Inflation, SUSY breaking, and the cosmological constant

Andrei Linde

with Kallosh, Ferrara, Roest, Carrasco, Galante, Porrati, Scalisi, Vercnocke, Wrase

Rome, September 2016

Major ideas in high energy theoretical physics versus data

Supersymmetry, 1971-1974

Supergravity, 1976

Inflation, 1981

Superstring theory, 1984

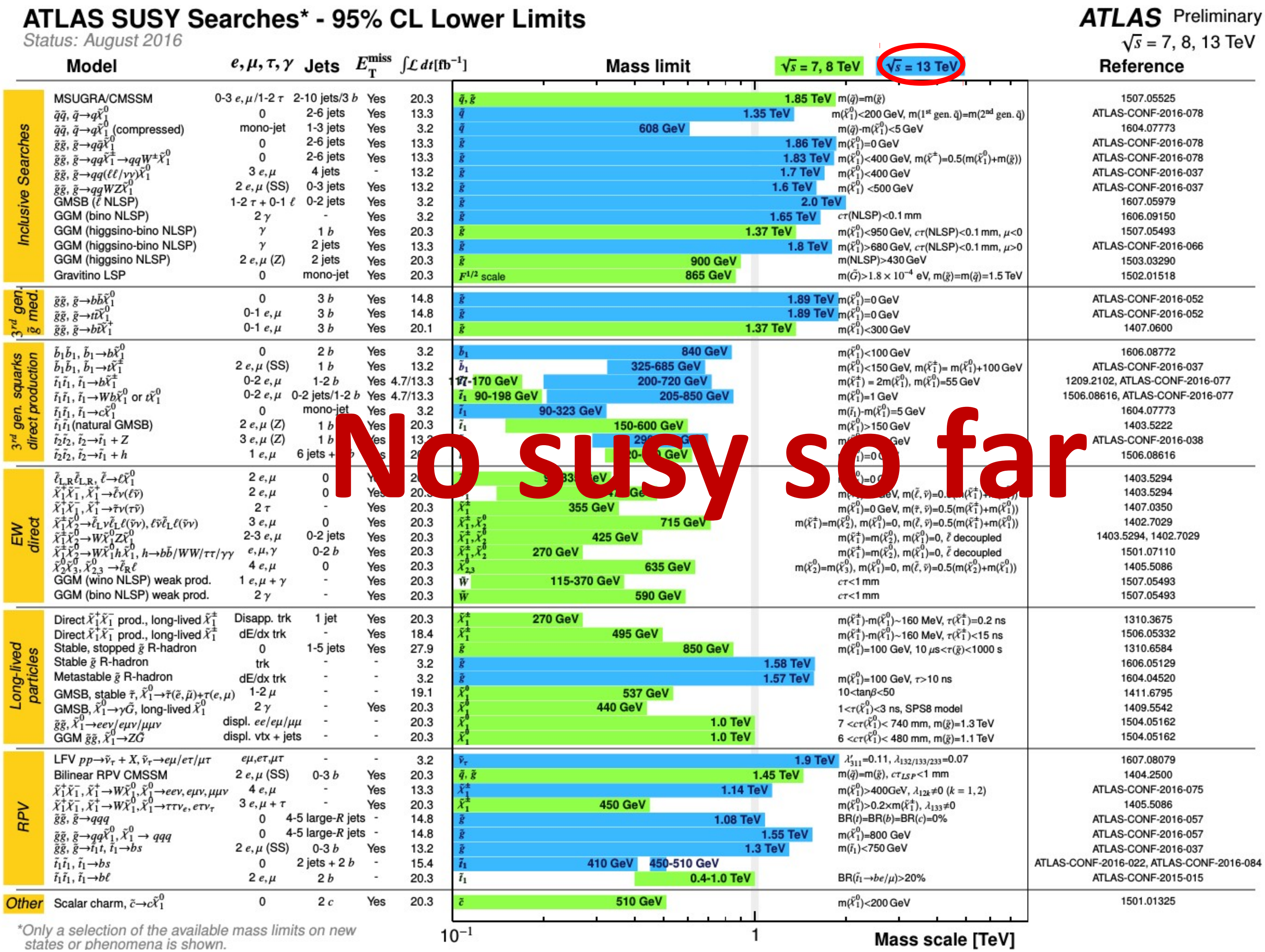
Particle physics experiments and cosmological observations, many years later

SUSY 2016, COSMO 2016, ICHEP 2016 (International Conference on High Energy Physics)

No SUSY so far

Standard Cosmological Model
Inflation, Dark Energy, Dark Matter

SUSY Summary (selection)



Fine-tuning versus anthropic selection

Does the Higgs mass require SUSY protection? Even in that case, why is it small prior to quantum corrections?

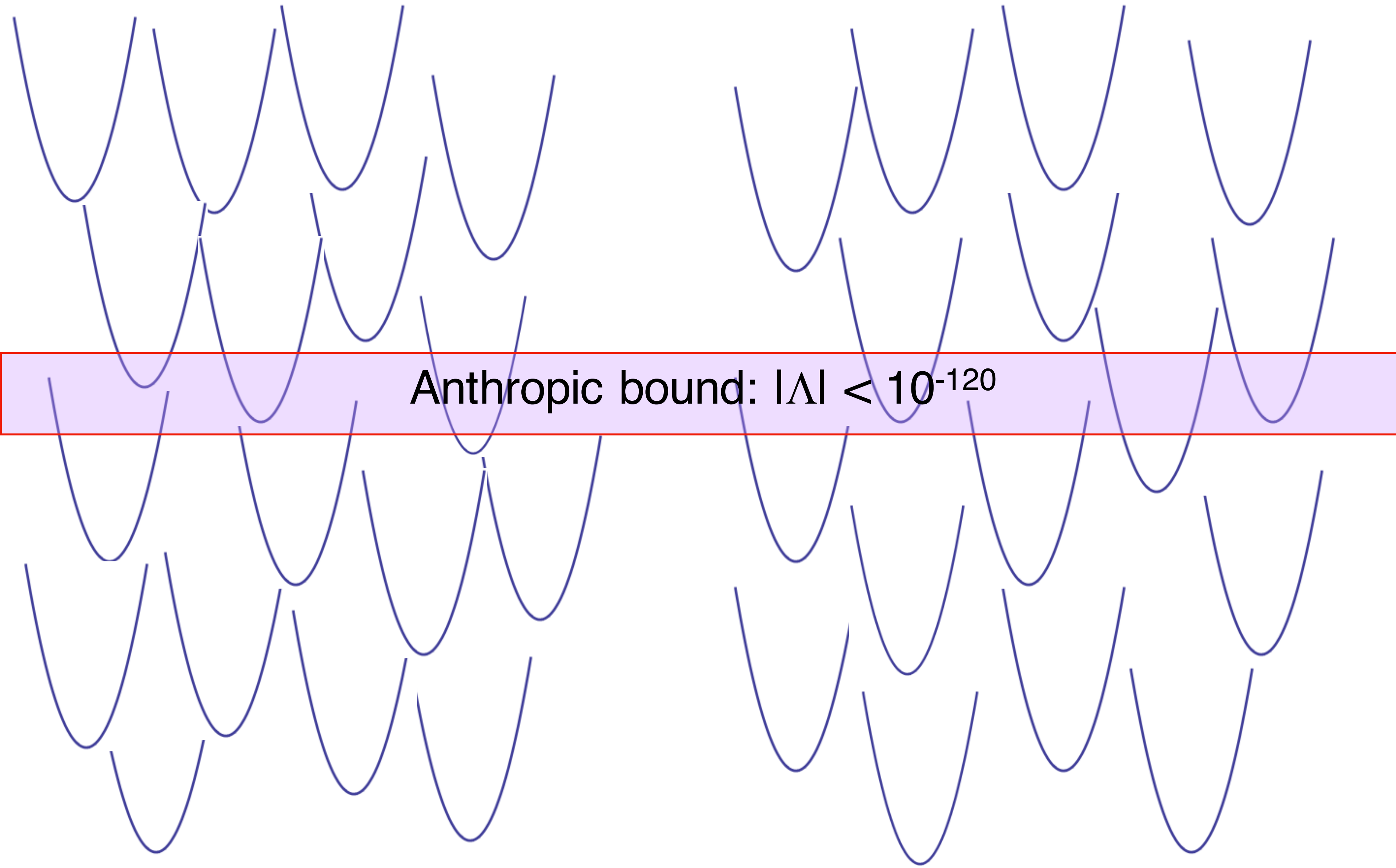
Agrawal, Barr, Donoghue and Seckel, Phys. Rev. D 57, 5480 (1998) [hep-ph/9707380]

Does the cosmological constant require SUSY protection? At which scale of SUSY breaking? Even in that case, why is the cosmological constant small prior to quantum corrections?

AL 1984, Sakharov 1984, Weinberg 1987, Bousso, Polchinski 2000, KKLT 2003, Douglas 2003, Susskind 2003

Landscape and anthropic considerations: Lots of vacua, quantum corrections modify their properties, but even after these corrections, there are always many vacua that are suitable for life (with a small cosmological constant and small Higgs mass). Thus, **smallness of the quantum corrections is NOT required**.

Example: Vacuum energy in string theory:



Before quantum corrections After quantum corrections

What can we learn about SUSY, SUGRA, string theory from cosmology?

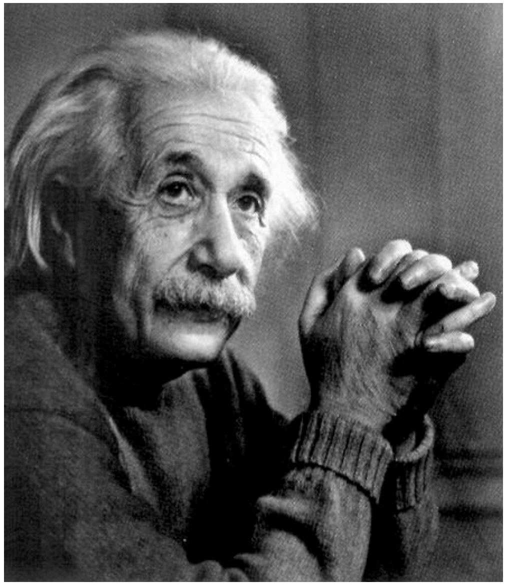
Lots of cosmological problems with models with small SUSY breaking: gravitino problem, Polonyi problem, KKLT destabilization, fine tuning of the same order as tuning the Higgs mass, unitarity violation problem, no-go theorem for small SUSY breaking.

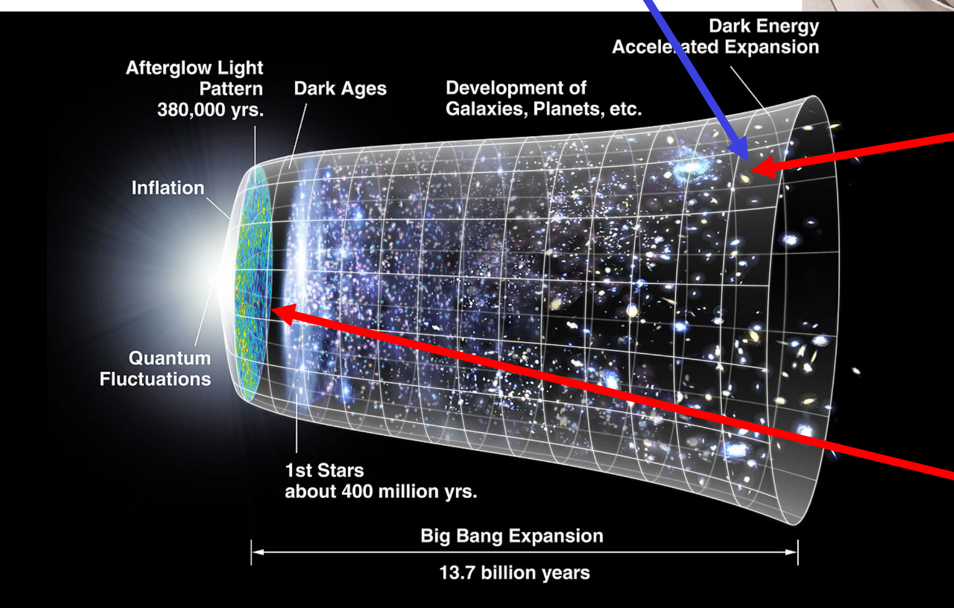
Kallosh, AL, Vercnocke, Wrase 1406.4866

It is possible to solve each of these problems, and to construct SUGRA models explaining current data, though it is easier if SUSY breaking is large. Models with nonlinearly realized supersymmetry (nilpotent fields) are helpful for dark energy, for SUSY breaking and for inflation. Future observational data might shed light on the origin of supersymmetric models describing the universe.

More on related issues – in talks by Karlsson, Scalisi, Wrase and Vercnocke at this conference

Gravitational waves detected!



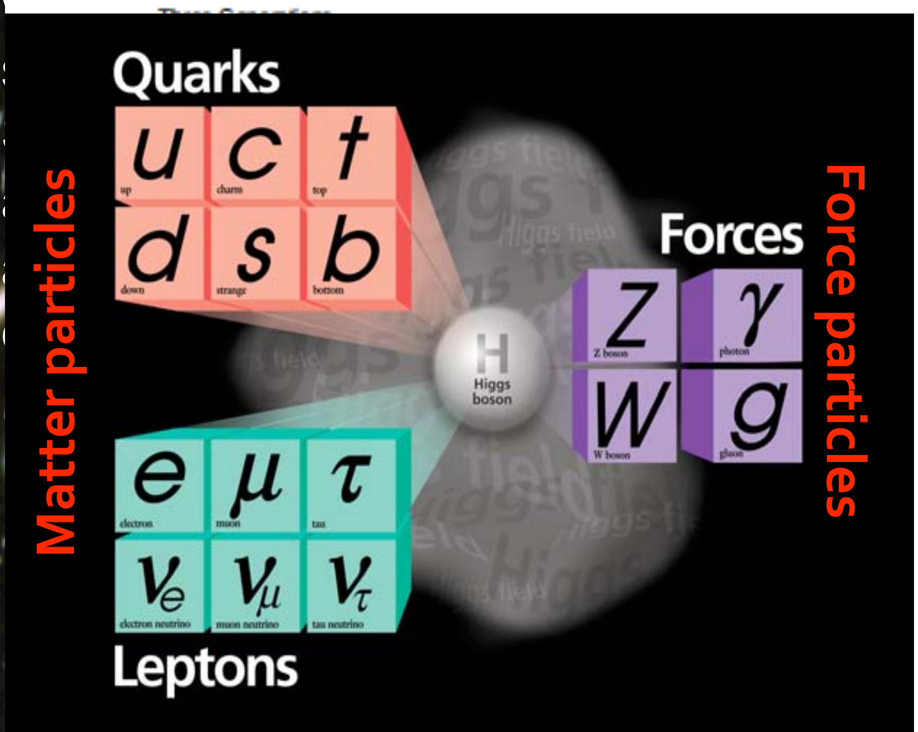


Classical general relativity predicted gravity waves from black hole merger which took place about 1 billion years ago, predicted about 100 years ago

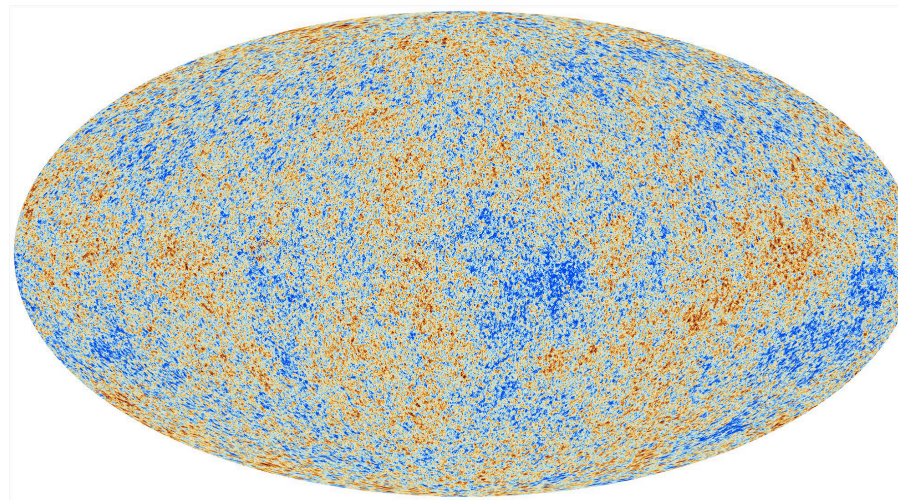
Primordial gravity waves from inflation, from 13.8 billion years ago, they are called B-modes, not detected so far. Tests **Quantum Gravity**. Holy Grail of observational cosmology. Predicted 37 years ago.

BUILDING AN UNDERSTANDING OF THE UNIVERSE: A WORK A CENTURY IN THE MAKING

- **PARTICLE STANDARD MODEL**



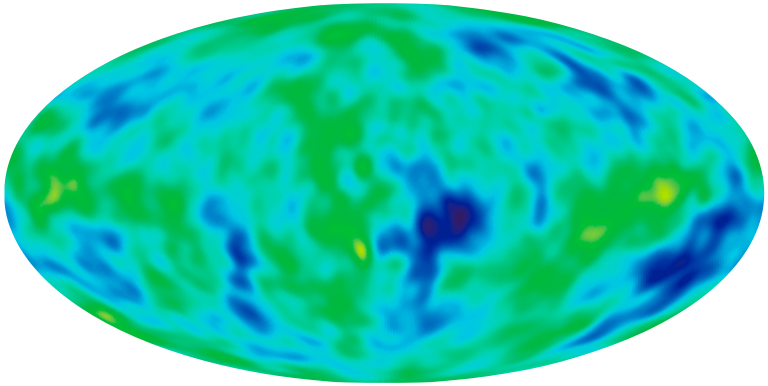
- **COSMOLOGY STANDARD MODEL**

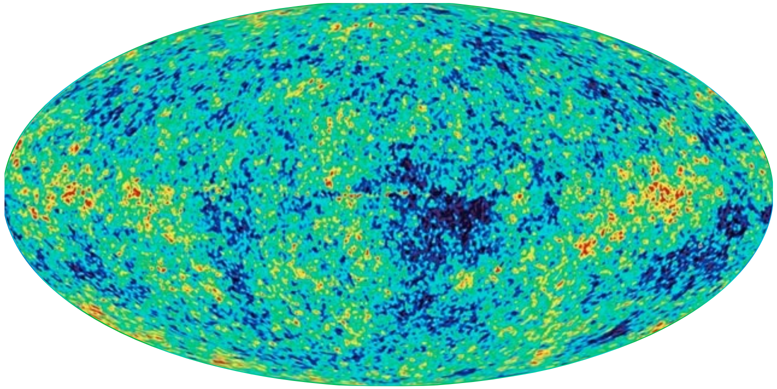


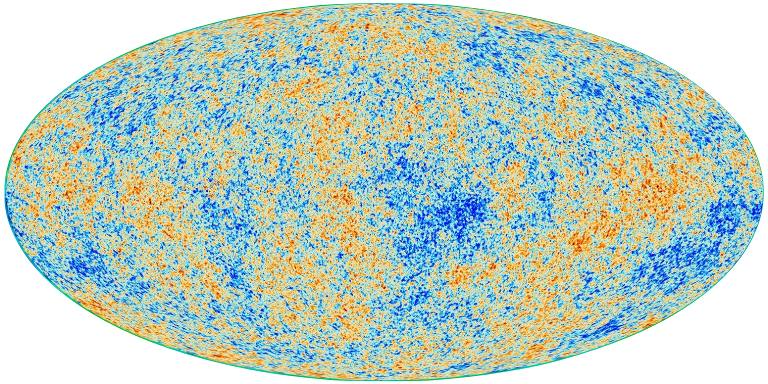
ΛCDM + “SIMPLE” INFLATION

CMB

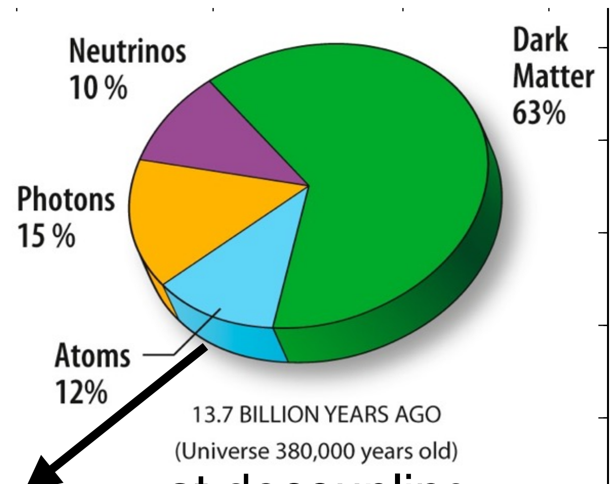
COBE → WMAP → Planck



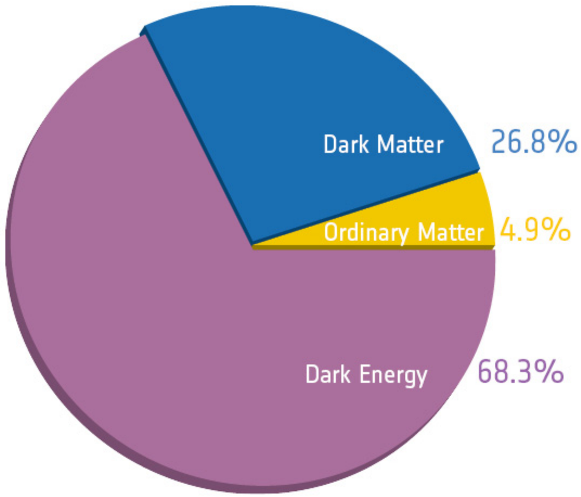




Cosmological Concordance model

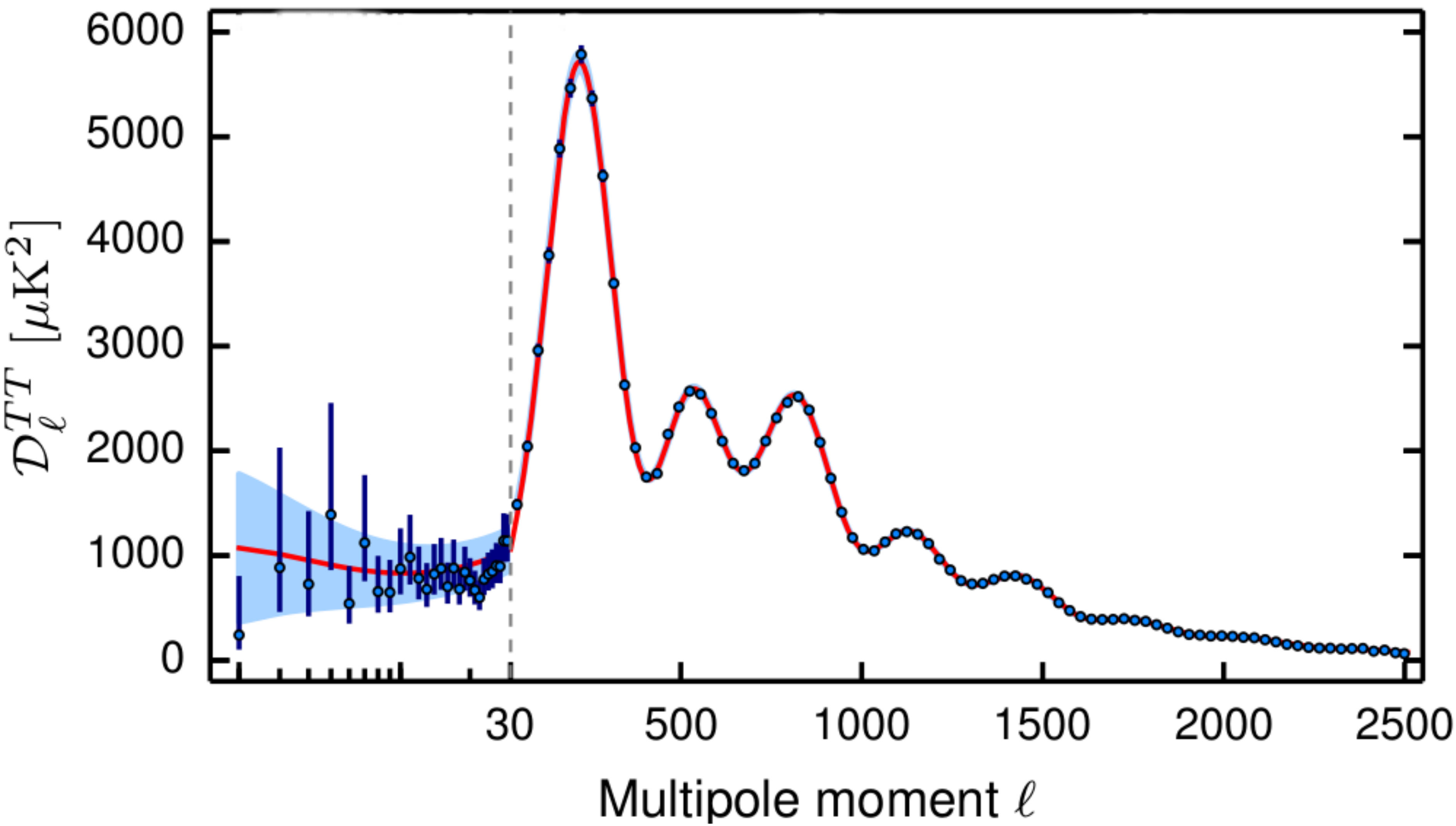


at decoupling

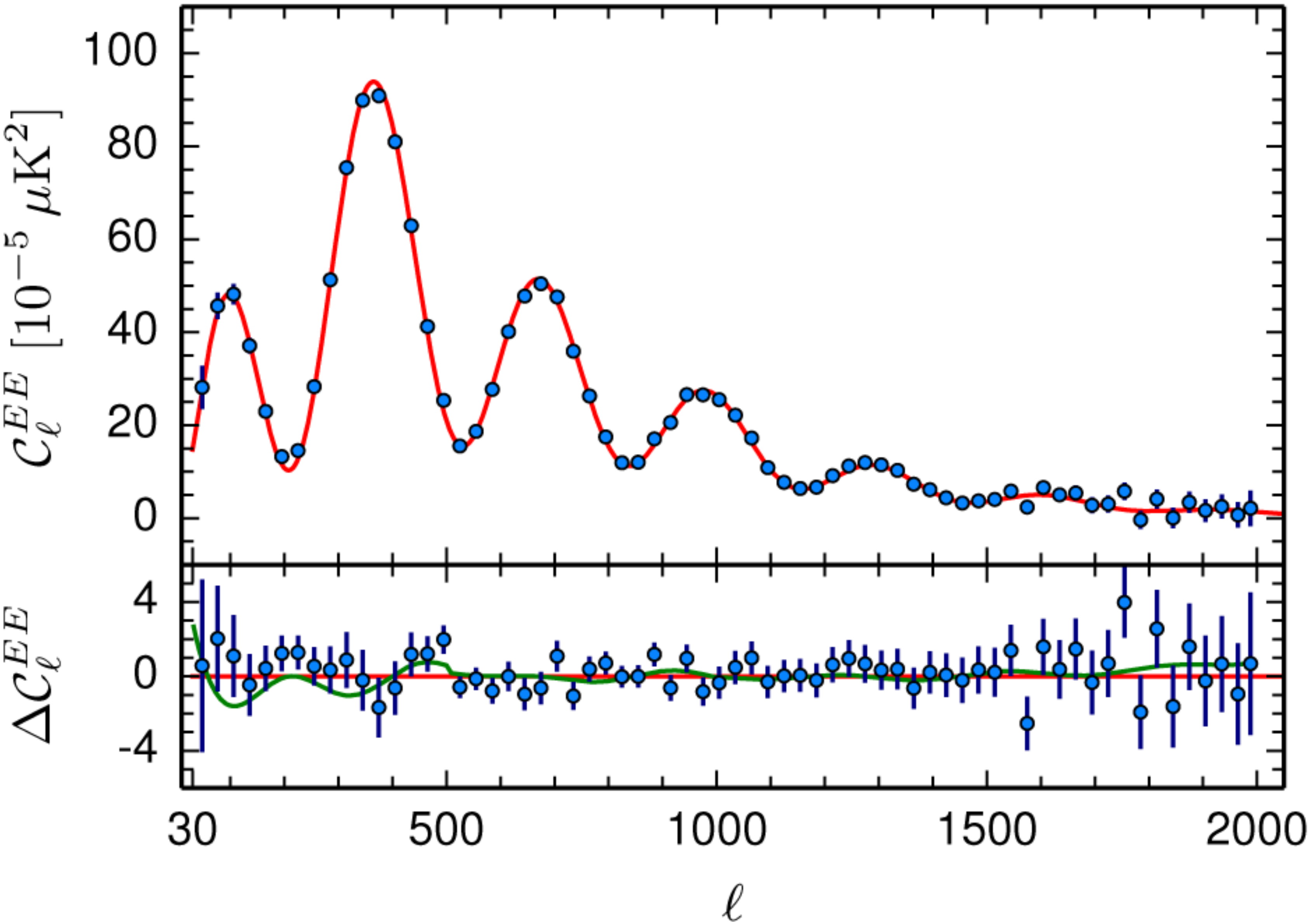


Today

Planck 2015: TT spectrum (blue dots) and predictions of inflationary theory (red line)

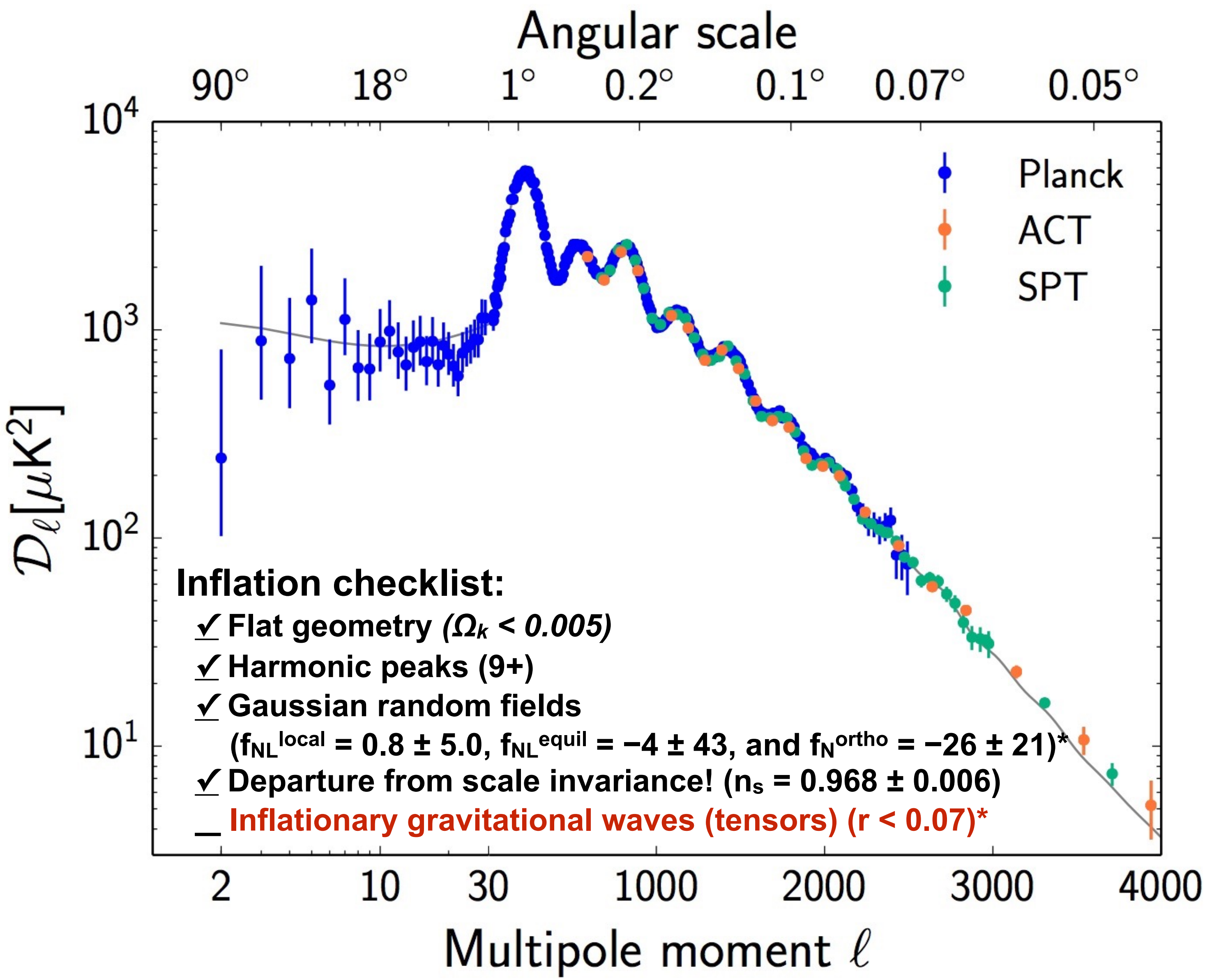


Planck 2015: EE correlations (blue dots) and predictions of inflationary theory (red line)



Inflation?

ICHEP, talk by J. Carlstrom



*constraints include CMB polarization data

Cosmological Concordance Model

Early Universe Inflation: first 10^{-35} sec

Model building to explain data using supergravity motivated by string theory (can't use global SUSY, has to solve Einstein equations)

Absence of non-Gaussianity: preference to a single light scalar, inflaton, all other moduli should play only secondary roles

Tilt of the power spectrum $n_s \approx 0.96$

Primordial gravity waves $r < 0.07$

Slow roll inflation, near de Sitter space

Current Universe acceleration: during the last few billion years

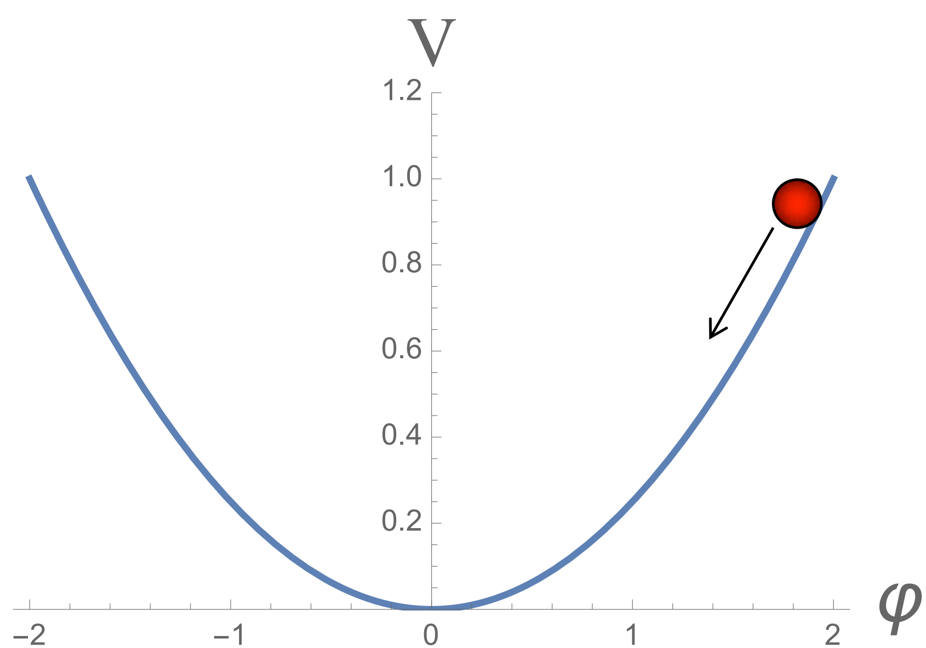
Cosmological constant, de Sitter space, provides a good fit to data

$$\Lambda \approx 10^{-120} M_{Pl}^4$$

Dark Matter ???

Simplest inflationary model: $V = \frac{m^2\phi^2}{2}$

To have inflation starting at the Planck density, it is sufficient to have a single Planck size domain with a potential energy V of the same order as kinetic and gradient density.



Scalar and tensor perturbations

$$A_s = \frac{V^3(\phi)}{12\pi^2 V_\phi^2(\phi)} \qquad\qquad A_t = \frac{2V(\phi)}{3\pi^2}$$

By relating ϕ and k, one can write, approximately,

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

$$r \equiv \frac{A_t(k_*)}{A_s(k_*)}.$$

Observations tell us about perturbations produced during the last 50 – 60 e-foldings of inflation, which are described by the number N.

Slow roll parameters and observables

$$\epsilon = \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2, \quad \eta = \frac{V_{\phi\phi}}{V}$$

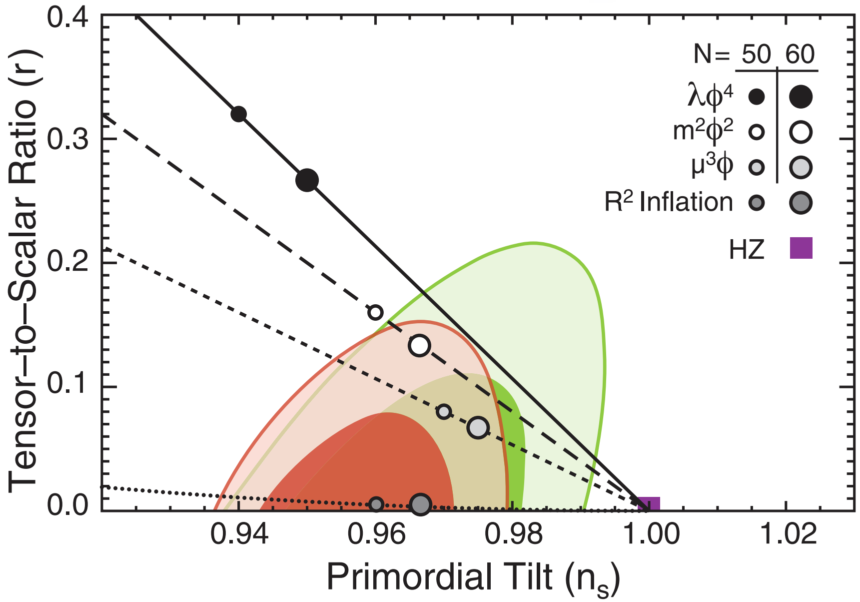
$$A_s = \frac{V}{24\pi^2\epsilon} ,$$

$$n_s = 1 - 6\epsilon + 2\eta = 1 - 3\left(\frac{V'}{V}\right)^2 + 2\frac{V''}{V}$$

$$r = 16\epsilon,$$

$$n_t = -2\epsilon = -\frac{r}{8} .$$

WMAP 2012: 9 years summary



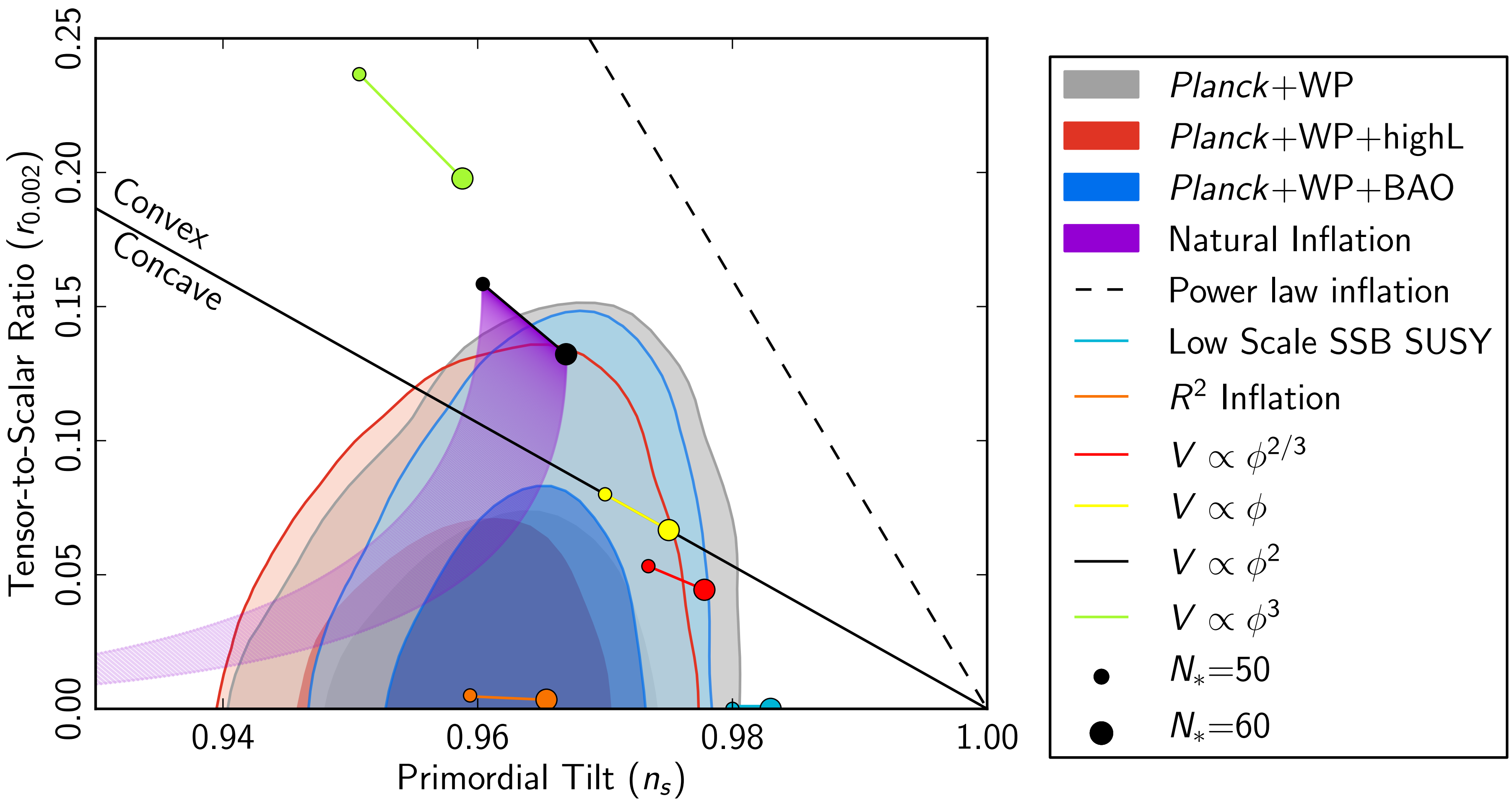
$$f_{NL}^{\rm loc} = 37.2 \pm 19.9 \qquad\qquad (-3 < f_{NL}^{\rm loc} < 77 \text{ at } 95\% \text{ CL})$$

This level of non-Gaussianity would kill 99% of all inflationary models, predicting f_{NL} < 1. Everyone tried to construct ugly models belonging to the remaining 1%...

"Happy families are all alike; every unhappy family is unhappy in its own way."

Anna Karenina by L. Tolstoy

Revolution of 2013: Planck 2013



$$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$$

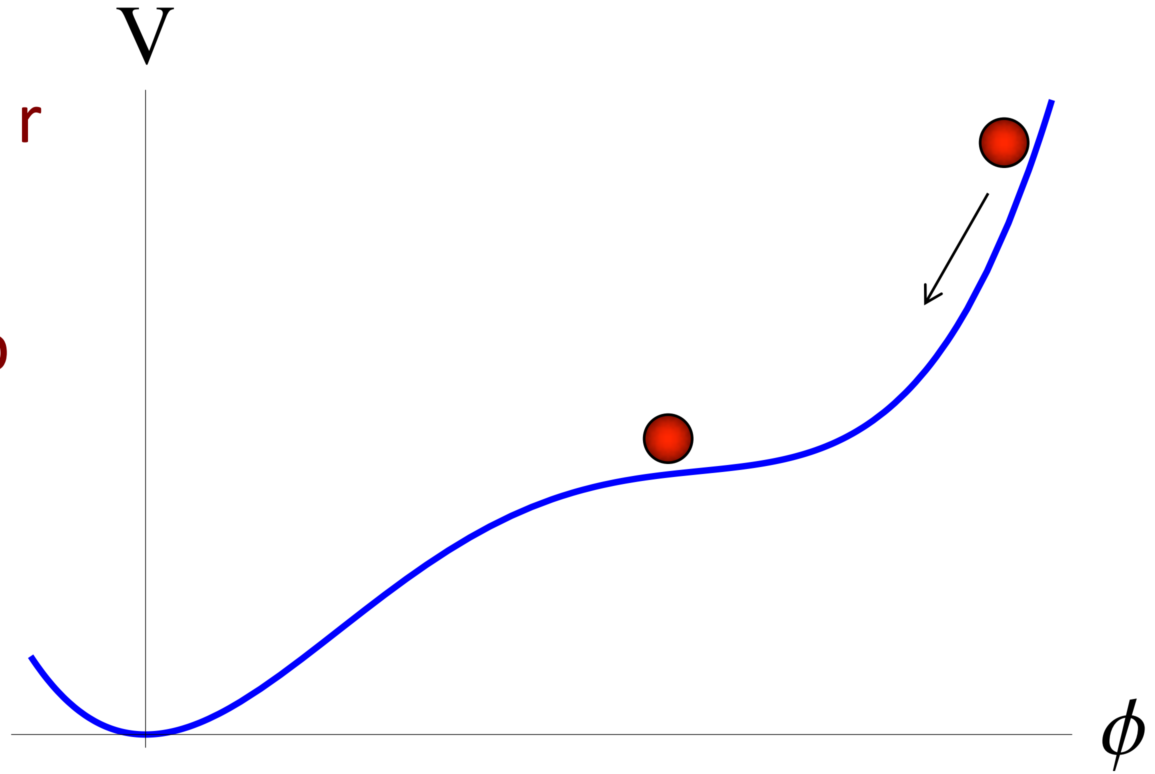
we can relax and concentrate on beautiful models again

One can fit all Planck data by a polynomial, with inflation starting at the Planck density

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

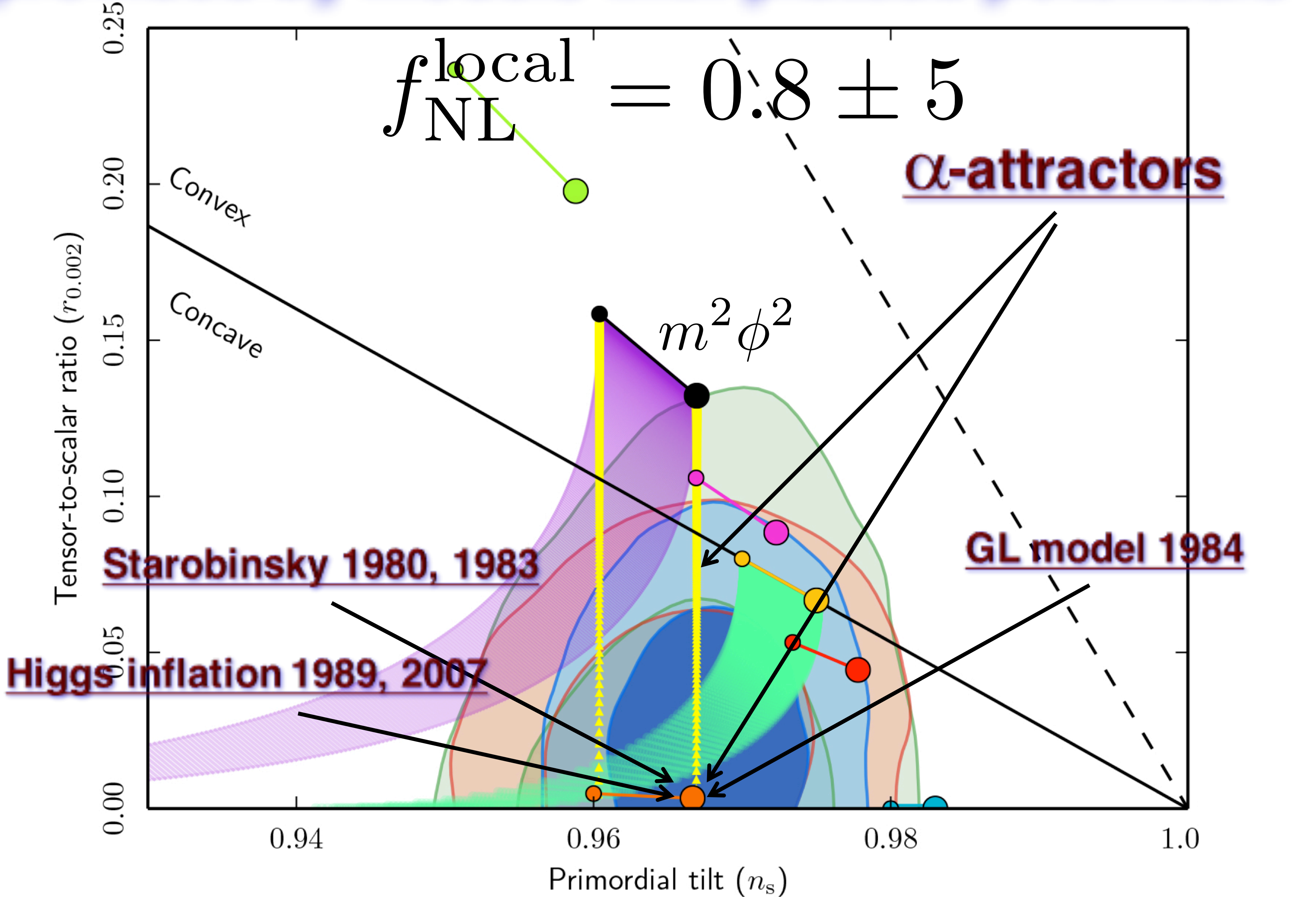
3 observables: A_s, n_s, r

3 parameters: m, a, b

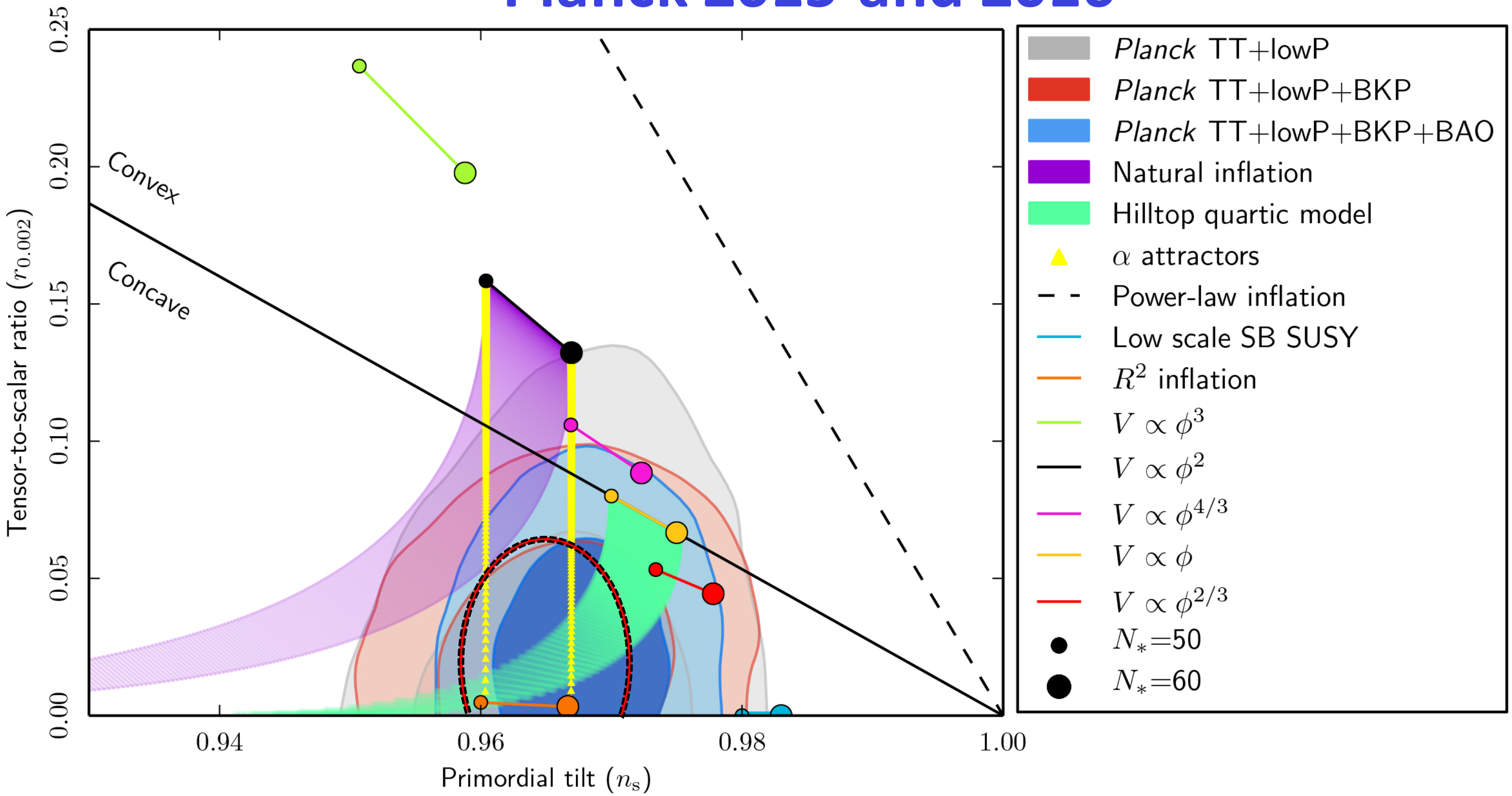


But the best fit is provided by models with plateau potentials

Planck 2015 + BICEP2. The best fit is provided by models with plateau potentials



Planck 2015 and 2016



Planck 2016 results 1605.02985 suggest that the dark blue area may shift to the left by ½ of the error bar:

$$\Delta n_s \sim -0.0026$$

This may further improve the status of α attractors, **as indicated by the** (Planck non-authorized) **red arc** in the figure above.

For the real answer we should wait until the next Planck data release.

De Sitter from spontaneously broken conformal symmetry

Kallosh, AL 2013, motivated by Kallosh, Kofman, AL, Van Proeyen 2000

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\partial_\mu\chi\partial_\nu\chi\, g^{\mu\nu} + \frac{\chi^2}{12}R(g) - \frac{\lambda}{4}\chi^4\right]$$

This theory is locally conformal invariant

$$\tilde{g}_{\mu\nu} = \mathrm{e}^{-2\sigma(\mathrm{x})} g_{\mu\nu}\,, \qquad \tilde{\chi} = \mathrm{e}^{\sigma(\mathrm{x})}\chi$$

The field χ (x) is referred to as a conformal compensator, which we will call `**conformon**.' It has negative sign kinetic term, but this is not a problem because it can be removed from the theory by fixing the gauge symmetry, for example

$$\chi = \sqrt{6}$$

This gauge fixing can be interpreted as a spontaneous breaking of conformal invariance due to existence of a classical field $\chi = \sqrt{6}$

The action in this gauge: dS or AdS

$$\mathcal{L} = \sqrt{-g}\left[\frac{R(g)}{2} - 9\lambda\right]$$

The simplest conformally invariant two-field model of dS or AdS space and the SO(1,1) invariant conformal gauge

$$\mathcal{L} = \frac{\sqrt{-g}}{2}\left[(\partial_\mu\chi\partial^\mu\chi - \partial_\mu\phi\partial^\mu\phi) + \frac{\chi^2-\phi^2}{6}R(g) - \frac{\lambda(\phi^2-\chi^2)^2}{2}\right]$$

Local conformal symmetry

$$\tilde{g}_{\mu\nu} = \mathrm{e}^{-2\sigma(\mathrm{x})} g_{\mu\nu}\,, \qquad \tilde{\chi} = \mathrm{e}^{\sigma(\mathrm{x})}\chi\,, \qquad \tilde{\phi} = \mathrm{e}^{\sigma(\mathrm{x})}\phi$$

The global SO(1,1) transformation is a boost between these two fields.

SO(1,1) invariant conformal gauge $\chi^2 - \phi^2 = 6$

This gauge condition represents a hyperbola which can be parameterized by a canonically normalized field φ

$$\chi = \sqrt{6}\cosh\frac{\varphi}{\sqrt{6}}\,, \qquad \phi = \sqrt{6}\sinh\frac{\varphi}{\sqrt{6}}$$

The action in this gauge, dS/AdS

$$L = \sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - 9\lambda\right]$$

Chaotic inflation from conformal theory: T-Model

$$\mathcal{L} = \frac{\sqrt{-g}}{2}\left[(\partial_\mu\chi\partial^\mu\chi - \partial_\mu\phi\partial^\mu\phi) + \frac{\chi^2-\phi^2}{6}R(g) - \frac{(\phi^2-\chi^2)^2}{18}F\left(\phi/\chi\right)\right]$$

Here F is an arbitrary function of the ratio phi/chi. When this function is present, it breaks the SO(1,1) symmetry of the de Sitter model. Note that this is the only possibility to keep local conformal symmetry and to deform the SO(1,1) symmetry!

In the gauge $\chi^2 - \phi^2 = 6$ it becomes

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

The attractor behavior near a critical point where SO(1,1) symmetry is restored is the following: start with generic F(tanh), always get

$$n_s \approx 0.967 \qquad\qquad r \approx 0.0032$$

Superconformal Description of the Cosmological Evolution

Kallosh, AL 1311.3326

In the superconformal formulation of supergravity, the standard supergravity action appears as a result of spontaneous symmetry breaking when the conformal compensator scalar field, the conformon, acquires a nonzero value, giving rise to the Planck mass. After that, some symmetries of the original theory become well hidden, and therefore they are often ignored.

However, superconformal invariance is more than just a tool. In particular, **inflation can be equivalently described as the conformon instability, and creation of the universe `from nothing' can be interpreted as spontaneous symmetry breaking due to emergence of a classical conformon field.**

What is the meaning of α-attractors?

Start with the simplest chaotic inflation model

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\partial\phi^2 - \frac{1}{2}m^2\phi^2$$

Modify its kinetic term

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\phi^2$$

Switch to canonical variables $\phi = \sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}$

The potential becomes

$$V = 3\alpha\, m^2 \tanh^2\frac{\varphi}{\sqrt{6\alpha}}$$

General chaotic inflation model

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\partial\phi^2 - V(\phi)$$

Modify its kinetic term

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\underline{\frac{\phi^2}{6\alpha}})^2} - V(\phi)$$

Switch to canonical variables $\phi = \sqrt{6\alpha}\,\tanh\frac{\varphi}{\sqrt{6\alpha}}$

The potential becomes

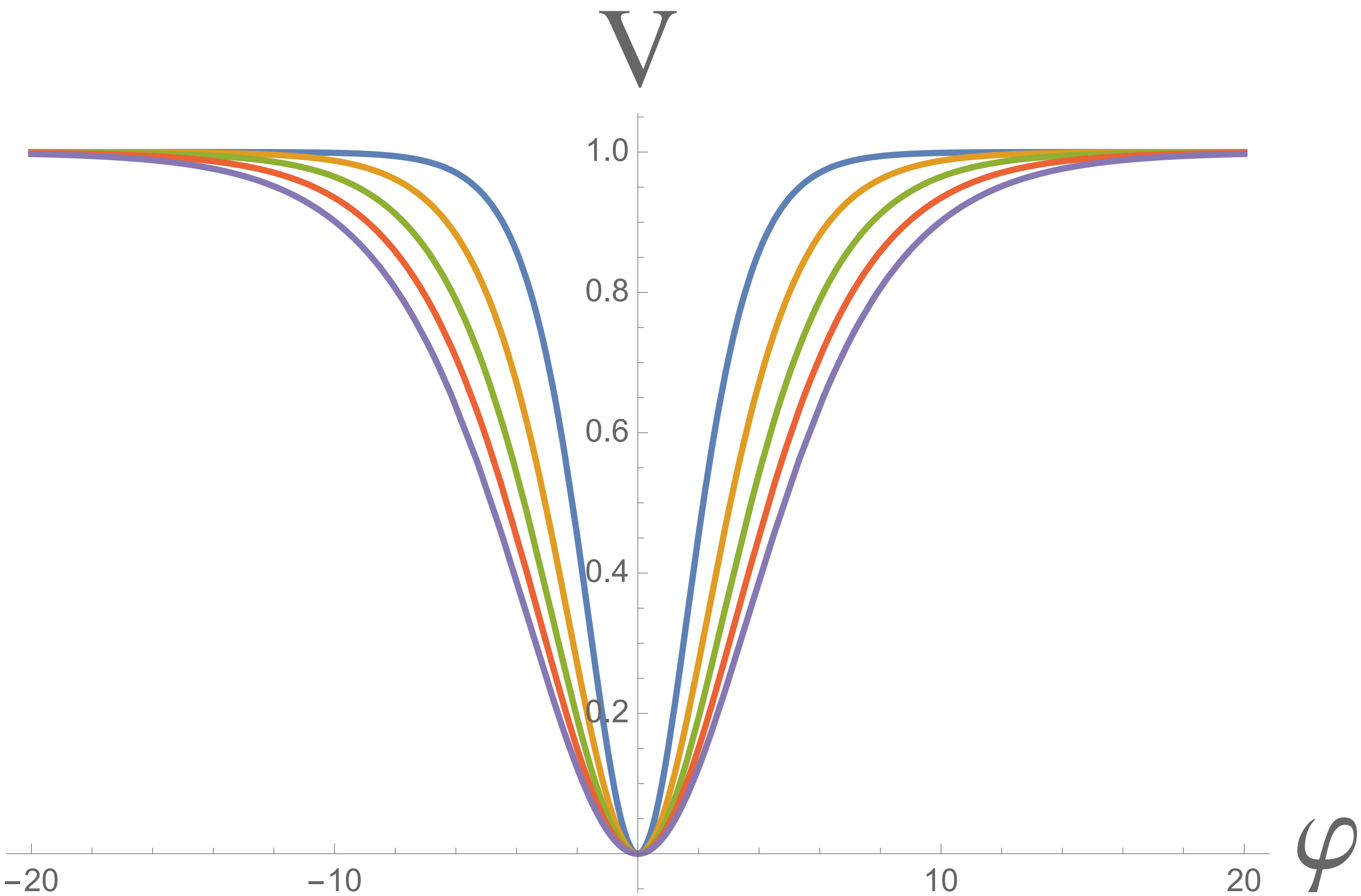
$$V = V(\tanh\frac{\varphi}{\sqrt{6\alpha}})$$

This is a **plateau potential** for any nonsingular $V(\phi)$

T-models

$$V = f^2(\tanh \frac{\varphi}{\sqrt{6\alpha}})$$

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



Similar model has been proposed 32 years ago by Goncharov and AL in JETP **59**, 930 (1984). It was the first paper on chaotic inflation in supergravity, but it was nearly forgotten. It corresponds to

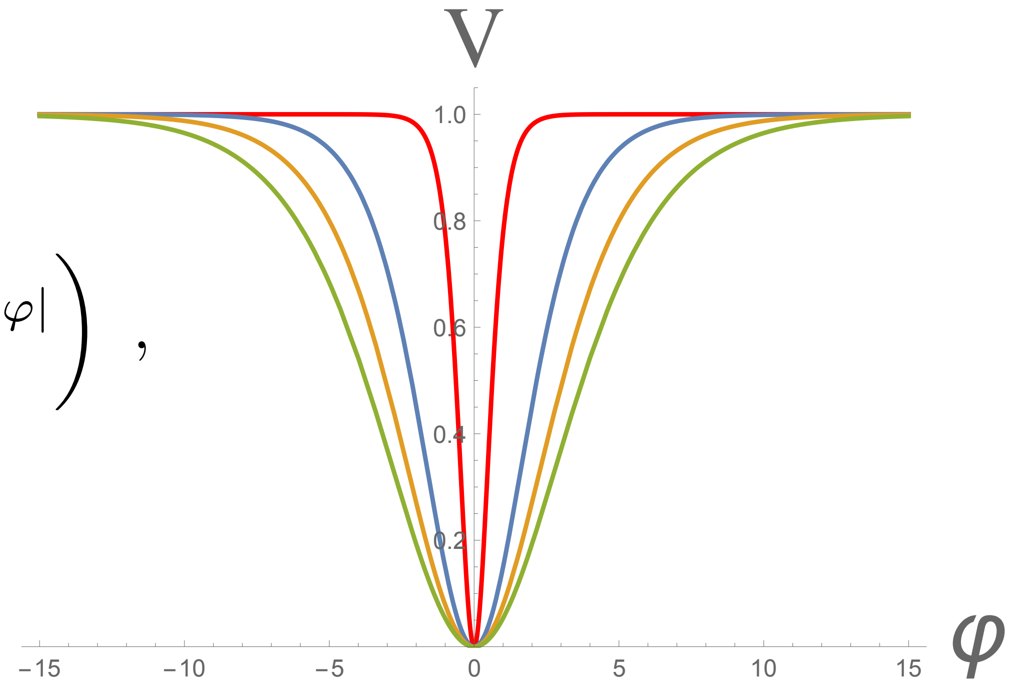
$$\alpha = 1/9$$

$$n_s = 1 - \frac{2}{N} \approx 0.967, \qquad r \sim 4 \times 10^{-4}$$

Red line – GL model 1984

$$V(\varphi) = \frac{\mu^2}{9}\left(1 - \frac{8}{3}\,e^{-\sqrt{6}|\varphi|}\right) ,$$

for $\varphi \gtrsim 1$

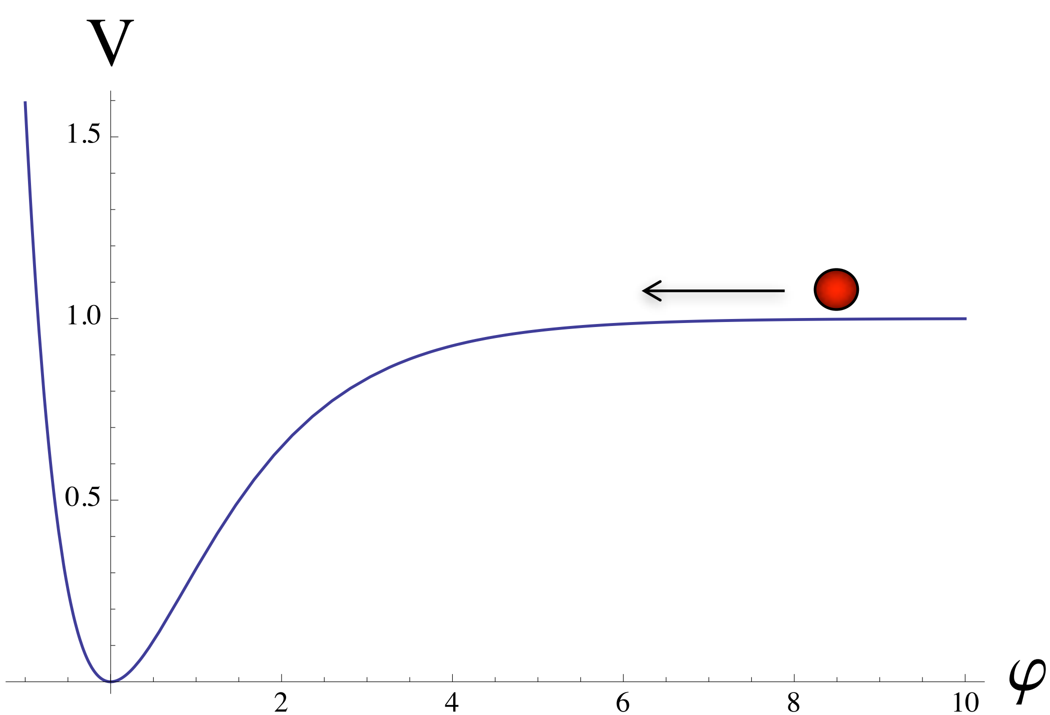


Starobinsky model

$$L = \sqrt{-g}\left(\frac{1}{2}R + \frac{R^2}{12M^2}\right)$$

$$\tilde{g}_{\mu\nu} = (1 + \phi/3M^2)g_{\mu\nu} \qquad \varphi = \sqrt{\tfrac{3}{2}}\ln\left(1 + \tfrac{\phi}{3M^2}\right)$$

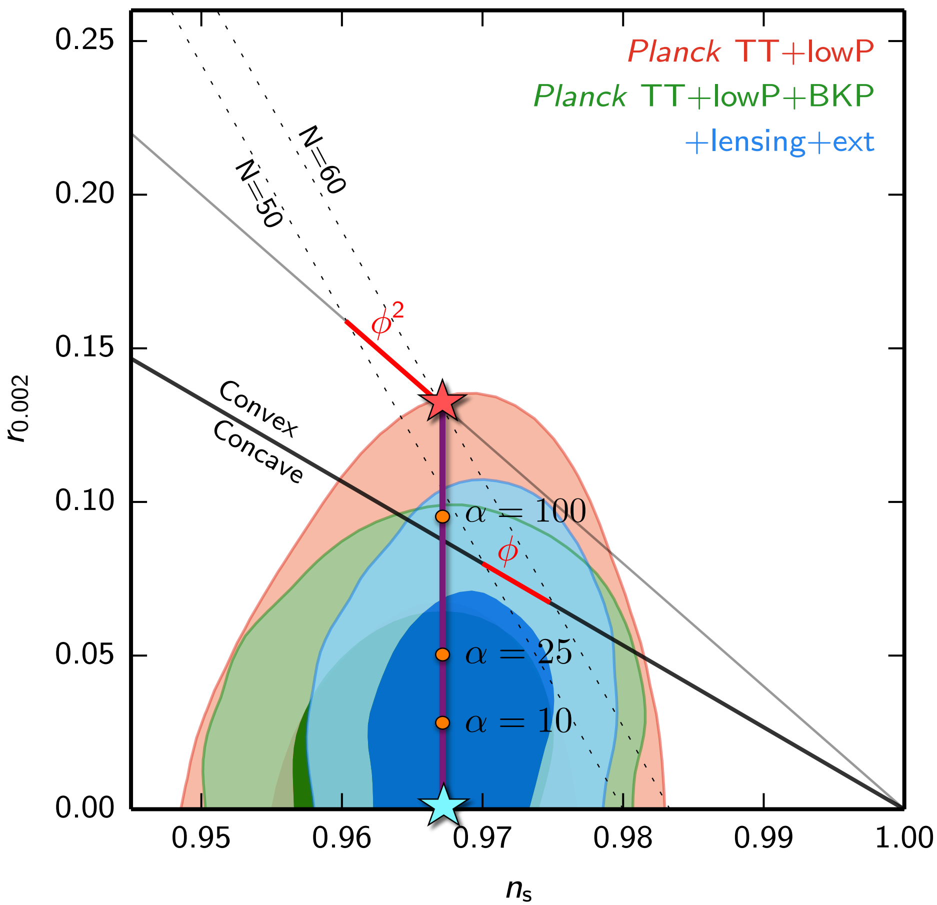
$$L = \sqrt{-\tilde{g}}\left[\frac{1}{2}\tilde{R} - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{3}{4}M^2\left(1 - e^{-\sqrt{2/3}\,\varphi}\right)^2\right]$$

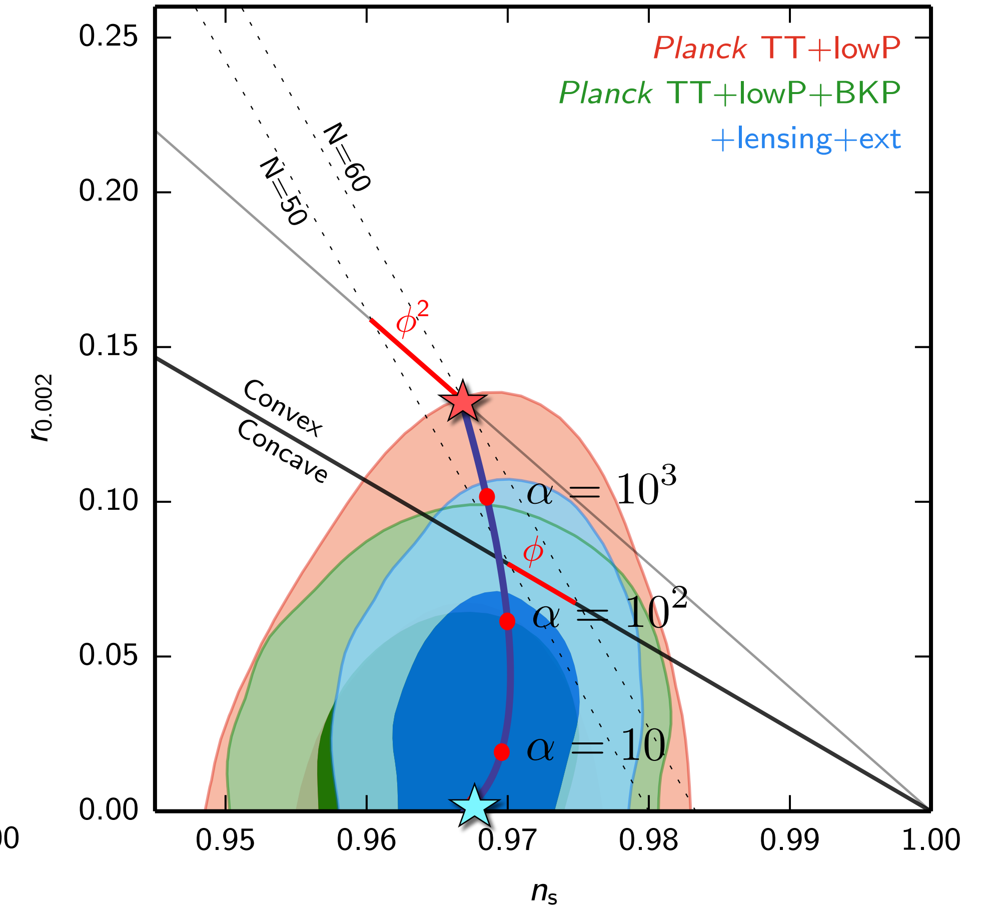


Whitt 1984

Identified with the Starobinsky model only in 1988:

Barrow 1988
Maeda 1988
Coule, Mijic 1988





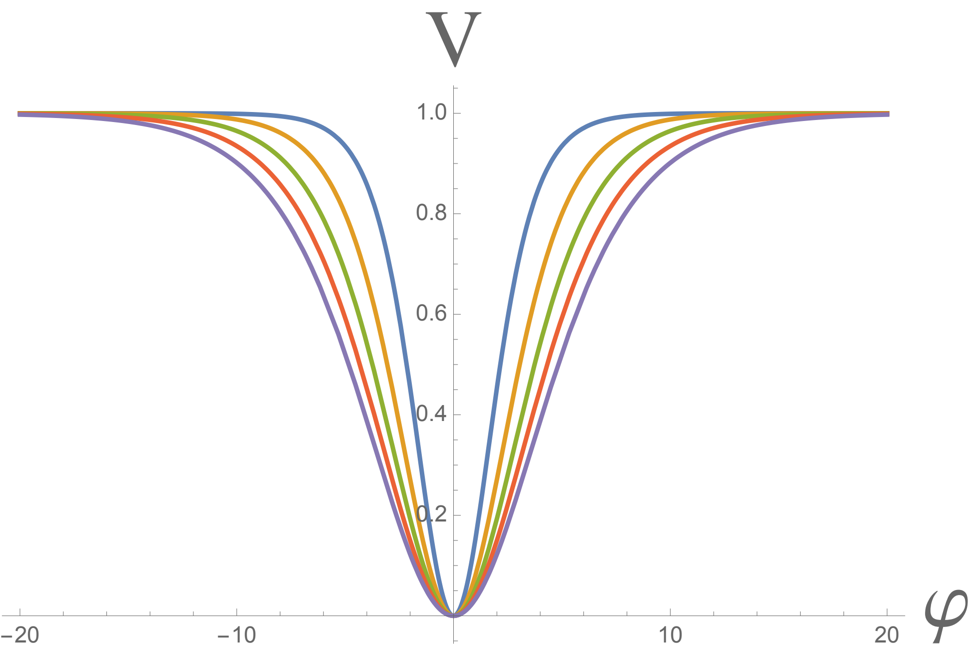
$$\frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\phi^2$$

$$\frac{1}{2}R - \frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\frac{\phi^2}{(1+\frac{\phi}{\sqrt{6\alpha}})^2}$$

Simplest T-models **Simplest E-models**

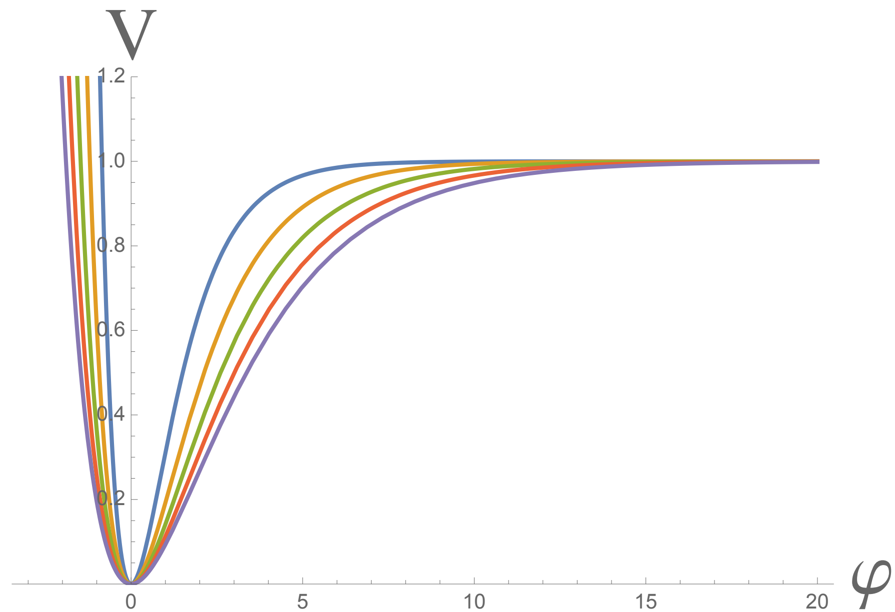
Ferrara, Kallosh, AL, Porrati, 2013, Kallosh, AL, Roest 2013

Simplest T-models



$$\frac{1}{2}R - \frac{1}{2}\partial\varphi^2 \; - \alpha\mu^2\left(\tanh\frac{\varphi}{\sqrt{6\alpha}}\right)^2$$

Simplest E-models



$$\frac{1}{2}R - \frac{1}{2}\partial\varphi^2 \; - \alpha\mu^2\left(1 - e^{\sqrt{\frac{2}{3\alpha}}\varphi}\right)^2$$

Coincides with the Starobinsky model for $\alpha = 1$.

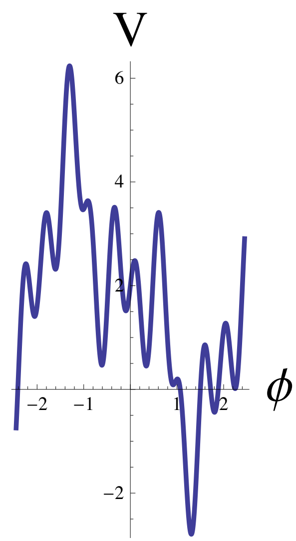
Why different models have similar cosmological predictions nearly independent of the choice of the potential?

Stretching and flattening of the potential is similar to stretching of inhomogeneities during inflation

Kallosh, AL 2013

Potential in the **original variables** with kinetic term

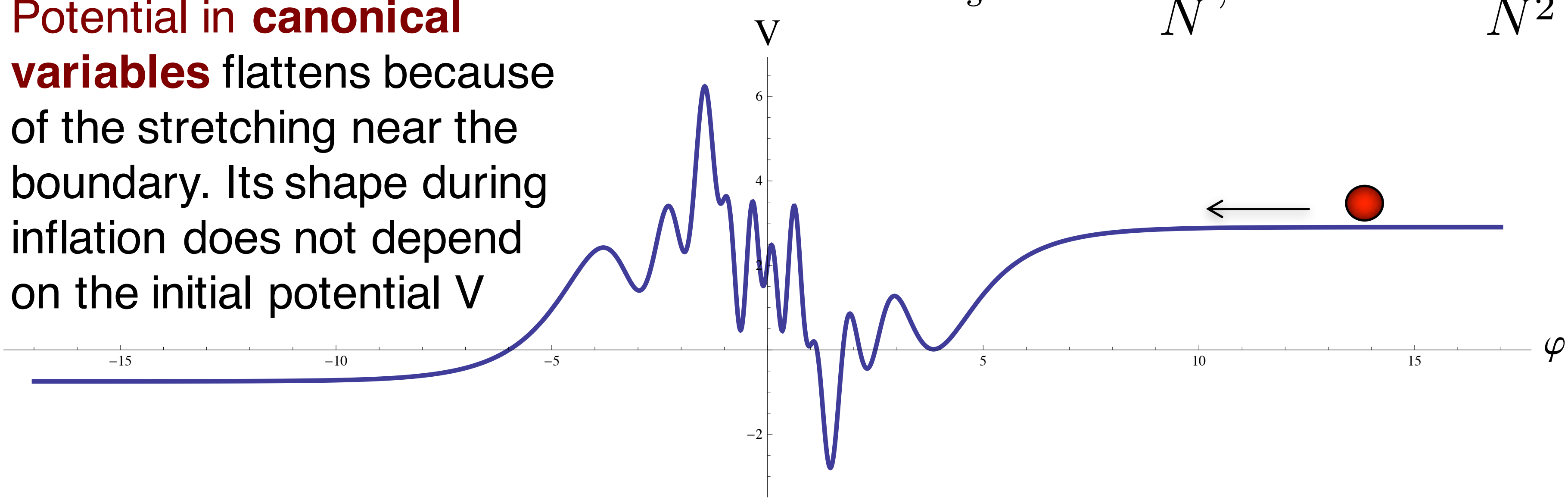
$$\frac{1}{2}\frac{\partial\phi^2}{(1-\frac{\phi^2}{6\alpha})^2}$$



All of these models predict

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

Potential in **canonical variables** flattens because of the stretching near the boundary. Its shape during inflation does not depend on the initial potential V



The essence of α-attractors

Galante, Kallosh, AL, Roest 1412.3797

$$\frac{1}{2}R - \frac{3}{4}\alpha\left(\frac{\partial t}{t}\right)^2 - V(t)$$

Suppose inflation takes place near the pole at t = 0, and V(0) > 0, V'(0) >0, and V has a minimum nearby. Then in canonical variables

$$\frac{1}{2}R - \frac{1}{2}(\partial\varphi)^2 - V_0(1 - e^{-\sqrt{\frac{2}{3\alpha}}\varphi} + \ldots)$$

Then in the leading approximation in 1/N

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

The essence of α-attractors

Galante, Kallosh, AL, Roest 2014

THE BASIC RULE:

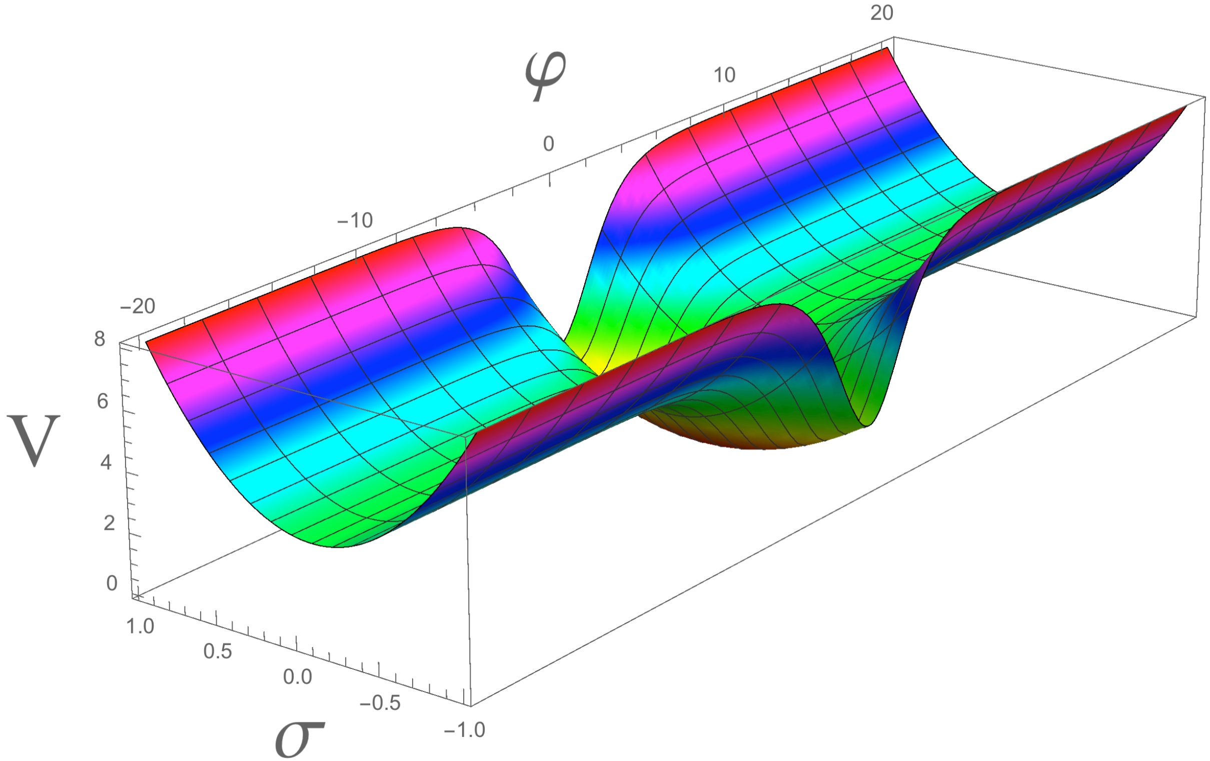
For a broad class of cosmological attractors, the spectral index $\mathbf{n_s}$ depends mostly on the order of the pole in the kinetic term, while the tensor-to-scalar ratio $\mathbf{r}$ depends on the residue. Choice of the potential almost does not matter, as long as it is non-singular at the pole of the kinetic term. Geometry of the moduli space, not the potential, determines much of the answer.

An often discussed concern about higher order corrections for large field inflation does not apply to these models.

Adding other fields

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{(\partial\phi)^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}m^2\phi^2 - \frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}M^2\sigma^2 - \frac{g^2}{2}\phi^2\sigma^2$$

Potential in canonical variables has a plateau at large values of the inflaton field, and it is quadratic with respect to σ.



Asymptotic freedom of the inflaton

$$\frac{1}{\sqrt{-g}}\mathcal{L} = \frac{1}{2}R - \frac{1}{2}\frac{(\partial\phi)^2}{(1-\frac{\phi^2}{6\alpha})^2} - \frac{1}{2}(\partial\sigma)^2 - V(\phi,\sigma)$$

Couplings of the canonically normalized fields are determined by derivatives such as

$$\lambda_{\varphi,\sigma,\sigma} = \partial_\varphi \partial_\sigma^2 V(\phi,\sigma) = 2\sqrt{\frac{2}{3\alpha}}\, \underline{e^{-\sqrt{\frac{2}{3\alpha}}\varphi}}\, \partial_\phi \partial_\sigma^2 V(\phi,\sigma)|_{\phi\to\sqrt{6\alpha}}$$

As a result, **couplings of the inflaton field to all other fields are exponentially suppressed during inflation**. The asymptotic shape of the plateau potential of the inflaton is **not** affected by quantum corrections.

α-attractors in supergravity, cosmological constant, and SUSY breaking

Escher in the Sky, Kallosh, AL 2015

Disk or **half-plane**

$$ds^2 = \frac{3\alpha}{(1 - Z\bar{Z})^2} dZ d\bar{Z}$$

$$ds^2 = \frac{3\alpha}{(T + \bar{T})^2} dT d\bar{T}$$

$$\mathcal{R}_K = -\frac{2}{3\alpha}$$

Special choices of α and future data

$\alpha = 1$	$r \approx 4 \times 10^{-3}$	Critical point of superconformal α=1 attractors, Higgs inflation, Starobinsky model
$\alpha = 1/3$	$r \approx 10^{-3}$	Maximal superconformal $\mathcal{N}$=4 model, maximal supergravity $\mathcal{N}$=8
$\alpha = 1/9$	$r \approx 4 \times 10^{-4}$	1984 Goncharov-Linde supergravity model
Any $\alpha < 20$	$r < 0.07$	Generic $\mathcal{N}$=1 supergravity

All of these models fit the current data

Example: GL model of 1984 in modern formulation

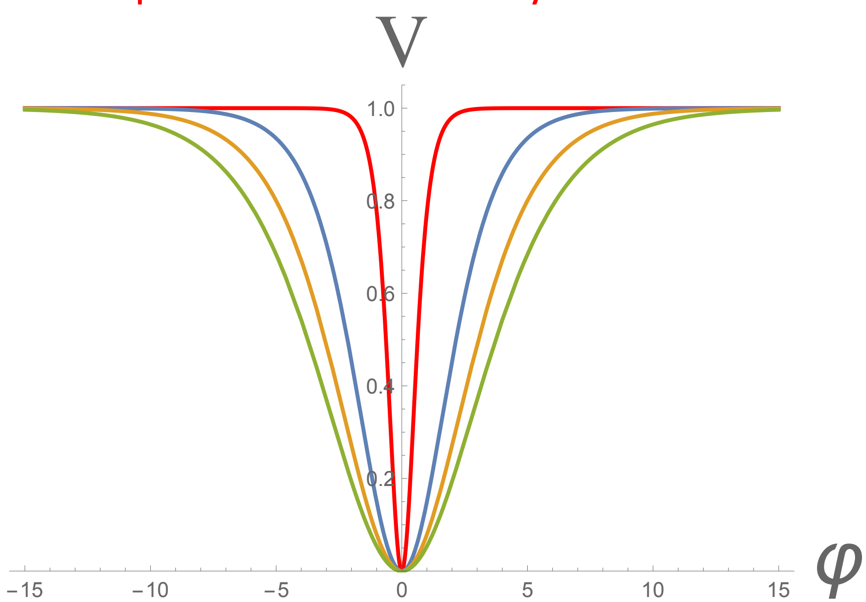
$$K = -3\log\left(1 - Z\bar{Z} + \frac{\alpha - 1}{2}\frac{(Z-\bar{Z})^2}{1 - Z\bar{Z}}\right) \qquad \alpha = 1/9$$

Goncharov, AL 1984
AL 2015
Kallosh, AL 2015
Roest, Scalisi 2015, 2016

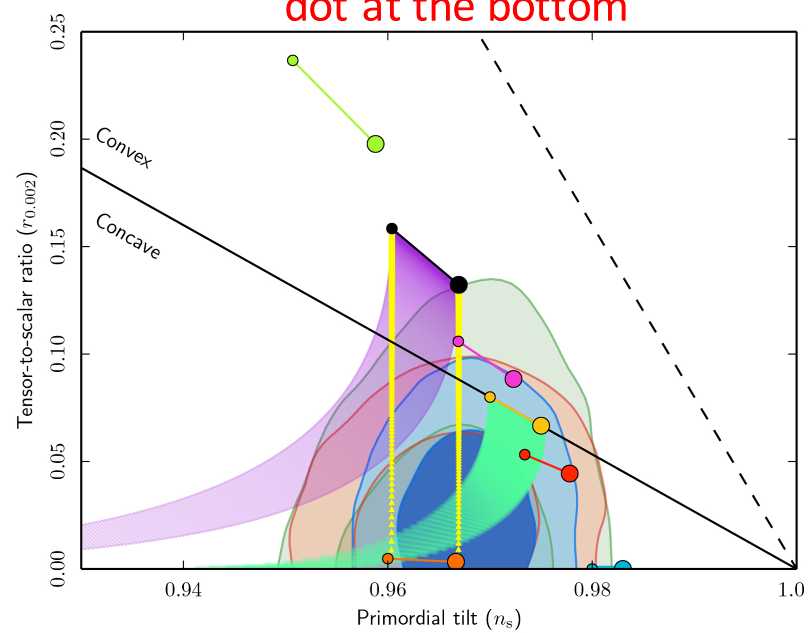
$$W = \frac{\mu}{9}\, Z^2\,(1 - Z^2)$$

$$V(\phi) = \frac{m^2}{4}\left(1 - \frac{8}{3}\, e^{-\sqrt{6}|\phi|}\right)$$

GL potential is shown by red line



Prediction is shown by the orange dot at the bottom



Two-field T–model with $\alpha = 1$

$$K = -3\log(1 - Z\bar{Z}) + S\bar{S}, \qquad W = mSZ$$

There is a boundary of the moduli space at $|Z|^2=1$

The minimum of the potential is at Im Z = S = 0.

$$Z = \bar{Z} = \tanh\frac{\varphi}{\sqrt{6}}, \qquad S = 0$$

$$V = m^2 \tanh^2\frac{\varphi}{\sqrt{6}}$$

Potential of α-attractors in terms of disk variables Z

A projection of the Escher disk of the radius $\sqrt{3\alpha}$ on the quadratic inflationary potential

If we want to make sure that $S = 0$ (and $\text{Im } Z = 0$) generically, and describe potentials with a minimum with SUSY breaking and non-vanishing V (cosmological constant), a novel ingredient helps a lot:

Nilpotent (orthogonal) chiral superfields

Supersymmetry is there, but fermions may not have scalar partners. More generally, superpartners may not be there.

The nilpotent chiral superfield

- SUSY 101: supersymmetry relates bosons and fermions

Not necessarily!

- If we break supersymmetry we expect a massless goldstone fermion, the goldstino

- Volkov, Akulov 1972, 1973

- Non-perturbative string theory: on D-branes there are nilpotent and orthogonal multiplets, 2014-2016

Volkov, Akulov, 1972 Non-linearly realized supersymmetry: only fermions are present

Rocek, Lindstrom, 1978-1979, Komargodski, Seiberg 2009: nilpotent superfields
Antoniadis, Dudas, Ferrara and Sagnotti, 2014

Ferrara, Kallosh, AL, 2014 application to cosmology, generic superconformal case

Dall'Agata, Zwirner 2014, elegant construction of realistic models

Nilpotent superfields: the main rule for cosmology

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.

Using nilpotent orthogonal fields (S =Im Φ = 0)

Ferrara, Kallosh, Thaler 1512.00545; Carrasco, Kallosh, AL 1512.00546, Dall'Agata, Farakos 1512.02158

Consider a theory

$$K = -\frac{3}{2}\alpha \log\left[\frac{(1-\Phi\bar{\Phi})^2}{(1-\Phi^2)(1-\bar{\Phi}^2)}\right] + S\bar{S} \qquad W = Sf(\Phi) + g(\Phi)$$

$$V = f^2(\phi) - 3g^2(\phi)$$

Nearly arbitrary potential

The cosmological constant and the gravitino mass in the minimum are

$$\Lambda = f^2(0) - 3g^2(0) \qquad m_{3/2} = g(0)$$

The canonical inflaton field φ is related to the original field ϕ in the usual way:

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

α-Attractors: Planck, LHC and Dark Energy

Carrasco, RK, Linde 1512.00546

Example 1:

$$f(\phi) = \sqrt{F^2(\phi) + a^2}, \quad g(\phi) = \sqrt{G^2(\phi) + b^2}$$

$$V = F^2(\phi) - 3G^2(\phi) + a^2 - 3b^2, \quad m_{3/2} = \sqrt{G^2(\phi) + b^2}.$$

In canonical variables,

$$V = F^2(\tanh \frac{\varphi}{\sqrt{6\alpha}}) - 3G^2(\tanh \frac{\varphi}{\sqrt{6\alpha}}) + a^2 - 3b^2$$

Full functional freedom to chose any α-attractor potential, with any cosmological constant and gravitino mass.

$$\Lambda = a^2 - 3b^2, \quad m_{3/2} = b.$$

α-Attractors: Planck, LHC and Dark Energy

Carrasco, RK, Linde 1512.00546

Example 2:

$$f(\phi) = \sqrt{(1-\phi)^2 + a^2}, \qquad g(\phi) = b$$

$$V = M^2(1-\phi)^2 + \Lambda, \quad \Lambda = a^2 - 3b^2, \quad m_{3/2} = b$$

In canonical variables,

$$V = M^2 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\varphi}\right)^2 + \Lambda$$

E-model alpha-attractors, generalizing the Starobinsky model, but with arbitrary SUSY breaking and cosmological constant

Example 3:

AL 1608.00119

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

and

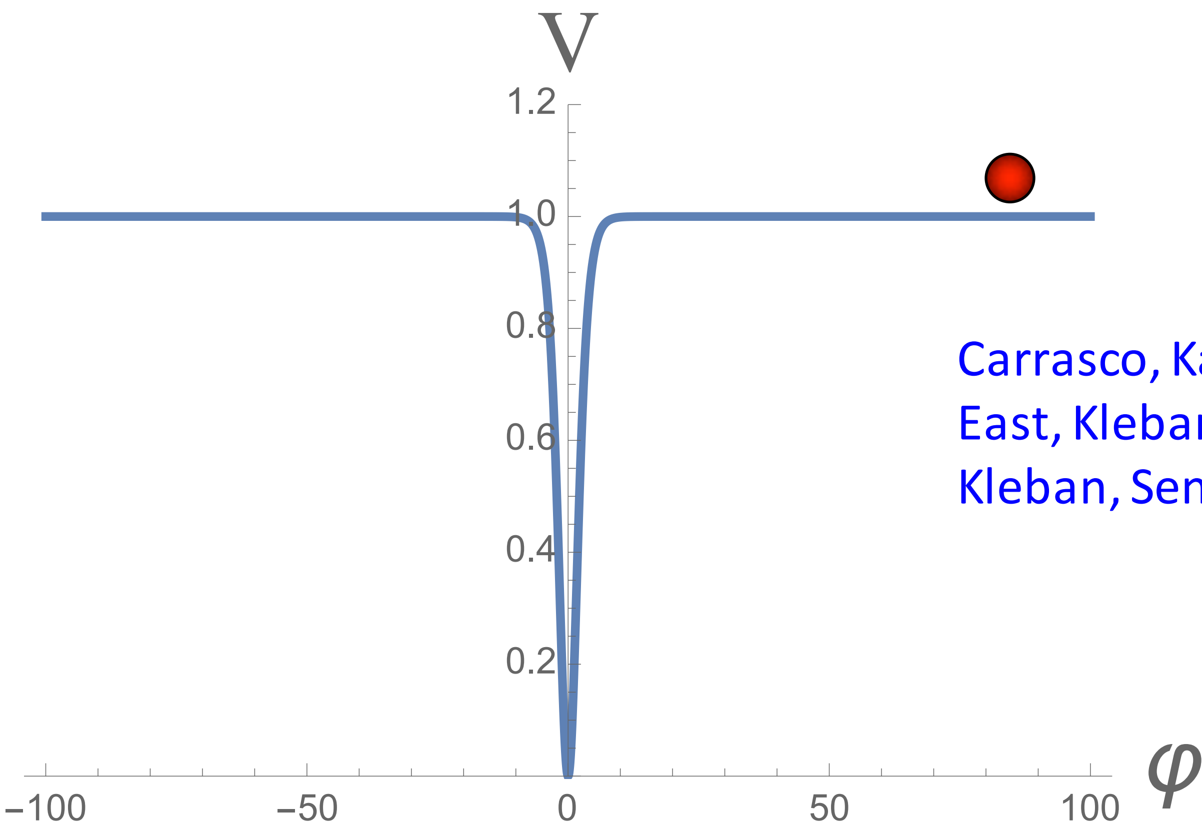
$$W = m\ S\,\Phi + (\sqrt{3+\delta}\,P + 1)\, m_{3/2}\ .$$

Here S and Φ are usual unconstrained chiral, and P is a nilpotent Polonyi-type field, which breaks SUSY, gives rise to a non-vanishing cosmological constant, and then disappears, without causing the infamous Polonyi field problem, which plagued SUGRA cosmology for more than 3 decades. S is non-zero but very small during inflation, and

$$V = m^2 \tanh^2 \frac{\varphi}{\sqrt{6\alpha}}\ +\ \delta\, m_{3/2}^2$$

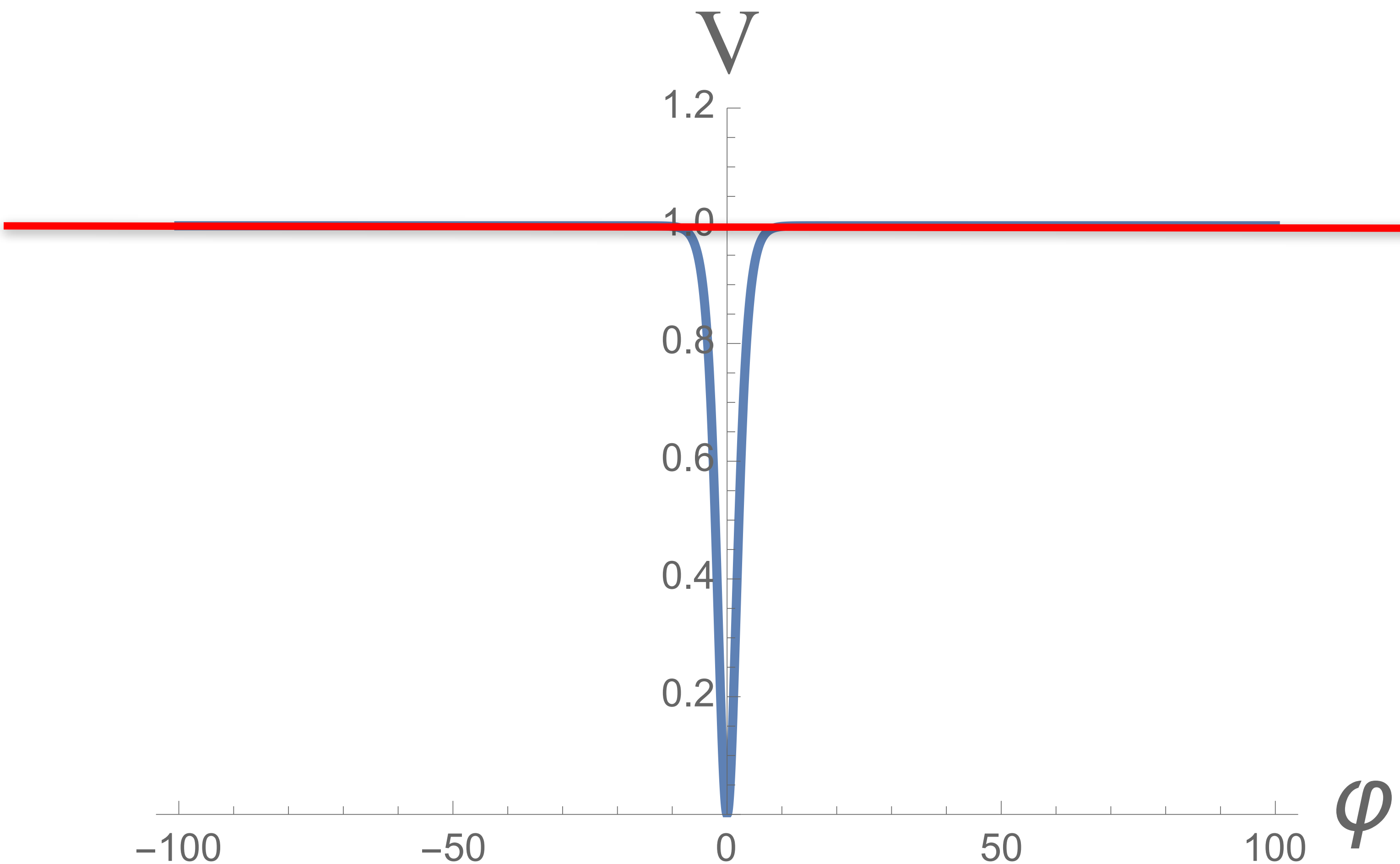
α-attractors: Initial conditions for inflation

At large fields, this potential remains 10 orders of magnitude below Planck density. Can we have inflation with natural initial conditions here? The same question applies for the Starobinsky model and Higgs inflation.



Carrasco, Kallosh, AL 1506.00936
East, Kleban, AL, Senatore 1511.05143
Kleban, Senatore 1602.03520

To explain the main idea, note that this potential coincides with the cosmological constant almost everywhere.



For the universe with a cosmological constant, the problem of initial conditions is nearly trivial.

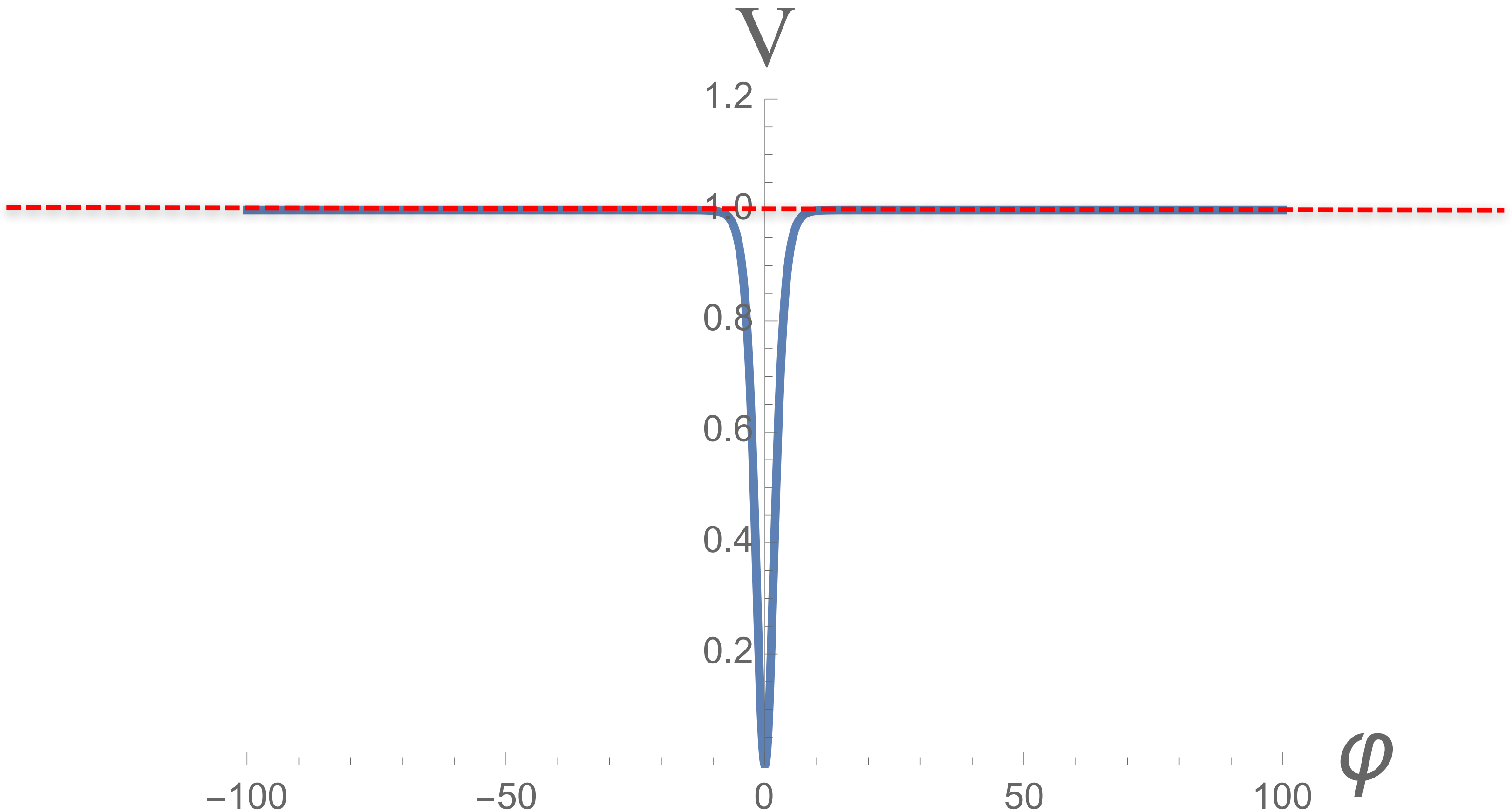
Start at Planck density, in an expanding universe dominated by inhomogeneities. The energy density of matter is diluted by the cosmological expansion as $1/t^2$. **What could prevent exponential expansion of the universe which becomes dominated by the cosmological constant Λ after the time t = $\Lambda^{-1/2}$?**

Inflation does NOT happen in the universe with the cosmological constant Λ =10^{-10} only if the whole universe collapses within 10^{-28} seconds after its birth.

In other words, only instant global collapse could allow the universe to avoid exponential expansion dominated by the cosmological constant. If the universe does not instantly collapse, it inflates.

This optimistic conclusion related to the cosmological constant applies to α-attractors as well, because their potential coincides with the cosmological constant almost everywhere.

Carrasco, Kallosh, AL 1506.00936
East, Kleban, AL, Senatore 1511.05143



Conclusions:

During the last 3 years, a new class of inflationary models was constructed: cosmological attractors. These models give predictions matching Planck data, generalize Starobinsky model, GL model and Higgs inflation, can be implemented in supergravity, and can simultaneously describe inflation, the cosmological constant, and SUSY breaking.

New ideas initiated by cosmological discoveries may lead to novel possibilities in particle phenomenology: Some superpartners may not be found because of the non-linear realized supersymmetry involving nilpotent superfields.

Dreaming about the future

The total cost of finding the Higgs boson ran about **$10 billion**… which seems like a **bargain**… especially when you consider the fact that LHC and its associated experiments are bringing us much closer to understanding the **mysteries of the universe**.

Forbes Magazine 7/05/2012

The total cost of the Planck satellite, which, arguably, brings us much closer to understanding the mysteries of the universe than LHC, is about **$1 billion**.

Long way to go!