21世紀の宇宙論

2002年冬学期　東京大学物理学教室

宇宙物理学　　須藤　靖

第6回講義　2003年1月29日

ビッグバンモデル：3つの観測的証拠

ハッブルの法則

十分遠方にある銀河はすべて我々に対して遠ざかっている

軽元素の起源

現在の宇宙には大量のヘリウムが存在する（質量密度にして全元素の約25％）

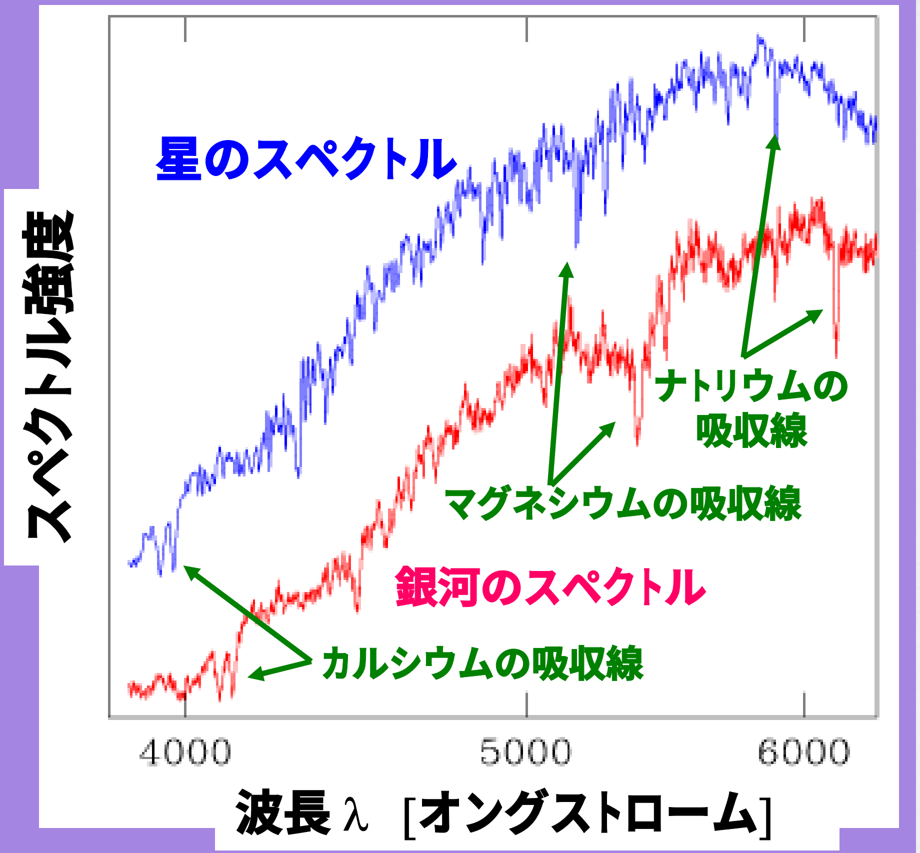
宇宙マイクロ波背景輻射

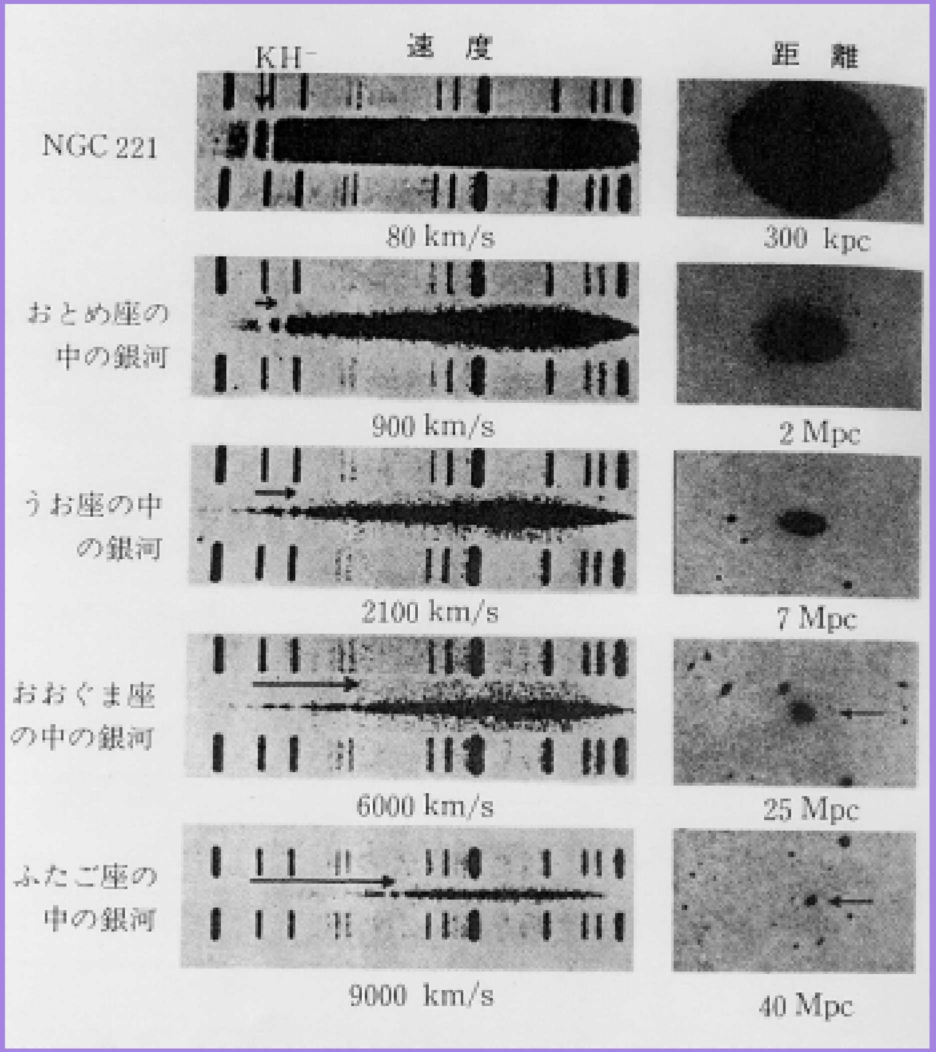
現在の宇宙は、等方的な強度分布を示す電磁波（絶対温度約2.7Kに対応する熱放射）に満たされている

1. ハッブルの法則とハッブル定数

$$H_0 = 72 \pm 8 \text{ km/s/Mpc}$$

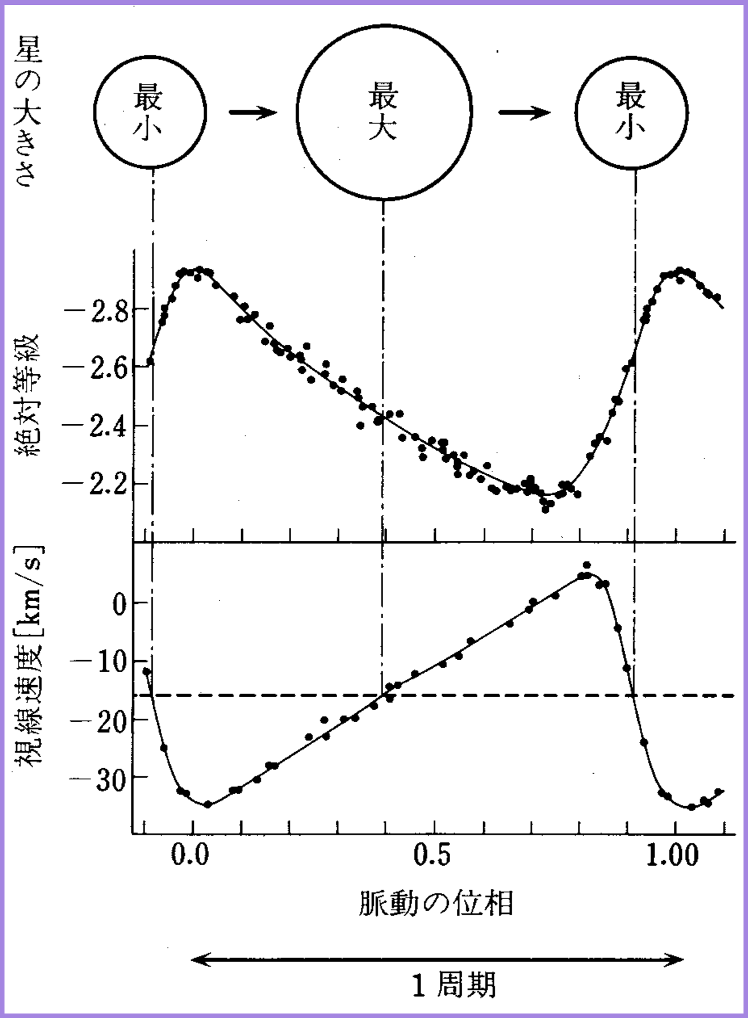
銀河の分光観測と後退速度

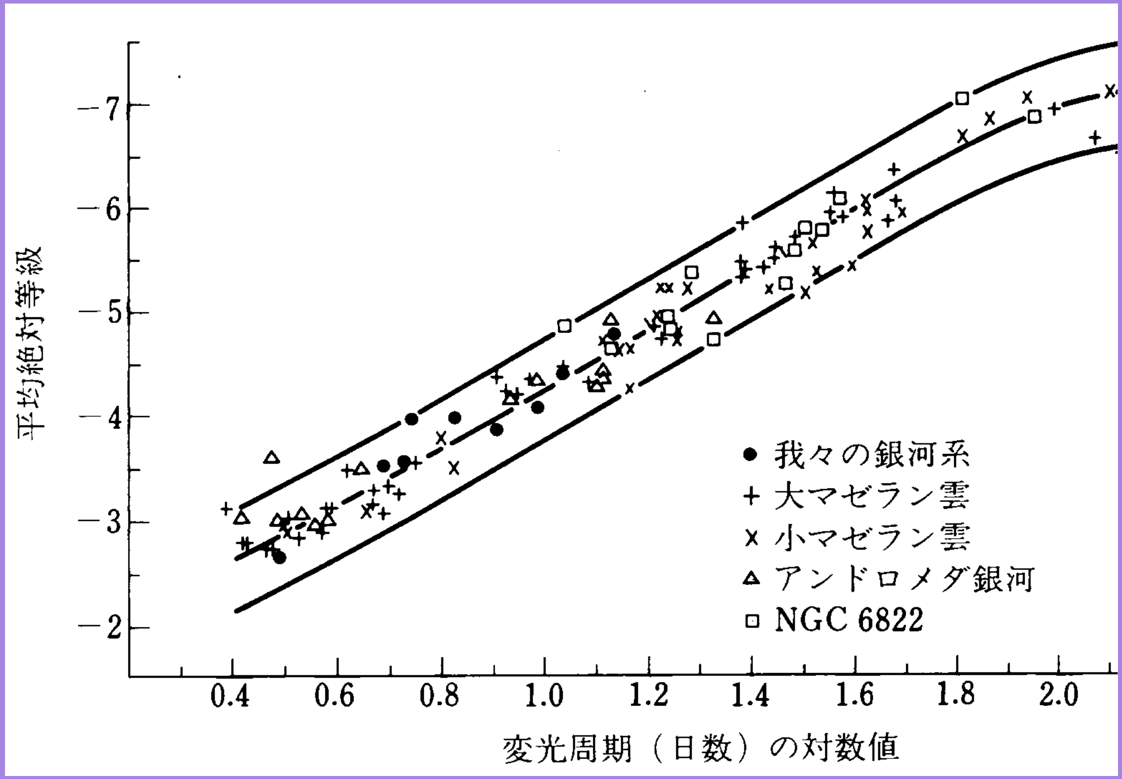




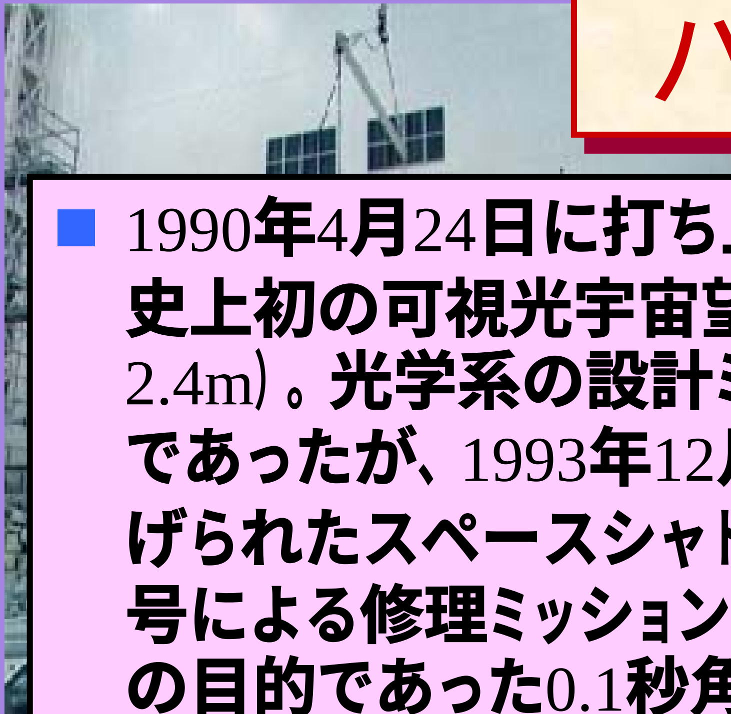
セファイド型変光星

- 1日から100日程度の規則的な周期で半径が振動する変光星。その絶対強度と脈動周期の間に規則的な関係が知られており、周期から絶対光度が推定できる。遠方天体の距離指標として最も信頼されている。

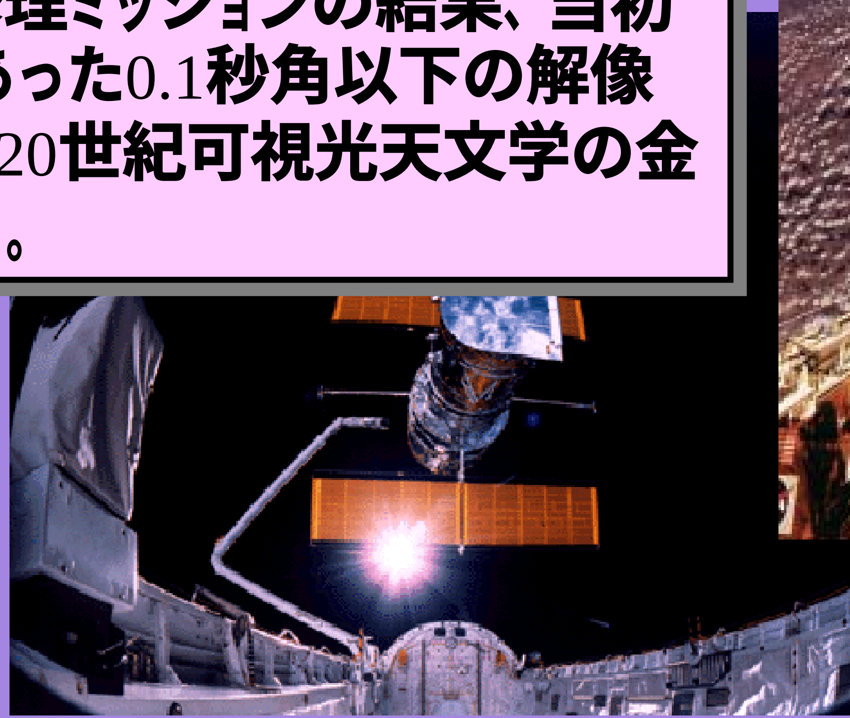




ハッブル宇宙望遠鏡

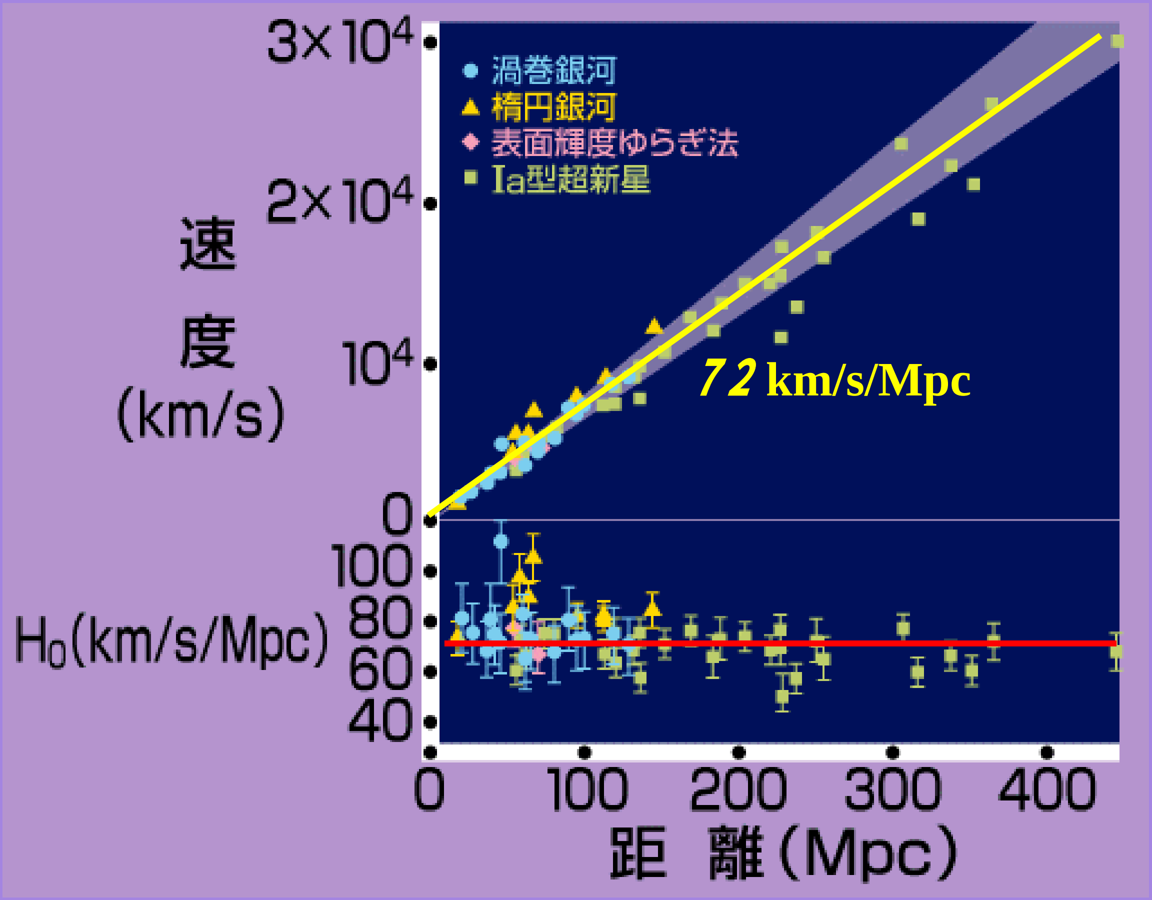


- 1990年4月24日に打ち上げられた、史上初の可視光宇宙望遠鏡（口径2.4m）。光学系の設計ミスでピンボケであったが、1993年12月2日に打ち上げられたスペースシャトルエンデバー号による修理ミッションの結果、当初の目的であった0.1秒角以下の解像度を達成。20世紀可視光天文学の金字塔である。



ハッブル定数と宇宙の距離尺度

■ **遠方銀河の距離推定 ⇒ H_0 = 72 ± 8 km/s/Mpc**



ハッブル宇宙望遠鏡によるセファイド変光星の観測から較正された銀河距離指標を用いて、ハッブル定数の値は約1割の精度で決定されている

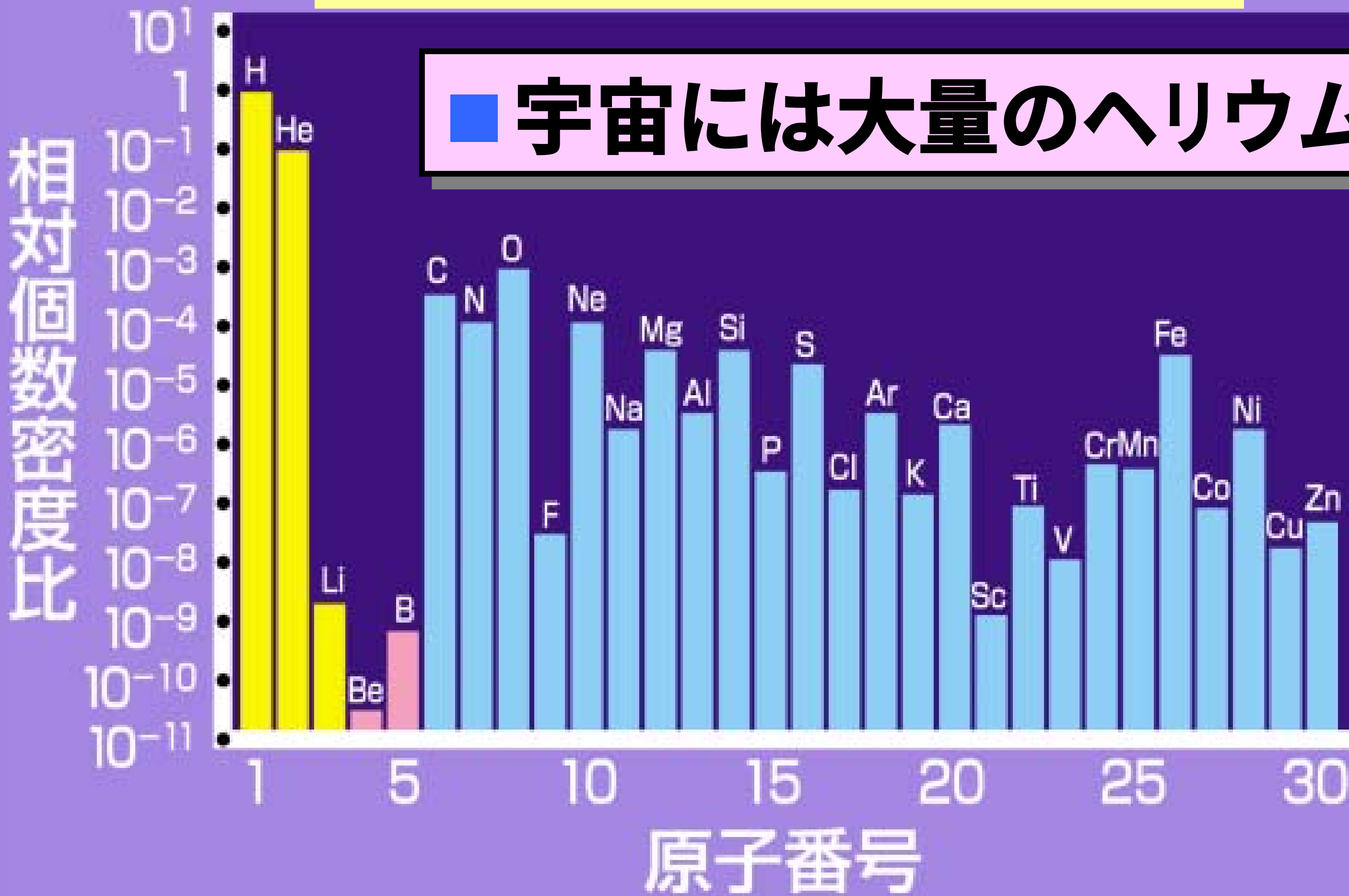
W.L.Freedman: Phys.Rep.333-334(2000)13

2．ビッグバン元素合成とバリオン密度パラメータ

$$\Omega_b h^2 = 0.02$$

宇宙に存在する元素の起源

水素の個数密度度に対する、元素の組成比



■宇宙には大量のヘリウムが存在

ヘリウムが全元素に占める割合は個数にして10%、質量にして25%

宇宙初期？
vs
星の内部？

２つの元素合成理論の比較

	ビッグバン元素合成	星元素合成
場所	初期宇宙	星の内部
時間スケール	分	億年
温度	10億度 時間とともに 急速に下がる	1000万度 時間とともに ゆっくりと上昇
密度	0.00001 g/cc	100 g/cc
フォトンバリオン比	10^9	1以下
生成元素	軽元素 (ヘリウム、重水素、 リチウム)	重元素 (炭素、窒素、酸素、 など)

ジョージ・ガモフ

- ホットビッグバン理論の提唱者
- 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

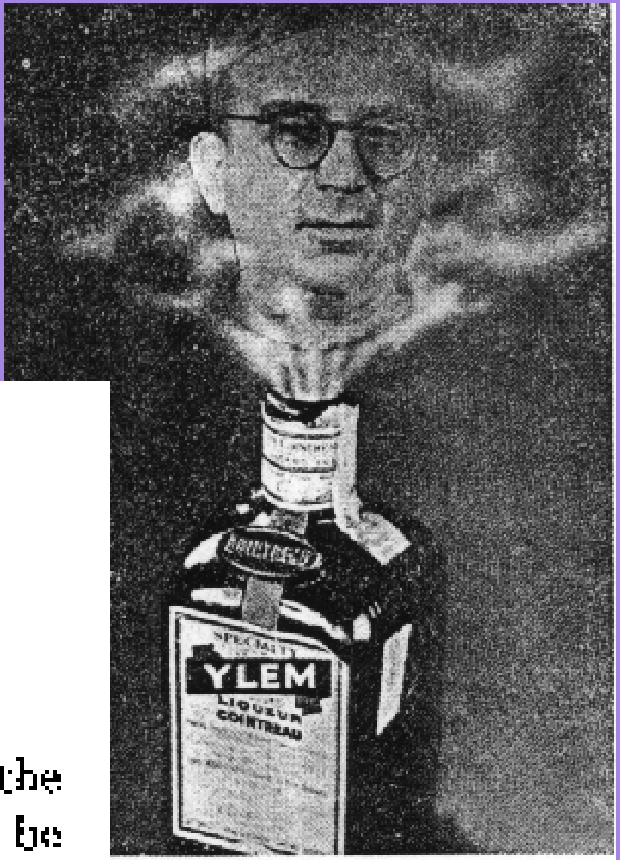
ガモフの逸話

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 $1.7\times10^{-27}(-1)^{\frac{1}{2}}\times l = 1.7\times10^{-7}(-1)^{\frac{1}{2}}$ 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.



魔法の"イレム"ビンから出てくるガモフ

α β γ 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*
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

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:

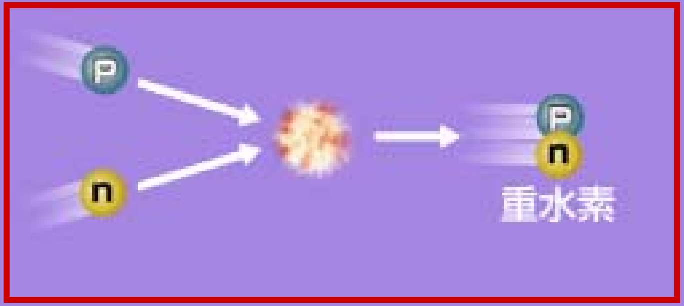
origin of "β"

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]

ビッグバン元素合成

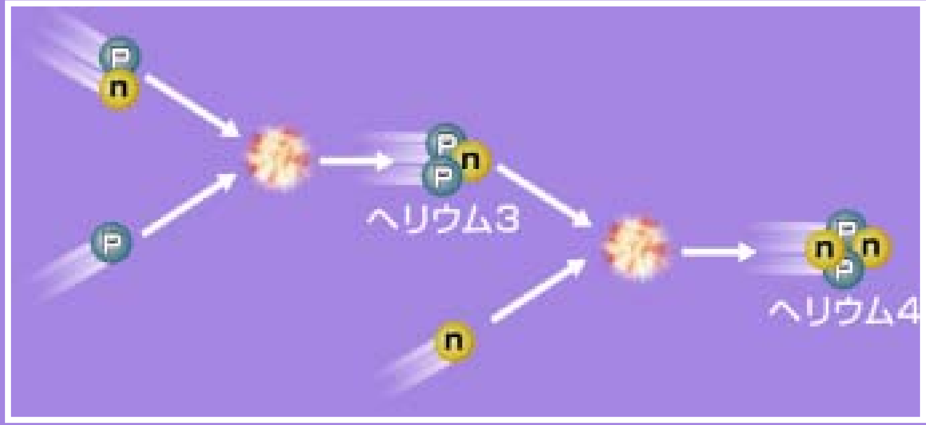
■宇宙誕生最初の三分間

重水素合成が第一ステップ



ただし、質量数5，8をもつ安定な原子核が存在しないため、それ以上の重元素の合成は起こらない

いったん重水素ができると二体反応の積み重ねによって直ちにヘリウムが合成される



ヘリウムの存在量

■ 星の内部での元素合成

- トリプルアルファ反応と呼ばれる過程を通じて、ヘリウム以上の重元素（炭素、窒素、酸素など）を合成することが可能
- ヘリウムと重元素がほぼ同じ量だけつくられる（質量比にして、水素75%、ヘリウム13%、それ以上の重元素12%）

■ ビッグバン元素合成

- ヘリウム以上の重元素は合成されず、元素合成開始直前に存在した中性子がほとんどすべてヘリウムになる
- 宇宙誕生1分後の陽子と中性子の個数密度比(n_p:n_n)はおよそ7:1（弱い相互作用の理論からの予言）

→
$$\frac{m_{\mathrm{He}} n_{\mathrm{He}}}{m_{\mathrm{H}} n_{\mathrm{H}} + m_{\mathrm{He}} n_{\mathrm{He}}} \approx \frac{4(n_{\mathrm{n}}/2)}{(n_{\mathrm{p}} - n_{\mathrm{n}}) + 4(n_{\mathrm{n}}/2)} \approx \frac{1}{4} \; (!)$$

林忠四郎と中性子陽子比

C.Hayashi: Prog.Theor.Phys., 5(1950)224

H.Kragh “Cosmology and Controversy” (1996)

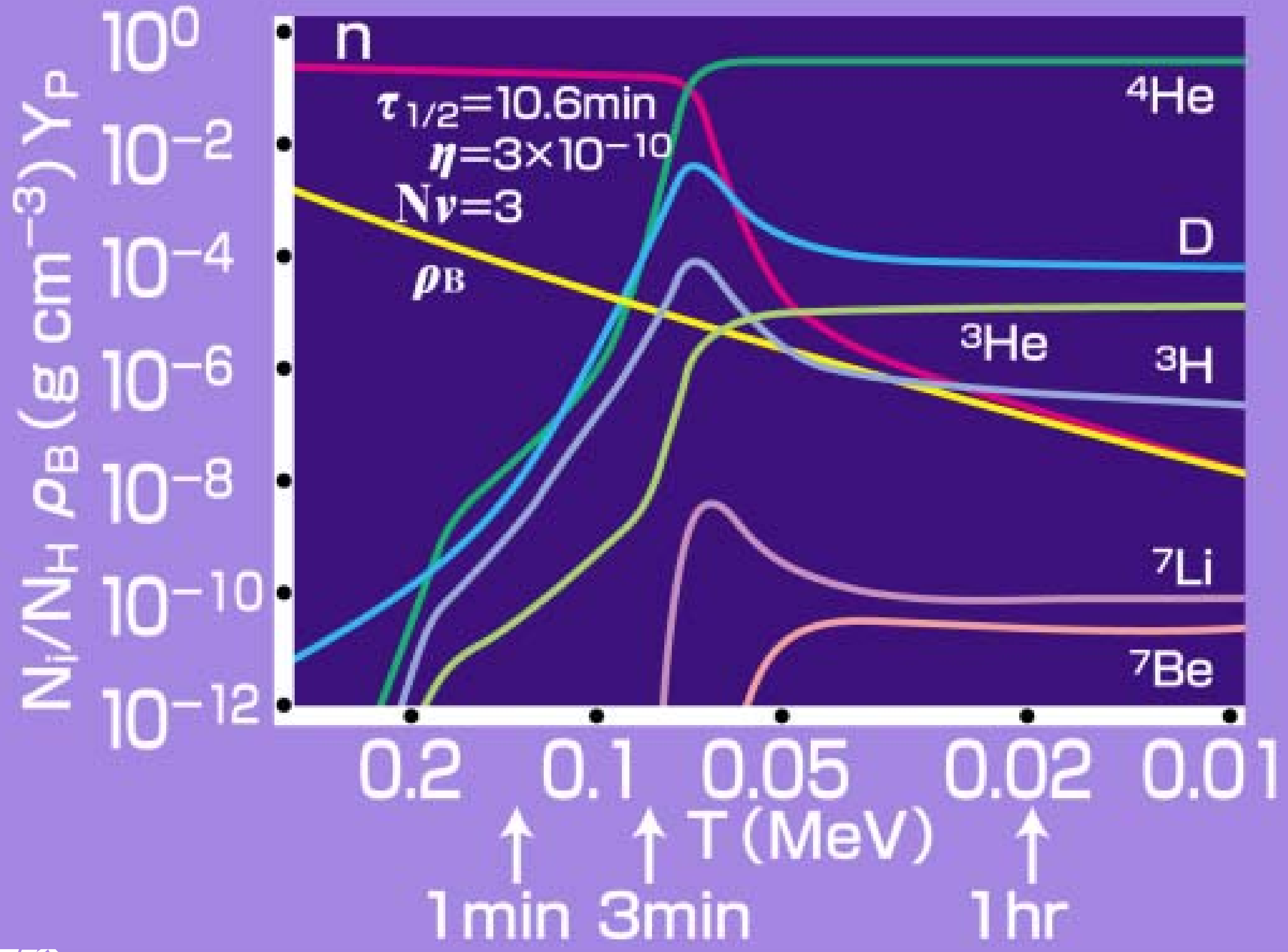
The assumption that the ylem consisted only of neutrons simplified the picture of the earliest universe, but it was realized that it was merely an assumption. In early 1950, Chushiro Hayashi of Nanikawa University in Japan reconsidered the question and suggested that at the very high temperatures in the initial phase of the expansion, other processes than radioactive neutron decay should also be taken into account. Specifically, he considered an initial temperature of about 10^{12} K, corresponding to a time after the big bang of the order of 10^{-4} s.[126] He argued that even if only neutrons and photons were initially present, electron-positron pairs would be created from the electromagnetic field. At the high temperatures, induced beta processes such as $n + e^+ \rightarrow p + \bar{\nu}$ and $n + \nu \rightarrow p + e^-$ would have a major effect on the ratio between protons and neutrons (ν and $\bar{\nu}$ denote a neutrino and an antineutrino, respectively). In the thermal equilibrium existing at the highest temperatures, the proton-to-neutron ratio would be given by $n_p/n_n = \exp[(m_n - m_p)c^2/kT]$ and thus would be larger than 1. This ratio would become frozen when the universe cooled and equilibrium was no longer possible, and Hayashi calculated that this required a ratio between the numbers of neutrons and protons at the beginning of element formation of around $n/p = 1/4$. In other words, the ylem would be far richer in protons than assumed by Gamow, Alpher, and Herman, namely, 50% by weight corresponding to equilibrium.

Hayashi later became professor of physics at the University of Kyoto and did important work on stellar formation and other topics of astrophysics.

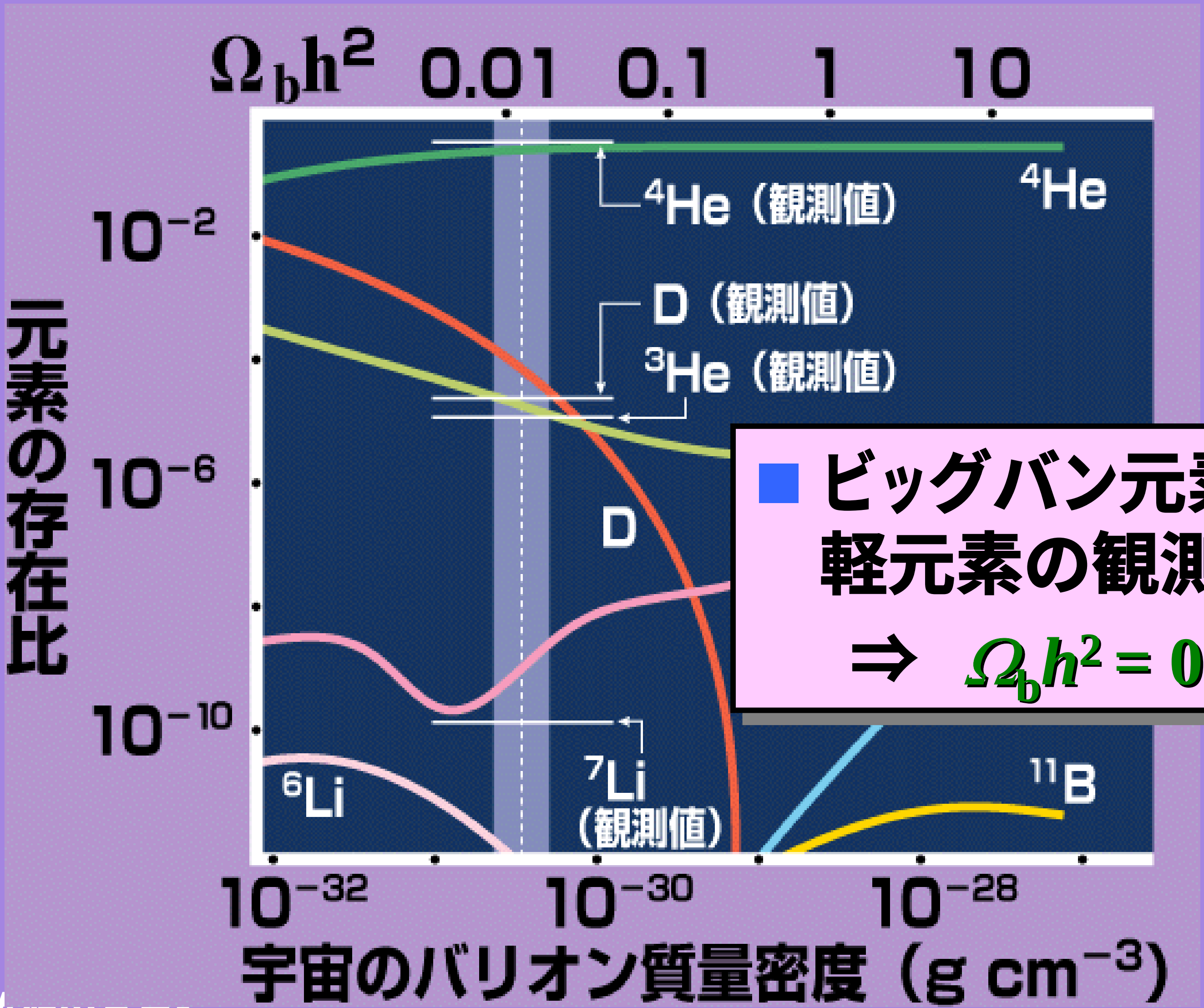
Alpher and Herman found Hayashi's approach interesting, but also pointed out that it was an oversimplification and that the neutron-proton ratio of 1:4 failed to yield a sufficient number of heavier elements. Among other things, Hayashi had used in his calculations a neutron half-life of 30 min, very different from the 13 min currently established experimentally; this alone meant that his conclusions had to be modified. All the same, Hayashi's work inspired

初期宇宙の軽元素量進化

■ ヘリウムの質量存在比 25%が自然に説明される



ビッグバン元素合成とバリオン密度



- ビッグバン元素合成理論と軽元素の観測量の比較

⇒ $\Omega_b h^2 = 0.02$

3．宇宙マイクロ背景輻射とMAP衛星

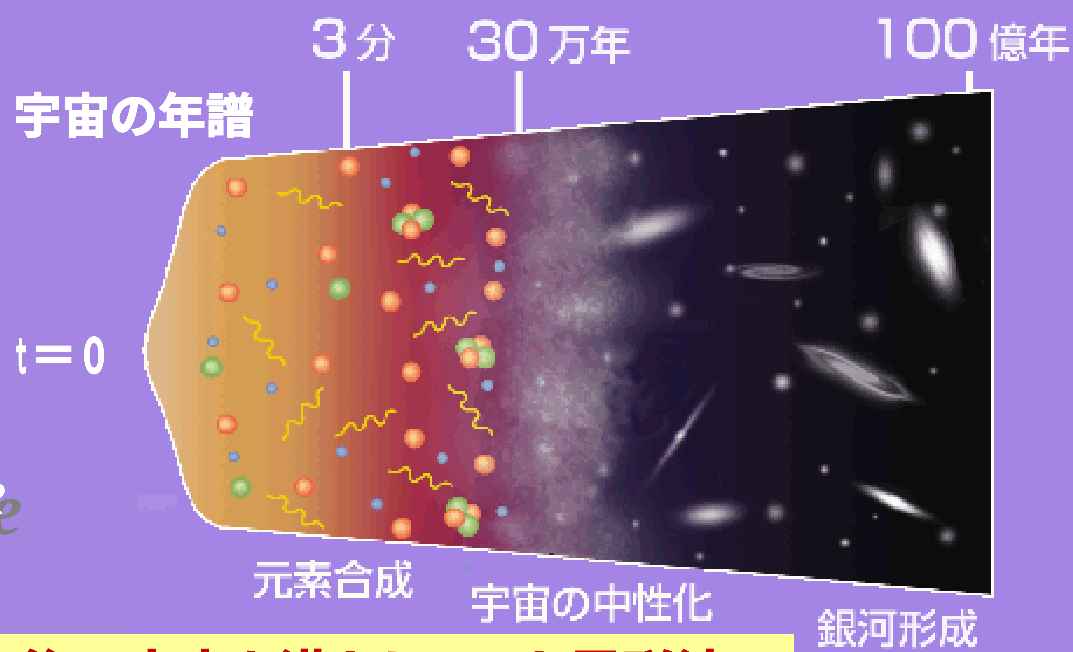
宇宙マイクロ波背景輻射

- **電子と陽子の再結合（宇宙の中性化）**

  それまで完全に電離していた宇宙は、温度が約3000度以下（宇宙誕生後約30万年）になると電子と陽子が結合して水素原子となる

- **宇宙の晴れ上がり**

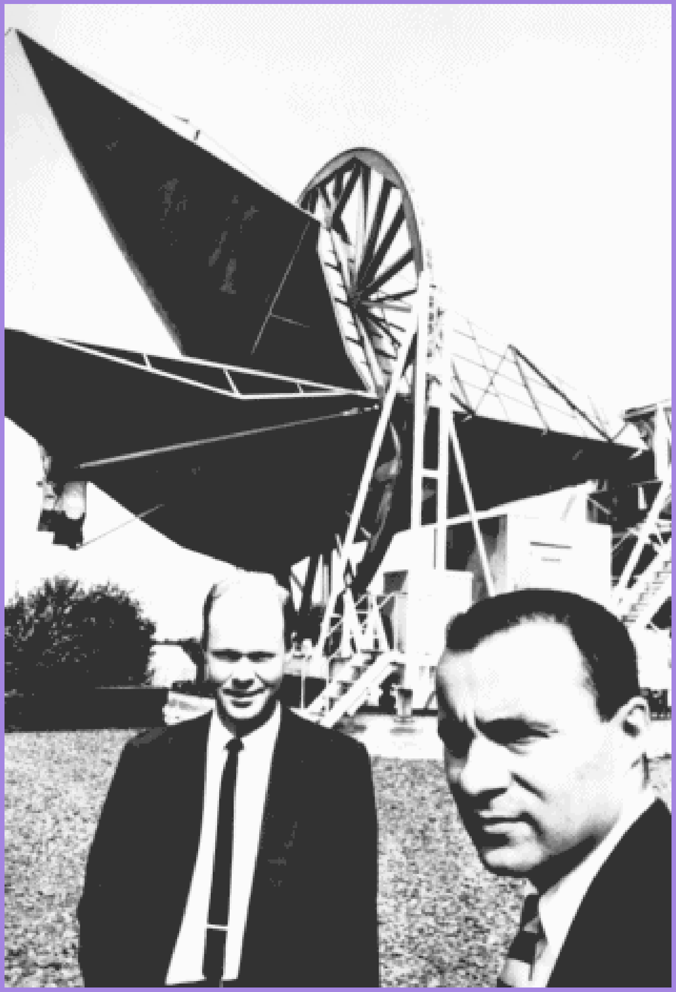
  その結果、電磁波（光）の直進を妨げていた電子が無くなり、宇宙は電磁波に対して透明となる



CMB:
***C**osmic **M**icrowave **B**ackground*

CMBは、晴れ上がり直後の宇宙を満たしていた電磁波（今から100億年以上も前の宇宙の光の化石）

CMB: 発見の歴史



Bell Labs/Lucent Technologies　提供画像

- 1940年代にガモフとその学生達が元素の起源の研究から、理論的に存在を予言
- 1960年前半からプリンストン大学のディッキーを中心とするグループが検出実験を計画
- 1964年に、ベル研究所のペンジアスとウィルソンが発見

Dicke et al. ApJ 142(1965)414

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.

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

REFERENCES

Alpher, R. A , Bethe, H. A , and Gamow, G 1948, *Phys. Rev.*, **73**, 803
Alpher, R A., Follin, J W., and Herman, R. C. 1953, *Phys. Rev* , **92**, 1347.

Penzias & Wilson: ApJ 142(1965)419

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

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

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 course, 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 Sept 29th 1963
Gamow Dacha
785 - 6th Street
Boulder, Colorado

Dear Dr. Penzias,

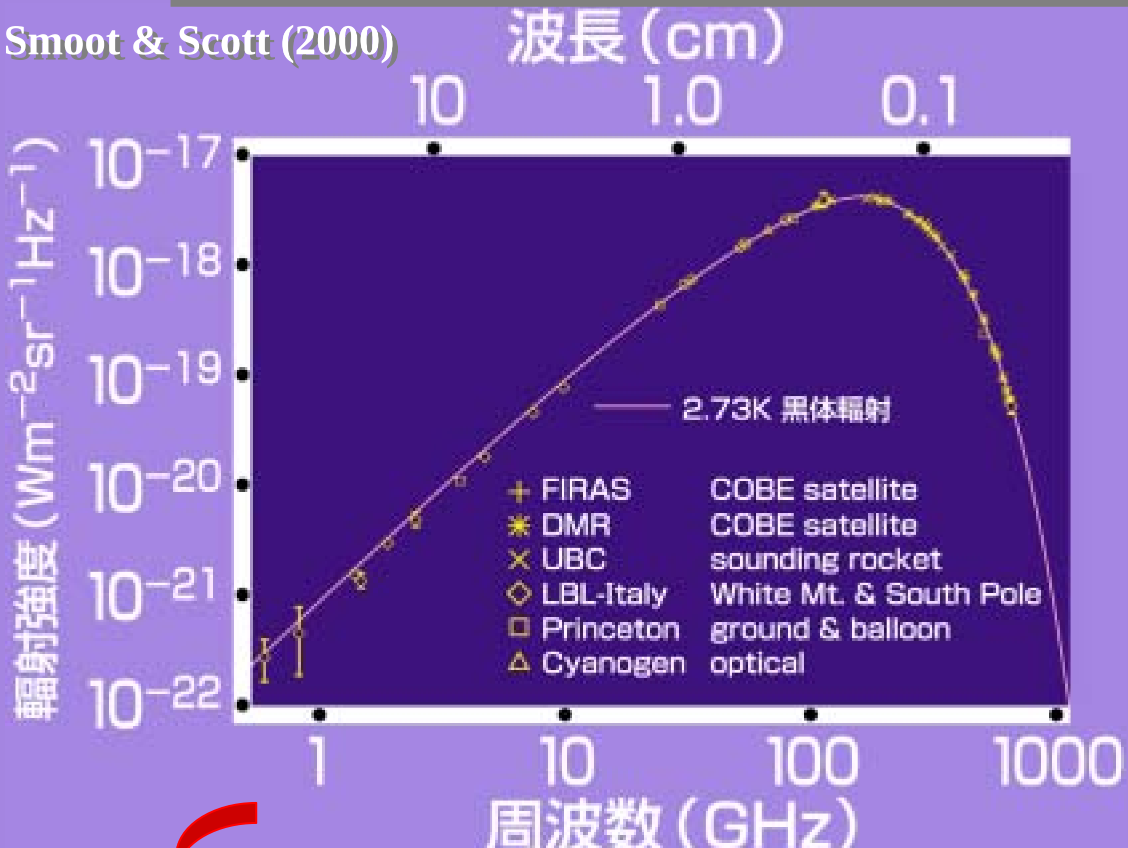
~~Send~~ Thank you for sending me your paper on 3 °K radiation. It is very nicely written except that "early history" is not "quite complete". The theory of, what is now knows as "primeval fireball" was first developed by me in 1946 (Phys. Rev. 70, 572, 1946; 74, 505, 1948; Nature 162, 680, 1948). The 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*.

CMB: エネルギースペクトル

■ 10^{-4}の精度で熱輻射分布（プランク分布）と一致

Smoot & Scott (2000)



温度T の熱平衡にある光子の単位時間・単位面積・単位周波数・単位立体角あたりのエネルギー分布

$$I_\nu = \frac{2h\nu^3}{c^2(e^{h\nu/kT}-1)}$$

ν：周波数、c：光速度
h：プランク定数
k：ボルツマン定数

温度T だけがパラメータ！

現在の“宇宙”の温度： $T_{CMB} = 2.728 \pm 0.002$ [K]

CMB: 全天温度地図

$T_{CMB} = 2.73\,[\mathrm{K}]$

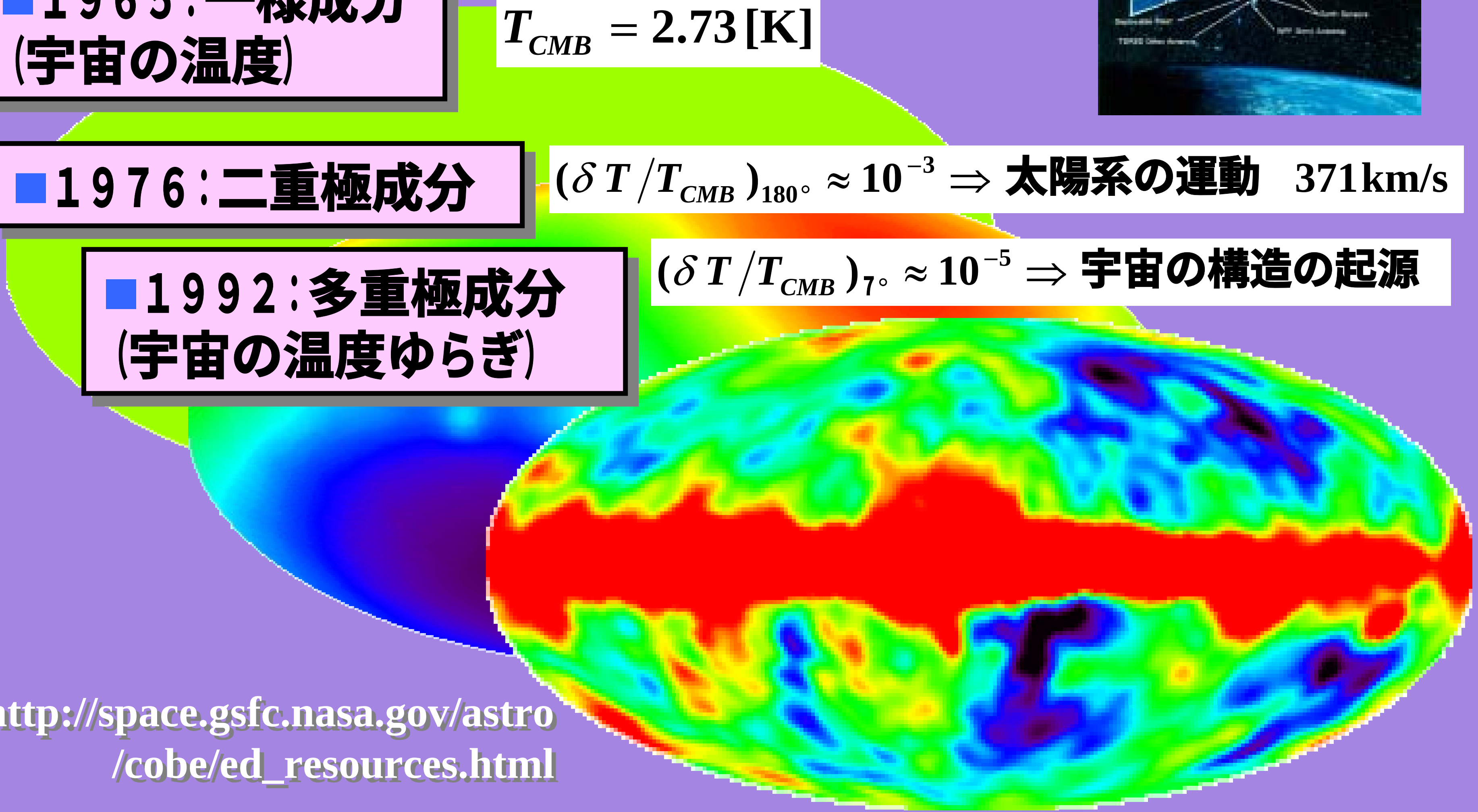
■1965：一様成分（宇宙の温度）

■1976：二重極成分

$(\delta T/T_{CMB})_{180^\circ} \approx 10^{-3} \Rightarrow$ 太陽系の運動　371km/s

■1992：多重極成分（宇宙の温度ゆらぎ）

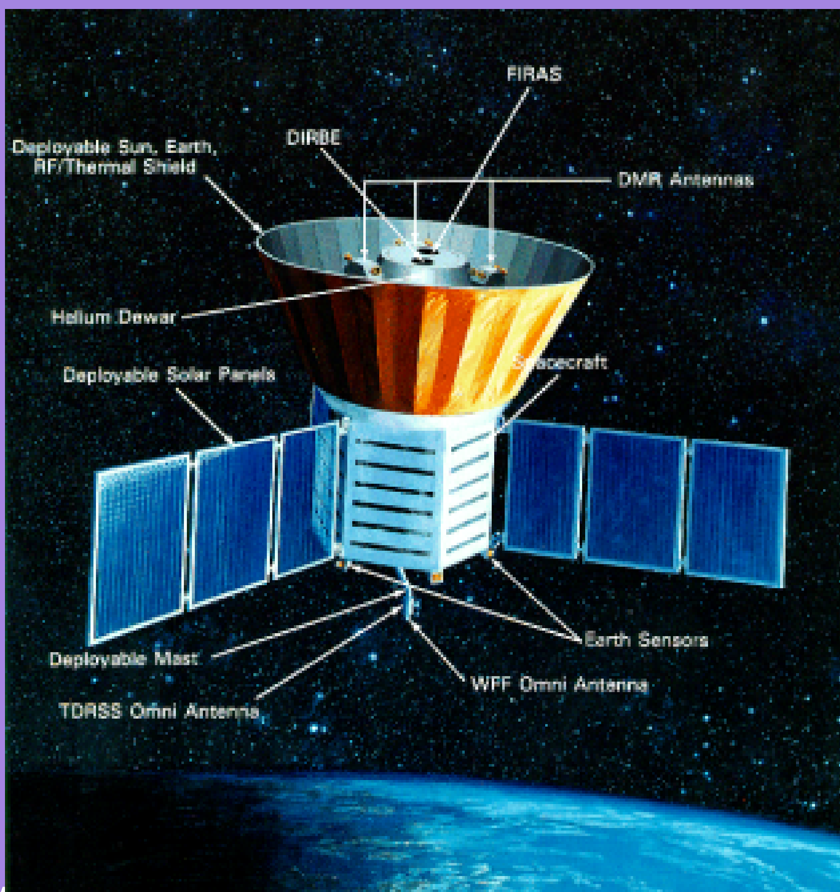
$(\delta T/T_{CMB})_{7^\circ} \approx 10^{-5} \Rightarrow$ 宇宙の構造の起源



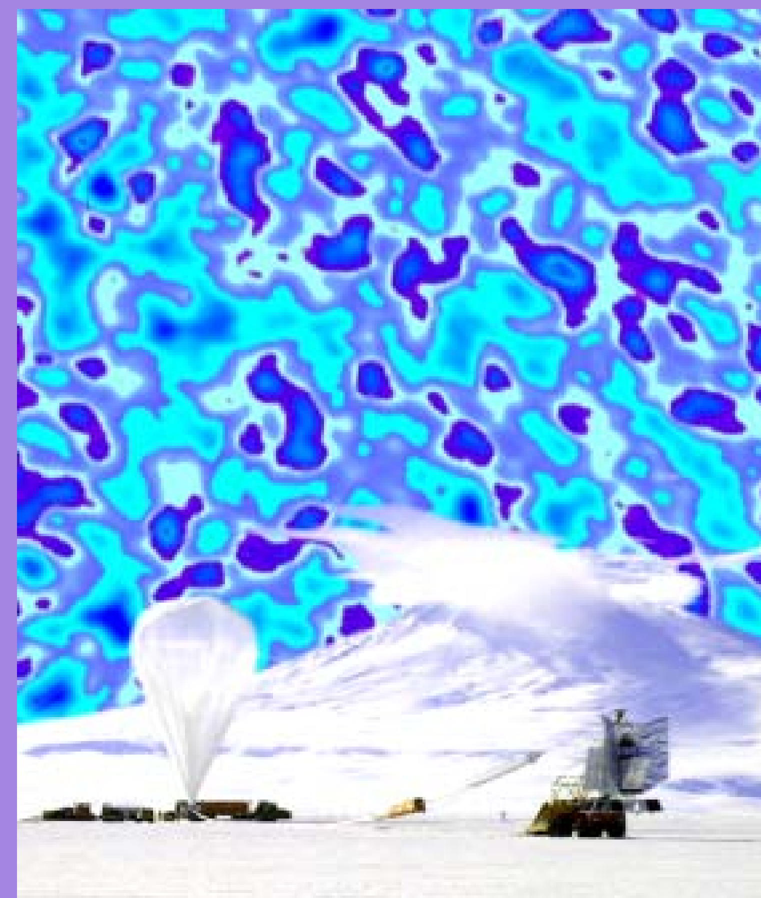
http://space.gsfc.nasa.gov/astro/cobe/ed_resources.html

CMB温度ゆらぎの観測

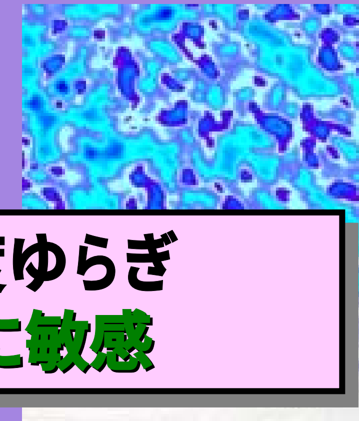
COBE　衛星
http://space.gsfc.nasa.gov/astro/cobe/ed_resources.html



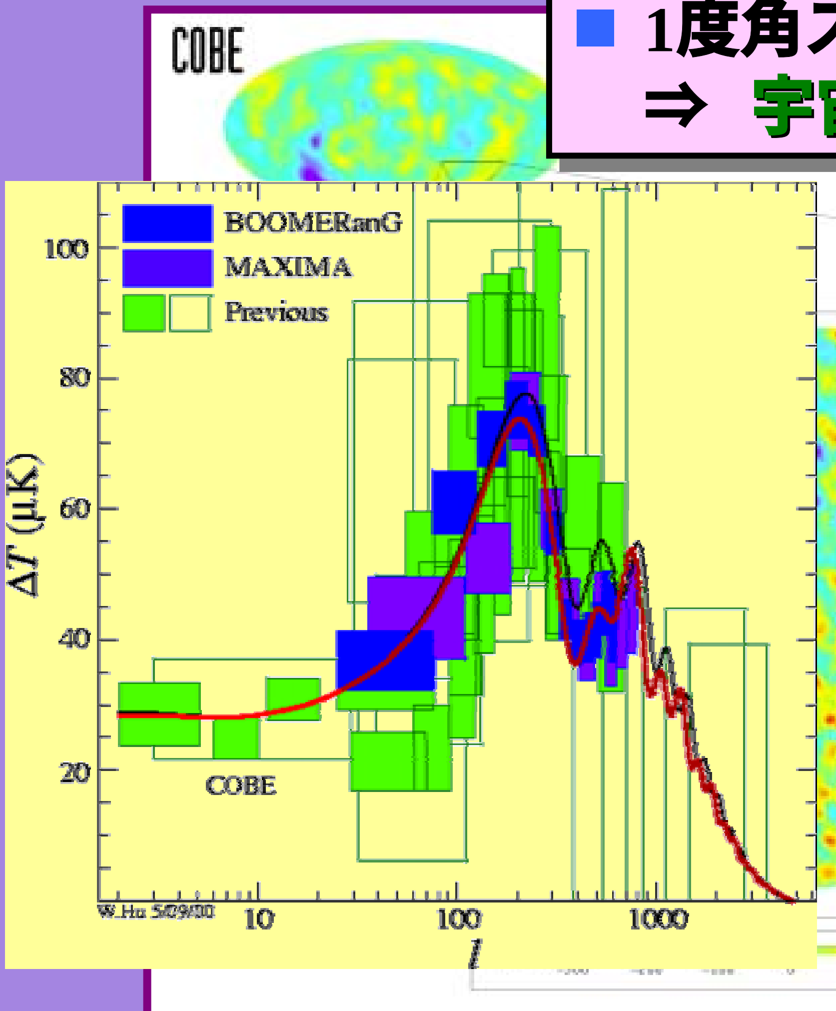
BOOMERanG　気球実験
http://www.physics.ucsb.edu/~boomerang

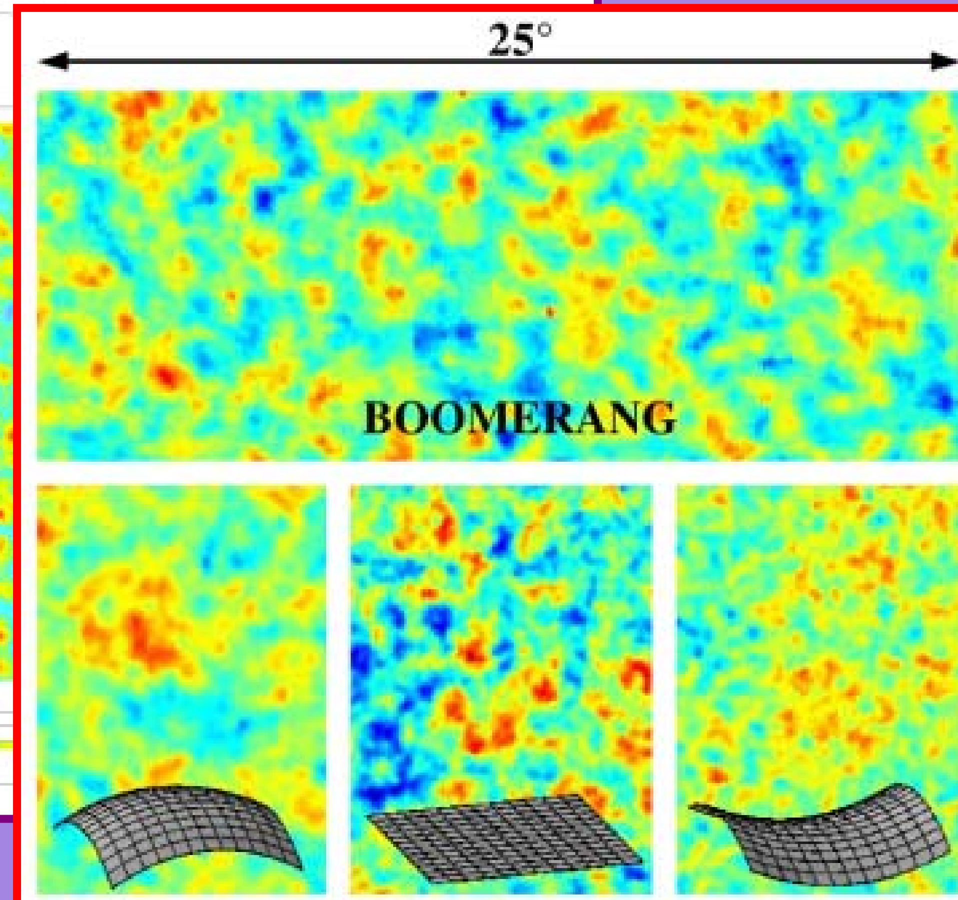


CMB温度地図と宇宙の曲率



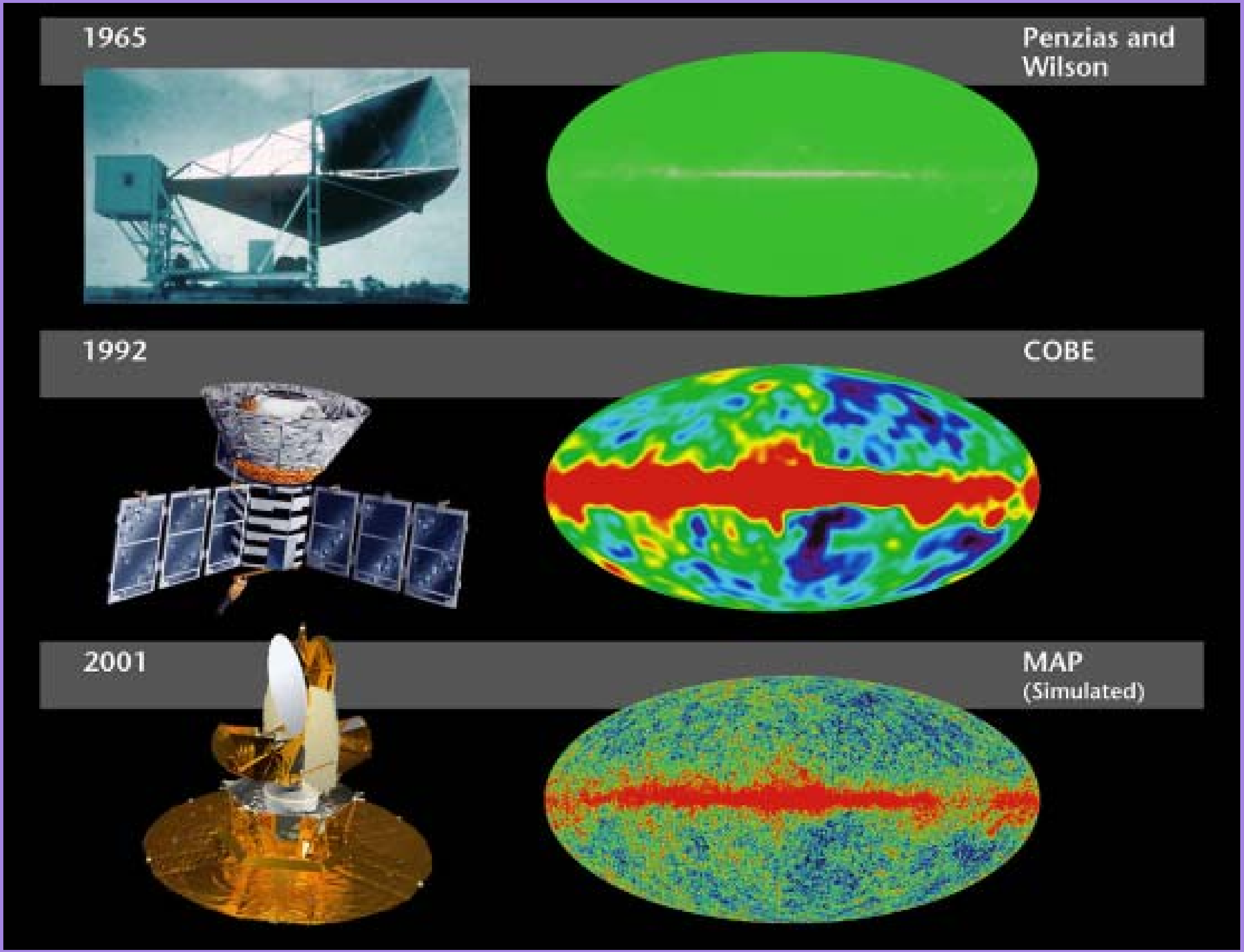
- 1度角スケールでのCMB温度ゆらぎ
  ⇒ **宇宙の曲率= $\Omega_0 + \lambda_0 - 1$ に敏感**





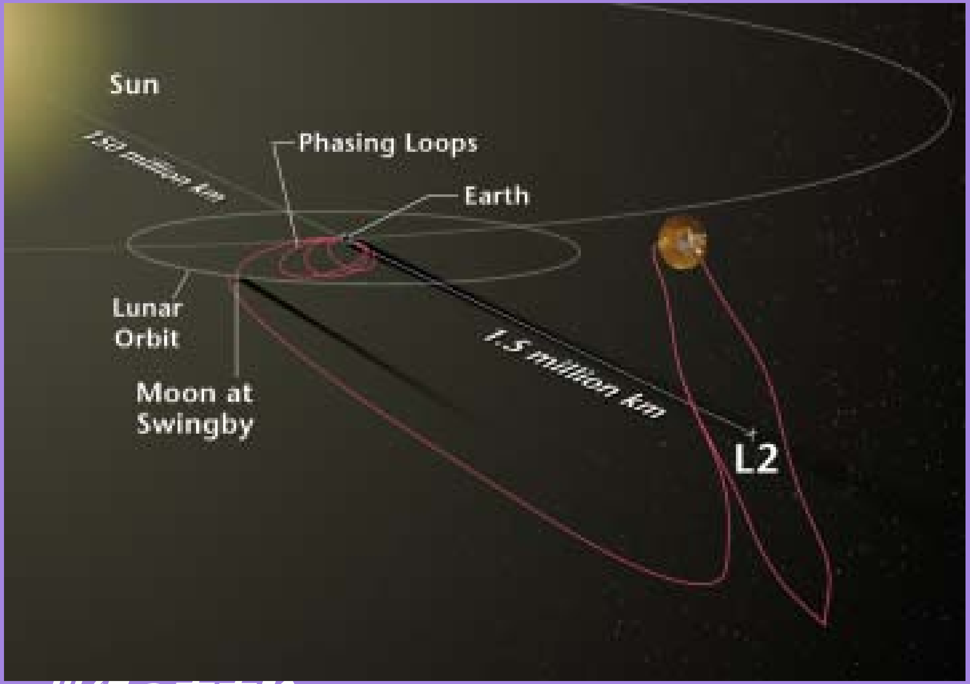
BOOMERanG 観測

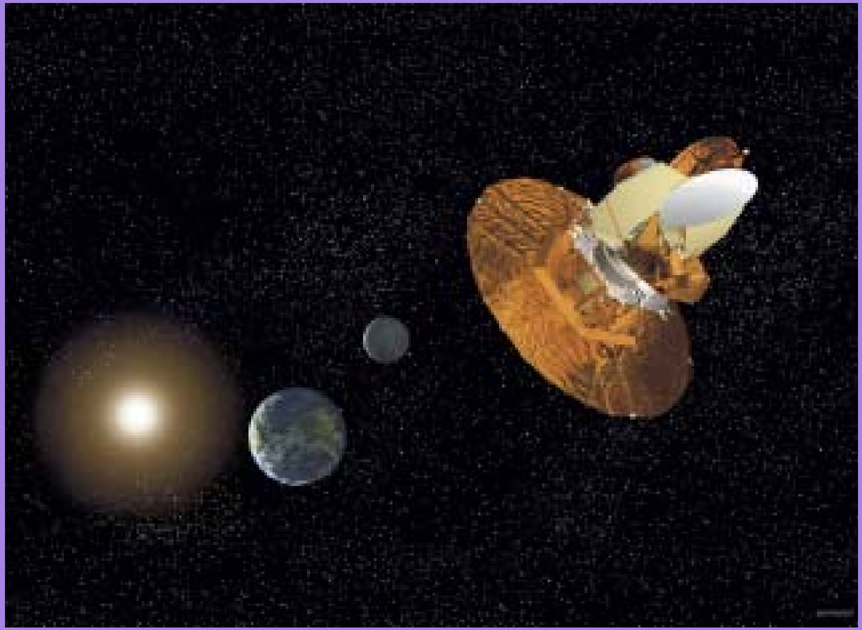
MAP (*M*icrowave *A*nisotropy *P*robe)衛星



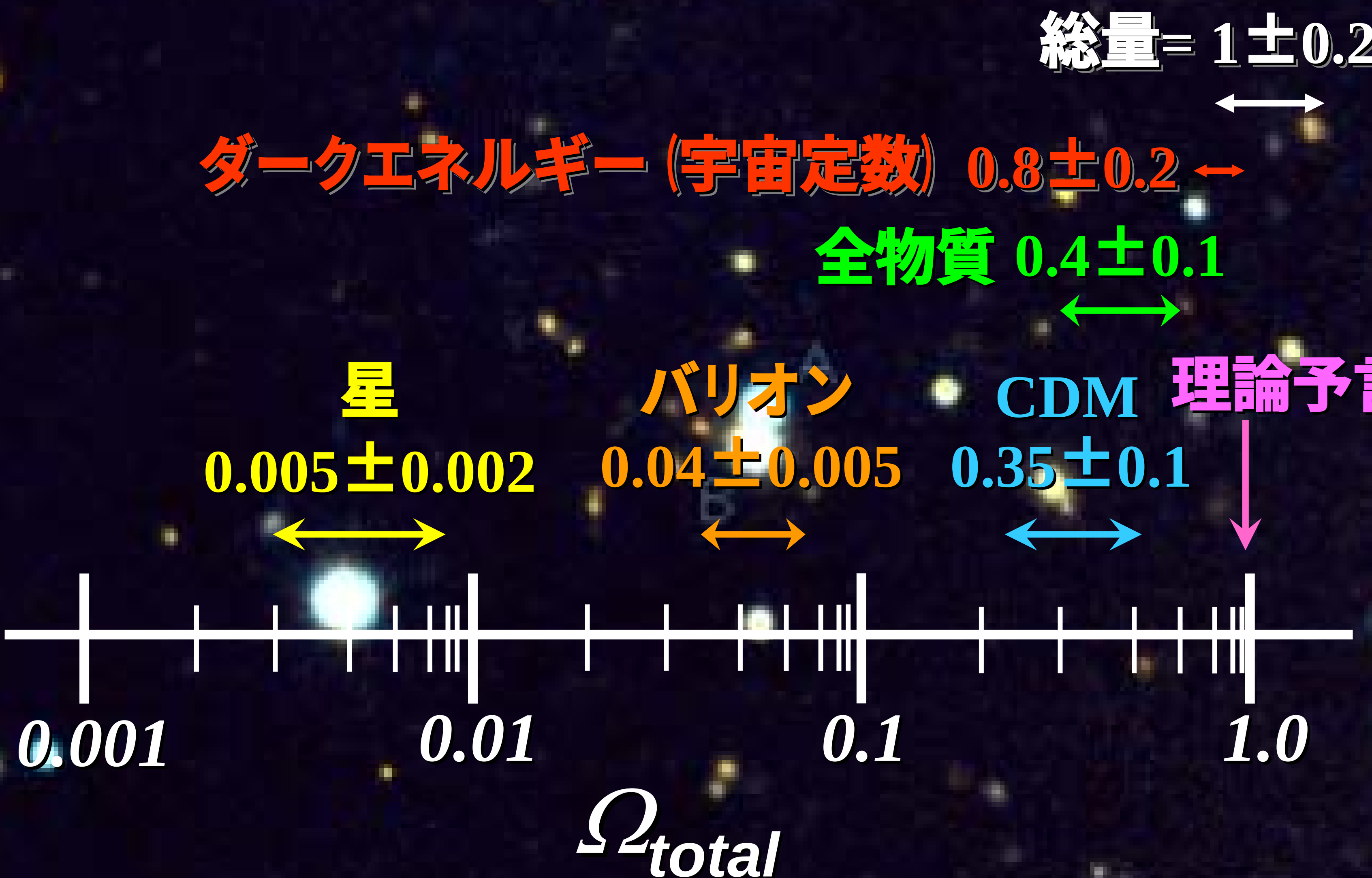
MAPの打ち上げ: 2001年6月30日15:46:46 EDT

MAP launched !



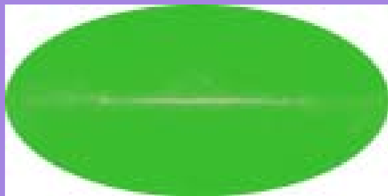


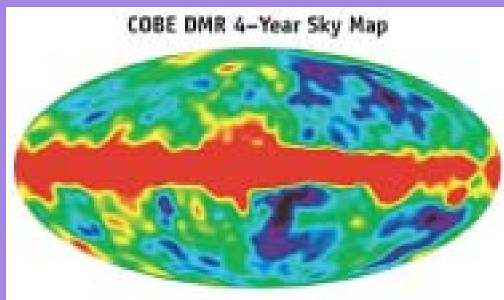
宇宙の質量密度の内訳

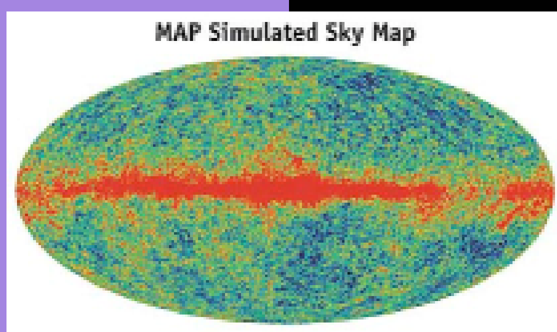


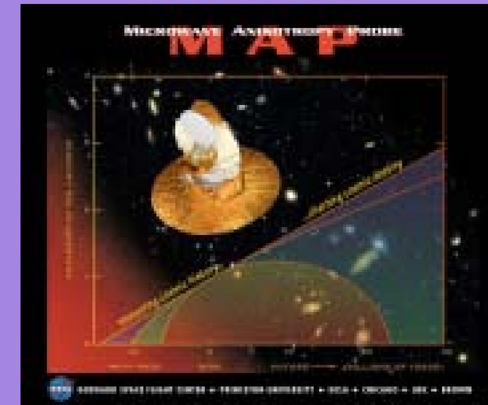
総量= 1±0.2
ダークエネルギー (宇宙定数) 0.8±0.2
全物質 0.4±0.1
星
0.005±0.002
バリオン
0.04±0.005
CDM
0.35±0.1
理論予言
0.001
0.01
0.1
1.0
Ωtotal

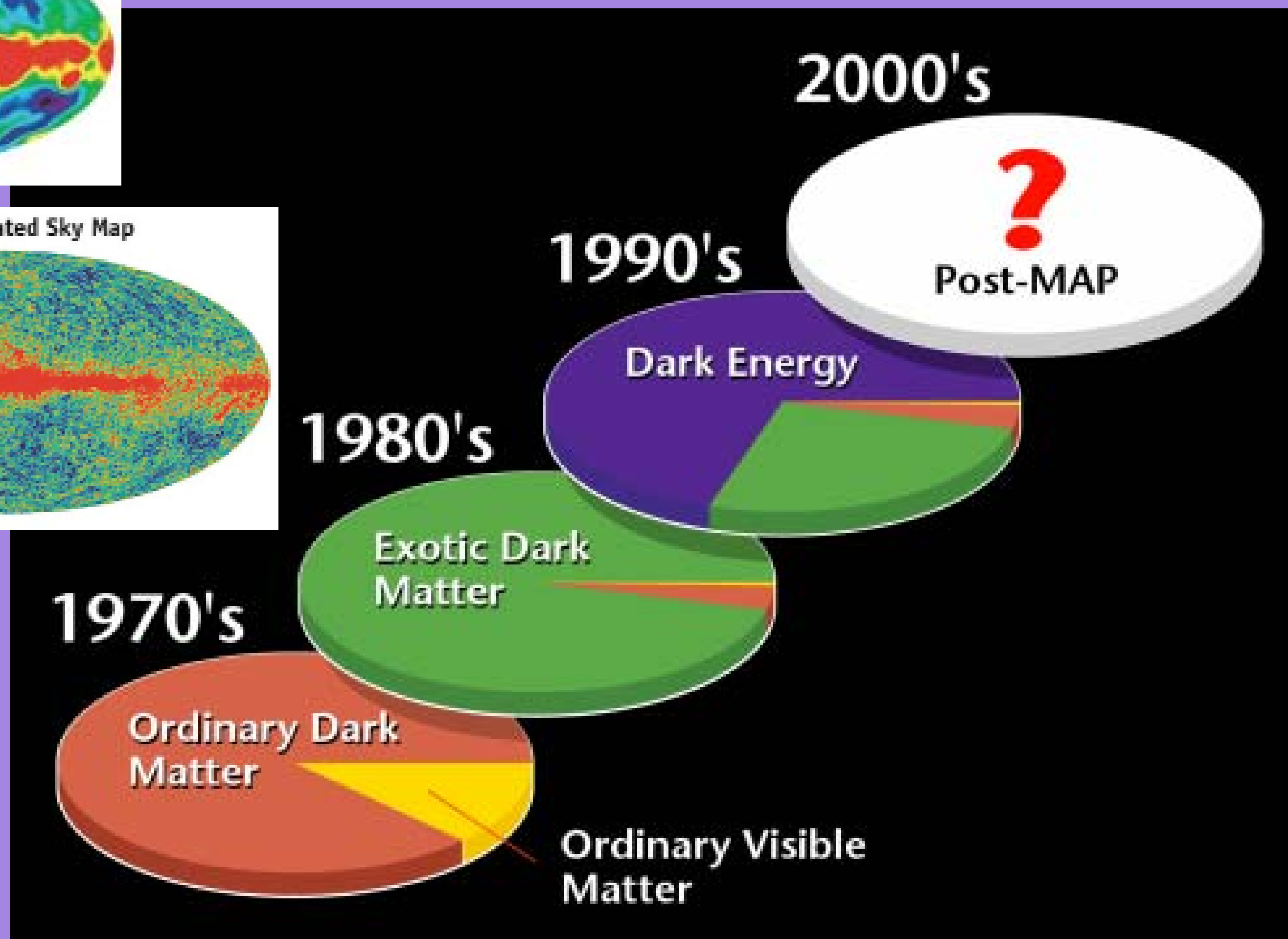
MAP Science




COBE DMR 4–Year Sky Map


MAP Simulated Sky Map




2000's
Post-MAP
1990's
Dark Energy
1980's
Exotic Dark Matter
1970's
Ordinary Dark Matter
Ordinary Visible Matter

20世紀宇宙論の総括

- 1980年代以降、宇宙論は急速に進歩
  - 暗黒物質の存在が決定的
  - マイクロ波背景輻射の温度ゆらぎ発見
  - ハッブル定数が10%の精度で決定される
  - 銀河系内MACHOの検出
  - 宇宙定数が存在する可能性
  - 素粒子論的宇宙論による初期条件
- 物理科学として十分成熟･発展を遂げた

21世紀宇宙論の展望

- 20世紀最後の数年間で急速に進展した宇宙を特徴付けるパラメータの値をさらに確定

  ⇒ **精密宇宙論の時代へ**
- 宇宙の起源の理論的解明

  ⇒ **量子宇宙論の完成へ**

  (素粒子論の進展を待つしかない、、、)
- さらなる謎・未知の領域を探る

  ⇒ **第一世代の原始天体**

  生命誕生の環境としての宇宙

研究の漸近的振る舞い？

The historical record here and in other physical sciences suggests that as the puzzles and conundrums we know about are laid to rest, they will be replaced by still more interesting ones.

宇宙論界の重鎮： P.J.E.Peebles (1993)

``Principles of Physical Cosmology'' p.683

Expanding the *expanding* universe

0th order	一様等方宇宙モデル	宇宙論パラメータ
1st order	密度揺らぎの線形摂動論	宇宙の大構造 マイクロ波背景輻射
2nd order	非線型重力進化	ダークマターの構造形成
3rd order	バリオンガスの進化	第一世代天体と元素の起源
4th order	銀河、星、惑星の形成進化	光り輝く銀河宇宙の誕生
・・・		
L-th order	生命の起源・進化	宇宙論的生物発生学
M-th order	知的生命体への進化	宇宙論的生物進化学
N-th order	文化・文明・宗教	宇宙論的社会学
・・・		

宇宙論研究はまだ始まったばかり ！

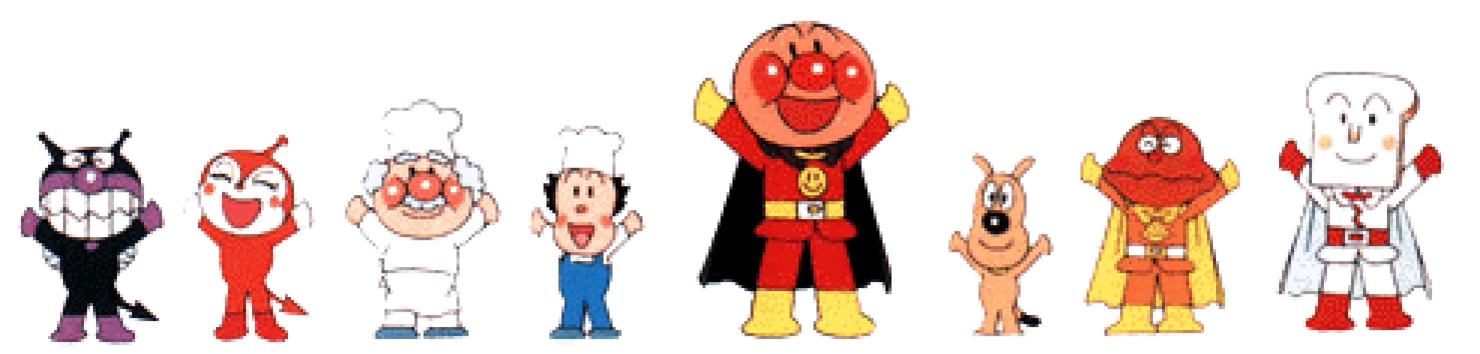
栄枯盛衰：研究の花道のパターン

- **パターン I:** すべての重要な問題に答を見つけて栄誉ある終焉を迎える
- **パターン II：**徐々にではあるが着実に理論的進歩を遂げることで少しずつ歴史的な難問を解決しながら半永久的に発展を続ける
- **パターン III：**重要な問題を多く残していながら、観測的にも理論的にも新 たなブレークスルーを見出すことができず、もはや普通の問題意識 とは遊離した重箱の隅をつつくような研究に終始するオタク集団としてほそぼそと生きながらえていく

アンパンマン オープニングテーマ

■作詞：やなせたかし

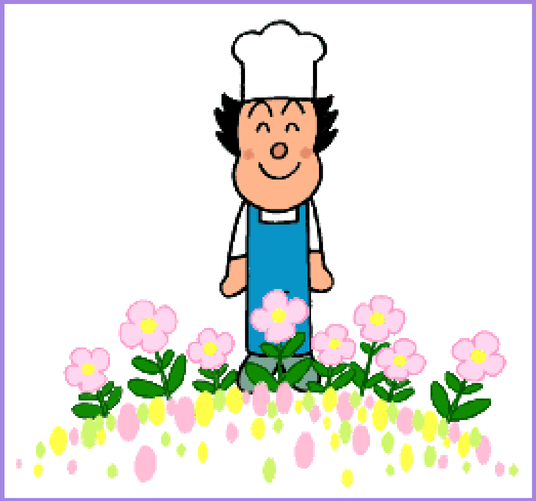
なんのために生まれて
なにをして生きるのか
こたえられないなんて
そんなのは　いやだ！



アンパンマン
エンディングテーマ

■ 作詞：やなせたかし

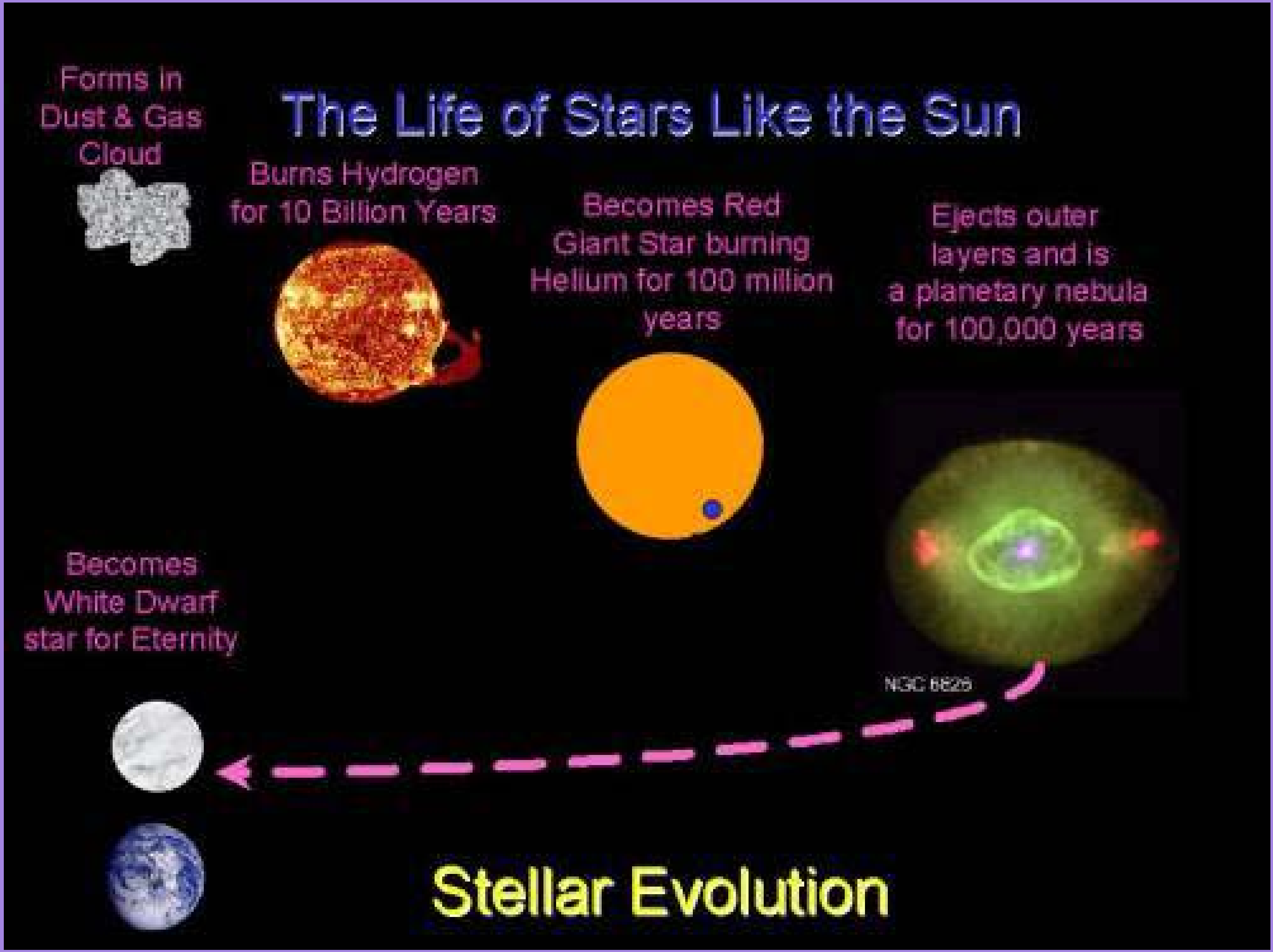
もし自信をなくして
くじけそうになったら
いいことだけ
いいことだけ
思い出せ



４．宇宙定数（暗黒エネルギー）

$$\lambda_0 = 0.7$$

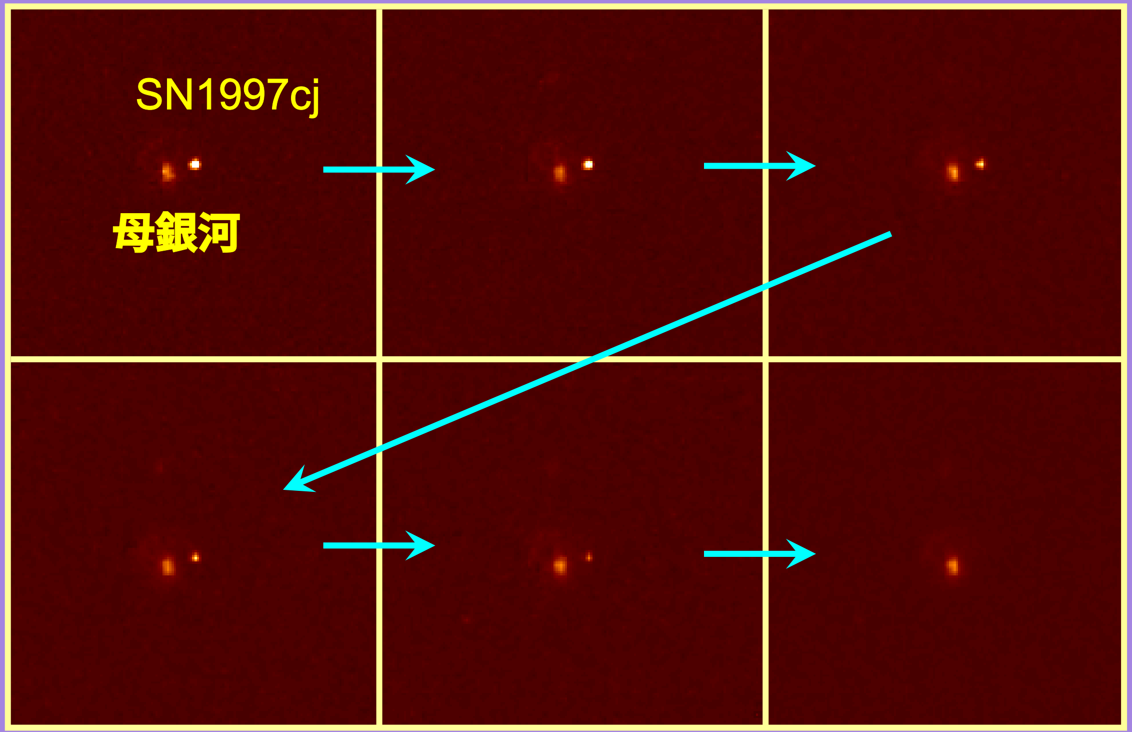
超新星爆発



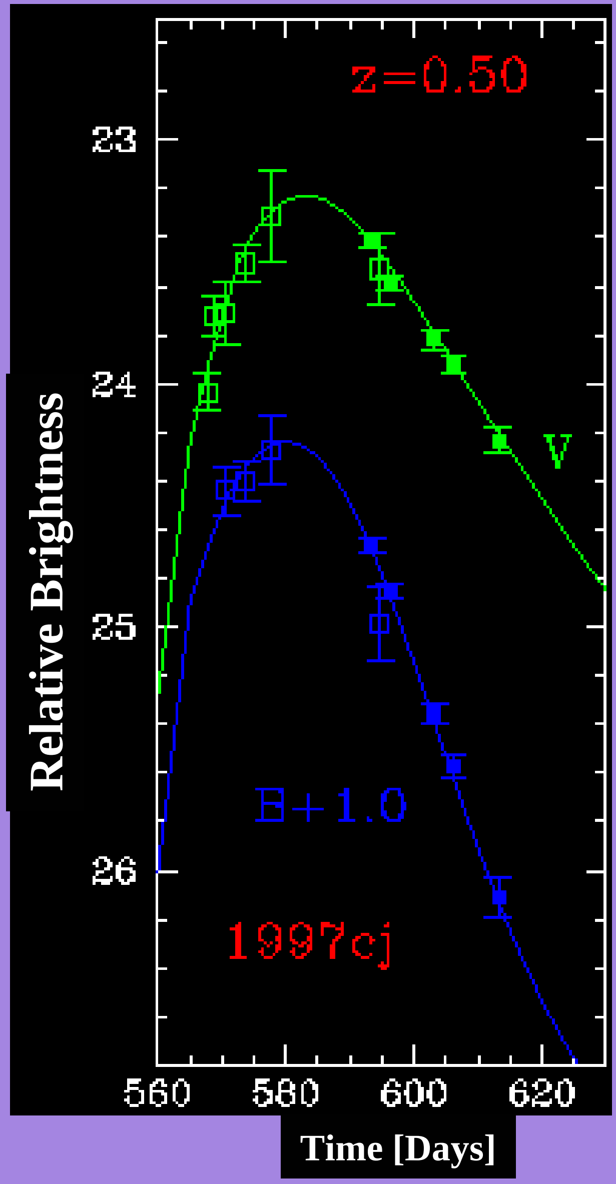
The Life of Stars Like the Sun
Forms in Dust & Gas Cloud
Burns Hydrogen for 10 Billion Years
Becomes Red Giant Star burning Helium for 100 million years
Ejects outer layers and is a planetary nebula for 100,000 years
NGC 6826
Becomes White Dwarf star for Eternity
Stellar Evolution

Ia型超新星の光度曲線の測定

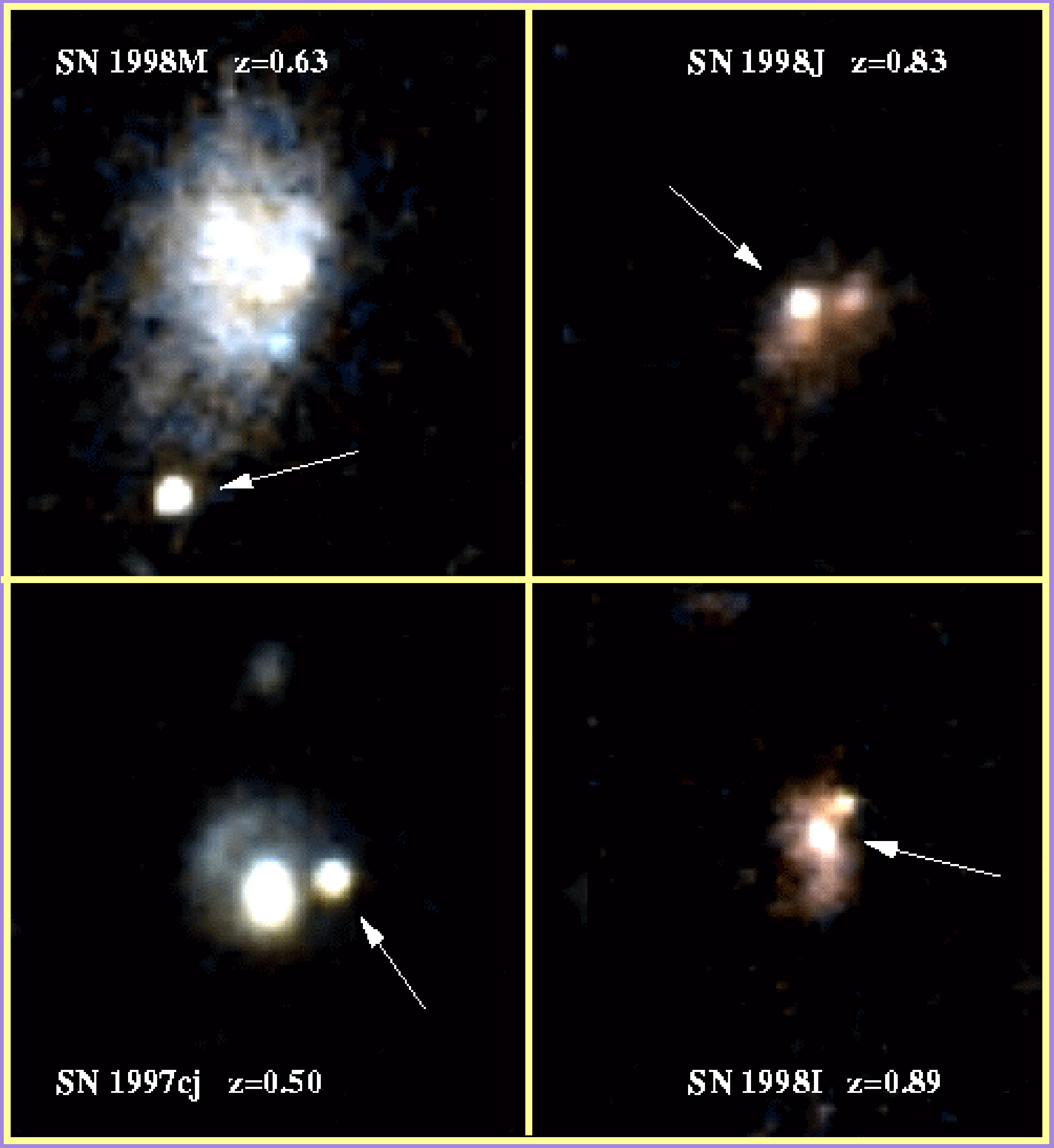
- 現在距離の知られているすべてのIa型超新星の最大絶対光度は約10パーセントの精度で一致
- Ia型超新星を発見し、定期的にその光度変化をモニターできれば距離決定の標準光源となる



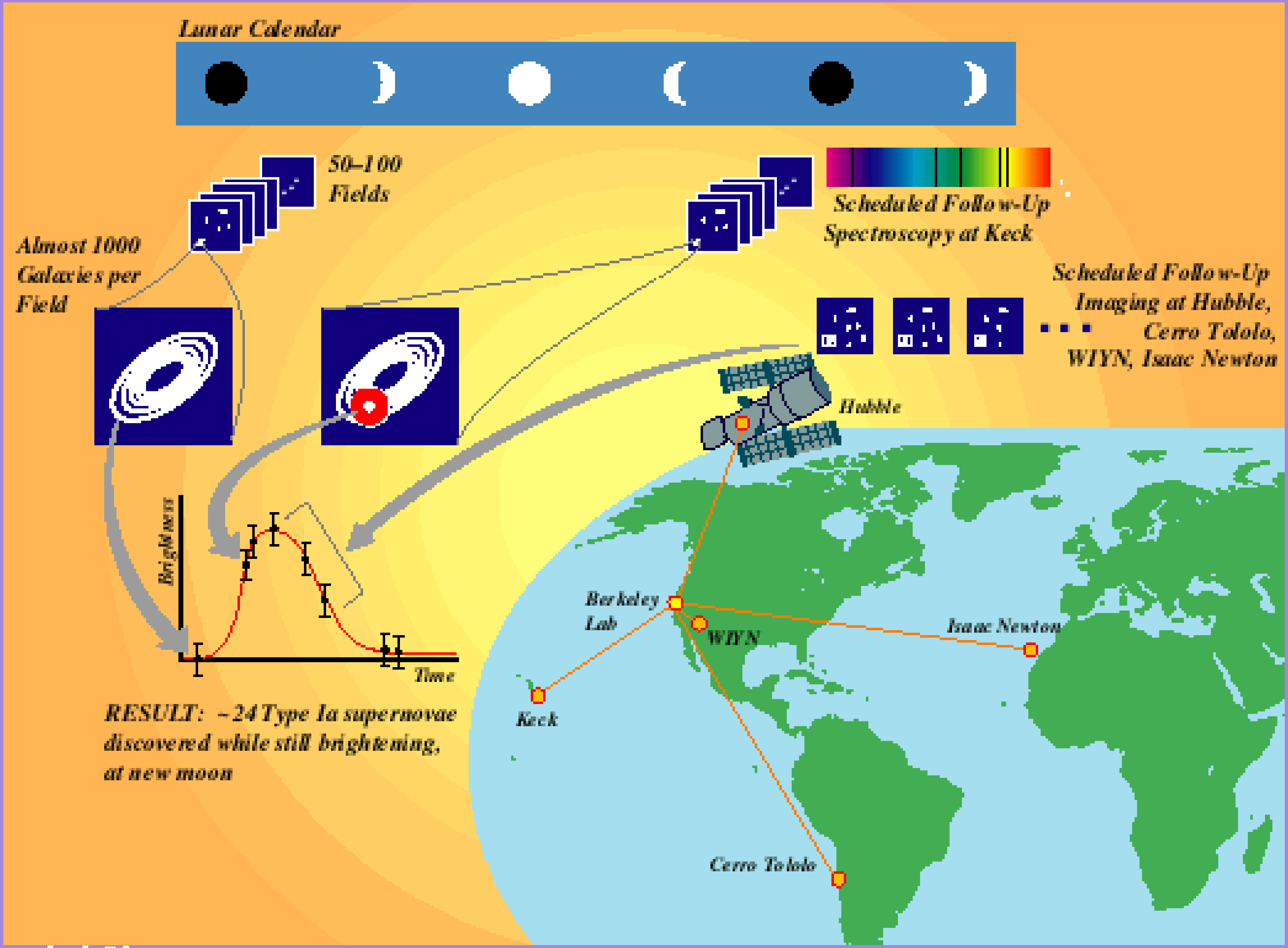
HSTで測定したSN 1997cjの明るさの時間変化



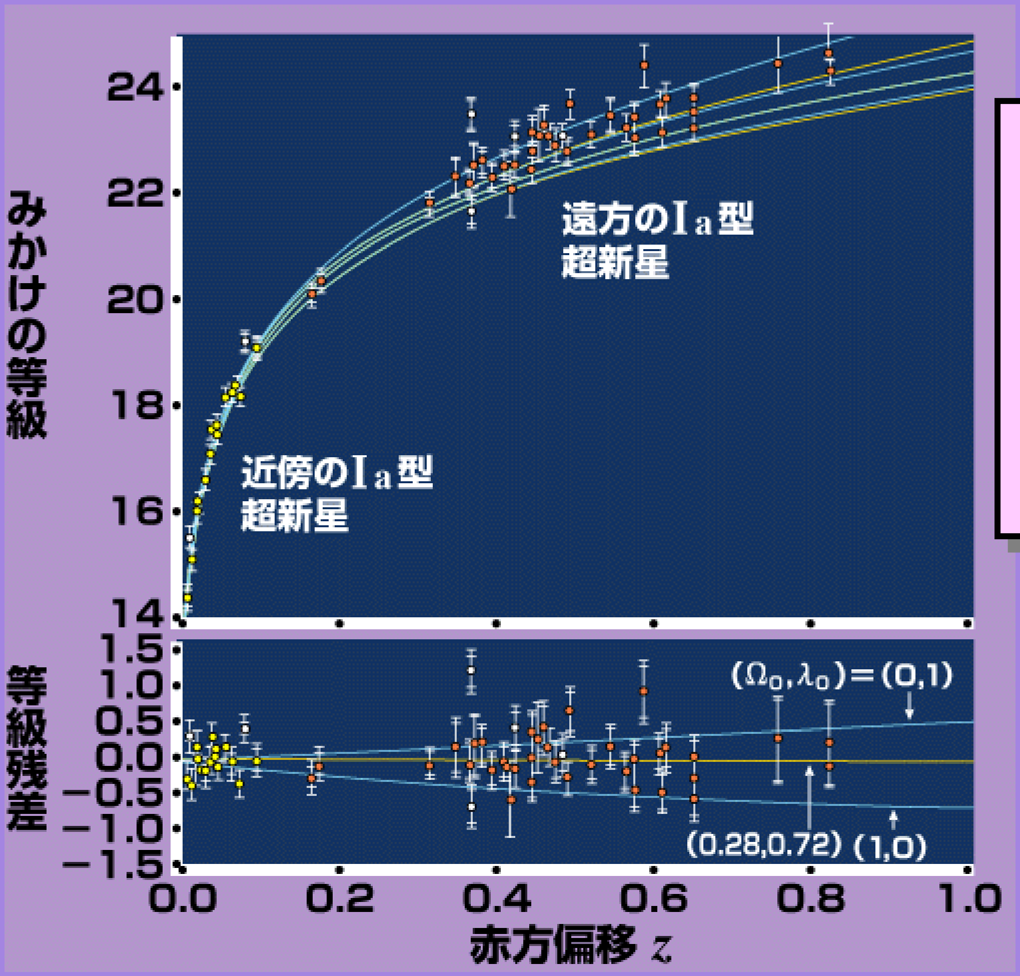
遠方のIa型超新星のHST画像例



Supernova Cosmology Project: Strategy



超新星と宇宙定数



- 遠方超新星までの距離推定

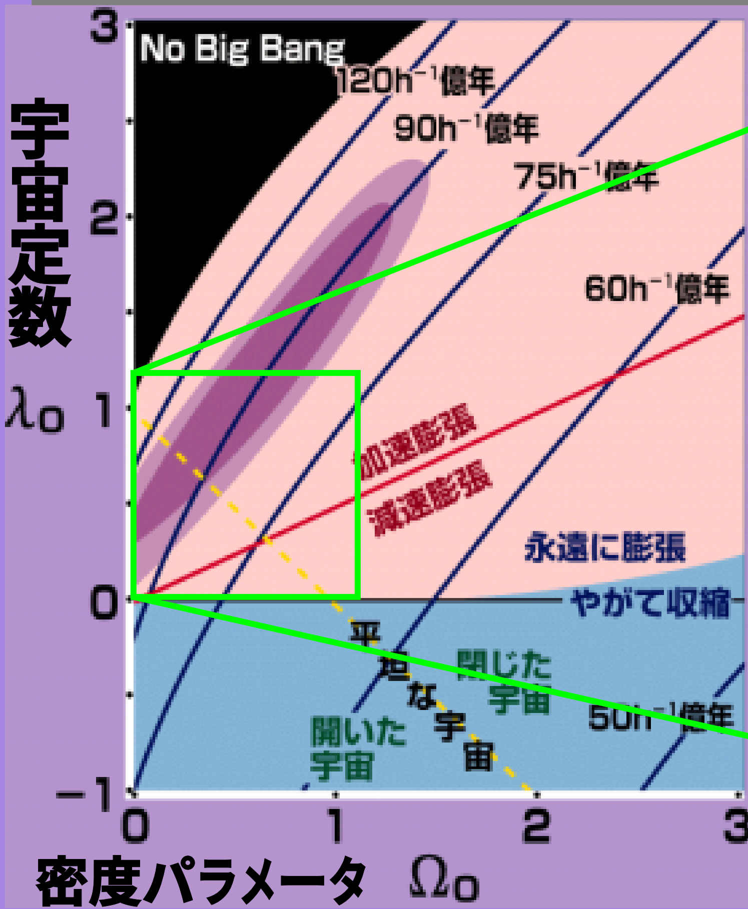
⇒ $\Omega_0 \ll 1$, $\lambda_0 > 0$

宇宙定数の存在！

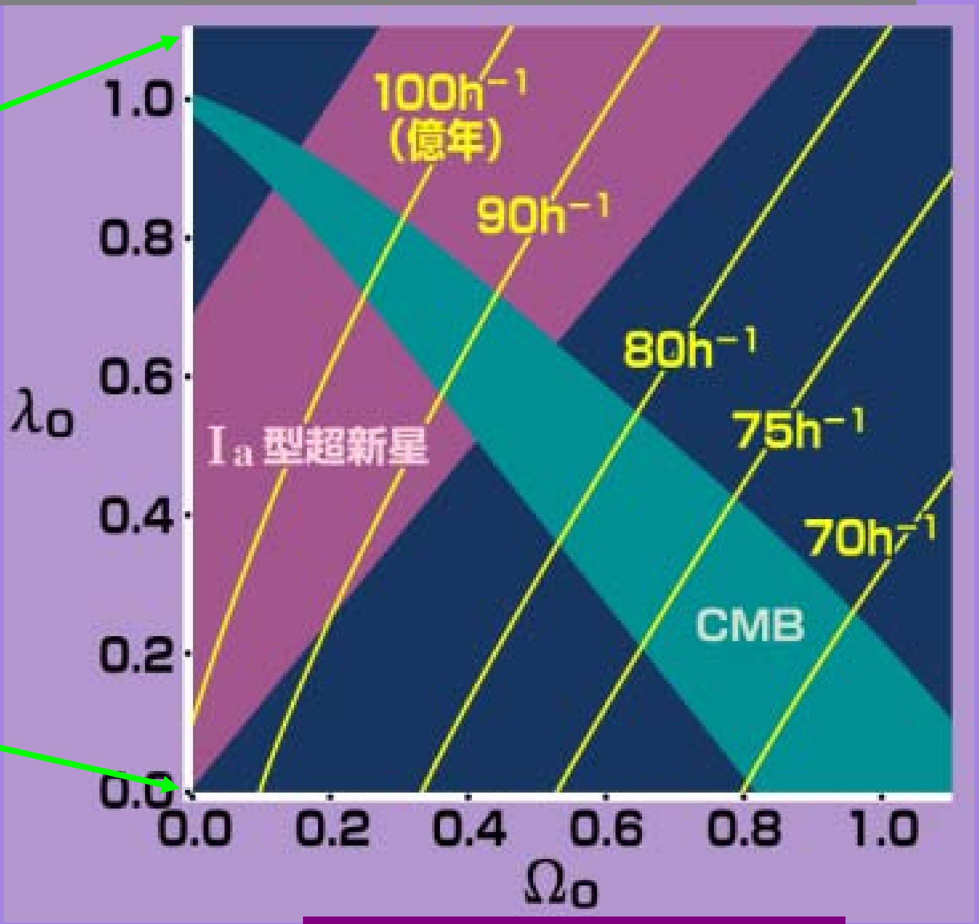
Perlmutter et al. :
The Astrophysical Journal
517(1999)565

質量密度パラメータと宇宙定数

■ $\Omega_0=0.3,\ \lambda_0=0.7$ ⇒ 宇宙は平坦 ($k_0=0$) ?



超新星観測からの制限



CMB 観測からの制限