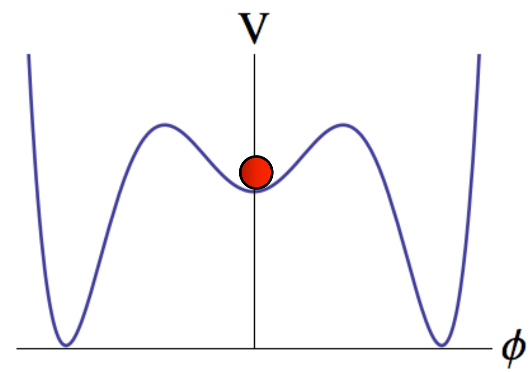
Fundamental Physics and Formation of the Universe

Andrei Linde

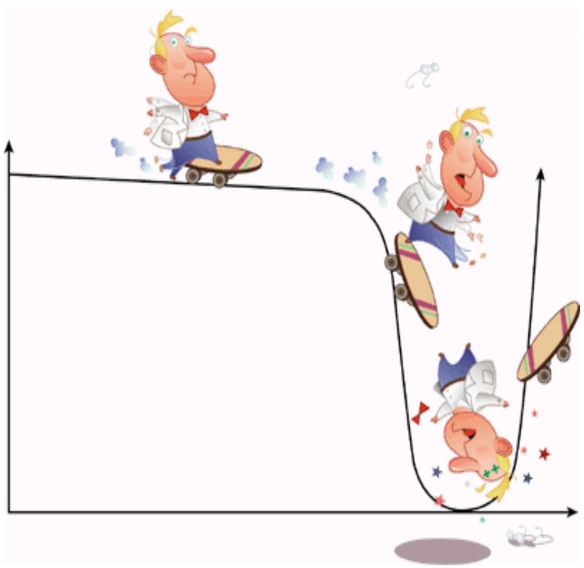
Inflation

Starobinsky, 1980 – modified gravity, R + R^2 a complicated but almost working model

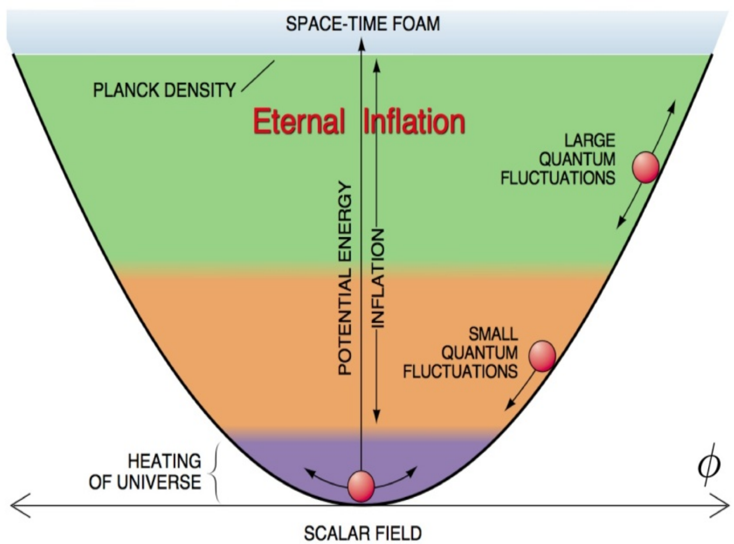
Guth, 1981 - old inflation. Great idea, first outline of the new paradigm, but did not quite work, and did not predict inflationary perturbations



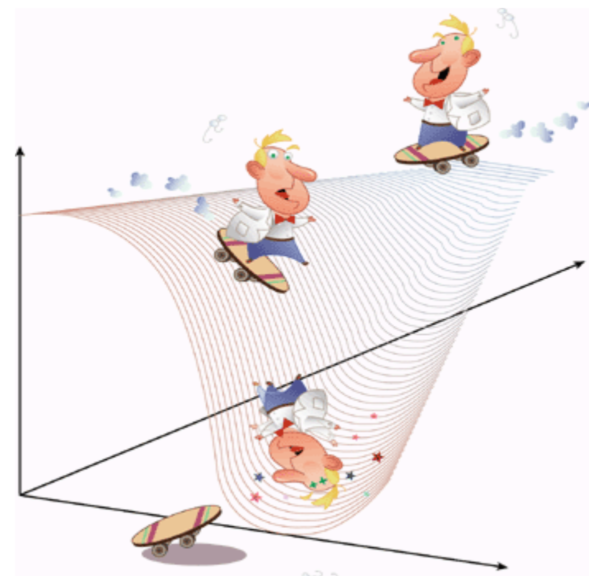
$$V(\phi) = \frac{m^2}{2}\phi^2$$



A.L., 1982 - new inflation (also Albrecht, Steinhardt)



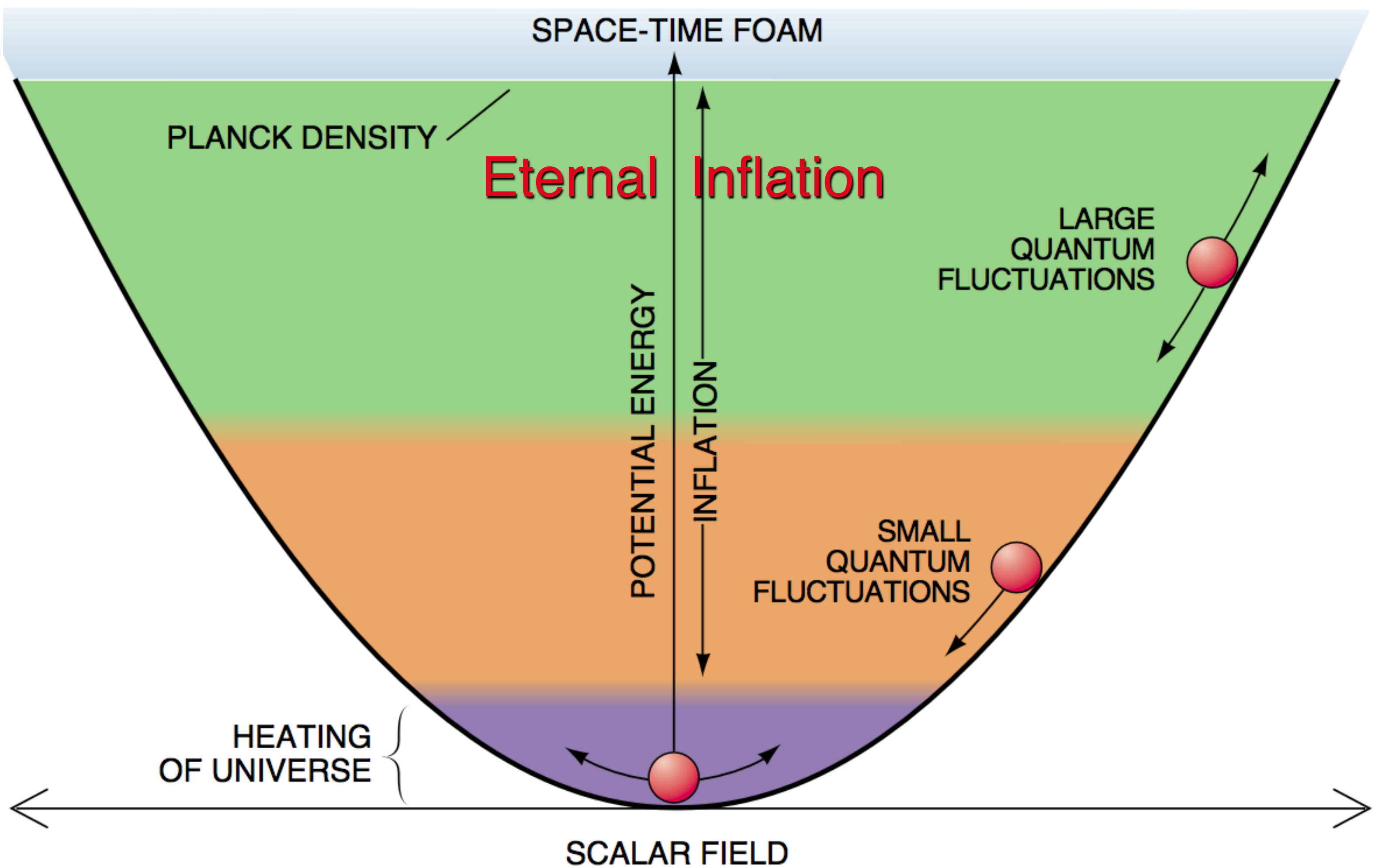
1983 - chaotic inflation



1991 - hybrid inflation

Chaotic Inflation

No need for false vacua, thermal equilibrium, and phase transitions. Just use any sufficiently flat potential.



Equations of motion:

- **Einstein equation:**

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{m^2}{6}\phi^2$$

- **Klein-Gordon equation:**

$$\ddot{\phi} + 3H\dot{\phi} = -m^2\phi$$

Compare with equation for the harmonic oscillator with friction:

$$\ddot{x} + \alpha\dot{x} = -kx$$

Logic of Inflation:

Large φ → large H → large friction

→ field φ moves very slowly, so that its potential energy for a long time remains nearly constant

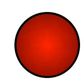
$$H = \frac{\dot{a}}{a} = \frac{m\phi}{\sqrt{6}} \approx \text{const}$$

⇓

$$a \sim e^{Ht}$$

This is the stage of inflation

Inflationary universe



$$l \sim 10^{-33} \text{ cm}$$

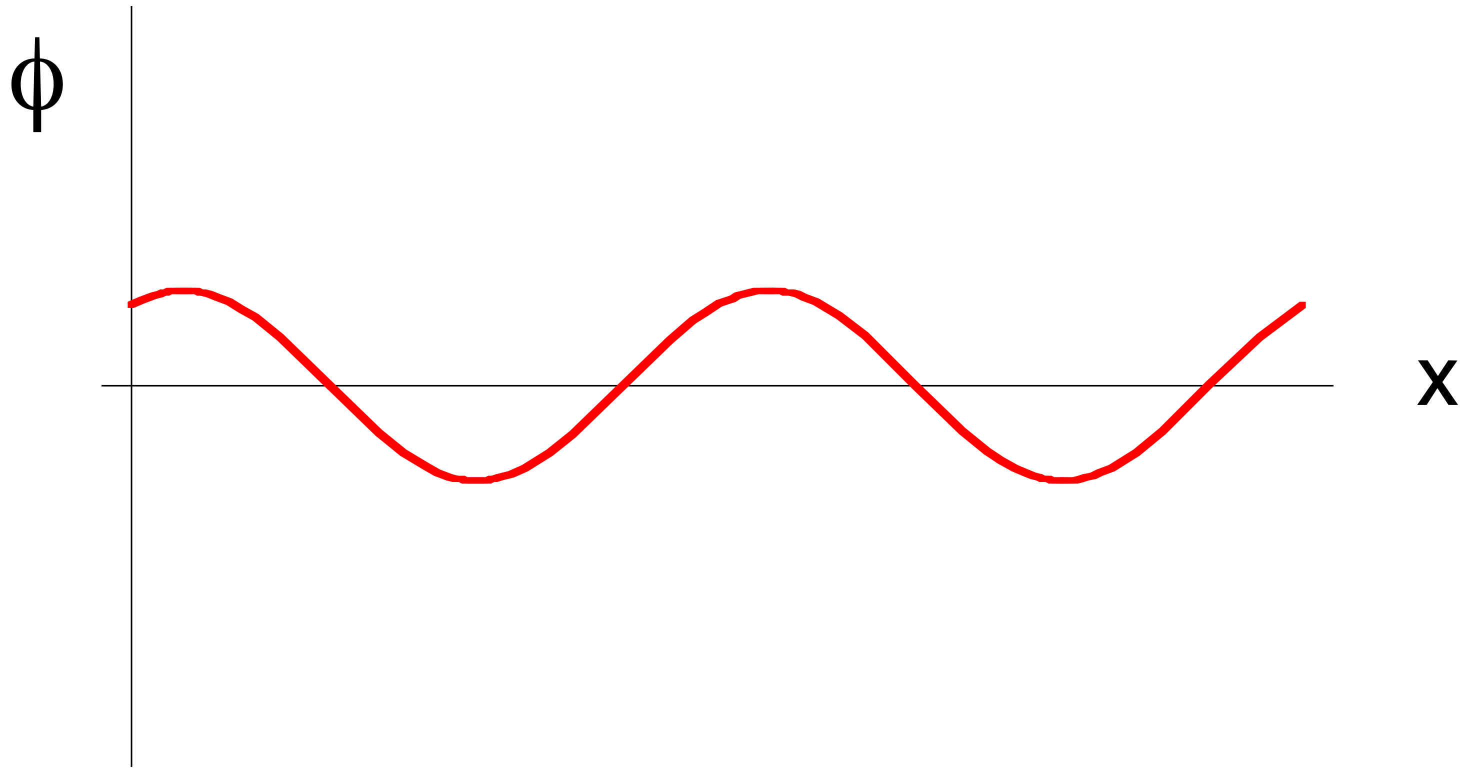
$$m \sim 10^{-5} \text{ g}$$

Inflationary universe

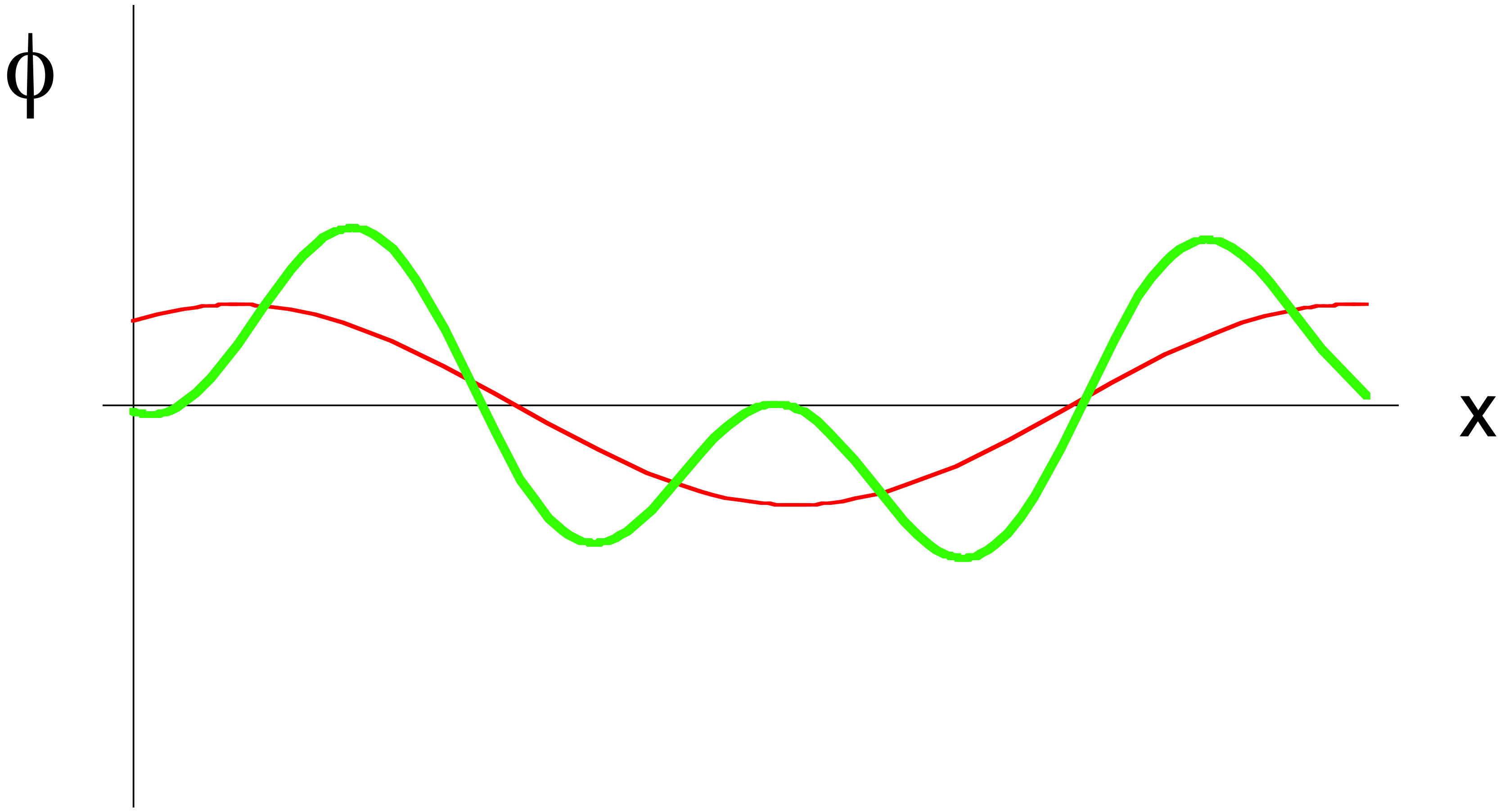
$$10^{10000000000}$$

in ANY units of length

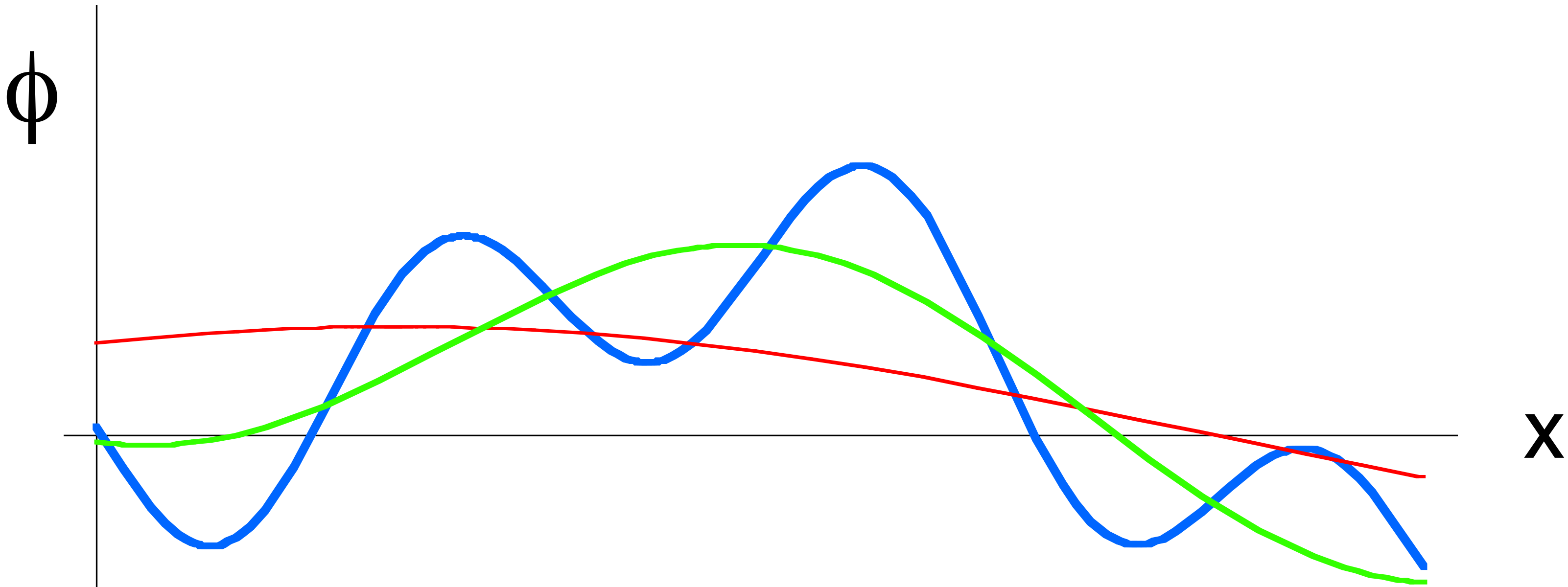
Quantum fluctuations produced during inflation



Small quantum fluctuations of all physical fields exist everywhere. They are similar to waves, which appear and then rapidly oscillate, move and disappear. Inflation stretched them, together with stretching the universe. When the wavelength of the fluctuations becomes sufficiently large, they stop moving and oscillating, and do not disappear. They look like frozen waves.



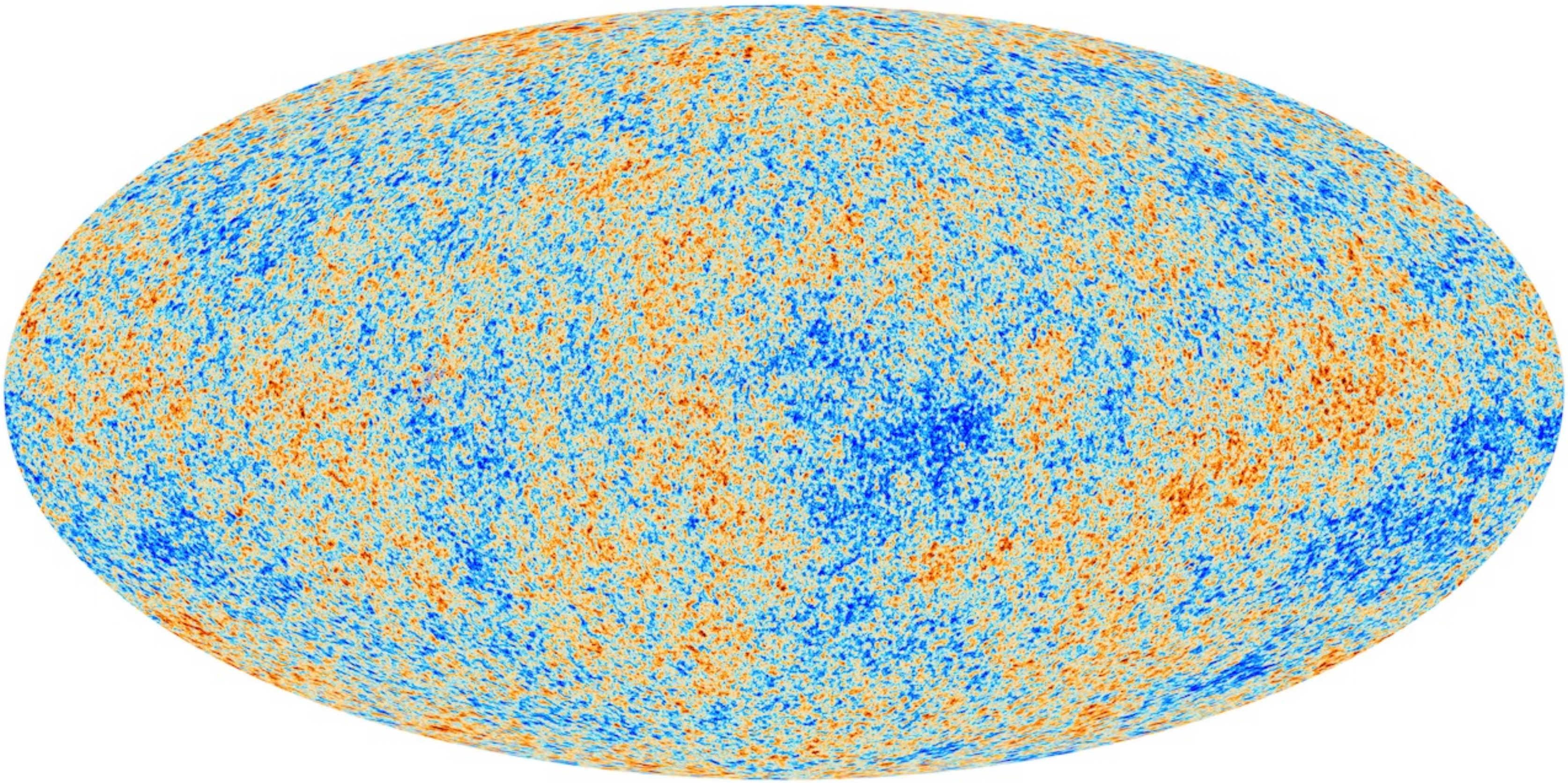
When expansion of the universe continues, new quantum fluctuations become stretched, stop oscillating, and freeze on top of the previously frozen fluctuations.



This process continues, and eventually the universe becomes populated by inhomogeneous scalar field. Its energy takes different values in different parts of the universe. These inhomogeneities are responsible for the formation of galaxies (Chibisov, Mukhanov 1981)

Sometimes these fluctuations are so large that they can increase the value of the scalar field in some parts of the universe. Then inflation in these parts of the universe occurs again and again. In other words, the process of inflation becomes eternal (Vilenkin 1983, A.L. 1986)

CMB observations use sky as the largest ever photographic plate: We see imprints of quantum fluctuations produced perhaps 10^{-30} seconds after the Big Bang (!!!), and then stretched all over the observable part of the universe.



Why Quantum?

J. Wheeler

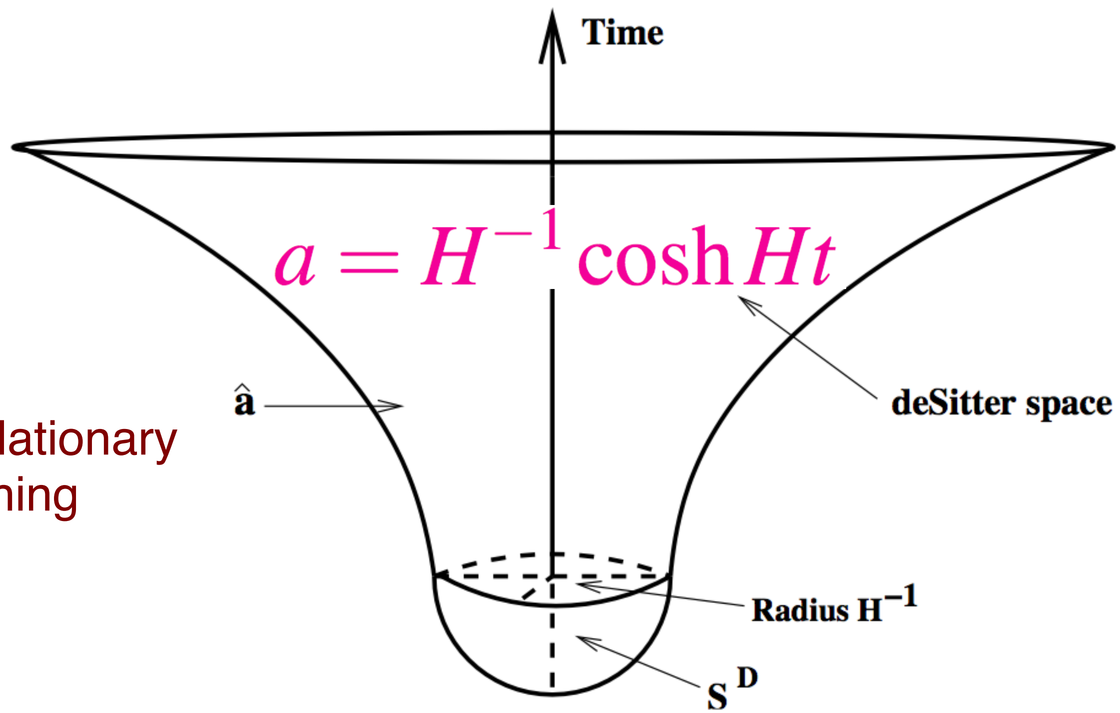
Without inflation, the universe is small. Without quantum, the universe is empty.

According to inflationary theory, all matter in the universe was produced due to quantum creation of particles in the post-inflationary reheating process, and the large scale structure of the universe was produced due to inflationary quantum fluctuations.

Creation of all matter and formation of the large scale structure is **not** a result of "unpacking" of pre-existing information. The world around us could be produced from a tiny speck of space containing no pre-packaged information and no elementary particles altogether.

Once the wave function of the universe is "reduced" (or we learn in which of the many versions of the quantum universe we live), we cannot "play the movie back" and see how the universe exponentially collapses into a single Planck size ball with less than 1 milligram of matter.

Do we even need 1 mg of matter?



Creation of the inflationary universe from nothing
Vilenkin 1982,
A.L. 1984,
Vilenkin 1984

Closed dS space cannot continuously grow from the state with a = 0, it must tunnel. For the Planckian H, as in chaotic inflation, the action is O(1), tunneling is easy. For very small H, as in stringy inflation, creation of the universe is **exponentially suppressed**.

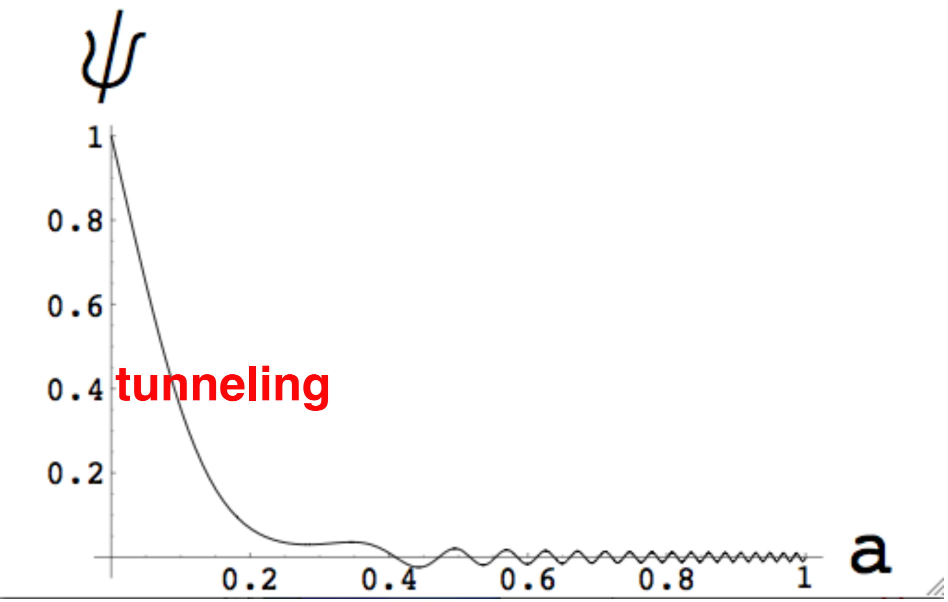
Thus it is difficult to start expansion of a closed universe with a low-scale inflation.

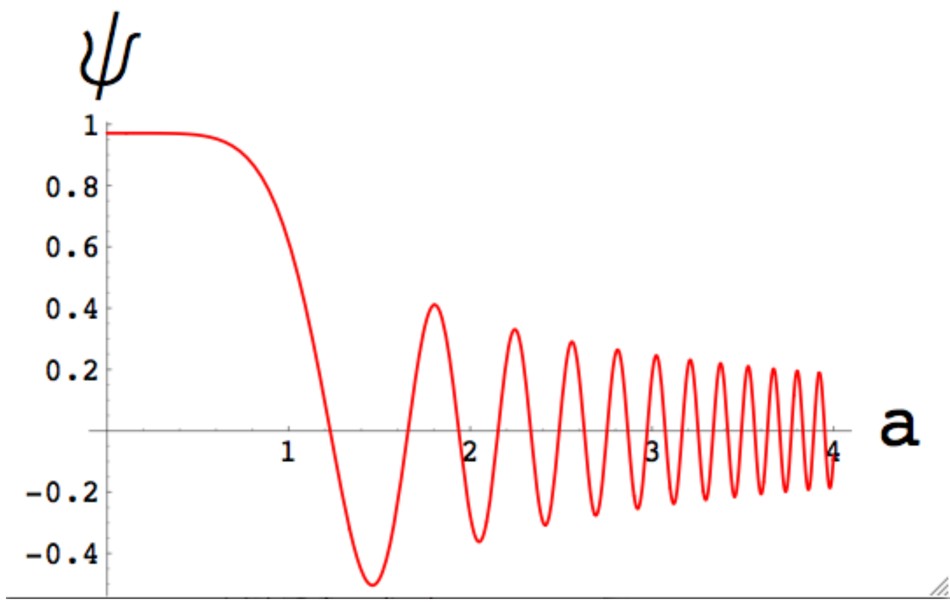
Not a problem!

Take a box (a part of a flat universe) and glue its opposite sides to each other. What we obtain is a **torus**, which is a topologically nontrivial flat universe.

No need to tunnel: A compact open inflationary universe may be arbitrarily small

Closed versus compact flat universe in quantum cosmology





Closed universe

Wave function is exponentially suppressed at large scale factor a

A.L. 1984, Vilenkin 1984

Compact flat universe

Wave function is not exponentially suppressed

Zeldovich, Starobinsky 1984, Coule, Martin 2000, A.L. 2004

WKB approximation becomes valid (wave function becomes oscillating in a semiclassical way) for scale factor

$$a > V^{-1/6}$$

The total energy of the universe at that time was

$$E \sim V a^3 \sim V^{1/2}$$

So for inflation at $V = 10^{-10}$ the total mass of the universe at the moment when its classical description becomes possible was 10^{-5} in Planck units, so it was 10^{-10} g. And there were no curvature singularity to start with.

Thus it is **much easier** to create a topologically nontrivial inflationary universe.

Many inflationary models. Which ones can be implemented in the context of string theory and supergravity?

We will give only a small sample of available models.

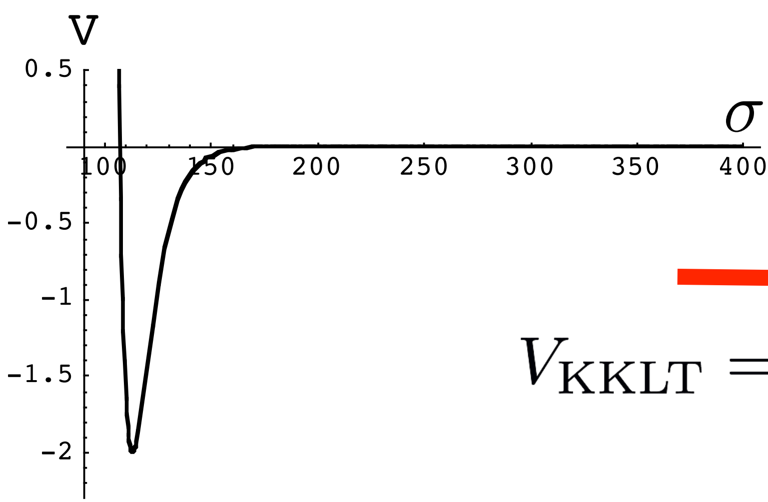
More about it – tomorrow at the parallel session

String Theory

First step – vacuum stabilization. Several different approaches; perhaps the simplest one is the KKLT construction.

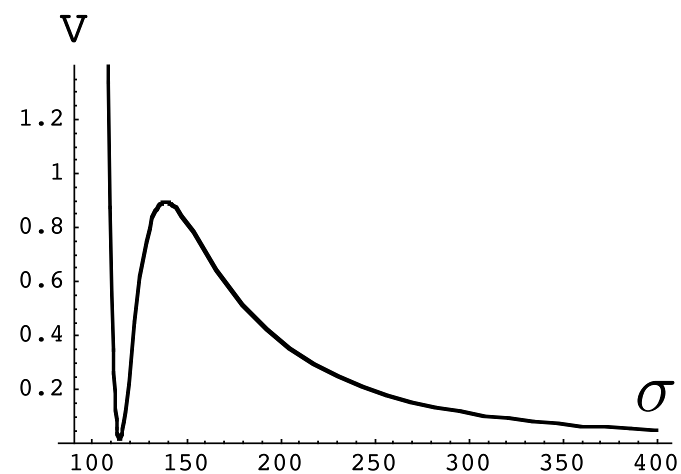
$$W = W_0 + A e^{-a\rho} \qquad \mathcal{K} = -3\ln[(\rho+\bar{\rho})]$$

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



Stabilization in a supersymmetric AdS minimum

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

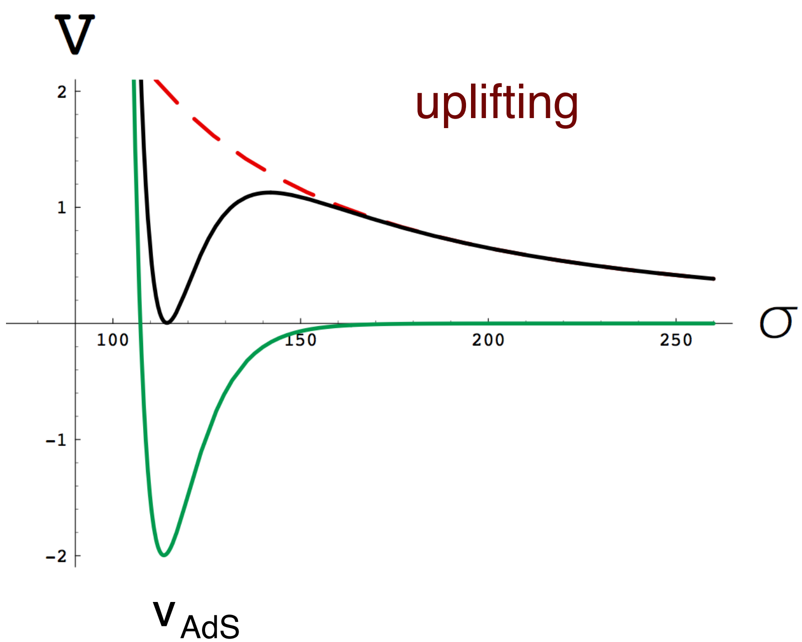


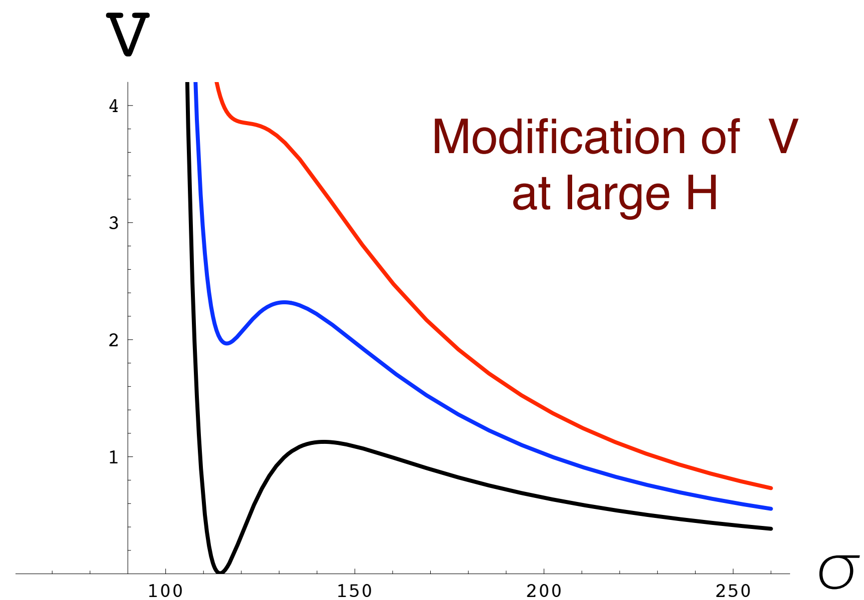
Uplifting to dS breaks SUSY

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 $H^2 = V_{infl}/3 < |V_{AdS}/3| \sim m^2_{3/2}$.





Constraint on the Hubble constant in this class of models:

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

Tensor modes in CMB and gravitino

Kallosh, A.L. 2007

$$H \lesssim m_{3/2}$$

$$m_{3/2} \sim 1 \text{ TeV} \longrightarrow r \sim 10^{-24}$$

unobservable

A discovery or non-discovery of tensor modes would be a crucial test for string theory and SUSY phenomenology

Modern versions of string theory

Discovery of SUSY particles at LHC

Discovery of gravity waves

Any 2 of these 3 items are compatible with each other. Can all 3 of them live in peace?

We will describe the simplest way to address this issue

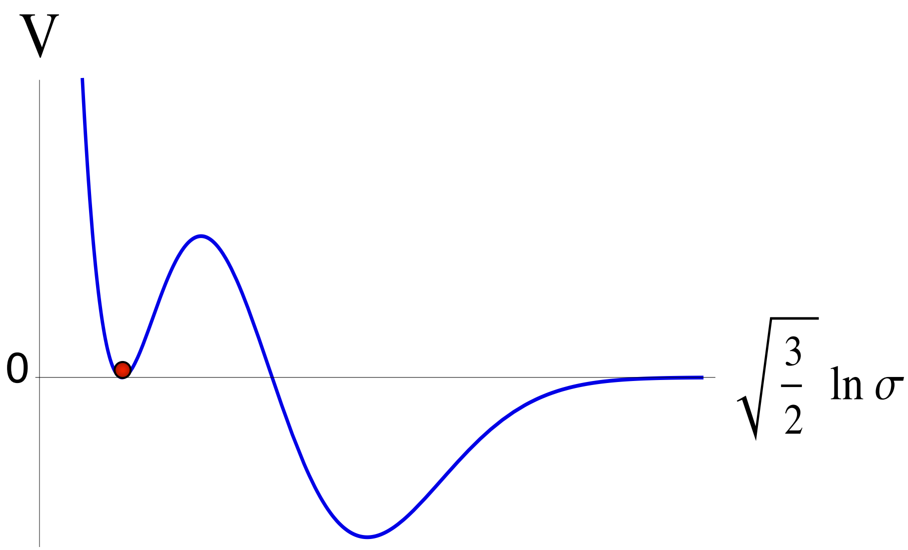
KL model

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

Kallosh, A.L. 2004

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

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



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

Δ makes it a supersymmetric AdS.

Uplifting breaks SUSY

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

Thus one **can** have a high barrier and a tiny gravitino mass

H can be arbitrarily large, r becomes observable

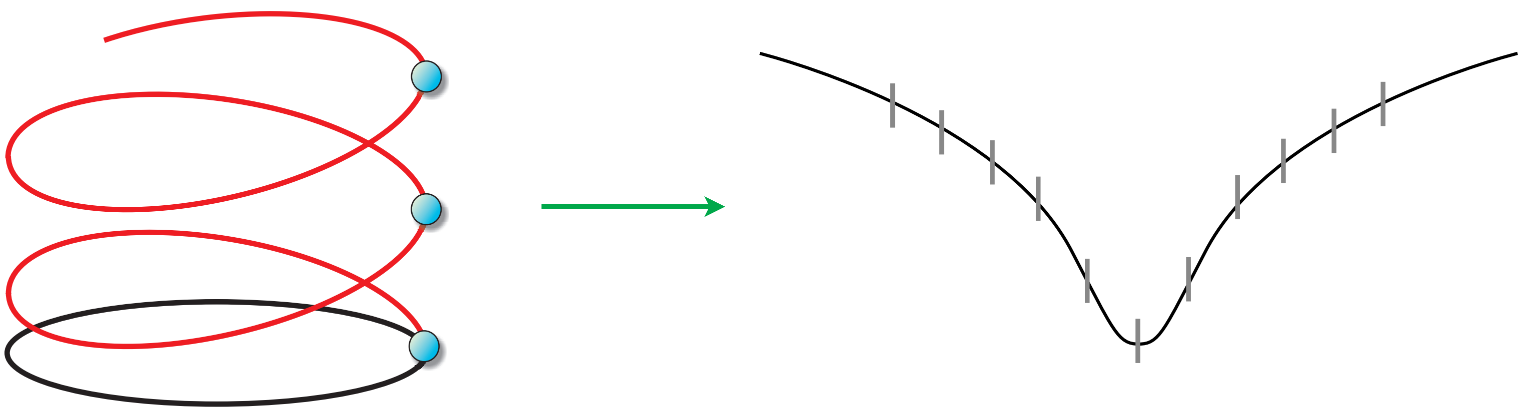
Chaotic Inflation in String Theory

An elegant example: Axion monodromy

Silverstein, Westphal 0803.3085
McAllister, Silverstein, Westphal 0808.0706

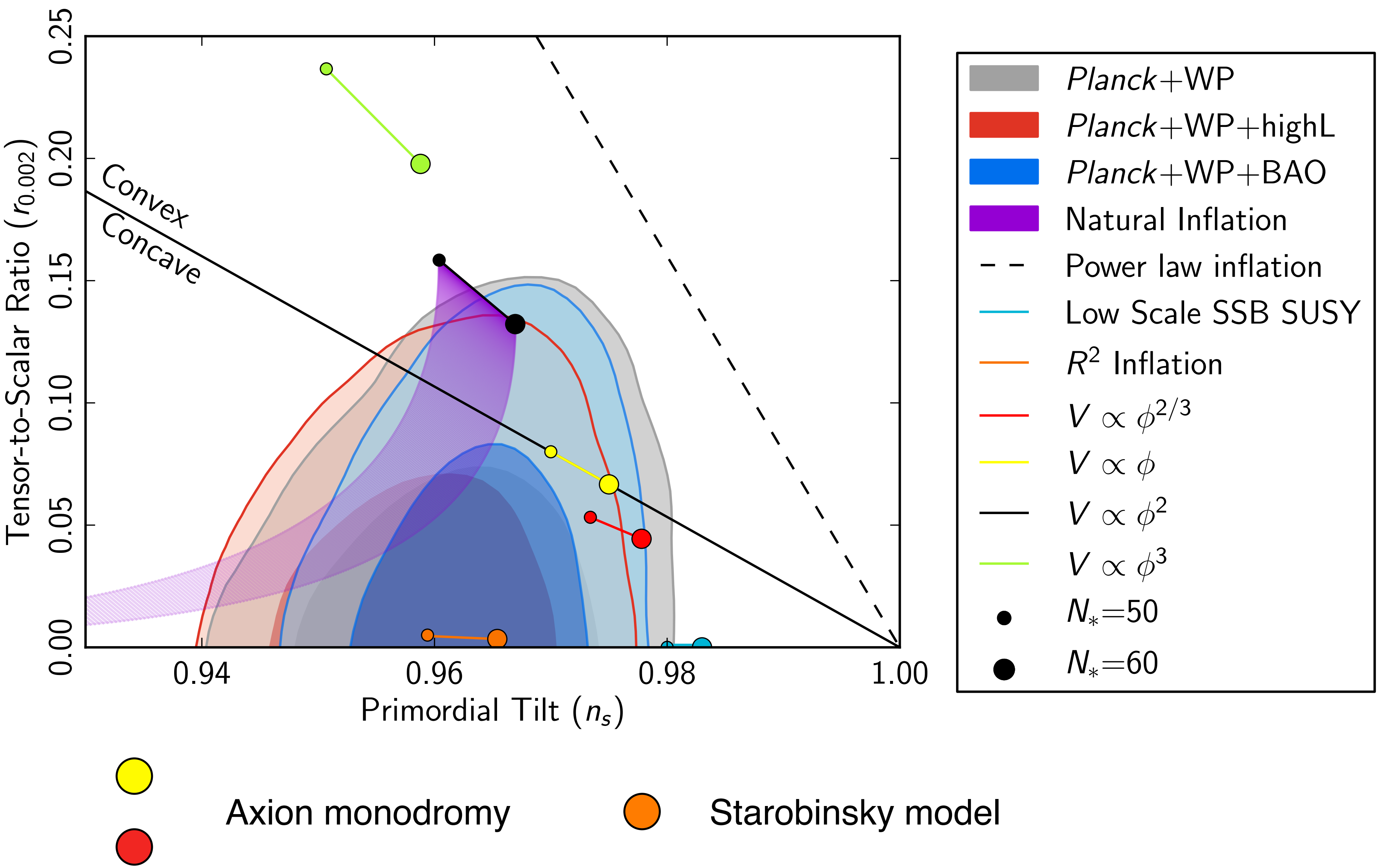
- unwind a periodic field direction into a *monodromy*

  → e.g. by employing a wrapped brane



$$V \sim \phi^{2/3} \quad \text{or} \quad V \sim \phi$$

Requires something like KL mechanism of strong moduli stabilization



Tensor-to-Scalar Ratio ($r_{0.002}$)
0.00
0.05
0.10
0.15
0.20
0.25
Primordial Tilt (n_s)
0.94
0.96
0.98
1.00
Convex
Concave
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
Axion monodromy
Starobinsky model

Natural Inflation in supergravity/string theory

One could expect it to be readily available, but stabilization of the large radius of the axion potential was a problem. A consistent version was constructed only relatively recently (Kallosh 2007).

$R + R^2$ in supergravity

Work in progress, see Ketov et al 2012.

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, A.L. 1008.3375, Kallosh, A.L., 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 at Φ = 0 is

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

FUNCTIONAL FREEDOM in choosing inflationary potential

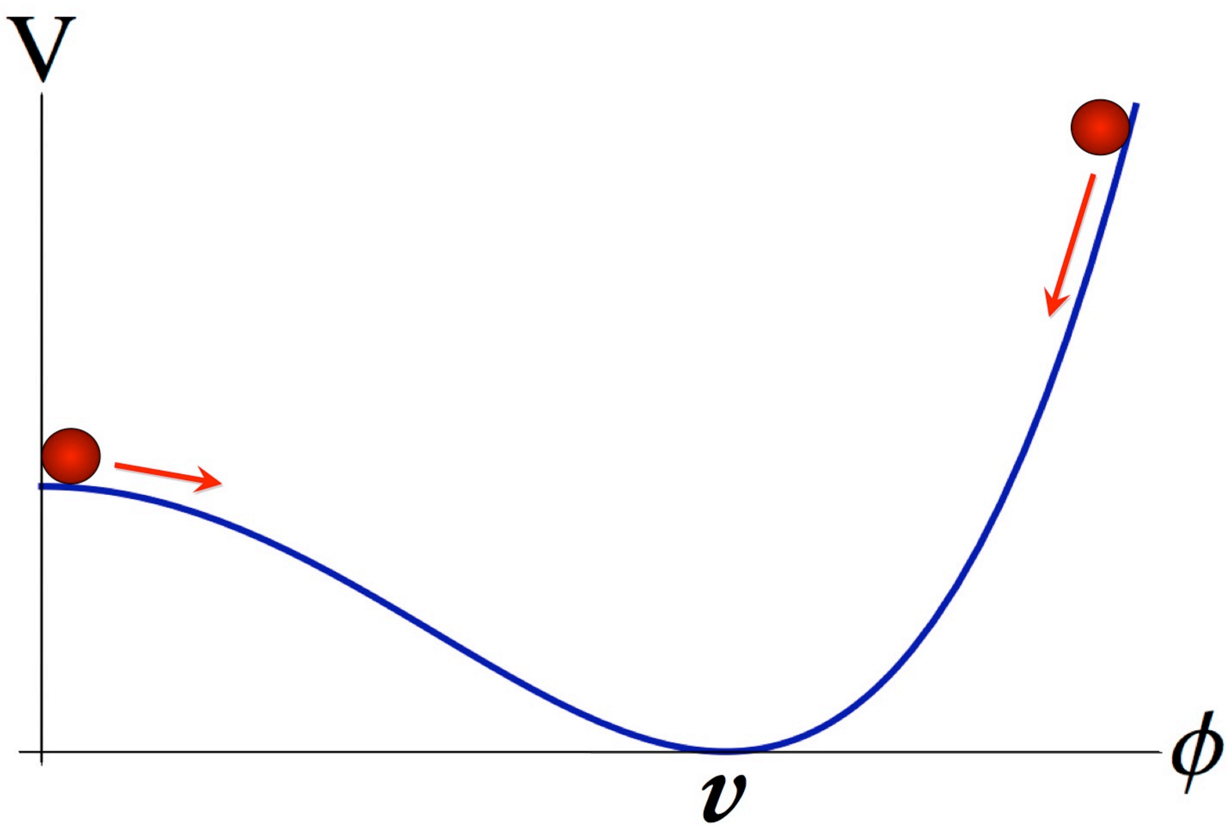
In this new class of supergravity inflation models, one can have **arbitrary potential for the inflaton field**.

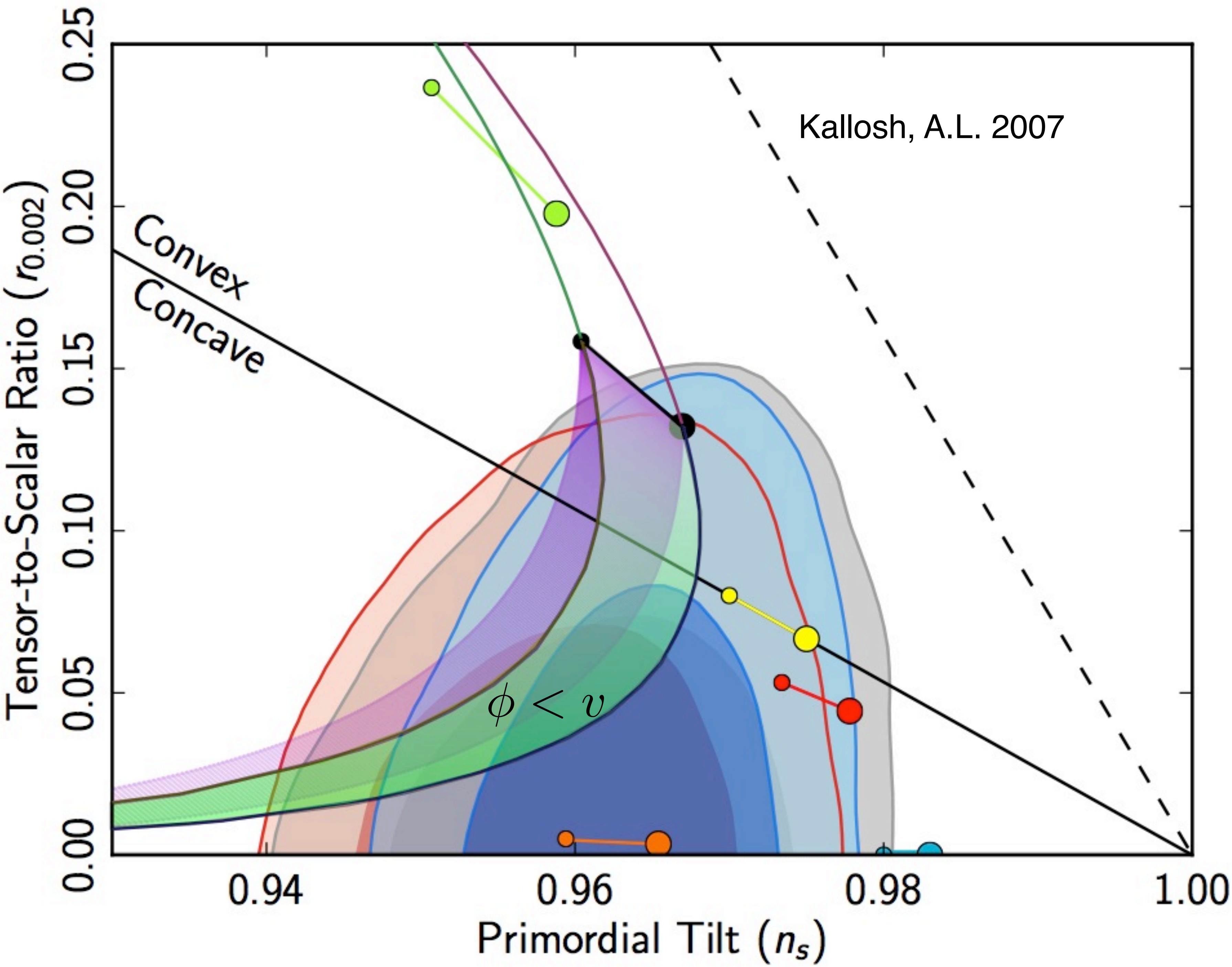
Thus one can have **ANY desirable values of n_s and r.** Moreover, one can generalize this scenario to describe production of non-gaussian perturbations and cosmic strings, to be discussed on Thursday.

Example: $W = -\lambda S(\Phi^2 - v^2/2)$

During inflation $S = 0,\ \mathrm{Im}\,\Phi = 0,\ \mathrm{Re}\,\Phi = \sqrt{2}\,\phi$

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



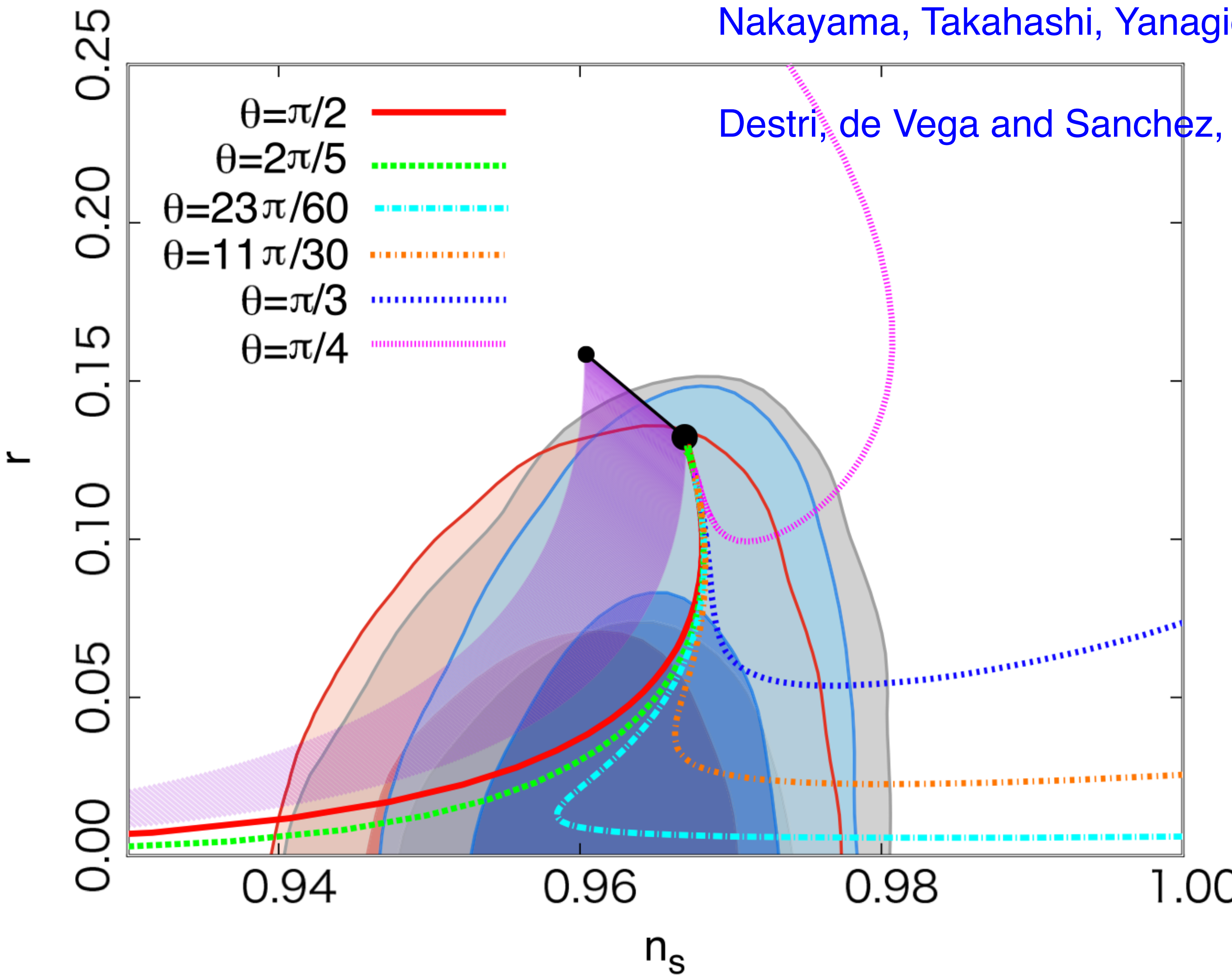


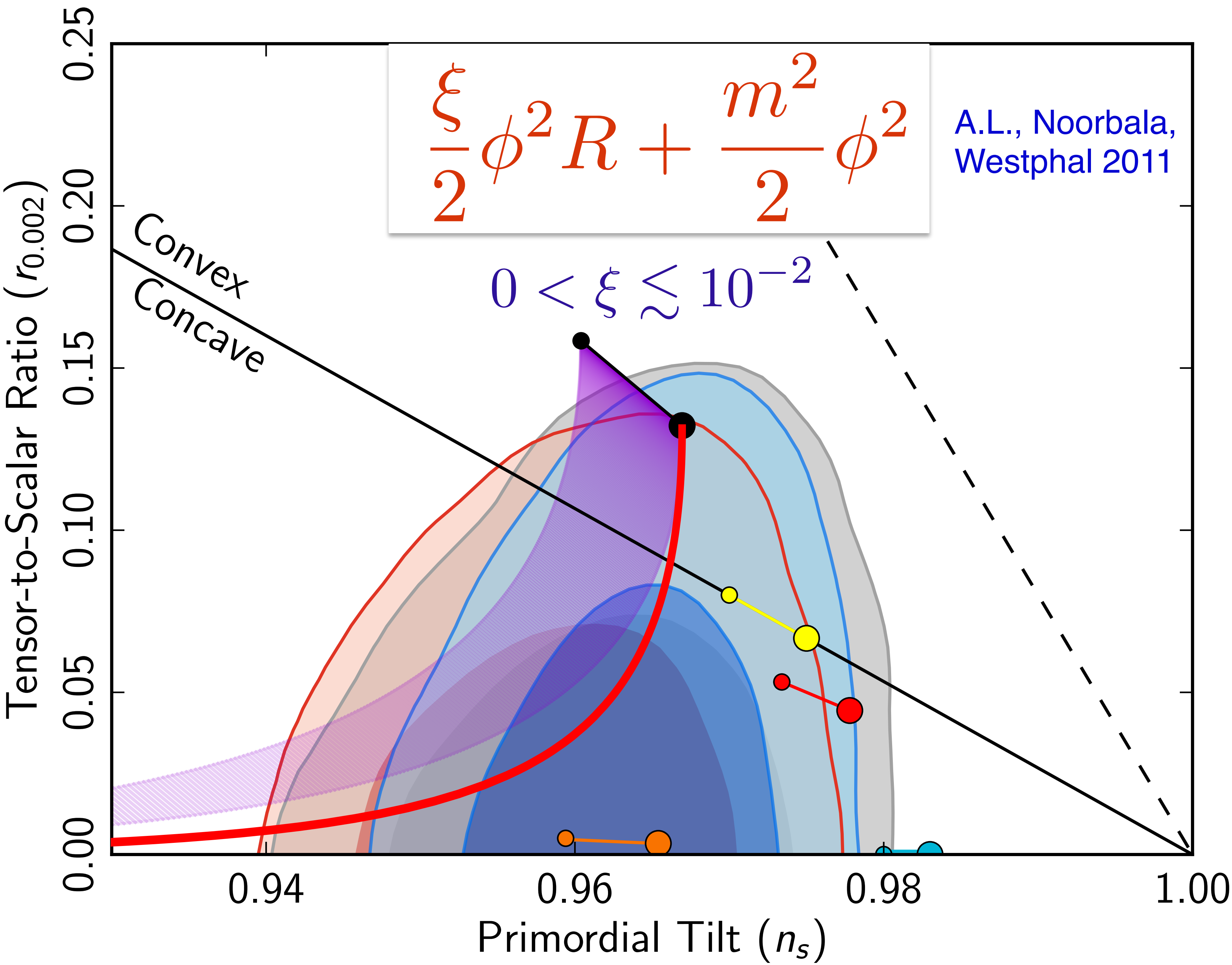
Kallosh, A.L. 2007
Convex
Concave
$\phi < v$
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00

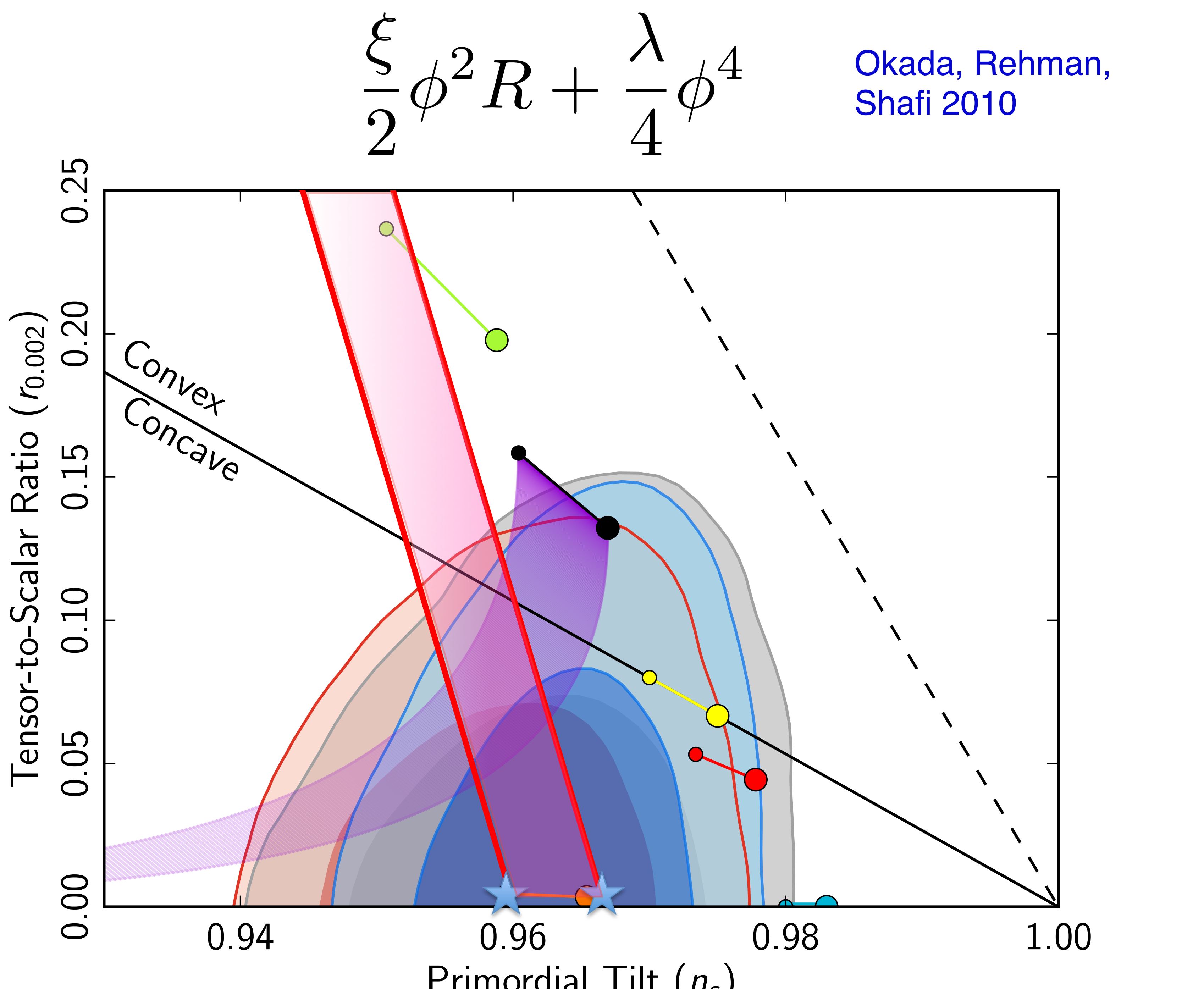
$$V = \frac{\phi^2}{2}\left(m^2 - \sqrt{2}m\lambda\sin\theta\,\phi + \frac{\lambda^2}{2}\phi^2\right)$$

Nakayama, Takahashi, Yanagida 2013

Destri, de Vega and Sanchez, 2007




$\frac{\xi}{2}\phi^2 R + \frac{m^2}{2}\phi^2$
A.L., Noorbala, Westphal 2011
$0 < \xi \lesssim 10^{-2}$
Convex
Concave
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00

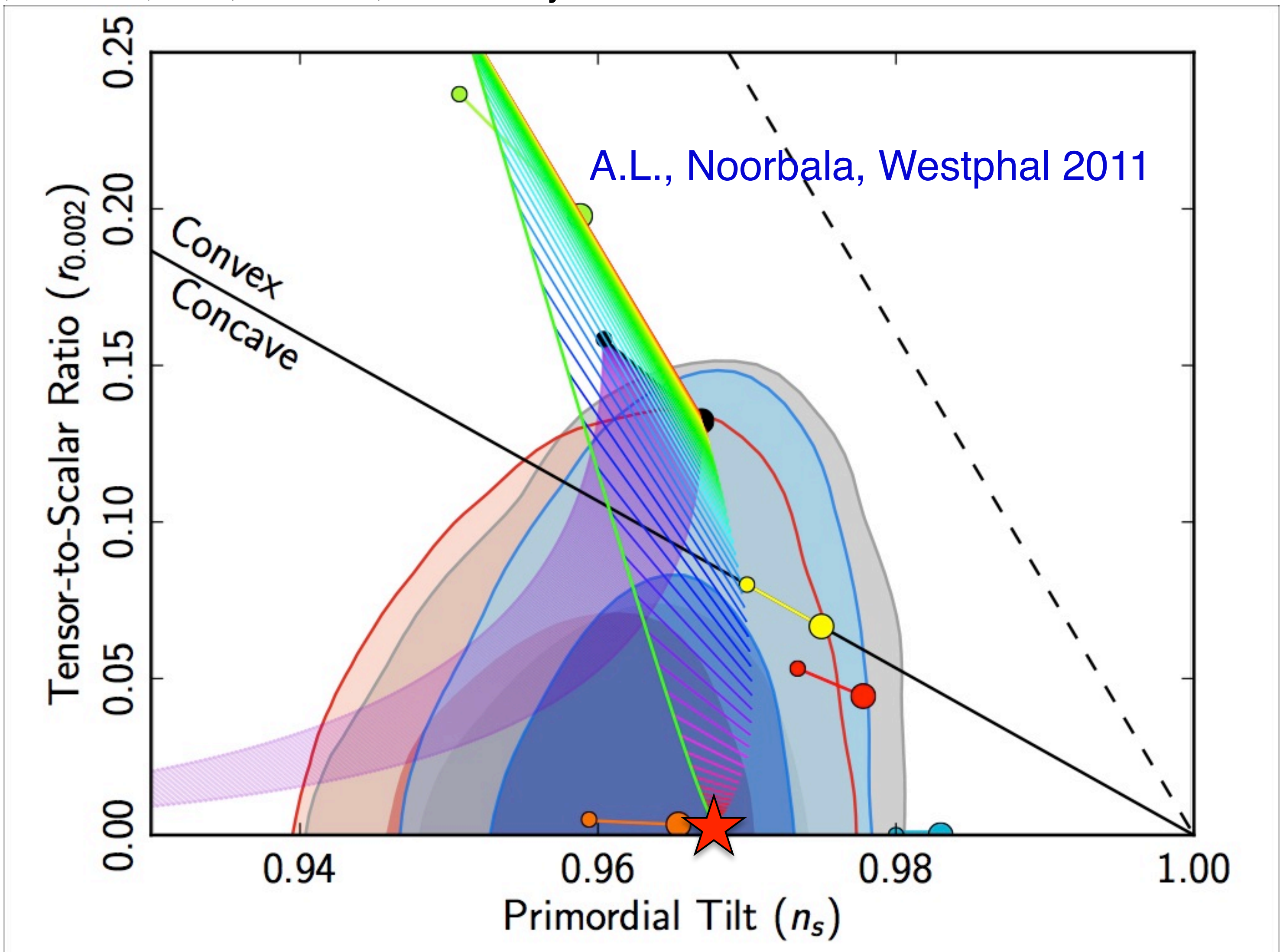


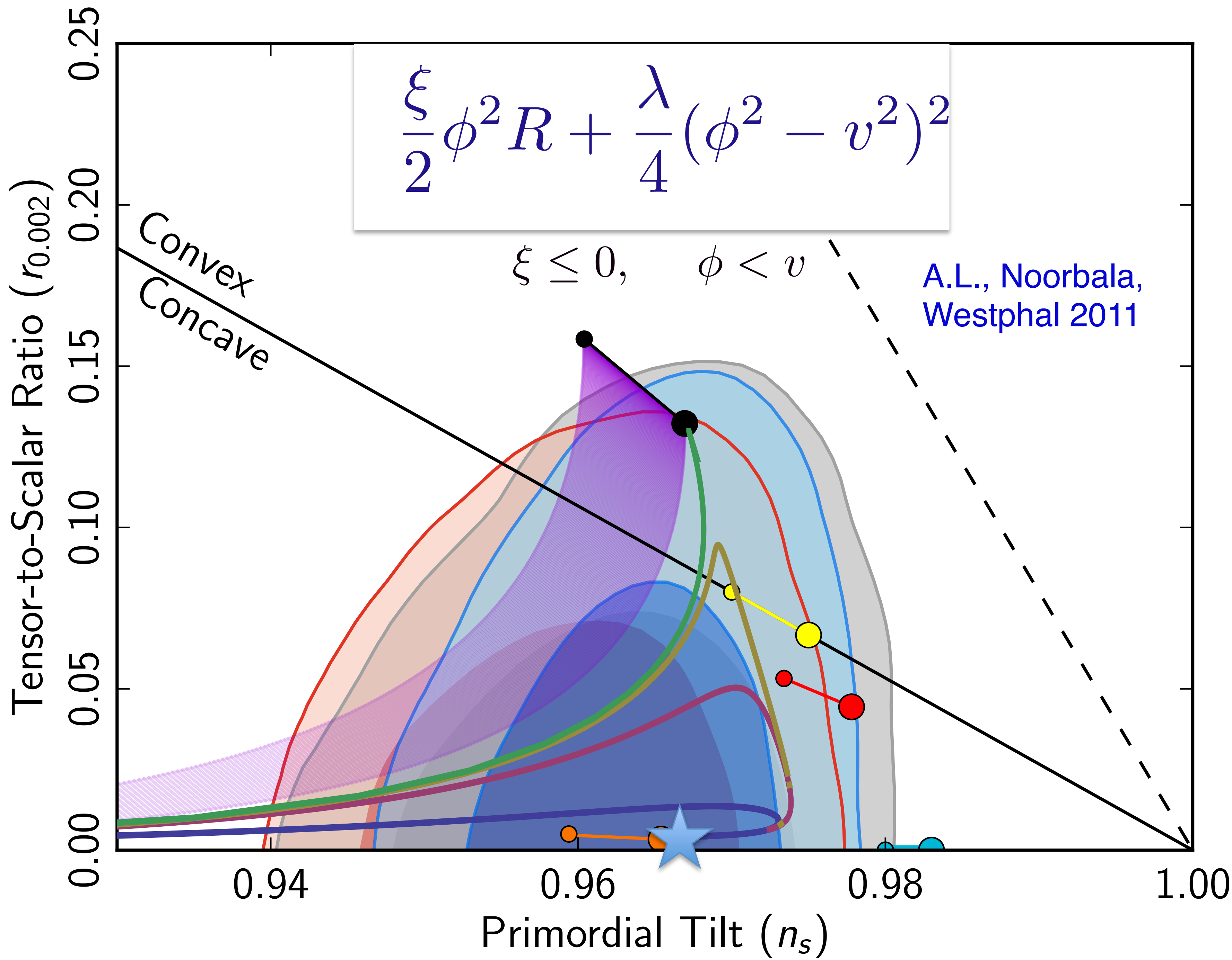
$\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}\phi^4$
Okada, Rehman, Shafi 2010
Convex
Concave
Tensor-to-Scalar Ratio ($r_{0.002}$)
Primordial Tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00

"Higgs Inflation"

Futamase and Maeda, 1989,
Salopek, J. R. Bond and J. M. Bardeen, 1989
Bezrukov, Shaposhnikov 2008
Ferrara, Kallosh, A.L., Marrani, Van Proeyen 2011

$$\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}(\phi^2 - v^2)^2$$





$\frac{\xi}{2}\phi^2 R + \frac{\lambda}{4}(\phi^2 - v^2)^2$
$\xi \leq 0, \quad \phi < v$
A.L., Noorbala, Westphal 2011
Convex
Concave
Tensor-to-Scalar Ratio ($r_{0.002}$)
0.00
0.05
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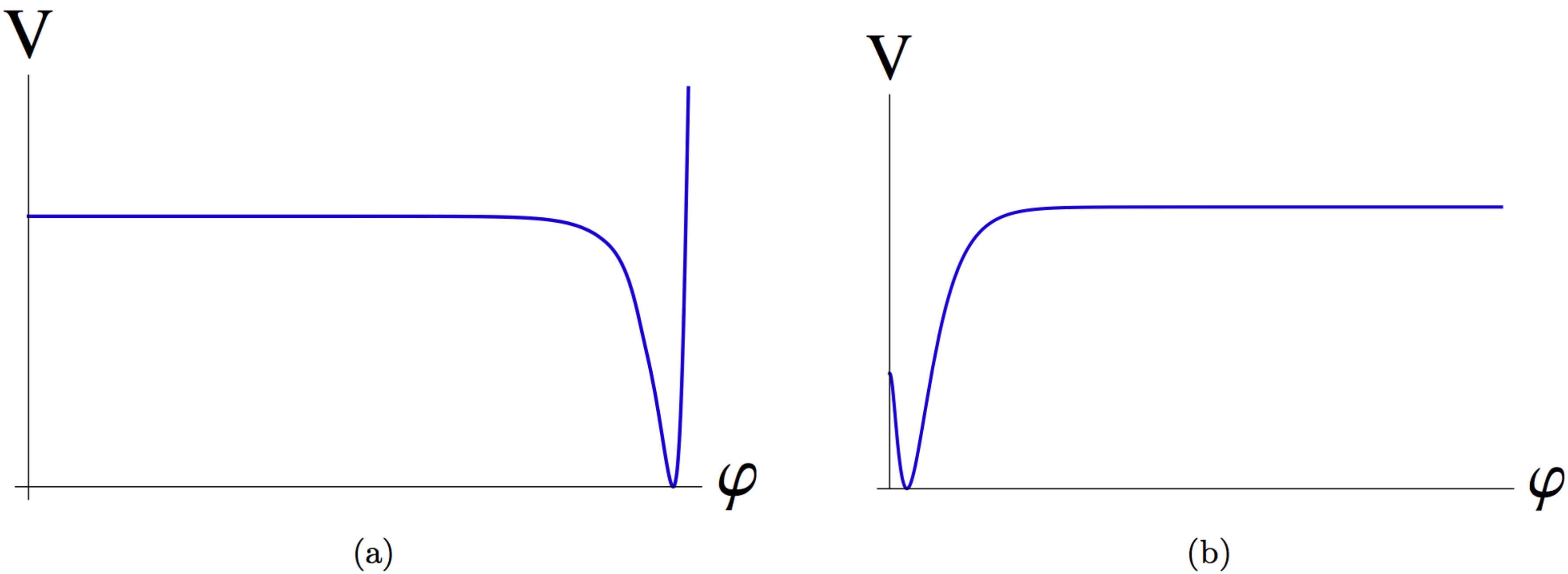
1.00
Primordial Tilt (n_s)

Potential for non-minimal Higgs inflation in Einstein frame for $\xi < 0$, $\phi < v$, and for $\xi > 0$, $\phi > v$



Potential for Starobinsky model is very similar, the same prediction for n_s and r.

Thus for ANY Planck-compatible set of n_s and r one can find MANY sets of supergravity based inflationary models nicely fitting the data. Degeneracy can be removed by a possible discovery of a tiny non-flatness of the universe, non-Gaussianity, cosmic strings, anomalies, etc.

For example, in some models of open inflation, one may suppress the quadrupole. In some versions of chaotic inflation in supergravity one can realize the curvaton mechanism, generate non-Gaussianities due to vector field production, produce superhorizon (or nearly superhorizon) cosmic strings, and may do many other "bad things" to our universe, in order to produce tiny imperfections which may appeal to certain people☺

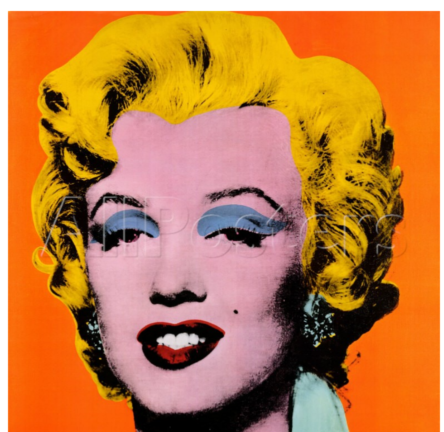
Indeed, some claim that the secret of beauty is in a slight asymmetry between left and right sides of a face, which may become enhanced by a dark spot of a proper size.

This observation was confirmed by measurements in all channels.







ti Design

Here comes the multiverse

Genetic code of the Universe

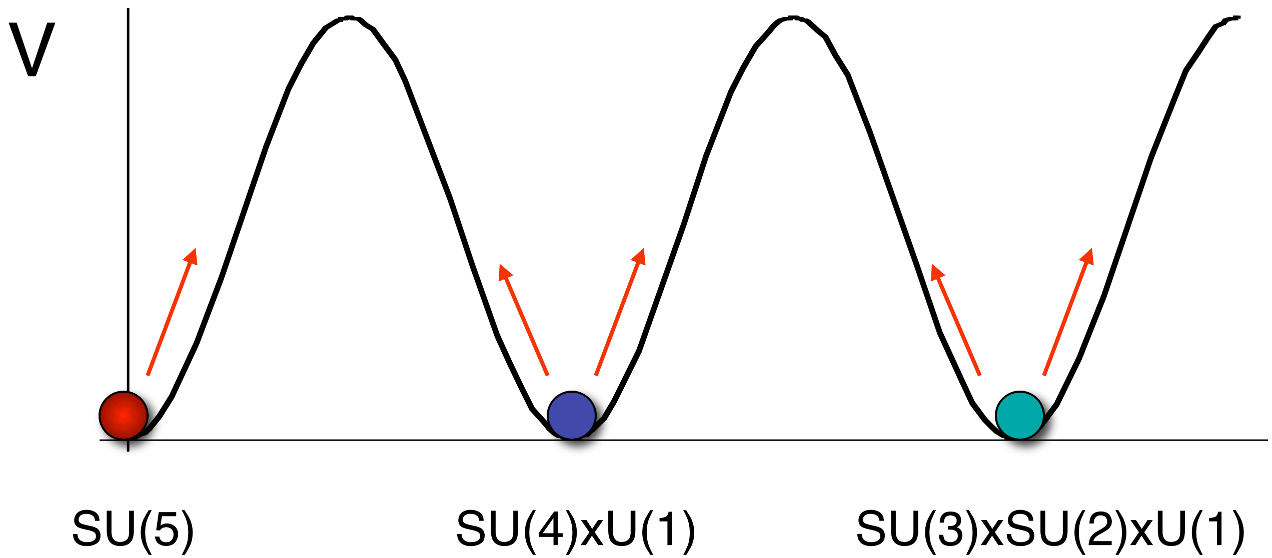
There may be **one** fundamental law of physics, like a single genetic code for "unpacking" the Universe. However, this law may have different realizations. For example, water can be liquid, solid or gas. In elementary particle physics, the effective laws of physics depend on the values of the scalar fields, and the process of compactification.

Quantum fluctuations during inflation can take scalar fields from one minimum of their potential energy to another, altering its genetic code. Once it happens in a small part of the universe, inflation makes this part exponentially big.

This is the cosmological mutation mechanism

From the Universe to the Multiverse

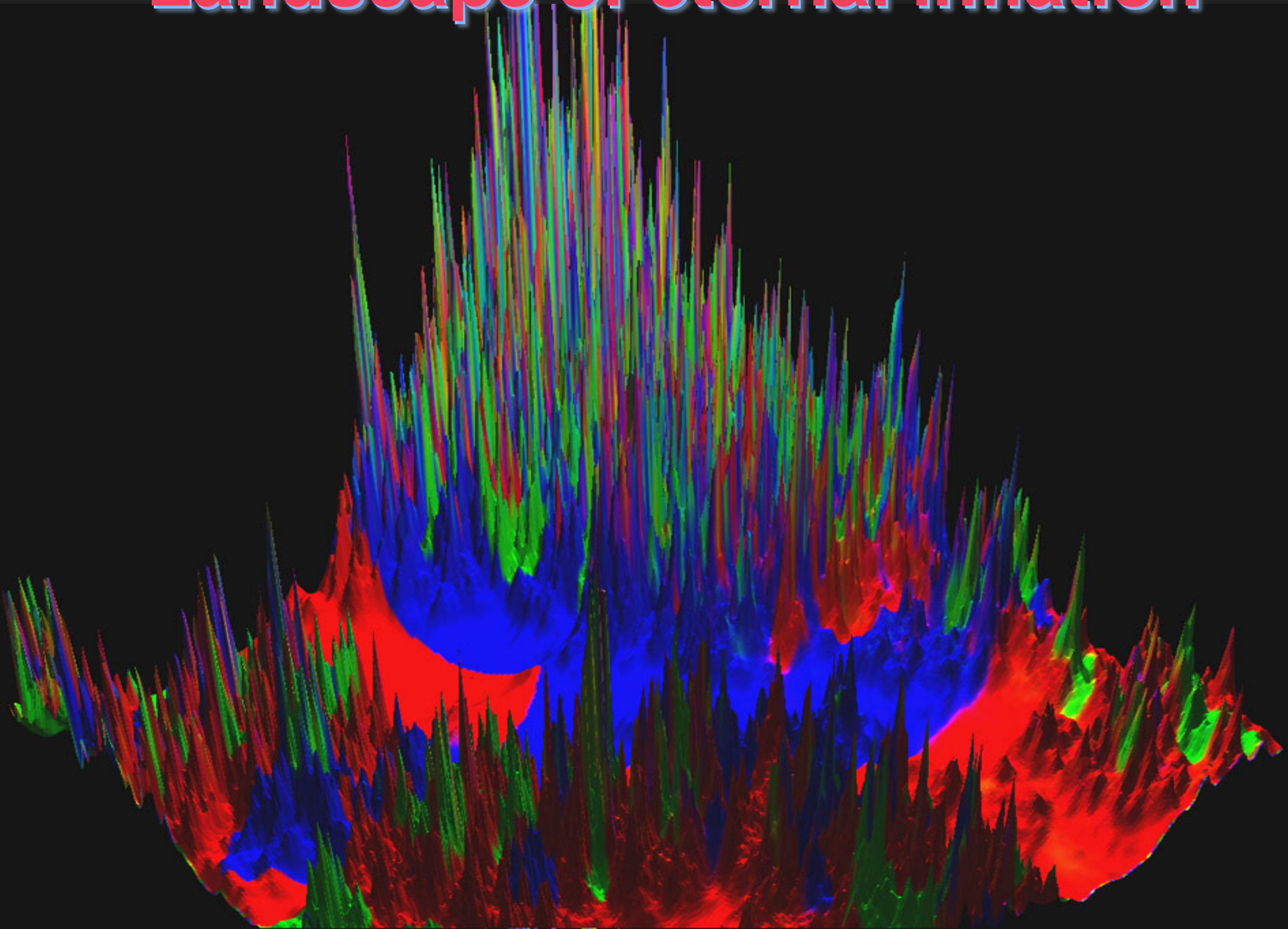
There are **many scalar fields**, and their potential energy has **many different minima**. Each minimum corresponds to different masses of particles and different laws of their interactions.



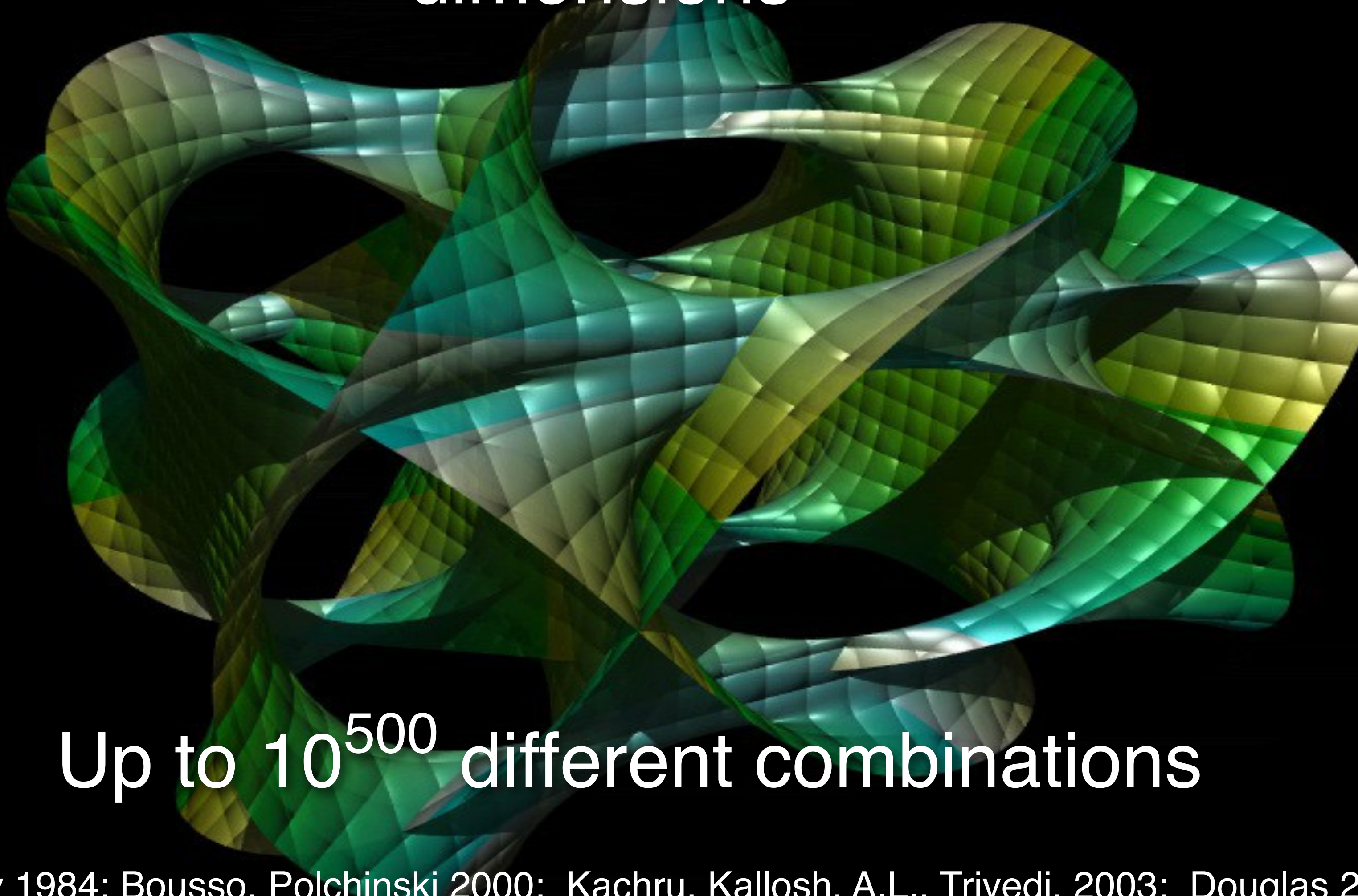
Quantum fluctuations during eternal inflation can bring the scalar fields to different minima in different parts of the universe. The universe becomes divided into many exponentially large parts with **different laws of physics** operating in each of them.

A.L. 82, 83

Landscape of eternal inflation



In string theory, genetic code is written in properties of compactification of extra dimensions



Up to 10^{500} different combinations

Sakharov 1984; Bousso, Polchinski 2000; Kachru, Kallosh, A.L., Trivedi, 2003; Douglas 2003

Thus, **uniformity** of our world can explained by **inflation**: Exponential stretching of the universe makes **our part** of the universe almost exactly uniform.

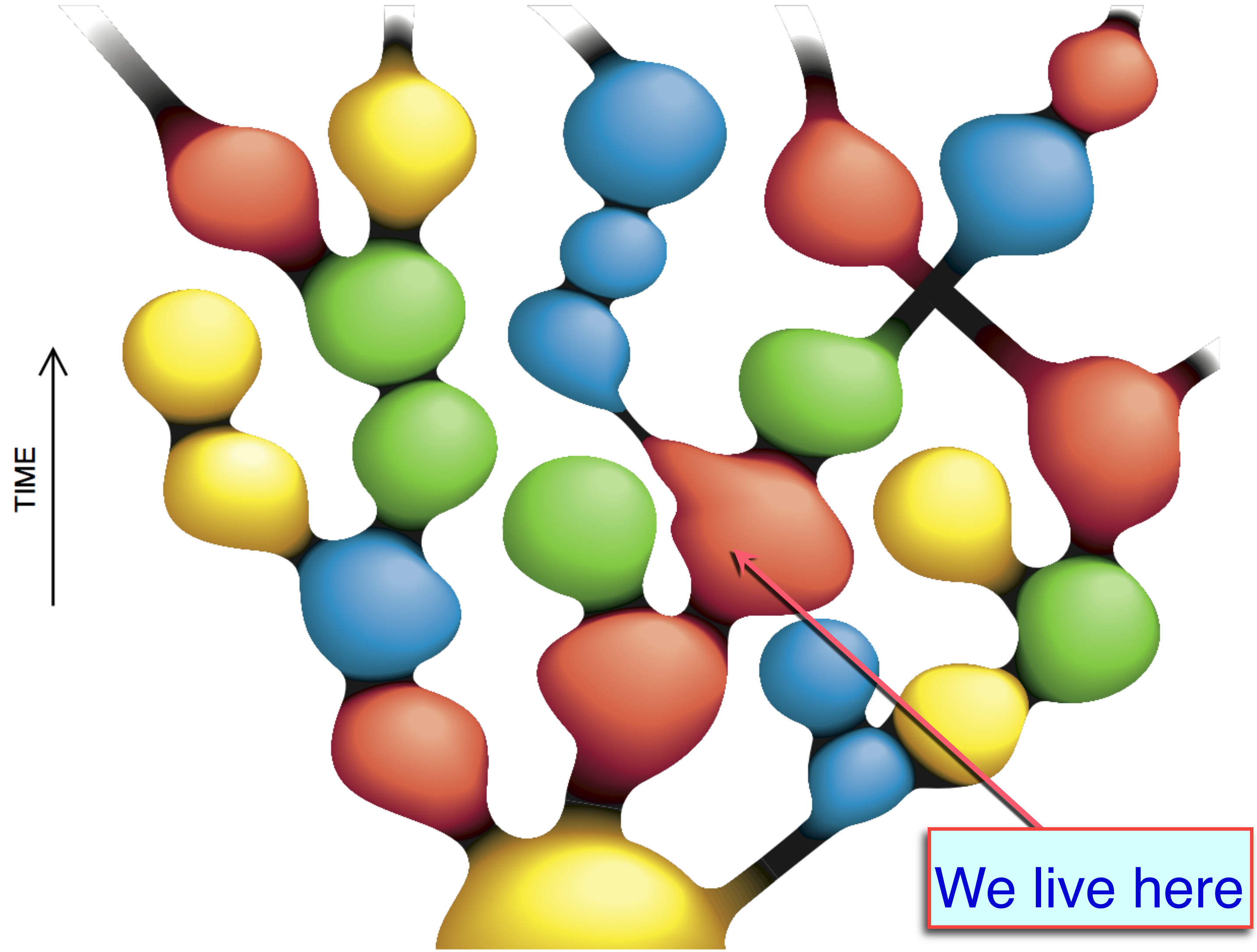
However, the same theory predicts that on a much greater scale, the universe is 100% non-uniform.

Inflationary **universe** becomes a **multiverse**

This allows us to justify the anthropic principle:

We live in those parts of the multiverse where we can live.

Self-reproducing Inflationary Universe



Big Bang ?

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

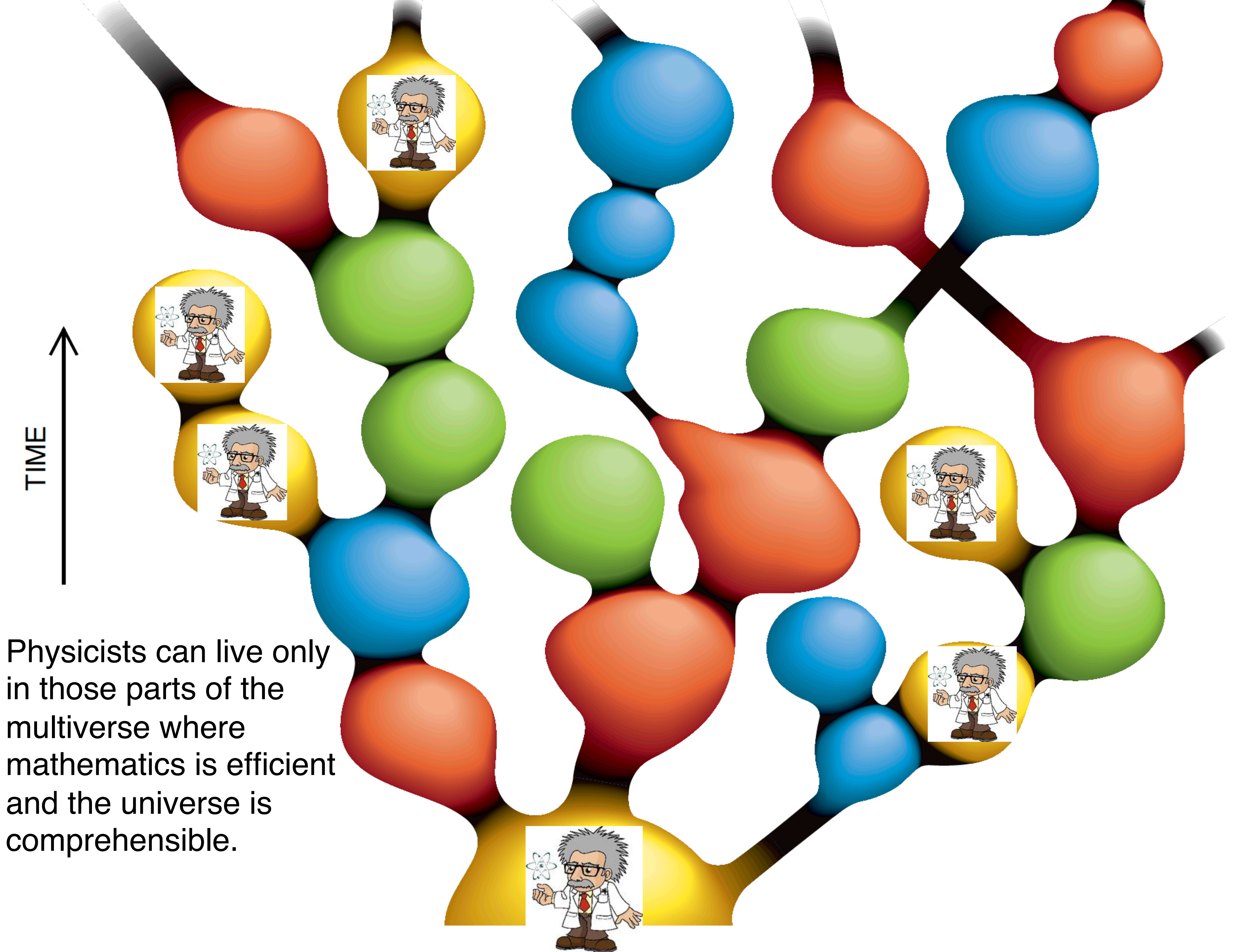
Eugene Wigner

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**.


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

Feeling lucky…

Our present position is extremely fine-tuned in terms of the cosmological evolution. 10^{-8} AU (age of the universe) ago we did not even know that other galaxies exist. 3 x 10^{-9} AU ago we did not see the CMB anisotropy. 10^{-9} AU ago we did not know about dark energy. 3 x 10^{-10} AU ago the Planck satellite did not yet fly. Happy epoch of great cosmological discoveries probably will be over in 10^{-8} AU. We are creating the map of the universe which is not going to change much during the next billion years…

The fact that we were born just in time to participate in this magnificent process and witness great cosmological discoveries is a 6 σ anomaly, the one that we should be very happy about.

But is it actually an anomaly or a superselection rule? Cosmologists can only live at the time when investigation of the universe is possible and financially feasible.

Efstathiou, private communication ☺