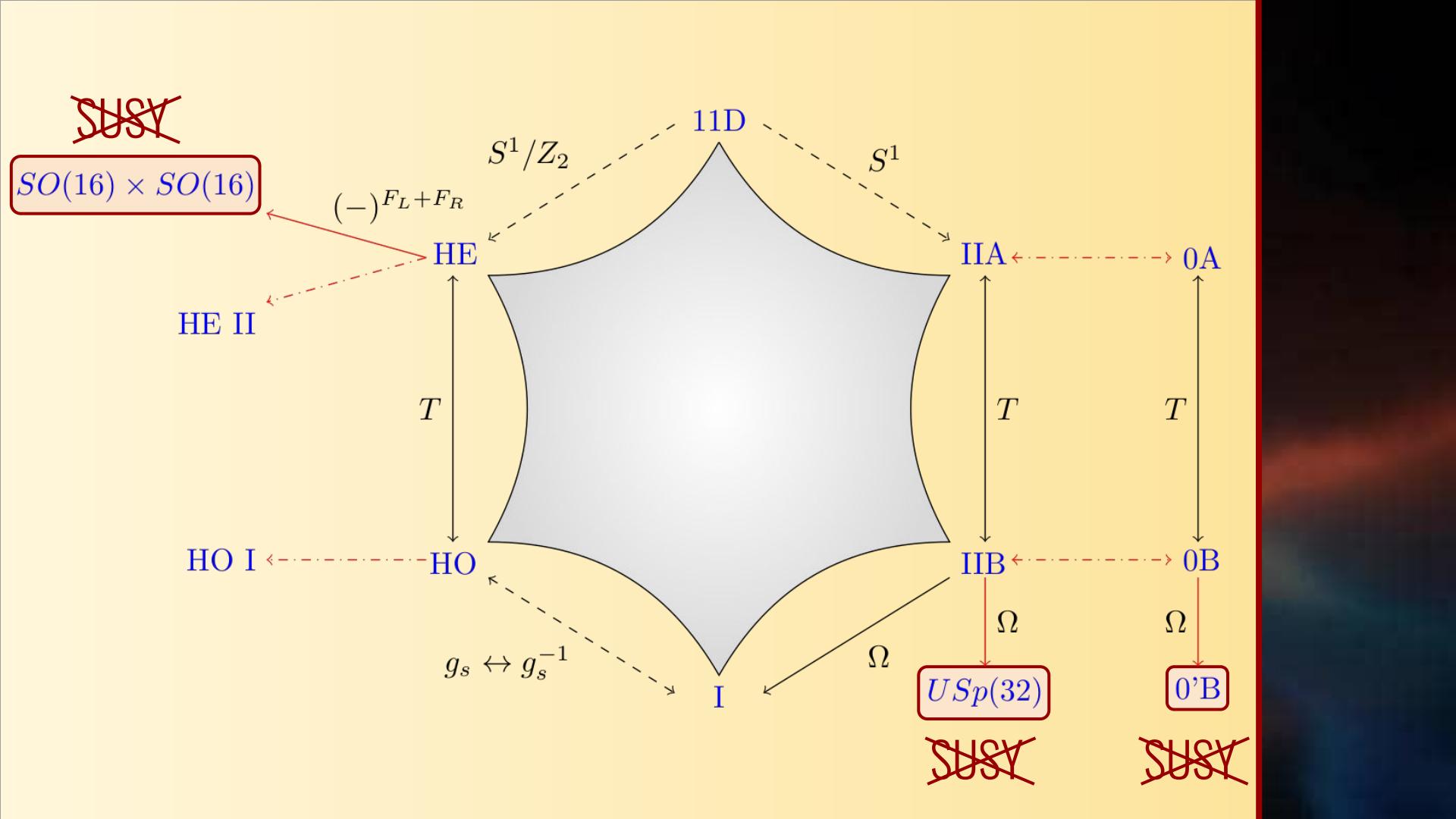
$$G_{ab}^{4d} = T_{ab}^{\text{brane}} + T_{ab}^{\text{sources}}$$

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

extended strings

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





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

*non-SUSY models:*

- ❖ Sugimoto USp(32)  $\longrightarrow$  *D1, D5 branes + fluxes*
- ❖ Sagnotti O'B U(32)  $\longrightarrow$  *D1, **D3**, D5, D7 branes + fluxes*
- ❖ heterotic SO(16) x SO(16)  $\longrightarrow$  *NS5 branes + flux*

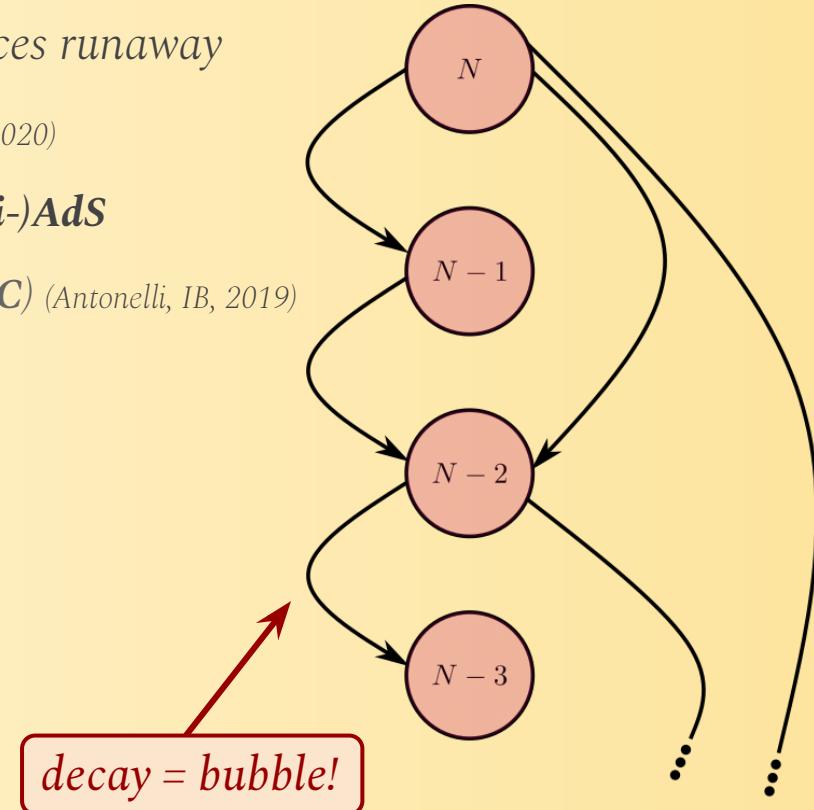
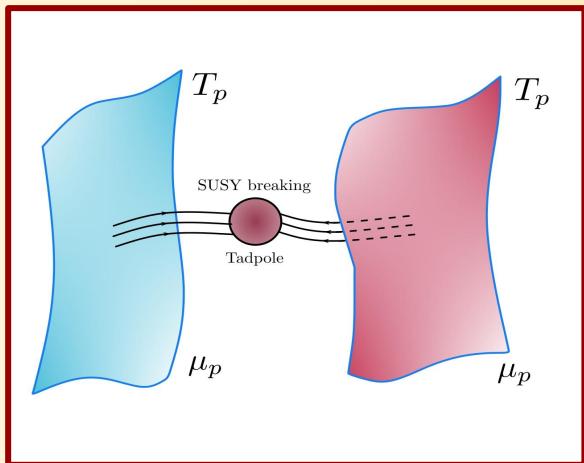
(Alvarez-Gaume, Ginsparg, Moore, Vafa, 1986) (Dixon, Harvey, 1986)

*all models: string-scale ~~SUSY~~ produces dilaton potential*

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

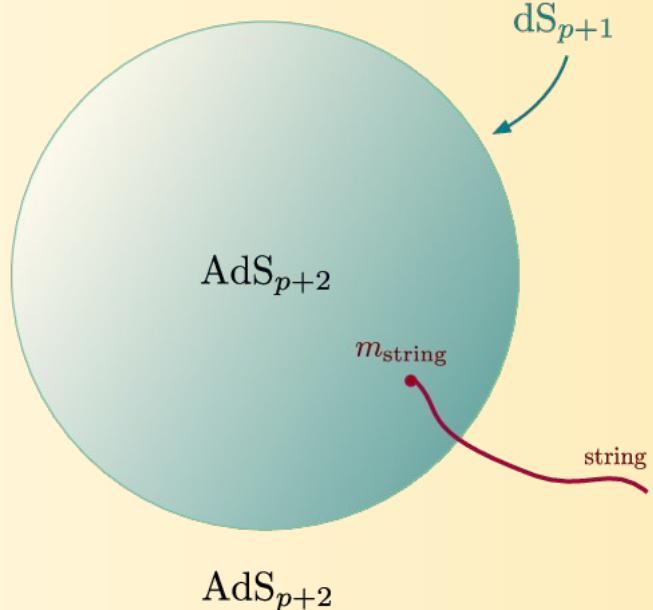
# Getting down to business — AdS vacua

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



# 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)*

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

# Concrete model: D3-branes in O'B

(Angelantonj, Armoni, 1999-2000) (IB, 2021)

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

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

quasi-extremal: parametric scale separation?

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

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

*control on EFT > Hubble time*



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

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

# Outlook

- ❖ different “model-building pipeline”
- ❖ different pros & cons
  - instability **exploited**: small, running, 4d dark energy
  - (quasi-)**dS braneworlds** from (0'B) ~~SUSY~~ strings?
  - how does a **full EFT** (gravity + matter QFT) work?

*thank you!*



# Breaking SUSY: heterotic



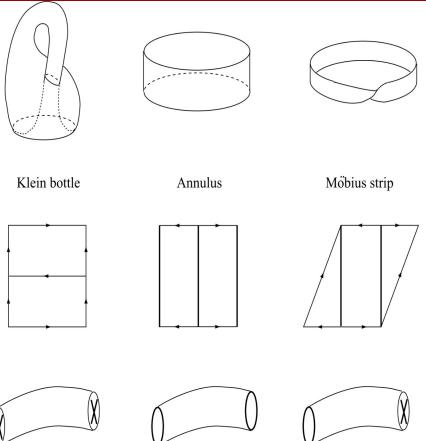
$$\mathcal{T}_{E_8 \times E_8} = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^6} \frac{1}{|\eta(\tau)|^{16}} \left[ (V_8 - S_8) \overline{(O_{16} + S_{16})^2} \right]$$

$\downarrow$   
*projection + modular invariance*

$$\begin{aligned} \mathcal{T}_{SO(16) \times SO(16)} = & \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^6} \frac{1}{|\eta(\tau)|^{16}} \left[ O_8 \overline{(V_{16} C_{16} + C_{16} V_{16})} + \right. \\ & \quad \left. V_8 \overline{(O_{16} O_{16} + S_{16} S_{16})} - \right. \\ & \quad \left. \mathbf{128}_1 + \mathbf{128}_2 \text{ left fermions } \bar{S}_8 \overline{(O_{16} S_{16} + S_{16} O_{16})} - \right. \\ & \quad \left. (\mathbf{16}, \mathbf{16}) \text{ right fermions } C_8 \overline{(V_{16} V_{16} + C_{16} C_{16})} \right] \end{aligned}$$

# 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**  $\boxed{N}^2$

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

**O9 tension**

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

**O9 charge**

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

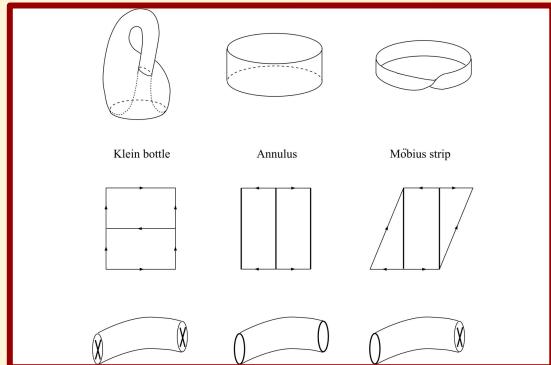
*orientifold models:*

$$O9 + 32 \text{ anti-}D9 = \text{residual tension}$$

*heterotic models:*

$$\text{quantum effects} = \text{vacuum energy}$$

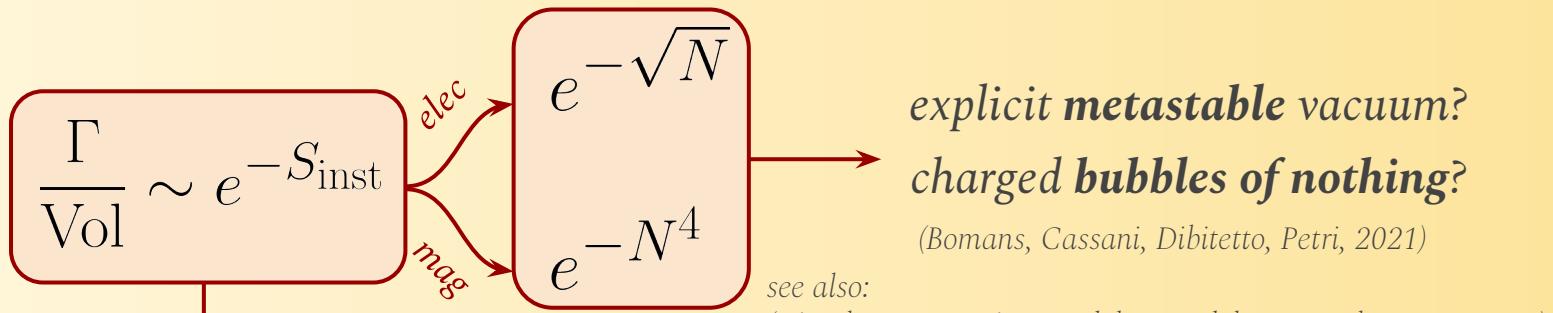
$$(32T_{D9} + T_{O9})e^{-\phi}$$



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

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

# Nonperturbative instabilities: brane nucleation



consistency *requires/predicts*:

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

$$T_{\text{dressed}} = \frac{T}{g_s} \boxed{\sigma=1,2,\dots}$$

