Dark bubbles and the equivalence principle

Based on [2502.20438], [2507.03748], with I. Basile and A. Borys.

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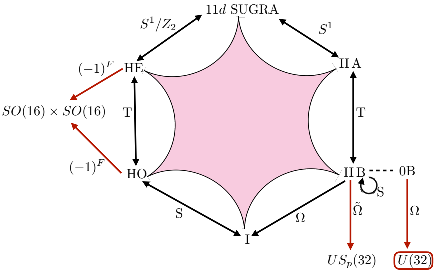
Non supersymmetric string theories

$U(32)$ or 0'B string [Sagnotti, 1995]

- Type 0B orientifold $O9^- +$ 32 D9 branes.
- D1 and D5 branes coupling to a RR 2-form field.
- D3 branes couple to RR 4-form field with self dual field strength.
- NS-NS tadpole from the uncancelled brane tension $T = 32 T_{D_9}$.



$$S = \frac{1}{2\kappa} \int d^{10}x \sqrt{-g} \left(R - \frac{1}{2}(\partial\phi)^2 - Te^{-\frac{3}{2}\phi} - \frac{e^{\phi}}{12} F_3^2 - \frac{1}{24} F_5^2 \right)$$

- Ideal to try and realize $d = 4$ braneworlds.

The Dark Bubble

- A spherical shell separating non-susy AdS_5 vacua with $\Lambda_- < \Lambda_+ < 0$ nucleates $(\Lambda_\pm = -k_\pm^2)$. [Banerjee, Danielsson, Dibitetto, Giri, and Schillo, 2019, Danielsson, Henriksson, and Panizo, 2023]
- Einstein equations in 4d are then implied by Gauss-Codazzi equations

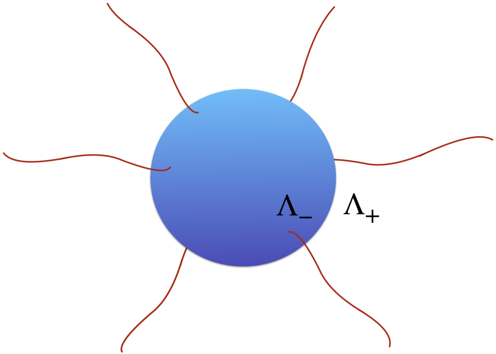
$$\sigma = \frac{3}{8\pi G_5}\left(\sqrt{k_-^2 + \frac{1+\dot{a}^2}{a^2}} - \sqrt{k_+^2 + \frac{1+\dot{a}^2}{a^2}}\right), \quad ds^2_{\text{brane}} = -d\tau^2 + a(\tau)^2 d\Omega_3^2 \,.$$

- The effective 4d dynamics are then

$$\Lambda_4 = \frac{3(k_- - k_+)}{8\pi G_5} - \sigma = \sigma_c - \sigma \,, \quad G_4 = \frac{2k_- k_+}{k_- - k_+} G_5 ,$$

The Dark Bubble

- The brane nucleates, dynamically realizing the decay of the Λ_+ vacuum.

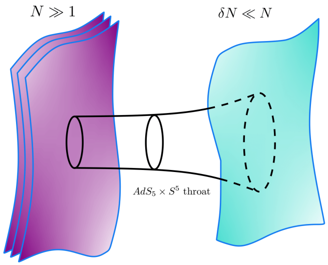


The Dark Bubble in the 0'B string

- The near horizon geometry of Dp branes coupled to F_{p+2} in the 0'B string will be approximated by $AdS_{p+2} \times S^{8-p}$.
- Given a stack of N Dp branes sourcing the geometry and a probe stack δN we find a tree level probe potential

$$V_{\text{probe}}(Z) = \tau_p \left(\frac{L}{Z}\right)^{p+1} \left[1 - \frac{\sigma}{\sigma_c}\right],$$

- $\frac{\sigma}{\sigma_c} > 1$ for p=1,5; $\frac{\sigma}{\sigma_c} \simeq 1$ for $p = 3$ branes
[Basile and Lanza, 2020]
- Only D3 braneworlds lead to scale separated vacua!



The Dark Bubble in the 0'B string

- The near horizon geometry for a stack of D3-branes in the 0'B string is approximately $AdS_5 \times S^5$

$$ds^2 = R^2(U)\,\frac{dU^2}{U^2} + \frac{\alpha'^2\,U^2}{R^2(U)}\,dx_{1,3}^2 + \widetilde{R}^2(U)\,d\Omega_5^2\,,$$

- Sourced by a self dual 5 form flux

$$F_5 = (1+\star)\,f_5\,N\,\mathrm{vol}_{S^5}$$

- We can find the C_4 potential as

$$C_4 \simeq c_4(U)d^4x\ldots\,,\quad \frac{c_4'(U)}{\alpha'} = \frac{f_5\,N}{\widetilde{R}(U)^5}\left(\frac{\alpha'\,U}{R(U)}\right)^3$$

$$\frac{R^2(U)}{R_\infty^2} \sim 1 - \frac{3}{16}\,g_s\,\alpha' T\,\log\left(\frac{U}{u_0}\right)\,,$$

$$\frac{\widetilde{R}^2(U)}{R_\infty^2} \sim 1 - \frac{3}{16\sqrt[4]{8}}\,g_s^2\,N\,\alpha' T\,\log\left(\frac{U}{u_0}\right)\,,$$

$$\frac{1}{N}\,e^{-\phi} \sim \frac{1}{g_s\,N} + \frac{3}{8\sqrt[4]{8}}\,g_s\,\alpha' T\,\log\left(\frac{U}{u_0}\right)\,,$$

$$R_\infty^2 = \sqrt{4\pi g_s N}\alpha'\,,\quad g_s^2 N \ll 1 \ll g_s N.$$

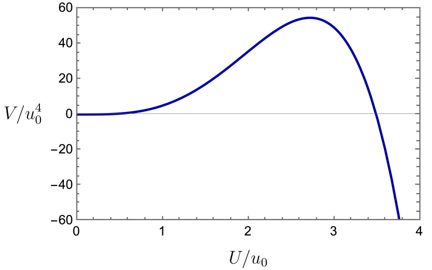
$$\frac{1}{2\kappa_{10}^2}\int_{S^5} F_5 = \mu_3\,N\,,$$

$$F_5 = dC_4.$$

The Dark Bubble in the 0'B string

- The braneworld action is then given by

$$\mathcal{L}_{\text{DBI+CS}} = \frac{N_3 N U^4}{2\pi^2\lambda^2}\left[-\left(1+\frac{3\lambda^2\alpha' T}{128\sqrt[4]{8}\pi^2 N}\log\frac{U}{u_0}\right)\sqrt{1-\frac{\lambda\dot{U}^2}{U^4}} + 1 - \frac{15\lambda^2\alpha' T}{2048\sqrt[4]{8}\pi^2 N}\left(1-4\log\frac{U}{u_0}\right)\right],$$



- The probe potential is then

$$V^{\text{D3}}_{\text{probe}}(U) = N_3 T_3 \left(\frac{\alpha' U}{R(U)}\right)^4 e^{-\phi(U)} - N_3\mu_3\, c_4(U) \simeq \frac{U^4}{5}\left[1-\frac{4}{5}\log\left(\frac{U}{u_0}\right)\right]$$

- The extremality parameter is $\simeq 1$.

The Dark Bubble in the 0'B string

- We can parameterize the metric on the brane as $ds^2_{\text{brane}} = -d\tau^2 + a(\tau)^2 d\mathbf{x}^2$ with flat spacelike slices. The scale factor is identified with the bubble radius as $a = \frac{\alpha' U}{R}$, and the cosmological time is defined as $\left(\frac{d\tau}{dt}\right)^2 = -\frac{R(U)^2}{U^2}\dot{U}^2 + \frac{\alpha'^2 U^2}{R(U)^2}$.
- The Hamiltonian is given by

$$\mathcal{H} = \dot{U}\frac{\partial \mathcal{L}}{\partial \dot{U}} - \mathcal{L} \sim \frac{N_3 N U^4}{2\pi^2\lambda^2}\left[\frac{1}{\sqrt{1-\frac{\lambda \dot{U}^2}{U^4}}} - 1 + \frac{\epsilon}{2}\left(\frac{5}{4} - \log\frac{U}{u_0}\right)\right] , \quad \epsilon \equiv \frac{3}{2^{\frac{7}{4}}\pi^2} g_s^2 N$$

- The leading term between both contributions will cancel in the large U limit. Then by conservation of energy, the term inside the brackets must vanish as U^4 blows up, this implies

$$\left(\frac{1}{a}\frac{da}{d\tau}\right)^2 \equiv H^2 \sim \epsilon R_\infty^{-2} \log\left(\frac{a}{a_*}\right) , \; H^2 = \epsilon M^2 \log\left(\frac{a}{a_*}\right) , \; a(\tau) = a_0 \exp(H_0\,\tau + \frac{\epsilon M^2 \tau^2}{4})$$

- Where $M = R_\infty^{-1}$, and $H_0 = H(0)$.

Consequences for particle physics and cosmology

- The scale $a(\tau) = exp(H_0\tau + \epsilon M^2\tau^2/4)$ describes a cosmological scenario often dubbed LSBR, in which there is an spacetime singularity at infinite time.
- Can be realized exactly via a phantom scalar

$$S = \int d^4xa^3(t)\left[-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)\right], \; V(\phi) = \epsilon\frac{M^2}{2} + \epsilon\frac{3M^2}{4}\phi^2$$

- Within slow roll approximation we have

$$\varepsilon \simeq -\frac{1}{2}\left(\frac{V'}{V}\right)^2, \eta =\simeq -2\left(\frac{V'}{V}\right)^2 + 2\left(\frac{V''}{V}\right)$$

$$n_s - 1 = -2\epsilon - \eta\,, \quad r = -16\epsilon\,.$$

- However we found the scalar description to be valid at all times, so we can use

$$\varepsilon \equiv -\frac{\dot{H}}{H^2} = -\frac{\frac{\epsilon M^2}{2}}{(H_0 + \frac{\epsilon M^2}{2}\tau)^2}, \qquad \eta \equiv \frac{\dot{\varepsilon}}{H\varepsilon} = -\frac{\epsilon M^2}{(H_0 + \frac{\epsilon M^2}{2}\tau)^2}$$

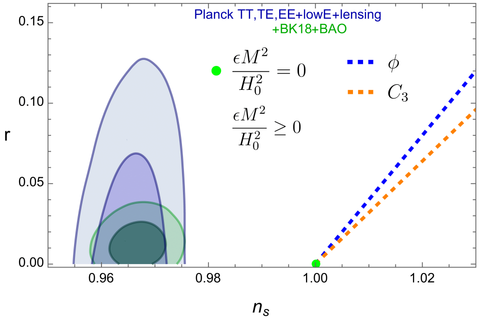
- LSBR can also be realized via massive 3 forms

$$S = \int d^4x\sqrt{-g}\left(R - \frac{1}{g^2}F_4^2 - V(C_3^2)\right),$$

the spectral tilt will be given by
[Koivisto and Nunes, 2009]

$$n_s - 1 \simeq -2\varepsilon - \frac{3}{2}\eta\,.$$

- As $\epsilon, \eta < 0$, the spectrum will be blue-shifted. Absolute scale invariance is recovered for $\epsilon = 0$, as expected since one recovers pure dS in this case. $\epsilon = 0$ also corresponds to having no NS-NS tadpole, leading to DB models with fixed H.



Consequences for particle physics and cosmology

- The 0'b bubble can be parameterized as a $w_0 w_a CDM$ model

$$w = w_0 + (1-a) w_a \,, \quad w_0 = -0.957 \pm 0.08 \,, \; w_a = -0.29^{+0.32}_{-0.26} \text{ [Planck, 2018]}.$$

$$w_{0'B} \simeq -1 - \frac{\epsilon M^2}{3H_0^2} - (1-a)\frac{\epsilon^2 M^4}{3H_0^4}$$

- Given Hubble today $H_0 \approx 5.9 \times 10^{-61} M_{\text{Pl}}$ this imposes the bound

$$\epsilon M^2 \approx g_s^2 M_{\text{Pl}}^2 \lesssim 10^{-122} M_{\text{Pl}}^2 \,.$$

- Requiring large t'Hooft coupling then implies

$$g_s \lesssim 10^{-61} \,, \quad N \gtrsim 10^{61} \,.$$

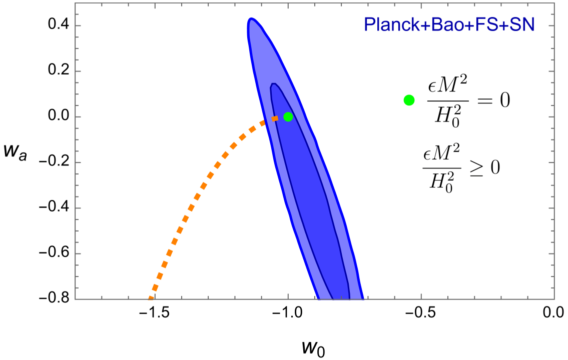
- This sets the scales in the model as

$$M \lesssim M_s \lesssim M_{10} \lesssim M_{\text{Pl}} \ll M_5 \,, \text{ with } M \lesssim \text{meV} \,, \quad M_{10} \lesssim \text{TeV}.$$

Consequences for particle physics and cosmology

- Dark Dimension like scenario is realized, but string coupling is too small to realize SM gauge couplings on the brane.
- $\epsilon M^2 \simeq 0$ is favored, favoring models with constant equation of state.

[Danielsson et al., 2023].



Gauge Fields in the Dark Bubble

- Given the DBI action, a $U(1)$ gauge field naively couples incorrectly to the induced gravity ($\mathcal{F} = F - B/2\pi\alpha'$):

$$\left(\frac{\dot{a}}{a}\right)^2 \delta^a_b = \frac{\Lambda_4}{3}\delta^a_b + \frac{\kappa_4}{3}\left(\mathcal{F}^{ac}\mathcal{F}_{bc} - \frac{1}{4}\delta^a_b\mathcal{F}^2\right),$$

- We also have that the equation of motion for the B field, assuming it is vanishing inside and at the bubble are

$$\Delta H^{r\mu\nu}\big|_{r=a} = H^{r\mu\nu}\big|_{r=a} = \frac{\kappa_5 ka}{\pi^2\alpha'}\mathcal{F}_{\mu\nu}\big|_{r=a}$$

- The bulk B field is then sourced by the gauge field living on the brane. Taking into account the back reaction of the B-field gives the correct coupling [Basile, Danielsson, Giri, and Panizo, 2024]

$$\left(\frac{\dot{a}}{a}\right)^2 \delta^a_b = \frac{\Lambda_4}{3}\delta^a_b - \frac{\kappa_4}{3}\left(\mathcal{F}^{ac}\mathcal{F}_{bc} - \frac{1}{4}\delta^a_b\mathcal{F}^2\right),$$

Gauge Fields in the Dark Bubble

- We can do the same for RR fields. Given

$$S_{CS} = \mu_p \bigoplus_n \int_W C_n \wedge \sqrt{\frac{\hat{A}(TW)}{\hat{A}(NW)}} \wedge e^{2\pi\alpha' F} \supset \mu_3 \int_W 2\pi\alpha' \mathcal{F} \wedge C_2$$

- The total action is

$$S_5 = \frac{1}{2\kappa_5} \int d^5x \sqrt{-g_5} \left(R - \frac{1}{12 g_s} H^2 - \frac{1}{12 g_s} F_3^2 \right) - \int d^4x \sqrt{-g_4} \left(T_3 + \frac{1}{4g^2} \mathcal{F}^2 \right) + \mu_3 \int_W 2\pi\alpha' \mathcal{F} \wedge C_2$$

- The equations of motion for the B and C_2 fields are then

$$\Delta H^{r\mu\nu} = \frac{\kappa_5 ka}{\pi^2 \alpha'} \mathcal{F}^{\mu\nu} , \qquad \Delta F^{r\rho\sigma} = \frac{\kappa_5 ka}{4\pi^2 \alpha'} \tilde{\mathcal{F}}^{\rho\sigma} .$$

- $H = dB$ in the bulk is sourced by the electromagnetic field-strength on the brane, while $F_3 = dC_2$ in the bulk is sourced by its electromagnetic dual.

Gauge Fields in the Dark Bubble

- We can correctly couple $U(1)$ gauge fields to the brane, what about the non-abelian case?

$$S_{\mathrm{D3}} \sim - \int d^4x \, \mathrm{STr}\sqrt{-\det(g_{\mu\nu} + 2\pi\alpha' \mathcal{F}_{\mu\nu})}$$

[Tseytlin, '97, Myers '99]

- TrF is now vanishing! We need to go in higher order in α'.

$$\Delta H \sim \mathrm{Tr}[F^3]$$

- Similarly for couplings to bulk Ramond-Ramond fields

$$\Delta F_1 \sim Tr[F^2]$$

Gauge Fields in the Dark Bubble

- Several potential problems with this:
- Severe fine tuning necessary to engineer precise cancellations (if possible).
- Coupling non abelian gauge fields with the correct sign now requires balancing terms at different orders in α', signaling a breakdown of the perturbative framework.
- Even if one could somehow resolve this, one cannot simultaneously couple abelian and non-abelian gauge fields to the brane.

$SU(3)_c$ and the Weak Equivalence Principle

- Let us assume that one can construct a Dark Bubble in which everything couples correctly to the "apparent" 4d gravity except for non-abelian gauge fields. What would such a universe look like? Bounds on the WEP are given by [Andreas et al.,2011, Heiße et al., 2017, MICROSCOPE, 2022]

$$\frac{m_g - m_i}{m_i} \lesssim 10^{-15} \quad , \frac{m_p^{(g)} - m_p^{(i)}}{m_p^{(i)}} \leq 7 \times 10^{-3}$$

- LQCD computations show that the proton gravitational form factors are given by

$$\langle N(\vec{p}\,', s')|\hat{T}^{\mu\nu}|N(\vec{p}, s)\rangle =$$

$$\frac{1}{m}\,\bar{u}(\vec{p}\,', s')\left[A(t)\,P^\mu P^\nu + J(t)\,i\,\sigma^{\rho\{\mu}P^{\nu\}}\Delta_\rho + D(t)\,\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4}\right]u(\vec{p}, s)$$

- The contributions to $\hat{T}_{\mu\nu}$ can be decomposed as

$$\hat{T}^{\mu\nu} = \hat{T}_q^{\mu\nu} + \hat{T}_g^{\mu\nu}, \quad \hat{T}_g^{\mu\nu} = 2\mathrm{Tr}\left[F^{\mu\alpha}F^\nu{}_\alpha - \frac{1}{4}g^{\mu\nu}F^{\alpha\beta}F_{\alpha\beta}\right], \quad \hat{T}_q^{\mu\nu} = \left[\frac{i}{2}\bar{\psi}_f\left(\gamma^\mu D^\nu + \gamma^\nu D^\mu\right)\psi_f\right]$$

$SU(3)_c$ and the Weak Equivalence Principle

- For gauge fields coupling normally to gravity

$$\langle N|\hat{T}^{00}|N\rangle = A_g(0)m_p + A_q(0)m_p = m_p$$

- With form factors at rest [Hackett et al., 2024]

$$A(0)_g = 0.51 \pm 0.03, \;\; A(0)_q = 0.5 \pm 0.03$$

- If the gauge part were to couple with a negative sign to "gravity" we would have a gravitational proton mass

$$\langle N|\hat{T}^{00}_q - \hat{T}^{00}_g|N\rangle = (0.009 \pm 0.037)\, m_p$$

- Compared to experimental tests, this leads to large violations of the WEP

$$\frac{m_p^{(g)} - m_p^{(i)}}{m_p^{(i)}} \simeq 0.99$$

Conclusions

- We have studied a novel realization of a Dark Bubble scenario in the 0'B non-susy string.
- The 0'B Dark Bubble leads to a LSBR sort of cosmological accelerated expansion.
- This is unsuitable to realize early universe accelerated expansion, late time acceleration can fit within experimental results, but the resulting string coupling $g_s \simeq 10^{-60}$ makes it unlikely to realize the SM in the brane.
- It is not possible to couple non-abelian gauge fields to the brane via bulk fields.
- This leads to large violations of the equivalence principle.


Thank You!

The Dark Bubble in the 0'B string

- The near horizon geometry for a stack of D3-branes in the 0'B string is approximately $AdS_5 \times S^5$

$$ds^2 = R^2(U)\,\frac{dU^2}{U^2} + \frac{\alpha'^2\,U^2}{R^2(U)}\,dx_{1,3}^2 + \widetilde{R}^2(U)\,d\Omega_5^2\,,$$

- Sourced by a self dual 5 form flux

$$F_5 = (1+\star)\,f_5\,N\,\mathrm{vol}_{S^5}$$
$$= f_5\,N\,\mathrm{vol}_{S^5} + \frac{f_5\,N}{\widetilde{R}(U)^5}\left(\frac{\alpha'\,U}{R(U)}\right)^3 d(\alpha' U)\wedge d^4x$$

- We can find the C_4 potential as

$$C_4 \simeq c_4(U)d^4x\ldots\,,\quad \frac{c_4'(U)}{\alpha'} = \frac{f_5\,N}{\widetilde{R}(U)^5}\left(\frac{\alpha'\,U}{R(U)}\right)^3$$

$$\frac{R^2(U)}{R_\infty^2} \sim 1 - \frac{3}{16}\,g_s\,\alpha'\,T\,\log\left(\frac{U}{u_0}\right),$$
$$\frac{\widetilde{R}^2(U)}{R_\infty^2} \sim 1 - \frac{3}{16\sqrt[4]{8}}\,g_s^2\,N\,\alpha'\,T\,\log\left(\frac{U}{u_0}\right),$$
$$\frac{1}{N}\,e^{-\phi} \sim \frac{1}{g_s\,N} + \frac{3}{8\sqrt[4]{8}}\,g_s\,\alpha'\,T\,\log\left(\frac{U}{u_0}\right),$$
$$R_\infty^2 = \sqrt{4\pi g_s N}\alpha'\,,\quad g_s^2 N \ll 1 \ll g_s N.$$

$$\frac{1}{2\kappa_{10}^2}\int_{S^5} F_5 = \mu_3\,N\,,$$

$$F_5 = dC_4.$$

Consequences for particle physics and cosmology

- We would like to study if the parametric dependence on ϵ can be modified by looking at a different toy model. To this we consider realizing the bubble on D5-branes wrapping a 2 cycle Σ_2. We further assume the S^5 can be replaced by a suitable manifold with non trivial homology. The effective action is then

$$S \sim -\int_W d^4x\sqrt{-g_4}\, T_5 N_5 \left(\frac{\alpha' U}{R(U)}\right)^4 e^{-\phi(U)}\tilde{R}(U)^2\sqrt{1-\frac{\lambda \dot{U}^2}{U^4}} + \mu_5 N_5 \int_{W\times\Sigma_2} C_4 \wedge 2\pi\alpha'\mathcal{F}$$

- We assume that we can induce C_4 charge on the brane according to

$$Q_{\text{eff}} = \int_{\Sigma_2} e^{2\pi\alpha'\mathcal{F}} \simeq R_\infty^2 .$$

- Energy conservation at large AdS radius will again imply LSBR cosmological solutions with $\varepsilon \propto g_s^2 N$, making it extremely unlikely to realize SM gauge fields on the brane.