α-attractors:

Planck, LHC and Dark Energy

Renata Kallosh

String Phenomenology 2015, Madrid

Based on Carrasco, RK, Linde, 1506.01708, 1506.00936
and earlier work, mostly with Ferrara and Roest

We develop four-parameter string-inspired supergravity models of inflation and dark energy, constrained so that $\delta\rho/\rho$, n_s and the cosmological constant Λ take their known observable values, but where the mass of gravitino $m_{3/2}$ and the tensor-to-scalar ratio r are free parameters

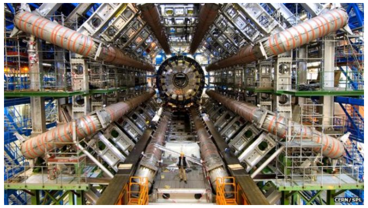
We will introduce supersymmetric KKLT:
RK, Wrase,
Bergshoeff, Dasgupta, Van Proeyen

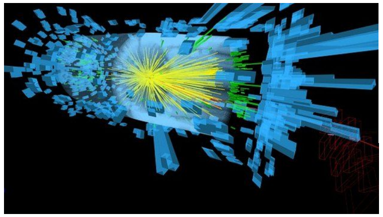
The Race is On

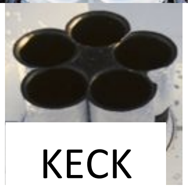
B-mode detection or a new bound on r

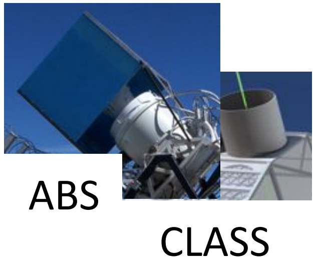
$$r < 0.1$$

Supersymmetry discovery, or a new bound on scale of SUSY breaking M





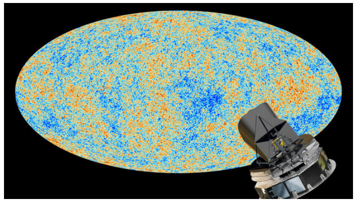




Can we describe all this using only the `primordial sector of supergravity': the inflaton+ goldstino?

The answer is YES!

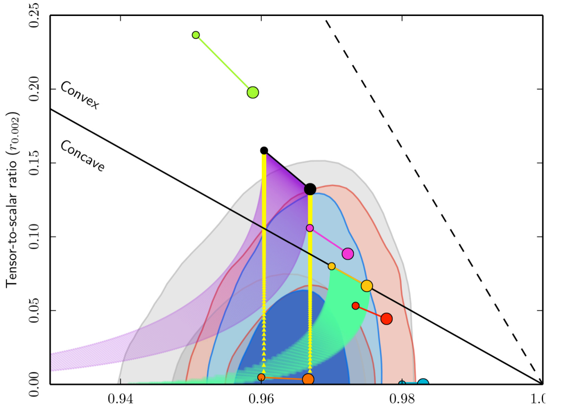
Rather Well Established Over the Last Decade



CMB anisotropy $$\frac{\delta\rho}{\rho} \approx 10^{-5}$$

Inflationary tilt of spectrum $$n_s \approx 1 - \frac{2}{N}$$

Dark Energy/ CC $$\Lambda \approx 10^{-120}$$



Combining Planck data with other astrophysical data, including Type Ia supernovae, the equation of state of dark energy is constrained to *w* = - 1.006 ± 0.045

CC is a good fit to data : need string landscape + anthropic reasoning

String Theory ?

Massive N=2a Supergravity in Ten-Dimensions
L.J. Romans, **Phys.Lett. B169 (1986)**

Cited by 384 records

384.**Supergravity In Ten Space-time Dimensions**
B. de Wit. Apr 1986.

383. **Dirichlet Branes and Ramond-Ramond charges**
Joseph Polchinski **Phys.Rev.Lett. 75 (1995)**

… strong evidence that the Dirchlet-branes are intrinsic to type II string theory and are the Ramond-Ramond sources required by string duality. We also note the existence of a previously overlooked 9-form potential in the IIa string, which has a cosmological constant of undetermined magnitude. This is surprising, but has been partially anticipated by Romans [19], who found the corresponding supergravity theory (for fixed cosmological constant)

Fluxes: gauged supergravity in d=4 and massive d=10 supergravity

become part of string theory after discovery of D-branes

d=4 supergravity with a nilpotent chiral multiplet (Volkov-Akulov fermionic goldstino) extremely useful in cosmology:

1. Supersymmetric KKLT de Sitter uplift
2. Inflation, Planck, LHC, Dark Energy in one framework!

previously overlooked feature of fermions on D-brane

RK, Wrase, 2014

Bergshoeff, Dasgupta, RK, Van Proeyen,Wrase, 2015

$\overline{\mathbf{D3}}$ and dS

Uranga; Sugimoto; Antoniadis, Dudas, Sagnotti 1999

Grana, 2002; McGuirk, Shiu, Ye 2012

Supersymmetric KKLT

$\overline{\mathrm{D3}}$ and dS

Bergshoeff, Dasgupta, RK, Van Proeyen,Wrase, 2015

S. Kachru, R. Kallosh, A. D. Linde, J. M. Maldacena, L. P. McAllister and S. P. Trivedi, 2003

Without fermions
KKLT uplift

$$S^q = S_{DBI} + q\, S_{WZ} = -T_3 \int d^4\sigma \sqrt{-g} \Big(\frac{r_0}{R}\Big)^4 + q\, T_3 \int C_4 \quad C_4 = \left(\tfrac{r_0}{R}\right)^4 d^4\sigma .$$

$$S^{\mathrm{D3}} = 0\,, \qquad S^{\overline{\mathrm{D3}}} = -2T_3 \Big(\frac{r_0}{R}\Big)^4 \int d^4\sigma \sqrt{-g}$$

This leads to an effective positive energy for the $\overline{\mathrm{D3}}$ at position r_0 in a background with unbroken supersymmetry, so that

$$V = 2T_3 \Big(\frac{r_0}{R}\Big)^4\,, \quad \text{which can uplift the vacuum to a dS one.}$$

With fermions on the brane,
starting with a kappa-symmetric action
in superspace

$$S^q = -T_3 \int d^4\sigma \sqrt{-g_{\mu\nu} + \mathcal{F}_{\mu\nu}} + q\, T_3 \int C e^{\mathcal{F}}$$

$$S^{\mathrm{D3}}_{\mathrm{DBI+WZ}}|_{\theta^2 - \Gamma_{0123}\theta^1 = \mathcal{F}_{\mu\nu} = \Pi^{\tilde{a}}_{\mu} = 0} = -T_3 \int d^4\sigma \det E \, + \, T_3 \int d^4\sigma \det E = 0$$

$$\boxed{S^{\overline{\mathrm{D3}}}_{\mathrm{DBI+WZ}}|_{\theta^2 - \Gamma_{0123}\theta^1 = \mathcal{F}_{\mu\nu} = \Pi^{\tilde{a}}_{\mu} = 0} = -2T_3 \int d^4\sigma \det E}$$

$$E^a(x,\theta) = e^a_m(x,\theta) dx^m + e^a_{\beta I}(x,\theta) d\theta^{\beta I}$$

Manifestly supersymmetric Volkov-Akulov action: supersymmetric version of the KKLT uplifting

Effective d=4 N=1 supergravity
with a godstino multiplet

$$S^2(x,\theta) = 0$$

$$W = MS \qquad K = S\bar{S} \qquad V = M^2$$

Goldstino action gives a positive contribution to the energy

A universal role of the goldstino multiplet at the minimum of the inflationary potential

$$\Lambda = \underset{\substack{\uparrow \\ \text{SUSY breaking} \\ \text{parameter}}}{M^2} - 3\underset{\substack{\uparrow \\ \text{Gravitino mass}}}{m_{3/2}^2} > 0$$

$$M \equiv e^{\frac{K}{2}} D_S W$$

$$m_{3/2} \equiv e^{\frac{K}{2}} W$$

VA non-linearly realized supersymmetry of the purely fermionic multiplet is spontaneously broken. A tiny CC results from an incomplete cancellation of the positive goldstino and negative gravitino contribution to supergravity energy.

Nilpotent chiral superfield

$$S(x,\theta) = s(x) + \sqrt{2}\,\theta\,\psi(x) + \theta^2 F_S(x) \qquad S^2(x,\theta) = 0$$

$$s = \frac{\psi\psi}{2F_s}$$

sgoldstino is not a fundamental scalar but it is a bilinear combination of fermionic goldstino's divided by the value of the auxiliary field

There is no non-trivial solution if SUSY is unbroken and F_s=0, i.e. only $s = \psi = 0$ solve the equation S^2=0. Thus by requiring to have a fermion Volkov-Akulov goldstino nilpotent multiplet in supergravity theory we end up with the universal value of the supergravity potential at its minimum, with $e^K\,|F_S\,|^2 = M^2$

Volkov, Akulov, Is the neutrino a Goldstone particle? (1973)

$$S=\frac{1}{a}\int\omega_0\times\omega_1\times\omega_2\times\omega_3$$

$$\omega_\mu=\mathrm{d}x_\mu+\frac{u}{2\mathrm{i}}(\psi^+\sigma_\mu\mathrm{d}\psi-\mathrm{d}\psi^+\sigma_\mu\psi),$$

Rocek, Lindstrom, 1978-1979

$$S^2(x,\theta)=0$$

Casalbuoni, De Curtis, Dominici, Feruglio, Gatto, 1989

Komargodski, Seiberg 2009

Antoniadis, Dudas, Ferrara and Sagnotti, 2014

Ferrara, RK, Linde, 2014 application to cosmology, generic superconformal case

D-brane connection

$$S^{\mathrm{D3}}=0\,,\qquad S^{\overline{\mathrm{D3}}}=-2T_3\int d^4\sigma\,\det E=-2T_3\int E^0\wedge E^1\wedge E^2\wedge E^3$$

RK, Wrase, 2014

Bergshoeff, Dasgupta, RK, Van Proeyen,Wrase, 2015

$$E^a=\delta^a_m dx^m+\bar\lambda\gamma^a d\lambda$$

$$\mathcal{L}_{VA}=-M^2+\partial_a\bar\psi\bar\sigma^a\psi+\frac{1}{4M^2}\bar\psi^2\partial^2\psi^2-\frac{1}{16M^6}\psi^2\bar\psi^2\partial^2\psi^2\partial^2\bar\psi^2$$

$$\psi=M\lambda$$

Goldstino action in absence of fermions just adds a positive term to energy

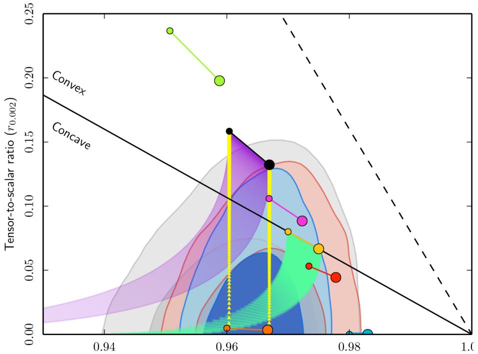
$$\boxed{\delta_\zeta\psi=\zeta+\frac{1}{M^2}\bar\psi\gamma^a\zeta\partial_a\psi}$$

Explicit VA supergravity

Supersymmetric KKLT

Bergshoeff, Freedman, RK, Van Proeyen, work in progress

On to cosmology α-attractor models compatible with inflationary data from Planck/Bicep II



Supergravity with 2 superfields: inflaton superfield and a nilpotent superfield

$\frac{\delta\rho}{\rho}, n_s$ agree with the data, r is flexible

$$n_s = 1 - \frac{2}{N}\,, \qquad r = \alpha\frac{12}{N^2}\,, \qquad r \approx 3\,\alpha \times 10^{-3}$$

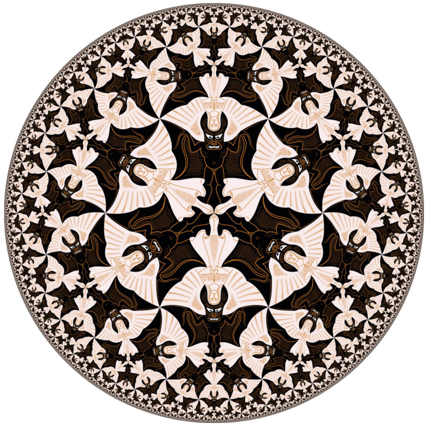
Meaning of α $K = -3\alpha\ln(T+\bar{T})$ $\mathcal{R}_K = -\frac{2}{3\alpha}$ Moduli space curvature

In Escher's paintings

$$ds^2 = \frac{3\alpha}{(T+\bar{T})^2}dTd\bar{T} \qquad T+\bar{T}>0$$

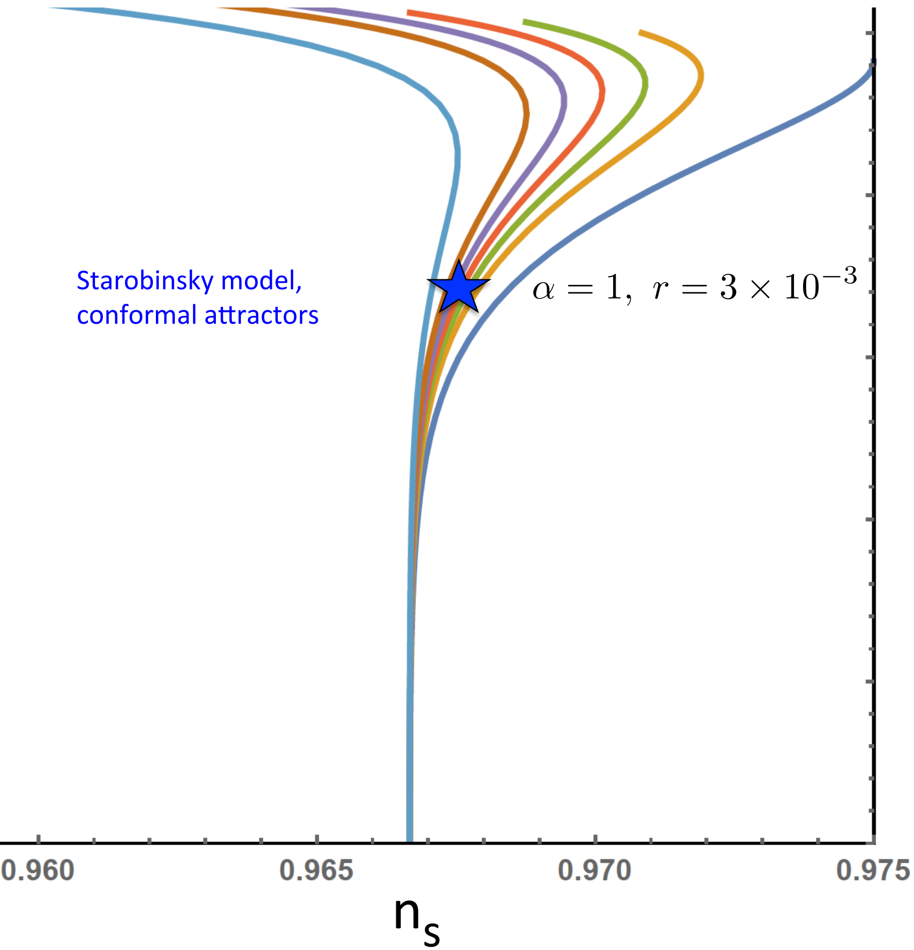
$$ds^2 = \frac{3\alpha}{(1-Z\bar{Z})^2}dZd\bar{Z} \qquad Z\bar{Z}<1$$

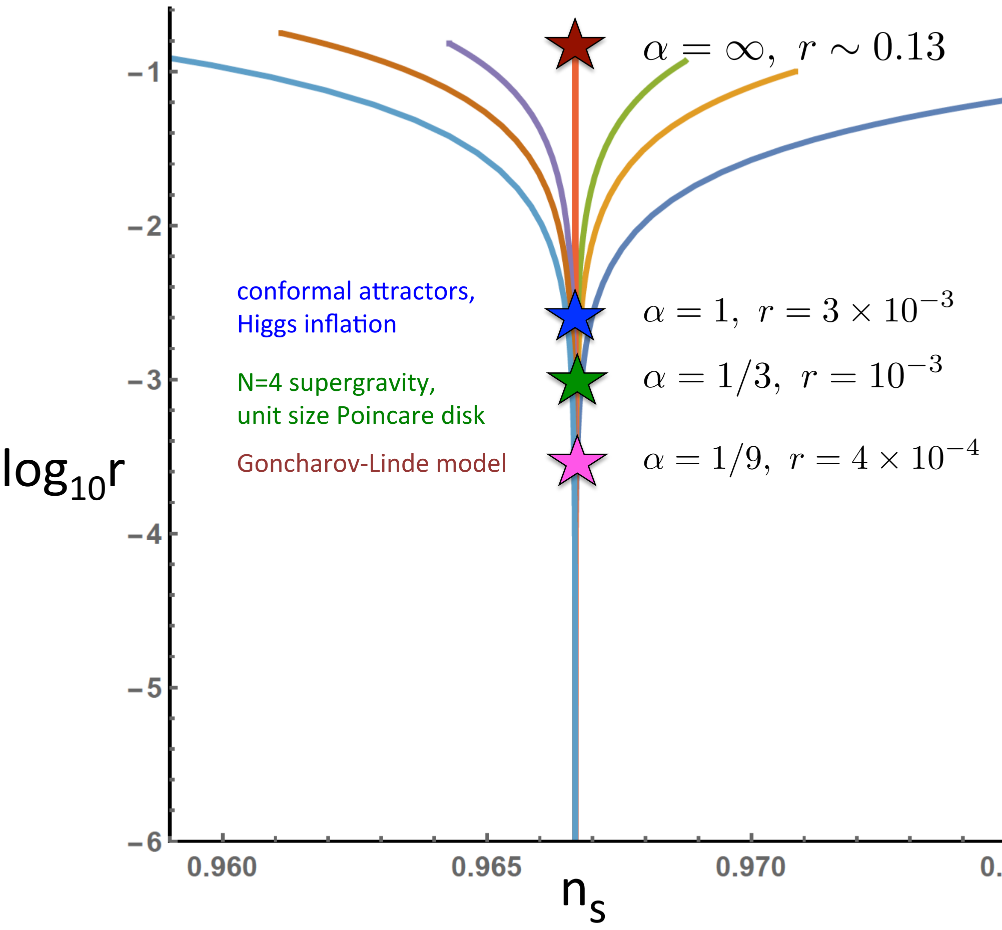
$$3\alpha = R^2_{\text{Escher}} \approx 10^3 r$$



Disk or **half-plane**:
Manifolds with boundaries

Escher in the Sky
RK and Linde 1503.06785

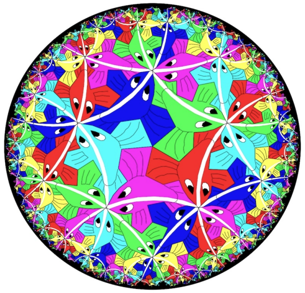




Any $\alpha < 27$ $\qquad r < 0.09$

Generic $\mathcal{N}$=1 supergravity

$$3\alpha = R^2_{\text{Escher}} \approx 10^3 r$$



Moduli space geometry of α-attractor models has 3 useful set of coordinates:

Earlier work on susy breaking and CC in inflationary sector of supergravity

RK, Linde, Dall'agata, Zwirner, Scalisi, Lanas, Tamvakis

Disk variables Z, Half-plane variables T, Killing variables

Killing-adapted choice of coordinates where the metric does not depend on the inflaton Kahler potential has an inflaton shift symmetry

$$ds^2 = -3\alpha \frac{dZ d\bar{Z}}{(1 - Z\bar{Z})^2} = -3\alpha \frac{dT d\bar{T}}{(T + \bar{T})^2} = \frac{\partial\Phi \partial\bar{\Phi}}{2\cos^2\left(\sqrt{\frac{2}{3\alpha}}\, \mathrm{Im}\Phi\right)}$$

$$K = -3\alpha \log\left(1 - Z\bar{Z}\right) + S\bar{S}$$

$$\text{Killing variables } \Phi = \varphi + i\vartheta$$

$$K = -3\,\alpha \log\left(T + \bar{T}\right) + S\bar{S}$$

The choice of coordinates $Z = \tanh\frac{\Phi}{6\alpha}$ *and* $T = e^{\sqrt{\frac{2}{3\alpha}}\Phi}$ *in the disk/half-plane geometry corresponds to a Killing-adapted choice of coordinates where the metric does not depend on* $\varphi = \mathrm{Re}\,\Phi$

$$ds^2 = \frac{d\varphi^2 + d\vartheta^2}{2\cos^2\sqrt{\frac{2}{3\alpha}}\vartheta}$$

$$\vartheta = 0$$

During inflation and at the minimum of the potential the inflaton is a canonical variable

`Refined' α-attractor models

$$S^2(x,\theta)=0$$

$$K=-3\alpha\log\left(1-Z\bar{Z}\right)+S\bar{S}$$

$$T=\frac{1+Z}{1-Z},\quad T^{-1}=\frac{1-Z}{1+Z}$$

$$K=-3\,\alpha\log\left(T+\bar{T}\right)+S\bar{S}$$

Change the Kahler frame
And use the most general W

$$T=e^{\sqrt{\frac{2}{3\alpha}}\Phi},\qquad Z=\tanh\frac{\Phi}{\sqrt{6\alpha}}$$

$$K=-\frac{3}{2}\alpha\log\left[\frac{(1-Z\bar{Z})^2}{(1-Z^2)(1-\overline{Z}^2)}\right]+S\bar{S}$$

$$W=A(Z)+SB(Z)$$

$$K=-\frac{3}{2}\,\alpha\log\left[\frac{(T+\bar{T})^2}{4T\bar{T}}\right]+S\bar{S}$$

$$W=G(T)+SF(T)$$

$$\boxed{K=-3\alpha\log\left[\cosh\frac{\Phi-\bar{\Phi}}{\sqrt{6\alpha}}\right]+S\bar{S}}$$

$$\boxed{W=g(\Phi)+Sf(\Phi)}$$

Moduli stabilization in `refined' α-attractor models

1. There is no sgolstino to stabilize since S has no fundamental scalar!

2. The inflaton muliplet has an inflaton partner, which has be be heavy to quickly reach its minimum and do not affect the universe evolution.

For any of our choice of variables (disk, half-plane, Killing) there is one field to stabilize

$$Z-\bar{Z} \quad \text{or} \quad T-\bar{T} \quad \text{or} \quad \Phi-\bar{\Phi}$$

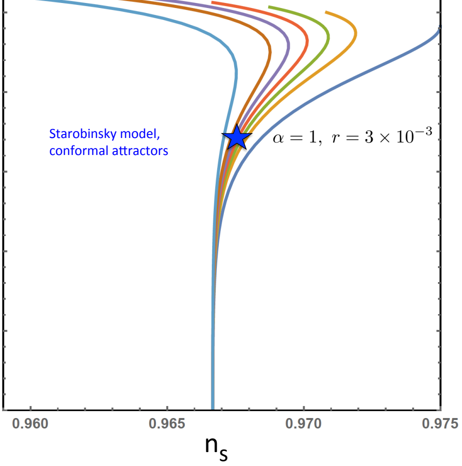
When S is outside the log this field, the inflaton partner is heavy, no need to stabilize for $\alpha > 0.02$

$$K=-3\,\alpha\log\left(T+\bar{T}\right)+S\bar{S}$$

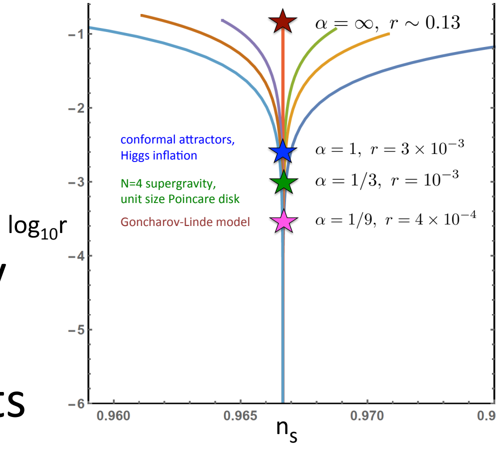
For smaller $\alpha < 0.02$ adding the bisectional curvature leads to stabilization

$$A(T,\bar{T})\,S\bar{S}\,(T-\bar{T})^2$$

Nice and simple



Starting with refined α-attractor models which fit inflation and future B-modes we modify the superpotentials to get spontaneous breaking of supersymmetry and dark energy, inside the `primordial sector' INFLATON +GOLDSTINO multiplets



1. Reconstruction method. Given a choice of a potential during inflation V, reconstruct W with susy breaking. This method was first suggested for vanishing CC and shift-symmetric canonical K by Dall'agata, Zwirner. We extend it to geometric log K and non-vanishing CC

$$W=(S+\frac{1}{b})f(\Phi)\qquad\qquad V_{\rm min}=\Lambda=M^2\Big(1-\frac{3}{b^2}\Big)>0$$

2. General method based on attractor nature of our models

$$\boxed{K=-3\alpha\log\left[\cosh\frac{\Phi-\bar\Phi}{\sqrt{6\alpha}}\right]+S\bar S}\qquad\qquad\boxed{W=g(\Phi)+Sf(\Phi)}$$

$$\boxed{K = -3\alpha \log \left[\cosh \frac{\Phi - \bar{\Phi}}{\sqrt{6\alpha}} \right] + S\bar{S}}$$

Reconstruction method

$$W = (S + \frac{1}{b})f(\Phi)$$

$$D_\Phi W = \partial_\Phi W = \frac{1}{b} f'(\Phi)\,, \qquad D_S W = \partial_S W = f(\Phi)$$

$$V = \left(1 - \frac{3}{b^2}\right)|f(\varphi)|^2 + \frac{2}{b^2}|f'(\varphi)|^2$$

At the minimum

$$f(0) = D_S W = M \neq 0\,, \qquad f'(0) = b\, D_\Phi W = 0$$

$$V|_{\Phi=0} = \Lambda\,, \qquad \Lambda \equiv \left(1 - \frac{3}{b^2}\right) M^2\,, \qquad b^2 = \frac{3}{1 - \frac{\Lambda}{M^2}}$$

The choice of Λ is generic, as in string landscape, it can be 10^{-120}

Solution

If the potential during inflation is expected to be given by the function

$$V(\varphi) = \mathcal{F}^2(\varphi) \qquad \text{take} \qquad \partial_\varphi f(\varphi) = \frac{b}{\sqrt{2}}\mathcal{F}(\varphi)$$

$$f(\varphi) = \frac{b}{\sqrt{2}} \int \mathcal{F}(\varphi) \qquad f(\varphi)|_{\varphi=0} = M$$

The total potential at $\vartheta = 0$ is therefore given by

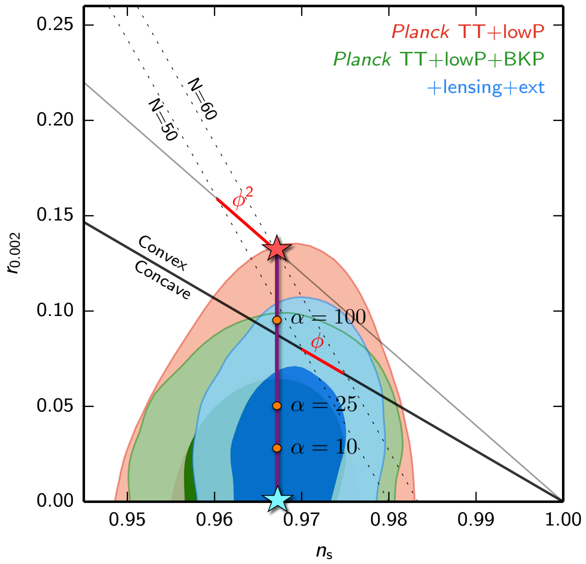
$$V^{\text{total}} = \Lambda \frac{|f(\varphi)|^2}{M^2} + |\mathcal{F}(\varphi)|^2$$

$$V^{\text{total}}_{\text{min}} = \Lambda = M^2 - 3m^2_{3/2}$$

$$m_{3/2} = \frac{M}{b} = \frac{M}{\sqrt{3}}\left(1 - \frac{\Lambda}{M^2}\right)^{1/2}$$

The simplest T-model with broken SUSY and dS exit

$$K = -3\alpha \log\left[\cosh\frac{\Phi-\bar\Phi}{\sqrt{6\alpha}}\right] + S\bar S$$



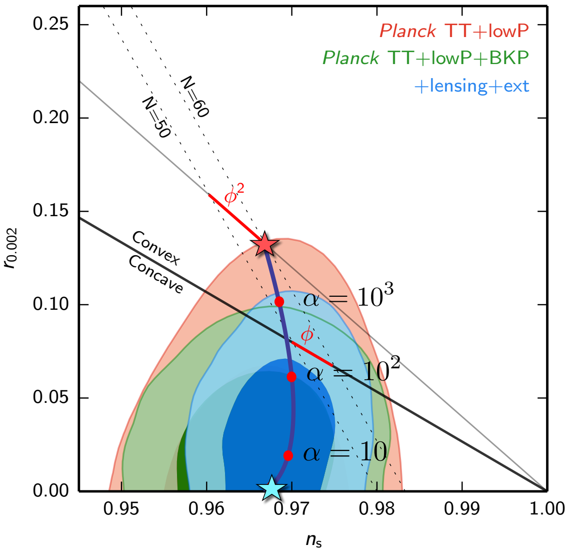
$$W = \left(S+\frac{1}{b}\right)\left[\sqrt{3}\,\alpha\,\mu\,b\,\log\left[\cosh\frac{\Phi}{\sqrt{6\alpha}}\right]+M\right]$$

$$V_{\rm total} = \Lambda\frac{|f(\varphi)|^2}{M^2} + \alpha\,\mu^2\tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

The simplest E-model with broken SUSY and dS exit

$$K = -3\alpha \log\left[\cosh\frac{\Phi-\bar{\Phi}}{\sqrt{6\alpha}}\right] + S\bar{S}$$

$$W = \left(S+\frac{1}{b}\right)\left[\frac{mb}{\sqrt{2}}(\Phi+\sqrt{\frac{3\alpha}{2}}e^{-\sqrt{\frac{2}{3\alpha}}\Phi}-1)+M\right]$$



Ferrara, RK, Linde, Porrati 2013 with Λ=M=0

$$V_{\text{total}} = \Lambda\frac{|f(\varphi))|^2}{M^2} + m^2\left(1-e^{-\sqrt{\frac{2}{3\alpha}}\varphi}\right)^2$$

General models of inflation with SUSY breaking and dark energy

$$K = -3\alpha \log\left[\cosh\frac{\Phi - \bar{\Phi}}{\sqrt{6\alpha}}\right] + S\bar{S} \qquad W = g(\Phi) + S f(\Phi)$$

$$V_{\rm total} = 2|g'(\varphi)|^2 - 3|g(\varphi)|^2 + |f(\varphi)|^2$$

Example in disk variables

$$K = -\frac{3}{2}\alpha \log\left[\frac{(1 - Z\bar{Z})^2}{(1 - Z^2)(1 - \bar{Z}^2)}\right] + S\bar{S} \qquad W = \left(S + \frac{1 - Z^2}{b}\right)(\sqrt{3}\alpha\, m^2\, Z^2 + M)$$

$$W = \left(\frac{1}{b}\cosh^{-2}\left(\frac{\Phi}{\sqrt{6\alpha}}\right) + S\right)\left(\sqrt{3\alpha}\, m^2 \tanh^2\left(\frac{\Phi}{\sqrt{6\alpha}}\right) + M\right)$$

In Killing variables

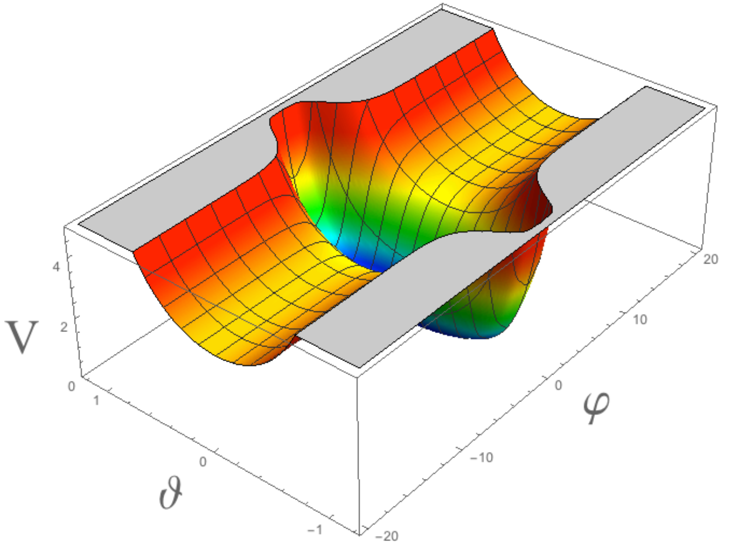
$$\alpha > 0.02$$
$$m_\vartheta^2 > 0$$

everywhere

$$\frac{m_\vartheta^2}{H^2} = 6$$

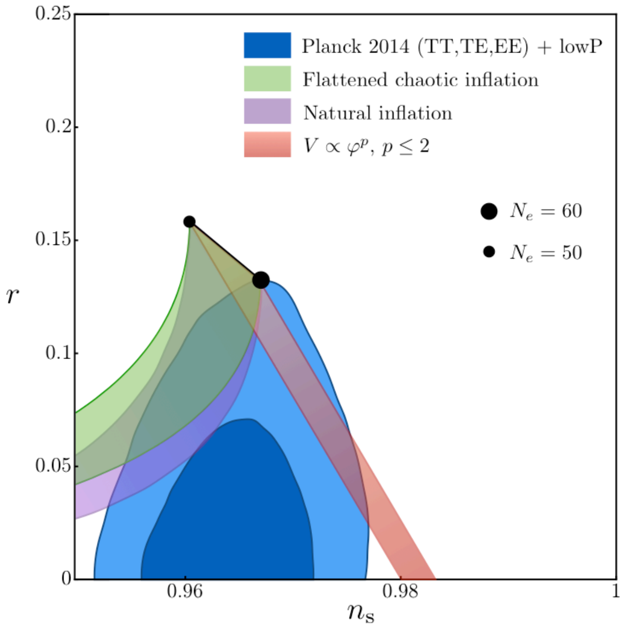
During inflation

No need for stabilization



Challenges for Large-Field Inflation and Moduli Stabilization

Buchmuller, Dudas, Heurtier, Westphal, Wieck, Winkler 1501.05812



three prominent examples of moduli stabilization: KKLT stabilization, Kahler Uplifting, and the Large Volume Scenario

Traditional string-inspired supergravity inflation models

Our new string-inspired supergravity models enhance the α-attractor models compatible with inflationary data from Planck/Bicep II using only the `primordial supergravity sector' :

the inflaton + goldstino.

The susy breaking M (mass of gravitino) is controllable and can be any number > 10^{-13} $M_{P.}$

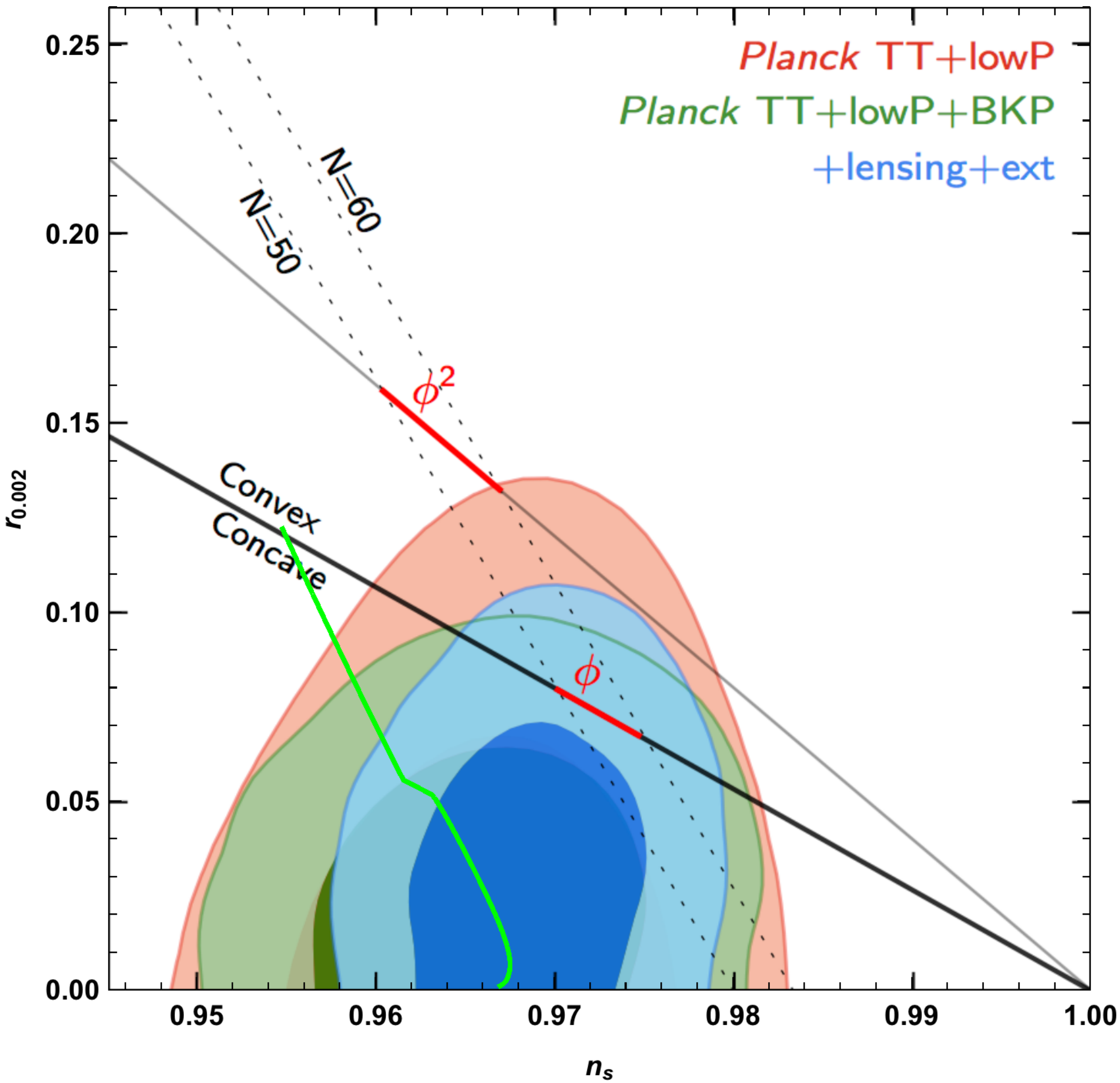
Waiting for LHC

The level r of primordial gravity waves is controllable and can be any number < 0.1

Waiting for B-modes

Dark Energy is taken care in `primordial supergravity sector' by goldstino energy being a tiny bit higher than gravitino relying on string theory landscape

$$\Lambda = M^2 - 3m_{3/2}^2$$



General models of inflation with SUSY breaking and dark energy

An example