Dark energy as a probe of quantum gravity

Can we put string theory under pressure with forthcoming dark energy dedicated surveys?

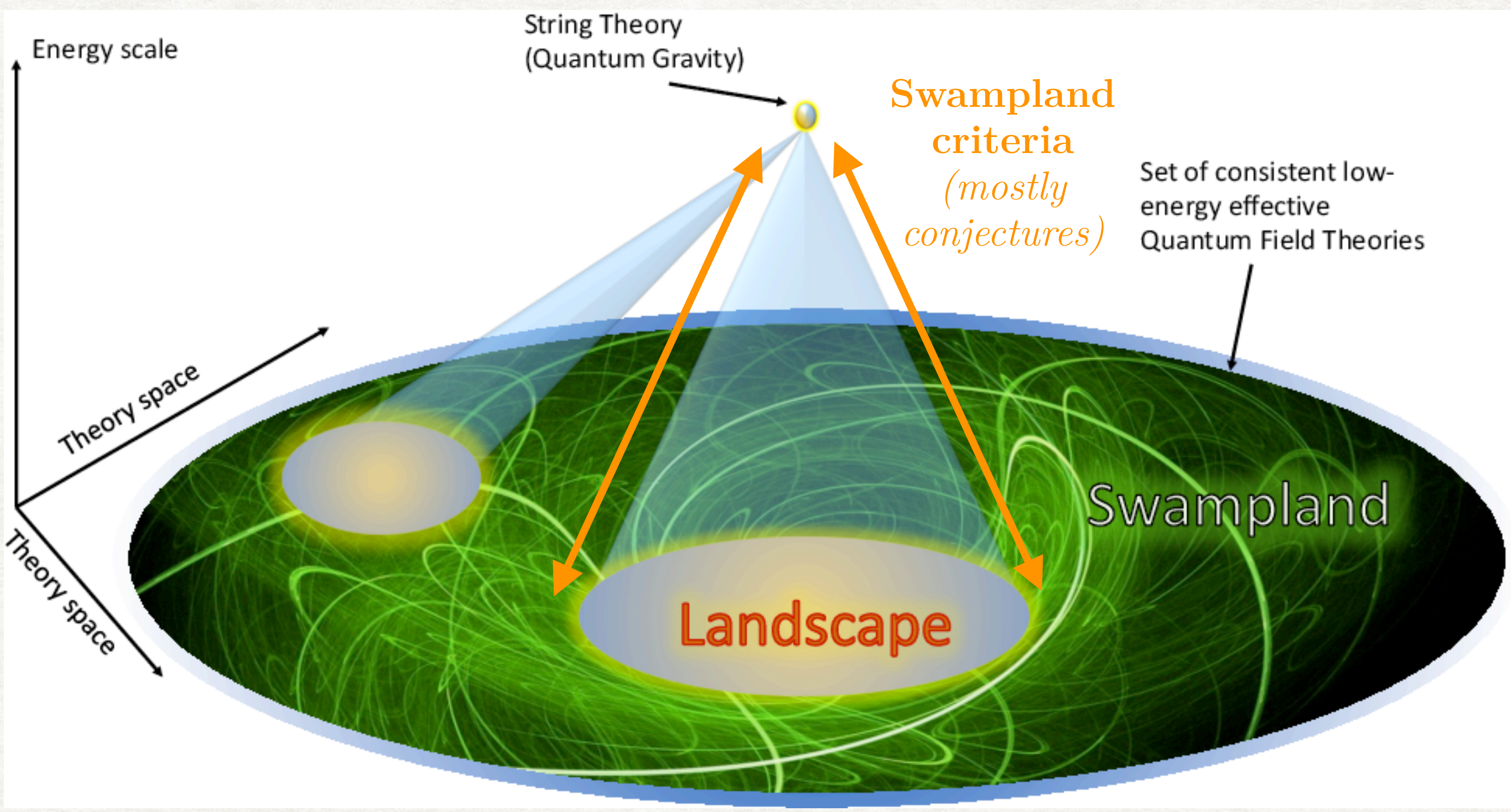
Based on a work done in collaboration with A. Barrau and C. Renevey

A. Barrau, C. Renevey, K.M (2021), Astrophys.J. 912, arXiv:2101.02942

The string swampland

Landscape vs Swampland

- **Landscape**: Set of (apparently) consistent effective field theories that **can** be completed into string theory / quantum gravity at higher energies.
- **Swampland**: Set of (apparently) consistent effective field theories that **cannot** be completed into string theory / quantum gravity at higher energies.



Huge and very active area of research in string theory

Scheme borrowed from: An Introduction to the String Theory Swampland (Lectures for BUSSTEPP), Eran Palti, 2018

The string swampland

A Swampland criterion: The de-Sitter conjecture

- **Scalar fields in a low energy effective theory lying in the landscape should satisfy:**

$$\lambda(\phi(t)) \equiv -\frac{V'(\phi(t))}{V(\phi(t))} \qquad |\lambda(\phi(t))| = \left|\frac{V'(\phi(t))}{V(\phi(t))}\right| > \lambda_c \sim \mathcal{O}(1)$$ *(In Planck units)*

G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa (2018), arXiv:1806.08362

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- **Some reliability criteria for this conjecture:**
  - Maldacena-Nunez no-go theorem for supergravity: $|\lambda(\phi(t))| \geq \frac{6}{\sqrt{(d-2)(11-d)}}$ *For a d-dimensional theory*
    J. Maldacena, C. Nunez (2000), arXiv:hep-th/0007018
  - Compactification of Type IIA on Calabi-Yau manifolds: $|\lambda(\phi(t))| \gtrsim 2$
    M. P. Hertzberg, S. Kachru, W. Taylor, M. Tegmark (2007), arXiv:0711.2512
  - Trans-Planckian Censorship Conjecture $\Rightarrow$ $|\lambda(\phi(t))| \geq \frac{6}{\sqrt{(d-1)(d-2)}} = \sqrt{\frac{2}{3}} \simeq 0.81(\text{ for } d=4)$
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Questions:

→ What are the perspectives for the constraints set by the Vera Rubin observatory, Euclid and SKA on λ_c?

→ Will those constraints be compatible with the de Sitter conjecture?

DOES THE OBSERVABLE UNIVERSE LIE IN THE SWAMPLAND?

Does our Universe lie in the Swampland?

Based on: A. Barrau, C. Renevey, K.M (2021), Astrophys.J. 912, arXiv:2101.02942

- **Main goal of this study:**

Probe the de-Sitter conjecture exclusion power from the viewpoint of **future** surveys.

Two major implications

- **First: assume a parametrization for w(z)**

M. Chevallier, D. Polarski, arXiv:gr-qc/0009008

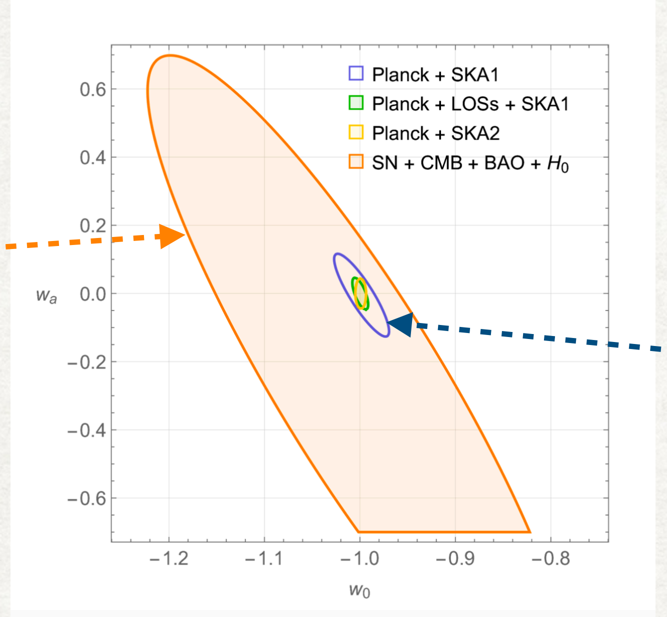
First order of a Taylor development: $$w(a(t)) = w_0 + (1 - a(t))w_a$$

Measure the contemporary value of w(a(t))

Measure the deviation in time of w(a(t))

- **Second: Forecasts for the forthcoming galaxy surveys and SKA in the w_0-w_a plane**

Current constraints (at 95% CL)



Expected improvements (at 95% CL)

Contour plots based on a bayesian MCMC developed by T. Sprenger, M. Archidiacono, T. Brinckmann, S. Clesse and J. Lesgourgues, JCAP 1902,047 (2019), arXiv 1801.08331

Does our Universe lie in the Swampland?

Context: Quintessence models for Dark Energy with one scalar field

- **Our set of equations**

Rewriting of the Friedmann and Klein-Gordon equations:

$$\frac{dw}{dt} = (w-1)\left[3(1+w) - \lambda\sqrt{3(1+w)\Omega_\phi}\right] \qquad \lambda(\phi(t)) \equiv -V'\phi(t)/V\phi(t)$$

$$\frac{d\Omega_\phi}{dt} = -3w\Omega_\phi(1-\Omega_\phi)$$

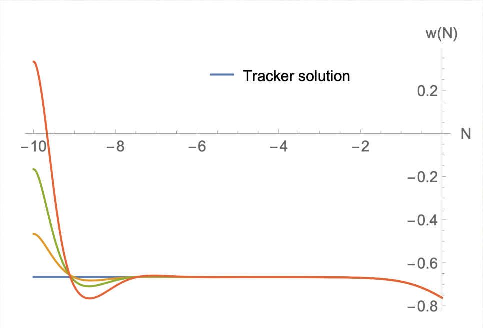
$$\frac{d\lambda}{dt} = -\sqrt{3(1+w)\Omega_\phi}(\Gamma - 1)\lambda^2 \qquad \Gamma(\phi(t)) \equiv V(\phi(t))V''(\phi(t))/\left[V'(\phi(t))\right]^2$$

- **Methodology**

→ i) Choose a model (i.e a scalar field potential)

→ ii) Fix a value for the parameters entering the model

→ iii) Set initial conditions for w, Ω_ϕ and λ - - - *No big dependence* - - →



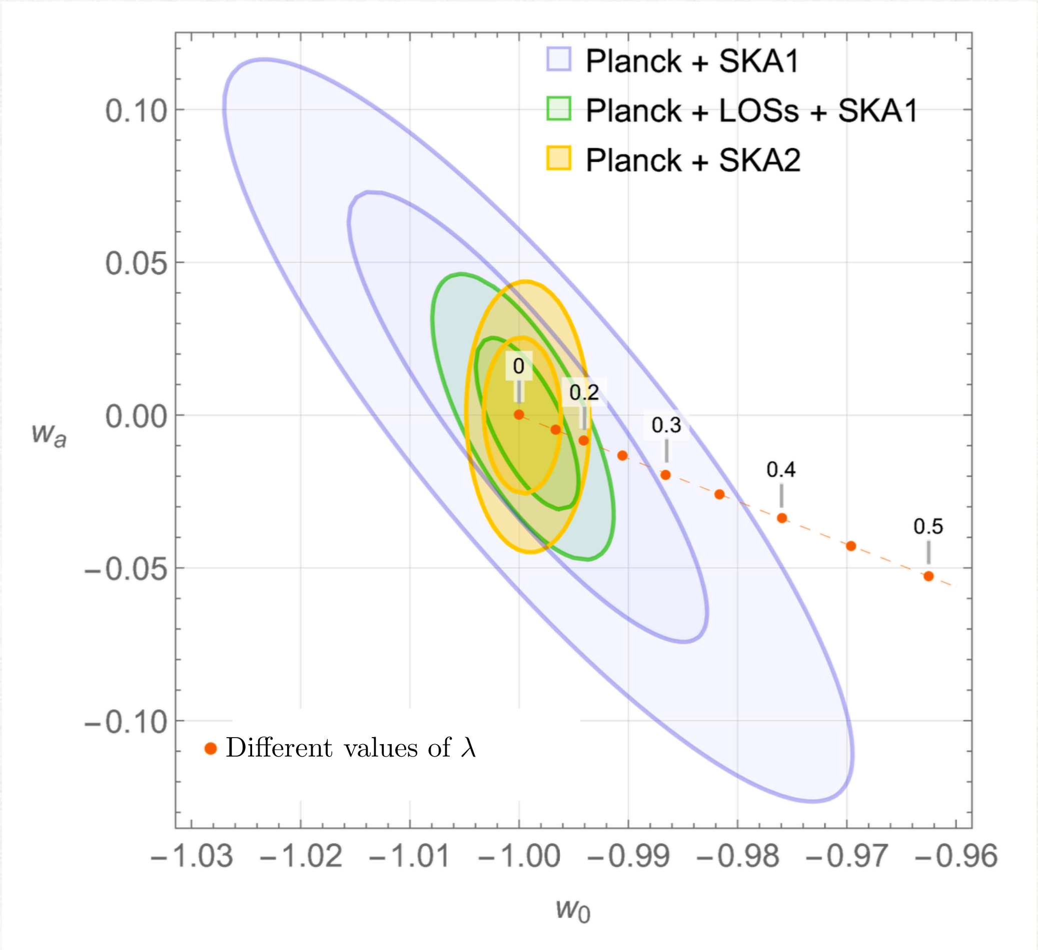
→ iv) Evaluate $|\lambda| = |V'/V|$ along the trajectory and keep its smallest value

→ v) To remain conservative, keep the highest of those lambda values (at fixed values of the parameters) within a 95% confidence level (CL) ellipse in the w_0 - w_a plane

Does our Universe lie in the Swampland?

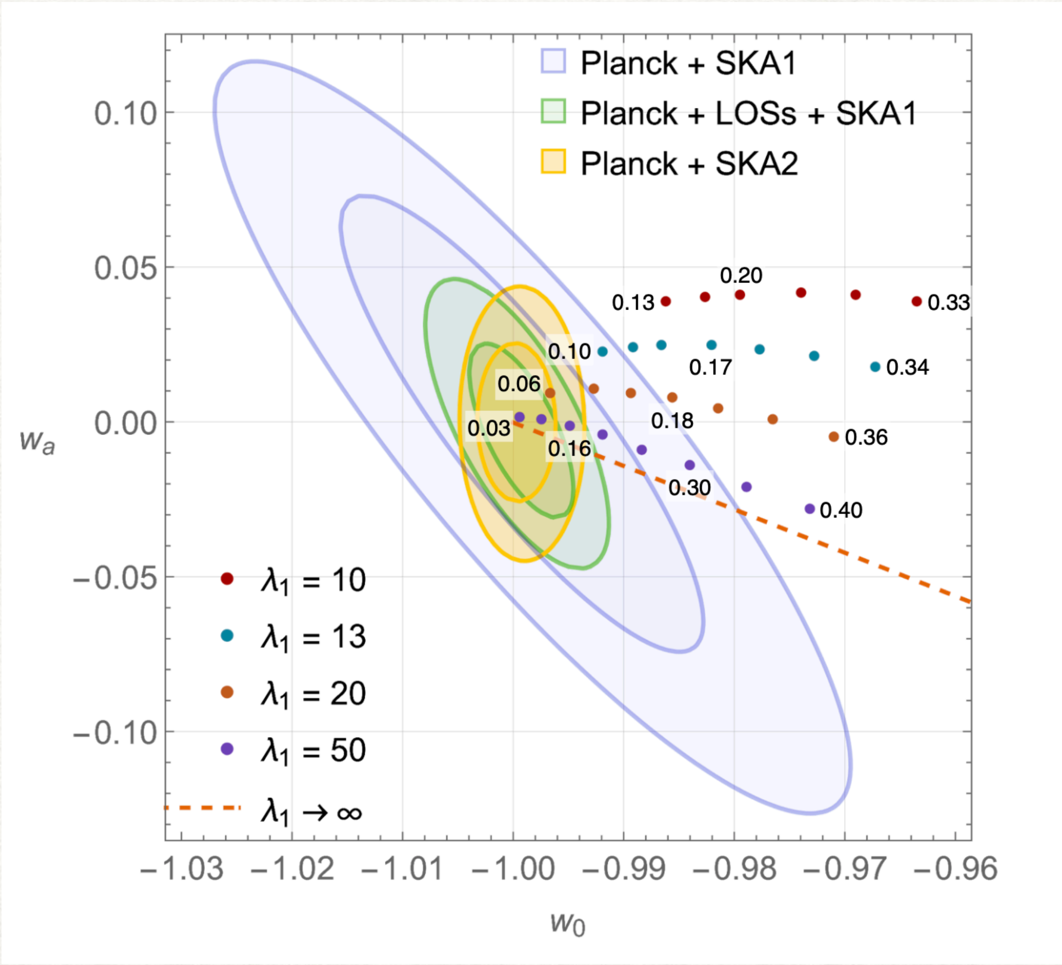
For scaling freezing models

Scalar field potential:
$V(\phi) = V_0 e^{-\lambda\phi}$



	Pl. + SKA1	Pl. + LOSs + SKA1	Pl. + SKA2
67% CL	$\lvert\lambda\rvert < 0.28$	$\lvert\lambda\rvert < 0.17$	$\lvert\lambda\rvert < 0.16$
95% CL	$\lvert\lambda\rvert < 0.36$	$\lvert\lambda\rvert < 0.22$	$\lvert\lambda\rvert < 0.20$

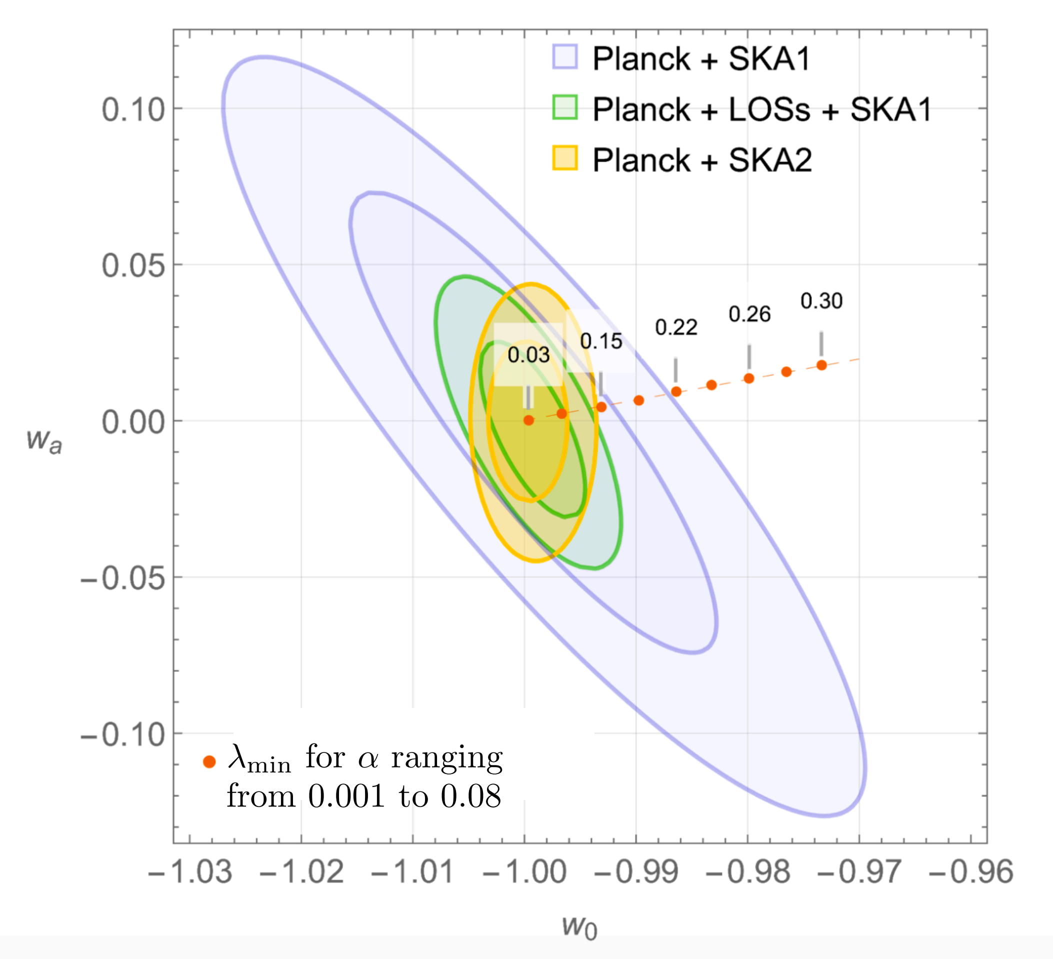
Scalar field potential:
$V(\phi) = V_1 e^{-\lambda_1\phi} + V_2 e^{-\lambda_2\phi}$



Does our Universe lie in the Swampland?

For tracking freezing models

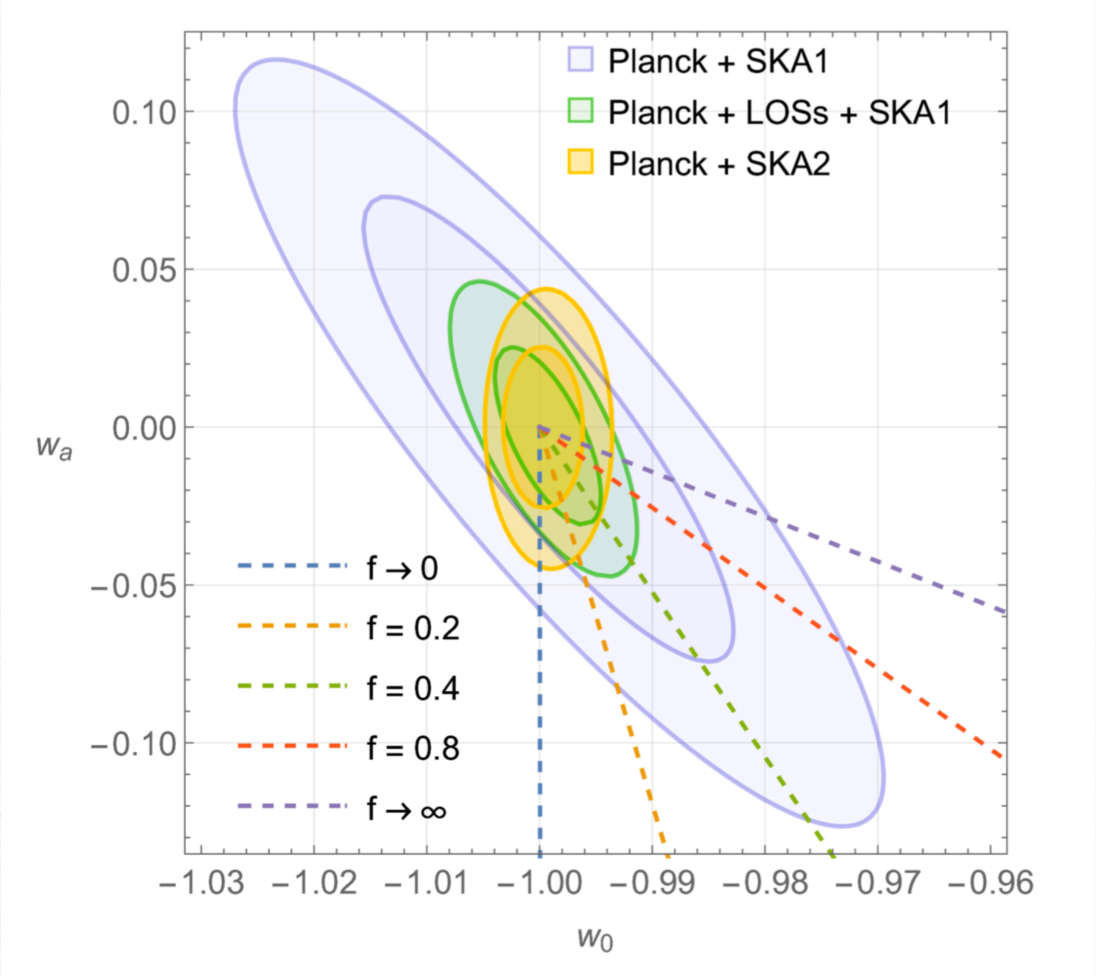
Scalar field potential:
$V(\phi) = M^{4+\alpha}/\phi^{\alpha},\ \alpha > 0$



	Pl. + SKA1	Pl. + LOSs + SKA1	Pl. + SKA2
67% CL	$\|\lambda\| < 0.16$	$\|\lambda\| < 0.11$	$\|\lambda\| < 0.11$
95% CL	$\|\lambda\| < 0.21$	$\|\lambda\| < 0.14$	$\|\lambda\| < 0.15$

For thawing models

Scalar field potential:
$V(\phi) = V_0 \cos(\phi/f)$



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Conclusion

Current observations: $|\lambda| = |V'/V| < 0.65$ at 95% C.L.

(SNIa, CMB and BAO data) *P. Agrawal, G. Obied, P. J. Steinhardt, C. Vafa (2018), arXiv:1806.09718*

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- **Main result:**

Putting all the constraints together and always keeping the most conservative one:

	Planck + (Vera Rubin + Euclid) + SKA1	Planck + SKA2
At 67% C.L.	$|\lambda| = |V'/V| < 0.16$	$|\lambda| = |V'/V| < 0.17$
At 95% C.L.	$\boxed{|\lambda| = |V'/V| < 0.22}$	$\boxed{|\lambda| = |V'/V| < 0.20}$

Whereas String theory requires: $\boxed{|V'/V| > \mathcal{O}(1)}$ **or** $\boxed{|V'/V| > \sqrt{2/3} \simeq 0.81}$

(Under the assumption of the de-Sitter conjecture)

In the large field limit, D. Andriot, et al. (2020), arXiv:2004.00030

Net improvement of the tension!

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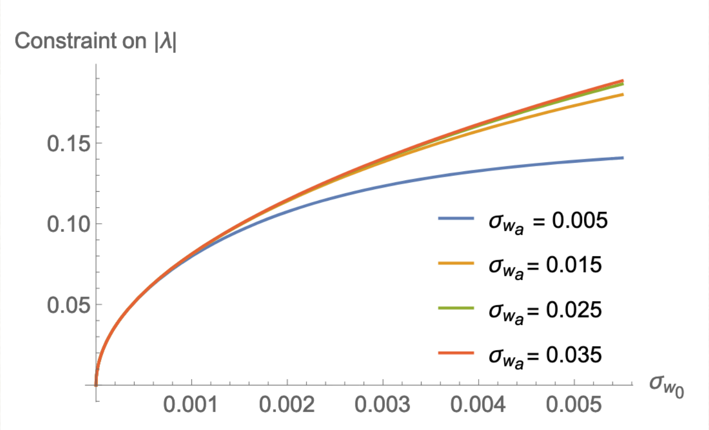
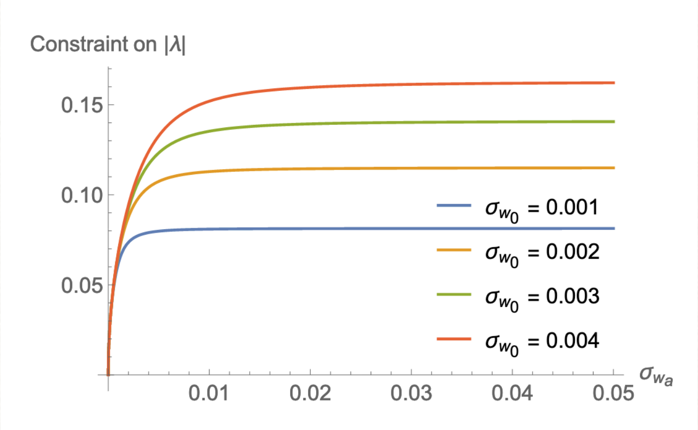
- **Prospects:**

Evolution of the constraint on $|\lambda|$ with ameliorations of the sensitivities on w_0 or w_a





Conclusion

Importance of the hypothesis

Weak

- **Drawbacks/hypotheses of this study**

→ Depends on a specific parametrization for w(z)
(Even though we picked the most commonly used and justified)

→ It exists a refined version of the de-Sitter conjecture

$$\left|\frac{V'}{V}\right| > \lambda_c \quad \textbf{OR} \quad \frac{V''}{V} < -\alpha_c$$

The one we used: $\left|\frac{V'}{V}\right| > \lambda_c$

(Does not change anything for tracking freezing and scaling freezing models as they always fail to satisfy the new condition)

→ The computation of the exact value of the minimal |λ| authorized by the de-Sitter conjecture is still work in progress

→ This study lie in the context of quintessence models with one scalar field

→ Based on a conjecture
But at this day not a single stable de-Sitter vacuum has been built in string theory!

Stronger

- **The final word**

The forthcoming Dark Energy surveys might put String Theory under serious pressure!

Thank you!