2. 宇宙論研究の歴史年表

- 1916年～　一般相対論的宇宙モデル
- 1929年　　宇宙膨張の発見（ハッブル）
- 1946年～　ビッグバンモデルの提唱（ガモフ）
- 1965年　　CMBの発見（ペンジアス、ウィルソン）
- 1980年～　宇宙の大構造の発見
  素粒子論的宇宙論の誕生
  宇宙論的数値シミュレーション
- 1992年　　CMB温度ゆらぎの検出（COBE）
- 1990年代後半～　宇宙論パラメータの精密決定
  平坦な宇宙、暗黒物質、宇宙定数（暗黒エネルギー）

一般相対論的宇宙論モデルの歴史

- 1916年：一般相対論
- 1917年：アインシュタインの静的宇宙モデル
- 1980年代以降：真空のエネルギー密度

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

宇宙定数
（時空の幾何学量）

移項

物質場
（真空のエネルギー密度？）

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G \left(T_{\mu\nu} - \frac{\Lambda}{8\pi G} g_{\mu\nu} \right)$$

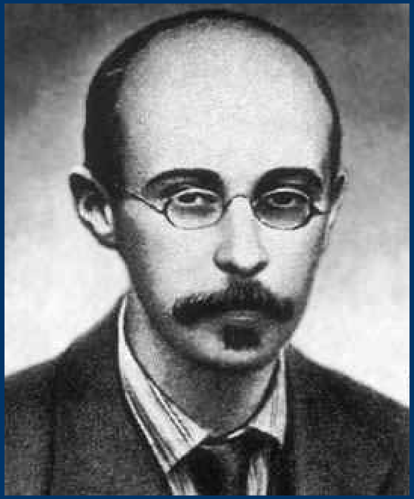
- 宇宙定数の自然な大きさはプランク密度

$$\Lambda = \frac{c^5}{\hbar G} \approx 5.2 \times 10^{93} \mathrm{g/cm^3} \quad \Leftrightarrow \quad \Omega_\Lambda \equiv \frac{\Lambda}{3H_0^2} \approx 10^{121}$$

- 観測的制限：　$\Omega_\Lambda \approx 0.7$

物理学史上最大の理論と観測の不一致！

フリードマン方程式



Alexander Friedmann
(1888-1925)

Albert Einstein
(1879-1955)

Georges Édouard Lemaître
(1894-1966)

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

（アインシュタイン方程式）

フリードマン方程式

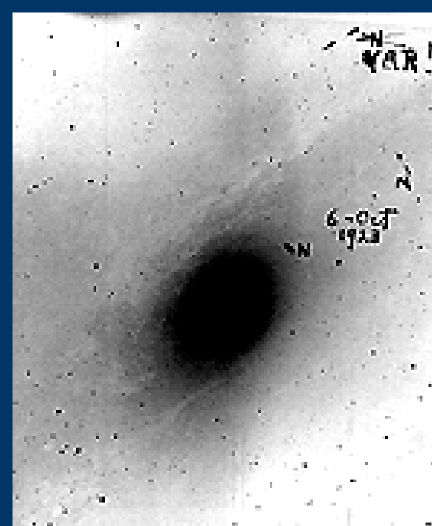
$$H^2(t) = \left(\frac{\dot{a}(t)}{a(t)} \right)^2 = \frac{8\pi G}{3} \rho(t) - \frac{K}{a^2(t)} + \frac{\Lambda}{3}$$

ハッブルパラメータ　スケールファクター　平均質量密度　宇宙の曲率　宇宙定数

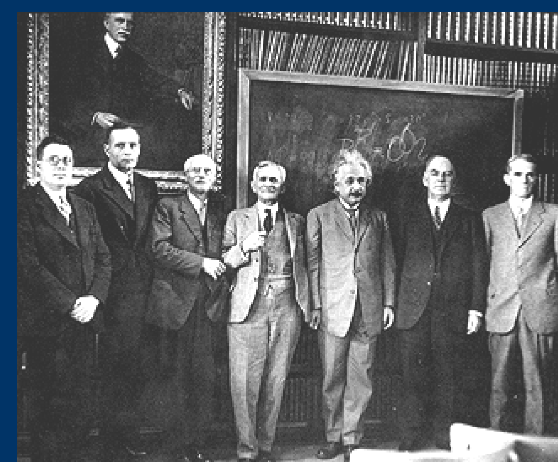
エドウィン ハッブル (1889–1953)

- アンドロメダ星雲中にセファイド型変光星を見つけてその距離を決定し、遠方の星雲は我々の銀河系内の星の集団ではなく、独立した銀河であることを示した (1923年)
- さらに遠方の銀河はその距離に比例した速度で遠ざかっていることを発見し、宇宙が膨張していることを観測的に明らかにした (1929年)

ハッブルが発見したアンドロメダ銀河のセファイド変光星



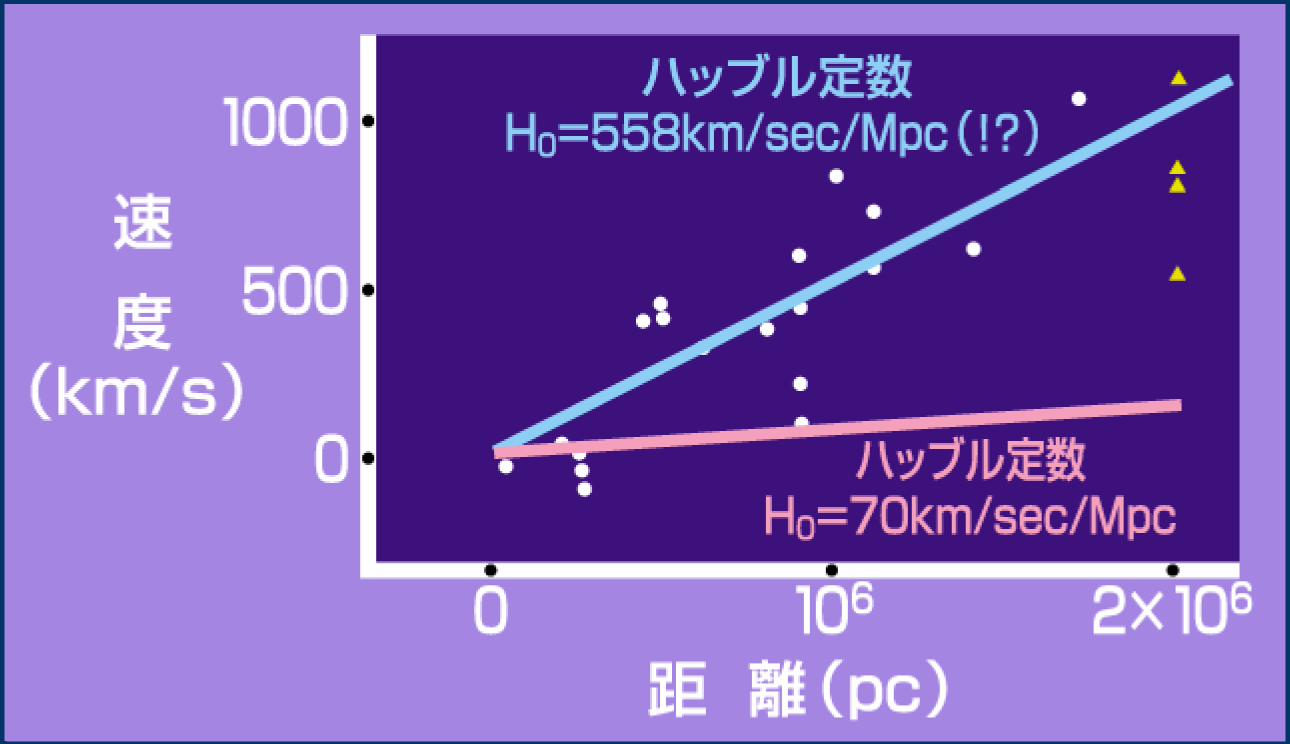
1931年にウィルソン山天文台を訪問したアインシュタイン



http://www.mtwilson.edu/History

ハッブルの法則 (1929)

- 遠方銀河は我々に対して遠ざかっている
- その後退速度は、銀河までの距離に比例している

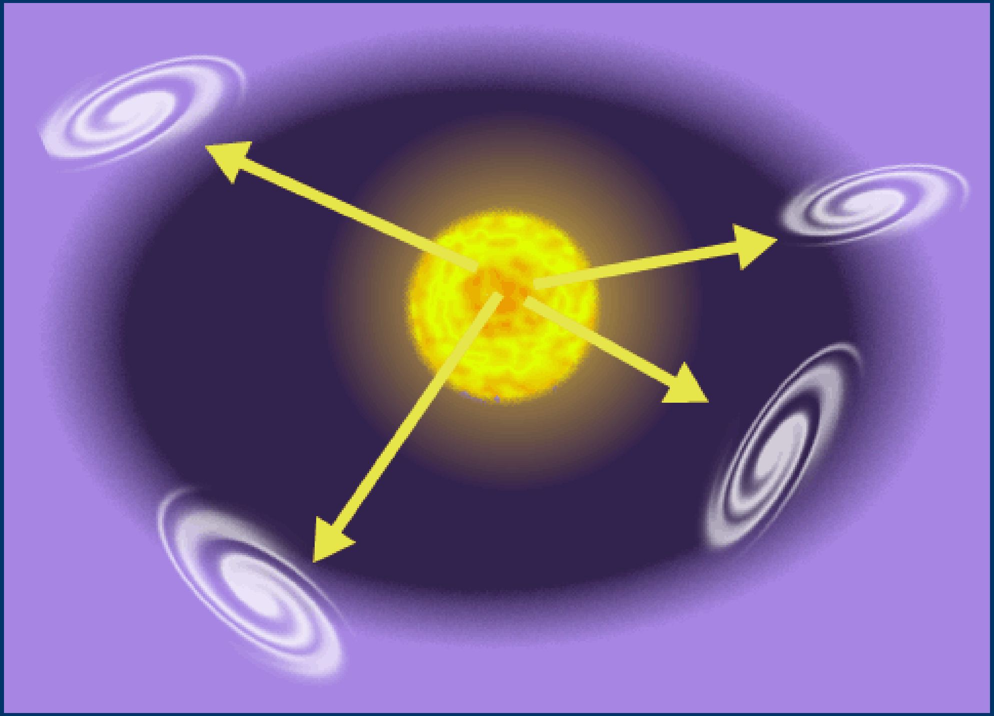


ハッブルの法則
$v = H_0 d$

ハッブルが得た
遠方銀河の
距離速度関係

ハッブルの法則の解釈(1)

- *我々の銀河系は宇宙の中心に位置する(?)*

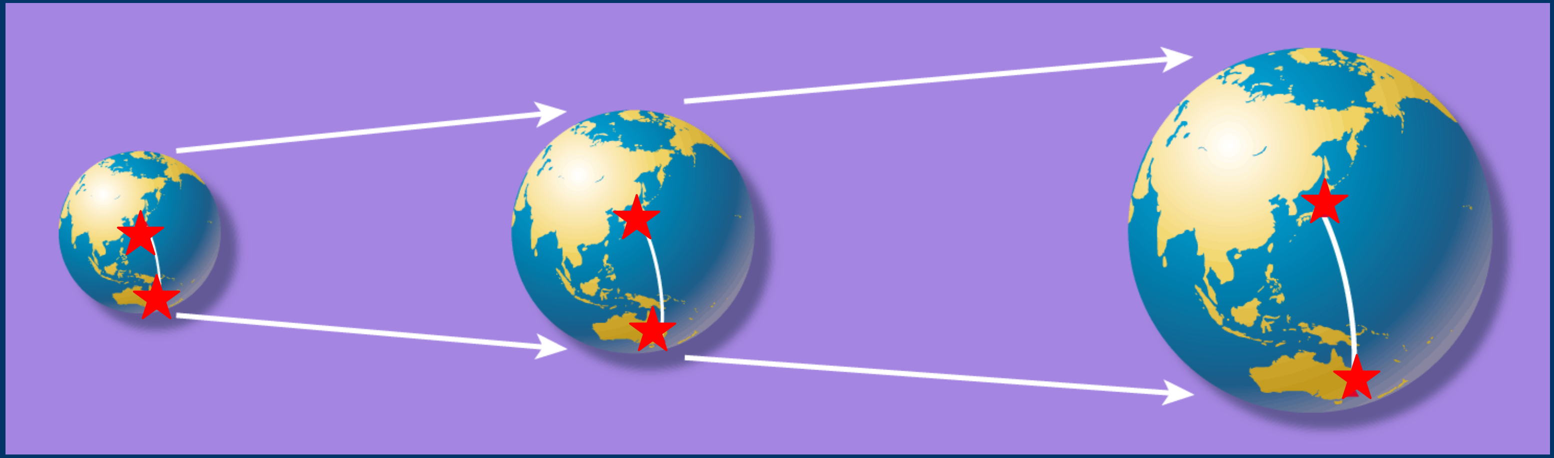


すべての銀河が我々の銀河系を中心にして、かつその後退速度が距離に比例するような特殊な関係を満たしながら運動している

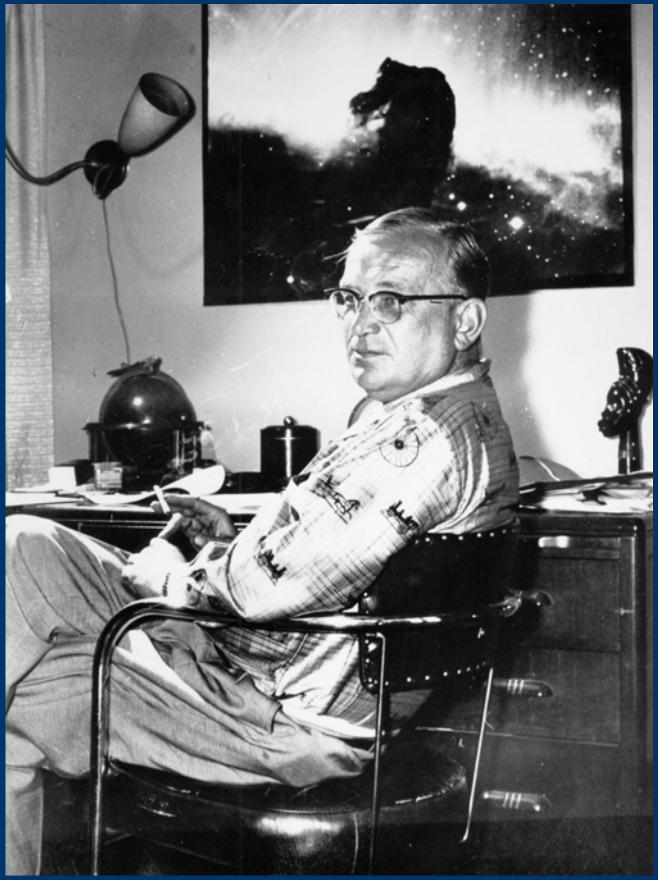
ハッブルの法則の解釈(2)

- **ハッブルの法則は、我々の銀河系に対してだけではなく宇宙のどこでも成り立つ**

　この法則は、単に個々の銀河の運動ではなく、宇宙があらゆる場所で全体として一様等方に膨張していることを示している



ジョージ ガモフ（1904–1968）



- 宇宙の元素の起源を説明するべく、ホットビッグバン理論を提唱
- その帰結として、宇宙マイクロ波背景輻射の存在を予言
- 原子核物理、宇宙論、分子生物学等の多岐の分野にわたり、極めて独創的なアイディアを発表するとともに、優れた啓蒙書を著した

α β γ 理論の原論文 (Phys.Rev. 73, 1948, 803)

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* α
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE β
Cornell University, Ithaca, New York

AND

G. GAMOW γ
The George Washington University, Washington, D. C.
February 18, 1948

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./cm^3.

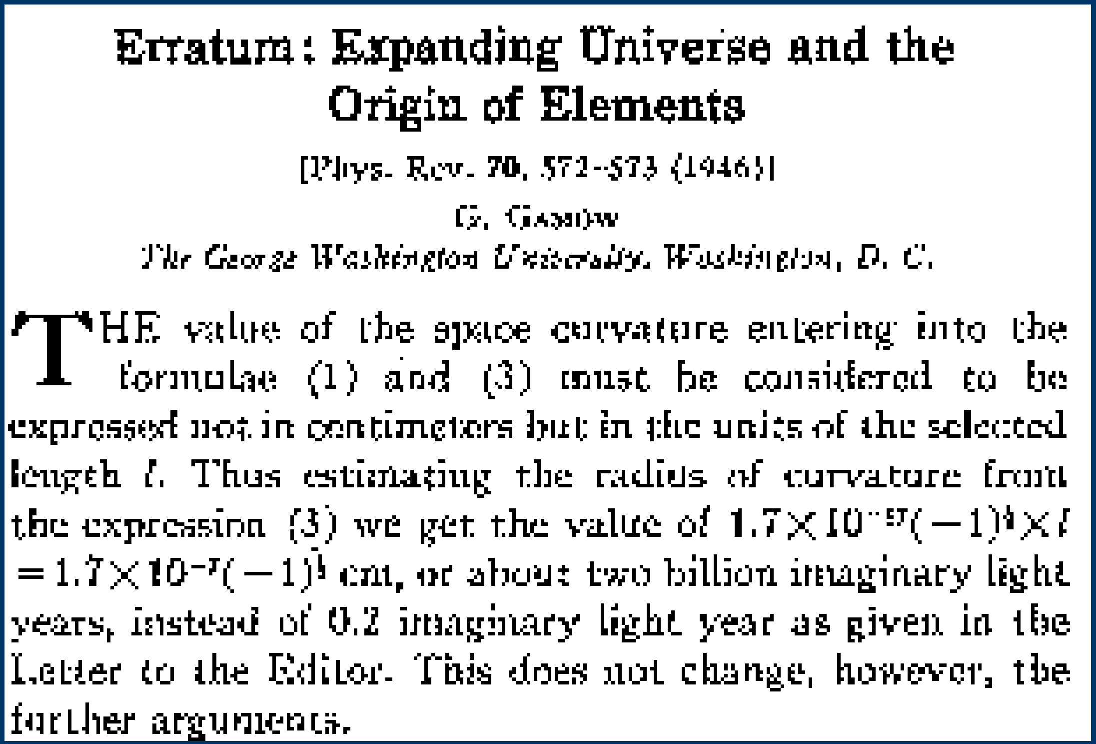
On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying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

origin of “ β ”

The paper by Gamow and Alpher is generally known as the “$\alpha\beta\gamma$ paper.” Quite apart from its content, the paper has a famous history, which has made it part of the physics folklore. As it appeared in *Physical Review*, it was co-authored by Bethe, although he did not, in fact, contribute at all. Gamow recalled the story behind the $\alpha\beta\gamma$ terminology as follows: “In writing up the preliminary communication of this work, I was unhappy that the letter β was missing between α and γ. Thus, sending the manuscript for publication in *Phys. Rev.*, I put in the name of Hans Bethe (in absentia) between our names. This was planned as a surprise to Hans when he would unexpectedly find his name as co-author and I was sure that, being my old friend, and having a good sense of humor he would not mind. What I did not know was that at that time he was one of the reviewers for *Phys. Rev.* and that the manuscript was sent to him for evaluation. But he did not make any changes in it except to strike out the words “in absentia” after his name, thus endorsing the idea and the results.”[94] Gamow even tried to make Herman change his name to Delter so the $\alpha\beta\gamma$ theory would become an $\alpha\beta\gamma\delta$ theory. Although Herman resisted the temptation, in a later paper Gamow referred to “the neutron-capture theory of the origin of atomic species recently developed by Alpher, Bethe, Gamow and Delter,” a reference which must have caused some confusion.[95] Bethe, who was not foreign to this kind of fun, took the joke with good humor as Gamow expected. As he later told Alpher and Herman, “I felt at the time that it was rather a nice joke, and that the paper had a chance of being correct, so that I did not mind my name being added to it.”[96] The last word on the matter was added by Gamow in 1960: “There was . . . a rumor that later, when the $\alpha\beta\gamma$ theory went temporarily on the rocks, Dr. Bethe seriously considered changing his name to Zacharias.”[97]

超非精密宇宙論

ultra-unprecision cosmology



Erratum: Expanding Universe and the Origin of Elements

[Phys. Rev. 70, 572–573 (1946)]

G. Gamow

The George Washington University, Washington, D. C.

THE value of the space curvature entering into the formulae (1) and (3) must be considered to be expressed not in centimeters but in the units of the selected length l. Thus estimating the radius of curvature from the expression (3) we get the value of $1.7\times10^{27}(-1)^{\frac{1}{2}}\times l = 1.7\times10^{27}(-1)^{\frac{1}{2}}$ cm, or about two billion imaginary light years, instead of 0.2 imaginary light year as given in the Letter to the Editor. This does not change, however, the further arguments.

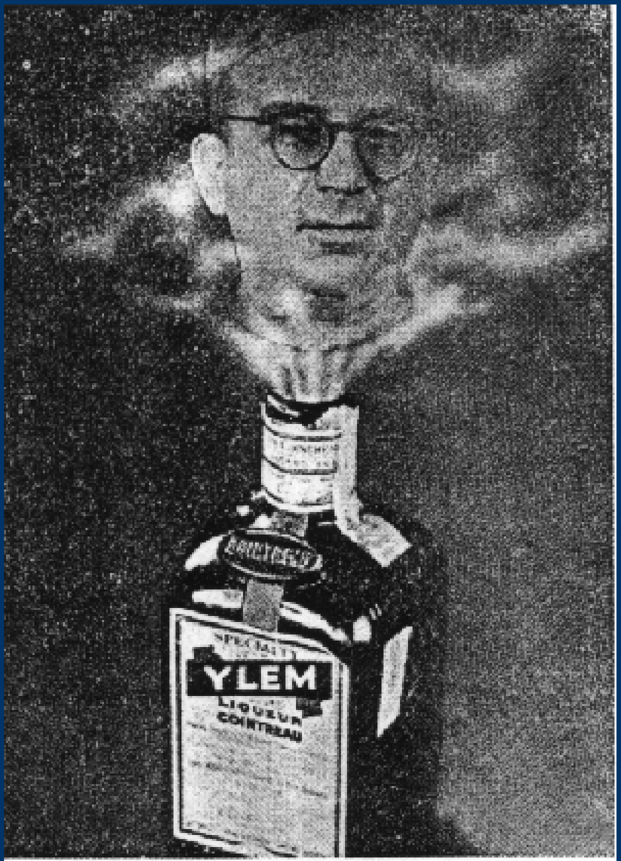
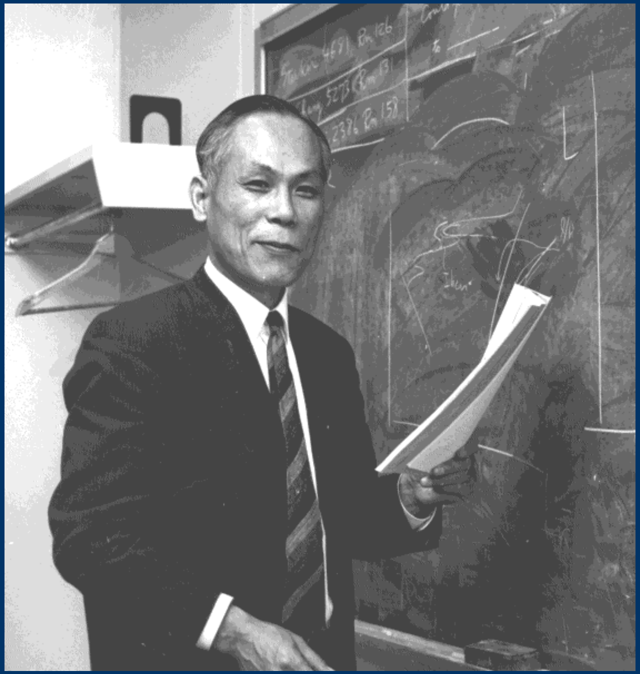


図 1　魔法の"イレム"ビンから出てくるガモフ

- *H.Kragh "Cosmology and controversy"*
  - P.138 **With the exception of Hayashi, no one outside America contributed to the big-bang theory**. Furthermore, it is noteworthy that the physicists involved in the program were East Coast or Chicago physicists with, in most cases, personal connections to Gamow.

林忠四郎先生

- **1940年　東大物理学科卒業！**
- 私の先生である佐藤勝彦氏の先生
- 宇宙論、星の進化論、太陽系形成論においていずれも偉大な業績を成し遂げられた



- *H.Kragh “Cosmology and controversy”* (Princeton Univ. Press, 1996)
  - P.126 The assumption that the ylem consisted only of neutrons simplified the picture of the earliest universe, but it was realized that it was merely as an assumption. **In early 1950, Chushiro Hayashi of Nanikawa University in Japan reconsidered the question** and suggested that at the very high temperatures in the initial phase of the expansion, other processes than radioactive neutron decay should also be taken into account… **Hayashi was the first of the rather few physicists who took an interest** in the work of Alpher and Herman, and his contribution was important in indicating a new insight into the isotropic composition of the early universe.

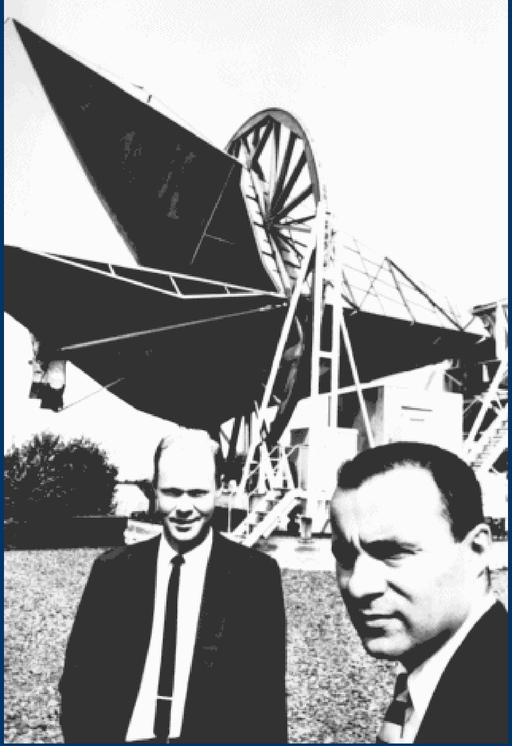
宇宙マイクロ波背景輻射（CMB）

CMB: Cosmic Microwave Background

- 現在の宇宙を満たす等方的な電磁波の熱輻射分布
- 熱い火の玉宇宙（ビッグバン）の名残
- ペンジアスとウィルソンの観測的発見(1964年)によって、ビッグバン理論が初めて市民権を得た
- 10^{-4}の精度で温度2.7Kの熱輻射のスペクトルと一致
- 相対的に10^{-5}程度の温度非等方性
- 宇宙論パラメータについての重要な情報源

CMB: 発見の歴史

- 1940年代にジョージ ガモフ (ビッグバン宇宙モデルの創始者) とその学生達が元素の起源の研究から、理論的にその存在を予言
- 1964年に、ベル研究所のペンジアスとウィルソンが偶然発見（1978年ノーベル賞）



Bell Labs/Lucent Technologies 提供画像

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

free from seasonal variations (July, 1964–April, 1965). A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter in this issue.

A. A. PENZIAS
R. W. WILSON

May 13, 1965
BELL TELEPHONE LABORATORIES, INC
CRAWFORD HILL, HOLMDEL, NEW JERSEY

The Astrophysical Journal **142(1965)419**

ガモフの書簡

THE INSTITUTE FOR ADVANCED STUDY
SCHOOL OF MATHEMATICS
PRINCETON, NEW JERSEY

August 4,1946

Professor G.Gamov
Ohio State University
Columbus,Ohio

Dear Mr.Gamov:

After receiving your manuscript I read it immediately and then forwarded it to Dr.Spitzer. I am convinced that the abundance of elements as function of the atomic weight is a highly important starting point for cosmogonic speculations. The idea that the whole expansion process started with a neutron gas seems to be quite natural too. The explanation of the abundance curve by formation of the heavier elements in making use of the known facts of probability coefficients seems to me pretty convincing. Your remarks concerning the formation of the big units (nebulae) I am not able to judge for lack of special knowledge.

Thanking you for your kindness,I am

yours sincerely,

A. Einstein.

Albert Einstein.

Of cause, the old man agrees with almost ~~every~~ anything nowaday.
Geo.

Thanks for slides.
G.

図 4　アインシュタインがガモフに宛てた手紙*

The Gamow Dacha
785 - 6th Street
Boulder, Colorado

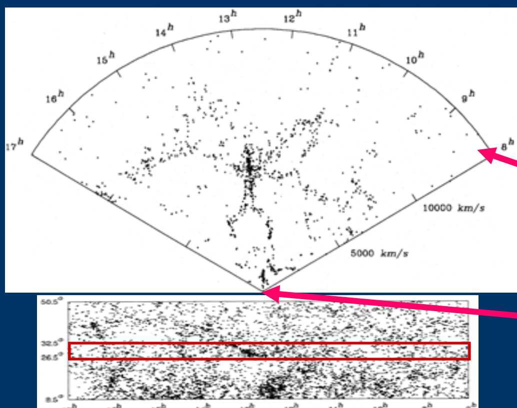
Sept 29th 1963

Dear Dr. Penzias,
~~Send~~ Thank you for sending me your paper on 3 °K radiation. It is very nicely written except that "early history" is not "quite complete". The theory of, what is now knows as "primeval fireball" was first developed by me in 1946 (Phys. Rev. 70, 572, 1946; 74, 505, 1948; Nature 162, 680, 1948). The prediction of the numerical value of the present (residual) temperature could ~~can~~ be found in Alpher & Hermann's paper (Phys. Rev. 75, 1093, 1949) who estimate it as 5 °K, and in my paper (Kong Dansk. Ved. Sels. 27 no 10, 1953) with the estimate of 7 °K. Even in my popular book "Creation of Universe" (Viking 1952) you can find (on p. 42) the formula $T = 1.5 \cdot 10^{10}/t^{1/2}$ °K, and the upper limit of 50 °K. Thus, you see the world did not start with almighty Dicke.
Sincerely G. Gamow

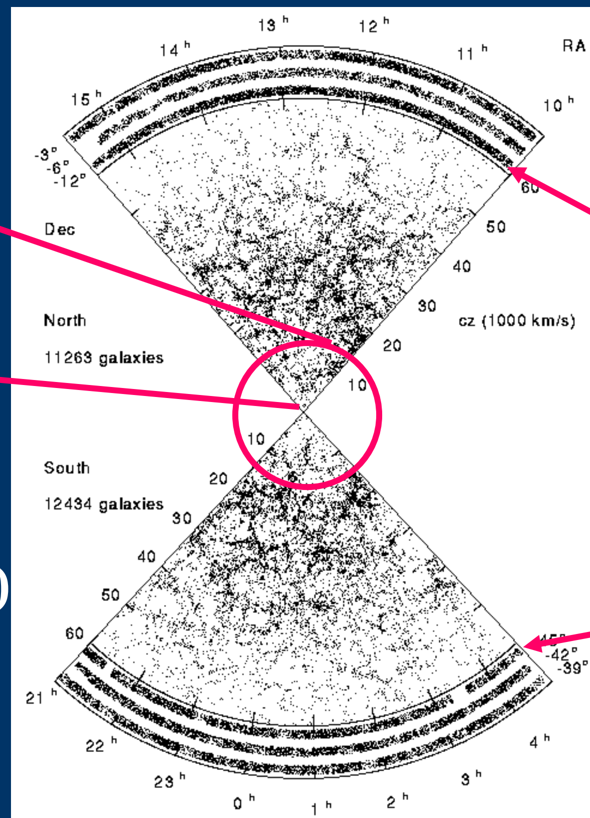
図 3　G. ガモフの手紙．奇妙なことに日付が間違って 1963 年となっている*．

赤方偏移サーベイと宇宙の大構造

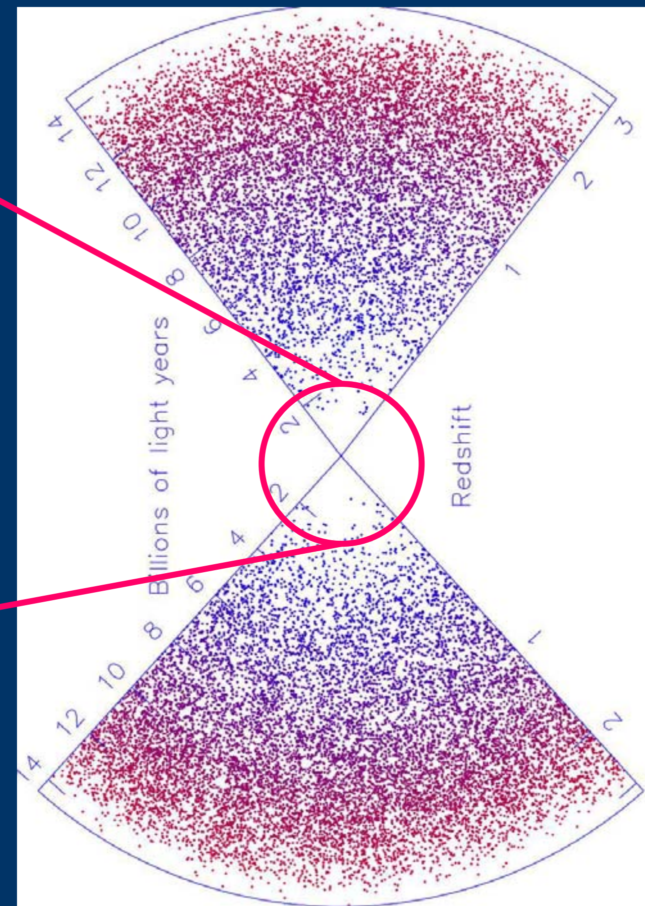
1986年



1996年



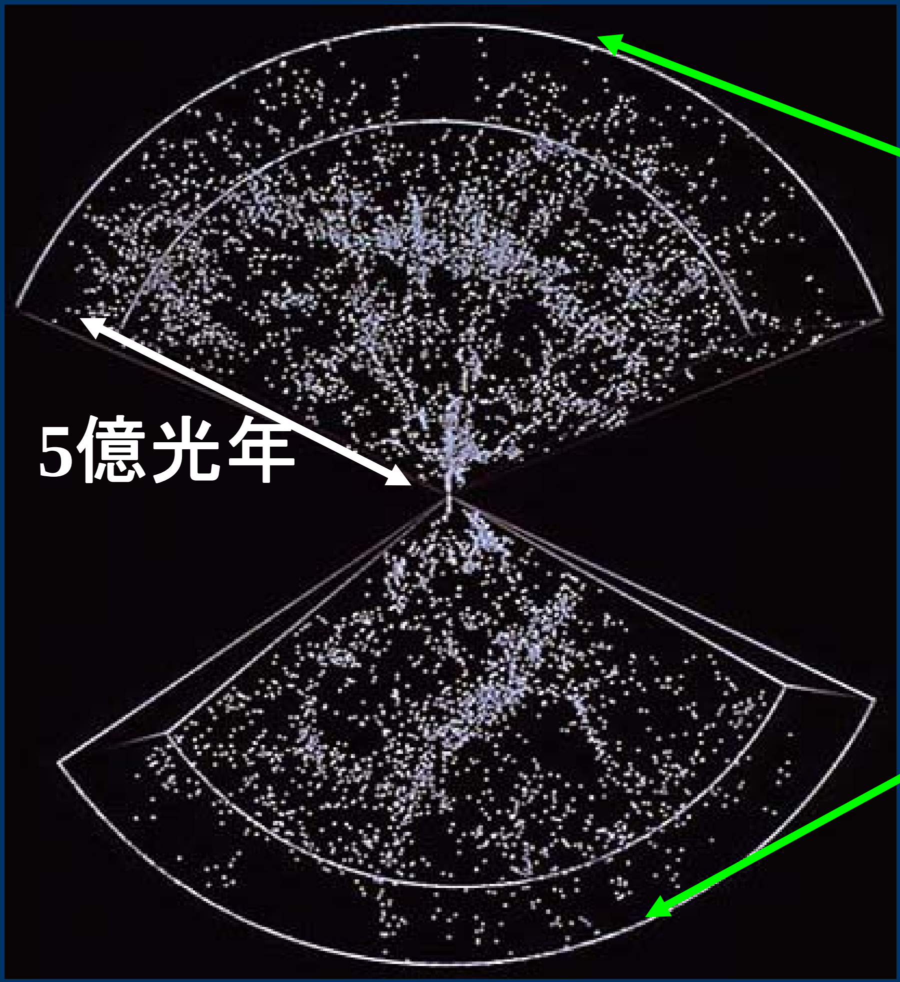
2001年

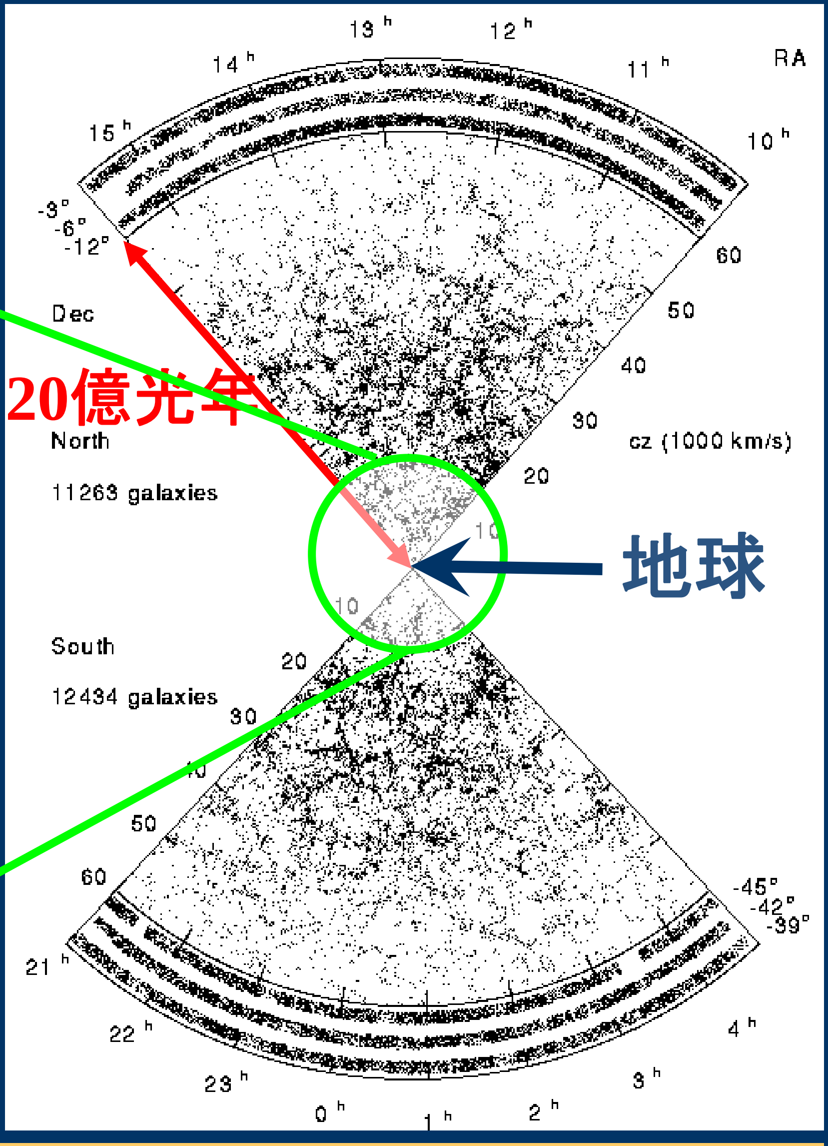


CfA galaxy survey
(de Lapparent et al. 1986)
Las Campanas survey
(Schectman et al. 1996)
2dF QSO survey
(http://www.2dfquasar.org)

宇宙の大構造の発見にとどまらず、その形成進化を時系列として宇宙の果てまで見通せる時代

銀河の3次元分布地図



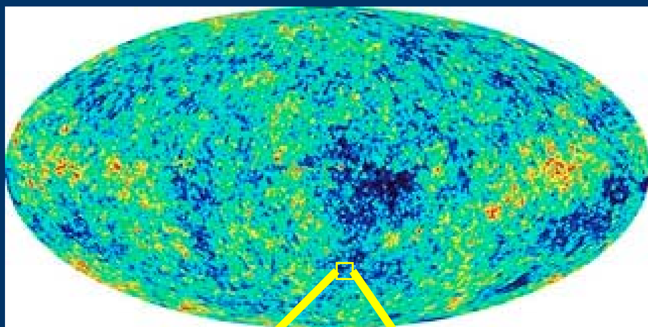


**CfA galaxy redshift survey:
Geller, da Costa & Huchra (1992)**

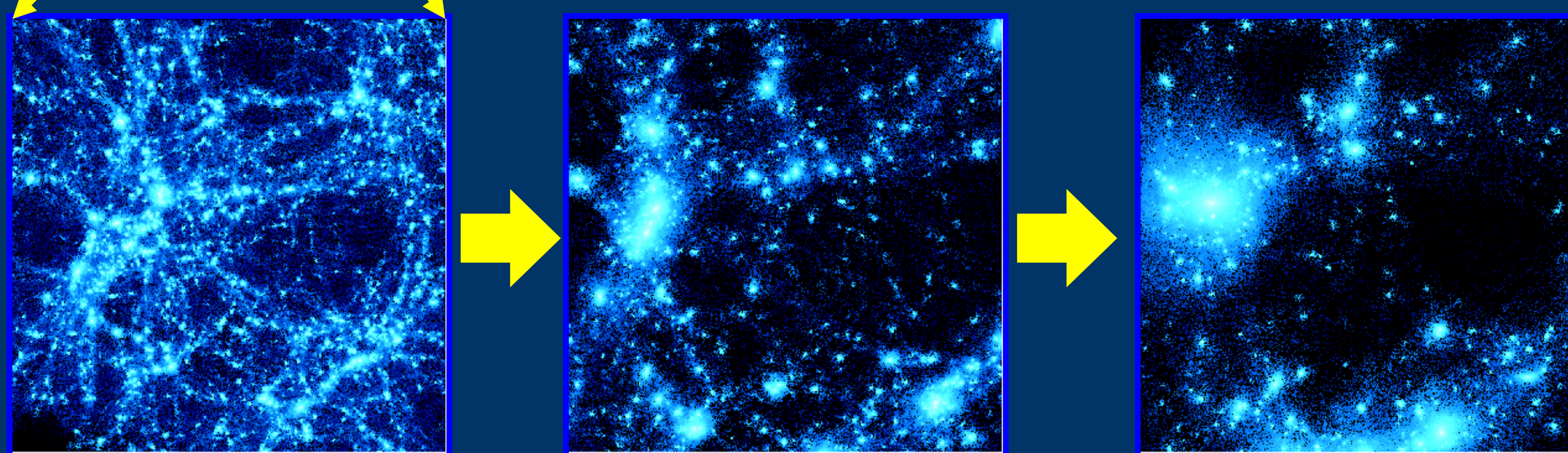
**Las Campanas redshift survey:
Schectman et al. (1996)**

宇宙の構造形成標準理論

宇宙初期の空間ゆらぎ



- 小さなスケールの構造ほど初期に形成される
- いったんできた構造が重力的に合体あるいは集団化することで、より大きなスケールの構造へと進化する



万有引力（重力）によってでこぼこ度合いがどんどん成長する

宇宙構造進化シミュレーションの例

吉川 耕司、
樽家 篤史、
景 益鵬、
須藤 靖
（2001）

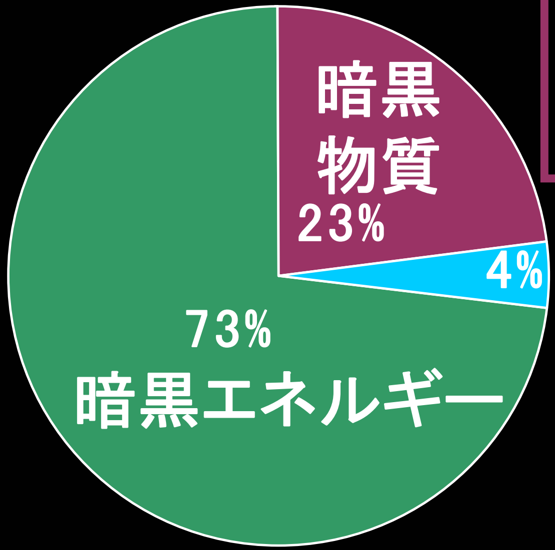
ダークマター分布の進化
⇒ X線で見る現在の高温ガス分布
⇒ 可視光で見える現在の宇宙の銀河分布

20世紀宇宙論研究の到達点

- マイクロ波背景輻射の温度ゆらぎ発見（1992年COBE)
- 銀河系内MACHOの検出 (1993年 MACHOグループ)
- 10%精度でのハッブル定数の決定
（1999年 Hubble Space Telescope key project)
- 宇宙定数(暗黒エネルギー)が存在する可能性
（1999年 Ia型超新星）
- 非バリオン暗黒物質の存在が決定的
（冷たい暗黒物質モデルパラダイムの確立）
- 素粒子論的宇宙論による初期条件
（インフレーション、密度揺らぎのスペクトル）

まとめ:我々の宇宙は何からできている？

宇宙の組成



- 銀河·銀河団は星の総和から予想される値の10倍以上の質量をもつ
- 未知の素粒子が正体？

通常の物質 (バリオン)

- 元素をつくっているもの（主に、陽子と中性子）
- 現時点で知られている物質（の質量）は実質的にはすべてバリオン

- 宇宙空間を一様に満たしているエネルギーが宇宙の主成分！
- 万有斥力（負の圧力）
- アインシュタインの宇宙定数？