# Early Dark Energy in Type IIB String Theory

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# Hubble tension

$5\sigma$ discrepancy between Planck[1] and SH0ES[2] inference of $H_0$.
Planck measured $100\theta_s = 1.0411 \pm 0.0003$ with

$$\theta_s = \frac{r_s(z_*)}{D_A(z_*)}\,, \tag{1}$$

having defined

$$r_s(z_*) = \int_{z_*}^{z_{\rm re}} \frac{\mathrm{d}z}{H(z)} c_s(z)\,, \quad D_A(z_*) = \int_0^{z_*} \mathrm{d}z \frac{1}{H(z)}\,. \tag{2}$$

The 0.03% measurement of the angle $\theta_s$ can accommodate the $\approx 10\%$ increase in $H_0$ if there is a commensurate increase in $H(z \sim z_*)$.

[1] Planck collaboration, 2018
[2] A. G. Riess et al., 2021

# Early Dark Energy

Proposal: reduce the sound horizon with an ultralight scalar axion[3] satisfying

$$\ddot{\varphi} + 3H\dot{\varphi} + V' = 0 \tag{3}$$

where the best fitting potential is given by

**EDE potential**

$$\begin{aligned} V(\varphi) &= V_0 \left[1 - \cos\left(\frac{\varphi}{f}\right)\right]^3 \\ &= V_0 \left[\frac{5}{2} - \frac{15}{4}\cos\left(\frac{\varphi}{f}\right) + \frac{3}{2}\cos\left(\frac{2\varphi}{f}\right) - \frac{1}{4}\cos\left(\frac{3\varphi}{f}\right)\right]. \end{aligned} \tag{4}$$

with $V_0 = m^2 f^2$. This is such at the minimum $V \propto \phi^6$ and thus the energy density redshifts as $a^{-9/2}$.

[3] V. Poulin, T. L. Smith, T. Karwal and M. Kamionkowski, 2019

The parameter at which we are aiming are

- Recombination of electron and protons when $T \sim$ eV giving us $V_0 \sim \text{eV}^4$
- mass comparable to the Hubble scale at recombination $H \sim T^2/M_P$ giving $m \sim 10^{-27}$ eV and from fit one singles out $f \sim 0.2M_P$ as the preferred value[4]

We will construct our models in the context of moduli stabilisation of Type IIB String Theory.

[4] E. McDonough, M.-X. Lin, J. C. Hill, W. Hu and S. Zhou, 2022

# Useful equations

Given the superpotential $W$ and the Kähler potential $K$, in the SUGRA approximation of Type IIB we compute the scalar potential as

$$V = e^K \left( D_I W \, K^{I\bar{J}} D_{\bar{J}} \overline{W} - 3|W|^2 \right) \,, \tag{5}$$

with $D_I W = W_I + W K_I$.

Then, the gravitino mass is given by

$$m_{3/2} = e^{K/2} |W| \,. \tag{6}$$

# KKLT

Chiral field $T$ and nilpotent field $X$

$$W = W_0 + MX + Ae^{-aT}\,, \tag{7}$$

$$K = -3\ln\left(T+\bar{T}\right) + 3\frac{X\bar{X}}{T+\bar{T}}\,, \tag{8}$$

leading to

$$V_{\mathrm{KKLT}} = \frac{\mathfrak{a}^2 A^2 e^{-2\mathfrak{a}\tau}}{6\tau} + \frac{\mathfrak{a}A^2 e^{-2\mathfrak{a}\tau}}{2\tau^2} - \frac{\mathfrak{a}A|W_0|e^{-\mathfrak{a}\tau}}{2\tau^2} + \frac{M^2}{12\tau^2}\,. \tag{9}$$

Imposing a Minkowski minimum we find

$$|W_0| = \frac{2}{3} A\, \mathfrak{a}\tau\, e^{-\mathfrak{a}\tau} \left(1 + \frac{5}{2\mathfrak{a}\tau}\right) ,$$
$$M = \sqrt{2\mathfrak{a}} A\, e^{-\mathfrak{a}\tau} \sqrt{\mathfrak{a}\tau + 2} \,. \tag{10}$$

Thus, the gravitino mass is

$$m_{3/2} = \frac{A\, \mathfrak{a}}{3\sqrt{2\tau}}\, e^{-\mathfrak{a}\tau} . \tag{11}$$

# LVS

$$K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right) + \frac{\bar{X}X}{\mathcal{V}^{2/3}}\,, \tag{12}$$

having defined the volume as

Swiss-Cheese CY: $$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} \tag{13}$$

Fibrated CY: $$\mathcal{V} = \sqrt{\tau_1}\tau_2 - \tau_s^{3/2} \tag{14}$$

with chiral fields $T_k = \tau_k + i\theta_k$ ($k = b, s$ or $k = 1, 2, s$ respectively). Moreover the superpotential is

$$W = W_0 + MX + \sum_k A_k\, e^{-\mathfrak{a}_k T_k}\,, \tag{15}$$

obtaining

$$V_{\rm LVS} = \frac{8\mathfrak{a}_s^2 A_s^2 e^{-2\mathfrak{a}_s\tau_s}\sqrt{\tau_s}}{3\mathcal{V}} - \frac{4\mathfrak{a}_s A_s \tau_s |W_0|\, e^{-\mathfrak{a}_s\tau_s}}{\mathcal{V}^2} + \frac{3|W_0|^2\hat{\xi}}{4\mathcal{V}^3} + \frac{M^2}{\mathcal{V}^{4/3}}\,.$$

The potential admits a global Minkowski minimum at

$$\mathcal{V} \simeq \frac{3|W_0|\sqrt{\tau_s}}{4\mathfrak{a}_s A_s}\, e^{\mathfrak{a}_s \tau_s} \simeq |W_0|\, e^{\frac{\mathfrak{a}_s}{g_s}\left(\frac{\xi}{2}\right)^{2/3}}, \tag{16}$$

$$\tau_s = \left(\frac{\xi}{2}\right)^{2/3} \frac{1}{g_s}, \tag{17}$$

$$M^2 = \frac{27}{20} \frac{|W_0|^2}{\mathfrak{a}_s} \frac{\sqrt{\tau_s}}{\mathcal{V}^{5/3}}. \tag{18}$$

Moreover, the gravitino mass turns out to be

$$m_{3/2} = \frac{|W_0|}{\mathcal{V}} \simeq e^{-\frac{\mathfrak{a}_s}{g_s}\left(\frac{\xi}{2}\right)^{2/3}}. \tag{19}$$

# Odd axions

We define the 4-dimensional axion fields as,

$$b^a = \int_{\Sigma_a} B_2 \,, \qquad c^a = \int_{\Sigma_a} C_2 \,, \qquad \theta^\alpha = \int_{D_\alpha} C_4 \,, \tag{20}$$

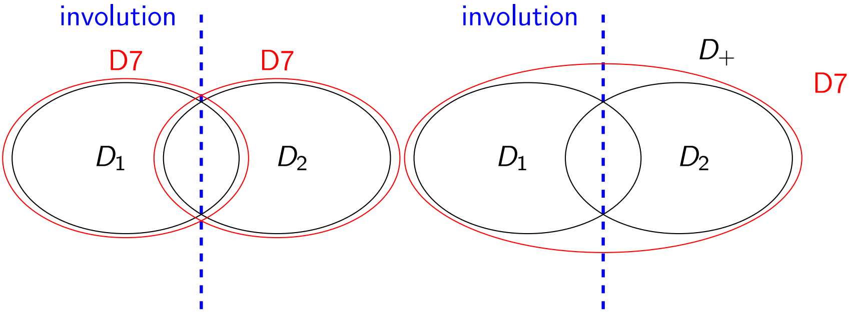
giving the chiral coordinates

$$G^a = \bar{S} b^a + \mathrm{i} c^a = \frac{b^a}{g_s} + \mathrm{i}(c^a - C_0 b^a) \,, \quad \tau_\alpha = \frac{1}{2} k_{\alpha\beta\gamma} t^\beta t^\gamma \,, \tag{21}$$

$$T_\alpha = \tau_\alpha + \mathrm{i}\theta_\alpha - \frac{1}{4} g_s k_{\alpha a b} G^a (G + \bar{G})^b \,. \tag{22}$$

In order to introduce the axions in the EFT we need non-perturbative effects.

# D7-branes




$$W_{\rm D7} = A\, e^{-\frac{2\pi}{N} f_{\rm D7}}\,, \qquad (23)$$

where $f_{\rm D7}$ reads

$$\text{D7 on } D_1: \quad f_{\rm D7} = T + k\,(\mathfrak{f}_+ + \mathfrak{f}_-)\,G + \frac{1}{2}\left(k\mathfrak{f}_-^2 + \tilde{k}\mathfrak{f}_+^2 + 2k\mathfrak{f}_+\mathfrak{f}_-\right)\bar{S}\,,$$

$$\text{D7 on } D_+: \quad f_{\rm D7} = T + k\mathfrak{f}_-\,G + \frac{1}{2}\left(k\mathfrak{f}_-^2 + \tilde{k}\mathfrak{f}_+^2\right)\bar{S}\,.$$

# ED1-instatons and gaugino condensation on D5-branes

We propose for ED1 instantons

$$K_{\mathrm{ED1}} = -3\ln\left(\mathrm{Re}\,(T) - \frac{2\gamma}{g_s^2}\,b^2 + \ldots + \sum_{\substack{n\in\mathbb{N}\\ \hat{\mathfrak{f}}_-\in\mathbb{Z}}} A_{n,\hat{\mathfrak{f}}_-}\, e^{-2\pi n\left(\frac{t}{\sqrt{g_s}}+k\hat{\mathfrak{f}}_- G\right)}\right), \tag{24}$$

with $t = \sqrt{\frac{2}{\tilde{k}}\left(\mathrm{Re}\,(T) - \frac{2\gamma}{g_s^2}\,b^2\right)}$.

Furthermore, we propose for gaugino condensation on D5-branes

$$K_{\mathrm{D5}} = -3\ln\left(\mathrm{Re}\,(T) - \frac{2\gamma}{g_s^2}\,b^2 + \ldots + \sum_{i=1}^{p} A_i\, e^{-\frac{2\pi}{N_i}\left(\frac{t}{\sqrt{g_s}}+k\mathfrak{f}_i G\right)}\right). \tag{25}$$

# EDE in KKLT

We need three contributions to construct the $(1-\cos)^3$ potential

$$K = -3\ln\left[T+\bar{T}-\gamma(G+\bar{G})^2\right]+3\,\frac{\bar{X}X}{T+\bar{T}}\,, \tag{26}$$

$$W = W_0+MX+A\,e^{-\mathfrak{a}T}+\sum_{n=1}^{3}A_n\,e^{-\tilde{\mathfrak{a}}(T+nk\mathfrak{f}\,G)}\,, \tag{27}$$

with $\mathfrak{a}=\frac{2\pi}{N}<\tilde{\mathfrak{a}}=\frac{2\pi}{M}\Leftrightarrow M<N$.

Computing we reproduce the EDE potential with the field defined as

$$\varphi=\sqrt{\frac{6\gamma}{\tau}}\,c\,, \tag{28}$$

with $\gamma=-\frac{1}{4}g_s k$, and having defined $A_1=15\,\tilde{A}/4$, $A_2=-3\,\tilde{A}/2$ and $A_3=\tilde{A}/4$.

The important quantities are

## EDE in KKLT with $C_2$ axion

$$f = \sqrt{\frac{6\,\gamma}{\tau}}\,\frac{1}{\tilde{\mathfrak{a}}|k|\mathfrak{f}} = \sqrt{\frac{3g_s}{2|k|\,\tau}}\,\frac{1}{\tilde{\mathfrak{a}}\mathfrak{f}}\,, \tag{29}$$

$$V_0 = \frac{N\,\tilde{A}}{\sqrt{2}\,\tau^{3/2}}\left(\frac{2}{M}-\frac{3}{N}\right)\left(\frac{m_{3/2}}{M_P}\right) e^{-\frac{3}{4\pi}\frac{g_s M}{|k|\mathfrak{f}^2}\left(\frac{M_P}{f}\right)^2} M_P^4\,. \tag{30}$$

Imposing $f = 0.2 M_P$, $V_0 \sim \mathrm{eV}^4$ and $m_{3/2} > \mathrm{TeV}$

| $g_s$ | $\tilde{A}$ | $M$ | $N$ | $\tau$ | $V_0\,10^{108}\,M_P^{-4}$ | $m_{3/2}$ (TeV) | $m_\tau$ (TeV) |
|---|---|---|---|---|---|---|---|
| 0.1 | 1 | 340 | 3200 | 10980.7 | 1.4 | 4.6 | 155.5 |
| 0.3 | 1 | 114 | 1000 | 3703.4 | 2.0 | 4.6 | 155.2 |
| 0.3 | $10^{-11}$ | 100 | 750 | 2849.7 | 1.6 | 3.8 | 129.6 |
| 0.3 | $10^{-27}$ | 80 | 470 | 1823.8 | 0.9 | 4.6 | 154.8 |
| 0.3 | $10^{-61}$ | 36 | 85 | 369.3 | 2.2 | 3.0 | 104.0 |

Ranks of the condensing gauge group are too high.

# EDE in LVS: $C_4$ axion

Taking a Swiss-Cheese CY we have

$$K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right) + \frac{\bar{X}X}{\mathcal{V}^{2/3}}\,, \tag{31}$$

$$W = W_0 + MX + A_s\, e^{-\mathfrak{a}_s T_s} + \sum_{n=1}^{3} A_n\, e^{-n\,\mathfrak{a} T_b}\,, \tag{32}$$

with $\mathfrak{a}_s = 2\pi/N_s$ and $\mathfrak{a} = 2\pi/N_b$.

We reproduce the EDE potential with the field

$$\varphi = \sqrt{\frac{3}{2}}\frac{\theta_b}{\tau_b}\,, \tag{33}$$

and introduced $A_1 = 15\,A_b/4$, $A_2 = -3\,A_b/2$ and $A_3 = A_b/4$.

## EDE in LVS with $C_4$ axion

$$f = \sqrt{\frac{3}{2}} \frac{1}{\mathfrak{a}_b \tau_b} \simeq 0.2 \frac{N_b}{\tau_b} \qquad \text{for} \qquad \mathfrak{a}_b = \frac{2\pi}{N_b}\,, \tag{34}$$

$$V_0 = \frac{64\pi^3}{3} \left( \frac{|W_0|\, A_b}{N_b^3} \right) \left( \frac{f}{M_P} \right)^2 M_P^4\, e^{-\sqrt{\frac{3}{2}}\frac{M_P}{f}}\,. \tag{35}$$

This model requires an heavy fine tuning

| $N_b$ | $N_s$ | $\tau_b$ | $\lvert W_0 \rvert$ | $A_b$ | $A_s$ | $V_0\, 10^{108}\, M_P^{-4}$ |
|---|---|---|---|---|---|---|
| 100 | 3 | 97.5 | $6.0 \times 10^{-10}$ | $5 \times 10^{-92}$ | 0.29 | 1.8 |
| 1000 | 4 | 974.6 | $1.1 \times 10^{-7}$ | $2 \times 10^{-91}$ | 0.28 | 1.3 |

Similar (fine-tuned) results for a fibrated CY.

# EDE in LVS: $C_2$ axion

First model: gaugino condensation on D7-branes (Swiss-Cheese CY)

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} = \frac{1}{2\sqrt{2}}\left[\left(T_b + \bar{T}_b - \gamma(G+\bar{G})^2\right)^{3/2} - \left(T_s + \bar{T}_s\right)^{3/2}\right],$$

with

$$K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right) + \frac{\bar{X}X}{\mathcal{V}^{2/3}}, \tag{36}$$

$$W = W_{\mathrm{LVS}} + \sum_{n=1}^{3} A_n\, e^{-\tilde{\mathfrak{a}}(T_b + nk\mathfrak{f}G)}. \tag{37}$$

We reproduce the EDE potential with the field

$$\varphi = \sqrt{\frac{6\gamma}{\tau_b}}\, c\,. \tag{38}$$

## EDE in LVS with $C_2$ axion: D7 gaugino condensation

$$f = \frac{1}{\tilde{\mathfrak{a}}|k|\mathfrak{f}}\sqrt{\frac{6\gamma}{\tau_b}} = \sqrt{\frac{3g_s}{8\pi^2|k|\mathfrak{f}^2}}\frac{M}{\sqrt{\tau_b}} \qquad \text{for} \qquad \tilde{\mathfrak{a}} = \frac{2\pi}{M}\,, \tag{39}$$

$$V_0 = \frac{16(2\pi)^5|k|^2\mathfrak{f}^4}{9g_s^2M^5}|W_0|\,\tilde{A}\left(\frac{f}{M_P}\right)^4 e^{-\frac{3}{4\pi}\frac{g_sM}{|k|\mathfrak{f}^2}\left(\frac{M_P}{f}\right)^2} M_P^4\,. \tag{40}$$

Setting $\tilde{A}=1$ we get

| $g_s$ | $N_s$ | $M$ | $\lvert W_0\rvert$ | $\mathcal{V}=\tau_b^{3/2}$ | $V_0\,10^{108}\,M_P^{-4}$ | $A_s$ | $m_{\mathcal{V}}$ (TeV) |
|---|---|---|---|---|---|---|---|
| 0.3 | 1 | 128 | 1 | $3.2\times10^5$ | 2.6 | 1.70 | $3.2\times10^7$ |
| 0.3 | 1/2 | 121 | $2.8\times10^{-6}$ | $2.7\times10^5$ | 2.7 | 1.51 | 50 |
| 0.1 | 2 | 362 | $3.3\times10^{-5}$ | $1.4\times10^6$ | 2.2 | 2.96 | 50 |

Similar results for a fibred CY.

Second model: gaugino condensation on D5-branes.
One takes standard Swiss-Cheese LVS with substitution

$$\tau_b \to \tau_b - \gamma\left(G + \bar{G}\right)^2 + e^{-\tilde{\mathfrak{a}} t_b/\sqrt{g_s}} \sum_{n=1}^{3} A_n \,\mathrm{Re}\left[e^{-n\tilde{\mathfrak{a}} k \mathfrak{f} G}\right], \qquad (41)$$

reproducing again the EDE potential with axion field

$$\varphi = \sqrt{\frac{6\gamma}{\tau_b}}\, c\,. \qquad (42)$$

**EDE in LVS with $C_2$ axion: D5 gaugino condensation**

$$f = \frac{1}{\tilde{\mathfrak{a}}\mathfrak{f}}\sqrt{\frac{3g_s}{2|k|\tau_b}} = \frac{1}{\mathfrak{f}}\sqrt{\frac{3g_s}{8\pi^2|k|}}\frac{M}{\sqrt{\tau_b}}\,, \tag{43}$$

$$V_0 = \frac{3\tilde{A}\,|W_0|^2\tilde{\mathfrak{a}}^2}{2g_s^2\mathcal{V}^2}\,e^{-\frac{1}{\mathfrak{f}}\sqrt{\frac{3}{\tilde{k}|k|}}\left(\frac{M_P}{f}\right)}M_P^4\,. \tag{44}$$

Imposing the right values of $f$ and $V_0$ we find the necessity of an exponentially small fine tuning of $\tilde{A}$.

# Conclusions

Best model:

**LVS with $C_2$ axion from D7 gaugino condensation**

**Achievements**

- Controlled de Sitter moduli stabilization
- Decoupling of non-EDE modes
- Absence of fine-tuning
- Explicit Calabi-Yau realization

**Outlooks**

- Gravitational Waves from coupling with gauge[5]
- Incorporate with Inflation and/or Dark Matter

[5] Z. J. Weiner, P. Adshead and J. T. Giblin,,2021

*Thanks for the attention!*