Asymptotic Acceleration in Light of the Landscape and the Stars

Susha Parameswaran

University of Liverpool

String Pheno 2024
Padova

based on
2405.09323 [hep-th] w/ Andriot, Tsimpis, Wrase & Zavala
2405.17396 [astro-ph.CO] w/ Battacharya, Borghetto, Malhotra, Tasinato & Zavala
and 2407.XXXXX w/ Marco Serra

Asymptotic Acceleration

	Opening Remarks		*Institute for Basic Science, Daejeon*	08:55 - 09:00
09:00	**Challenges of Stringy de Sitter and Asymptotic Acceleration**	*Arthur Hebecker*	*Institute for Basic Science, Daejeon*	09:00 - 09:30
	Scalar potentials from (classical) string theory	*David Andriot*	*Institute for Basic Science, Daejeon*	09:30 - 10:00
10:00	**Asymptotic limits in moduli space**	*Timm Wrase*	*Institute for Basic Science, Daejeon*	10:00 - 10:30
	Coffee break		*Institute for Basic Science, Daejeon*	10:30 - 11:00
11:00	**Late-time Attractors and Cosmic Acceleration**	*Gary Shiu*	*Institute for Basic Science, Daejeon*	11:00 - 11:30
	Quantum Gravity Constraints on Cosmic Acceleration	*Marco Scalisi*	*Institute for Basic Science, Daejeon*	11:30 - 12:00
12:00	**A non-perturbative test of the DGKT vacuum**	*Miguel Montero*	*Institute for Basic Science, Daejeon*	12:00 - 12:30

Can there be accelerated expansion in asymptotic regions of moduli space, with runaway moduli, where we have most control in g_s and α' expansions...

Observational hints beyond ΛCDM?

Recent Dark Energy surveys measuring $w_{DE}(a)$ are finding intriguing hints of deviations from Λ, whilst asymptotic acceleration may naturally deviate from ΛCDM with a rolling modulus.

DESI, assuming parametrisation $w_{\rm DE}(a) = w_0 + w_a(1-a)$, finds:

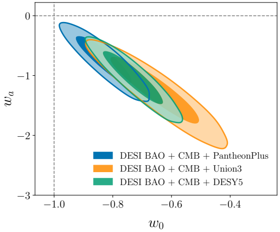

Figure reproduced from DESI '24

and preference over ΛCDM at 2.5σ, 3.5σ or 3.9σ depending on SN 1a data set used.

Early days... statistics or new physics?

See e.g. Cortês & Liddle '24; Ó Colgain, Dainotti, Capozziello, Pourojaghi, Sheikh-Jabbari & Stojkovic '24; Shlivko & Steinhardt for some debate

So far, first year of data analysed out of planned 5 years...

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

Plan

- Interlude - asymptotic dS from Scherk-Schwarz susy breaking?
- Asymptotic acceleration, event horizons and the swampland
- Quintessence in an open universe - dynamical systems analysis and observational constraints
- Outlook

Asymptotic dS from Scherk-Schwarz susy breaking?

SLP & Serra, to appear soon; see Marco Serra's parallel session talk!

- Might non-susy strings provide an arena for parametrically controlled de Sitter solutions? see talks from Schachner, Quevedo, McAllister for dS in sugra

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- Break susy spontaneously à la Scherk-Schwarz torus – $\mathcal{T}^n_{\text{ss}} = \mathcal{T}^n/g$ with $g = (-1)^F \delta_{KK}$ and $\delta_{KK} : X^i \to X^i + \pi R_{\text{ss}}$: see Dudas's talk

$$M_{3/2} \sim \frac{1}{R_{\text{ss}}} \quad \text{and} \quad M^2_{\text{tach}} = -\frac{2}{\alpha'} + \frac{R^2_{\text{ss}}}{\alpha'^2}$$

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- Type II on $\mathcal{M}_{1,d-1} \times \mathcal{T}^n_{ss} \times \mathcal{Y}^{10-d-n}$ with 1-loop casimir potential, curvature and fluxes – solve BIs with no localised sources and unbounded flux numbers.
  see De Luca, Silverstein & Torroba '22 for dS from Casimir in M-theory; see also Montero's talk & Bruno Bento's parallel session
- 10D eoms $\Rightarrow$ no-gos and necessary conditions for dS and dS (and adS) solutions to full 10D eoms can be found...

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- Further insights from d-dimensional EFT:

$$V(g_s, R, R_{ss}) = -\frac{C_{\mathcal{Y}}}{R^2} + \frac{n^2_{H_3,p_3}}{R^{2p_3} R_{ss}^{6-2p_3}} + \frac{n^2_{q,s_q} g_s^2}{R^{2s_q} R_{ss}^{2q-2s_q}} - \frac{\xi_{\mathcal{T}_{ss}} g_s^2}{R_{ss}^{10}}$$

- We see that $R \gg R_{ss}$ and unbounded fluxes allows dS solutions...

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- Parametrically controlled adS are possible!
see De Luca, De Ponti, Mondino & Tomasiello '23 for scale-separated adS from Casimir

Quint-essen(ce)-tial questions I won’t discuss...

See also e.g. Cicoli, De Alwis, Maharana, Muia & Quevedo’18; Hebecker, Skrzypek & Wittner ’19; Cicoli, Cunillera, Padilla & Pedro ’ and Pedro’s talk

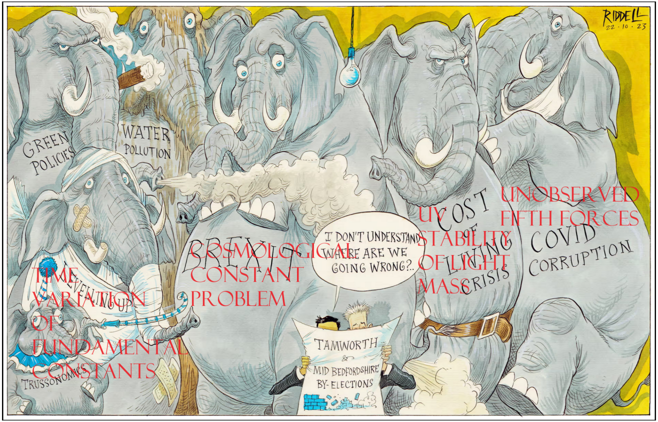

Figure adapted from The Guardian

Eternal acceleration at large volume and weak coupling?

- Moduli potentials typically runaway with $V(\phi) \sim e^{-\lambda\phi}$ as $\phi \to \infty$ for canonically normalised fields.

  Dine & Seiberg '85

- Sources eternal acceleration if $\lambda = \frac{|\nabla V|}{V} < \sqrt{2}$ (and transient acceleration is possible for $\lambda > \sqrt{2}$).

  Townsend & Wohlfarth '03, ..., Russo & Townsend '19

- Fitting exponential quintessence $V(\phi) \sim e^{-\lambda\phi}$ to the cosmological data bounds $\lambda \lesssim 0.6$.

  Agrawal, Obied, Steinhardt & Vafa '18; Akrami, Kallosh, Linde & Vardanyan '18; Raveri, Hu & Sethi '18; Schöneberg, Vacher, Dias, Carvalho & Martin '23

- Widely believed that stringy potentials *at the asymptotics* obey:

  Obied, Ooguri, Spodyneiko & Vafa '18; H. Ooguri, E. Palti, G. Shiu & C. Vafa '18; Bedroya & Vafa '20; Rudelius '21

$$\frac{|\nabla V|}{V} \geq \sqrt{2} \text{ for } d = 4 \quad (*)$$

  No known counter-example *at the asymptotics*.

  For some interesting attempts see e.g. Hebecker & Wrase '18; Calderón-Infante, Ruiz & Valenzuela '22; Cremoini, Gonzalo, Rajaguru, Tang & Wrase '23

- Difficulty in finding eternal quintessence in string theory consistent with early insights that it has same conceptual challenges as de Sitter, including event horizons.

  Hellerman, Kaloper & Susskind '01
  Fischler, Kashani-Poor, McNees & Paban '01

Loop hole - quintessence in an open universe

- There do exist 10/11D solutions with eternal acceleration – they are time-dependent and have negatively curved 3D spatial slices.

Chen, Ho, Neupane, Ohta & Wang '03; Andersson & Heinzle '06; Marconnet & Tsimpis '23

$$ds_{10}^2 = e^{2A(t)}\left(g_{\mu\nu}^{FRW,k=-1}dx^\mu dx^\nu + g_{mn}dy^m dy^n\right)$$

- Corresponding 4D EFTs with potentials such as: Marconnet & Tsimpis '23

$$V = \begin{cases} 72\, c_3^2\, e^{-\phi-12A} + \frac{3}{2}\, c_4^2\, e^{\frac{\phi}{2}-14A} & \text{CY with internal 3- and 4-form fluxes} \\ \frac{1}{2}\, c_{4,\mathrm{ext}}^2\, e^{-\frac{\phi}{2}-18A} + \frac{1}{2}\, m_0^2\, e^{\frac{5\phi}{2}-6A} - 6\, k_6\, e^{-8A} & \text{Einstein with external 4-form flux} \\ \frac{3}{2}\, c_4^2\, e^{\frac{\phi}{2}-14A} + \frac{1}{2}\, m_0^2\, e^{\frac{5\phi}{2}-6A} - 6\, k_6\, e^{-8A} & \text{EK with internal 4-form flux} \\ \frac{1}{2}\, c_{4,\mathrm{ext}}^2\, e^{-\frac{\phi}{2}-18A} + \frac{3}{2}\, c_2^2\, e^{\frac{3\phi}{2}-10A} - 6\, k_6\, e^{-8A} & \text{EK with internal 2-form, external 4-form} \end{cases}$$

E.g. IIA on compact hyperbolic manifold with only one geometric modulus – volume – and no fluxes, after fixing dilaton:

$$V \sim e^{-\sqrt{\frac{8}{3}}\varphi} \text{ for canonically normalised } \varphi$$

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- 4D analysis of $V \sim e^{-\lambda\phi}$ in otherwise empty open universe $k = -1 \Rightarrow$ one can have eternal acceleration precisely when $\lambda > \sqrt{2}$. Small g_s and α' and no event horizon! Andriot, Tsimpis, Wrase '23

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  Andriot, Tsimpis, Wrase '23
- Open universes produced by CDL tunnelling in landscape.

  Freivogel, Kleban, Rodriguez Martinez & Susskin '05; but see Buniy, Hsu, Zee '06; Horn '17; Cespedes, de Alwis, Muia & Quevedo '20, '23 for alternatives

4D cosmology - quintessence in an open universe

Andriot, SLP, Tsimpis, Wrase & Zavala '24
see also Alestas, Delgado, Ruiz, Akrami, Montero, Nesseris '24 and Yashar Akrami's parallel session!

Can 'stringy' steep ($\lambda > \sqrt{2}$), exponential quintessence w/ curved spatial slices lead to a realistic cosmology?

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Can 'stringy' steep ($\lambda > \sqrt{2}$), exponential quintessence w/ curved spatial slices lead to a realistic cosmology? We need to include matter and radiation!

Consider the full 4d cosmology w/ $V(\phi) = V_0 e^{-\lambda\phi}$ in an open FRW universe ($k = -1$):

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\Omega_2^2\right) .$$

Contributions to energy-momentum:

n	component	ρ_n	p_n	$w_n \equiv \frac{p_n}{\rho_n}$
r	radiation	$\propto a^{-4}$	$\propto a^{-4}$	$\frac{1}{3}$
m	matter	$\propto a^{-3}$	$\propto a^{-3}$	0
k	curvature	$-\frac{3k}{a^2}$	$\frac{k}{a^2}$	$-\frac{1}{3}$
ϕ	scalar field	$\frac{\dot\phi^2}{2} + V(\phi)$	$\frac{\dot\phi^2}{2} - V(\phi)$	w_ϕ

*Recall: $\rho_n \sim a^{-3(1+w_n)}$ and we also use 'density parameters' $\Omega_n \equiv \frac{\rho_n}{3H^2}$ ($H \equiv \frac{\dot a}{a}$). For a universe dominated by single fluid $a(t) \sim t^{\frac{2}{3(1+w_n)}}$ and we have accelerated expansion when $w_{\rm eff} \equiv \sum_n w_n\Omega_n < -\frac{1}{3}$.

Dynamical Systems Analysis

see Bahamonde et al '17 for a review; Shiu, Tonioni & Tran '22-'24 for recent work;
see also Flavio Tonioni's parallel session!

The eoms can be expressed as an autonomous system defining:

$$x = \sqrt{\Omega_\phi \frac{(1+w_\phi)}{2}}\,, \quad y = \sqrt{\Omega_\phi - x^2}\,, \quad z = \sqrt{\Omega_k}\,, \quad u = \sqrt{\Omega_r}$$

with $\Omega_m = 1 - x^2 - y^2 - z^2 - u^2$ and $' = \frac{d}{dN}$ where $N = \ln a$:

$$\begin{aligned}
x' &= \sqrt{\frac{3}{2}}\, y^2 \lambda + x \left(3\,(x^2-1) + z^2 + \frac{3}{2}\Omega_m + 2u^2\right)\,, \\
y' &= y\left(-\sqrt{\frac{3}{2}}\, x\,\lambda + 3\,x^2 + z^2 + \frac{3}{2}\Omega_m + 2u^2\right)\,, \\
z' &= z\left(z^2 - 1 + 3\,x^2 + \frac{3}{2}\Omega_m + 2u^2\right)\,, \\
u' &= u\left(z^2 - 2 + 3\,x^2 + \frac{3}{2}\Omega_m + 2u^2\right)\,,
\end{aligned}$$

Analysis of fixed points $(x'(N), y'(N), z'(N), u'(N)) = (0,0,0,0)$ gives insight into global cosmology – cosmological solutions correspond to orbits in the phase space (x, y, z, u) passing between fixed points.

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Flat case ($z = 0$) is an invariant subspace - stable fixed point is P_ϕ for $\lambda \leq \sqrt{3}$ – acceleration for $\lambda < \sqrt{2}$:

(x, y, u)	Ω_m	Existence	$w_{\rm eff}$	Stability
$P_{\rm kin}^{\pm} = (\pm 1, 0, 0)$	0	$\forall\ \lambda$	1	unstable/saddle
$P_\phi = \left(\frac{\lambda}{\sqrt{6}}, \pm\frac{\sqrt{6-\lambda^2}}{\sqrt{6}}, 0\right)$	0	$\lambda < \sqrt{6}$	$\frac{\lambda^2}{3} - 1$	stable for $\lambda \leq \sqrt{3}$/saddle for $\lambda > \sqrt{3}$
$P_{m\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{3}{2}}, \pm\frac{1}{\lambda}\sqrt{\frac{3}{2}}, 0\right)$	$1 - \frac{3}{\lambda^2}$	$\lambda > \sqrt{3}$	0	stable
$P_m = (0, 0, 0)$	1	$\forall\ \lambda$	0	saddle
$P_r = (0, 0, \pm 1)$	0	$\forall\ \lambda$	$\frac{1}{3}$	saddle
$P_{r\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{8}{3}}, \pm\frac{2}{\lambda\sqrt{3}}, \pm\sqrt{1-\frac{4}{\lambda^2}}\right)$	0	$\lambda > 2$	$\frac{1}{3}$	saddle

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$$x = \sqrt{\Omega_\phi \frac{(1+w_\phi)}{2}}\,, \quad y = \sqrt{\Omega_\phi - x^2}\,, \quad z = \sqrt{\Omega_k}\,, \quad u = \sqrt{\Omega_r}$$

With curvature – for $\lambda > \sqrt{2}$ – $P_{k\,\phi}$ with $w_{\rm eff} = -\frac{1}{3}$ is global attractor.

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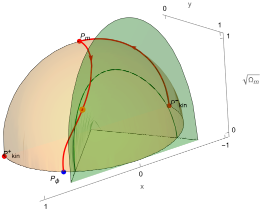
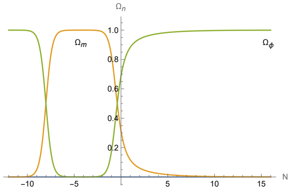
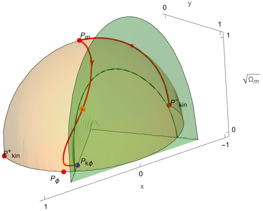
$P_{k\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{2}{3}}, \pm\frac{2}{\lambda\sqrt{3}}, \pm\sqrt{1-\frac{2}{\lambda^2}}, 0\right)$	0	$\lambda > \sqrt{2}$	$-\frac{1}{3}$	stable
$P_\phi = \left(\frac{\lambda}{\sqrt{6}}, \pm\frac{\sqrt{6-\lambda^2}}{\sqrt{6}}, 0, 0\right)$	0	$\lambda < \sqrt{6}$	$\frac{\lambda^2}{3} - 1$	stable for $\lambda \leq \sqrt{2}$/saddle for $\lambda > \sqrt{2}$
$P_{m\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{3}{2}}, \pm\frac{1}{\lambda}\sqrt{\frac{3}{2}}, 0, 0\right)$	$1 - \frac{3}{\lambda^2}$	$\lambda > \sqrt{3}$	0	saddle
$P_m = (0, 0, 0, 0)$	1	$\forall\,\lambda$	0	saddle
$P_r = (0, 0, 0, \pm 1)$	0	$\forall\,\lambda$	$\frac{1}{3}$	saddle
$P_{r\,\phi} = \left(\frac{1}{\lambda}\sqrt{\frac{8}{3}}, \pm\frac{2}{\lambda\sqrt{3}}, 0, \pm\sqrt{1-\frac{4}{\lambda^2}}\right)$	0	$\lambda > 2$	$\frac{1}{3}$	saddle

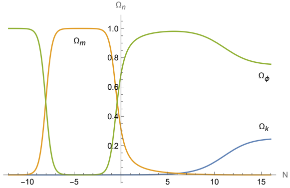
Impact of curvature on past, future and present

For $\lambda = \sqrt{\frac{8}{3}}$:









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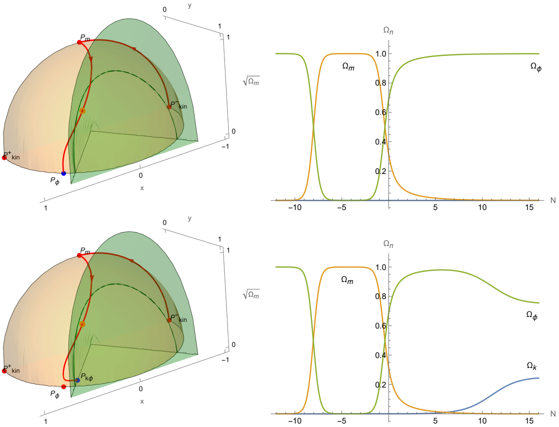

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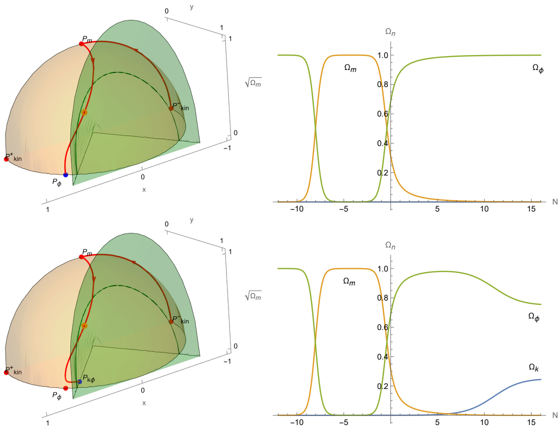

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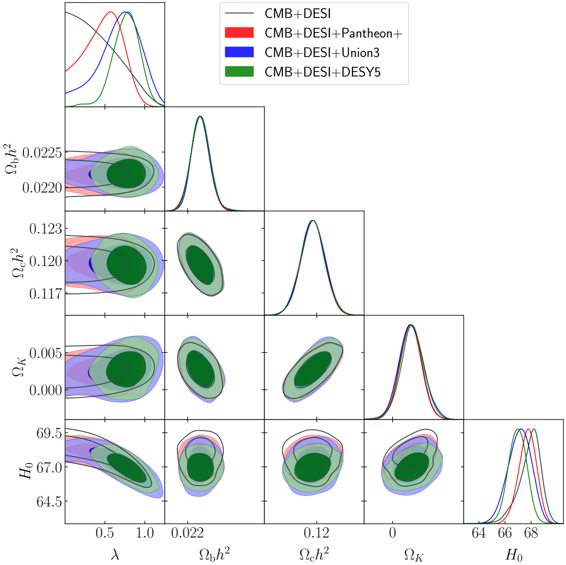
Minimal requirements of (1) past radiation domination and (2) acceleration today leads to upper bound $\lambda \lesssim \sqrt{3}$ (sensitive to $\Omega_{\phi 0}$ and Ω_{k0}, and pushed slightly up with curvature) $\Rightarrow$ viable stringy window $\sqrt{2} < \lambda \lesssim \sqrt{3}$?

Cosmological Constraints

Bhattacharya, Borghetto, Malhotra, SLP, Tasinato, Zavala '24;
Alestas, Delgado, Ruiz, Akrami, Montero, Nesseris '24
and Yashar Akrami's parallel session!
see also Ramadan, Sakstein, Rubin '24 for flat case

Solve background and perturbations to compute observables and use MCMC search for best fit parameters $\Rightarrow \lambda < \sqrt{2}$, eternal acceleration, event horizon.



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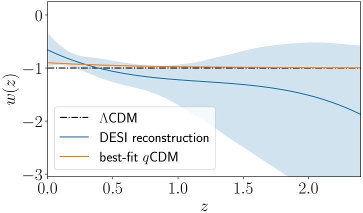
- Parameter means and 68% confidence limits:

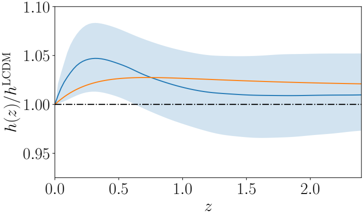
Parameter	CMB+DESI	+Pantheon+	+Union3+	+DESY5
λ	< 0.537	$0.48^{+0.28}_{-0.21}$	$0.68^{+0.31}_{-0.20}$	$0.77^{+0.18}_{-0.15}$
Ω_k	0.0026 ± 0.0015	0.0025 ± 0.0015	$0.0028^{+0.0016}_{-0.0019}$	0.0027 ± 0.0016
$\Omega_c h^2$	0.1196 ± 0.0012	0.1197 ± 0.0012	0.1195 ± 0.0012	0.1195 ± 0.0012
H_0	$67.89^{+0.96}_{-0.61}$	$67.73^{+0.72}_{-0.64}$	$67.12^{+0.97}_{-0.83}$	66.95 ± 0.72
$\Omega_b h^2$	0.02219 ± 0.00014	0.02219 ± 0.00013	$0.02220^{+0.00013}_{-0.00015}$	0.02221 ± 0.00013

- Model comparison using AIC $\equiv 2n - 2\ln \mathcal{L}_{\max}$: e.g. for CMD+DESI+Union3

$$\mathrm{AIC}_{w_0 w_a CDM} - \mathrm{AIC}_{qCDM} = -3 \quad \text{and} \quad \mathrm{AIC}_{qCDM} - \mathrm{AIC}_{\Lambda CDM} = -2.3.$$

- Model independent reconstruction of $w_{\mathrm{DE}}(z)$ and $h(z)$





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- More cosmological data to come - we can hope to know much more about Dark Energy in the near future and begin to rule out models and have favoured ones!