Dark Energy in String Theory

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String Phenomenology
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based on work with
Yessenia Olguín-Trejo, Gianmassimo Tasinato and Ivonne Zavala
Dark Energy

- So far, observational constraints on Dark Energy are consistent with a tiny Cosmological Constant:

\[ \langle V \rangle_0 = 7 \times 10^{-121} M_{pl}^4 \quad \text{and} \quad w_0 = -1.028 \pm 0.032 \]

Planck '18
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- Growing tension between direct measurements of \( H_0 \) and CMB fit using \( \Lambda CDM \):

4.4 \( \sigma \) discrepancy...

\textit{early dark energy, } \( N_{\text{eff}}, \) \textit{phantom DE, fading dark matter...?}

Kawal & Kamionkowski ’16; Calabrese, Huterer, Linde, Melchiott & Pagano ’11; Planck ’15; Agrawal, Obied & Vafa ’19; ...
Plan

- dS string vacua and the dS swampland conjecture
- No-go for simplest models of quintessence from a runaway string modulus
- An alternative to dS and quintessence?
dS vacua in String Theory

- In string models of DE, we typically look for compactification to 4D dS with moduli potential $\langle V(\phi^i) \rangle > 0$. 

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We have long known that this would be hard:

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    Dine & Seiberg ’85

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    \[
    \frac{|\nabla V|}{V} \geq \sqrt{\frac{54}{13}}
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    Hertzberg, Kachru & Taylor ’07

- Over the last two decades technical progress in understanding string compactifications and moduli stabilisation has brought us close to concrete de Sitter vacua from string theory

  for reviews from different perspective see Cicoli, de Alwis, Maharana Muia & Quevedo ’18; Danielsson & van Riet ’18
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dS achieved by some fine-tuned combination of perturbative and non-perturbative corrections and localised sources.

starting with Kachru, Kallosh, Linde & Trivedi ’03
Scalar potential constrained by target-space modular-invariance:

\[
K = -\log(S + \bar{S}) - \sum_{j} \log(\phi_j + \bar{\phi}_j) + |A_\alpha|^2 \prod_{j} (\phi_j + \bar{\phi}_j)^{n^{\beta}_{\alpha}}.
\]

\[
W_{gc} \approx \sum_{a} d_a \exp\left(\frac{24\pi^2}{b_a^0} f_a\right) \quad \text{with} \quad f_a = k_a S + \Delta^{Md}_{a}(T_i) + \Delta^{Ms}_{a}(T_i, U_m).
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dS Vacua in Heterotic Orbifolds

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for top-down models many dS vacua found... all with tachyonic instabilities

for string scenarios towards metastable dS see Anderson, Gray, Lukas & Ovrut '11; Cicoli, de Alwis & Westphal '13
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For metastable dS we have 21 conditions for 10 moduli and 4 free parameters.
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For metastable dS we have 21 conditions for 10 moduli and 4 free parameters.

Consider modular invariant toy model \( K = - \ln(S + \bar{S}) - 3 \ln(T + \bar{T}) \)

\[
W = \frac{A_1 e^{-a_1 S} + A_2 e^{-a_2 S}}{\eta(T)^p} + \frac{B_1 e^{-b_1 S} + B_2 e^{-b_2 S}}{\eta(T)^q} + C e^{cT}.
\]

with 11 conditions for 4 moduli and 12 parameters... still only find unstable dS...

see also Gonzalo, Ibañez & Uranga '19

but also Blaback, Roest & Zavala '13 and Kallosh, Linde, Vercnocke & Wrase '14
**dS Swampland Conjecture**

What if string theory has no de Sitter vacua? *may be fruitful question even if metastable dS constructions prove to be robust...*

Danielsson & Van Riet '18

**Conjecture:** The scalar potential in the LEEFT of any consistent quantum gravity must satisfy either:

\[
\sqrt{\nabla^i \nabla_j V} \geq \frac{c}{M_{pl}} V
\]

or:

\[
\min(\nabla^i \nabla_j) V \leq -\frac{c'}{M_{pl}^2} V
\]

for some universal constants \( c, c' > 0 \) of order 1.

Rules out metastable dS, allows sufficiently unstable dS.

Obied, Ooguri, Spodyneiko & Vafa '18
Garg & Krishnan '18
Ooguri, Palti, Shiu & Vafa '18
for possible generalisation see Gautason, Van Hemelryck & Van Riet '18 and Lüst, Palti & Vafa '19
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Heterotic dS vacua above satisfy conjecture with \(c, c' = 1\).
Implications for Dark Energy

Dark energy may be quintessence field:

\[ V(\phi) \]

- Cosmological Constant
- Dynamical Dark Energy

Figure from Palti’s recent review
Implications for Dark Energy

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\[ \phi \]

Cosmological Constant

Dynamical Dark Energy

Assuming convex potential, current observations on \( w(z) \) constrain \( c \) in \( |\nabla V| M_{pl} > cV \) to \( c \lesssim 0.6 \)

Can string theory give \( c \lesssim 0.6 \)?
Implications for Dark Energy

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Assuming convex potential, current observations on \( w(z) \) constrain \( c \) in \( |\nabla V| M_{pl} > cV \) to \( c \lesssim 0.6 \)

Can string theory give \( c \lesssim 0.6? \) \( V(\phi) \) is not typically \( V \sim C e^{-c\phi} \) ...
String Models of Quintessence

Quintessence – a slowly-rolling ultra-light string modulus with:

\[ \langle V \rangle \approx 10^{-120} M_{pl}^4 \quad \text{and} \quad m \lesssim 10^{-32} \text{eV} \]
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Challenges:

- two fine-tuning problems
- fifth forces
- time variation of fundamental constants
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String candidates:

- axion - need large \( f_a \) or hilltop fine-tuning of initial conditions

- local string modulus - \( \Delta \phi \gtrsim M_{pl} \) ? sequestering?

See Cicoli, de Alwis, Maharan, Muia & Quevedo ’18 for a review.

Berg, Marsh, McAllister & Pajer ’10
Cicoli, Pedro & Tasinato ’12
Acharya, Maharana, Muia ’18
Heckman & Vafa ’19
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Most constructions have similar ingredients and challenges to dS constructions.
String Models of Quintessence

Choi '99 "String or M theory axion as quintessence"
Albrecht, Burgess, Ravndal & Skordis '01 "Natural quintessence and LEDs"
Hellerman, Kaloper & Susskind '01 "String theory and quintessence"
Kaloper & Sorbo '08 "Where in the string landscape is quintessence"
Panda, Sumitomo & Trivedi '10 "Axions as quintessence in string theory"
Cicoli, Pedro & Tasinato '12 "Natural quintessence in string theory"
Blabäck, Danielsson & Dubitetto '14 "Accelerated Universes from type IIA"
Cicoli, de Alwis, Maharana Muia & Quevedo '18 "dS vs quintessence in string theory"
Acharya, Maharana, Muia '18 "Hidden sectors, kinetic mixings, 5th forces and quintessence"
Emelin & Tatar '18 "Axion hilltops, Kahler modulus quintessence and the swampland criteria"
D'Amico, Kaloper & Lawrence '18 "Strongly coupled quintessence"
Hertzberg, Sandora & Trodden '19 "Quantum fine-tuning in stringy quintessence models"

Shout if I missed your favourite model!
Assume early Universe scenario (e.g. inflation) that ends in susy Minkowski with most moduli stabilised and heavy:

\[ \langle D_i W_{\text{susy}} \rangle = 0, \quad \langle W_{\text{susy}} \rangle = 0, \quad \langle \Phi^i \rangle \text{ heavy} \]
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- Assume a single flat direction (for simplicity):

\[ \Phi = \phi + i\theta \]

with \( \phi \) a string coupling constant – saxion – and \( \theta \) its axion.

\[ K = -n \ln(\Phi + \bar{\Phi}) \]

e.g. \( n = 3 \) for overall volume modulus, \( n = 1 \) for other volumes, complex structure, dilaton (easily extend to e.g. blow-up moduli)
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- \( K \) does receive perturbative corrections, but so long as \( W = 0 \) this will not lift flat direction.
Runaway String Modulus

- $W$ receives non-perturbative corrections at some scale, say, before BBN:

$$W_{np} = Ae^{-\alpha \Phi} \text{ at leading order}$$

e.g. by worldsheet instantons, gaugino condensation in bulk or brane, Euclidean D-branes, ...
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- $A$ and $\alpha$ are model dependent constants – $A$ may be itself exponentially suppressed in heavy moduli vevs, e.g. gaugino condensation with 1-loop threshold corrections:

$$W_{gc} = \mu^2 e^{-\alpha f} \text{ with } f = \Phi + \sum_i c_i \ln(d_i \Phi_i)$$
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- Scalar potential for saxion:

$$V = \frac{A^2}{2^n n} e^{-2\alpha \phi} \phi^{-n} \left(n^2 + 4\alpha^2 \phi^2 + n(-3 + 4\alpha \phi)\right)$$

with axion flat direction at leading order.
Runaway modulus with dS maximum

\[ V(\phi) \text{ for } K = -n \log(\Phi + \bar{\Phi}) \text{ and } W = Ae^{-\alpha \Phi} \]
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- Starting from susy Minkowski – well under control – corrections from \( K_p \) and \( W_{np\ sub} \) suppressed for small coupling constant
- For \( n = 1 \) dS maximum at \( \phi_{max} = \frac{1}{\sqrt{2\alpha}} \)
- Giving up dS minimum – no fine tuning of perturbative and non-perturbative corrections against each other
Runaway modulus with dS maximum

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Susy breaking in visible sector... discuss later.
Quintessence from a runaway modulus

- Cosmological eqns in a FRW bkgd:

\[ 3M_{pl}^2 H^2 = \frac{M_{pl}^2 \dot{\phi}^2}{2} + V + 3M_{pl}^2 H_0^2 \Omega_M a(t)^{-3} + 3M_{pl}^2 H_0^2 \Omega_r a(t)^{-4} \]

\[ 0 = \ddot{\phi} + 3H \dot{\phi} + \Gamma_{ab}^{\phi} \dot{\phi}^a \dot{\phi}^b + M_{pl}^{-2} g^{\phi b} \frac{\partial V}{\partial \phi^b} \]
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- For a slowly rolling \( \phi \) we need \( \frac{1}{2} \dot{\phi}^2 \ll V \Rightarrow \)

\[ \epsilon_{sr} \equiv \frac{|\nabla V(\phi)|^2}{V(\phi)} \ll M_{pl}^2 H^2 \]

Along tail \( \epsilon_{sr} \rightarrow e^{-2\alpha \phi} 16A^2 \alpha^4 \phi^3 \rightarrow 0 \) as \( \phi \rightarrow \infty \), so field easily frozen by \( H \) sourcing a c.c..
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- For late time domination \( V \sim 3M_{pl}^2 H^2 \Rightarrow \):

\[
\epsilon_q \equiv 3 \frac{|\nabla V(\phi)|^2}{V(\phi)^2} \ll 1
\]

Along tail \( \epsilon_q \to 24 \alpha^2 \phi^2 \to \infty \) as \( \phi \to \infty \), so we cannot source quintessence along runaway tail.
Near hilltop we have a viable frozen or thawing quintessence model consistent with dS swampland conjecture and distance conjecture but fine-tuned initial conditions with no anthropic explanation...

Cosmological evolution for $A = e^{-138.122}$ and $\alpha = \sqrt{2}$
Thawing Quintessence at the Hilltop

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Suppose \( \phi \) is in thermal equilibrium with a thermal bath where some masses \( M \) go as \( \langle \phi \rangle \).

For \( T \gg m \) vev is shifted from \( \phi_0 \) to \( \phi = 0 \) ⇒ vacuum energy:

\[ V_{\text{vac}}(0) = \frac{1}{2} m^2 \phi_0^2 \]

E.g. for \( T_{\text{hid}} \sim 2 \times 10^{-4} \) eV, \( m \sim 1 \times 10^{-4} \) eV and \( \phi_0 \sim 10^{2} \) eV we would have \( V_{\text{vac}} \sim (10^{-3} \text{ eV})^4 \).

DE with \( w = -1 \) consistent with swampland conjectures...
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For \( T \gg M \) finite temperature effects contribute to potential:

\[ V_{tot}(\phi) = \frac{1}{2} m^2 (\phi - \phi_0)^2 + bT^2 \phi^2 \]
Thermal Dark Energy

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For \( T \gg m \) vev is shifted from \( \phi_0 \) to \( \phi = 0 \) ⇒ vacuum energy:

\[ V_{\text{vac}}(0) = \frac{1}{2}m^2\phi_0^2 \]

E.g. for \( T^{\text{hid}} \sim 2.5 \times 10^{-4}\text{eV} \), \( m \sim 1 \times 10^{-4}\text{eV} \) and \( \phi_0 \sim 10^2\text{eV} \) and we would have \( V_{\text{vac}} \sim (10^{-3}\text{eV})^4 \).
Consider a hidden sector including a light scalar field with non-vanishing vev in Minkowski vacuum:

\[ V(\phi) = \frac{1}{2} m^2 (\phi - \phi_0)^2 \]

Suppose \( \phi \) is in thermal equilibrium with a thermal bath where some masses \( M \) go as \( \langle \phi \rangle \).

For \( T \gg M \) finite temperature effects contribute to potential:

\[ V_{\text{tot}}(\phi) = \frac{1}{2} m^2 (\phi - \phi_0)^2 + bT^2 \phi^2 \]

For \( T \gg m \) vev is shifted from \( \phi_0 \) to \( \phi = 0 \) \( \Rightarrow \) vacuum energy:

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DE with \( w = -1 \) consistent with swampland conjectures? ...
Existence or not of metastable dS vacuum in string theory remains an open question, though we’ve long known it would be hard and progress has been made.

Very few candidates for quintessence in string theory - usually in tension with Swampland constraints and/or have control issues.

The simplest string runaway moduli do not source quintessence.

Hilltop in runaway potential – and hilltop axions – can source frozen/thawing quintessence consistently with observations and swampland conjectures, but need finely tuned initial conditions.

Can a hidden dark sector with finite temperature effects explain Dark Energy with $w = -1$ without need for dS vacuum or slow roll quintessence? If so, what are observational consequences?

Interesting to explore alternative models for Dark Energy.
Axion, axino, visible sector

The hilltop quintessence model from a runaway string saxion comes with axion and axino:

- **Axion lifted by subleading** $W_{np\ sub} \Rightarrow$ axion DE with $m_\theta < m_\phi$
e.g. $W_{np\ sub} = Be^{-\beta \Phi}$ with $\beta = 2\alpha$, $B = -A/20 \Rightarrow w = -0.99$.

- **Axino has light mass** $m_{axino} \sim 2\phi^2 e^{K/2} D_\Phi D_\Phi W$
e.g. with parameters above $m_{axino} \sim 4.2 \times 10^{-33}\text{eV} \Rightarrow$ axino DR

Relic abundance is model dependent, e.g. via thermal scattering or decays or out of equilibrium decay via lightest stabilised modulus – might this help resolve $H_0$ discrepancy?

- So far mild susy breaking by runaway - effect of susy breaking in visible sector must be sequestered, e.g. if modulus describes local feature in string compactification, distant from SM:

\[
\Delta m^2 \sim \frac{M_{sb}^4}{M_{pl}^4} M_{sb}^2 \sim H_0^2
\]

Tree-level decoupling ensures radiative stability, supression of fifth forces and time variation of fundamental constants.
In terms of slow roll parameters, conjecture reads

\[ \text{either } \epsilon_V \geq \frac{c^2}{2} \quad \text{or} \quad \eta_V \leq -c' \]

whereas slow-roll inflation requires \( \epsilon_V \ll 1 \) and \( |\eta_V| \ll 1 \).

Slow-roll relates \( n_s = 1 - 6\epsilon_V + 2\eta_V \) and \( r = 16\epsilon_V \), then \( r < 0.064 \) and \( n_s = 0.96 \) imply:

\[ c < 0.09 \quad \text{or} \quad c' < 0.01 \]

Go beyond vanilla slow roll models, e.g. multi-field effects