SI 2019
20 August, 2019

Inflation & Cosmology I

- A Historical Perspective on Particle Cosmology -

Misao Sasaki

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YITP, Kyoto University
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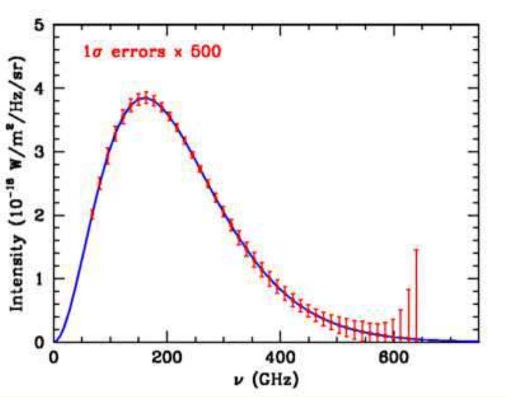
Progress in Particle Cosmology (1)

1^{st} stage: 1945 ~ 1975

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

- 1916~ GR/Friedmann-Lemaitre model
- 1929 Hubble's law: $V=H_0 R$
- 1946~ Big-Bang theory/Nuclear astrophysics
- 1960~ High redshift objects/Quasars
- 1965 Discovery of relic radiation from Big-Bang
  Cosmic Microwave Background (CMB) ~ 3K
- 1966 Sakharov's condition
  (but didn't attract much attention)
- 1970~ Big-Bang Nucleosynthesis vs Observed Abundance
  → Existence of Dark Matter (DM)



matter-antimatter asymmetry

Big Bang Nucleosynthesis (BBN)

George Gamov: pioneer in particle cosmology (1940's)

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we might imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt} = f(t)(\sigma_{i-1}n_{i-1} - \sigma_i n_i) \quad i = 1, 2, \cdots 238, \tag{1}$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundance[illegible]ted by the resonances[illegible] According to Hughes,[2] [illegible] of various elements ([illegible]ev) increase exponentia[illegible] the periodic system, r[illegible] for heavier elements.

Using t[illegible] integrating Eqs. (1) as[illegible]undances of various nu[illegible] the lighter elements a[illegible] for the elements hea[illegible]e calculated curve with[illegible] necessary to assume the[illegible]-up period is equal to 5[illegible]

On the [illegible]tic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t = 0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5 \times 10^4 \tag{2}$$

which gives $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5 \times 10^5$ g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^5 g sec./cm³ which can possibly be understood if we

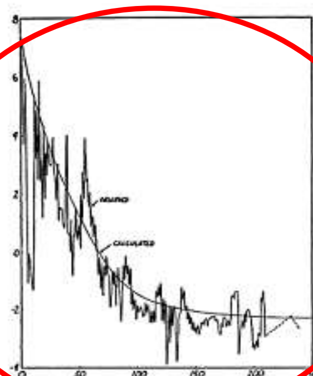


FIG. 1.
Log of relative abundance
Atomic weight

Alpher–Bethe–Gamow (αβγ) 1948

discovery of neutron by Chadwick 1932

- 1st application of nuclear physics to cosmology
- explain light element abundance in the Universe

Chushiro Hayashi: father of astro-particle physics in Japan

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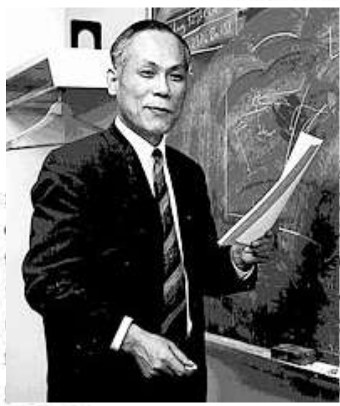
Progress of Theoretical Physics, Vol. 5, No. 2, March~April, 1950.

Proton-Neutron Concentration Ratio in the Expanding Universe at the Stages preceding the Formation of the Elements.

Chushiro HAYASHI.

Department of Physics, Naniwa University.



(Received January 12, 1950)

§ 1. Introduction.

...gin of the elements by Gamow, Alpher, and colabo- ...ylem) of the universe, which afterwards has been ...pansion of the universe and has formed the elements ...ch as radiative capture and beta-decays, is assumed ... At early stages, however, of high temperatures ...ron mass) in the expanding universe before the ...duced beta-processes caused by energetic electrons, ...eutrinos, in addition to the natural decay of neutrons, such as

$$n + e^{+} \rightleftarrows p + a\nu, \quad (1a)$$

$$n + \nu \rightleftarrows p + e^{-}, \quad (1b)$$

$$n \rightleftarrows p + e^{-} + a\nu, \quad (1c)$$

must have proceeded, their rates being faster at higher temperatures, and had a effect on the proton-neutron concentration ratio. At still higher temperatures $kT \gtrsim \mu c^2$ (μ is the mesons' mass), where large number of mesons are expected to be in existence, n-p conversion process induced by mesons would have been much more rapid owing to their stronger interactions with nucleons than the processes induced by light particles. Consequently, the n-p ratio must have been determined by the rates of such processes and those of changes in temperature and density in the universe resulting from its expansion.

- αβγ incorrectly assumed the Universe was totally filled by neutrons.
- Hayashi realized that the weak interaction must be in thermal equilibrium. (1950)

⇩

correct initial cond. for BBN

$$\frac{n_N}{n_P} = \exp\left[-\frac{m_N - m_P}{T}\right]$$

$$m_N - m_P = 1.293 \text{ MeV}$$

⇨ $$\frac{n_N}{n_P} \approx 0.2 \text{ at } T = 10^{10}\text{K}$$

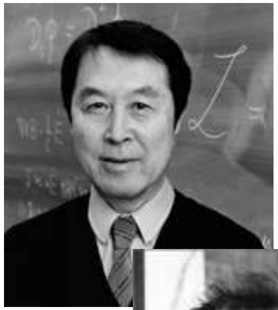
discovery of CMB (1964) = victory of Bing Bang Theory

- Experiment
  - 60's ~70's : golden age of particle physics
  - dawn of high energy physics: $E \gg$ GeV
  - accelerator experiments > cosmic ray observations

    CERN, Fermilab, DESI, SLAC, KEK, …

    neutral current 1973, J/ψ 1974, …

discovery of many "elementary" particles



- Theory

"Spontaneous Symmetry Breakdown"

Nambu '60
Goldstone '61

- success of Gauge Unification: Weinberg-Salam (1967)

⇨ Standard (Glasho-Weinberg-Salam) Model

Strong+Weak+EM
$SU(3)\times SU(2)\times U(1)$

- but no much was done in particle cosmology except for BBN computations…

Progress in Particle Cosmology (2)

2^{nd} stage: 1975 ~ 1995

motivation/ driving force

- 1975 Sato-Sato: Cosmological Constraints on Higgs
- 1977 Sato-Kobayashi: Constraints on Neutrino Mass & Species
- 1977 Yoshimura: Baryogenesis in Grand Unified Theory (GUT)

Brout, Englert & Gunzig '77, Starobinsky '79, Guth '81, Sato '81, Linde '81, …

Dawn of Particle Cosmology/Inflationary Universe

- 1980~ Large Scale Structure : Cold DM (CDM)

Slow-roll Inflation / Cosmological Perturbation Theory

- 1992 CMB anisotropy by COBE: 1^{st} Evidence for Inflation

hundreds of models of inflation

Katsuhiko Sato: a great mind of our time

pioneer of modern particle cosmology

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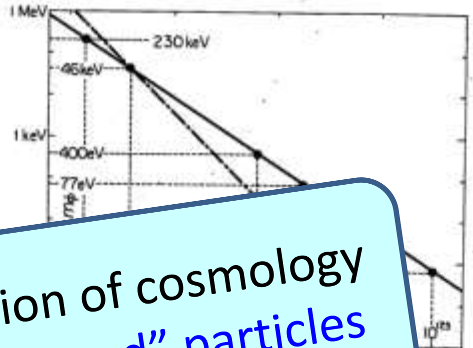
Prog. Theor. Phys. Vol. 54 (1975), Sept.

Primordial Higgs Mesons and Cosmic Background Radiations

Katsuhiko SATO and Humitaka SATO

Research Institute for Fundamental Physics
Kyoto University, Kyoto

May 12, 1975



1st application of cosmology to "undiscovered" particles

The unified theory o... magnetic interactions, ... berg and Salam, has be... by the discovery of n... CERN and NAL. On ... this theory, the presence ... meson, "Higgs meson", is also inevitable but its mass m_ϕ, is arbitrary in this theory.

Rec... Higgs... range... exper... Howe... cept f... range... 1 keV... berg...

...ife (τ) rela... temperature... relation in ... end tim... e" whe... the Pla... ...ork on ... if they ... tter de... exchar... is stil... stages

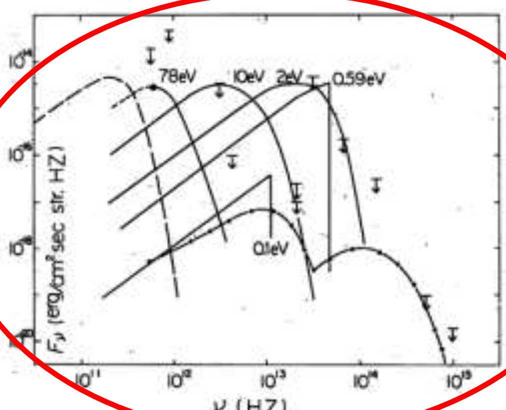


Fig. 2. Energy spectrum of the background radiation created by Higgs meson decay. The dashed curve represents the 2.7°K black body radiation. The observational upper limits of the flux are shown by the arrows and the theoretical estimations by Longair and Sunyaev[8] is shown by dot-dashed line.

Progress of Theoretical Physics, Vol. 58, No. 6, December 1977

Cosmological Constraints on the Mass and the Number of Heavy Lepton Neutrinos

Katsuhiko SATO and Makoto KOBAYASHI

Department of Physics, Kyoto University, Kyoto 606

(Received May 23, 1977)

1st systematic study on ν mass & no. of species

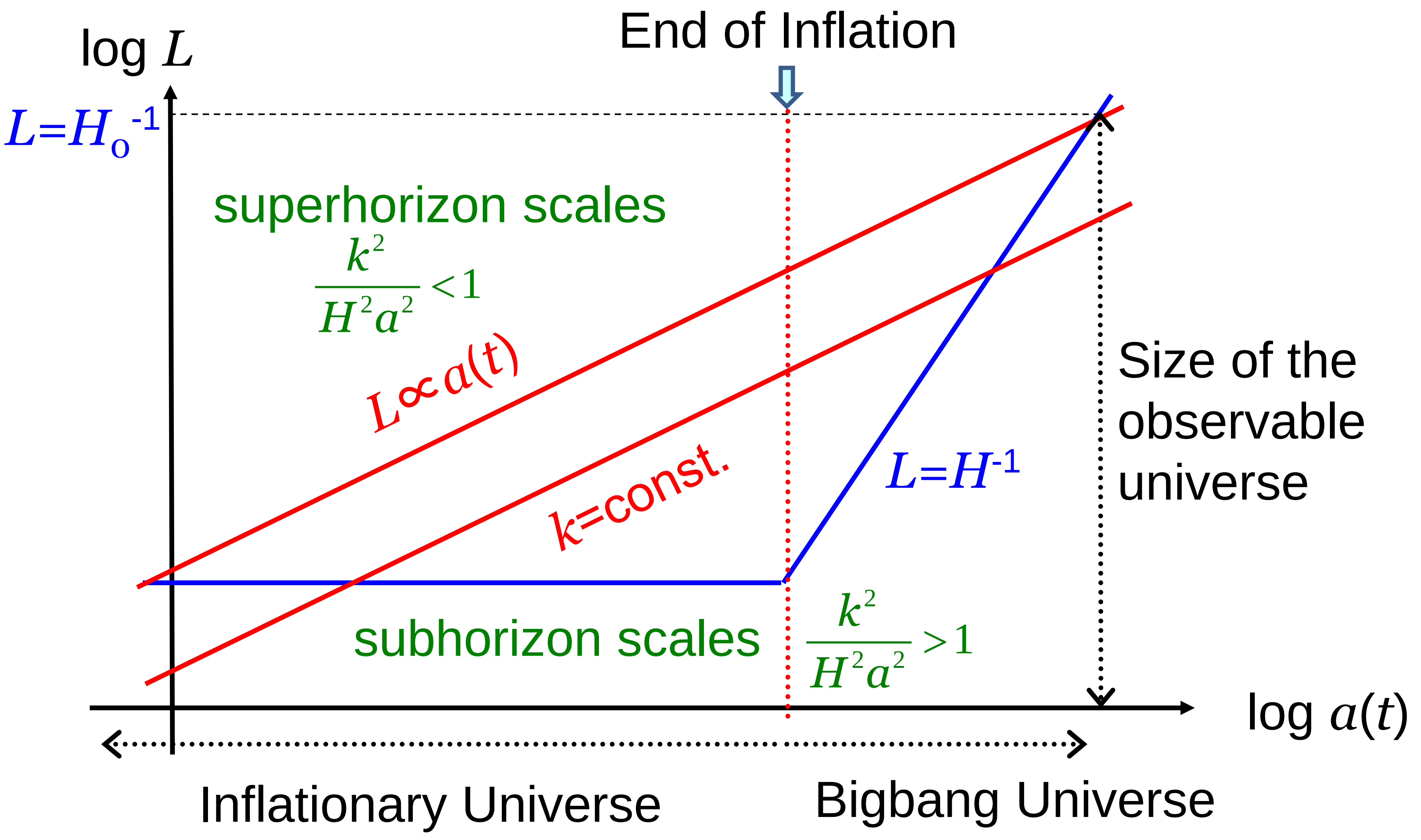
If the neutrinos associated with t... into the lower mass neutrinos. We... neutrinos in the standard big bang mo... masses and the number from the cosm... ...wer limit of the age of the universe and the upper limi... ...parameter, 2) the upper limit of the observed cosmic background radiation and 3) the upper limit of the primordial abundance of ⁴He. The following results are then obtained: 1) No neutrinos should exist in the mass range 70 eV $< m_\nu <$ 23 MeV. 2) If the muon and electron neutrinos are also massive, number of neutrinos lighter than 70 eV should be less than four. 3) A limit to the number of the neutrinos heavier than 23 MeV but lighter than 50 MeV is obtained as a function of the mass of neutrinos.

What is Inflation?

Brout, Englert & Gunzig '77, Starobinsky '79, Guth '81, Sato '81, Linde '81,…

- Inflation is a quasi-exponential expansion of the Universe at its very early stage; perhaps at t~10^{-36} sec.
- It is the origin of Hot Bing-Bang Universe
- It was meant to solve the initial condition (singularity, horizon & flatness, etc.) problems in Big-Bang Cosmology:
  - if any of them can be said to be solved depends on precise definitions of the problems.
- Quantum vacuum fluctuations during inflation turn out to play the most important role. They give the initial condition for all the structures in the Universe.
- Cosmic gravitational wave background is also generated.

Length Scales of Inflationary Universe



Pioneers of Inflation

Brout, Englert & Gunzig '77

The Creation of the Universe as a Quantum Phenomenon

R. Brout, F. Englert, and E. Gunzig

Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium

Received July 7, 1977

In summary, the picture that emerges is in complete accord with the kinematic generalities of causal cosmology presented in Section 2. For $y < y_0$, one has $p < 0$ ($p \simeq -\sigma$). For $y > y_0$, p becomes positive and λ undergoes an inflection. The situation is summarized in Figs. 1 and 2.

温故知新

(learning from the past)

$$ds^2 = -dt^2 + a^2(t)dH_{(3)}^2;$$

$$a(t) \simeq H^{-1}\sinh Ht$$

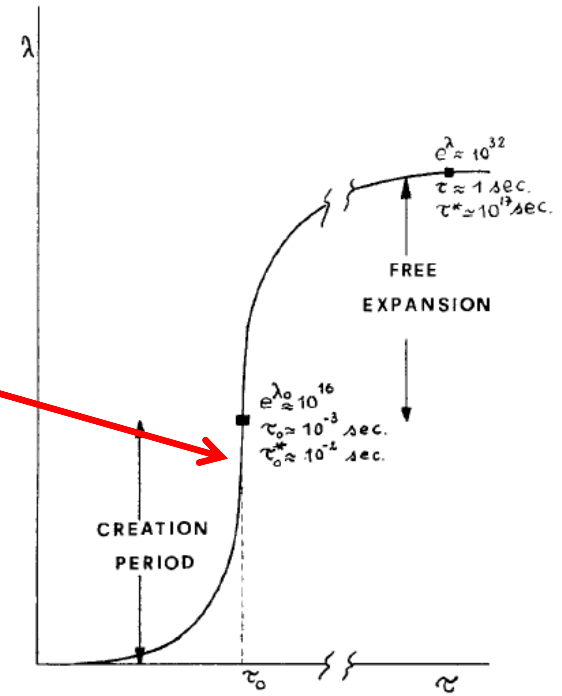


Fig. 1. λ as a function of kinematical time τ for $\delta = 0$. Time scales are calculated for $m = 1$ GeV.

Creation of
Open Universe!

Now in the context of
String Theory Landscape

Pioneers of Inflation 2

Starobinsky '79 ~ '80

Spectrum of relict gravitational radiation and the early state of the universe

A. A. Starobinskiĭ
L.D. Landau Institute of Theoretical Physics, USSR Academy of Sciences

(Submitted 25 October 1979)
Pis'ma Zh. Eksp. Teor. Fiz. **30**, No. 11, 719–723 (5 December 1979)

A phenomenological model of the universe, in which, the universe was in a maximum symmetrical quantum state before the beginning of the classical Friedman expansion, is examined. The spectrum of long-wave, background, gravitational radiation is calculated in this model. The possibility of detecting this radiation in the range $10^{-3} - 10^{-5}$ Hz is promising.

tensor perturbation spectrum from de Sitter space

$$\frac{d^2\chi_n}{d\eta^2} + \left(n^2 - \frac{1}{a}\frac{d^2a}{d\eta^2}\right)\chi_n = 0$$

$$\epsilon(\nu) = \frac{2}{3\pi} s^2 \epsilon_0 \nu^{-1}$$

$$s = \frac{H}{M_{pl}}$$

$$P_T(k) \simeq \left(\frac{H}{M_{pl}}\right)^2 \simeq \frac{\Omega_{GW}}{\Omega_{\rm rad}}$$

A NEW TYPE OF ISOTROPIC COSMOLOGICAL MODELS WITHOUT SINGULARITY

A.A. STAROBINSKY
Department of Applied Mathematics and Theoretical Physics, Cambridge University, Cambridge, England [1]
and The Landau Institute for Theoretical Physics, The Academy of Sciences, Moscow, 117334, USSR [2]

Received 11 January 1980

The Einstein equations with quantum one-loop contributions of conformally covariant matter fields are shown to admit a class of nonsingular isotropic homogeneous solutions that correspond to a picture of the Universe being initially in the most symmetric (de Sitter) state.

Old Inflation

inflation as a 1st order phase transition

Sato ’81, Guth ’81

1st appearance of “inflation”

Mon. Not. R. astr. Soc. (1981) **195**, 467–479

First-order phase transition of a vacuum and the expansion of the Universe

Katsuhiko Sato *Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark** *and Department of Physics, Kyoto University, Kyoto, Japan†*

Received 1980 September 9; in original form 1980 February 21

Summary. The progress of a first-order phase transition of a vacuum in the expanding Universe is investigated. The expansion of bubbles of a stable vacuum is calculated simultaneously with the cosmic expansion with the aid of the following two simplified nucleation rates of bubbles p: (i) $p = p_T T_c \delta(T - T_c)$ in the hot Universe models, (ii) $p = 0$ for $n > n_c$ and $p = p_Q$ for $n < n_c$ in the cold Universe models, where T is the cosmic temperature, T_c the critical temperature, n the cosmic number density of the fermions coupled to the order parameter of the vacuum, n_c the critical density, and p_T and p_Q are parameters.

The following results are obtained: (1) If the nucleation rates are small and the vacuum stays at the metastable state for a long time, the Universe begins to expand exponentially. As a result, the progress of the phase transition is delayed more and more by the rapid cosmic expansion. In particular, in model (i), if p_T is less than a critical value, the phase transition never finishes. (2) The lower limits of the nucleation parameter p_T and p_Q are obtained from observation of the number ratio of photons to baryons in the present Universe. (3) If the phase transition of the vacuum in SU(5) GUT is of first order or if there exists a hypothetical first-order phase transition of the vacuum in the very early stage in which baryon number is not conserved, the density and the velocity fluctuations created by the phase transition may account for the origin of galaxies.

PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 1981

Inflationary universe: A possible solution to the horizon and flatness problems

!!

Alan H. Guth*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 11 August 1980)

The standard model of hot big-bang cosmology requires initial conditions which are problematic in two ways: (1) The early universe is assumed to be highly homogeneous, in spite of the fact that separated regions were causally disconnected (horizon problem); and (2) the initial value of the Hubble constant must be fine tuned to extraordinary accuracy to produce a universe as flat (i.e., near critical mass density) as the one we see today (flatness problem). These problems would disappear if, in its early history, the universe supercooled to temperatures 28 or more orders of magnitude below the critical temperature for some phase transition. A huge expansion factor would then result from a period of exponential growth, and the entropy of the universe would be multiplied by a huge factor when the latent heat is released. Such a scenario is completely natural in the context of grand unified models of elementary-particle interactions. In such models, the supercooling is also relevant to the problem of monopole suppression. Unfortunately, the scenario seems to lead to some unacceptable consequences, so modifications must be sought.

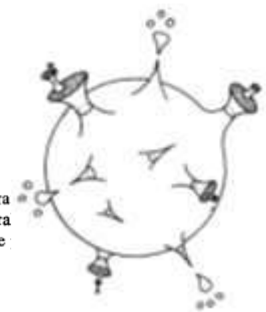
Volume 108B, number 2 PHYSICS LETTERS 14 January 1982

MULTI-PRODUCTION OF UNIVERSES BY FIRST-ORDER PHASE TRANSITION OF A VACUUM

Katsuhiko SATO, Hideo KODAMA, Misao SASAKI [a] and Kei-ichi MAEDA
Department of Physics, Kyoto University, Kyoto 606, Japan
[a] *Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan*

Received 8 June 1981
Revised manuscript received 6 October 1981

Gauge theories with spontaneously broken symmetries give rise to a cosmological phase tra that if the phase transition is strongly of first order, such gauge theories combined with genera prediction; although the Creator might have made a unitary universe, many mini-universes are ward as a result of the phase transition.



multiverse!

New (slow-roll) Inflation

+ almost scale-invariant spectrum from vacuum fluctuations

Linde '81, Mukhanov & Chibisov '81

A NEW INFLATIONARY UNIVERSE SCENARIO: A POSSIBLE SOLUTION OF THE HORIZON, FLATNESS, HOMOGENEITY, ISOTROPY AND PRIMORDIAL MONOPOLE PROBLEMS

A.D. LINDE
Lebedev Physical Institute, Moscow 117924, USSR

Received 29 October 1981

A new inflationary universe scenario is suggested, which is possible solution of the horizon, flatness, homogeneity and isc mordial monopole problem in grand unified theories.

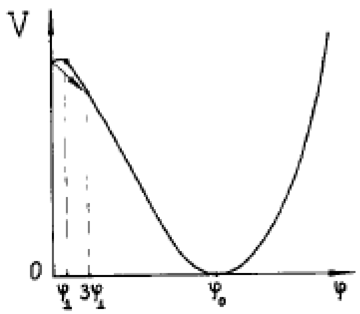


Fig. 1. Effective potential in the Coleman–Weinberg theory for $T \ll \varphi_0$. The arrow indicates the direction of the tunneling with bubble formation.

CHAOTIC INFLATION

A.D. LINDE
Lebedev Physical Institute, Moscow 117

Received 6 June 1983

$$H = (\tfrac{8}{3}\pi V(\varphi)/M_p^2)^{1/2} = (\tfrac{2}{3}\pi\lambda)^{1/2}\varphi^2/M_p \,. \qquad (1)$$

The equation of motion of the field φ inside this domain is

$$\ddot{\varphi} + 3H\dot{\varphi} = -\lambda\varphi^3 \,, \qquad (2)$$

slow-roll EoM

A new scenario of the very early stages of the evolution of the universe is suggested. According to this scenario, inflation is a natural (and may be even inevitable) consequence of chaotic initial conditions in the early universe.

Quantum fluctuations and a nonsingular universe

V. F. Mukhanov and G. V. Chibisov
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

(Submitted 26 February 1981; resubmitted 15 April 1981)
Pis'ma Zh. Eksp. Teor. Fiz. **33**, No. 10, 549–553 (20 May 1981)

Over a finite time, quantum fluctuations of the curvature disrupt the nonsingular cosmological solution corresponding to a universe with a polarized vacuum. If this solution held as an intermediate stage in the evolution of the universe, then the spectrum of produced fluctuations could have led to the formation of galaxies and galactic clusters.

$$Q(k) \approx 3\hbar M \left(1 + \frac{1}{2}\ln\frac{H}{k}\right) .$$

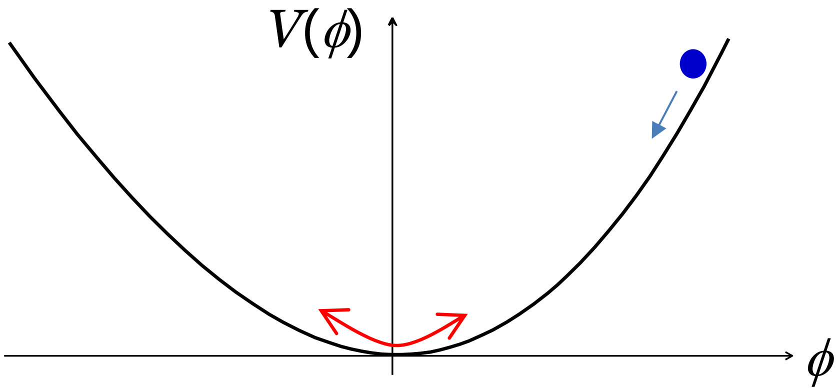
The fluctuation spectrum is thus nearly flat.

Slow-roll Inflation

Linde (1981),…

Universe dominated by a scalar (inflaton) field

For sufficiently flat potential:



$$H^2 \approx \frac{8\pi G}{3} V(\phi) \quad \left(\Leftarrow \frac{1}{2}\dot{\phi}^2 \ll V(\phi) \right)$$

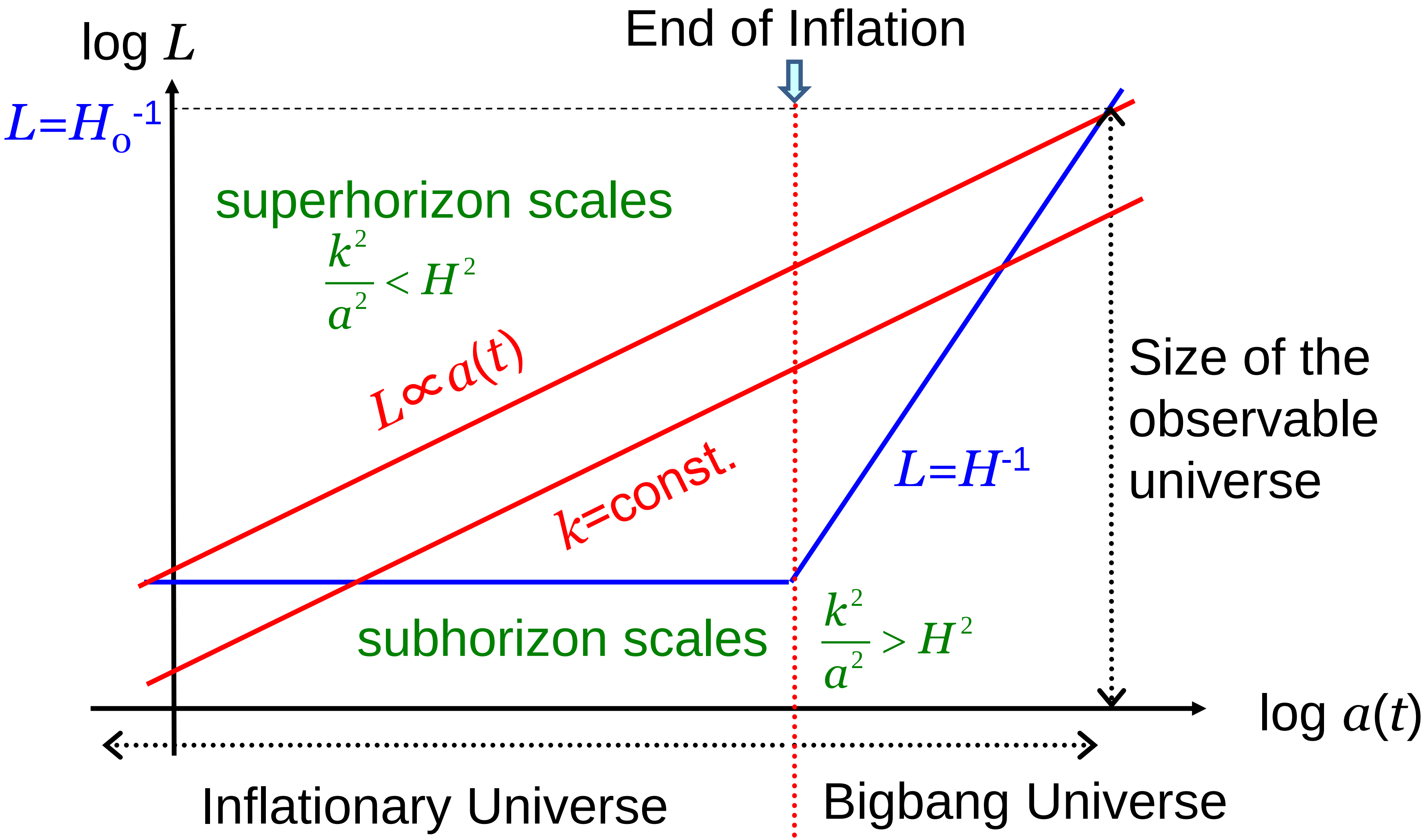
$$\Rightarrow \quad \frac{|\dot{H}|}{H^2} = \frac{3\dot{\phi}^2}{2V(\phi)} \ll 1$$

- H is almost constant ~ exponential expansion = inflation
- ϕ slowly rolls down the potential: slow-roll (chaotic) inflation
- Inflation ends when ϕ starts damped oscillation.

⇨ ϕ decays into thermal energy (radiation)

Birth of Hot Bigbang Universe

Length Scales of Inflationary Universe



Generation of curvature perturbation

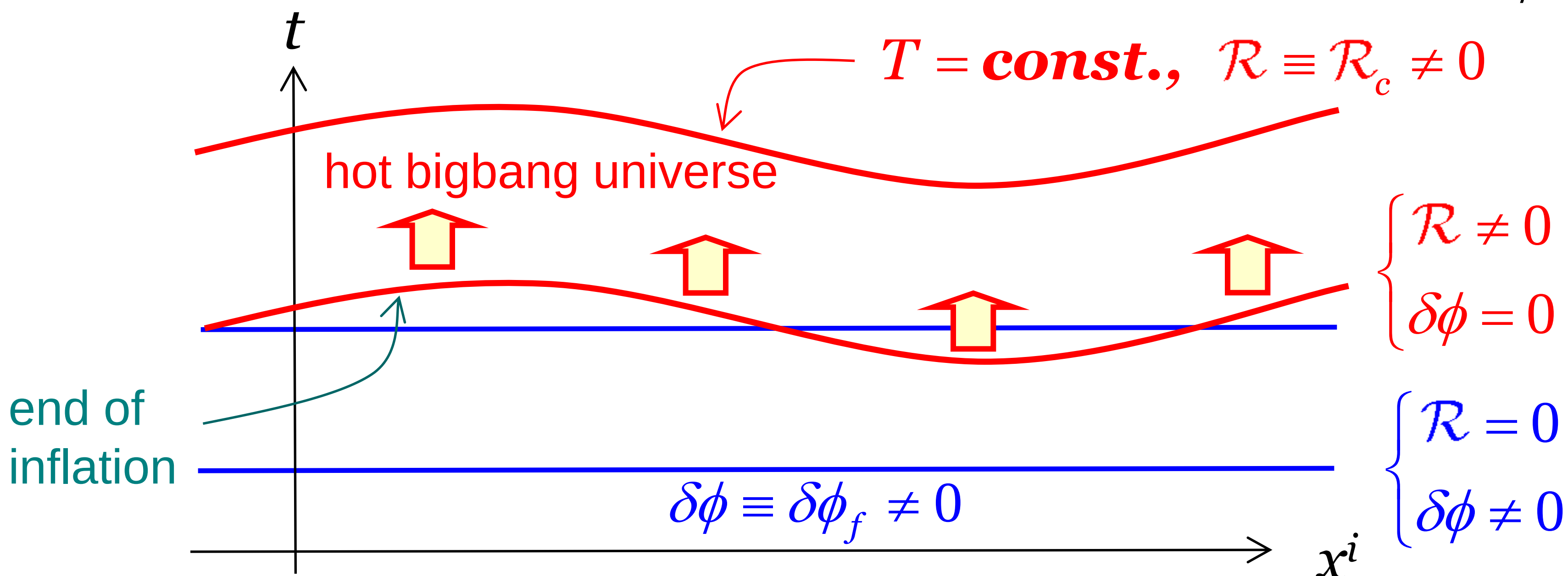
scalar field vacuum fluctuation (on "flat" slices): $\delta\phi_f$ (on "superhorizon")

$$\delta\ddot{\phi}_{f,k} + 3H\delta\dot{\phi}_{f,k} + \frac{k^2}{a^2(t)}\delta\phi_{f,k} \approx 0 : \ \delta\phi_{f,k} \to const. \text{ as } \frac{k^2}{H^2a^2} \to 0$$

comoving curvature perturbation $\mathcal{R}_c$ ~ - Newton potential

- $\delta\phi$ is frozen on "flat" ($\mathcal{R}$=0) 3-surface (t=const. hypersurface)
- Inflation ends/damped osc starts on ϕ=const. 3-surface.

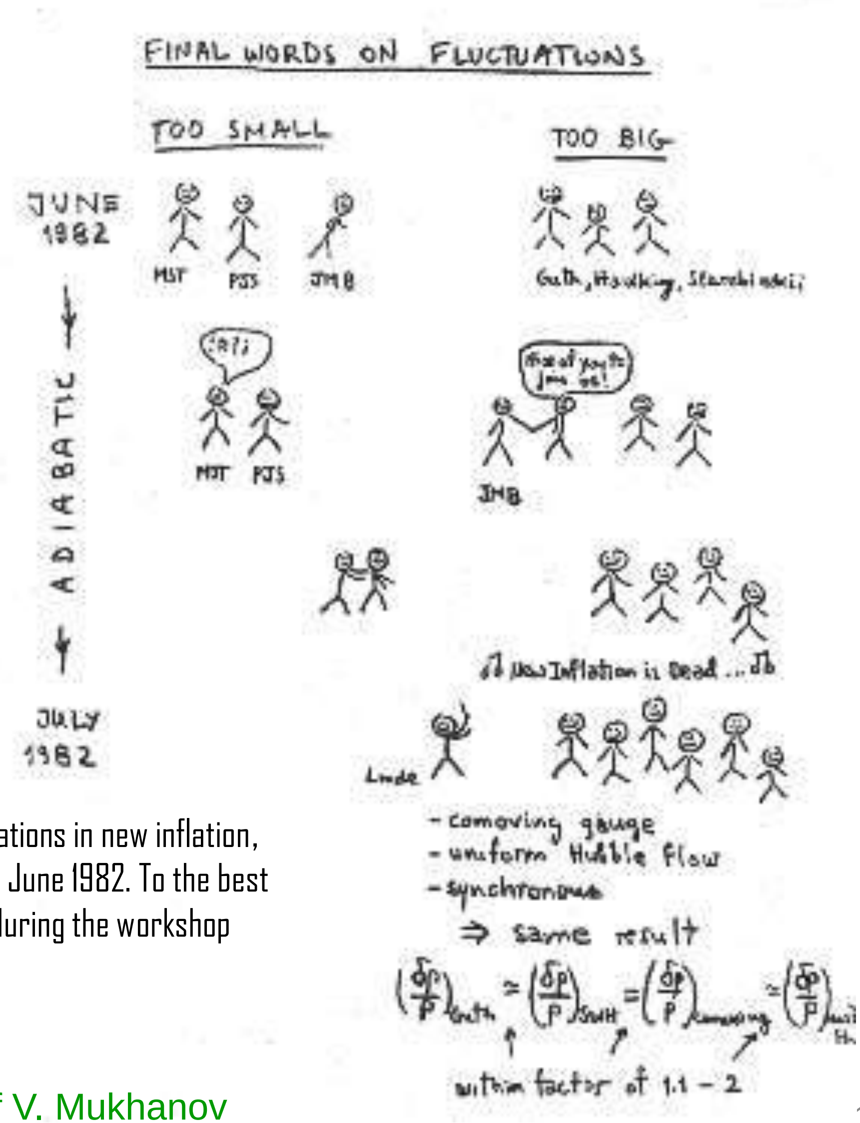
$$\mathcal{R}_c = -\frac{H}{\dot{\phi}}\delta\phi_f$$



Intermission: going back and forth…

Nuffield Workshop
June-July 1982

apparently, a lot of confusion even among "big names".



The history of the derivation of the spectrum of adiabatic perturbations in new inflation, as presented in the talk by M.S. Turner at the Nuffield workshop in June 1982. To the best of my knowledge, the only person who did not change his results during the workshop was Alexei Starobinsky.

figure and text: courtesy of V. Mukhanov

Curvature Perturbation Formula

Mukhanov-Sasaki variable: $\mathcal{R}_m$ (now often denoted by ζ)

Gravitational instability of the universe filled with a scalar field

V. F. Mukhanov
Institute of Nuclear Research, Academy of Sciences of the USSR

(Submitted 21 February 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 9, 402–405 (10 May 1985)

A self-consistent problem involving the behavior of small perturbations in an isotropic homogeneous universe filled with a scalar field is considered. Solutions describing the evolution of perturbations in the case of an arbitrary scalar-field potential are obtained.

$$ds^2 = (1+2\Phi)dt^2 - (1-2\Phi)a^2(t)\delta_{\alpha\beta}dx^\alpha dx^\beta ,$$

$$\Phi = \frac{3}{5}H\left(\frac{\delta\varphi}{\dot\varphi_0}\right)_{d.S}$$

at MD stage

Progress of Theoretical Physics, Vol. 76, No. 5, November 1986

Large Scale Quantum Fluctuations in the Inflationary Universe

Misao SASAKI

Research Institute for Theoretical Physics Hiroshima University, Takehara, Hiroshima 725

(Received June 21, 1986)

Quantum fluctuations of an inflation-driving scalar field are evaluated in a way manifestly independent of the choice of coordinate gauge conditions. It is found that the dynamical degree of freedom of the fluctuating field is represented in terms of a nearly massless conformal scalar field in the unperturbed de Sitter background. Implications of the result are discussed. In particular, it is argued that classical cosmological density perturbations may not be generated in the sense as discussed in the literature.

$$\Phi = \frac{3(1+w)}{3w+5} = -\frac{3}{5}\mathcal{R}_m \quad \text{for} \quad w=0$$

Quantum theory of gauge-invariant cosmological perturbations

V. F. Mukhanov

Institute of Nuclear Research, USSR Academy of Sciences

(Submitted 13 January 1988)
Zh. Eksp. Teor. Fiz. **94**, 1–11 (July 1988)

Metric perturbations of longitudinal type in an isotropic universe filled with a scalar field are considered. The action for the perturbations is obtained, and this action is expressed in terms of a gauge-invariant variable which completely characterizes the perturbations. A consistent quantum theory of such perturbations is constructed. The spectrum of inhomogeneities in inflationary models of the evolution of the universe is calculated.

ones once they are outside the horizon, a typical amplitude of the perturbations on a comoving scale k^{-1} approaches the value

$$\sqrt{\langle \mathcal{R}_m{}^2\rangle_k} \equiv \sqrt{\frac{4\pi k^3}{(2\pi)^3}}|r_k|^2 \approx \frac{H^2}{2\pi\dot\varphi},$$

$$v = a\left(\delta\varphi + \frac{\varphi_0'}{\alpha}\psi\right) = a\left(\delta\bar\varphi + \frac{\varphi_0'}{\alpha}\Psi\right).$$

$$v = -a\frac{\varphi'}{\alpha}\mathcal{R}_m = -a\frac{\dot\varphi}{H}\mathcal{R}_m \qquad (\alpha = Ha)$$

Theoretical Predictions

- Amplitude of curvature perturbation:

$$\mathcal{R}_c = \left.\frac{H^2}{2\pi\dot{\phi}}\right|_{k/a=H}$$

Mukhanov (1985), MS (1986)

- Power spectrum index:

$$M_{pl} \equiv \frac{1}{\sqrt{8\pi G}} \sim 2.4\times10^{18}\,\text{GeV: Planck mass}$$

$$\frac{4\pi k^3}{(2\pi)^3}P_S(k) = \left[\frac{H^2}{2\pi\dot{\phi}}\right]^2_{k/a=H} = Ak^{n_S-1} \;;\; n_S - 1 = M_P^2\left(2\frac{V''}{V} - 3\frac{V'^2}{V^2}\right)$$

Stewart-Lyth (1993)

- Tensor (gravitational wave) spectrum:

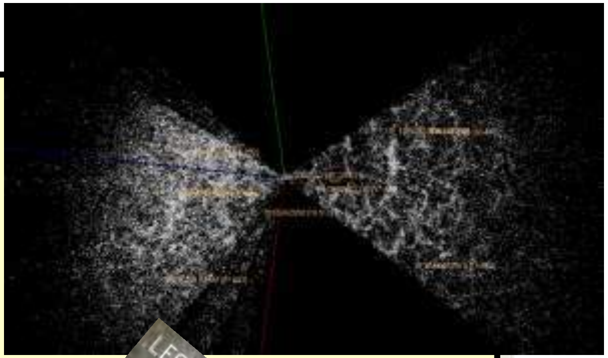
$$\frac{4\pi k^3}{(2\pi)^3}P_T(k) = Ak^{n_T} \;;\; n_T = -\frac{1}{8}\frac{P_S(k)}{P_T(k)} \equiv -\frac{r}{8}$$

Liddle-Lyth (1992)

"consistency relation"

Progress in Particle Cosmology (3)

3^{rd} stage: 1995~ 2015

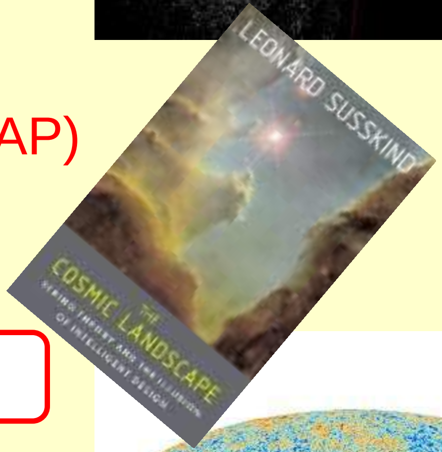


- 1995 Hubble Deep Field: z ~ 4-5
- 1998 2dF Galaxy Redshift Survey

  3×10^5 galaxies, z~0.2
- 1998 Accelerated Expansion (SCP/HZT)
- 2003 Accurate CMB angular spectrum (WMAP)

  Confirming Flatness of the Universe

  Strong evidence for Dark Energy

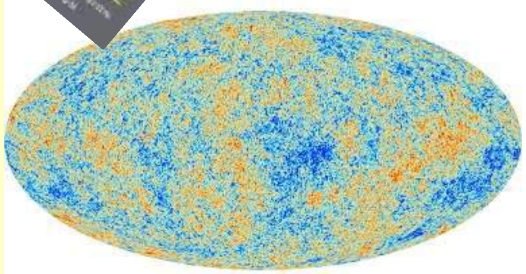


2005~ Cosmic (String Theory) Landscape!

- 2000~ SDSS I/II/III, 2014- SDSS-IV, …

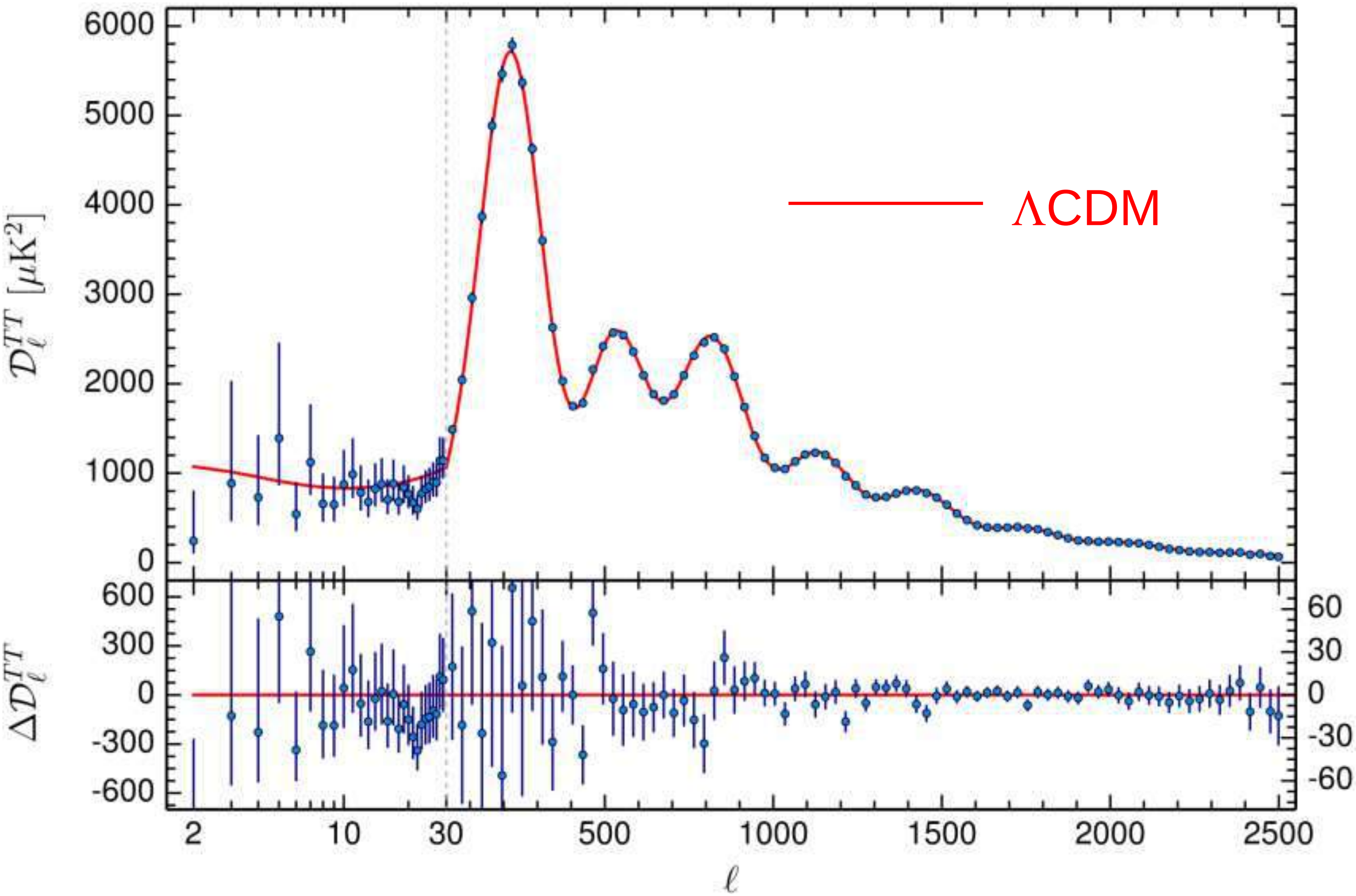
  > 10^6 galaxies, high precision LSS data
- 2013 High precision CMB spectrum (Planck)

  Very strong evidence for Inflation



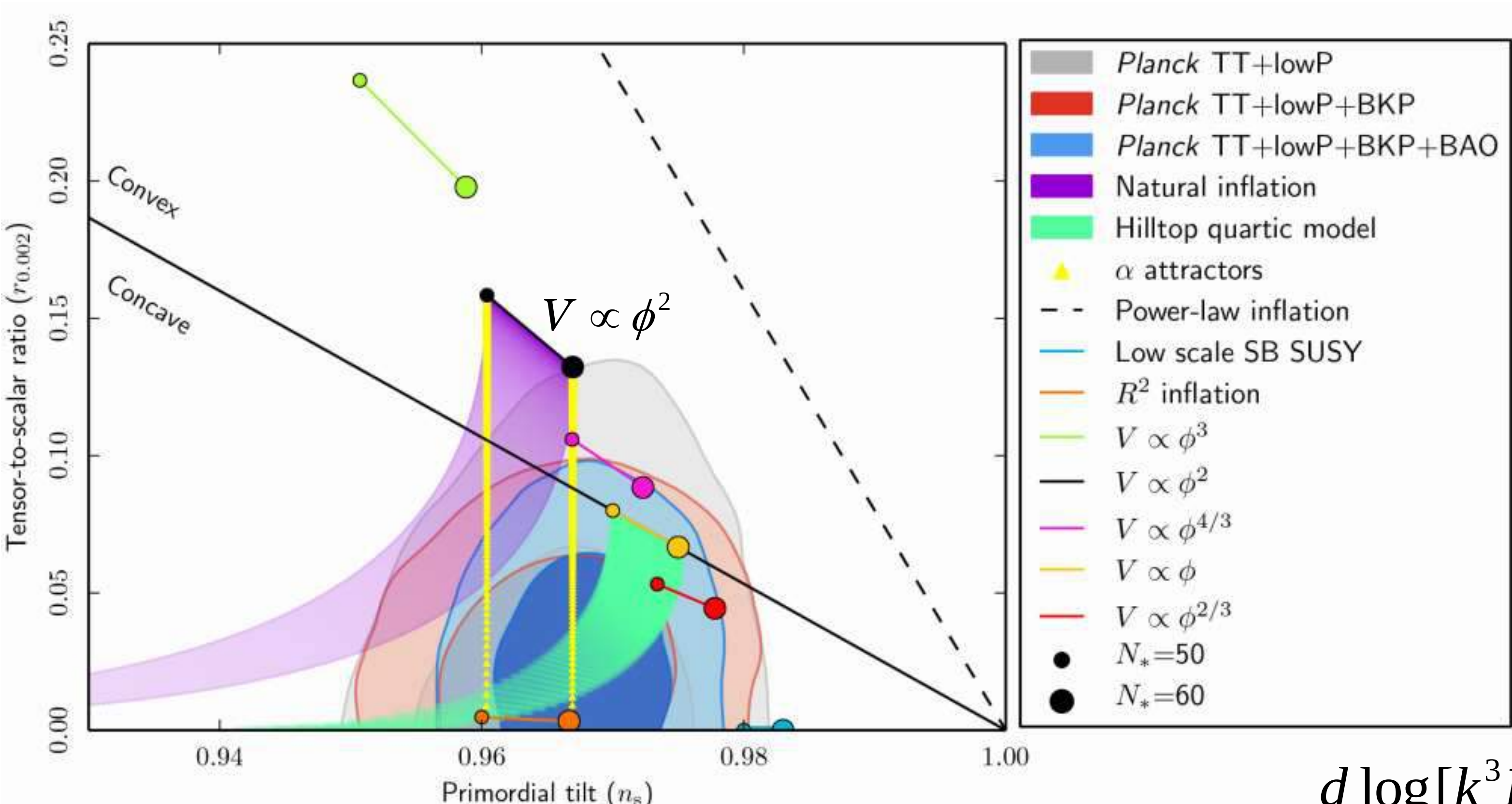
CMB anisotropy spectrum

Planck 2015 XI



Planck+LSS constraints on inflation

Planck 2015 XX



$$n_s - 1 \equiv \frac{d \log[k^3 P_S(k)]}{d \log k}$$

- scalar spectral index: $n_s \sim 0.96$
- tensor-to-scalar ratio: $r < 0.1$
- simplest $V \propto \phi^2$ model is almost excluded

$$r \equiv \frac{P_T(k)}{P_S(k)}$$

Summary: Current Status

- Standard (single-field, slow-roll) inflation predicts almost scale-invariant Gaussian curvature perturbations.
- Observational data are consistent with theoretical predictions.
  - almost scale-invariant spectrum: $n_S = 0.965 \pm 0.005 \ \ (68\%\ \mathrm{CL})$
  - highly Gaussian fluctuations: $f_{NL}^{\mathrm{local}} = 2.5 \pm 5.7 \ \ (68\%\ \mathrm{CL})$

$$\mathcal{R} = \mathcal{R}_{\mathrm{gauss}} + \frac{3}{5} f_{NL}^{\mathrm{local}} \mathcal{R}_{\mathrm{gauss}}^2 + \cdots$$

- Simple standard models seem to be almost excluded…
  - detection of $f_{NL}^{\mathrm{local}} = O(1)$ would kill all the standard models.
- Tensor (gravitational wave) perturbation remains to be detected

$$r = \frac{P_T(k)}{P_S(k)} \lesssim 0.05$$

Progress in Particle Cosmology (4)

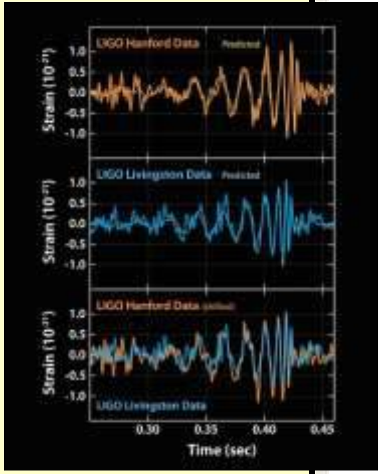
4^{th} stage: 2015 ~ 20??

- 2015 First detection of GWs from Binary Black Holes (LIGO)

  Dawn of GW Astronomy

- 2017 First detection of GWs & EMWs from Binary Neutron Stars (LIGO+VIRGO)

  Multi-messenger Astronomy



- 2020+ Upgraded LIGO+VIRGO +KAGRA start operating
- 2020+ Deep & Wide LSS surveys (HSC-SSP/LSST/…)

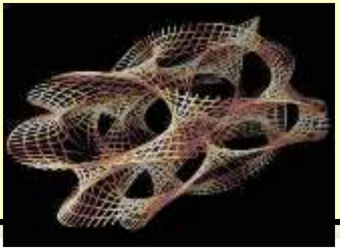
  Data precision will reach <1 %

- 2020+ CMB primordial B-modes (LiteBIRD/CORE/…)

  Proving Inflation!?

- 2020+ Ultimate Theory of Inflation?

  Evidence for Cosmic Landscape/Multiverse?



String Theory as driving force

signature of primordial GWs

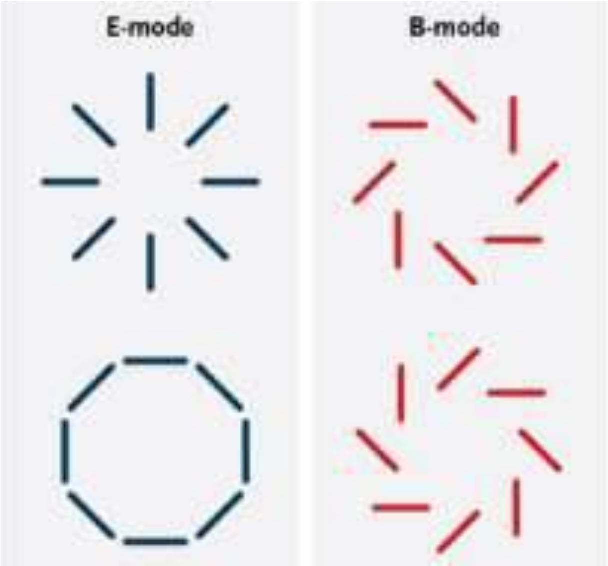
spacetime(~graviton) vacuum fluctuations from inflation

GWs: quadrupolar in nature

Starobinsky (1979)

➡ B-mode polarization in CMB anisotropy

Seljak & Zaldarriaga (1996)



- E-mode (even parity)

⇕

- B-mode (odd parity)
  = cannot be produced from density fluctuations

Cosmic Landscape/Multiverse?

string theory suggests an intriguing picture of the early universe

Maybe we live in one of these vacua…

Swampland conjecture?

$$|\nabla V| < c\, V / M_P\,; \qquad c = O(1)$$

Obied, Ooguri, Spodyneiko & Vafa '18

$$|\nabla V| < c\, V / M_P\,; \qquad c = O(1)$$

Ooguri, Palti, Shiu & Vafa '18

or

$$\min(\nabla_i \nabla_j V) \leq \frac{-c' V}{M_P^2}; \quad c' = O(1)$$

In particular, de Sitter (dS) space is in swampland!

If dS exists in nature,
either swampland conjecture is false
or string theory is false !

let us assume (hope?) that the conjecture is false!

Universe jumps around string landscape by quantum tunneling

expansion rate

- it can go up to a vacuum with larger ρ_v

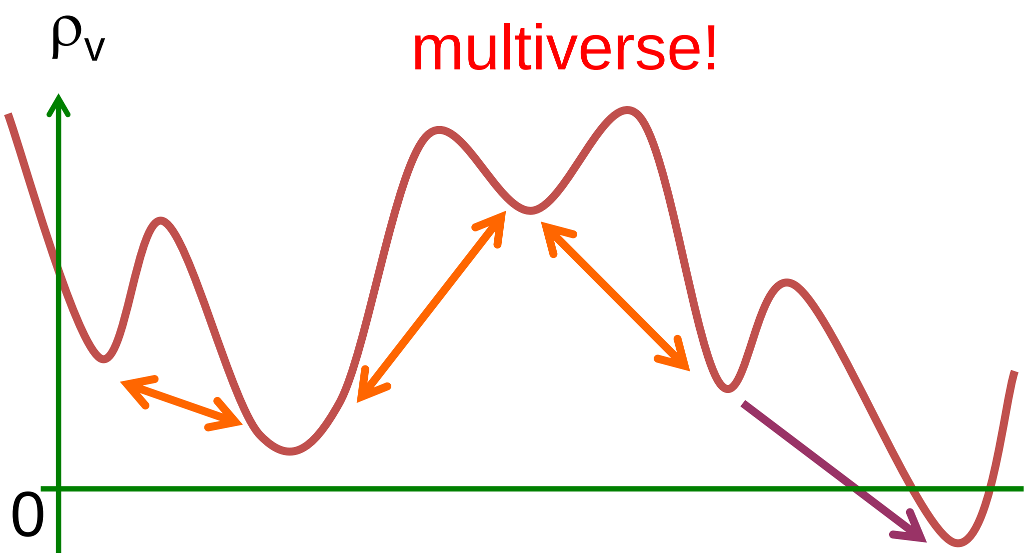
de Sitter (dS) space ~ thermal state with $T = H/2\pi$
SO(4,1)

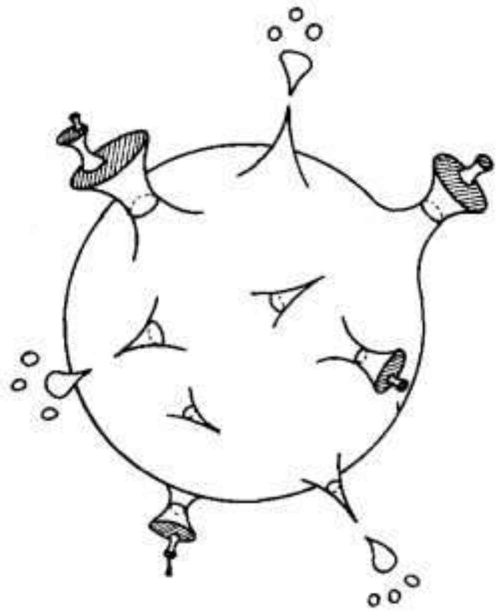
- if tunnels to a vacuum with $\rho_v < 0$, it collapses in $t \sim M_P/|\rho_v|^{1/2}$

⇨ focus on $\rho_v > 0$

- inside a bubble with $\rho_v > 0$ is Open dS universe
SO(3,1)

multiverse!





Sato, Kodama, MS & Maeda ('81)

What if this is the case?

- a few possibilities

N: number of e-folds

1. inflation after tunneling was short enough (N~60)

$$\Omega_{K,0} = 1 - \Omega_0 = 10^{-2} \sim 10^{-3}$$ "open universe"

⇨ signatures in large angle CMB anisotropies?

Kanno, MS & Tanaka ('13), White, Zhang & MS ('14), …

2. inflation after tunneling was long enough (N>>60)

$$\Omega_{K,0} = 1 - \Omega_0 \ll 1$$ "flat universe"

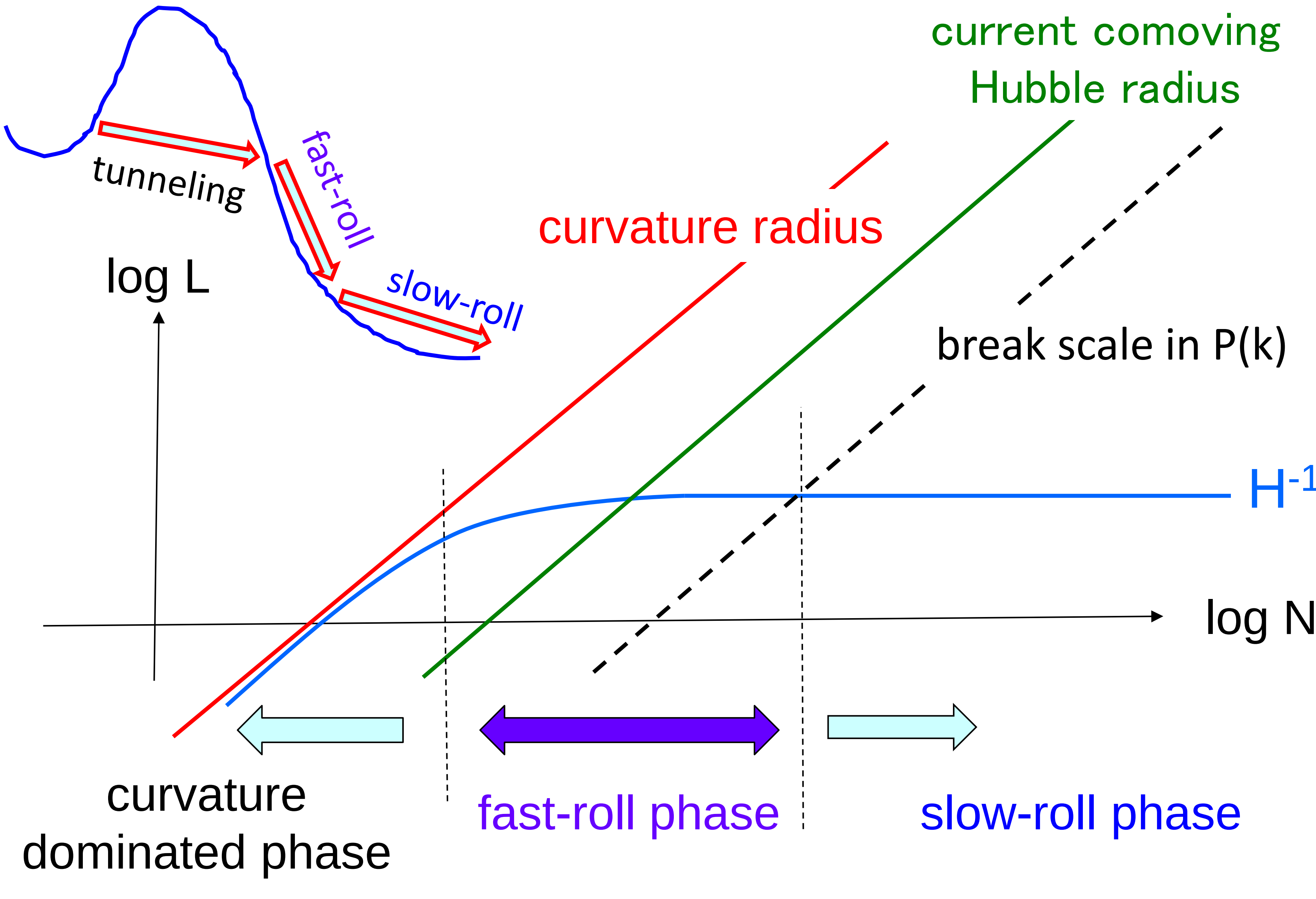
⇨ signatures from bubble collisions

Sugimura, Yamauchi & MS ('12), …

3. quantum entanglement among multiverse?

Maldacena & Pimentel ('13), Kanno ('14), …

length scales in open inflation



Inflationary cosmology in 21st Century

- High Precision Cosmology
  - gravitational waves from Inflation
  - extra dimensions / string cosmology
  - origin of dark energy
  - …
- Gravitational Wave Astronomy has begun
  - LIGO (+VIRGO) detected GWs from BH & NS binaries

Era of Multi-messenger Astronomy

fundamental laws of nature may be revealed.
(“ultimate” theory?)

inflation = testbed for ultimate theory