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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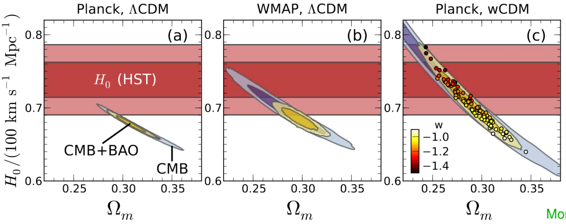
- Current and upcoming observations will further constrain dark energy and its $w(z)$
- Growing tension between direct measurements of H_0 and CMB fit using ΛCDM:



Mortonson et al '14

4.4 σ discrepancy...

Reiss et al '19

early dark energy, N_{eff}, phantom DE, fading dark matter...?

Karwal & Kamionkowski '16; Calabrese, Huterer, Linde, Melchiorri & 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

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- We have long known that this would be hard:
  - string couplings are runaways in perturbative regime unless there are parameters to fine tune — Dine & Seiberg '85
  - two-derivative sugra with positive tension objects does not admit dS — Maldacena & Nuñez '00
  - extensions e.g. classical iia on CY orientifolds with geometric fluxes: $\frac{|\nabla V|}{V} \geq \sqrt{\frac{54}{13}}$ — Hertzberg, Kachru & Taylor '07

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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

dS Vacua in Heterotic Orbifolds

Parameswaran, Ramos-Sanchez & Zavala '10
Olguin-Trejo, Parameswaran, Tasinato & Zavala '18

Scalar potential constrained by target-space modular-invariance:

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

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

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

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

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:

Obied, Ooguri, Spodyneiko & Vafa '18
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$$\sqrt{\nabla^j V \nabla_j V} \geq \frac{c}{M_{pl}} V$$

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.

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Heterotic dS vacua above satisfy conjecture with $c, c' = 1$.

Implications for Dark Energy

Dark energy may be quintessence field:

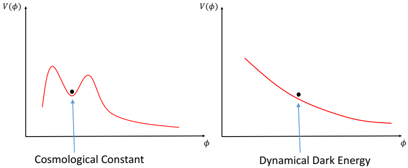

Figure from Palti's recent review

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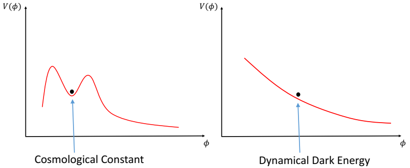

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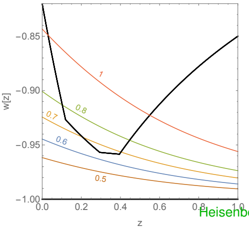
Assuming convex potential, current observations on $w(z)$ constrain c in $|\nabla V| M_{pl} > cV$ to $c \lesssim 0.6$



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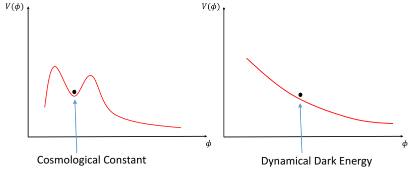

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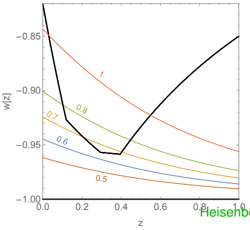

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Can string theory give $c \lesssim 0.6$? *$V(\phi)$ is not typically $V \sim Ce^{-c\phi}$...*

String Models of Quintessence

see Cicoli, de Alwis, Maharan, Muia & Quevedo '18 for a review

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

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

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- two fine-tuning problems
- fifth forces
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- axion - need large f_a or hilltop fine-tuning of initial conditions
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- local string modulus - $\Delta\phi \gtrsim M_{pl}$? sequestering?
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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 & Dibitetto '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!

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 volumes, complex structure, dilaton (easily extend to e.g. blow-up moduli)

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- W protected to all finite orders by non-renormalisation theorem
- 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:

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

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

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- 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:

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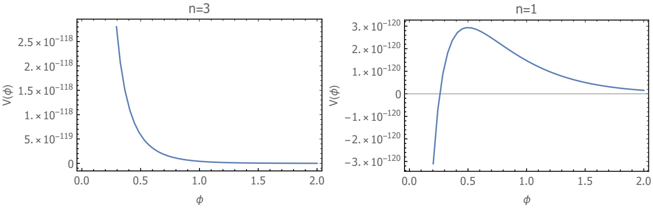
- Scalar potential for saxion:

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

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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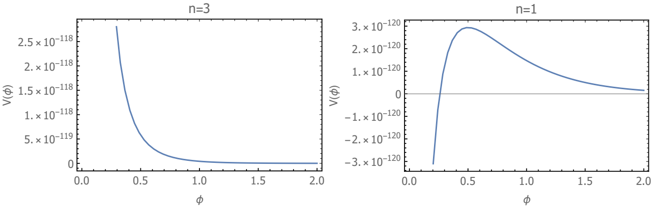

- Starting from susy Minkowski – well under control – corrections from K_p and $W_{np\ sub}$ suppressed for small coupling constant
- For $n = 1$ dS maximum at $\phi_{max} = \frac{1}{\sqrt{2}\alpha}$
- Giving up dS minimum – no fine tuning of perturbative and non-perturbative corrections against each other

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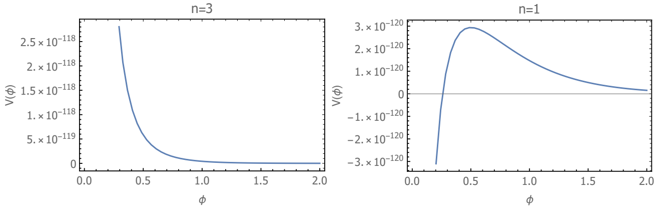

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Susy breaking in visible sector... discuss later.

Quintessence from a runaway modulus

- Cosmological eqns in a FRW bkgd:

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

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

Along tail $\epsilon_{sr} \rightarrow e^{-2\alpha\phi} 16 A^2 \alpha^4 \phi^3 \rightarrow 0$ as $\phi \rightarrow \infty$, so field easily frozen by H sourcing a c.c..

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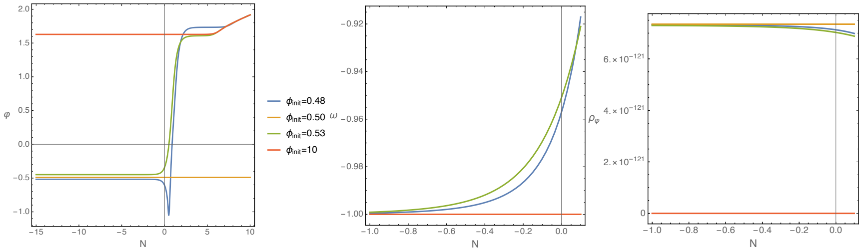
- For late time domination $V \sim 3M_{pl}^2H^2 \Rightarrow$:

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

Along tail $\epsilon_q \to 24\alpha^2\phi^2 \to \infty$ as $\phi \to \infty$, so we cannot source quintessence along runaway tail.

Thawing Quintessence at the Hilltop



Cosmological evolution for $A = e^{-138.122}$ and $\alpha = \sqrt{2}$

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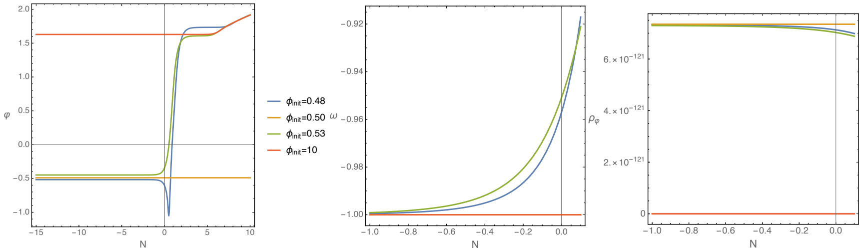

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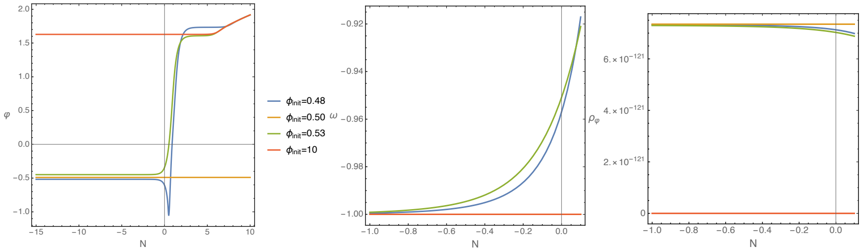

Cosmological evolution for $A = e^{-138.122}$ and $\alpha = \sqrt{2}$

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...

Thermal Dark Energy

cf. Thermal Inflation, Lyth & Stewart '95

- Consider a hidden sector including a light scalar field with non-vanishing vev in Minkowski vacuum:

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

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- DE with $w = -1$ consistent with swampland conjectures? ...

Summary

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

dS Conjecture and Inflation

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

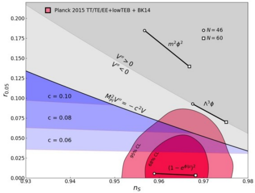
- In terms of slow roll parameters, conjecture reads

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

  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