String theory realisations of early dark energy

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Outline

Part I. Early dark energy

Hubble tension. 5σ disagreement:

$H_0 = 67.37 \pm 0.54$ (km/s)/Mpc *Planck CMB inference*[1]
$H_0 = 73.04 \pm 1.04$ (km/s)/Mpc *SH0ES cosmic distance ladder measurement*[2]

$$
\begin{aligned}
&H(t) = \frac{\dot{a}(t)}{a(t)}\,, \qquad 1 + z(t) = \frac{a(t_0)}{a(t)}\,, \qquad a : \text{scale factor}\,, \\
&H(z) = H_0\sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\mathrm{rad}(1+z)^4 + \Omega_\Lambda + \cdots}\,, \\
&\cdots : \text{additional components} \notin \Lambda\text{CDM}\,.
\end{aligned}
\tag{1}
$$

t_0: present epoch, $\quad H_0 = H(t_0)\,, \quad z(t_0) = 0\,.$

[1] Planck collaboration, 2018
[2] Using type Ia supernovae, A. G. Riess et al., 2021

Early dark energy

Planck measures: $100\theta_s = 1.0411 \pm 0.0003$

$$\theta_s = \frac{r_s(z_*)}{D_A(z_*)}\,, \quad r_s(z_*) = \int_{z_*}^{z_{\rm rh}} \frac{dz\ c_s(z)}{H(z)}\,, \quad D_A(z_*) = \int_0^{z_*} \frac{dz}{H(z)}\,. \qquad (2)$$

$z_{\rm rh}$: reheating after cosmic inflation , $z_* \approx 1100$: last scattering ,
c_s : sound speed in photon-baryon plasma .

r_s: comoving sound horizon at last scattering
D_A sensitive to H_0: comov. distance from an obs. to last scatter. surface

10% increment in $H_0 \implies$ decrement in D_A .

To keep θ_s fixed, we need to decrease r_s . Increase $H(z)$ for $z \gtrsim z_*$.

EDE proposal. An ultralight scalar: at early times i.e. $z \gtrsim z_{\rm eq} \approx 3000$, behaves as cosmological constant, and at later times, dilutes away like radiation or faster[3]

Dynamics:
$$\ddot{\phi} + 3H\dot{\phi} + V' = 0 \,. \tag{3}$$

At early times, frozen by Hubble drag term. Later, decays when $H^2 \sim V''$.

Best fitted potential:
$$\begin{aligned} V(\phi) &= V_0\left[1 - \cos(\frac{\phi}{f})\right]^3 \\ &= V_0\left[\frac{5}{2} - \frac{15}{4}\cos(\frac{\phi}{f}) + \frac{3}{2}\cos(\frac{2\phi}{f}) - \frac{1}{4}\cos(\frac{3\phi}{f})\right], \end{aligned} \tag{4}$$

with $V_0 = m^2 f^2$.

[3] V. Poulin, T.L. Smith, T. Karwal and M. Kamionkowski, 2018

Early dark energy

Best fitted values: $m \sim 10^{-27}\text{eV}\,, \quad f \sim 0.2 M_P\,, \quad V_0 \sim \text{eV}^4\,,$ (5)

$M_P = 2.4 \times 10^{18}\text{GeV}$: reduced Planck mass .

E. McDonough, M.-X. Lin, J. C. Hill, W. Hu, S. Zhou, 2021

At matter-radiation equality, $T \sim \text{eV}$, $H \sim \frac{T^2}{M_P}$. EDE field decays.

For unaltered post-CMB physics, EDE field should decay before e^-, p^+ recombination. Yet, to have sizeable effect on r_s, it should decay only shortly before recombination.

We aim at realisation of EDE potential $V(\phi)$ with the EDE field identified as either a C_4 or C_2 axion in type IIB string theory within framework of KKLT or LVS.[4]

[4] Extending the attempt in E. McDonough and M. Scalisi, 2022.

Part II. Elements from type IIB string compactifications

Given W : superpotential, K : Kähler potential, in SUGRA approx. of type IIB string compactification we compute scalar potential as

$$V = e^K \left(D_I W \ K^{I\bar{J}} D_{\bar{J}} \overline{W} - 3|W|^2 \right) , \tag{6}$$

I labels chiral superfields. $D_I W \equiv \partial_I W + W \partial_I K$, $K^{I\bar{J}} \equiv (\partial_I \partial_{\bar{J}} K)^{-1}$.

Gravitino mass: $$m_{3/2} = e^{K/2} |W| . \tag{7}$$

W depends only on chiral fields, K depends on chiral and anti-chiral fields.

KKLT[5]

Chiral fields: $T = \tau + i\theta$ (Kähler modulus), X (nilpotent superfield)

$$W = W_0 + MX + A\, e^{-\mathfrak{a} T}\,, \qquad K = -3\ln(T+\bar{T}) + 3\,\frac{X\bar{X}}{T+\bar{T}}\,. \tag{8}$$

Compute scalar potential, then set $X = 0$:

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

With a choice: $W_0 = -|W_0|, A > 0$, axion minimum: $\theta = 0$.

[5] S. Kachru, R.a Kallosh, A. Linde and S. P. Trivedi, 2003

KKLT

Minkowski minimum i.e. $\partial V = V = 0$:

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

Gravitino mass:

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

Large Volume Scenario (LVS)

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

Volume is given by

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

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

Kähler moduli: $T_k = \tau_k + i\theta_k$, $k = b, s$, or $k = 1, 2, s$. & superpotential

$$W = W_0 + MX + \sum\nolimits_k A_k e^{-\mathfrak{a}_k T_k}. \tag{15}$$

$$V_{\rm LVS}(\mathcal{V}, \tau_s, \theta_s) = \frac{8\mathfrak{a}_s^2 A_s^2 e^{-2\mathfrak{a}_s\tau_s}\sqrt{\tau_s}}{3\mathcal{V}} - \frac{4\mathfrak{a}_s A_s \tau_s |W_0|\, e^{-\mathfrak{a}_s\tau_s}}{\mathcal{V}^2}\cos(\mathfrak{a}_s\theta_s) + \frac{3|W_0|^2\hat{\xi}}{4\mathcal{V}^3} + \frac{M^2}{\mathcal{V}^{4/3}}. \tag{16}$$

Plus, subleading potential(s) stabilising axion(s) θ_b or θ_1, θ_2

LVS[6]

Minkowski minimum i.e. $\partial V = V = 0$:

$$\begin{aligned} \mathcal{V} &\simeq \frac{3|W_0|\sqrt{\tau_s}}{4\mathfrak{a}_s A_s}\, e^{\mathfrak{a}_s \tau_s} \simeq |W_0|\, e^{\frac{\mathfrak{a}_s}{g_s}\left(\frac{\xi}{2}\right)^{2/3}}\,, \\ \tau_s &= \left(\frac{\xi}{2}\right)^{2/3} \frac{1}{g_s}\,, \\ M^2 &= \frac{27}{20}\frac{|W_0|^2}{\mathfrak{a}_s}\frac{\sqrt{\tau_s}}{\mathcal{V}^{5/3}}\,. \end{aligned} \tag{17}$$

Gravitino mass:

$$m_{3/2} = \frac{|W_0|}{\mathcal{V}} \simeq e^{-\frac{\mathfrak{a}_s}{g_s}\left(\frac{\xi}{2}\right)^{2/3}}\,. \tag{18}$$

[6] V. Balasubramanian, P. Berglund, J.P. Conlon and F. Quevedo (2005); M. Cicoli, J.P. Conlon and F. Quevedo (2008)

Odd axions

NS-NS: B_2 potential, R-R: C_0, C_2, C_4 potentials.
4-dim. axion fields:

$$\text{odd:} \quad b^a = \int_{\Sigma_a} B_2\,, \qquad c^a = \int_{\Sigma_a} C_2\,, \qquad a = 1, \ldots, h_-^{1,1} \tag{19}$$

$$\text{even:} \quad \theta^\alpha = \int_{D_\alpha} C_4\,, \qquad \alpha = 1, \ldots, h_+^{1,1}\,. \tag{20}$$

Σ_a, D_α : bases for 2-cycles and 4- cycles, $h^{1,1} = h_+^{1,1} + h_-^{1,1}$: # of (1,1)-forms.

Combining,

$$\text{odd moduli:} \quad G^a = \bar{S} b^a + i c^a = \frac{b^a}{g_s} + i(c^a - C_0 b^a)\,, \tag{21}$$

$$\text{moduli:} \quad T_\alpha = \tau_\alpha + i\theta_\alpha - \frac{1}{4} g_s k_{\alpha ab} G^a (G^b + \bar{G}^b)\,, \quad \tau_\alpha = \frac{1}{2} k_{\alpha\beta\gamma} t^\beta t^\gamma\,.$$

t^α : Kähler form $J = t^\alpha \hat{D}_\alpha$, $\hat{D}_\alpha \in H_+^{1,1}$; k: intersection numbers.

Non-perturbative effects: ~~axion shift symmetries~~

Simple case. $h^{1,1} = 2, h^{1,1}_{\pm} = 1$. D_1, D_2 : divisors, related by orientifold involution . $D_+ = D_1 \cup D_2, D_- = D_1 \cup (-D_2)$: even & odd 4-cycles .

Kähler modulus:
$$T = \tau + i\theta - \frac{1}{4} g_s k G (G + \bar{G}) . \tag{22}$$

Gaugino condensation on D7-branes. Gauge theory lives on a stack of N D7-branes. Allow 2-form flux: $F_2 = \mathfrak{f}_+ \hat{D}_+ + \mathfrak{f}_- \hat{D}_-$.

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

D7 wrap D_+ : $$f_{\rm D7} = T + k\mathfrak{f}_-\, G + \frac{1}{2}(k\mathfrak{f}_-^2 + \tilde{k}\mathfrak{f}_+^2)\bar{S} , \tag{24}$$

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

ED1 instantons and gaugino condensation on D5-branes

ED1/D5-branes wrapped on an internal 2-cycle t with non-zero odd gauge flux.

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

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

... : some corrections involving α', g_s, but not axions. And,

$$t = \sqrt{\frac{2}{\tilde{k}}\left(\Re(T) - \frac{2\gamma}{g_s^2}\,b^2\right)}. \tag{26}$$

Part III. EDE models in KKLT and LVS

EDE in KKLT. Gaugino condensation on 4 stacks of D7-branes wrapping same cycle. 1 unfluxed stack of N D7, 3 differently fluxed stacks each of M D7 branes.

$$K = -3\ln\left[T + \bar{T} - \gamma(G+\bar{G})^2\right] + 3\,\frac{\bar{X}X}{T+\bar{T}}\,,$$
$$W = W_0 + MX + A\,e^{-\mathfrak{a}T} + \sum_{n=1}^{3} A_n\,e^{-\tilde{\mathfrak{a}}(T+nk\mathfrak{f}\,G)}\,, \quad (27)$$
$$\mathfrak{a} = \frac{2\pi}{N} < \tilde{\mathfrak{a}} = \frac{2\pi}{M} \quad \Leftrightarrow \quad M < N \quad \textit{(to ensure natural suppression of EDE scale w.r.t. std. KKLT potential)}\,.$$

Give rise to, $V = V_{\rm KKLT} + V_{\rm EDE}$ with EDE field identified as canonically normalised C_2 axion

$$\phi = \sqrt{\frac{6\gamma}{\tau}}\,c\,, \qquad \gamma \equiv -\frac{1}{4}g_s k\,, \quad (28)$$

when we set $A_1 = 15\,\tilde{A}/4$, $A_2 = -3\,\tilde{A}/2$ and $A_3 = \tilde{A}/4$.

EDE (as C_2 axion) in KKLT

EDE decay constant and energy scale @ Minkowski min. of KKLT,

$$f \equiv \sqrt{\frac{6\,\gamma}{\tau}}\,\frac{1}{\tilde{\mathfrak{a}}|k|\mathfrak{f}} = \sqrt{\frac{3g_s}{2|k|\,\tau}}\frac{M}{2\pi\mathfrak{f}}\,,$$
$$V_0 = \frac{N\,\tilde{A}}{\sqrt{2}\,\tau^{3/2}}\left(\frac{2}{M}-\frac{3}{N}\right)\left(\frac{m_{3/2}}{M_P}\right)\,e^{-\frac{3}{4\pi}\frac{g_s M}{|k|\mathfrak{f}^2}\left(\frac{M_P}{f}\right)^2}\,M_P^4\,. \tag{29}$$

With $f = 0.2M_P$, $\mathfrak{f} = |k| = 1$, to keep $g_s \lesssim 0.3$, $V_0 \sim 100^{-108}\,M_P^4$, $m_{3/2} >$ TeV:

g_s	$\tilde{A}$	M	N	τ	$V_0\,10^{108}\,M_P^{-4}$	$m_{3/2}$ (TeV)	m_τ (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 condensing gauge groups are likely too high for D7 tadpole cancellation!

EDE in LVS: C_2 axion

Swiss-Cheese CY, $h^{1,1}_+ = 2, h^{1,1}_- = 1$. Orientifold-odd modulus mixes only with big modulus. Gaugino condensation on fluxed stack of M D7-branes wrapping big divisor .

$$\mathcal{V} = \tau_b^{\frac{3}{2}} - \tau_s^{\frac{3}{2}} = \frac{1}{2^{3/2}}\left[\left(T_b + \bar{T}_b - \gamma(G+\bar{G})^2\right)^{\frac{3}{2}} - \left(T_s + \bar{T}_s\right)^{\frac{3}{2}}\right], \qquad (30)$$

$$K = -2\ln(\mathcal{V} + \frac{\hat{\xi}}{2}) + \frac{\bar{X}X}{\mathcal{V}^{\frac{2}{3}}}, \; W = W_{\rm LVS} + \sum_{n=1}^{3} A_n e^{-\tilde{\mathfrak{a}}(T_b + nk\mathfrak{f}G)}, \; \tilde{\mathfrak{a}} = \frac{2\pi}{M}.$$

Give rise to, $V = V_{\rm LVS}(\mathcal{V}, \tau_s, \theta_s) + V_b(\theta_b, b) + V_{\rm EDE}(c)$. Set $A_1 = 15\,\tilde{A}/4$, $A_2 = -3\,\tilde{A}/2$ and $A_3 = \tilde{A}/4$. Identify EDE field ϕ with canonically normalised C_2 axion c .

EDE (as C_2 axion) in LVS

EDE decay constant and energy scale,

$$
\begin{aligned}
f &= \sqrt{\frac{3g_s}{2|k|\tau_b}\,\frac{M}{2\pi\mathfrak{f}}}\,, \\
V_0 &= \frac{16(2\pi)^5|k|^2\mathfrak{f}^4}{9g_s^2M^5}|W_0|\,\tilde{A}\left(\frac{f}{M_P}\right)^4 e^{-\frac{3}{4\pi}\frac{g_s M}{|k|\mathfrak{f}^2}\left(\frac{M_P}{f}\right)^2} M_P^4\,.
\end{aligned}
\tag{31}
$$

With $f = 0.2M_P$, $\tilde{A} = 1$, $\mathfrak{f} = |k| = 1$, $\tau_s \sim \mathcal{O}(1-10)$:

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	3.2×10^5	2.6	1.70	3.2×10^7
0.3	1/2	121	2.8×10^{-6}	2.7×10^5	2.7	1.51	50
0.1	2	362	3.3×10^{-5}	1.4×10^6	2.2	2.96	50

Correct EDE scale without tuning $\tilde{A}$. $M \sim \mathcal{O}(100)$ is realisable. Similar results for fibred CY.

Other studied models

- EDE as C_2 axion in LVS, realised using non-perturbative corrections to Kähler potential K arising from ED1-instantons/gaugino condensation on D5-branes. To get correct EDE scale and decay constant, require fine tuning: exponentially small $\tilde{A}$.

- EDE as C_4 axion in LVS, realised using non-perturbative corrections $\supset \sum_{n=1}^{3} A_n e^{n a_b T_b}$, to superpotential W, arising from gaugino condensation on *unfluxed* stacks of D7-branes. This requires a double fine tuning in coefficients $A_n = A_b \tilde{A}_n$: exponentially small A_b & exponential hierarchy among $\tilde{A}_n$, $n = 1, \ldots, 3$.

Conclusion & outlook

Conclusions.

- Several working models for EDE in type IIB string theory.
- Most promising candidates: C_2 axions in LVS with 3 non-perturbative corrections to the W generated by gaugino condensation on D7-branes with non-zero world-volume fluxes.

Outlook.

- Explicit CY realisation (a rigorous description of underlying CY threefold, orientifold involution & brane setup in a way compatible with tadpole cancellation) with all the features outlined by us.
- Incorporate with (fiber)inflation and/or (fuzzy)dark matter.

Thanks for your attention!