Inflation in Supergravity and String Theory

Brief history of the multiverse

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Two of my heroes: Stephen Hawking and Andrei Sakharov

Visionaries, creating new ways of thinking, pushing their ideas to the limit, inspirational leaders, whose impact on our world goes well beyond their tremendous contribution to science.

Many ways to think about the multiverse

1. Many different **universes** described by quantum cosmology

Everett 1957, DeWitt 1967, Vilenkin 1982, Hartle and Hawking 1983

2. Many different exponentially large **parts** of the same inflationary universe

A.L. 1982, Vilenkin 1983, A.L. 1986, Bousso, Polchinski 2000, Susskind 2003

Both of these lines of thought were in full display in 1982 at the famous Nuffield Symposium at Cambridge, organized by **Stephen Hawking, Gary Gibbons and Stephen Siklos**.

Before discussing these ideas I will make a quick step back to 1973.

Creating the universe, an idea of an idea

Tryon 1973

"If it is true that our Universe has a zero net value for all conserved quantities, then it may simply be a fluctuation of the vacuum.

Vacuum fluctuations on the scale of the universe are probably quite rare. The logic of the situation dictates, however, that observers always find themselves in universes capable of generating life, and such universes are impressively large. We could not have seen this universe if its expansion-contraction time had been less than 10^{10} years required for Homo sapience to evolve."

Subsequent important developments in the context of the Starobinsky model: Zeldovich 1980, Grischuck and Zeldovich 1980.

Problems:

1. One cannot create our universe from nothing if the number of baryons is conserved.

Solved by Sakharov in 1967; his idea was accepted only 10 years later

2. Anthropic considerations do not require the universe to be uniform on scale much greater than the size of the solar system. In general, creation of a quantum fluctuation with mass ~ 10^{80} tons may seem ridiculous.

Solved by inflation

3. No real theoretical description of creation of the universe was given.

Solved by Alex Vilenkin in 1982

Remaining problems:

Probability:

1. Vilenkin 1982, Hartle and Hawking 1983:
   (closed universe)

$$P \sim e^{+\frac{24\pi^2}{V(\phi)}}$$

2. A.L. 1984, Vilenkin 1984:
   (closed universe)

$$P \sim e^{-\frac{24\pi^2}{V(\phi)}}$$

3. Starobinsky and Zeldovich 1984, Coule and Martin 1999, A.L. 2004:

No exponential suppression for creation of compact topologically nontrivial open or flat universes. Spheres are expensive, toruses are free!

Which of these results is most relevant and what is the proper interpretation of creation from nothing?

Applying it to the cosmological constant:

Hawking 1984:

Suppose the cosmological constant is determined by the (time-independent) contribution F^2 of the 4-index antisymmetric tensor field, and the cosmological constant is the function of F^2. Use the previous result, and find that the cosmological constant must exactly vanish:

$$P \sim e^{\frac{24\pi^2}{\Lambda(F)}}$$

(Duff 1989: If one quantizes F-field properly, zero cosmological constant is the least probable configuration.)

Revival of this idea, baby-universe theory: Coleman, Giddings, Strominger 1988

The prediction of exactly vanishing Λ was even stronger

$$P \sim e^{e^{\frac{24\pi^2}{\Lambda}}}$$

What if we use the tunneling wave function?

Consider V(ϕ,F) = V(ϕ) + V(F), and assume that the probability of quantum creation of the universe is given by the tunneling wave function,

$$P \sim e^{-\frac{24\pi^2}{V(\phi,F)}}$$

or assume that P is not exponentially suppressed at all.

In this case one can show that the probability distribution to live in the universe with a given cosmological constant is flat near $\Lambda = 0.$ This leads to the anthropic expectation

$$|\Lambda| \sim 10^{-120}$$

A.L. 1984

This is still a valid argument, one can use it now if one does not reward the probability by the exponential growth of volume.

Anthropic bound ~10^{-120} was expected by many people at that time, but it was really derived only 3 years later, in 1987, by Weinberg.

What if we have KK compactification?

If the dimensionality of the compactified space is sufficiently large, it can be compactified in an enormously large number of ways. Each of these ways corresponds to a different vacuum state. We can only live in a vacuum with $|\Lambda| < 10^{-120}$. For the success of this scenario one must have more than 10^{120} vacua.

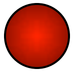
Sakharov 1984

This idea in the context of string theory was proposed by Bousso and Polchinski in 2000.

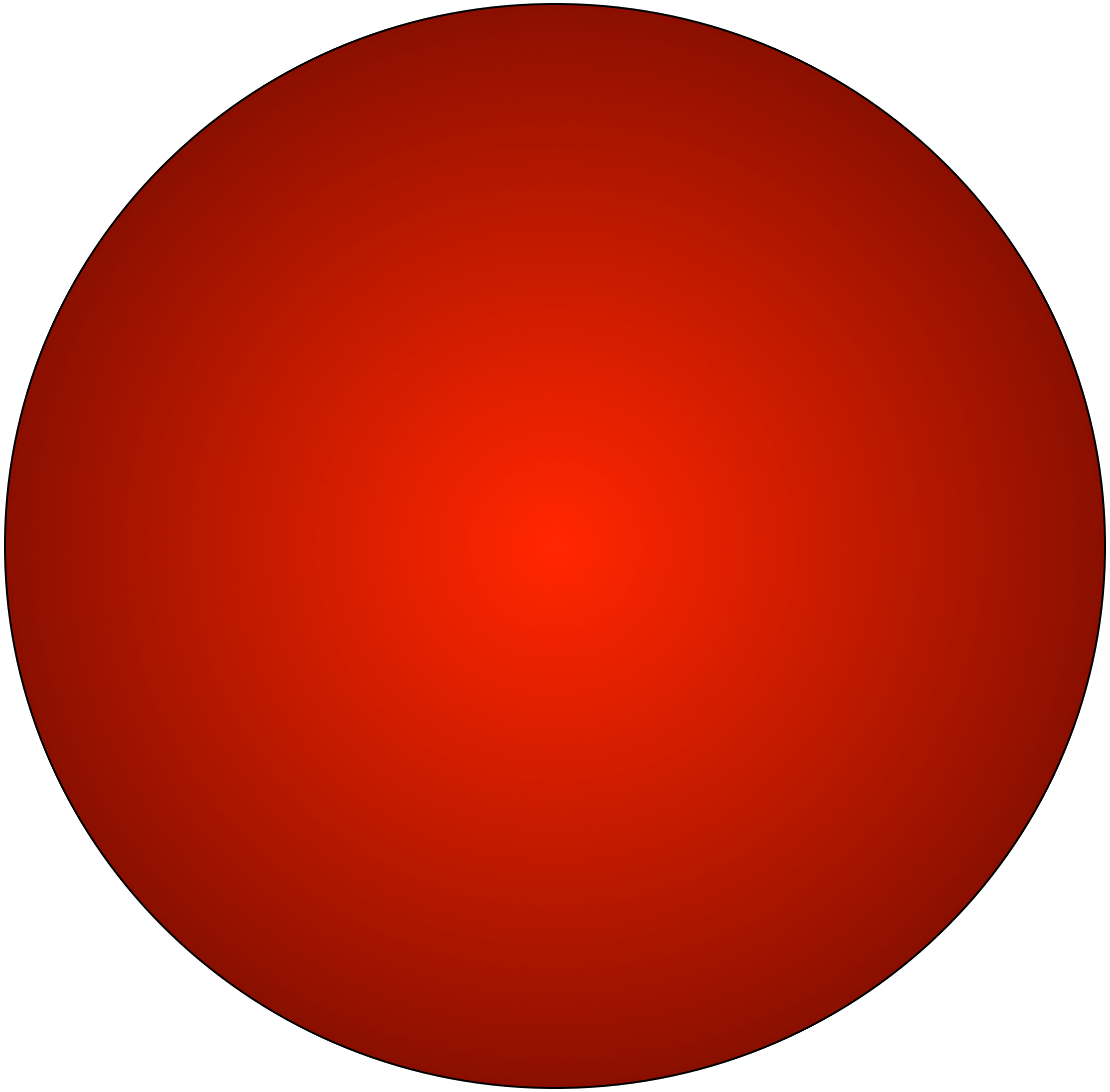
The approach based on quantum cosmology is most general and powerful, but it may take us much more time to learn how to use it properly. After 30 years of debates, various people still have different opinions about the probability of quantum creation of the universe, and about interpretation of this effect.

Recent developments in the theory of the multiverse and string theory landscape mostly follow another approach, which is somewhat easier to understand.

Inflationary universe



Inflationary universe



Here comes the multiverse

Pessimist:

If each part of the multiverse is so large, we will never see its other parts, so it is impossible to **prove** that we live in the multiverse.

Optimist:

If each part of the multiverse is so large, we will never see its other parts, so it is impossible to **disprove** that we live in the multiverse.

This scenario is **more general** (otherwise one would need to explain why all colors but one are forbidden). Therefore the theory of the **multi**verse, rather than the theory of the **uni**verse, is the basic theory.

Moreover, even if one begins with a single-colored universe, quantum fluctuations make it multi-colored.

This picture of the universe, divided into many exponentially large parts with different laws of low-energy physics operated in each of them, was first proposed in 1982 at the famous Nuffield Symposium at Cambridge.

“In the scenario suggested above the universe contains an infinite number of mini-universes (bubbles) of different size, and in each of these universes the masses of particles, coupling constants etc. may be different due to the possibility of different symmetry breaking patterns inside different bubbles. This may give us a possible basis for some kind of Weak Anthropic Principle: There is an infinite number of causally unconnected mini-universes inside our universe, and life exists only in sufficiently suitable ones.”

A.L. Cambridge University preprint,
Nuffield Symposium, July 1982

“As was claimed by Guth, the inflationary universe is the only example of a free lunch. Now we can add that inflationary universe is the only lunch at which ALL possible dishes are available.”

A.L. in Proceedings of the Nuffield Symposium

Subsequent developments included the detailed theory of eternal inflation in the new inflation scenario (Vilenkin 1983) and the theory of eternal chaotic inflation (A.L. 1986). However, for nearly two decades this theory was followed only by few experts in inflationary cosmology. The situation changed relatively recently because of the string theory developments.

Soon after invention of string theory it was realized that the number of different vacua in string theory can be very large, perhaps 10^{1500} (Lerche, Lust, Schellekens 1987). For many string theorists, this was a disappointment. But this multiplicity is exactly what we want in the theory of the multiverse:

“Enormously large number of possible types of compactification, which exist e.g. in the theories of superstrings, should be considered **not as a difficulty but as a virtue** of these theories, since it increases the probability of the existence of mini-universes in which life of our type may appear."

A.L. 1986

The multiplicity of string theory vacua in combination with eternal inflation attracted special attention when Bousso and Polchinski (2000) suggested to use it to solve the cosmological constant problem.

However, despite various estimates of an incredibly large number of string theory vacua, not a single example of a stable dS or Minkowski string theory vacuum was known at that time.

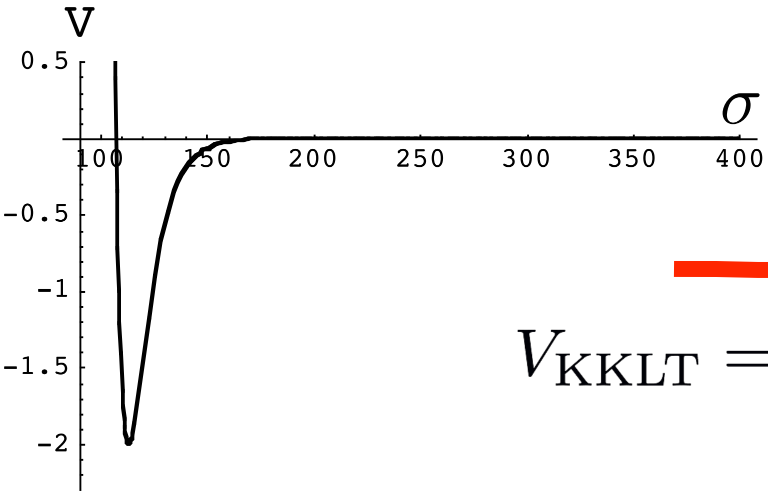
The situation changed in 2003 with the development of the KKLT mechanism of moduli stabilization.

Kachru, Kallosh, A.L., Trivedi 2003

KKLT mechanism of moduli stabilization

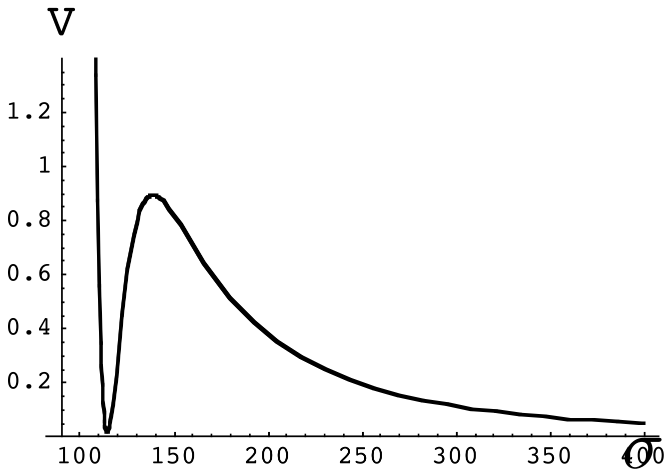
$$W = W_0 + Ae^{-a\rho} \qquad \mathcal{K} = -3\ln[(\rho + \bar{\rho})]$$

$$\rho = \sigma + i\alpha$$



Stabilization in a supersymmetric AdS minimum

$$V_{\text{KKLT}} = V_{\text{AdS}} + \frac{D}{\sigma^2}$$



Uplifting to dS breaks SUSY

$$m_{3/2}^2 = |V_{\text{AdS}}/3|$$

Once we learned how to stabilize vacua in string theory, we also learned (Douglas 2003) that there may be 10^{500} such vacua. This is often called “string theory landscape” (Susskind 2003)

Note that inflationary multiverse is an automatic consequence of modern string theory with stable moduli. One cannot avoid it by developing alternatives to inflation in the context of string theory.

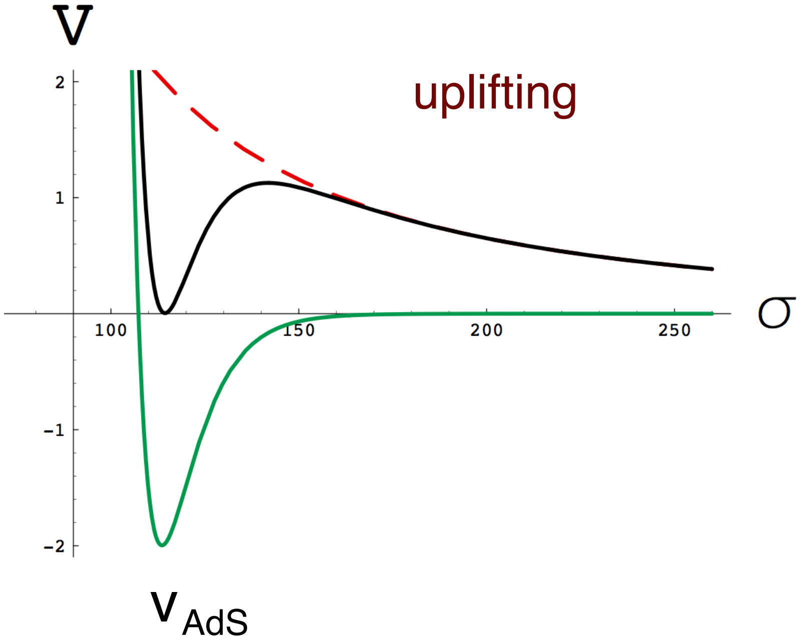
There are many inflationary models in string theory, including an interesting realization of the chaotic inflation scenario Silverstein, Westphal and McAllister, 0803.3085, 0808.0706.

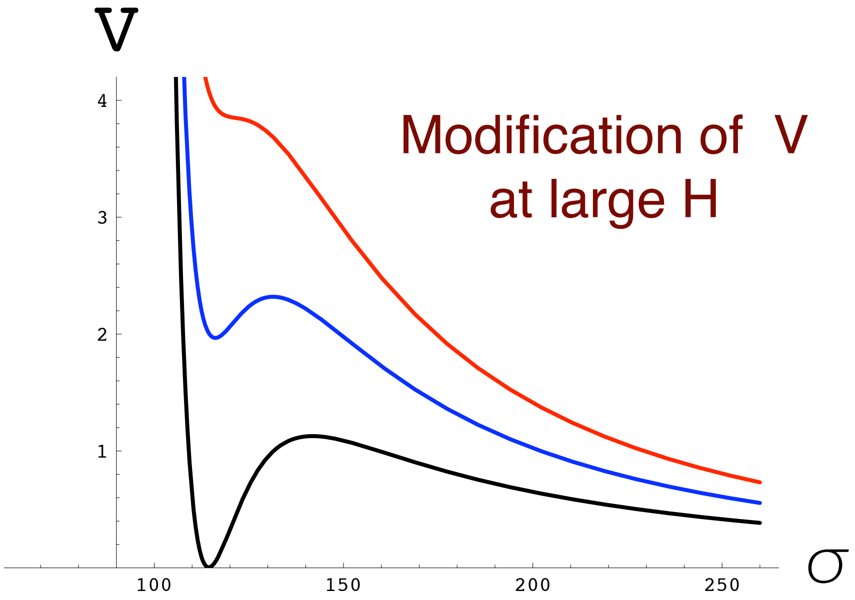
Here we will concentrate on some remaining problems and their possible solutions.

Vacuum destabilization during inflation

Kallosh, A.L. 2004

The height of the KKLT barrier is smaller than $|V_{AdS}| = 3m^2_{3/2}$. The inflationary potential V_{infl} cannot be much higher than the height of the barrier. Inflationary Hubble constant is $H^2 = V_{infl}/3 < |V_{AdS}/3| \sim m^2_{3/2}$.





$$H < m_{3/2}$$

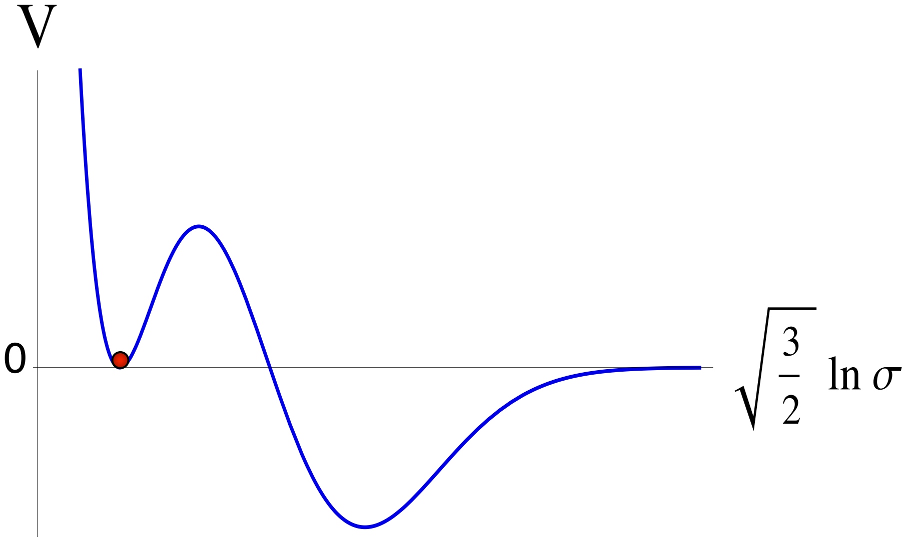
Strong moduli stabilization: KL model

Kallosh, A.L. 2004

$$\mathcal{K} = -3\ln[(\rho + \bar{\rho})]$$

$$W = W_0 + Ae^{-a\rho} - Be^{-b\rho}$$

$$W_0 = -A\left(\frac{a\,A}{b\,B}\right)^{\frac{a}{b-a}} + B\left(\frac{a\,A}{b\,B}\right)^{\frac{b}{b-a}} \quad +\Delta W$$



It has a supersymmetric Minkowski vacuum for $\Delta W = 0$, with a high barrier.

ΔW makes it a supersymmetric AdS.

Uplifting breaks SUSY

$$m_{3/2} \sim |\Delta W|$$

Thus one can have a high barrier for any gravitino mass

H can be arbitrarily large !!

Problems with inflation in supergravity

Main problem:

$$V(\phi) = e^{K}\left(K^{-1}_{\Phi\bar{\Phi}}\,|D_{\Phi}W|^2 - 3|W|^2\right)$$

Canonical Kahler potential is $K = \Phi\bar{\Phi}$

Therefore the potential blows up at large |φ|, and slow-roll inflation is impossible:

$$V \sim e^{|\Phi|^2}$$

Too steep, no inflation…

Chaotic inflation in supergravity

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:

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

Quantum corrections do not change this result

More general models

Kallosh, AL 1008.3375, Kallosh, AL, Rube,1011.5945

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

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

In our new class of supergravity models we can obtain an **arbitrary** potential for the inflaton field

Stability conditions do not depend on the potential during slow roll inflation, they depend only on the curvature of the Kahler manifold

Therefore we can obtain any desirable value of the parameters n_s and r.

Bringing it all together: Chaotic inflation + KL stabilization

Kallosh, A.L., Olive, Rube, 1106.6025

$$K = K_{\rm inf}((\Phi - \bar{\Phi})^2, S\bar{S}) - 3\log(\rho + \bar{\rho})$$

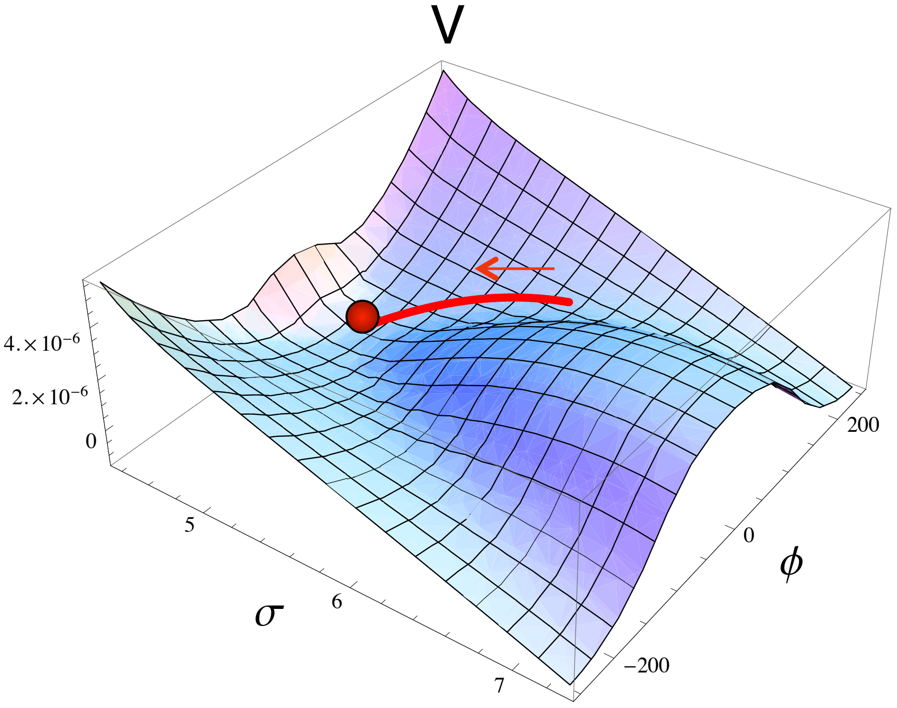
$$W = Sf(\Phi) + W_0 + Ae^{-a\rho} - Be^{-b\rho} + \Delta W$$

Even if one does not ensure stabilization of the S field, inflation is possible, especially if its energy scale is much smaller than the height of the KL barrier

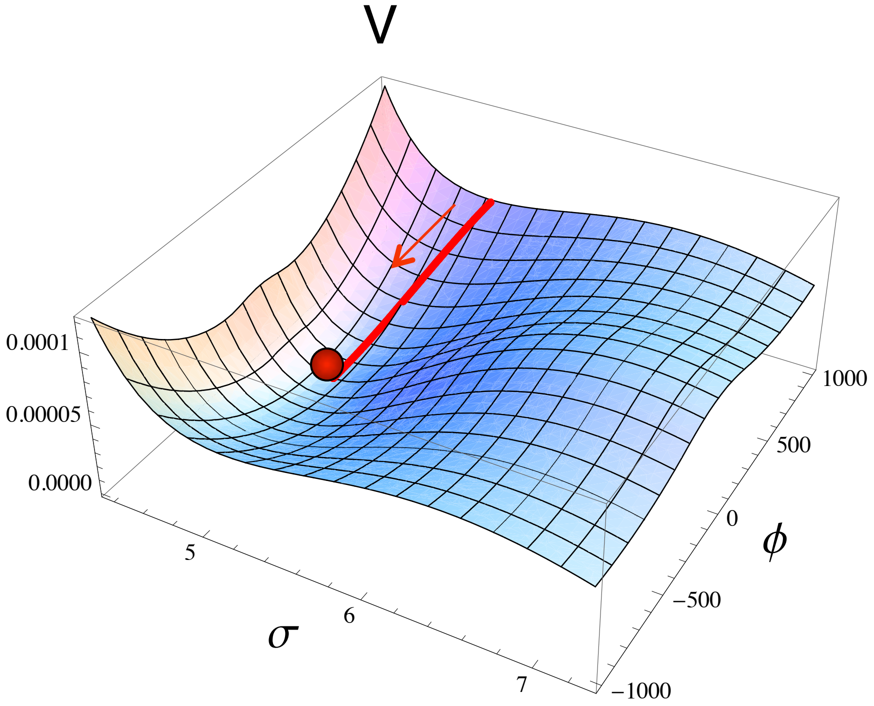
Davis, Postma 2008

However, if one firmly stabilizes S field near S = 0, e.g. by terms S^4 in the Kahler potential, inflation inflation occurs in a much greater range of the values of the inflaton field. The description of inflation decouples from the KL sector, which becomes important only for the low-scale SUSY breaking.

Bringing it all together: Chaotic inflation + KL stabilization



no S stabilization
relatively short inflation
Davis, Postma 2008



S and σ are stabilized
long inflation
Kallosh, A.L., Olive, Rube 2011

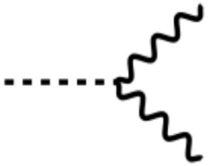
Conclusion on new models

A simple class of chaotic inflation models in supergravity is developed. The inflaton potential can have arbitrary shape determined by the choice of the superpotential $W = S\, f(\Phi)$. This allows to describe observations with any values of n_s and r.

Depending on the choice of the Kahler potential, these models may describe a single-field inflation with gaussian perturbations of metric, or a curvaton scenario with large non-gaussianity.

One can unify this scenario with a special class of KKLT models with strongly stabilized volume modulus. This solves the problem of vacuum destabilization during string theory inflation, as well as the cosmological moduli problem.

Reheating occurs due to scalar-vector coupling inspired by string theory/extended supergravities. Natural suppression of reheating temperature in these models solves the gravitino problem.



Strong moduli stabilization in this class of models leads to a specific mass pattern in phenomenological models, which can be tested at LHC.

The most incomprehensible thing about the universe is that it is comprehensible

Albert Einstein

The unreasonable efficiency of mathematics in science is a gift we neither understand nor deserve

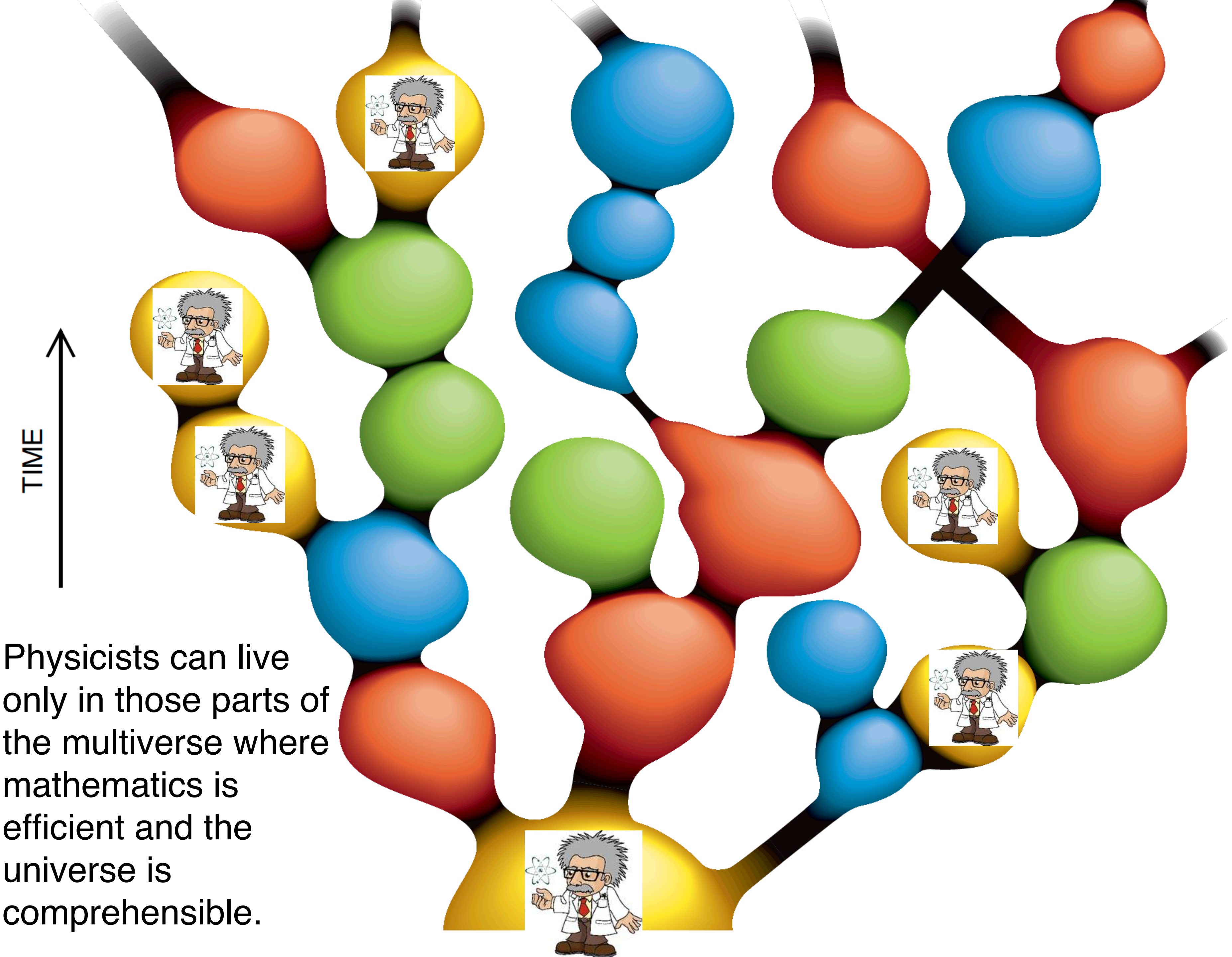
Eugene Wigner

The reason why Einstein was puzzled by the efficiency of physics and Wigner was puzzled by the efficiency of mathematic is very simple:

If the universe is everywhere the same (no choice), then the fact that it obeys so many different laws that we can discover, remember and use can be considered as an “undeserved gift of God” to physicists and mathematicians.

In the inflationary multiverse, this problem disappears. The laws of mathematics and physics are efficient only if they allow us to make reliable predictions. The possibility to make reliable predictions is necessary for our survival. There are some parts of the multiverse where information processing is inefficient; we cannot live there.

We can only live in those parts of the multiverse where the laws of mathematics and physics allow stable information processing and reliable predictions. That is why physics and mathematics are so efficient **in our part of the multiverse**.



Physicists can live only in those parts of the multiverse where mathematics is efficient and the universe is comprehensible.

But we still do not know why do we live in the same part of the multiverse as Stephen Hawking.

I guess some of the most important things in life do appear because of **pure luck**, and this is one of them.

Happy birthday, Stephen!