Quantum Gravity Meets Cosmological Observations at a WISPy Hilltop

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University of Liverpool

WISPs in String Cosmology
Bologna, 24th October 2024

based on work to appear soon
w/ Battacharya, Borghetto, Malhotra, Tasinato & Zavala

Observational constraints on Dark Energy

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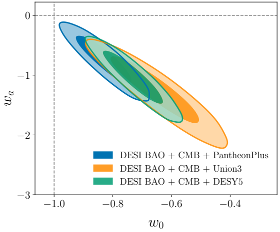

Figure reproduced from DESI '24

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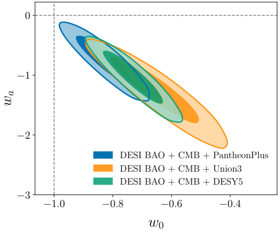

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Early days... statistics or new physics? Y3 analysis to come soon!

eBOSS 2014-20, SuMIRe 2014-29, DESI 2021-26, Euclid 2023-29, VRO/LSST 2025-35, Roman Telescope 2027-32

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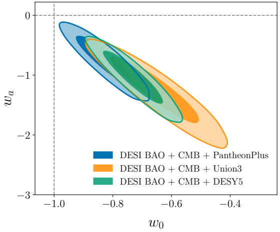

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Theorists should be ready with well-motivated models and parametrisations that cosmologists can test against the data...

Dark Energy in string theory

Given relation with gravitational response to vacuum energy, is Dark Energy an opportunity to connect quantum gravity to observations?

Elephant in the Room by Banksy

Might synergies between swampland and observational constraints reveal more about the fundamental nature of DE?

Plan

- dS minima, plateaus, runaways, maxima and saddles vs the swampland
- Cosmological constraints on different dS maxima vs dS minima and runaways

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To what extent can cosmological observations help distinguish if we are in a dS maximum vs a dS minimum or runaway? Could they have preference for a particular shape around the dS maxima? Can they constrain the fundamental parameters in the dS maxima? If so, are the data-preferred values consistent with swampland constraints?

metastable dS, plateaus, runaways, hilltops and saddles vs Swampland

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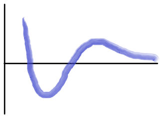

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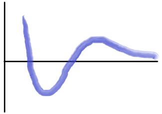

... though all explicit dS maxima/saddles so far have control issues...

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'Stringy' hilltop quintessence models

We consider three classes of single-field hilltop quintessence models.

- **Axion hilltops** with potential: Frieman, Hill, Stebbins & Waga '95, ...

$$V(\theta) = V_0 \left(1 - \cos\left(\frac{\theta}{f}\right)\right) \qquad \text{and} \qquad \theta_{\text{max}} = \pi f$$

  with $V_0 \sim e^{-S_{\text{inst}}}$ and $S_{\text{inst}} \gg 1$ for control.

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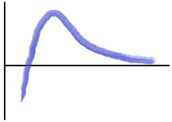

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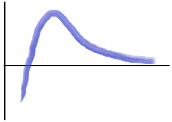

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- **Generic quadratic hilltop** with potential:

$$V(\phi) = V_0\left(1 - \left(\frac{\phi}{\phi_0}\right)^2\right)^2 \qquad \phi_{\text{max}} = 0$$

  So long as ϕ stays close to its hilltop, this is a good approximation to any quadratic hilltop $V(\phi) = V_0 - \frac{1}{2}m^2\phi^2$.

Axion quintessence quality

Frieman, Hill, Stebbins & Waga '95, onwards...

Axion hilltops are especially promising:

$$V(\theta) \sim e^{-S_{\rm inst}} \left(1 - \cos\left(\frac{\theta}{f}\right)\right)$$

- Shift symmetry protects axion mass and potential energy from UV corrections - scales are generated non-perturbatively and are exponentially suppressed.

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- WGC $\Rightarrow fS_{\rm inst} \lesssim 1$ so $f \ll 1$ for controlled instanton expansion $S_{\rm inst} \gg 1 \Rightarrow$ slow-roll acceleration then requires hilltop quintessence. Arkani-Hamed, Motl, Nicolis & Vafa '06, ...

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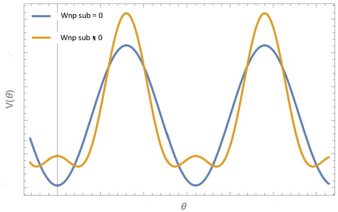
- Initial conditions at the hilltop could be set up dynamically:



Dutta-Scherrer parametrisation for hilltops

Dutta & Scherrer '08
Chiba '09

All hilltop models can be analysed in a model-independent way using the Dutta-Scherrer parametr'n (K, w_0):

$$\frac{1+w_\phi(a)}{1+w_0} = \left(\frac{a}{a_0}\right)^{3(K-1)} \left[\frac{(K-F(a))(1+F(a))^K + (K+F(a))(F(a)-1)^K}{(K-F_0)(1+F_0)^K + (K+F_0)(F_0-1)^K}\right]^2$$

with $K = \sqrt{1 - \frac{4}{3}\frac{V''_{\rm max}}{V_{\rm max}}}$ and $F(a) = \sqrt{1 + \left(\frac{a}{a_0}\right)^{-3}\left(\frac{1-\Omega_{\phi,0}}{\Omega_{\phi,0}}\right)}$.

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- Relate to fundamental parameters:

$$K_{\rm ax} = \sqrt{1+\frac{2}{3f^2}}, \quad K_{\rm sugra} = 3.2, \quad K_{\phi^2} = \sqrt{1+\frac{16}{3\phi_0^2}}$$

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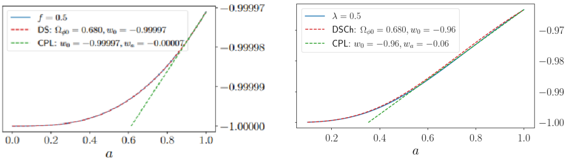
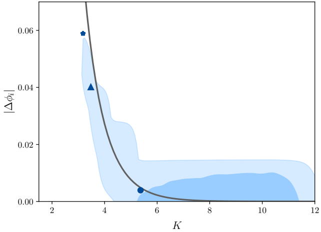
- Works v. well throughout evolution and much better than CPL... and generalisation works for **all** thawing models!



Bounds on – and from – initial conditions



- The DS-parametrisation allows us to express in initial displacement from hilltop in terms of K:

$$\Delta\phi_i(K) = 4K\Omega_{\phi,0}\sqrt{\frac{(1+w_0)}{3}} \times \frac{(1-\Omega_{\phi,0})^{\frac{K-1}{2}}}{\left(K\sqrt{\Omega_{\phi,0}}-1\right)\left(1+\sqrt{\Omega_{\phi,0}}\right)^K + \left(K\sqrt{\Omega_{\phi,0}}+1\right)\left(1-\sqrt{\Omega_{\phi,0}}\right)^K}$$

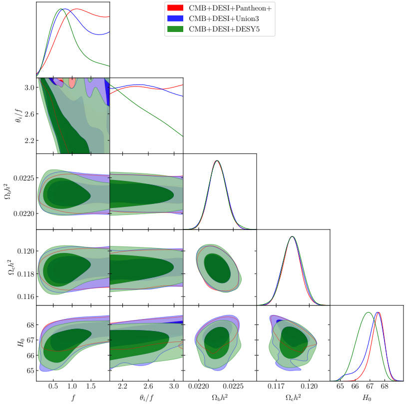
- Once initial conditions have been set up, quantum diffusion must not kick field outside viable range:

$$H_{\mathrm{rh}} \ll 2\pi\Delta\phi_i$$

- After fitting to cosmological data, bound on H_{rh} turns outto be very mild.

Cosmological constraints on Axion Hilltop Quintessence

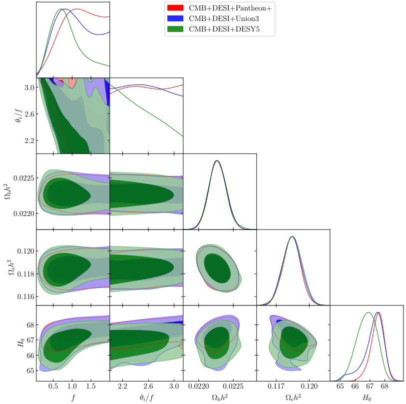
We fit Axion Hilltop model to the cosmological data using CMB, DESI BAO, and Type 1a Supernovae catalogues, with parameters f and θ_i.



Parameter	+Pantheon+	+Union3	+DESY5
f	> 0.946	> 0.779	$0.88^{+0.24}_{-0.54}$
θ_i	$3.1^{+1.1}_{-1.4}$	$2.73^{+0.93}_{-1.6}$	$2.11^{+0.40}_{-1.2}$

Cosmological constraints on Axion Hilltop Quintessence

We fit Axion Hilltop model to the cosmological data using CMB, DESI BAO, and Type 1a Supernovae catalogues, with parameters f and θ_i.



Parameter	+Pantheon+	+Union3	+DESY5
f	> 0.946	> 0.779	$0.88^{+0.24}_{-0.54}$
θ_i	$3.1^{+1.1}_{-1.4}$	$2.73^{+0.93}_{-1.6}$	$2.11^{+0.40}_{-1.2}$

Note $f \gtrsim 0.7 \Rightarrow 1 \lesssim S_{inst} \lesssim 1.4 \Rightarrow$ instanton expansion at limits of control and offers only mild suppression of $V_0 \sim e^{-S_{inst}}$ – further effects needed if we want to explain $\rho_{DE} \sim 10^{-120}$, e.g. suppression from polyinstanton effects.

Cicoli, Cunillera, Padilla & Pedro '24

Model Comparison

We can similarly fit saxion, quadratic and DS parametrisation to the data.

- Compare qualities of fits using AIC = $2n - 2\ln \mathcal{L}_{\max}$:

AIC	Axion	Sugra	Higgs	DS	ΛCDM	CPL	Exp
CMB+DESI+Pantheon+	12409.55	12409.40	12409.07	12408.9	12406.04	**12401.70**	12407.19
CMB+DESI+Union3	11030.07	11029.49	11030.38	11027.9	11028.69	**11019.62**	11029.00
CMB+DESI+DESY5	12644.67	12645.65	12644.89	12641.2	12649.01	**12637.79**	12644.73

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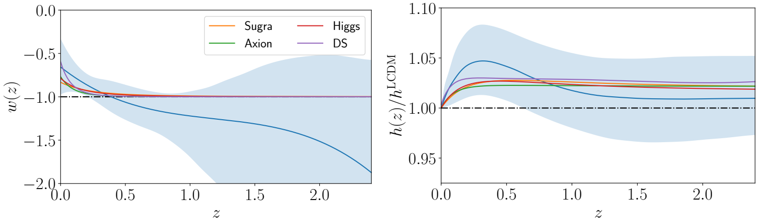
- CPL is currently favoured - likely due to rapid evolution in $w(a)$ and phantom behaviour:



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- More cosmological data to come - used together with swampland criteria (e.g. WGC), we can hope to discover more about Dark Energy and – if we're lucky – begin to rule out models and have favoured ones...