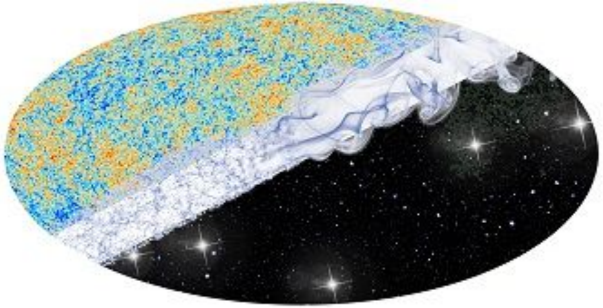
TAsP Meeting

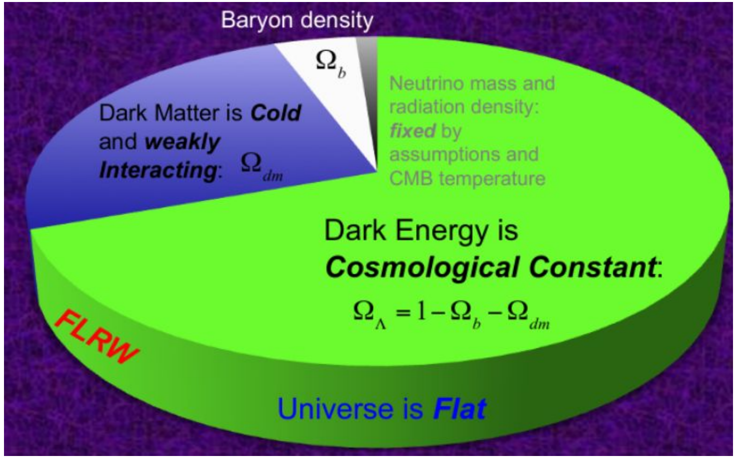
Extended gravity models for inflation in light of the CMB data

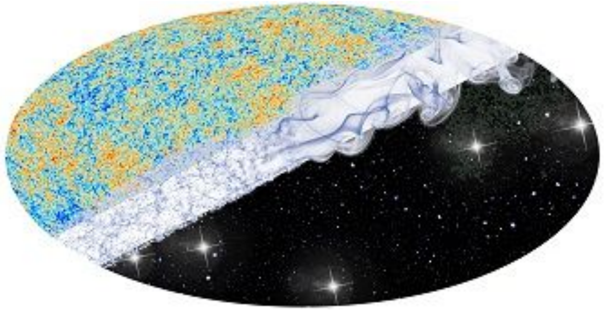
Simony Santos da Costa and collaborators

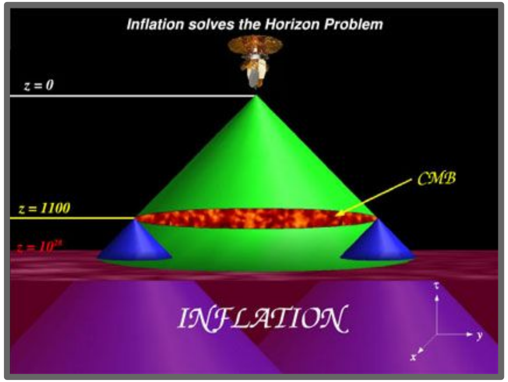


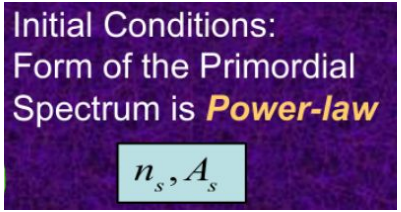
January 18, 2024

The concordance model - ΛCDM: a set of assumptions confirmed by observational data

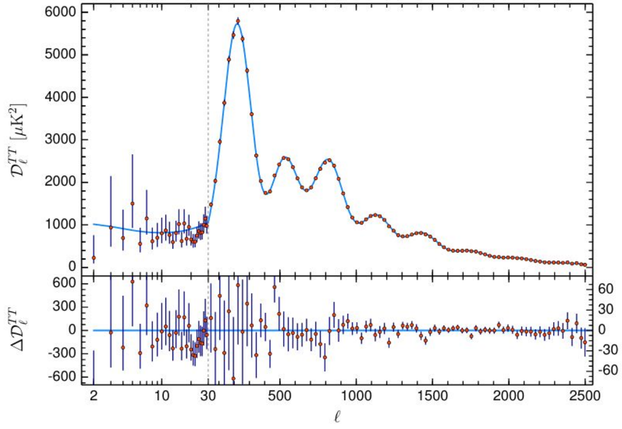


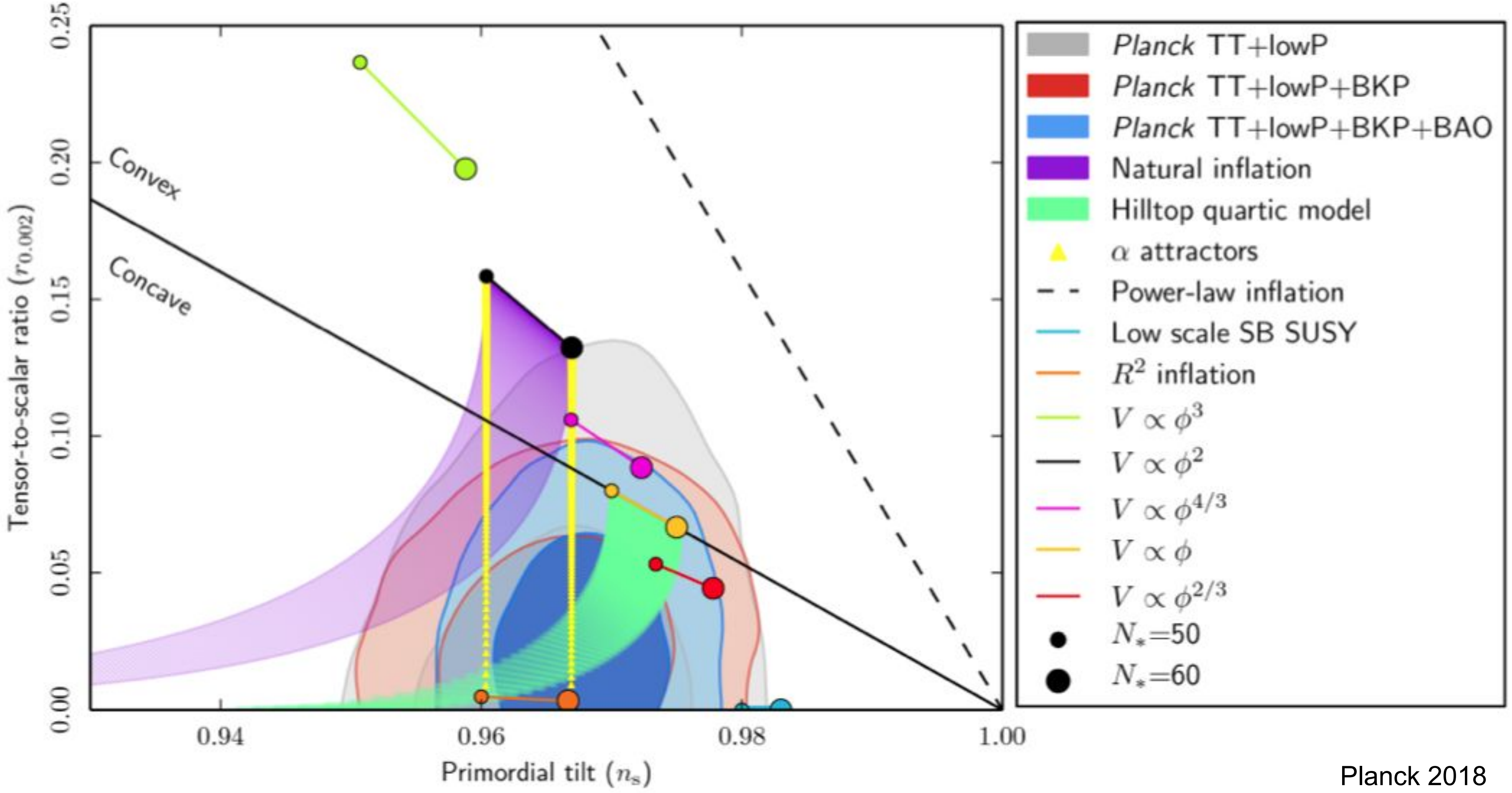






$$P_R = A_s \left(\frac{k}{k_{pivot}} \right)^{n_s - 1}$$





Tensor-to-scalar ratio ($r_{0.002}$)
0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.96
0.98
1.00
Primordial tilt (n_s)
Convex
Concave
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
R^2 inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60

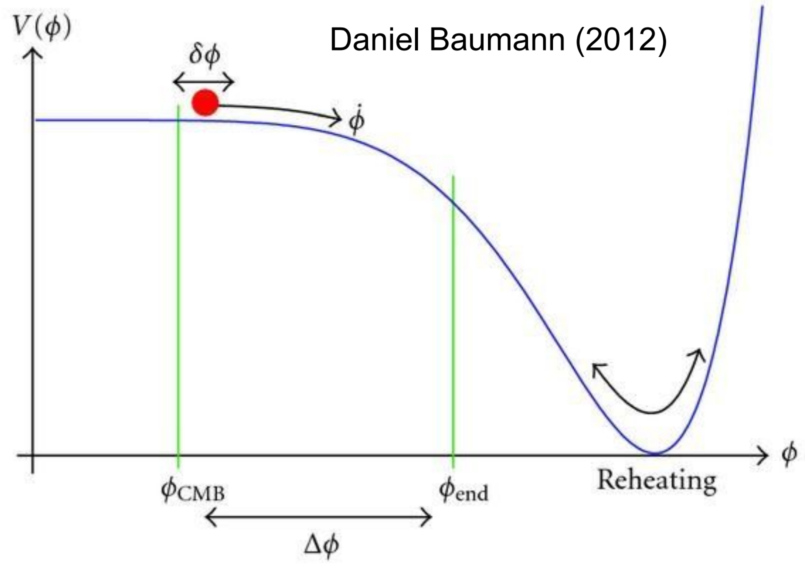
Planck 2018

Slow-roll

$$H^2 = \frac{1}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$
$$\ddot{\phi} = -3H\dot{\phi} - V'(\phi)$$

$$\dot{H} \sim 0.$$

$$\frac{\dot{H}}{H^2} \ll 1,$$



$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{M_{Pl}^2}{2}\left(\frac{V'}{V}\right)^2$$
$$\eta = -\frac{1}{H}\frac{\ddot{\phi}}{\dot{\phi}} = M_{Pl}^2\frac{V''}{V}$$

$$\downarrow$$

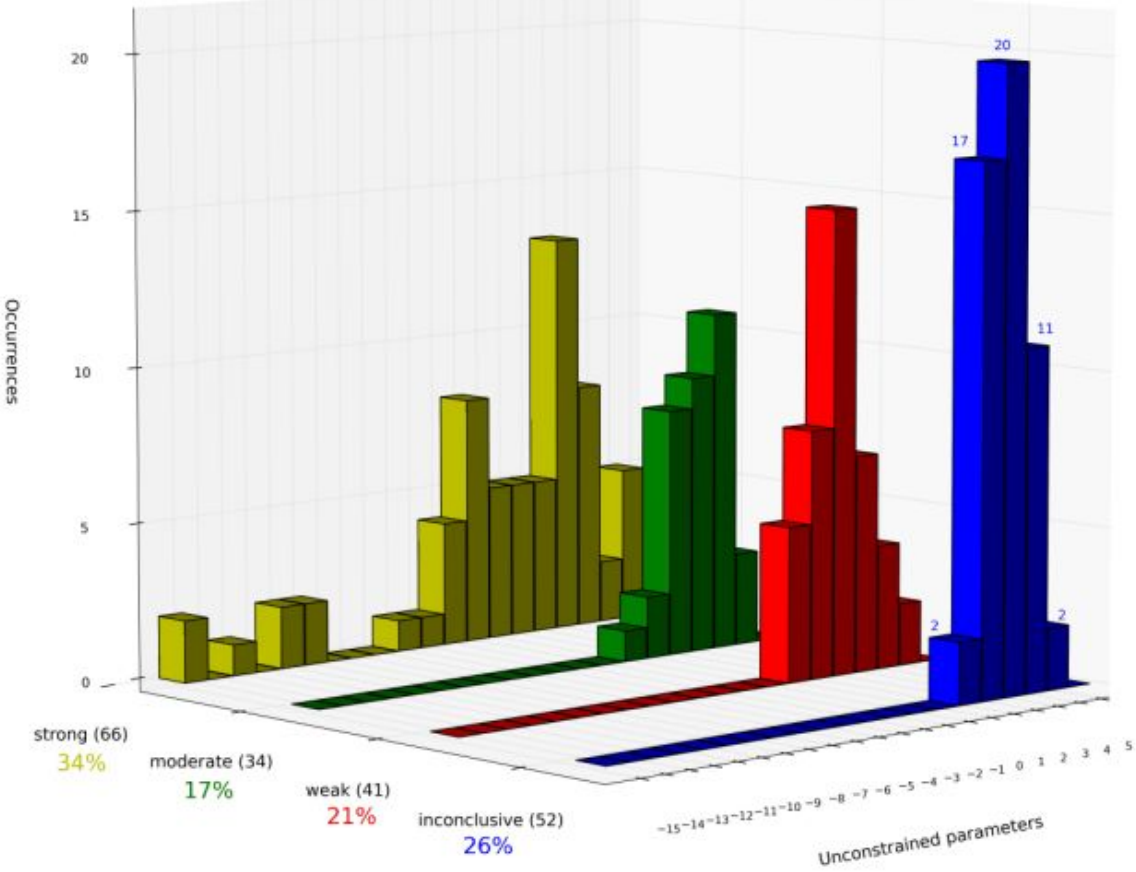
$\epsilon \ll 1$ $\quad$ $\eta \ll 1$

$$N \equiv \int_{a_{ini}}^{a_{end}} d\ln a = \int_{t_{ini}}^{t_{end}} H\,dt = \int_{\phi_{ini}}^{\phi_{end}} \frac{H}{\dot{\phi}}\,|d\phi| = \int_{\phi_{end}}^{\phi_{ini}} \frac{|d\phi|}{\sqrt{2\epsilon}}$$

A lot of models

Best performance:

Starobinsky



[Martin *et al.* (2014)]

Theoretical Motivation

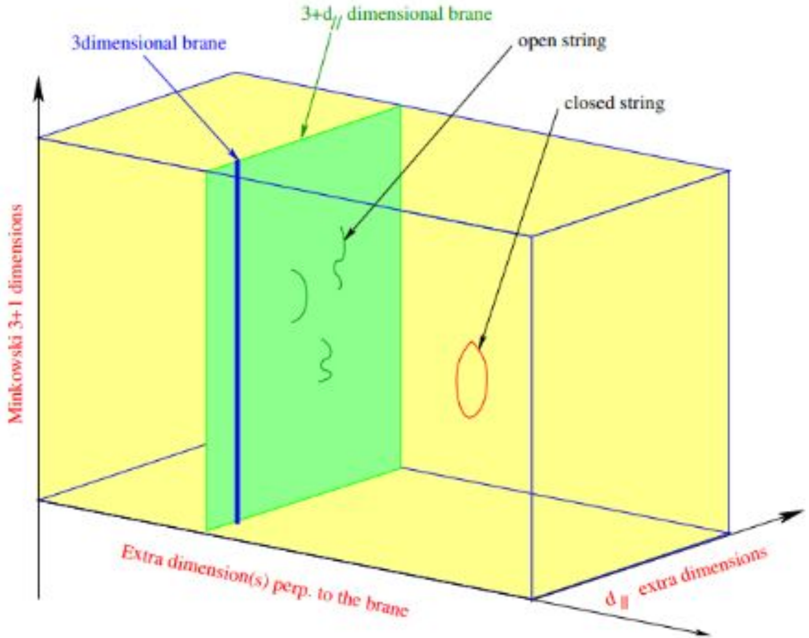
$$V(\phi) = V_0\left[1 - \exp\left(-\sqrt{\frac{2}{3}}\frac{\phi}{M_{Pl}}\right)\right]^2$$

- Higgs model with a non-minimal coupling to gravity, $\frac{\xi}{2}\phi^2 R - \frac{\lambda}{4}(\phi^2 - v^2)^2$, for $\xi < 0$ in the limit $1 + \xi v^2 \ll 1$ [Linde *et al.* (2011)];
- Higgs inflation in the theory $\frac{\lambda}{4}\phi^4$ with a sufficiently large non-minimal coupling to gravity $\frac{\xi}{2}\phi^2 R$ [Bezrukov *et al.* (2008)];
- Simple locally conformally invariant theory with spontaneous symmetry breaking [Kallosh *et al.* (2013)];
- Superconformal theory and supergravity [Kallosh *et al.* (2013)];
- $f(R)$ theories [Huang (2014)] and higher order polynomial corrections [Artymowski *et al.* (2015)];
- From a wide family of string models by using the Noether Symmetry Approach Capozziello *et al.* (2016)].

Brane inflation and the robustness of the Starobinsky inflationary model

Eur.Phys.J.Plus 136 (2021) 1, 84

S. Santos da Costa[1], M. Benetti[2,3,4], R.M.P. Neves[5], F. A. Brito[5,6], R. Silva[7,8], and J. Alcaniz[1]



Antoniadis , I. (2007)

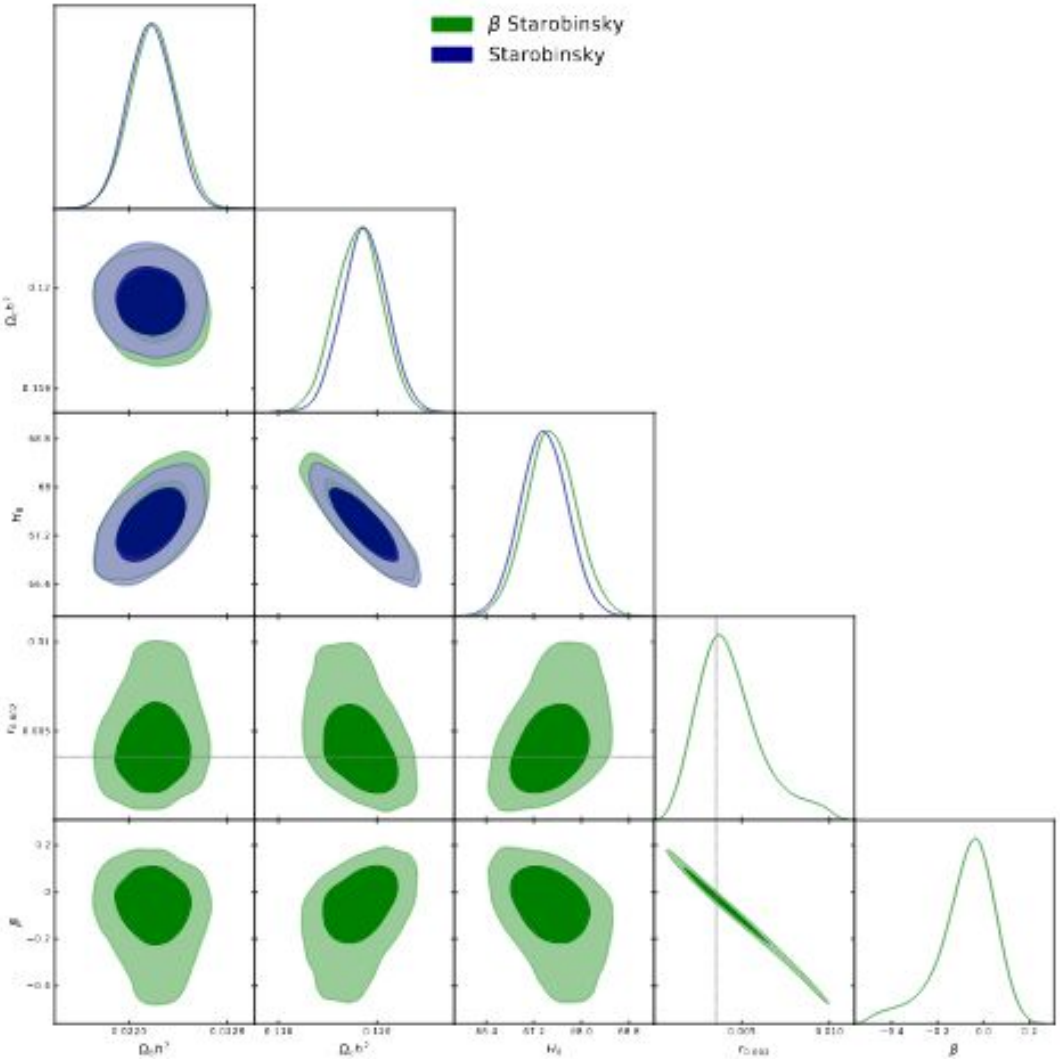
$$S = \int d^D x \sqrt{-g} \left(-\frac{1}{4} R + \frac{1}{2} \partial_M \phi_i \partial^M \phi_i - V(\phi_i) \right),$$

$$V_{\text{eff}}(L) = A_0 (1 - c_1 L)^{\frac{1}{\lambda c_1}} + \frac{1}{2} \sigma,$$

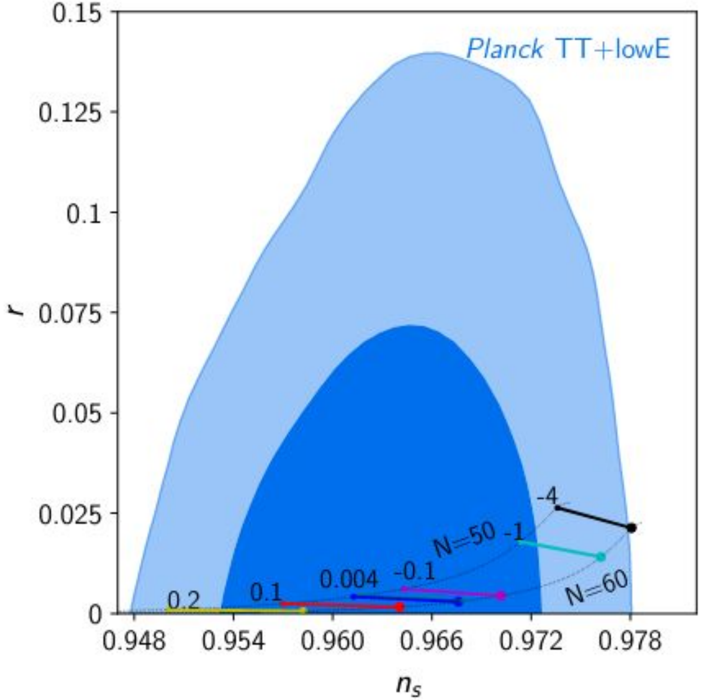
Extended Starobinsky

$$V(\phi) = V_0 \left[1 - \left(1 - \beta \sqrt{\frac{2}{3}} \frac{\phi}{M_{\rm Pl}} \right)^{\frac{1}{\beta}} \right]^2,$$

$$\exp_{1-\beta}(f) = [1 + \beta f]^{1/\beta}$$



Extended Starobinsky



$$n_s = 1 + \frac{8}{3}\frac{\chi^{\frac{1}{\beta}-2}}{\left(1-\chi^{\frac{1}{\beta}}\right)^2}\left[\beta\left(1-\chi^{\frac{1}{\beta}}\right) - 1 - \chi^{\frac{1}{\beta}}\right],$$

$$r = \frac{64}{3}\chi^{\frac{2}{\beta}-2}\left(1-\chi^{\frac{1}{\beta}}\right)^{-2},$$

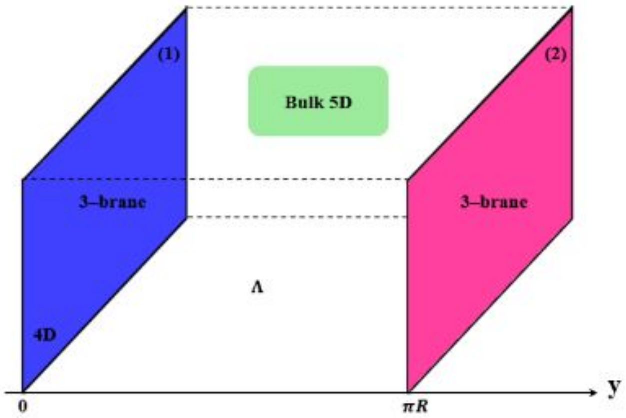
$$\chi \equiv 1 - \beta\sqrt{\tfrac{2}{3}}\frac{\phi}{M_{Pl}}.$$

Brane inflation driven by an arctan potential: CMB constraints and Reheating

JCAP 07 (2022) 07, 024

$$e^{-1}\mathcal{L}_{sugra} = -\frac{1}{4}M_*^3 R_{(5)} + G_{AB}\partial_\mu\phi^A\partial^\mu\phi_B - \frac{1}{4}G^{AB}\frac{\partial W(\phi)}{\partial\phi^A}\frac{\partial W(\phi)}{\partial\phi^B} + \frac{1}{3}\frac{1}{M_*^3}W(\phi)^2. \quad (3.5.40)$$

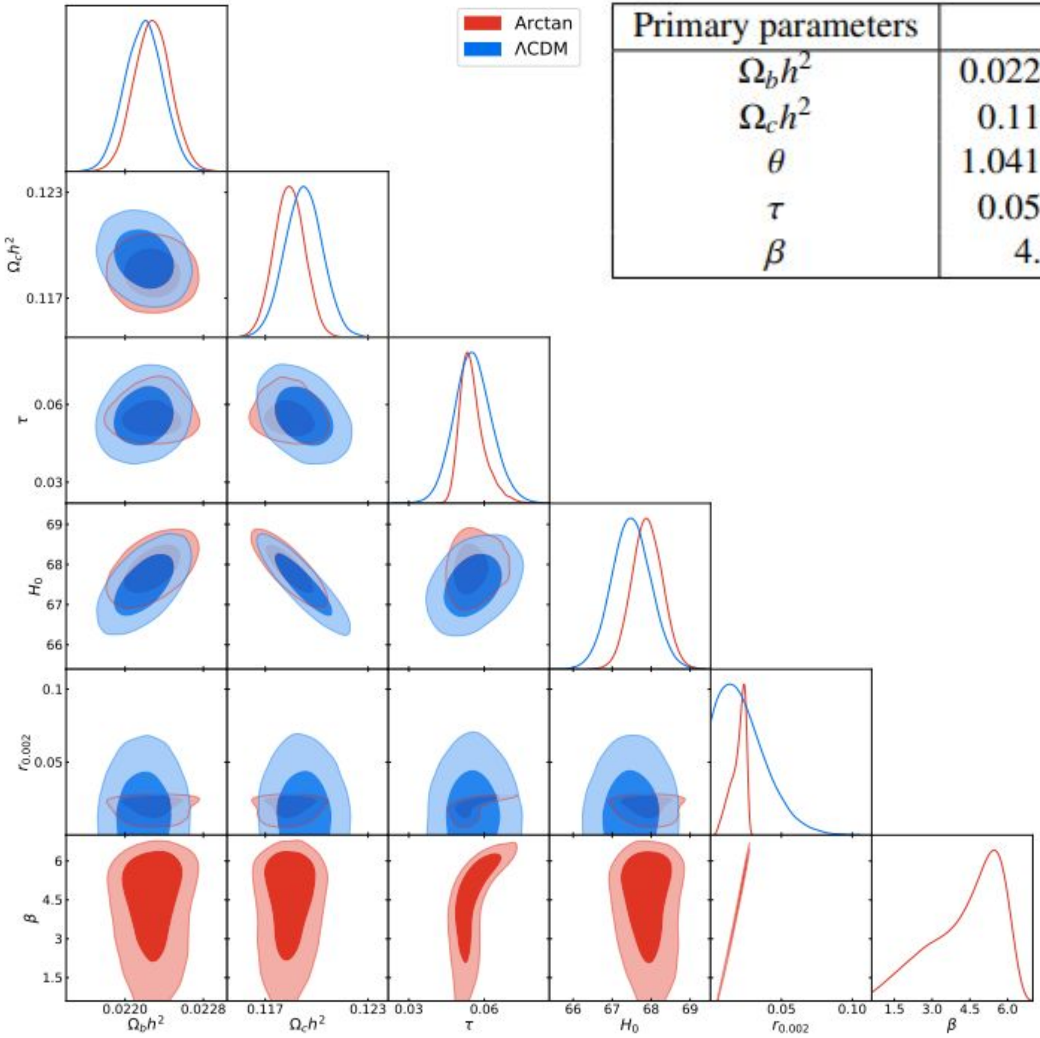
R. M. P. Neves[a] S. Santos da Costa[b] F. A. Brito[a,c] J. S. Alcaniz[b]



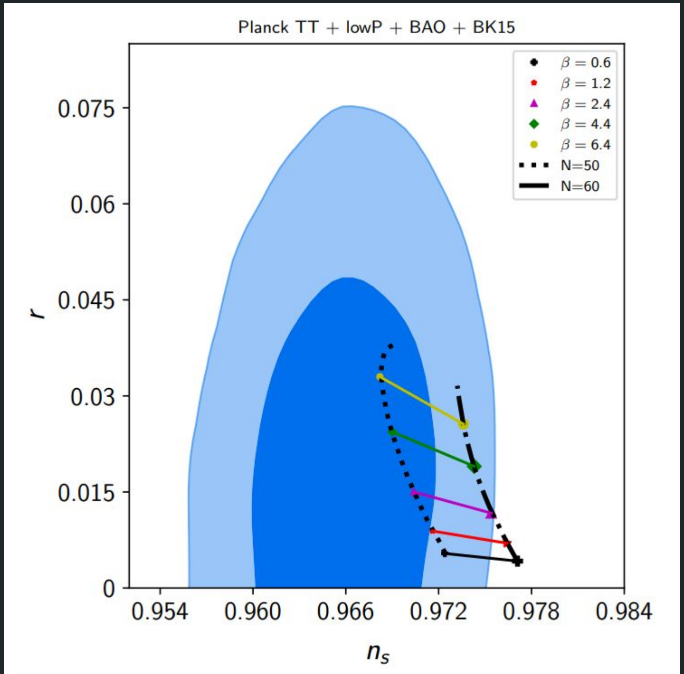
$$V(\phi) = K\beta\arctan\left(\frac{\phi}{\beta}\right),$$

$$n_s = 1 - \frac{4}{\beta^2\arctan\left(\frac{\phi}{\beta}\right)\left(1+\frac{\phi^2}{\beta^2}\right)^2} - \frac{3}{2\beta^2\arctan^2\left(\frac{\phi}{\beta}\right)\left(1+\frac{\phi^2}{\beta^2}\right)^2},$$

$$r = \frac{8}{\beta^2\arctan\left(\frac{\phi}{\beta}\right)\left(1+\frac{\phi^2}{\beta^2}\right)^2}$$



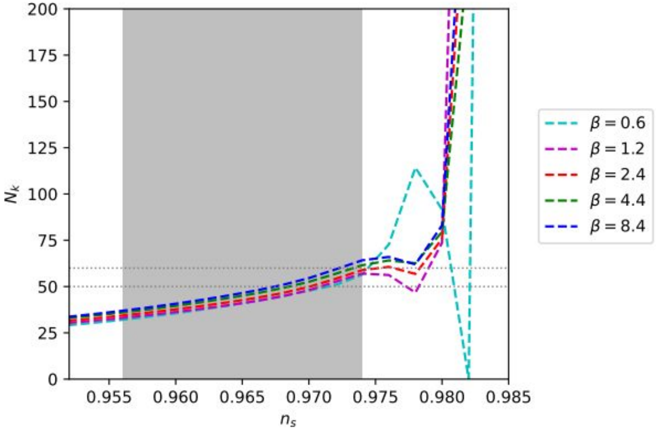
Primary parameters		Derived parameters	
$\Omega_b h^2$	0.02228 ± 0.00018	H_0	67.89 ± 0.38
$\Omega_c h^2$	0.1184 ± 0.0009	Ω_m	0.307 ± 0.005
θ	1.04107 ± 0.00041	Ω_Λ	0.693 ± 0.005
τ	0.0553 ± 0.0049	n_s	0.9719 ± 0.0562
β	4.37 ± 1.38	$r_{0.002}$	0.0196 ± 0.0052

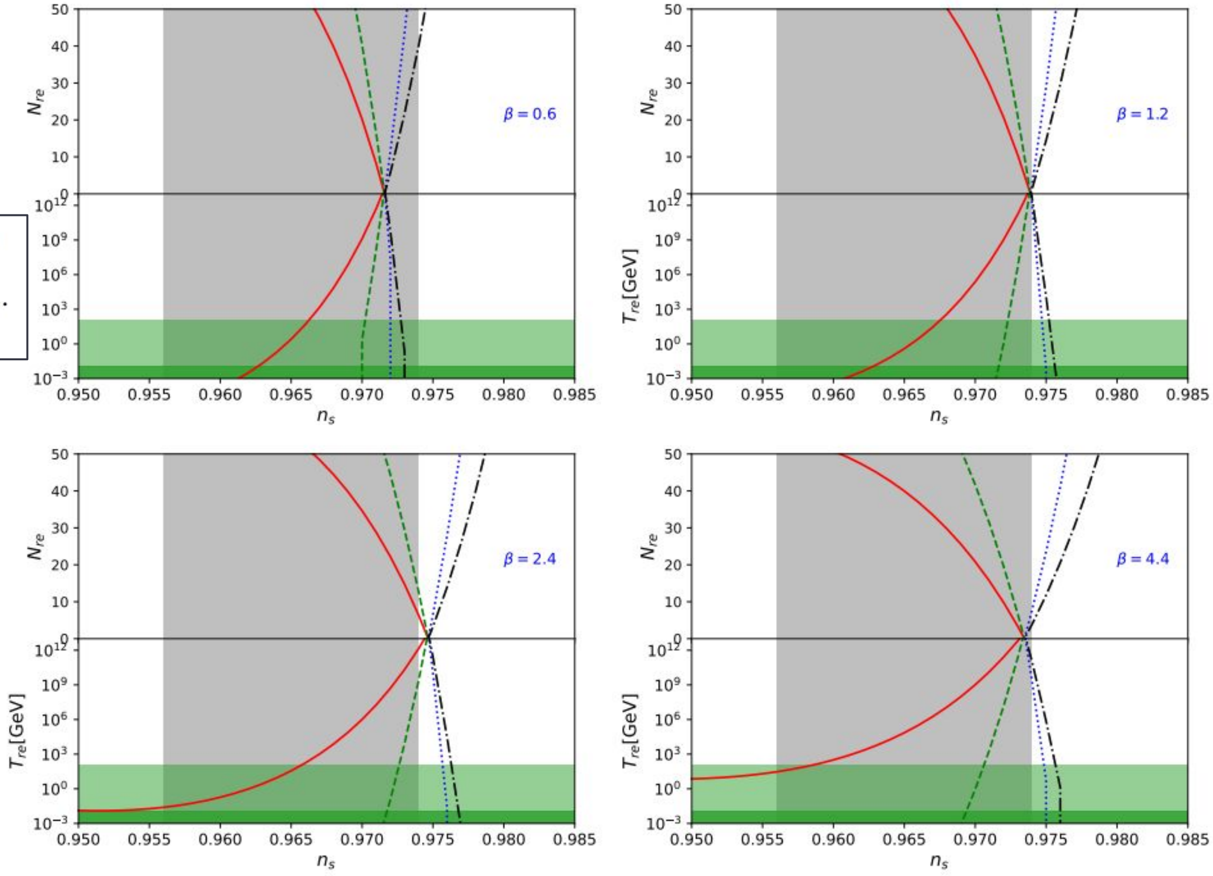


Reheating constraints

$$\mathcal{N}_{re} = \frac{4}{1-3w_{re}}\left[61.6 - \ln\left(\frac{V_{end}^{\frac{1}{4}}}{H_k}\right) - \mathcal{N}_k\right],$$

$$T_{re} = \left[\left(\frac{11 g_{re}}{43}\right)^{\frac{1}{3}}\left(\frac{k}{a_0 T_0}\right) H_k e^{-\mathcal{N}_k}\left(\frac{45 V_{end}}{\pi^2 g_{re}}\right)^{-\frac{1}{3(1+w_{re})}}\right]^{\frac{3(1+w_{re})}{3w_{re}-1}}.$$





Observational constraints on α-attractor inflationary models with a Higgs-like potential

Phys.Lett.B 815 (2021) 136156

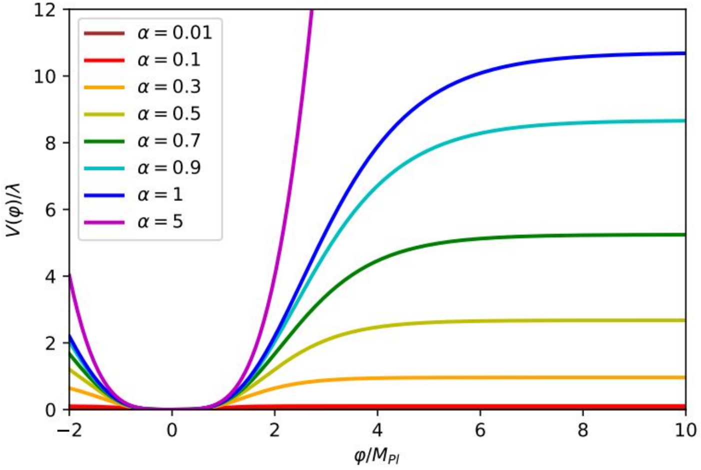
J. G. Rodrigues[a], S. Santos da Costa[b], J. S. Alcaniz[b]

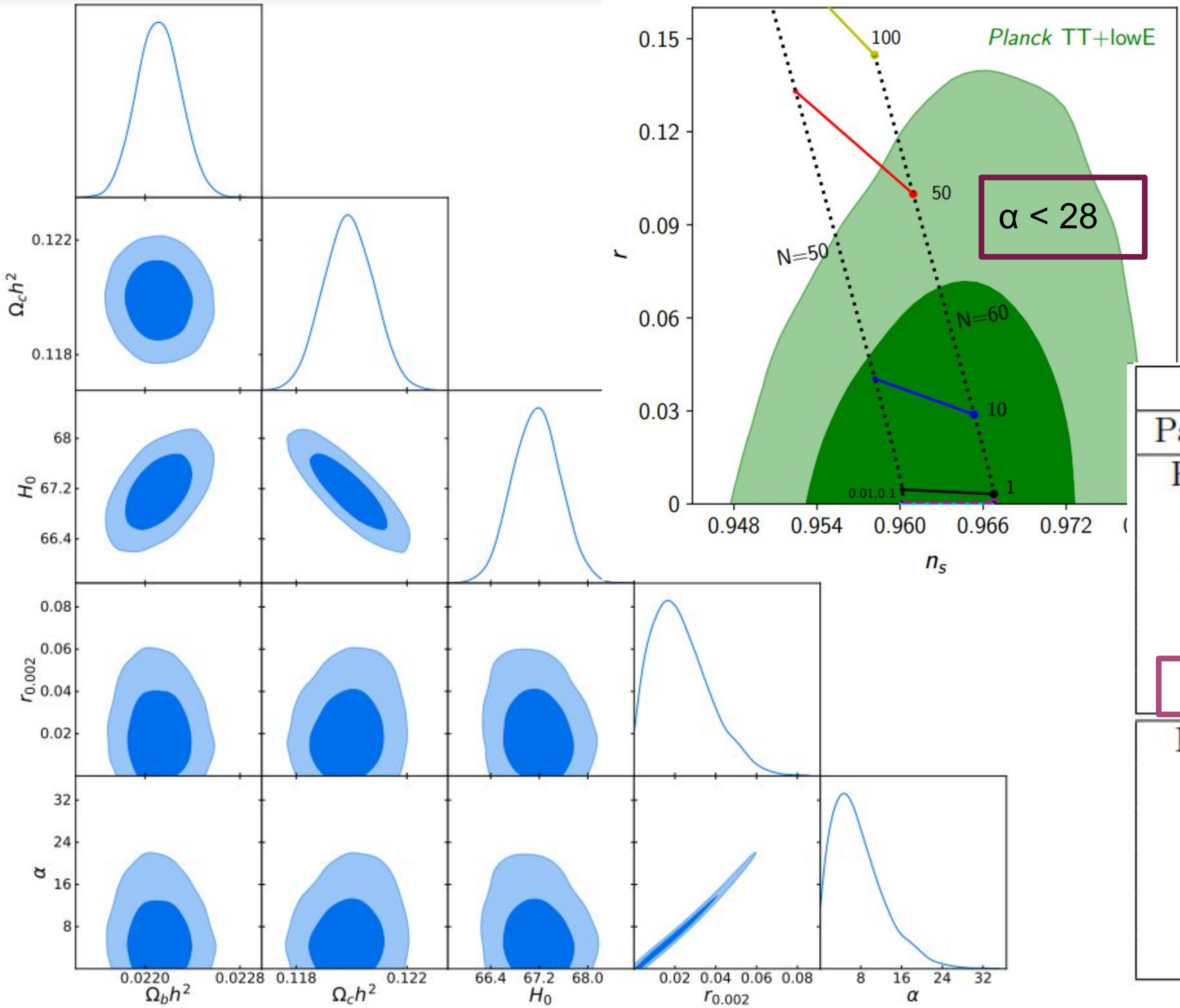
$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2,$$

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}R - \frac{(\partial\varphi)^2}{2} - V(\sqrt{6\alpha}\tanh\frac{\varphi}{\sqrt{6\alpha}})\right].$$

$$\phi = \sqrt{6\alpha}\tanh\frac{\varphi}{\sqrt{6\alpha}},$$

$$V(\varphi) = 9\alpha^2\lambda\left(\tanh\frac{\varphi}{\sqrt{6\alpha}}\right)^4,$$





	Higgs-like	
Parameter	mean	best fit
Primary		
$\Omega_b h^2$	0.02212 ± 0.018	0.02208
$\Omega_c h^2$	0.1199 ± 0.0009	0.1196
θ	1.04085 ± 0.00040	1.04108
τ	0.048 ± 0.003	0.048
α	7.56 ± 5.15	9.82
Derived		
H_0	67.16 ± 0.38	67.21
Ω_m	0.316 ± 0.005	0.320
Ω_Λ	0.684 ± 0.005	0.680
n_s	0.963 ± 0.001	0.9621
$r_{0.002}$	0.023 ± 0.014	0.030

Constraining non-minimally coupled β-exponential inflation with CMB data

JCAP 06 (2022) 06, 001

F. B. M. dos Santos[a] S. Santos da Costa[b] R. Silva[a,c] M. Benetti,[d,e] J. S. Alcaniz[b]

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

$$F^2(\phi) \equiv \frac{1+\kappa^2\xi\phi^2(1+6\xi)}{(1+\kappa^2\xi\phi^2)^2},$$

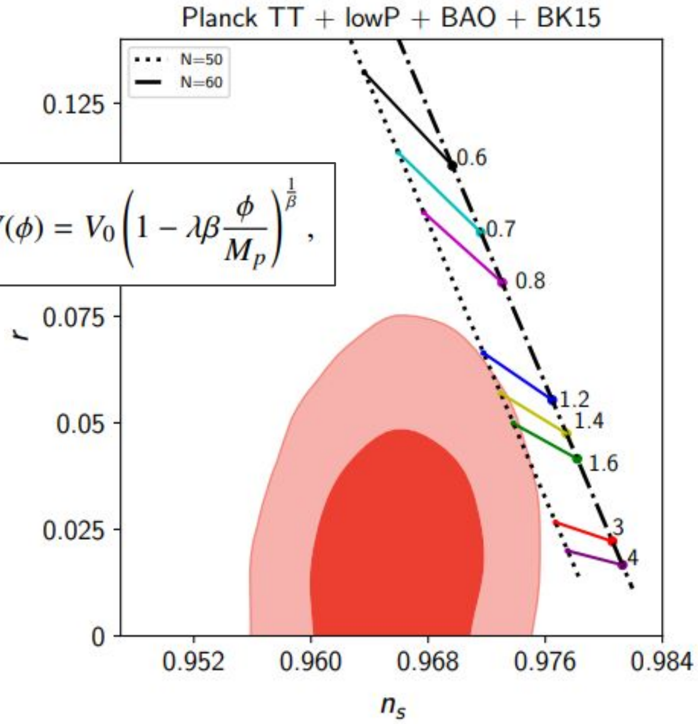
$$\hat{V}(\chi) \equiv \frac{V(\phi)}{(1+\kappa^2\xi\phi^2)^2}.$$

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

$$\chi_\phi \equiv \frac{d\chi}{d\phi} = \sqrt{\frac{1+\kappa^2\xi\phi^2(1+6\xi)}{(1+\kappa^2\xi\phi^2)^2}},$$

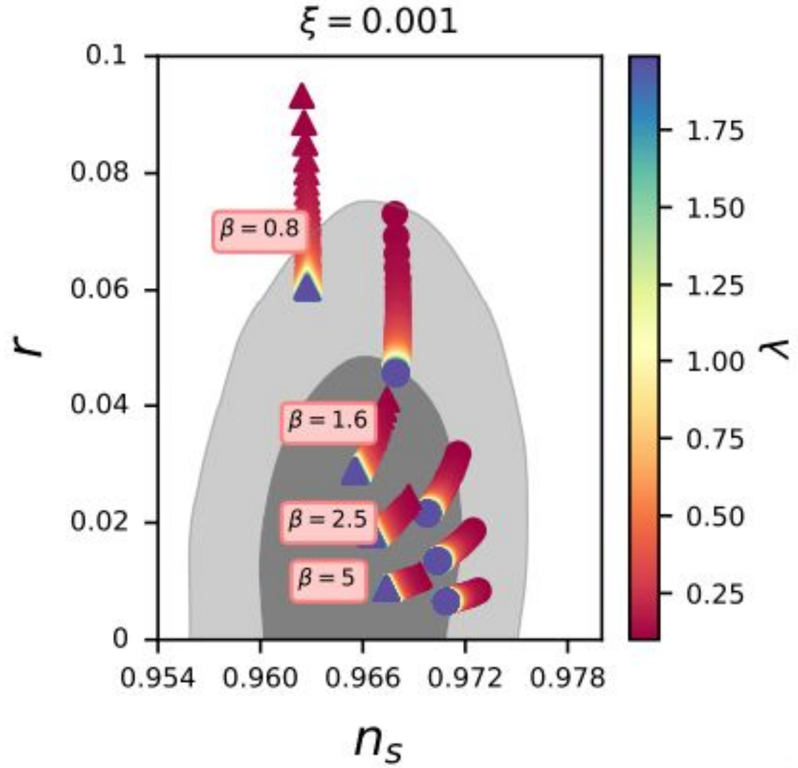
$$\epsilon = \frac{M_p^2}{2}\left(\frac{V_\phi}{V\chi_\phi}\right)^2, \quad \eta = M_p^2\left(\frac{V_{\phi\phi}}{V\chi_\phi^2} - \frac{V_\phi\chi_{\phi\phi}}{V\chi_\phi^3}\right), \quad \zeta^2 = M_p^4\frac{V_\phi}{V^2\chi_\phi^2}\left(\frac{V_{\phi\phi\phi}}{\chi_\phi^2} - \frac{3V_{\phi\phi}\chi_{\phi\phi}}{\chi_\phi^3} + \frac{3V_\phi\chi_{\phi\phi}^2}{\chi_\phi^4} - \frac{V_\phi\chi_{\phi\phi\phi}}{\chi_\phi^3}\right).$$

The β-exponential potential



$$V(\phi) = V_0\left(1 - \lambda\beta\frac{\phi}{M_p}\right)^{\frac{1}{\beta}},$$

Minimally coupled



Non-minimally coupled

$$\hat{V}(\chi(\phi)) = \frac{V_0(1-\lambda\beta\phi)^{1/\beta}}{(1+\xi\phi^2)^2}.$$

Cosmological models for $f(R,T) - \Lambda(\phi)$ gravity

[1]Joao R. L. Santos,* [2] S. Santos da Costa,† and [3]Romario S. Santos‡

$$S = \int d^4x\sqrt{-g}\left(f(R,T) - \frac{\Lambda(\phi)}{2} + \mathcal{L}\right),$$

Phys.Dark Univ. 42 (2023) 101356

First order formalism

$$H \equiv h(\phi)\,; \qquad \dot{H} = h_\phi \dot{\phi}\,,$$

$$\dot{\phi} = -W_\phi\,; \qquad W_\phi = \frac{dW(\phi)}{d\phi}\,,$$

$$h_\phi = \left(1 - 2f'\right)W_\phi\,.$$

$$V_\phi = \frac{(3hh_\phi - W_\phi h_{\phi\phi} - \rho_{\Lambda\,\phi})\,W_\phi}{2h_\phi - W_\phi}\,.$$

A. First Model - $f_\phi = \alpha\, T_\phi$

$$W = b_1\left(-\phi + \frac{\phi^3}{3}\right) + \frac{b_2}{(1-2\alpha)}\,.$$

$$W_\phi = b_1\left(\phi^2 - 1\right)\,; \qquad h(\phi) = (1-2\alpha)\,W\,,$$

Cosmological models for $f(R,T) - \Lambda(\phi)$ gravity

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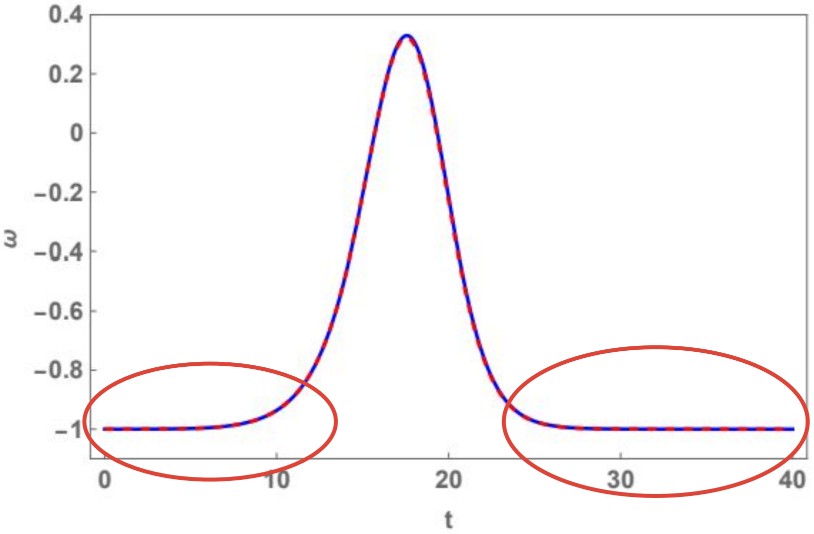
$$= \int d^4x\sqrt{-g}\left(f(R,T) - \frac{\Lambda(\phi)}{2} + \mathcal{L}\right),$$

Phys.Dark Univ. 42 (2023) 101356

First order formalism



A. First Model - $f_\phi = \alpha\, T_\phi$

$$W = b_1\left(-\phi + \frac{\phi^3}{3}\right) + \frac{b_2}{(1-2\alpha)}\,.$$

$$W_\phi = b_1\left(\phi^2 - 1\right)\,; \qquad h(\phi) = (1-2\alpha)\,W\,,$$

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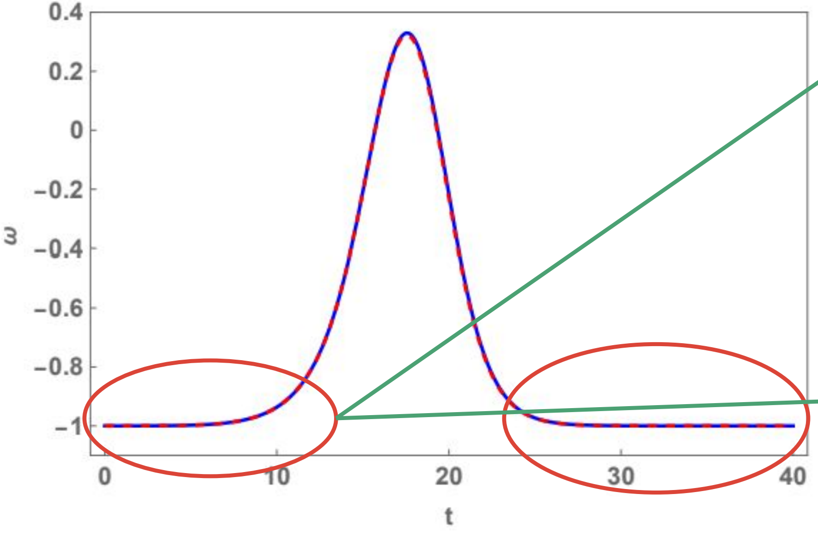
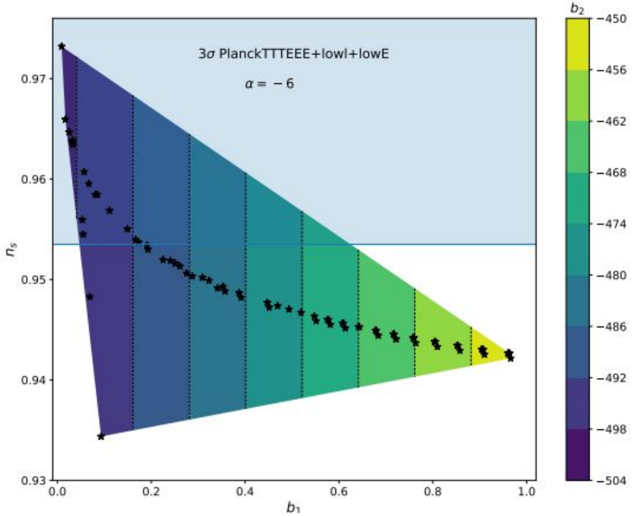
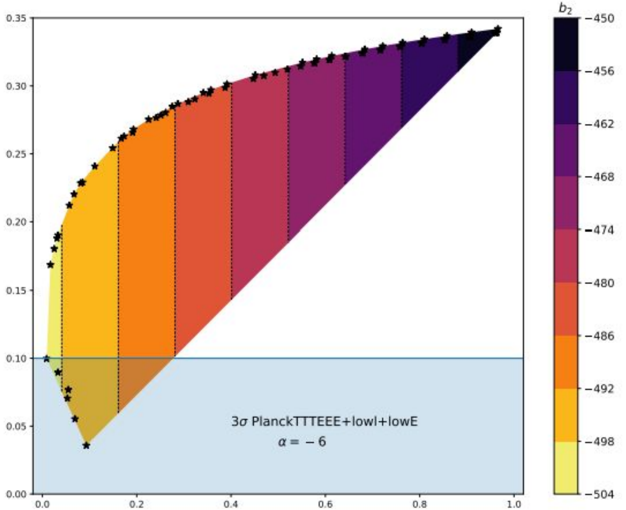
[1]Joao R. L. Santos,[*] [2] S. Santos da Costa,[†] and [3]Romario S. Santos[‡]

Phys.Dark Univ. 42 (2023) 101356

First order formalism







Gauge invariant quantum backreaction in $U(1)$ axion inflation

Davide Campanella Galanti[a,b,*], Pietro Conzinu[a,b,†], Giovanni Marozzi[a,b,‡] and Simony Santos da Costa[b,§]
[a] Dipartimento di Fisica, Università di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
[b] Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Italy

Without matter and metric fluctuations

C. Natural Inflation

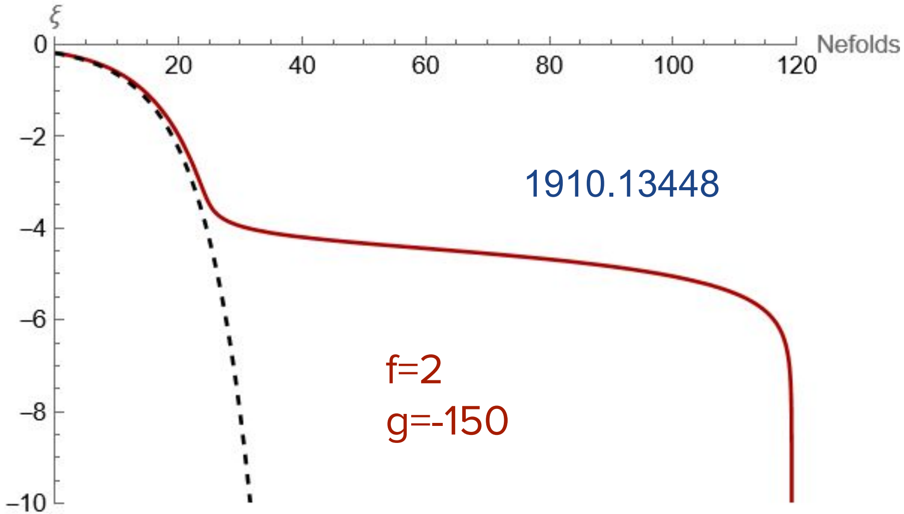
We now compute the gauge invariant backreaction effect to the case of a natural inflation where we have

$$V(\phi) = \Lambda^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right] , \tag{61}$$

$$H^2 = \frac{1}{3m_{Pl}^2}\left[\frac{\dot{\phi}^2}{2} + V(\phi) + \frac{\langle \mathbf{E}^2 + \mathbf{B}^2\rangle}{2}\right],$$

$$\dot{H} = -\frac{1}{2m_{Pl}^2}\left[\dot{\phi}^2 + \frac{2}{3}\langle \mathbf{E}^2 + \mathbf{B}^2\rangle\right].$$

$$\xi \equiv g\dot{\phi}/(2H). \qquad g = \alpha/f,$$



1910.13448

Gauge invariant quantum backreaction in $U(1)$ axion inflation

Davide Campanella Galanti[a,b,*] Pietro Conzinu[a,b,†] Giovanni Marozzi[a,b,‡] and Simony Santos da Costa[b,§]
[a] Dipartimento di Fisica, Università di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy
[b] Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Italy

Second order perturbative equations

$$H^2 = \frac{1}{3m_{Pl}^2}\left[\frac{\dot{\phi}^2}{2} + V(\phi) + \frac{\langle \mathbf{E}^2 + \mathbf{B}^2\rangle}{2}\right],$$

$$\dot{H} = -\frac{1}{2m_{Pl}^2}\left[\dot{\phi}^2 + \frac{2}{3}\langle \mathbf{E}^2 + \mathbf{B}^2\rangle\right].$$

f>>M_Pl

$$H_{eff}^2 = H^2\left[1 - \frac{2}{H}\langle \dot{\bar{\psi}}^{(2)}\rangle\right]$$
$$= H^2\left[1 + \frac{1}{3H^2M_{Pl}^2}\frac{\langle \mathbf{E}^2 + \mathbf{B}^2\rangle}{2}\right],$$

Full regime

$$H_{eff}^2 = H^2\left\{1 + \frac{1}{M_{Pl}^2}\left[\frac{1}{3H^2} + \left(\frac{M_{Pl}}{f}\right)^4 \frac{1}{\dot{H}}\left(\frac{G(H)}{6} + \frac{1}{144}\right)\right]\frac{<\vec{E}^2 + \vec{B}^2>}{2}\right\}$$

Final remarks

- There is still space to play with inflationary models:
  - Advantage >> Theoretically motivated models - foundation of an extended theory of gravity;
- We investigated different braneworld scenarios: extended Starobinsky + ArcTan potentials;
- We have constrained for the first time the parameters associated with the alpha attractor Higgs-like potential;
- We can recover the observational viability of models by coupling the scalar field to the gravity sector;
- Implementation of the *first order formalism* to study the inflationary phase;
- Work in progress with interesting perspectives:
  - **Backreaction in U(1) axion inflation**

Grazie
Thank You
Obrigado
Merci
Kiitos
Juspaxar
Mochchakkeram
Spasibo
Kia Ora
Asante
Maake
Mamana
Terma Kasih
Cam on ban
Vinaka
Dyakuyu
Arigato
Salamat
Multumesc
Matur Nuwun
Danke
Dankon
Dank Je
Chokrane