日本物理学会 2020年9月17日

ビッグバンと宇宙マイクロ波背景放射の物理

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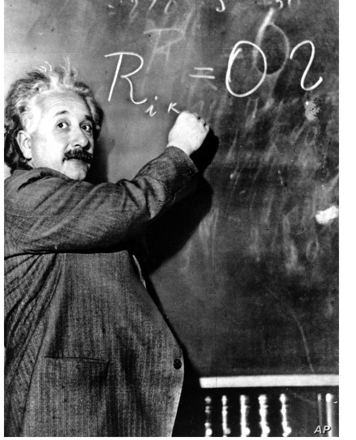
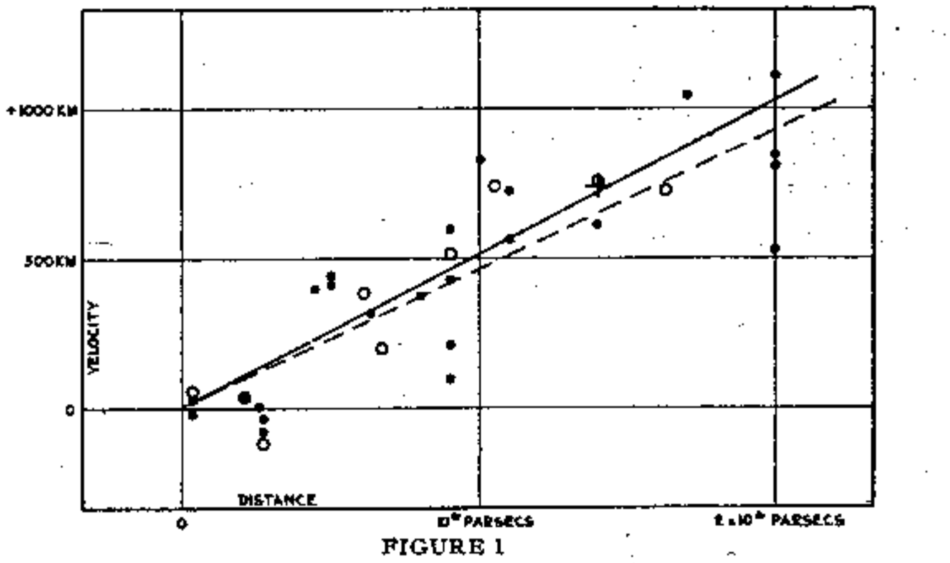
ビッグバンの成立



- 宇宙の膨張
  - 1930年ごろまでには、宇宙が膨張していること明らかになった
  - ハッブルールメートルの法則 v=Hd

Mount Wilson Observatory's Hale Library, 1931



Hubble 1929

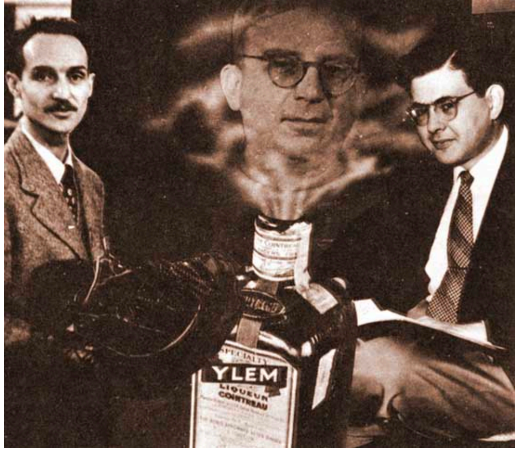
ビッグバンのアイデア：その原型

1930年代には早くも、ジョルジュ・ルメートル、Primeval Atom (cosmic egg)のアイデアを提案

- 1927, MITの博士論文で膨張宇宙を提唱
- 1931, 有限年齢の宇宙モデルとPrimeval Atom
  - 膨張を逆回しすれば、すべてが一点に収縮
  - 極端に高い密度の宇宙の始まり
  - 宇宙全体が一個の原子Primeval Atom
  - 「宇宙卵が創生の瞬間に爆発した」
  - 宇宙線が宇宙始まりの爆発の証拠

ジョルジュ・ルメートル

ガモフとビッグバン



- 元素の起源をhot & dense Universeに求めた
  - ”Expanding Universe and the Origin of Elements”, Gamow, 1946 Phys. Rev. 非平衡が重要
  - ”The Origin of Chemical Elements”, Alpher, Bethe, Gamow, 1948, Phys. Rev. 実際の数値計算を実行
  - “The Evolution of the Universe”, Gamow, 1948 Nature 物質と放射の量からジーンズ質量を計算 $2.7x10^7 M_{SUN}$
- 宇宙マイクロ波背景放射の予測は、AlpherとHerman
  - “Evolution of the Universe”, Alpher, Herman, 1948 Nature: “the temperature in the universe at the present time is found to be about 5° K”

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 equilib-

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 abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm³.

On the other hand, according to the relativistic 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:

$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5\times10^4, \qquad (2)$$

宇宙初期は中性子のみ（中性子と陽子の平衡が成り立っていたことに気づいたのは京都の林先生）

αβγ論文

Alpher and Herman
Nature 1948

light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K.

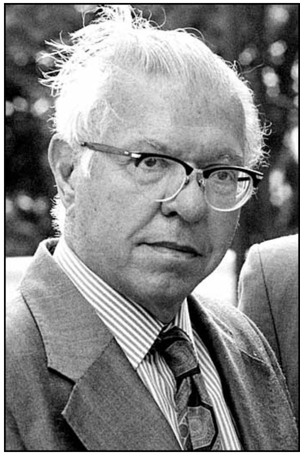
We hope to publish the details of these calculations in the near future.

Our thanks are due to Dr. G. Gamow for the proposal of the topic and his constant encouragement during the process of error-hunting. We wish also to thank Dr. J. W. Follin, jun., for his kindness in performing the integrations required for the determination of α, on a Reeves Analogue Computer. The work described in this letter was supported by the United States Navy, Bureau of Ordnance, under Contract NOrd-7386.

Ralph A. Alpher
Robert Herman

Big Bang vs. Steady State

- Big Bang Cosmology (Gamow)
  - 始まりのある宇宙
  - 熱く、密度の高い状態から宇宙が始まる
  - フリードマン宇宙モデル（スケール因子が時間のpower law）
- Steady State Cosmology (Hoyle)
  - 始まりも終わりもない宇宙
  - 物質は場から供給される
  - de Sitter宇宙モデル（スケール因子が時間のExponential）



ビッグバンは、15年間はマイナーな理論だった

- 定常宇宙論がむしろ定説
  - 宇宙には、始まりもなく終わりもない
  - 当時の指導的天体物理学者たちが提唱

    代表が、ケンブリッジ大学プルミア教授職　フレッド・ホイル卿

    じつは、名古屋大学の早川幸男先生は、晩年まで、「隠れ定常宇宙論者」だった？
- ビッグバン対定常宇宙論
  - 宇宙の元素の起源が論争の中心

宇宙マイクロ波背景放射CMBの発見

田中他1951 (早川幸男、名大着任1959)

- 1964年、PenziasとWilsonが、謎の「雑音」に気づく
  - 中性水素の21cm線を検出する目的で、7.35cmで検出器・アンテナのテストを実施
  - アンテナ温度6.7Kの雑音を検出
    - 大気雑音2.3K、アンテナの抵抗損失0.9K以外が見つからない
    - 3.5±1Kの正体不明の雑音
- 二人は、MITのBernard Burkeに相談
  - Peeblesのプレプリを紹介（初期の爆発の名残の電波の存在指摘）
  - BurkeはDickeに会うようにPenziasにアドバイス

プリンストングループ

- Robert Dickeのグループは
  宇宙マイクロ波背景放射の存在を予想
  - 膨張宇宙の初期特異点の問題について、膨張・収縮を繰り返す周期宇宙を提案
  - 最大収縮したときに10^{10}Kを超えていれば熱平衡状態:黒体放射
  - 現在の温度については、放射だけで宇宙を閉じさせないことから、40K以下と評価
  - Peeblesは、ヘリウム存在量から最小で3.5Kと見積もる
  - Dickeの指示に基づいて、P.RollとD.T.Wilkinsonはホーンアンテナと検出器を作成していた。波長3cm（これより短いと大気吸収、長いと銀河成分の雑音）で観測を予定していた。

3つの1965年ApJ論文

- ApJ Letter, Vol 142
  - Dicke, Peebles, Roll, Wilkinson, “COSMIC BLACK-BODY RADIATION” p414-419：電波の発見が宇宙初期の熱平衡を示す
  - Penzias, Wilson, ”A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s” p419-421：電波の発見（実質2ページの論文）
- ApJ Vol 142
  - Peebles, “THE BLACK-BODY RADIATION CONTENT OF THE UNIVERSE AND THE FORMATION OF GALAXIES” p1317: マイクロ波背景放射と銀河形成の関係（ジーンズ不安定性）

COSMIC BLACK-BODY RADIATION*

One of the basic problems of cosmology is the singularity characteristic of the familiar cosmological solutions of Einstein's field equations. Also puzzling is the presence of matter in excess over antimatter in the universe, for baryons and leptons are thought to be conserved. Thus, in the framework of conventional theory we cannot understand the origin of matter or of the universe. We can distinguish three main attempts to deal with these problems.

略

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. DICKE
P. J. E. PEEBLES
P. G. ROLL
D. T. WILKINSON

May 7, 1965

PALMER PHYSICAL LABORATORY
PRINCETON, NEW JERSEY

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Hoyle, F. 1948, *M N* , **108,** 372.
Hoyle, F , and Tayler, R J 1964, *Nature*, **203,** 1108
Liftshitz, E M., and Khalatnikov, I. M 1963, *Adv. in Phys* , **12,** 185.
Oort, J H 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf [Brussels: Éditions Stoops]), p. 163.
Peebles, P J. E. 1965, *Phys. Rev.* (in press).
Penzias, A. A., and Wilson, R. W. 1965, private communication.
Wheeler, J. A , 1958, *La Structure et l'évolution de l'universe* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14,** 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

ノーベル賞：CMBの発見

- 1978年のノーベル物理学賞、PenziasとWilsonへ
- “for their discovery of cosmic microwave background radiation” (1/4ずつ）
- 半分は、低温物理での貢献でP.Kapitsaへ
- Dickeらプリンストングループは漏れる
  - Peeblesは、”Dicke should have been included. He invented key technology, and he initiated the experiment that led to the recognition of this most informative fossil from the Big Bang.”とコメント
- Gamowはすでに亡くなっていた

ビッグバンの物理過程を追って

CMBの発見で、ビッグバンの存在は疑いがなくなってきた。次は、そこで何が起こっているか検証する

- 元素合成
- 中性化 Recombination Process
- 構造（密度揺らぎ）の形成と成長

Recombination Process

- 陽子、ヘリウムが電子を捕獲して水素原子、ヘリウム原子になる過程
  - 最初にビッグバン・膨張宇宙での計算をしたのがPeebles。”Recombination of the Primeval Plasma”, ApJ 153, 1, 1968。ただしここでは、水素のみを取り上げている。
  - 同時期にソ連では、Zel’dovich, Kurt, Sunyaev 1968
  - ヘリウムを入れて計算したのは、Matsuda, Sato, Takeda, 1971 PThPh（京都の林グループ）
  - 陽子・電子・中性水素の間、温度が下がってくるまでは平衡（Sahaの式）。3000Kぐらいで急激に変化、非平衡過程を数値的に解く必要がある

THE ASTROPHYSICAL JOURNAL, Vol. 153, July 1968

RECOMBINATION OF THE PRIMEVAL PLASMA*

P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
Received December 11, 1967

ABSTRACT

A theory is presented for the plasma recombination that would have taken place when the Universe had expanded and cooled to a Primeval Fireball temperature of about 4000° K. The computed residual ionization of the hydrogen following this recombination is in the range of 2×10^{-5} to 2×10^{-4}, depending on the assumed cosmological model. In the closed cosmological model the matter temperature would have effectively decoupled from the radiation at a temperature of 1200° K, while in the lowest density model the matter temperature would not have fallen much below the radiation temperature before the galaxies formed. Also computed is the effect of the recombination radiation on the spectrum of the Primeval Fireball.

TABLE 1

RECOMBINATION OF THE PLASMA*

Temperature (° K)	Fractional Ionization x_e	C†
5000	0.996	0 00017
4500	.92	0.00018
4000	.40	0.00059
3500	.072	0 0027
3000	.0098	0 020
2500	00092	0.25
2000	.000123	0.96
1500	0.000053	1.00

* Flat cosmological model, $\rho_0 = 1.8 \times 10^{-29}$ gm cm^{-3} is the present mean mass density.

† Equation (31).

$$-\frac{d}{dt}\left(\frac{n_e}{n}\right) = \left[\frac{\alpha_c n_e^2}{n} - \beta_c \frac{n_{1s}}{n} e^{-(B_1 - B_2)/kT}\right] C ,$$

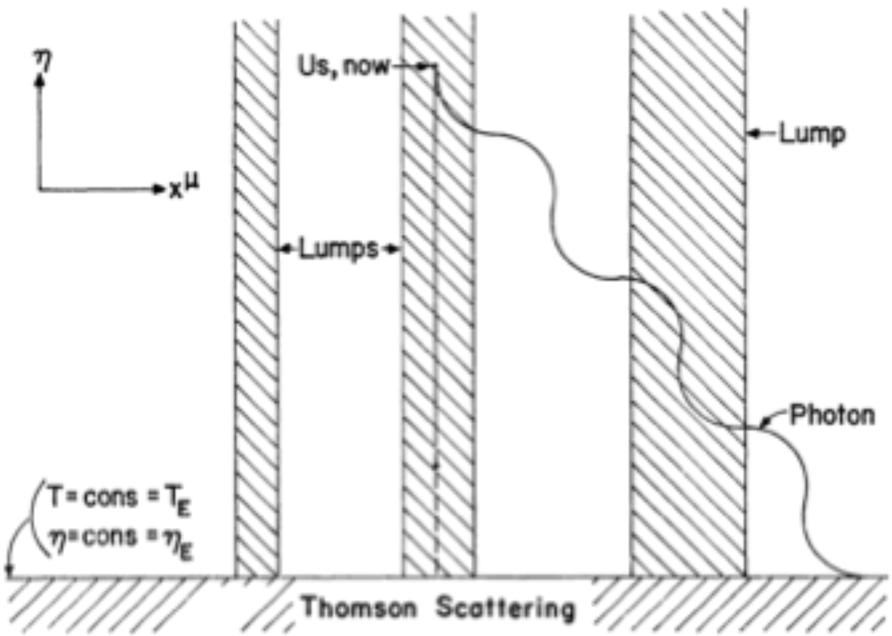
$$C = \frac{[1 + K\Lambda_{2s,1s} n_{1s}]}{[1 + K(\Lambda_{2s,1s} + \beta_c) n_{1s}]} .$$

一様等方からのずれ：揺らぎ

- 一様等方宇宙（Friedamnn Univ.）からのずれ
  - ずれを（線形）揺らぎで表す
  - メトリックの揺らぎhと、物質の揺らぎδ、アインシュタイン方程式を通じて結びつく
  - Evgeny Lifshitzがパイオニア
  - ゲージ不変形式：Bardeen 1980にまとめられる
  - 重力のみがCMBに及ぼす影響、SachsとWolfeが最初に評価
    - Sachs, Wolf, “Perturbations of a Cosmological Model and Angular Variations of the Microwave Background ”1967, ApJ 147 p73

PERTURBATIONS OF A COSMOLOGICAL MODEL AND ANGULAR VARIATIONS OF THE MICROWAVE BACKGROUND

R. K. SACHS AND A. M. WOLFE
Relativity Center, The University of Texas, Austin, Texas
Received May 13, 1966



$$\frac{\delta T_R}{T_R} = \frac{1}{10}\{B(0) - B[\,e^\mu(\eta_R - \eta_E)\,]\}$$

ホットプラズマ中での揺らぎの発展

- 陽子・電子・光子をviscous fluidと扱う
  - ソ連ではSunyaev
  - Richard Michie (病気のためプレプリのみ)
  - Joseph Silk 粘性流体
- Radiative transfer（光子と電子の間の相互作用）を取り入れた：Peebles, Yu 1970 ApJ
  - 音響振動を導出
  - ただし、ダークマターは入れていない

THE ASTROPHYSICAL JOURNAL, 162:815–836, December 1970

PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

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Joseph Henry Laboratories, Princeton University

AND

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Goddard Institute for Space Studies, NASA, New York
Received 1970 January 5; revised 1970 April 1

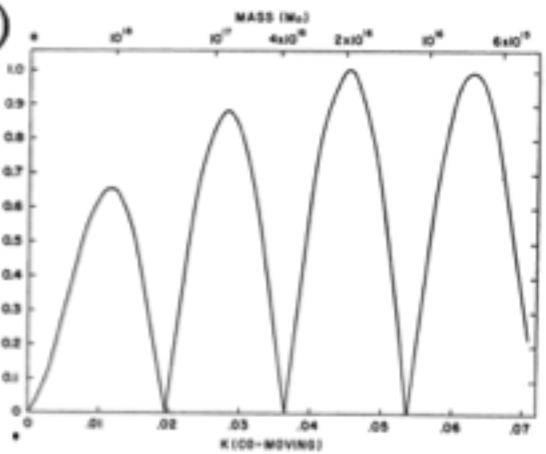
$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x^a}\frac{dx^a}{dt} + \frac{\partial f}{\partial \gamma_a}\frac{d\gamma_a}{dt} + \frac{\partial f}{\partial p_0}\frac{dp_0}{dt} = \sigma n_e \frac{p'_0}{p_0}(f_+ - f) .$$

$$\frac{\partial \delta}{\partial t} + \frac{\gamma_a}{a}\frac{\partial \delta}{\partial x^a} - 2\gamma_a\gamma_\beta \frac{\partial h_{a\beta}}{\partial t} = \sigma n_e(\delta_r + 4\gamma_a v^a - \delta) .$$

$$\frac{d\bar{\delta}}{dt} + \frac{ik\mu}{a}\bar{\delta} = 0 ,$$

$$\delta(t_1) = \bar{\delta}_f \exp(-ik\mu\tau) ,$$

$$\bar{\delta}_f = \delta_f + \frac{2ia_f\mu}{k}\frac{dh_f}{dt} - \frac{2a_f}{k^2}\frac{d}{dt}\left(a\frac{dh}{dt}\right)_f , \qquad \tau = \int_{t_f}^{t_1}\frac{dt}{a(t)} .$$



CMB揺らぎの計算

- 定式化
  - Peebles Yuまででほぼ完成
  - Wilson, Silk 1981, Wilson 1983
    - Boltzmann Hierarchy, 開いた時空に適用できるように拡張

THE ASTROPHYSICAL JOURNAL 243:14–25, 1981 January 1

ON THE ANISOTROPY OF THE COSMOLOGICAL BACKGROUND MATTER AND RADIATION DISTRIBUTION. I. THE RADIATION ANISOTROPY IN A SPATIALLY FLAT UNIVERSE

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Received 1980 April 18; accepted 1980 July 25

$$\delta = \sum_{l=0}^{\infty} \delta_l(t) P_l(\hat{k} \cdot \hat{\gamma}) \exp(i\boldsymbol{k} \cdot \boldsymbol{x}) .$$

The evolution equations for this plane wave are then

$$\dot{\delta}_m = -ikTcv + \tfrac{1}{2}\dot{h} ,$$

$$\dot{v} = \frac{\dot{T}}{T} v + \tfrac{1}{3} n_e \sigma_T c \frac{aT}{b} (\delta_1 - 4v) ,$$

$$\ddot{h} = 2\frac{\dot{T}}{T}\dot{h} + 8\pi G(bT^3\delta_m + 2aT^4\delta_0) ,$$

$$\dot{\delta}_0 = -\tfrac{1}{3}ikTc\delta_1 + \tfrac{2}{3}\dot{h} ,$$

$$\dot{\delta}_1 = -n_e\sigma_T c(\delta_1 - 4v) - ikTc(\delta_0 + \tfrac{2}{5}\delta_2) ,$$

$$\dot{\delta}_2 = -\tfrac{9}{10} n_e \sigma_T c\delta_2 + \tfrac{4}{3}\dot{h} - \frac{32\pi G i}{kTc}(bT^3 v + \tfrac{1}{3}aT^4\delta_1) - ikTc(\tfrac{2}{3}\delta_1 + \tfrac{3}{7}\delta_3) ;$$

$$l > 2, \quad \dot{\delta}_l = -n_e \sigma_T c\delta_l - ikTc\left(\frac{l}{2l-1}\delta_{l-1} + \frac{l+1}{2l+3}\delta_{l+1}\right) ,$$

$$\dot{T} = -T^3\left(\frac{8\pi G}{3}\right)^{1/2} (a + b/T)^{1/2} .$$

Boltzmann Hierarchy

CMB揺らぎの計算

- 定式化
  - Peebles Yuまででほぼ完成
  - Wilson, Silk 1981, Wilson 1983
    - Boltzmann Hierarchy, 開いた時空に適用できるように拡張
- 観測量との比較
  - Vittorio, Silk
    - ダークマター入り
  - Bond, Efstathiouの一連の研究
    - ダークマター入り
    - 統計についての詳細な議論、C_lの導入など大きな進展
    - 宇宙論パラメターへの依存性

dark energy density Ω_Λ, Matter Density Ω_M , Curvature Ω_K, Hubble parameter H_0 (h), Baryon Density Ω_B

CMBによる精密宇宙論

THE ASTROPHYSICAL JOURNAL, 285:L39–L43, 1984 October 15

FINE-SCALE ANISOTROPY OF THE COSMIC MICROWAVE BACKGROUND IN A UNIVERSE DOMINATED BY COLD DARK MATTER

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AND
JOSEPH SILK

THE ASTROPHYSICAL JOURNAL, 285:L45–L48, 1984 October 15

COSMIC BACKGROUND RADIATION ANISOTROPIES IN UNIVERSES DOMINATED BY NONBARYONIC DARK MATTER

J. R. BOND[1,2] AND G. EFSTATHIOU[2,3]
Received 1984 June 4; accepted 1984 July 17

TABLE 1

COLD DARK MATTER FLUCTUATION PARAMETERS

Ω (1)	Ω_B (2)	h_0 (3)	a(Mpc) (4)	b(Mpc) (5)	c(Mpc) (6)	ν (7)	θ_c (arc min) (8)	β (9)	$C(0)^{1/2}$ $\times 10^5$ (10)	$\Delta\dot{T}/T$ $\times 10^5$ (11)	$J_3(x_0)$ $(h^{-3}$ Mpc$^3)$ (12)	(13)	z_{nl} (14)	z_{reh} (15)	Ω_{BC} (16)
1.0	0.03	0.75	11.3	5.29	3.10	1.13	8.4	0.94	1.2	0.28	210	340	30	117	1.9×10^{-6}
1.0	0.03	0.50	23.1	11.4	6.48	1.25	8.8	1.25	2.8	0.42	190	380	20	151	6.9×10^{-15}
0.4	0.03	0.75	23.5	17.3	7.15	1.07	5.2	0.90	3.0	1.1	180	450	25	86	1.2×10^{-5}
0.3	0.03	0.75	37.1	21.1	10.8	1.12	4.5	0.88	4.4	1.8	170	470	20	79	4.2×10^{-6}
0.2	0.03	0.75	48.2	31.6	15.6	1.30	3.7	0.94	8.0	3.6	160	520	19	70	1.9×10^{-5}
0.2	0.10	0.75	76.2	71.1	27.7	2.15	5.2	1.82	22.0	7.9	150	580	15	32	2.6×10^{-3}
0.2	0.03	1.00	37.9	18.4	10.1	1.21	3.9	0.75	5.4	2.3	170	490	23	58	2.7×10^{-4}
0.2	0.03	0.50	207.0	47.9	38.5	1.73	3.6	1.22	15.6	7.2	160	530	24	91	1.1×10^{-5}
CfA Survey											180	550			
$x_0 h$ Mpc											7.5	15			

The statistics of cosmic background radiation fluctuations

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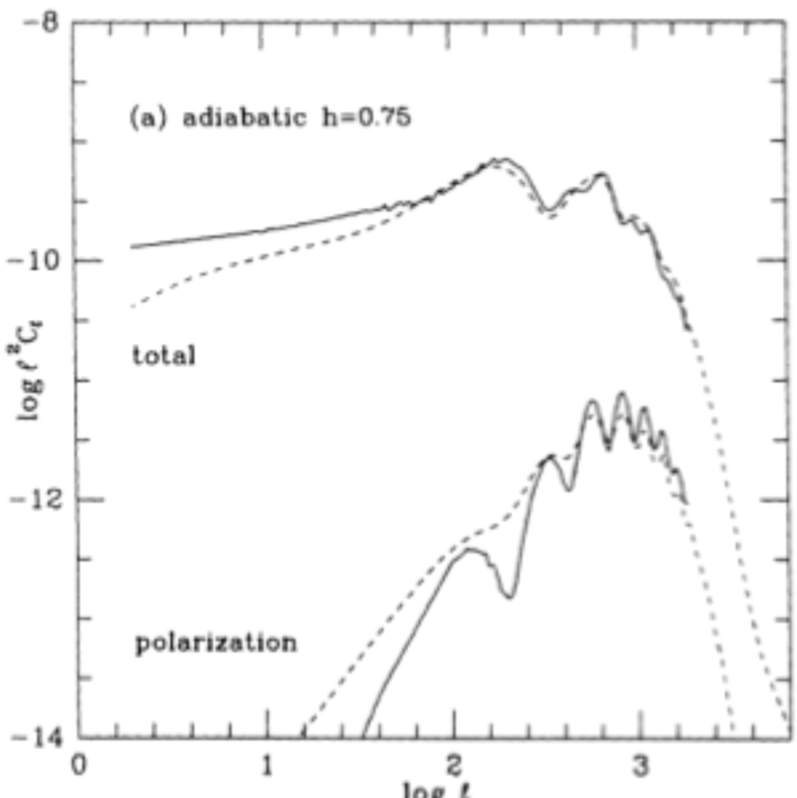
Accepted 1987 January 9. Received 1986 November 25

Cosmic ba



$$C(\theta) \equiv 1/16 \langle \Delta_T(\hat{q}_1)\, \Delta_T(\hat{q}_2) \rangle \qquad \cos(\theta) \equiv \hat{q}_1 \cdot \hat{q}_2,$$

$$C(\theta) = \frac{1}{4\pi} \sum_l (2l+1)\, C_l P_l(\cos\theta).$$

$$T(\hat{q}) \equiv T_0[1 + \Delta_T(\hat{q}, \mathbf{x}=0, \tau_0)/4]$$

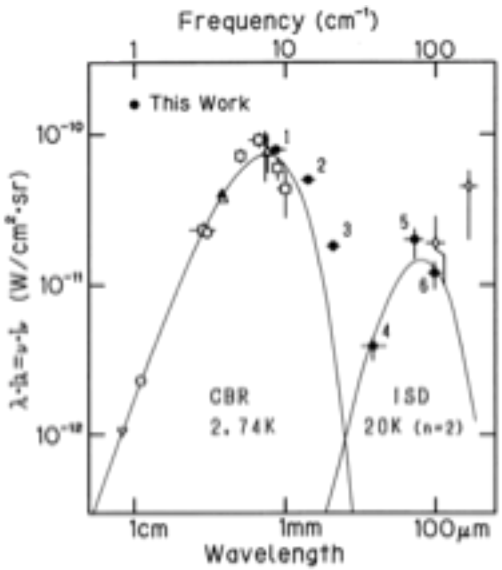
$$\equiv T_0 \sum_{lm} a_l^m Y_l^m(\hat{q}).$$

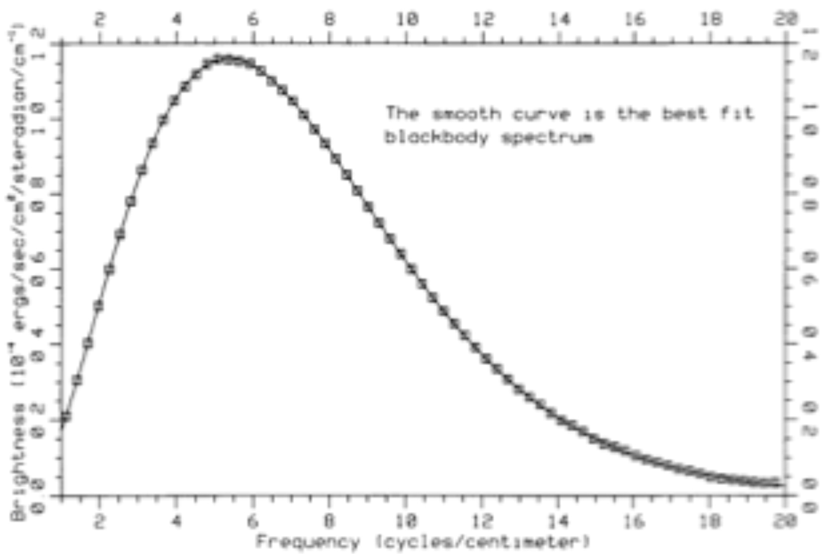
$$\langle a_l^m a_{l'}^{m'} \rangle = \delta_{ll'} \delta_{mm'} C_l, \qquad l \neq 0.$$

$$C_l = \frac{V_x}{8\pi} \int_0^\infty k^2\, dk\, |\Delta_{Tl}(k, \tau_0)|^2.$$

CMBの観測

- 黒体放射の最終確認
  - 1988年、Nagoya-Berkley Exp.の黒体放射からの大幅なずれ報告 Matsumoto et el., ApJ 329 567
  - 1989年、COBE/FIRASによって決着、10^{-4}レベルでは黒体と一致 Mather et al., 1990 ApJ 354 L37





CMBの観測

- 温度揺らぎ COBE/DMRが1992年に発見を報告

THE ASTROPHYSICAL JOURNAL, 396: L1–L5, 1992 September 1

STRUCTURE IN THE *COBE*[1] DIFFERENTIAL MICROWAVE RADIOMETER FIRST-YEAR MAPS

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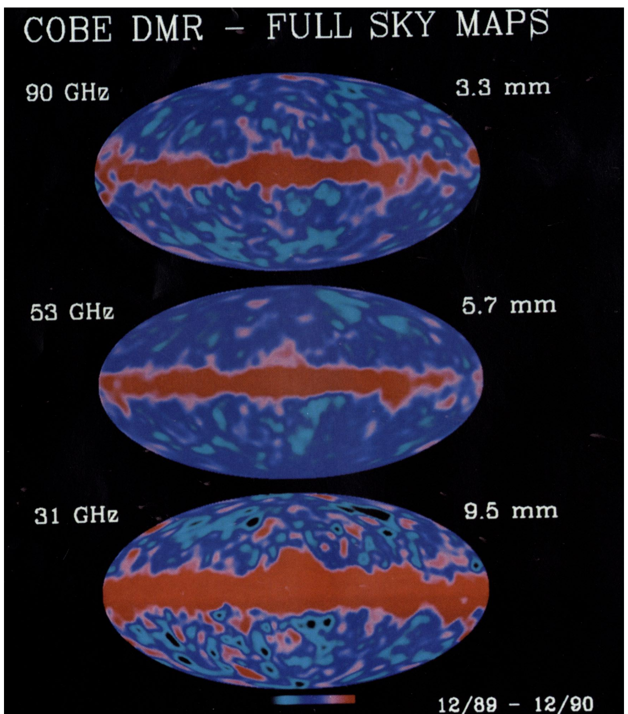
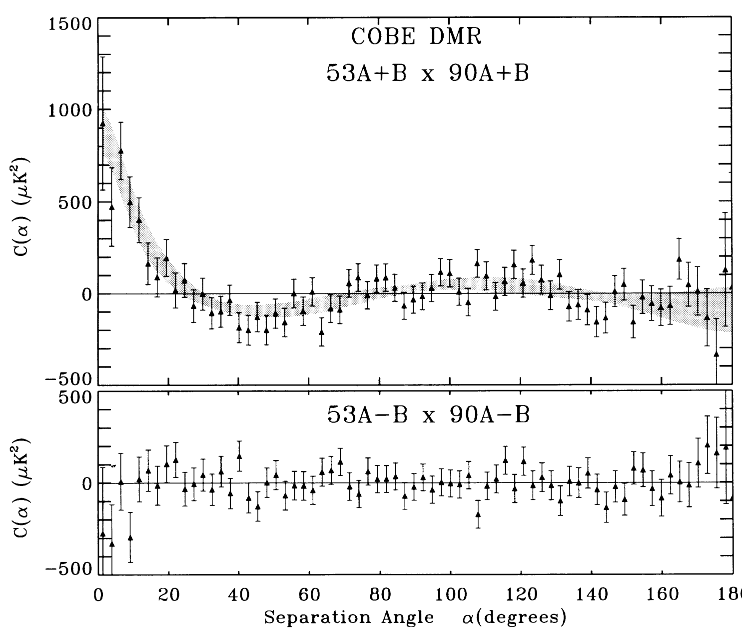
Received 1992 April 21; accepted 1992 June 12

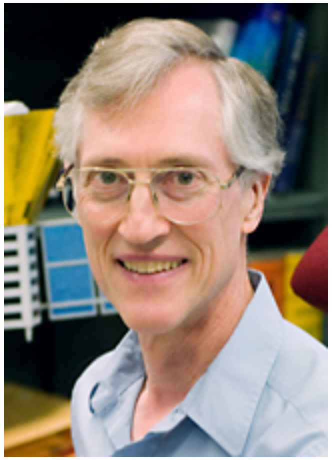


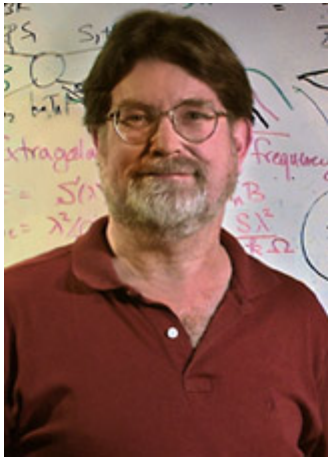
SMOOT ET AL.

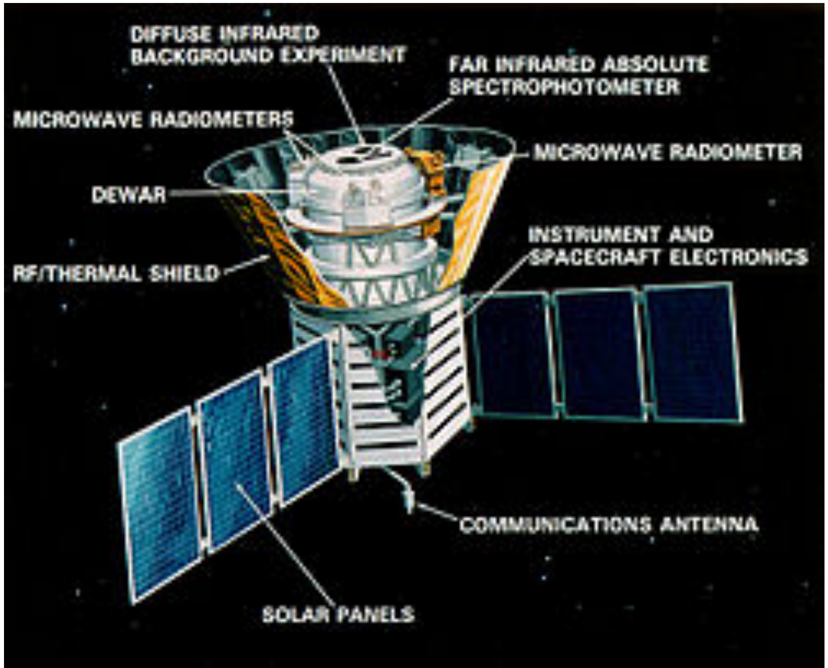


ノーベル賞(2006)：COBEの発見

- John Mather
  - 黒体放射を証明したFIRASのPI
  - COBE計画全体のPI
- George Smoot
  - 揺らぎを発見したDMRのPI







ApJ **395**: L59-L63, 1992 **August 20**

COBE
より前！

THE ASTROPHYSICAL JOURNAL, 395:L59–L63, 1992 August 20

SURVIVING COSMOLOGICAL MODELS AFTER THE DISCOVERY OF LARGE-ANGLE ANISOTROPIES OF THE COSMIC MICROWAVE BACKGROUND

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ABSTRACT

Using new and first detections of the rms temperature fluctuations at 10° and the quadrupole anisotropy on the cosmic microwave background radiation by the *COBE* group together with the upper limits on small-scale anisotropies, constraints on various cosmological models are obtained. Complete analysis of the quadrupole anisotropy for flat and open universe models has been done. We calculate not only the Sachs-Wolfe effect and the effect of time variation of the gravitational potential, but also the intrinsic fluctuations from the initial perturbations at the decoupling time which play an important role in many cosmological models, in particular, models with initially isocurvature perturbations. With the results of *COBE* and the upper limits on small-angle observations of temperature fluctuations, we found that CDMs with $h = 1.0$ and HDMs with $h = 0.5$ are surviving if we consider only models which are consistent with the inflationary scenario. On the other hand, provided that the density parameter Ω is very low, there is no model which is consistent with all scale observations of temperature fluctuations and observations of galaxy correlation functions.

Subject headings: cosmology: cosmic microwave background — dark matter

TABLE 1

CONSTRAINTS ON COSMOLOGICAL MODELS

Model	7:15	1°	Quadrupole	All
BDM adiabatic:				
$h = 1.0, n = 0$	No constraint	No constraint	$0.75 < \Omega < 0.82$	$0.75 < \Omega < 0.82$
$h = 1.0, n = 1$	$0.16 < \Omega < 0.86$	$0.10 < \Omega < 0.74$	$0.62 < \Omega < 0.90$	$0.62 < \Omega < 0.74$
$h = 1.0, n = 2$	No region	No region	$0.40 < \Omega$	No region
$h = 0.5, n = 0$	$0.17 < \Omega$	$0.22 < \Omega$	No region	No region
$h = 0.5, n = 1$	No region	No region	$0.65 < \Omega < 0.81$	No region
$n = 0.5, n = 2$	No region	No region	$0.40 < \Omega$	No region
BDM isocurvature:				
$h = 1.0, n = 0$	No constraint	No constrant	$0.75 < \Omega < 0.92$	$0.75 < \Omega < 0.92$
$h = 1.0, n = 1$	No constraint	No constraint	$0.55 < \Omega$	$0.55 < \Omega$
$h = 1.0, n = 2$	No region	No region	$0.30 < \Omega$	No region
$h = 0.5, n = 0$	No constraint	$0.13 < \Omega$	No region	No region
$h = 0.5, n = 1$	$0.10 < \Omega$	$0.27 < \Omega$	$0.26 < \Omega < 0.89$	$0.27 < \Omega < 0.89$
$h = 0.5, n = 2$	No region	No region	No constraint	No region
Peebles:				
$h = 1.0, n = 1$	No constraint	No constraint	$\Omega < 0.84$	$\Omega < 0.84$
$h = 1.0, n = 2$	No constraint	No region	No constraint	No region
$h = 1.0, n = 3$	No constraint	No region	$\Omega < 0.18$	No region
$h = 0.5, n = 1$	No constraint	No constraint	$\Omega < 0.74$	$\Omega < 0.74$
$h = 0.5, n = 2$	No constraint	No region	No constraint	No region
$h = 0.5, n = 3$	No constraint	No region	$\Omega < 0.49$	No region
CDM adiabatic:				
$h = 1.0, n = 0$	$0.13 < \Omega$	$0.13 < \Omega$	No region	No region
$h = 1.0, n = 1$	$0.63 < \Omega$	$\Omega \sim 1.0$	$0.62 < \Omega$	$\Omega \sim 1.0$
$h = 1.0, n = 2$	No region	No region	$0.53 < \Omega$	No region
$h = 0.5, n = 0$	No constraint	No constraint	No region	No region
$h = 0.5, n = 1$	$0.80 < \Omega$	No region	$0.64 < \Omega$	No region
$h = 0.5, n = 2$	No region	No region	$0.53 < \Omega$	No region
CDM isocurvature:				
$h = 1.0, n = 0$	No constraint	No constraint	$\Omega < 0.54$	$\Omega < 0.54$
$h = 1.0, n = 1$	No constraint	No constraint	No constraint	No constraint
$h = 1.0, n = 2$	$0.55 < \Omega$	No region	No constraint	No region
$h = 0.5, n = 0$	No constraint	No constraint	$\Omega < 0.55$	$\Omega < 0.55$
$h = 0.5, n = 1$	No constraint	$0.10 < \Omega$	No constraint	$0.10 < \Omega$
$h = 0.5, n = 2$	$0.40 < \Omega$	No region	No constraint	No region
HDM adiabatic:				
$h = 1.0, n = 0$	No constraint	No constraint	$0.40 < \Omega < 0.60$	$0.40 < \Omega < 0.60$
$h = 1.0, n = 1$	$0.65 < \Omega$	No region	No constraint	No region
$h = 1.0, n = 2$	No region	No region	$\Omega < 0.59$	No region
$h = 0.5, n = 0$	No constraint	No constraint	No region	No region
$h = 0.5, n = 1$	$0.78 < \Omega$	$0.72 < \Omega$	No constraint	$0.78 < \Omega$
$h = 0.5, n = 2$	No region	No region	$\Omega < 0.68$	No region

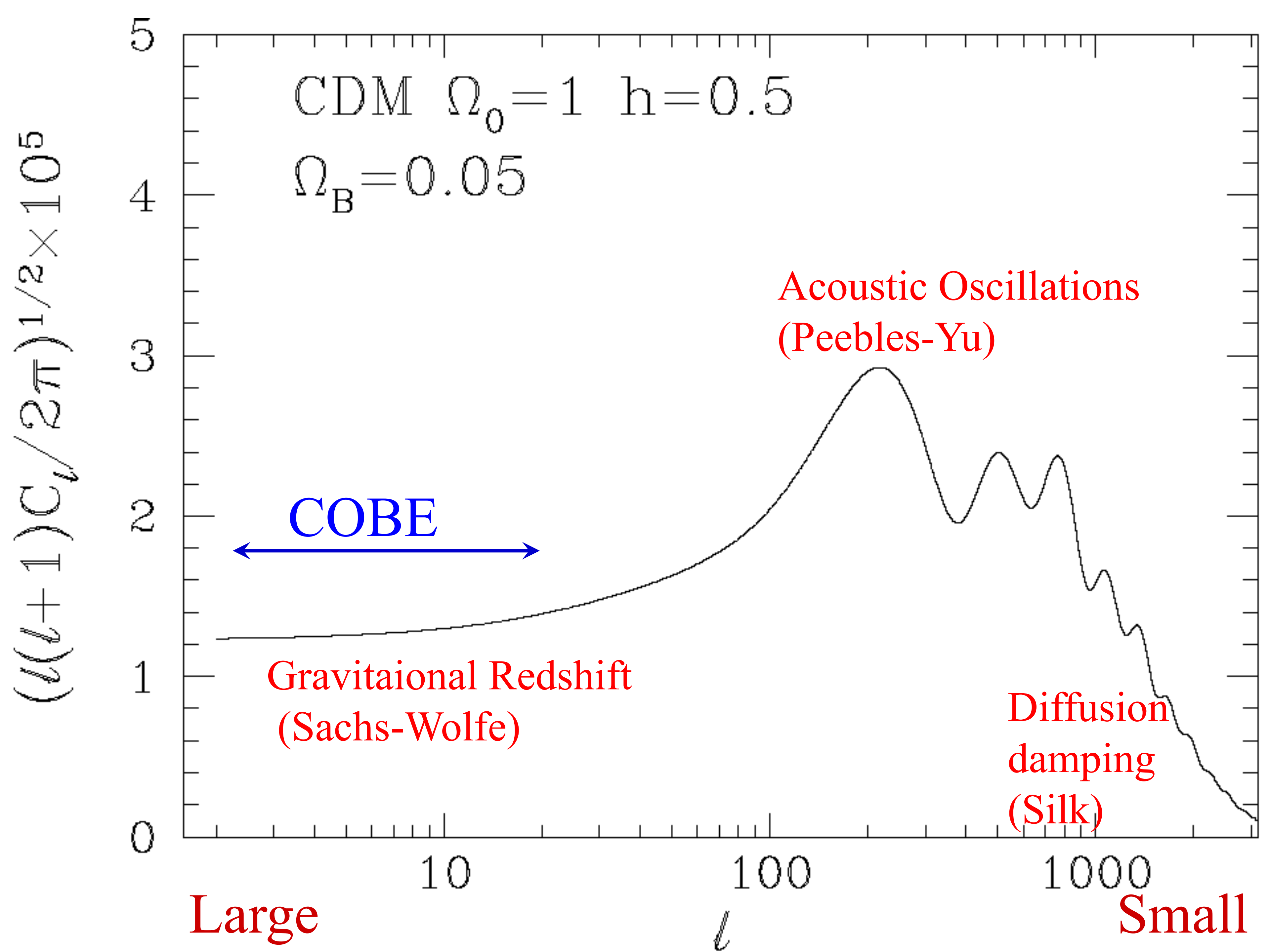
NOTE.—If there remains no allowed region on the density parameter, we indicate No region. If the model is not constrained, we indicate No constraint.

COBEを超えて

- COBE/DMRは大角度成分のみ測定（ピンボケ）
  - 物理的には、Sachs-Wolfe効果のみ
- 小スケールの揺らぎの測定の必要性、理論研究から明らかにされる
  - Peebles, YuのAcoustic Oscillation
  - Silkのdiffusion damping

↓

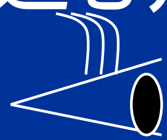
宇宙論パラメターの決定に使える

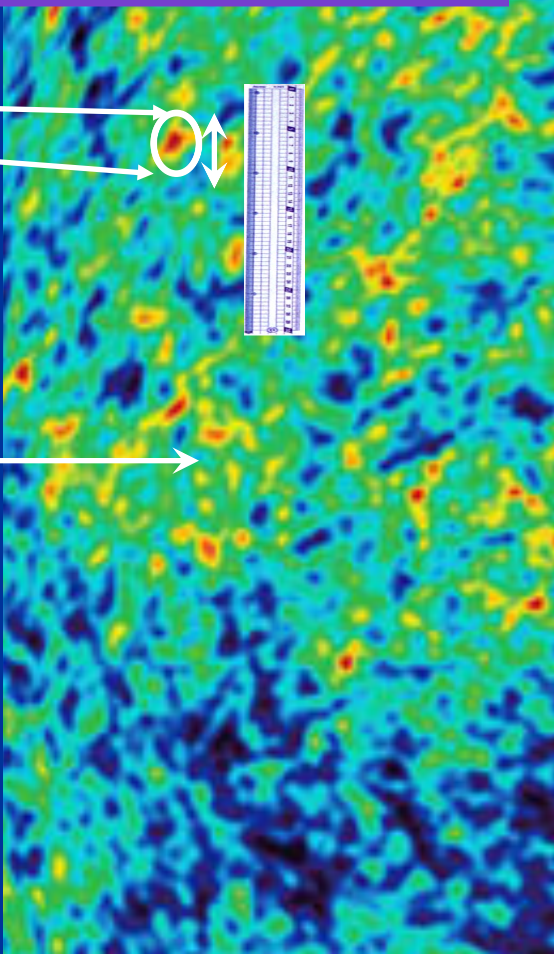

CDM Ω0=1 h=0.5
ΩB=0.05
Acoustic Oscillations
(Peebles-Yu)
COBE
Gravitaional Redshift
(Sachs-Wolfe)
Diffusion
damping
(Silk)
(ℓ(ℓ+1)Cℓ/2π)^1/2×10^5
0
1
2
3
4
5
10
100
1000
ℓ
Large
Small

温度揺らぎの典型的サイズは、物理過程によって決定される:
$\Omega_m h^2$（物質密度）
$\Omega_B h^2$（バリオン密度）

光の電波

見込む角度



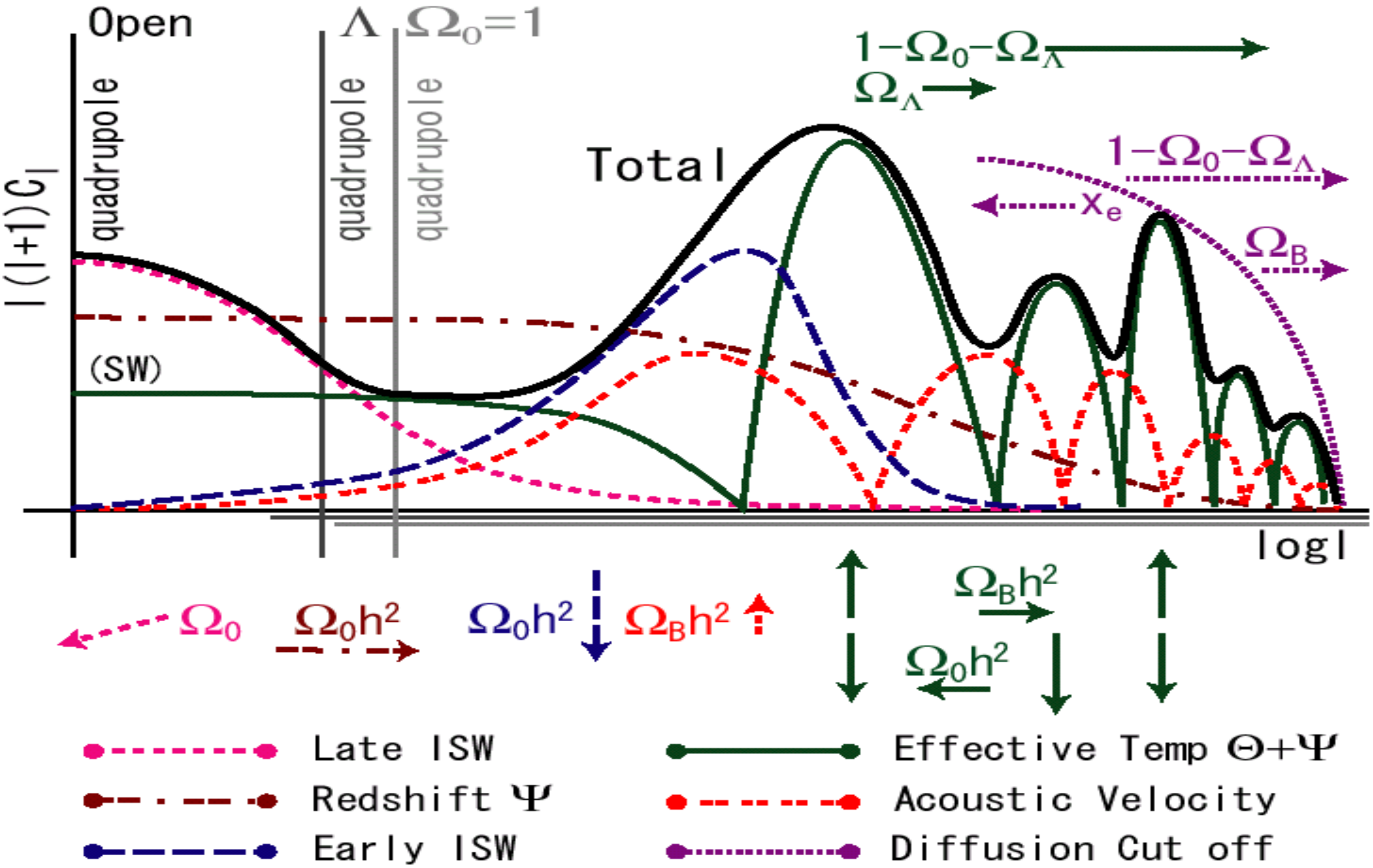


観測者

138億光年

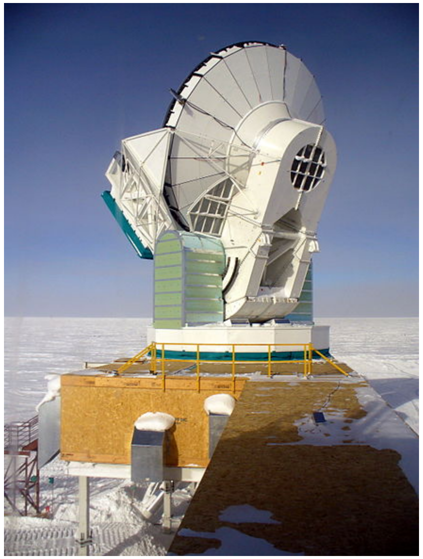
距離、見かけのサイズは曲率やハッブル定数に依存：
Ω_K, h

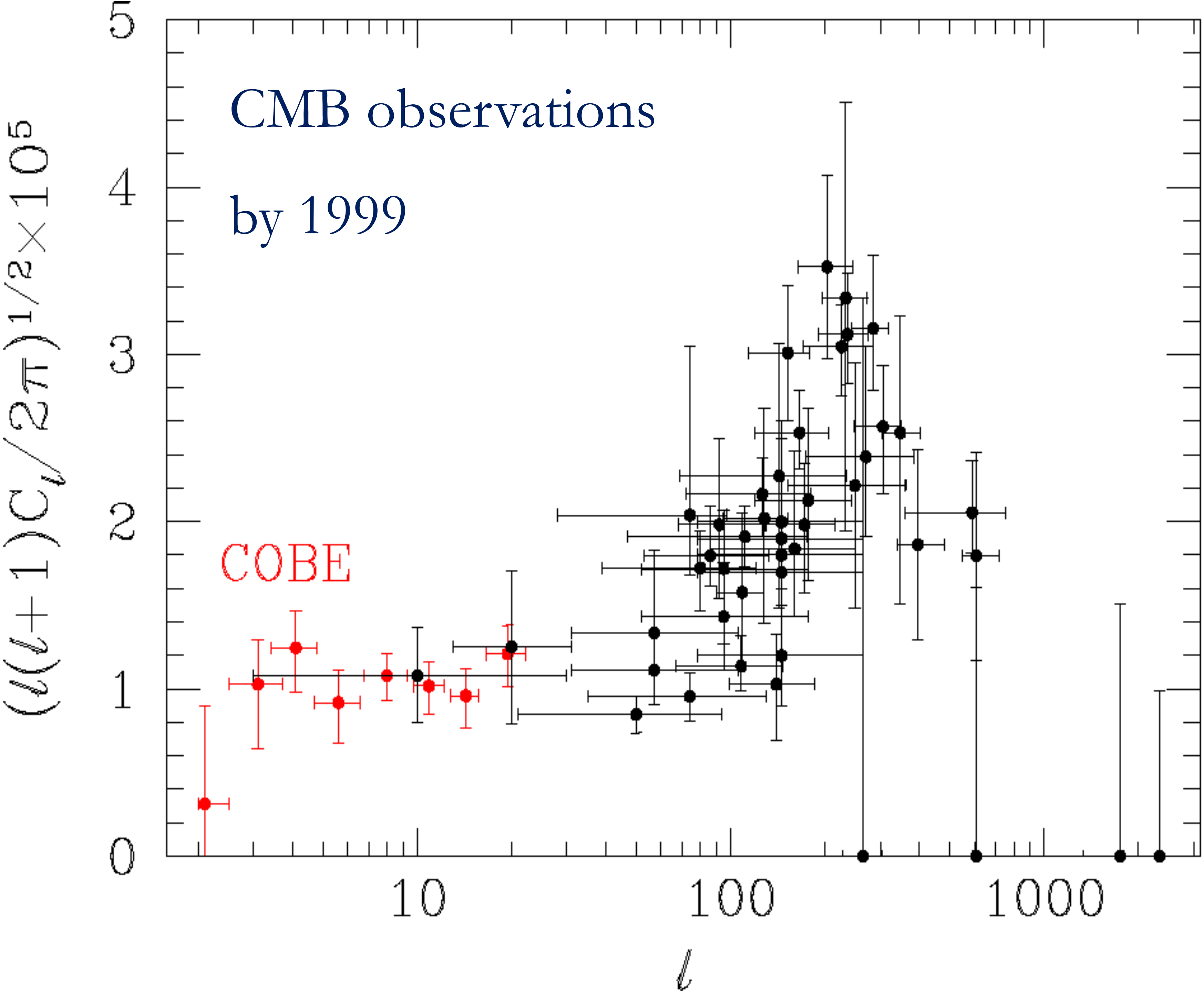
Hu, Sugiyama, Silk, Nature 1997



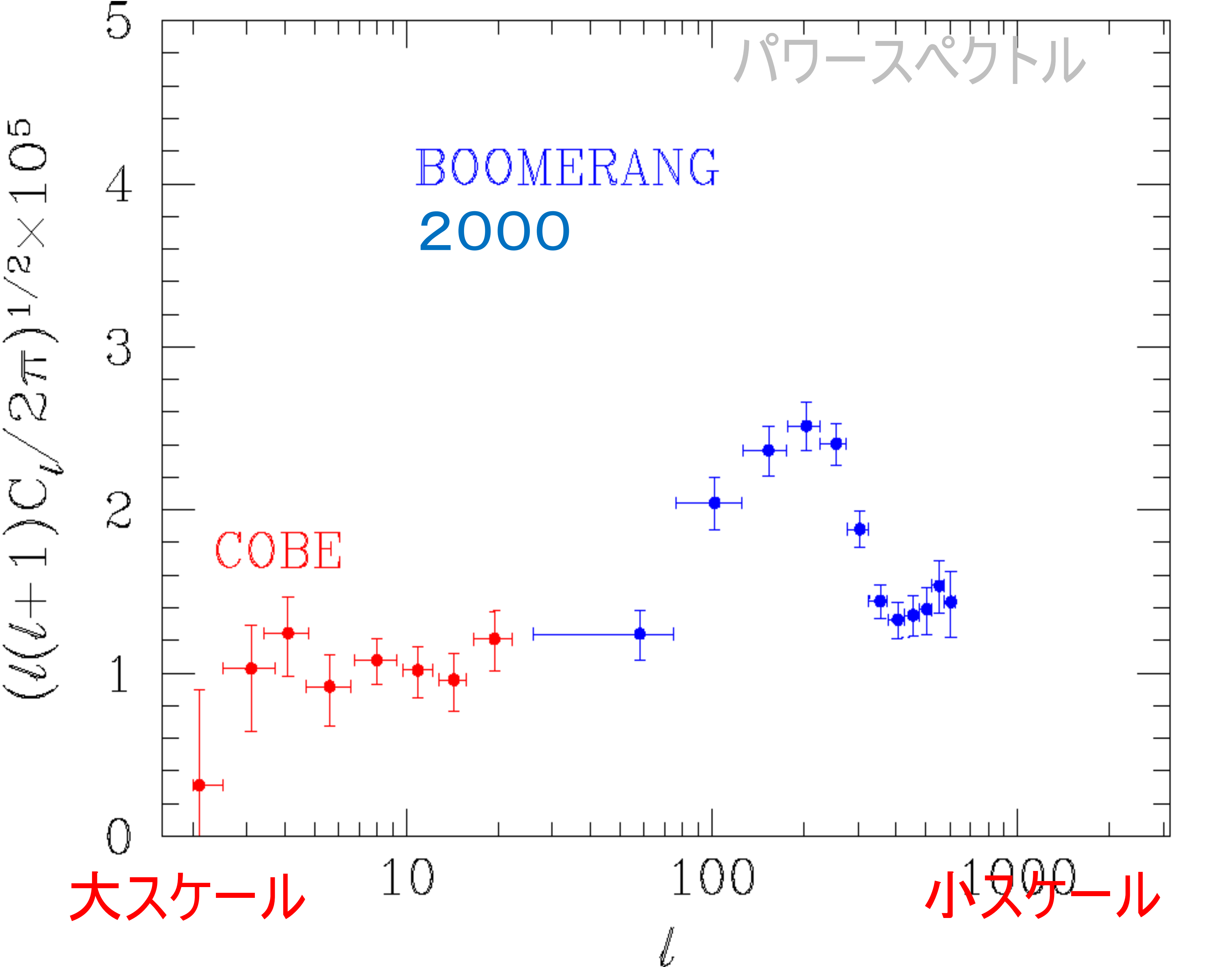
観測の爆発的進展

- COBE/DMRは大角度(l<20)
- 気球・地上（南極など）の観測進展
  - 2000年（BOOMERanG実験）までには最初のピーク@l~200の存在、ほぼ確実
  - その後も、南極、Atacamaなどで観測は続けられる

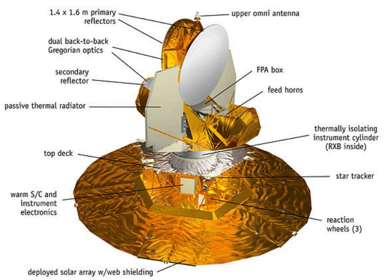



CMB observations
by 1999
COBE
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times10^5$
ℓ
0
1
2
3
4
5
10
100
1000



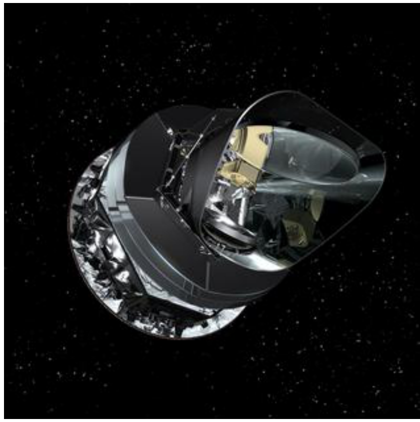
パワースペクトル
BOOMERANG
2000
COBE
$(\ell(\ell+1)C_\ell/2\pi)^{1/2}\times10^5$
0
1
2
3
4
5
10
100
1000
ℓ
大スケール
小スケール

２つの人工衛星プロジェクト



- WMAP衛星
  - アメリカ(NASA/Goddard, Princeton Uなど）のプロジェクト
  - 中規模の衛星で準備期間を少なくしてすぐに打ち上げた
  - CMBでも長波長側の５バンドで観測(22-90GHz)
  - 角度分解能は、3番目のピークぐらいまでをターゲット（l<1000)
  - 1996年にセレクション、2001年には打ち上げ

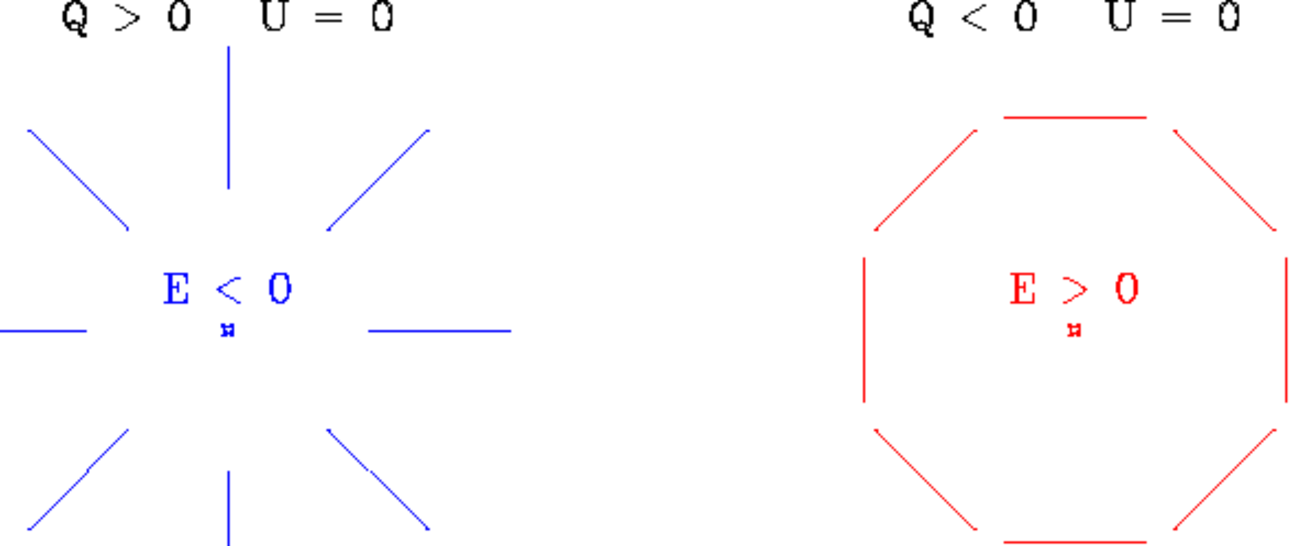
２つの人工衛星プロジェクト



- Planck衛星
  - ヨーロッパESAとNASA/JPLなどのプロジェクト
  - 大型の衛星で広い波長帯をカバー(９バンド、30-857GHz)
  - 角度分解能は、Silk Damping(l<2000)までをターゲット
  - イタリアとフランスのプロジェクトを合体させるなど紆余曲折して、2009年に打ち上げ

偏光

- 衛星の準備中に、偏光観測の重要性が指摘
  - 特に、Parity OddのB-modeに、宇宙初期のインフレーションの証拠となる重力波が潜んでいること明らかになる
  - 衛星計画は、いまさら偏光に強い装置に変更することは間に合わなかった

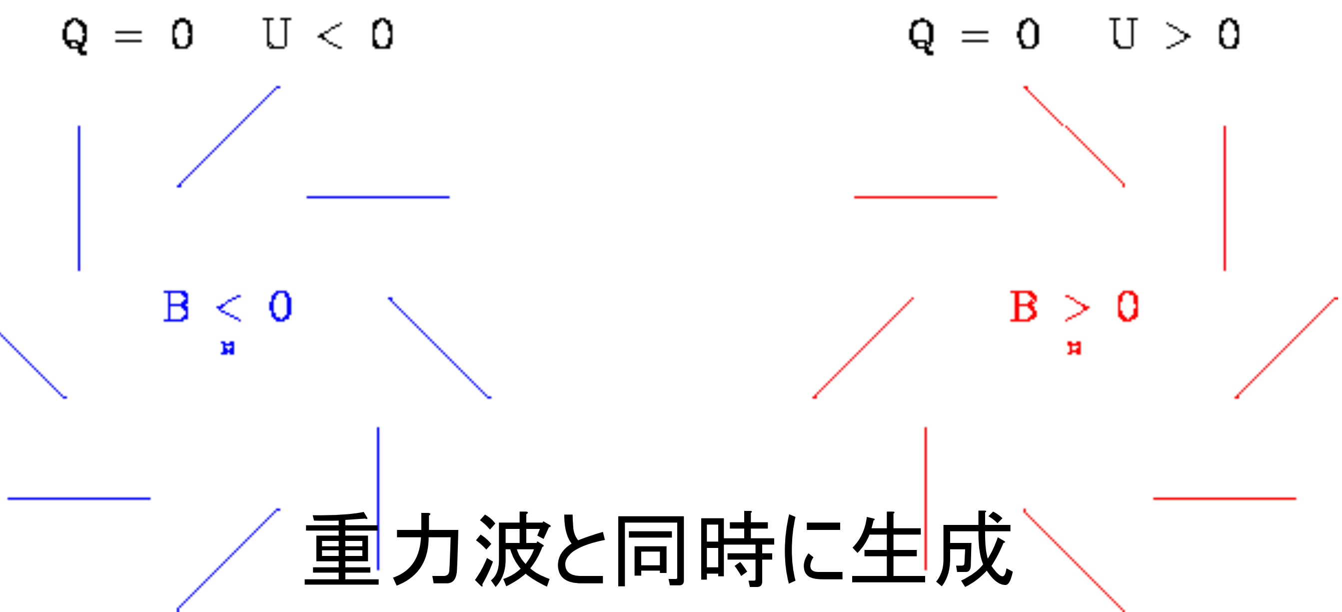


E-mode

温度揺らぎと同時に生成

2 independent

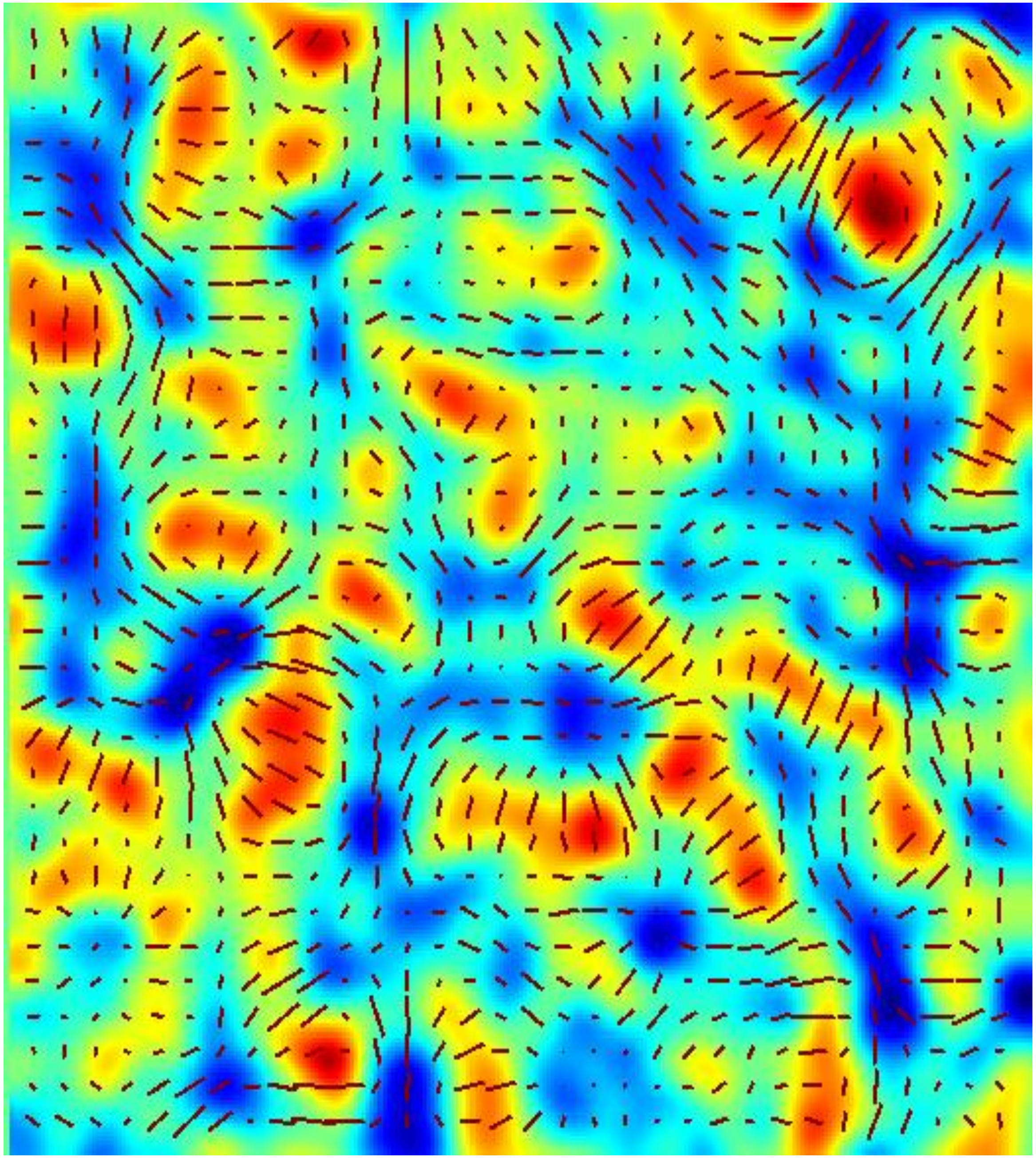
parity modes



B-mode

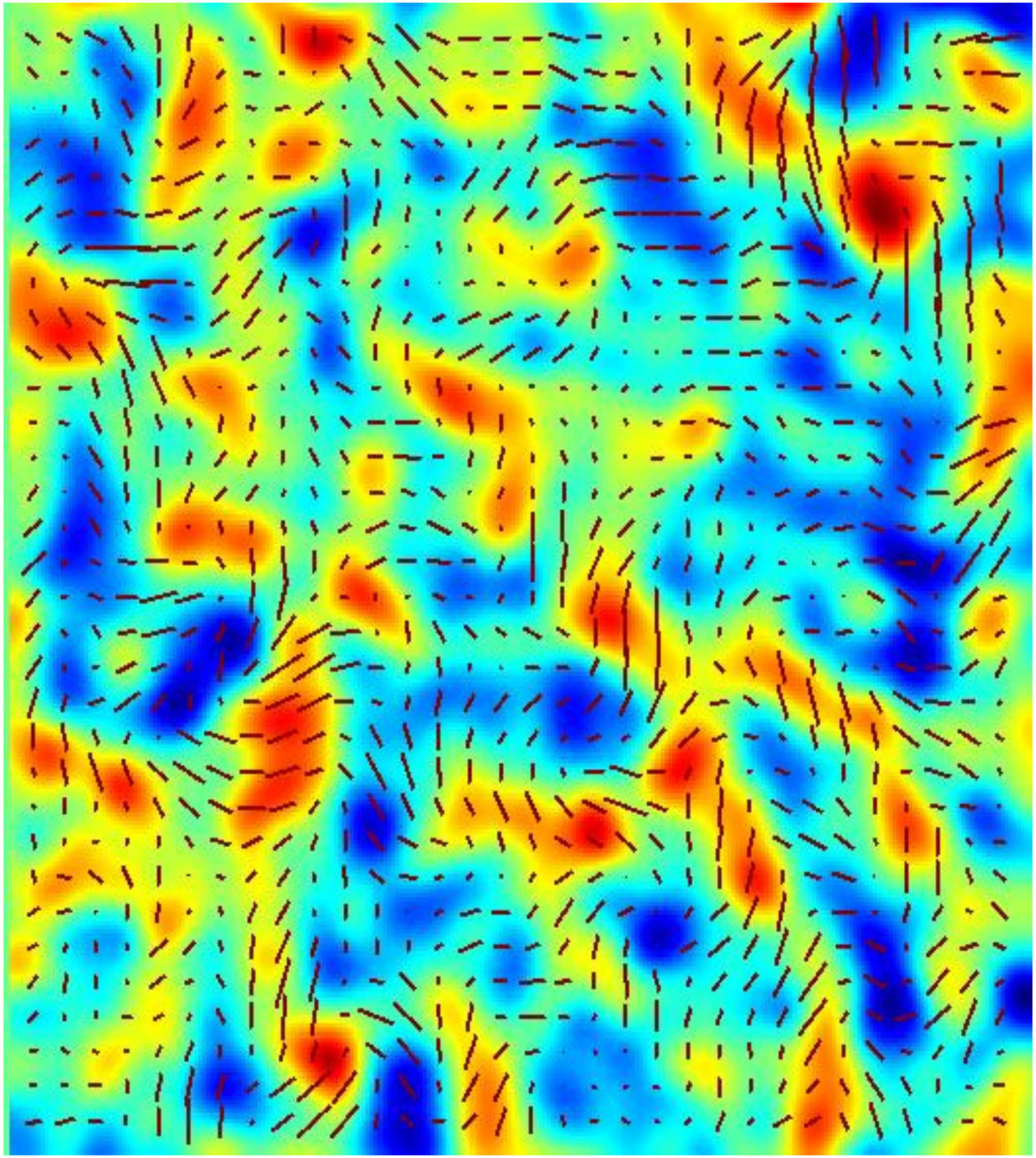
重力波と同時に生成

E-mode



Scalar Perturbations only produce E-mode

Seljak

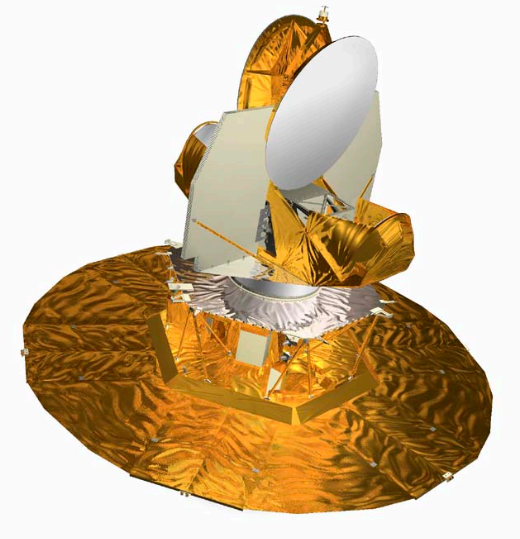


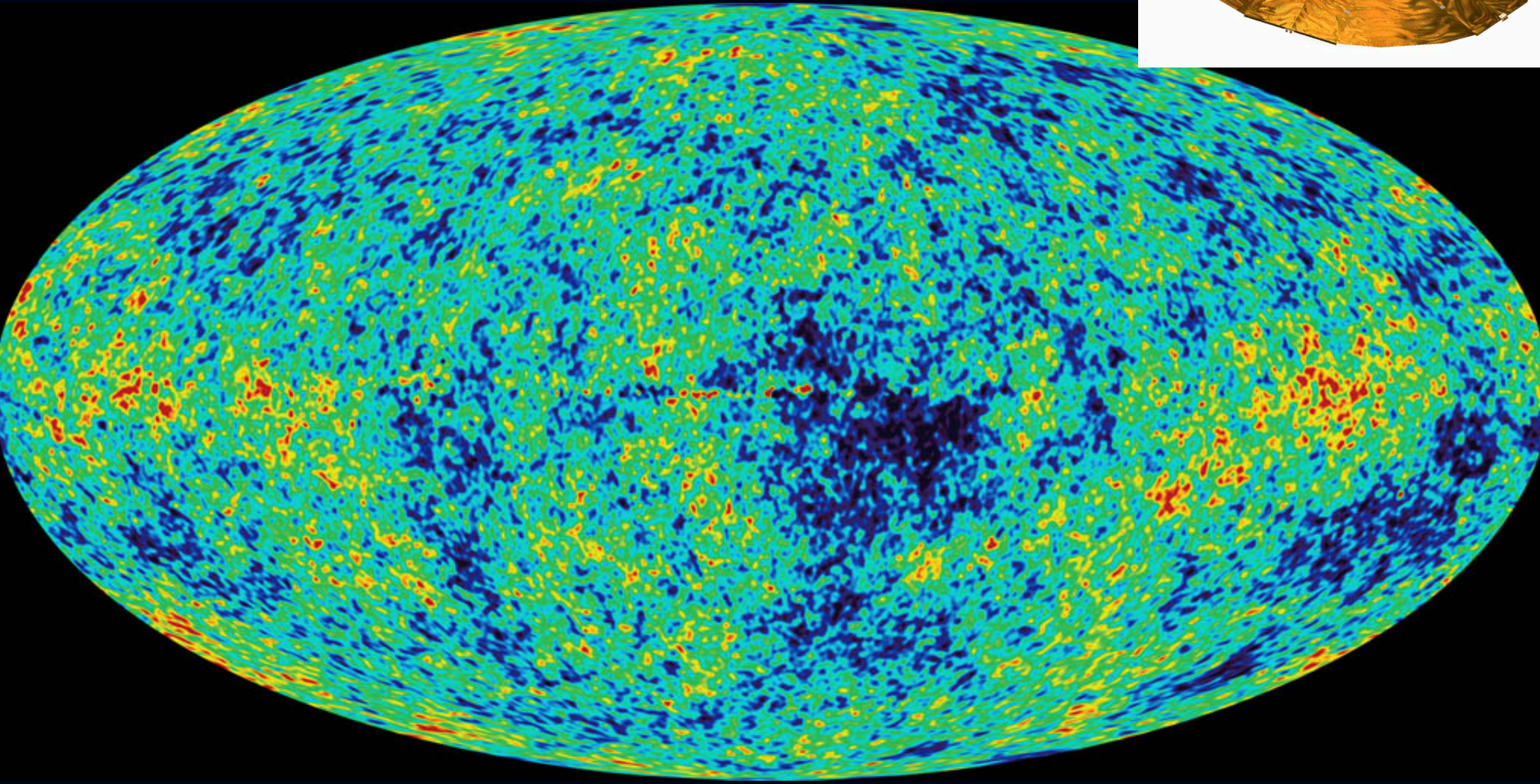
B-mode

Tensor perturbations produce both E- and B- modes

WMAP

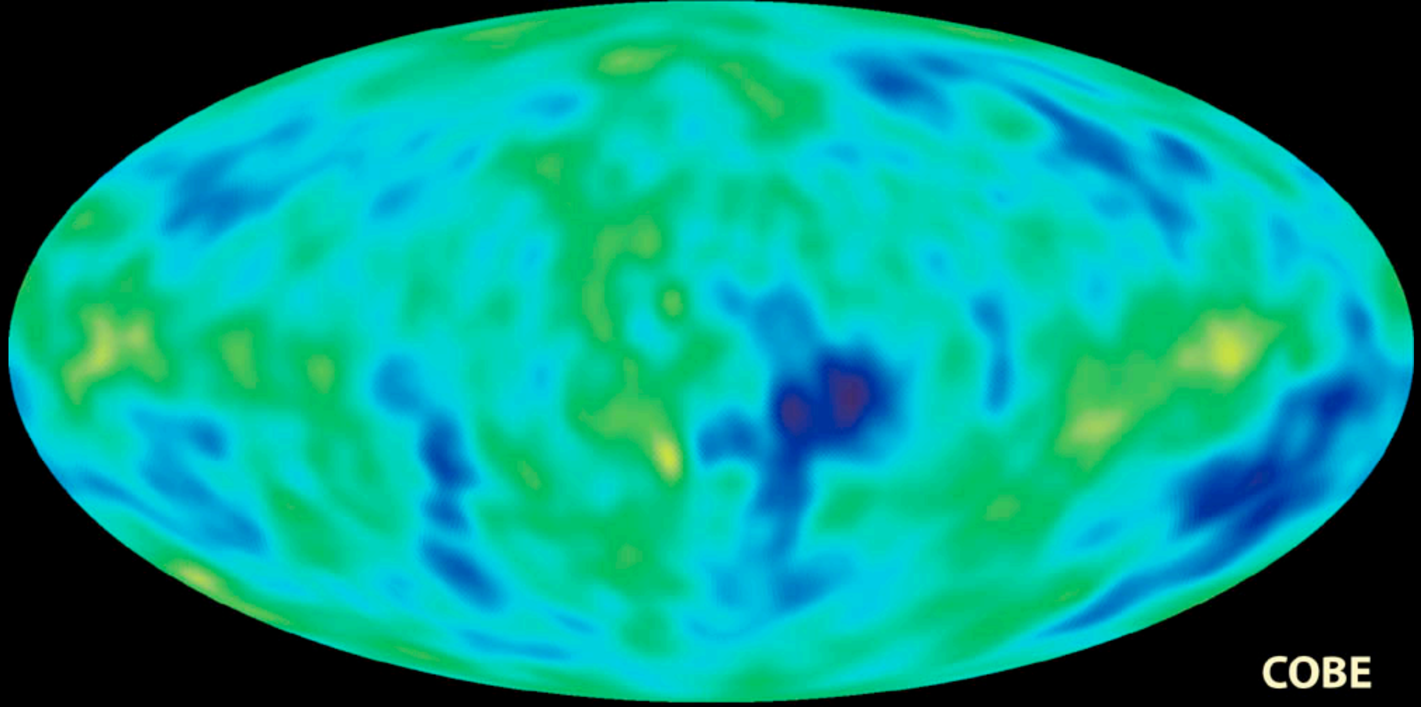
9年間の成果を発表し
使命を終えた



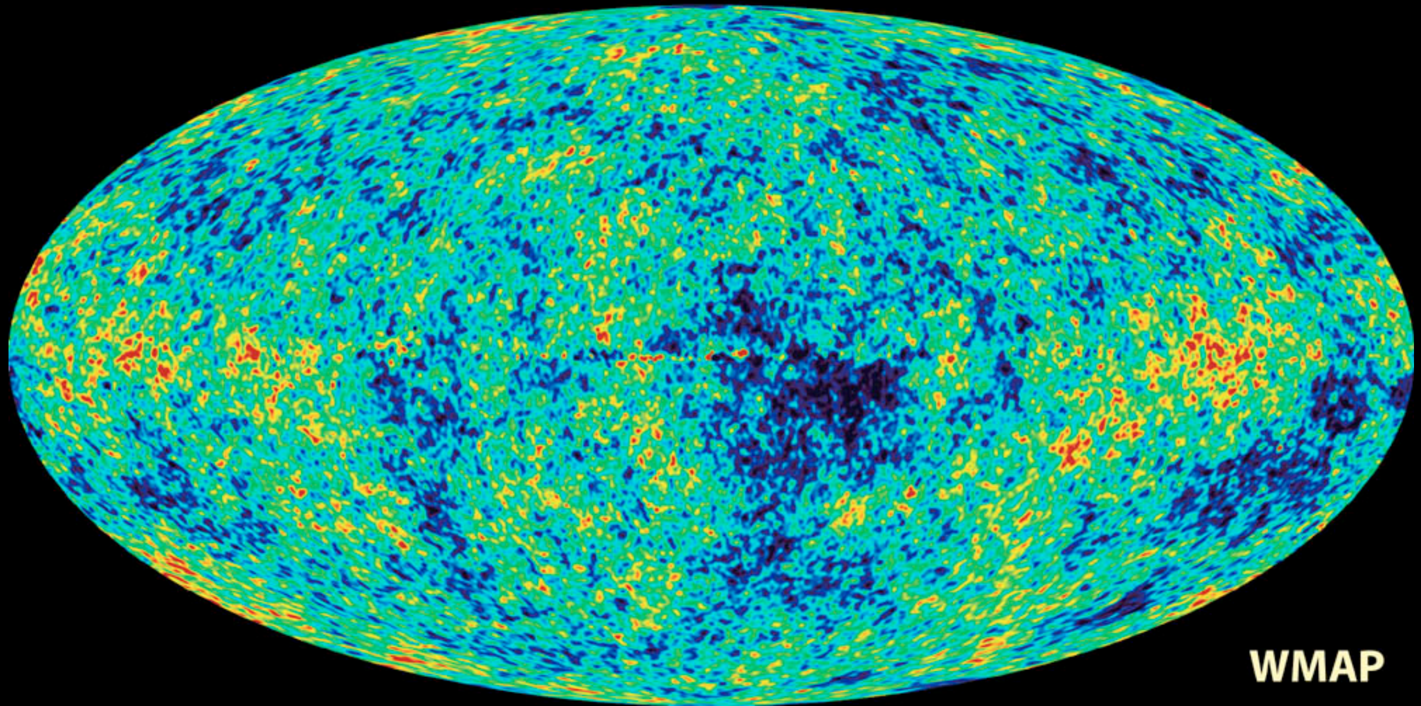


COBE &
WMAP

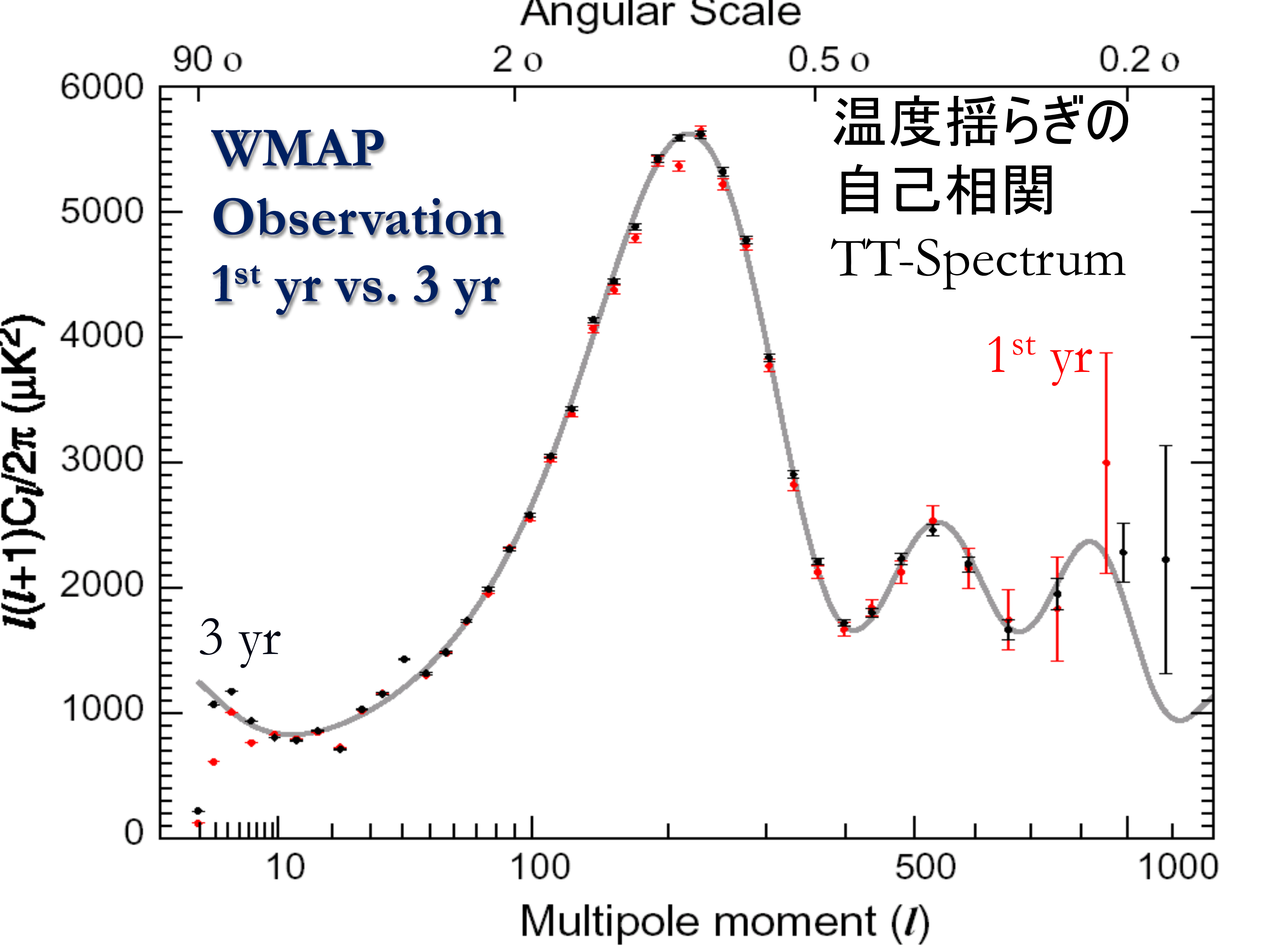
温度揺らぎ



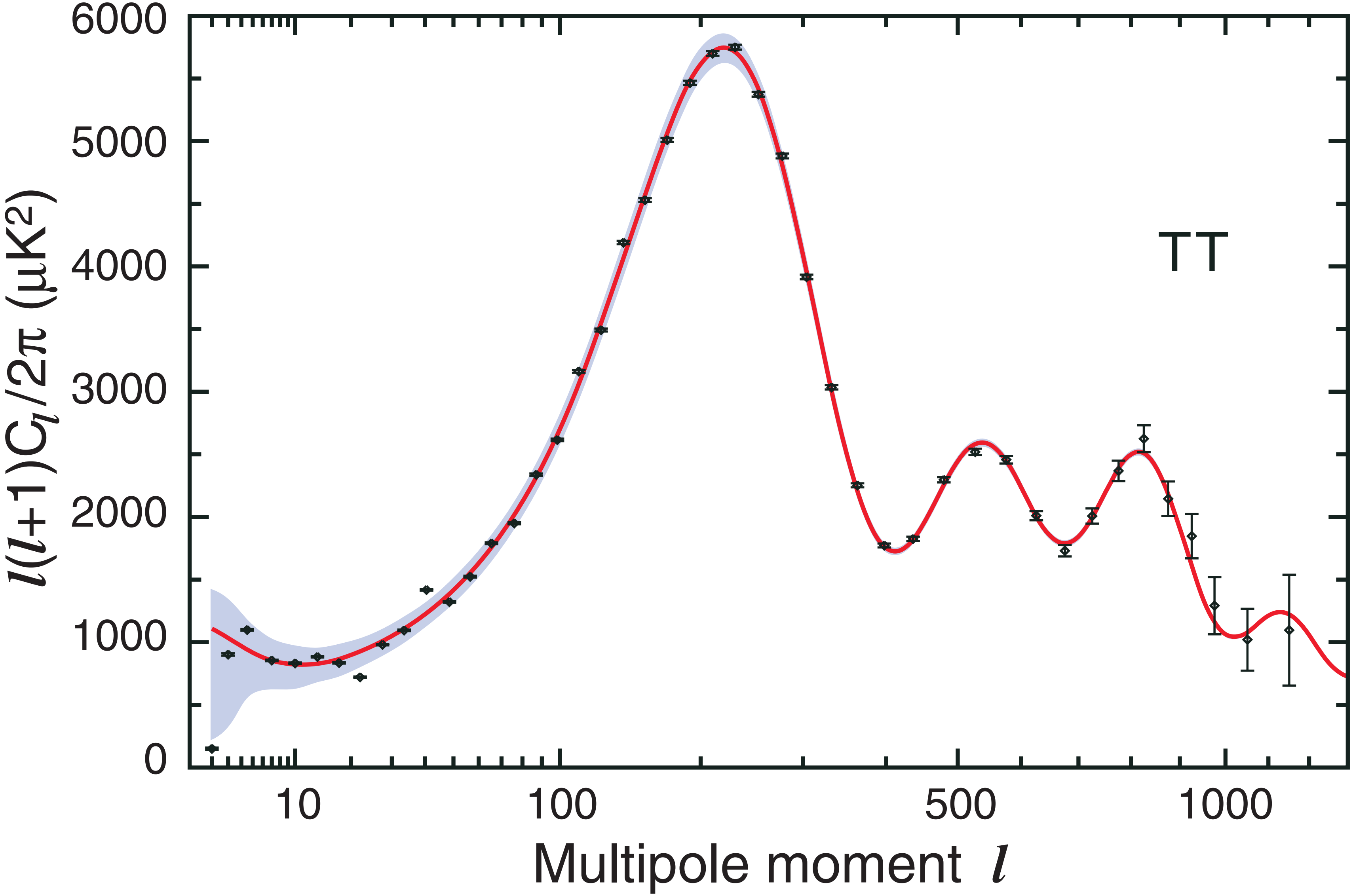
COBE



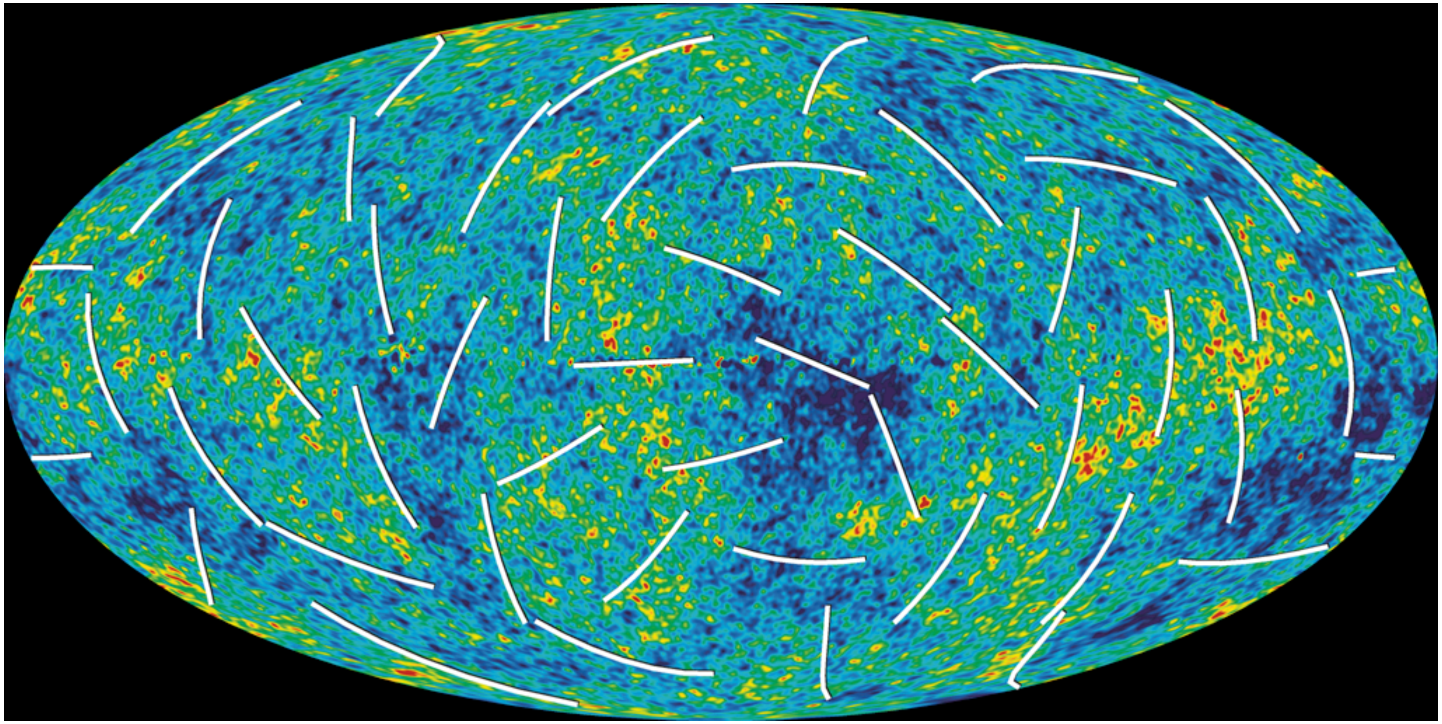
WMAP

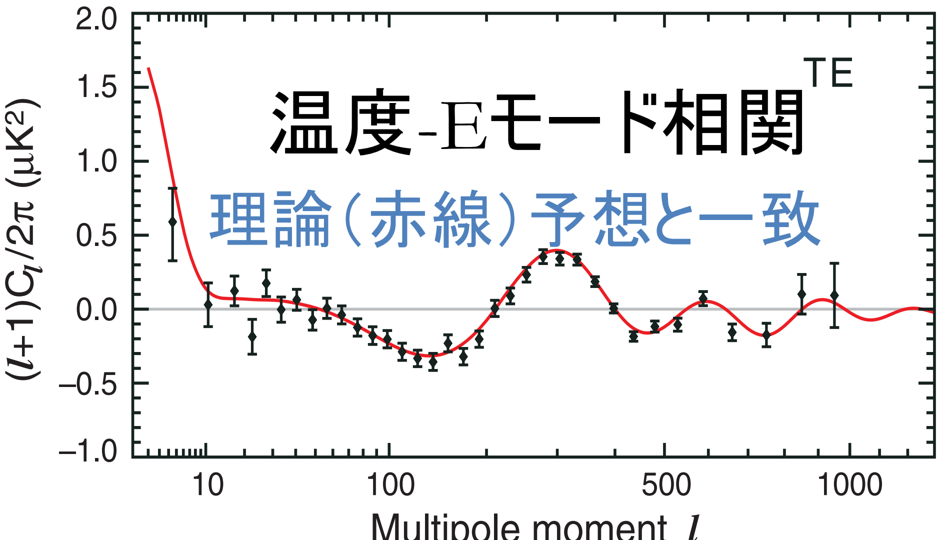


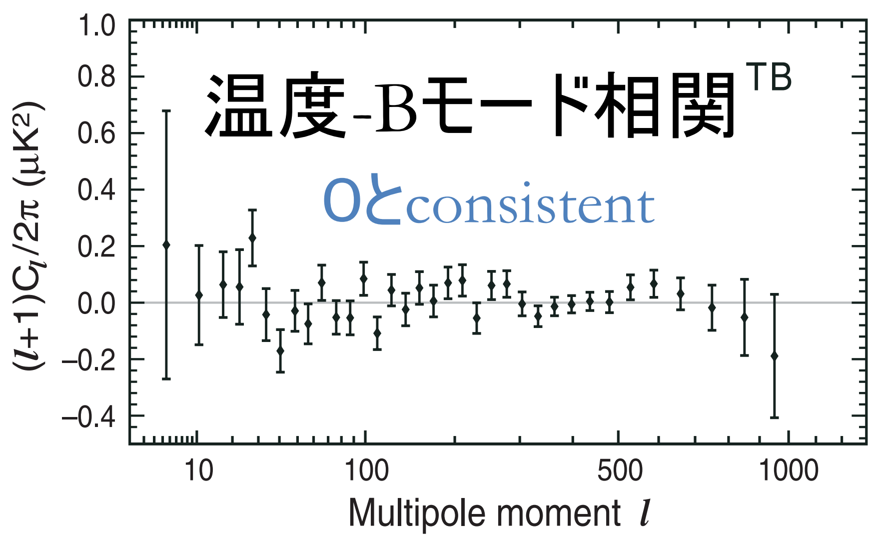
Angular Scale
90 o
2 o
0.5 o
0.2 o
WMAP
Observation
1st yr vs. 3 yr
温度揺らぎの
自己相関
TT-Spectrum
1st yr
3 yr
l(l+1)Cl/2π (μK2)
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
Multipole moment (l)



WMAP final result: 9年分







WMAP偏光

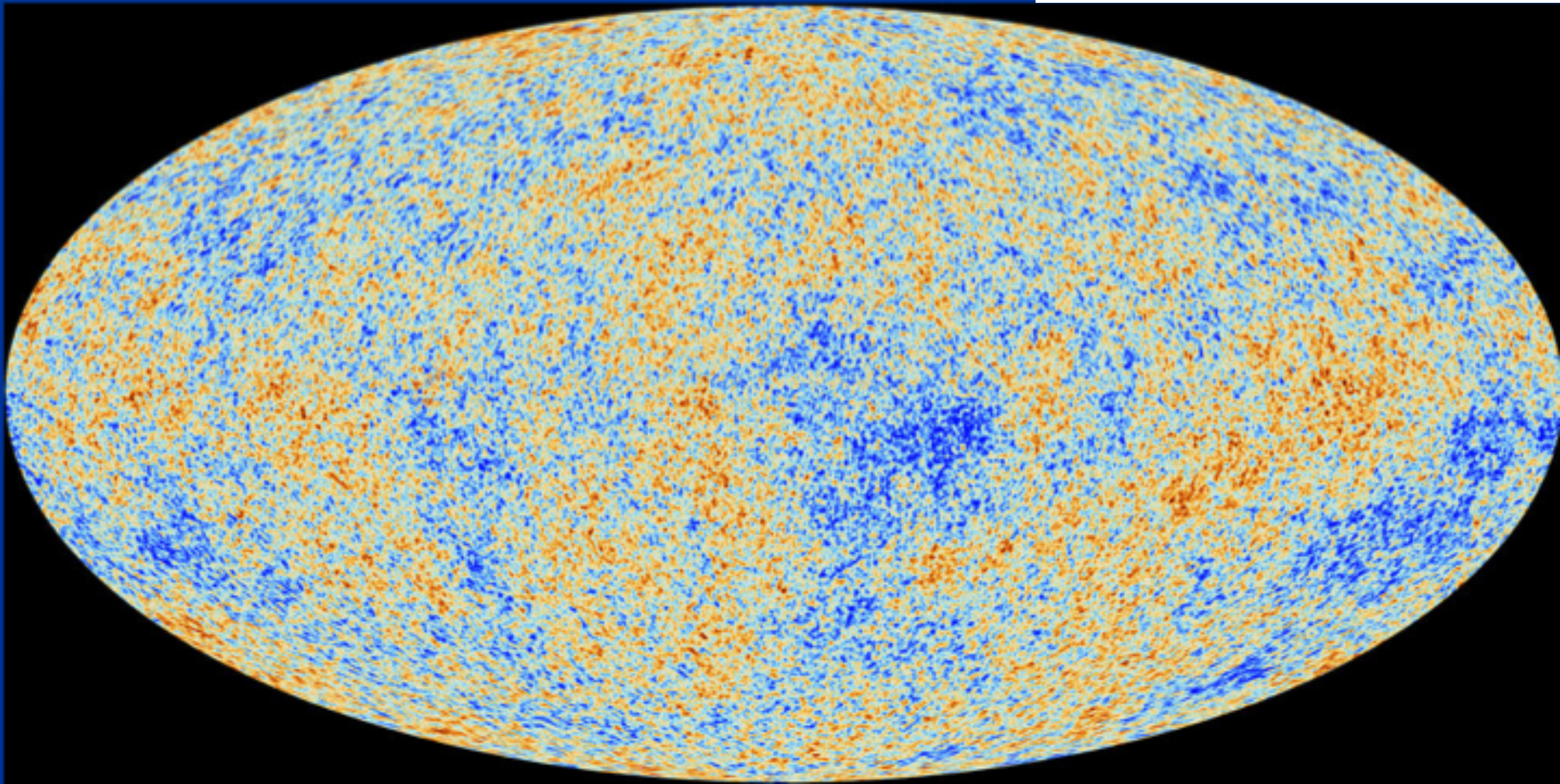
Bennett et al. 2013 ApJ Suppl

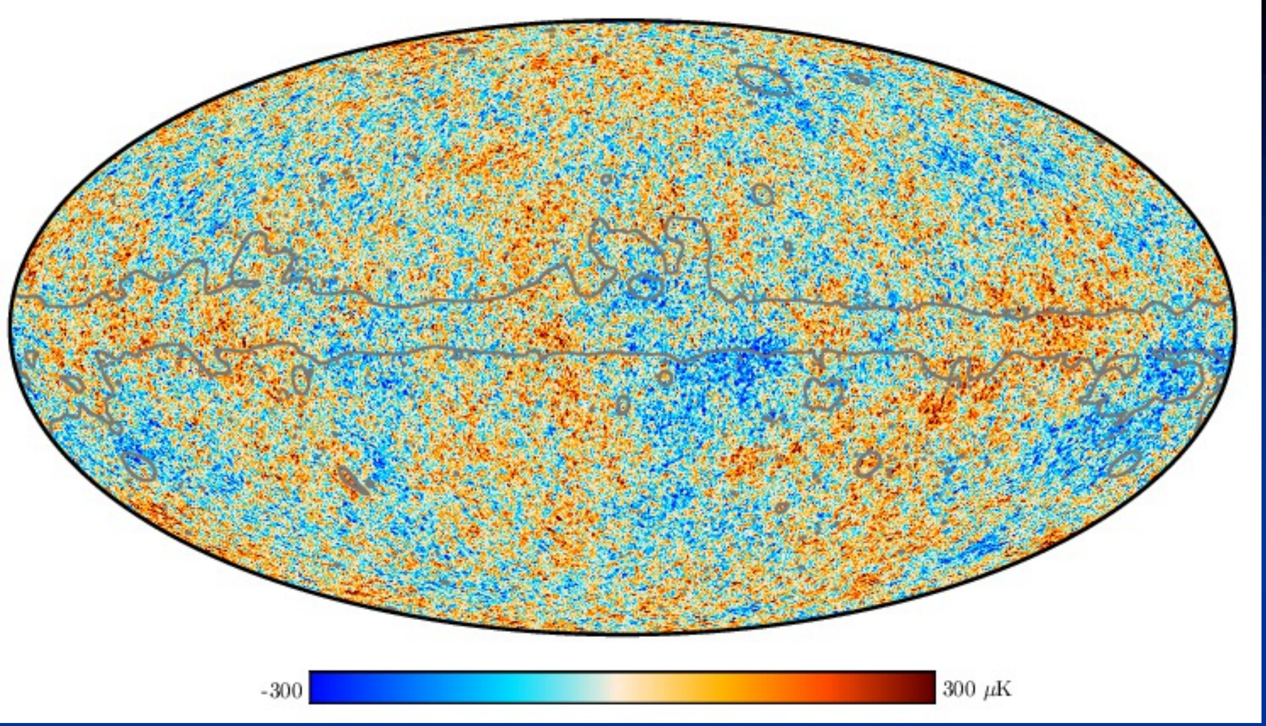
Bennett et al. 2013 ApJ Suppl

Table 17
Cosmological Parameter Summary

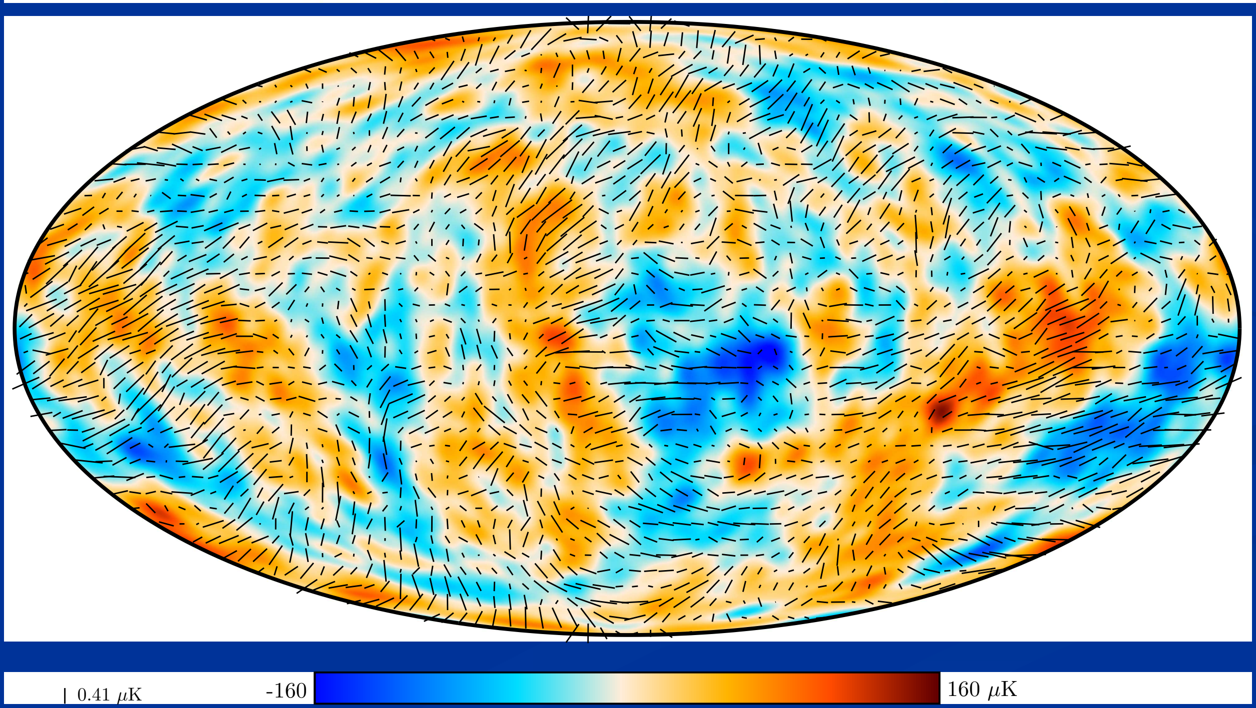
Parameter	Symbol	*WMAP*[a]	*WMAP*+eCMB+BAO+H_0[a,b]
Six-parameter ΛCDM fit parameters[c]			
Physical baryon density	$\Omega_b h^2$	0.02264 ± 0.00050	0.02223 ± 0.00033
Physical cold dark matter density	$\Omega_c h^2$	0.1138 ± 0.0045	0.1153 ± 0.0019
Dark energy density ($w = -1$)	Ω_Λ	0.721 ± 0.025	$0.7135^{+0.0095}_{-0.0096}$
Curvature perturbations ($k_0 = 0.002$ Mpc^{-1})[d]	$10^9 \Delta^2_{\mathcal{R}}$	2.41 ± 0.10	2.464 ± 0.072
Scalar spectral index	n_s	0.972 ± 0.013	0.9608 ± 0.0080
Reionization optical depth	τ	0.089 ± 0.014	0.081 ± 0.012
Amplitude of SZ power spectrum template	A_{SZ}	<2.0 (95% CL)	<1.0 (95% CL)
Six-parameter ΛCDM fit: derived parameters[e]			
Age of the universe (Gyr)	t_0	13.74 ± 0.11	13.772 ± 0.059
Hubble parameter, $H_0 = 100\,h$ (km s^{-1} Mpc^{-1})	H_0	70.0 ± 2.2	69.32 ± 0.80
Density fluctuations @ 8 h^{-1} (Mpc)	σ_8	0.821 ± 0.023	$0.820^{+0.013}_{-0.014}$
Velocity fluctuations @ 8 h^{-1} (Mpc)	$\sigma_8 \Omega_m^{0.5}$	0.434 ± 0.029	0.439 ± 0.012
Velocity fluctuations @ 8 h^{-1} (Mpc)	$\sigma_8 \Omega_m^{0.6}$	0.382 ± 0.029	0.387 ± 0.012
Baryon density/critical density	Ω_b	0.0463 ± 0.0024	0.04628 ± 0.00093
Cold dark matter density/critical density	Ω_c	0.233 ± 0.023	$0.2402^{+0.0088}_{-0.0087}$
Matter density/critical density ($\Omega_c + \Omega_b$)	Ω_m	0.279 ± 0.025	$0.2865^{+0.0096}_{-0.0095}$
Physical matter density	$\Omega_m h^2$	0.1364 ± 0.0044	0.1376 ± 0.0020
Current baryon density (cm^{-3})[f]	n_b	$(2.542 \pm 0.056) \times 10^{-7}$	$(2.497 \pm 0.037) \times 10^{-7}$
Current photon density (cm^{-3})[g]	n_γ	410.72 ± 0.26	410.72 ± 0.26
Baryon/photon ratio	η	$(6.19 \pm 0.14) \times 10^{-10}$	$(6.079 \pm 0.090) \times 10^{-10}$
Redshift of matter-radiation equality	z_{eq}	3265^{+106}_{-105}	3293 ± 47
Angular diameter distance to z_{eq} (Mpc)	$d_A(z_{eq})$	14194 ± 117	14173^{+66}_{-65}
Horizon scale at z_{eq} (h/Mpc)	k_{eq}	0.00996 ± 0.00032	0.01004 ± 0.00014
Angular horizon scale at z_{eq}	l_{eq}	139.7 ± 3.5	140.7 ± 1.4
Epoch of photon decoupling	z_*	$1090.97^{+0.85}$	1091.64 ± 0.47

Planck衛星の成果、
2013年3月に最初の発表
2018 resultsが最新・最終

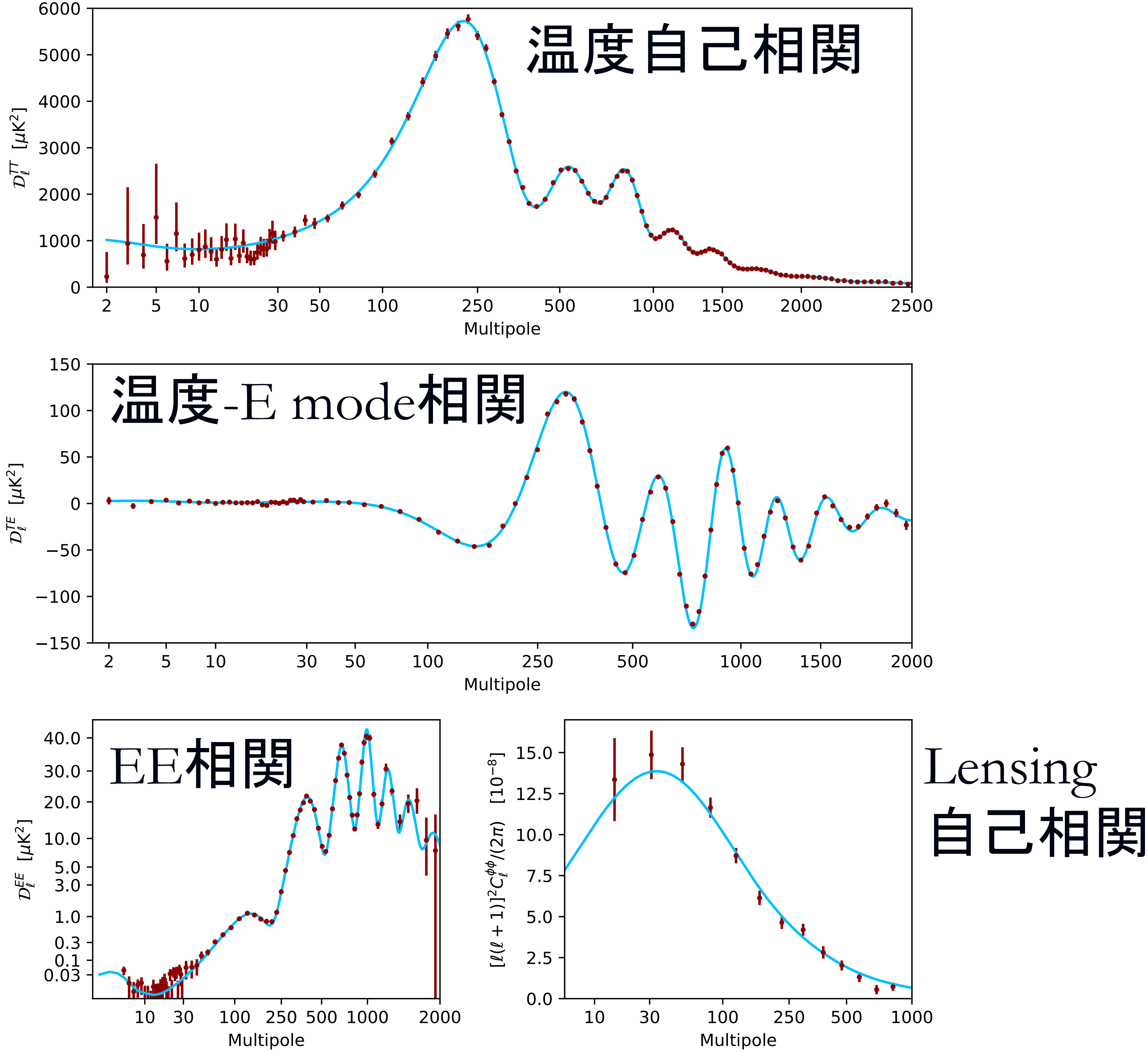




Planck
温度分布



偏光

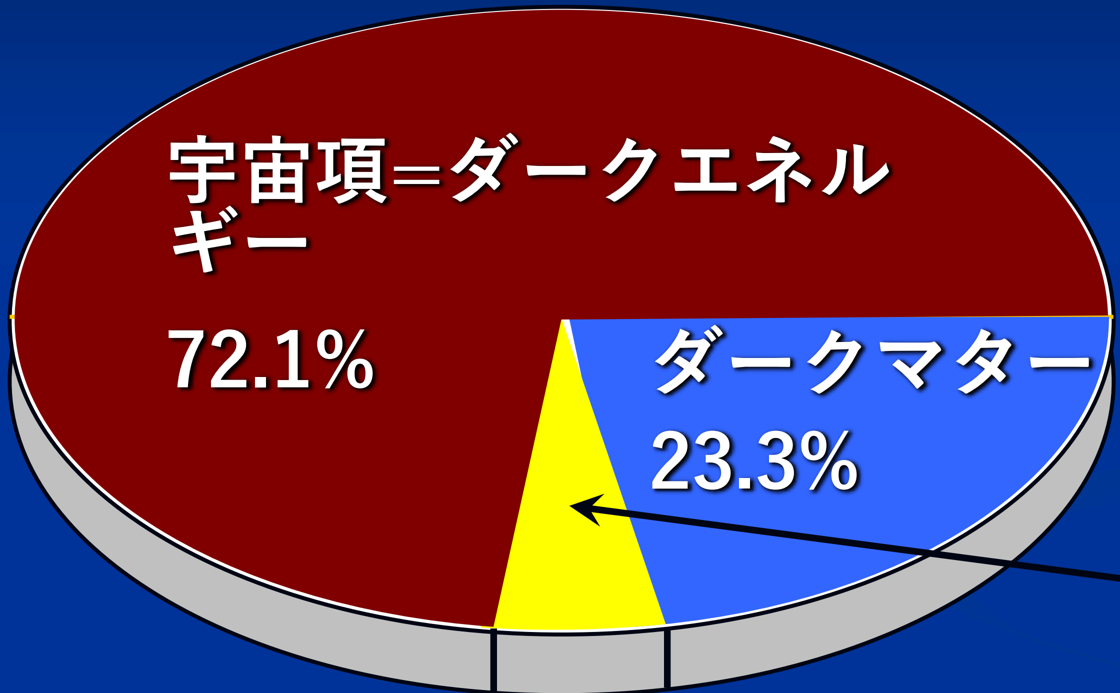

温度自己相関
$\mathcal{D}_\ell^{TT}$ [μK^2]
Multipole
温度-E mode相関
$\mathcal{D}_\ell^{TE}$ [μK^2]
Multipole
EE相関
$\mathcal{D}_\ell^{EE}$ [μK^2]
Multipole
$[\ell(\ell+1)]^2 C_\ell^{\phi\phi}/(2\pi)$ [10^{-8}]
Multipole
Lensing
自己相関

Planck Collaboration, 2019

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

明らかになった宇宙の姿

137億歳

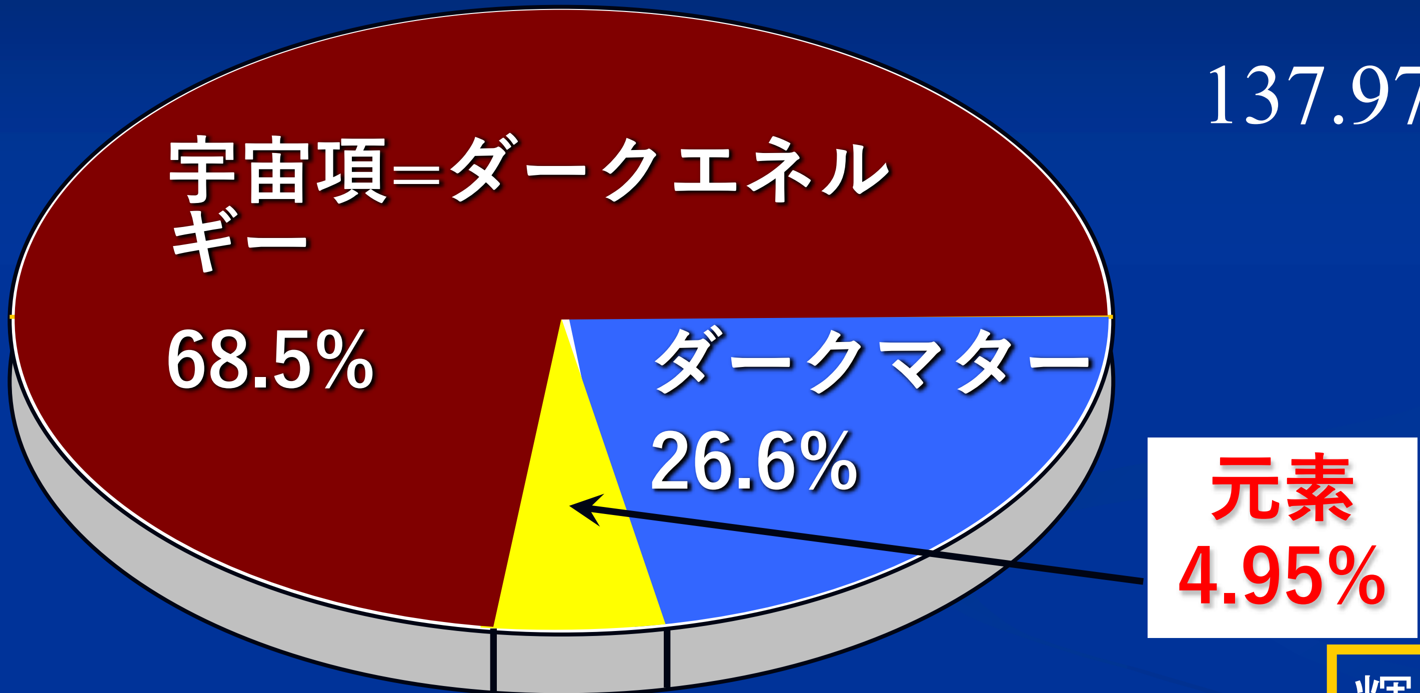


輝いているのはわずか1%

ダークエネルギー、ダークマターに支配される宇宙

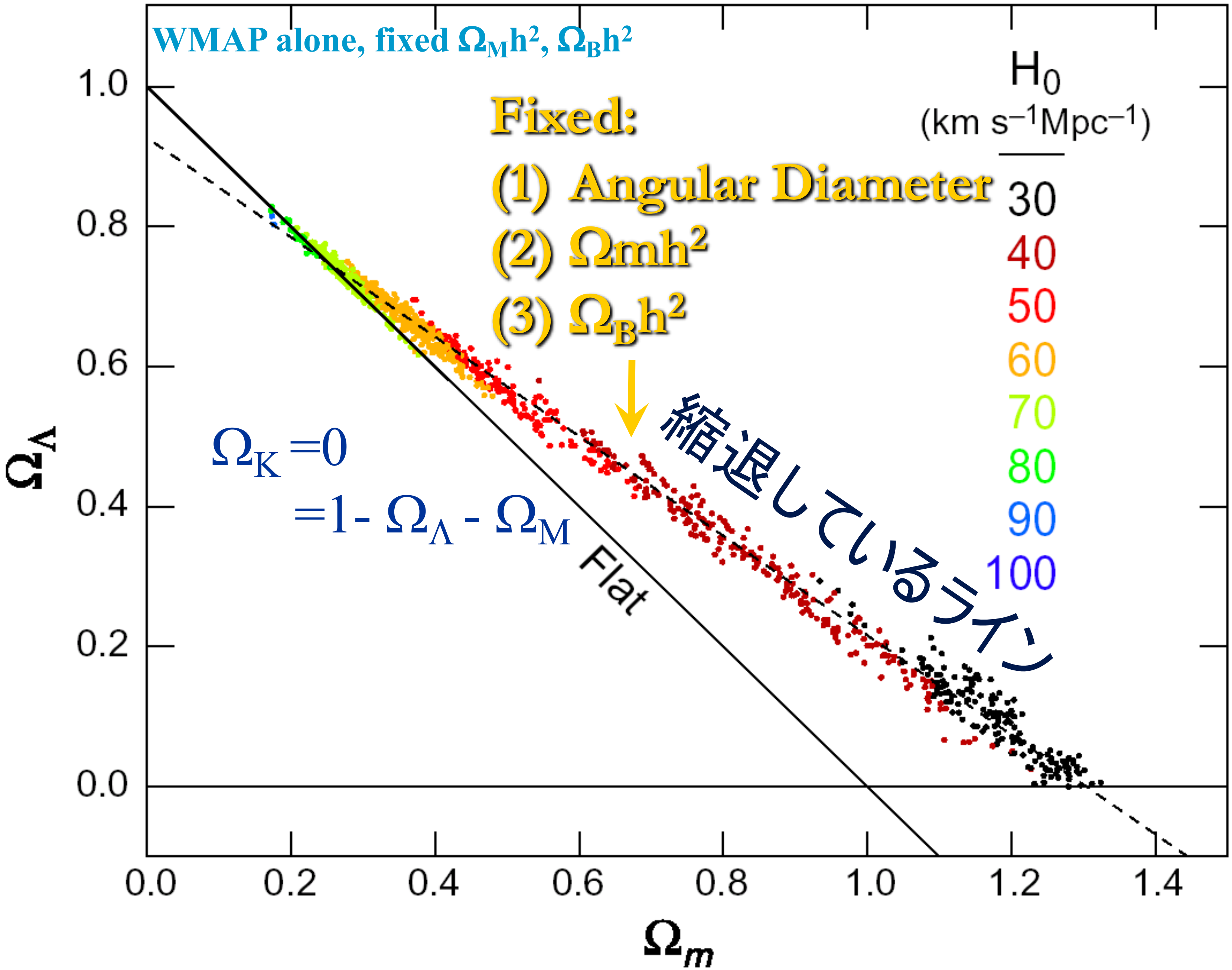
PLANCKでは？

137.97億歳



ダークエネルギー、ダークマターに支配される宇宙

輝いているのはわずか1%

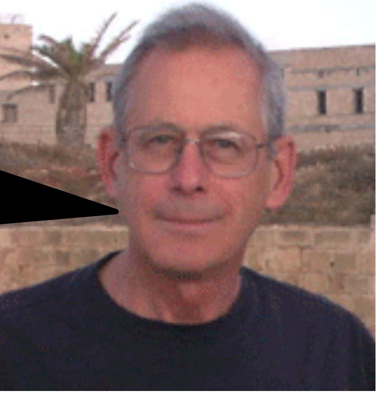


WMAP alone, fixed $\Omega_M h^2$, $\Omega_B h^2$
Fixed:
(1) Angular Diameter
(2) $\Omega m h^2$
(3) $\Omega_B h^2$
H_0
(km s^{-1}Mpc^{-1})
30
40
50
60
70
80
90
100
縮退しているライン
$\Omega_K = 0$
$= 1 - \Omega_\Lambda - \Omega_M$
Flat
Ω_Λ
Ω_m
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

精密宇宙論

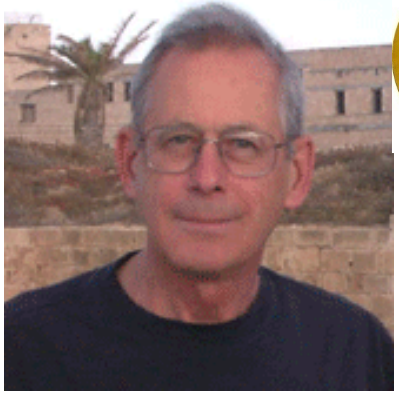
- Likelihoodをデータに適用すれば、どこまでも精密な結果得られる。

精密（precision）と正確(accurate)は別
目指すべきはAccurate Cosmology



Jim Peebles

まとめと今後



- CMBの物理
  - Peeblesの1965-1970の仕事でほぼ理解された
  - 業績を積分すればノーベル賞は当然：おめでとうございます
- 精密宇宙論はどこまでも進められる
  - CMBは全天で精密に計測
  - 現在は、大規模構造の詳細なデータも続々と登場
  - その桁に何の意味があるのか、accurate cosmologyになっているのか、常に注意が必要
- CMBの残されたフロンティア
  - B mode偏光 (羽澄さんの講演)