String Cosmology

Andrei Linde

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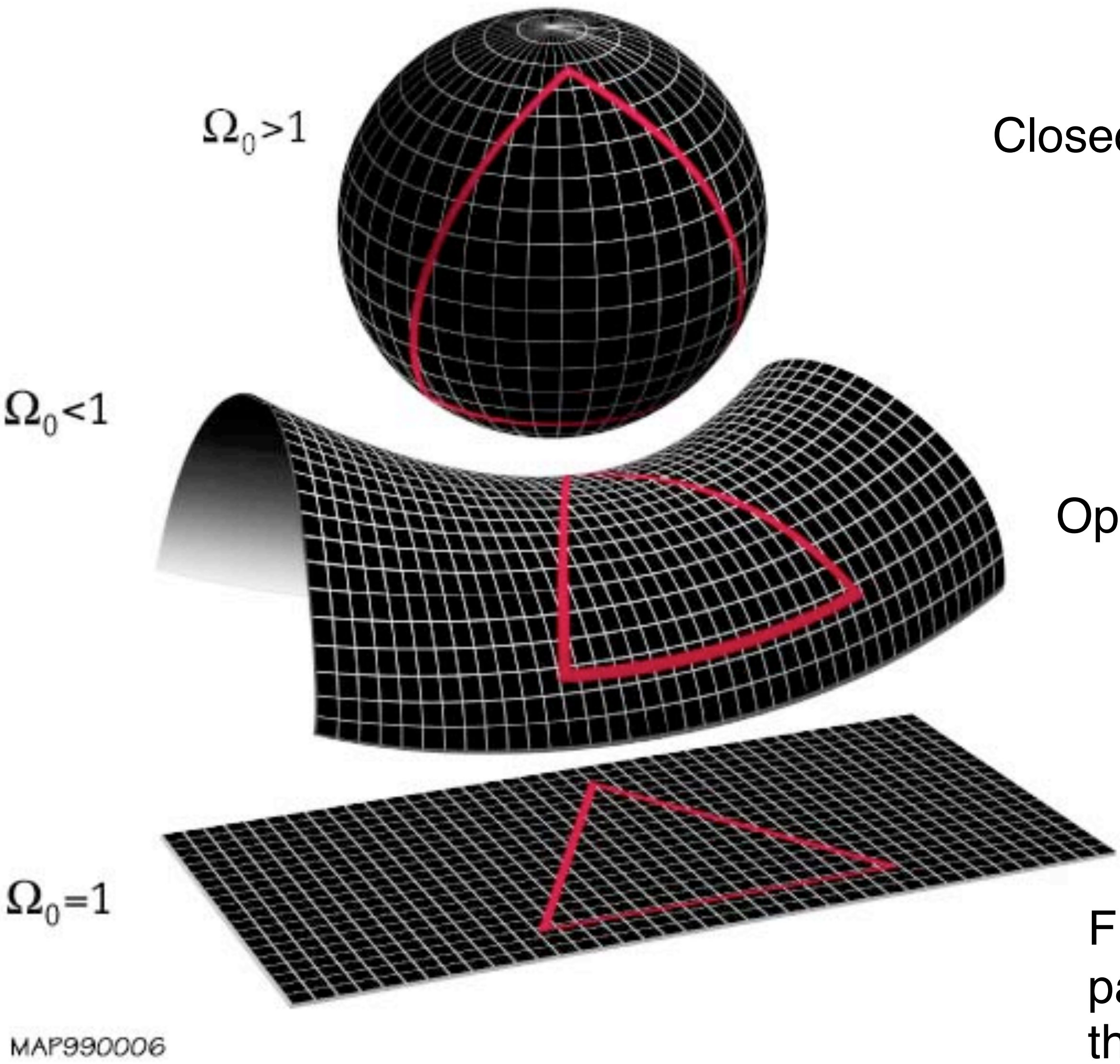
Closed, open or flat universe



Closed universe. Parallel lines intersect

Open universe. Parallel lines diverge

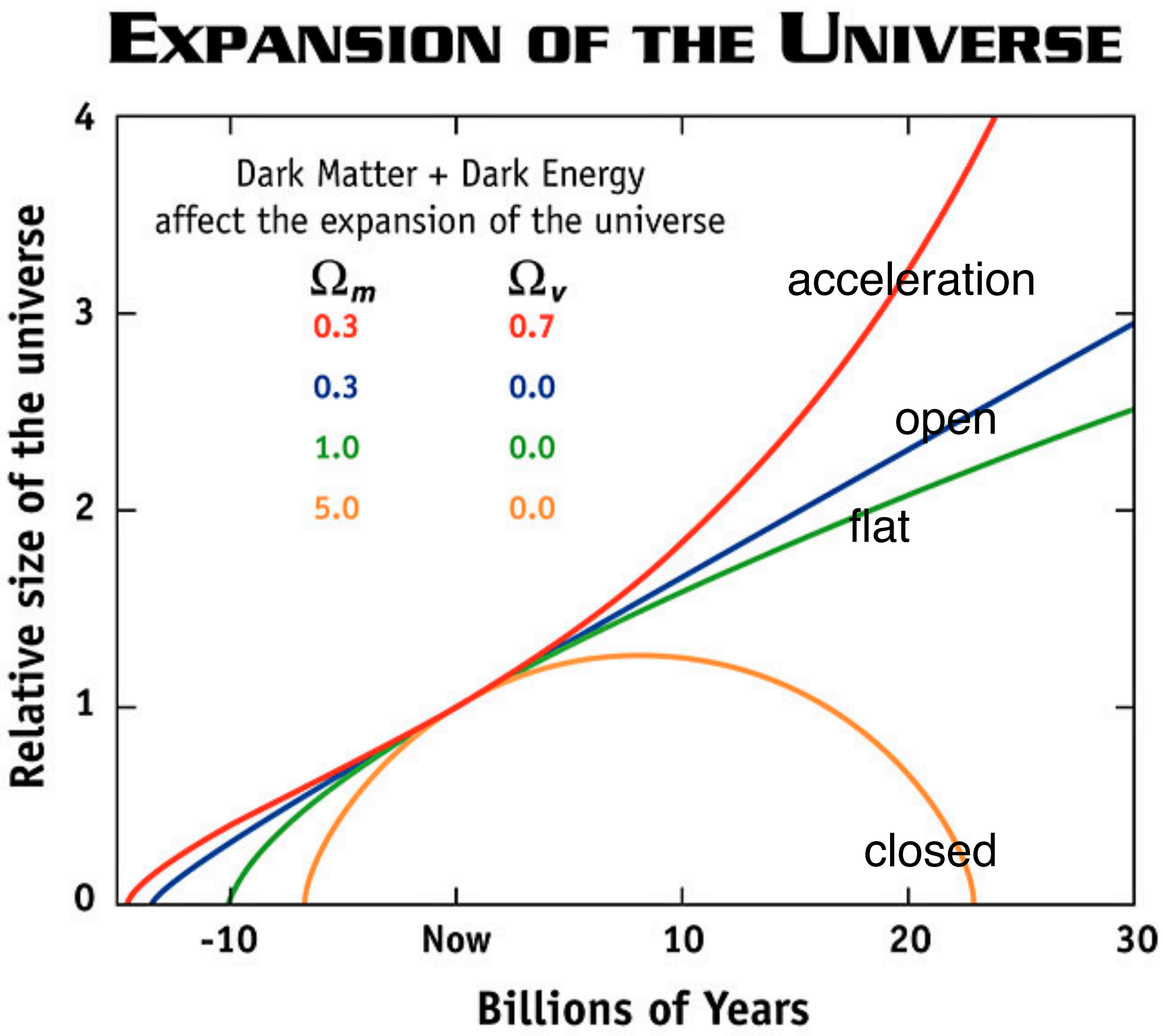
Flat universe. Parallel lines remain parallel, but the distance between them grow with time

Two stages of acceleration:

The new-born universe experienced rapid acceleration (inflation)

A new (slow) stage of acceleration started 5 billion years ago (dark energy)

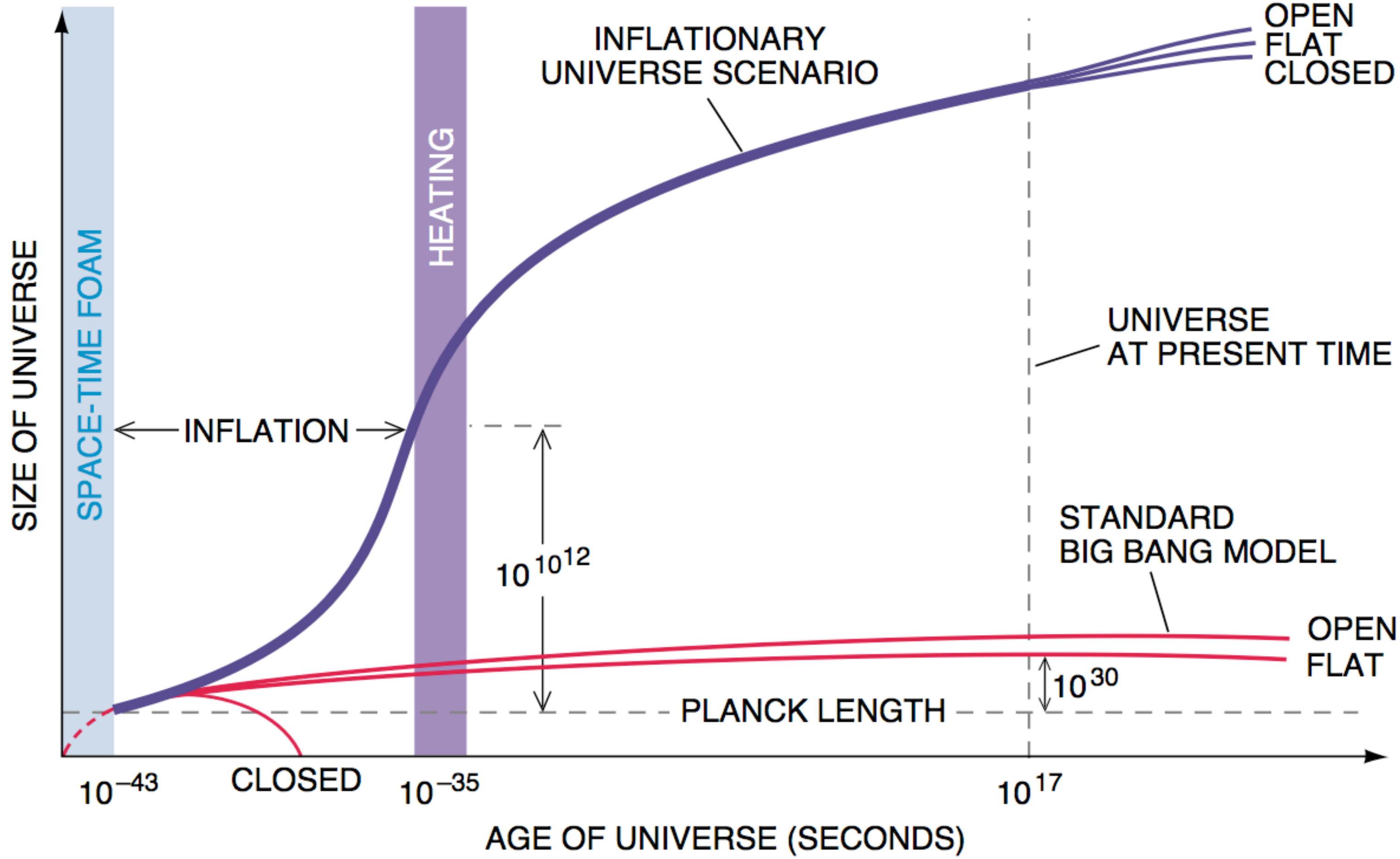
Big Bang Theory



If vacuum has positive energy density (dark energy), the universe may accelerate, as it is shown on the upper curve. Such universe may not collapse even if it is closed.

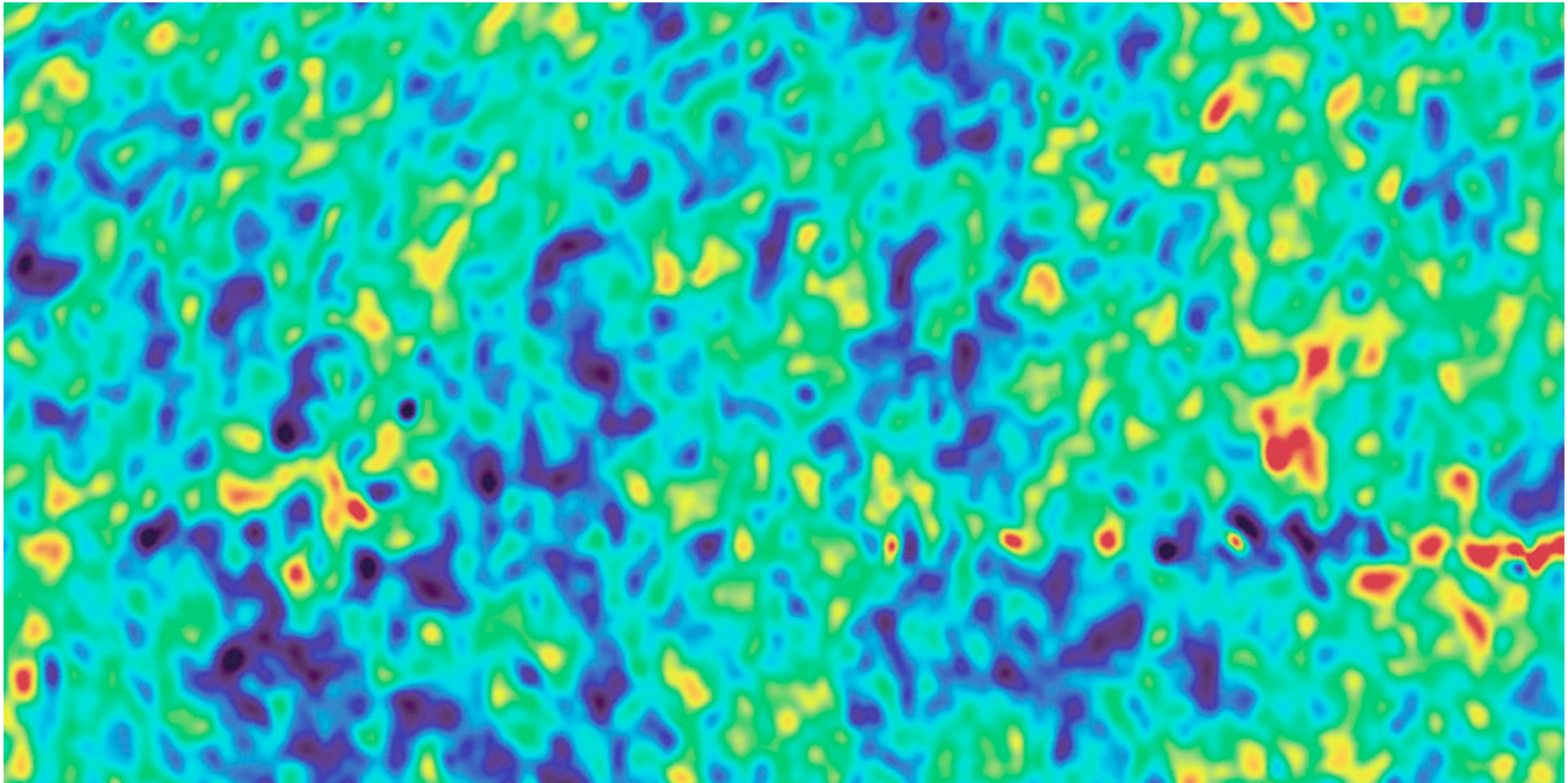
If vacuum energy is negative, the universe will collapse even if it is open.

Inflationary Universe



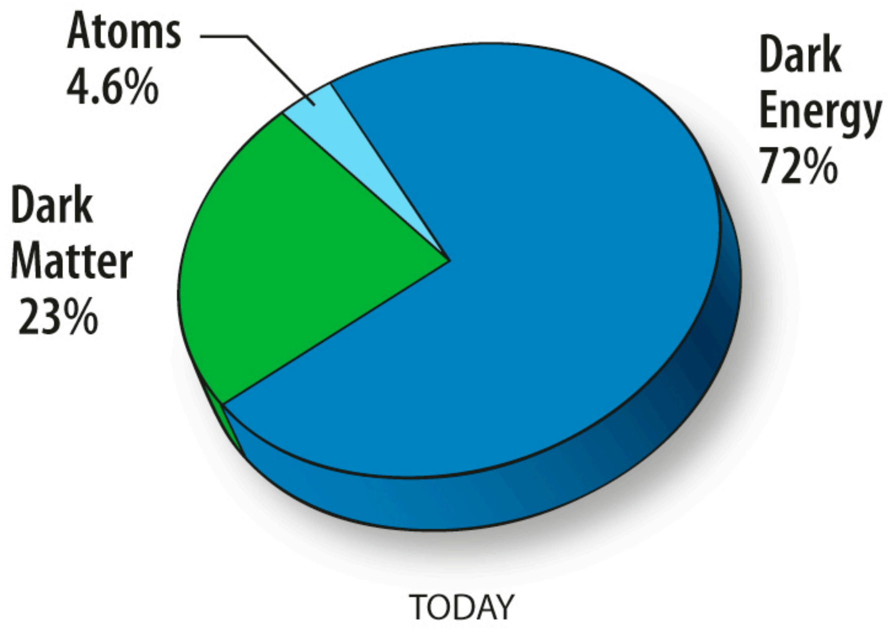
Inflation is an extremely rapid expansion of the universe soon after its creation

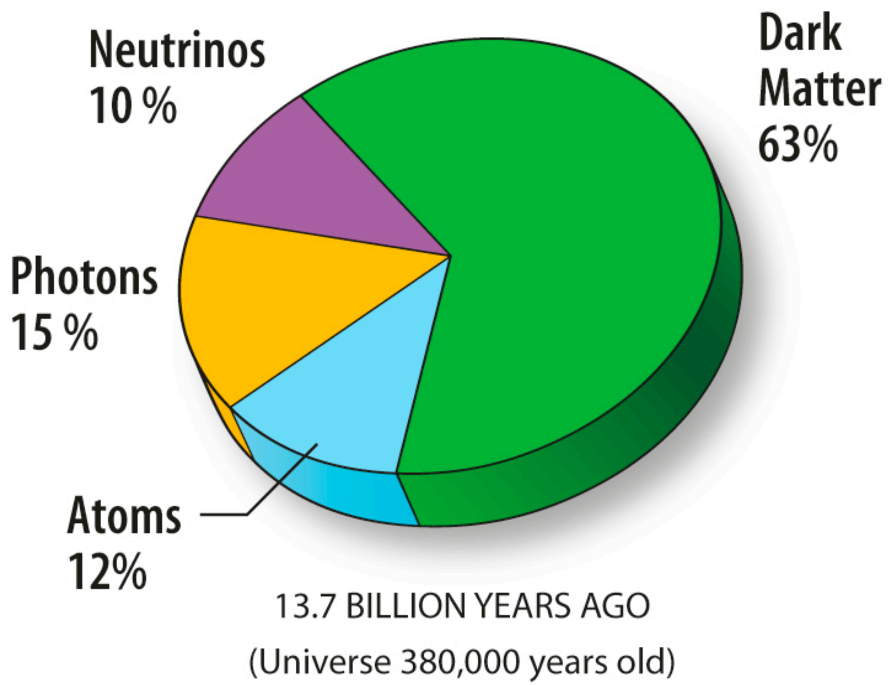
$$a \sim e^{Ht}$$



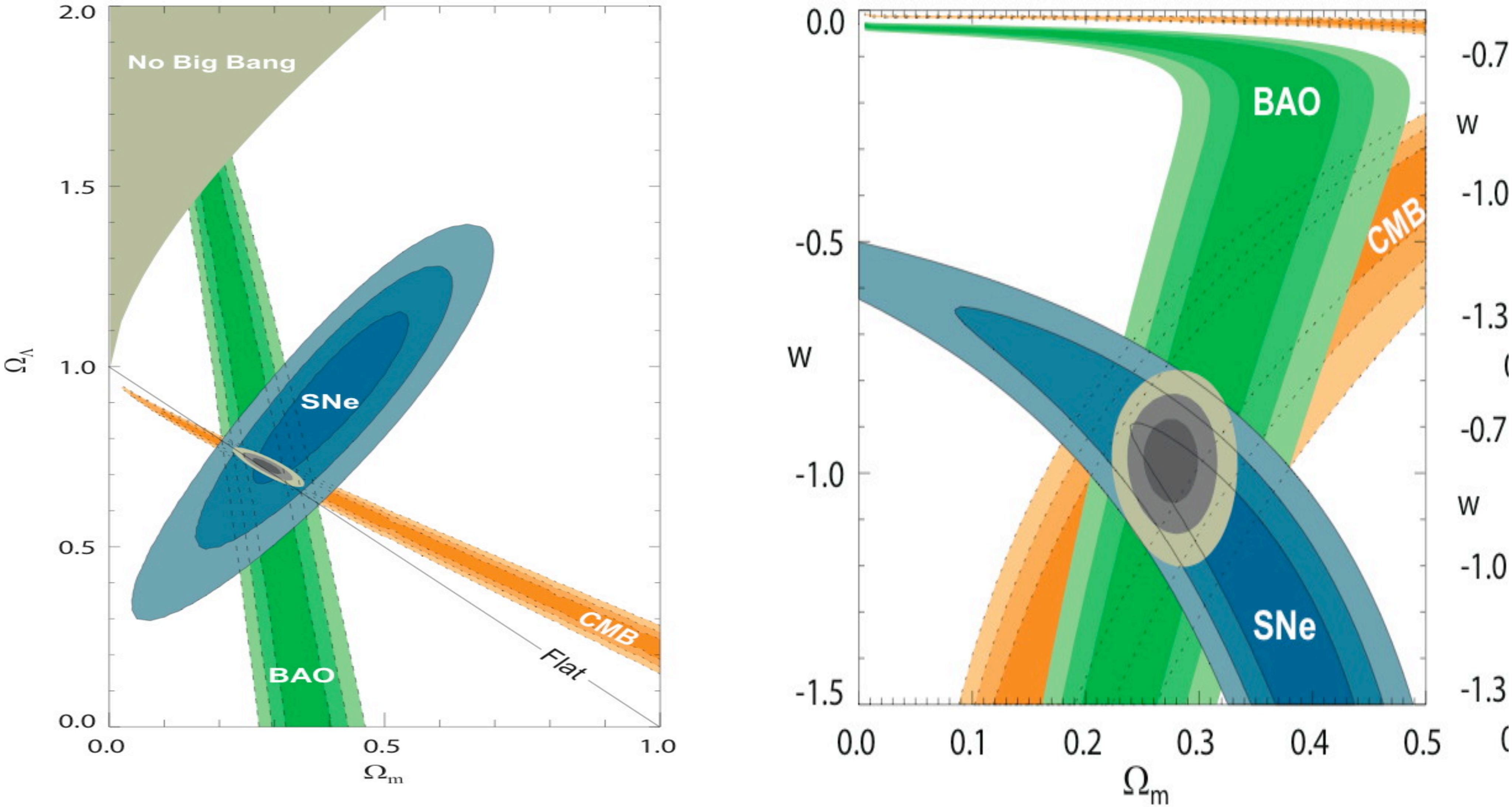

Observations

WMAP 5-Year Pie Chart





Concordance and simplicity: Ω = 1, w = -1



$$\Omega = \Omega_\Lambda + \Omega_m = \rho_\Lambda/\rho_0 + \rho_m/\rho_0 \qquad p_\Lambda = w\rho_\Lambda$$

Many, many questions:

What was before the Big Bang?

Still do not know

Why is our universe so **homogeneous**?
Why is it **not exactly** homogeneous?
Why is it **isotropic** (same in all directions)?
Why all of its parts started expanding simultaneously?
Why is it **flat** (**Ω = 1**)?
Why is it so **large**?
Where are monopoles and other unwanted relics?

Answered by inflation

Why vacuum (dark) energy is so small but not zero?
Why there is 5 times more dark matter than normal matter?
Why there is about 4 times more dark energy than dark matter?
Why **$w = -1$**?

Possible answers are given by a combination of particle physics, string theory and eternal inflation

Inflationary cosmology

1) Starobinsky model (1979-80).

Complicated, different goals, but (almost) worked

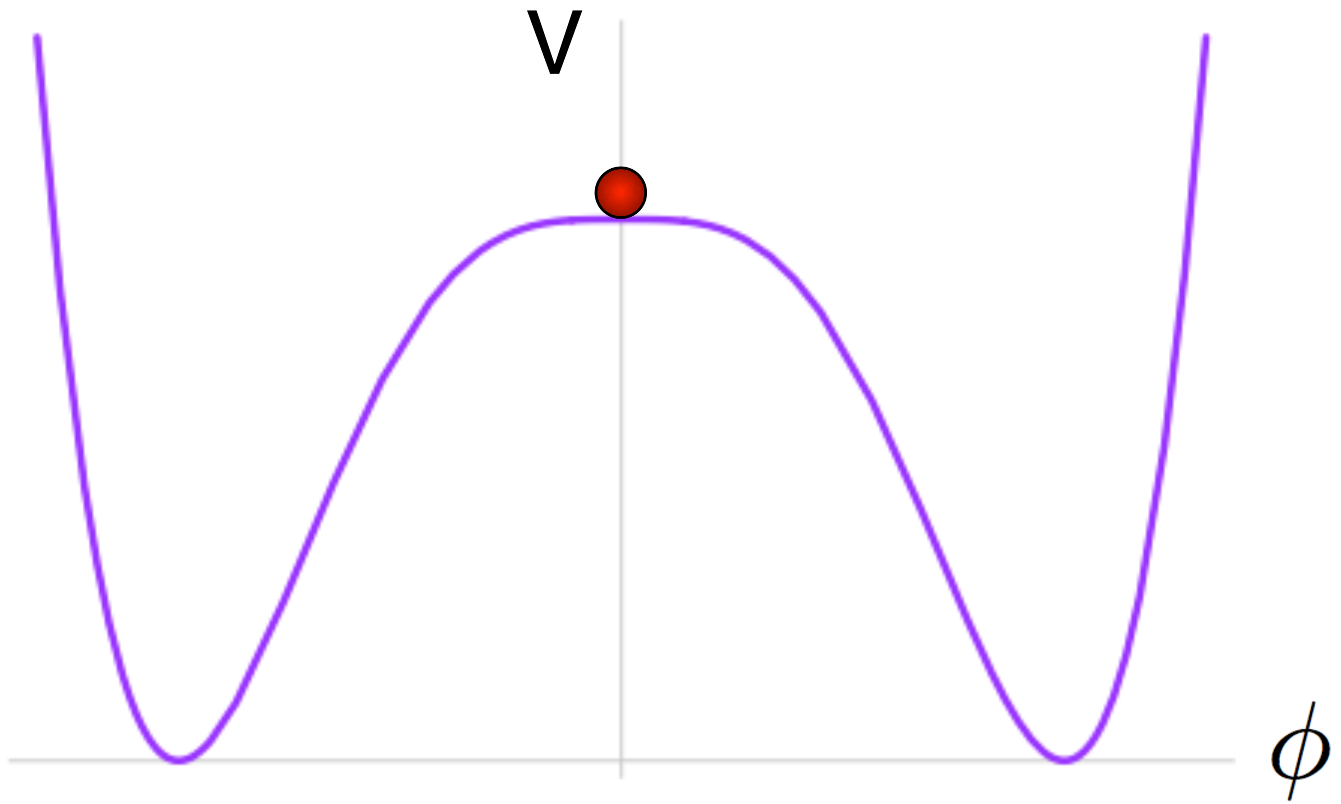
2) Old inflation (Guth) (1981):

A very clear motivation, main ideas of inflation proposed, but did not work

New Inflation

1981 - 1982

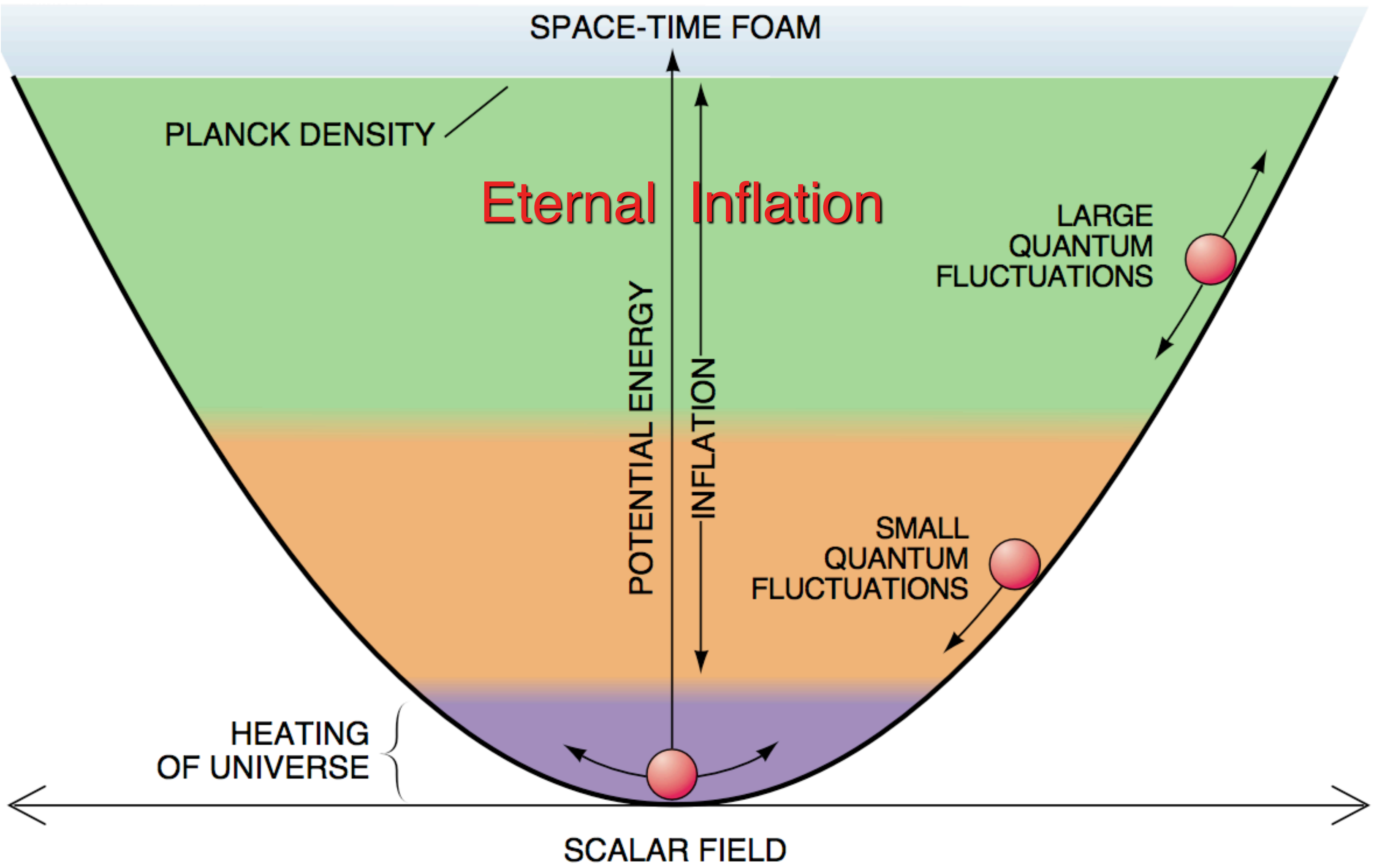
$$V = g^4 \left(\phi^4 \ln \phi - \phi^4/4 + 1/4\right)$$



Chaotic Inflation

1983

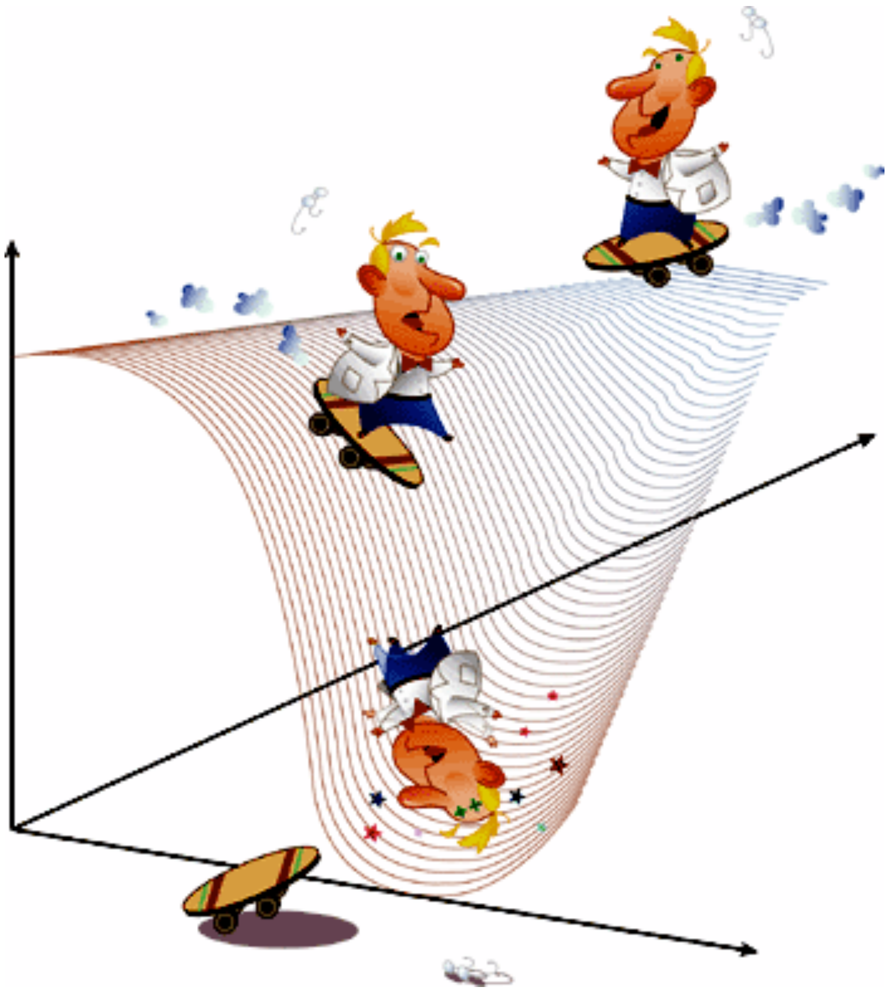
$$V(\phi) = \frac{m^2}{2}\phi^2$$



Hybrid Inflation

1991

$$V(\sigma,\phi) = \frac{1}{4\lambda}(M^2 - \lambda\sigma^2)^2 + \frac{m^2}{2}\phi^2 + \frac{g^2}{2}\phi^2\sigma^2$$



Equations of motion for chaotic inflation

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:

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

At large ϕ the Hubble constant is large, friction is large, ϕ remains nearly constant, and the Einstein equation has a simple (inflationary) solution

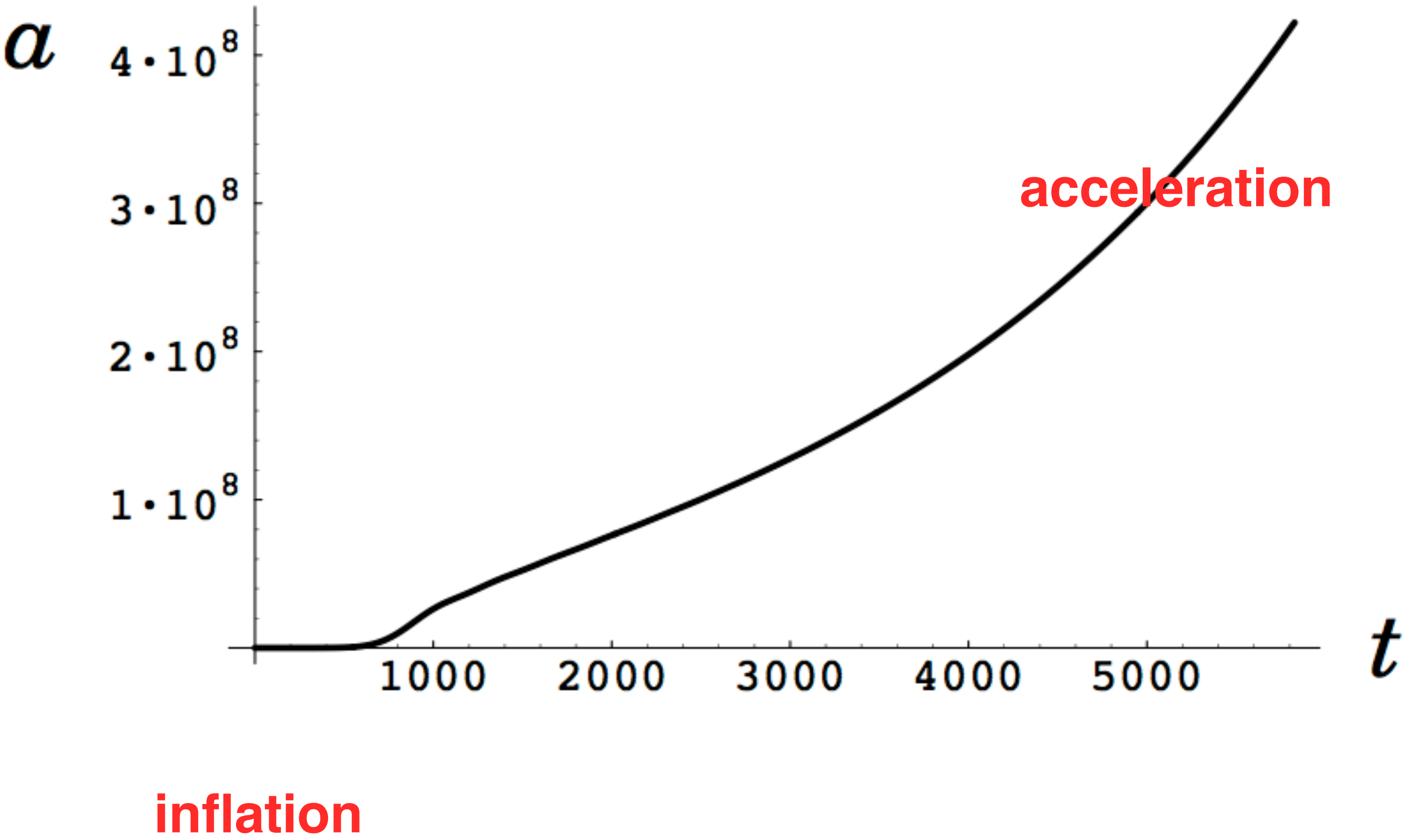
$$a \sim e^{Ht}$$

Add a constant to the inflationary potential

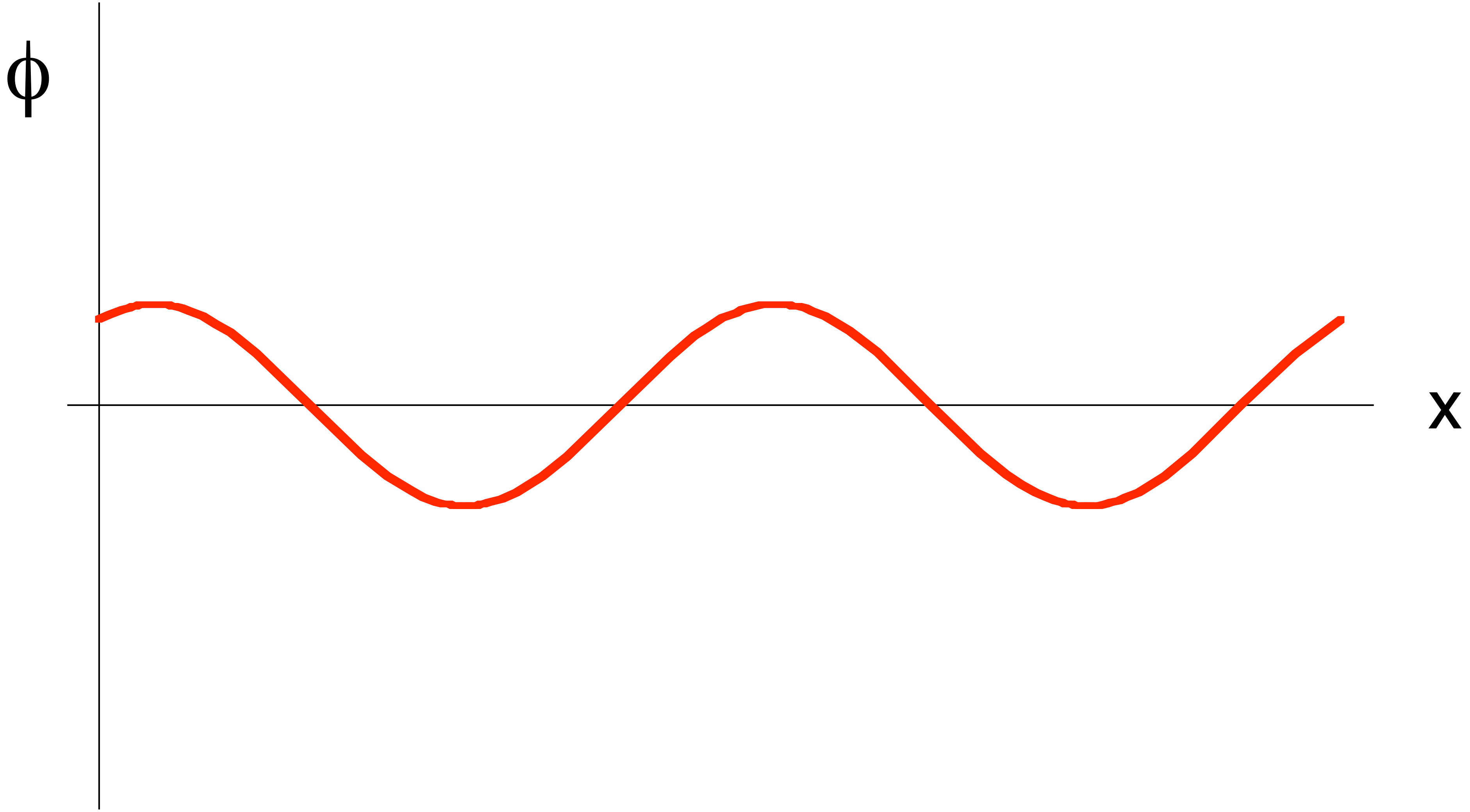
- obtain inflation and acceleration

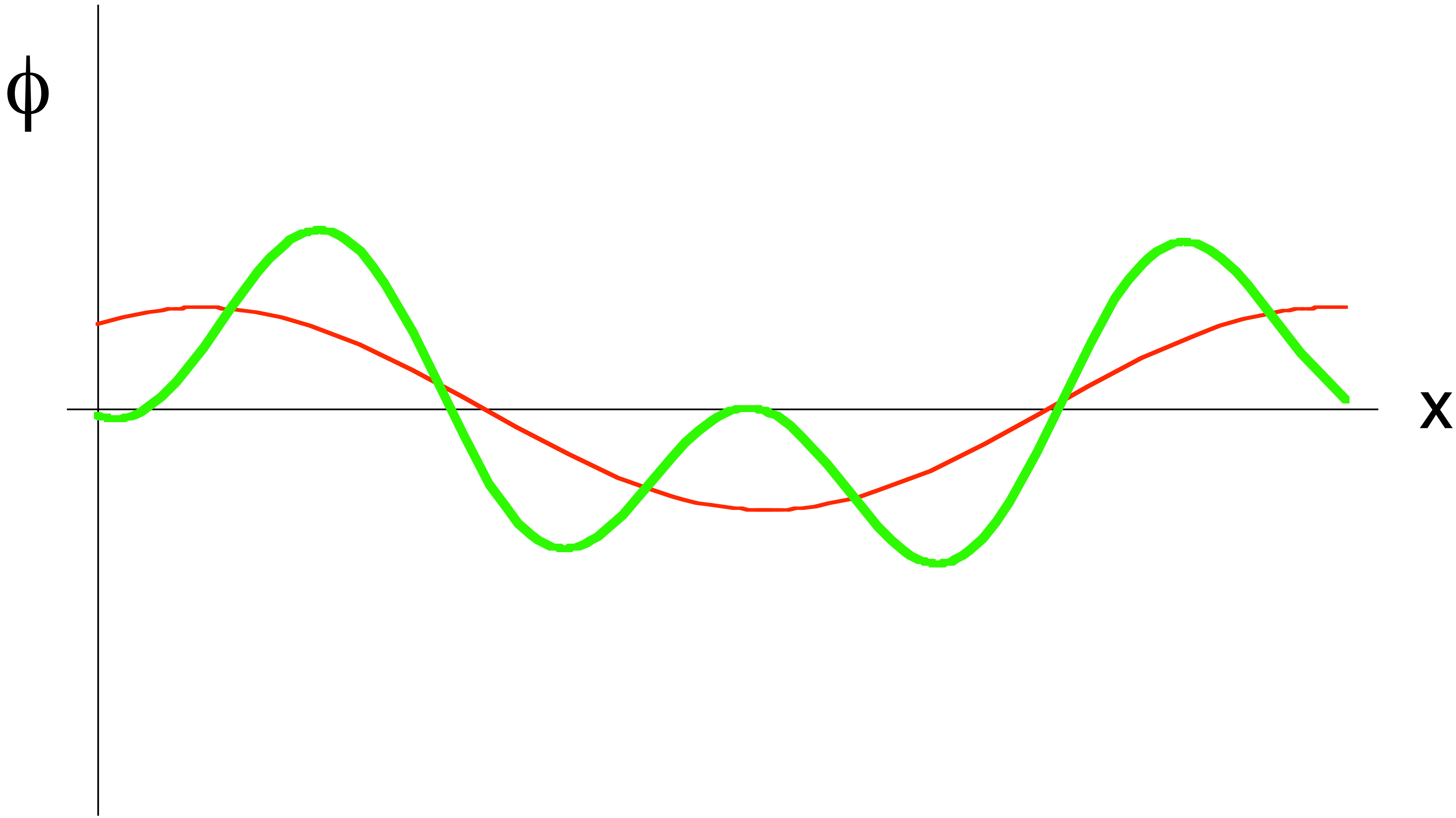
$$V = \frac{m^2}{2}\phi^2 + \Lambda$$

The simplest model of inflation AND dark energy

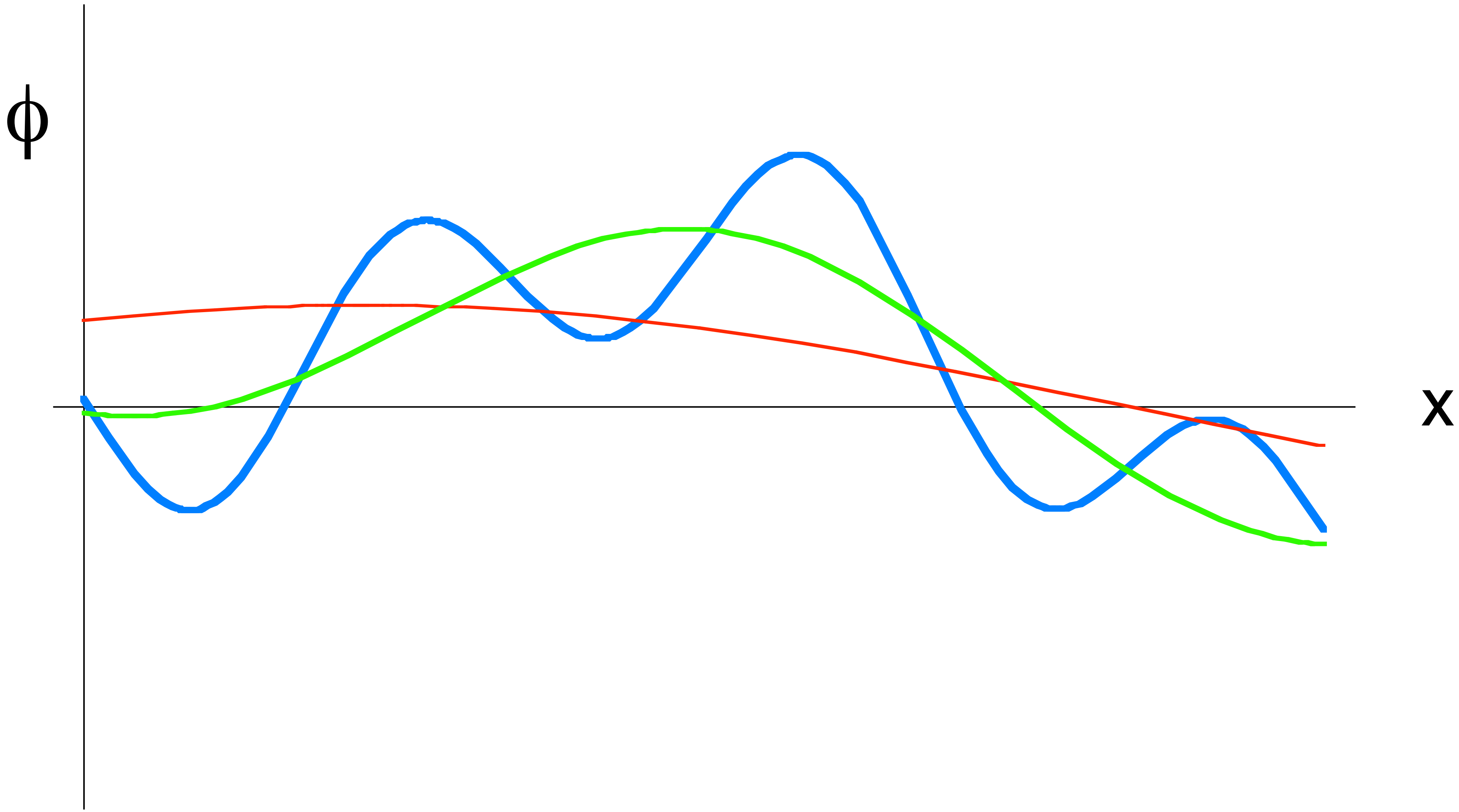


Quantum fluctuations produced during inflation



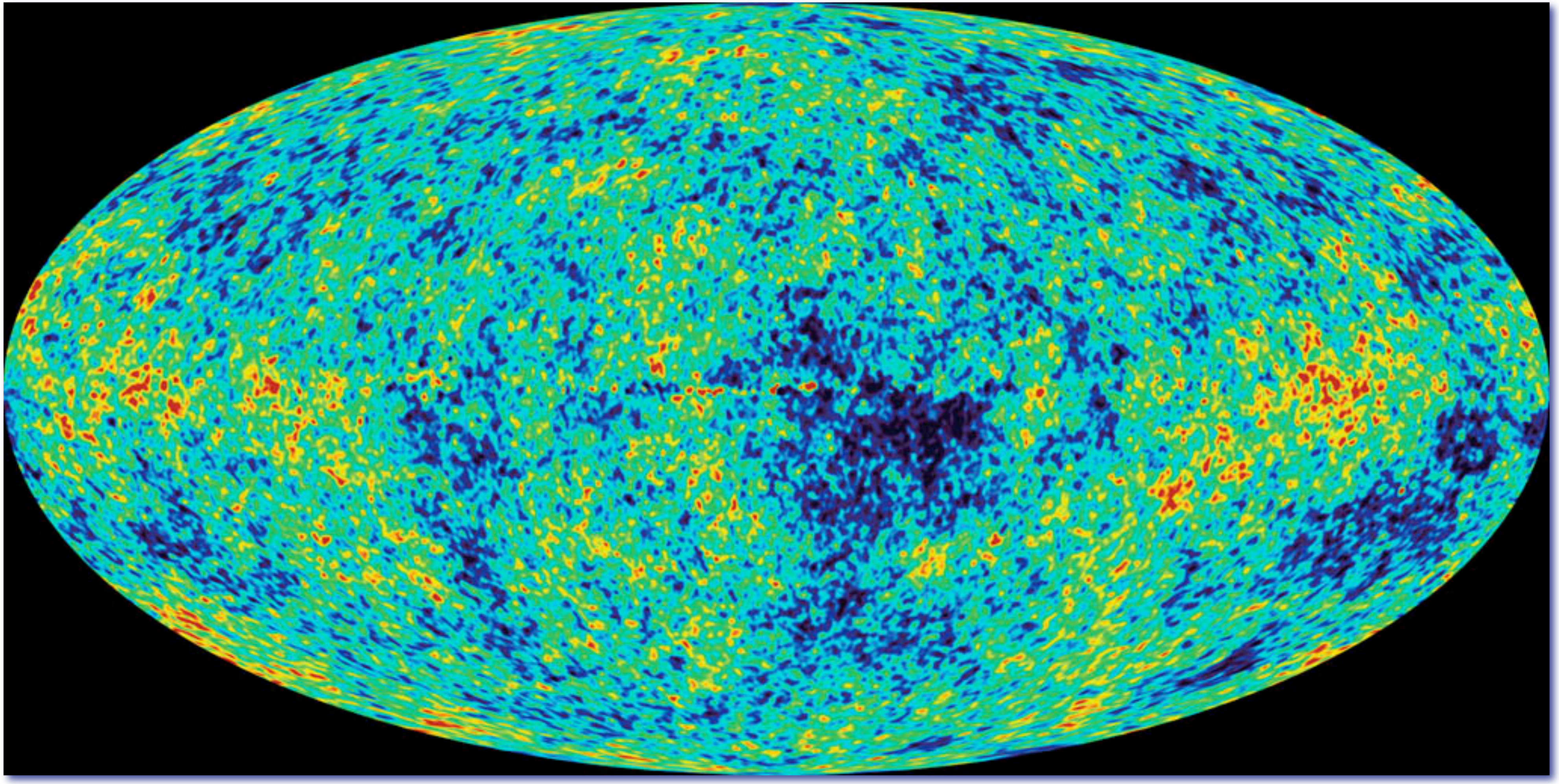


φ
x

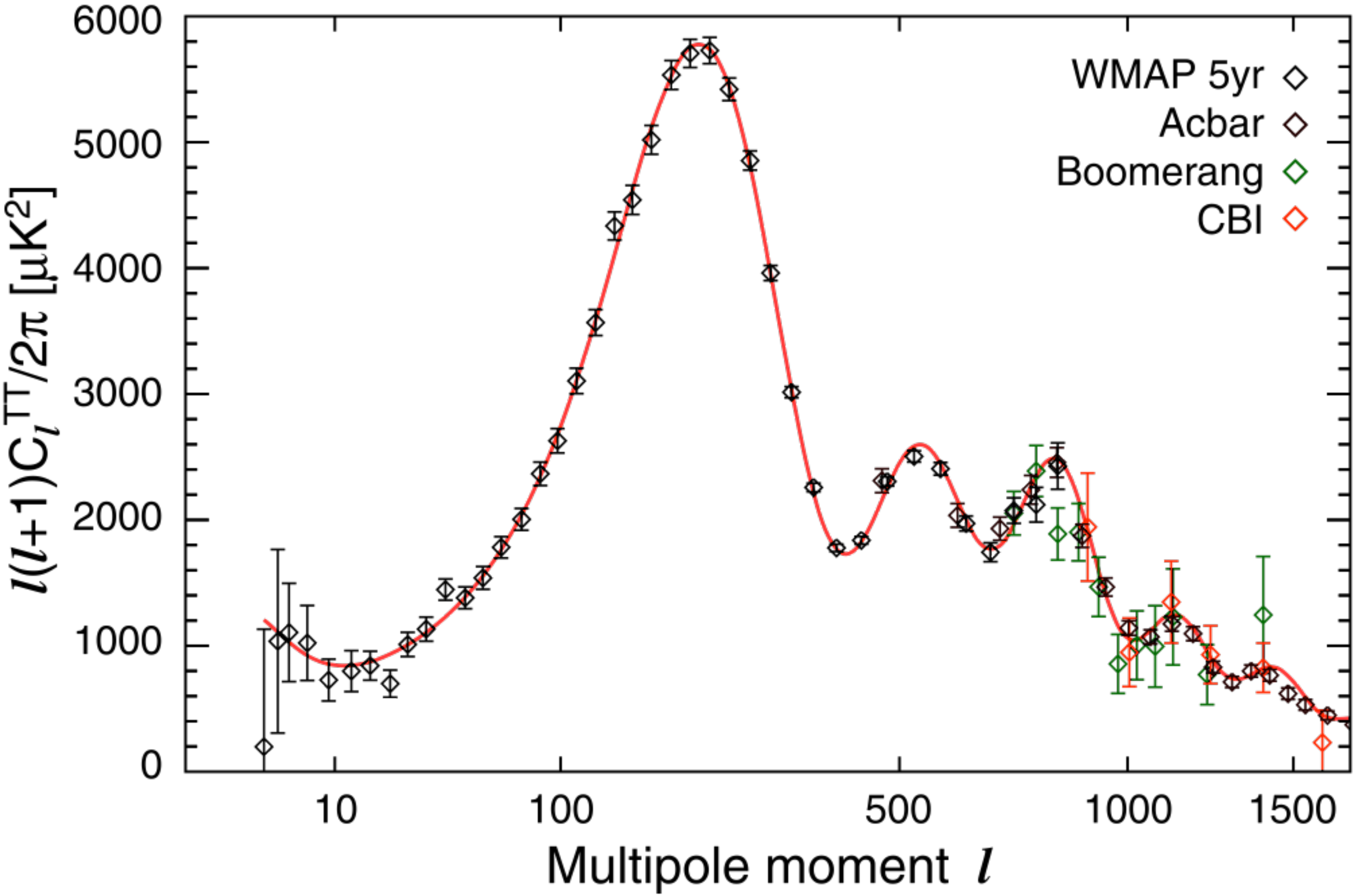


φ
x

WMAP and the temperature of the sky

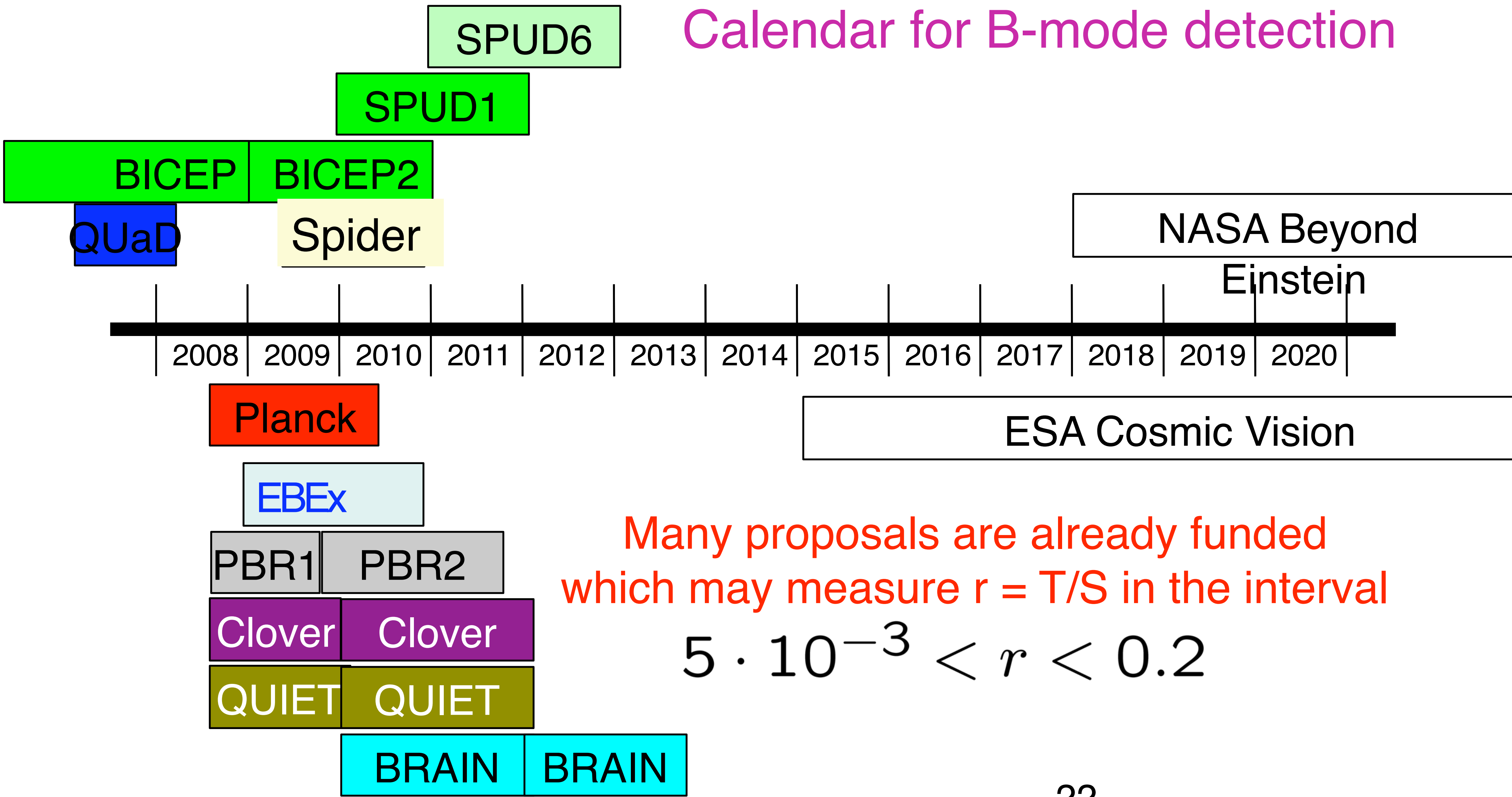


WMAP5 + Acbar + Boomerang + CBI



Holy grail of observational cosmology

Calendar for B-mode detection



Many proposals are already funded which may measure r = T/S in the interval

$$5 \cdot 10^{-3} < r < 0.2$$

Predictions of Inflation:

1) The universe should be homogeneous, isotropic and flat,

$\Omega = 1 + O(10^{-4})$ $[\Omega=\rho/\rho_0]$

Observations: it is homogeneous, isotropic and flat:

$$\Omega = 1.005 \pm 0.013$$

2) Inflationary perturbations should be gaussian and adiabatic, with flat spectrum, $n_s = 1 + O(10^{-1})$. Spectral index n_s slightly differs from 1. (This is an important prediction, similar to asymptotic freedom in QCD.)

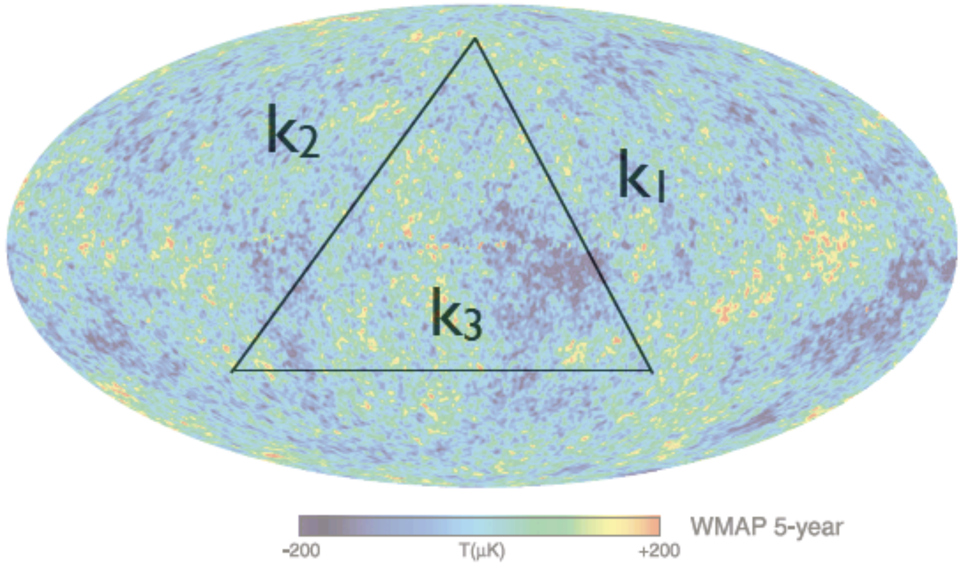
Observations: perturbations are gaussian (?) and adiabatic, with flat spectrum:

$$n_s = 0.959 \pm 0.013$$

Nongaussianity?

Komatsu 2008

So, what is f_{NL}?



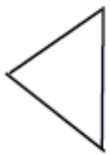
- **f_{NL} = the amplitude of three-point function**, or also known as the "bispectrum," $B(k_1,k_2,k_3)$, which is
  - $=\langle\Phi(k_1)\Phi(k_2)\Phi(k_3)\rangle = f_{NL}(2\pi)^3\delta^3(k_1+k_2+k_3)b(k_1,k_2,k_3)$
  - where $\Phi(k)$ is the Fourier transform of the curvature perturbation, and $b(k_1,k_2,k_3)$ is a model-dependent function that defines the shape of triangles predicted by various models.

Komatsu & Spergel (2001); Babich, Creminelli & Zaldarriaga (2004)

Two f_{NL}'s

- Depending upon the shape of triangles, one can define various f_{NL}'s:
- "Local" form 
  - which generates non-Gaussianity locally (i.e., at the same location) via $\Phi(x)=\Phi_{gaus}(x)+f_{NL}^{local}[\Phi_{gaus}(x)]^2$

Earlier work on the local form:
Salopek&Bond (1990); Gangui et al. (1994);
Verde et al. (2000); Wang&Kamionkowski (2000)

- "Equilateral" form 
  - which generates non-Gaussianity in a different way (e.g., k-inflation, DBI inflation)

Komatsu 08

Gaussianity is confirmed at 0.1% level, but there are interesting developments when we are moving further.

The best estimates of primordial non-Gaussian parameters from the bispectrum analysis of the WMAP 5-year data are

- $-9 < f_{NL}^{local} < 111$ (95% CL)
- $-151 < f_{NL}^{equil} < 253$ (95% CL)

–In 5-10 years, we will know **flatness** to **0.1%** level.

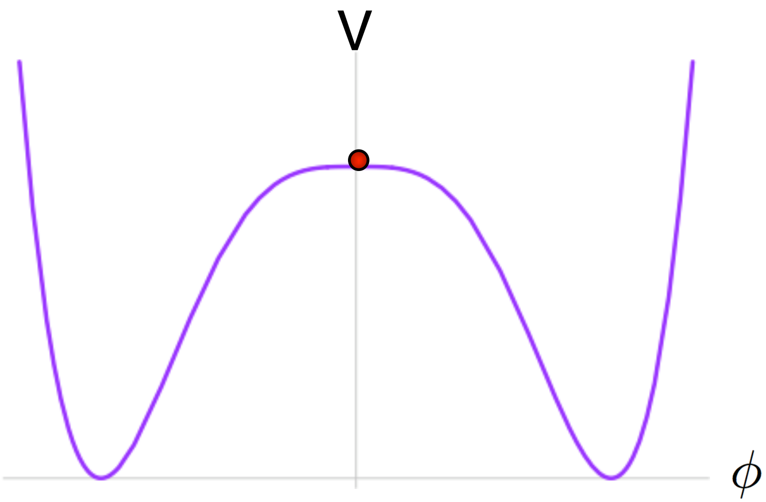
–In 5-10 years, we will know **Gaussianity** to **0.01%** level (f_{NL}~10), or even to **0.005%** level (f_{NL}~5), at 95% CL.

Can we have large nongaussianity ?

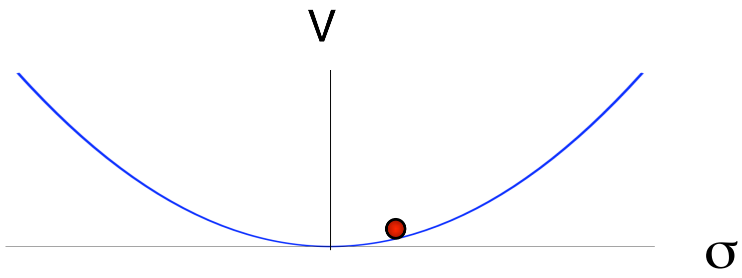
A.L., Kofman 1985-1987, A.L., Mukhanov, 1996,

Lyth, Wands, Ungarelli, 2002

Lyth, Wands, Sasaki and collaborators - many papers up to 2008



Inflaton



Curvaton

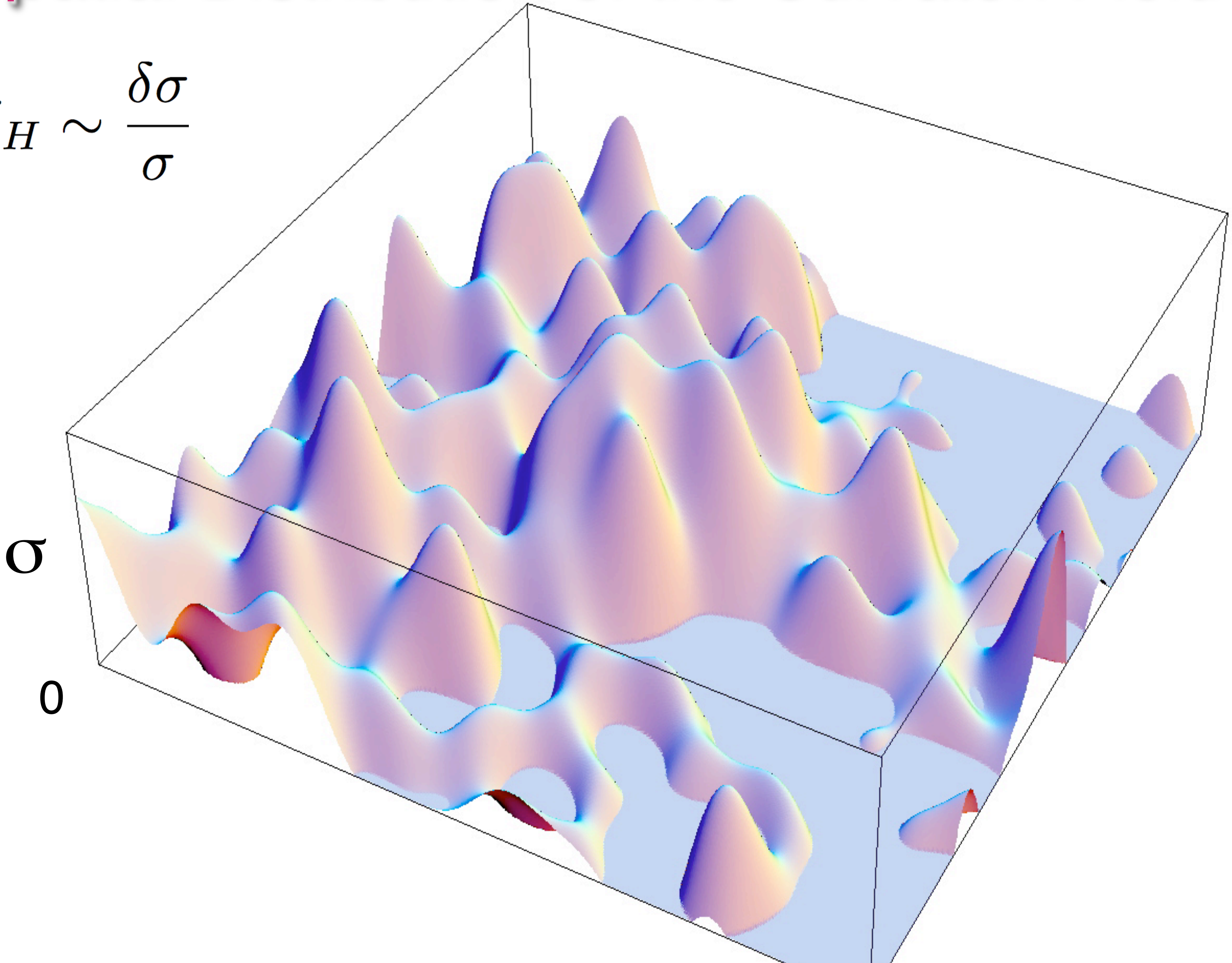
Isocurvature perturbations → adiabatic perturbations

$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$

σ is determined by quantum fluctuations, so the amplitude of perturbations is different in different places

Spatial Distribution of the Curvaton Field

$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$



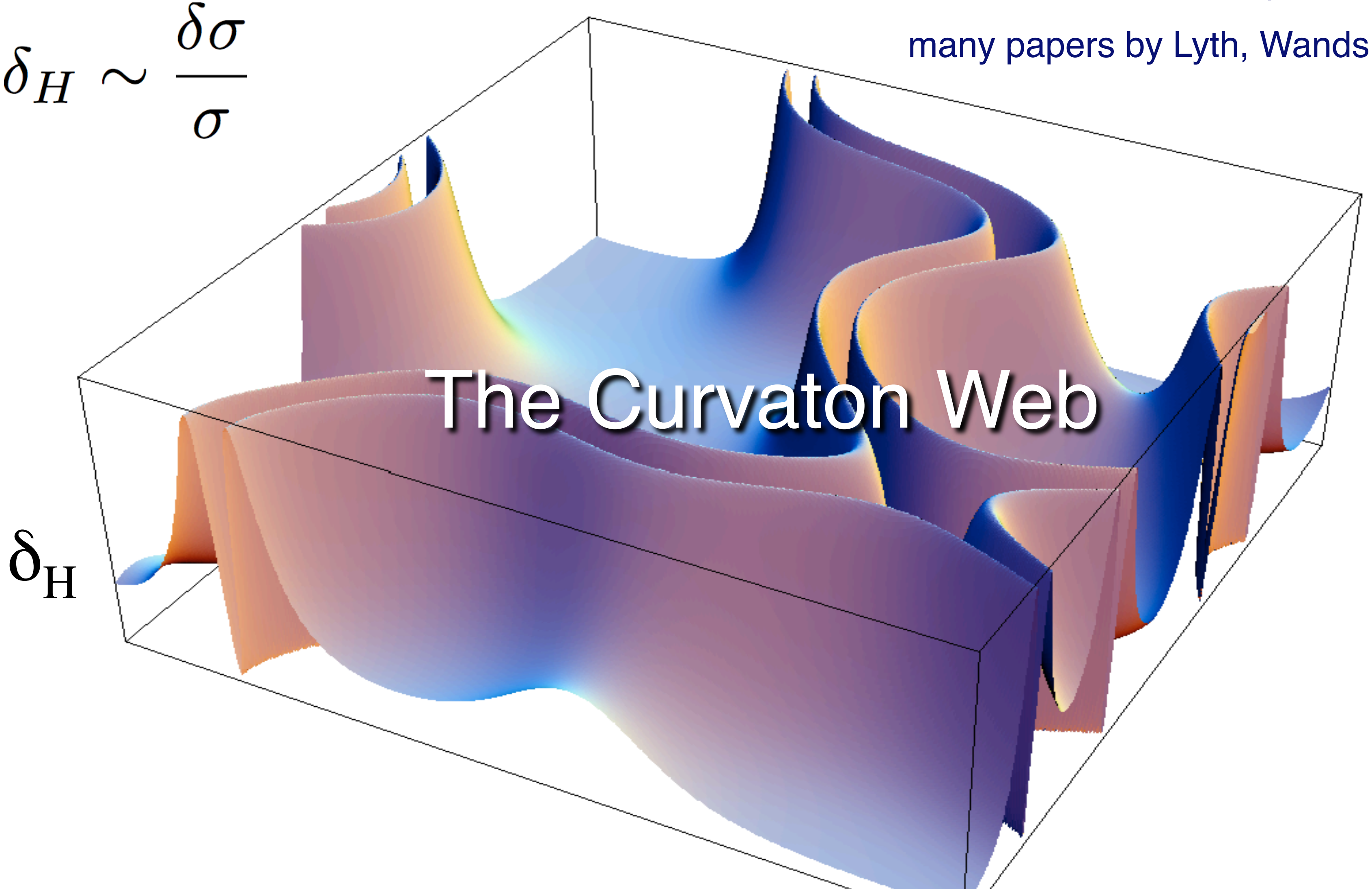
The Curvaton Web and Nongaussianity

Usually we assume that the amplitude of inflationary perturbations is constant, $\delta_H \sim 10^{-5}$ everywhere. However, in the curvaton scenario δ_H can be different in different parts of the universe. This is a clear sign of nongaussianity.

A.L., Mukhanov, astro-ph/0511736

many papers by Lyth, Wands, Sasaki

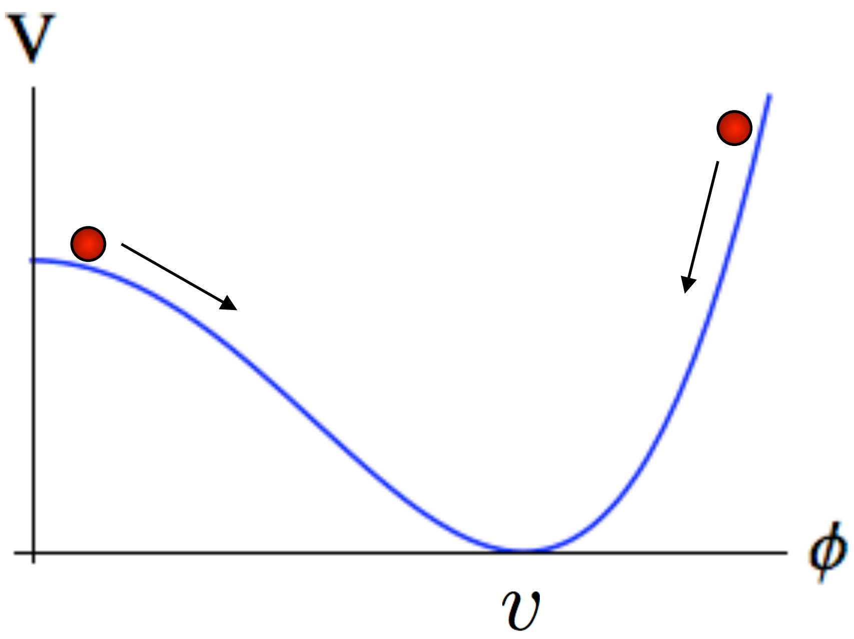
$$\delta_H \sim \frac{\delta\sigma}{\sigma}$$

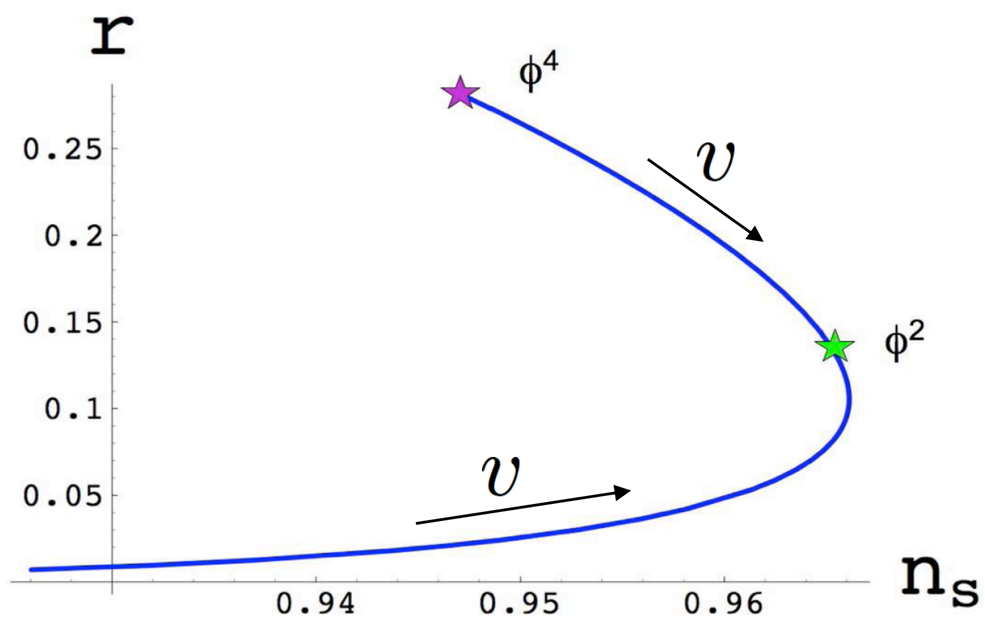


Tensor modes:

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

Kallosh, A.L. 2007

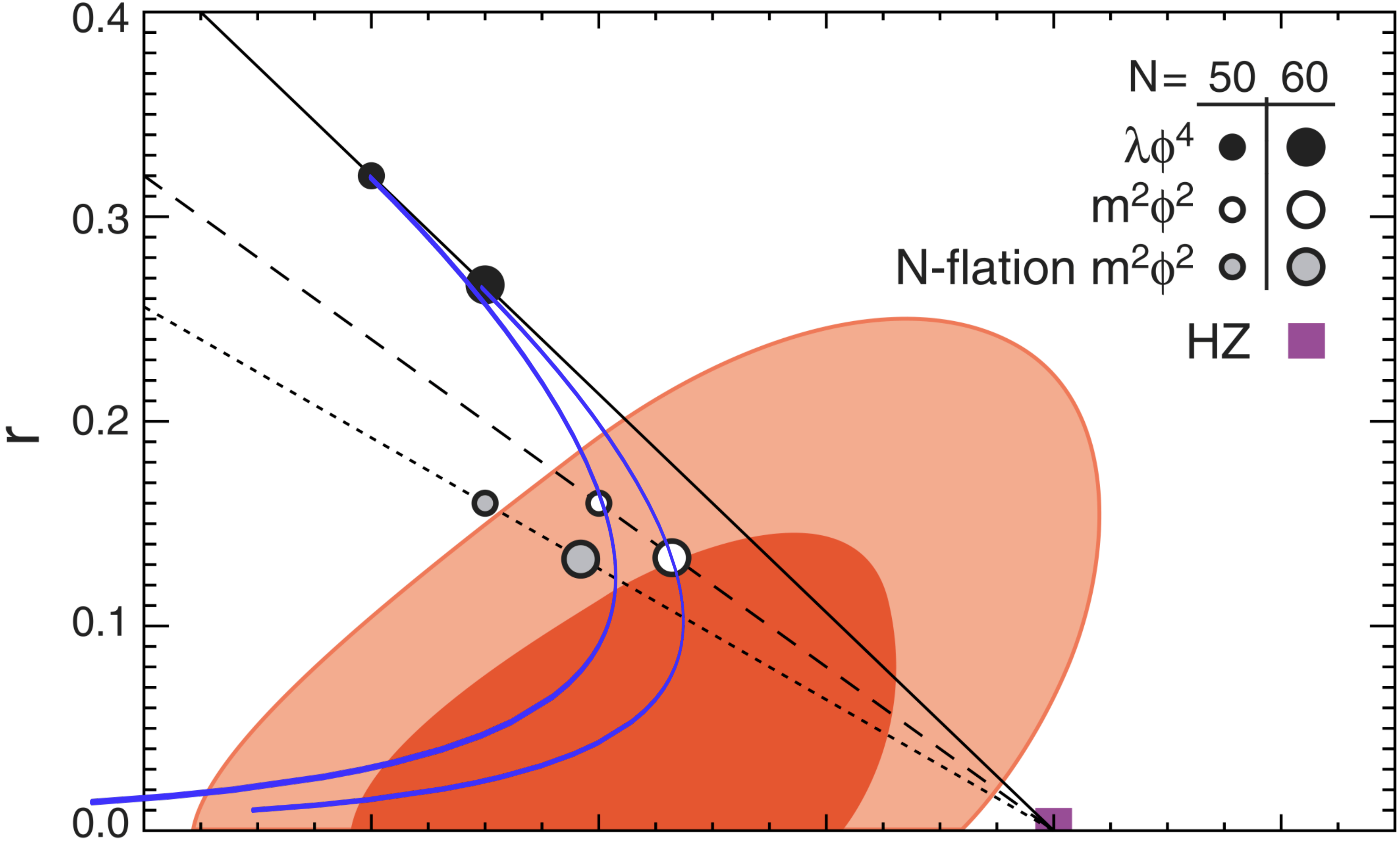




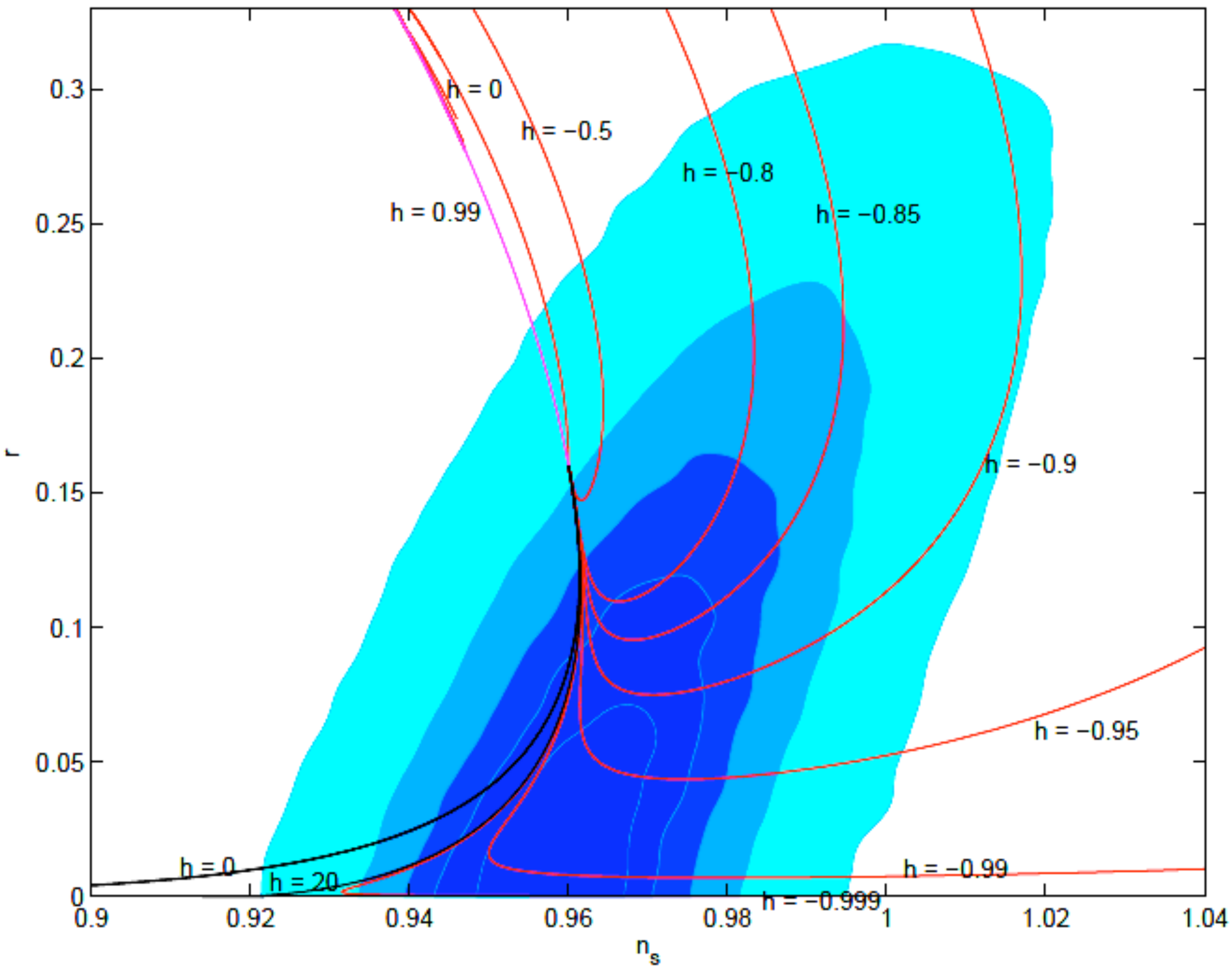
It <u>does</u> make sense to look for tensor modes even if none are found at the level r ~ 0.1 (Planck). Best bound now is r < 0.15.

Observers are more optimistic now than a year ago about the possibility to measure r at the level r ~ 0.01 after 2011

Chaotic Inflation



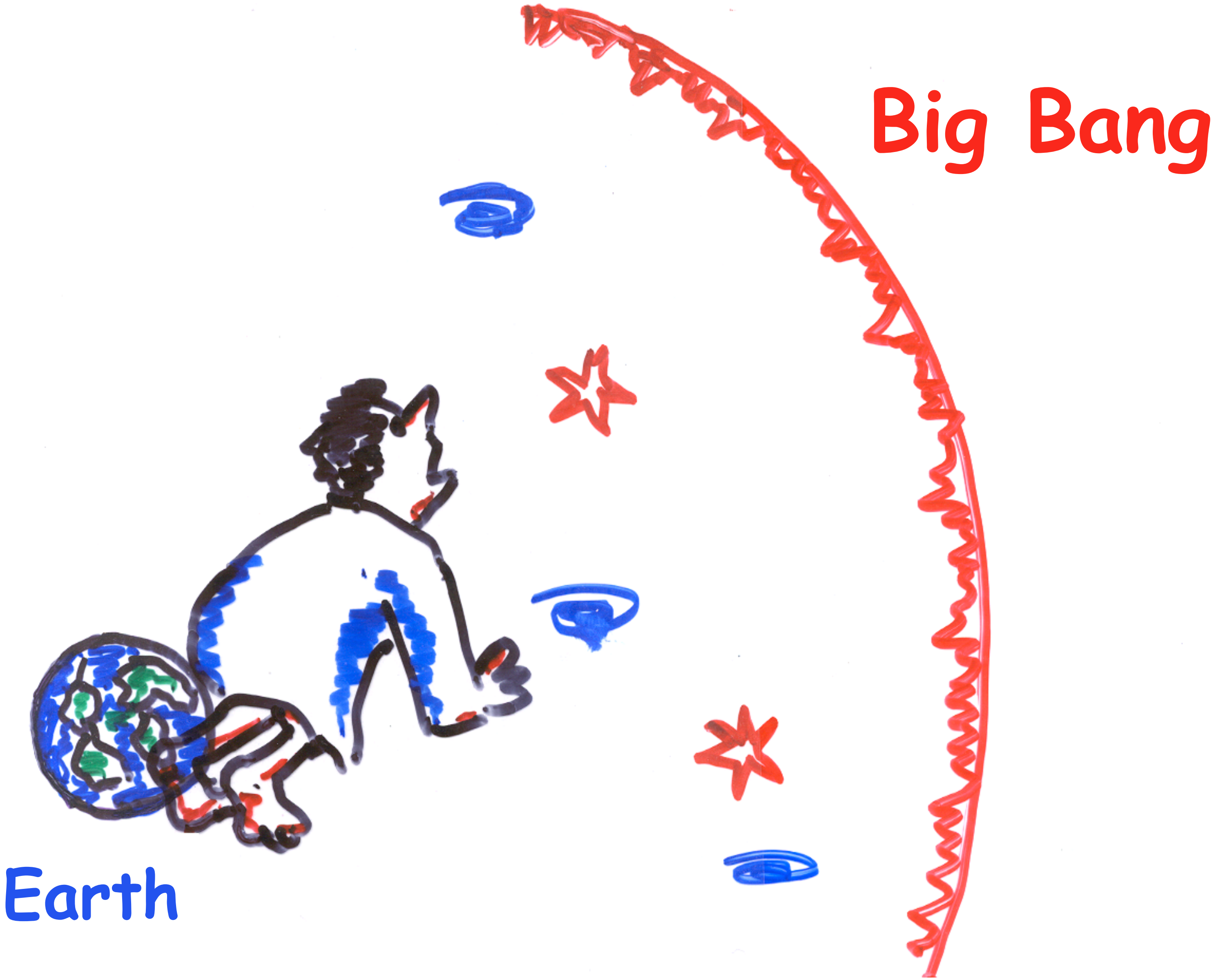
Blue lines – chaotic inflation with the simplest spontaneous symmetry breaking potential $-m^2\phi^2 + \lambda\phi^4$ for N = 50 and N = 60



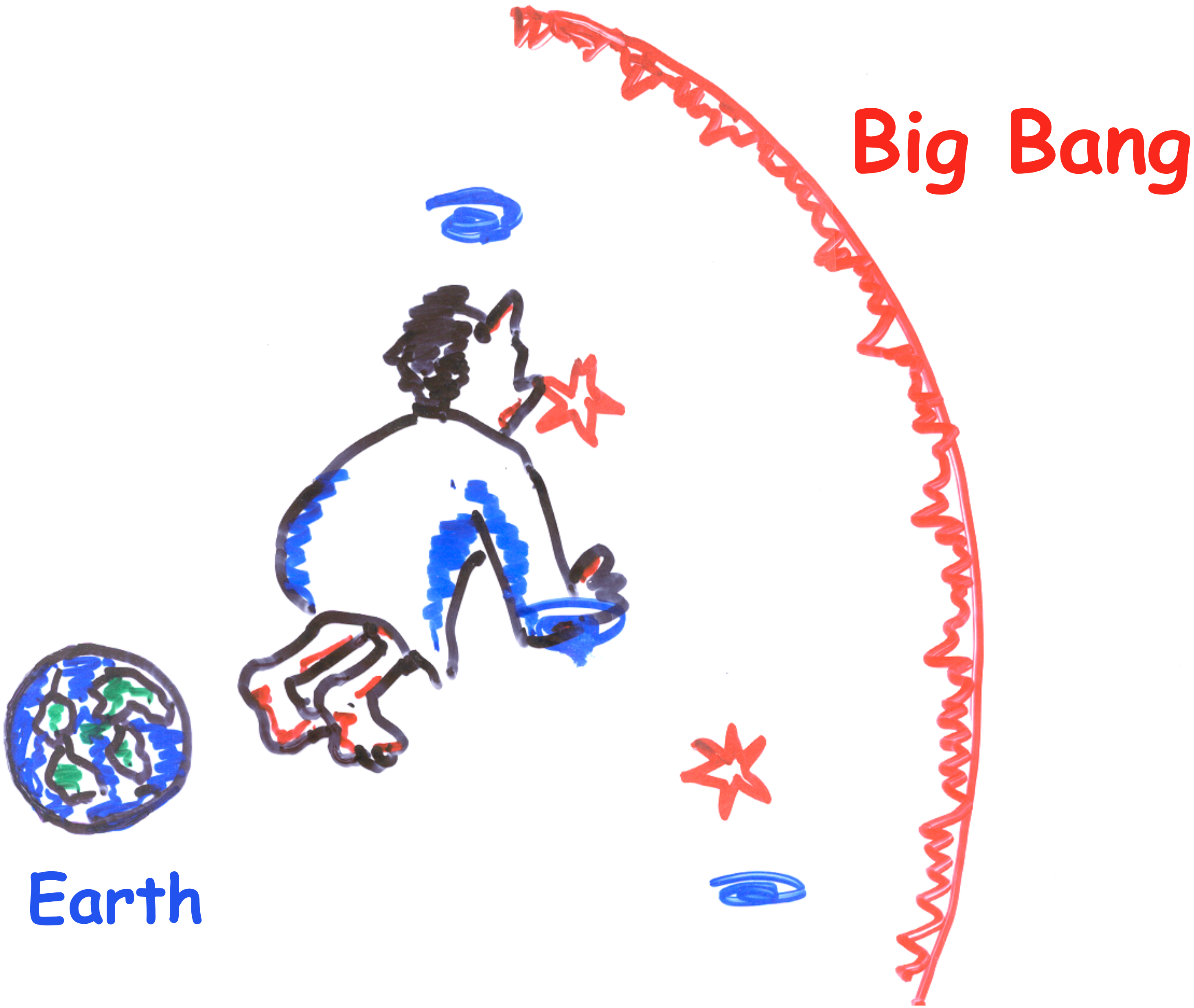
Destri, de Vega, Sanchez, 2007

Possible values of r and n_s for chaotic inflation with a potential including terms ϕ^2, ϕ^3, ϕ^4 for N = 50. The color-filled areas correspond to various confidence levels according to the WMAP3 and SDSS data.

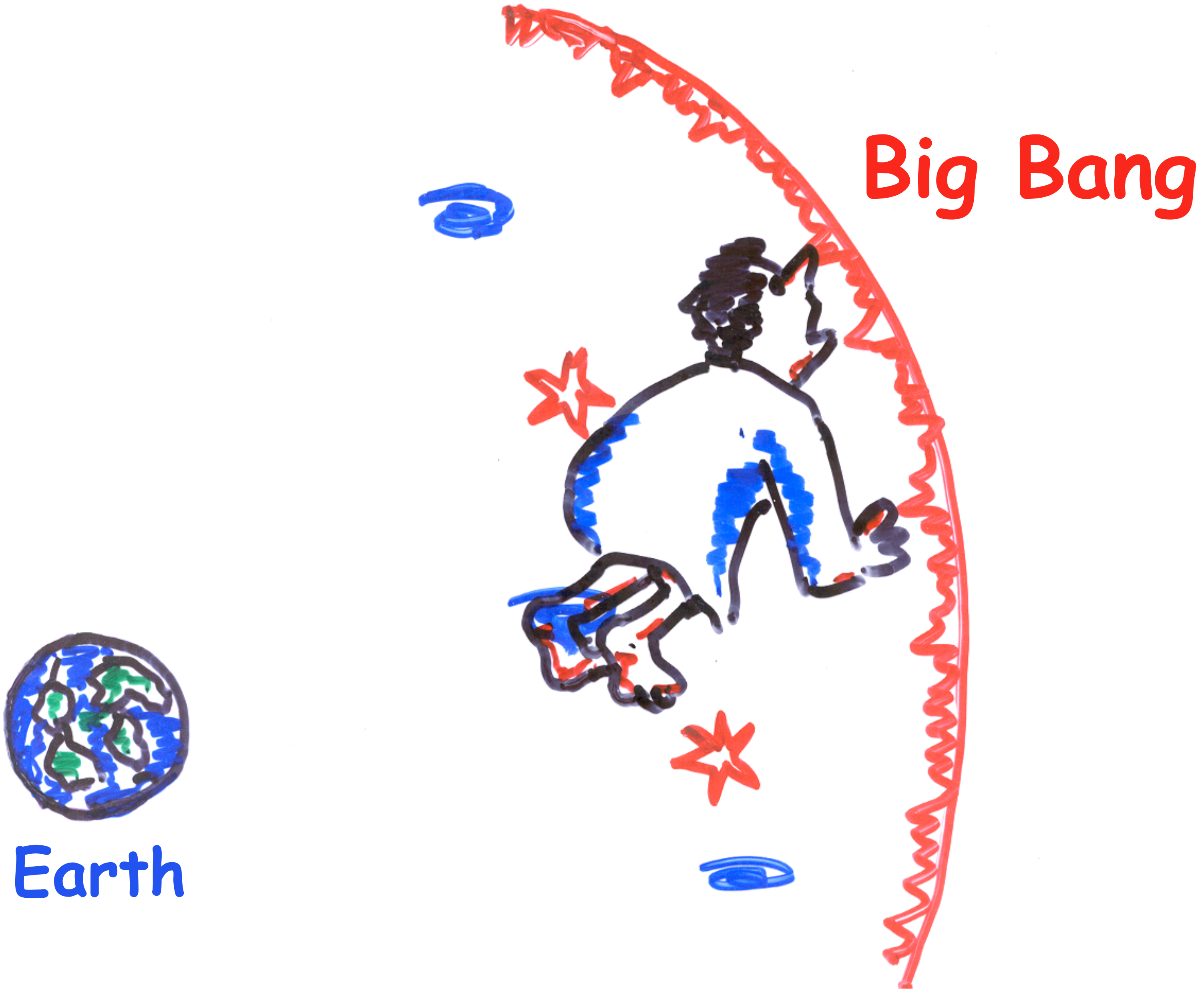
Almost all points in this area can be fit by chaotic inflation including terms ϕ^2, ϕ^3, ϕ^4



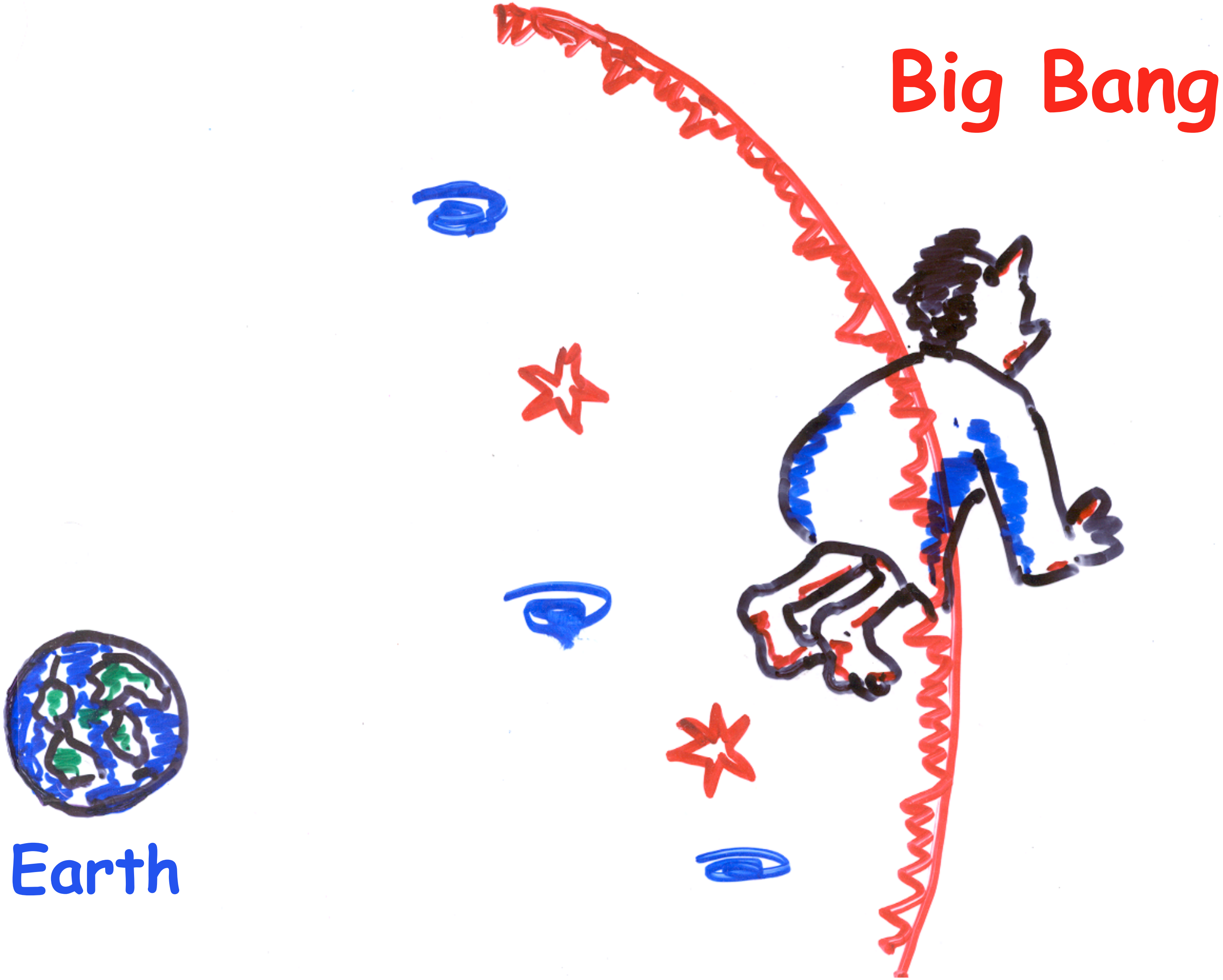
Astronomers use our universe as a “time machine”. By looking at the stars close to us, we see them as they were several hundreds years ago.



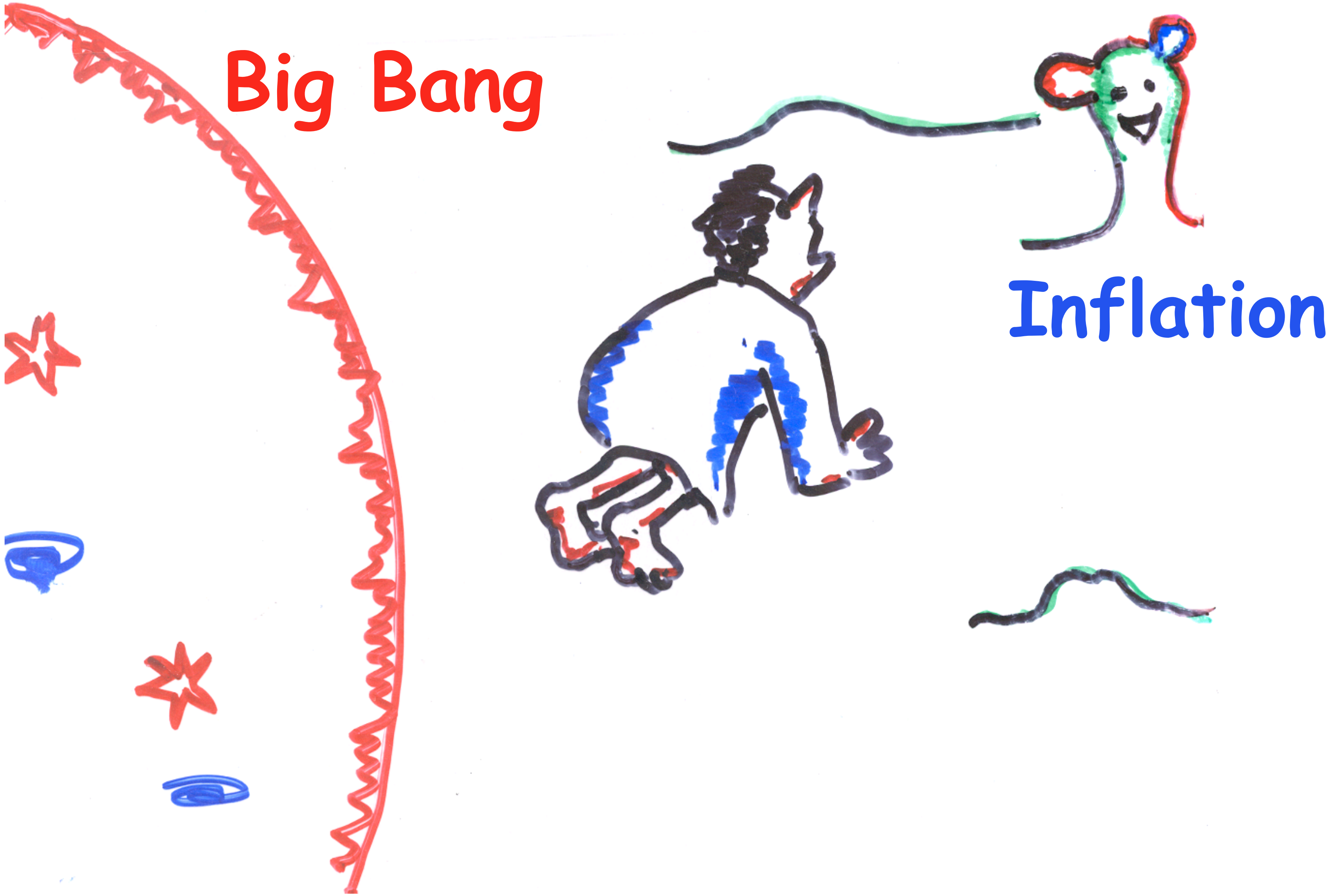
The light from distant galaxies travel to us for billions of years, so we see them in the form they had billions of years ago.



Looking even further, we can detect photons emitted 400000 years after the Big Bang. But 30 years ago everyone believed that there is nothing beyond the cosmic fire created in the Big Bang at the time t = 0.



Inflationary theory tells us that this cosmic fire was created not at the time t = 0, but after inflation. If we look beyond the circle of fire surrounding us, we will see enormously large empty space filled only by a scalar field.



If we look there very carefully, we will see small perturbations of space, which are responsible for galaxy formation. And if we look even further, we will see how new parts of inflationary universe are created by quantum fluctuations.

Chaotic 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…

A solution: shift symmetry

Kawasaki, Yamaguchi, Yanagida 2000

Equally good Kahler potential $K = \frac{1}{2}(\Phi + \bar{\Phi})^2 + X\bar{X}$

and superpotential $W = m\Phi X$

The potential is very curved with respect to X and Re Φ, so these fields vanish.

But Kahler potential does not depend on

$$\phi = \sqrt{2}\ \mathrm{Im}\,\Phi = (\Phi - \bar{\Phi})/\sqrt{2}$$

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

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

Volume stabilization

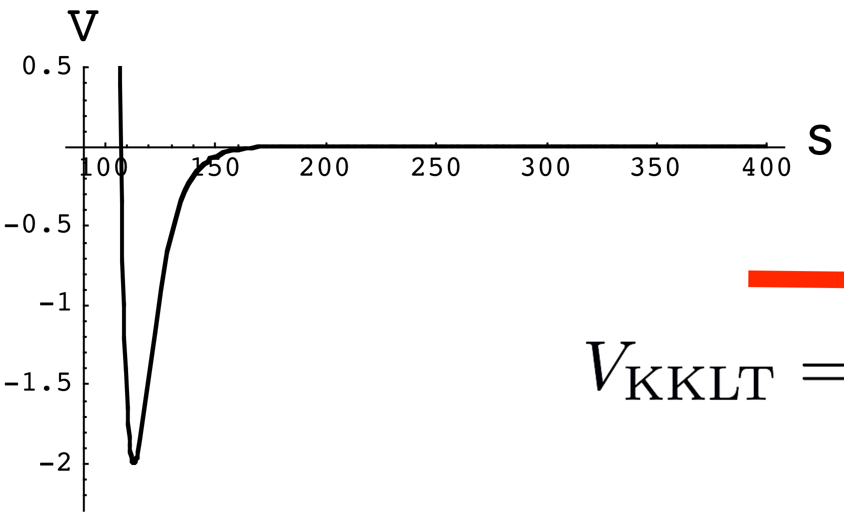
Kachru, Kallosh, A.L., Trivedi 2003

Basic steps of the KKLT scenario:

1) Start with a theory with runaway potential discussed above

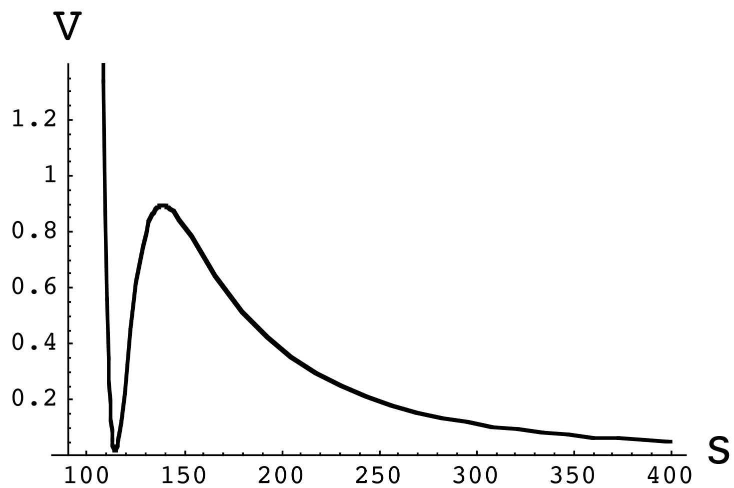
2) Bend this potential down due to (nonperturbative) quantum effects

3) Uplift the minimum to the state with positive vacuum energy by adding a positive energy of an anti-D3 brane in warped Calabi-Yau space



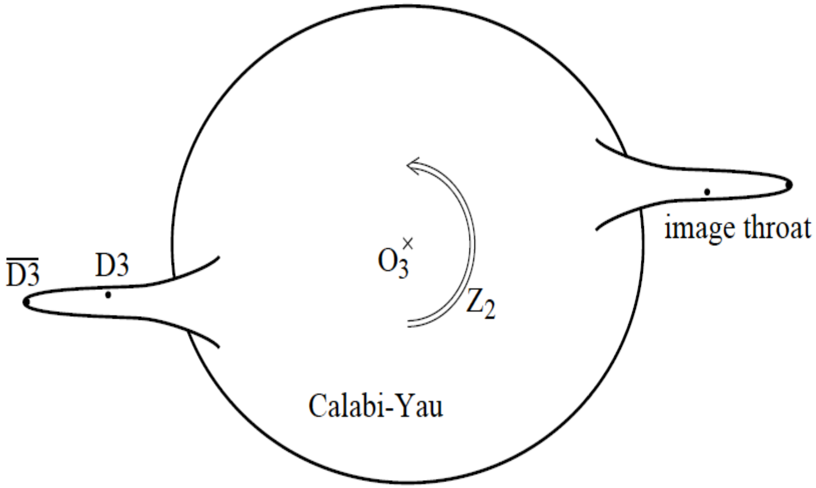
AdS minimum

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

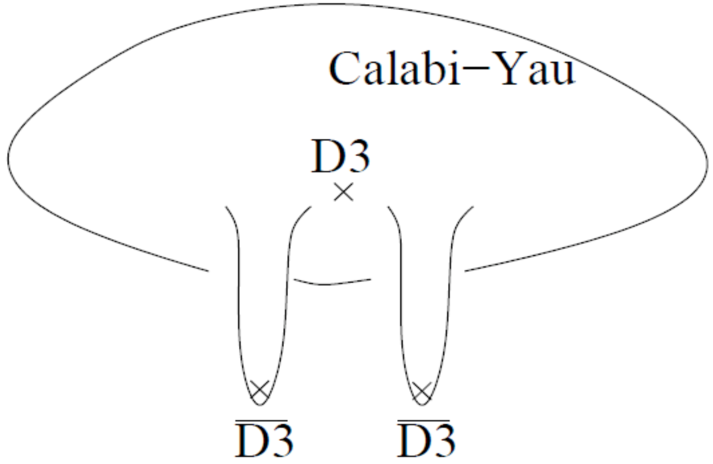


Metastable dS minimum

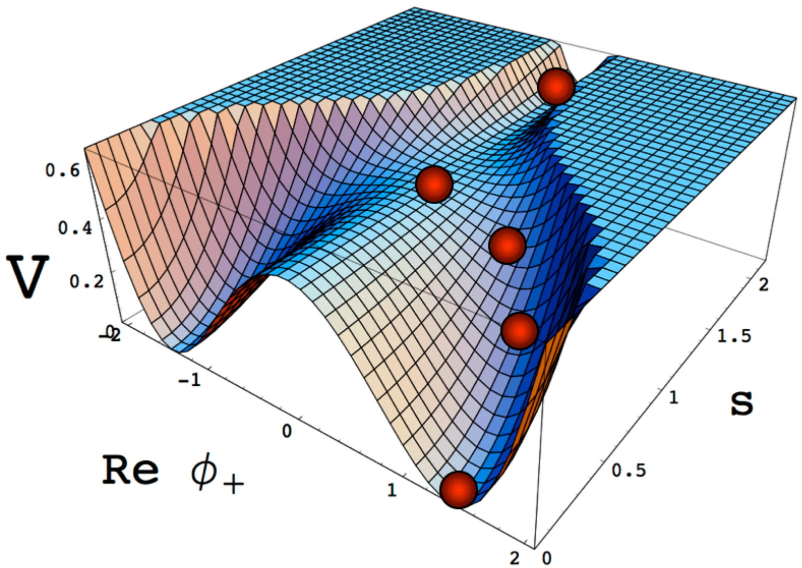
Brane Inflation in string theory



KKLMMT brane-anti-brane inflation



Two-throat model



Hybrid D3/D7 brane inflation

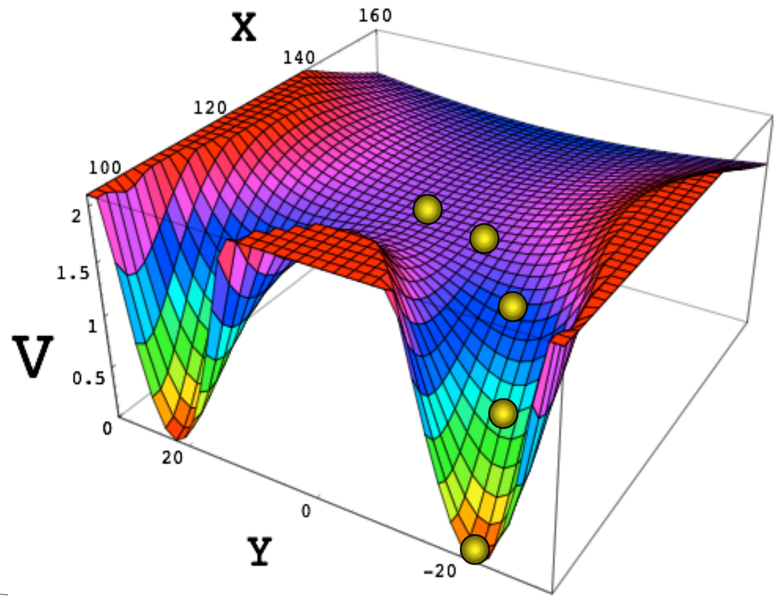
(Stringy D-term inflation)

Dirac-Born-Infeld inflation

$$\sqrt{1 + f(\phi) g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi}$$

Nil manifold inflation
Gravity waves!

Modular Inflation models



Racetrack inflation

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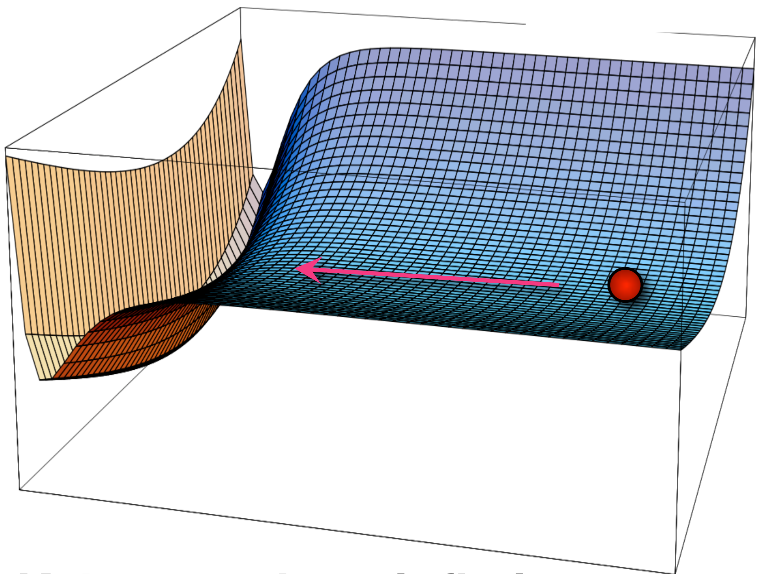
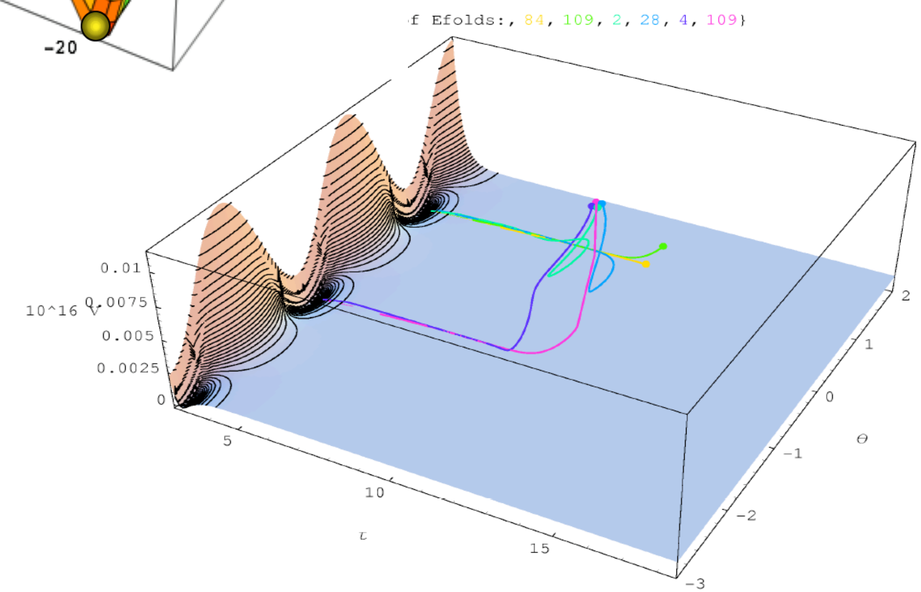


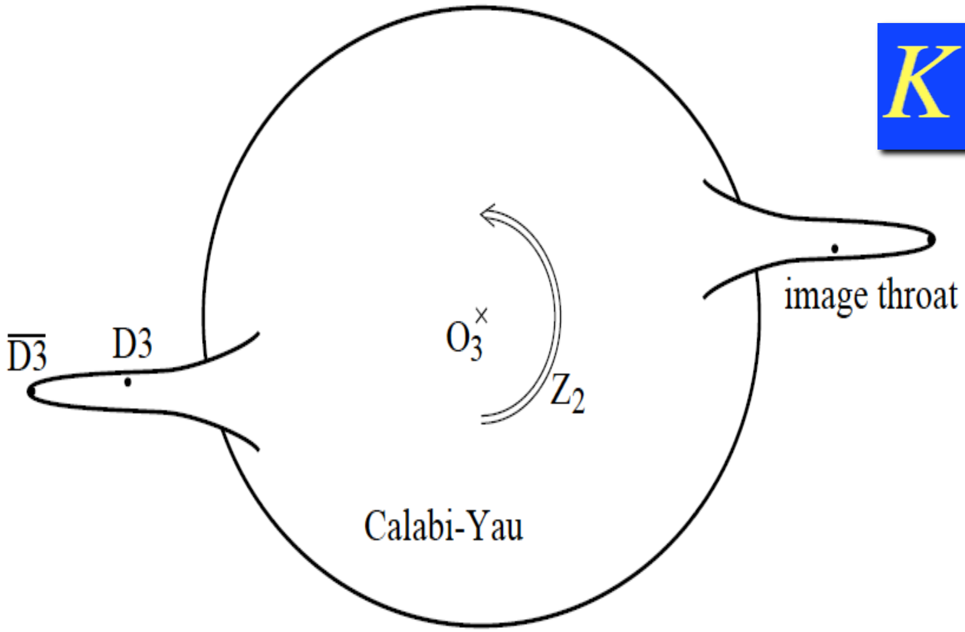
Kahler modular inflation



Roulette inflation

The KLMT model

Kachru, Kallosh, A.L., Maldacena, McAllister, and Trivedi 2003



$$K = -3\log(\rho + \bar{\rho} - \phi\bar{\phi})$$

$$W = W_0 + e^{-a\rho}$$

$$m_\phi^2 = 2H^2$$

Meanwhile for inflation with a flat spectrum of perturbations one needs

$$m_\phi^2 \sim 10^{-2} H^2$$

This can be achieved by taking W depending on ϕ and by fine-tuning it at the 1% level. Later I will say about recent developments of this model.

Racetrack Inflation

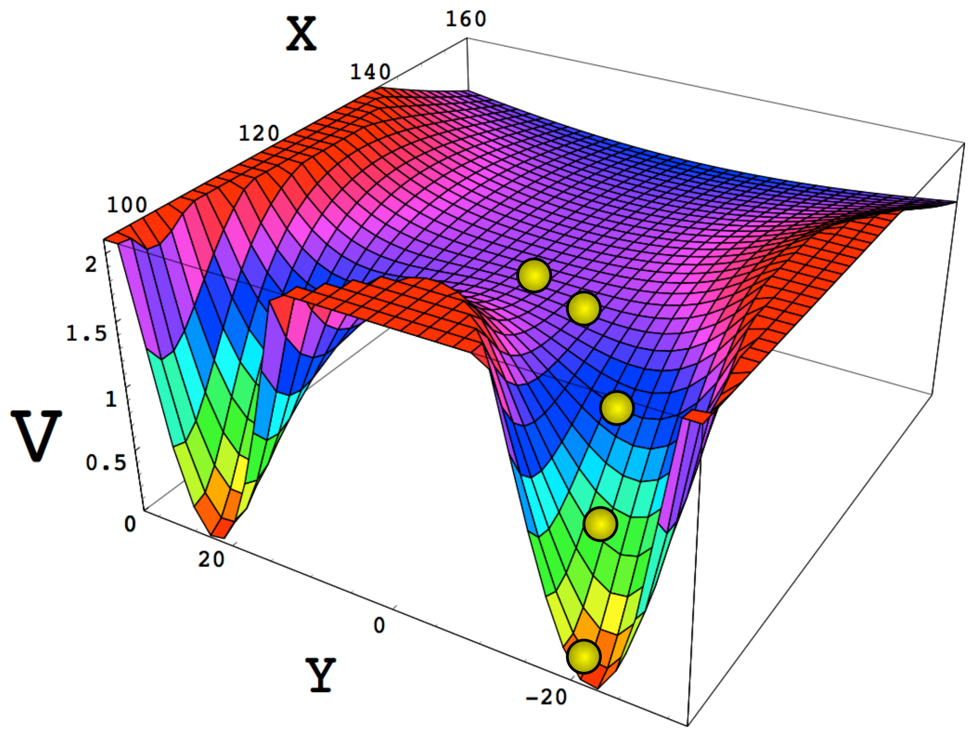
the first working model of the **moduli inflation**

Blanco-Pilado, Burgess, Cline, Escoda, Gomes-Reino, Kallosh, AL, Quevedo

Superpotential: $W = W_0 + A\, e^{-aT} + B\, e^{-bT}$

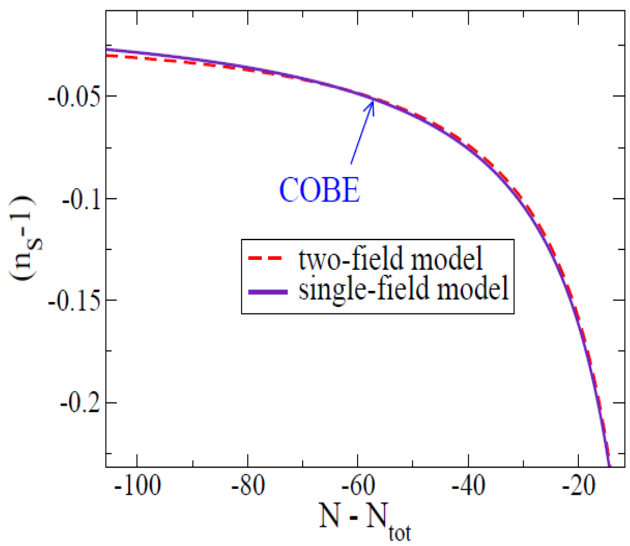
Kahler potential: $K = -3 \log(T + T^*)$

$$A = \frac{1}{50}, \qquad B = -\frac{35}{1000}, \qquad a = \frac{2\pi}{100}, \qquad b = \frac{2\pi}{90}, \qquad W_0 = -\frac{1}{25000}$$

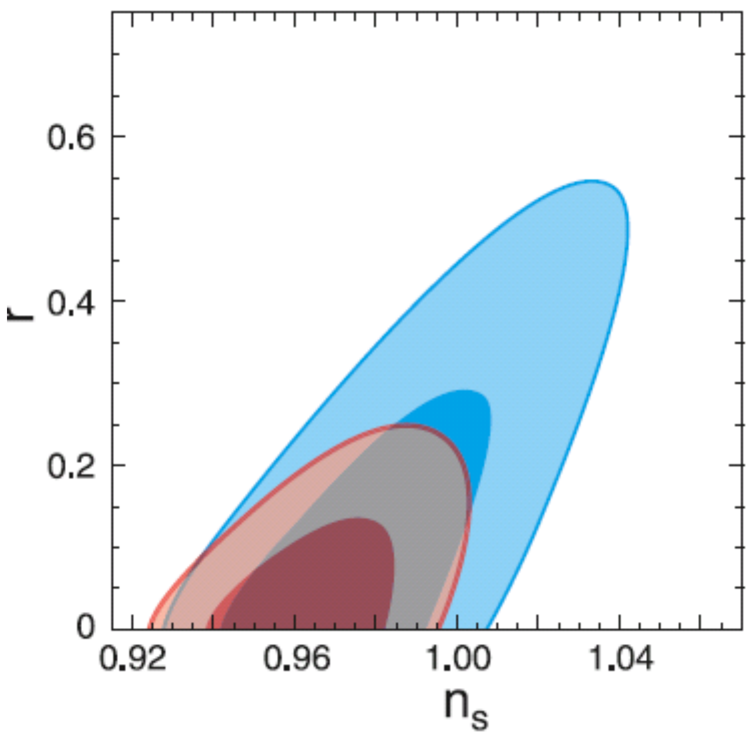


waterfall from the saddle point

Racetrack Inflation



Spectral index as a function of the number of e-foldings (minus the total number of e-foldings)



No cosmic strings

n_s=0.95

No grav. waves

A toy model of SUGRA inflation:

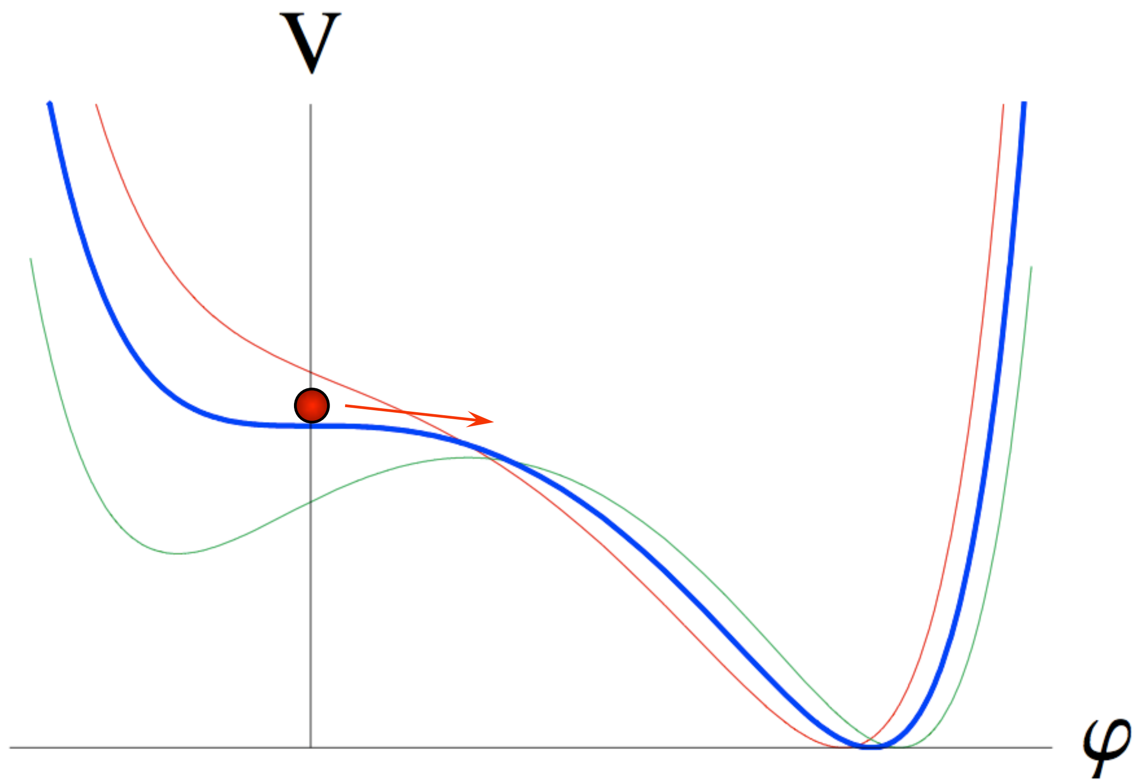
Holman, Ramond, Ross, 1984

Superpotential: $$W = c\,(\Phi - \Phi_0)^2$$

Kahler potential: $$K = \Phi\bar{\Phi}$$

Inflation occurs for $\Phi_0 = 1$

Requires fine-tuning, but it is simple, and it works

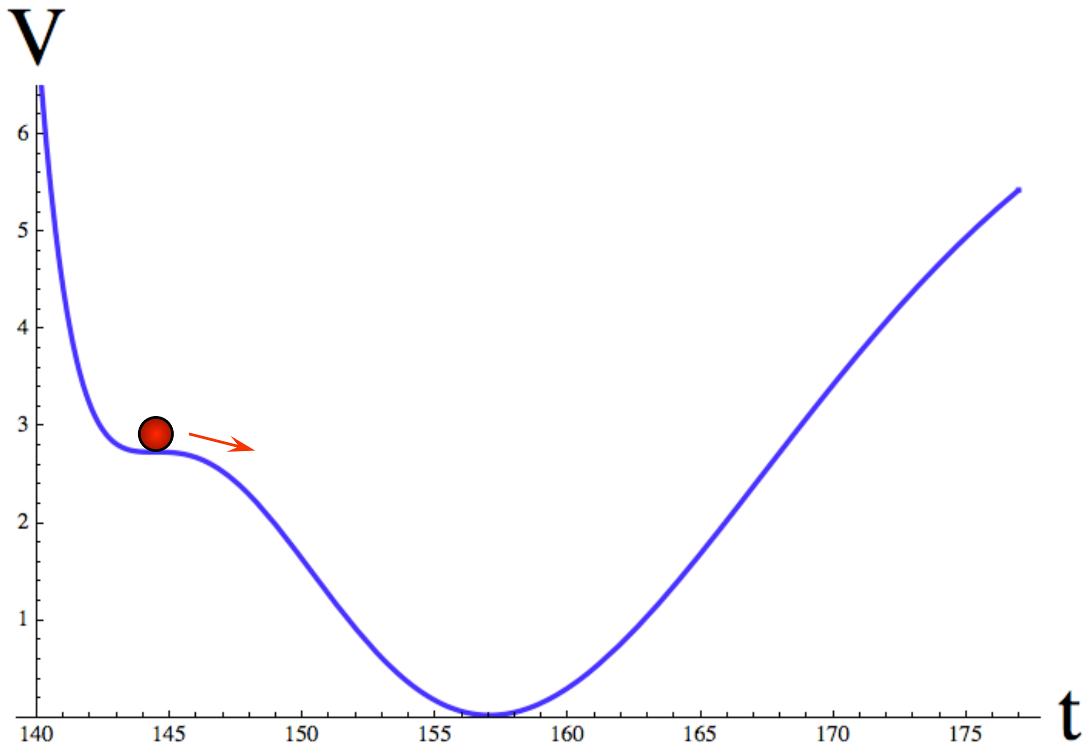


A toy model of string inflation:

A.L., Westphal, 2007

Superpotential: $$W = W_0 + A\,e^{-aT} + B\,e^{-bT}$$

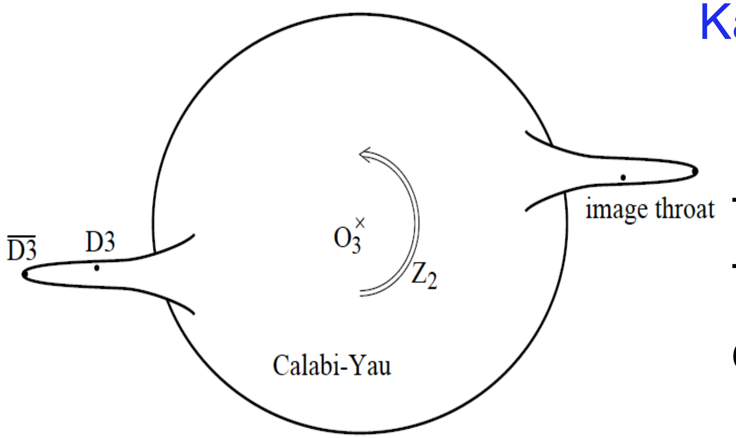
Kahler potential: $$K = -3\log(T + T^*)$$



Volume modulus inflation

Requires fine-tuning, but works without any need to study complicated brane dynamics

Update on the KKLMMT model, 2008



Kachru, Kallosh, AL, Maldacena, McAllister, Trivedi 2003

Relatively simple, directly follows from KKLT, but the inflaton mass generically $O(H^2)$. One may try to cancel this mass by adding quantum corrections $\sim \phi^2$, but it requires fine-tuning

Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan, Steinhardt, 2007

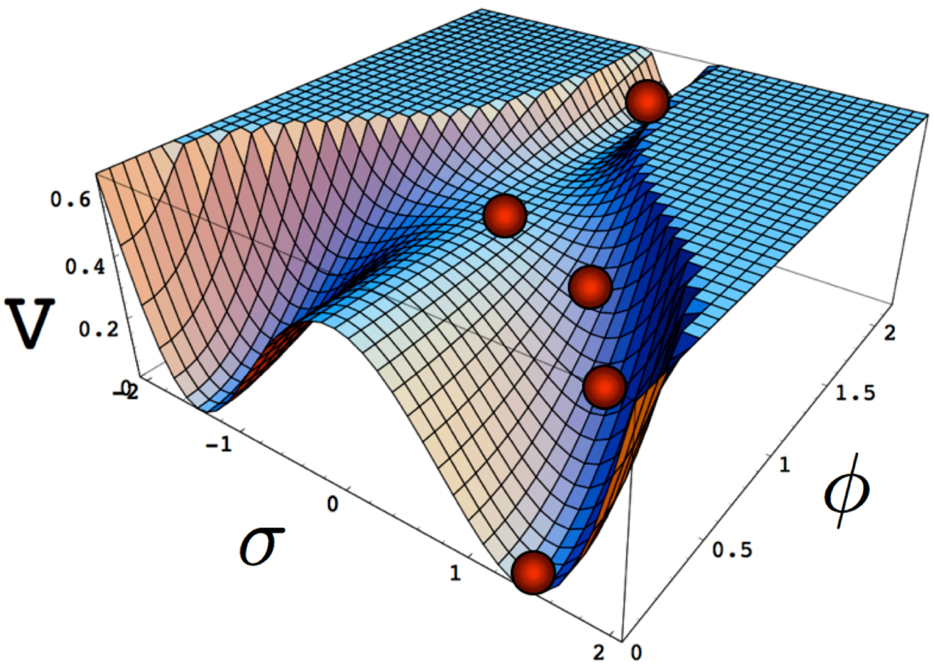
One does not have terms ϕ^2, only $\phi^{3/2}$. Inflation is possible near the inflection point of the potential, as in the model shown in the previous slide.

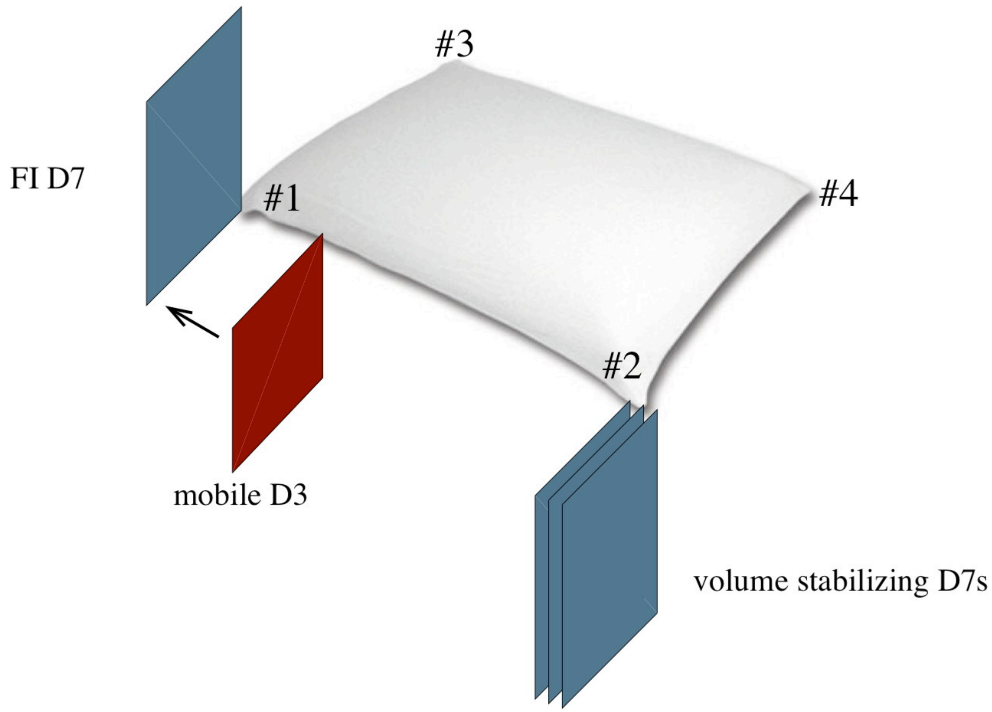
Baumann, Dymarsky, Kachru, Klebanov, McAllister, arXiv:0808.2811

If there are some discrete symmetries, the term $\phi^{3/2}$ is absent. Then one can fine-tune terms ϕ^2 and the original KKLMMT scenario with the tuned inflaton mass is valid.

D3/D7 hybrid inflation

Haack, Kallosh, Krause, AL, Lust, Zagermann 2008



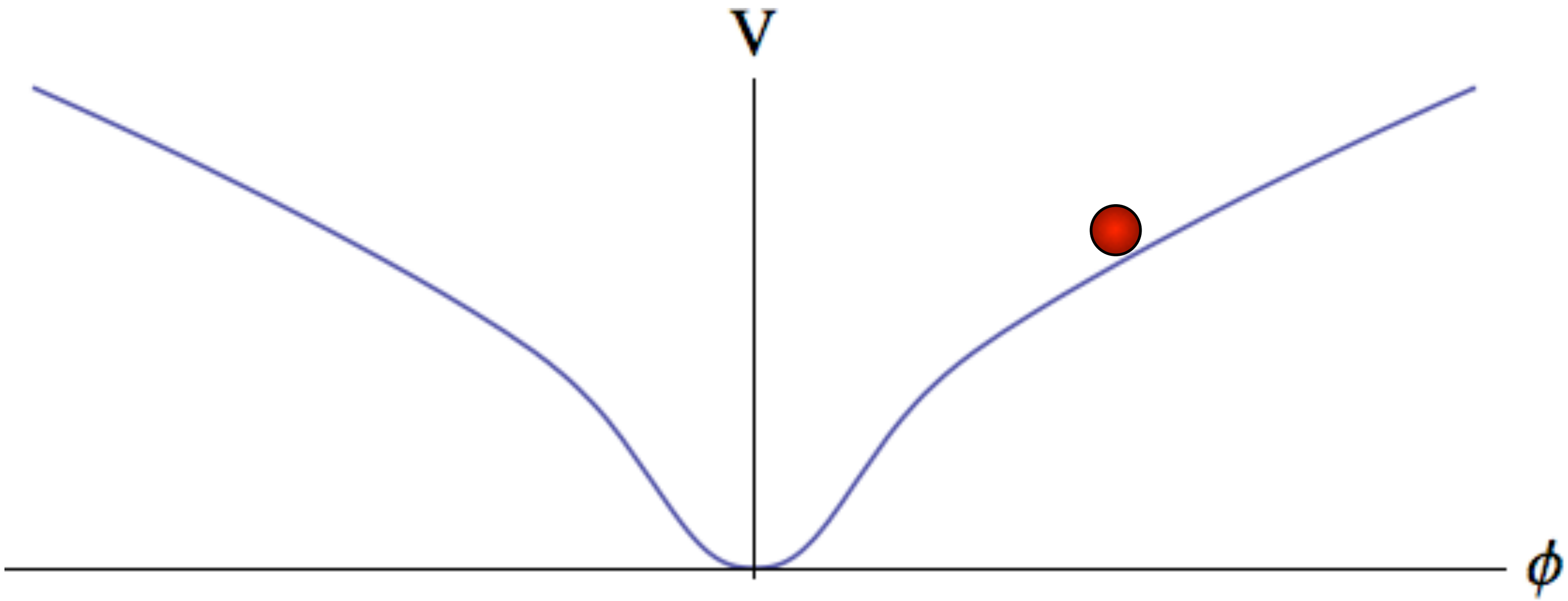


Naturally flat inflaton direction, string theory corrections can be computed and are under control, eternal inflation regime, one can get $n_s = 1$ and a controllably small amount of cosmic strings. This possibility nicely fits the observational data.

Can we have chaotic inflation in string theory?

The answer is “yes”; the potential is ϕ^2 at small ϕ and $\phi^{2/3}$ at large ϕ:

Silverstein, Westphal, 2008



Type IIA models, based on Nil manifolds, rather than on the CY spaces. Large SUSY breaking.

Gravity Waves from Monodromies

Silverstein, Westphal, 2008
McAllister, Silverstein, Westphal, 2008

tensor/scalar

- Lyth bound: $\frac{\Delta\phi}{M_P} \sim \left(\frac{r}{0.01}\right)^{1/2} \geq 1 \Leftrightarrow \begin{cases} \text{observable!} \\ \text{UV sensitive} \end{cases}$

chaotic inflation [Linde '83]
natural inflation [Freese et al. '90]

$\Rightarrow$ $\Delta\phi > M_P$ protected by symmetry:
Can this arise naturally in string theory?

- **Yes:** Monodromy $\begin{cases} \text{would-be periodic direction (brane position, axions, ...)} \\ \textbf{not} \text{ periodic in presence of } \textbf{wrapped} \text{ brane:} \end{cases}$

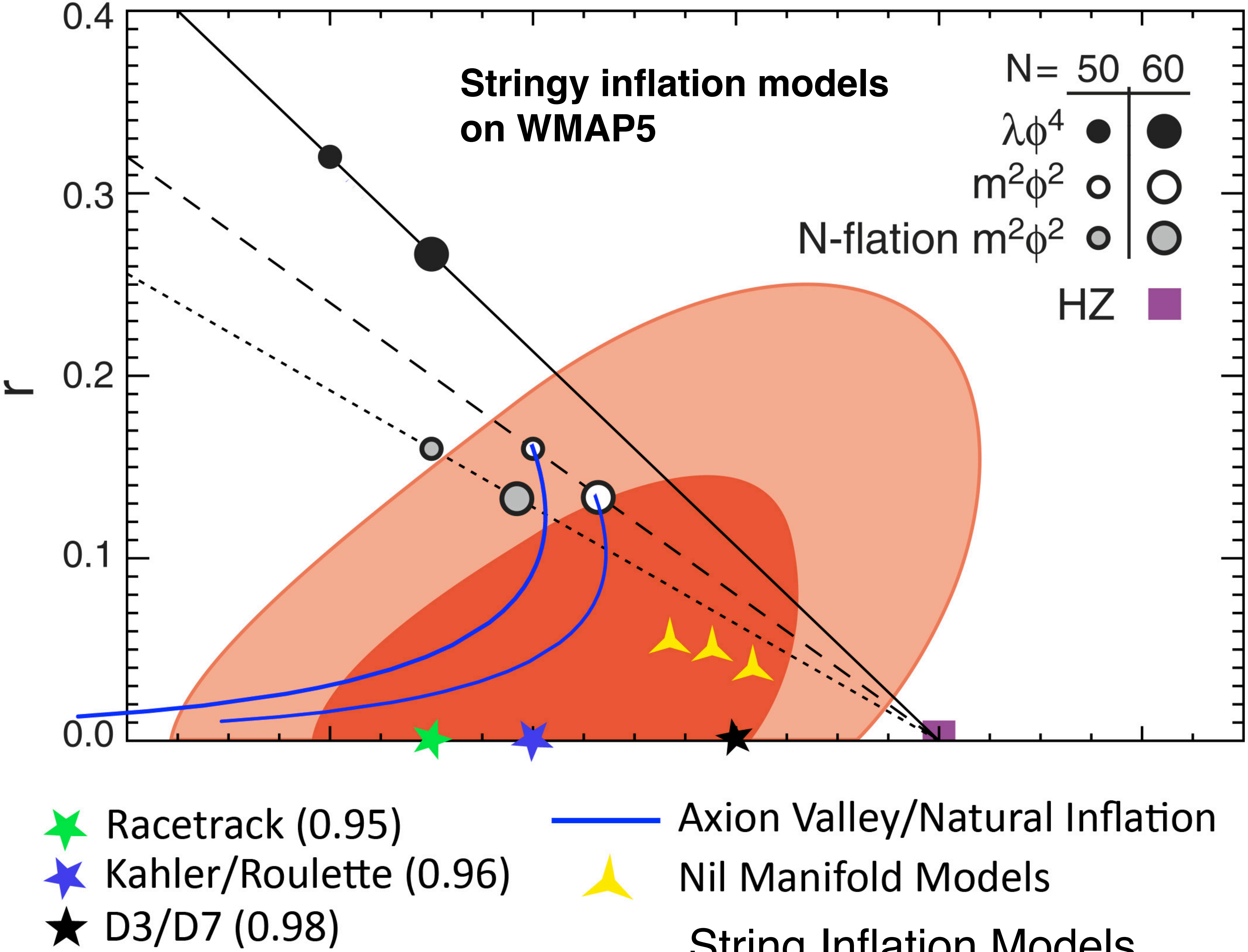
$\rightarrow$ kinematically unbounded field range; potential from brane action:

$$\mathcal{L} \sim \begin{cases} u\dot{u}^2 - \sqrt{1+u^2} \Rightarrow V(\phi) \sim \phi^\alpha\,,\ \alpha = 2/3\,, & \text{Nil manifold} \\ f_a^2 \dot{a}^2 - \sqrt{\ell^4 + a^2} \Rightarrow V(\phi) \sim \phi^\alpha\,,\ \alpha = 1\,, & \text{axions in e.g. CYs} \end{cases}$$

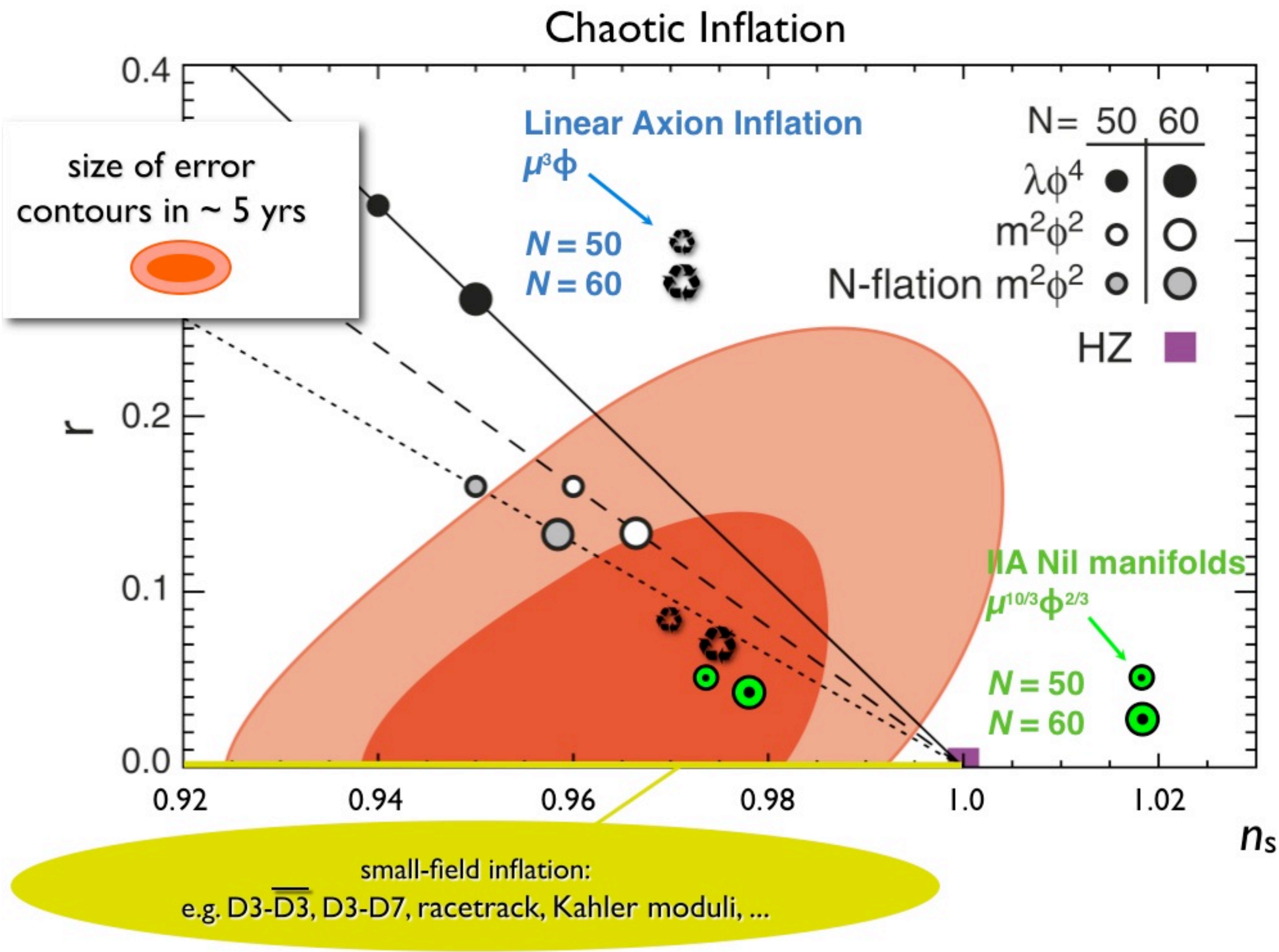
- Systematic control:

predictive: $n_s = 0.98 \quad r = 0.04$
$n_s = 0.975 \quad r = 0.07$

shift symmetry weakly broken by $V(\phi)$;
Nil manifold case: simple & explicit construction, $O(1\%)$ tuning
Calabi-Yau case: holomorphy & exponential suppression of instantons
control corrections naturally for axion monodromies



String Inflation Models

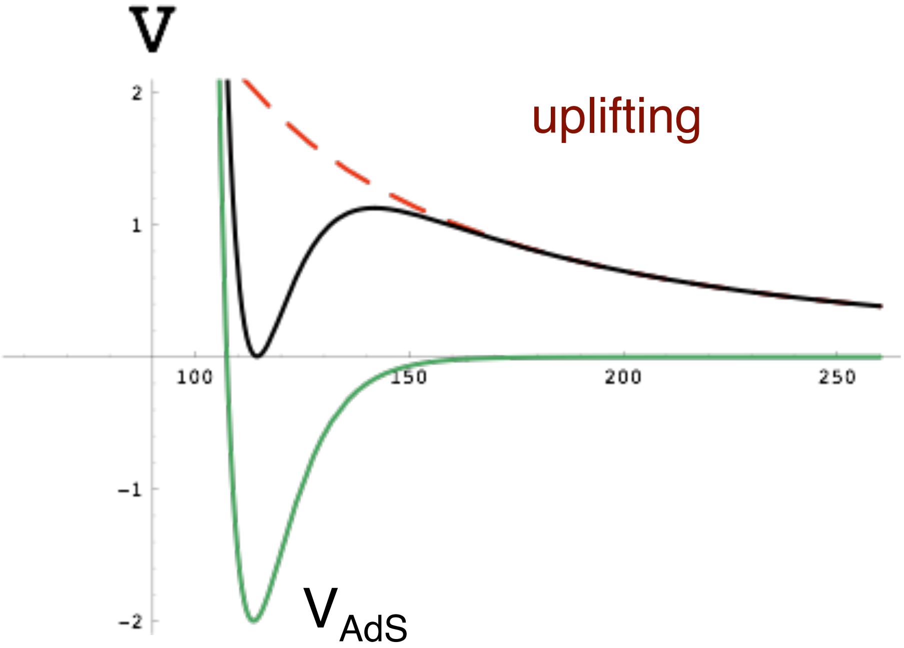


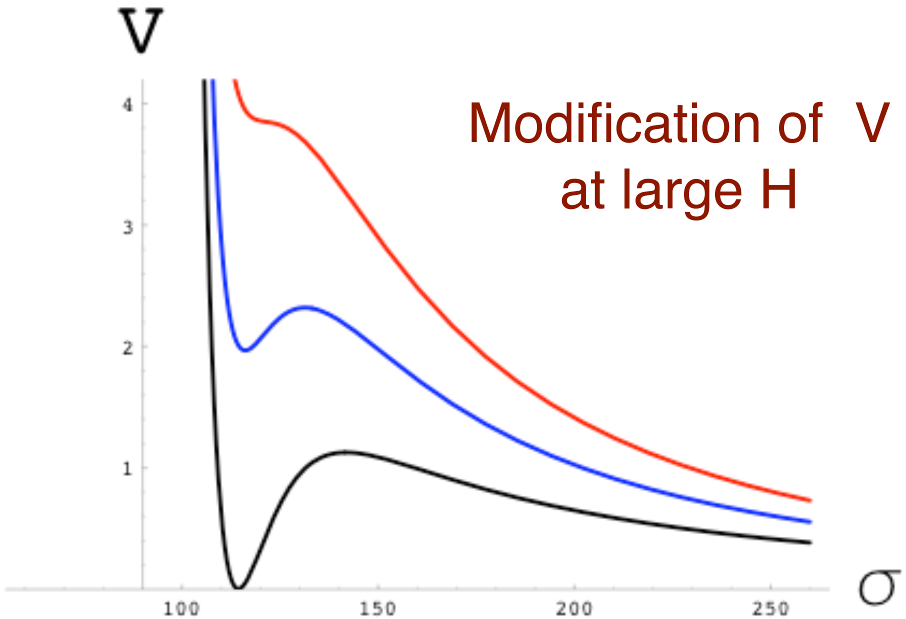
Chaotic Inflation
size of error
contours in ~ 5 yrs
Linear Axion Inflation
μ³φ
N = 50
N = 60
N= 50 60
λφ⁴
m²φ²
N-flation m²φ²
HZ
IIA Nil manifolds
μ^{10/3}φ^{2/3}
N = 50
N = 60
r
0.4
0.2
0.1
0.0
0.92
0.94
0.96
0.98
1.0
1.02
n_s
small-field inflation:
e.g. D3-D3, D3-D7, racetrack, Kahler moduli, ...

String Cosmology and the Gravitino Mass

Kallosh, A.L. 2004

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





Constraint on the Hubble constant in this class of models:

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

Can we avoid these conclusions?

Recent model of chaotic inflation is string theory (Silverstein and Westphal, 2008) also requires $H < m_{3/2}$.

In more complicated theories one can have $H \gg m_{3/2}$. But this requires fine-tuning (Kallosh, A.L. 2004, Badziak, Olechowski, 2007)

In models with large volume of compactification (Quevedo et al) the situation is even more dangerous: $H < m_{3/2}^{3/2} < 1\ KeV$

It is possible to solve this problem, but it is rather nontrivial, and, once again, requires fine tuning.

Conlon, Kallosh, A.L., Quevedo, 2008

Remember that we are suffering from the light gravitino and the cosmological moduli problem for the last 25 years.

The problem which we discussed is especially difficult in the models with very light gravitino.

For example, in the conformal gauge mediation with gravitino mass O(1) eV one would need to have inflation with **H < 1 eV**, which is a real challenge!

The price for the SUSY solution of the hierarchy problem is high, and it is growing. Split supersymmetry? Anything else?

We are waiting for LHC...

Tensor Modes and GRAVITINO

$$r \sim 10^8 H^2$$

$$H \leq M_{3/2}$$

$$r \leq 10^8 \; M_{3/2}^2$$

Kallosh, A.L. 2007

$$r \sim 10^{-2} \longrightarrow M_{3/2} \sim 10^{13} GeV$$

superheavy gravitino

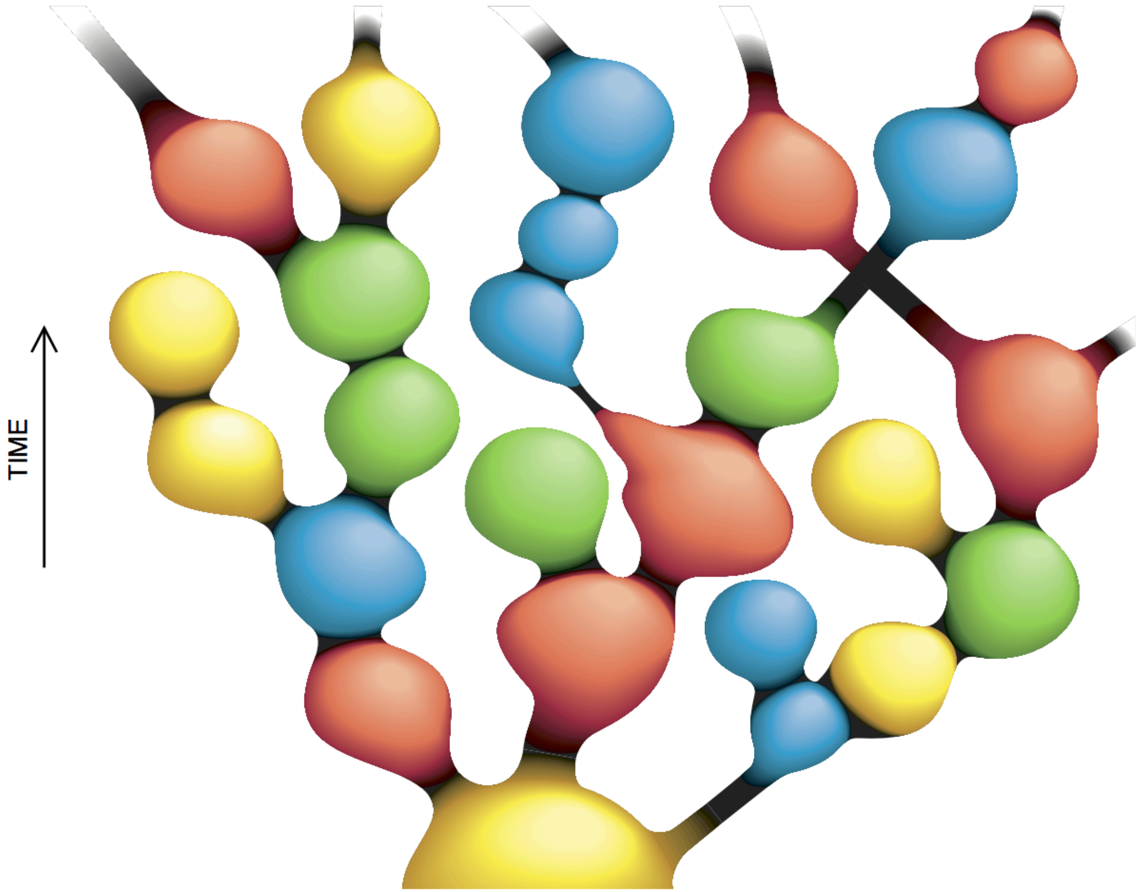
$$M_{3/2} \sim 1 TeV \longrightarrow r \sim 10^{-24}$$

unobservable

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

Inflationary Multiverse

Inflationary universe may consist of many parts with different properties depending on the local values of the scalar fields, compactifications, etc.



Perhaps 10^{1000} different uplifted vacua

Lerche, Lust, Schellekens 1986

Bousso, Polchinski 2000; KKLT 2003; Susskind 2003; Douglas, Denef 2003

Eternal inflation and string theory landscape

An 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

Now, Dr. Witten allowed, dark energy might have transformed this from a vice into a virtue, a way to generate universes where you can find any cosmological constant you want. We just live in one where life is possible, just as fish only live in water.

The New York Times

June 3, 2008

Example: Dark matter in the axion field

Old lore: If the axion mass is smaller than 10^{-5} eV, the amount of dark matter in the axion field contradicts observations, for a typical initial value of the axion field.

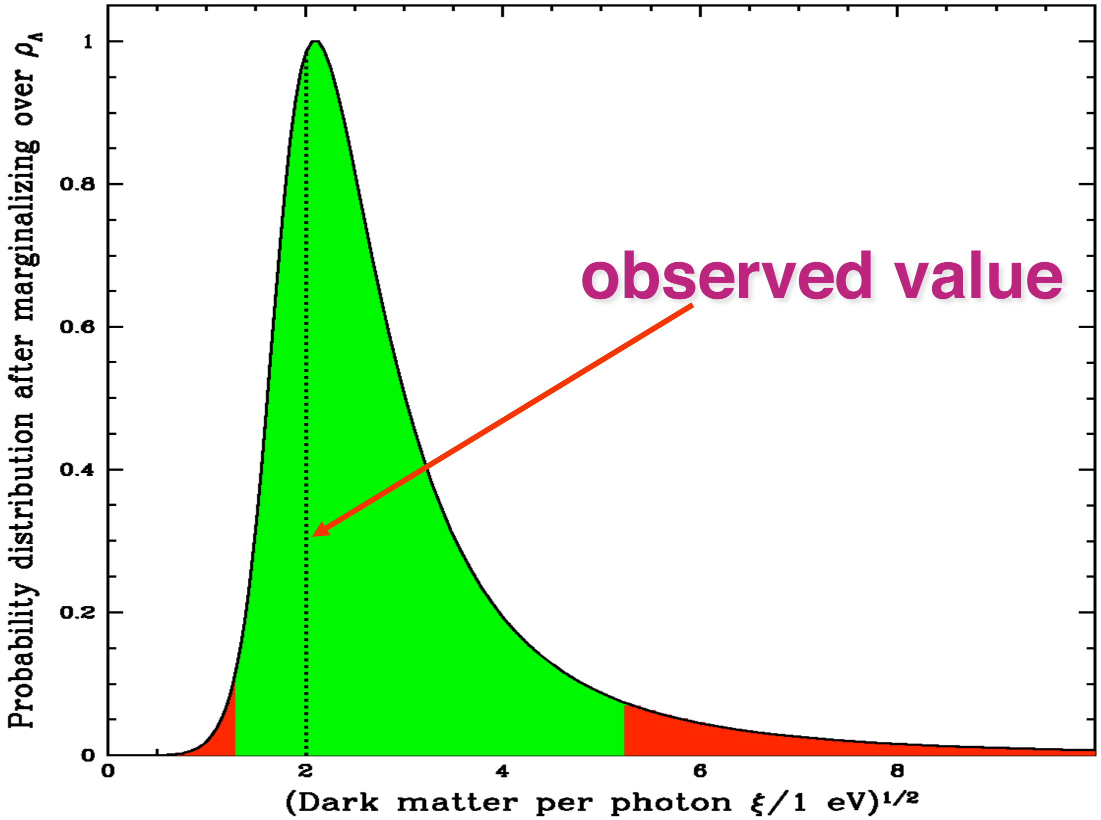
Can we give a scientific definition of "typical" ?

Anthropic argument: Inflationary fluctuations make the amount of the axion dark matter a CONTINUOUS RANDOM PARAMETER. We can live only in those parts of the universe where the initial value of the axion field was sufficiently small (A.L. 1988).

Recently this possibility was analyzed by Aguirre, Rees, Tegmark, and Wilczek.

Anthropic Constraints on the Axion Dark Matter

Aguirre, Rees, Tegmark, and Wilczek, astro-ph/0511774



This is a possible answer to the question why there is 5 times more dark matter than the ordinary matter.

One of the arguments in favor of light supersymmetric particles to be discovered at LHC is the possibility to explain the abundance of dark matter.

As we see now, the same goal can be achieved by axions violating the naïve bound $m_a > 10^{-5}$ eV.

While waiting for LHC, we must remember all of our options. Some of them are not widely recognized yet because they became “legitimate” only recently, with the growing acceptance of the string landscape scenario.

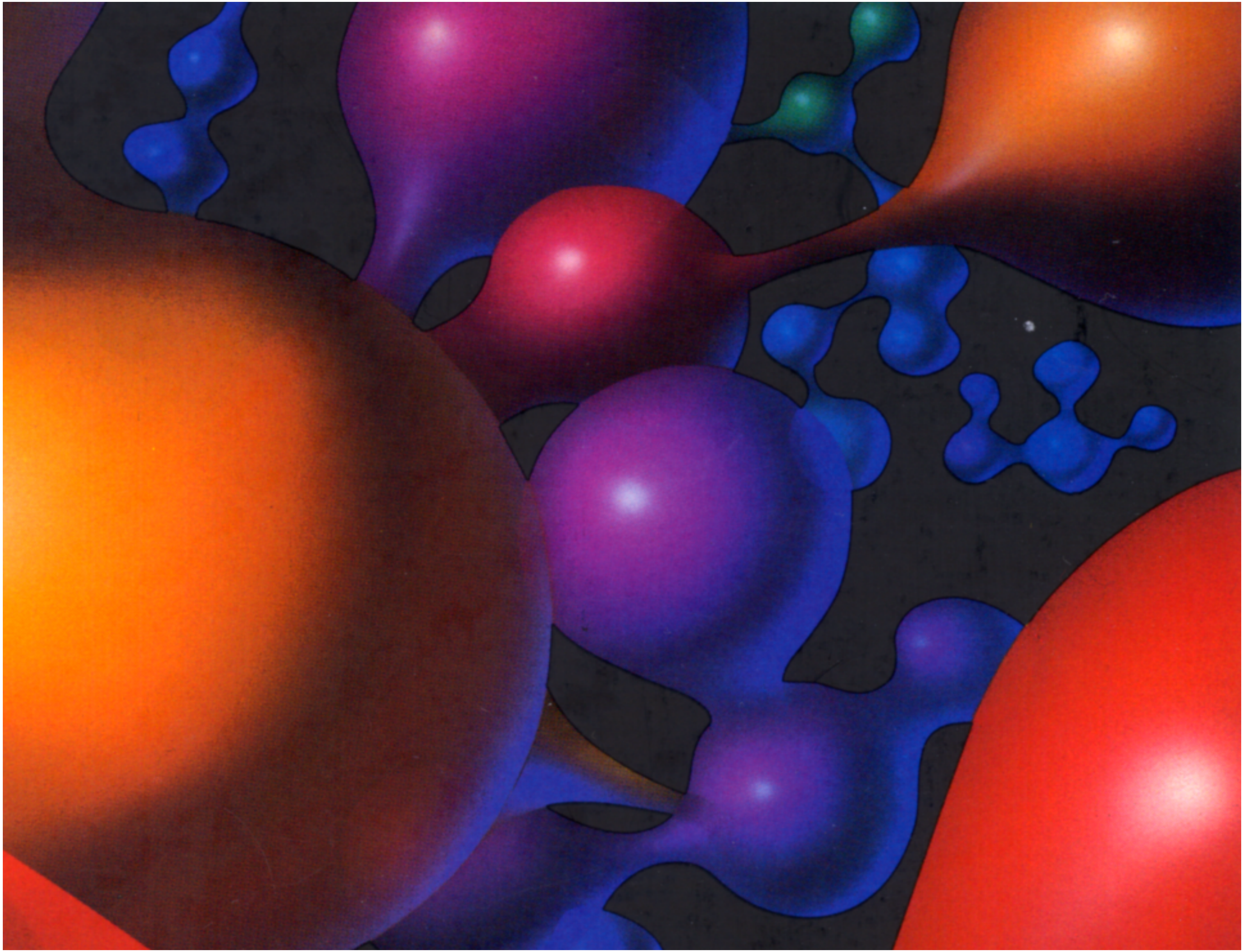
Conclusions:

There is an ongoing progress in implementing inflation in string theory. We are unaware of any consistent non-inflationary alternatives.

There is a tension between the standard solution of the hierarchy problem due to the low scale SUSY breaking and the high energy scale of inflation in string theory.

If inflationary tensor modes are discovered, we may need to reconsider standard ideas about string theory and/or low scale SUSY breaking.

Life in physics is interesting, and it is going to be even more interesting soon!



Alternatives?

Ekpyrotic/cyclic scenario

Original version (Khoury, Ovrut, Steinhardt and Turok 2001) did not work (no explanation of the large size, mass and entropy; the homogeneity problem even worse than in the standard Big Bang, Big Crunch instead of the Big Bang, etc.).

It was replaced by cyclic scenario (Steinhardt and Turok 2002) which is based on a set of conjectures about what happens when the universe goes through the singularity and re-emerges.

Despite many optimistic announcements, the singularity problem in 4-dimensional space-time and several other problems of the cyclic scenario remain unsolved.

Recent developments: "New ekpyrotic scenario"

Creminelly and Senatore, 2007, Buchbinder, Khoury, Ovrut 2007

Problems: violation of the null energy condition, absence of the ultraviolet completion, difficulty to embed it in string theory, violation of the second law of thermodynamics, problems with black hole physics.

The main problem: this theory contains terms with higher derivatives, which lead to new ekpyrotic ghosts, particles with negative energy. As a result, the vacuum state of the new ekpyrotic scenario suffers from a **catastrophic vacuum instability.**

Kallosh, Kang, Linde and Mukhanov, arXiv:0712.2040

The New Ekpyrotic Ghosts

New Ekpyrotic Lagrangian:

$$L = \sqrt{g}\left[M^4 P(X) - \frac{1}{2}\left(\frac{\Box\phi}{M'}\right)^2 - V(\phi)\right]$$

Dispersion relation:

$$\omega^2 = P_{,X}\, k^2 + \frac{(\omega^2 - k^2)^2}{m_g^2}$$

Two classes of solutions, for small $P_{,X}$:

$$\omega = \pm\, \omega_i \;, \quad \omega_1 = \frac{1}{2}\left(\sqrt{m_g^2 + 4k^2} - m_g\right), \quad \omega_2 = \frac{1}{2}\left(\sqrt{m_g^2 + 4k^2} + m_g\right)$$

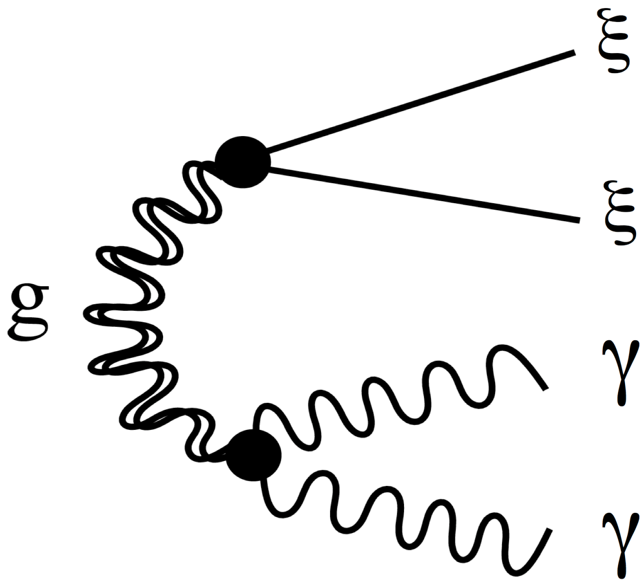
Hamiltonian describes normal particles with positive energy $+\,\omega_1$

and ekpyrotic ghosts with negative energy $-\,\omega_2$

$$H_{quant} = \int \frac{d^3k}{(2\pi)^3}\left(\omega_1 a_k^\dagger a_k - \omega_2 c_k^\dagger c_k\right)$$

Vacuum in the new ekpyrotic scenario instantly decays due to emission of pairs of ghosts and normal particles.

Cline, Jeon and Moore, 2003



Even if eventually someone modifies this theory and saves it from ghosts, then it will be necessary to check whether the null energy condition is still violated in the improved theory. Indeed, if, as expected, this correction will also remove the violation of the null energy condition, then the bounce from the singularity will become impossible.

We are unaware of any ghost-free theories where the null energy condition is violated, which would be necessary for the success of the new ekpyrotic scenario.

Can we save this theory?

Example:

$$\mathcal{L} = -\tfrac{1}{2}(\partial\phi)^2 + \frac{a}{2m_g^2}(\Box\phi)^2 - V_{\rm int}(\phi)$$

Can be obtained by integration with respect to χ of the theory with ghosts

$$\mathcal{L}' = -\tfrac{1}{2}(\partial\phi)^2 - a\,\partial_\mu\chi\partial^\mu\phi - \tfrac{1}{2}a\,m_g^2\,\chi^2 - V_{\rm int}(\phi)$$

By adding some other terms and integrating out the field χ one can reduce this theory to the ghost-free theory.

Creminelli, Nicolis, Papucci and Trincherini, 2005

But this can be done only for a = + 1, whereas in the new ekpyrotic scenario a = - 1

Kallosh, Kang, Linde and Mukhanov, arXiv:0712.2040