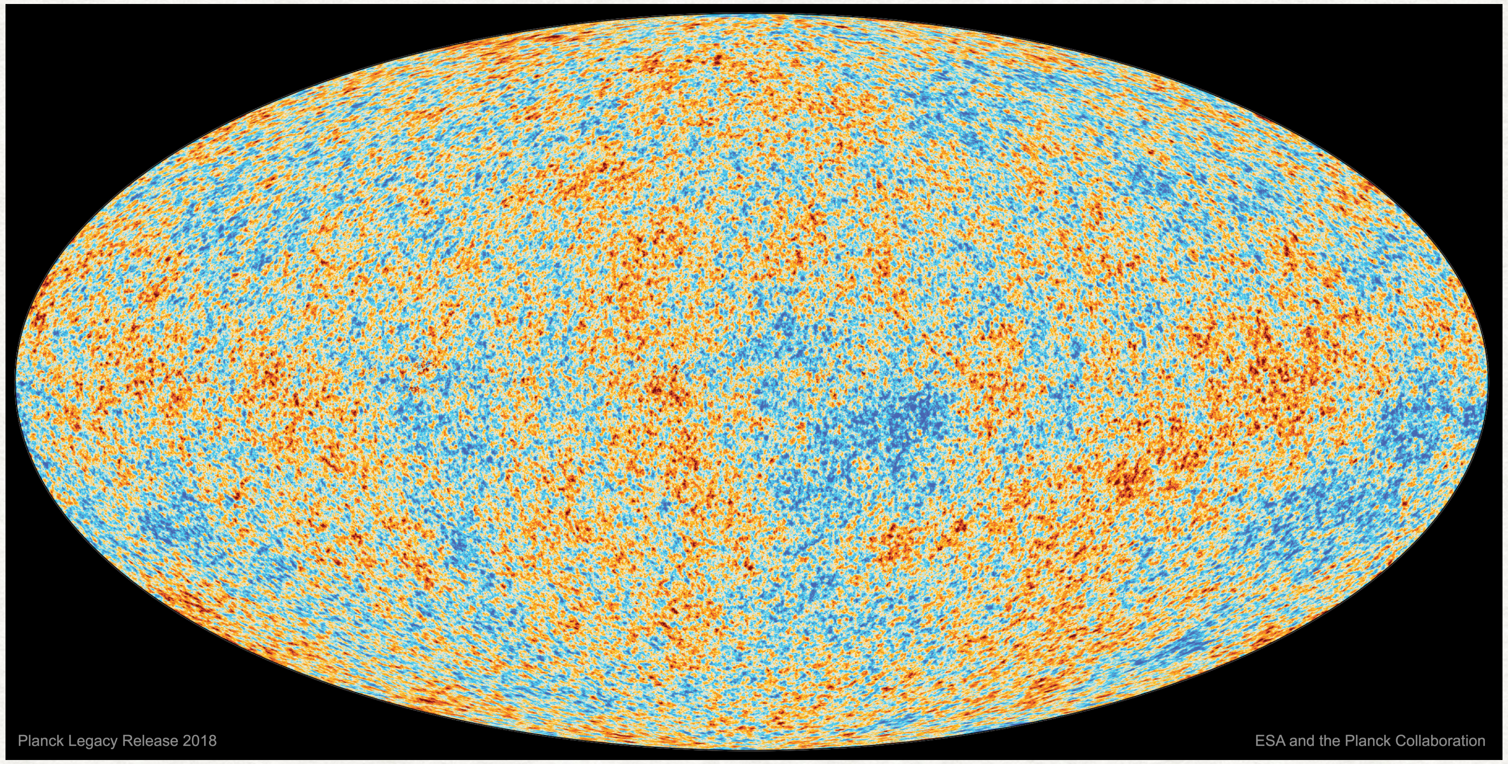
Some phenomenological implications of quantum gravity

Can we put quantum gravity theories under pressure with current or forthcoming astrophysical and cosmological data?

Based on works done in collaboration with A. Barrau, B. Bolliet, J. Grain, P. Jamet, J. Martinon, F. Moulin, C. Renevey, S. Schander

Can we put quantum gravity theories under pressure with actual or forthcoming astrophysical and cosmological data?

With the CMB
(primordial power spectra)

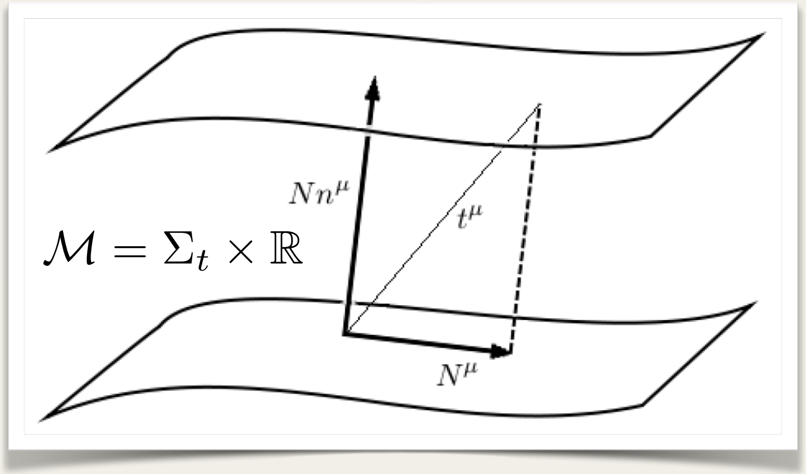


Planck Legacy Release 2018

About Loop Quantum Gravity (LQG)

"Dirac quantization scheme"

- Define canonical variables



✗ **Wheeler - De-Witt historical approach:**

3-metric q_{ab} and its conjugate momentum related to the extrinsic curvature K_{ab}

? Ashtekar variables: $\begin{cases} A_a^i \text{ (SAB connection)} \\ E_i^a \text{ (Densitized triads)} \end{cases}$

↓ *Smeared versions*

✓ **Holonomy of the connection and Flux of densitized triads**

$$h[A] \equiv \mathcal{P}\left[e^{\oint_\Gamma A}\right] \qquad F_i[E] \equiv \int_S d^2\sigma n_a E_i^a$$

General Relativity Hamiltonian: $\mathcal{H}_{RG}(h, F)$

- Promote those variables to be operators

$$h \to \hat{h} \qquad F \to \hat{F} \qquad [\hat{h}, \hat{F}] = i\hbar\{h, F\}\,\mathbb{1}_d$$

About Loop Quantum Gravity (LQG)

General relativity is a full constrained theory

Hamiltonian: sum of contraints

$$\mathcal{H}_{RG} = \frac{1}{16\pi}\int d^3x\,\left[\lambda^j \mathcal{G}_j + N^a \mathcal{C}_a + N\mathcal{C}\right] = 0$$

Construction of the Hilbert space of «physical» solutions : $\mathcal{F}_{\text{cin}} \xrightarrow{\hat{\mathcal{G}}_j\Psi=0} \mathcal{F}^0_{\text{cin}} \xrightarrow{\hat{\mathcal{C}}_a\Psi=0} \mathcal{F}_{\text{diff}} \xrightarrow{\hat{\mathcal{C}}\Psi=0} \mathcal{F}_{\text{phys}}$

Consequence of this quantization process

Geometrical quantities (areas, volumes) become operators with discrete spectra

$$\hat{A}(S)\Psi_\Gamma = 8\pi\gamma\ell_{\text{Pl}}^2 \sum_p \sqrt{j_p(j_p+1)}\Psi_\Gamma$$

In the cosmological sector

Modified Friedmann equation

$$H^2 = \frac{8\pi}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$$

ρ_c: critical (maximal) energy density

About Loop Quantum Gravity (LQG)

Usual cosmology

Friedmann equation

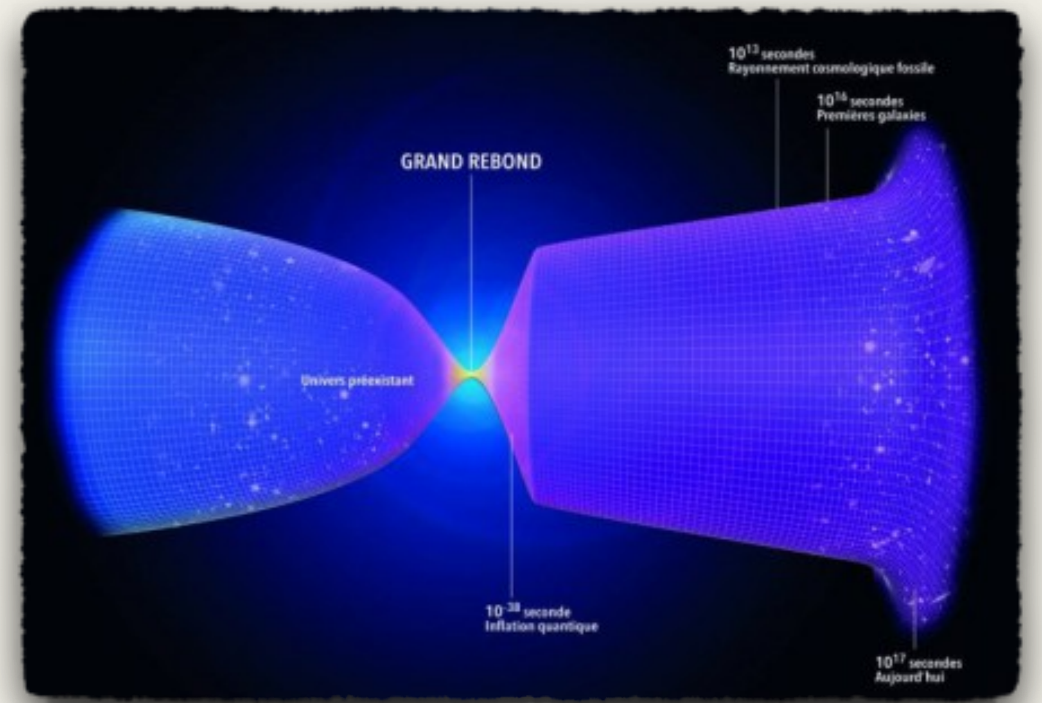
$$H^2 = \frac{8\pi G}{3}\rho$$

"Big Bang"

Loop Quantum Cosmology (LQC)

Modified Friedmann equation

$$H^2 = \frac{8\pi G}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$$



"Big Bounce"

At the (homogeneous) background level

- **<u>Exhaustive investigation of the predicted number of inflationary e-folds in LQC</u>**

K.M., A.Barrau, S.Schander, arXiv:1701.02703

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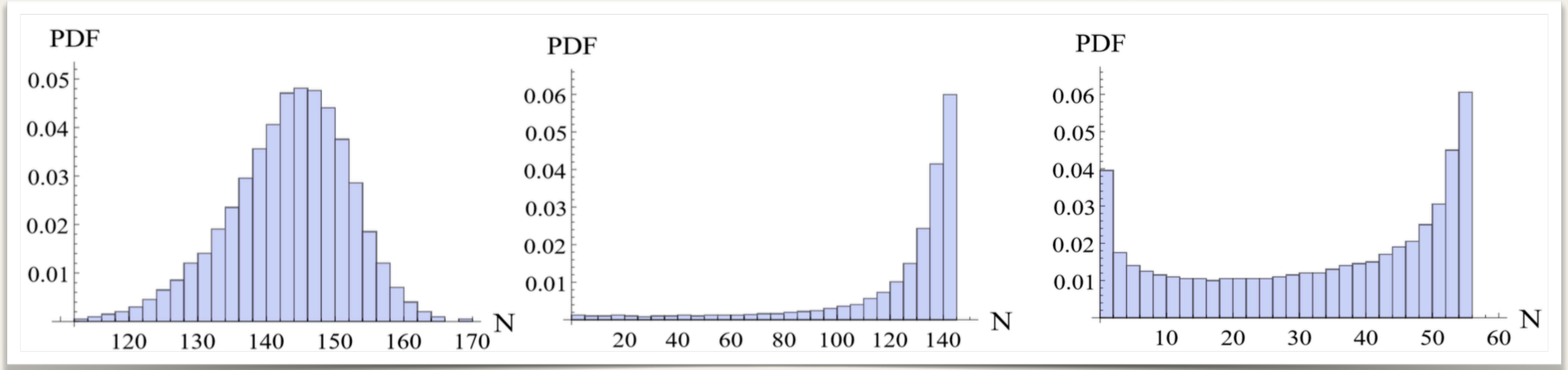
The number of inflationary e-folds is constrained in LQC

<u>Example</u> :
Quadratic potential
$V(\phi) = \frac{1}{2}m^2\phi^2$



Weak → Strong
Shear (anisotropies)

Prediction checked for other inflaton potentials ✓
As soon as the inflation potential is confining

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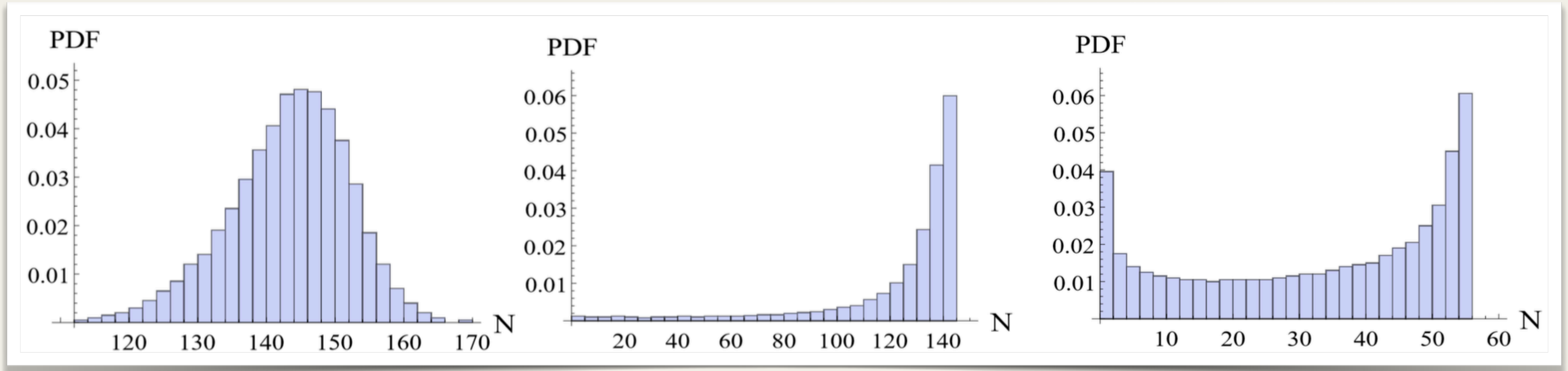

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As soon as the inflation potential is confining

- **Where do this predictive power come from?**

B.Bolliet, A.Barrau, K.M, F.Moulin, arXiv:1701.02282

Due to the initial conditions associated with the bounce dynamics
General prediction of bouncing models *(with a massive scalar field)*

Primordial power spectra in LQC

- Two dominant approaches to cosmological perturbations in LQC

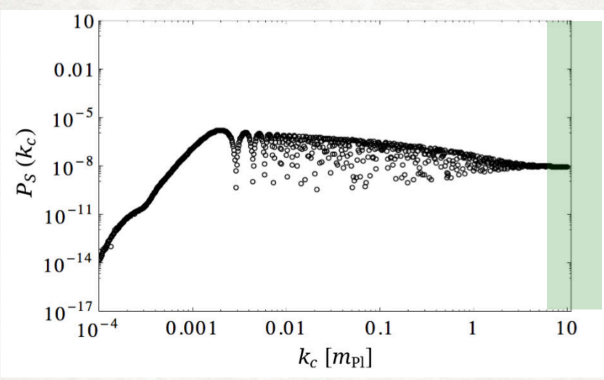
"Dressed Metric" (DM)

Mukhanov-Sasaki equation is **unchanged** w.r.t GR:

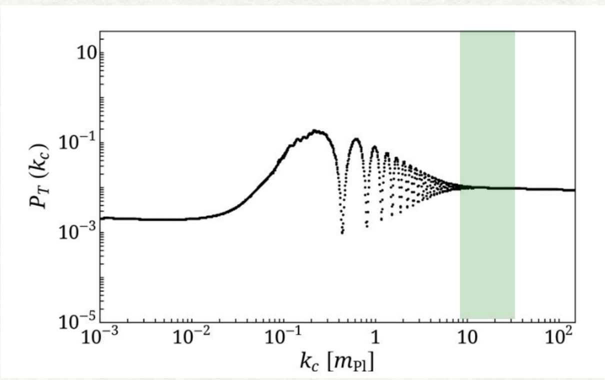
$$v_k''(\eta) + \left(k_c^2 - \frac{z''_{T/S}(\eta)}{z_{T/S}(\eta)}\right) v_k(\eta) = 0$$

: Observable window for N ~ 75

K.M., A.Barrau, J.Grain, arXiv:1709.03301



Scalar perturbations



Tensor perturbations

✓ **Compatible with CMB constraints**

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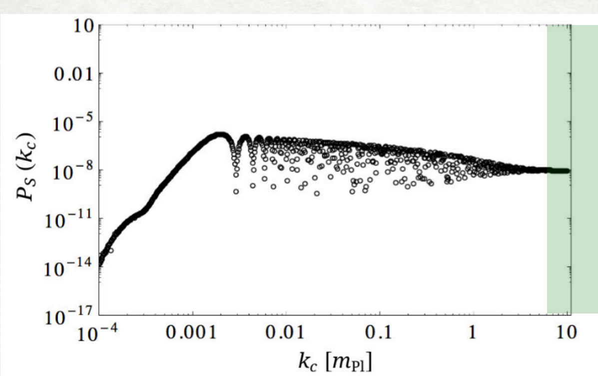

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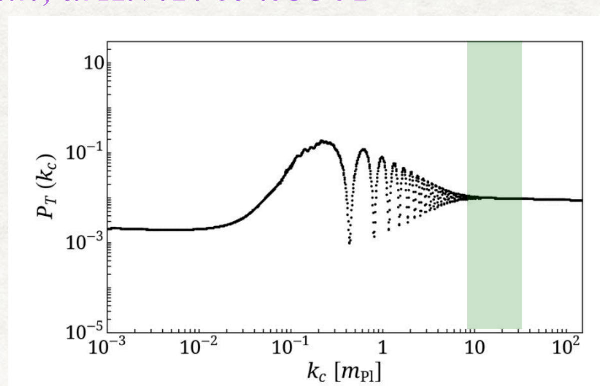


Tensor perturbations

✓ **Compatible with CMB constraints**

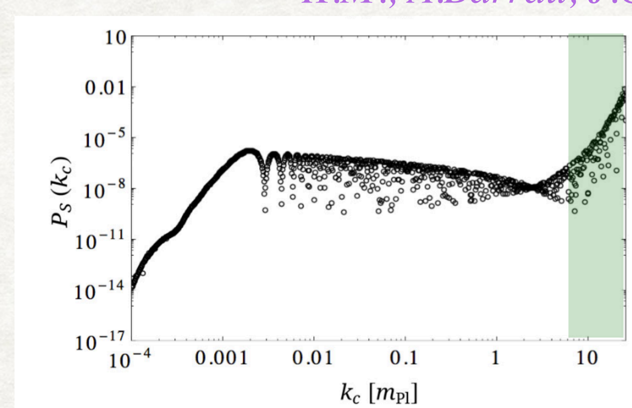
"Deformed Algebra" (DA)

Modification of the Mukhanov-Sasaki equation:

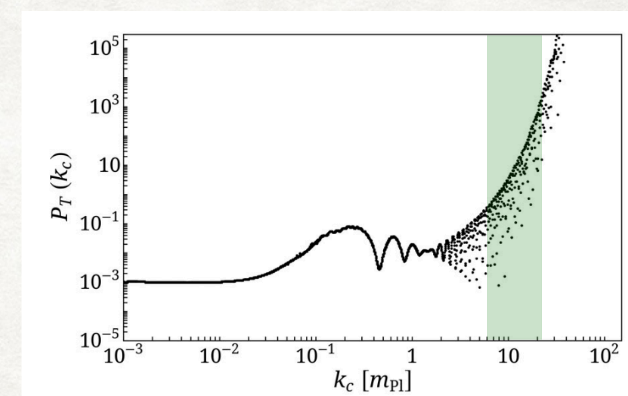
$$v_k''(\eta) + \left(\Omega(\eta) k_c^2 - \frac{z''_{T/S}(\eta)}{z_{T/S}(\eta)}\right) v_k(\eta) = 0$$

$$\Omega(\eta) = 1 - 2\frac{\rho(\eta)}{\rho_c} \qquad -1 < \Omega < 1$$

K.M., A.Barrau, J.Grain, arXiv:1709.03301



Scalar perturbations



Tensor perturbations

✗ **Excluded by CMB data**

Primordial power spectra vs trans-planckian problem

Trans-planckian problem: As soon as N > 70 e-folds, observed modes in the CMB were highly (~ $e^{N-70 \text{ times}}$) smaller than Planck length at the bounce

↳ Use of **Modified Dispersion Relations** (MDR):

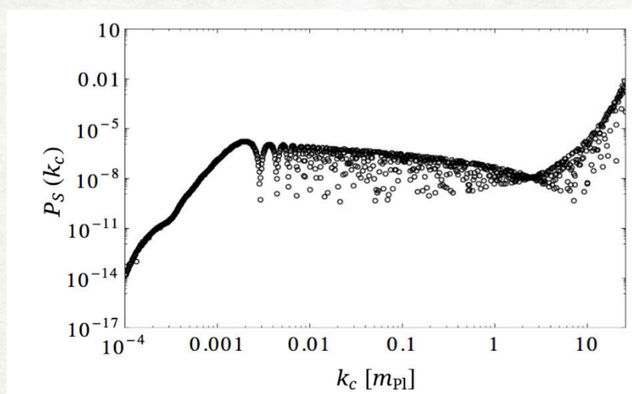
$$v_k''(\eta) + \left(\Omega(\eta)a^2(\eta)\boxed{\mathcal{F}(k_\varphi)^2} - \frac{z''_{T/S}(\eta)}{z_{T/S}(\eta)}\right)v_k(\eta) = 0$$

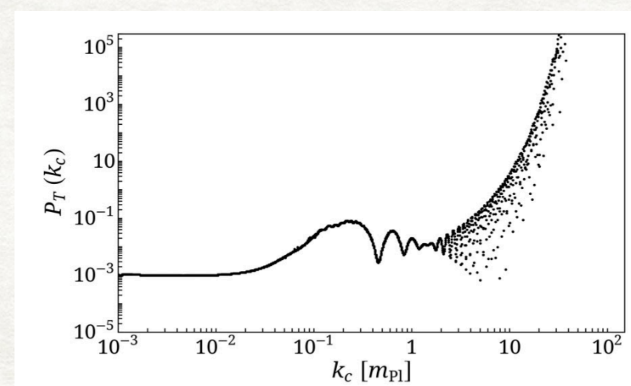
K.M., A.Barrau, J.Grain, arXiv:1709.03301

Deformed Algebra approach | *Scalar spectra* | *Tensor spectra*

Without MDR

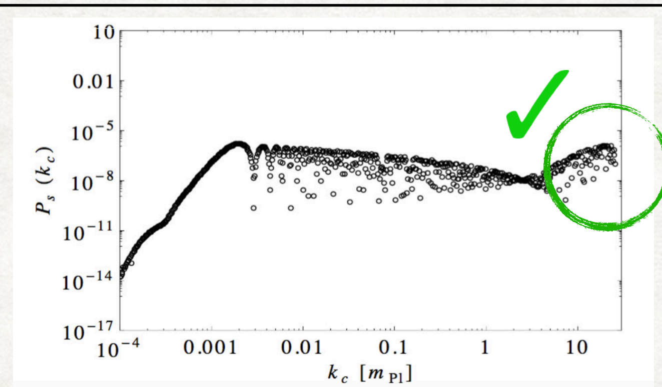
$\mathcal{F}(k_\varphi) = k_\varphi$

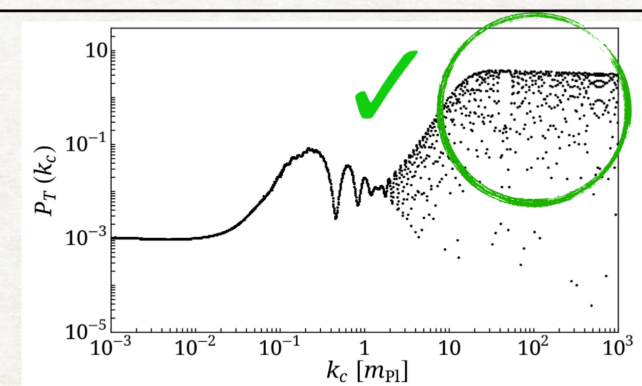




With the MDR:

$\mathcal{F}(k_\varphi) = k_0 \tanh\left[\left(\frac{k_\varphi}{k_0}\right)^p\right]^{\frac{1}{p}}$





Crucial to have a proper description of the perturbations trans-planckian behavior

Until now: emphasis put on density effect
New challenge: characterization of lengths effects

Generalized forms of the holonomy correction

C.Renevey, K.M, A.Barrau, arXiv:2109.14400

Hamiltonian formulation of GR	Hypotheses	Equation governing the background dynamics
In terms of Ashtekar variables (A,E)	*Homogeneity + Isotropy + flat space* →	$H^2 = \frac{8\pi}{3}\rho$ Friedmann equation
In terms of the LQG variables $\begin{cases} h[A] \equiv \mathcal{P}\left[e^{\oint_\Gamma A}\right] \\ F_i[E] \equiv \int_S d^2\sigma n_a E_i^a \end{cases}$	*Homogeneity + Isotropy + flat space* → **+ Holonomy correction** **In usual LQC:** $c^2 \to \frac{\sin^2(c\bar{\mu})}{\bar{\mu}^2}$ → $A_a^i(t) = c(t)\delta_a^i \quad \bar{\mu} = \sqrt{\Delta}/a$	**Modified** Friedmann equation $H^2 = \frac{8\pi}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$

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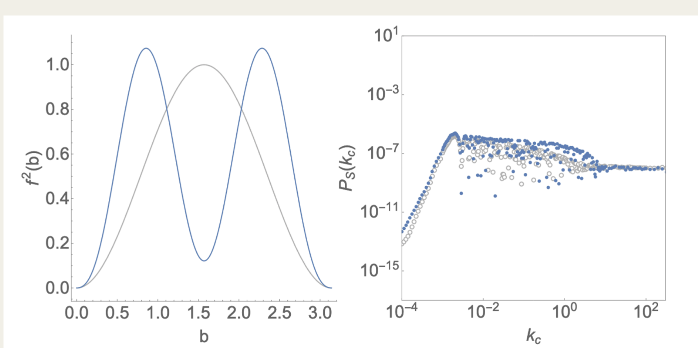
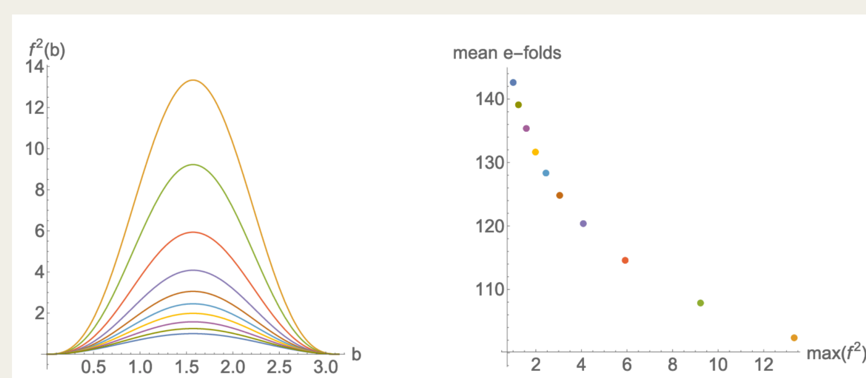
	In usual LQC: $c^2 \to \frac{\sin^2(c\bar{\mu})}{\bar{\mu}^2}$ → $A^i_a(t) = c(t)\delta^i_a \quad \bar{\mu} = \sqrt{\Delta}/a$	$H^2 = \frac{8\pi}{3}\rho\left(1 - \frac{\rho}{\rho_c}\right)$

Cosmological implications of other forms of the correction?

$$c^2 \to f^2(c, a^2) \qquad H^2 = \frac{8\pi}{3}\rho \times \left(f'(\bar{\mu}c)\right)^2$$



At the level of perturbations



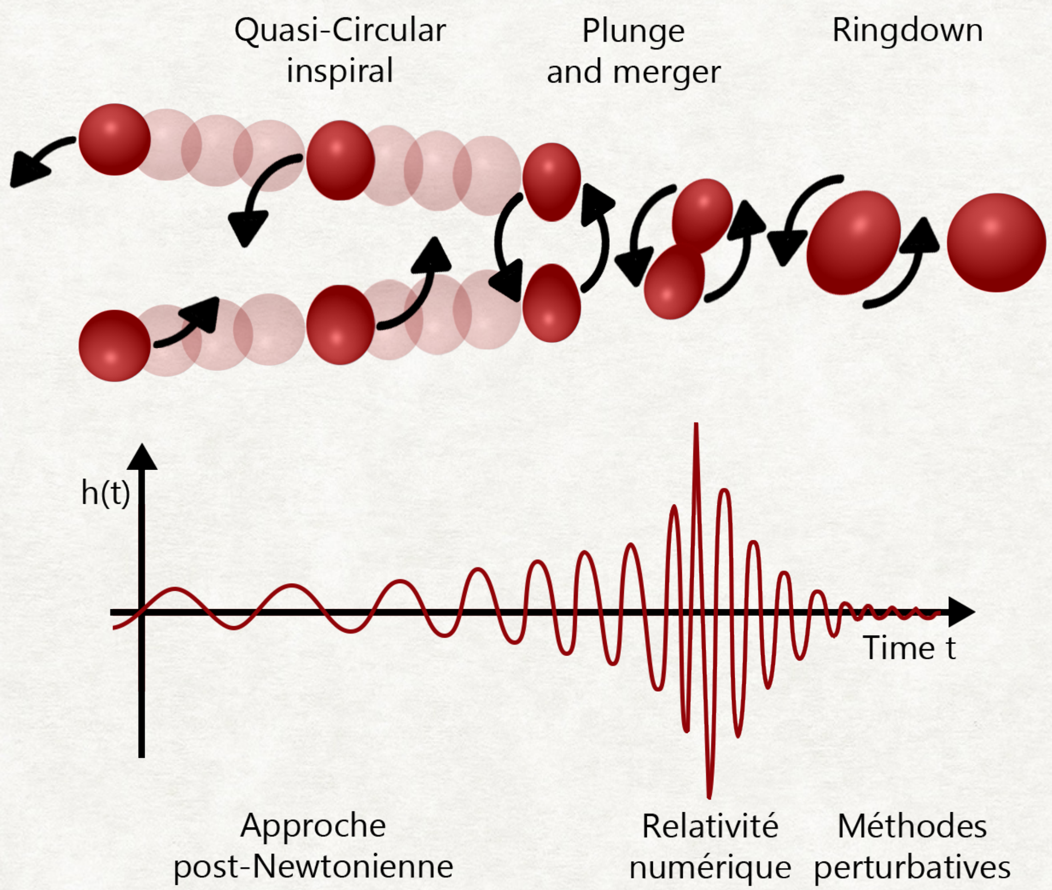
On the homogeneous background

Inflation from the holonomy correction?

Can we put quantum gravity theories under pressure with actual or forthcoming astrophysical and cosmological data?

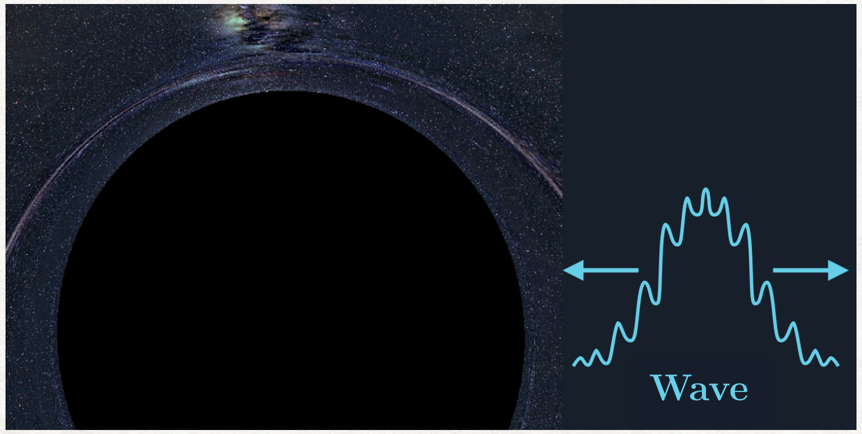
In the black holes sector
(Quasinormal modes)

Black holes quasinormal modes (QNMs)



Wave equation: $\frac{d^2R}{dr^{\star 2}} + \left(w^2 - \boxed{V(r)}\right) R = 0$

Depends on axial/polar modes
and on the model of gravity considered



Wave purely **ingoing** at the **horizon**
and purely **outgoing** at **infinity**

- **Discretization of the solutions** $\longrightarrow$ QNMs labeled by n
- **Non stationary regime** $\longrightarrow$ Radial part of the oscillation: $R \propto e^{-i\omega t}$, $\omega \in \mathbb{C}$

$$\boxed{\omega = \omega_R + i\omega_I}$$

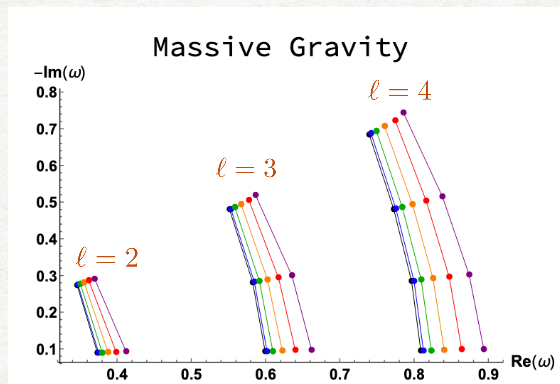
Real part (Wave frequency)

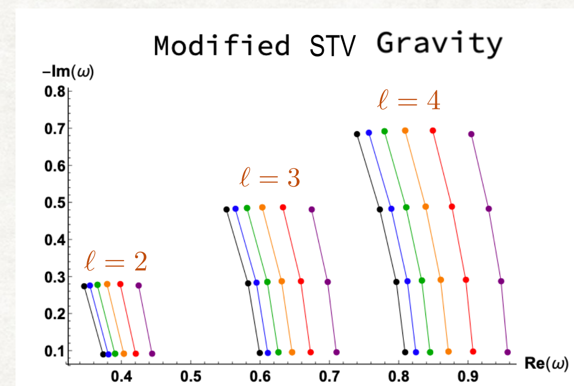
Imaginary part (Damping rate)

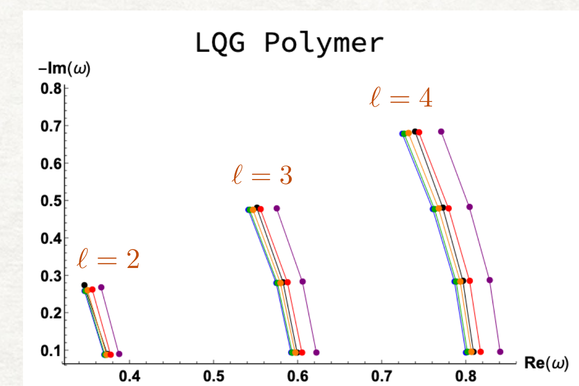
General trends in modified gravities

- **Computation of Schwarzschild black holes QNMs in different theories of gravity beyond General Relativity** *F.Moulin, A.Barrau, K.M, arXiv:1908.06311*

Massive gravity, Modified STV gravity, Hořava-Lifshitz gravity, $\hbar$ gravity, LQG







Parameter that we vary to obtain the QNMs deviation → *Graviton mass* | *Deviation w.r.t the Newton constant G* | *Polymerization of space-time*

→ **For all tested models, modifications w.r.t GR have a bigger impact on the QNMs frequencies than on their damping rates**

→ **A meaningful use of QNMs to investigate modified gravities require the measurement of several relaxation modes**

Cumulative quantum effects in the QNMs

A.Barrau, K.M., J.Martinon, F.Moulin, arXiv:1906.00603

Quantumness: $q = l_P \times \mathcal{R} \times \tau$ **is max at a radius** $R = 2M\left(1+\frac{1}{6}\right)$

(of spacetime)

Kretschmann scalar

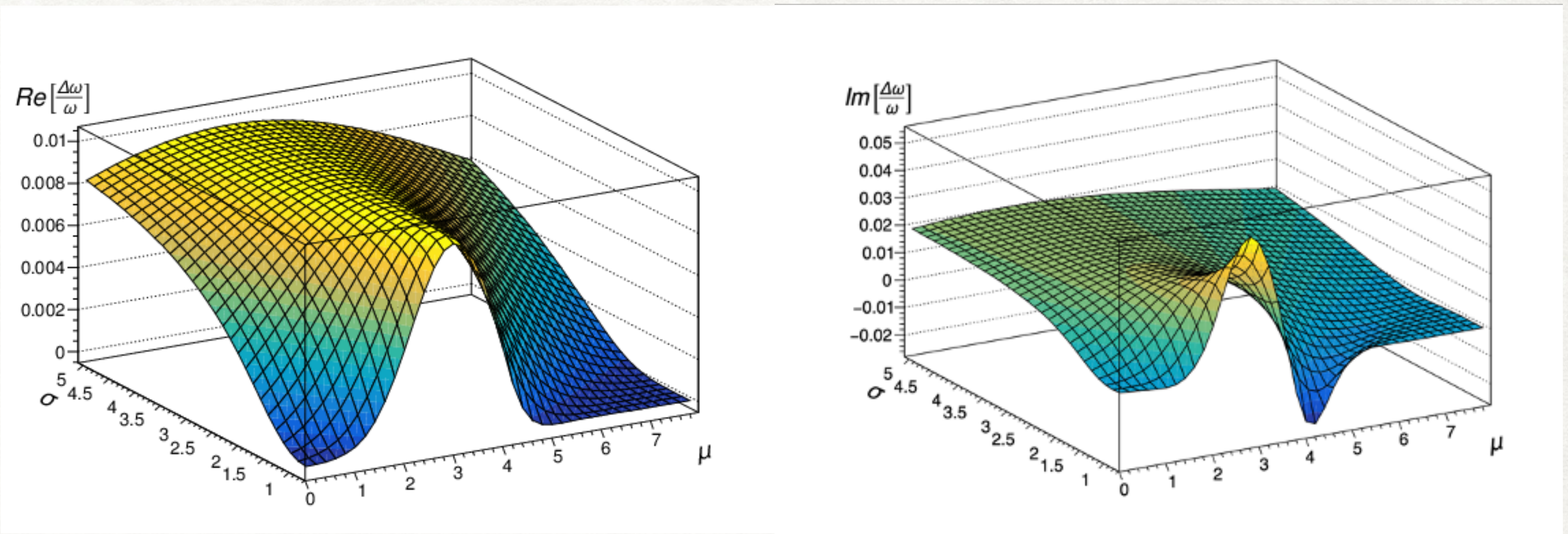
$\mathcal{R}^2 \equiv R_{\mu\nu\rho\lambda}R^{\mu\nu\rho\lambda}$

Quantum gravity effects are maximal outside the horizon!

Perturbed Schwarzschild metric:

$$ds^2 = -f(r)dt^2 + f^{-1}(r)dr^2 + r^2 d\Omega^2$$

$$f(r) = \left(1 - \frac{2M}{r}\right)\left(1 + Ae^{-\frac{(r-\mu)^2}{2\sigma^2}}\right)^2$$



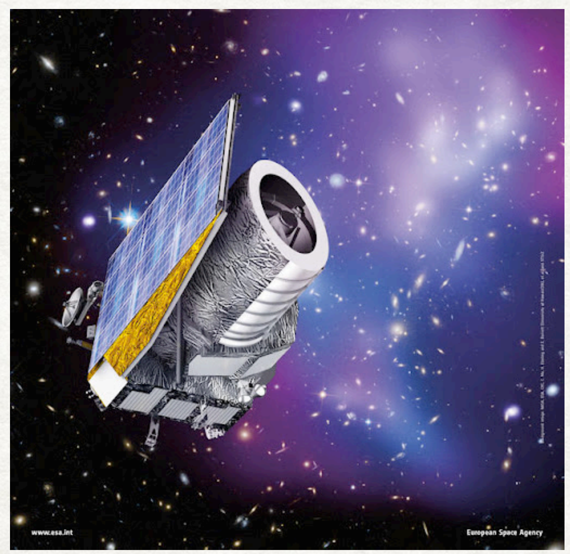
Real (left) *and* **Imaginary (right)** *parts of the relative displacement of the QNM (l=8,n=0) as a function of the parameters* μ *and* σ *describing the deformation w.r.t Schwarzschild (in units of M)*

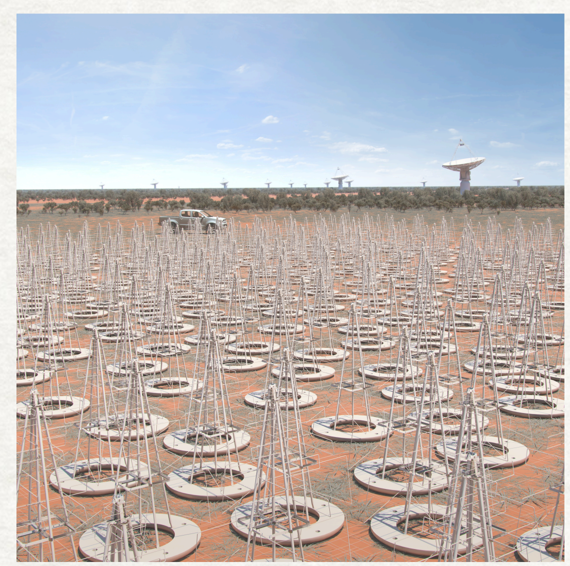
Deviation observable for BH masses $M < 10^{-8} M_\odot \gg M_{\rm Pl}$

Can we put quantum gravity theories under pressure with actual or forthcoming astrophysical and cosmological data?

With the late-times Universe

(Dark energy dedicated surveys)

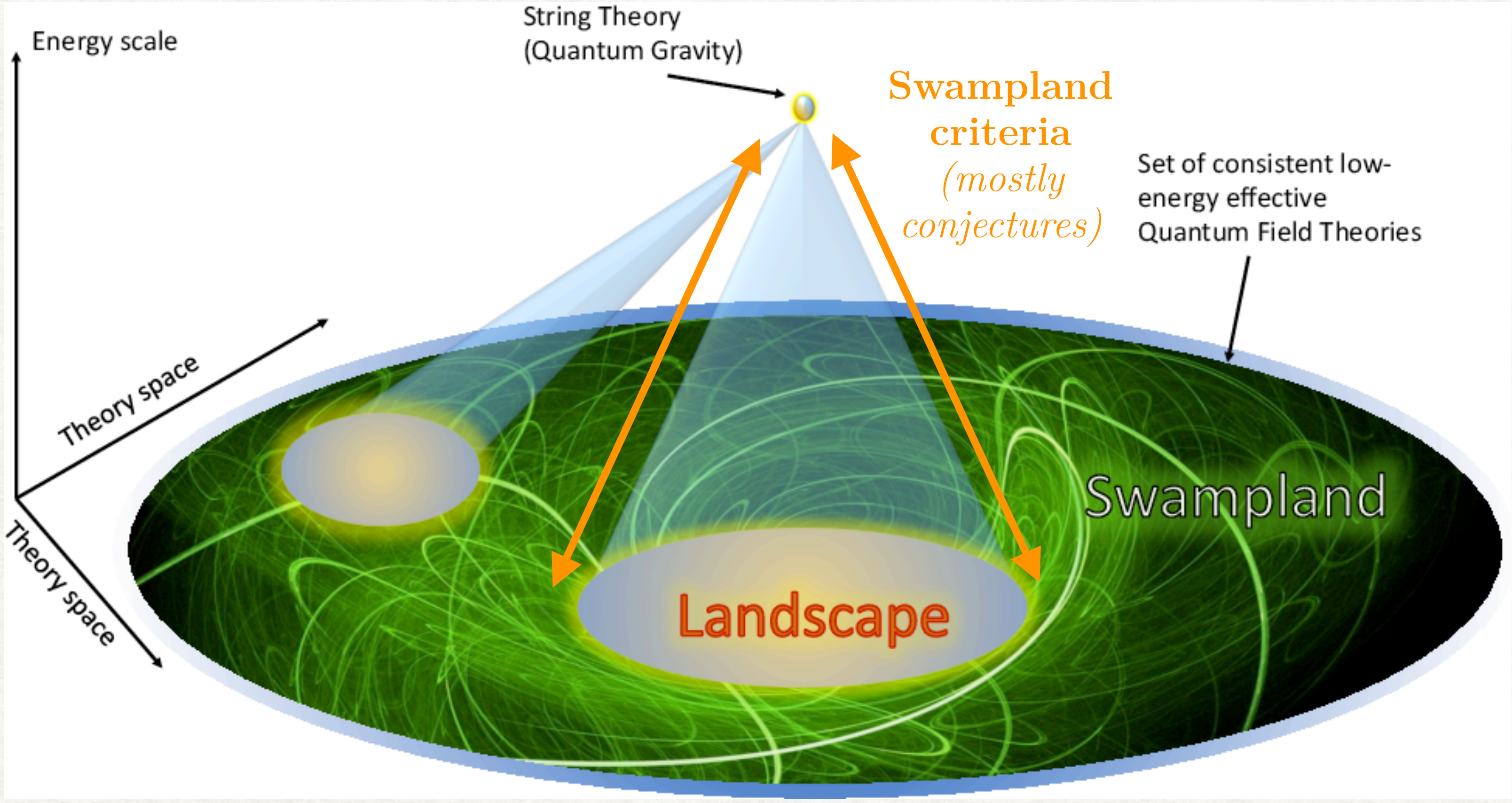




The string swampland

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: <u>The de-Sitter conjecture</u>

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

$$\lambda(\phi(t)) \equiv -\frac{V'(\phi(t))}{V(\phi(t))} \qquad |\lambda(\phi(t))| = \left|\frac{V'(\phi(t))}{V(\phi(t))}\right| > \lambda_c \sim \mathcal{O}(1)$$ *(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 $\Rightarrow$ $|\lambda(\phi(t))| \geq \frac{6}{\sqrt{(d-1)(d-2)}} = \sqrt{\frac{2}{3}} \simeq 0.81(\text{ for } d=4)$
    D. Andriot, N. Cribiori, D. Erkinger (2020), arXiv:2004.00030

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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

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

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

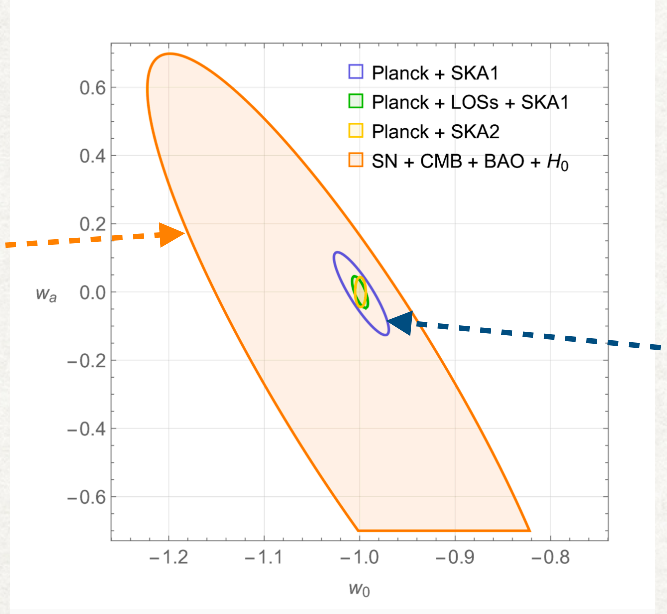
First order of a Taylor development: $w(a(t)) = w_0 + (1 - a(t))w_a$ $1 + z(t) = \frac{a(t)}{a(t_{\text{emission}})}$

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:

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

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

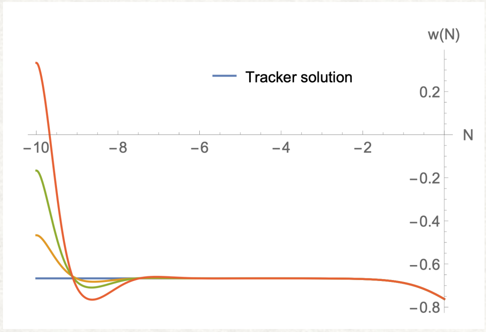
$$\frac{d\lambda}{dt} = -\sqrt{3(1+w)\Omega_\phi}(\Gamma - 1)\lambda^2 \qquad \Gamma(\phi(t)) \equiv V(\phi(t))V''(\phi(t))/\left[V'(\phi(t))\right]^2$$

- **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

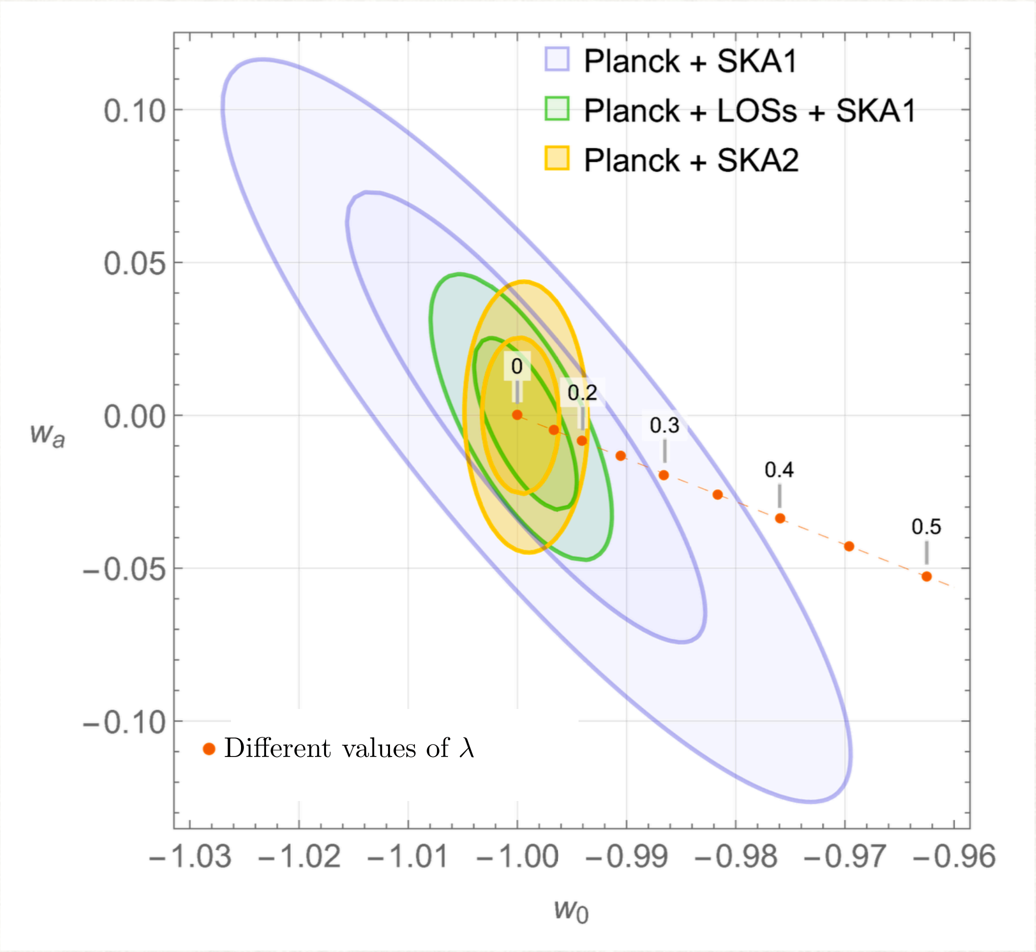
→ v) To remain conservative, keep the highest of those lambda values (at fixed values of the parameters) within a 95% confidence level (CL) ellipse in the w_0 - w_a plane

Does our Universe lie in the Swampland?

For scaling freezing models

Scalar field potential:

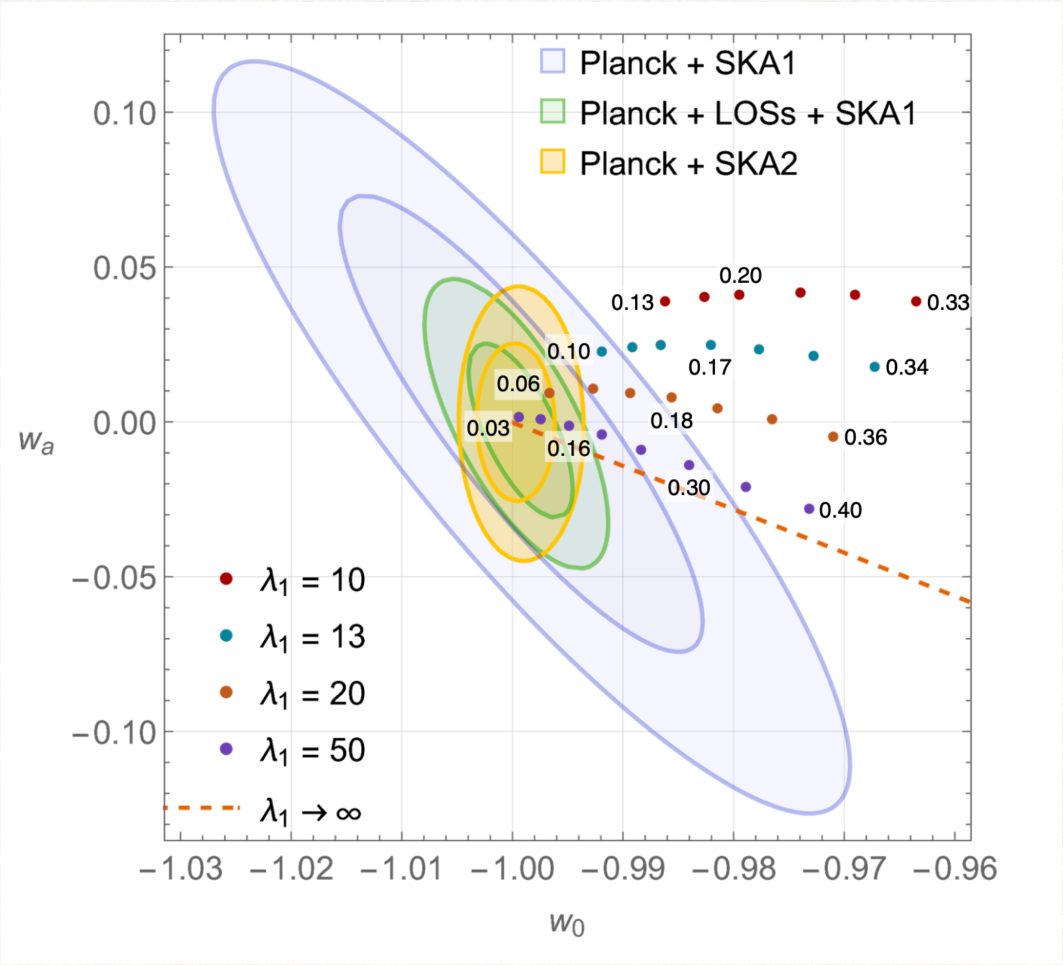
$$V(\phi) = V_0 e^{-\lambda\phi}$$



	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:

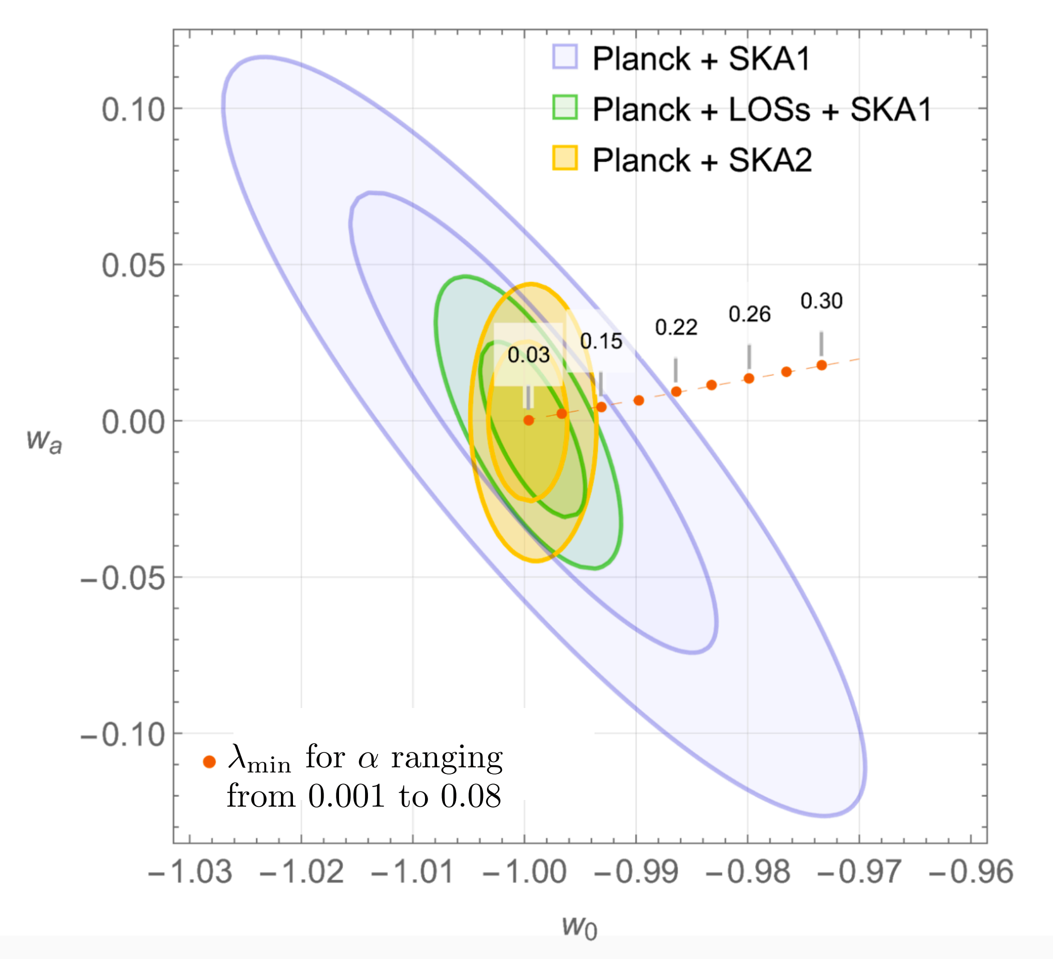
$$V(\phi) = V_1 e^{-\lambda_1\phi} + V_2 e^{-\lambda_2\phi}$$



Does our Universe lie in the Swampland?

For tracking freezing models

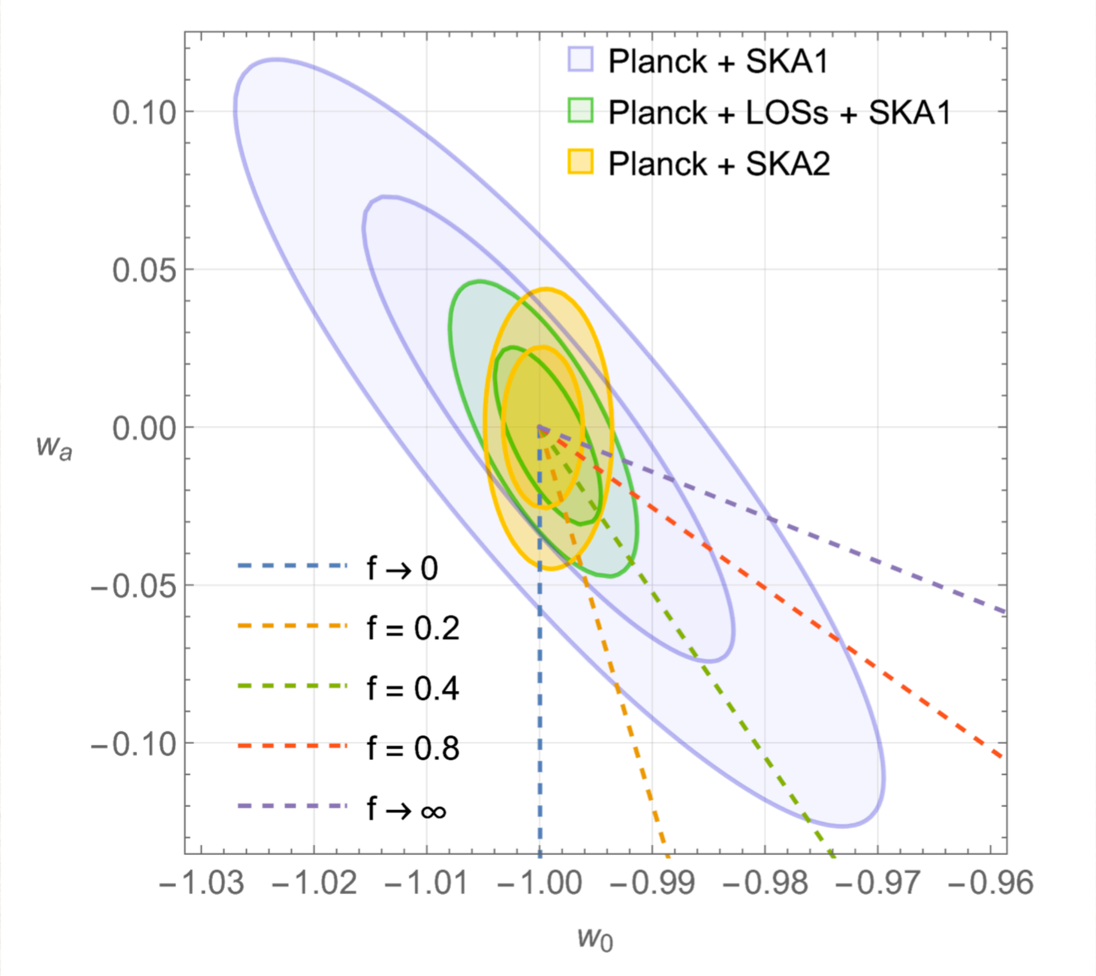
Scalar field potential:
$V(\phi) = M^{4+\alpha}/\phi^{\alpha},\ \alpha > 0$



	Pl. + SKA1	Pl. + LOSs + SKA1	Pl. + SKA2
67% CL	$\lvert\lambda\rvert < 0.16$	$\lvert\lambda\rvert < 0.11$	$\lvert\lambda\rvert < 0.11$
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	$\lvert\lambda\rvert < 0.35$	$\lvert\lambda\rvert < 0.22$	$\lvert\lambda\rvert < 0.20$

Expected improved constraints on $|\lambda| = |V'/V|$

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*

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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.	$\|V'/V\| < 0.16$	$\|V'/V\| < 0.17$
At 95% C.L.	$\|V'/V\| < 0.22$	$\|V'/V\| < 0.20$

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

(Under the assumption of the de-Sitter conjecture)

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

Net improvement of the tension!

Conclusion of this work

Importance of the drawback

Weak

- **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

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

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 exact value of the minimal $|\lambda|$ 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!

Stronger

- **In the end**

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

The final worlds

The gap separating quantum gravity from observations slowly reduces, step by step…

Quantum Gravity is no longer confined to pure theoretical or mathematical physics.