Falsifying STRING THEORY with the VERA RUBIN observatory?

on the de Sitter swampland conjecture

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The String Theory Swampland in the Euclid, Square Kilometer Array, and Vera Rubin Observatory Era

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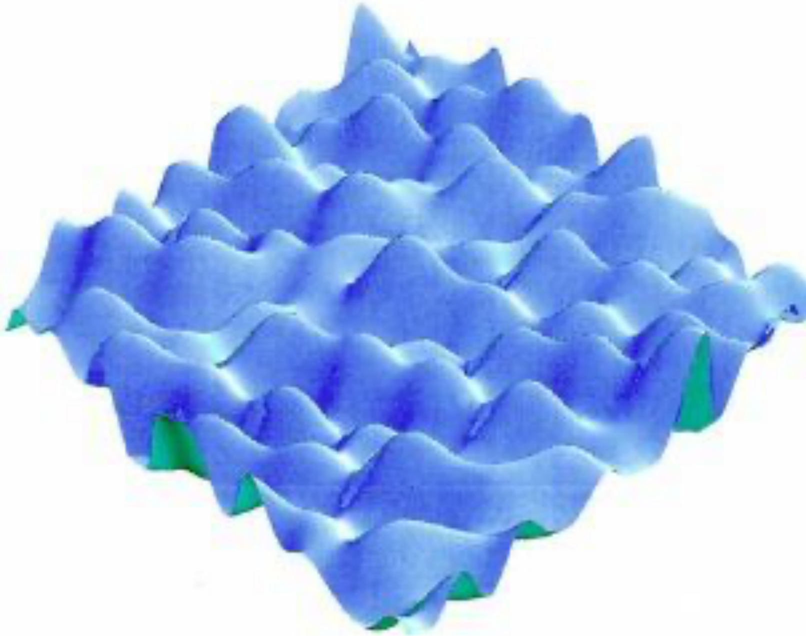
String theory

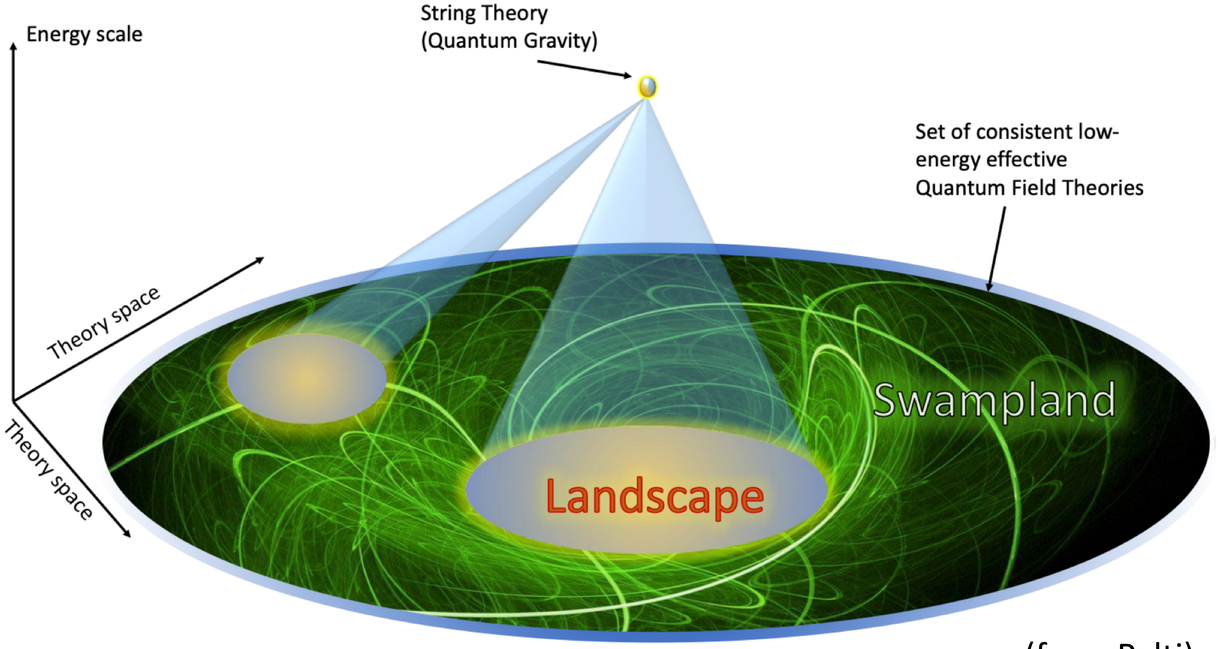
- Less a clearly defined axiomatic theory than a framework → Condensed matter, mathematics, black holes, etc.
- Falsifiability issue → cannot *anything* happening in Nature be accounted by string theory ? Is this science ?
- Many (unsuccessul) tests were suggested → we focus here on extremely « large-scale & low-energy » physics !

The swampland program



- String theory might be « unique » but its vacuua are not (C-Y manifolds + fluxes) !
- Landscape of effective low-energy theories → not necessarily a failure (multiverse)
  → It still raises falification issues at the *practical* level.
- However the size landscape might have been overestimated.

SWAMPLAND : the huge space of theories that seem compatible with (or possibly derived from) string theory but which, actually, are not.



(from Palti)

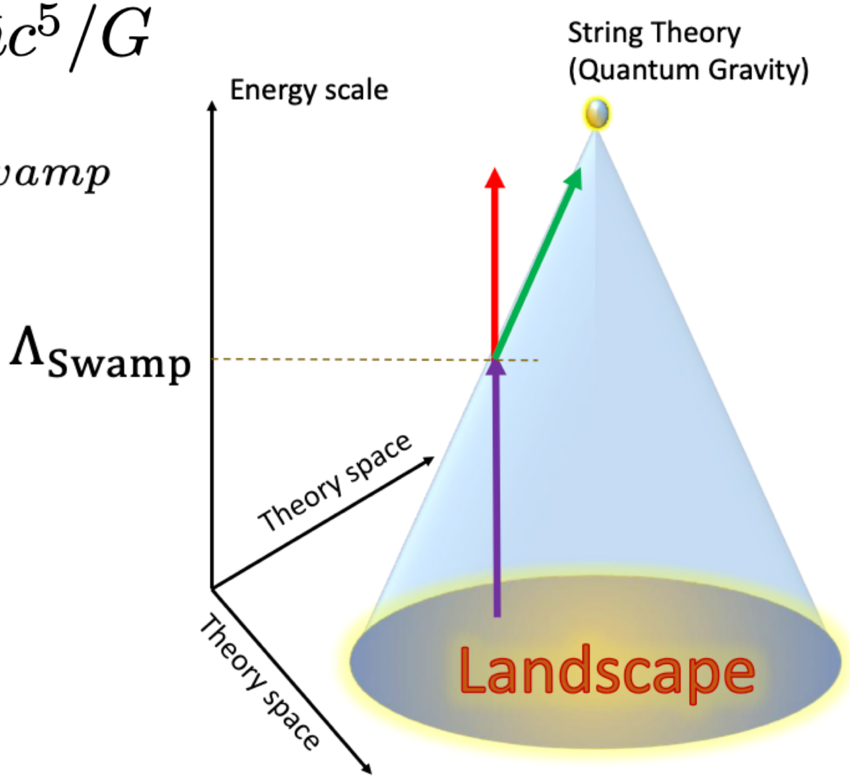
Huge space of theories that cannot be coupled to gravity.

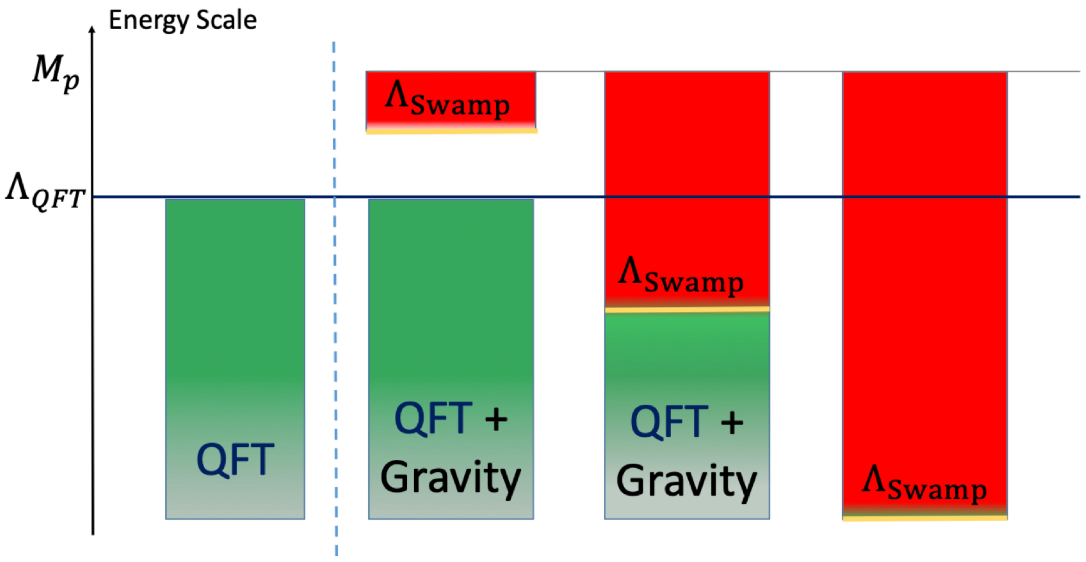
How to use this information ?
- as a guide for model building
- as a falsification tool

Stepping out of the « whater happens in Nature, string theory can account for it »

$\sqrt{\hbar c^5/G}$

E_{swamp}





(from Palti)

Ensemble of conjectures with very different reliability levels: from « theorems » to simple guesses.
A most important one is the distance conjecture. Many others : weak gravity, no global symmetry, completeness, emergence, non-SUSY AdS, Spin-2, etc.

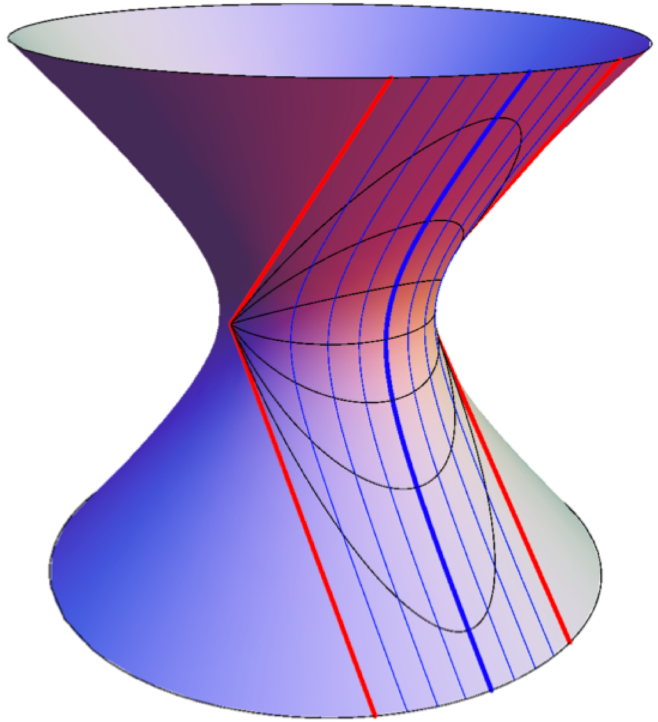
In the following, we focus on the *de Sitter conjecture* : **IT IS NOT POSSIBLE TO RESSEMBLE de SITTER TOO MUCH, that is a pure positive cosmological constant in Einstein's equations.**

The heart of the conjecture lies in the bet that the tremendous difficulties arising when trying to build a de Sitter vacuum are hints that such a state *does not exist at all* in the theory.

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Why is dS space so problematic ?

- SUSY
- AdS/CFT
- Stability
- Lifetime
- Transplanckian cencorship
- Unavoidable constraints



(from Fishler et al.)

→ it might be that the current acceleration is obtained dynamically by a scalar field rolling down a potential. In such a case, the conjecture might be compatible with the World but would constrain the shape of the potential.

$$S = \int d^4x \sqrt{-g} \left[R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right]$$

$$\frac{|V'|}{V} > \lambda_c$$

→ Particles physcis and EFTs. Adresses some coincidence problems.

$$\frac{|V'|}{V} > \lambda_c$$

In general, expected to be of order one. In some limits: $\lambda_c > \sqrt{2/3} \approx 0.82$

Current observations (Steinhardt, Vafa et al.) : $|V'|/V < 0.6$ Already in tension !

Why are we expecting V'/V not to be small ?

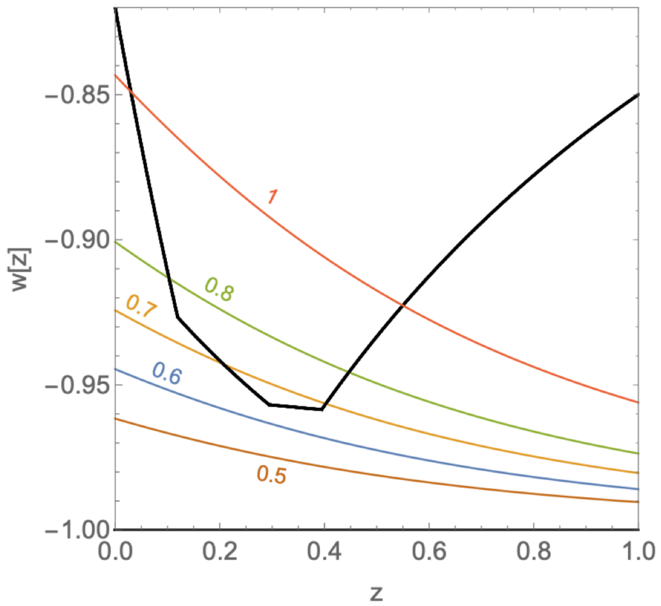
→ dS space is subtle. It has a horizon and an entropy.

→ the distance travelled by the field is linked with the dimension of the Hilbert space (itself linked with the entropy)

→ Thermodynamics (positive temp)

In principle, considering the primordial inflation leads to more stringent constraints. But this remains speculative.

→ We shall focus on DE quintessence models to investigate how the next generation of experiments can improve the limits on V'/V.



$$\lambda \equiv -V'/V$$

(from Agrawal et al.)

$$w \equiv p_\phi/\rho_\phi$$

Dark energy potentials

$$\frac{\ddot{a}}{a} = -\frac{1}{6}\sum_i (\rho_i + 3p_i) \qquad \frac{\ddot{a}}{a} = -\frac{1}{6}(\rho_m + 2\rho_R + \rho_\phi + 3p_\phi)$$

$p_\phi = \frac{1}{2}\dot{\phi}^2 - V$ is the only term that can be negative. This domination of the negative pressure of the scalar field has to happen very late in the cosmological history. And, if possible, for a wide range of initial conditions.

Big classes :

- in **freezing models** : the motion of the field gradually slows down because the potential becomes flat at low redshift.
- In **thawing model** : the field was initially frozen due to the Hubble friction (as during inflation) and it started evolving when the Hubble rate became small enough.

In a way, freezing models are more obviously answering the question of producing the required behavior of the Universe but thawing models are easier to build and, in this sense, more natural.

$$\Gamma \equiv VV''/(V')^2$$

$$\frac{dw}{dN} = (w-1)\left[3(1+w) - \lambda\sqrt{3(1+w)\Omega_\phi}\right],$$

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

$$\frac{d\lambda}{dN} = -\sqrt{3(1+w)\Omega_\phi}(\Gamma-1)\lambda^2,$$

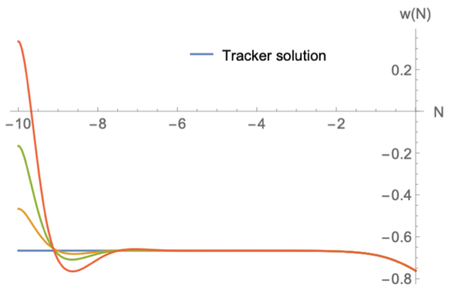
Tracking freezing

$$w \equiv p_\phi/\rho_\phi$$

$$V(\phi) = M^{4+\alpha}\phi^{-\alpha}$$

the scalar field “tracks” the background evolution. This means that the EOS parameter of the field, w, changes at the transition between radiation domination and matter domination. The field adapts itself to the scale factor behavior. Tracker and attractor.

(Epistemological point : iIn this case, the evolution begins at late times but has to remain weak to account for data.
In the limit t → ∞, this potential leads to w → −1 and −V ′/V → 0. This will inevitably violate the de Sitter conjecture at some point in the future.)



Scaling freezing

$$V(\phi) = V_0 e^{-\lambda\phi}; \qquad V(\phi) = V_1 e^{-\lambda_1\phi} + V_2 e^{-\lambda_2\phi}$$

The scaling solution itself corresponds to Ωm/Ωϕ = constant. It was shown to be realized at a known fixed point.

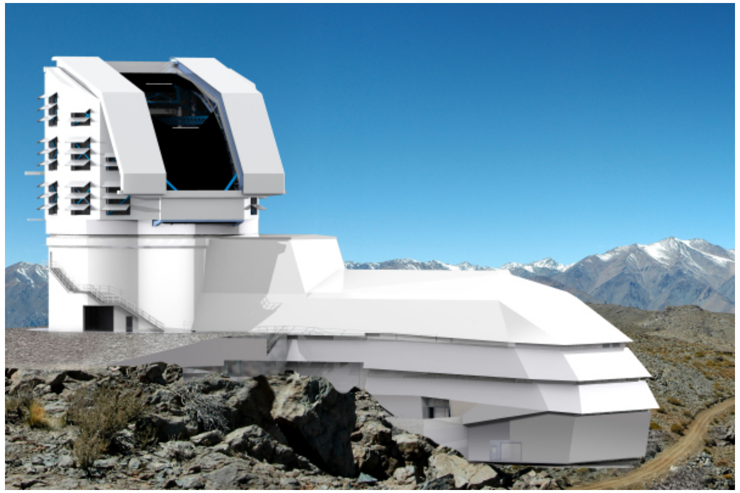
Thawing

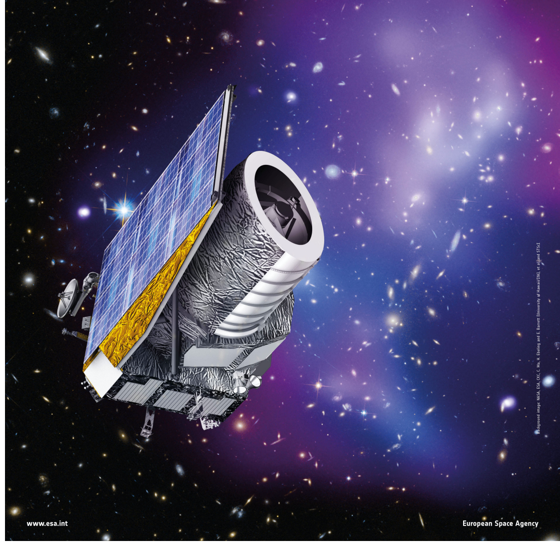
$$V(\phi) = V_0\left(1+\cos\left(\sqrt{2}\,\phi/f\right)\right) \quad \text{or}$$

$$V(\phi) = V_0\cos(\phi/f),$$

In this case, the evolution begins at late times but has to remain weak to account for data.

Experimental projections

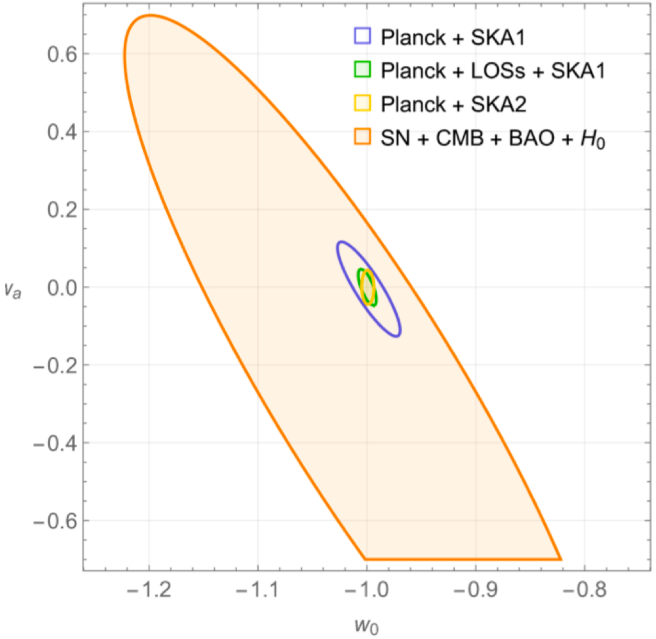




We use $w(a) = w_0 + (1-a)w_a$

The accurate evaluation of the constraints put on dark energy crucially depends on the way small scales are taken into account. This involves **general relativistic** corrections to the structure formation mechanisms, the **galaxy nonlinear bias**, the **intrinsic alignment** problem, the **feedback of baryons**, etc. The usual strategy has been to implement a cutoff scale below which data cannot be used. → Too crude.

We use non fully correlated nor fully uncorrelated errors.
MCMC simulation including massive neutrinos

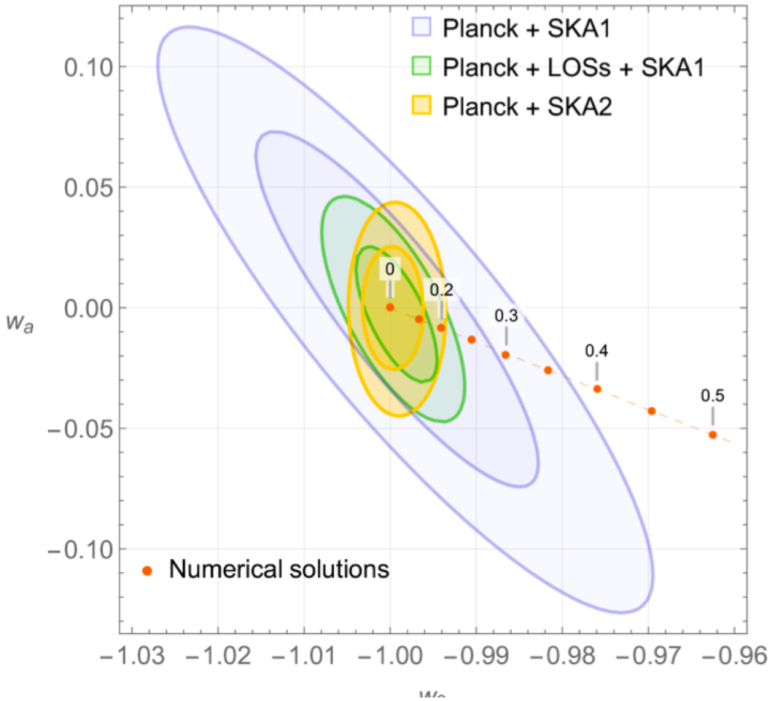


T. Sprenger, M. Archidiacono, T. Brinckmann, S. Clesse, and J. Lesgourgues, JCAP **1902**, 047 (2019), 1801.08331.

Methodology - Results

- For a given potential family, we vary both the initial conditions and the values of the parameters entering the model.
- For each simulation, we evaluate $|\lambda| = |V'|/V$ along the trajectory and keep its most relevant (that is smallest) value.
- Then, to remain conservative, we keep the highest of those $|\lambda|$ values within a given confidence level (CL) ellipse in the $w_0 - w_a$ plane for different forecasts

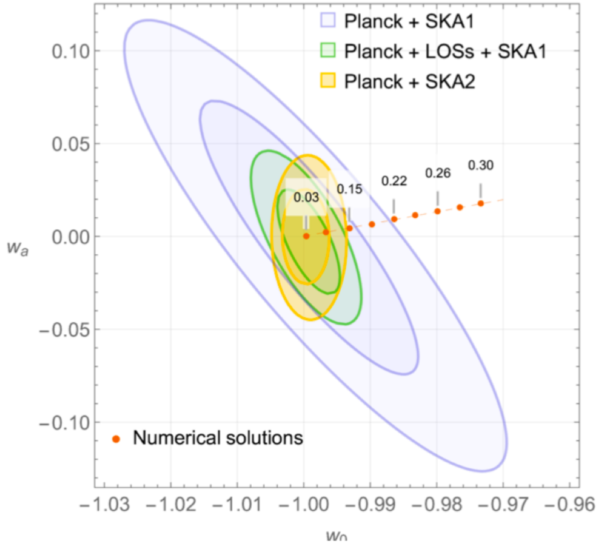
To summarize intuitively: for each parameter choice and initial conditions, we compute (w_0, w_a) and $-V'/V$ and evaluate how observational constraints on the first can constrain the second, in the most reliable and conservative way.



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

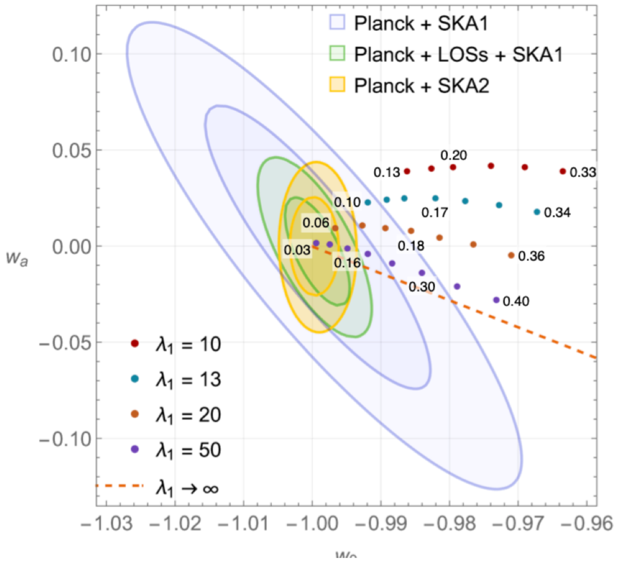
TABLE II. Expected constraints on $|V'|/V$ for *tracking freezing models*, based on the potential given by Eq. (9).

Results



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

TABLE I. Expected constraints on $|V'|/V$ for an exponential potential, as given by Eq. (11). Those constraints are also valid for generic *scaling freezing* models described by Eq. (14).



	Pl. + SKA1	Pl. + LOSs + SKA1	Pl. + SKA2
67% CL	$\|\lambda\| < 0.27$	$\|\lambda\| < 0.17$	$\|\lambda\| < 0.16$
95% CL	$\|\lambda\| < 0.35$	$\|\lambda\| < 0.22$	$\|\lambda\| < 0.20$

TABLE III. Expected constraints on $|V'|/V$ from different sets of experiments for *thawing* models with the potential given by Eq. (16). Unlike previous models the limit is obtained in the past. To remain conservative, the limit $f \to \infty$ was considered, which corresponds to the less stringent case.

Finally :

$|V'|/V < 0.16$ at 67% CL $\qquad$ $|V'|/V < 0.20$ at 95%

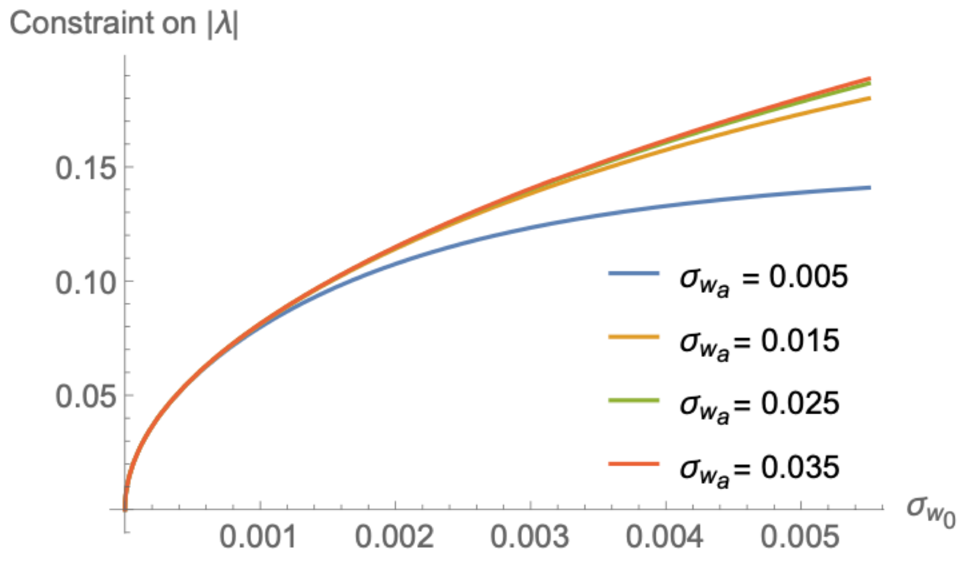
Refined conjecture – drawbacks

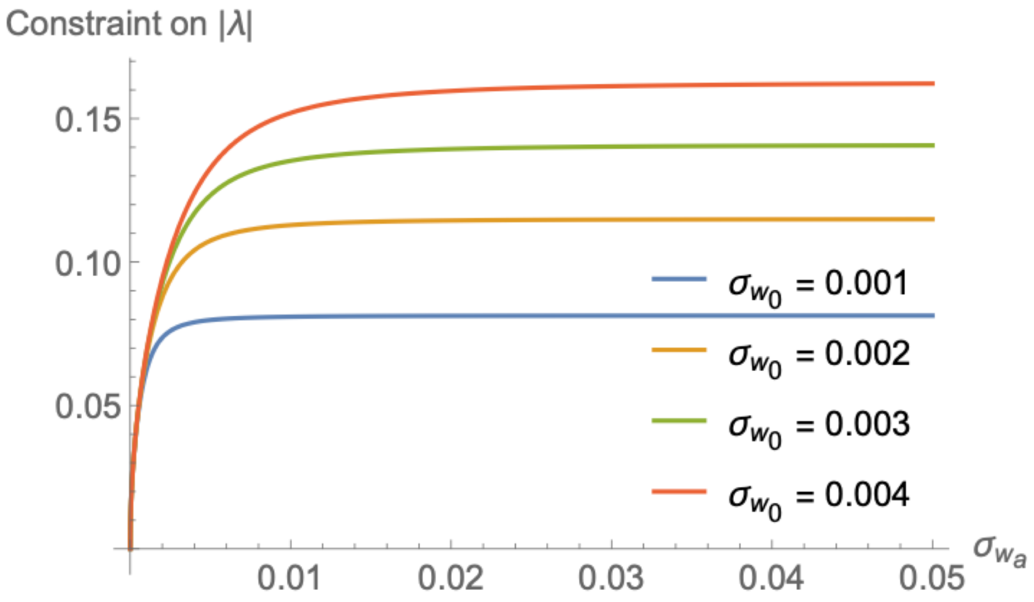
$$\frac{|V'|}{V} > \lambda_c \quad \text{or} \quad \frac{V''}{V} < -\alpha_c$$

Possible loophole in the methodology !

Fine with tracking freezing and scaling freezing models this always fails. However problematic with thawing models. → constraints on f expected from particle physics + the actual potential could be reconstructed by a combined cosmological analysis

Prospects





Conclusions 1

Is the de Sitter conjecture reliable ? My guess is : most probably **yes**.

The landscape of string theory does contain Minkowski solutions. **The richness of the structure is nearly infinite**. Each geometry can support more than 10^10^5 flux vacua and the number of compactification geometries is higher than 10^1000. However, **constructing a single metastable de Sitter solution is highly problematic** and this is the main underlying motivation for the conjecture.

It is well established that **de Sitter solutions cannot be found in regions of parametric control in string theory**.

Many no-go theorems were derived and quite a lot of concrete examples support the possibility that string theory just cannot admit any de Sitter vacuum.

Still, counterarguments are being built, around the Kachru-Kallosh-Linde-Trivedi (KKLT) proposal. Nothing is yet firmly established.

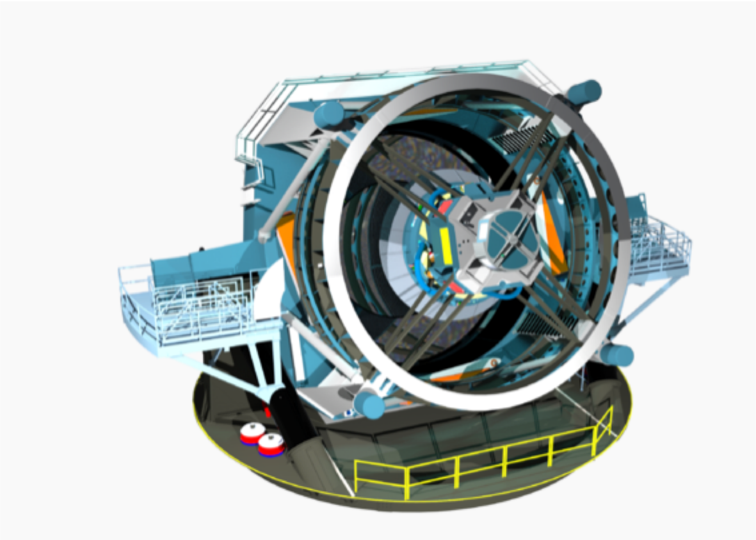
Conclusions 2

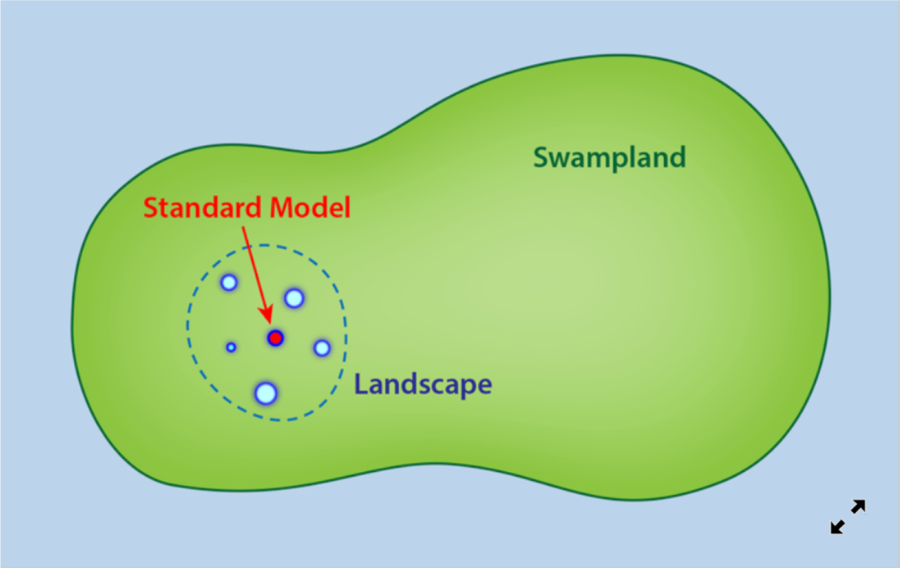
The next generation is expected to reach : $|V'|/V < 0.16$

Quite strong tension with the string swampland !

Howere showing that the real world does not fulfill the de Sitter conjecture would unquestionably not be enough to fully discard string theory (the swampland program might be wrong). But, among other indications, it might play a role in a possible paradigm shift.

A reliable theoretical lower bound is needed.





APS/Alan Stonebraker

Whatever the end of this story is, this is exciting both at the scientific and at the philosophical levels.