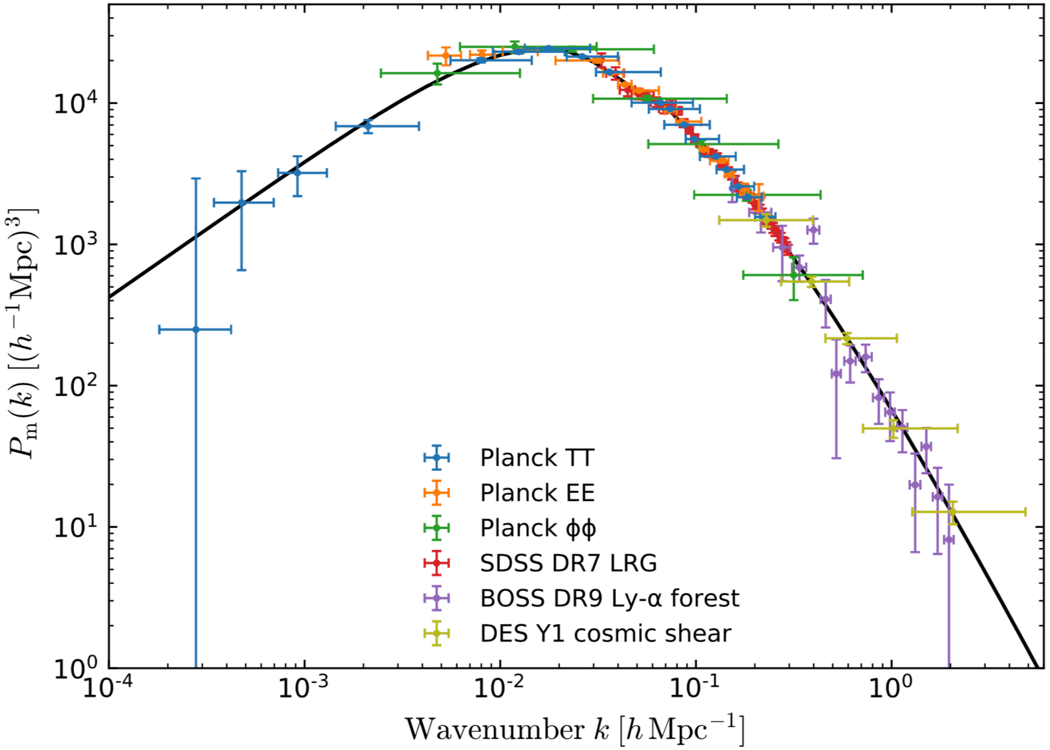
理論懇シンポジウム，京大基研　2018.12.19

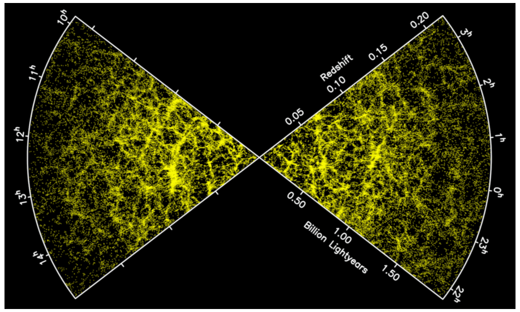
物理学は宇宙大規模構造の起源を明らかにできるのか？

神戸大学理学研究科

早田　次郎

物質密度のパワースペクトル





宇宙背景放射のパワースペクトル

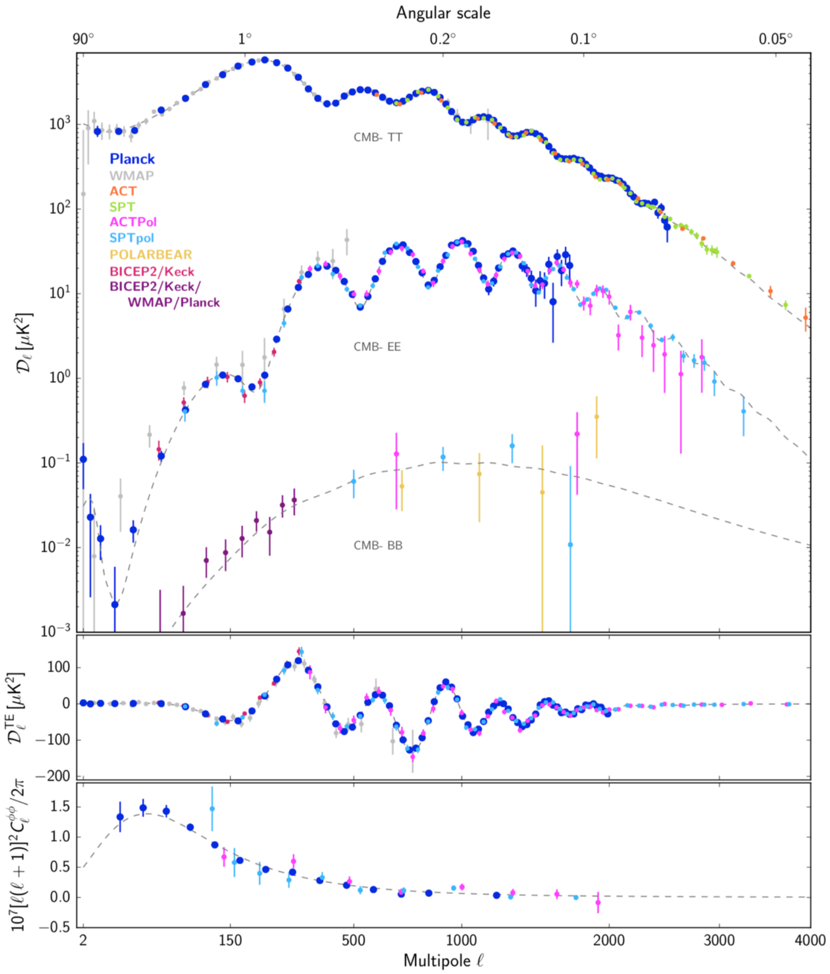
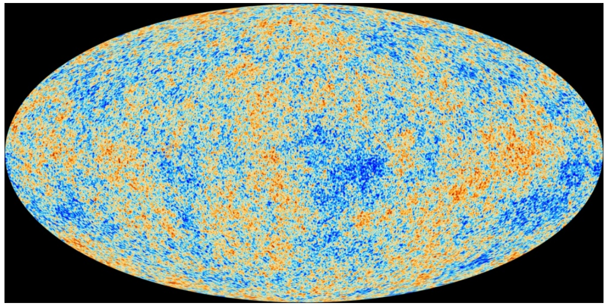
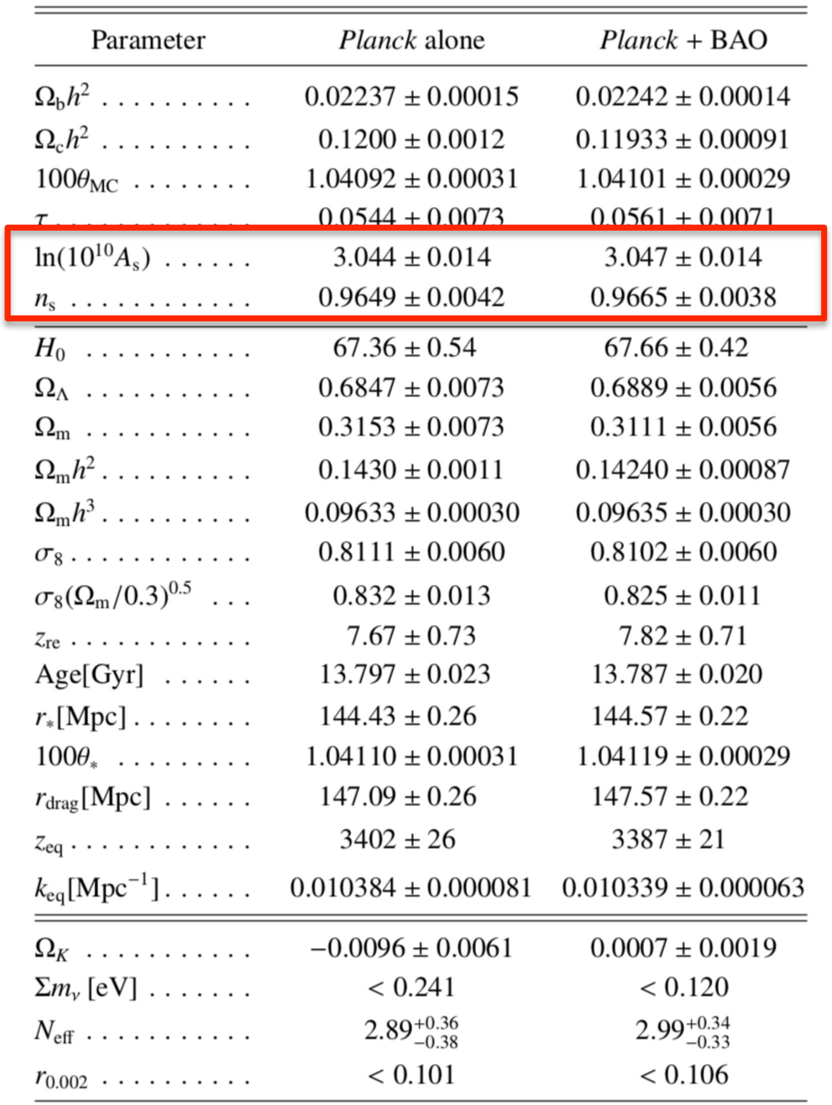


Fig. 18. A compilation of recent CMB angular power spectrum measurements from which most cosmological inferences are drawn. The upper panel shows the power spectra of the temperature and *E*-mode and *B*-mode polarization signals, the next panel the cross-correlation spectrum between *T* and *E*, while the lower panel shows the lensing deflection power spectrum. Different colours correspond to different experiments, each retaining its original binning. Note that for *Planck*, ACTPol, and SPTpol, the *EE* points with large error bars are not plotted (to avoid clutter). The dashed line shows the best-fit ΛCDM model to the *Planck* temperature, polarization, and lensing data. See text for details and references.



Planck 2018



Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

初期条件

$$\Delta_R^2 = A_s \left(\frac{k}{k_*} \right)^{n_s - 1}$$

物理的に説明できるか？

因果律 $\frac{d}{dt}\left(\frac{\lambda_H}{|H|^{-1}}\right)=\frac{d}{dt}\left(\frac{a}{|\dot{a}/a|^{-1}}\right)=\frac{d}{dt}|\dot{a}|>0$

$$\longrightarrow\quad \begin{cases} a(t)=t^{\alpha}, \quad \alpha>1 & \text{インフレーション} \\ a(t)=\left(-t\right)^{\alpha}, \quad \alpha<0 & \text{スーパーインフレーション} \\ a(t)=\left(-t\right)^{\alpha}, \quad 0<\alpha<1 & \text{収縮宇宙} \Rightarrow \text{バウンス宇宙} \end{cases}$$

$$ds^2=-dt^2+a^2(t)\left(dx^2+dy^2+dz^2\right)=a^2(\eta)\left[-d\eta^2+dx^2+dy^2+dz^2\right] \qquad a(\eta)=\left(-\eta\right)^{\frac{\alpha}{1-\alpha}}$$

$$u_k''+\left(k^2-\frac{a''}{a}\right)u_k=0$$

スケール不変

$$\frac{a''}{a}=\frac{2}{\eta^2}$$

➡

$\alpha=\infty \Rightarrow$ de Sitter

$\alpha=\frac{2}{3} \Rightarrow$ matter dominant

スーパーインフレーションの
可能性は消えた

初期条件を知らない

初期条件によらない生成機構	予言能力	
• 熱揺らぎ	ストリングガス宇宙論	収縮宇宙
• カオス的乱流		
• 量子揺らぎ	インフレーション	

収縮宇宙から抜け出すのは難しい　$\dot{H} = -4\pi G\left(\rho + p\right) < 0$

宇宙大規模構造の起源を物理で説明しようと思うと
インフレーションがほとんどユニークな可能性で
生成機構は量子揺らぎだろう

話の予定

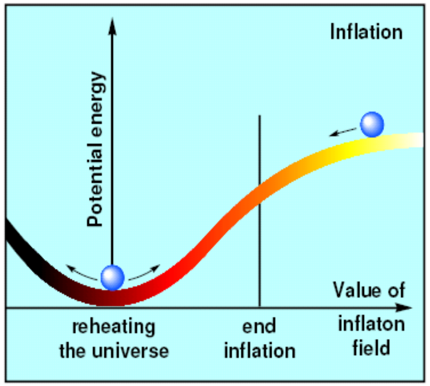
- プロローグ（これは終わった）
- インフレーションモデル
- インフレーションの歴史
- 提唱後38年の成果
- 残された課題
- 物理的な理解の階層性
- エピローグ

インフレーションモデル

インフレーションシナリオ

基礎方程式 $$H^2 = \frac{8\pi G}{3}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$ $$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

始めにホライズンの5倍くらいの範囲で一様であったと仮定する



□ インフラトンのダイナミクス

初期のエネルギーが大きいとする

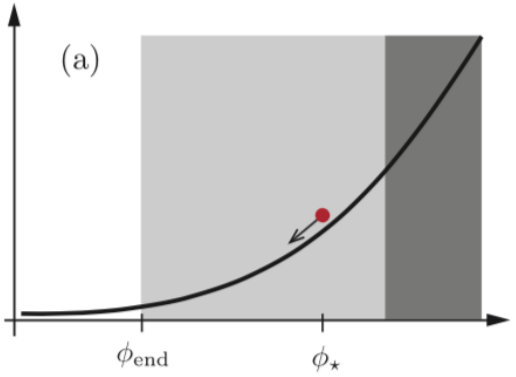
Hが大きい → 摩擦が大きいのでゆっくり転がる

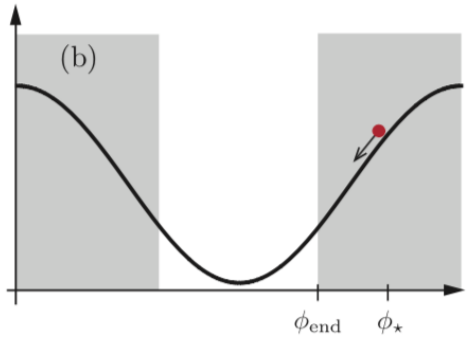
→ ポテンシャルが優勢となりドジッター膨張宇宙となる $a(t) = e^{Ht}$

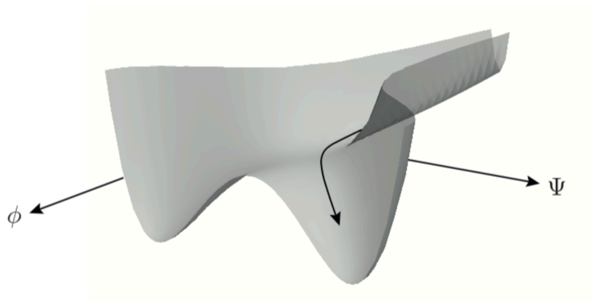
$H^2 \approx m^2 \equiv V''$ → 振動が始まりインフレーションが終わる 宇宙の再加熱

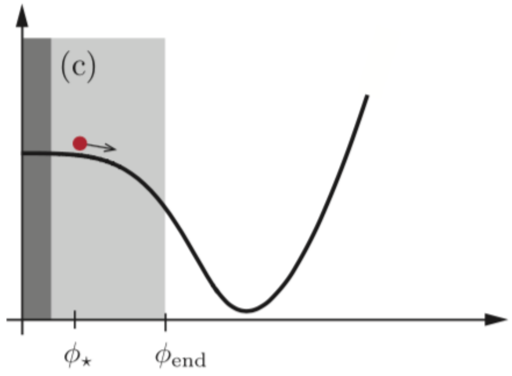
Big-bang 宇宙の始まり

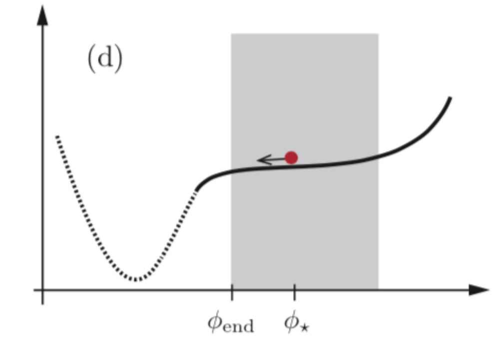
インフレーション動物園





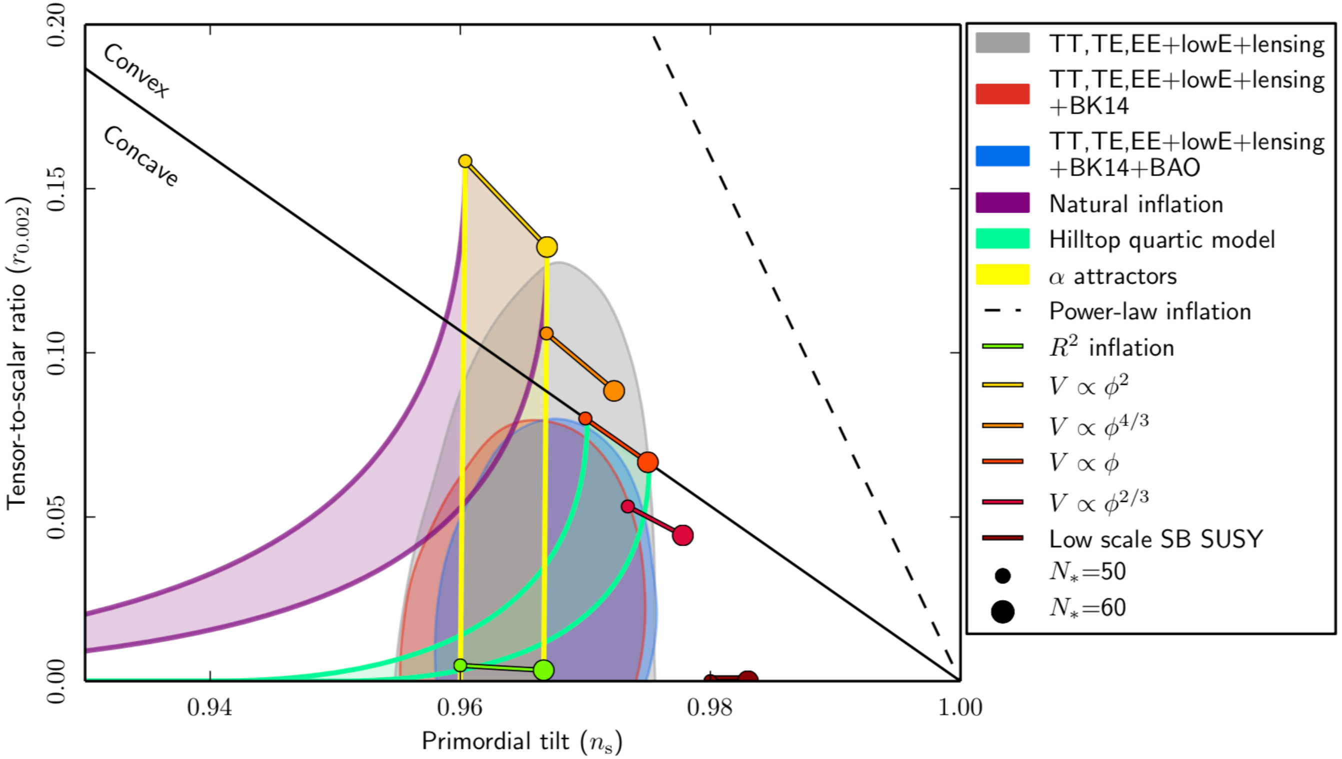






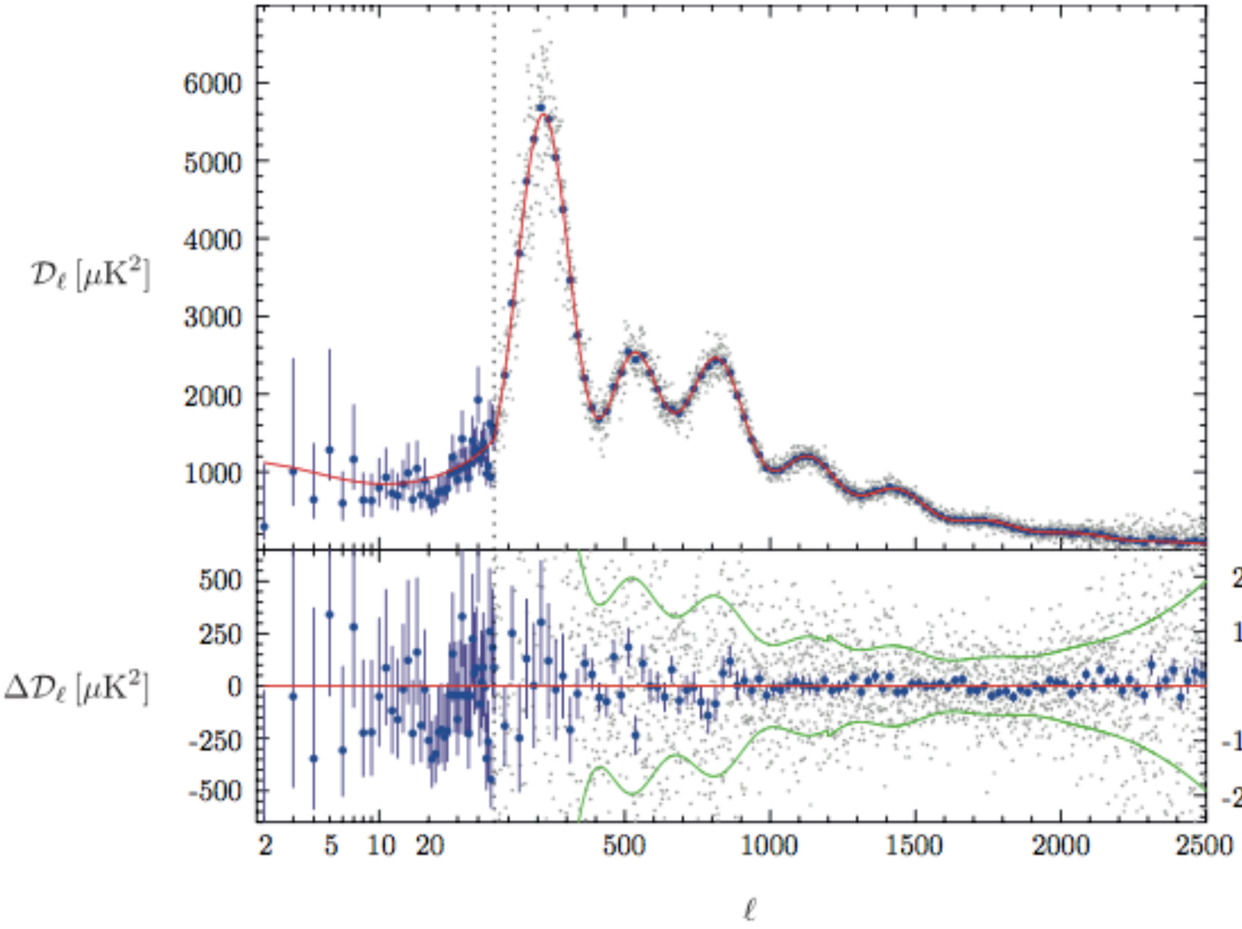
インフレーションモデルへの制限

$$\Delta_R^2 = A_s\left(\frac{k}{k_*}\right)^{n_s-1} \qquad \Delta_h^2 = A_t\left(\frac{k}{k_*}\right)^{n_t} \qquad r = \frac{\Delta_h^2}{\Delta_R^2}$$



物理学は宇宙大規模構造の起源を
明らかにできたのか？

インフレーションはデータをよく説明している



これで満足か？

インフレーションの歴史

超伝導の歴史

超伝導の理論

↓

ランダウ・ギンツブルグ理論

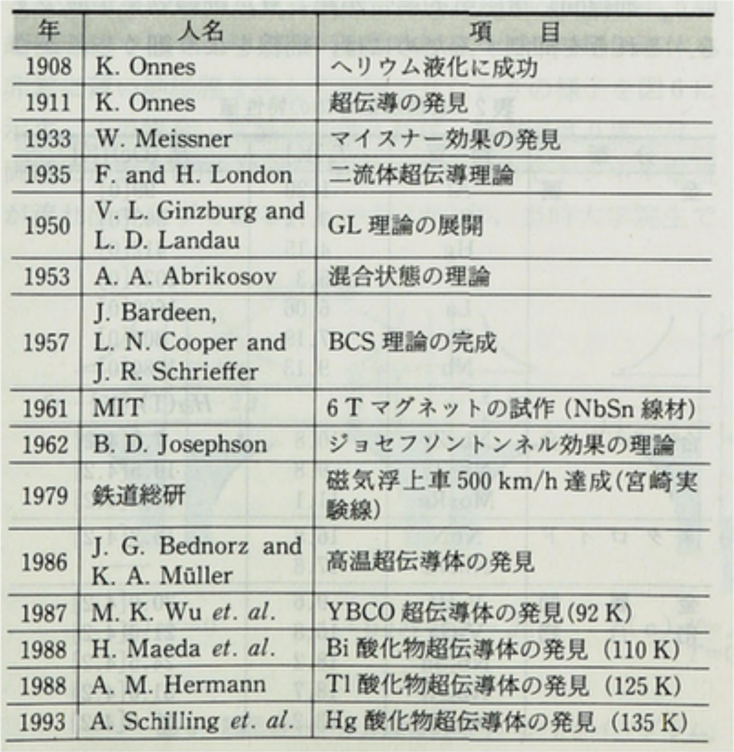
現象論的理解

↓

BCS理論

ミクロな理解

表1　超伝導の歴史



年	人名	項　目
1908	K. Onnes	ヘリウム液化に成功
1911	K. Onnes	超伝導の発見
1933	W. Meissner	マイスナー効果の発見
1935	F. and H. London	二流体超伝導理論
1950	V. L. Ginzburg and L. D. Landau	GL 理論の展開
1953	A. A. Abrikosov	混合状態の理論
1957	J. Bardeen, L. N. Cooper and J. R. Schrieffer	BCS 理論の完成
1961	MIT	6 T マグネットの試作 (NbSn 線材)
1962	B. D. Josephson	ジョセフソントンネル効果の理論
1979	鉄道総研	磁気浮上車 500 km/h 達成(宮崎実験線)
1986	J. G. Bednorz and K. A. Müller	高温超伝導体の発見
1987	M. K. Wu *et. al.*	YBCO 超伝導体の発見(92 K)
1988	H. Maeda *et. al.*	Bi 酸化物超伝導体の発見 (110 K)
1988	A. M. Hermann	Tl 酸化物超伝導体の発見 (125 K)
1993	A. Schilling *et. al.*	Hg 酸化物超伝導体の発見 (135 K)

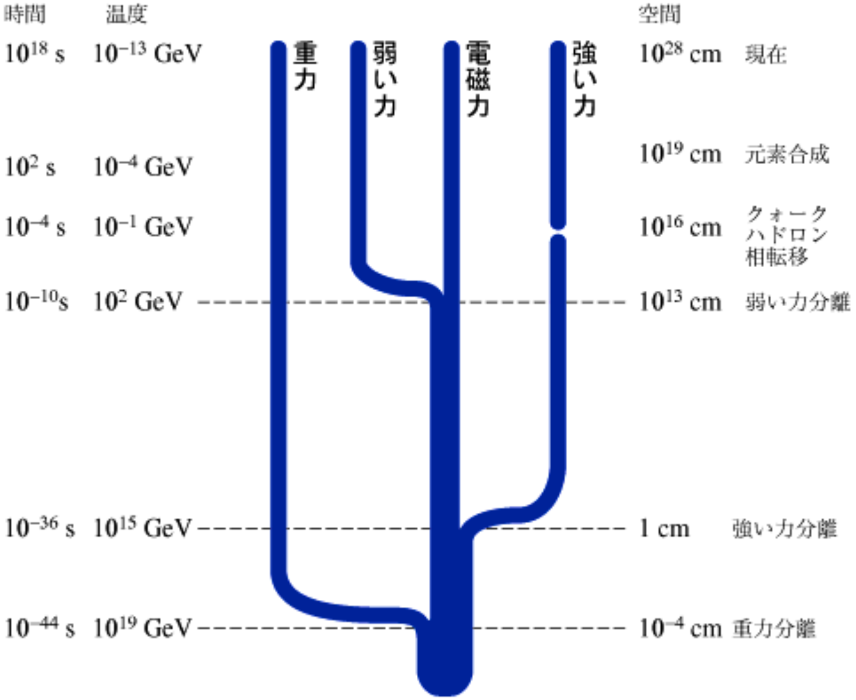
1911　水銀における超伝導の発見(Kamerlingh Onnes; ノーベル賞1913)
1924　ボース・アインシュタイン凝縮の理論(Bose & Einstein)
1957　超伝導のBCS理論 (Bardeen, Cooper & Schrieffer; ノーベル賞1972)
1960　南部理論 (Nambu; ノーベル賞2008)
1960-61 南部-ゴールドストーン定理(Nambu, Goldstone)
1963-66 アンダーソン・ヒッグス理論(Anderson, Higgs)
1967-68 電弱理論　(Weinberg & Salam; ノーベル賞1979)
1986　銅酸化物における高温超伝導の発見(Bednorz & Muller; ノーベル賞1987)
1995　冷却原子におけるボース・アインシュタイン凝縮の発見
　(Cornell, Ketterle & Wieman; ノーベル賞2001)

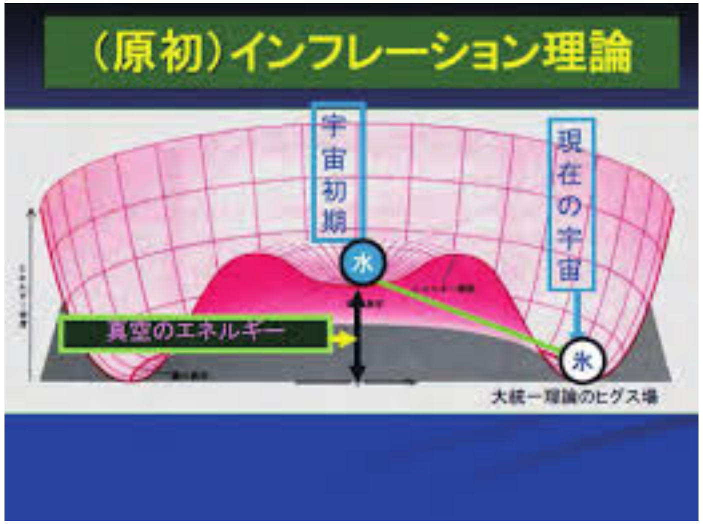
超伝導からインフレーション

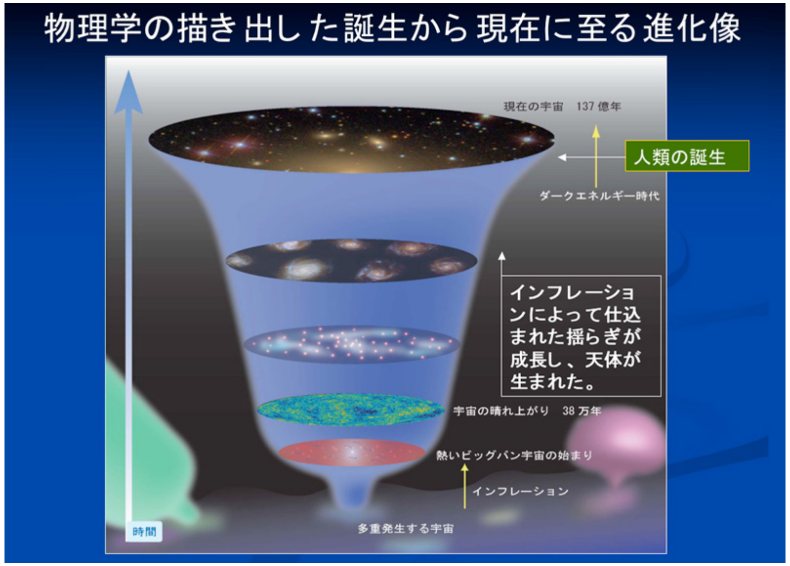
対称性の自発的な破れ

大統一理論

インフレーション理論

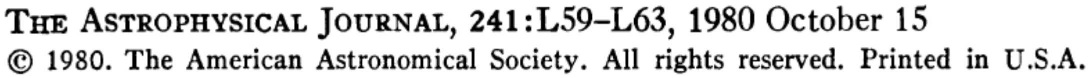






インフレーションによって仕込まれた揺らぎが成長し、天体が生まれた。

具体的なモデルは？



THE ASTROPHYSICAL JOURNAL, 241:L59–L63, 1980 October 15

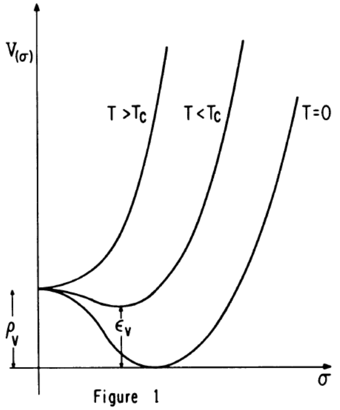
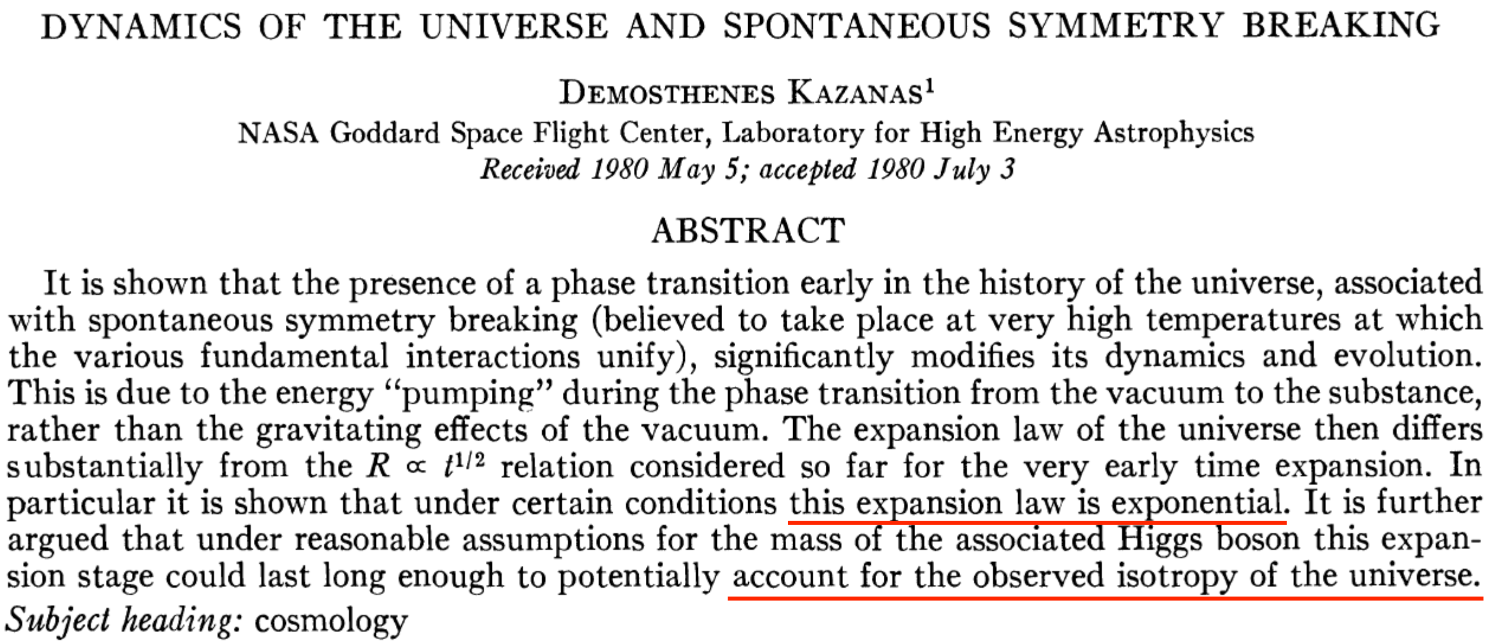


FIG. 1.—The Higgs potential for different temperature regimes



DYNAMICS OF THE UNIVERSE AND SPONTANEOUS SYMMETRY BREAKING

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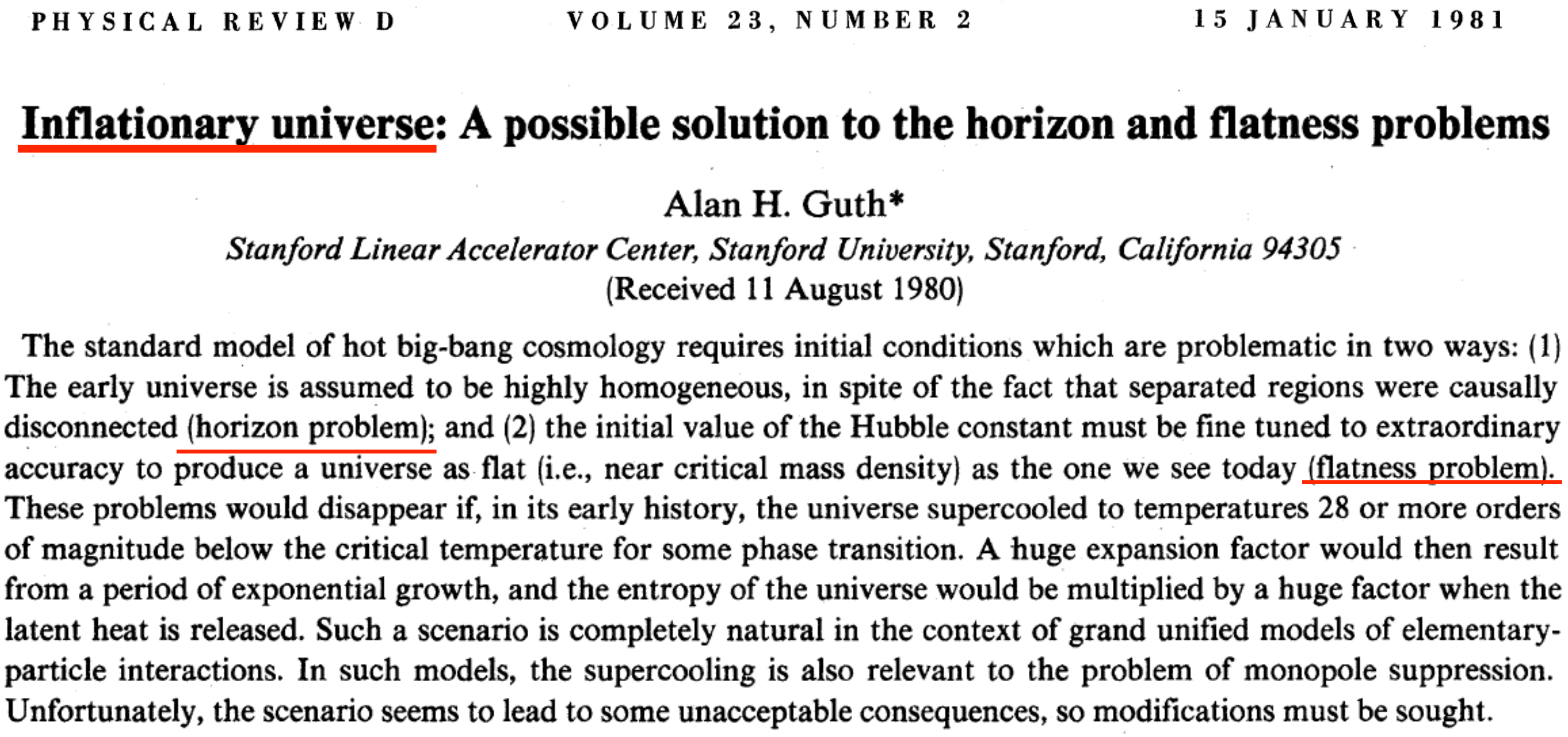
NASA Goddard Space Flight Center, Laboratory for High Energy Astrophysics

Received 1980 May 5; accepted 1980 July 3

ABSTRACT

It is shown that the presence of a phase transition early in the history of the universe, associated with spontaneous symmetry breaking (believed to take place at very high temperatures at which the various fundamental interactions unify), significantly modifies its dynamics and evolution. This is due to the energy "pumping" during the phase transition from the vacuum to the substance, rather than the gravitating effects of the vacuum. The expansion law of the universe then differs substantially from the $R \propto t^{1/2}$ relation considered so far for the very early time expansion. In particular it is shown that under certain conditions this expansion law is exponential. It is further argued that under reasonable assumptions for the mass of the associated Higgs boson this expansion stage could last long enough to potentially account for the observed isotropy of the universe.

Subject heading: cosmology

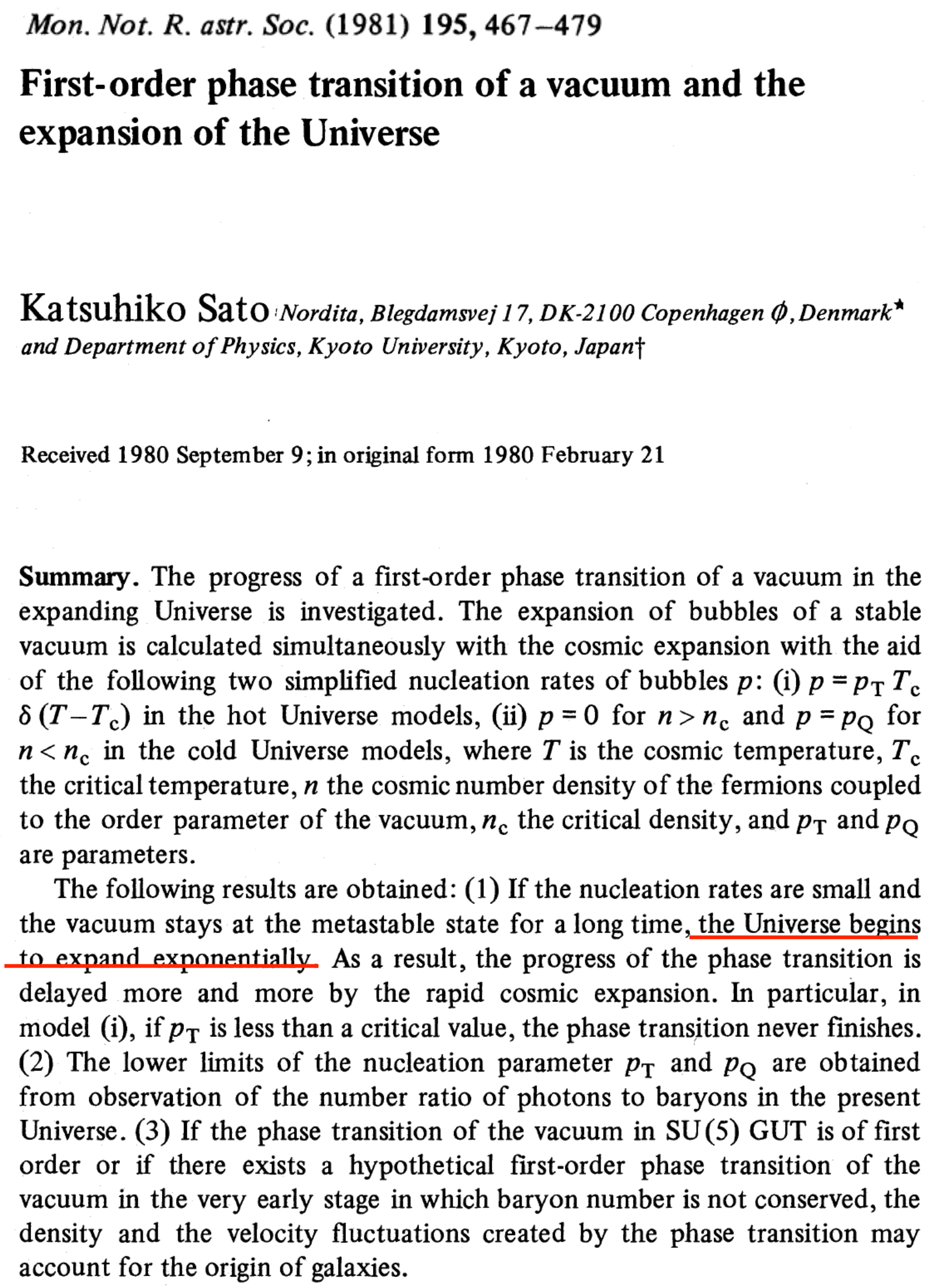


PHYSICAL REVIEW D VOLUME 23, NUMBER 2 15 JANUARY 1981

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.



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

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

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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) $p = p_{\mathrm{T}} T_{\mathrm{c}} \delta (T - T_{\mathrm{c}})$ in the hot Universe models, (ii) $p = 0$ for $n > n_{\mathrm{c}}$ and $p = p_{\mathrm{Q}}$ for $n < n_{\mathrm{c}}$ 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.

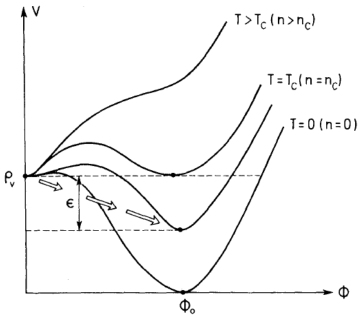

Figure 1. The schematic diagram of the effective potential of the vacuum energy density.

Volume 108B, number 6 PHYSICS LETTERS 4 February 1982

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 free of the shortcomings of the previous one and provides a possible solution of the horizon, flatness, homogeneity and isotropy problems in cosmology, and also a solution of the primordial monopole problem in grand unified theories.

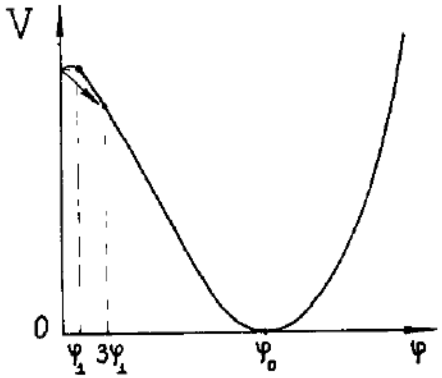

Fig. 1. Effective potential in the Coleman–Weinberg theory for $T \ll \varphi_0$. The arrow indicates the direction of the tunneling with bubble formation.

VOLUME 48, NUMBER 17 PHYSICAL REVIEW LETTERS 26 APRIL 1982

Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking

Andreas Albrecht and Paul J. Steinhardt
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 25 January 1982)

The treatment of first-order phase transitions for standard grand unified theories is shown to break down for models with radiatively induced spontaneous symmetry breaking. It is argued that proper analysis of these transitions which would take place in the early history of the universe can lead to an explanation of the cosmological homogeneity, flatness, and monopole puzzles.

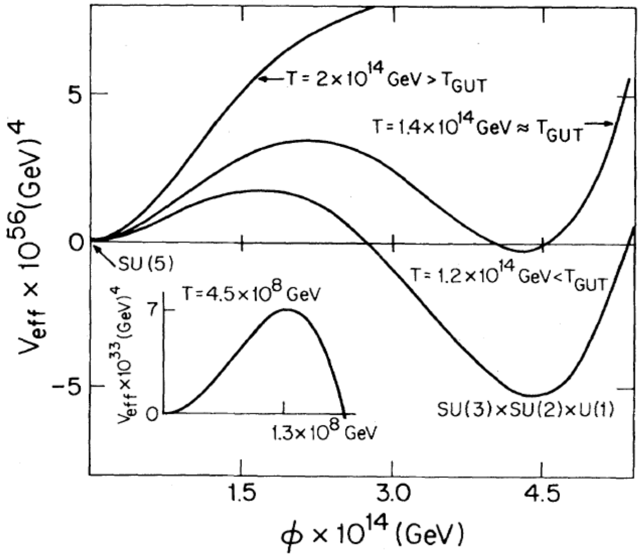

FIG. 1. Effective potential vs φ for various values of T.

Volume 129B, number 3,4 PHYSICS LETTERS 22 September 1983

CHAOTIC INFLATION

A.D. LINDE
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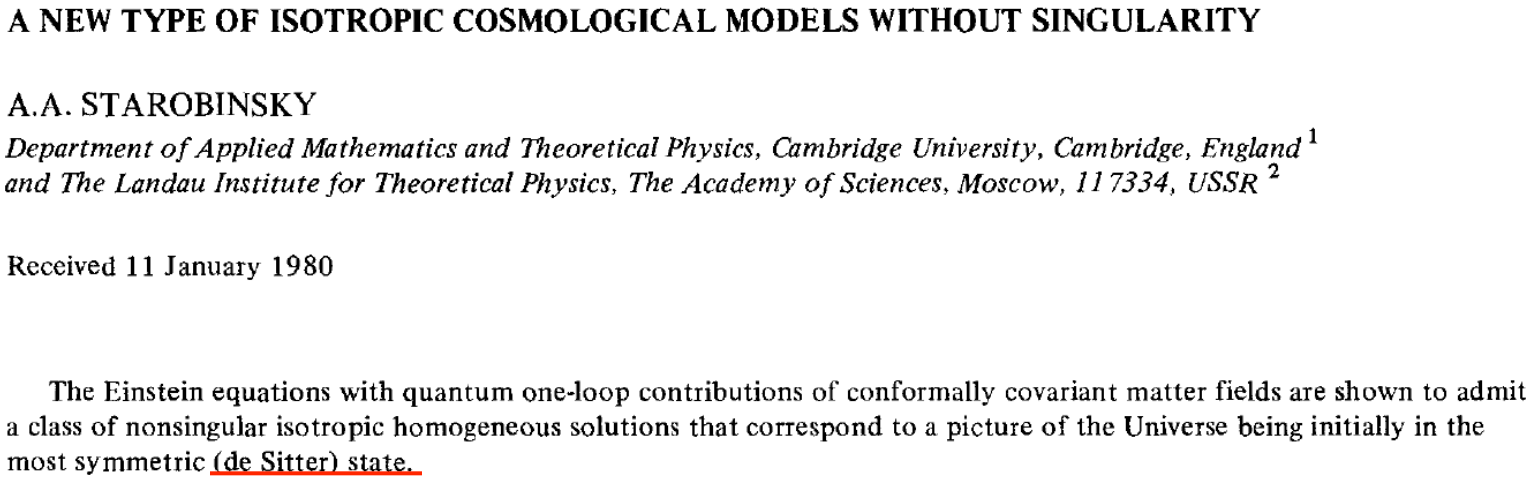
Received 6 June 1983

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.

伏兵がいた。。。



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.

$$S = \int d^4x \sqrt{-g}\, f(R)$$

⟹ 結果的には、chaotic inflation と等価

- 量子補正を考慮すると宇宙初期に de Sitter
- 動機は初期特異点の解消

誰がノーベル賞をとるのか？

Higher curvature Inflation

- 1980 Jan. Starobinski (Landau Institute)

Old Inflation

- 1980 May. Kazanas (NASA)
- 1980 Aug. Guth (SLAC)
- 1980 Sep. Sato (Kyoto)

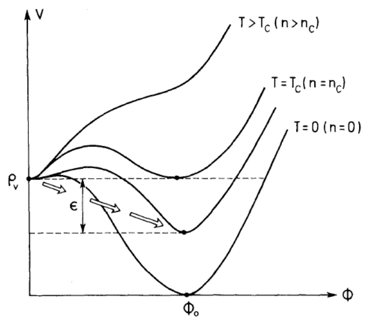
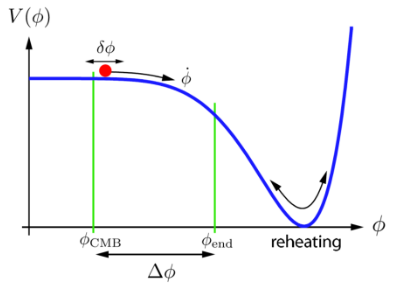


Figure 1. The schematic diagram of the effective potential of the vacuum energy density.

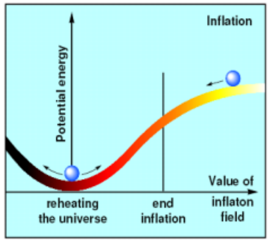
New Inflation

- 1981 Oct. Linde (Lebedev Physical Institute)
- 1982 Jan. Albrecht & Steinhardt (U of Pen.)

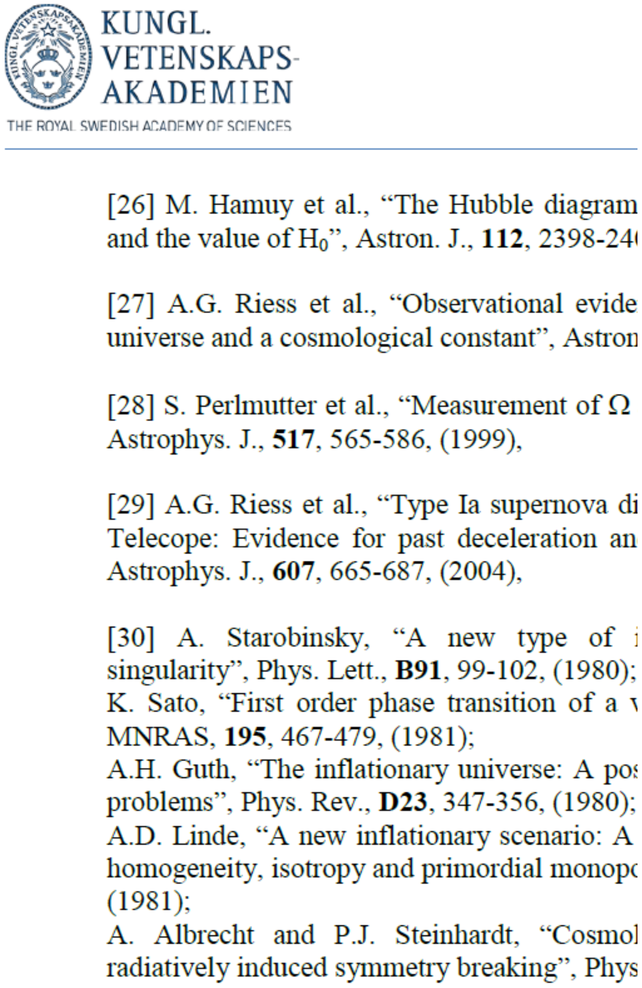


Chaotic Inflation

- 1983 Jun. Linde (Lebedev Physical Institute)



もう一つのインフレーション



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[27] A.G. Riess et al., "Observational evide universe and a cosmological constant", Astron

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[29] A.G. Riess et al., "Type Ia supernova di Telecope: Evidence for past deceleration an Astrophys. J., **607**, 665-687, (2004),

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K. Sato, "First order phase transition of a MNRAS, **195**, 467-479, (1981);
A.H. Guth, "The inflationary universe: A po problems", Phys. Rev., **D23**, 347-356, (1980);
A.D. Linde, "A new inflationary scenario: A homogeneity, isotropy and primordial monop (1981);
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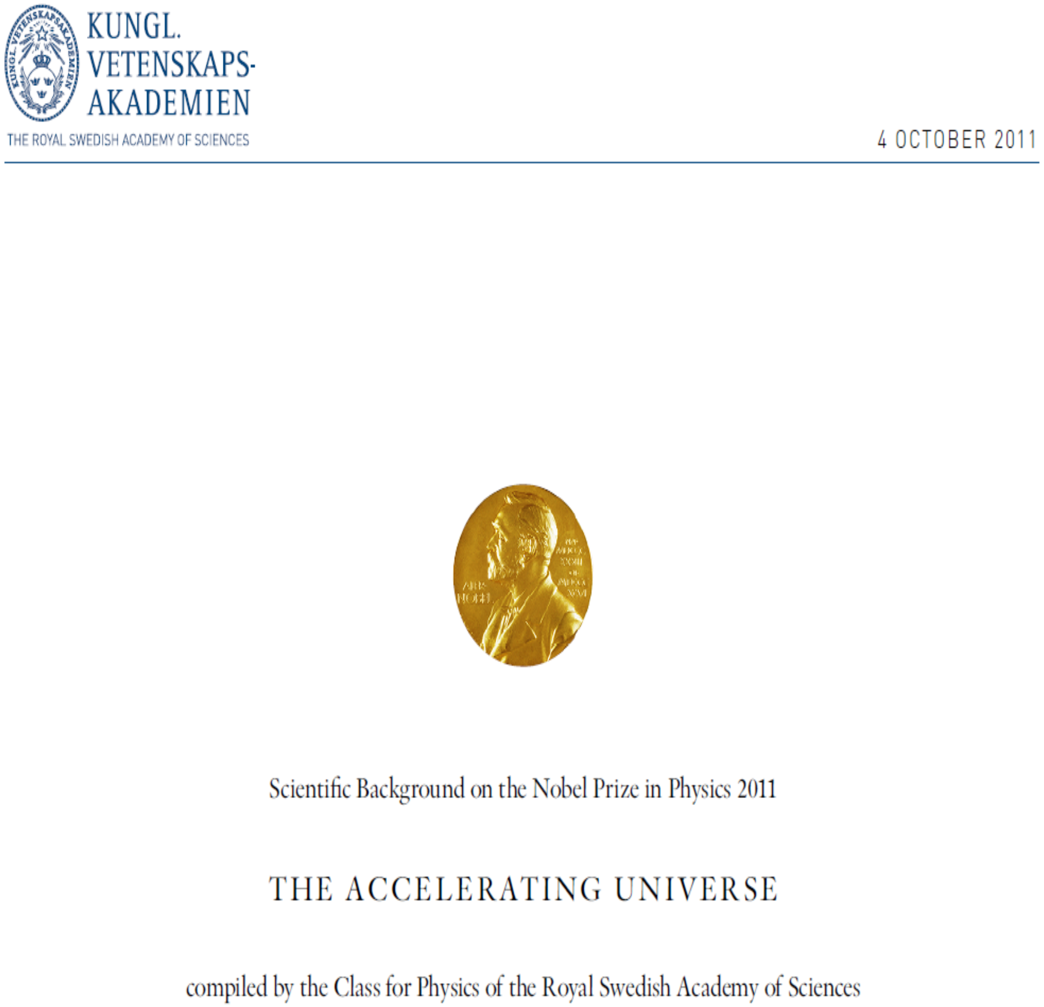

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4 OCTOBER 2011

Scientific Background on the Nobel Prize in Physics 2011

THE ACCELERATING UNIVERSE

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

なぜ、Kazanas がサイトされていないのか？

ひとつの可能性

InSPIREで検索すると

Guth　7,086件

Linde　4,394件

Starobinski　3,870件

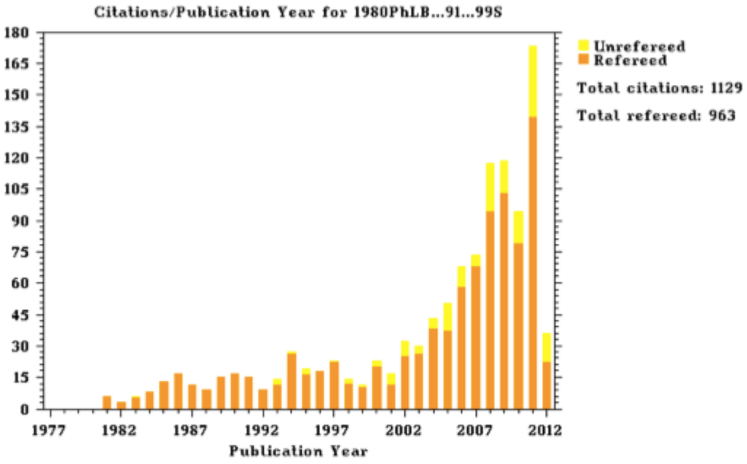
Albrecht & Steinhardt　3,856件

Sato　1,151件

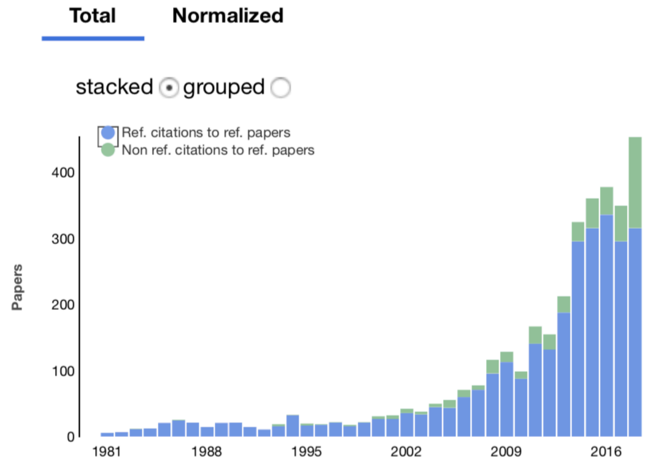
Kazanas　374件

NASA/ADSのデータを見ると

starobinsky



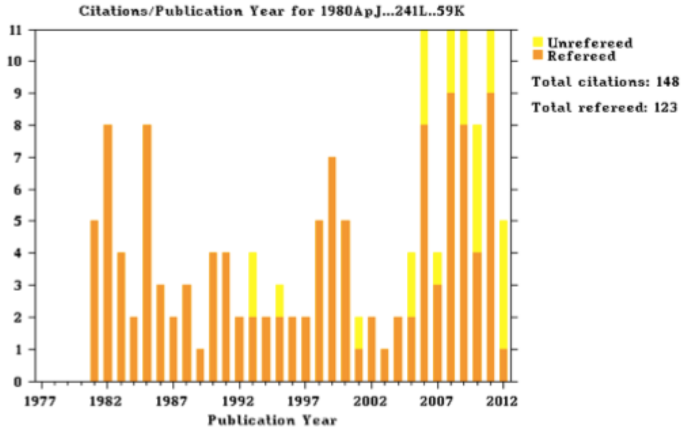
Total citations	3497
Normalized citations	3497
Refereed citations	2997
Normalized refereed citations	2997



Total **Normalized**

stacked ● grouped ○

Kazanas



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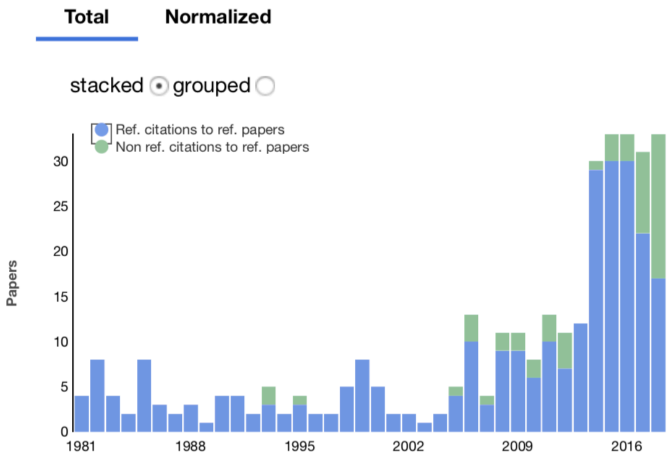
Normalized citations	333
Refereed citations	280
Normalized refereed citations	280

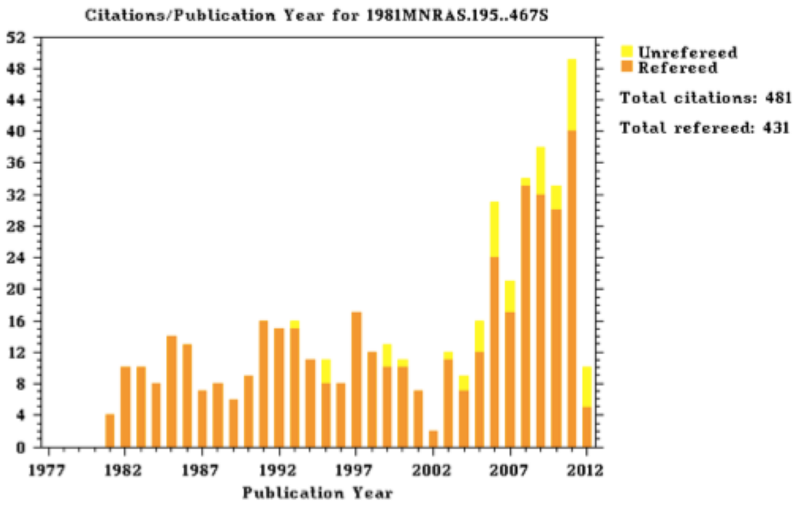


Total **Normalized**

stacked ● grouped ○

Bicep transition

Sato



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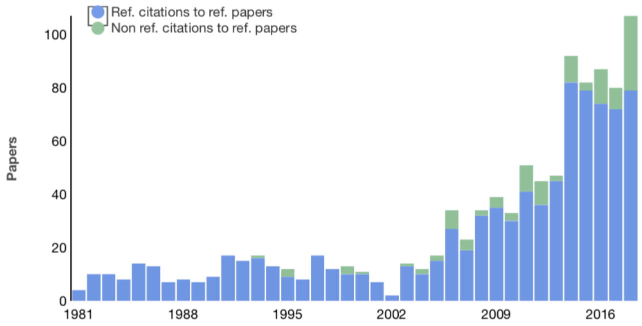
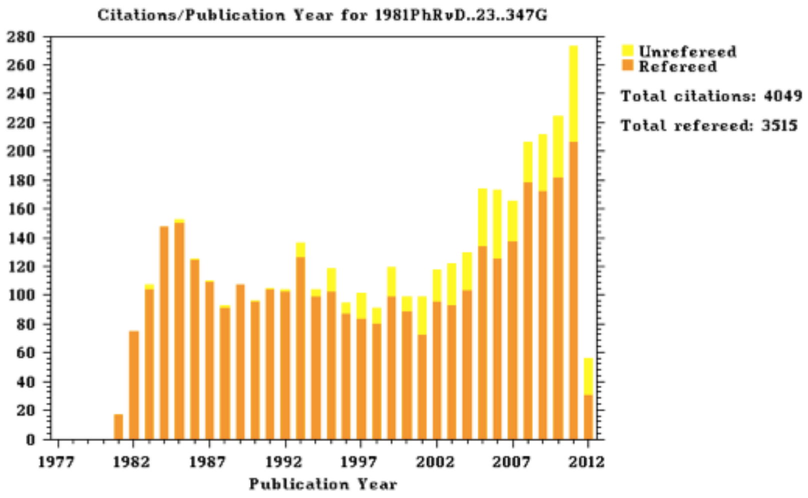
Normalized citations	1031
Refereed citations	915
Normalized refereed citations	915

Total **Normalized**

stacked ● grouped ○



Guth



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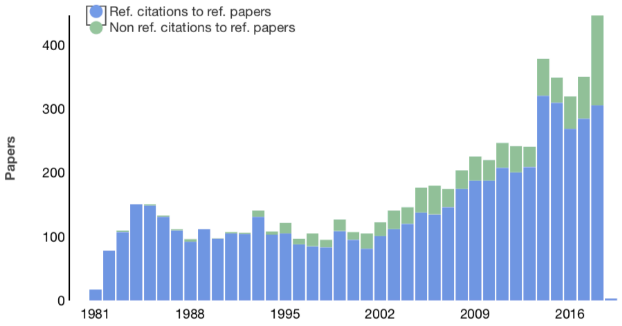
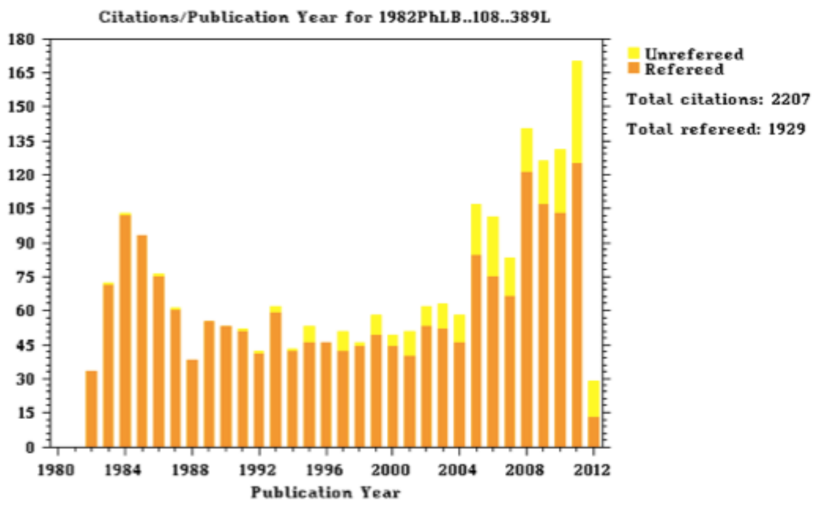
Normalized citations	6450
Refereed citations	5548
Normalized refereed citations	5548

Total **Normalized**

stacked ● grouped ○



Linde



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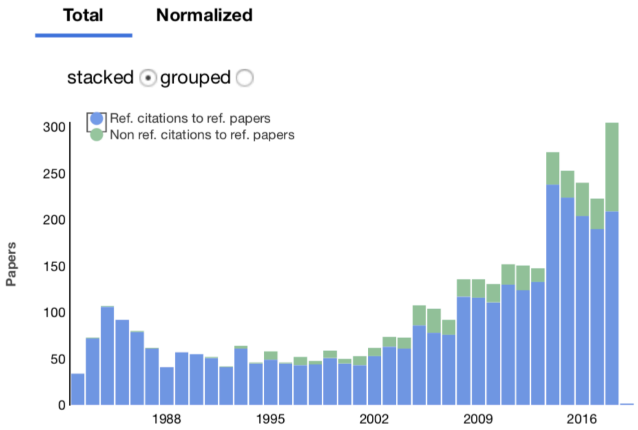
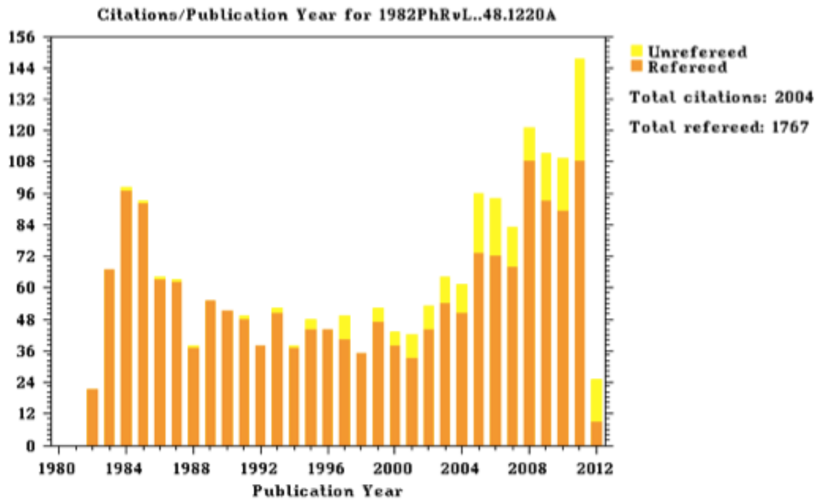
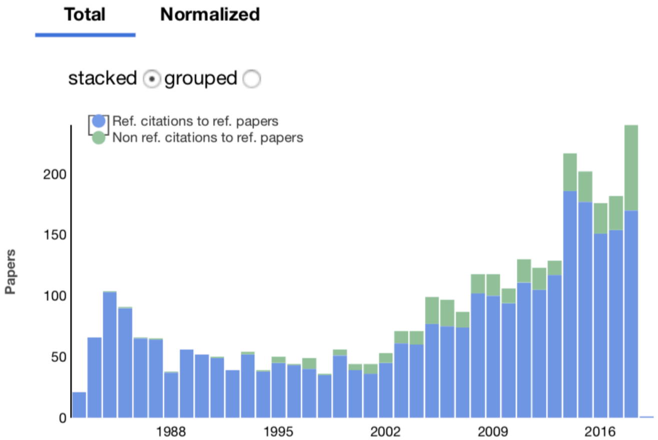
Normalized citations	3834
Refereed citations	3330
Normalized refereed citations	3330



Albrecht & Steinhardt



Total citations	3284
Normalized citations	1642
Refereed citations	2881
Normalized refereed citations	1440.5



提唱後38年の成果

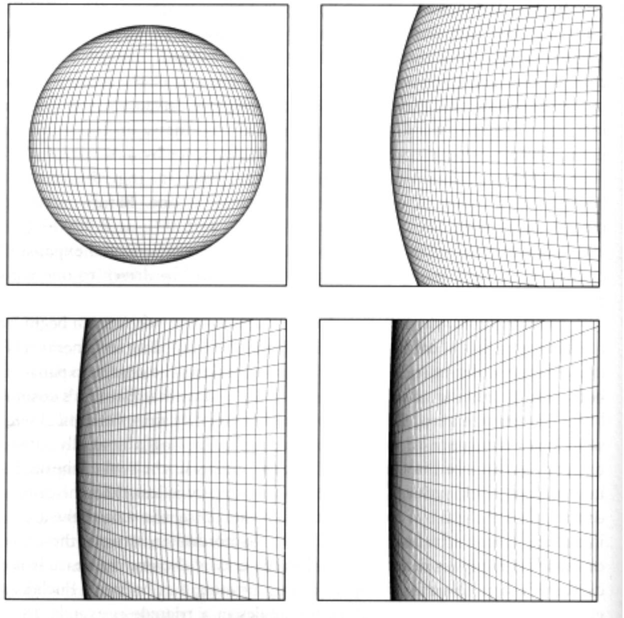
成果1:宇宙は平坦　$\Omega_{total} = 1$

密度パラメータ　$\Omega \equiv \frac{8\pi G\rho}{3H^2}$

フリードマン方程式　$H^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$

$\Omega_{curvature} = -\frac{k}{a^2 H^2}$　を定義すると

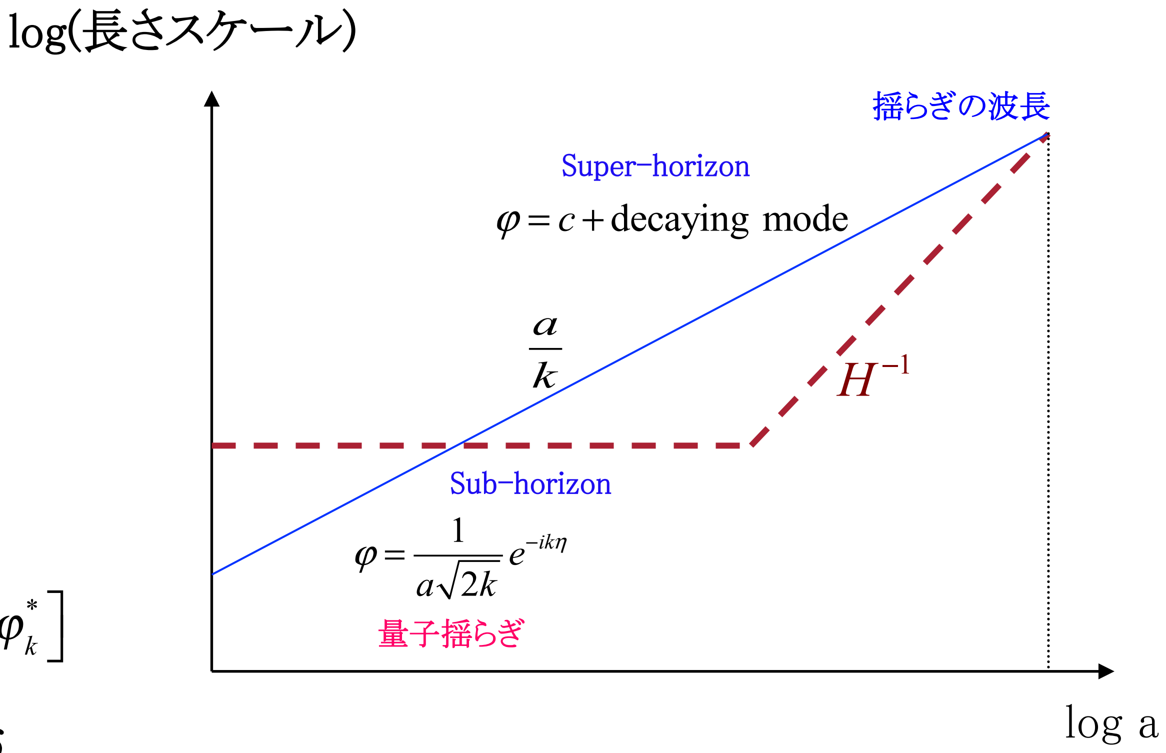
$$1 = \Omega_{total} + \Omega_{curvature}$$



加速膨張 $\Longrightarrow$ $\Omega_{curvature} = 0$

Parameter	Planck	$\cdots$ + WMAP + ACT	CMB + BAO
Ω_K	-0.072 ± 0.081	-0.037 ± 0.049	-0.0005 ± 0.0066

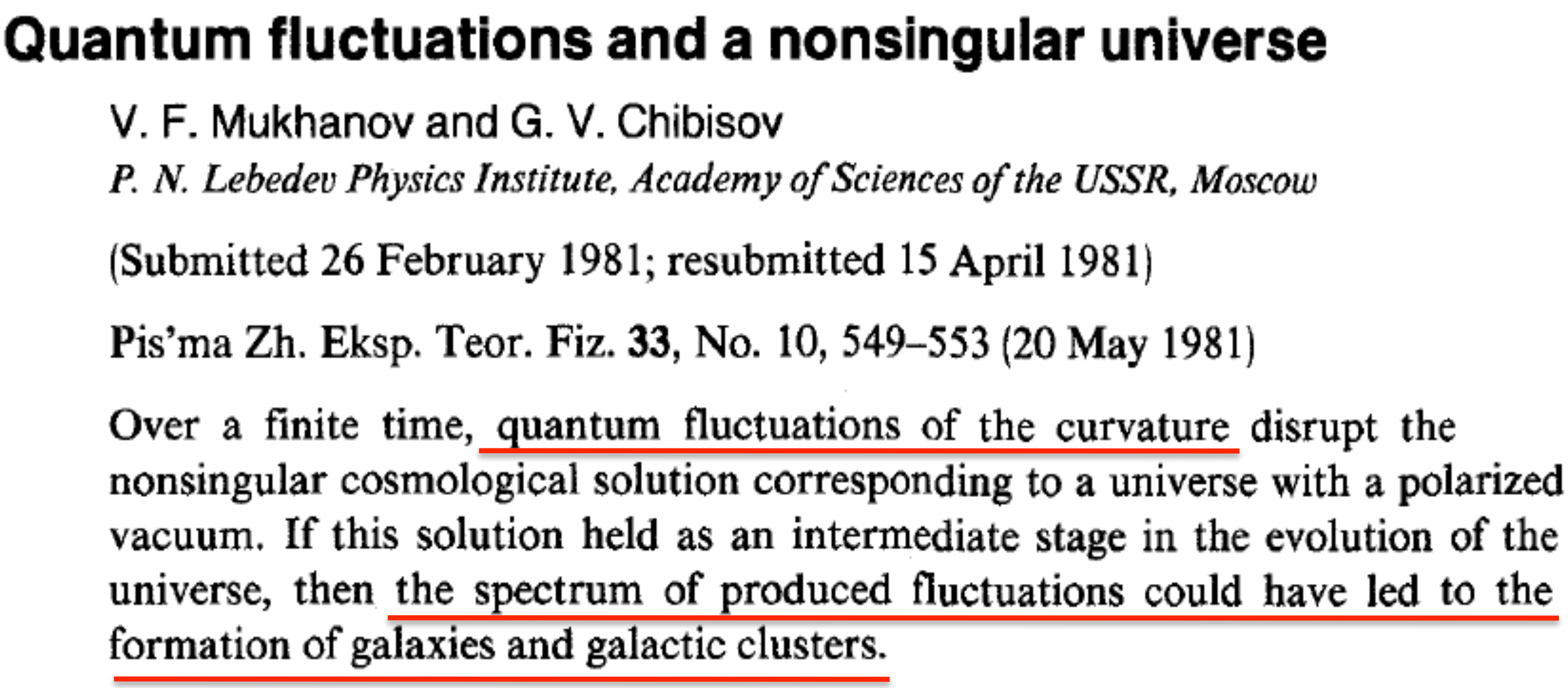
成果2:宇宙の構造の起源は量子揺らぎ！



量子化　$\hat{\varphi} = \sum \left[a_k \varphi_k + a_k^{+} \varphi_k^{*} \right]$

$$\left[a_i,\, a_j^{\dagger} \right] = \delta_{ij}$$

$$\langle 0 | \varphi^2 | 0 \rangle = \int \frac{dk}{k} \frac{k^3}{2\pi^2} |\varphi_k|^2 \approx \left(\frac{H}{2\pi} \right)^2$$



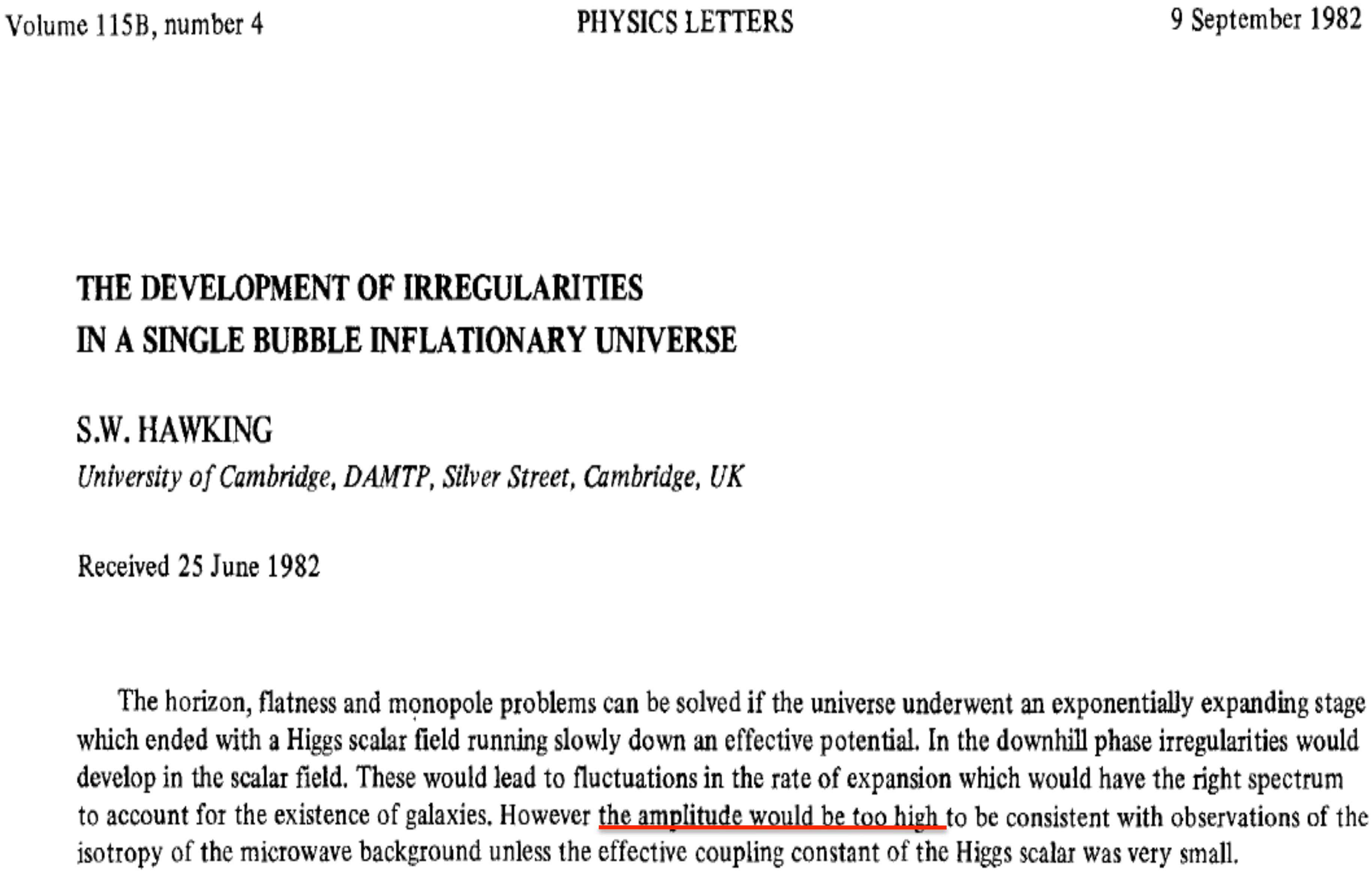
Quantum fluctuations and a nonsingular universe

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.



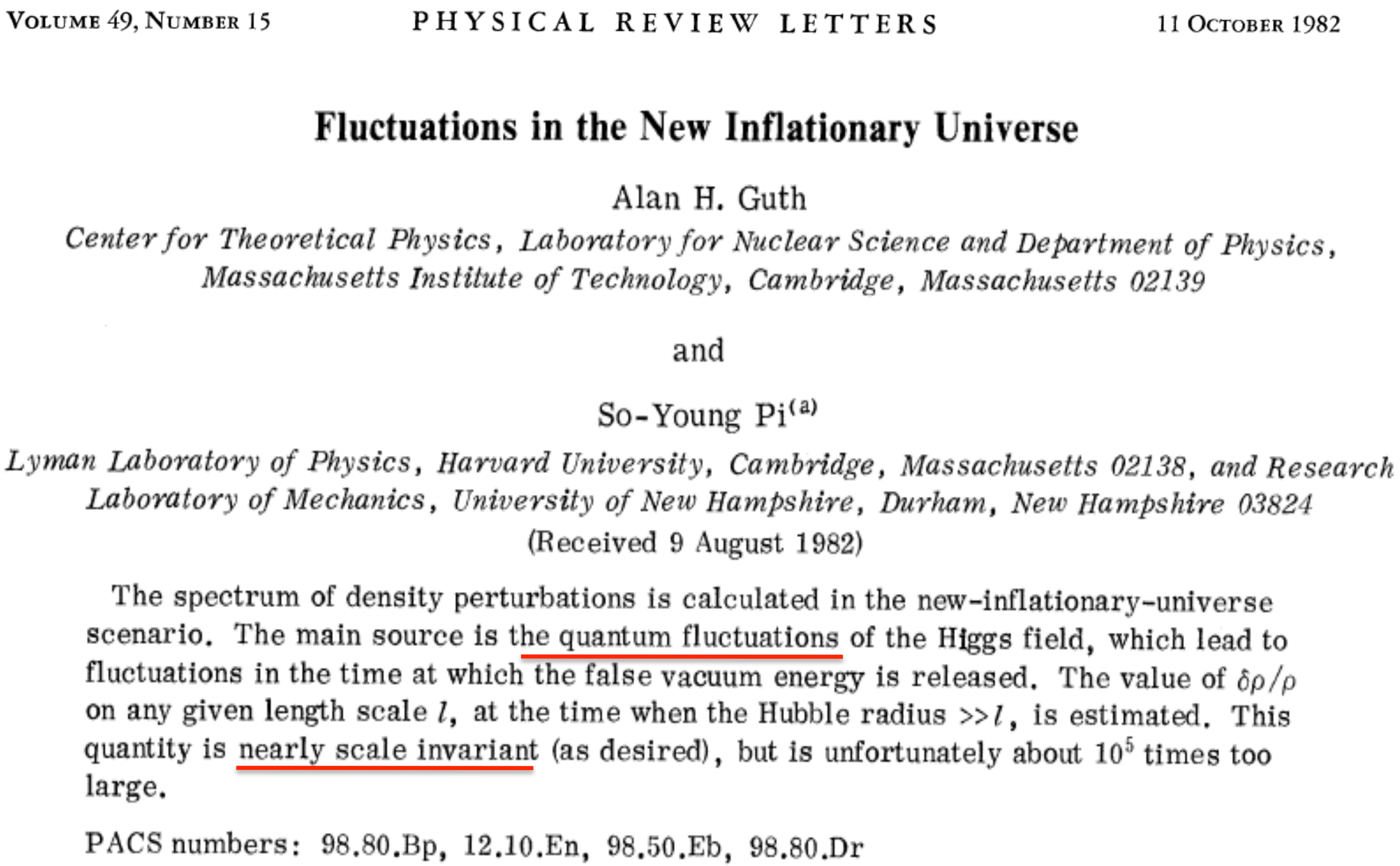
Volume 115B, number 4 PHYSICS LETTERS 9 September 1982

THE DEVELOPMENT OF IRREGULARITIES IN A SINGLE BUBBLE INFLATIONARY UNIVERSE

S.W. HAWKING
University of Cambridge, DAMTP, Silver Street, Cambridge, UK

Received 25 June 1982

The horizon, flatness and monopole problems can be solved if the universe underwent an exponentially expanding stage which ended with a Higgs scalar field running slowly down an effective potential. In the downhill phase irregularities would develop in the scalar field. These would lead to fluctuations in the rate of expansion which would have the right spectrum to account for the existence of galaxies. However the amplitude would be too high to be consistent with observations of the isotropy of the microwave background unless the effective coupling constant of the Higgs scalar was very small.



VOLUME 49, NUMBER 15 PHYSICAL REVIEW LETTERS 11 OCTOBER 1982

Fluctuations in the New Inflationary Universe

Alan H. Guth
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

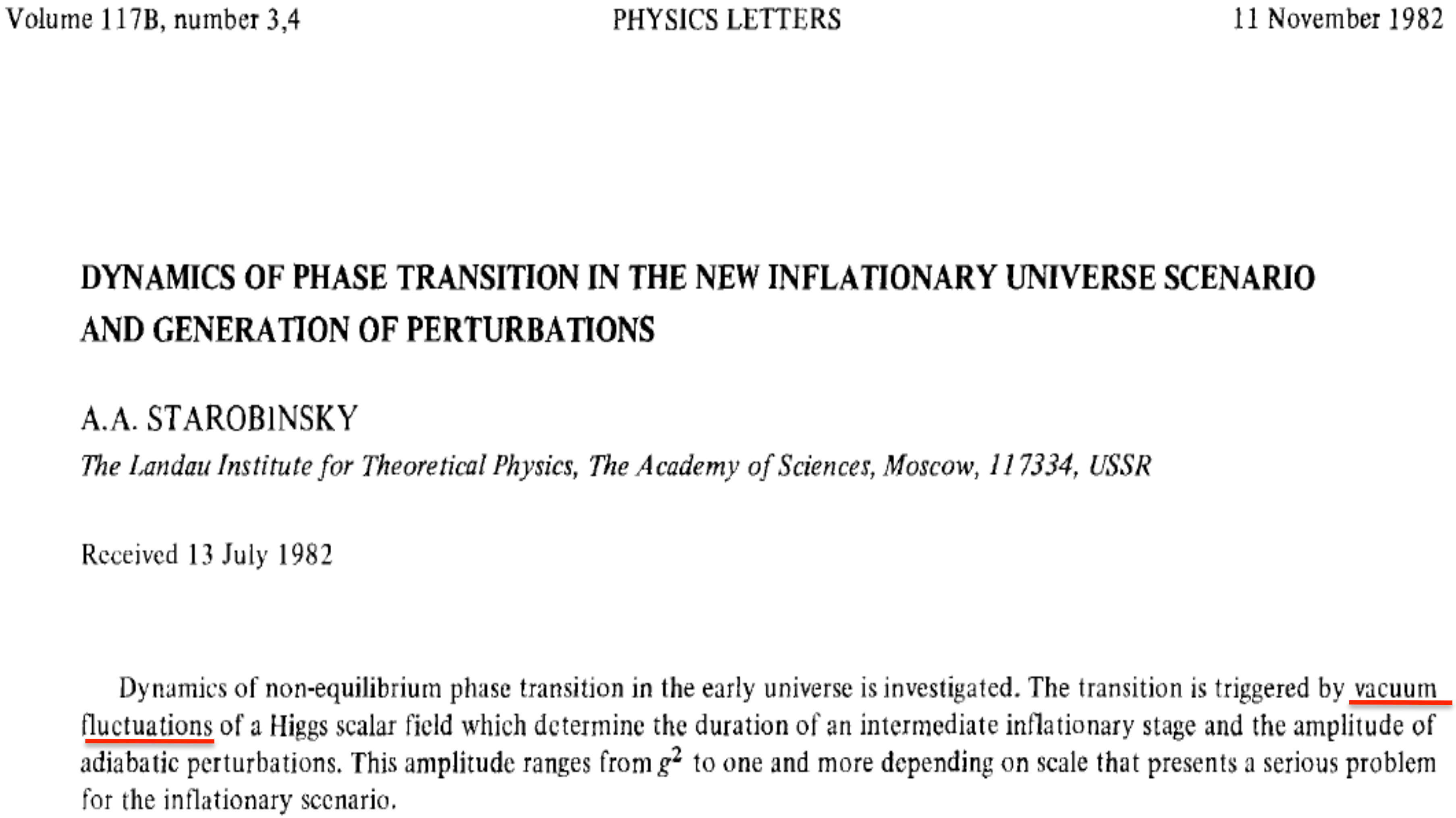
and

So-Young Pi[a]
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, and Research Laboratory of Mechanics, University of New Hampshire, Durham, New Hampshire 03824

(Received 9 August 1982)

The spectrum of density perturbations is calculated in the new-inflationary-universe scenario. The main source is the quantum fluctuations of the Higgs field, which lead to fluctuations in the time at which the false vacuum energy is released. The value of $\delta\rho/\rho$ on any given length scale l, at the time when the Hubble radius $\gg l$, is estimated. This quantity is nearly scale invariant (as desired), but is unfortunately about 10^5 times too large.

PACS numbers: 98.80.Bp, 12.10.En, 98.50.Eb, 98.80.Dr



Volume 117B, number 3,4 PHYSICS LETTERS 11 November 1982

DYNAMICS OF PHASE TRANSITION IN THE NEW INFLATIONARY UNIVERSE SCENARIO AND GENERATION OF PERTURBATIONS

A.A. STAROBINSKY
The Landau Institute for Theoretical Physics, The Academy of Sciences, Moscow, 117334, USSR

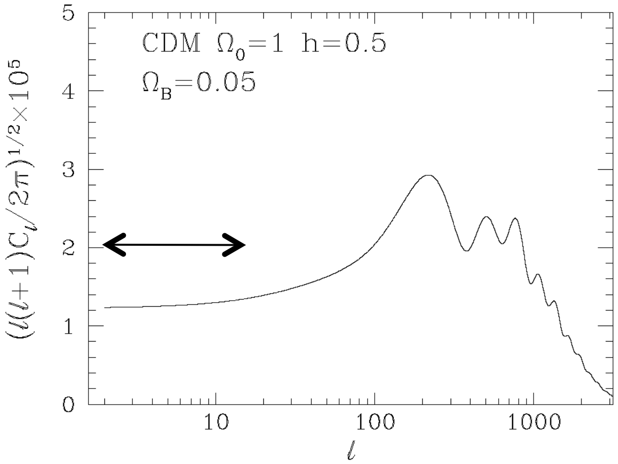
Received 13 July 1982

Dynamics of non-equilibrium phase transition in the early universe is investigated. The transition is triggered by vacuum fluctuations of a Higgs scalar field which determine the duration of an intermediate inflationary stage and the amplitude of adiabatic perturbations. This amplitude ranges from g^2 to one and more depending on scale that presents a serious problem for the inflationary scenario.

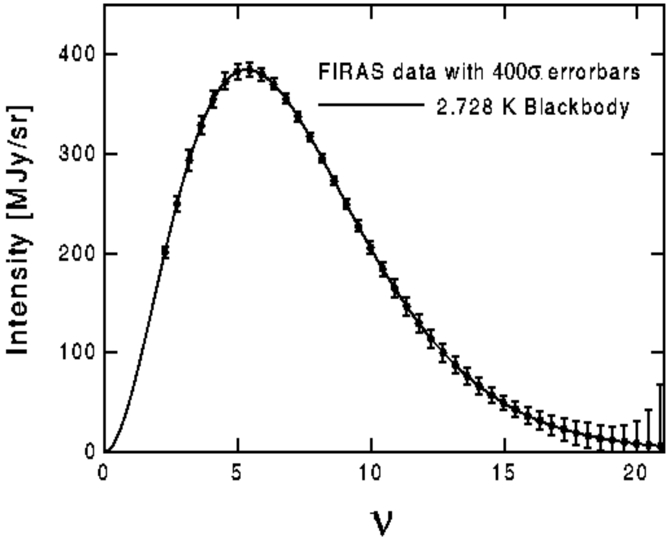
インフレーションノーベル賞をもたらす

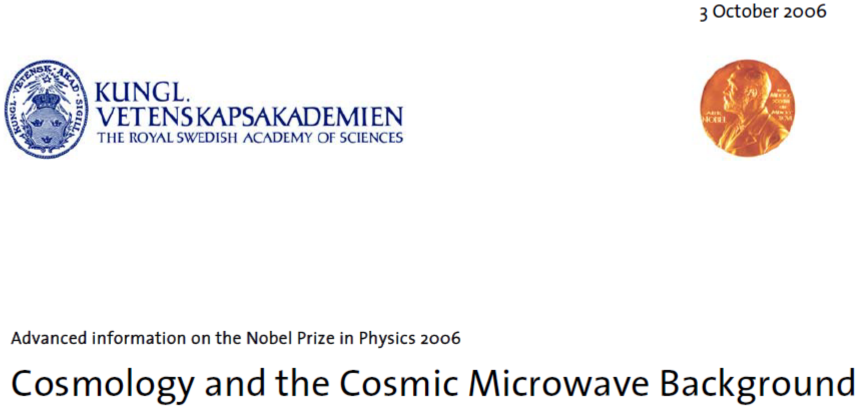
構造の起源

量子揺らぎ



COBEが証明！





3 October 2006

KUNGL.
VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Advanced information on the Nobel Prize in Physics 2006

Cosmology and the Cosmic Microwave Background

成果3：精密観測の時代をもたらした

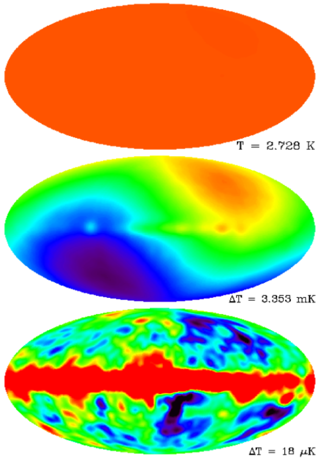
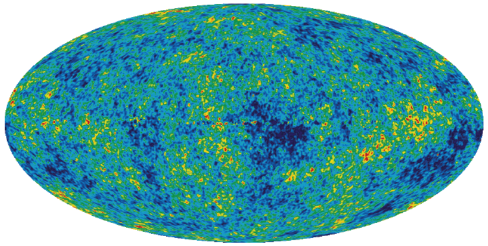
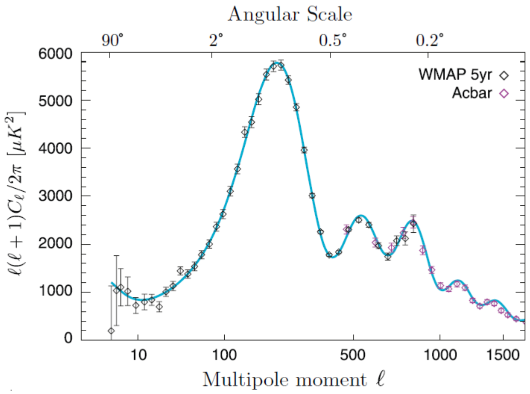


Fig. 5. DMR results (Smoot et al. 1992, http://lambda.gsfc.nasa.gov/product/cobe/) in galactic coordinates (horizontally longitude from + 180° to -180°, vertically latitude from + 90° to -90°, centre approximately on the Milky Way centre. The data from the 53 GHz band (6 mm wavelength) showing the near uniformity of the CMB (top), the dipole (middle) and the quadrupole and higher anisotropies with the dipole subtracted (bottom). The relative sensitivities from top to bottom are 1, 100 and 100,000. The background from the Milky Way, not following a blackbody spectrum (visible as a horizontal red band in the bottom panel), has not been subtracted.

WMAP 5-year data

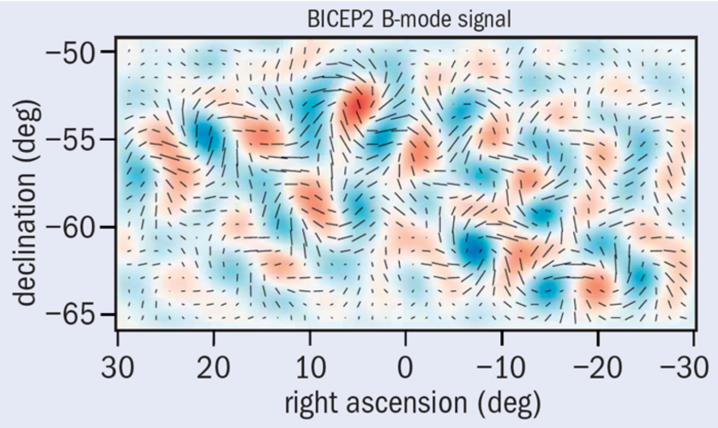




残された課題

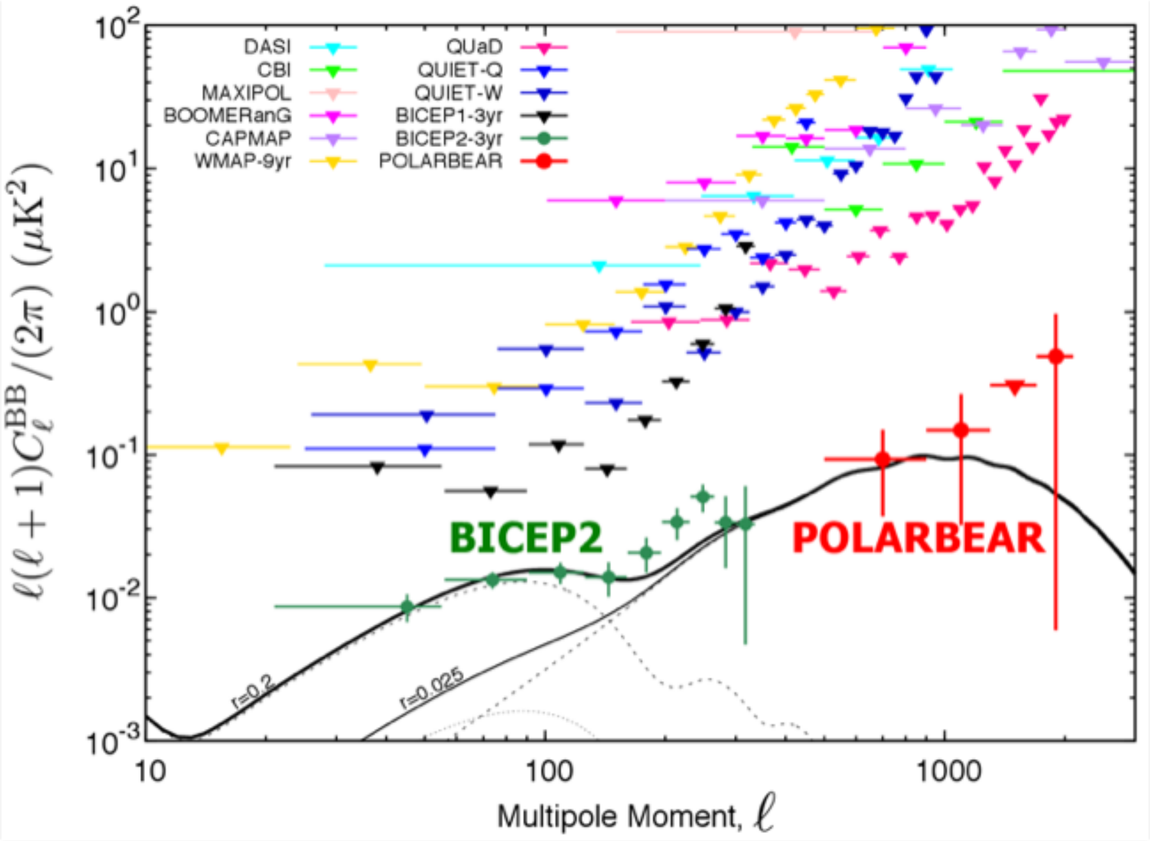
個人的なバイアスをかけて。。。

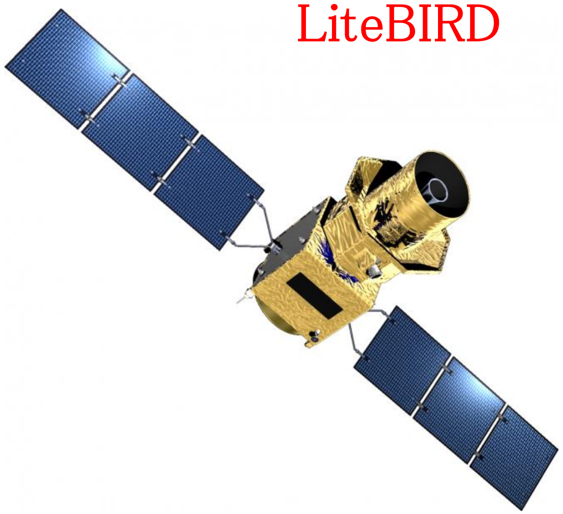
課題1：原始重力波の発見



Bモードの発見は

インフレーション理論の強固な証拠

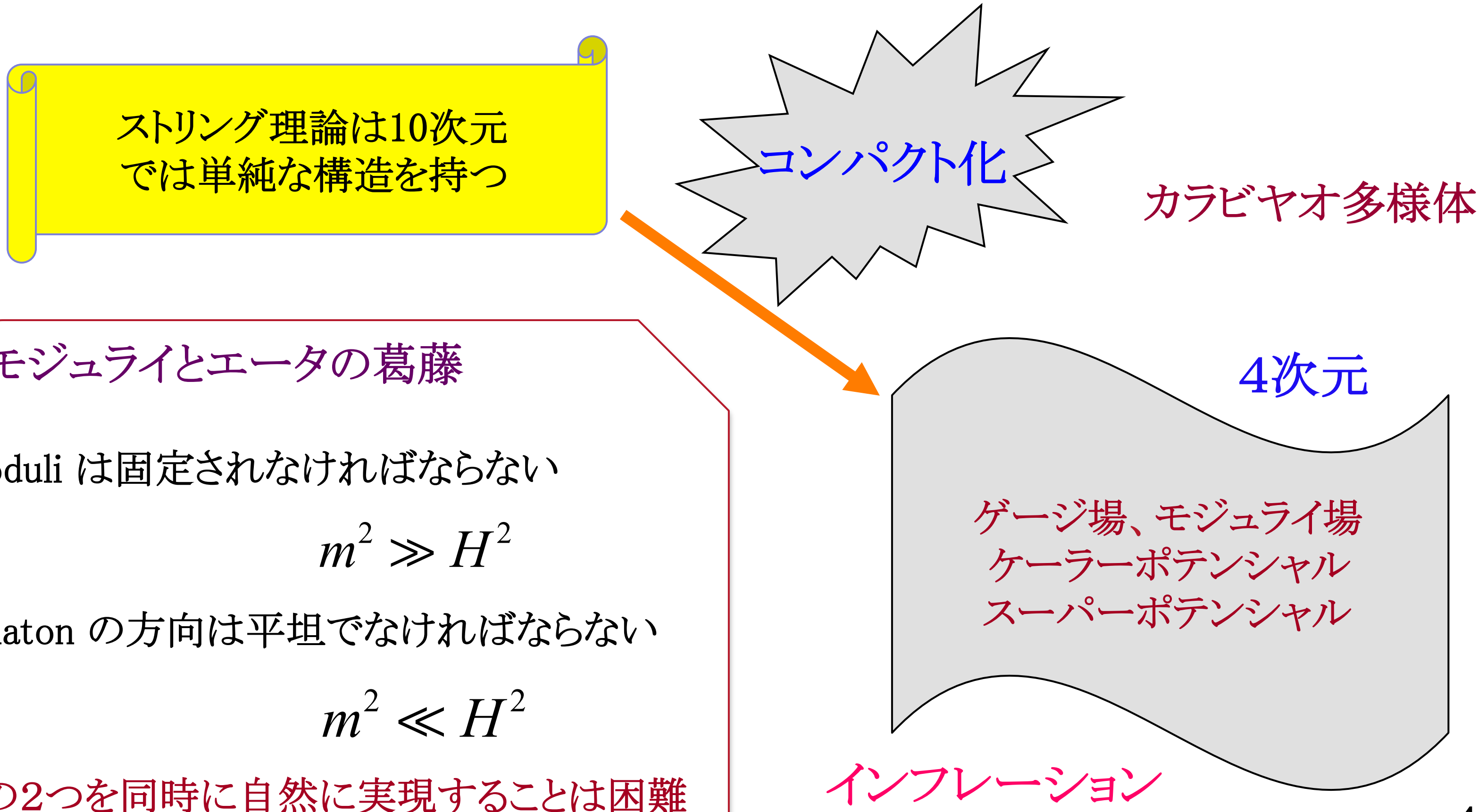




課題2：インフラトンの正体：揺らぎの振幅の説明

温度揺らぎの振幅はモデルに依存する $P_{R_c} = \frac{H^4}{4\pi\dot{\phi}^2} = \frac{1}{8\pi^2\varepsilon}\frac{H^2}{M_p^2}$ ⟷ $P_h = \frac{2}{\pi^2}\frac{H^2}{M_p^2}$

トップダウンで振幅を予言



ストリング理論は10次元
では単純な構造を持つ

コンパクト化

カラビヤオ多様体

4次元

ゲージ場、モジュライ場
ケーラーポテンシャル
スーパーポテンシャル

インフレーション

モジュライとエータの葛藤

Moduli は固定されなければならない

$$m^2 \gg H^2$$

Inflaton の方向は平坦でなければならない

$$m^2 \ll H^2$$

この2つを同時に自然に実現することは困難

課題3：　揺らぎの量子性

宇宙の大規模構造はインフレーションによって説明されている

インフレーションシナリオは本当に正しいのか？

原始重力波を観測することがインフレーションの証明を与えると信じられている

しかし、ゲージ場によって古典的に生成される原始重力波も存在する

インフレーションのもう一つの特性は量子揺らぎが構造の起源であるということ

原始重力波の量子性を観測することができれば、完全なインフレーションの証明となる

統計性を見る

古典論 → スーパーポアッソン $\langle n \rangle < \Delta n^2$

サブポアッソン $\langle n \rangle > \Delta n^2$ → 量子論

インフレーション中に物質があれば

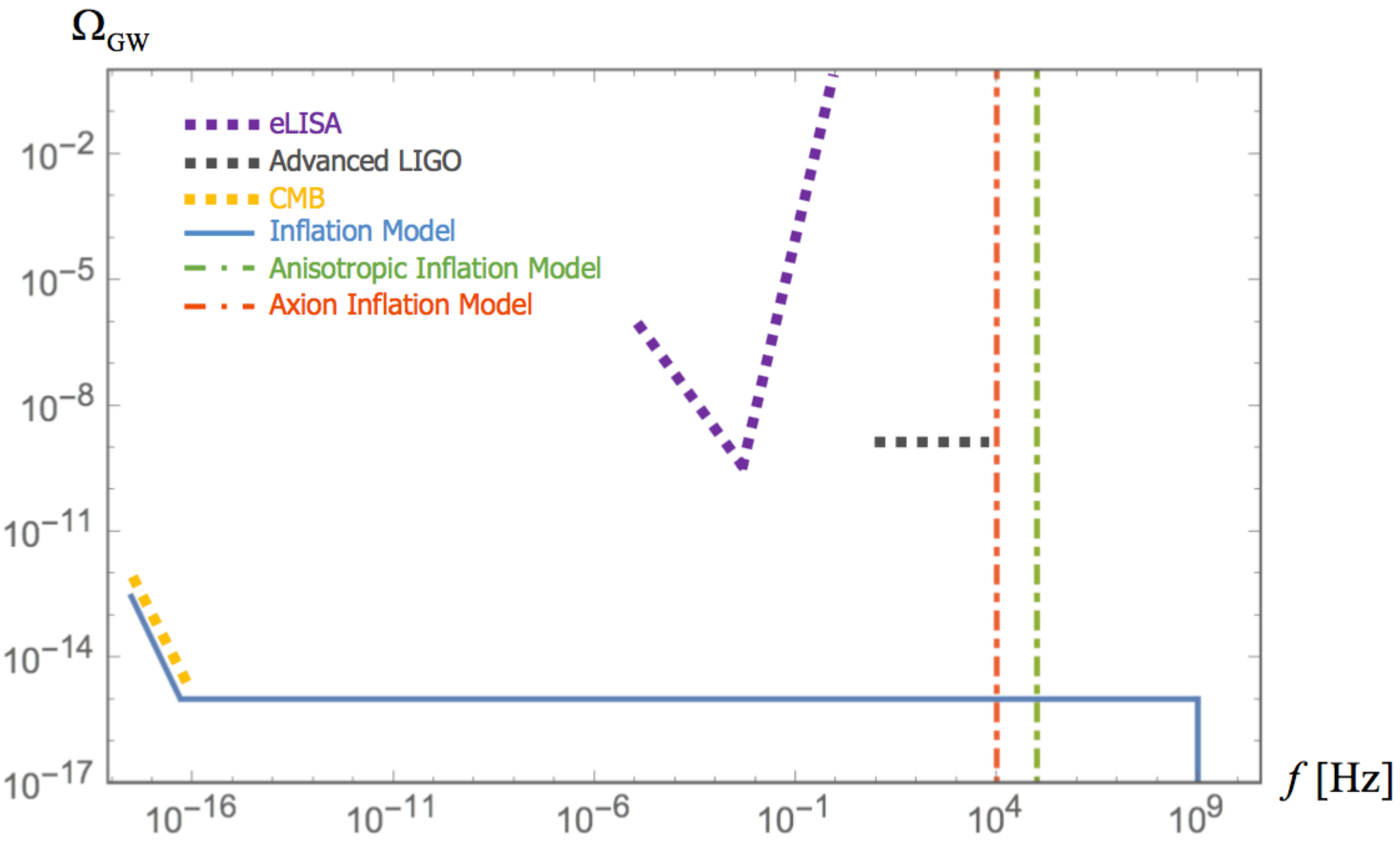
$$\left| h^{cl} \right\rangle = \exp\left[\int \frac{d^3k}{(2\pi)^{3/2}\sqrt{2k}} \sum_{s=\pm} \left[-\alpha_{\mathbf{k}}^{s*} \hat{a}_s(\mathbf{k}) + \alpha_{\mathbf{k}}^{s} \hat{a}_s^{\dagger}(-\mathbf{k}) \right] \right] \left| BD \right\rangle$$

$$\alpha_{\mathbf{k}}^{s} = 2i\kappa^2 e_{ij}^{*s}(-\mathbf{k}) u_k^*(\eta) T^{ij}(\mathbf{k})$$

Kanno & Soda 2018

$f > 10^9 |\alpha|^{-\frac{1}{6}} \left(\frac{H}{10^{-4} M_p} \right)^{\frac{1}{2}}$ Hz → サブポアッソン

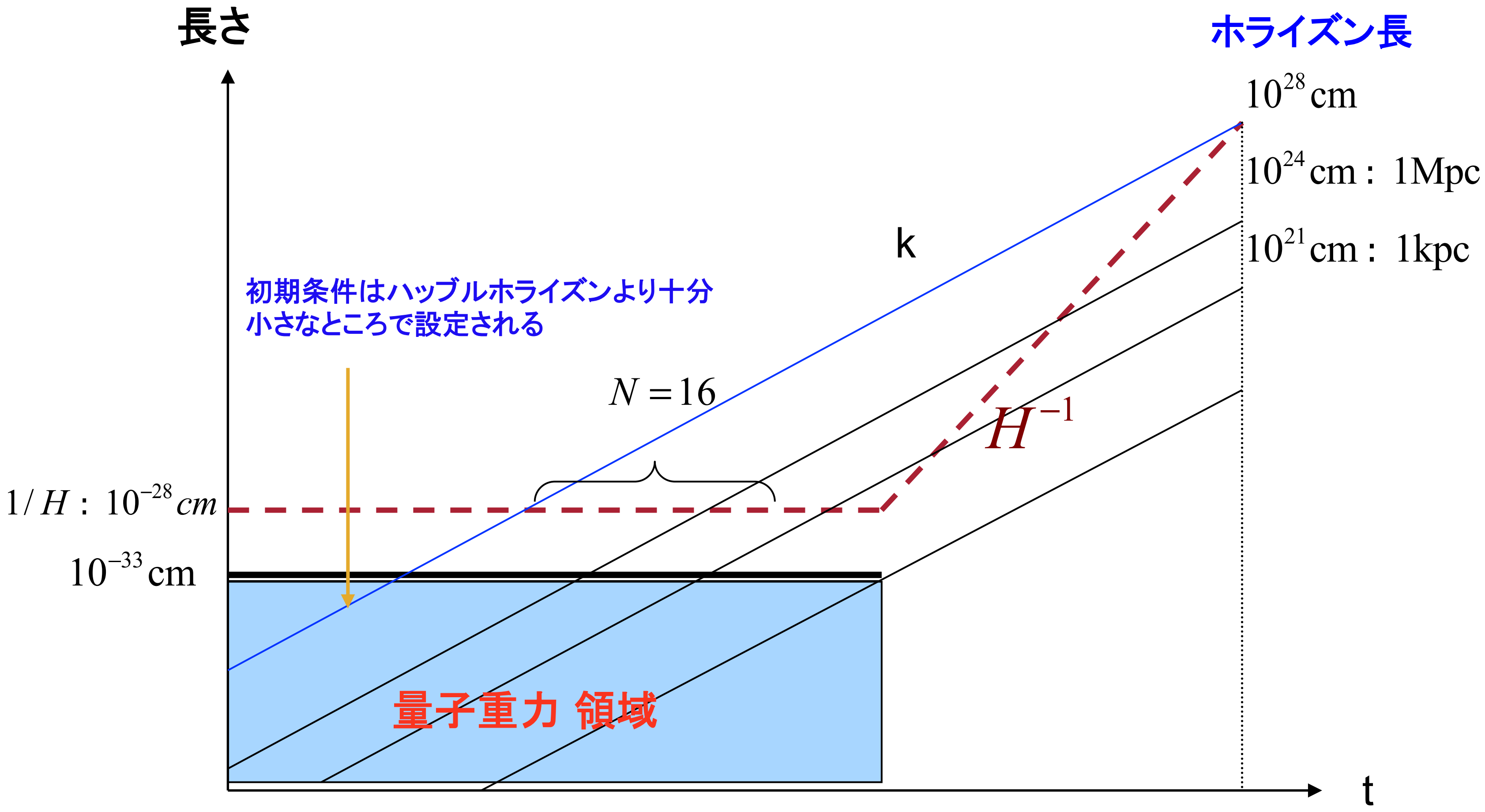
量子性を示す周波数帯



Ω_{GW}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
eLISA
Advanced LIGO
CMB
Inflation Model
Anisotropic Inflation Model
Axion Inflation Model
10^{-16}
10^{-11}
10^{-6}
10^{-1}
10^{4}
10^{9}
f [Hz]

課題4：初期特異点の解消

GUT scale のインフレーションだとすると。。。



超プランクスケール問題

物理的な理解の階層性

超伝導からインフレーション再考

超伝導

Onnes 1911

BCS理論

Badeen,Coper,Schrieffer 1957

↓

自発的対称性の破れ

Nambu 1958, Higgs 1964

相互作用の統一理論

Weinberg 1967

↓

インフレーション

Sato 1980, Kazanas 1980, Guth 1980

高温超伝導

Bednorz & Muller 1986

- 異方的超伝導
  Anisotropic superconductivity
- 時間反転対称性の破れた超伝導
- 空間反転対称性の破れた超伝導

新奇な物質の発見

新奇なインフレーションはあるのか？
新奇な物質を探さないといけない。

我々はどこにいるのか？

我々の理解はランダウ･ギンツブルク理論レベルか？

超弦理論に基づいたモデル構築には成功していない

超弦理論に答えを求めるべきかもわからない　Cf. Swampland conjecture

そもそも、BCS理論が物理として上か？

歴史的には有用だったのはランダう･ギンツブルク理論の方だった

遠回りなようだが、ランダう･ギンツブルク理論的な理解を徹底させる
方が有益かもしれない。

揺らぎの性質と対称性

- □ インフレーションを起こすためには、さらにポテンシャルが十分平坦でなければならない。

  シフト対称性 より **ガウス統計** $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\rangle = P(\mathbf{k}_1,\mathbf{k}_2)$

- □ インフレーションを起こすためには 初期にある程度の一様性 を仮定しなければならない。

  一様性 より **統計的に一様** $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\rangle = \delta(\mathbf{k}_1+\mathbf{k}_2)P(\mathbf{k}_1)$

- □ 一旦、インフレーションが起きたら 宇宙無毛仮説 が正しければ非等方性は指数関数的に消滅する

  空間の回転対称性 より **統計的に等方** $\langle \zeta(\mathbf{k}_1)\zeta(\mathbf{k}_2)\rangle = \delta(\mathbf{k}_1+\mathbf{k}_2)P(k_1 = |\mathbf{k}_1|)$

- □ de Sitter 時空 ではハッブルパラメータが定数、すなわち時間的な対称性がある

$$ds^2 = -dt^2 + e^{2Ht}\left(dx^2+dy^2+dz^2\right) \qquad t \to t+c \qquad x \to e^{-Hc}x,\ y \to e^{-Hc}y,\ z \to e^{-Hc}z$$

  時間的な対称性 より **スケール不変** $P(k) \approx const.$

これらの 予言 はモデルの詳細にはよらない強固なものである

曲率揺らぎ：南部・ゴールドストーンボゾン

$$ds^2 = -dt^2 + e^{2Ht}\left(dx^2 + dy^2 + dz^2\right)$$

$$t \to t + c$$

$$x \to e^{-Hc}x, \quad y \to e^{-Hc}y, \quad z \to e^{-Hc}z$$

厳密にはドジッター宇宙ではない

vev of matter field $\psi_m(t)$ 時間推進対称性の自発的な破れ

$$t \to t + \pi\left(t, \mathbf{x}\right)$$ Nambu-Goldstone boson

$$g_{ij} \equiv a^2(t)\delta_{ij} \qquad \delta\psi_m(t, \mathbf{x}) \equiv \psi(t + \pi(t, \mathbf{x})) - \psi(t)$$

$$g_{ij} \equiv a^2(t)e^{2\Re(t,\mathbf{x})}\delta_{ij} \qquad \delta\psi_m(t, \mathbf{x}) \equiv 0 \qquad \Re(t, \mathbf{x}) = -H\pi(t, \mathbf{x})$$

対称性の自発的破れと新奇なインフレーション

時間並進×スケール変換対称性の破れ –> スペクトルの傾き

破れの度合いはドジッターからのずれ、つまりスローロールパラメータで決まる。
従って、スペクトルの傾きもスローロールパラメータで与えられる。

シフト対称性の破れ –> 非ガウス統計

非ガウス性もスローロールのオーダーで与えられる。 Maldacena 2003

この流れでいくと、回転対称性の破れを期待してしまう。。。

新奇な物質は、高温超伝導のときのセラミックスように身近なところにある。。。

新奇な物質としてのゲージ場 $S=\int d^4x\left[\sqrt{-g}R+g_{i\bar{j}}\partial^\mu\phi^i\partial_\mu\phi^{\bar{j}}-\frac{1}{4}f_{ab}(\phi^i)F^{a\mu\nu}F^b_{\mu\nu}\right]$

非等方インフレーション

$$ds^2=-dt^2+e^{2Ht}\left[e^{-4\Sigma t}dx^2+e^{2\Sigma t}\left(dy^2+dz^2\right)\right]$$

Watanabe, Kanno, Soda 2009

回転対称性の自発的破れがインフレーション中に起きる

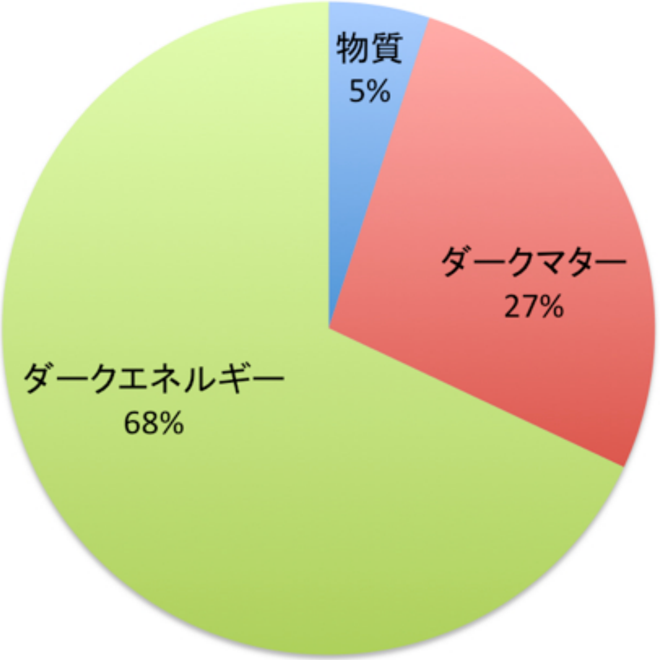
物理学は宇宙大規模構造の起源を
未だ理解していない

エピローグ

"The Inflation Debate"

インフレーション
理論は完全か

P. J. スタインハート



In 1900, **Lord Kelvin** gave a lecture “Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light.”

""Beauty and clearness of theory" was overshadowed by "two clouds”, *the null result of the Michelson-Morley experiment*

and the problems of blackbody radiation.”

1900年

力学、電磁気学、熱力学の成功

物理学の終焉???

Kelvin の 2 つの暗雲

光速一定の問題

特殊相対論

一般相対論

宇宙論

黒体放射の問題

量子論

場の量子論

素粒子論、物性理論

現代物理学の3つの暗雲

暗黒物質の問題

⬇

超対称性？

暗黒エネルギーの問題

⬇

修正重力理論？

インフラトンの問題

⬇

量子重力理論?

新たな理論が誕生する前兆