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Workshop: Eternal Inflation

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The Lifetime of Stringy dS

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The Lifetime of Stringy dS

with Ben Freivogel

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What is the maximum lifetime of dS?

No eternal dS

- Observables (Banks & Fischler, Witten, etc.)
- Boltzmann Brains (DKS, etc.)
- No string theory examples

Poincaré Recurrence Time: $t_r \sim e^{\mathbf{S}_{dS}} = e^{\frac{24\pi^2}{G_4^2 V_{dS}}}$

Upper bound: $t_d \leq t_r \sim e^{M_p^2/H^2}$ (Susskind, Giddings, etc)

Can we do better?

Boltzmann Brains

What are BBs?

observers formed by fluctuations

violation of 2nd law

not "ordinary" observers

Estimate BB entropy S_{BB} (rough)

S_{BB} ~ minimum S for observer

estimate: # of dof ~ # of particles

$\mathbf{S}_{BB} > 10^{15}$ bacterium

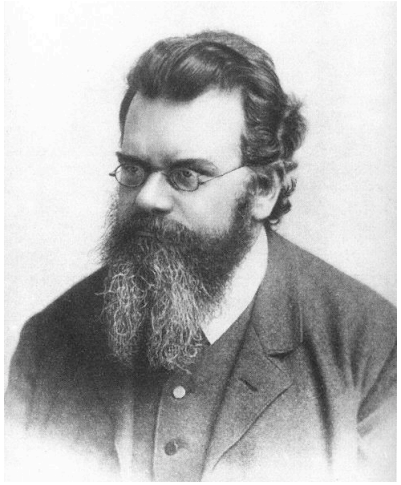
$\mathbf{S}_{BB} < 10^{50}$ earth

Time to nucleate a BB

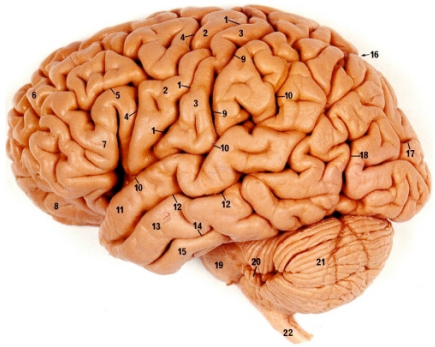
$$t_{BB} \gtrsim H^{-1} e^{\mathbf{S}_{BB}}$$

$$\boxed{t_{BB} \approx H^{-1} e^{10^{40\pm 20}}}$$

Imprecise, but $t_{BB} \ll t_r$



Boltzmann



Brain

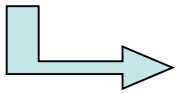
Boltzmann Brain Bound

How many BB in a causal patch? $N_{BB} \sim \frac{t_d}{t_{BB}}$

BB problem: don't want to be swamped by BBs

precise statement depends on measure

Want $t_d < t_{BB}$ to avoid conflict with observation



nontrivial bound because $t_{BB} \ll t_r$

Is BB bound obeyed in string landscape?

Naively, easy to make $t_d \approx t_r$

→ Depends on potential, which can be anything

In string theory

potential constrained

illustrative example: KKLT

SUSY AdS → uplifted to dS

small ~~SUSY~~ (fined tuned)

CDGKL estimate $t_d \sim e^{M_p^2/m_{3/2}^2}$

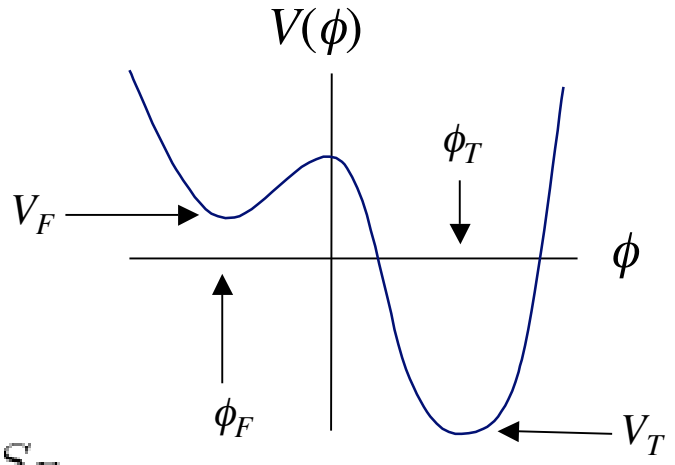
We find: this is an overestimate

False Vacuum Decay

CdL Formalism

- Scalar coupled to gravity
- Euclidean instanton for tunneling from ϕ_F to ϕ_T
- Decay rate: $t_d = \Gamma^{-1} \sim e^B$

where $B = S_{CdL} - S_F$



Lorentzian dynamics

expanding bubble of true vacuum

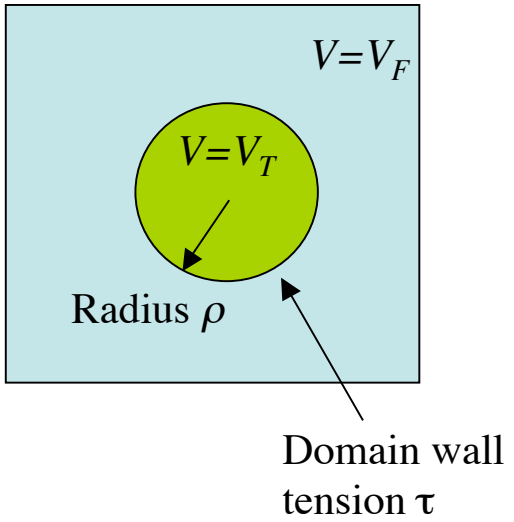
- $V_T > 0$ ➔ dS
- $V_T = 0$ ➔ open FRW
- $V_T < 0$ ➔ big crunch

Thin-wall Limit

Transition from V_F to $V_T \approx$ Domain Wall

$$B = \underbrace{B_0(\tau, \delta V)}\ \underbrace{r(x, y)} \rightarrow \text{GR correction}$$

$$B_0 = \frac{27\pi^2\tau^4}{2\delta V^3} \quad \text{QFT result}$$



where $x = \dfrac{\tau^2}{\tau_c^2}$ $\quad y = \dfrac{V_F + V_T}{\delta V}$

Critical Tension $\tau_c = \sqrt{\dfrac{4\delta V}{3G_4}}$

Bubble radius

$$\rho = \frac{\rho_0}{\sqrt{1 + 2xy + x^2}} \quad \text{where} \quad \rho_0 = \frac{3\tau}{\delta V} \quad \text{QFT result}$$

Metastable dS decay

False vacuum - dS

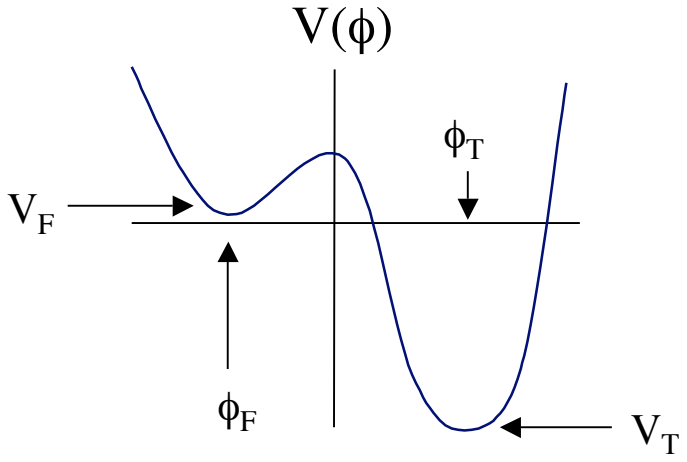
$$V_{dS} = V_F \gtrsim 0$$

True vacuum - AdS

$$V_{AdS} = V_T < 0$$

$$|V_{AdS}| \gg V_{dS}$$

$$E_{\cancel{SUSY}} = m_{3/2} \sim 1/R_{AdS} \sim \sqrt{G_4 V_{AdS}}$$



Decay Time bounded

$$B = S_{CdL} - S_F \leq -S_F = \frac{24\pi^2}{G_4^2 V_{dS}} \quad \Rightarrow \quad t_d \leq t_r$$

Limits

Subcritical Tension $x \ll 1$

gravity unimportant, use QFT results

$$B = B_0 \propto \frac{\tau^4}{\delta V^3}$$

$$\rho \sim \sqrt{x}\, R_{AdS} \ll R_{AdS} \ll R_{dS}$$

Critical Tension $x = 1$

gravity important

$$\rho = R_{dS}$$

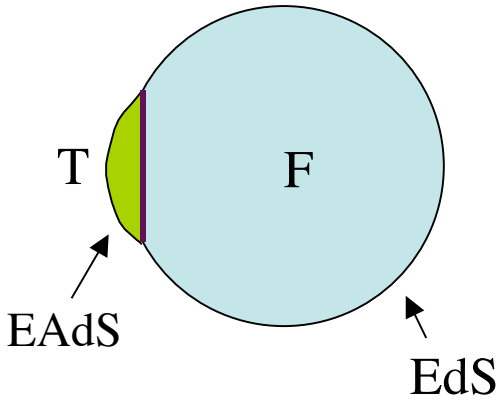
Supercritical Tension $x \gg 1$

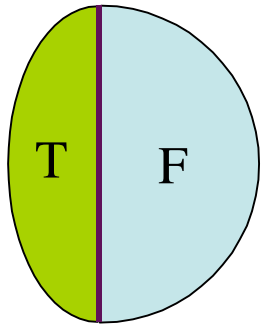
gravity important

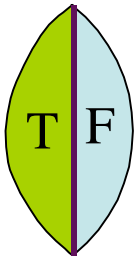
$$B^0_{KPV} \approx \frac{24\pi^2}{G_4^2 V_{dS}} = \mathbf{S}_{dS}$$

$$\rho \sim \frac{R_{AdS}}{\sqrt{x}}$$

Instanton







KKLT de Sitter Vacua

Flux Compactification

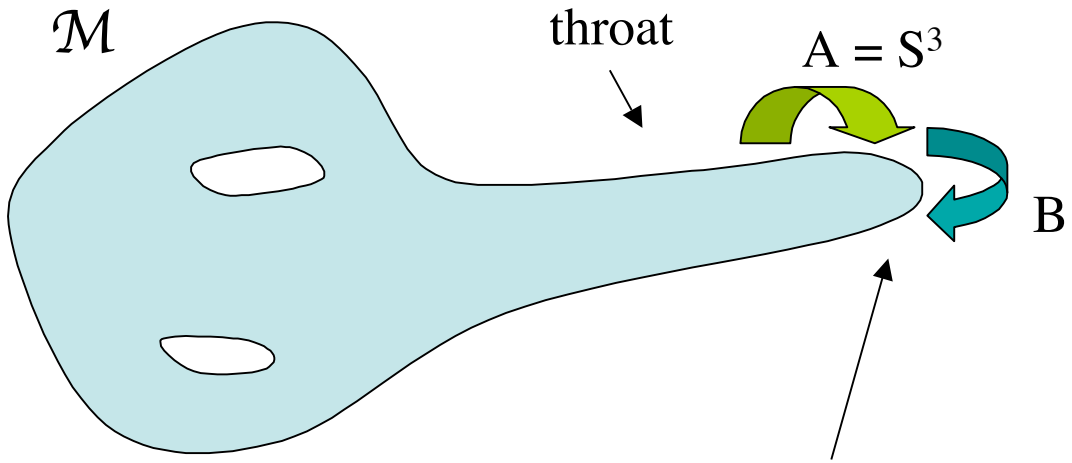
F theory compactified on elliptically fibered CY 4-fold

IIB compactified on 6d Orientifold $\mathcal{M}$ w/ D7's

Turn on ISD flux $G_3 = F_3 - \tau H_3$ on 3-cycles of $\mathcal{M}$

$$ds^2 = h^{-1/2} g_{\mu\nu}(x) dx^\mu ds^\nu + h^{1/2} e^{2u} dy^m dy^n$$

$\mathcal{M}$ near Conifold point ~ Warped Deformed Conifold (KS throat)

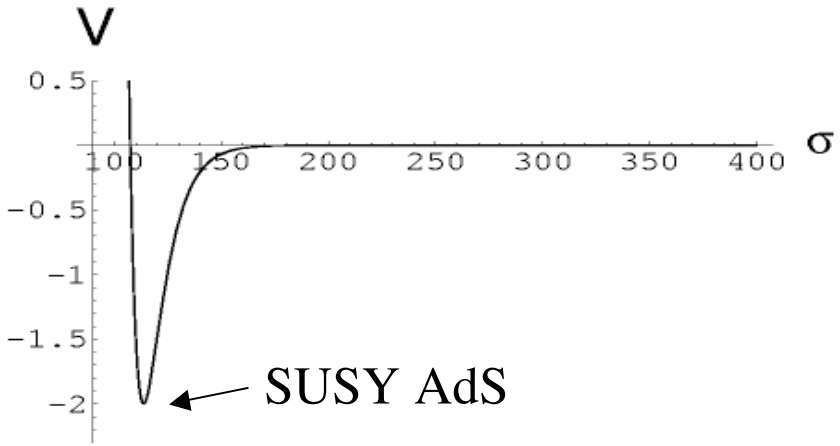


Fluxes

$$M \sim \int_A F_3$$

$$K \sim -\int_B H_3$$

Non-pert. effects generate potential for $\sigma = e^{4u}$
(other moduli fixed)

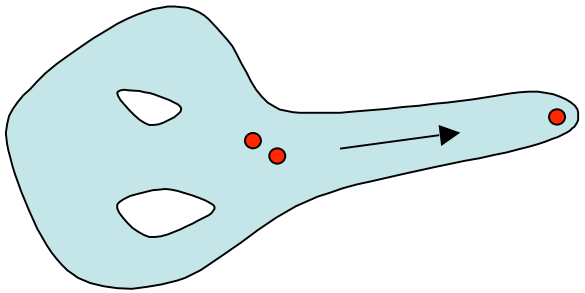


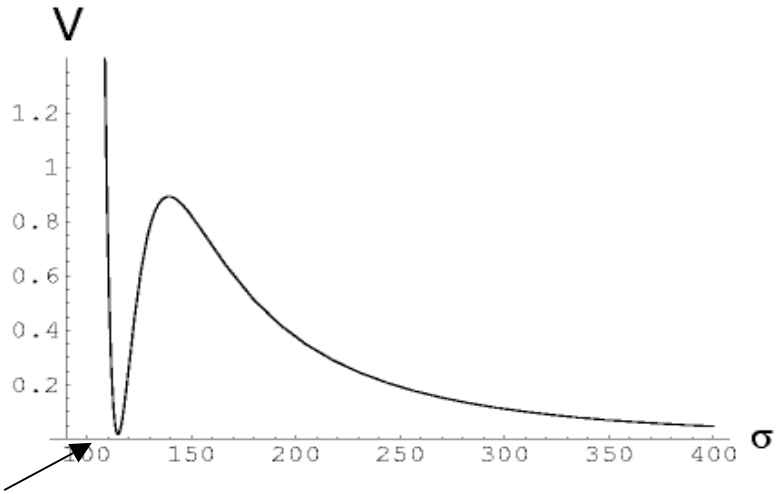
Add $N_{\overline{D3}}$ $\overline{D3}$s

~~SUSY~~

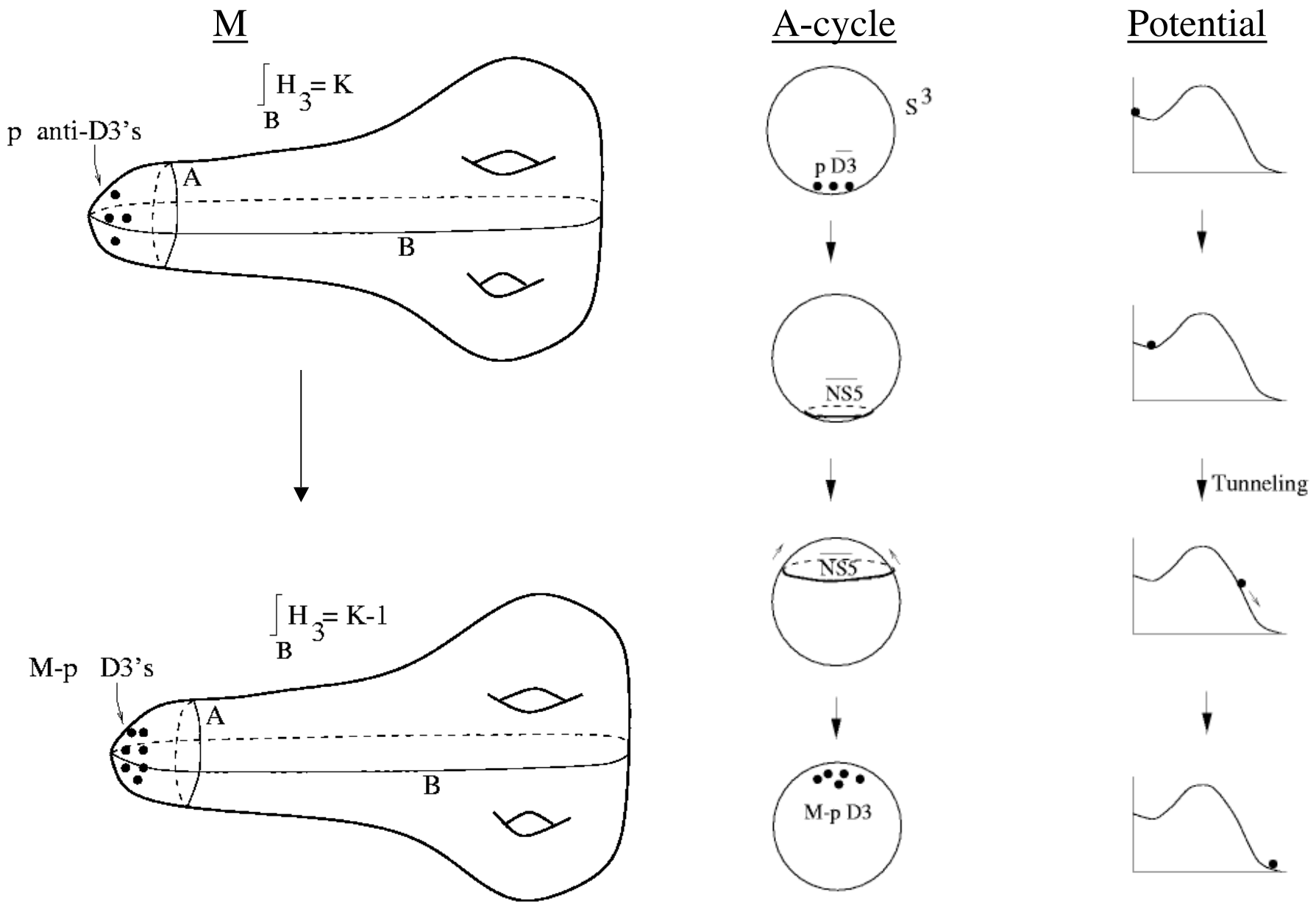
migrate to tip

contribute δV





Brane/Flux Annihilation (KPV)



KPV decay - QFT approx

Instanton (thin-wall) = NS5 wrapped on S^3, bubble in spacetime

4d tension $\tau = \tau_{NS5} V_{S^3} h_{tip}^{-3/4} = \dfrac{M^{3/2}}{16\pi^3 g_s^{1/2} l_s^3} h_{tip}^{-3/4}$

Energy difference $\delta V \approx |V_{AdS}| = \dfrac{2N_{\overline{D3}}}{8\pi^3 g_s l_s^4} h_{tip}^{-1}$

$$B^0_{KPV} = 3 \cdot 10^{-3} \frac{g_s M^6}{(N_{\overline{D3}})^3}$$

Why doesn't this depend on h_{tip}?

- everything localized at tip
- measure relative to bulk → h_{tip} factors
- use proper quantities → independent of h_{tip}

How big can this be?

$$B^0_{KPV} = 3 \cdot 10^{-3} \frac{g_s M^6}{(N_{\overline{D3}})^3}$$

choose $N_{\overline{D3}} = 1$

tadpole $MK < \frac{\chi_{CY_4}}{24}$

KS throat $K > g_s M > 1$

$$\Big\} \quad M < \frac{\chi_{CY_4}}{24}$$

$$B^0_{KPV} < 4 \cdot 10^{-10} \chi^5_{CY_4}$$

Largest known $\chi_{CY_4} \sim 10^6$

Assume this is a bound → $t_d < H^{-1} e^{10^{22}}$

Gravity Corrections

So far ignored gravity

Ok if $x \ll 1$ $\Longleftrightarrow$ $\rho \ll R_{dS}, R_{AdS}$

$$x = \frac{3\pi^4 g_s^2 M^3}{2e^{6u} N_{\overline{D3}}} h_{tip}^{-1/2}$$

Can x ever be > 1?

CY > throat $e^{4u} > 3\pi^3 g_s M K$

KS throat $K > g_s M > 1$

$\Big\}$ $x < 10^4 h_{tip}^{-1/2}$

h_{tip} $\begin{cases} > 10^8 & \text{long throat} \Longrightarrow \text{QFT result ok} \\ < 10^8 & \text{short throat} \Longrightarrow t_{KPV} \approx t_r \ ! \end{cases}$

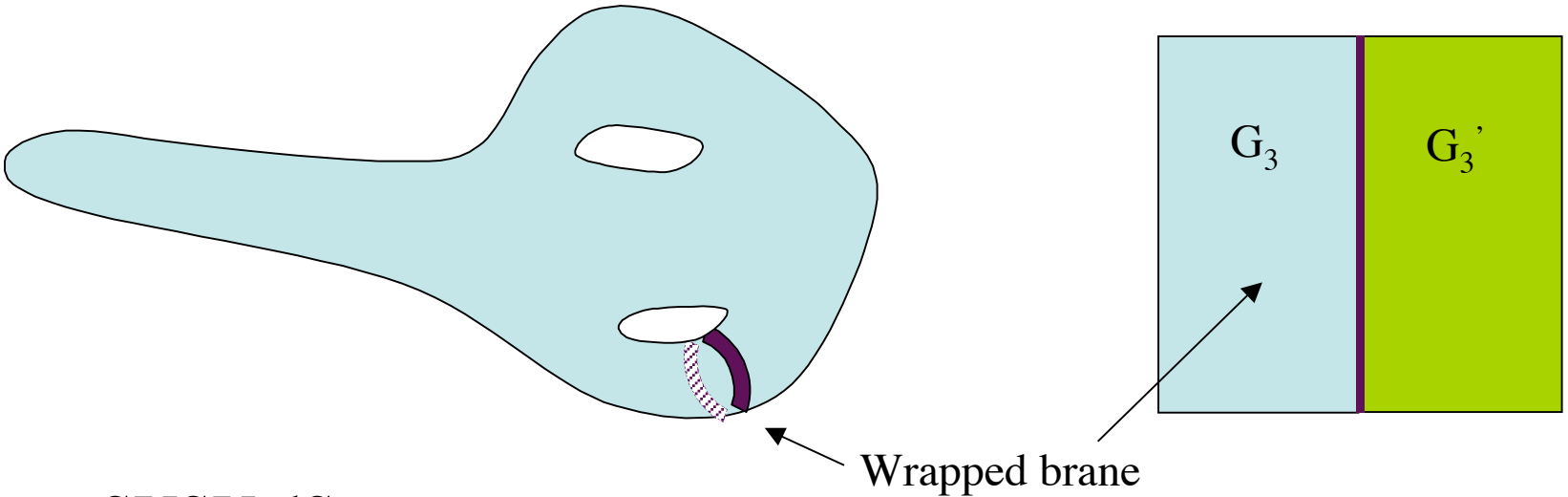
Bulk Flux Decay

KPV not the only decay channel

Before uplifting to dS ➡ SUSY AdS

wrapped branes change flux vacua

BPS domain walls



~~SUSY~~ dS

near-BPS walls ➡ instantons (CDGKL)

estimate action

$$B_{CDGKL} = \frac{6\pi^2}{G_4^2 V_{AdS}}$$

KPV vs flux decay

$$B_{CDGKL} \sim \frac{1}{G_4^2 V_{AdS}} \sim R_{AdS}^4 V_{AdS}$$

use $R_{AdS} = G_4 V_{AdS}$

$$\sim \underbrace{\frac{R_{AdS}^4}{\rho_0^4}}_{x^{-2}} \underbrace{V_{AdS}\rho_0^4}_{B^0_{KPV}}$$

For long throat $x < 1$ ➡ $B = B^0_{KPV}$ KPV

For short throat $x > 1$ ➡ $B = B^0_{KPV}/x^2$ Bulk flux

⬇

$B < B^0_{KPV}$ $\forall\, x$

Bound on KKLT lifetime

$$B^0_{KPV} < 4 \cdot 10^{-10}\, \chi^5_{CY_4}$$

$$t_d < H^{-1} e^{4\cdot 10^{-10}\chi^5_{CY_4}} < H^{-1} e^{10^{22}}$$

Compare with BB time

$$t_{BB} \approx H^{-1} e^{10^{40\pm 20}}$$

What's not to like?

- Not airtight bound

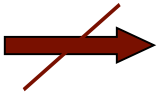
  e.g. CDGKL estimate

- Depends sensitively on bound on χ_{CY_4}

- Only one tiny corner of landscape

  Is this a general feature of string landscape?

Slogans

Nearly SUSY  Nearly stable

Here, t_d independent of $m_{3/2}$ (for small $m_{3/2}$)

String vacua make V_{dS} small by accident

need ingredients at scales other than V_{dS}

t_d set by these scales

Conjecture: $t_d < t_{BB}$ for all string vacua

long-lived string vacua hard to make

HW: find counter-example