Dark energy as a probe of quantum gravity

Can we put quantum gravity theories under pressure with forthcoming dark energy dedicated surveys?

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

About Dark Energy

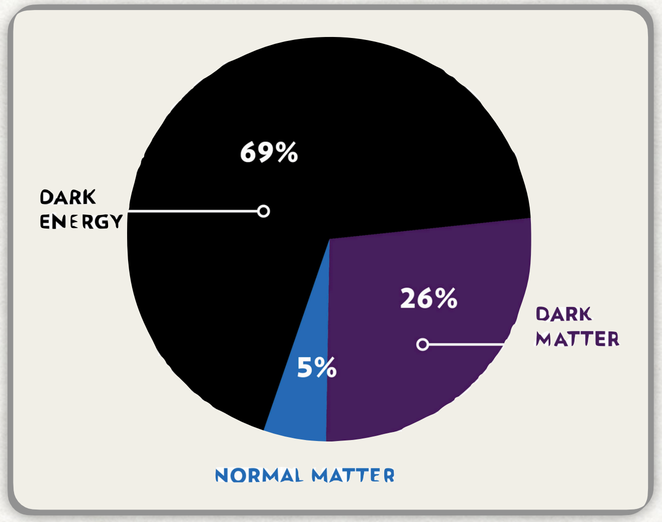
- Dark Energy is responsible for the acceleration of the Universe expansion

- Observed by different probes
  - → Type IA supernovae
  - → Cosmic Microwave Background (CMB)
  - → Baryon Acoustic Oscillations (BAO)

- Which fraction of the Universe is under the form of Dark Energy (DE)?

$$\boxed{\Omega_\Lambda = 0.6889 \pm 0.0056}$$

Planck 2018: TT, TE, EE + lowE + Lensing + BAO



- What it teaches us
  - → Most of the energy in the Universe is not matter
  - → Most of the energy in the Universe is not gravitationally attractive!

About Dark Energy

First possibility: a cosmological constant

- **Einstein equations:**

Space-time geometry

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

Energy content

Cosmological constant

$\sim 10^{-43} \ll 1$ *Space-time is extremely hard to distord*

- **Hypotheses:**

Homogeneous and isotropic Universe + Ideal gas

- **First Friedmann equation:**

Universe dynamics

$$\boxed{H^2(t) \equiv \left(\frac{\dot{a}(t)}{a(t)}\right)^2} = \frac{8\pi G}{3}\boxed{(\rho_{\text{rad}}(t) + \rho_{\text{mat}}(t)) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}}$$

Energy content

$\propto a(t)^{-4}$ $\propto a(t)^{-3}$ $\propto a(t)^{-2}$ Constant

A cosmological constant would unavoidably dominate the energy content in an expanding Universe

About Dark Energy

First possibility: a cosmological constant

- **Stress-energy tensor conservation laws:**

$$T^{\mu\nu}{}_{;\nu} = 0$$

Covariant derivative

- **Hypotheses:**

Homogeneous and isotropic Universe + Ideal gas

- **Continuity equation:**

$$\dot{\rho}(t) = -3H(t)\left[\rho(t) + P(t)\right]$$

Energy density *Pressure*

Together with the first Friedmann equation

$$\Downarrow$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho(t) + 3P(t)\right] + \frac{\Lambda c^2}{3}$$

A Universe dominated by $\Lambda > 0$ undergoes an accelerated expansion with $\ddot{a} > 0$

About Dark Energy

First possibility: a cosmological constant

- **Some related ~~problems~~ → open questions?**

  - $$\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} = \frac{8\pi G}{c^4}\overset{= 0 \text{ in vacuum}}{\cancel{T_{\mu\nu}}} - \Lambda g_{\mu\nu}$$

    With a cosmological constant term, empty space is no longer flat!

    → Tempting to interpret Λ as the vacuum energy density

    Its interpretation in terms of QFT is « *The worst prediction ~~in~~ the history of physics* »

    Is it really the case?

  - **Phase transitions**

    Phase transitions (such as the electroweak or QCD phase transitions) contribute to the vacuum energy

    The vacuum energy cannot vanish **before and after** the phase transition!

  - **We live at a special moment in the Universe history**

    $\Omega_\Lambda \sim \Omega_{\text{matter}}$ « *Coincidence problem* »

About Dark Energy

An other possibility: generated by a scalar field dynamics

« Quintessence models »

- **How?**

Reminder: $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left[\rho(t) + 3P(t)\right] + \frac{\Lambda c^2}{3}$$

Instead of $\Lambda > 0$, vanishing cosmological constant and a matter content which satisfies:

$$w(t) = \frac{P(t)}{\rho(t)} < -\frac{1}{3} \Rightarrow \ddot{a}(t) > 0$$ *Accelerated expansion*

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- **For a scalar field:**

$$S_\phi = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] \xrightarrow[\text{Universe}]{\text{FLRW}} \begin{cases} T^0_0 = \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \\ T^i_j = -P_\phi\delta^i_j = -\left[\frac{1}{2}\dot{\phi}^2 - V(\phi)\right]\delta^i_j \end{cases}$$

$$\Rightarrow w(t) = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)} \xrightarrow{\frac{1}{2}\dot{\phi}^2 \ll V(\phi)} \boxed{w(t) = \frac{\cancel{\frac{1}{2}\dot{\phi}^2} - V(\phi)}{\cancel{\frac{1}{2}\dot{\phi}^2} + V(\phi)} \simeq -1}$$

Comparison with primordial inflation

- **This « slow-roll » regime is already a success for describing primordial inflation**

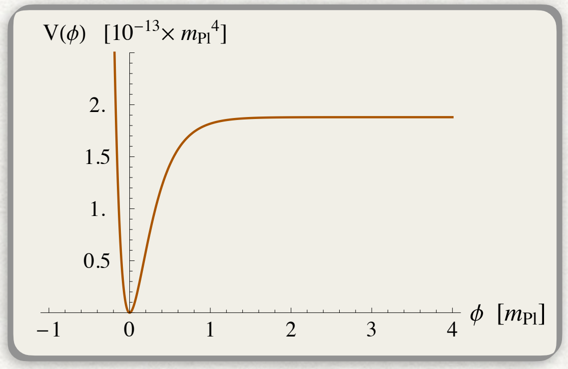
Requirement: $\frac{1}{2}\dot{\phi}^2 \ll V(\phi)$

→ *« Plateau-like » shaped potentials*

Example:
Starobinsky potential

$$V(\phi) = \frac{3m^2}{32\pi}\left(1 - e^{-\sqrt{\frac{16\pi}{3}}\phi}\right)^2$$

$$m = 2.51 \times 10^{-6}\mathrm{m}_{\mathrm{Pl}}$$



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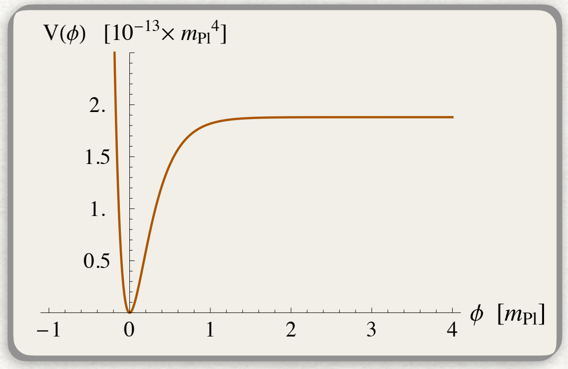

- **The Universe dynamics also slows-down the scalar field**

Klein-Gordon equation in an isotropic and homogeneous FLRW Universe:

$$\boxed{\ddot{\phi}(t) + \underbrace{\boxed{3H(t)\dot{\phi}(t)}}_{\text{Hubble friction}} + \frac{dV(\phi(t))}{d\phi(t)} = 0} \qquad H(t) \equiv \frac{\dot{a}(t)}{a(t)}$$

→ Important for primordial inflation because $H \simeq$ Inflation energy scale

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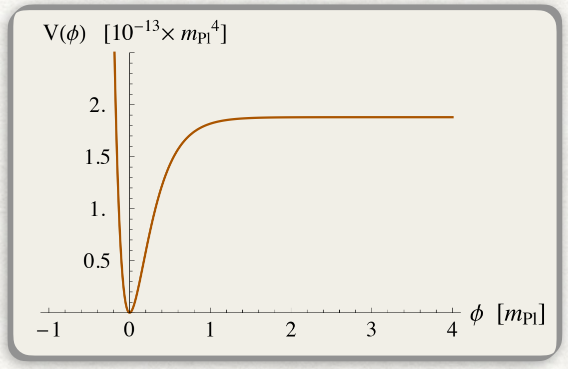

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- **Simplest models with only one scalar field are in very good agreement with data**

  (Almost) scale invariant primordial scalar power spectrum, no deviations from gaussian hypothesis, …

  BUT: Only toy models, less motivated by high energy physics → Need for more complex models?

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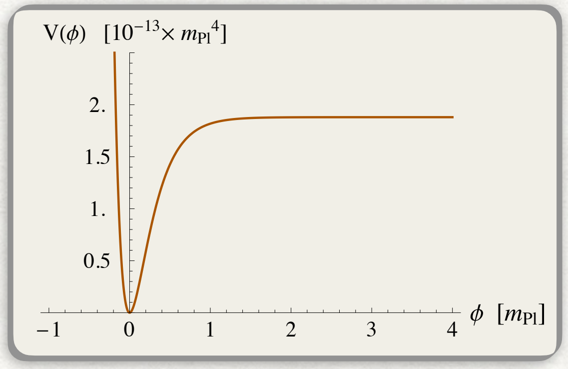

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◆ **Simplest models with only one scalar field are in very good agreement with data**

(Almost) scale invariant primordial scalar power spectrum, no deviations from gaussian hypothesis, …

BUT: Only toy models, less motivated by high energy physics → Need for more complex models?

- **BUT: additional difficulties when trying to apply the same method for DE**

The process needs to start at late times, Hubble friction is much much lower, …

Dark Energy models

1st class: Freezing models

- **Freezing models:** « **The motion of the field slows down because the potential flattens at low redshifts** »

BUT: *The energy density of the scalar field must remain subdominant in most of cosmological history and only emerge at late times*

- One possibility: **scaling freezing models**

ρ_ϕ mimics the background energy density

$\frac{\rho_b}{\rho_\phi} = \text{cste}$ ⟶ **Whatever the initial conditions are!**

But, in this regime: $w_\phi = w_b \longrightarrow \begin{cases} = 0 > -1/3 \text{ for cold matter} \\ = 1/3 > -1/3 \text{ for radiation} \end{cases}$

No acceleration of the expansion

- **Exit from scaling regime:**

Tracking solutions that acts as **attractors** and drive w towards $w <$ -1/3

Existence condition: $\Gamma(\phi(t)) \equiv V(\phi(t))V''(\phi(t))/\left[V'(\phi(t))\right]^2 > 1 \ , \forall t$

- **Example of associated scalar-field potential**

$$\boxed{V(\phi) = V_1 e^{-\lambda_1 \phi} + V_2 e^{-\lambda_2 \phi}} , V_1, V_2, \lambda_1, \lambda_2 = \text{cstes}$$

Dark Energy models

2nd class: Thawing models

- **Thawing models:**

- **The field is frozen due to the Hubble cosmic friction for most of the cosmic history**
- **With the decrease (in time) of H, friction becomes subdominant and a non-zero kinetic term develops**

$\Longrightarrow$ **The field begins to roll and w evolves away from -1 at late times!**

(But has to remain weak to account for data)

- **Example of associated scalar-field potential**

$$\boxed{V(\phi) = V_0\left(1 + \cos(\sqrt{2}\phi/f)\right)} \quad \textit{with } V_0,\ f\ = \textit{cstes}$$

Is Dark Energy dynamical or not?

- **Big forthcoming experiments will bring part of a solution**

Vera Rubin Observatory

- US-lead project
- First light in 2023, survey in 2024
- **Telescope:** 8.4m primary mirror
  focal length 10.3 m, 9.6 deg^2 field of view
- **Camera:** 3.2 Gigapixels (CCD)
- **The LSST** (the survey): $\simeq$ 18000 deg^2
  20 billions galaxies
  During 10 years
  In six filters (from UV to near IR)
  Cadence optimized for transients
  → **SNIa machine!**
- **Data:** 20 TB/night (= 4200 DVD/night)
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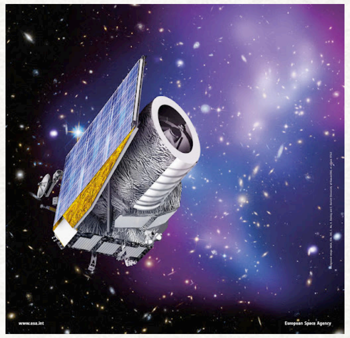
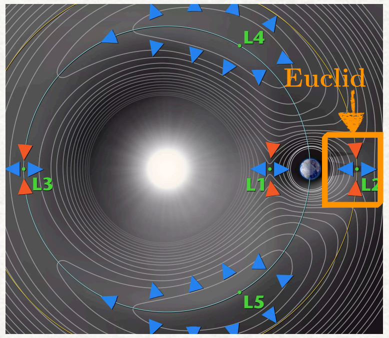
Euclid





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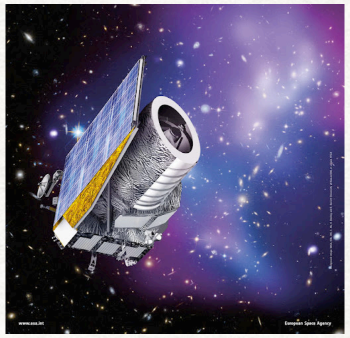

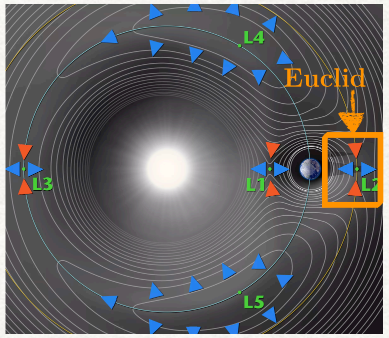

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Square Kilometer Array

- International project (more than 15 countries involved)
- Construction scheduled for 2021-2022
  Science observations: late 20's
- **Low-frequency telescope array:**
  In Australia: ~130 000 antennas
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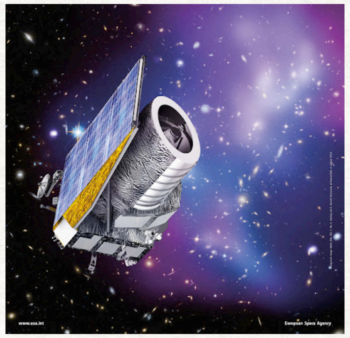

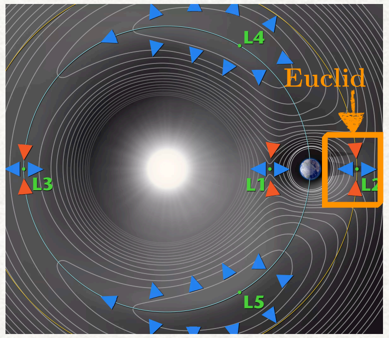

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Upcoming complementary experiments in cosmology

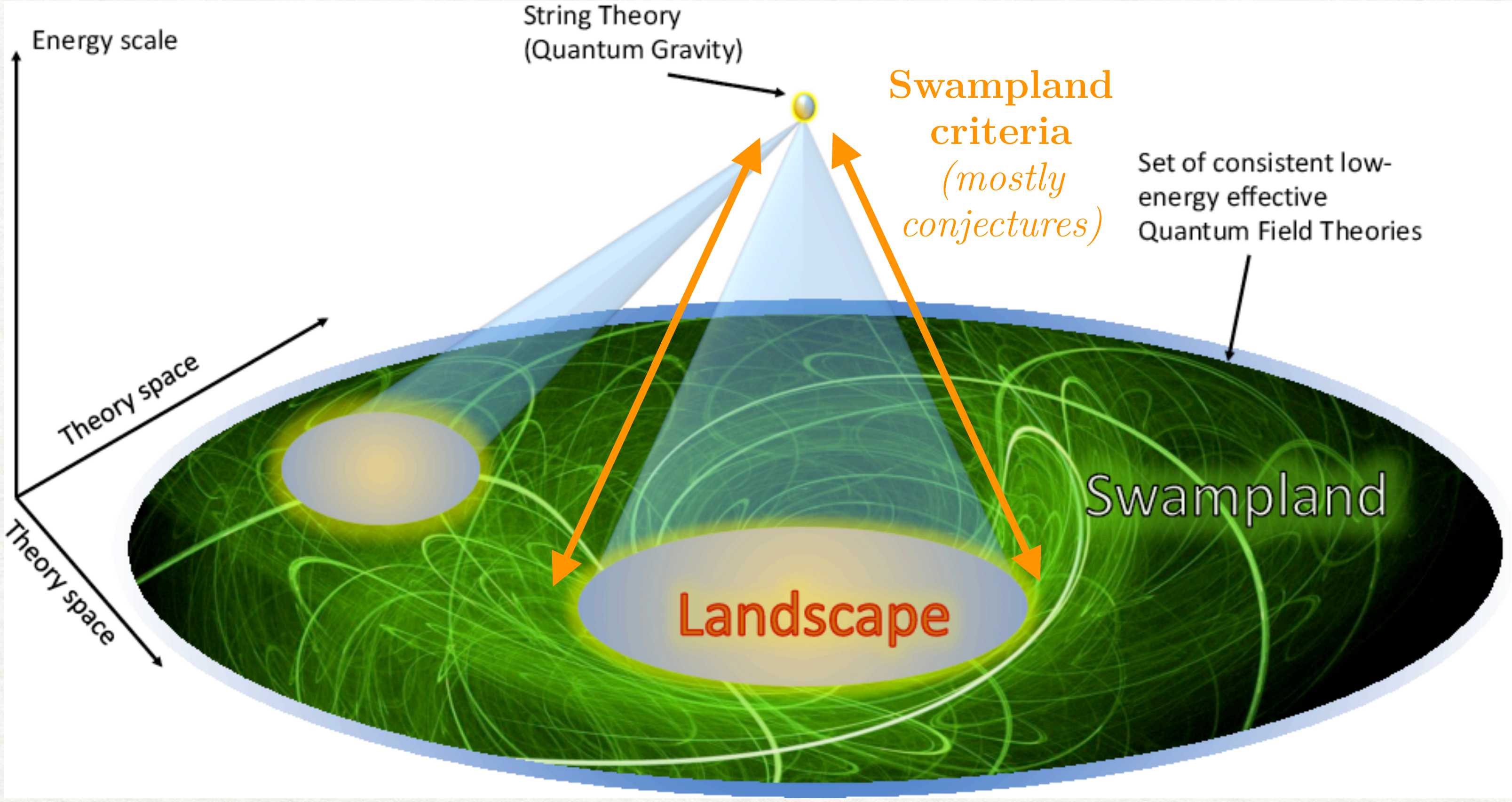
Synergies for photo-z, weak lensing, cluster masses estimates, transient measurements …

→ **Will enhance the (already existing) constraints on w(z)** ←

The string swampland

Swampland vs Landscape

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

- **An effective theory for quantum gravity, i.e not in the swampland, should satisfy:**

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

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 $\Rightarrow \boxed{|\lambda(\phi(t))| \geq \frac{6}{\sqrt{(d-1)(d-2)}} = \frac{2}{\sqrt{3}} \simeq 0.81(\text{ for } d=4)}$
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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:

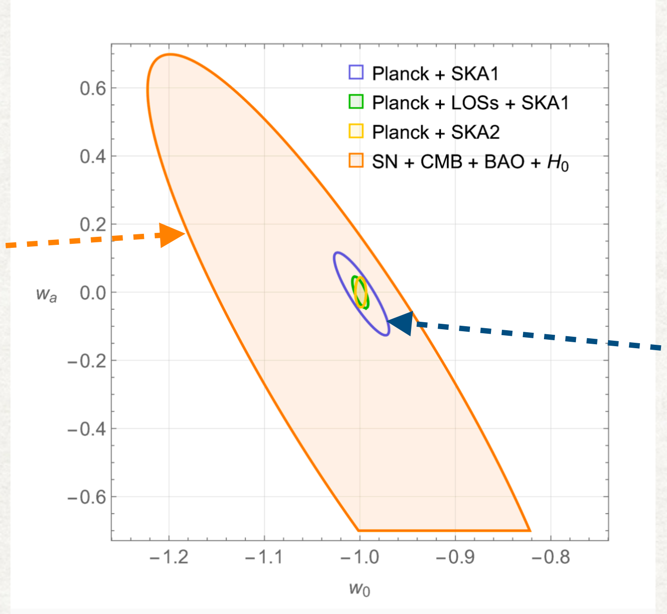
$$w(a(t)) = w_0 + (1 - a(t))w_a$$

$$1 + z(t) = \frac{a(t)}{a(t_{\text{emission}})}$$

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

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

- **Second: evaluate the theoretical uncertainties**



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?

- **Our set of equations**

Rewriting of the Friedmann and Klein-Gordon equations:

$$\boxed{\begin{aligned} \frac{dw}{dt} &= (w-1)\left[3(1+w) - \lambda\sqrt{3(1+w)\Omega_\phi}\right] \\ \frac{d\Omega_\phi}{dt} &= -3w\Omega_\phi(1-\Omega_\phi) \\ \frac{d\lambda}{dt} &= -\sqrt{3(1+w)\Omega_\phi}(\Gamma-1)\lambda^2 \end{aligned}}$$

$$\lambda(\phi(t)) \equiv -V'\phi(t)/V\phi(t)$$

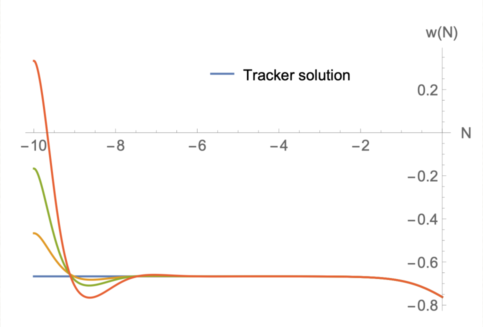
$$\Gamma(\phi(t)) \equiv V(\phi(t))V''(\phi(t))/\left[V'(\phi(t))\right]^2$$

- **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

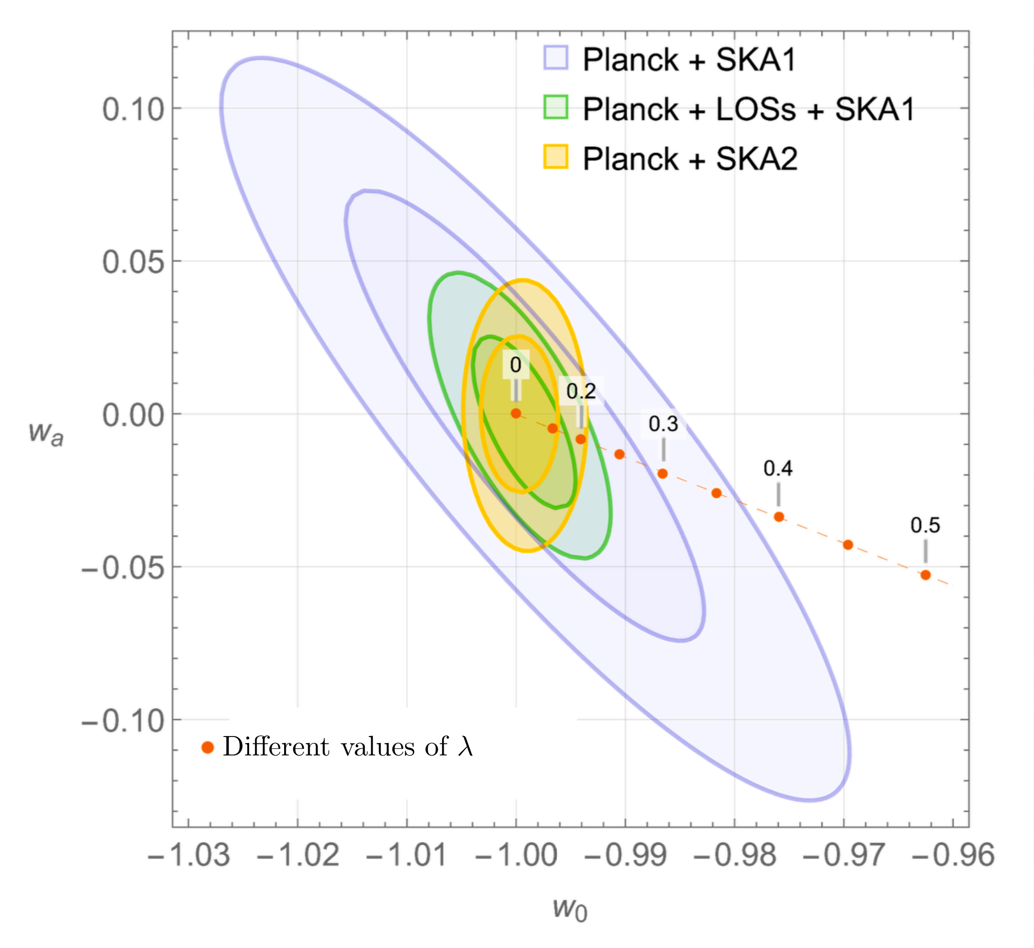
→ v) To remain conservative, keep the highest of those lambda values (at fixed values of the parameters) within a 95% confidence level (CL) ellipse in the w_0 - w_a plane

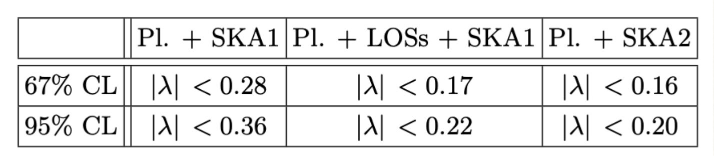
Does our Universe lie in the Swampland?

For scaling freezing models

Scalar field potential:

$$V(\phi) = V_0 e^{-\lambda\phi}$$

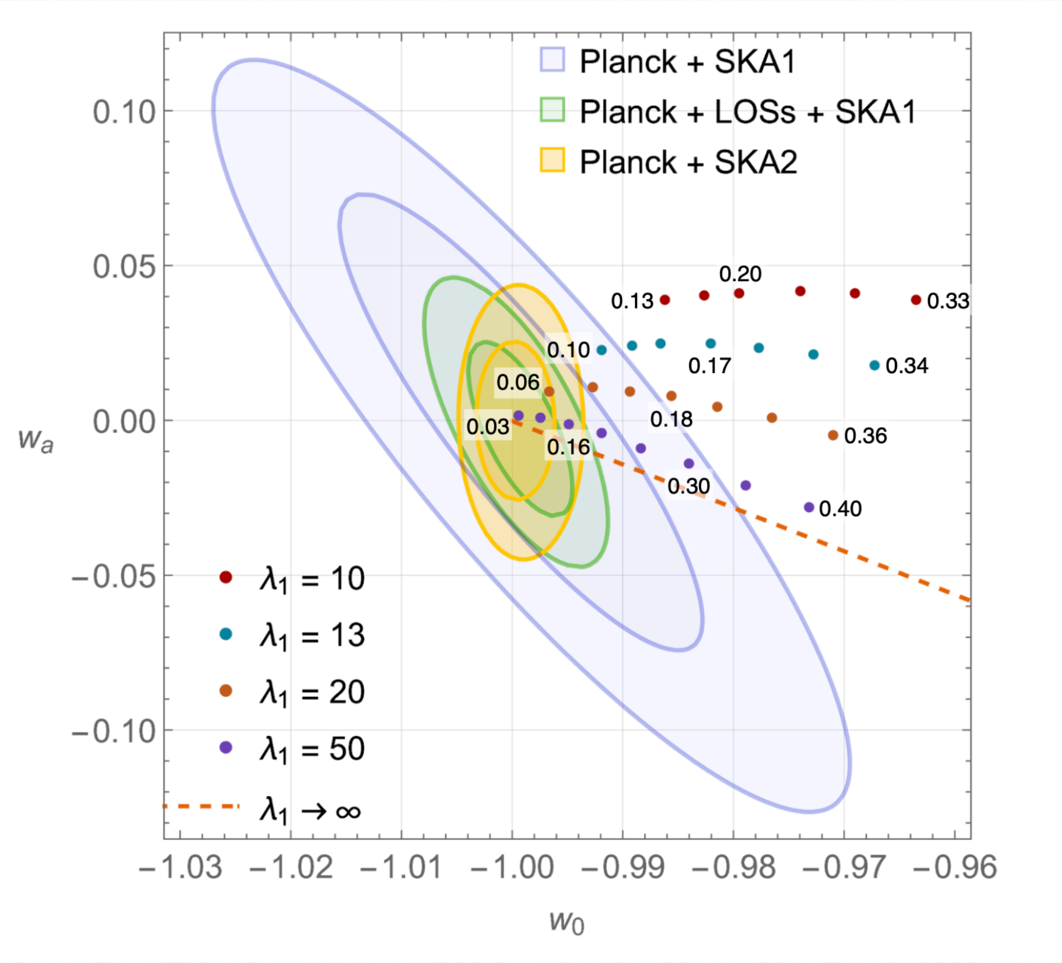




	Pl. + SKA1	Pl. + LOSs + SKA1	Pl. + SKA2
67% CL	$\lvert\lambda\rvert < 0.28$	$\lvert\lambda\rvert < 0.17$	$\lvert\lambda\rvert < 0.16$
95% CL	$\lvert\lambda\rvert < 0.36$	$\lvert\lambda\rvert < 0.22$	$\lvert\lambda\rvert < 0.20$

Scalar field potential:

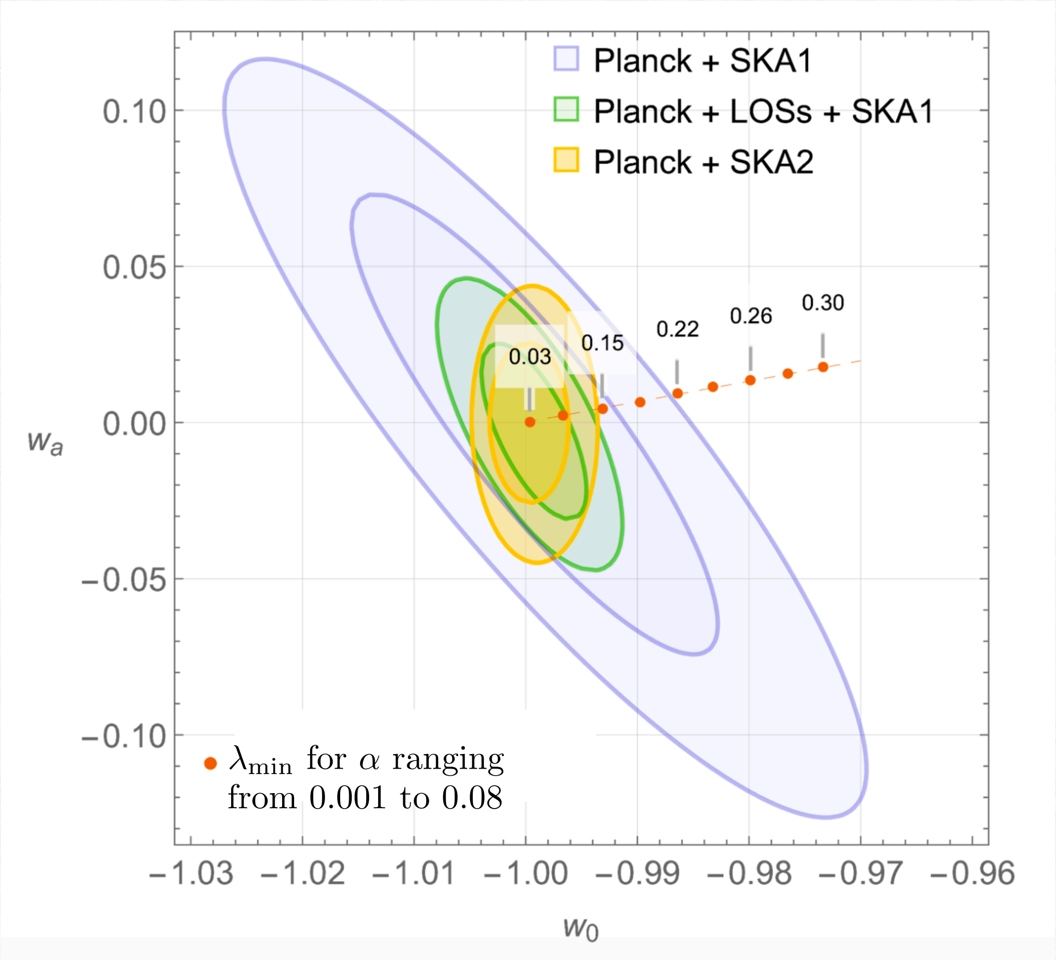
$$V(\phi) = V_1 e^{-\lambda_1\phi} + V_2 e^{-\lambda_2\phi}$$

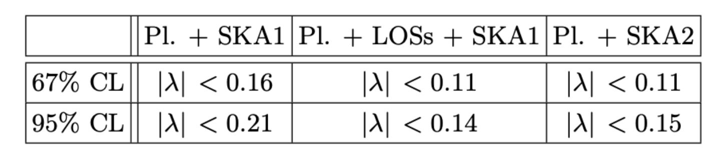


Does our Universe lie in the Swampland?

For tracking freezing models

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

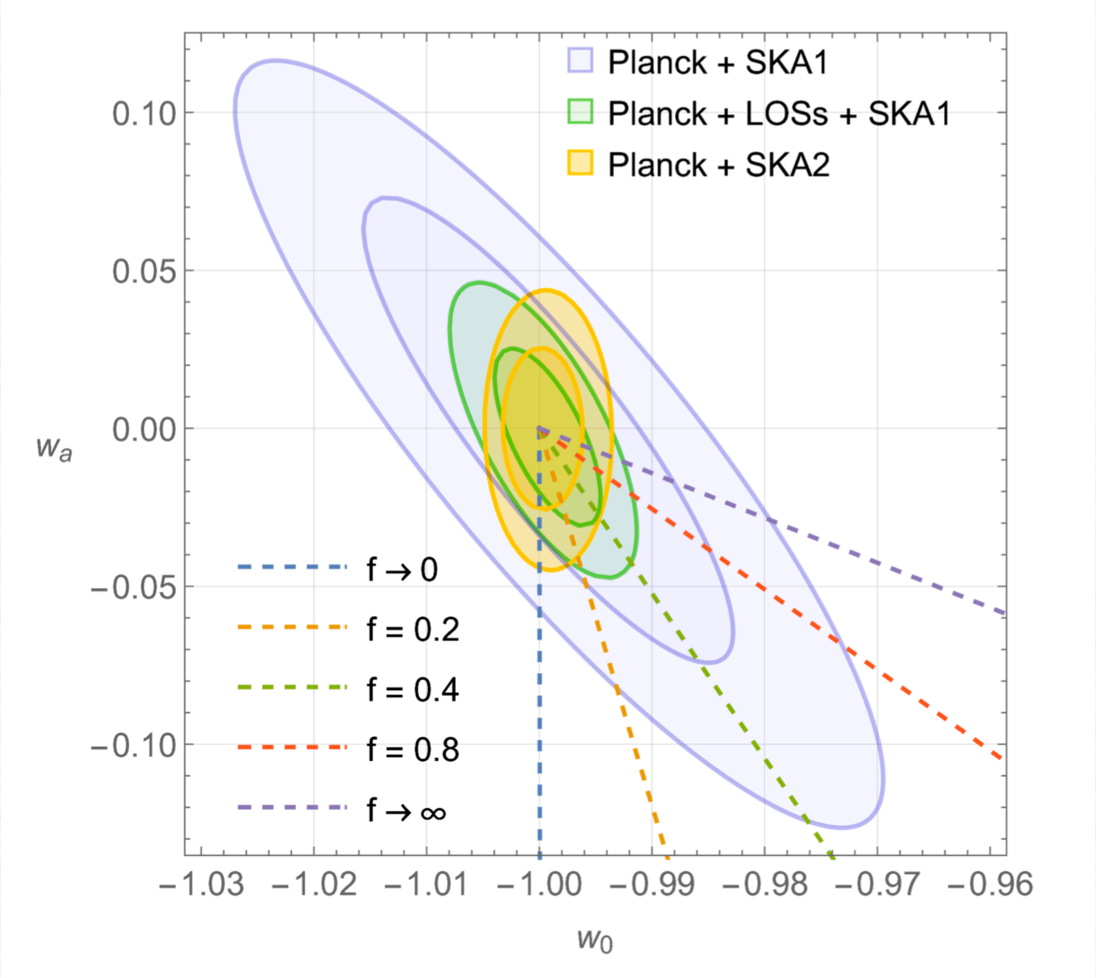


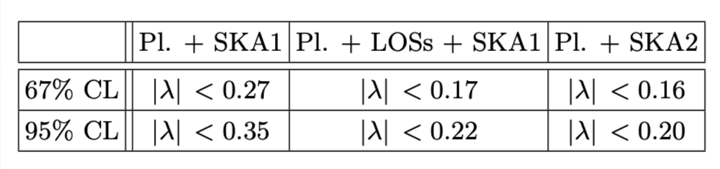


	Pl. + SKA1	Pl. + LOSs + SKA1	Pl. + SKA2
67% CL	$\lvert\lambda\rvert < 0.16$	$\lvert\lambda\rvert < 0.11$	$\lvert\lambda\rvert < 0.11$
95% CL	$\lvert\lambda\rvert < 0.21$	$\lvert\lambda\rvert < 0.14$	$\lvert\lambda\rvert < 0.15$

For thawing models

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





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

Conclusion

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

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

Conclusion

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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.	$\lvert V'/V\rvert < 0.16$	$\lvert V'/V\rvert < 0.17$
At 95% C.L.	$\boxed{\lvert V'/V\rvert < 0.22}$	$\boxed{\lvert V'/V\rvert < 0.20}$

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

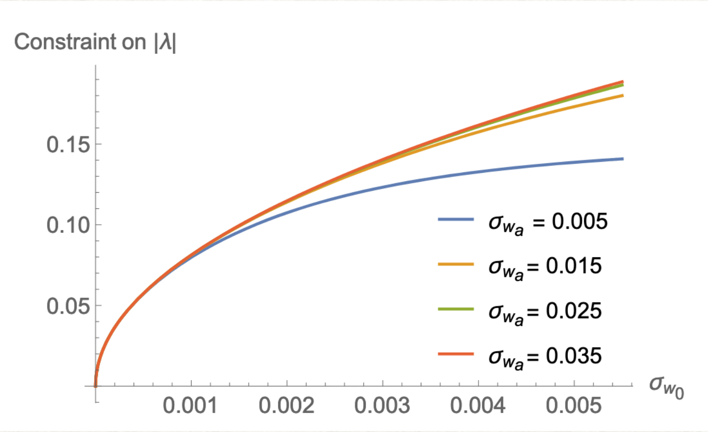
(Under the assumption of the de-Sitter conjecture)

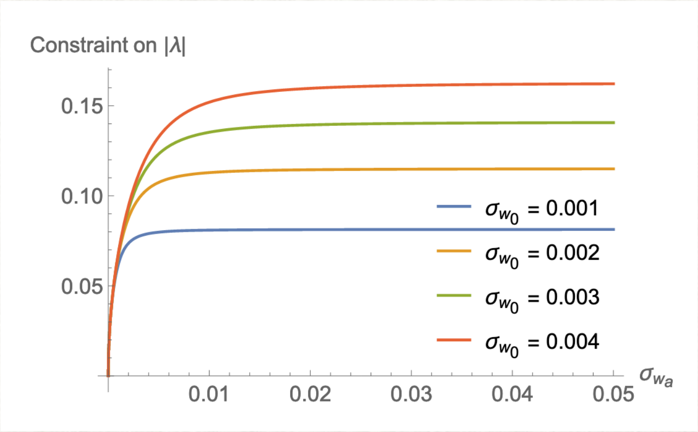
According to D. Andriot, et al. (2020), arXiv:2004.00030

Net improvement of the tension!

- **Prospects:**

Evolution of the constraint on |λ| with ameliorations of the sensitivities on w_0 or w_a





Conclusion

- **Drawbacks 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

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

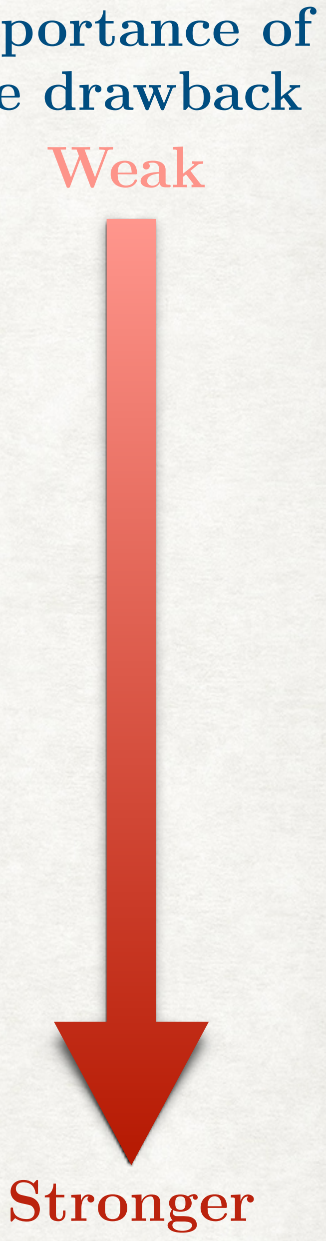
The one we used

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

→ The exact value of the minimal |λ| authorized by the de-Sitter conjecture is still source of debate

→ 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!



Importance of the drawback

Weak

Stronger

- **The final world**

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