Gravity: Past, Present, Future, from East to West

A.O.Barvinsky

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Plan of talk

Quantum gravity and cosmology in the last years of the Soviet Union

Problem of quantum initial conditions in cosmology: birth from "Everything" vs birth from "Nothing"

Alexander Friedman

1888 - 1925

"On the possibility of a world with constant negative curvature of space" (1924)

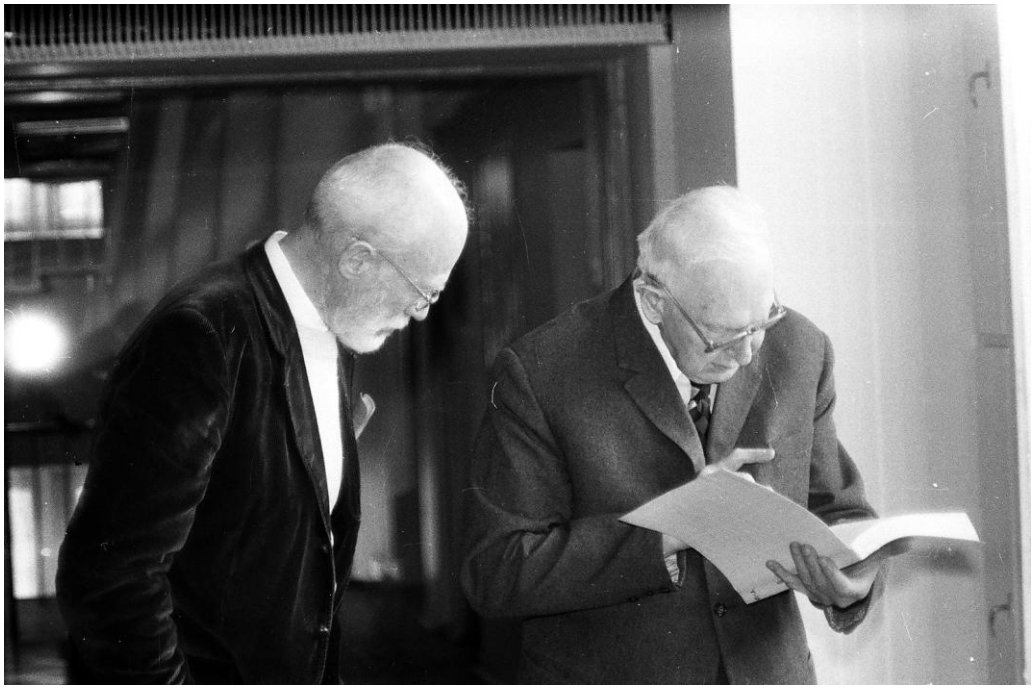
What happens if the Cosmological Constant (Λ) has different values?

What happens if the universe is expanding?

Ya.B.Zeldovich
(1914-1987)

Moscow Quantum Gravity Seminars, 1978-1995

Professor M.A.Markov (1908-1994)

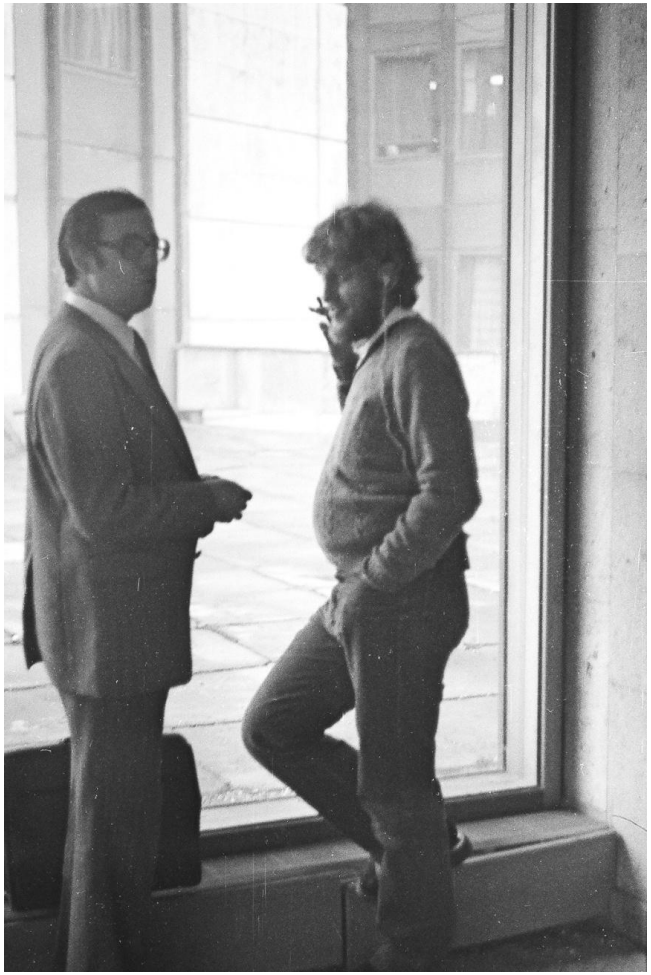


B.S.DeWitt and M.A.Markov

S.W.Hawking and M.A.Markov

Valery Frolov and Bob Wald

Valery Frolov and Werner Israel



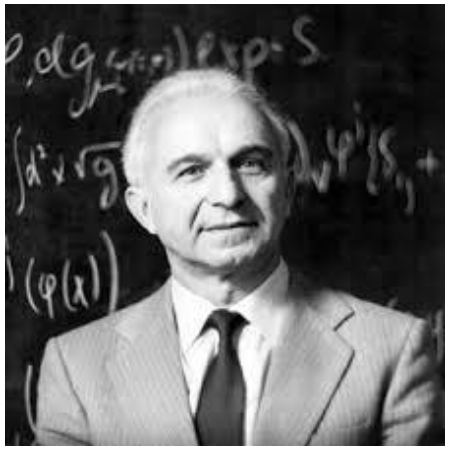
Valery Frolov and Bill Unruh

Victor Berezin and Jim Hartle

FDWFP → FV formalism → BFV formalism → BV formalism

L.D.Faddeev
(1934-2017)

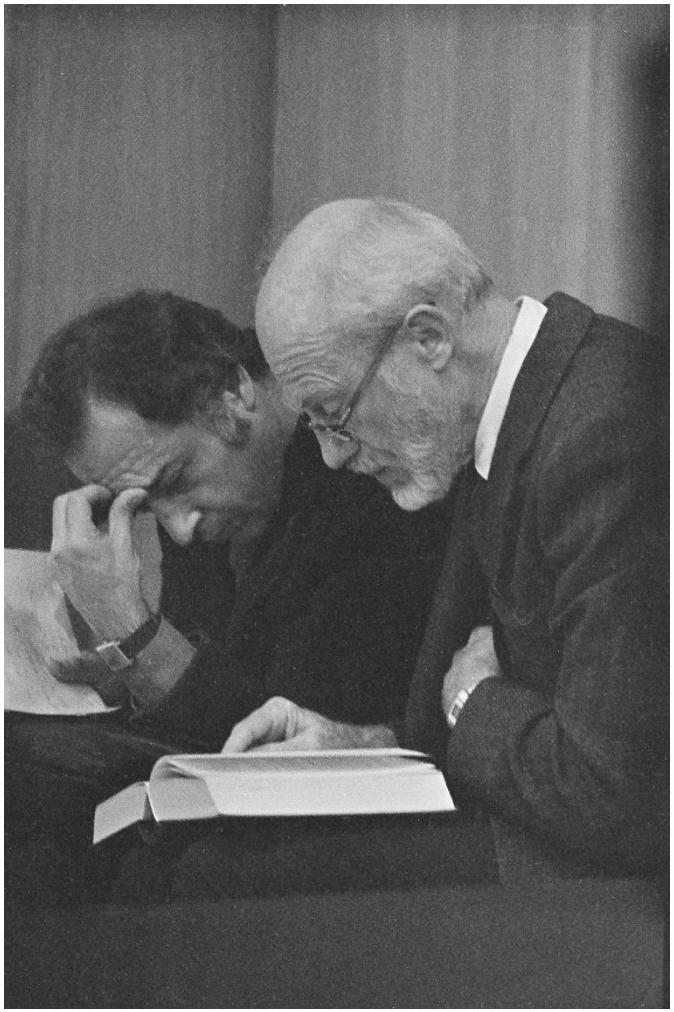
V.N.Popov
(1937-1994)



E.S.Fradkin
(1924-1999)

G.Vilkovisky and I.Batalin

G.Vilkovisky, B.DeWitt and A.B. at 5-th Moscow Quantum Gravity Seminar, 1990



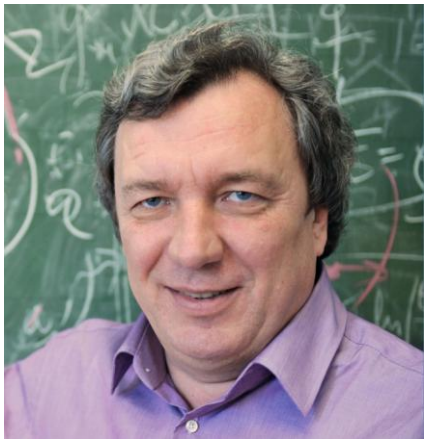
Inflation theory

Change of paradigm: initial state is a vacuum with only quantum fluctuations – everything originates from them

A.Starobinsky, 1978, *gravitational waves*

V.Mukhanov and G.Chibisov, 1981, *waves of density perturbations as seeds that grew to become galaxies -- the source for a formation of LSS*

A.Starobinsky



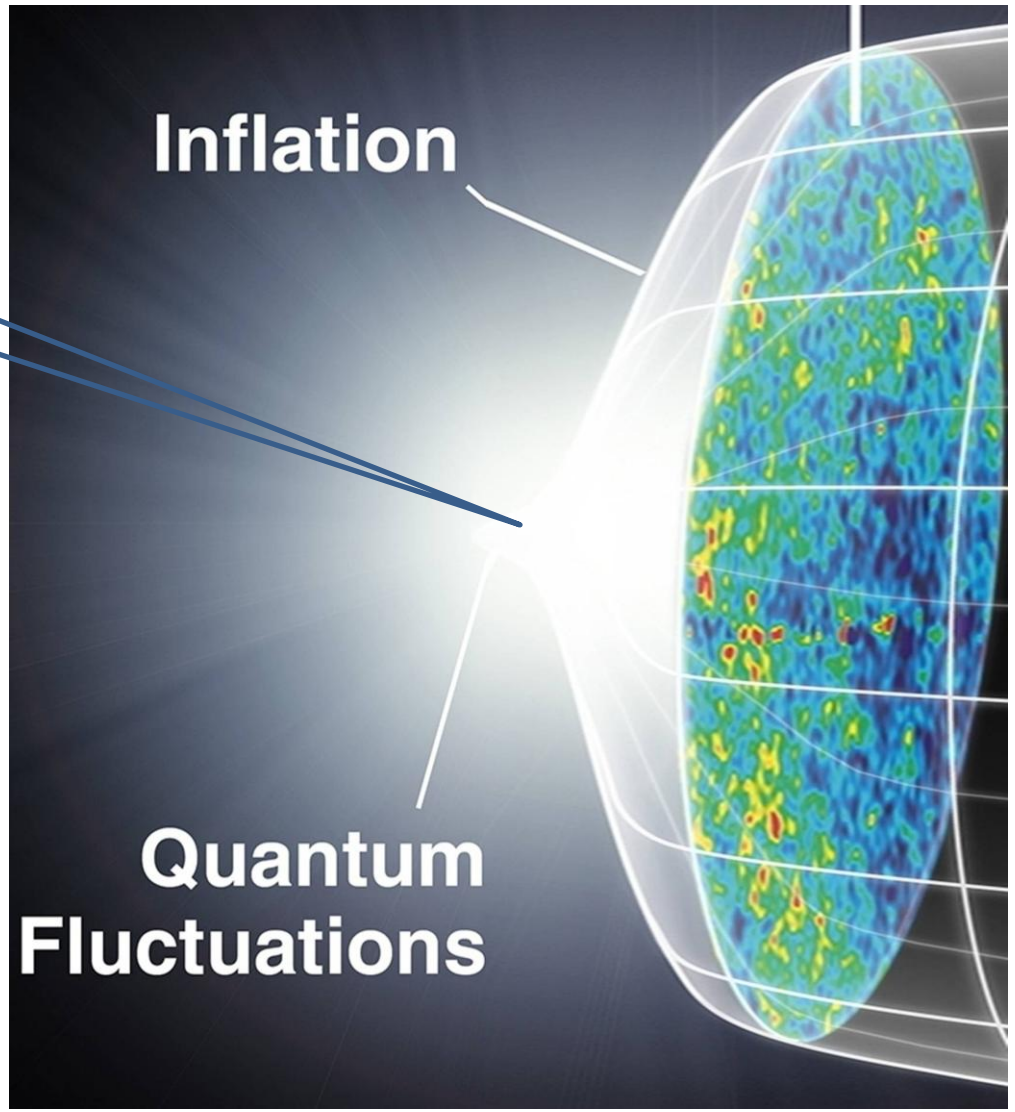
V.Mukhanov

Gennady Chibisov (1946-2008)

*Mechanism of inflation --- slow roll of the **INFLATON** field (A.Starobinsky, A.Linde)*

A.Linde

What was at the beginning?

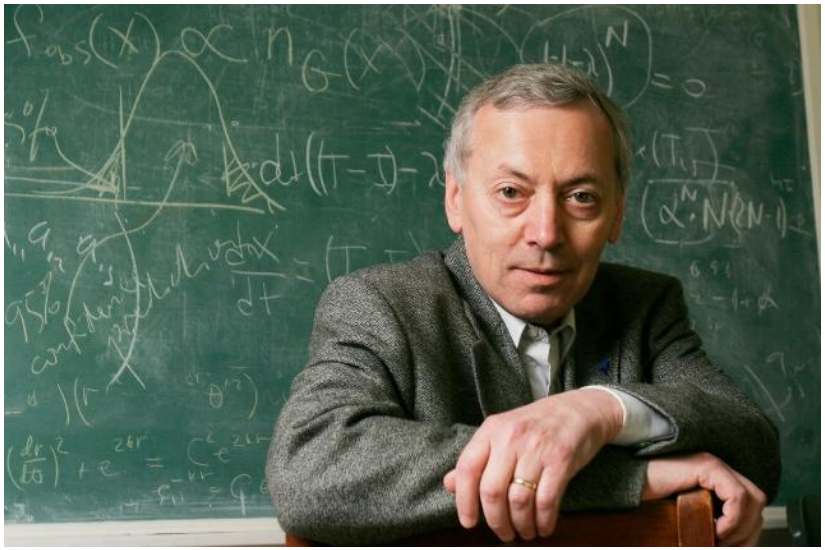


The space and time had both one beginning . The space was made not in time but simultaneously with time.

Saint Augustin of Hippo

Extrapolation of math to physics :"mathematical formalism is capable of its own interpretation" -- Bryce DeWitt

Tunneling wavefunction of the Universe

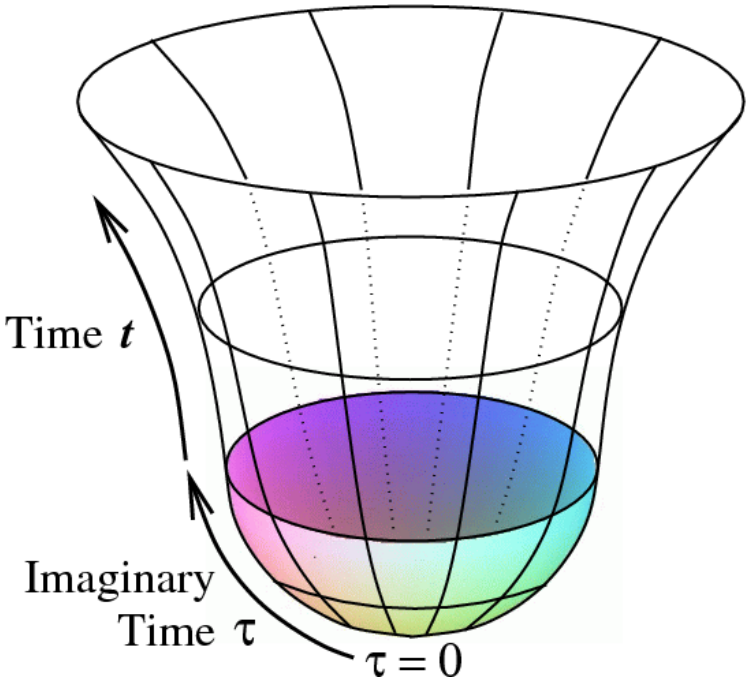


Alexander Vienkin

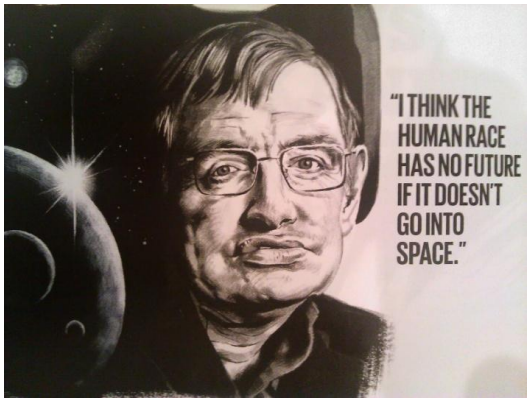
Starobinsky-Zeldovich, Linde, …

Valery Rubakov

Hartle-Hawking (no-boundary) wavefunction of the Universe



origin from a point – from “nothing”



Hartle-Hawking no-boundary wavefunction in observer-independent approach

vs observer-dependent top-down approach - - anthropic principle

$$\Psi_{HH} \sim \exp(-S_E) = \exp\left(\#\frac{M_P^4}{V(\varphi)}\right) \to \infty$$

$$\frac{V(\varphi)}{M_P^2} = \Lambda_{eff} \to 0$$

Most probable ***at the minimum*** *of inflaton potential* $\Lambda_{eff} \to 0$
-- insufficient *amount of inflation*

Ttunneling wavefunction

Cosmology debate: no-boundary vs tunneling

$$\Psi_T \sim \exp(+S_E)$$

No rigorous operator interpretation of both no-boundary and tunneling wavefunctions

What might be wrong with the "birth from nothing" wavefunctions ?

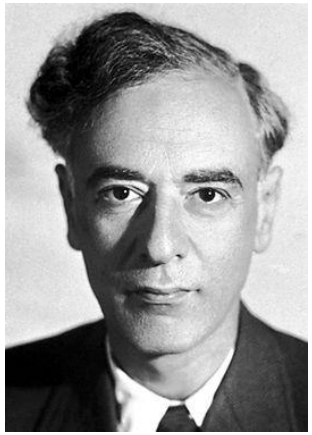
HH wavefunction is the de Sitter invariant vacuum state – the birth from "nothing"

A vacuum state (as any other single state) is not unique – so why from "nothing" rather than from "Something" or "Everything"?

So what can be the alternative?

This is a concept of transition from the wavefunction to the density matrix of the Universe:

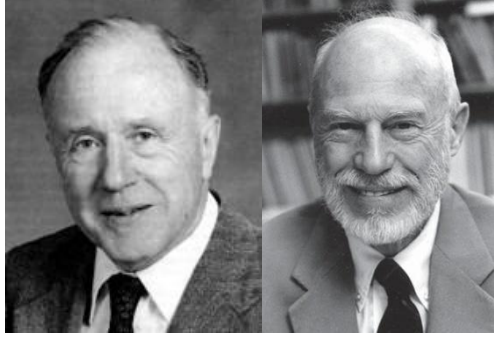
$$\Psi \longrightarrow \hat{\rho}$$



L.Landau

(1908-1968)

Wheeler-DeWitt equation(s) – basis of quantum cosmology



Quantum Dirac constraints on physical states:

$$\hat{H}_{\perp}(\mathbf{x})\,|\Psi\rangle = 0, \;\; \hat{H}_{i}(\mathbf{x})\,|\Psi\rangle = 0$$

$$\underbrace{\hat{H}_{\perp}(\mathbf{x}),\; \hat{H}_{i}(\mathbf{x})}$$

operators of the Wheeler-DeWitt equations

WDW equation is the ``most useless" equation in theoretical physics?

Grisha Vilkovisky (utmost left), Bryce and Cecile, John Wheeler, Grisha's daughter Lisa and myself

Microcanonical density matrix of the Universe

Microcanonical density matrix – projector onto subspace of quantum gravitational constraints

$$|\Psi\rangle \to \hat{\rho}, \qquad \hat{H}_\perp \hat{\rho} = 0, \qquad \hat{H}_i \hat{\rho} = 0$$

$$\hat{\rho} = e^{\Gamma} \prod_{i,\mathbf{x}} \delta\left(\hat{H}_\perp\right) \delta\left(\hat{H}_i\right)$$

A.B., Phys. Rev. Lett. 99, 071301 (2007)

Statistical sum

$$e^{-\Gamma} = \mathrm{Tr} \prod_{i,\mathbf{x}} \delta\left(\hat{H}_\perp\right) \delta\left(\hat{H}_i\right)$$

$$= \int_{\text{periodic}} D[\, g_{\mu\nu}, \phi\,]\, e^{-S[\, g_{\mu\nu}, \phi\,]}$$

Euclidean Quantum Gravity path integral

Motivation: aesthetic (minimum set of assumptions – Occam razor)

A simple analogy -- a system with a conserved Hamiltonian $\hat{H}$ *in the microcanonical state of a fixed energy* E

$$\hat{\rho} \sim \delta(\hat{H} - E)$$

Spatially closed cosmology does not have freely specifiable constants of motion. The only conserved quantities are the Hamiltonian and momentum constraints, all having a particular value --- zero

$$\hat{\rho} \sim \prod_{\mu,\mathbf{x}} \delta\left(\hat{H}_{\mu}(\mathbf{x})\right)$$

A.B., Phys.Rev.Lett. 99, 071301 (2007)

PRL 99, 071301 (2007) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2007

Why There is Something Rather than Nothing: Cosmological Constant from Summing over Everything in Lorentzian Quantum Gravity

A. O. Barvinsky
Theory Department, Lebedev Physics Institute, Leninsky Prospect 53, 119991 Moscow, Russia

$$\hat{\rho} = \sum_{\text{all } |\Psi\rangle} |\Psi\rangle\langle\Psi|$$

sum over "everything" that satisfies the Wheeler-DeWitt equation

An ultimate equipartition in the full set of states of the theory --- "Sum over Everything".

Creation of the Universe from Everything is conceptually more appealing than creation from Nothing, because the democracy of the microcanonical equipartition better fits the principle of the Occam razor than the selection of a concrete state.

Cosmological initial conditions – microcanonical density matrix of the Universe and its statistical sum

Application to CFT driven cosmology -- Universe dominated by quantum matter conformally coupled to gravity (CFT) :

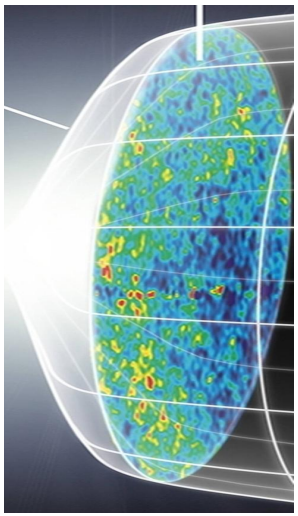
$$S[\,g_{\mu\nu},\Phi\,] = -\frac{M_P^2}{2}\int d^4x\, g^{1/2}\,(R-2\Lambda) + S_{CFT}[\,g_{\mu\nu},\Phi\,]$$

fundamental or effective (generated by inflaton) cosmological constant

Properties of the "newly born" Universe

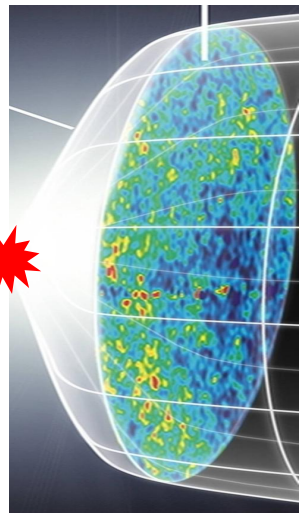
1) Initial thermal state with the primordial temperature T_{prim} of matter

Standard inflation scenario versus Density matrix scenario



Vacuum, absolute zero temperature

Inflation, hot big-bang → relic radiation



Thermal state, *primordial temperature* T_{prim}

Inflation, $T_{prim} \to 0$, hot big-bang → relic radiation

“SOME LIKE IT HOT” scenario

Known inflation paradigm retracted the BB concept by replacing it with the initial vacuum state.

“SOME LIKE IT HOT” scenario recovers a new incarnation of Hot Big Bang -- it incorporates effectively thermal state at the onset of the cosmological evolution but with finite temperature and free of singularity.

2) Limited range of effective cosmological constant Λ – subplanckian domain (limiting the string vacua landscape?):

$$\Lambda_{\min} \leq \Lambda \leq \Lambda_{\max} = \frac{12\pi^2 M_P^2}{\beta}$$

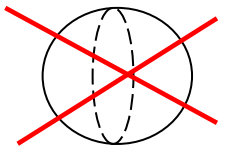
$$\beta = \sum_s \beta_s \, \mathbb{N}_s$$

N_s -- # of fields of spin *s*

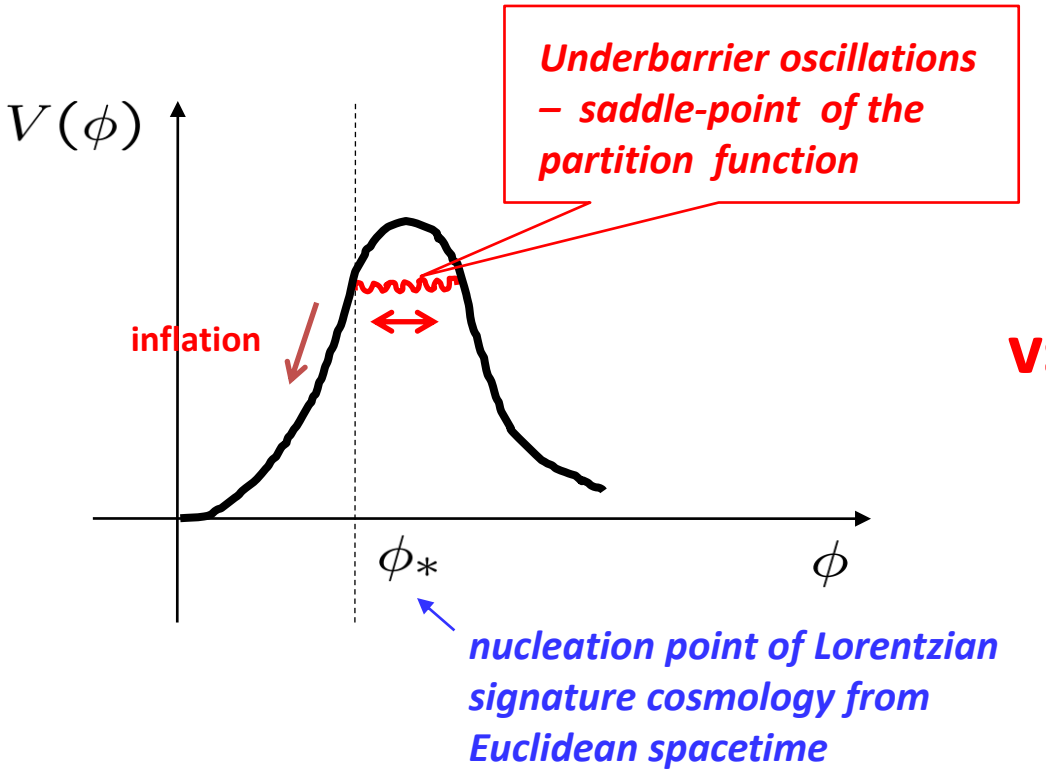
Coefficient of GB term in conformal anomaly

$$g_{\mu\nu}\frac{\delta \Gamma_{CFT}}{\delta g_{\mu\nu}} = \frac{1}{64\pi^2} g^{1/2}\left(\beta E + \alpha \Box R + \gamma C^2_{\mu\nu\alpha\beta}\right)$$

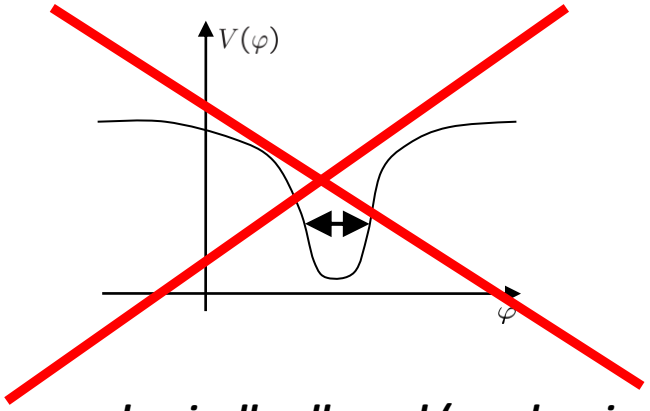
3) No-boundary instantons S^4 are ruled out by infinite positive Euclidean action – elimination of infrared catastrophe



4) Selection of inflaton potential maxima as initial conditions for inflation – new paradigm of HILL-TOP INFLATION



VS



classically allowed (overbarrier) oscillation --- ruled out because of underbarrier oscillations of scale factor

4) Model of initial conditions for Starobinsky R^2 model and non-minimal Higgs inflation:

Observable CMB parameters (WMAP, Planck,…):

$$\frac{\Delta T}{T} \sim 10^{-5}, \; n_s \simeq 0.96, \; r \simeq 0.003$$

F.Bezrukov M.Shaposhnikov

relation of CMB data to the Higgs mass
A.Kamenshchik, A.Starobinsky & A.B. (2008)
Bezrukov, Shaposhnikov (2008)

$$M_{\text{Higgs}} \simeq 126 GeV$$

Hidden sector of numerous ($\mathbb{N} \gg 1$) ***conformal higher spin fields (CHS): solution of hierarchy problem and stabilization of graviton loop corrections below the gravitational cutoff***

$$\Lambda \sim \frac{M_P^2}{\beta} \sim 10^{-12} M_P^2 \ll \Lambda_{\text{cutoff}}$$

CHS fields:

$$\frac{M_P^2}{\beta} \sim \frac{M_P^2}{\mathbb{N}^3} \ll \frac{M_P^2}{\mathbb{N}} \equiv \Lambda_{\text{cutoff}}$$

A.B. (2016)

Our cosmology is a subplanckian phenomenon – it remains semiclassical all the way from its "birth" till present time. Absence of consistent non-perturbative quantum gravity is not an obstacle to the description of the earliest possible Universe!