Recent Developments in String Theory/Supergravity Cosmology

Renata Kallosh

with Linde
and with Cecotti, Ferrara, Porrati, Van Proeyen, Bercnocke, Roest, Westphal, Wrase

We discuss inflationary models which are flexible enough to fit the data (Planck 2013 or BICEP2 or in between), which can be implemented in string theory/supergravity, and which may tell us something interesting and instructive about the fundamental theory from the sky

We describe new models of inflation and dark energy/cc. New results on de Sitter Landscape: how to avoid tachyons in string theory motivated supergravities

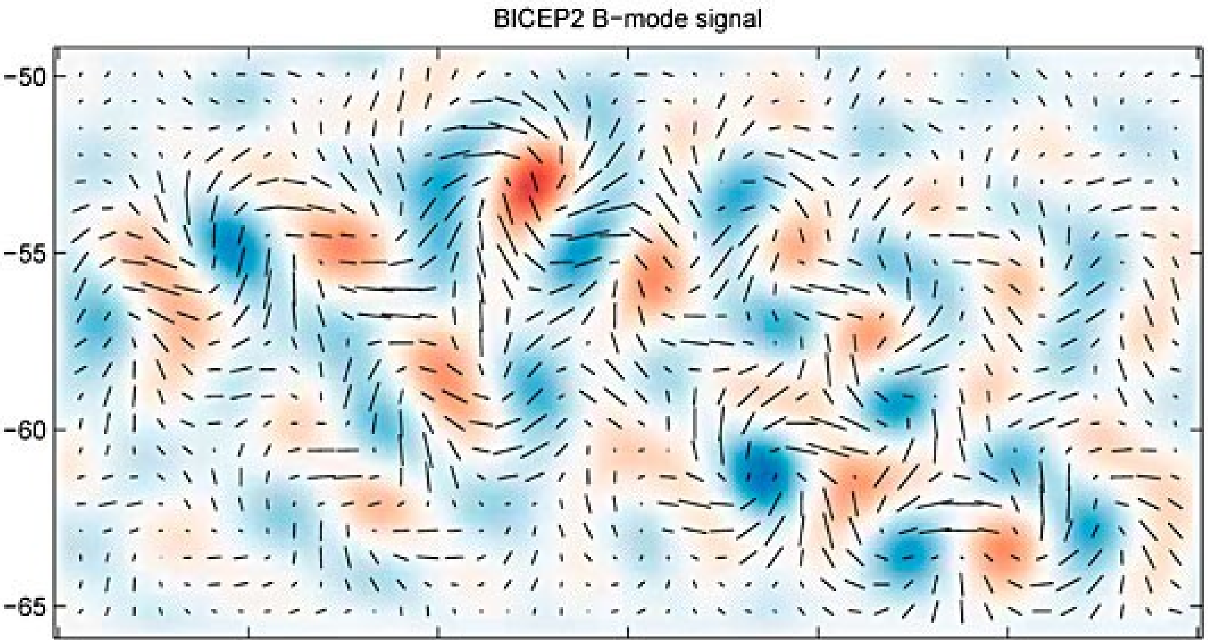
Recent new tools have allowed us to construct new simple models of inflation with dS uplifting in the context of spontaneously broken supersymmetry

A New Toy In Town!

A nilpotent chiral multiplet, Volkov-Akulov goldstino and D-brane physics

BICEP: Pretty Swirly Things

$r \sim 0.2$

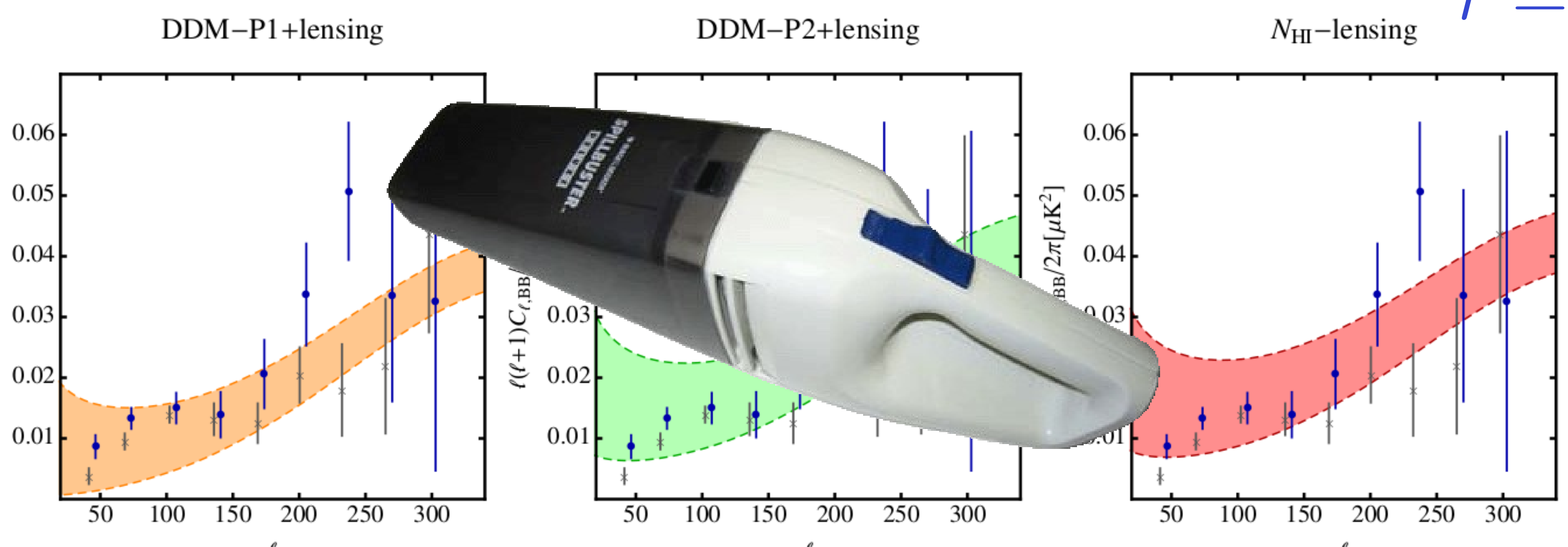


BICEP2 - Planck Drama

Is It Dust?

[Flauger, Hill, Spergel]
June 2014

$r = 0$



Genus Topology and Cross-Correlation of BICEP2 and Planck 353 GHz B-Modes: Further Evidence Favoring Gravity Wave Detection

Wesley N. Colley and J. Richard Gott, III, September 2014

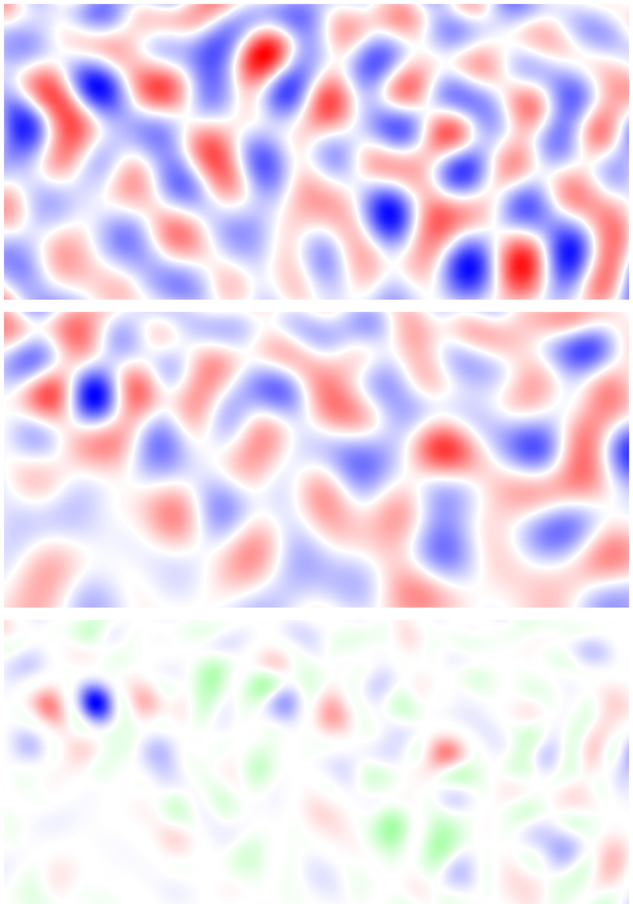


Figure 14. At top, the BICEP2 map (as in Fig. 1); in the middle, our Planck 353 GHz Map V (as in Fig. 7). At bottom is the correlation of these two maps. All maps are in Mercator projection in the region $|\mathrm{RA}| \leqslant 30°$, $-65° \leqslant \mathrm{Dec} \leqslant -50°$. Red shows positive-positive correlations; blue shows negative-negative correlations; green shows anti-correlations (negative-positive or positive-negative).

$$r \sim 0.1$$

Do not take it too seriously as it is based on redigitized plots of both BICEP2 and Planck.

However the basic idea to check Cross-Correlation of BICEP2 and Planck is a good one. This is what BICEP2 and Planck are doing now, using the actual combined data. And we are waiting…

$$r = ?$$

Planck intermediate results. XXX.
The angular power spectrum of polarized dust emission
at intermediate and high Galactic latitudes

Today's paper

Details on dust in the BICEP2 patch of the sky.

Current conclusion

Extrapolation of the Planck 353 GHz data to 150 GHz gives a dust power DBB ≡ l(l + 1)CBB/(2π) of 1.32 × 10−2 μK2 over the multipole range of the primordial recombination bump (40 < l < 120); l l CMB the statistical uncertainty is ±0.29 × 10−2 μK2CMB and there is an additional uncertainty (+0.28, −0.24) × 10−2 μK2CMB from the extrapolation. This level is the same magnitude as reported by BICEP2 over this l range, which highlights the need for assessment of the polarized dust signal even in the cleanest windows of the sky. The present uncertainties are large and will be reduced through an ongoing, joint analysis of the Planck and BICEP2 data sets.

Chaotic Inflation in Supergravity:

shift symmetry

Kawasaki, Yamaguchi, Yanagida 2000

Kahler potential $$\mathcal{K} = S\bar{S} - \frac{1}{2}(\Phi - \bar{\Phi})^2$$

and superpotential $$W = mS\Phi$$

The potential is very curved with respect to S and Im Φ, so these fields vanish. But Kahler potential does not depend on

$$\phi = \sqrt{2}\,\mathrm{Re}\ \Phi = (\Phi + \bar{\Phi})/\sqrt{2}$$

The potential of this field has the simplest form, as in chaotic inflation, without any exponential terms:

$$V = \frac{m^2}{2}\phi^2$$

More general models

RK, Linde, Rube 2010

$$W = S\, f(\Phi)$$

Superpotential must be a REAL holomorphic function. (We must be sure that the potential is symmetric with respect to ImΦ, so that Im Φ = 0 is an extremum (then we will check that it is a minimum). The Kahler potential is any function of the type

$$\mathcal{K}((\Phi - \bar{\Phi})^2,\ S\bar{S})$$

The potential as a function of the real part of Φ at S = 0 is

$$V = |f(\Phi)|^2$$

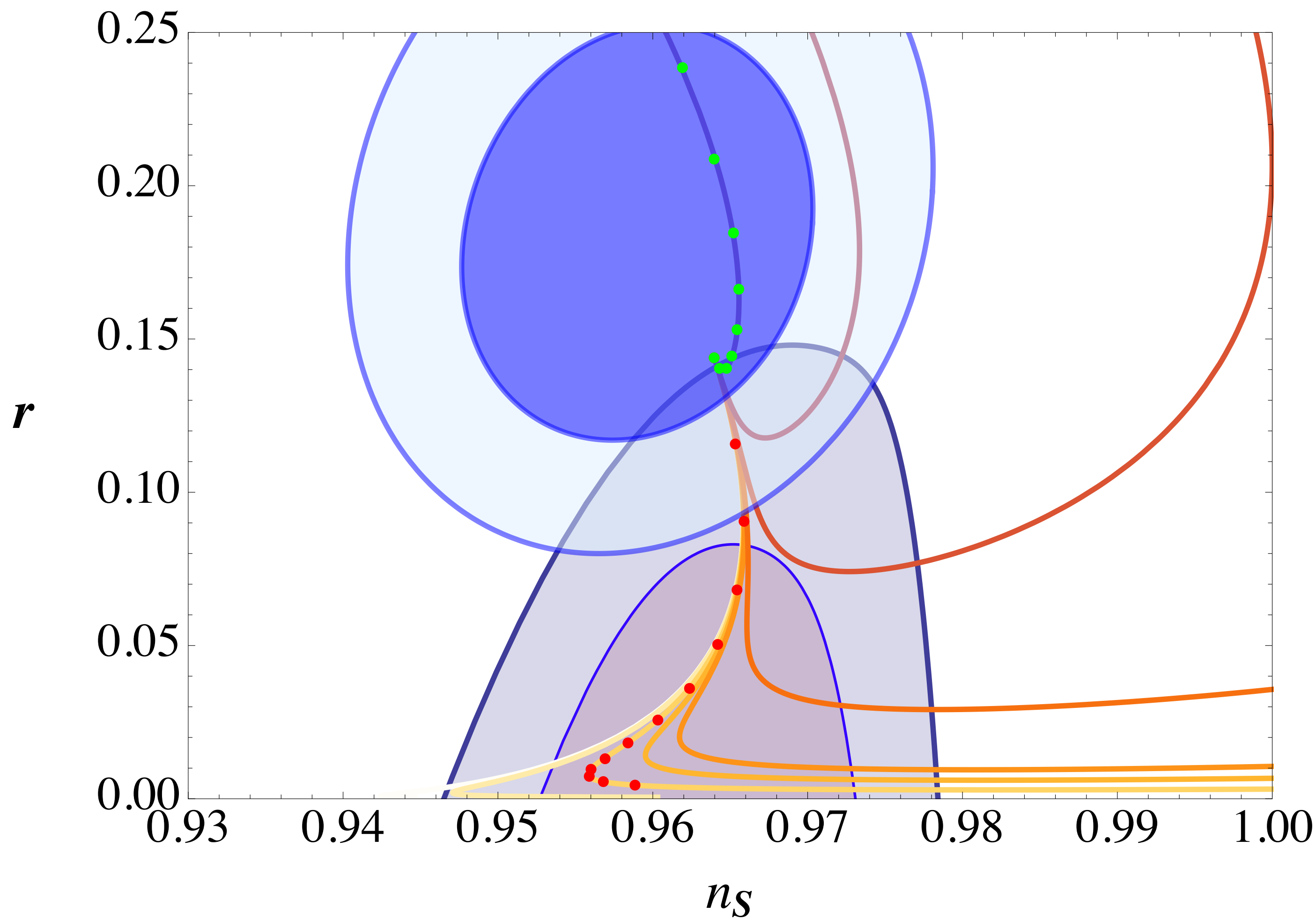
FUNCTIONAL FREEDOM in choosing inflationary potential

Here S is a goldstino multiplet: supersymmetry is broken only in the goldstino direction

FUNCTIONAL FREEDOM in choosing inflationary potential in supergravity allows us to fit any set of n_s and r.

$$V(\phi) = \frac{m^2\phi^2}{2}\left(1 - a\phi + a^2 b\,\phi^2)\right)^2$$

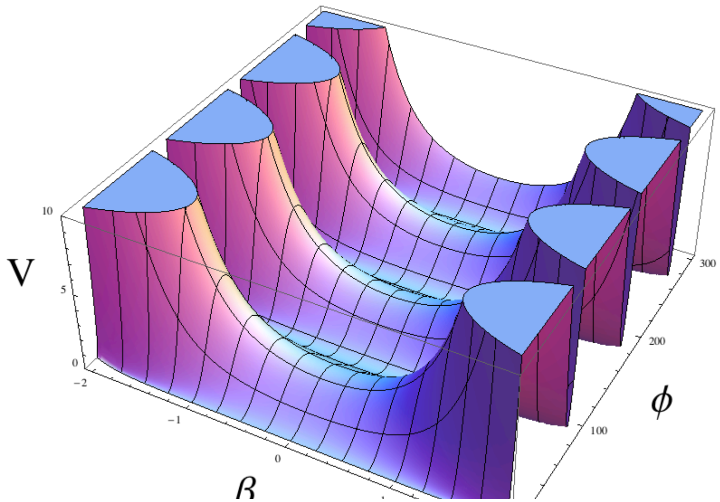
RK, Linde and Westphal, 1405.0270



$$\mathcal{K}((\Phi - \bar{\Phi})^2,\ S\bar{S}),\ W = S\,f(\Phi), V = |f(\Phi)|^2$$

Natural Inflation in Supergravity

Natural inflation in theories with axion potentials is known for nearly 25 years (Freese et al 1990), but **until now it did not have any stable supergravity generalization**. Invariably, there was an instability with respect to some moduli, or we needed some assumptions about string theory uplifting. The problem was solved only recently: RK, Linde, Vercnocke, 1404.6204



$$V|_{S=0,\,T+\bar T=0} = 2\,\Lambda^4\left(1-\cos\frac{a\phi}{\sqrt{2}}\right)$$

$$W = \Lambda^2 S(1-e^{-aT})\,, \quad K = \frac{1}{2}(T+\bar T)^2 + S\bar S - g(S\bar S)^2$$

All non-inflaton moduli stabilized

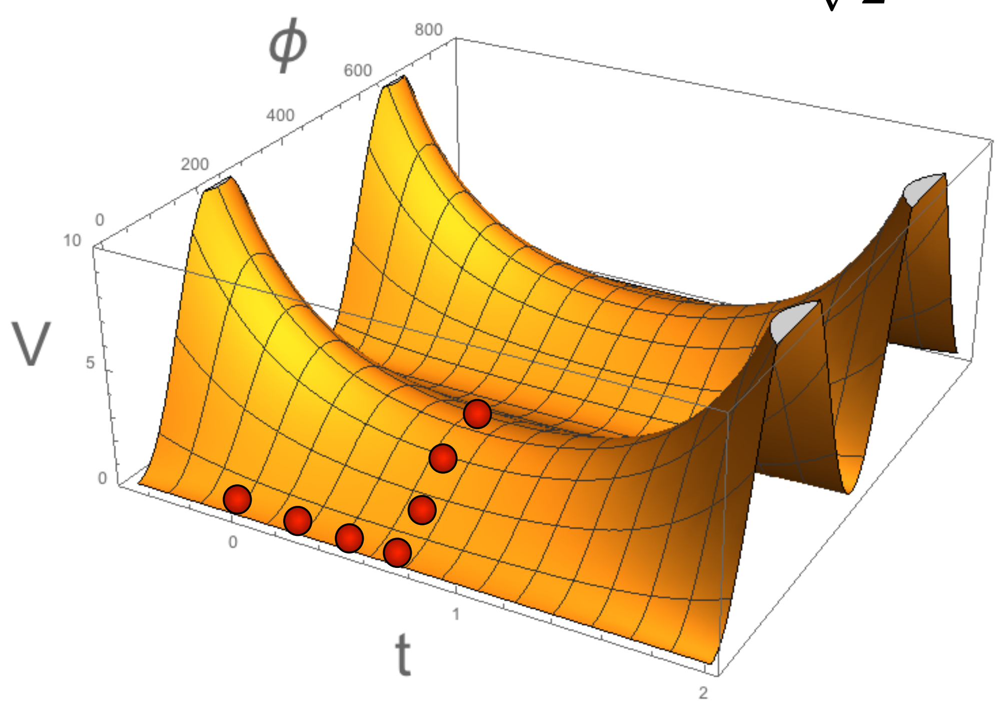
Large field natural inflation with a single axion

RK, Linde, Vercnocke, 1404.6204

$$W = \Lambda^2 S(e^{-aT} - e^{-bT}) \qquad K = \frac{(T+\bar{T})^2}{2} + S\bar{S} - g(S\bar{S})^2$$

Natural inflation occurs even in theories with a, b > 1, as suggested by string theory. For |a – b| << 1, **one can have natural inflation even in the theory with a single axion field**.

$$V = 2\Lambda^4 e^{-a^2/2}\left(1 - \cos\frac{(a-b)\,\phi}{\sqrt{2}}\right)$$



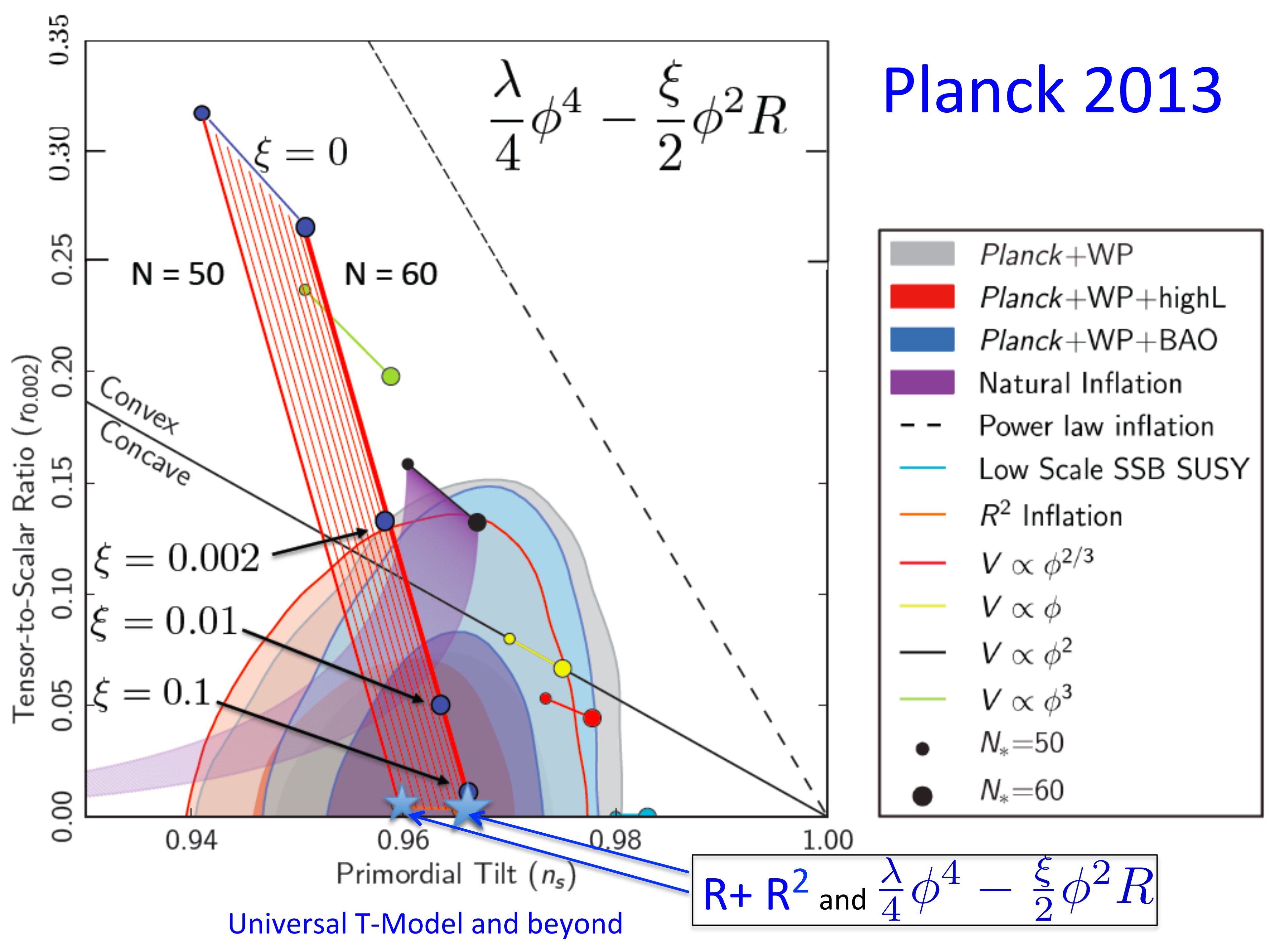
Models described above can easily explain large r. Good for BICEP2. They can also describe r << 1, but not without tuning. Can we do it naturally?

Let us return to Planck and some mysteries related to its results.

Cosmological attractors

RK, Linde 2013

We found a new class of chaotic inflation models with spontaneously broken conformal or superconformal invariance. Observational consequences of such models are stable with respect to strong deformations of the scalar potential.


Planck 2013
$\frac{\lambda}{4}\phi^4 - \frac{\xi}{2}\phi^2 R$
$\xi = 0$
N = 50
N = 60
Convex
Concave
$\xi = 0.002$
$\xi = 0.01$
$\xi = 0.1$
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.94
0.96
0.98
1.00
Planck+WP
Planck+WP+highL
Planck+WP+BAO
Natural Inflation
Power law inflation
Low Scale SSB SUSY
R^2 Inflation
$V \propto \phi^{2/3}$
$V \propto \phi$
$V \propto \phi^2$
$V \propto \phi^3$
N_*=50
N_*=60
R+ R^2 and $\frac{\lambda}{4}\phi^4 - \frac{\xi}{2}\phi^2 R$
Universal T-Model and beyond

Miracles to be explained:

MANY apparently **unrelated theories** make **same prediction**

$$1 - n_s = \frac{2}{N}, \qquad r = \frac{12}{N^2}$$

This point is at the sweet spot of the Planck allowed region.

Here N = O(60) is the required number of e-foldings of inflation corresponding to perturbations on the scale of the observable part of the universe.

Why predictions of different theories converge at the same point? Why convergence is so fast? What is the relation to non-minimal coupling to gravity? Anything related to broken conformal invariance? Any way to explain it or at least account for it in supergravity?

Significant sensitivity of inflationary models on a choice of the frame

$$\frac{1}{2}\,\Omega(z,\bar z)\,R = \frac{1}{2}\,e^{-\frac{1}{3}K(z,\bar z)}\,R$$

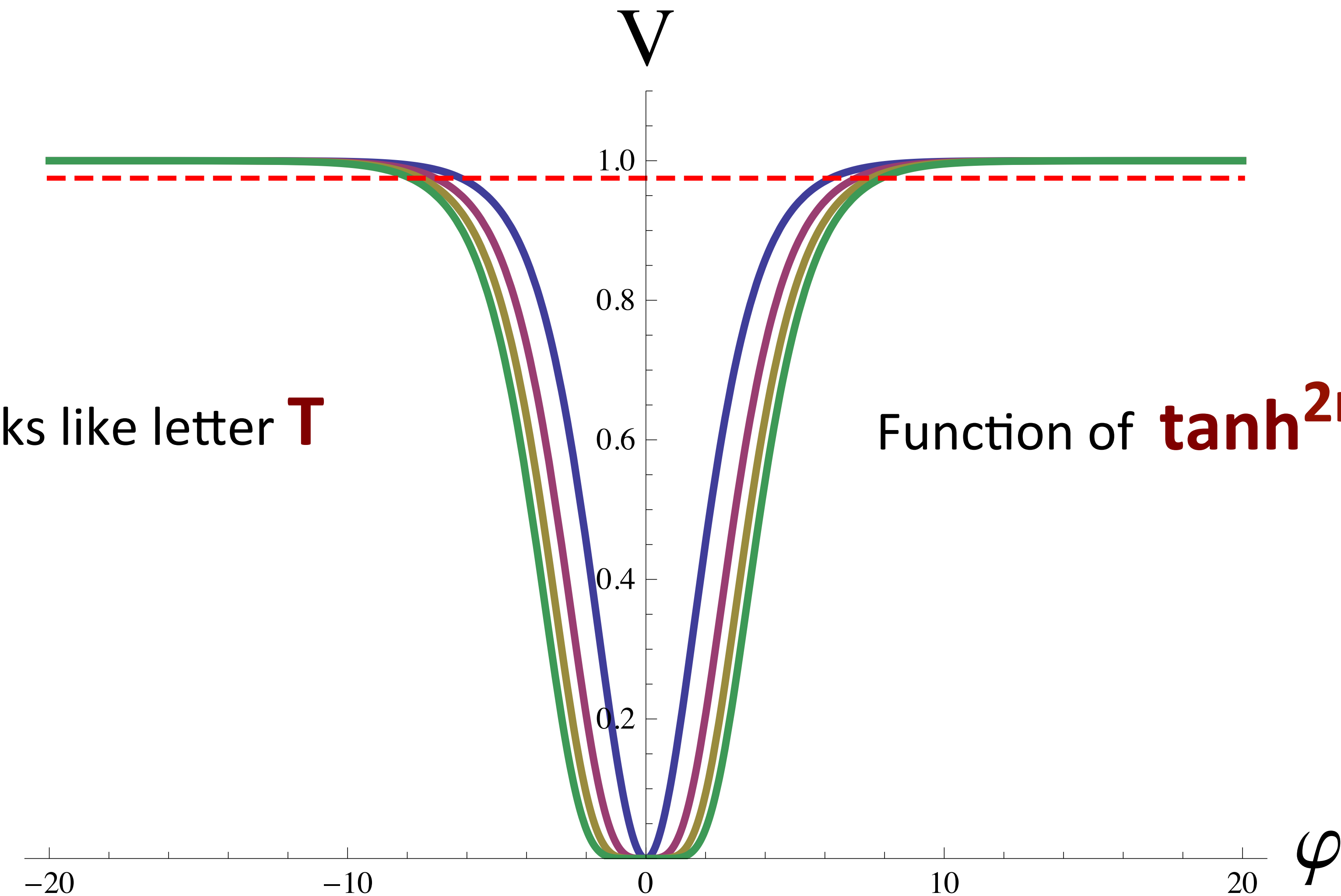
The superconformal theory underlying supergravity requires the choice of a Jordan frame

$$e\,\mathcal{N}(X,\bar X)\,R$$

The superconformal theory is defined by the Kahler potential of the embedding manifold, including the conformon.

T-Model

$$F\left(\phi/\chi\right) = \lambda \left(\phi/\chi\right)^{2n} \longrightarrow V(\varphi) = \lambda_n \tanh^{2n} \frac{\varphi}{\sqrt{6}}$$



Looks like letter **T**

Function of **tanh^{2n}**

Non-minimal coupling to gravity

RK, Linde, Roest 1310.3950

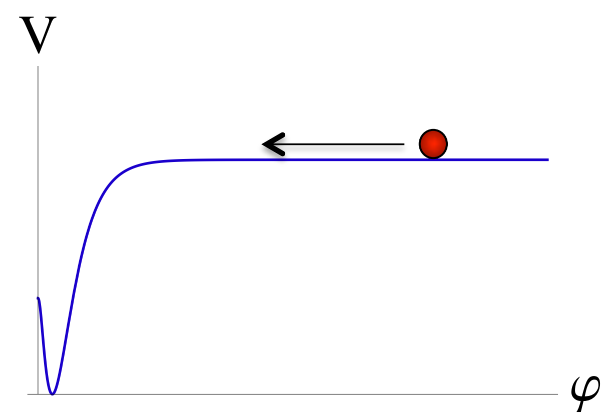
Jordan frame, arbitrary V(ϕ)

$$\mathcal{L}_{\rm J} = \sqrt{-g}[\tfrac{1}{2}R + \tfrac{1}{2}\zeta R\sqrt{V(\phi)} - \tfrac{1}{2}(\partial\phi)^2 - V(\phi)]$$

Einstein frame, large ζ

$$\mathcal{L}_{\rm E} = \sqrt{-g}\left[\tfrac{1}{2}R - \tfrac{1}{2}(\partial\varphi)^2 - \zeta^{-2}(1 - e^{-\sqrt{2/3}\varphi})^2\right]$$

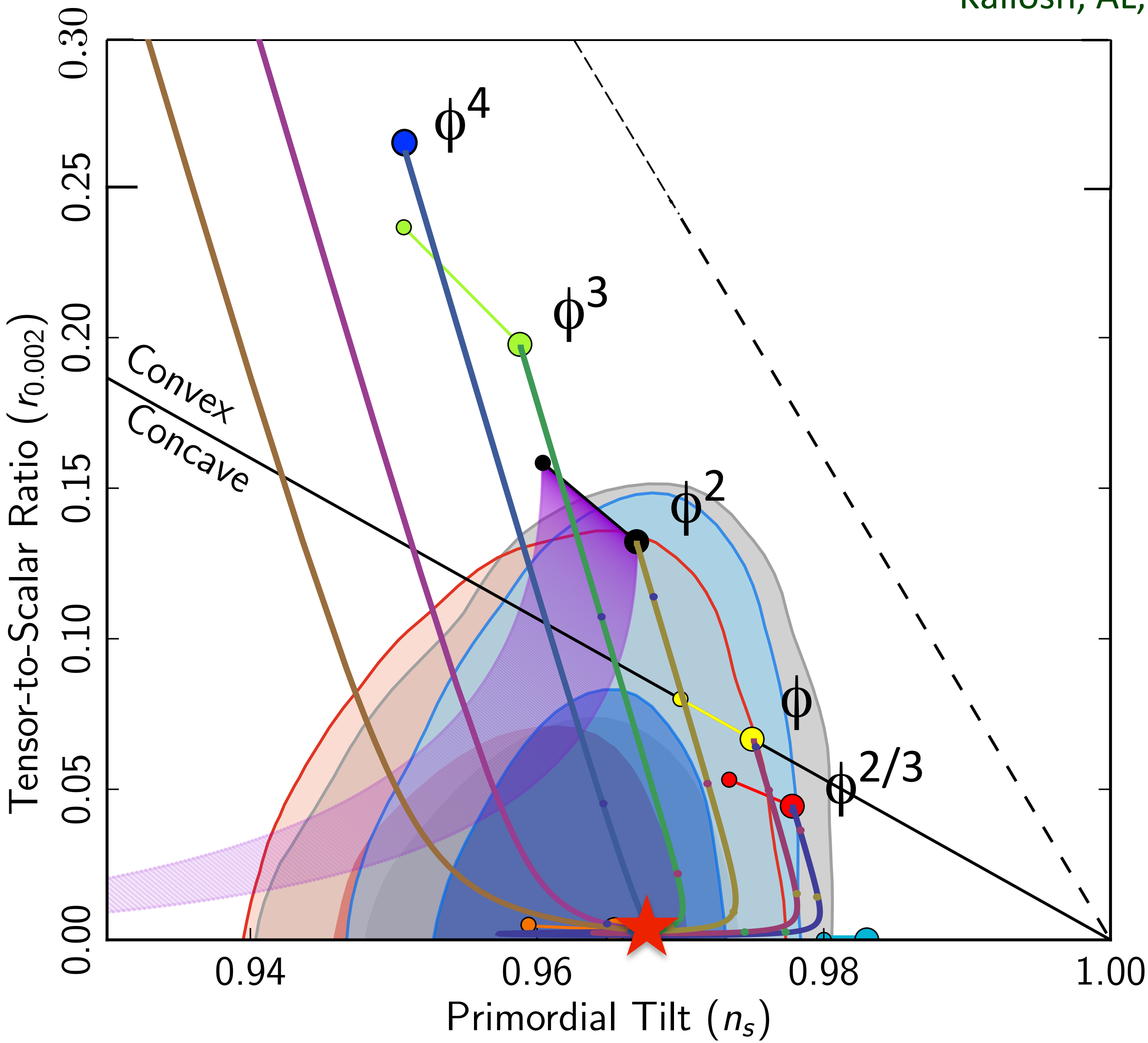
Just as before, with the same observational consequences, **independently of V(ϕ)**



But at small ζ it reduces to the original theory V(ϕ), so by changing ζ we can interpolate between the original theory and the universal attractor point at large ζ.

"Combing" Chaotic Inflation

Kallosh, AL, Roest 2013



$\alpha - \beta$ model in supergravity

Models with one real scalar from a vector multiplet

Ferrara, RK, Linde, Porrati

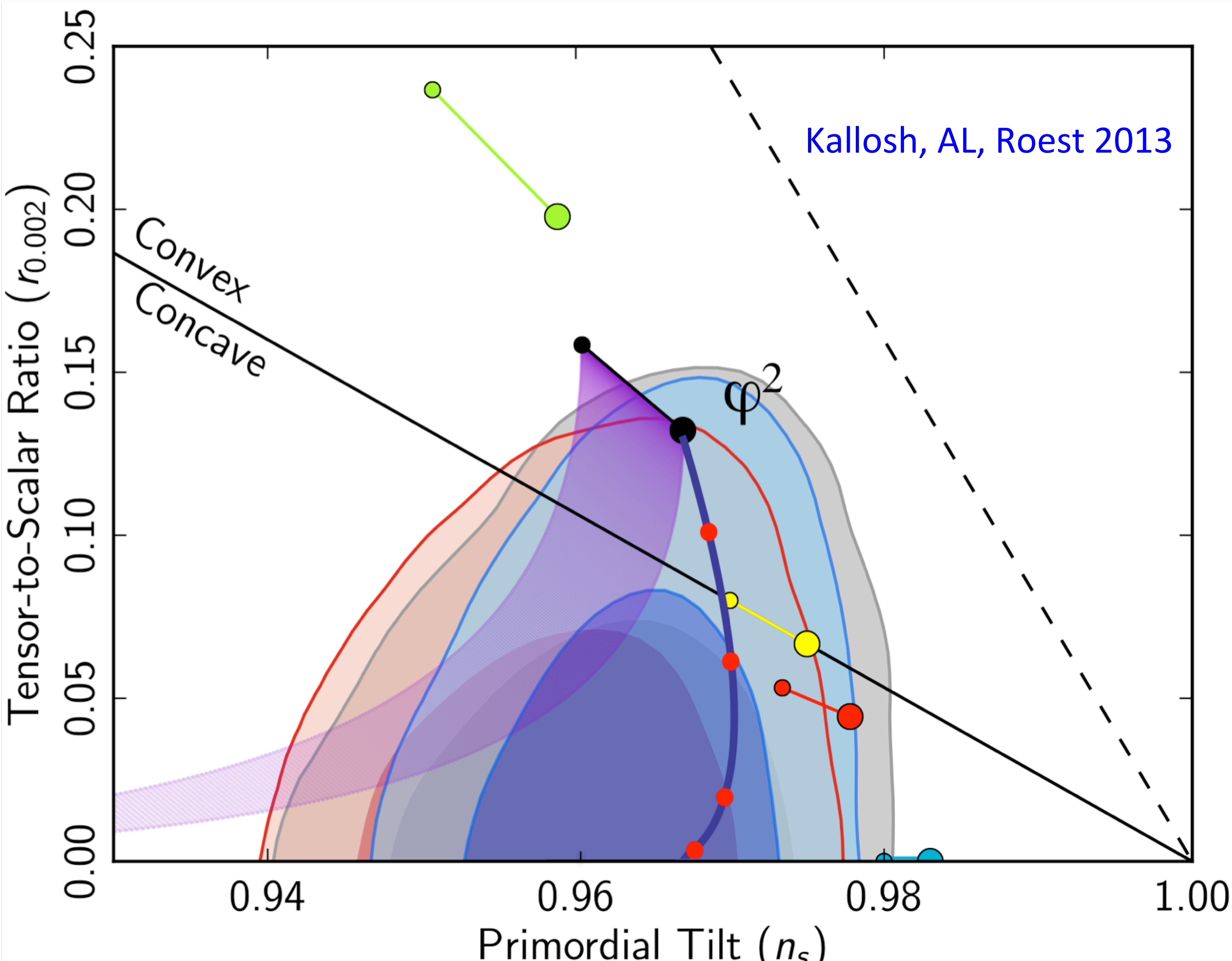
$$V \sim \left(\beta - \alpha e^{-\sqrt{\frac{2}{3\alpha}}\varphi}\right)^2$$

In this model, n_s and r do not depend on β. For α, $\beta = 1$, the potential is the same as in Starobinsky model. For small α

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

For large α the predictions are the same as in the simplest chaotic inflation with a quadratic potential:

$$n_s = 1 - \frac{2}{N}, \qquad r = \frac{8}{N}$$



Kallosh, AL, Roest 2013
Convex
Concave
φ²
0.25
0.20
0.15
0.10
0.05
0.00
Tensor-to-Scalar Ratio ($r_{0.002}$)
0.94
0.96
0.98
1.00
Primordial Tilt (n_s)

Superconformal α-attractors

RK, Linde, Roest 1311.0472

Another class of cosmological attractors naturally appears in superconformal theory and supergravity. This class includes, in particular, models

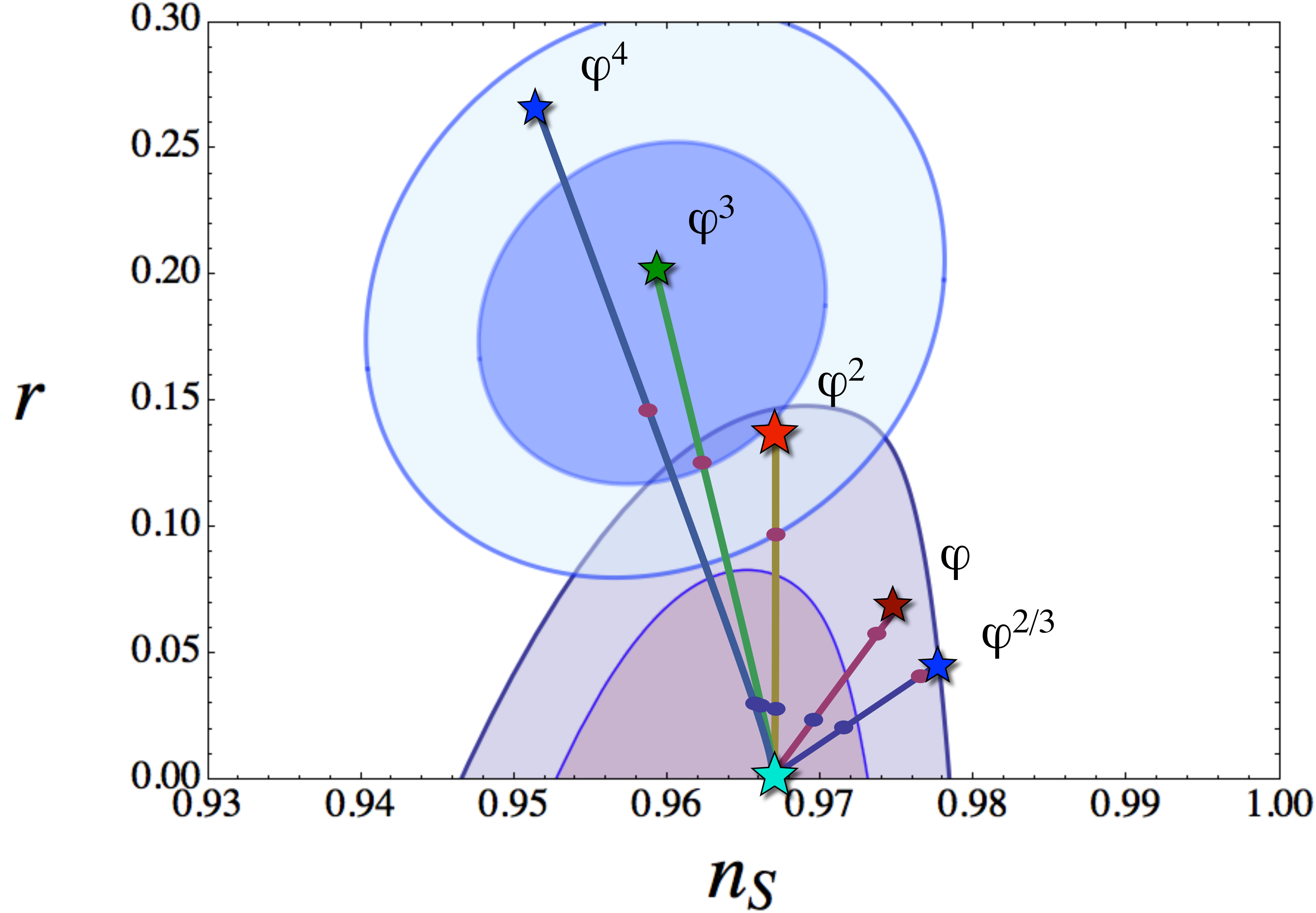
$$L = \sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - F(\tanh\frac{\varphi}{\sqrt{6\alpha}})\right]$$

At $\alpha \lesssim 1$ these models have universal prediction

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

However, for $\alpha \gg 1$ predictions depend on the choice of F(x). For the simplest choice $F = x^n$, the predictions coincide with those of the simplest chaotic inflation models

$$V \sim \varphi^n$$



0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00
r
n_S
φ^4
φ^3
φ^2
φ
$\varphi^{2/3}$

What is the meaning of α?

The curvature of the Kahler manifold is inversely proportional to α

Small α means high curvature, small r - good for Planck

Large α means small curvature, large r - good for BICEP2

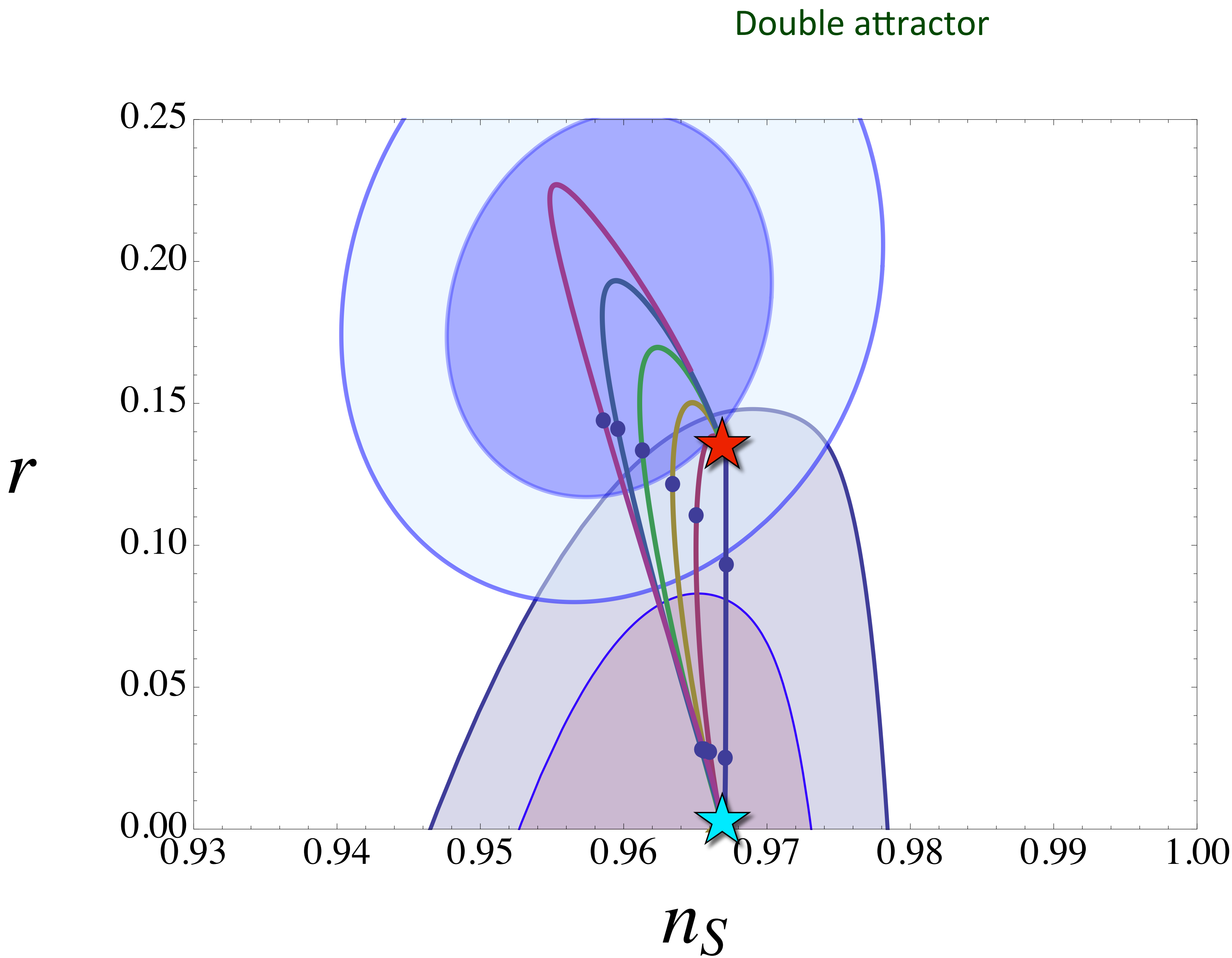
Thus, finding n_s and r may tell us something important about the nature of gravity and geometry of superspace.

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

What if instead of the monomial functions $F = x^n$ one considers $F = x + x^2 + x^3 + \ldots$?

Then in the large α limit, the predictions approach a single attractor point: The simplest chaotic inflation with a quadratic potential.

Kallosh, AL, Roest 1405.3646


Double attractor
0.25
0.20
0.15
0.10
0.05
0.00
r
0.93
0.94
0.95
0.96
0.97
0.98
0.99
1.00
n_S

By changing the strength of non-minimal coupling to gravity and the curvature of the Kahler manifold in supergravity, one can **continuously interpolate** between **two attractor points** for these classes of **large field models**: the predictions of the simplest chaotic inflation **models with large r**, favored by BICEP2, and **the lowest part of the n_s-r plane** favored by Planck.

Analytic Classes of Metastable de Sitter Vacua

RK, Linde, Vercnocke, Wrase, 1406.4866

From 2003 till recently: **De Sitter hunting in the landscape**

No underlying principle was known with broken supersymmetry as to how to achieve local stability for dS vacua: absence of tachyons

We have found how to generate analytically multiple dS vacua in supergravity which are locally stable. We use computers only to test the new principle, and to find examples, like the ones in STU models.

Our new strategy is to use the advantage of one of the fields in supergravity to be a no-scale one, as in KKLT, and to solve the following equations

$$V = \Lambda \,, \qquad \partial_a V = 0 \,, \qquad D_a W = F_a(\epsilon) \,, \qquad \partial_a \partial_b V = V_{ab}(\Lambda, \epsilon)$$

We have found certain conditions when it is possible to prove that all de Sitter solutions of these equations are locally stable! Hence, we can produce analytic de Sitter vacua in the landscape in abundance.
Our examples in STU models confirm the generic conditions required for the proof of stability.

To relate this new dS supergravity landscape to specific string theory compactifications is the next step.

First attempt: let us deform slightly the locally stable susy Minkowski vacua to get

$$W \to W + \delta W \qquad K \to K + \delta K$$

locally stable de Sitter vacua $\quad |DW|^2 - 3|W|^2 > 0$

It did not work

We proved a **no-go theorem** that small deformation of a W and/or K of a locally stable susy Minkowski vacua will not produce a locally stable de Sitter vacua

Therefore a part of the supergravity landscape with locally stable de Sitter vacua must be disconnected from the supersymmetric locally stable Minkowski vacua

The no-go theorem, therefore, predicts, that the limit from a locally stable de Sitter vacuum cannot be a supersymmetric locally stable Minkowski vacuum

This prediction is confirmed in our examples: the limits are either stable Minkowski with broken susy, or have flat directions.

A New Toy In Town!

A nilpotent chiral multiplet, Volkov-Akulov goldstino and D-brane physics

Observation: not a single version of string theory monodromy supergravity model is known as of today. There is always a problem of non-inflaton moduli stabilization or a consistency problem.

Meanwhile, numerous well working cosmological supergravity models of inflation and/or uplifting involving a goldstino multiplet have not been associated with string theory. See examples in earlier part of the talk.

All earlier attempts to associate string theory models with effective supergravity are based on standard unconstrained chiral multiplets: spin 0 <-> spin 1/2

Fermionic VA goldstino live on D-branes, have only spin 1/2

Unconstrained chiral superfield

$$S(x,\theta) = s(x) + \sqrt{2}\,\theta\,G(x) + \;\theta^2 F^S(x)$$

Nilpotent chiral superfield

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

$$S \;=\; \frac{GG}{2\,F^S} \;+\; \sqrt{2}\,\theta\,G \;+\; \theta^2 F^S$$

$$s(x) \qquad \Rightarrow \qquad \frac{G(x)G(x)}{2\,F^S(x)}$$

D-p-branes and Volkov-Akulov goldstino

$$S_{\mathrm{DBI+WZ}} = -\frac{1}{\alpha^2}\int \mathrm{d}^{10}x\,\sqrt{-\det G_{\mu\nu}} = \frac{1}{\alpha^2}\int E^{m_0}\wedge \ldots \wedge E^{m_9}\ ,$$

$$E^m = \mathrm{d}x^m + \alpha^2\bar{\lambda}\Gamma^m \mathrm{d}\lambda$$

Can we do cosmology much simpler?

Too many fields, some of them do not directly participate in inflation. We must add higher corrections to the Kahler potential to stabilize these fields near their zero values.

The cure: Volkov-Akulov nonlinear realization of supersymmetry does not require fundamental scalar degrees of freedom, they are replaced by bilinear fermionic combinations with zero vev.

Procedure: Replace standard unconstrained chiral superfields by **nilpotent superfields**, which do not have dynamical scalar components.

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

Ferrara, RK, Linde 1408.4096
RK, Linde 1408.5950
Antoniadis, Dudas, Ferrara, Sagnotti 1403.3269

Supergravity with nilpotent multiplets is a new theory requiring a very sophisticated analysis, especially when fermion interactions are involved. However, the bosonic sector is much simpler than before.

New rule:

Calculate potentials as functions of all superfields as usual, and then **DECLARE that S =0 for the scalar part of the nilpotent superfield**. No need to stabilize and study evolution of the S field.

So much simpler!!!

De Sitter Vacua and Dark Energy

We proposed a systematic procedure for building locally stable dS vacua without tachyons in stringy theory STU models, or using the Polonyi type superfield.

Polonyi type superfield was successfully used in the past in supergravity models, in particular to provide a supersymmetric version of an F-term uplifting for the KKLT De Sitter vacua. However, it was not known how to relate Polonyi to string theory

NEW: replace Polonyi by a nilpotent superfield

Nilpotent goldstino superfied $S^2=0$ is associated with the D-brane physics in string theory, via Volkov-Akulov theory. This leads to a supersymmetric KKLT uplifting in string theory.

$$W = W_{KKLT} - M^2 S, \qquad K = K_{KKLT} + S\bar{S}$$

$$V = V_{KKLT}(\rho, \bar{\rho}) + \frac{M^4}{(\rho + \bar{\rho})^3}$$

Ferrara, RK, Linde 1408.4096

For the first time using nilpotent superfield $S^2=0$ we have simple string theory motivated supergravity models for inflation with de Sitter vacua exit.

Example

RK, Linde 1408.5950

$$K = -\frac{(\Phi - \bar{\Phi})^2}{2} + S\bar{S}, \qquad W = SM^2(1 + c\Phi^2) + W_0$$

The field $\text{Im}\Phi$ is heavy and quickly vanishes, during inflation we find a quadratic potential for $\text{Re}\,\Phi$

No cosmological Polonyi model

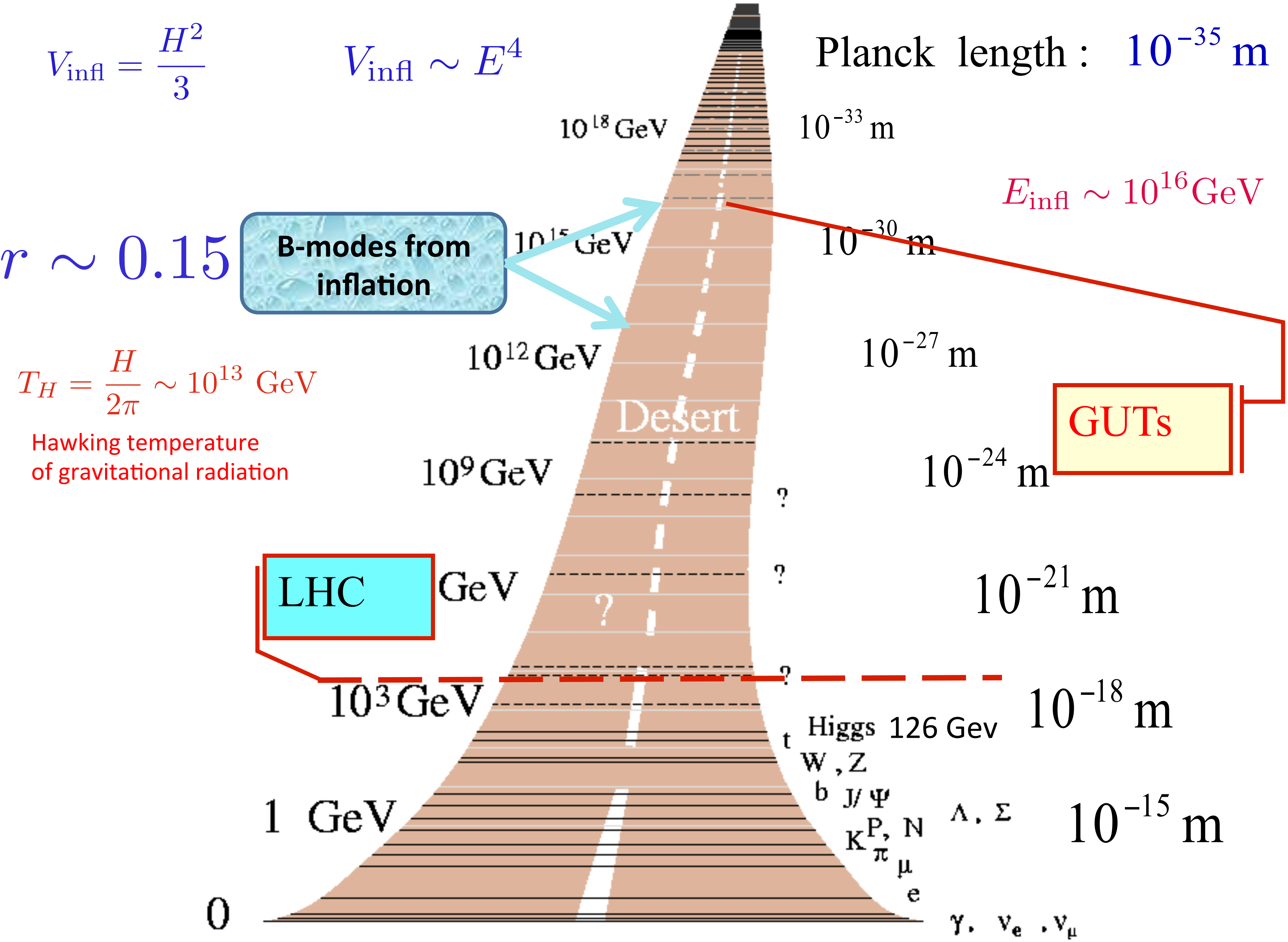
At the minimum Φ vanishes and the potential is

$$V_0 = M^4 - 3W_0^2 \sim 10^{-120}$$

SuperHiggs effect: gravitino eats goldstino from the S-multiplet and becomes fat!

$$D_\Phi W = 0 \qquad D_S W = M^2$$

Generalization to generic inflationary models with $V = f^2(\Phi)$ during inflation is straightforward



$V_{\rm infl} = \frac{H^2}{3}$
$V_{\rm infl} \sim E^4$
Planck length : 10^{-35} m
10^{18} GeV
10^{-33} m
$E_{\rm infl} \sim 10^{16}$GeV
$r \sim 0.15$
B-modes from inflation
GeV
10^{-30} m
10^{12} GeV
10^{-27} m
$T_H = \frac{H}{2\pi} \sim 10^{13}$ GeV
Hawking temperature of gravitational radiation
Desert
GUTs
10^{9} GeV
10^{-24} m
?
?
LHC
GeV
?
10^{-21} m
?
10^{3} GeV
10^{-18} m
Higgs 126 Gev
t
W , Z
b
J/ Ψ
Λ , Σ
1 GeV
10^{-15} m
K
P, N
π
μ
e
0
γ , ν_e , ν_μ