Dark Energy in String Theory and the Swampland

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Geometrical Tools for String Cosmology
Oaxaca
1st May 2019

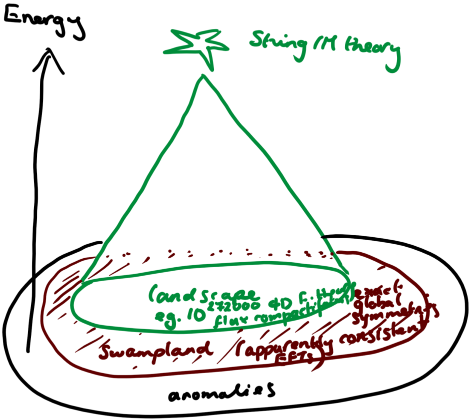
Feliz Día Internacional del Trabajador!

Plan

- The String Swampland Conjectures
- Dark Energy in String Theory (and inflation)
- Quintessence from a Runaway String Modulus
- Outlook

String Landscape vs. Swampland

Vafa '05
Brennan, Carta & Vafa '17
Palti '19
Taylor & Wang'15
see Oscar's talk



Swampland - set of all EFTs that do not admit a string theory UV completion.

Swampland Conjectures

Simple criteria conjectured to distinguish swampland from landscape:

Brennan, Carta & Vafa '17
Palti '19

1. No global symmetries
2. All charges must appear
3. Finite number of massless fields
4. No free parameters
5. Moduli space is non-compact
6. Moduli space is simply connected
7. Gravity is the weakest force (p-form/scalar "Weak Gravity Conjecture") Arkani-Hamed, Motl, Nicolis & Vafa '06, ..., Palti '17, Gonzalo & Ibañez '19, see Liam's talk
8. New physics from the boundaries of moduli space ("Distance Conjecture") see Irene's talk
9. No stable non-susy adS vacua
10. No metastable dS vacua?

Towards insights into QG and concrete predictions for our Universe?... $w_{DE} \neq -1$, quintessence strongly interacting with dark sector?

Concordance ΛCDM Model

Observations consistent with tiny cosmological constant

e.g. Planck $\Rightarrow \rho_{DE} \sim 7 \times 10^{-121} M_{pl}^4$ and $w_{DE} = -1.028 \pm 0.032$

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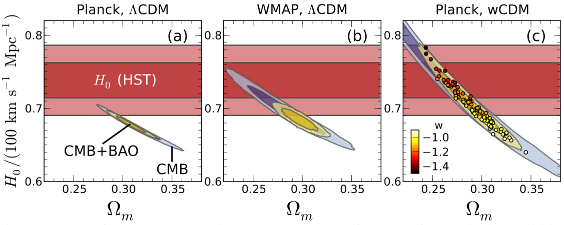

Mortonson et al '14

Hints at physics beyond ΛCDM in H_0 measurements:

- direct measurement: $H_0 = 74.22 \pm 1.84 km/s/Mpc$
- value inferred from CMB $H_0 = 67.4 \pm 0.5 km/s/Mpc$

giving 4.4σ discrepancy...

Riess et al '19
see Luisa's talk

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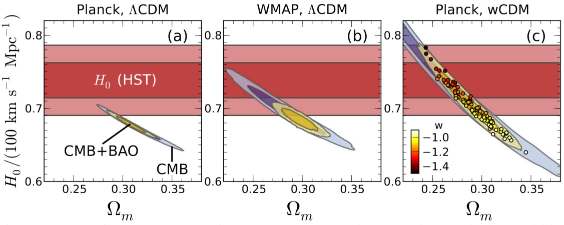

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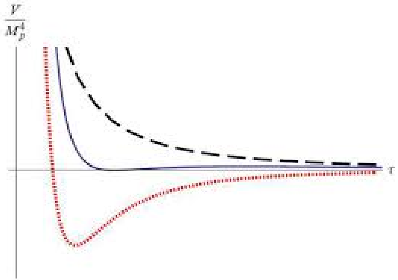
Physics beyond ΛCDM? exotic (e.g. phantom) dark energy, dark radiation, dark matter decay...

di Valentino, Melchiorri & Silk '16
Huang & Wang '16

Dark energy in string compactifications

In string compactifications, we typically look for 4D LEEFT with scalar potential with positive definite minimum $\langle V(\phi^i)\rangle_{min} > 0$.



Does not alone address the cosmological constant problem

$$\Lambda = \langle V \rangle + \mathcal{O}(M_{kk}^4)$$

where typically $M_{kk} \gtrsim 10^{-15} M_{pl}$... anthropics? something like SLED?

Metastable dS vacua are hard... progress so far

see Mariana's talk

- String coupling is runaway direction within perturbative regime, unless there is some parameter to fine-tune Dine & Seiberg '85

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Constructions tend to be at – or beyond – the limits of perturbative control and our understanding of 10D solutions.

dS Swampland Conjecture

Danielsson & Van Riet '18
Obied, Ooguri, Spodyneiko & Vafa '18
Garg & Krishnan '18
Ooguri, Palti, Shiu & Vafa '18

Might effective field theories with metastable de Sitter solutions be in the Swampland?

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

$$\sqrt{\nabla^j V \nabla_j V} \geq \frac{c}{M_{pl}} V$$

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.

Connections to axionic WGC, distance conjecture and discussions around quantum aspects of dS...

Witten '01, Banks '12, Susskind '16, Dvali & Gomez '18

One test of the dS Conjecture

Olguin-Trejo, Parameswaran, Tasinato & Zavala '18
see also Garg, Krishnan & Zaz '18

Revisit **modular invariant** scalar potentials in concrete heterotic orbifold compactifications with moduli S, T_1, T_2, T_3, U and only four parameters.

Parameswaran, Ramos-Sanchez & Zavala '10

$$K = -\log\left(S+\bar{S}\right) - \sum_j^{h^{1,1},h^{2,1}} \log(\phi_j+\bar{\phi}_j) + |A_\alpha|^2 \prod_j^{h^{1,1},h^{2,1}} (\phi_j+\bar{\phi}_j)^{n^j_\alpha} .$$

and

$$W_{gc} \approx \sum_a d_a \exp\left(\frac{24\pi^2}{b_a^0} f_a\right) \quad \text{with} \quad f_a = k_a S + \Delta_a^{M_d}(T_i) + \Delta_a^{M_s}(T_i, U_m)$$

Many unstable dS vacua; all satisfy dS conjecture with $c = 1, c' = 1$.

Similarly for $K = -\ln(S+\bar{S}) - 3\ln(T+\bar{T})$ and

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

see also Gonzalo, Ibañez & Uranga '19
Blaback, Roest & Zavala '13
Kallosh, Linde, Vercnocke & Wrase '14

Implications for Dark Energy

Dark energy may be quintessence field:

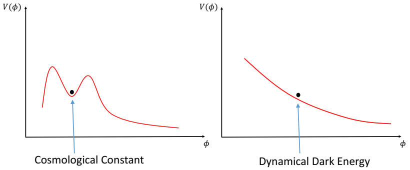
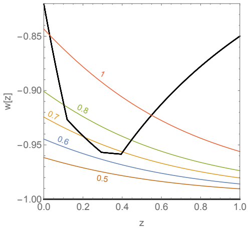


Figure from Palti's recent review

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



Agrawal, Obied, Steinhardt & Vafa '18

Relaxing semi-positive definite Hessian, can have $c, c' \sim 1$ and $w \sim -1$ by fine-tuning initial conditions...

String Models of Quintessence

Need a slowly-rolling ultra-light string modulus with:

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

so two fine-tuning problems...

Many of the same ingredients and challenges as in dS constructions

Choi '99 *"String or M theory axion as quintessence"*
Albrecht, Burgess, Ravndal & Skordis '01 *"Natural quintessence and LEDs"*
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String dilaton or volume modulus lead to fifth forces and varying fundamental constants.

Local modulus may be sequestered with weaker than Planck SM couplings

e.g. Cicoli, Pedro & Tasinato '12

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String axion evades 5th forces and can easily be light $m \sim e^{-\tau} M_{pl}$, but need $f \gtrsim 3 M_{pl}$... alignment?

Svrcek '06

Quintessence from a Runaway String Modulus

- Assume early Universe scenario (e.g. inflation) that ends in susy Minkowski with most moduli stabilised and heavy:

$$\langle D_i W_{susy} \rangle = 0, \quad \langle W_{susy} \rangle = 0, \quad \langle \Phi^i \rangle \quad \text{heavy}$$

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- Assume a single flat direction (for simplicity):

$$\Phi = \phi + i\theta$$

with ϕ a string coupling constant – saxion – and θ its axion.

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

e.g. $n = 3$ for overall volume modulus, $n = 1$ for other volume moduli, complex structure, dilaton, blow-up modulus.

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- W protected to all finite orders by non-renormalisation theorem:
  - Axionic shift symmetry $\Rightarrow$ W cannot depend on θ.
  - Holomorphy $\Rightarrow$ W cannot depend on ϕ.
- Note 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:

$$W_{np} = A e^{-\alpha \Phi} \quad \text{at leading order}$$

  e.g. by worldsheet instantons, gaugino condensation in bulk or brane, Euclidean D-branes, ...

- A and α are model dependent constants – A may be itself exponentially suppressed in heavy moduli vevs, e.g. gaugino condensation with 1-loop threshold corrections:

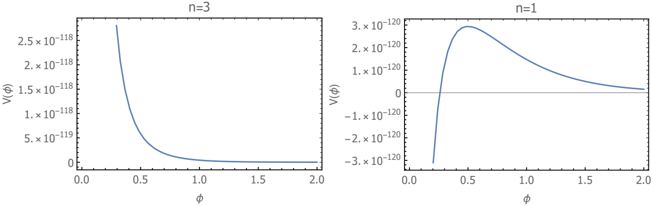
$$W_{gc} = \mu^2 e^{-\alpha f} \quad \text{with} \quad f = \Phi + \sum_i c_i \ln(d_i \Phi_i)$$

- 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



- dS maximum at $\phi_{max} = \frac{1}{\sqrt{2}\alpha}$ for $W_{np} = Ae^{-\alpha\Phi}$ (consistent with dS Swampland Conjecture)
- Corrections from K_p and $W_{np\ sub}$ suppressed for small coupling constant
- Starting from susy Minkowski – well under control
- Giving up dS minimum – no fine tuning of perturbative and non-perturbative corrections against each other

Quintessence from a runaway modulus

- Cosmological equations in a FRW background:

$$3\left(\frac{\dot{a}}{a}\right)^2 = \frac{1}{2}\frac{\dot{\phi}^2}{\phi^2} + M_{pl}^{-2}V + 3H_0^2\Omega_M a(t)^{-3} + 3H_0^2\Omega_r a(t)^{-4}$$
$$0 = \ddot{\phi} + 3\frac{\dot{a}}{a}\dot{\phi} + \Gamma^{\phi}_{ab}\dot{\phi}^a\dot{\phi}^b + M_{pl}^{-2}g^{\phi b}\frac{\partial V}{\partial \phi^b}$$
$$0 = \ddot{\theta} + 3\frac{\dot{a}}{a}\dot{\theta} + \Gamma^{\theta}_{ab}\dot{\phi}^a\dot{\phi}^b + M_{pl}^{-2}g^{\theta b}\frac{\partial V}{\partial \phi^b}\,,$$

- To source accelerated expansion:

$$\frac{1}{2}\dot{\varphi}^2 \ll V \quad \text{slow roll quintessence}$$

which implies:

$$2\phi^2\frac{V'(\phi)^2}{V} \ll M_{pl}^2 H^2$$

Slowly rolling runaway field

- Behaviour of the slow-roll parameter, $2\phi^2 V'(\phi)^2/V(\phi)$ in different regions of the potential:

$$
\begin{aligned}
2\phi^2 \frac{V'(\phi)^2}{V(\phi)} &\rightarrow -\frac{2A^2}{\phi} \quad \text{as} \quad \phi \rightarrow 0\,, \\
2\phi^2 \frac{V'(\phi)^2}{V(\phi)} &\rightarrow \#\, A^2 e^{-\sqrt{2}} \alpha^3 (\phi - \frac{1}{\sqrt{2}\alpha})^2 \quad \text{as} \quad \phi \rightarrow \phi_{max}\,, \\
2\phi^2 \frac{V'(\phi)^2}{V(\phi)} &\rightarrow \#\, A^2 \alpha \quad \text{as} \quad \phi \rightarrow \phi_{inflex}\,, \\
2\phi^2 \frac{V'(\phi)^2}{V(\phi)} &\rightarrow e^{-2\alpha\phi} 16 A^2 \alpha^4 \phi^3 \quad \text{as} \quad \phi \rightarrow \infty\,.
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- At hilltop or tail, while H is large, field remains frozen by Hubble friction – sourcing cosmological constant – for most of cosmological history.
- As H decreases, eventually $M_{pl}^2 H^2 \lesssim 2\phi_{init}^2 V'(\phi_{init})^2/V(\phi_{init})$ and field begins to roll.

Late-time quintessence on the runaway potential

For a quintessence that dominates the energy density $M_{pl}^2 H^2 \sim V/3$:

$$\epsilon_q \equiv 6\phi^2 \frac{V'(\phi)^2}{V^2} \ll \mathcal{O}(1)$$

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- At tail $\epsilon_q \to 24\alpha^2\phi^2$ as $\phi \to \infty$ so runaway potential cannot source quintessence at the tail.

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For a quintessence that dominates the energy density $M_{pl}^2 H^2 \sim V/3$:

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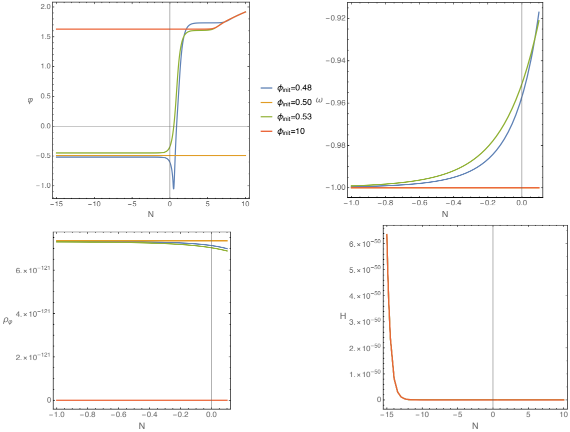
  At dS maximum $\frac{\min(\nabla^j\nabla_j V)}{V} = -2(2+\sqrt{2})M_{pl}^{-2}$, so consistent with dS Swampland Conjecture, $\frac{\min(\nabla^j\nabla_j V)}{V} < -c' M_{pl}^{-2}$, with $c' = 1$

Near hilltop we have a viable frozen or thawing quintessence model.

Thawing quintessence from a runaway string modulus

Choosing $A = e^{-138.122}$ and $\alpha = \sqrt{2}$ for ϕ_{init} to within 4% of hilltop value $\phi_{hilltop} = 0.5$, evolution consistent with current observations.



Quantum fluctuations $\Delta\phi \sim H/2\pi$ stay within viable window up to $H \lesssim 0.01 M_{pl}$.

Late time attractor behaviour

Independently of the initial conditions, the late time behaviour as $N \to \infty$:

$$\phi(N) \to \frac{1}{2a} \ln\left(\frac{12A^2\alpha}{H_0^2\Omega_M}\right) + \frac{3}{2\alpha}\left(N + \ln(N)\right)$$

$$\rho_\varphi \to e^{-3N} \frac{H_0^2\Omega_M}{2N^2} \to 0$$

$$\omega \to -\frac{3}{2}\frac{\ln N}{N} \to 0\,.$$

starting at right of hilltop.

Axion, axino, visible sector

- 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 $m_{axino} \sim 4.2 \times 10^{-33} eV \Rightarrow$ 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.

Summary

- Existence or not of metastable dS vacuum in string theory remains an open question, though we've long known it would be hard...
- Very few candidates for quintessence in string theory - usually tension with Swampland constraints and/or control issues.
- Late time dominating slow roll quintessence is impossible at runaway tail – no stringy example (and inconsistent with dS Conjecture).
- Hilltop in runaway potential can source frozen/thawing quintessence consistently with observations and QG conjectures - and under control!
- Comes with axion DE and axino DR.
- BUT need fine-tuned initial conditions... anthropics on a susy Landscape?
- Model dependent questions: susy breaking and vacuum energy in visible sector, fifth forces and time variation of fundamental constants...
- The cosmological constant problem...

dS Conjecture and Inflation

Agrawal, Obied, Steinhardt & Vafa '18
Fukuda, Saito, Shirai & Yamazaki '18
Kinney, Vagnozzi & Visinelli '18

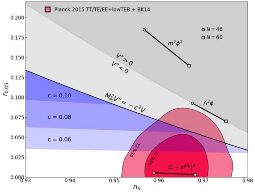
- In terms of slow roll parameters, conjecture reads

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

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:

$$c < 0.09 \quad \text{or} \quad c' < 0.01$$



Kinney, Vagnozzi & Visinelli '18

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

Palma & Achucarro '18
see Diederik's talk