Unifying the Universe

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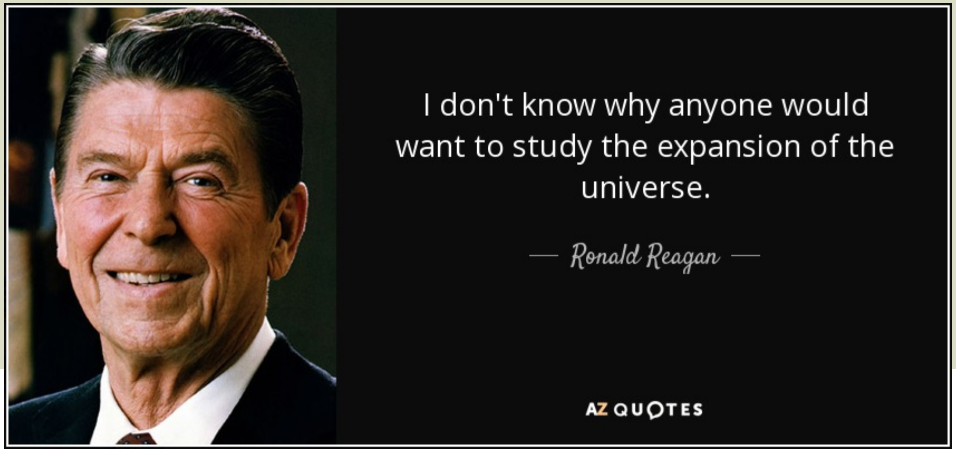
PITP public lecture, UBC,

Vancouver, 12 October, 2016

The efforts to understand the universe is one of the very few things that lifts human life a little above the level of farce...

S. Weinberg, 1977



Scales in the Universe

Cosmology, astrophysics

Size of the Universe — *90* billion light years » ***10^{28}*** cm

10000000000000000000000000000 **cm**

Galaxies and their clusters — *10-100* Mpc » ***10^{25}*** cm

Stars, orbit of Earth — *150* million km » ***10^{13}*** cm

…………………………

Chemistry, atomic and nuclear physics

Molecules — *1* angstrom » ***10^{-8}*** cm

Atomic nuclei — *1* fermi » ***10^{-13}*** cm

High energy particle physics

Higgs boson — » ***10^{-16}*** cm

…………………………

Quantum gravity

Planck length — » ***10^{-33}*** cm

0.000000000000000000000000000000001 **cm**

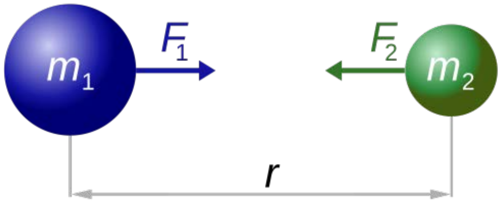
Constants of Nature and Planck scale

C ' 300 000 km/sec   speed of light

photon wavelength
(color of light)

~   Planck constant $E = \frac{\hbar c}{\lambda}$

G   gravitational
(Newton) constant



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Planck length $l_P = \sqrt{\frac{G\hbar}{c^3}}$

Planck energy $E_P = \frac{\hbar c}{l_P} \sim 10^{19} GeV \sim 10^{19}$ protons

10000000000000000000 Hydrogen atoms
energy enough to send 100 kg body into space

Unification of scales:

Size of the Universe — *90* billion light years

Dark energy, cosmological acceleration ?

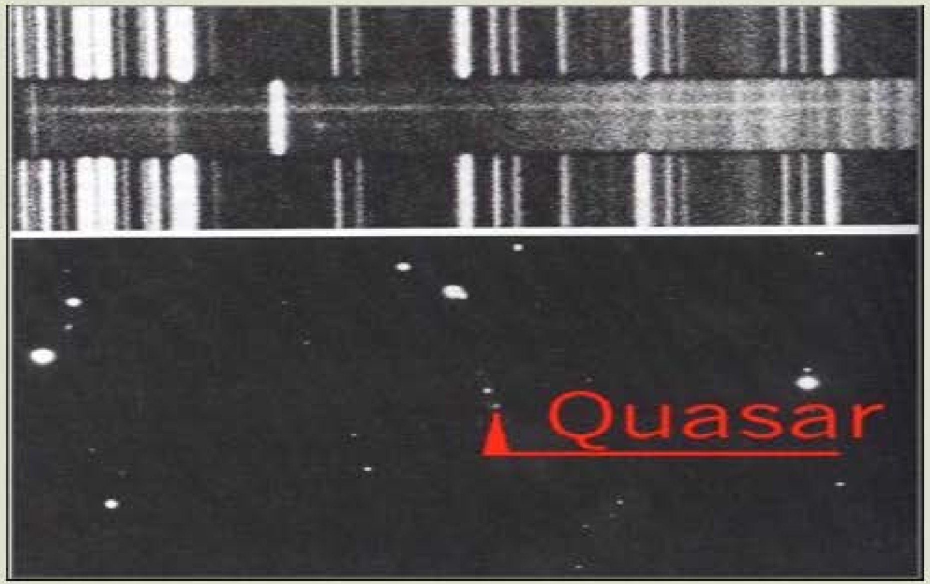
Galactic scales — *10-100* Mpc » ***10***^{25} cm

mechanism of unification INFLATION

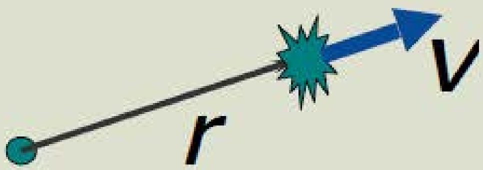
Higgs boson — » ***10***$^{-16}$ cm

Planck scale "birth" of the Universe — » ***10***$^{-33}$ cm

- The Universe expands



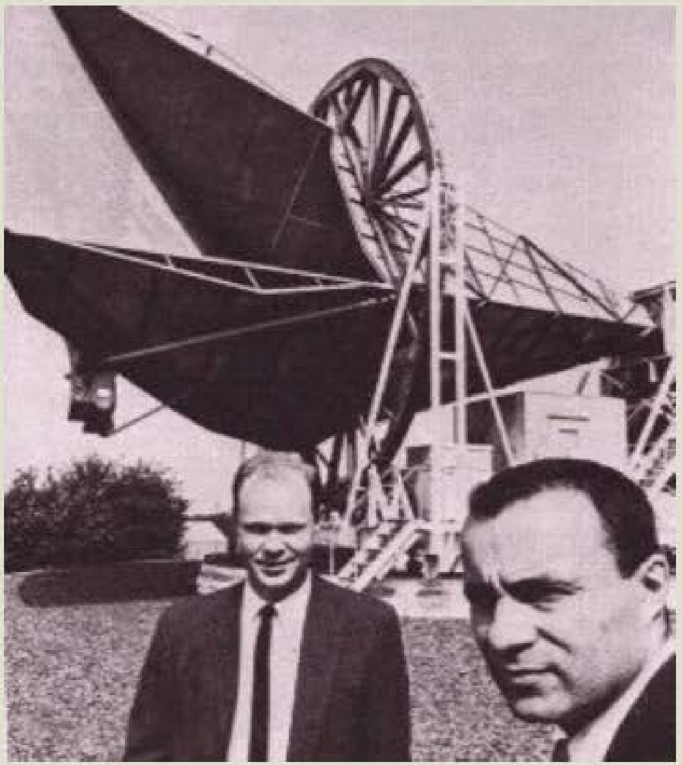
- Hubble law



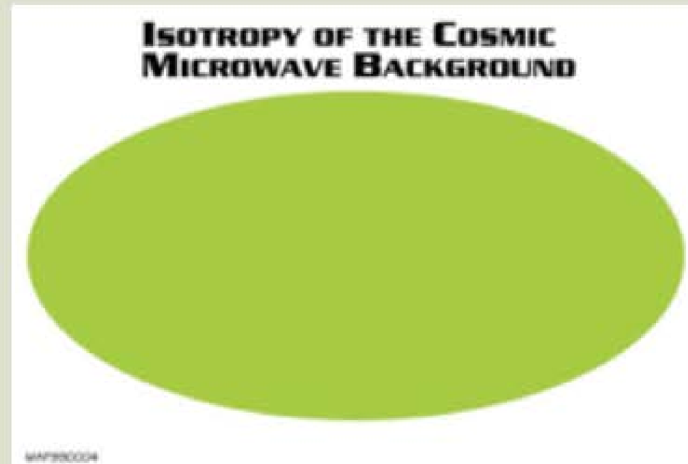
$$v = Hr$$

$$t \sim \frac{r}{v} = \frac{1}{H} \sim 13{,}7\ bil.\ years$$

- There exists background radiation with the temperature $T \approx 3K$

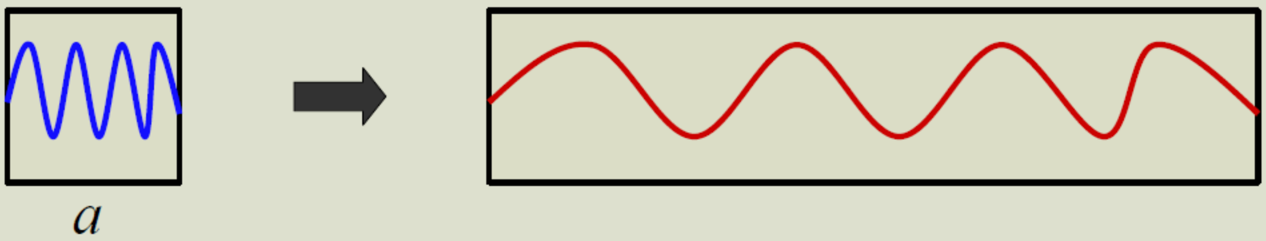


Penzias, Wilson 1965



$$\frac{\Delta T}{T} < 10^{-5} = \frac{1}{100000}$$

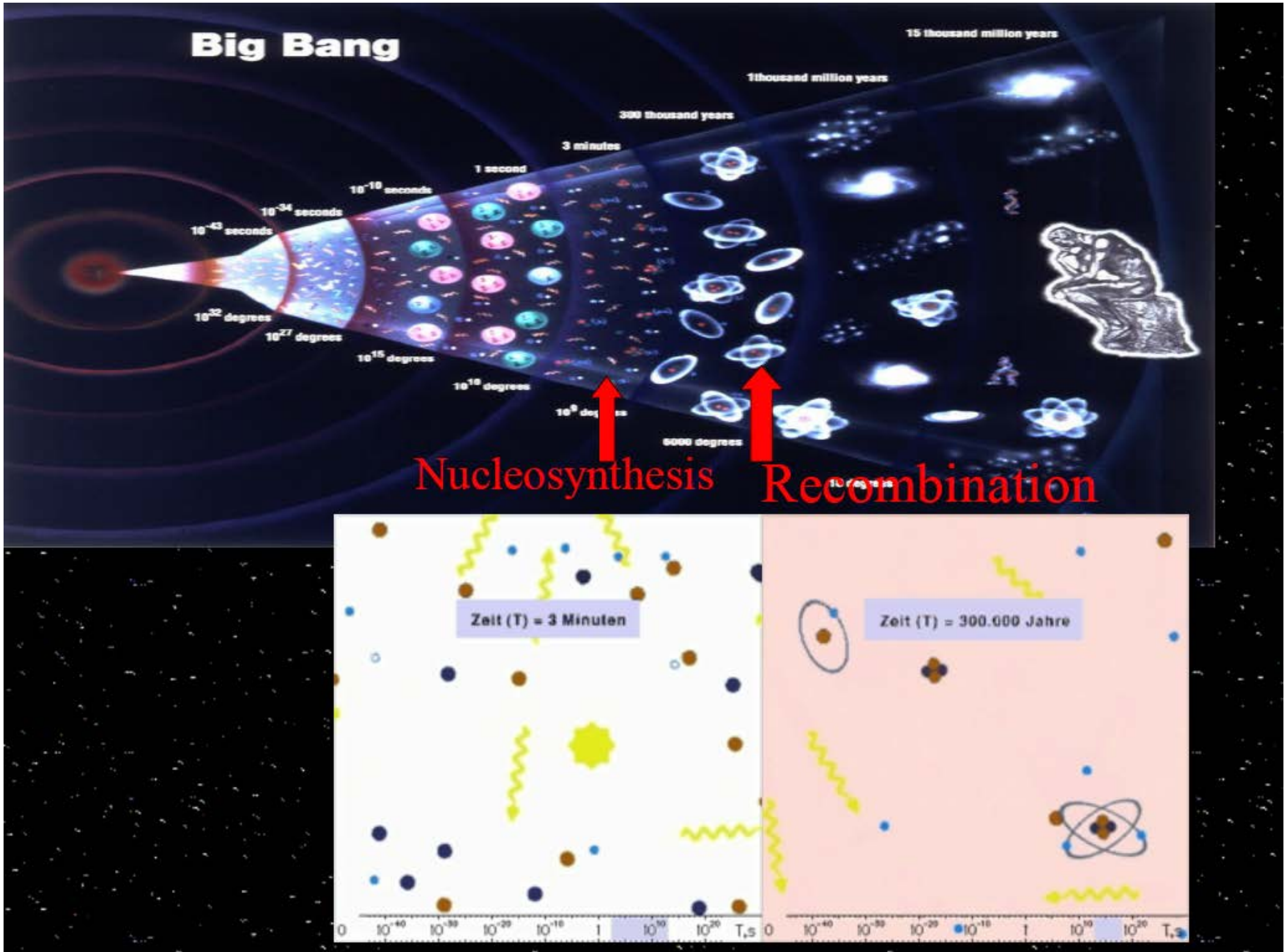
Decrease of temperature (of radiation – photon gas) during expansion



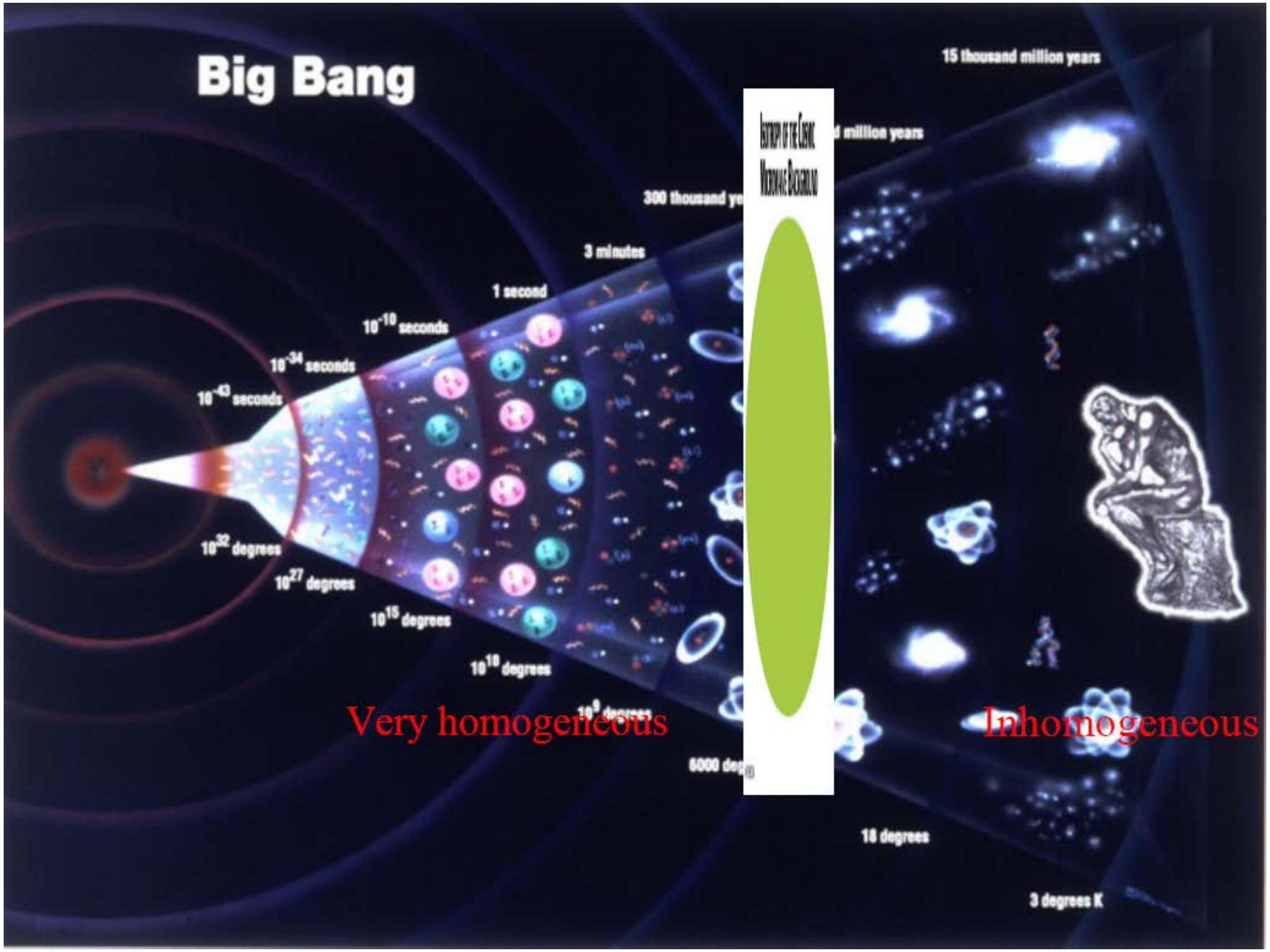
$$\lambda \propto a \quad \Rightarrow \quad T \propto \frac{1}{a}$$

When the Universe was 1000 times smaller its temperature was about $2725°K$

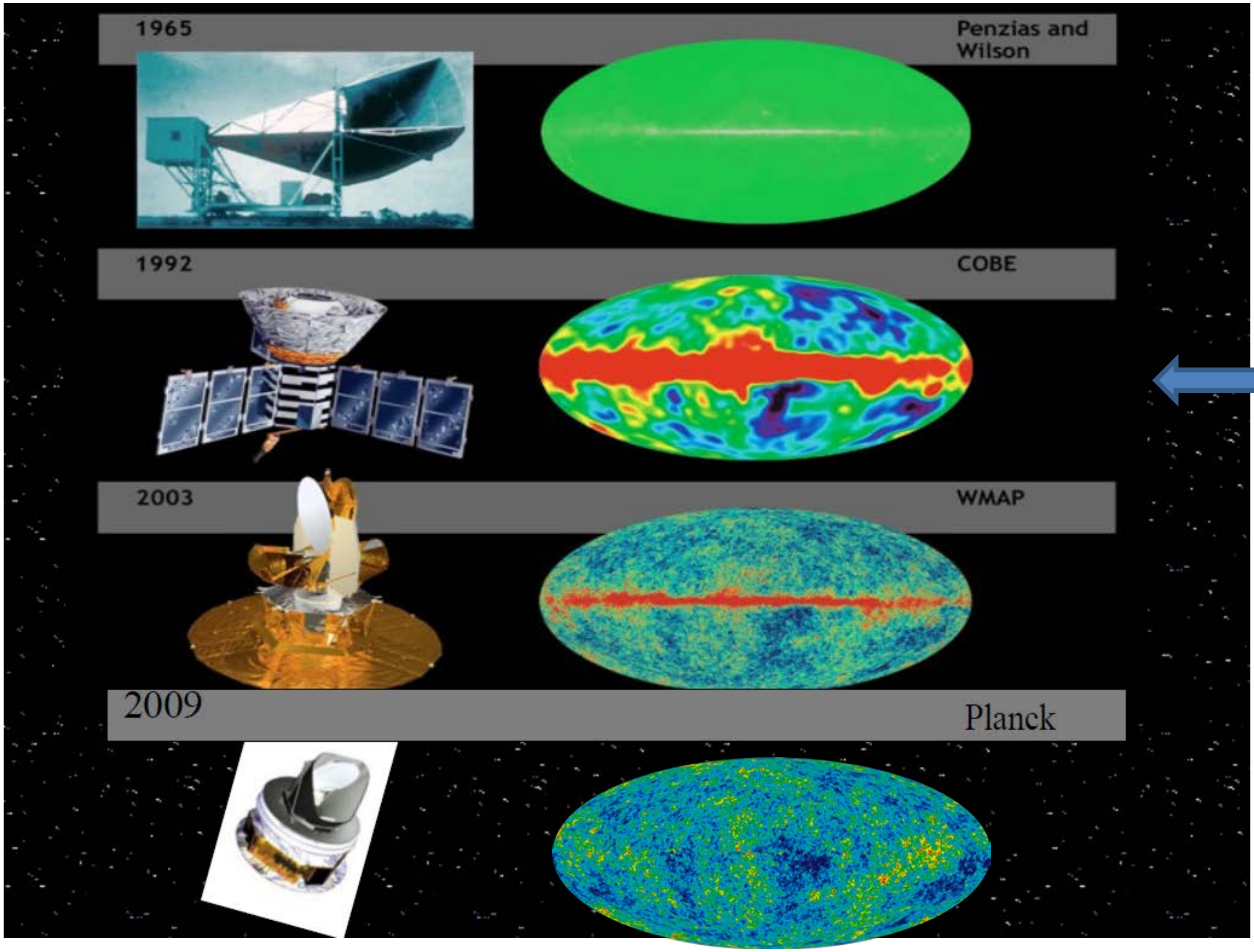
The schematic picture of Big Bang evolution of the Universe



Formation of the background (relic) radiation at the epoch of recombination

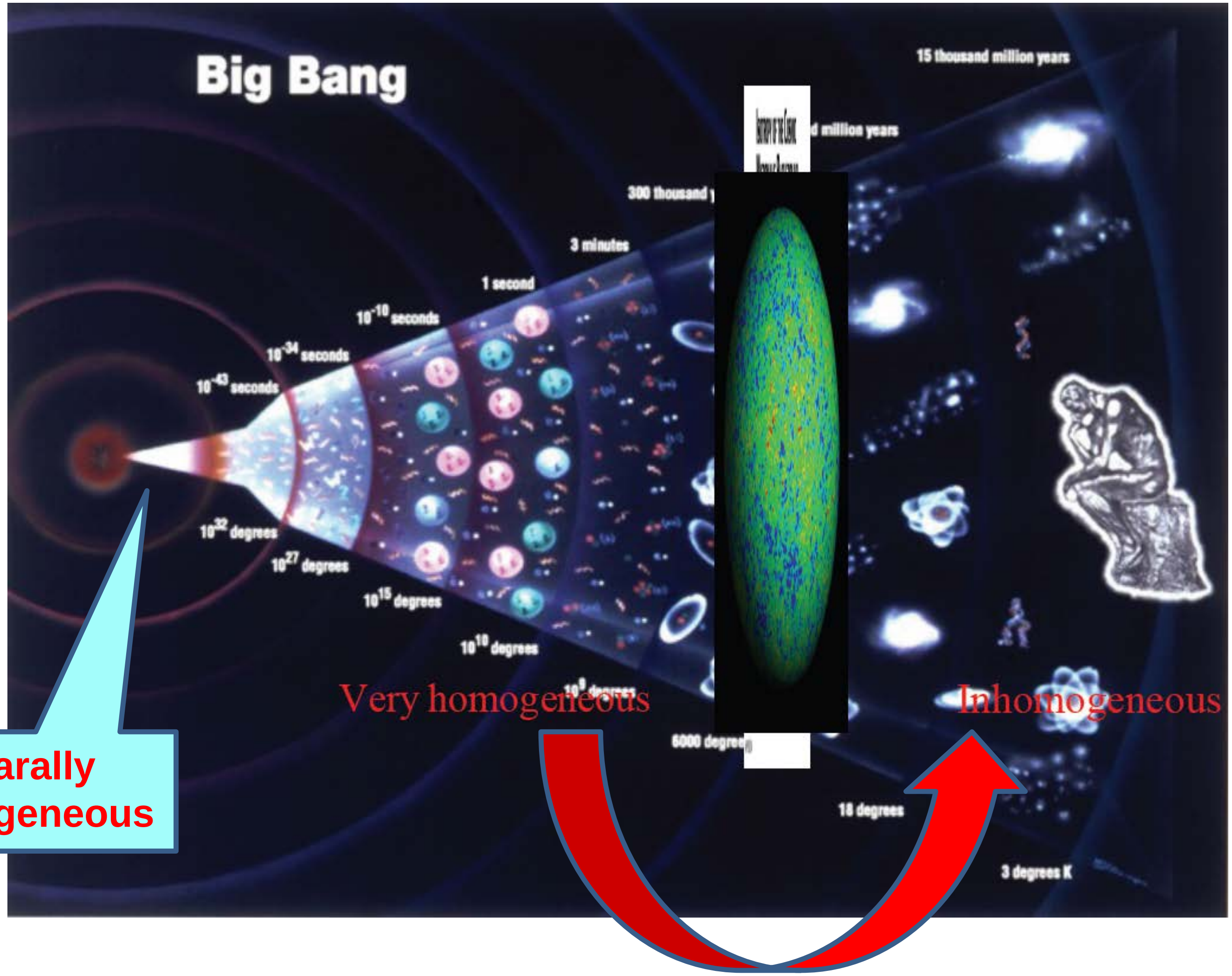


CMB observations: 1990-ies and on – the epoch of "precision" cosmology



$$\frac{\Delta T}{T} \neq 0$$

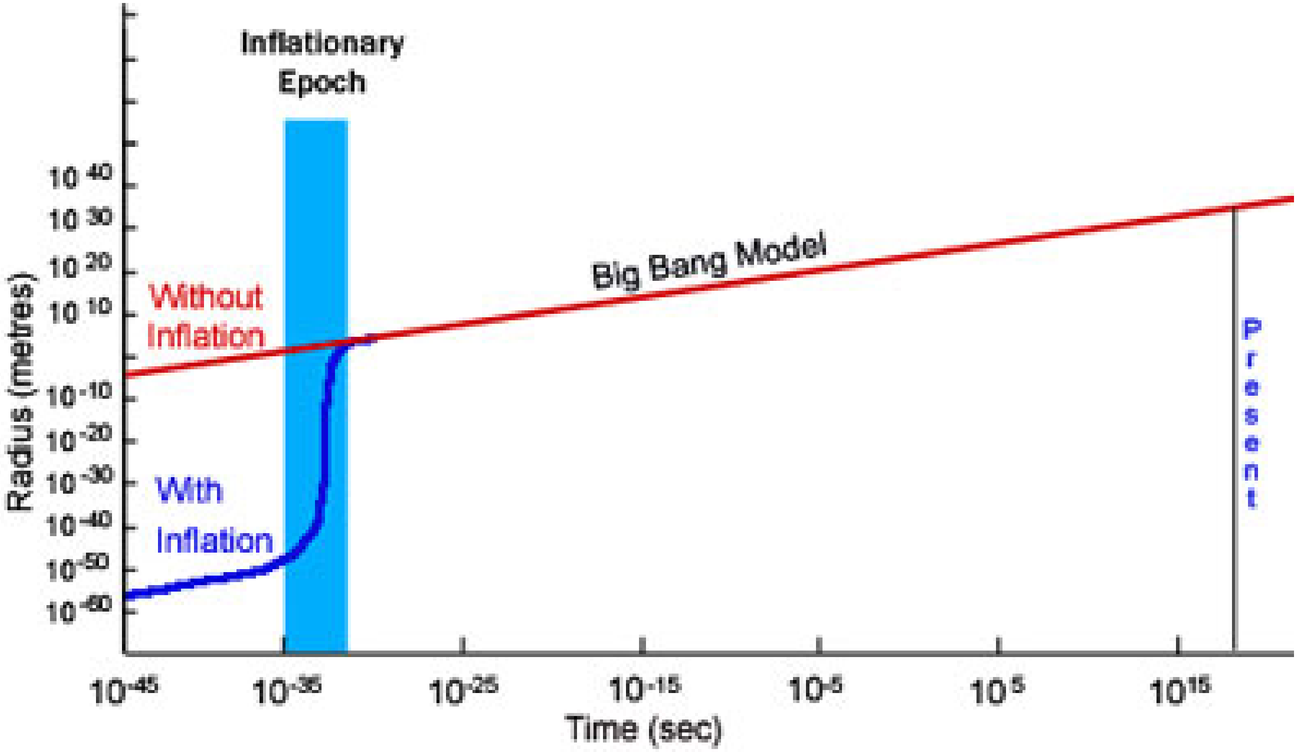
Problems with the **old** Big Bang scenario



unnatarally
homogeneous

contradiction

Stage of rapid accelerated expansion – inflation (A.Guth)



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

Exponential expansion law: when time grows twice the size gets squared, when time triples – the size gets raised to cubic power, etc.

$$H \sim \text{const}$$

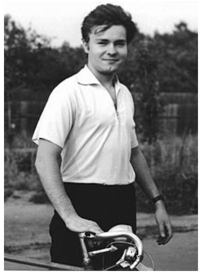
Hubble parameter of the inflation ≠ present Hubble

Theory of cosmological perturbations in the exponentially expanding Universe

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 (large scale structure of the Universe)
Hawking, Guth, Pi, Steinhardt, Turner, Albrecht





The theory is based on the Heisenberg uncertainty relation of quantum mechanics

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

$$\Delta p \Delta x \geq h$$

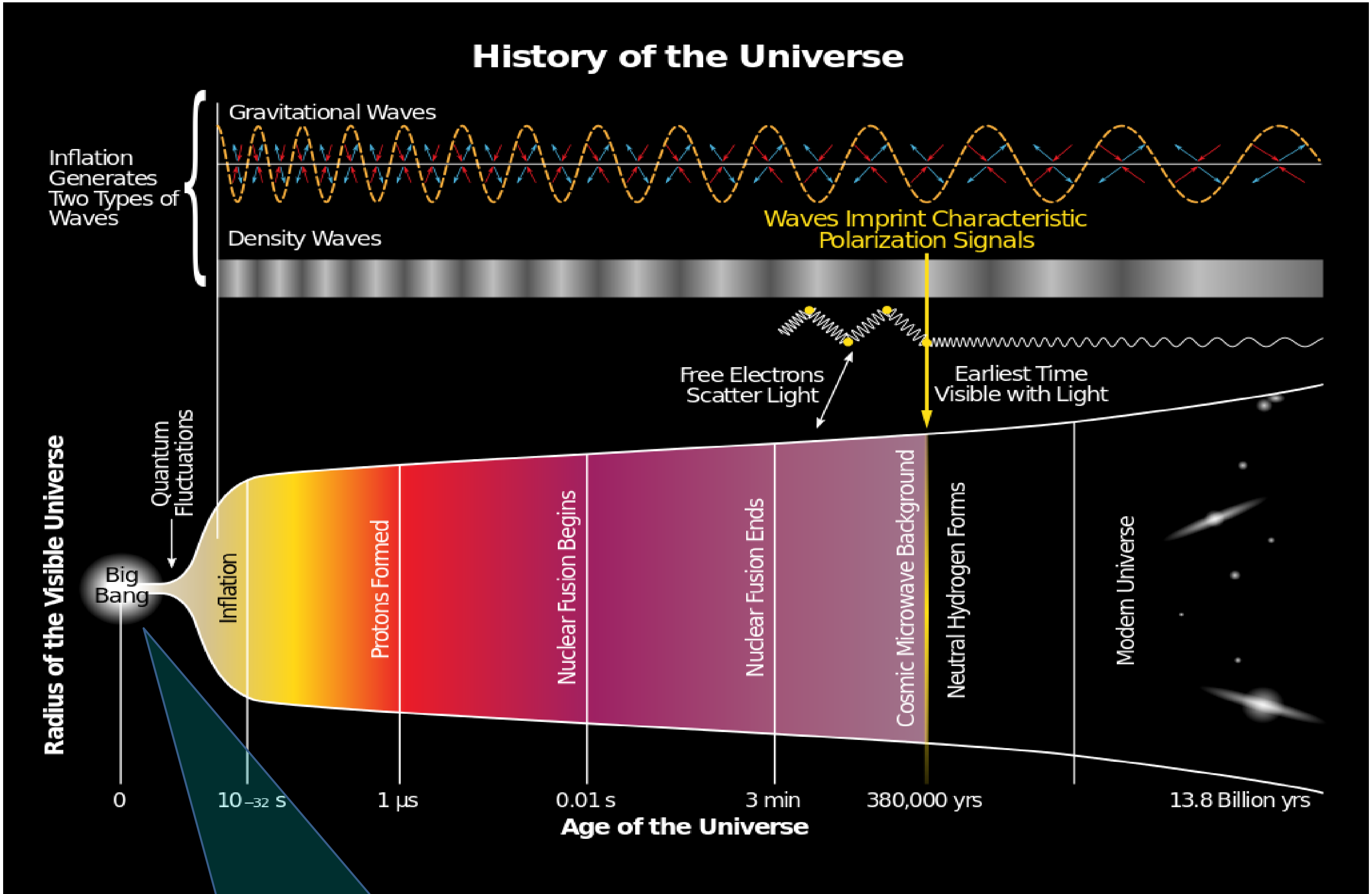
There always exist unavoidable Quantum Fluctuations

Quantum fluctuations in the density distribution are large (10^{-5})

only in extremely small scales (~ 10^{-33} cm),

but very small (~ 10^{-58}) on galactic scales (~ 10^{25} cm)

Can we transfer the large fluctuations from extremely small scales to large scales???



a vacuum or nearly vacuum state of zero temperature

Perturbations of matter and gravitational field:

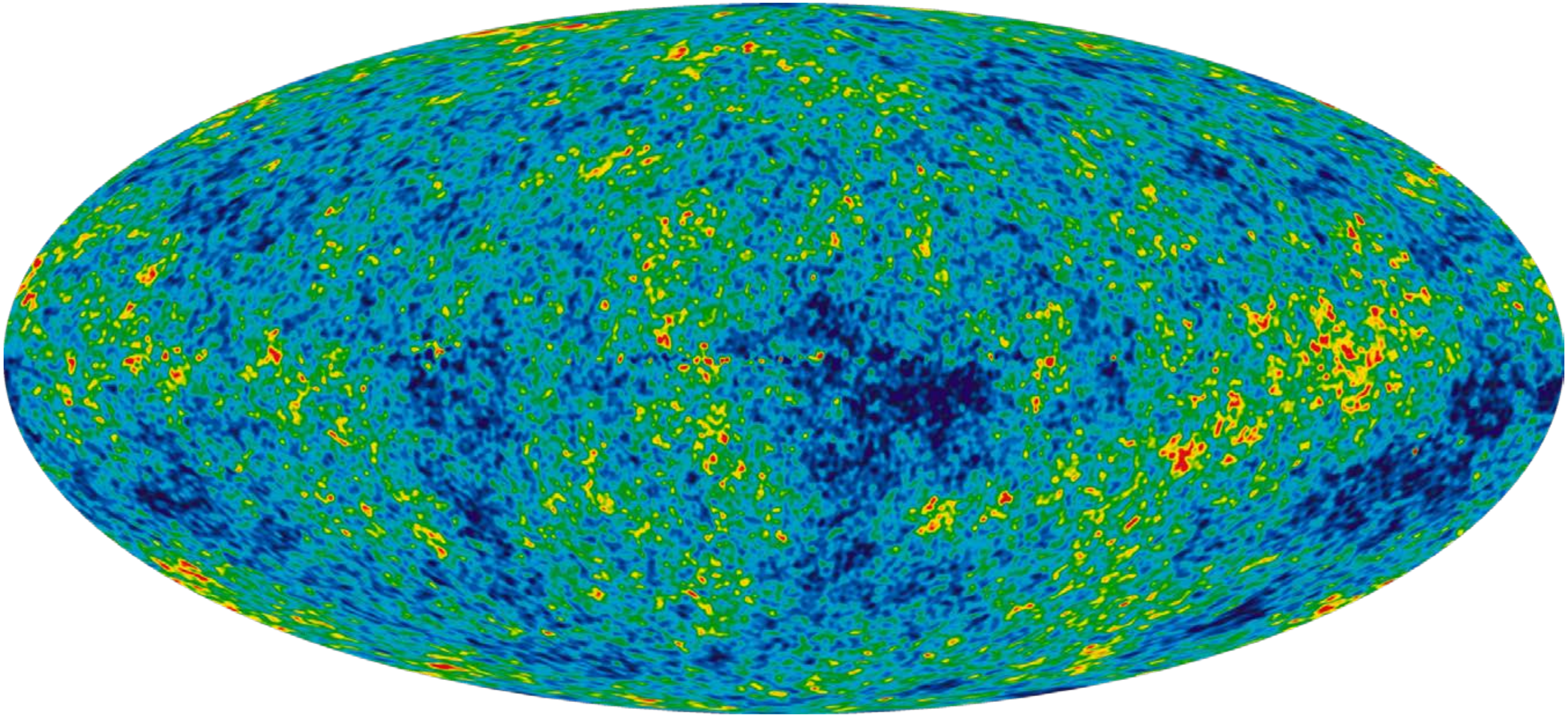
produce perturbations of temperature of relic radiation – CMB – which we observe now

eventually produce large scale structure of the Universe – stars, galaxies, galaxy clusters

have a logarithmic or power spectrum – amplitude increases by a few percent when the wavelength ¸ increases several times

$$\Phi \sim \lambda^{1-n_s}$$

n_s --- **spectral index**

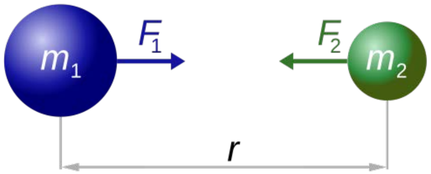


SKY http://map.gsfc.nasa.gov/media/121238/index.html The detailed, all-sky picture of the infant universe created from nine years of WMAP data. The image reveals 13.77 billion year old temperature fluctuations (shown as color differences) that correspond to the seeds that grew to become the galaxies. This image shows a temperature range of ± 200 microKelvin.
Credit: NASA / WMAP Science Team WMAP # 121238 Image.

$$n_s = 0.968 \pm 0.006$$

Planck 2015

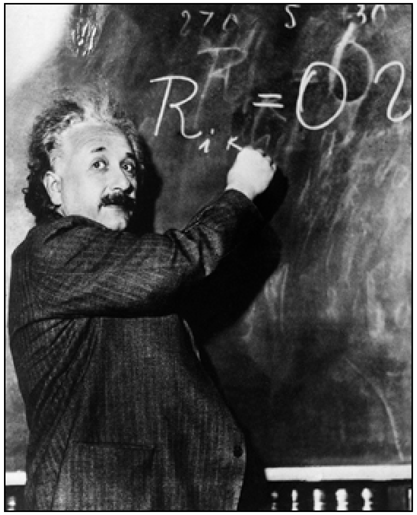
How comes that inflation expansion accelerates when gravity is an attraction force?



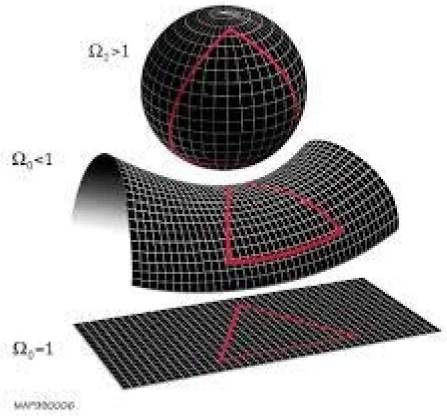
$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

"Spacetime curvature" = **"energy density and pressure"**

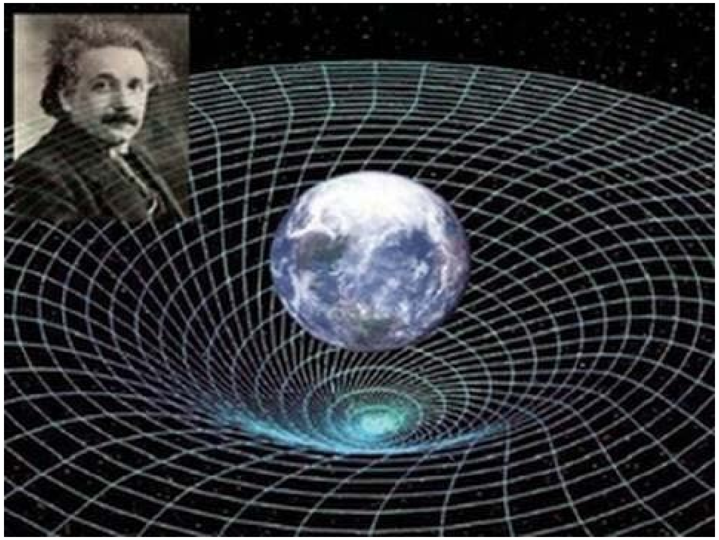


What is spacetime curvature?



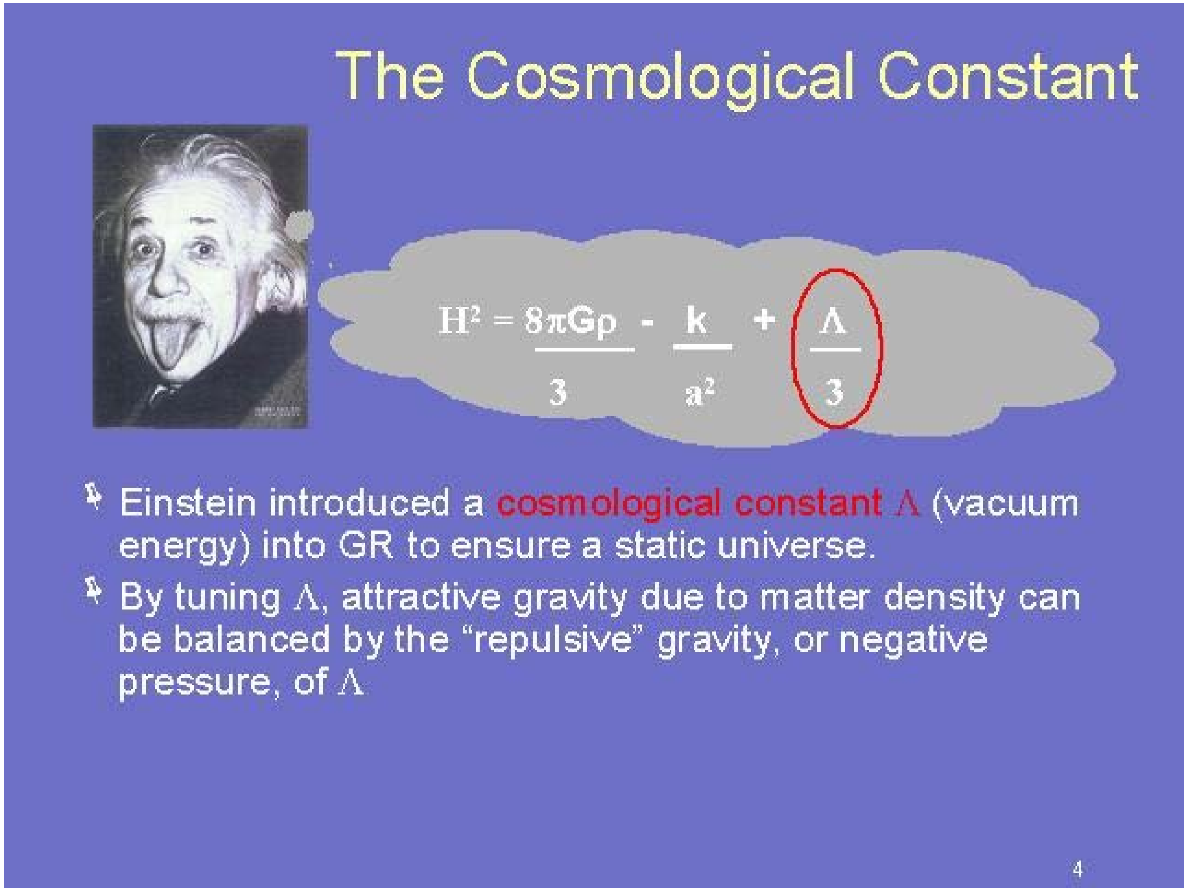
positive, negative and zero curvature of a 2-dimensional surface

“Picture” of 4-dimensional curved spacetime:



What is Λ ?

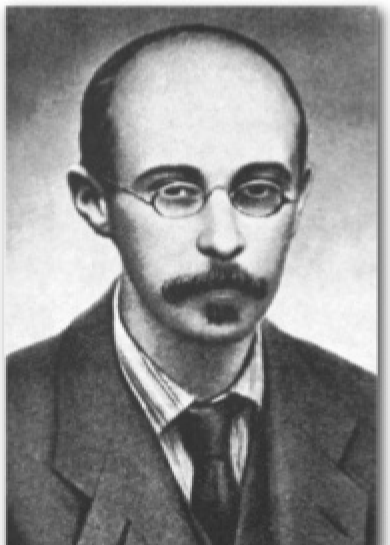
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} - \Lambda g_{\mu\nu}$$



Positive Λ -- repulsive force

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?

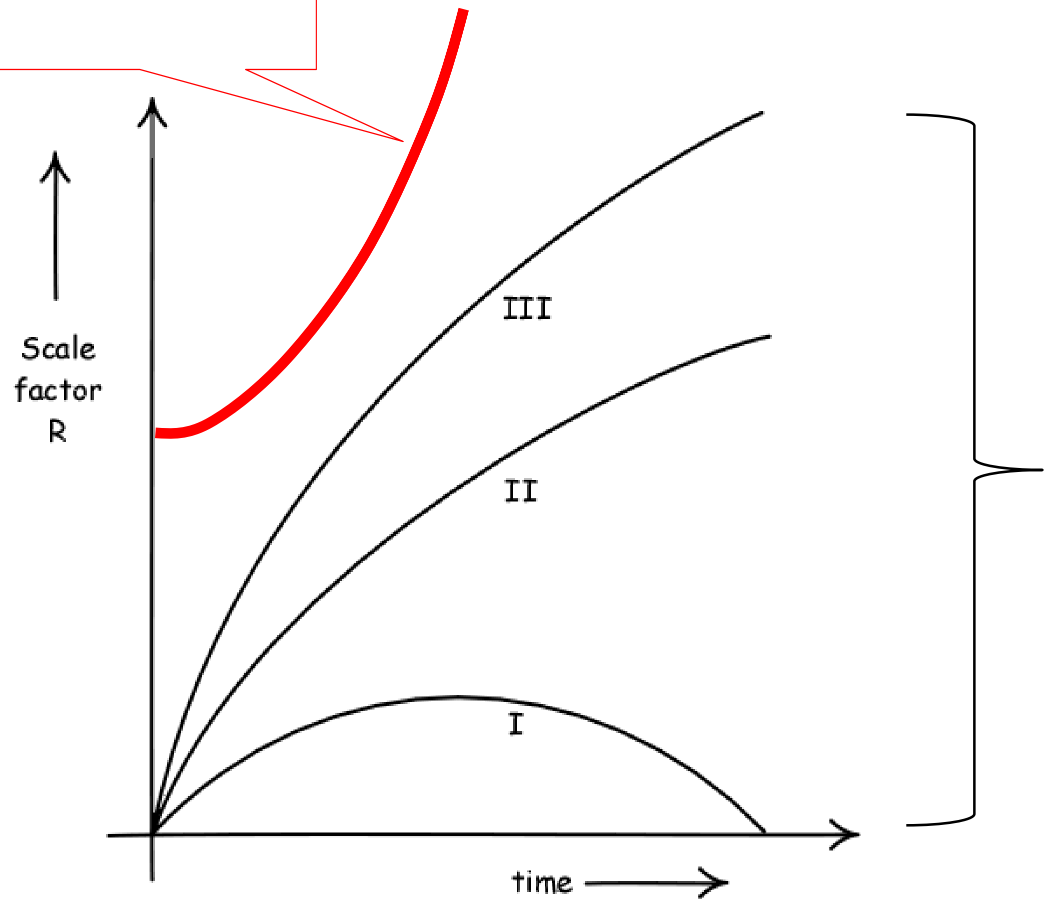
What happens if the universe is expanding?

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

$$H = \sqrt{\frac{\Lambda}{3}}$$

Fast exponential growth of the size of the Universe

Hubble constant – the parameter of Hubble law in the *early* Universe



Einstein GR: **1) Pressure also weighs**
2) pressure can be negative
3) pressure can play the role of ¤

Scalar field with a potential *V(Á)*

$$\varepsilon = \frac{\dot{\phi}^2}{2} + V(\phi)$$
$$p = \frac{\dot{\phi}^2}{2} - V(\phi)$$

Slow roll approximation $\dot{\phi} \simeq 0$

$$p = -\varepsilon, \quad \varepsilon = \frac{\Lambda}{8\pi G}$$

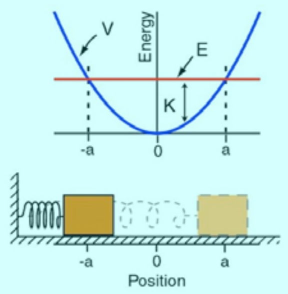
$$\Lambda = 8\pi G V(\phi) \simeq \text{const}$$

Mechanism of inflation --- slow roll of the

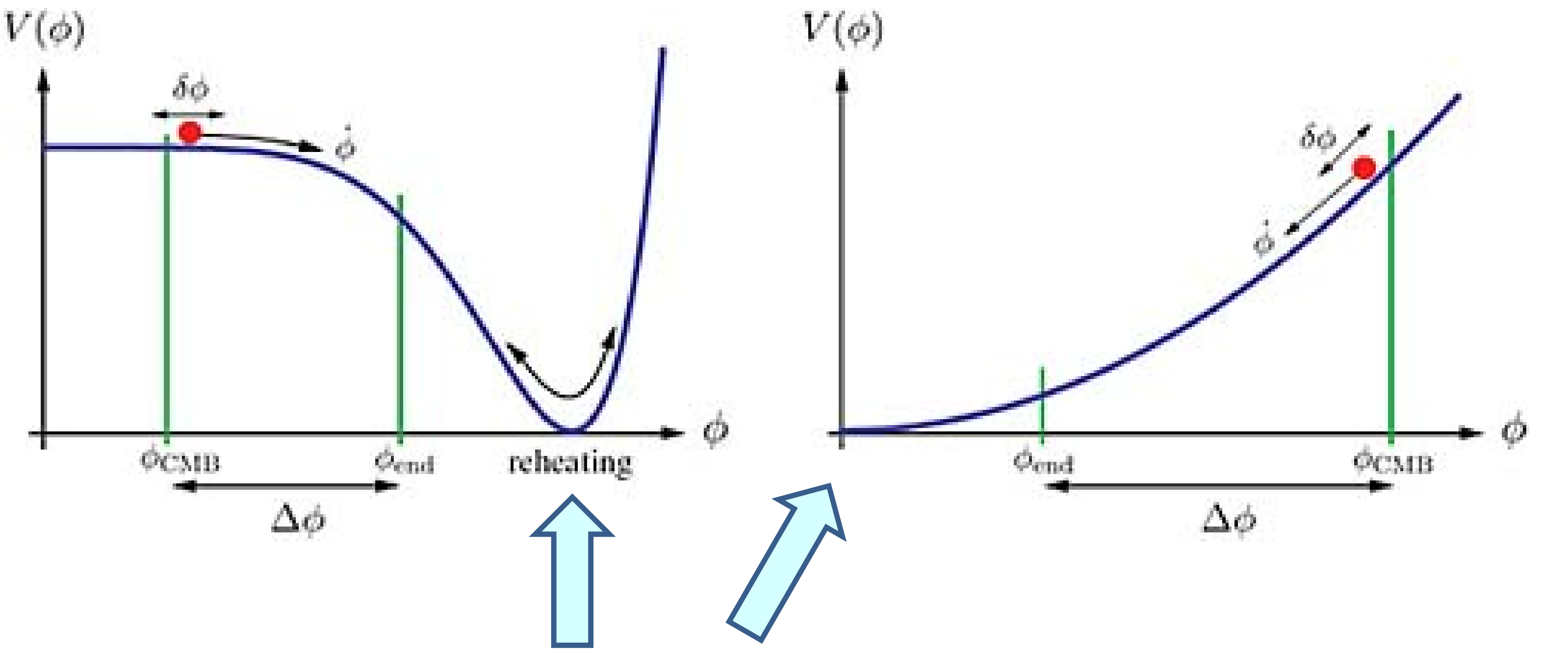
INFLATON field **Á** **(A.Starobinsky, A.Linde)**

Harmonic oscillator
with quadratic potential

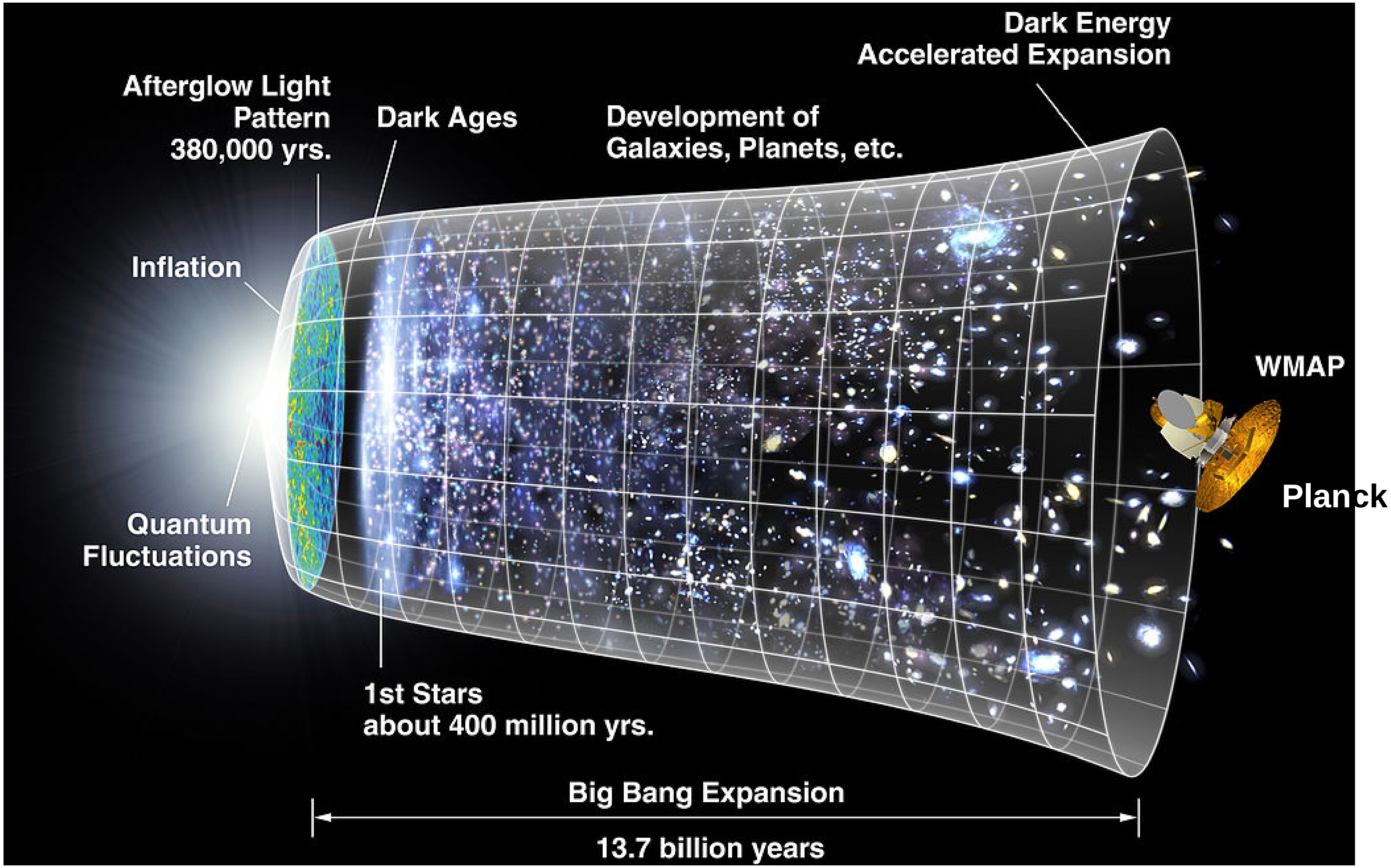
$$E = \frac{\dot{x}^2}{2} + \frac{\omega^2 x^2}{2}$$



Shapes of potential -- types of inflation: “new” inflation, “chaotic” inflation, etc.

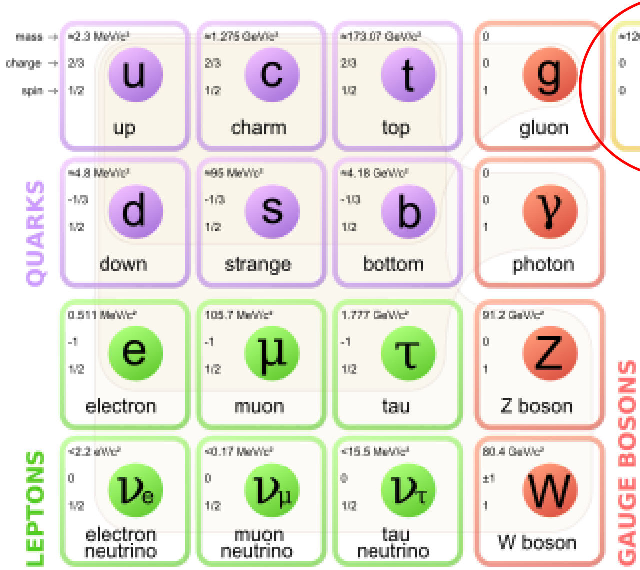


End of inflation, inflaton oscillations ⟶ reheating of the matter ⟶ further standard model of Big Bang



https://upload.wikimedia.org/wikipedia/commons/6/60/CMB_Timeline75.jpg
By NASA/WMAP Science Team [Public domain], via Wikimedia Commons

Candidate for the inflaton – Higgs boson



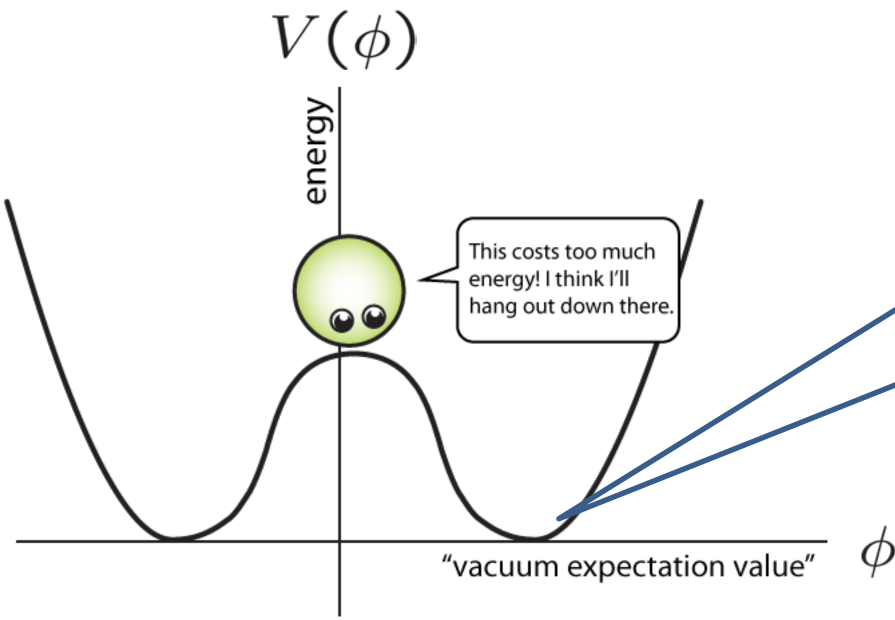
T.W.B.Kibble, G.S.Guralnik, C.R.Hagen, F.Englert, R.Brout (+ P. Higgs) (1964)

F. Englert, P.Higgs
Nobel Prize, 2013

Large Hadron Collider
CERN, Geneva
July 2012

M_{Higgs} ' **125 GeV**

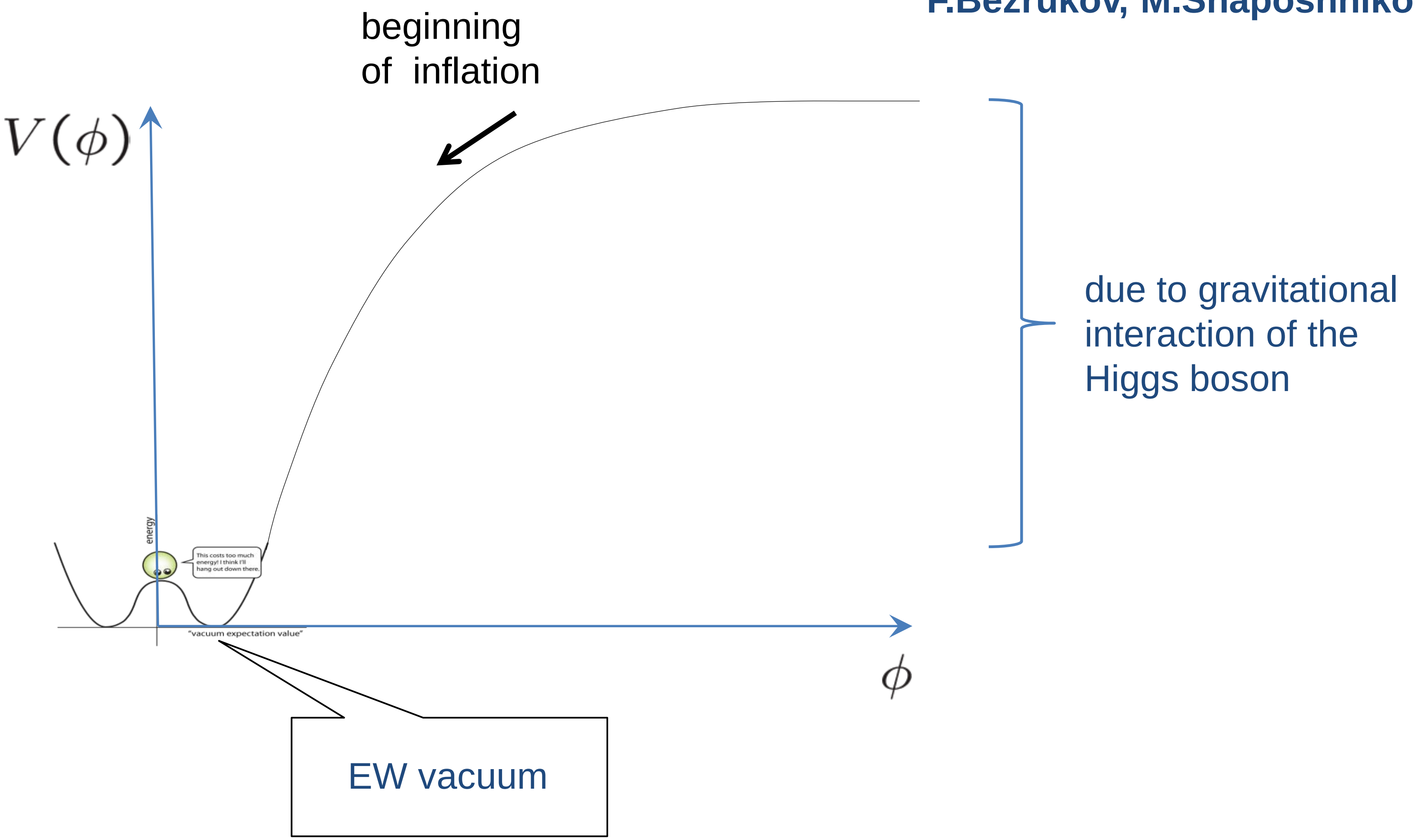
Why “God particle”?



Higgs boson endows other particles with masses via the vacuum expectation value **Á** at the minimum of ***V*(Á)** (electro-weak vacuum)

Higgs inflation – Higgs boson coupled to gravity

F.Bezrukov, M.Shaposhnikov



$n_s \simeq 0.96$ **prediction of the theory** → $M_{\text{Higgs}} \simeq 125$ GeV

Unification of scales mediated by inflation:

Galactic scales *10-100* Mpc **»** ***10***

Electroweak scale **»** $\boldsymbol{10^{-16}}$ cm

A.Kamenshchik, A.Starobinsky & A.Barvinsky 2008

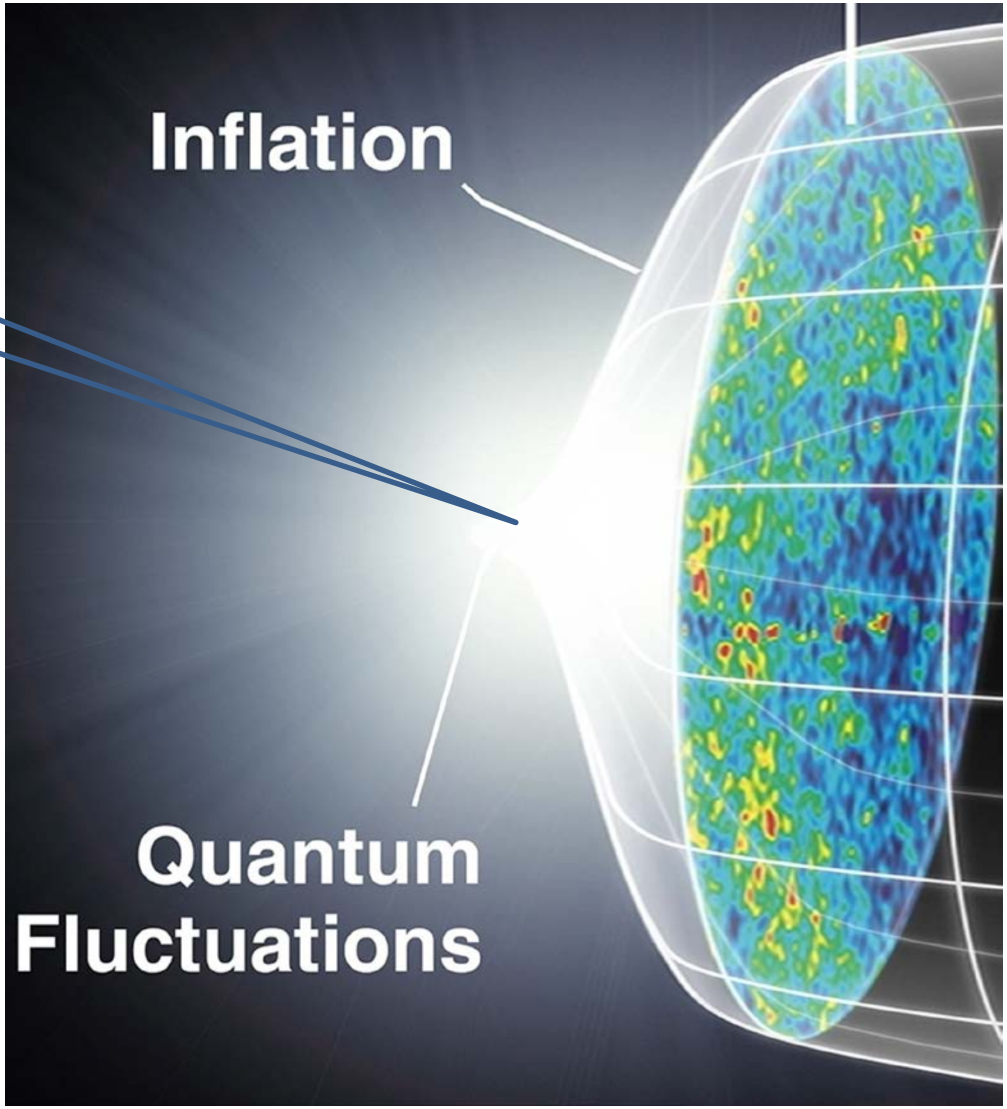
A.Kamenshchik, C.Kiefer, A.Starobinsky, C.Steinwachs & A.Barvinsky. 2009

Bezrukov,Shaposhnikov, 2008

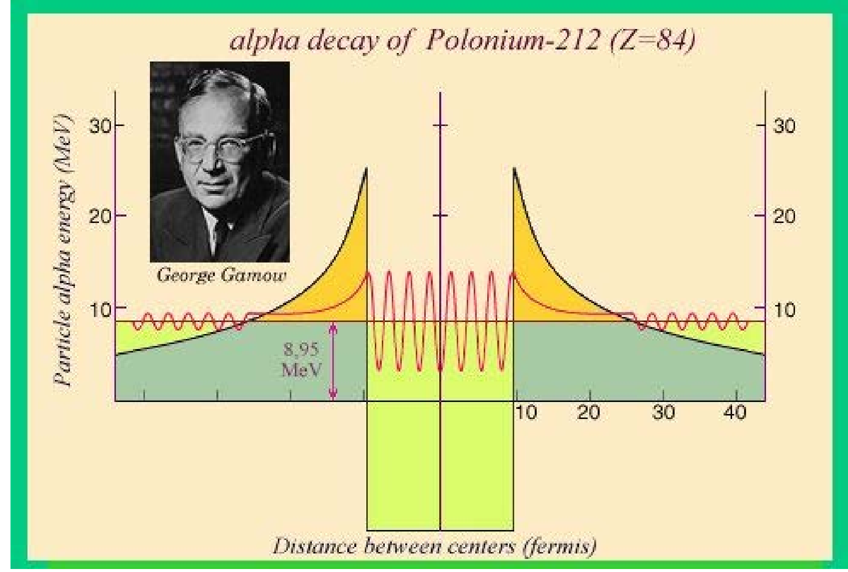
What was at the beginning?

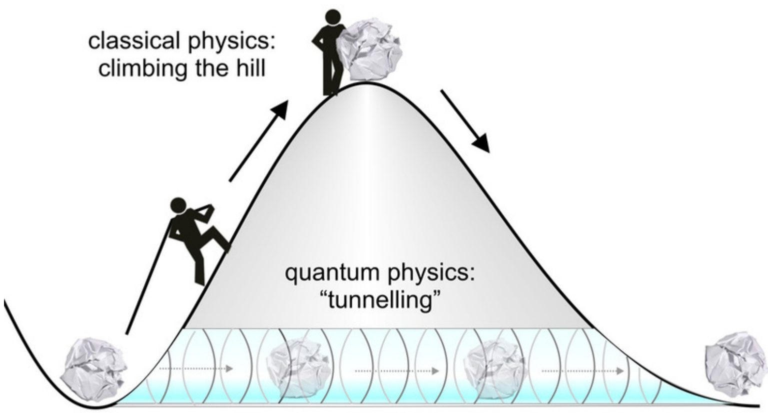
The space and time had both one beginning . The space was made not in time but simultaneously with time.

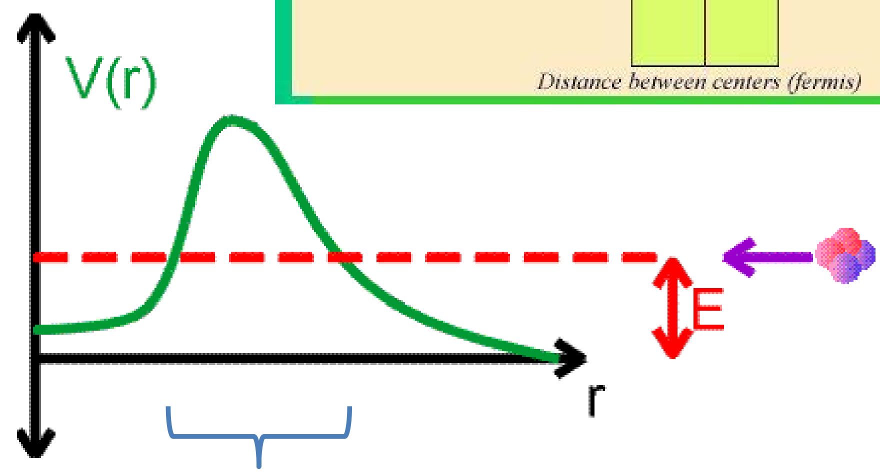
Saint Augustin of Hipo



Tunneling in QM:



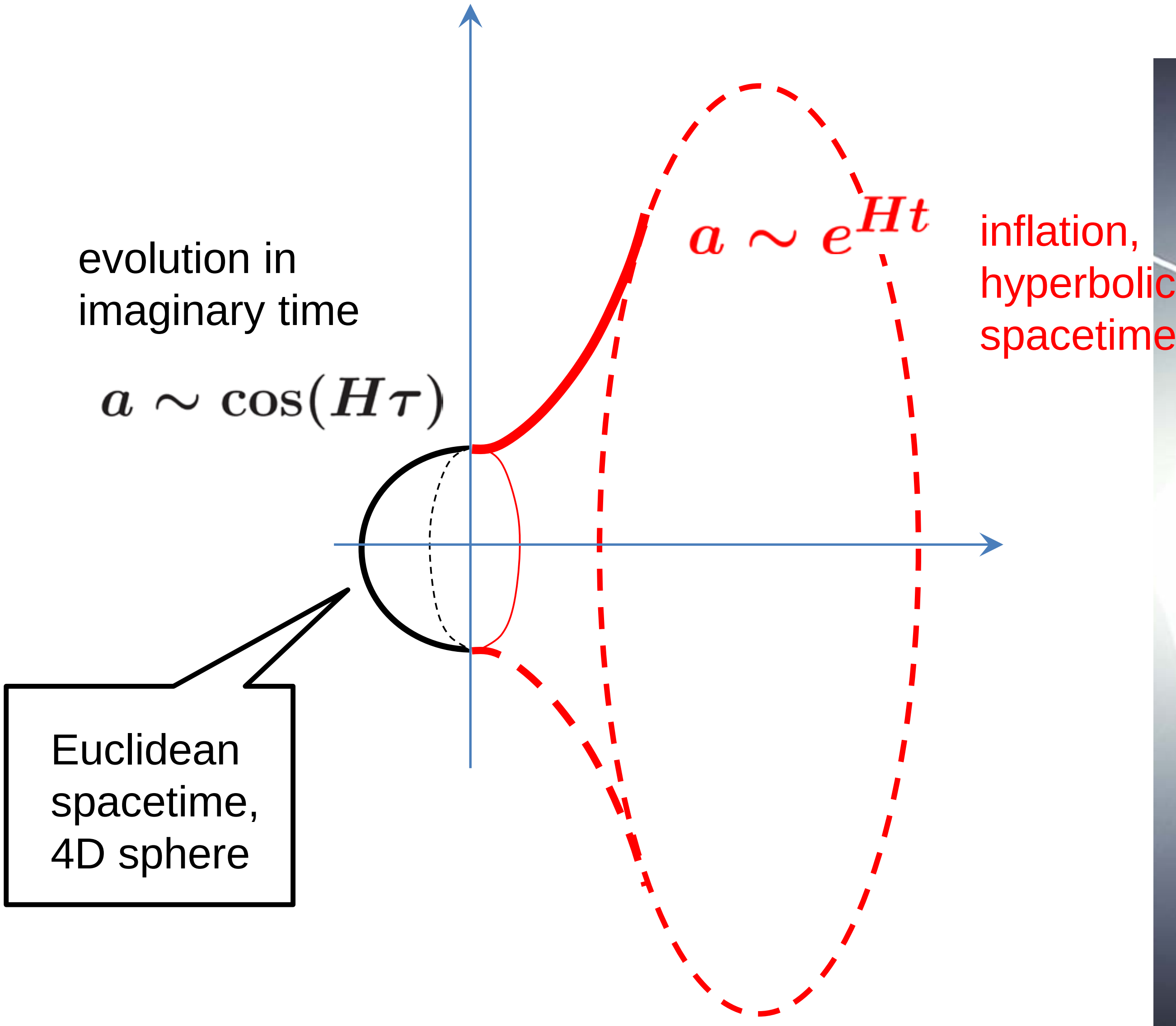




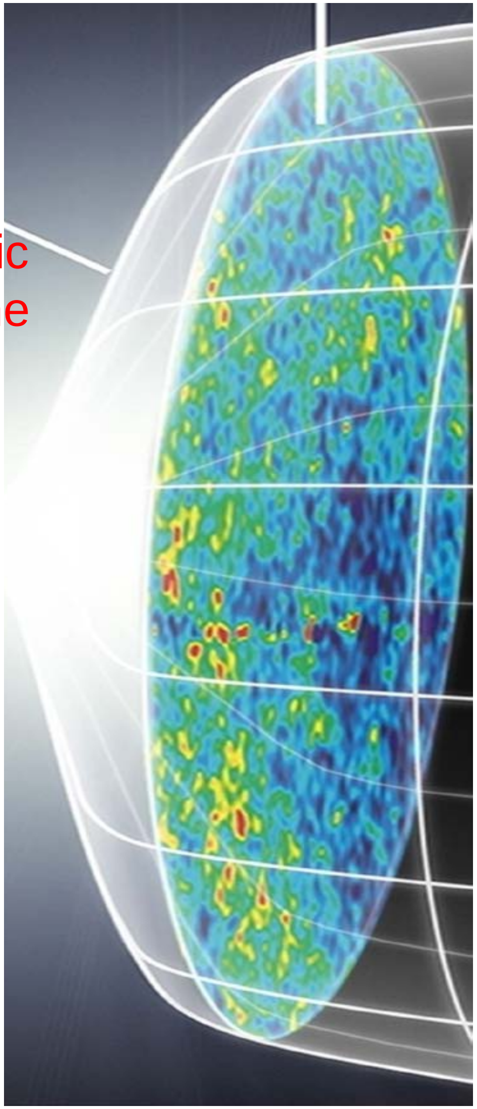
$$E = \frac{m\dot{r}^2}{2} + V(r)$$

$$\frac{dr}{dt} = \pm\sqrt{2\frac{E - V(R)}{m}} = \text{imaginary}, \quad t = i\tau, \quad E - V < 0$$

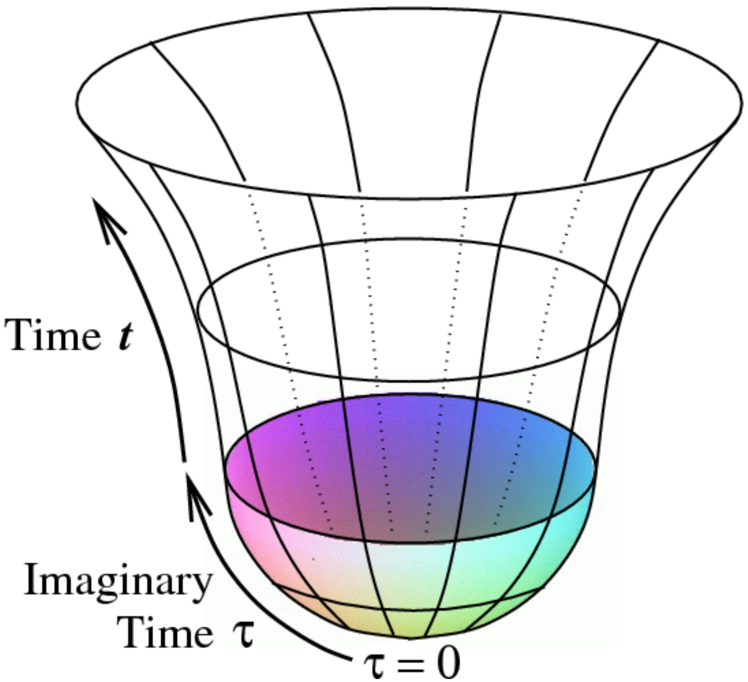
Underbarrier (classically forbidden) evolution in imaginary time ¿



evolution in
imaginary time
$a \sim \cos(H\tau)$
$a \sim e^{Ht}$
inflation,
hyperbolic
spacetime
Euclidean
spacetime,
4D sphere

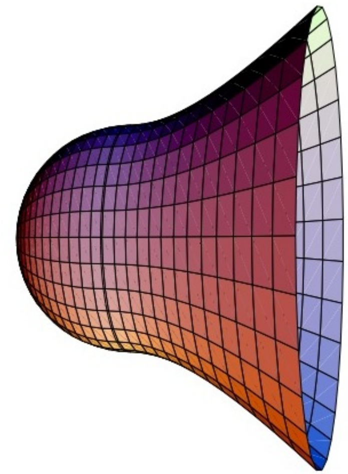


Hartle-Hawking wavefunction of the Universe



What might be wrong with the Hartle-Hawking wavefunction ?

Hartle-Hawking wavefunction is a vacuum state – the birth of the Universe from "nothing"



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

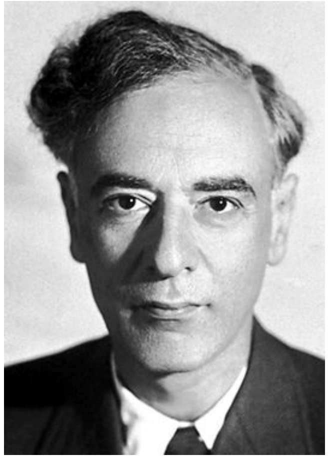
HH state does not generate good initial conditions for inflation – at the minimum of the inflaton potential rather than its maximum

So what can be the alternative?

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

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

What is density matrix?



L.Landau

In classical theory probabilities sum up: $p_1,\ p_2 \rightarrow p_1 + p_2$

In quantum theory quantum states (wavefunctions) sum up:

$$|\Psi\rangle = |\Psi_1\rangle + |\Psi_2\rangle$$

$$\langle\Psi|\mathcal{O}|\Psi\rangle = \underbrace{\langle\Psi_1|\mathcal{O}|\Psi_1\rangle}_{p_1} + \underbrace{\langle\Psi_2|\mathcal{O}|\Psi_2\rangle}_{p_2} + \langle\Psi_1|\mathcal{O}|\Psi_2\rangle + \langle\Psi_2|\mathcal{O}|\Psi_1\rangle$$

cross terms – interference between red and blue

$$\Psi \rightarrow \hat{\rho}$$

$$\langle\Psi|\mathcal{O}|\Psi\rangle = \langle\Psi_1|\mathcal{O}|\Psi_1\rangle + \langle\Psi_2|\mathcal{O}|\Psi_2\rangle + \cancel{\langle\Psi_1|\mathcal{O}|\Psi_2\rangle} + \cancel{\langle\Psi_2|\mathcal{O}|\Psi_1\rangle}$$

destruction of interference -- **decoherence**

Rules of the game:

$$| \Psi \rangle = | \Psi_1 \rangle + | \Psi_2 \rangle \rightarrow \hat{\rho} = | \Psi_1 \rangle \langle \Psi_1 | + | \Psi_2 \rangle \langle \Psi_2 |$$

$$\langle \Psi | \mathcal{O} | \Psi \rangle \rightarrow \mathrm{tr} \left(\mathcal{O} \hat{\rho} \right)$$

trace operation

$$\mathrm{tr} \left(\mathcal{O} | \Psi_1 \rangle \langle \Psi_1 | \right) = \langle \Psi_1 | \mathcal{O} | \Psi_1 \rangle$$

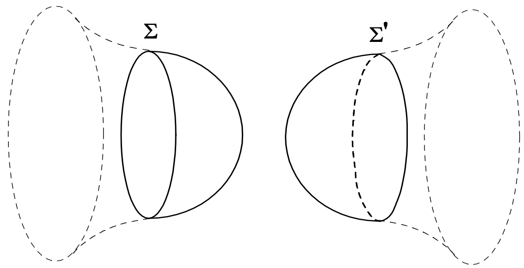
pure state $| \Psi \rangle \Leftrightarrow \hat{\rho} = | \Psi \rangle \langle \Psi |$ *pure* state density matrix

$$\hat{\rho} = | \Psi_1 \rangle \langle \Psi_1 | + | \Psi_2 \rangle \langle \Psi_2 | + \ldots$$

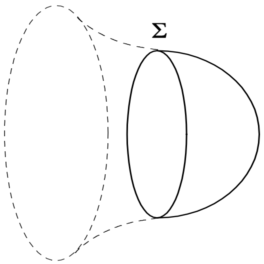
mixed state – *nonfactorizable* density matrix

From “vacuum” Hartle-Hawking state to the density matrix:

$$|\Psi\rangle\langle\Psi| = \hat{\rho}_{HH}$$



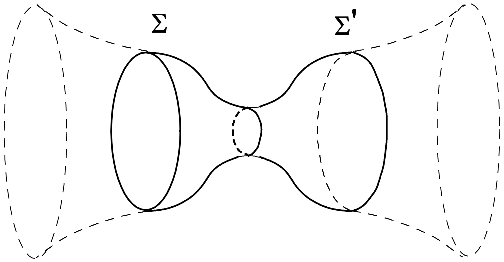
$\Longleftrightarrow$ $|\Psi\rangle$



density matrix picture of a pure Hartle-Hawking state – vacuum state *of zero temperature*

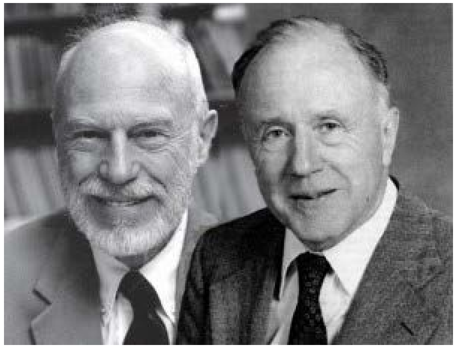
$\Downarrow$

$$\hat{\rho}_{\text{mixed}}$$



density matrix picture of a mixed state

All possible physical states (wavefunctions) and density matrices in quantum gravity satisfy the **Wheeler-DeWitt equation** which is symbolically



$$\hat{H}\,|\,\Psi\,\rangle = 0$$

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

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

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

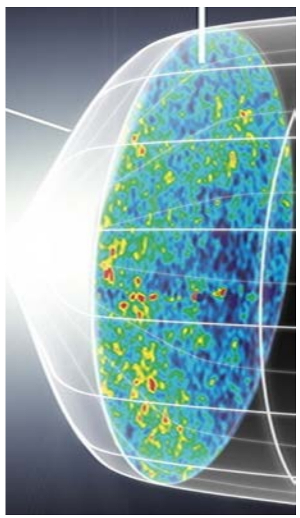
Motivation: aesthetic (minimum set of assumptions – Occam razor)

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.

Properties of the "newly born" Universe

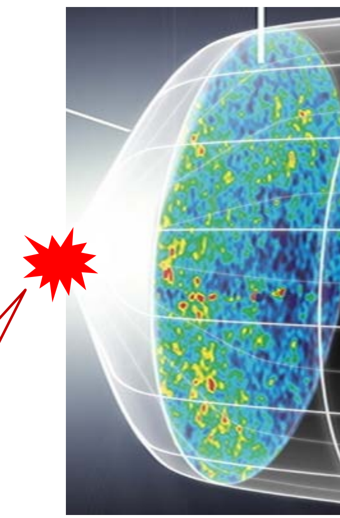
1) Initial thermal state with the primordial temperature T_{prim} of matter

Standard inflation scenario **vs** Density matrix scenario



Vacuum, absolute zero temperature *T=0*

Inflation, hot big-bang
→ relic radiation
$T'\ 3000^0$



Thermal state, *primordial temperature* T_{prim}

Inflation, $T_{prim} \to 0$,
hot big-bang
→ relic radiation
$T'\ 3000^0$

“SOME LIKE IT HOT” (SLIH) scenario

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

“SOME LIKE IT HO

-- it incorporates e

evolution.

ot Big Bang

gical

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Cosmological landscape from nothing: some like it hot

A O Barvinsky[1] and A Yu Kamenshchik[2,3]

2) Restriction of the range of the effective cosmological constant below the Planck energy scale

$$\Lambda \leq \Lambda_{\rm max} \ll M_P^2 \sim (10^{18}\mathrm{GeV})^2$$

↑

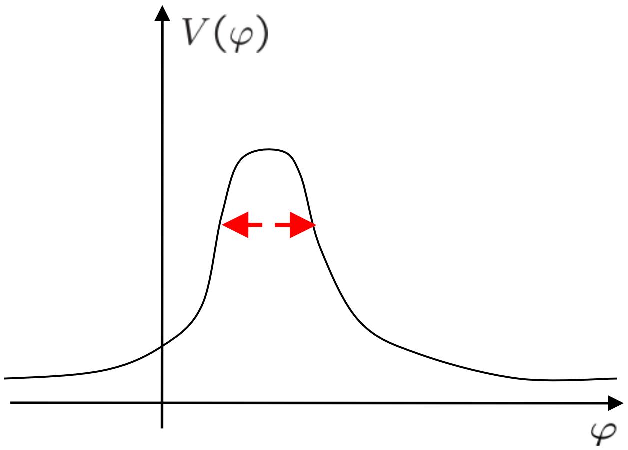
new quantum gravity scale

We do not have a consistent nonperturbative quantum gravity and have to use the powerful approximation method – semiclassical expansion – which is valid only below the Planck scale. This restriction of Λ justifies this method and its predictions!

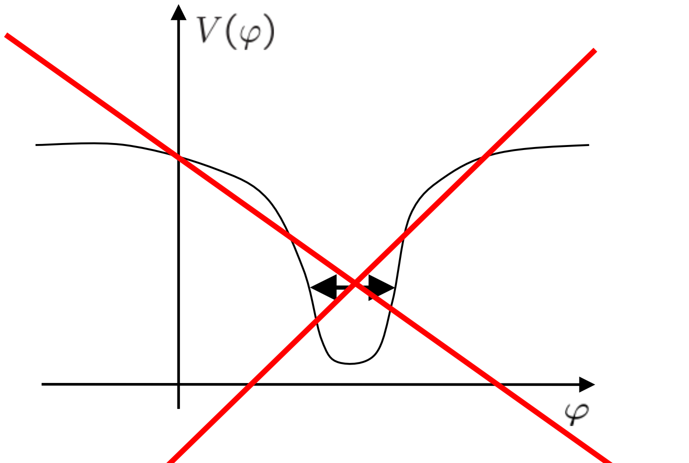
In string theory ("Theory of everything") this property might be provoke the solution of the so called "landscape problem" (selection among 10^{500} vacua).

TOO VERBOSE

3) Selection of inflaton potential *maxima* as initial conditions for inflation -- the major difficulty with the Hartle-Hawking state



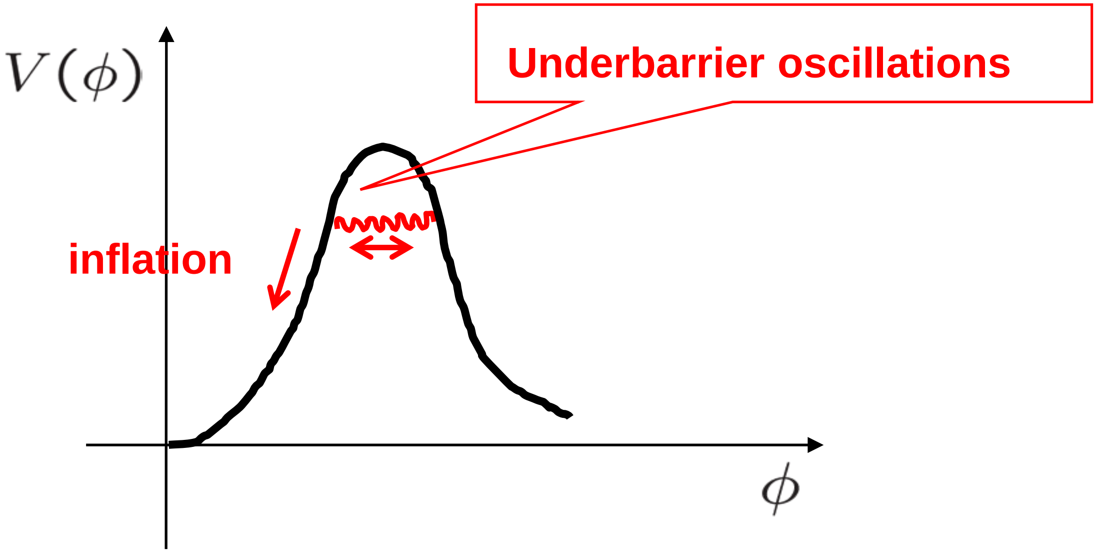
classically forbidden
(underbarrier) oscillation



classically allowed (overbarrier)
oscillation are ruled out

Initial conditions for a new type of hill-top inflation

Picture of a new type hill-top inflation



Origin of the hill-top potential from quantum effects: remarkable match with the Higgs inflation model

Higgs boson » $\boldsymbol{10^{-16}}$ cm

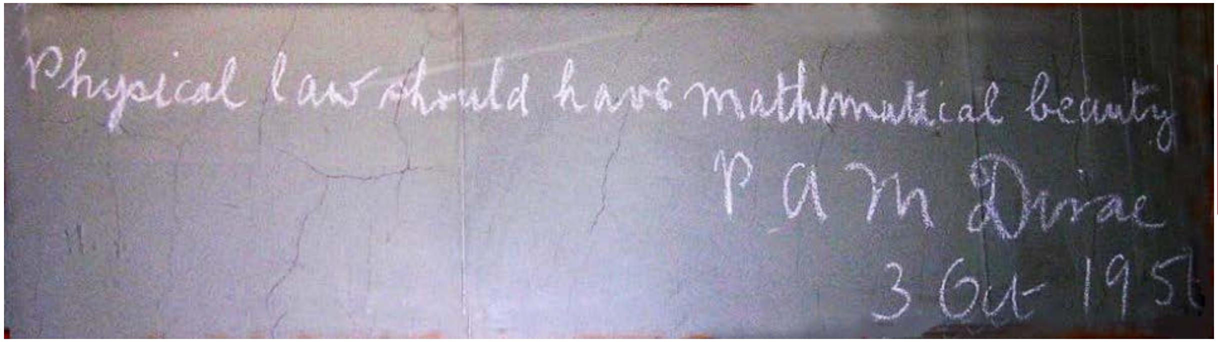
Planck scale “birth” of the Universe » $\boldsymbol{10^{-33}}$ cm

Our Universe embraces phenomena from quantum gravity –Planck -- scale *10^{-33} cm* to the Universe size of billions of light years

Unification of these phenomena is mediated by the transition from the quantum birth of the Universe at the Planck scale to the Higgs boson scale ***10^{-16}*** *cm* and further on to galactic scales

Our comprehension of this remarkable unity runs via the CMB observations -- gigantic microscope device provided to us by Nature in the form of inflation, the mechanism of enormous stretching of physical scales from ***10^{-16}*** *cm* to hundreds of *Mpc*

Remarkable beauty of this unification – absence of the redundant (in the spirit of Occam razor) culminates in the saying:



TOO VERBOSE