宇宙科学I (文科生)
宇宙の創世

土井靖生

2019/7/17(補講)

今回のポイント

- 宇宙は「ビッグバン」により始まった
  - 宇宙膨張・元素合成・宇宙背景放射の3つをきれいに説明
- 近年はより詳細な観測により、ビッグバン宇宙論はますます確実視されている
  - 宇宙は「通常の物質」「ダークマター」「ダークエネルギー」から成る

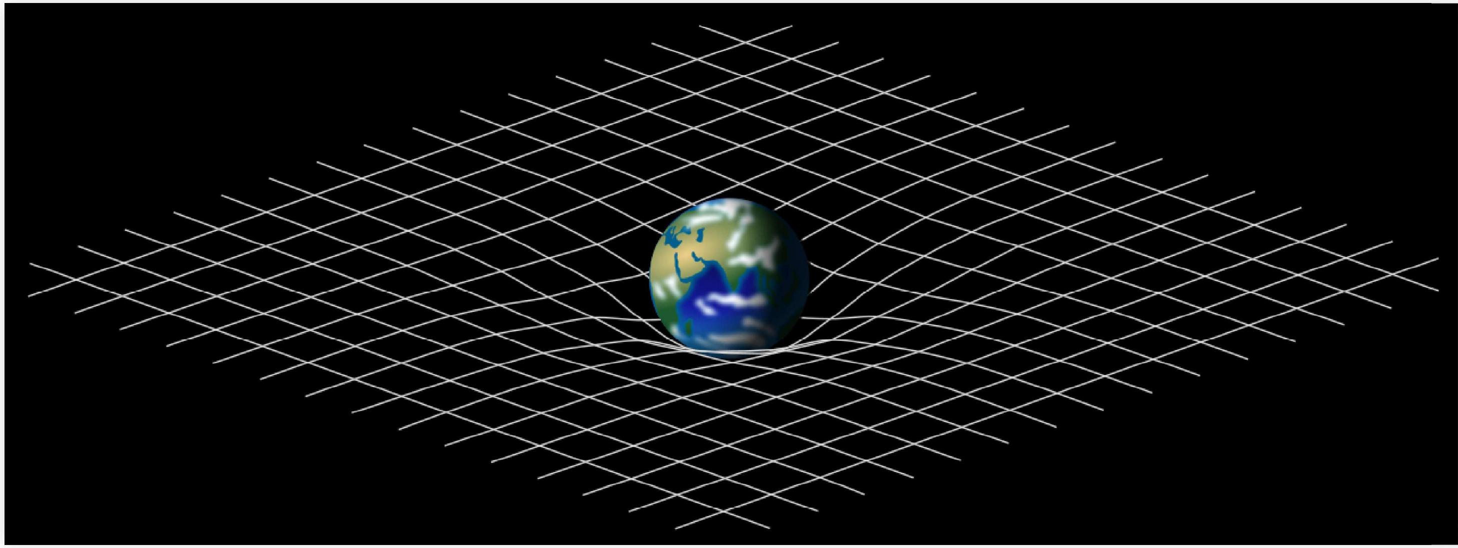
膨張宇宙論

アインシュタイン方程式 一般相対性理論 (Einstein 1915)

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

空間の曲率 ＝ エネルギー分布

($E = mc^2$ より、物質とエネルギーは等価であることに注意。)



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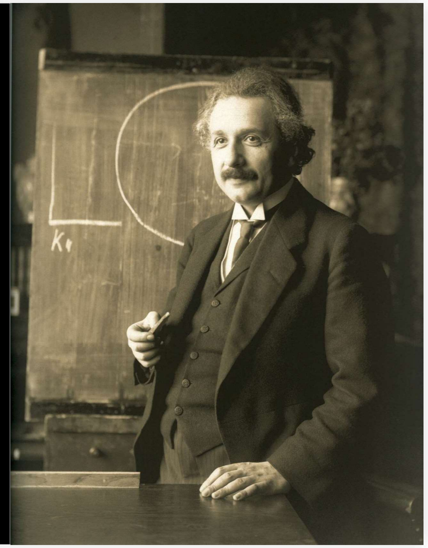

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重力で引き合い宇宙は潰れてしまい安定に存在出来ない。

「宇宙項」の導入 (Einstein 1917)

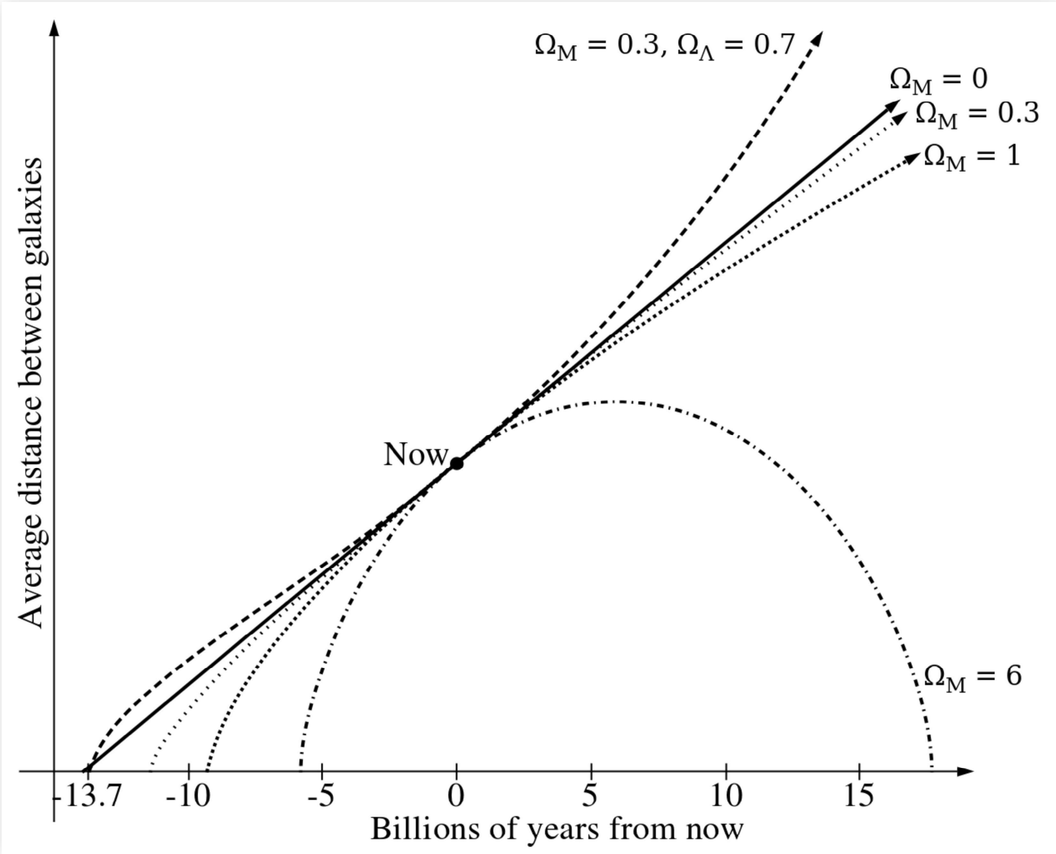
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

空間の曲率 ＋ 宇宙項 ＝ エネルギー分布

- 宇宙項：重力に逆らって空間を押し広げる力
- 安定した宇宙(静止宇宙)を実現するために導入
  - 後に取り消す

膨張する宇宙の予言 (Friedmann他 1922)

- 宇宙空間が膨張・収縮を続けると考える
- 宇宙の物質総量(と最初の膨張速度)で宇宙の運命が決まる
  - **宇宙は永遠ではない**



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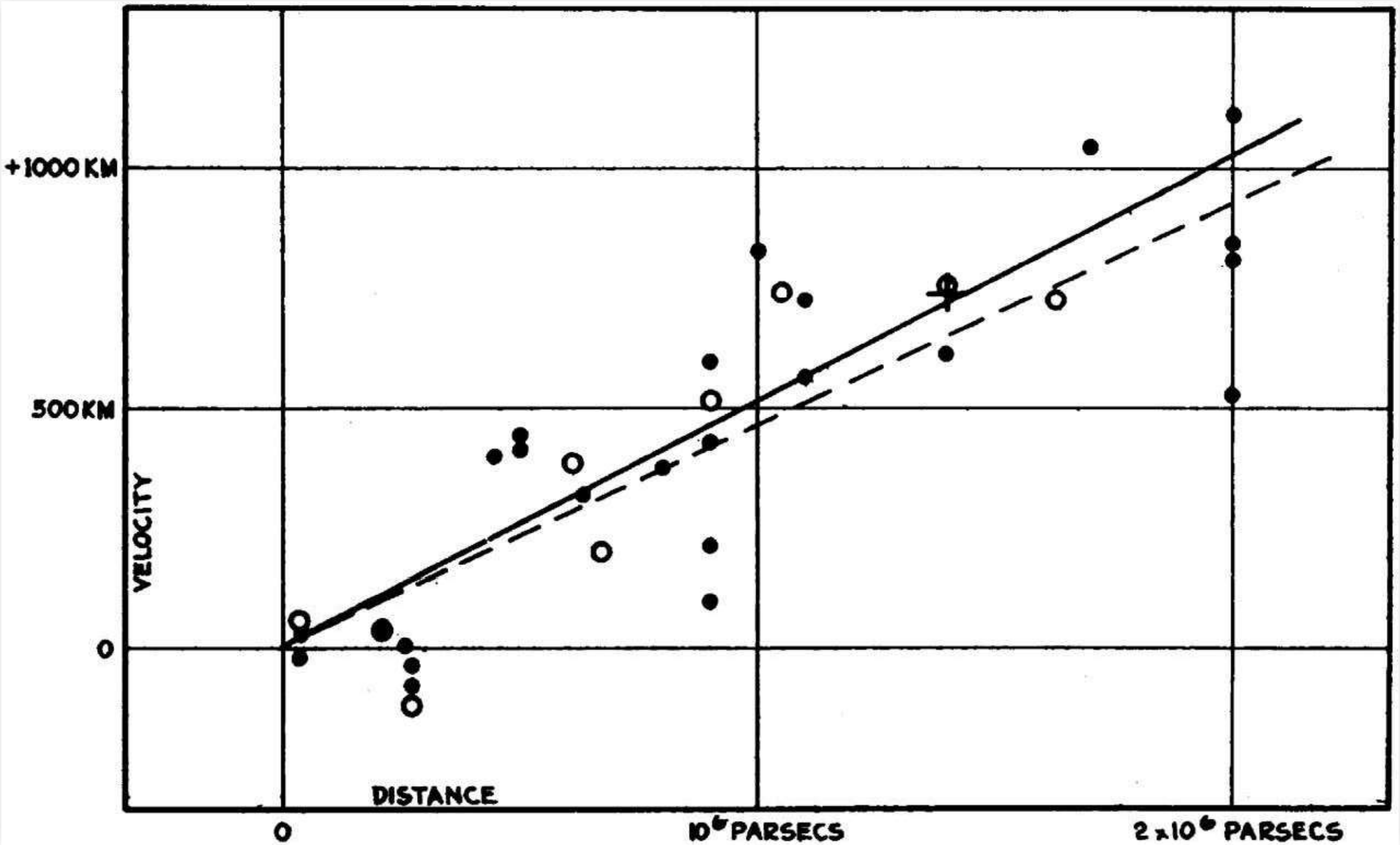
宇宙膨張の発見

ハッブルによる銀河後退の観測 (Hubble 1929)



Hubble, E. 1929, *Proceedings of the National Academy of Science*, **15**, 168

Wikipedia

横軸はセファイドから求めた距離: $10^6, 2 \times 10^6$ pc = 326万, 652万光年

このグラフの傾き:「ハッブル定数」$\left(\mathrm{km\ s^{-1}\ Mpc^{-1}}\right)$

宇宙の膨張による銀河の後退

- 静止宇宙 vs. 膨張宇宙 → 膨張宇宙論の確立

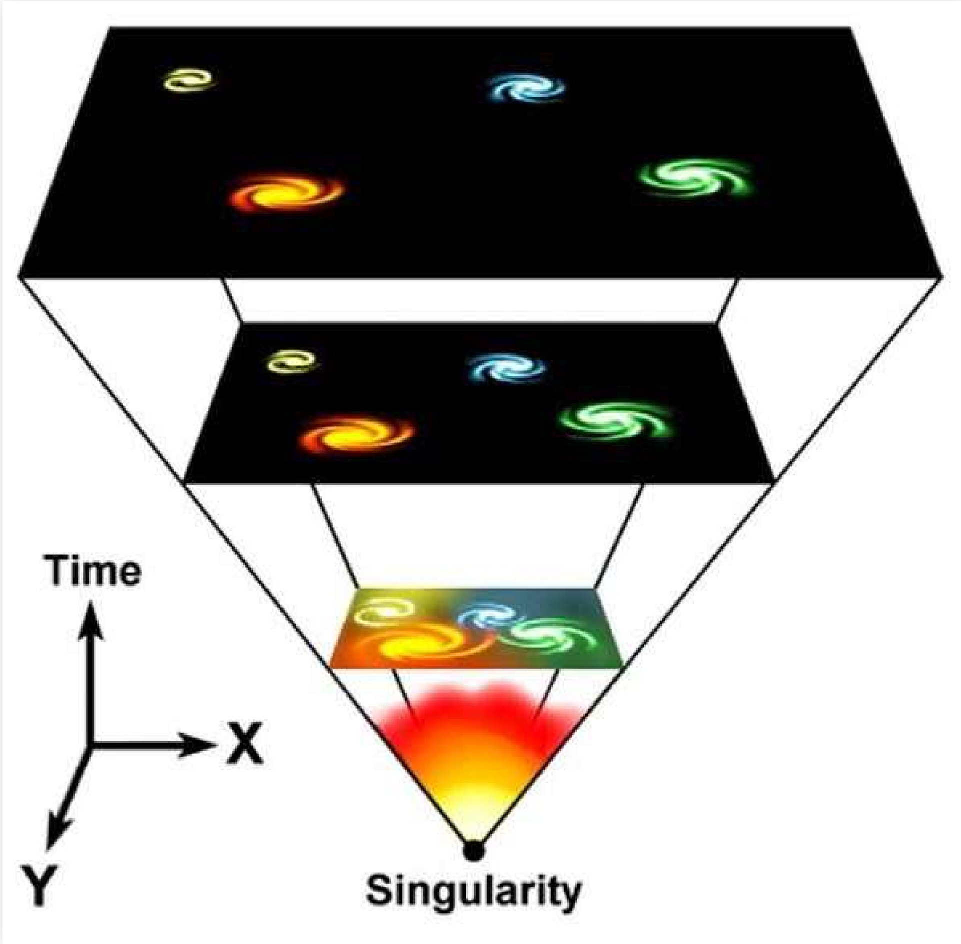


Image credit: Wikimedia Commons uploader Llull; image is public domain under CC-BY-SA-2.0.

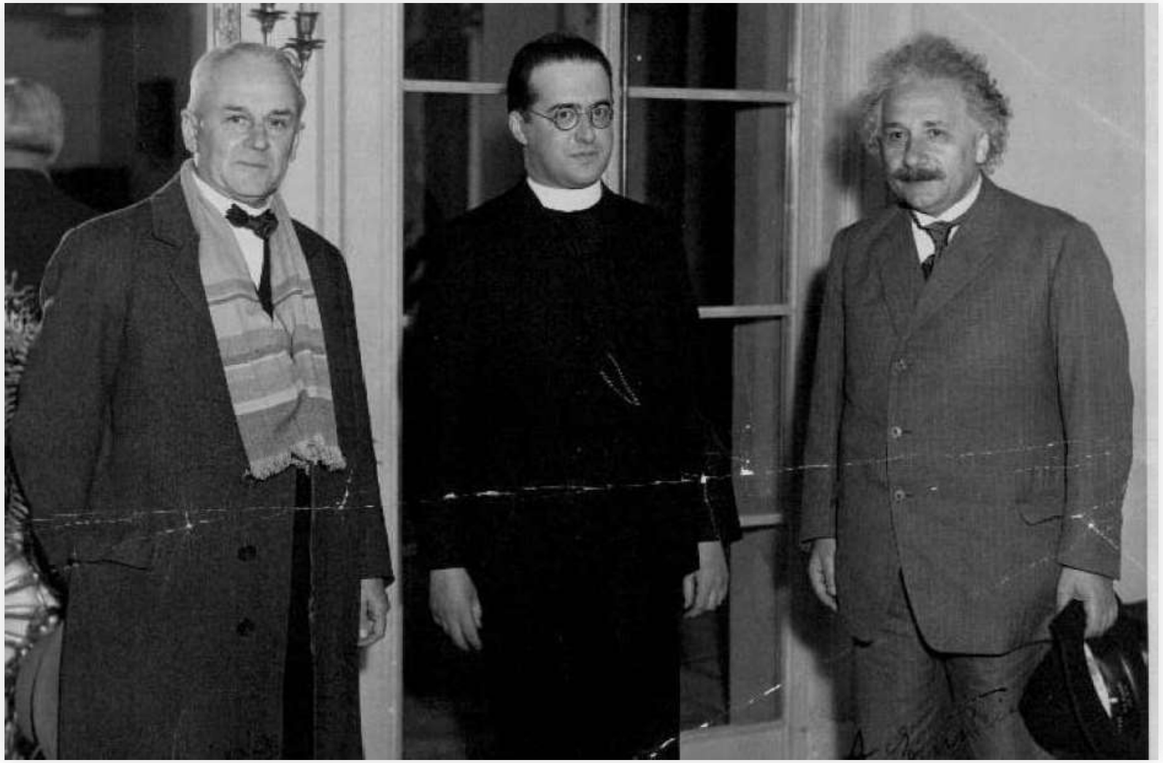
宇宙膨張の発見者

- ハッブルの論文発表は1929年
- ジョルジュ・ルメートルが同様の結果を1927年に発表
  - 論文タイトル「系外銀河の後退速度から導かれる質量一定で半径の増大する宇宙」
  - 1925年にスライファーが測定した赤方偏移と1926年にハッブルが発表した銀河までの距離とを組み合わせた成果
  - ベルギーの無名の仏語誌「ブリュッセル科学会年報（Annales de la Société Scientifique de Bruxelles）」に発表したため注目されず

宇宙膨張の発見者(続)

- 1931年に英王立天文学会月報 (Monthly Notices of the Royal Astronomical Society) の招きで論文の英訳を発表
  - **宇宙膨張に関する個所が何故か削除される**
- 削除はルメートル自身の希望だったことが確認される

(Livio 2011, *Nature*, **479**, 171–173)



ルメートル(中央)。両側はミリカンとアインシュタイン。

「ハッブル-ルメートルの法則」

- 「宇宙の膨張を表す法則は今後『ハッブル-ルメートルの法則』と呼ぶことを推奨する」(2018年10月 国際天文学連合による決議)
- 「ハッブルの法則」を「ハッブル-ルメートルの法則」に次第に移行することを推奨 (2018年12月26日 日本学術会議提言)
    1. 学校教育で用いられる教科書における記述変更は直近の改訂時に対応する。それまでは教科書に対する特別の補充資料は作らず、現場での解説で対応する。
    2. 各種試験で、宇宙膨張の法則の名称そのものを問うて、『ハッブルの法則』か『ハッブル-ルメートルの法則』かによって解答の正否が分かれるような問題は出さない。
    3. 学校教育現場に限らずしばらくの期間は、『ハッブルの法則』と『ハッブル-ルメートルの法則』のどちらが使われていても問題とはしない。
    4. 一般書やマスコミ等の記述、講演会などで用いる名称は担当者次第であるが、IAU 決議の趣旨を踏まえて『ハッブル-ルメートルの法則』を用いることが望ましい。

“ハッブル定数”と宇宙の年齢

ハッブル定数の最新値

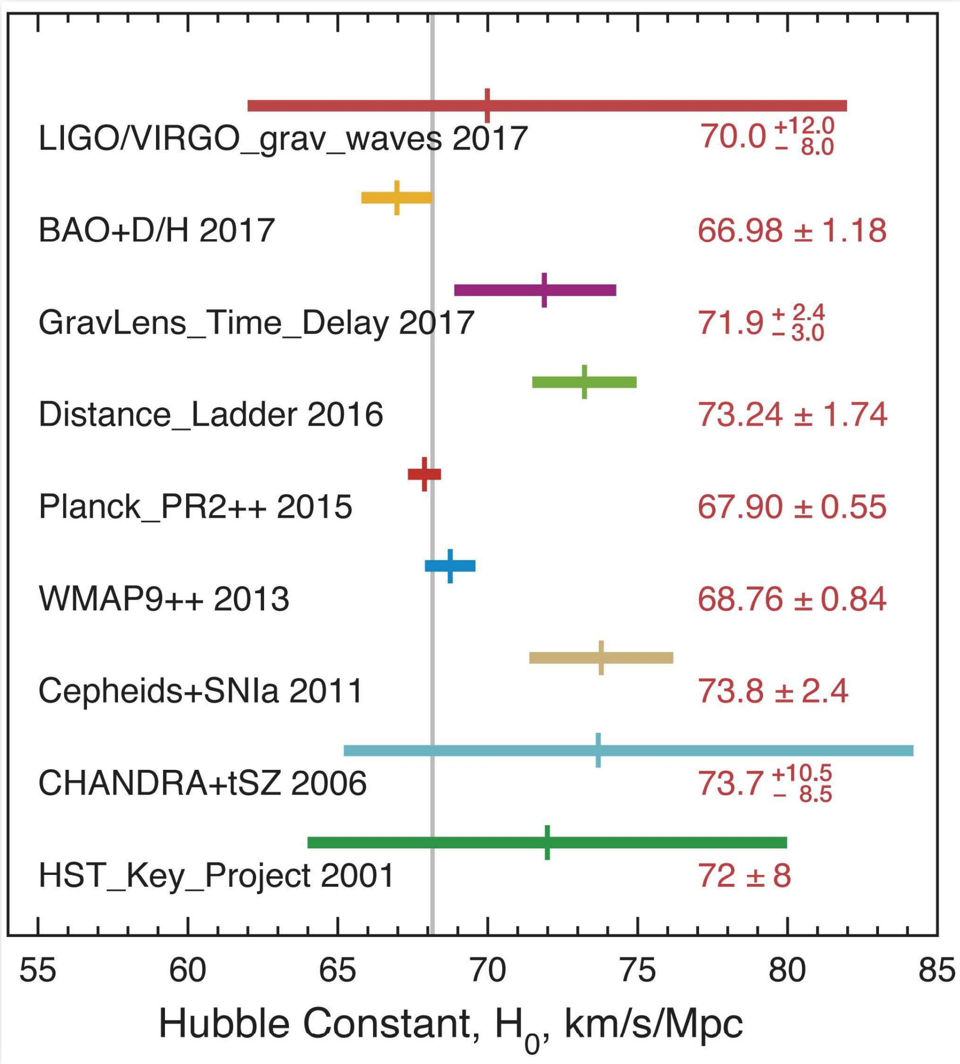


Image Credit: NASA

宇宙の年齢

- Planck Collaboration *et al.* (2018) によるハッブル定数の値: $\mathrm{H_0} = 67.66 \pm 0.42\ [\mathrm{km\ s^{-1} Mpc^{-1}}]$
- $1\ [\mathrm{Mpc}] = 3.09 \times 10^{19}\ [\mathrm{km}]$
- 宇宙の年齢
  $\simeq \frac{1\ [\mathrm{Mpc/km}]}{\mathrm{H_0}} = 4.6 \times 10^{17}\ [\mathrm{s}] = 1.4 \times 10^{10}\ [\mathrm{yr}]$

宇宙の年齢は約140億年

“火の玉宇宙論”と元素合成

初期宇宙の元素合成 (Gamow他 1948)

- 宇宙膨張から考えると初期宇宙は高温高密度の中性子のスープ
  - ルメートルの宇宙像を支持
  - 「火の玉宇宙」と呼ぶ
  - 宇宙背景放射の存在を予言(予想温度5K)
- 膨張と共に中性子がβ崩壊により陽子に転化し、核反応によって次々と重い原子核が形成されるはず

$\alpha-\beta-\gamma$理論 (Gamow他 1948)

Letters to the Editor

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

The Origin of Chemical Elements

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

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

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

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

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

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed 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 $\rho\cong10^6/t^2$. 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:

$$\int_{t_0}^{\infty}(10^6/t^2)dt\cong5\times10^4, \tag{2}$$

which gives us $t_0\cong20$ sec. and $\rho_0\cong2.5\times10^5$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^5 g sec./cm^3 which can possibly be understood if we

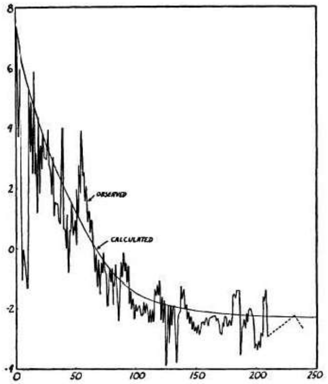


FIG. 1.
Log of relative abundance
Atomic weight

use the new type of cosmological solutions involving the angular momentum of the expanding universe (spinning universe).[5]

More detailed studies of Eqs. (1) leading to the observed abundance curve and discussion of further consequences will be published by one of us (R. A. Alpher) in due course.

* A portion of the work described in this paper has been supported by the Bureau of Ordnance U. S. Navy, under Contract NOrd-7386.

1 G. Gamow, Phys. Rev. **70**, 572 (1946).
2 D. J. Hughes, Phys. Rev. **70**, 106(A) (1946).
3 V. M. Goldschmidt, *Geochemische Verteilungsgesetz der Elemente und der Atom-Arten*. IX. (Oslo, Norway, 1938).
4 See, for example: R. C. Tolman, *Relativity, Thermodynamics and Cosmology* (Clarendon Press, Oxford, England, 1934).
5 G. Gamow, Nature, October 19 (1946).

Alpher, Bethe, Gamow 1948, *Phys.Rev.*, **73**, 803

- 「α–β–γ理論」と呼ばれる
- 実際には Bethe はこの論文に貢献しておらず、Gamow が語呂合わせのために連れてきた

陽子–中性子比の正確な計算 (林 1950)

- 宇宙年齢$<$ 1秒
  - 温度は$T \gg 10^{10}$ [K]
  - 中性子と陽子は互いにバランス(右の林論文の式)
  - n/p比は~ 1
- 宇宙年齢$\simeq$ 1秒
  - $T \simeq 10^{10}$ [K]
  - $\frac{n}{p} \simeq \frac{1}{6}$となる
- 宇宙年齢$\simeq$ 100秒
  - $T \sim 10^{9}$ [K]
  - 中性子は崩壊し
    $\frac{n}{p} \simeq \frac{1}{7}$に

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

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

Chushiro HAYASHI.

Department of Physics, Naniwa University.

(Received January 12, 1950)

§ 1. Introduction.

In the theory of the origin of the elements by Gamow, Alpher, and colaborators[1], primordial matter (ylem) of the universe, which afterwards has been cooled down owing to the expansion of the universe and has formed the elements through nuclear reactions such as radiative capture and beta-decays, is assumed to consist solely of neutrons. At early stages, however, of high temperatures ($kT \gtrsim mc^2$, m being the electron mass) in the expanding universe before the formation of the elements, induced beta-processes caused by energetic electrons, positrons, neutrinos and antineutrinos, in addition to the natural decay of neutrons, such as

$$n+e^+ \rightleftarrows p+a\nu, \qquad (1a)$$

$$n+\nu \rightleftarrows p+e^-, \qquad (1b)$$

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

must have proceeded, their rates being faster at higher temperatures, and had a effect on the proton-neutron concentration ratio. At still higher temperatures

Hayashi 1950, *Progress of Theoretical Physics*, **5**, 224

“Naniwa University”は現在の京都府立大

林忠四郎は他に原始星の進化や

惑星系形成モデルで重要な仕事

元素合成の開始

- $T \sim 10^9$ [K]で中性子が陽子と結合
- 水素より重い元素合成が開始
- 中性子は大半がヘリウム(陽子2+中性子2)となる
- 陽子：中性子 $\simeq 7:1$より、
  水素：ヘリウム(個数比) $\simeq 12:1$
  - ヘリウムの予測存在比: 約8%(個数比)、約25%(質量比)
  - 現在の観測値(7.8%, 24.7%)と良く合う
- 水素、ヘリウムの大半は宇宙の誕生時点で作られた
- ここまで宇宙誕生から約3分間

宇宙背景放射

定常宇宙論 (Hoyle他 1930–1965)

- 宇宙膨張の発見により「静止宇宙論」は衰退
- 「無」から定常的な物質の湧き出しにより「膨張はするが密度は一定(定常)」とする「定常宇宙論」が提唱される
- Fred Hoyle が急先鋒
- 火の玉宇宙論を“Big Bang theory”と揶揄する (BBC radio ,*Third Programme*, broadcast on 28 March 1949) ⟶ Gamow に気に入られ採用
- 水素、ヘリウム以外の重元素が出来ないことを批判、トリプルα反応の存在を予測 ⟶ Fowler により存在が確認される

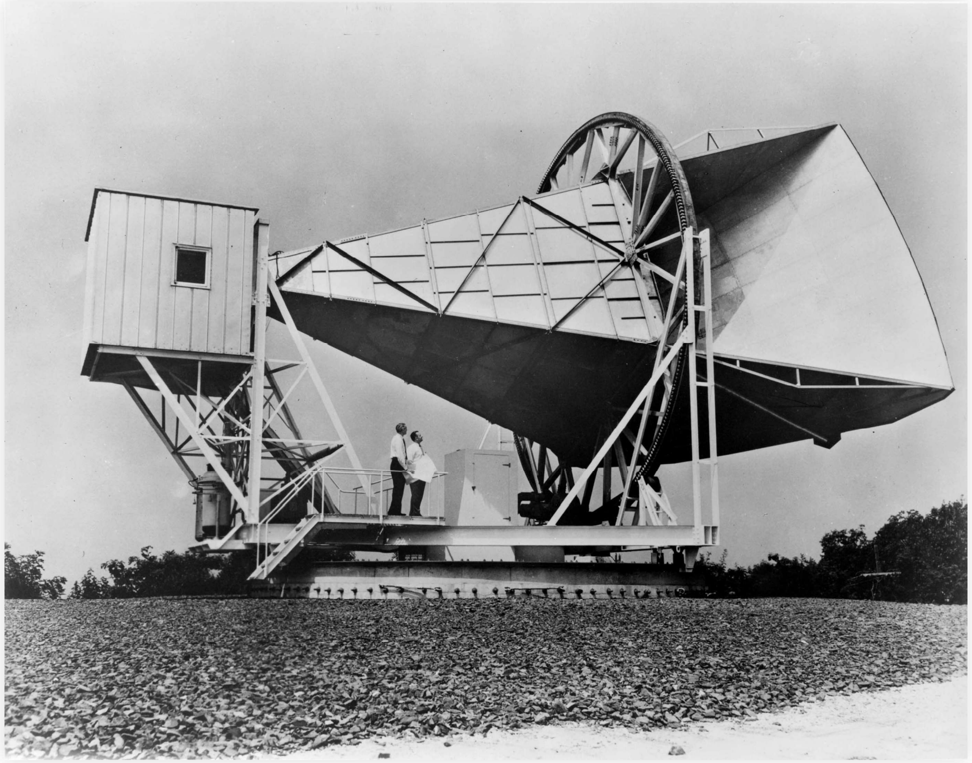
BBC

宇宙の「晴れ上がり」

- 宇宙背景放射の予測 (Gamow 1948)
- 濃い電離ガス(*ex.*太陽の中)の中は光はまっすぐ進めない ↔外からは太陽の表面しか見えない
- 薄い電離ガス(*ex.*星雲)の中は光は進める↔外から星雲の中が見える
- 宇宙の密度が十分下がったところは見通せる。それ以前は「見えない」。
  - 程なくガスは中性化
  - 星の表面の様に見える
  - 温度約3000[K]の黒体輻射
  - 宇宙年齢$\simeq$ 38万年
  - 宇宙の膨張と共に波長が伸びる→現在は約3Kの黒体輻射として見える(宇宙が1000倍に膨張)

宇宙背景放射の発見 (Penzias & Wilson 1965)

- ベル研の研究者
- 目的は「アンテナの高性能化」
- 原因不明の信号を発見(1964年5月20日が初検出)
  → ビッグバンの痕跡「宇宙背景放射」



NASA

A Measurement of Excess Antenna Temperature at 4080 Mc/s.

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

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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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.

The total antenna temperature measured at the zenith is 6.7° K of which 2.3° K is due to atmospheric absorption. The calculated contribution due to ohmic losses in the antenna and back-lobe response is 0.9° K.

The radiometer used in this investigation has been described elsewhere (Penzias and Wilson 1965). It employs a traveling-wave maser, a low-loss (0.027-db) comparison switch, and a liquid helium–cooled reference termination (Penzias 1965). Measurements were made by switching manually between the antenna input and the reference termination. The antenna, reference termination, and radiometer were well matched so that a round-trip return loss of more than 55 db existed throughout the measurement; thus errors in the measurement of the effective temperature due to impedance mismatch can be neglected. The estimated error in the measured value of the total antenna temperature is 0.3° K and comes largely from uncertainty in the absolute calibration of the reference termination.

The contribution to the antenna temperature due to atmospheric absorption was obtained by recording the variation in antenna temperature with elevation angle and employing the secant law. The result, $2.3° \pm 0.3°$ K, is in good agreement with published values (Hogg 1959; DeGrasse, Hogg, Ohm, and Scovil 1959; Ohm 1961).

The contribution to the antenna temperature from ohmic losses is computed to be $0.8° \pm 0.4°$ K. In this calculation we have divided the antenna into three parts: (1) two non-uniform tapers approximately 1 m in total length which transform between the $2\frac{1}{8}$-inch round output waveguide and the 6-inch-square antenna throat opening; (2) a double-choke rotary joint located between these two tapers; (3) the antenna itself. Care was taken to clean and align joints between these parts so that they would not significantly increase the loss in the structure. Appropriate tests were made for leakage and loss in the rotary joint with negative results.

The possibility of losses in the antenna horn due to imperfections in its seams was eliminated by means of a taping test. Taping all the seams in the section near the throat and most of the others with aluminum tape caused no observable change in antenna temperature.

The backlobe response to ground radiation is taken to be less than 0.1° K for two reasons: (1) Measurements of the response of the antenna to a small transmitter located on the ground in its vicinity indicate that the average back-lobe level is more than 30 db below isotropic response. The horn-reflector antenna was pointed to the zenith for these measurements, and complete rotations in azimuth were made with the transmitter in each of ten locations using horizontal and vertical transmitted polarization from each position. (2) Measurements on smaller horn-reflector antennas at these laboratories, using pulsed measuring sets on flat antenna ranges, have consistently shown a back-lobe level of 30 db below isotropic response. Our larger antenna would be expected to have an even lower back-lobe level.

From a combination of the above, we compute the remaining unaccounted-for antenna temperature to be $3.5° \pm 1.0°$ K at 4080 Mc/s. In connection with this result it should be noted that DeGrasse *et al.* (1959) and Ohm (1961) give total system temperatures at 5650 Mc/s and 2390 Mc/s, respectively. From these it is possible to infer upper limits to the background temperatures at these frequencies. These limits are, in both cases, of the same general magnitude as our value.

We are grateful to R. H. Dicke and his associates for fruitful discussions of their results prior to publication. We also wish to acknowledge with thanks the useful comments and advice of A. B. Crawford, D. C. Hogg, and E. A. Ohm in connection with the problems associated with this measurement.

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shakeshaft 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias
R. W. Wilson

May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

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Dicke, R H , Peebles, P. J. E., Roll, P G., and Wilkinson, D. T. 1965, *Ap J.*, **142**, 414.
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Penzias, A. A 1965, *Rev Sci. Instr.*, **36**, 68.
Penzias, A A , and Wilson, R W. 1965, *Ap J* (in press).

ERRATUM

In the paper "Stellar Evolution. I. The Approach to the Main Sequence" (*Ap. J.*, **141**, 993), the following corrections are to be made: page 993, line 1, replace "popuation" by "population"; page 997, line 18, delete the last word "energy"; page 999, line 2, replace "expanding" by "contracting"; page 1007, section heading VI—replace "8" by "9"; page 1007, line 1, replace "Figure 12" by "Figure 17"; page 1017, line 5, replace "equation (19)" by "equation (B9)"; page 1018, line 6, replace "W. Z. Fowler" by "W. A. Fowler."

Icko Iben, Jr.

June 7, 1965
Massachusetts Institute of Technology

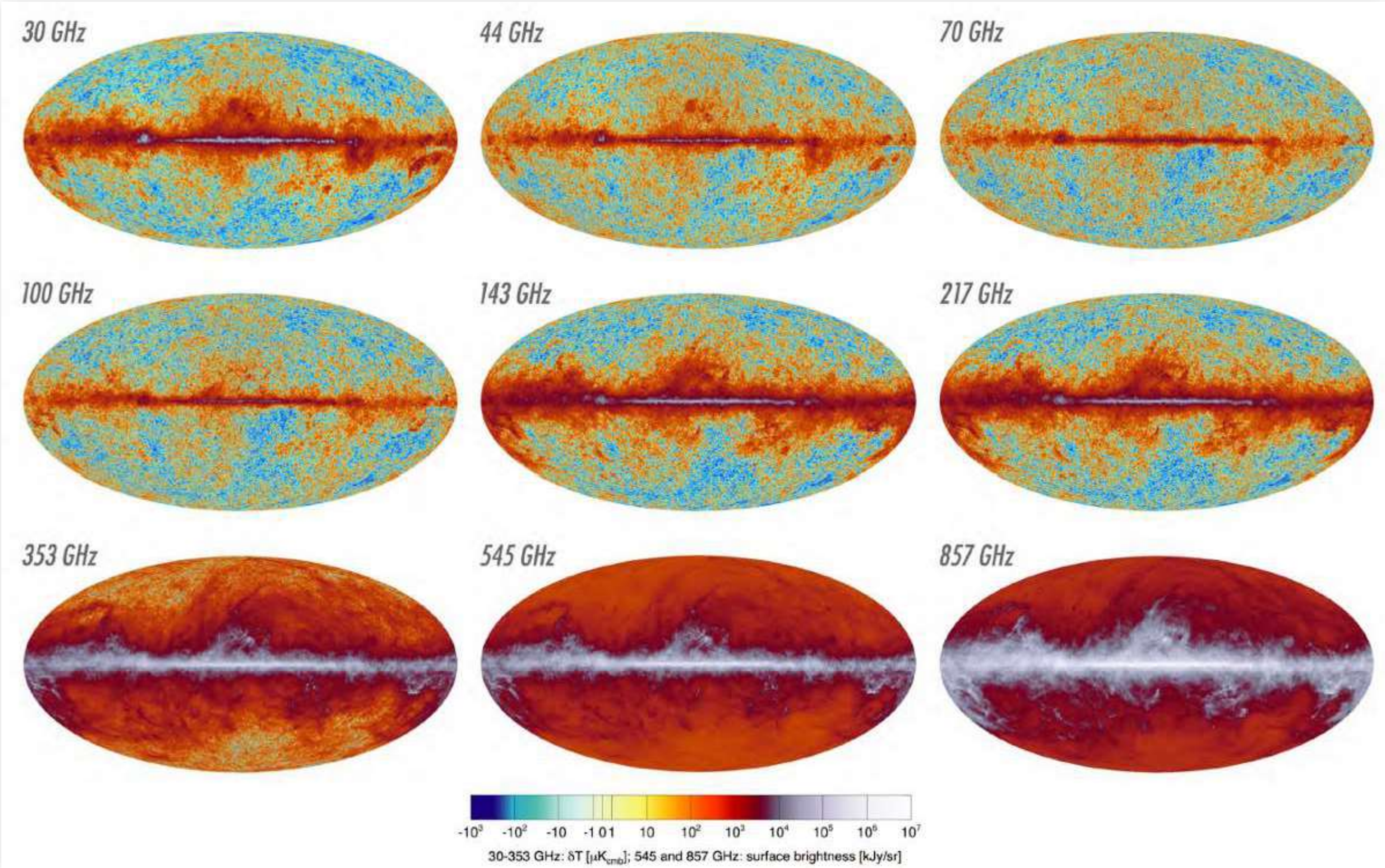
Penzias & Wilson 1965, *ApJ*, **142**, 419

直前に載っているのは"Cosmic Black-Body Radiation."(Dicke, Peebles, Roll, & Wilkinson 1965, *ApJ*, **142**, 414)

宇宙背景放射の観測

各周波数で見た宇宙

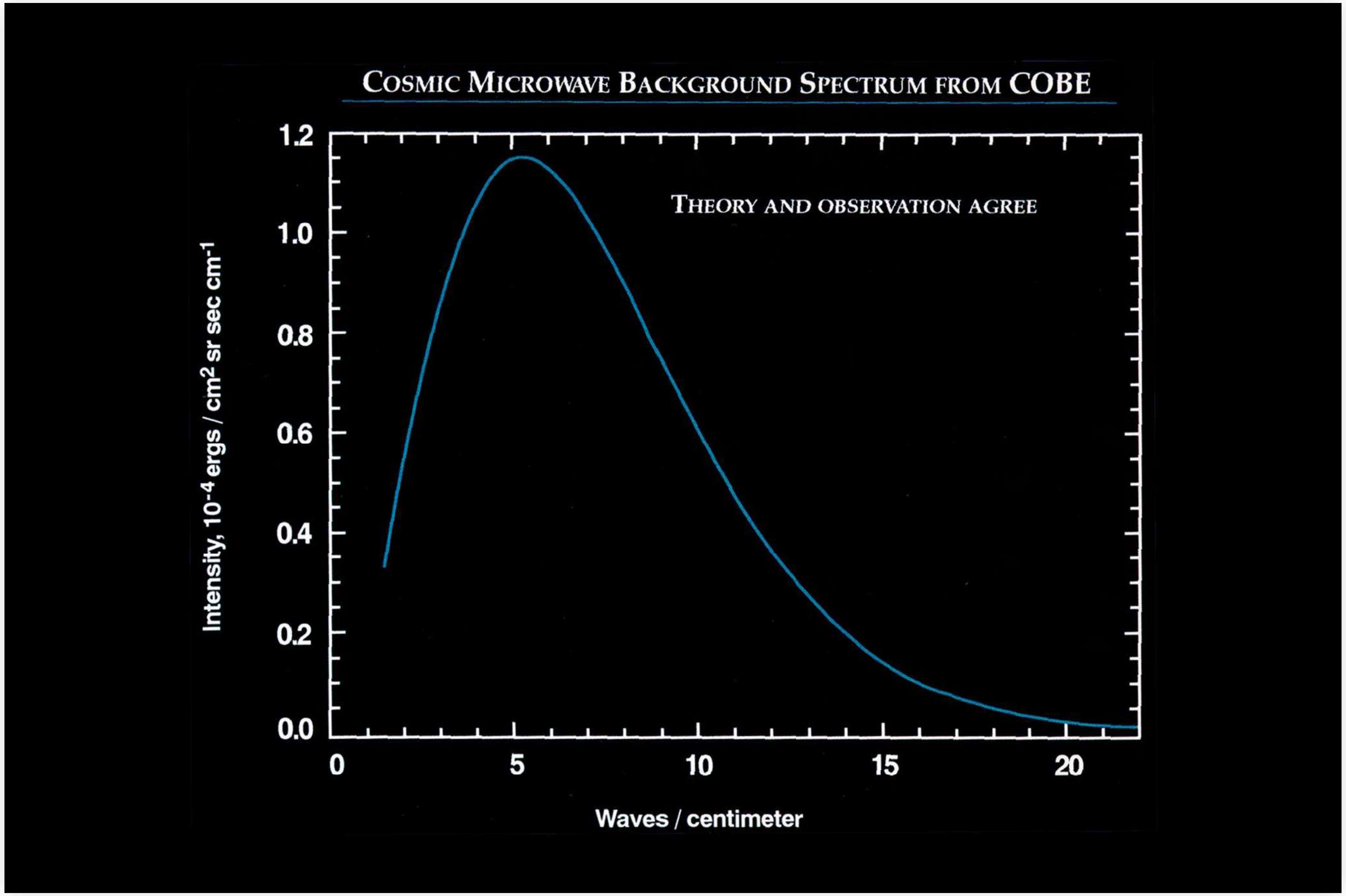
- ここから太陽系内や銀河系内の天体の出す輻射を取り除いたものが「宇宙背景放射」



Planck Collaboration *et al.* 2016, *A&A*, **594**, id.A1

宇宙背景放射のスペクトル

- 観測されるスペクトルは“ほぼ完璧”な黒体輻射
  - 温度2.725K

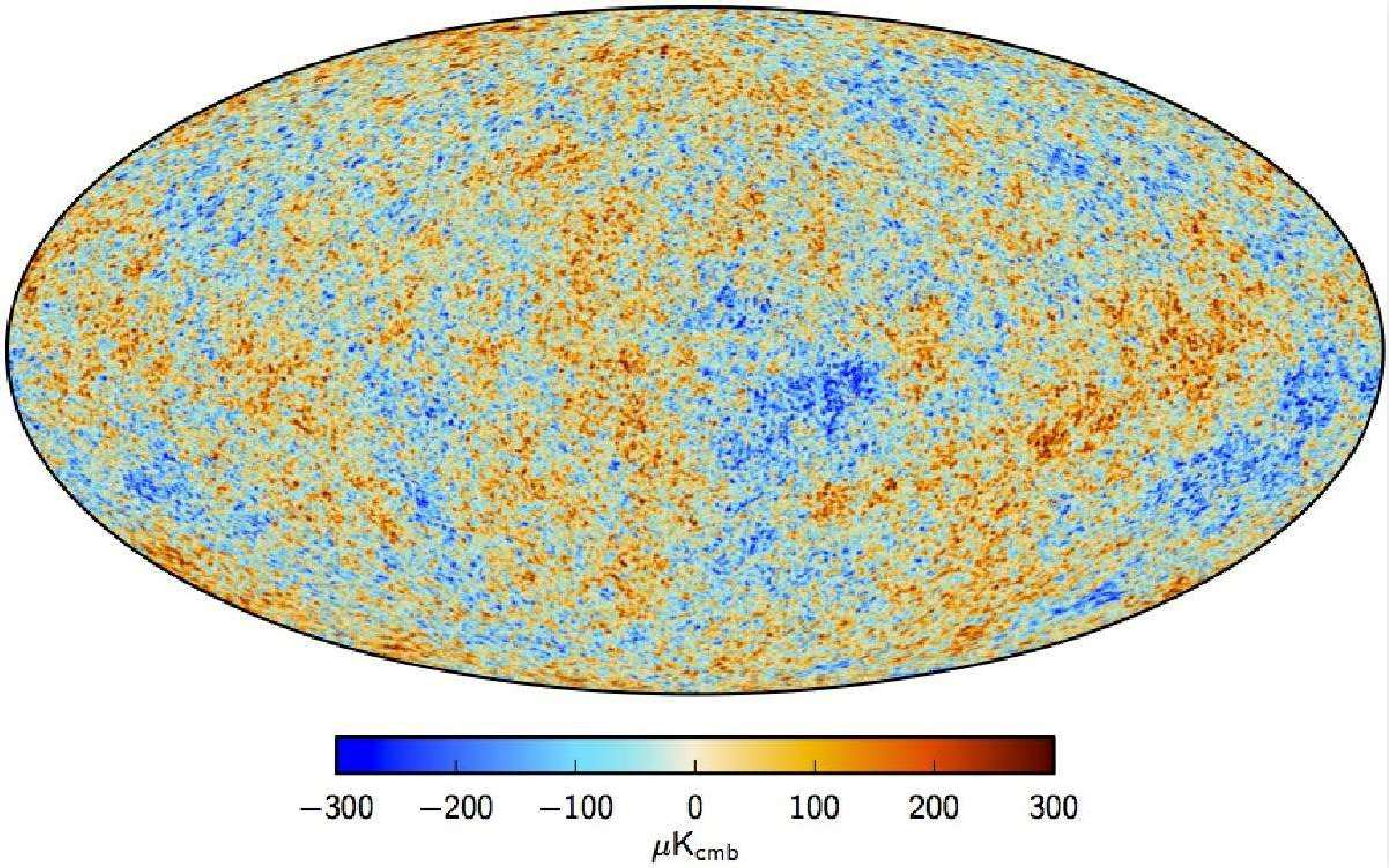


NASA/GSFC

宇宙背景放射の揺らぎ

- 背景放射は「ほぼ」一様分布
(宇宙のどの方向も同じに見える)
- 晴れ上がり時点の密度分布が
「ほぼ」一様だったことを示す
- このままでは銀河が出来ない
  - 場所ごとに密度の違い(揺らぎ)が
いくらかはあったはず
- 晴れ上がり時点で密度揺らぎがあれば、
背景放射の温度の揺らぎとして見えるはず
- COBE衛星により初検出(1992)
  - Smoot & Mather 2006年ノーベル賞受賞

観測された揺らぎ

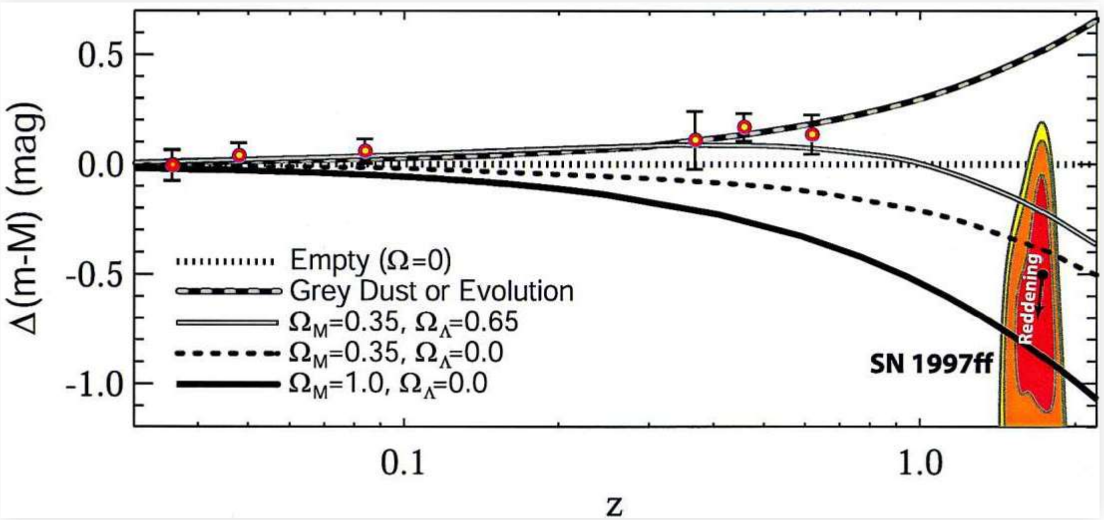


Planck Collaboration *et al*. 2016, *A&A*, **594**, id.A1

宇宙の加速膨張

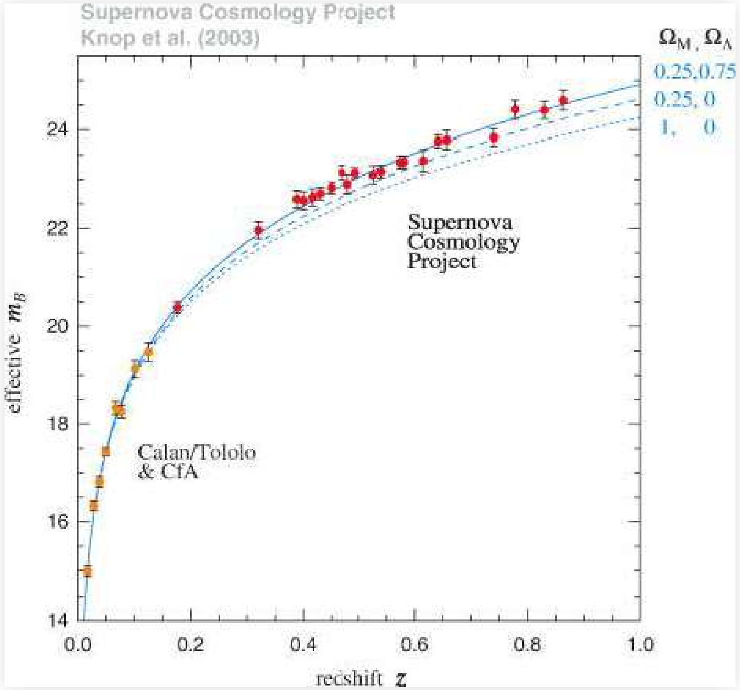
加速膨張の発見

- Ia型超新星が予想よりも暗く見える
- 星間塵による吸収では説明出来ない
  - 遠くの超新星は逆に明るく見える
- アインシュタインの「宇宙項」の復活！？



Riess, Nugent, Gilliland, *et al*. 2001, *ApJ*, **560**, 49

Perlmutter, Schmidt, Riess の３名は2011年ノーベル賞受賞

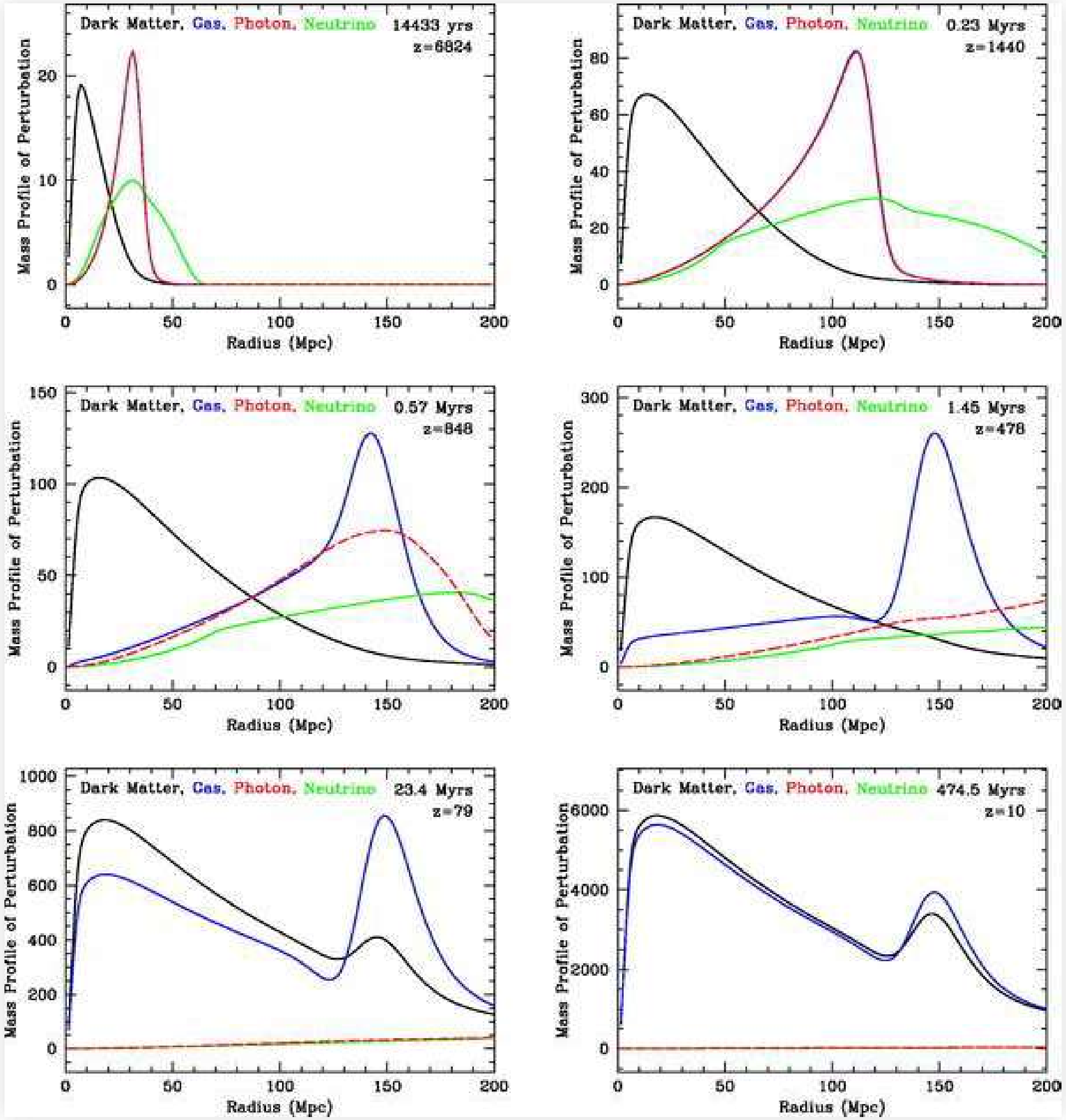


Knop *et al*. 2003, *ApJ*, **598**, 102

背景放射の
揺らぎのスペクトル

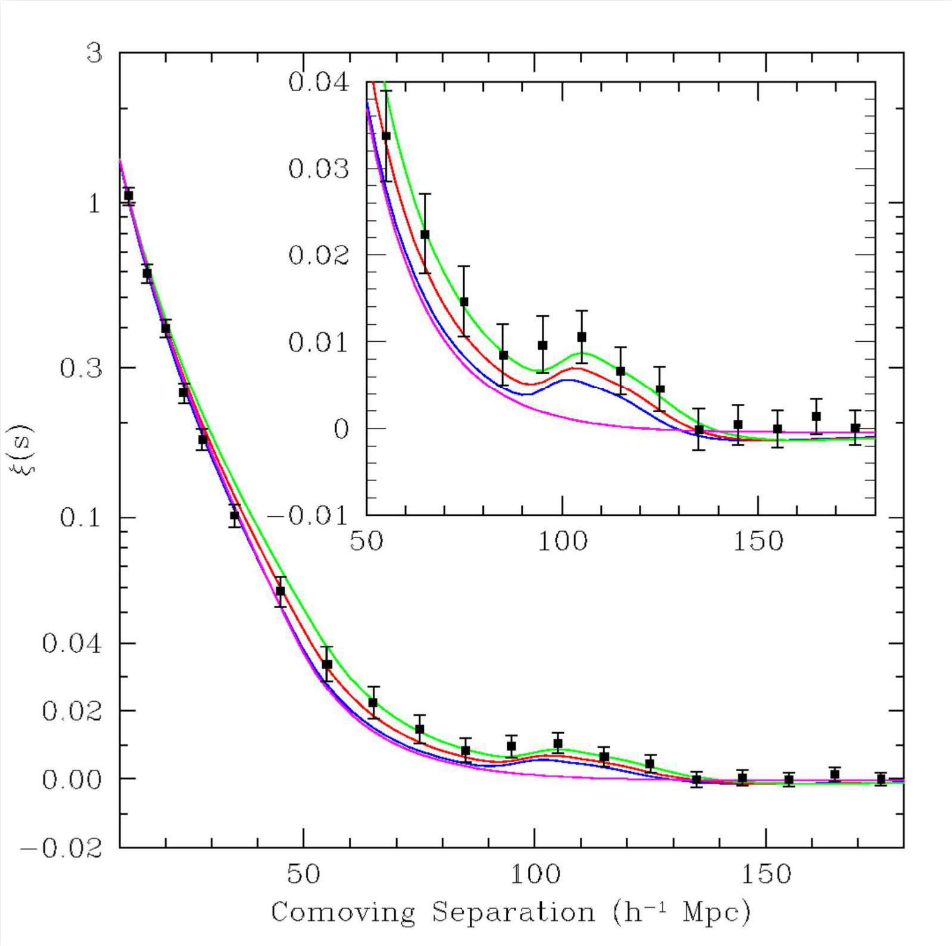
空間の揺らぎ

バリオン音響振動の伝搬

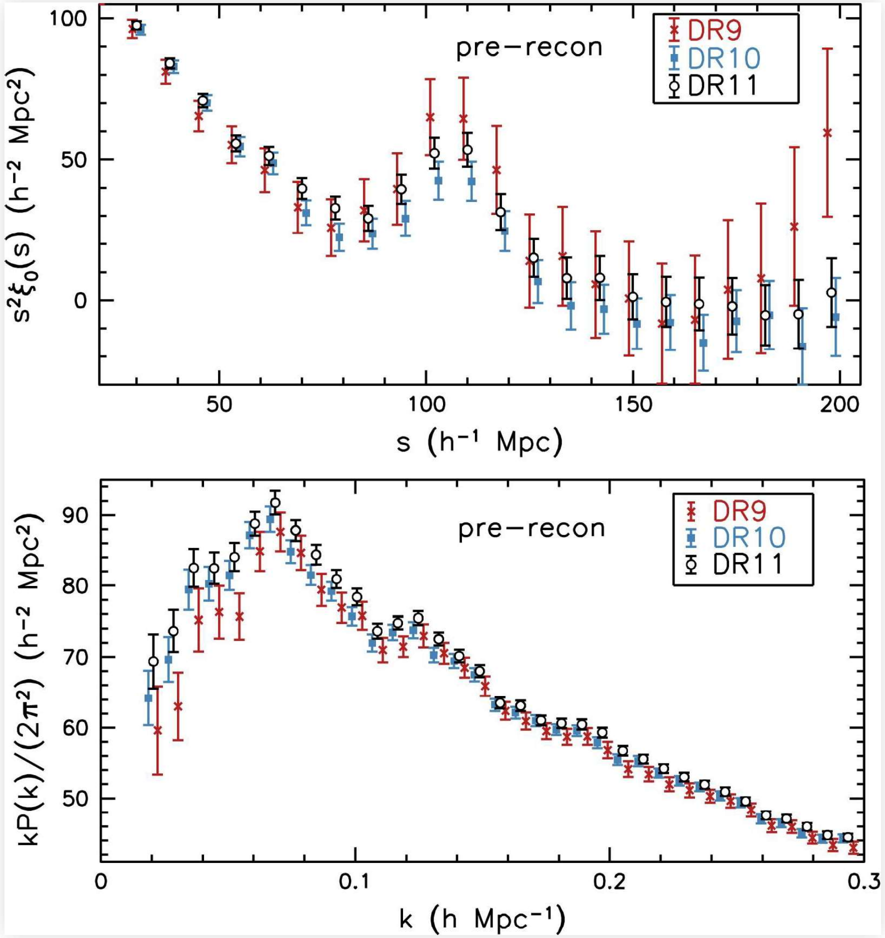


Eisenstein, Seo, & White 2007, *ApJ*, **664**, 660

銀河の二体相関関数

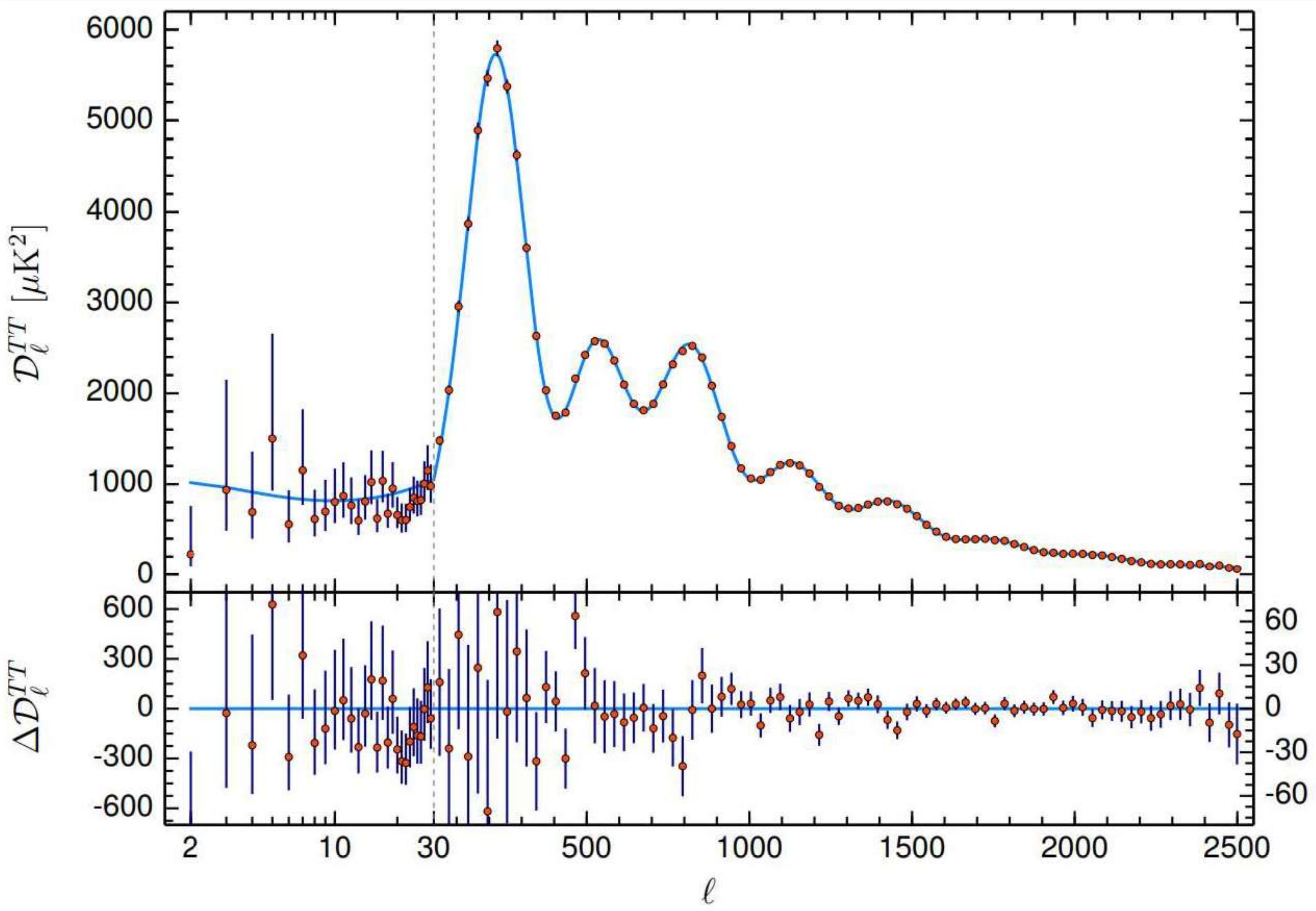


Eisenstein, Zehavi, Hogg, *et al*. 2005, *ApJ*, **633**, 560



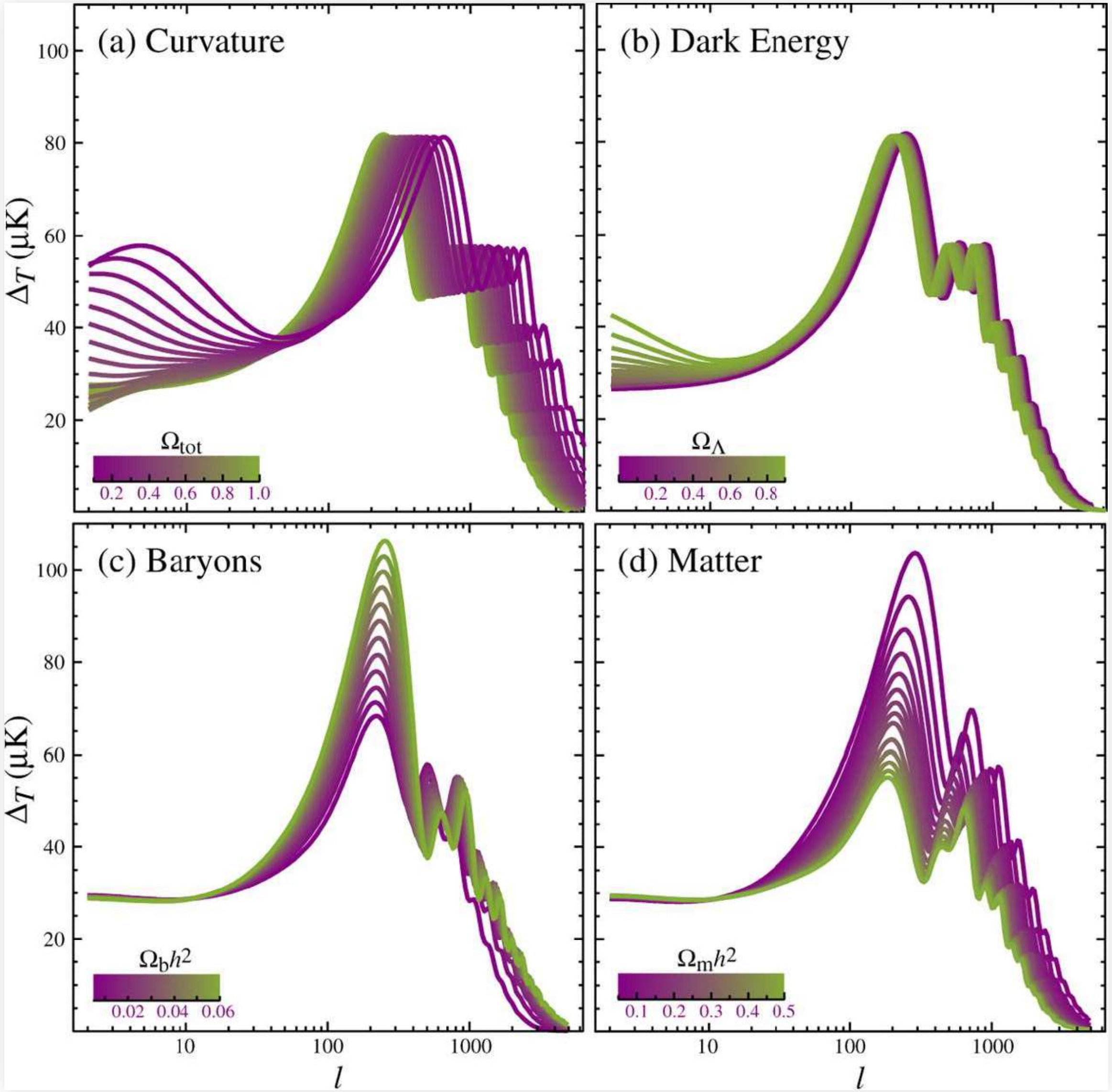
Anderson, Aubourg, Bailey, *et al*. 2014, *MNRAS*, **441**, 24

宇宙背景放射の揺らぎスペクトル



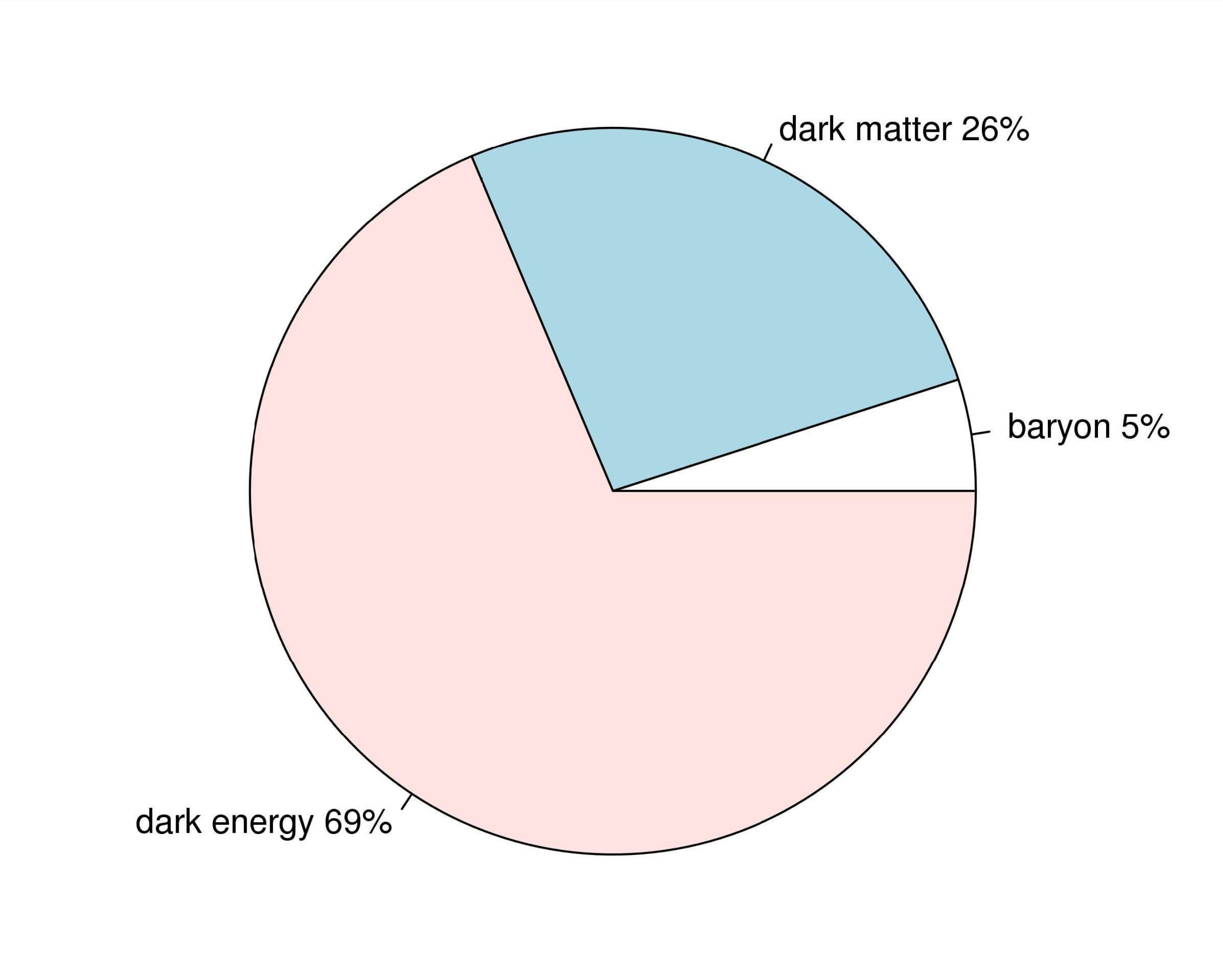
Planck Collaboration *et al.* 2018

スペクトルと宇宙の構成の関係



Hu & Dodelson 2002, *ARA&A*, **40**, 171–216

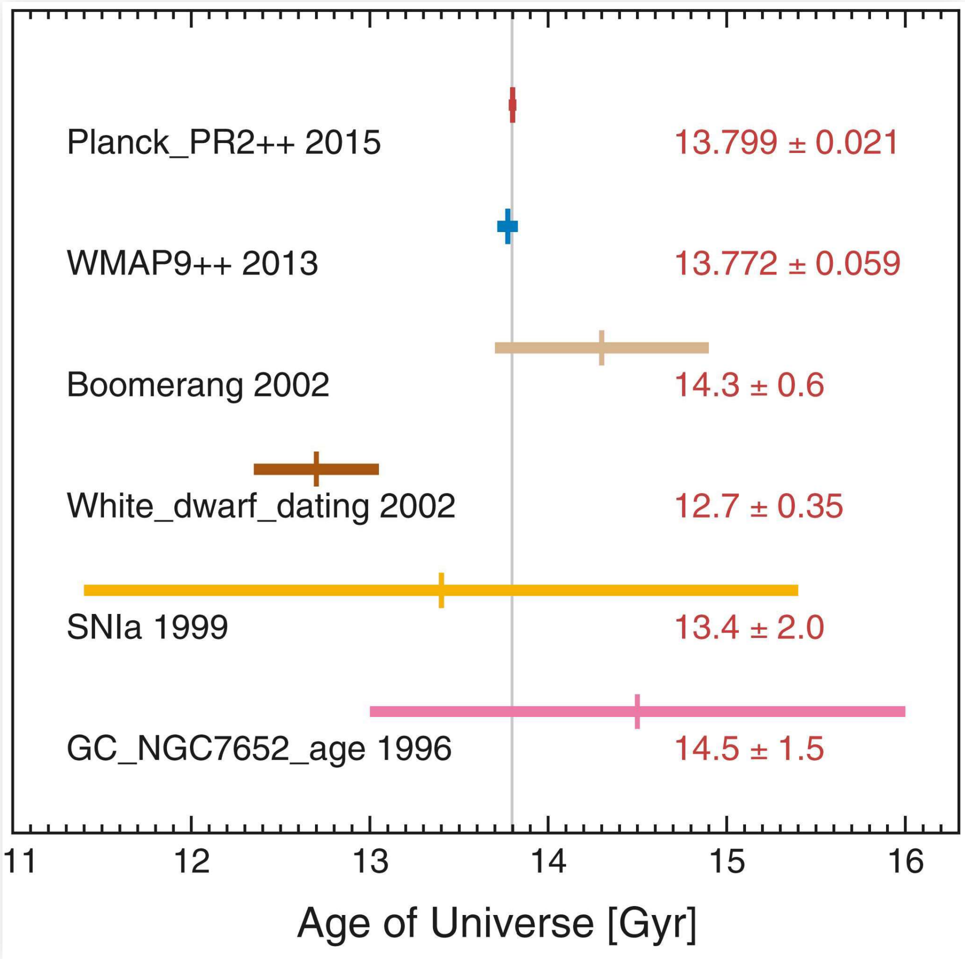
宇宙の質量-エネルギー構成比



Planck Collaboration *et al.* 2018

宇宙の年齢

137.87 ± 0.20 億年 (Planck Collaboration *et al.* 2018)



LAMBDA

インフレーション宇宙モデル

宇宙の地平線問題

- 背景放射温度がほぼ一様
  $\longrightarrow$宇宙はどこも一斉に晴れ上がった
- 宇宙誕生後38万年
  $\longleftarrow$光が進めるのは我々が見る角度で$\leq 3^\circ$
  - これより大きなスケールが一様になることは不可能

宇宙の平坦性問題

- 宇宙の密度が少しだけ小さい→膨張が早すぎて原子同士が結合できない(「開いた宇宙」)
- 宇宙の密度が少しだけ大きい→宇宙がすぐに収縮に転じてしまう(「閉じた宇宙」)
- 宇宙が「平坦」であるためには、あまりにも不自然なファインチューニングが必要

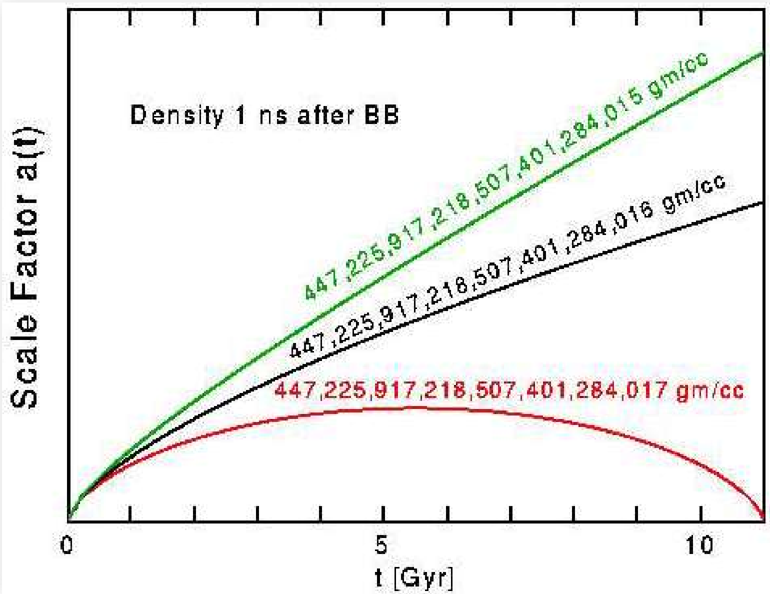


Image credit: David P. Bennett of Notre Dame, via http://bustard.phys.nd.edu/.

インフレーション理論

- 最初小さかった宇宙を急激に引き伸びしてしまえば良い
  - 地平線問題→互いにすぐ近くに居た領域が引き離されたと思えばよい
  - 平坦性問題→元々曲がっていた空間が大きく引き伸ばされて平らになったと思えば良い
- 宇宙誕生後10^{-36}秒の間に空間が$> 10^{28}$倍に引き伸ばされたとされる
  - 原子核一個を太陽系の大きさにまで引き伸ばす倍率
  - 0.1μmが銀河系サイズに引き伸ばされる倍率
- インフレーションを想定するといろいろな観測事実を都合よく説明出来ることは事実だが、その成因は不明

Universe timeline

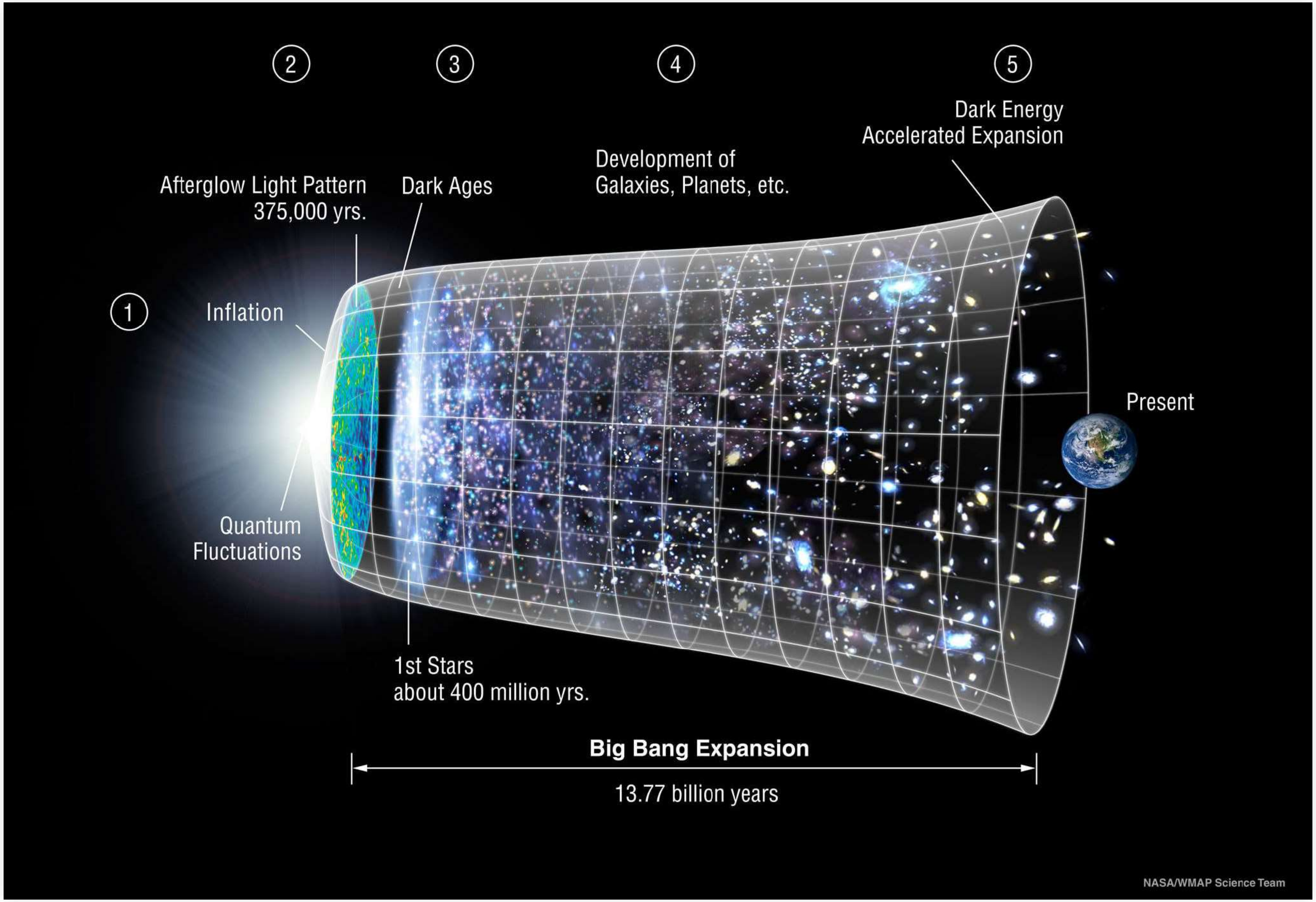
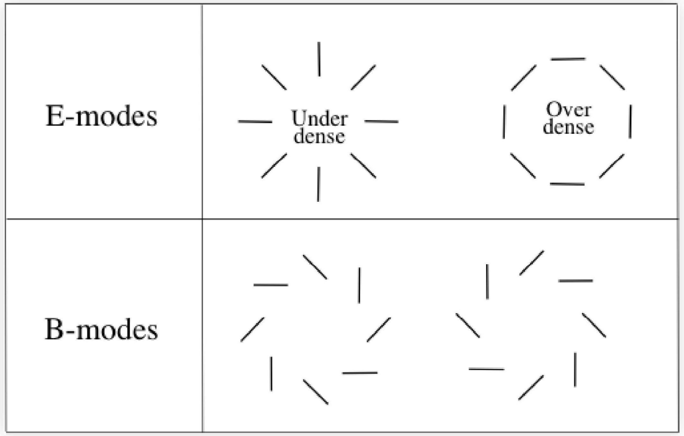


Image Credit: Adaptation of original NASA WMAP Science Team image

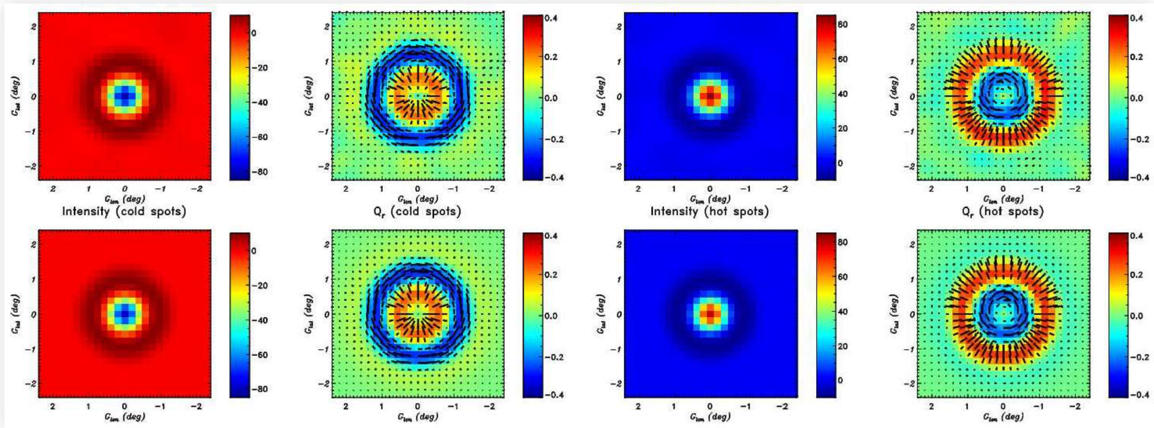
インフレーションの観測計画

インフレーション起源の原始重力波の探索

- 宇宙背景放射の「偏光」を捉える
- 光は横波 – 縦横の偏光の重ね合わせ
- 温度の濃淡(密度の濃淡)は“E-mode偏光”を作る
- インフレーション期の原始重力波は“E-mode”&“B-mode”を作る
- “B-mode”偏光の検出：インフレーション存在の検証



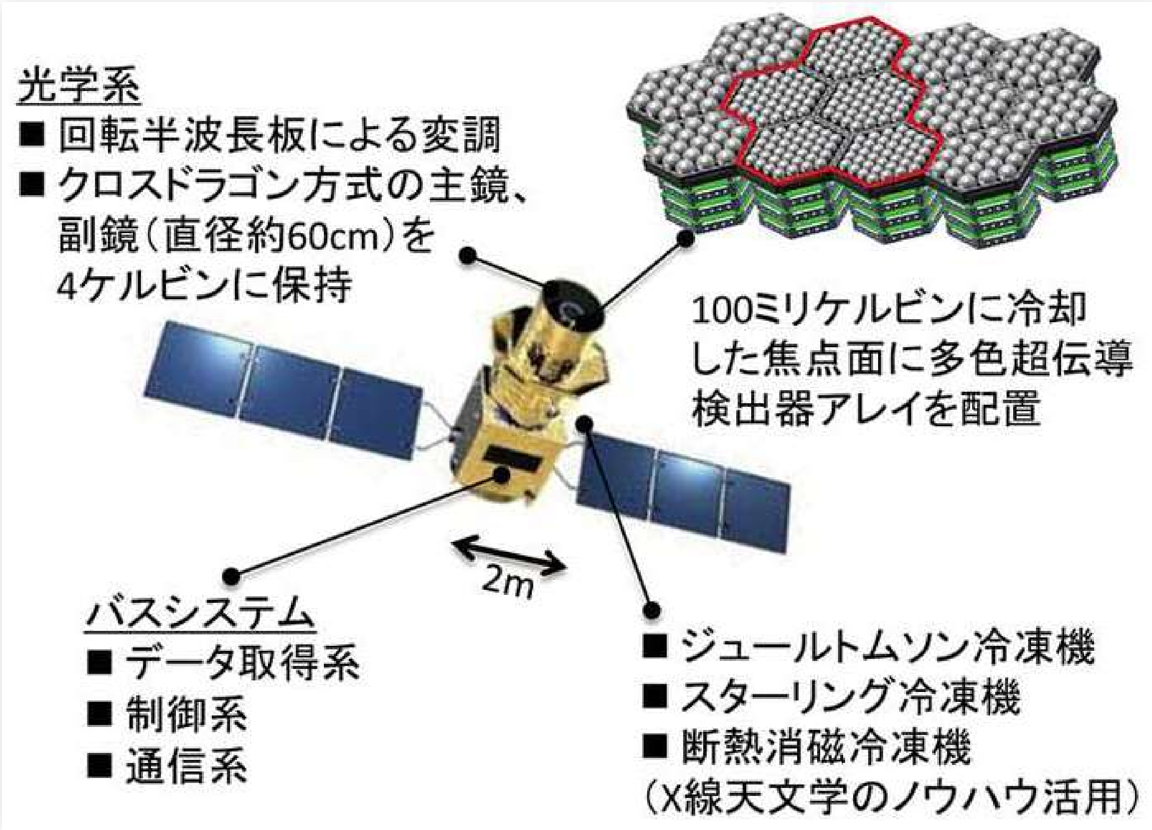
Gravitational Lensing – PBworks



Planck Collaboration, *et al.* 2014, *A&Ap*, **571**, A1

LiteBIRD

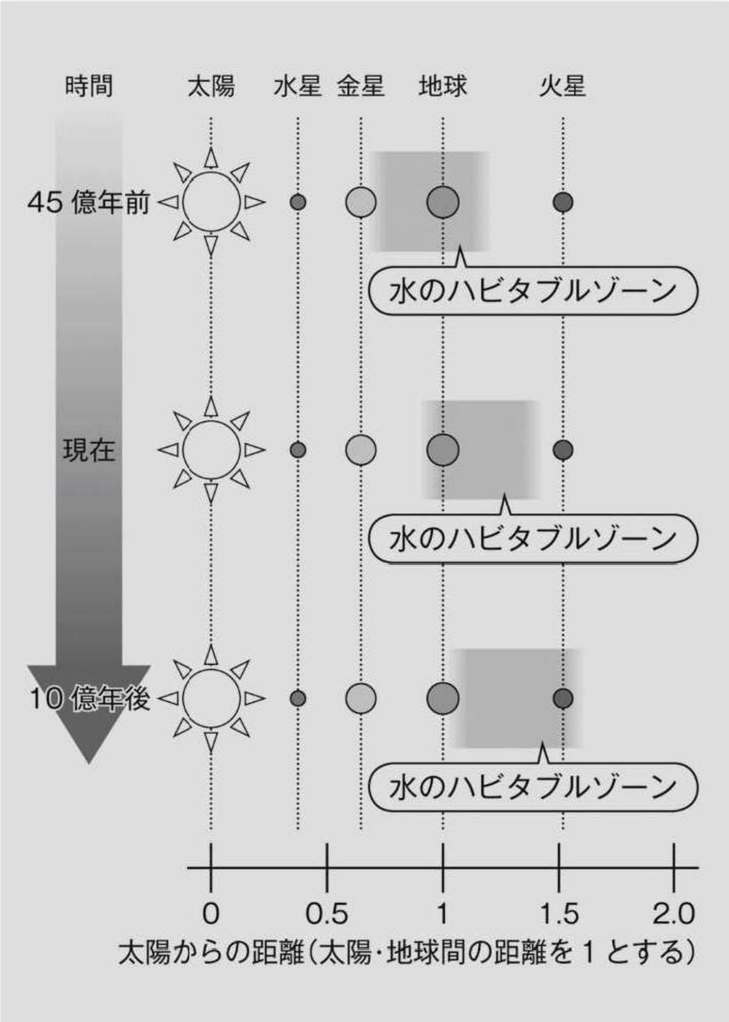
- 世界的に唯一の宇宙背景放射偏光観測衛星
- 宇宙研の将来ミッションの有力候補の１つ



ISAS/JAXA

宇宙の将来

地球のハビタビリティ

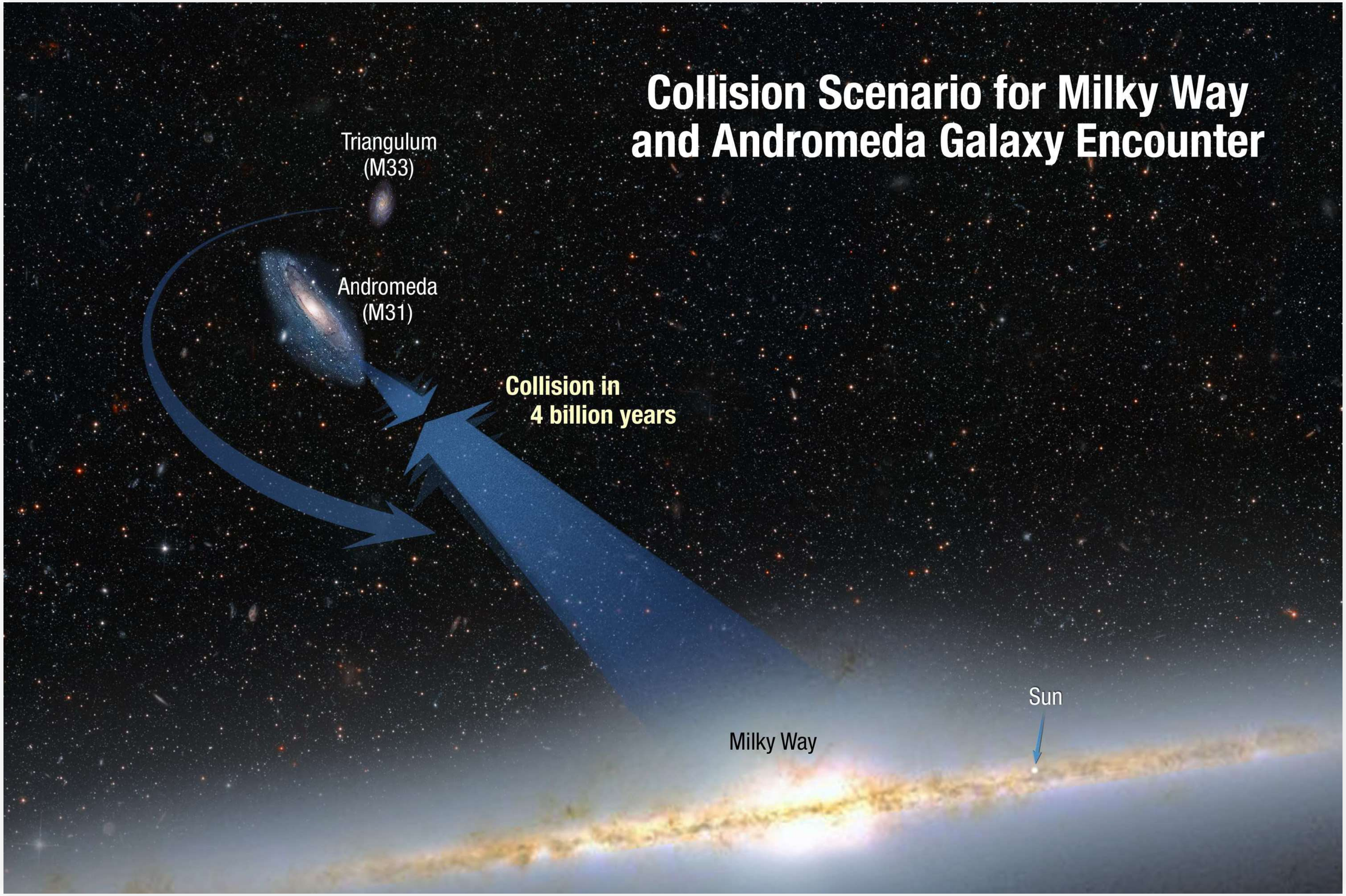


「土星の衛星タイタンに生命体がいる！」関根康人、

小学館

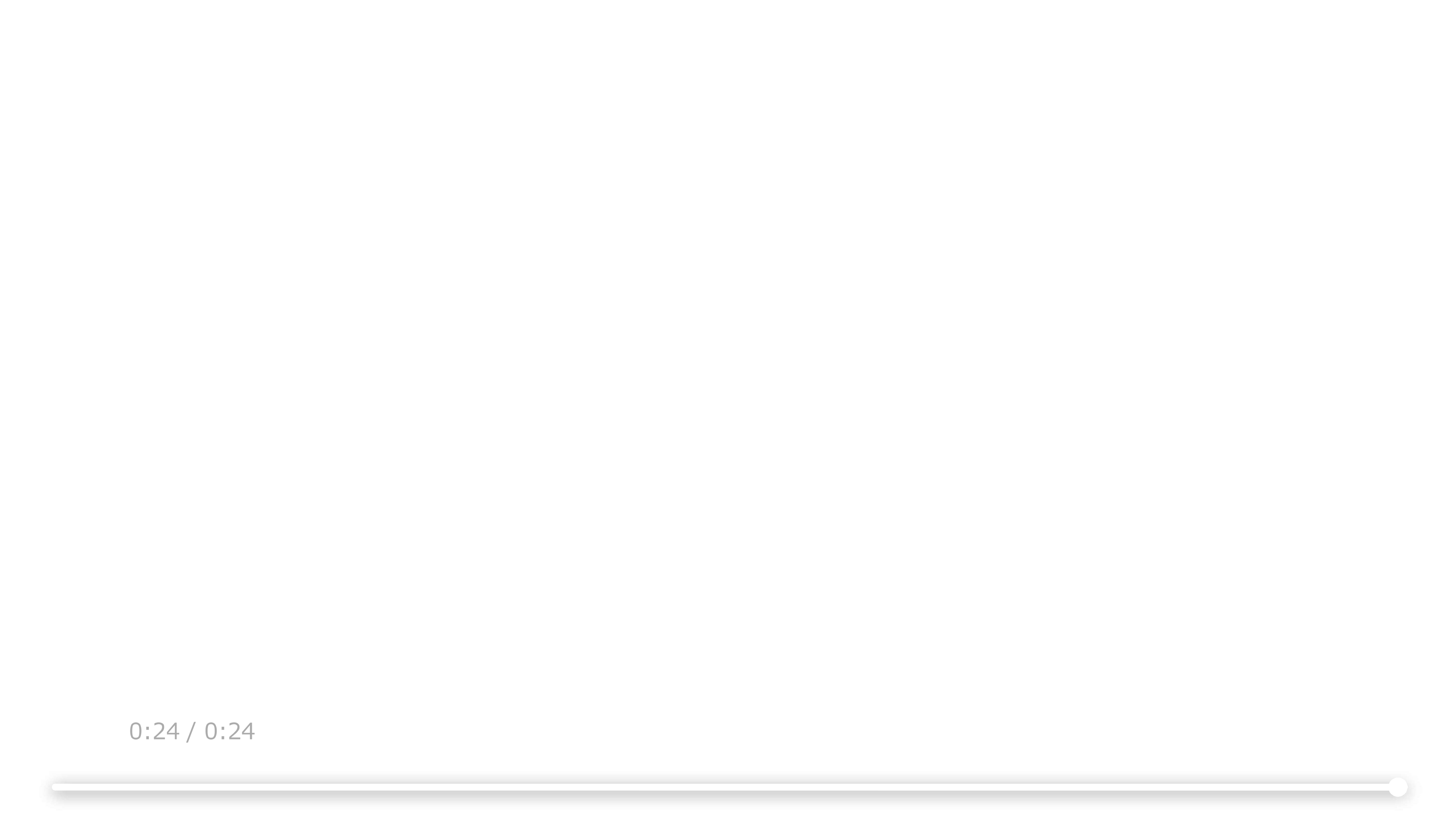
- 誕生直後の太陽は現在よりも30%程度暗かった。
- 現在から10億年後には地球はハビタブルゾーンを外れる。

40億年後: アンドロメダ銀河との衝突



Credit: NASA, ESA, and A. Feild and R. van der Marel (STScI)

アンドロメダ銀河との衝突合体



Credit: NASA, ESA, Z. Levay, R. van der Marel, and G. Bacon (STScI), T. Hallas, and A. Mellinger

100億年後の銀河系

- 星を産まない「楕円銀河」
- 衝突時に生まれた新しい太陽も100億年後には消失

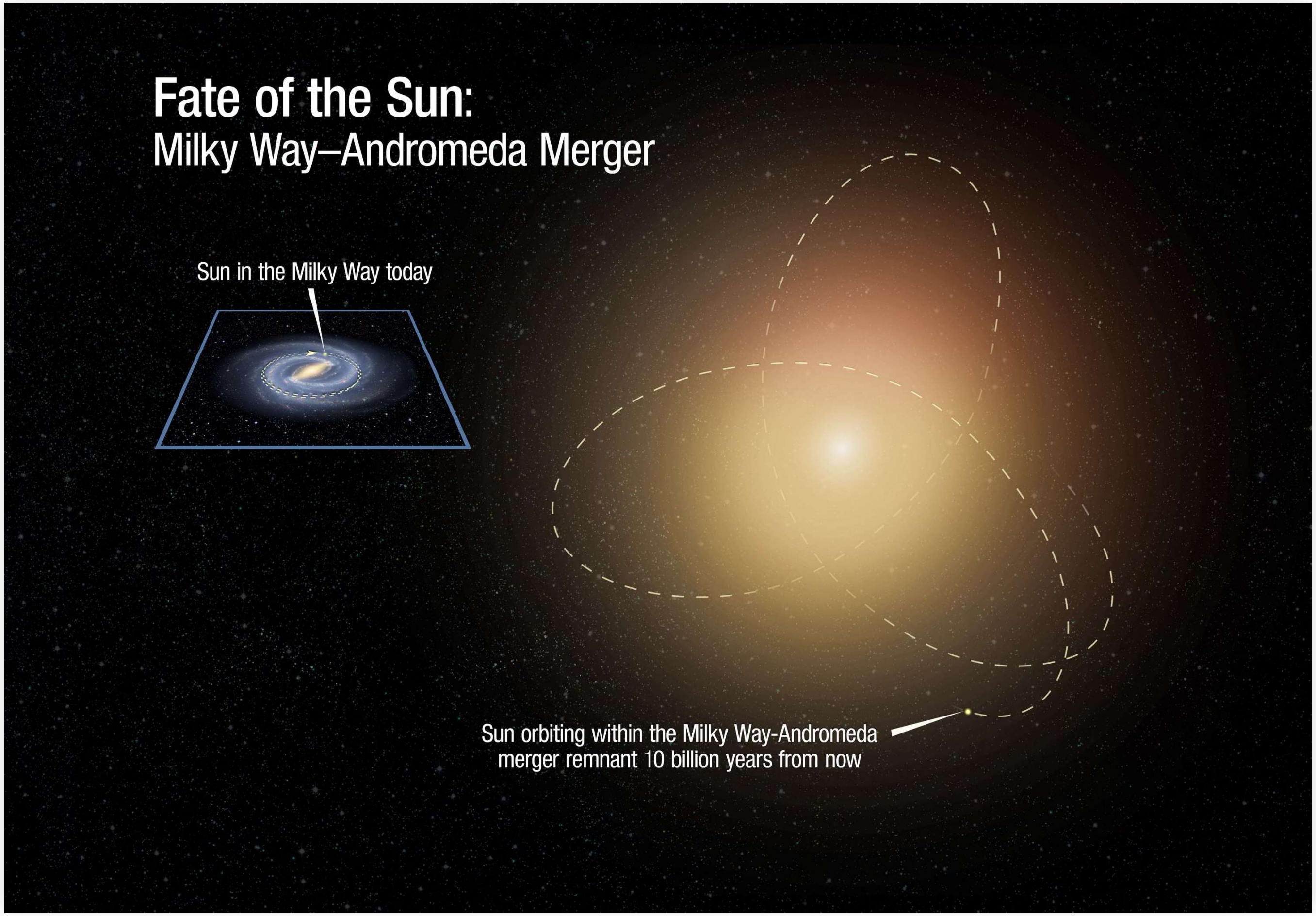
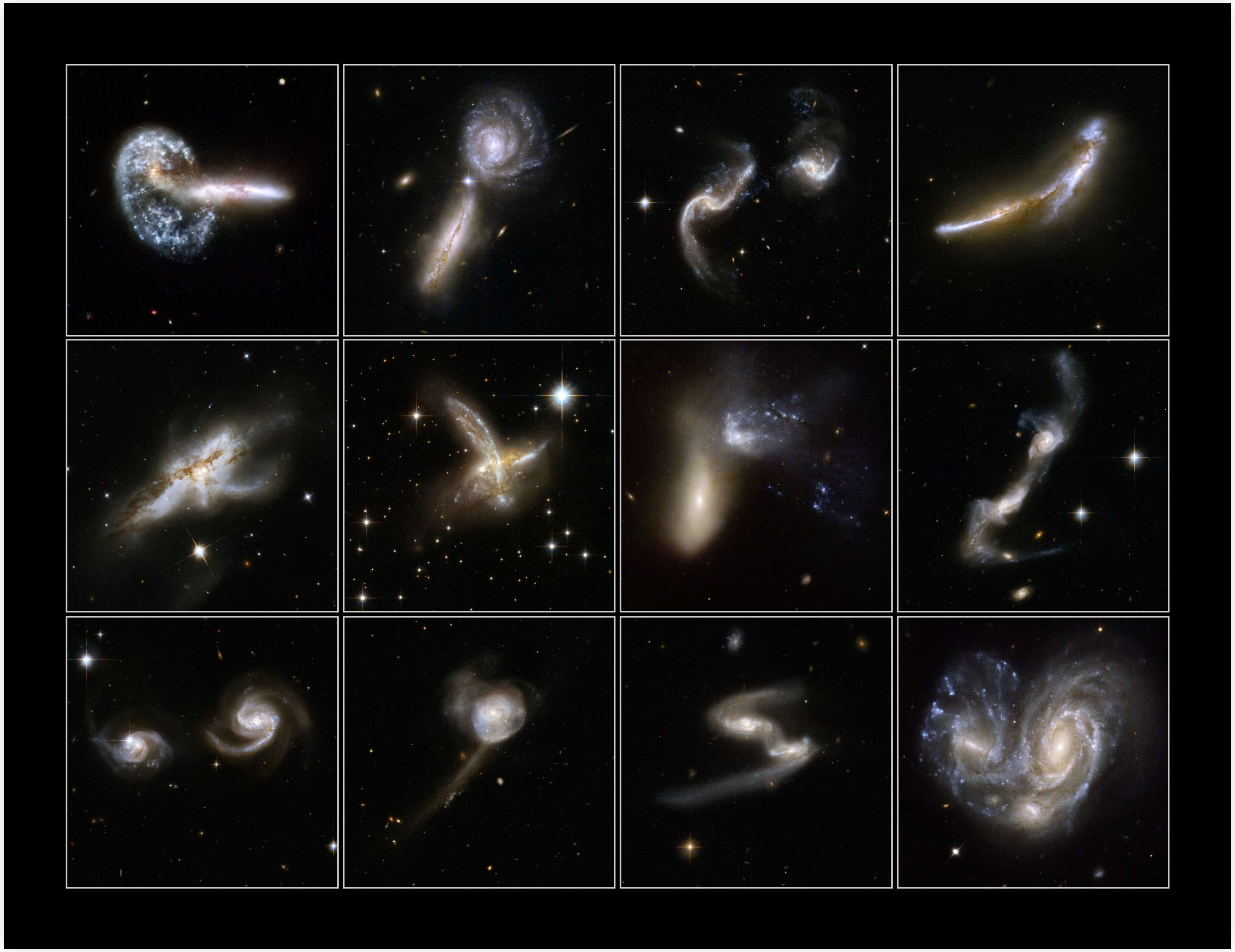


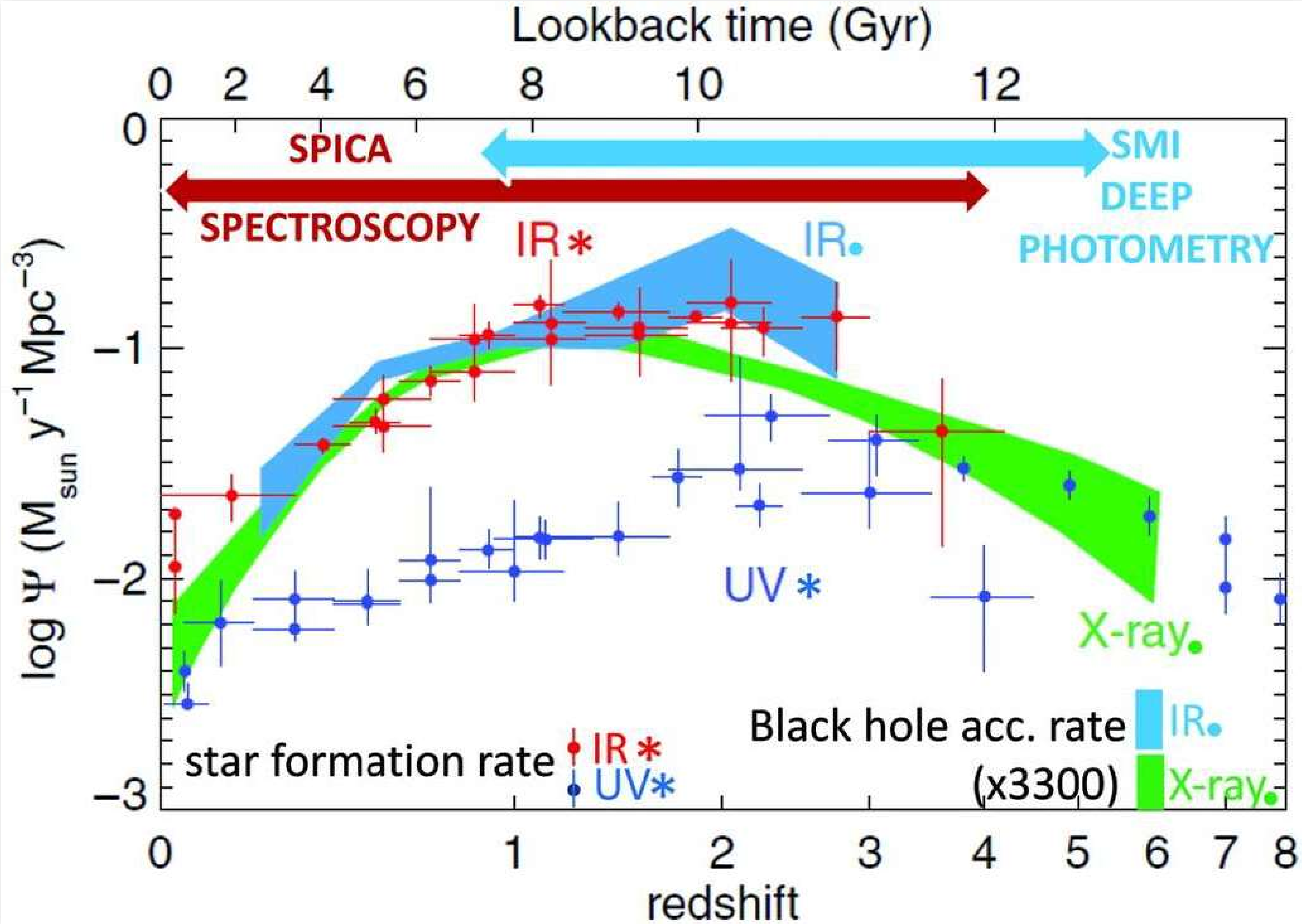
Image: NASA / STScI

スターバースト銀河と銀河衝突



NASA/ESA/STScI/AURA (The Hubble Heritage Team) - ESA/Hubble Collaboration/University of Virginia, Charlottesville, NRAO, Stony Brook University (A. Evans)/STScI (K. Noll)/Caltech (J. Westphal)

星形成史



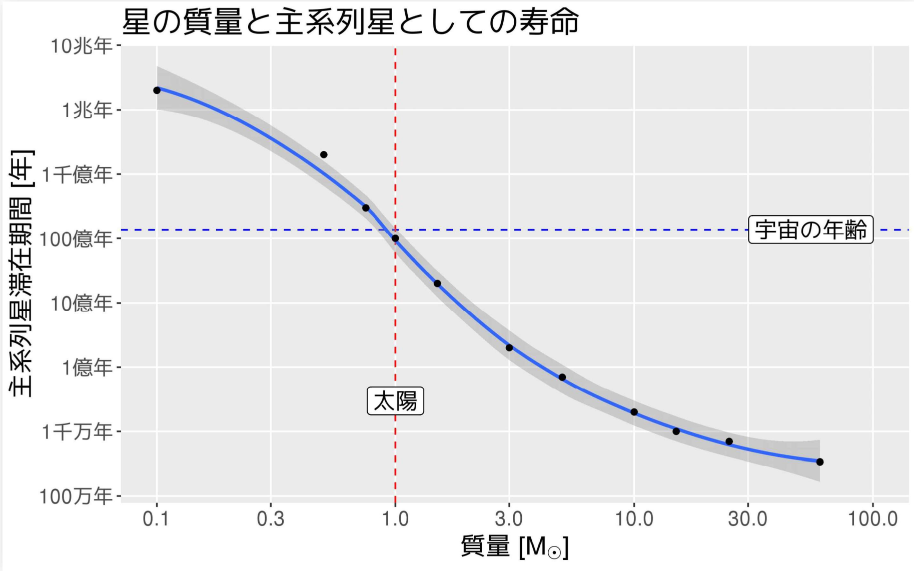
Spinoglio *et al.* 2017, *PASA* **35**, e057

宇宙の最後に残る星

- 太陽の半分以下の重さの星はヘリウム核融合に至らず、水素の枯渇の後に冷えて一生を終える

ただし低質量星の寿命は
宇宙の年齢よりも長い
ことに注意

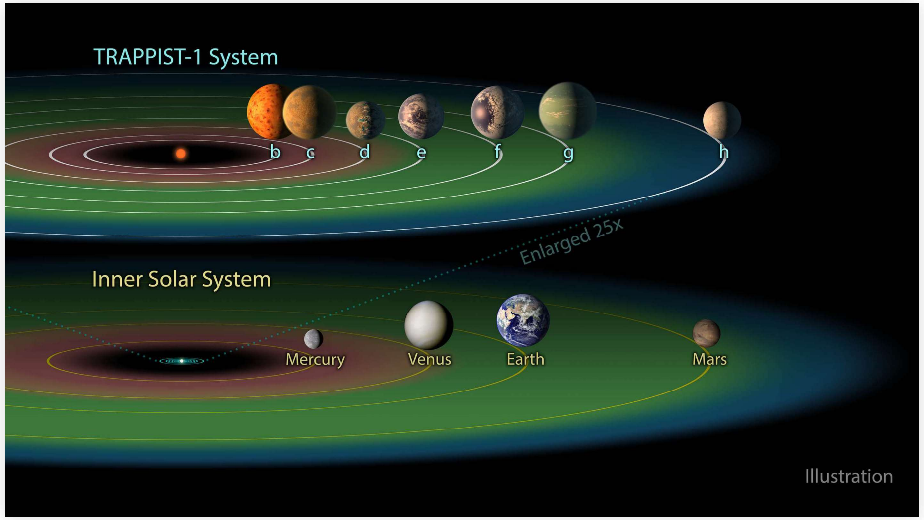
太陽の1/10の重さの星
寿命2兆年、表面温度2900度
→「赤色矮星」



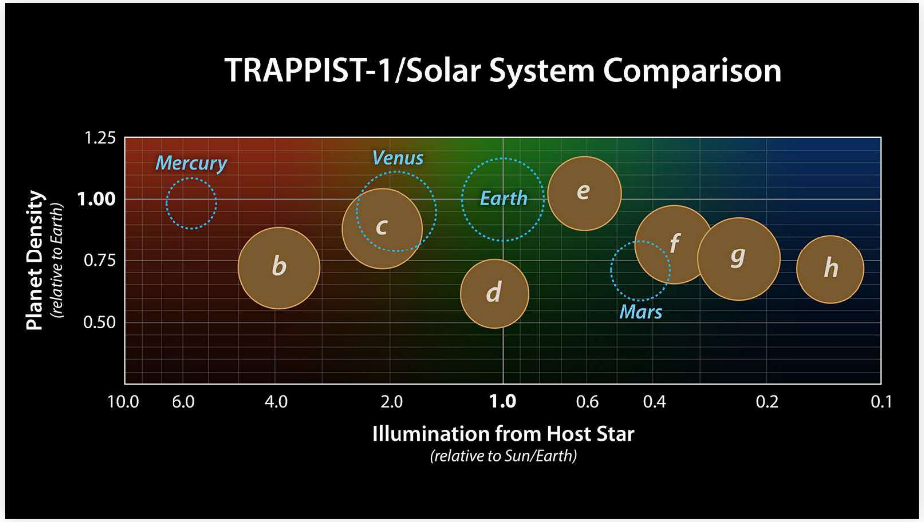
2900度はいわゆる「電球色」の温度。
朝日や夕日、白熱電球やろうそくの温度に相当。

生命居住可能な系外惑星！？

- TRAPPIST-1: 各惑星に地球の250倍の水が存在



NASA/JPL-Caltech



NASA/JPL-Caltech

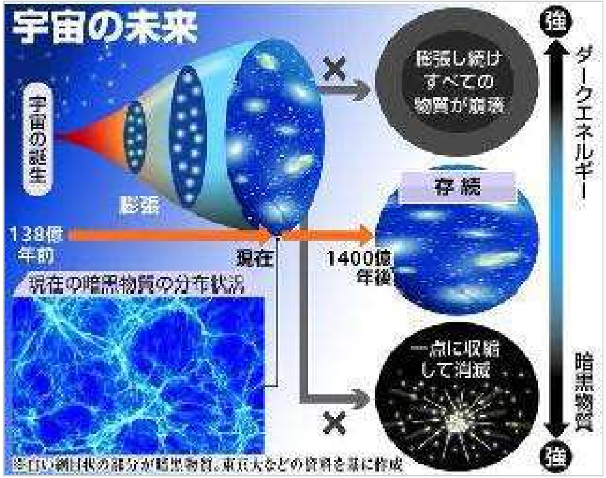
軽い星の周りの惑星

- 100kmを超える深さの海
- いつも同じ方向に見える赤外線の「太陽」
- 降り注ぐ強烈な紫外線・X線

TRAPPIST-1f 想像図

宇宙の余命は１４００億年以上　暗黒物質の分析で東大など将来予測　数百億年説を否定

2018.9.26 09:30



【拡大】

宇宙の物質の大半を占める正体不明の「暗黒物質」の分布を調べ、宇宙が今後１４００億年以上は存在し続けることが分かったと、東京大や国立天文台などの研究チームが２６日、発表した。従来は数百億年で最後を迎えるとの説もあったが否定された形だ。

宇宙がビッグバンで誕生したのは１３８億年前で、少なくともあと１０倍の“余命”がある計算になる。論文をインターネット上で公開した。

現在の宇宙は速度を上げながら膨張して

13.10

13.11

宇宙の加速膨張

- 宇宙は加速度的に膨張を続ける
  - 「あと1400億年は安泰」だが．．．
- 約1000億年後には隣の銀河団も「宇宙の果て」の外に
- 夜空には赤色矮星が鈍く光るのみ

宇宙の最期

10億年後	太陽系が生命居住不能に
40億年後	銀河系がアンドロメダ銀河と衝突
200億年後	赤色矮星のみの銀河
1000億年後	隣の銀河団が見えなくなる
2兆年後	最後の星が燃え尽きる