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An EFT for end-of-the-world branes and the creation of universes from nothing

Björn Friedrich (Heidelberg)

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End-of-the-world branes

c.f. [Witten, 1982, García Etxebarria et al., 2020, Buratti et al., 2021],

[Delgado,Makridou,Angius,Kneissl,Blumenhagen,Wang,Calderon-Infante,Huertas,Uranga,...]

Cobordism conjecture [McNamara and Vafa, 2019]

ETW branes generally exist in string theory

What is an ETW brane?

Take 1:[around 2000] Dynamical theory living on a spacetime boundary:

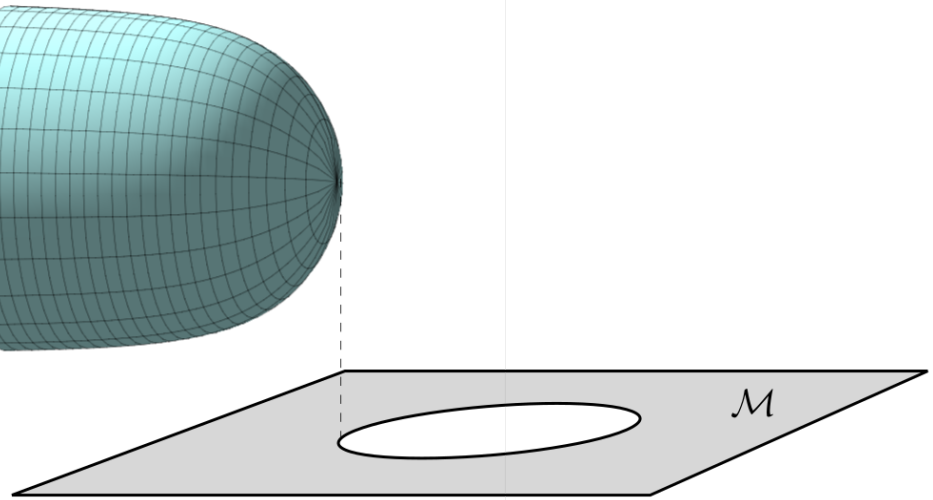
$$\int_{\partial\mathcal{M}} \sqrt{h}\,(\mathcal{K} + \mathcal{L}_{ETW})$$

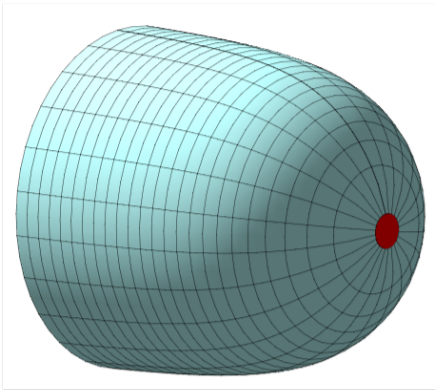
Take 2:[more recent] An ETW brane is defined by a scalar field running to infinite distance in field space over a finite distance in spacetime.

Connection?

Example: The Witten bubble [Witten, 1982]

Witten bubble of nothing (with defect)





Vacuum decay of $\mathbb{M}_4 \times S^1$
5d Schwarzschild solution (with deficit angle θ):

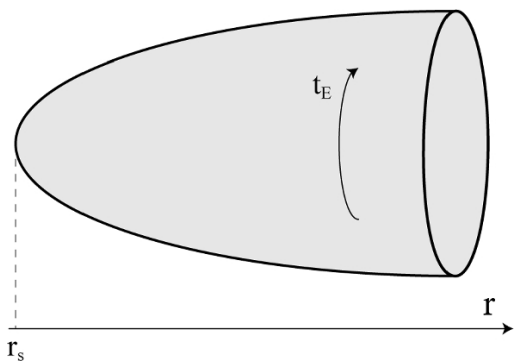
$$ds^2 = \left(1 - \frac{\alpha^2}{\tilde{r}^2}\right)^{-1} d\tilde{r}^2 + \tilde{r}^2 d\Omega_3^2 + \left(1 - \frac{\alpha^2}{\tilde{r}^2}\right) R_{KK}^2 dy^2 \,, \quad \alpha = \frac{R_{KK}}{1 - \theta/2\pi}$$

The 5d perspective

Action

$$S = -\frac{1}{2}\int_{\mathcal{W}} \sqrt{g_5}\mathcal{R}_5 - \int_{\partial\mathcal{W}} \sqrt{h}\mathcal{K}_5$$

On-shell action



- A single boundary at infinity
- Since $\mathcal{R}_5 = 0$, $S = S_{\partial M}$

4d perspective

Dimensional reduction

$R = \exp^{\sqrt{2/3}\phi}/2\pi$: Radius of internal S^1

$$S = \int_{\mathcal{M}} \sqrt{g_4}\left(-\frac{1}{2}\mathcal{R}_4 + \frac{(\partial\phi)^2}{2} + \frac{1}{\sqrt{6}}\Box\phi\right) - \int_{\partial\mathcal{M}} \sqrt{h}\left(\mathcal{K}_4 + \frac{1}{\sqrt{6}} n_\mu \partial^\mu \phi\right)$$

Bubble of nothing: $\phi \to -\infty$ in finite spacetime distance

The 4d perspective

- Proper EFT description: Boundaries at infinity and at the ETW brane
- Action should not contain total derivative terms such as $\Box\phi$

The EFT for ETW branes

General Problem: Loss of control when $(\partial\phi)^2$ becomes large

EFT proposal

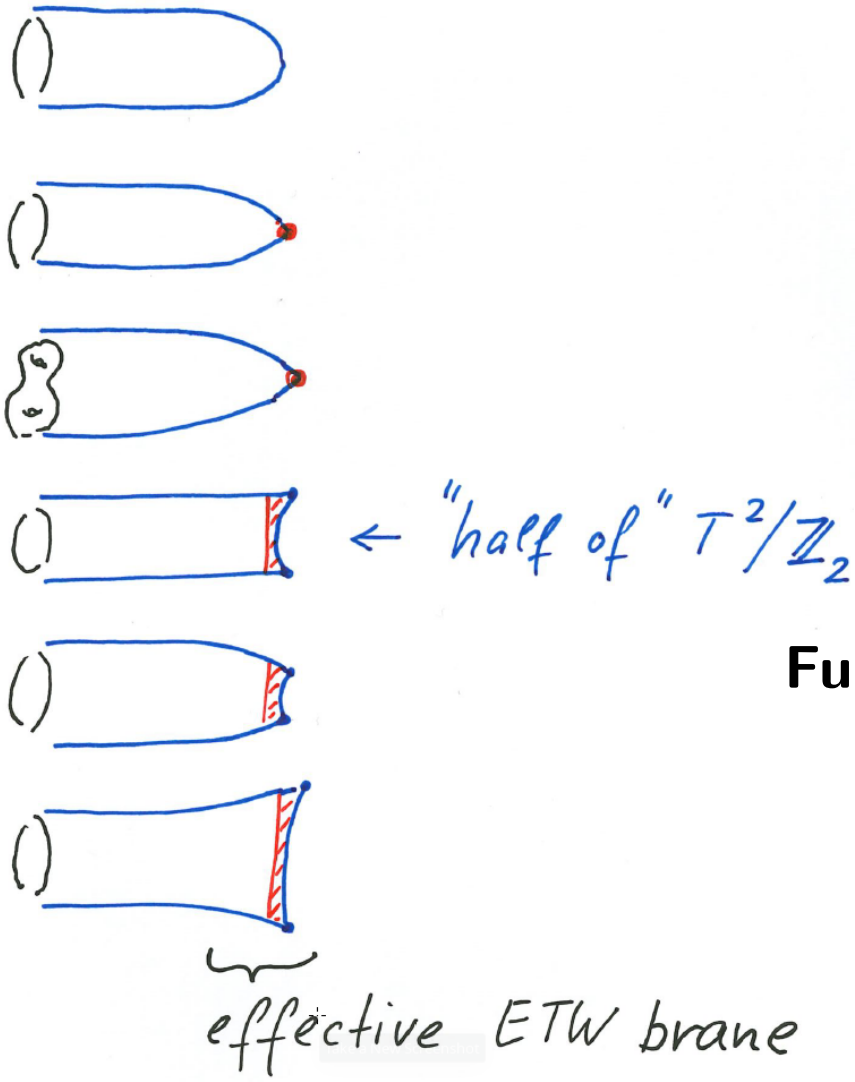
Introduce a **defect** of size η (at $\phi = \phi_\eta$) and tension T_4:

$$S = \int_{\mathcal{M}} \sqrt{g_4}\left(-\frac{1}{2}\mathcal{R}_4 + \frac{(\partial\phi)^2}{2}\right) - \int_{\partial\mathcal{M}} \sqrt{h}\,(\mathcal{K}_4 - T_4)$$

The defect is generally **natural** from higher dimensional and **needed** from 4d perspective.

For the Witten bubble with deficit angle: $T_4 = -\left(1 - \frac{\theta}{2\pi}\right)\frac{1}{\sqrt{2\pi\eta^3}}$

The EFT for ETW branes



Simple EFT describes many different options for the ETW brane

Furthermore: Explicit construction of an ETW brane for IIB CY-orientifold compactifications [Friedrich et al., 2023b]

The EFT for ETW branes

General Goal:

$$S = \int_{\mathcal{M}} \sqrt{g_4} \left(-\frac{1}{2}\mathcal{R}_4 + \frac{(\partial\phi)^2}{2} - V(\phi) \right) - \int_{\partial\mathcal{M}} \sqrt{h} \left(\mathcal{K}_4 + \mathcal{L}_{ETW} \right)$$

String theory question: Find $\mathcal{L}_{ETW}$ for string theoretic ETW branes

Why a 4d EFT description is useful

The Measure Problem

What universes are likely to be realized? [Friedrich et al., 2023a]

$$J_i = \sum_j \left(p_i \Gamma_{i\to j} - p_j \Gamma_{j\to i}\right) + p_i \sum_{y \in \mathit{Terminals}} \Gamma_{i\to y}$$

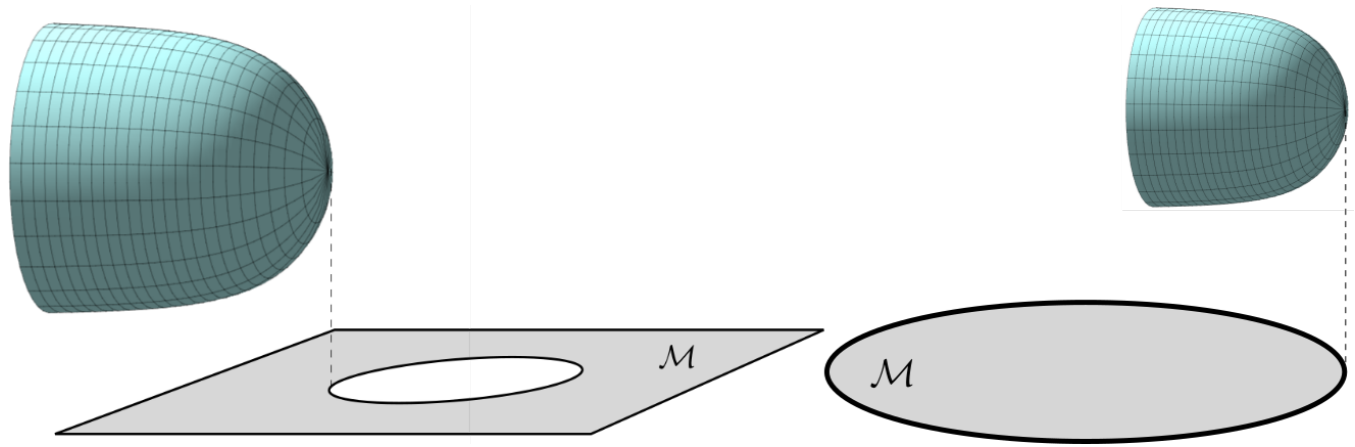
- p_i: Probability of vacuum i being realized
- $\Gamma_{i\to j}$: Vacuum **decay rates**
- J_i : Vacuum **creation rates**

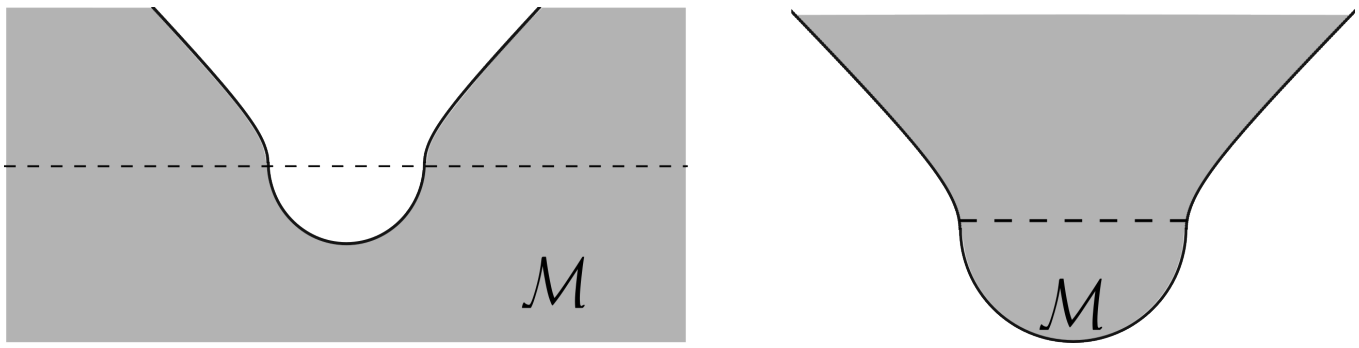
Vacuum creation/decay rates are essential for predictions in cosmology

Why is an EFT description of ETW branes useful?

The Measure Problem

Generally study vacuum creation and vacuum decay





Vacuum creation: Generalities

[Vilenkin, 1982, Vilenkin, 1983, Hartle and Hawking, 1983, Linde, 1984, Vilenkin, 1984]

Creation of universes with compact spherical topology

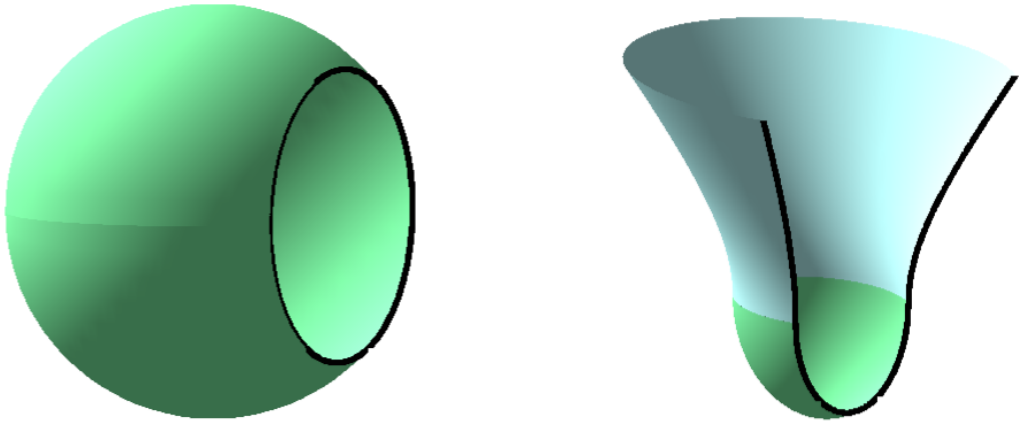
Hartle-Hawking: $\Gamma \sim \exp(-\mathcal{S}_{instanton}) = \exp\left(8\pi^2 M_P^2 \ell_{dS}^2\right)$

Linde/Vilenkin: $\Gamma \sim \exp(+\mathcal{S}_{instanton}) = \exp\left(-8\pi^2 M_P^2 \ell_{dS}^2\right)$

Bubbles of something

[Hawking and Turok, 1998, Turok and Hawking, 1998, Garriga, 1998, Blanco-Pillado et al., 2012, Friedrich et al., 2023b]

Creation of universes with boundary



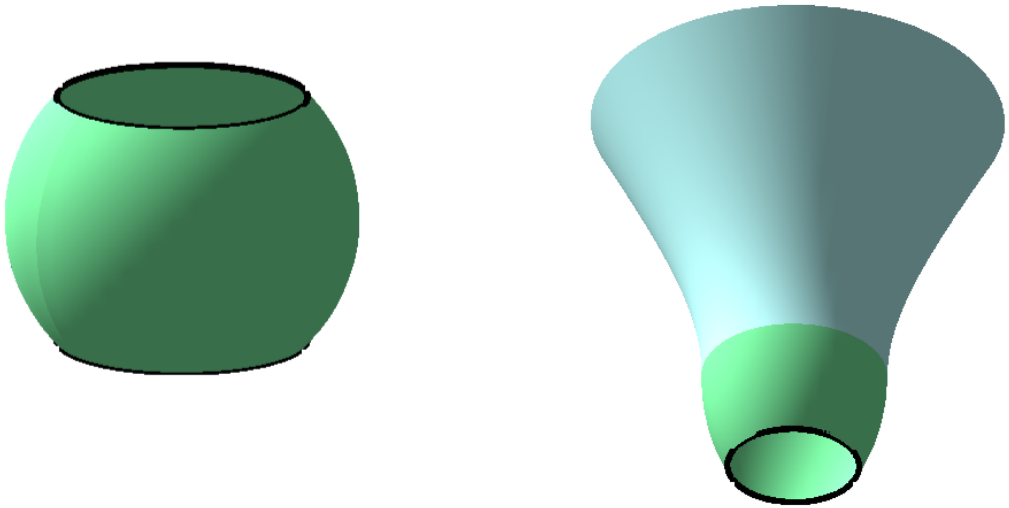
$$\mathcal{S}_{instanton} = -4\pi^2 M_P^2 \ell_{dS}^2 \left(1 - \frac{T\ell_{dS}}{\sqrt{T^2\ell_{dS}^2 + 4M_P^4}}\right)$$

Implications

- Linde/Vilenkin sign: More likely than creation of a sphere
- Especially dominant for $T\ell_{dS} \gg M_P^2$
- Minkowski/AdS can also be created

The boundary proposal [Friedrich and Hebecker, 2024]

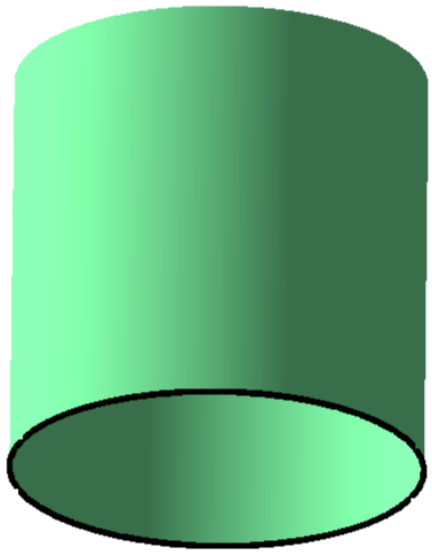
Creation of a spherical universe with ETW branes in the off-shell region



$$\mathcal{S}_{instanton} = -8\pi^2 M_P^2 \ell_{dS}^2 \sqrt{\frac{T^2 \ell_{dS}^2}{T^2 \ell_{dS}^2 + 4M_P^4}}$$

- Requires $T \leq 0$
- Linde/Vilenkin sign: More likely than creation of a sphere
- Especially dominant for $|T|\ell_{dS} \ll M_P^2$

The boundary proposal



- Consideration: Creation of toric universes (no spatial curvature) [Zeldovich and Starobinsky, 1984, Coule and Martin, 2000, Linde, 2004]
- To leading order: Toric universes can nucleate without any cost if $T = 0$
- Type IIA: O8+8D8 makes a $T = 0$ ETW brane

Implications for anthropic predictions [Friedrich, Hebecker, Westphal, Zell, to appear]

- Hartle-Hawking creation appears to be in conflict with observation
- For Linde/Vilenkin type creation: ETW brane creation from nothing dominates
- Observables like the scale of inflation are tight to properties of ETW branes
- Better understandings of available ETW branes and their EFT description are needed

ETW branes are a useful tool to understand the structure of quantum gravity and play a major role in cosmology.

Conclusions

- Propsal for universally applicable EFT description for ETW branes arising from $\phi \to \infty$
- The ETW tension T_4 is an important ingredient to study vacuum decay/creation processes
- Predictions in cosmology depend on vacuum creation rates
- Proposal for the creation of universes with ETW branes in the off-shell region
- ETW branes have direct impact on physical predictions such as our scale of inflation

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Thank you!