天文學觀測專注於單一星體，偶而，你會驚覺天際如此均勻！

節目 知識好好玩

EP09｜莊子與愛因斯坦的淵源：淺談宇宙論

主持人｜張嘉泓

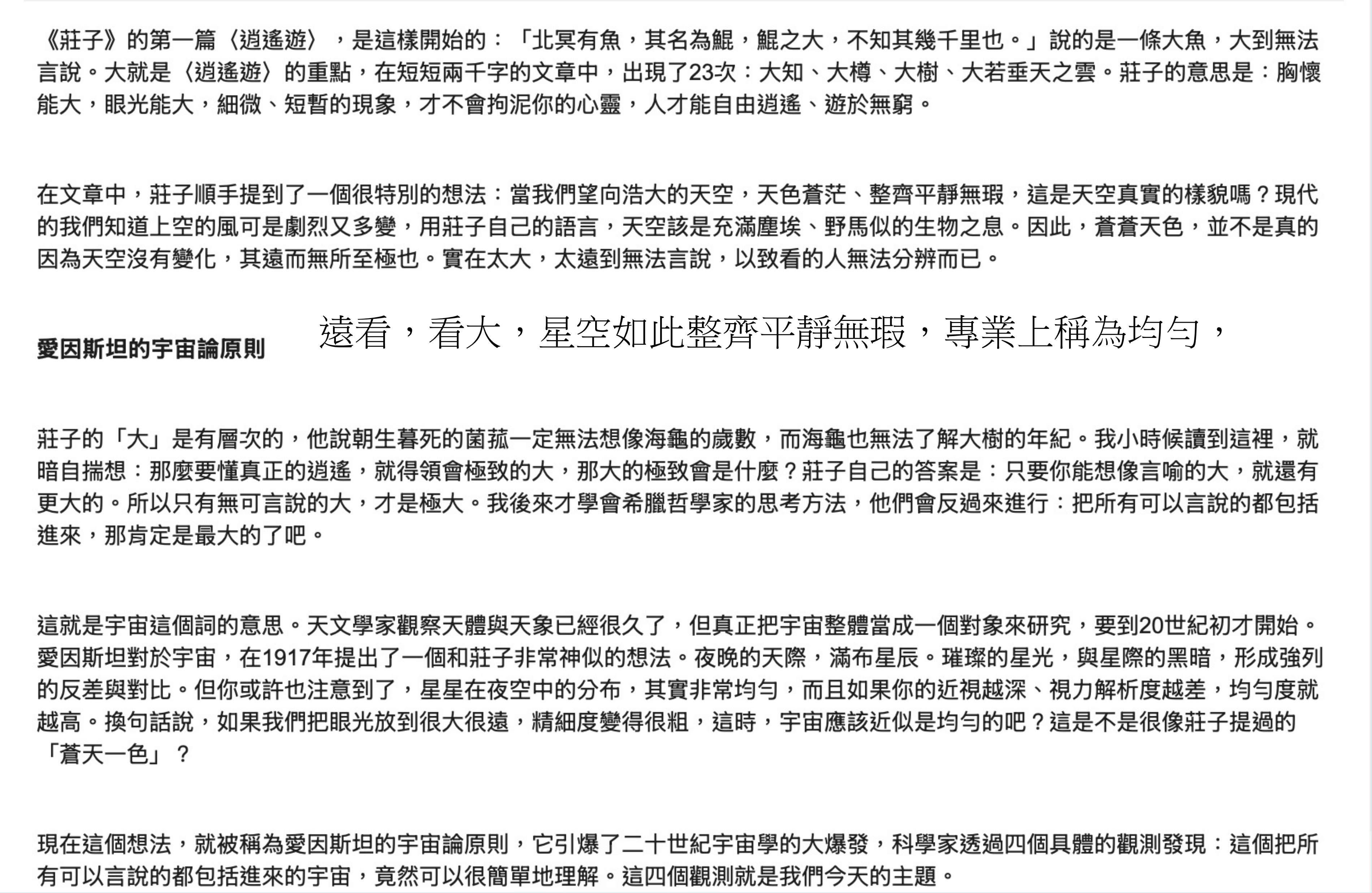
單曲長度｜00:27:54　發布時間｜2021-09-07

#張嘉泓 #物理好好玩 #海龜 #宇宙論 #逍遙遊 #菌菰 #銀河系 #宇宙背景輻射 #大霹靂

張嘉泓

專長是理論粒子物理，畢業於台大物理系，在美國哈佛大學取得博士學位後，曾在清華大學進行研究，現在於臺灣師範大學物理系任教。除...

追蹤 35｜作品 2



《莊子》的第一篇〈逍遙遊〉，是這樣開始的：「北冥有魚，其名為鯤，鯤之大，不知其幾千里也。」說的是一條大魚，大到無法言說。大就是〈逍遙遊〉的重點，在短短兩千字的文章中，出現了23次：大知、大樽、大樹、大若垂天之雲。莊子的意思是：胸懷能大，眼光能大，細微、短暫的現象，才不會拘泥你的心靈，人才能自由逍遙、遊於無窮。

在文章中，莊子順手提到了一個很特別的想法：當我們望向浩大的天空，天色蒼茫、整齊平靜無瑕，這是天空真實的樣貌嗎？現代的我們知道上空的風可是劇烈又多變，用莊子自己的語言，天空該是充滿塵埃、野馬似的生物之息。因此，蒼蒼天色，並不是真的因為天空沒有變化，其遠而無所至極也。實在太大，太遠到無法言說，以致看的人無法分辨而已。

愛因斯坦的宇宙論原則

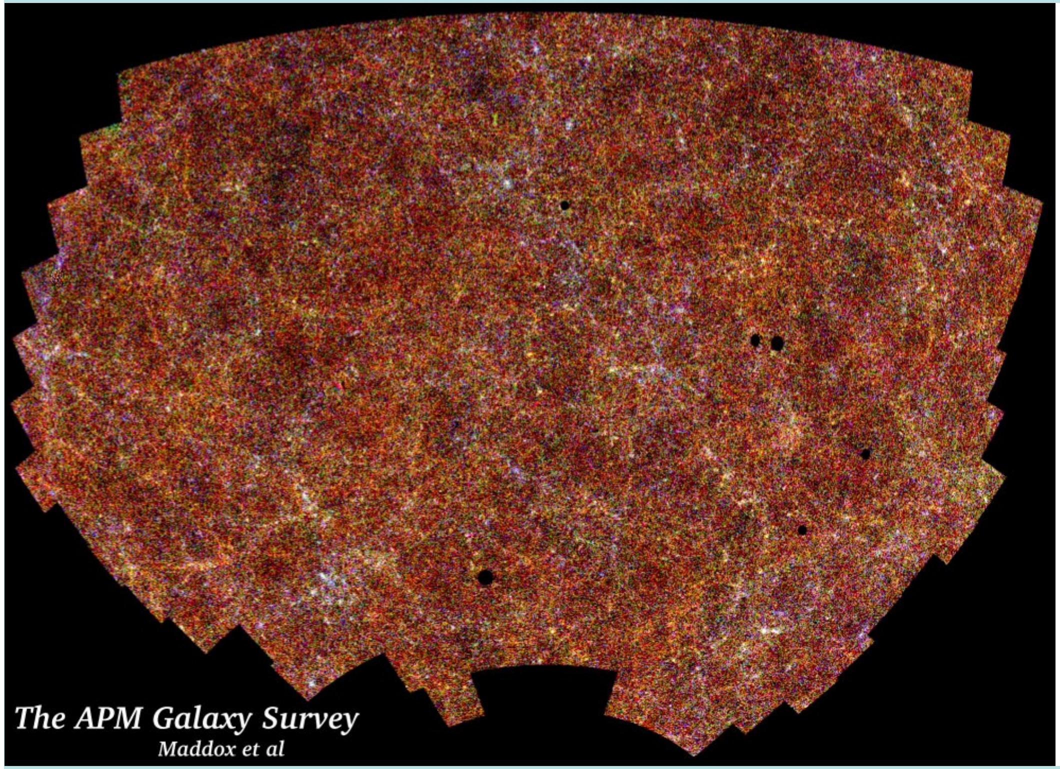
遠看，看大，星空如此整齊平靜無瑕，專業上稱為均勻，

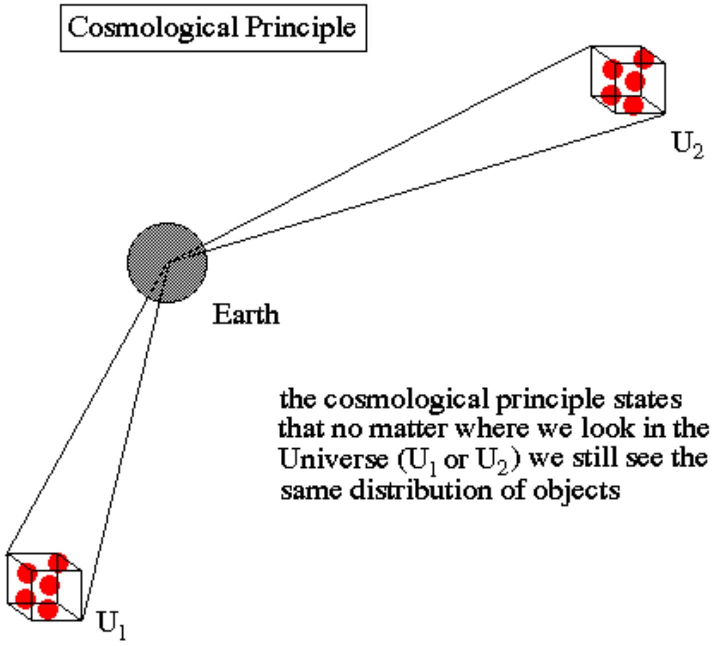
莊子的「大」是有層次的，他說朝生暮死的菌菇一定無法想像海龜的歲數，而海龜也無法了解大樹的年紀。我小時候讀到這裡，就暗自揣想：那麼要懂真正的逍遙，就得領會極致的大，那大的極致會是什麼？莊子自己的答案是：只要你能想像言喻的大，就還有更大的。所以只有無可言說的大，才是極大。我後來才學會希臘哲學家的思考方法，他們會反過來進行：把所有可以言說的都包括進來，那肯定是最大的了吧。

這就是宇宙這個詞的意思。天文學家觀察天體與天象已經很久了，但真正把宇宙整體當成一個對象來研究，要到20世紀初才開始。愛因斯坦對於宇宙，在1917年提出了一個和莊子非常神似的想法。夜晚的天際，滿布星辰。璀璨的星光，與星際的黑暗，形成強烈的反差與對比。但你或許也注意到了，星星在夜空中的分布，其實非常均勻，而且如果你的近視越深、視力解析度越差，均勻度就越高。換句話說，如果我們把眼光放到很大很遠，精細度變得很粗，這時，宇宙應該近似是均勻的吧？這是不是很像莊子提過的「蒼天一色」？

現在這個想法，就被稱為愛因斯坦的宇宙論原則，它引爆了二十世紀宇宙學的大爆發，科學家透過四個具體的觀測發現：這個把所有可以言說的都包括進來的宇宙，竟然可以很簡單地理解。這四個觀測就是我們今天的主題。

Cosmological principle





the cosmological principle states that no matter where we look in the Universe (U_1 or U_2) we still see the same distribution of objects

以大約~100Mpc的尺度方格作平均，宇宙在是均勻 homogeneous 的，

意思是觀察結果、特別是星體密度，與每一方格的位置無關！整齊平靜無瑕。

各向同性 isotropic：觀察結果與方向無關！

如此大尺度均勻的宇宙，星體應該什麼都看不清了，有什麼意思呢？

宇宙有大尺度的活動的度規 metric、以及背景輻射！宇宙論的對象！

擴張宇宙：Expanding Universe

Cosmic Microwave Background Radiation CMB 宇宙背景輻射

Hot Big Bang 大霹靂

原始電漿 Primordial Plasma

Big Bang Nucleosynthesis核合成

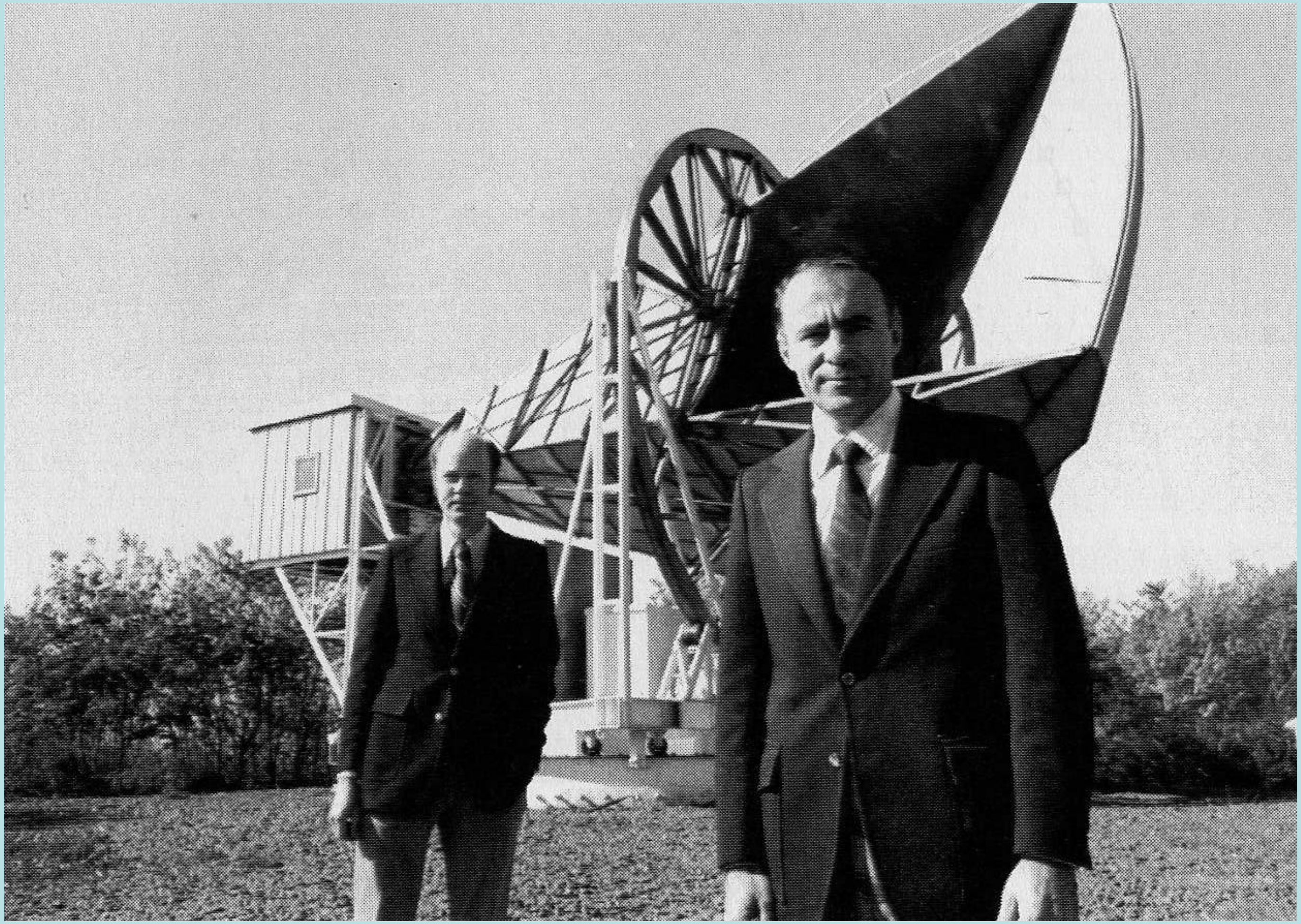
Recombination

宇宙背景輻射非同向性

標準模型

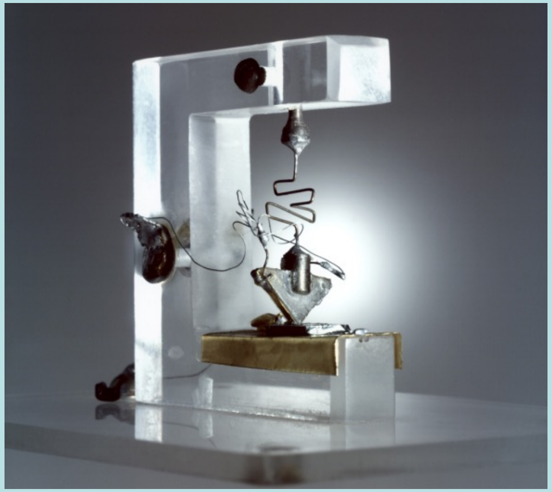
Cosmic Microwave Background Radiation CMB 宇宙背景輻射

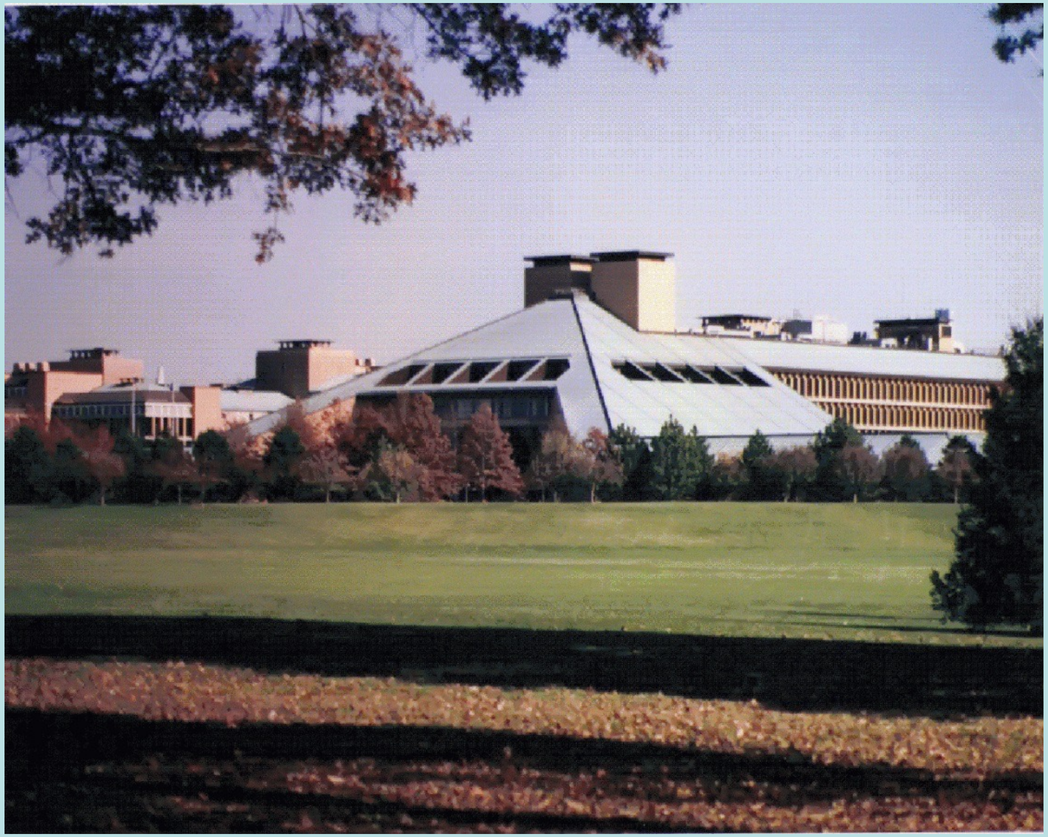
Penzias and Wilson found CMB accidentally in 1965 and won the 1978 Nobel



Bell Lab Home of Transistor

Bell Laboratories

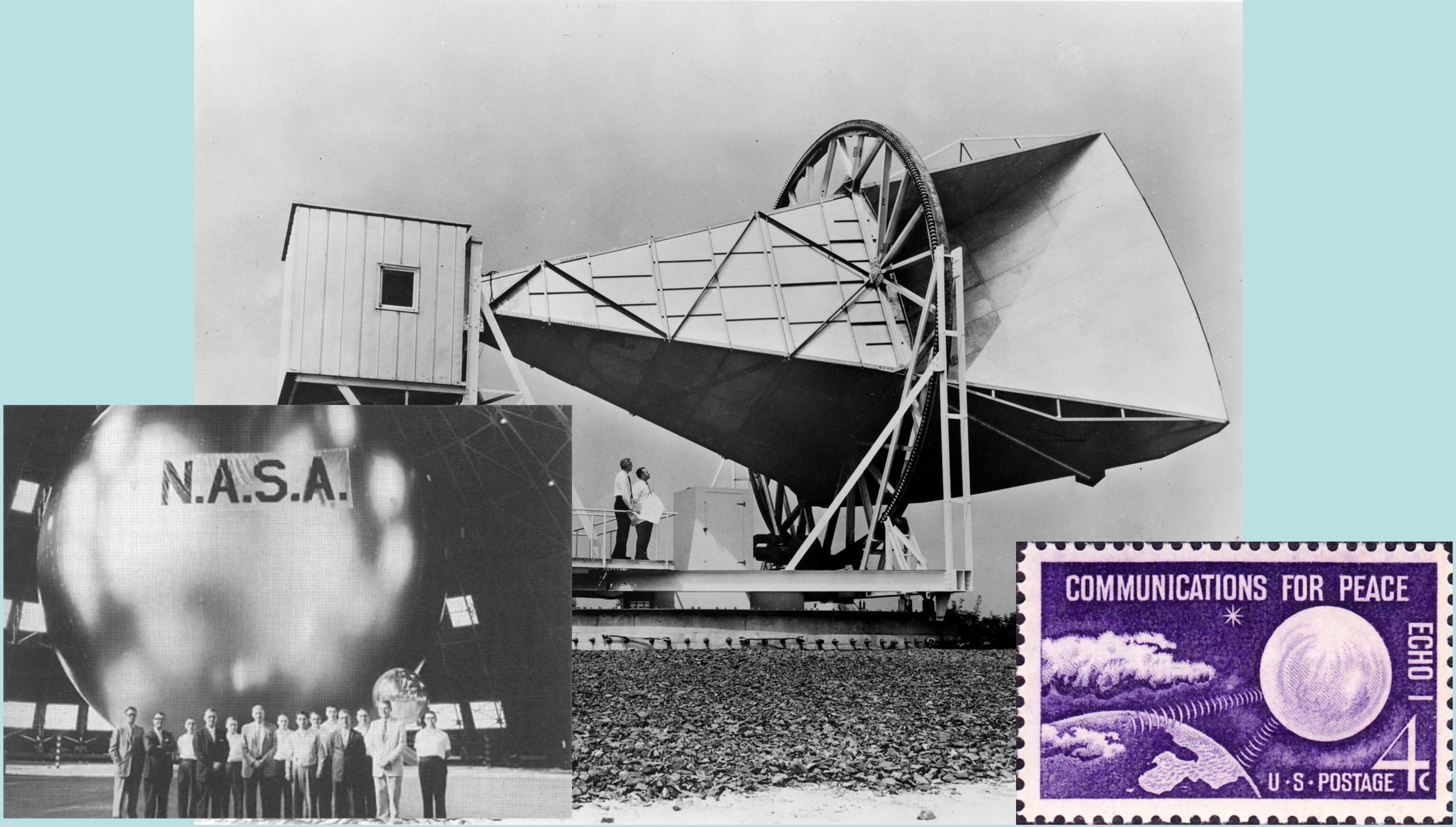




THE IDEA FACTORY

Bell Labs and the Great Age of American Innovation

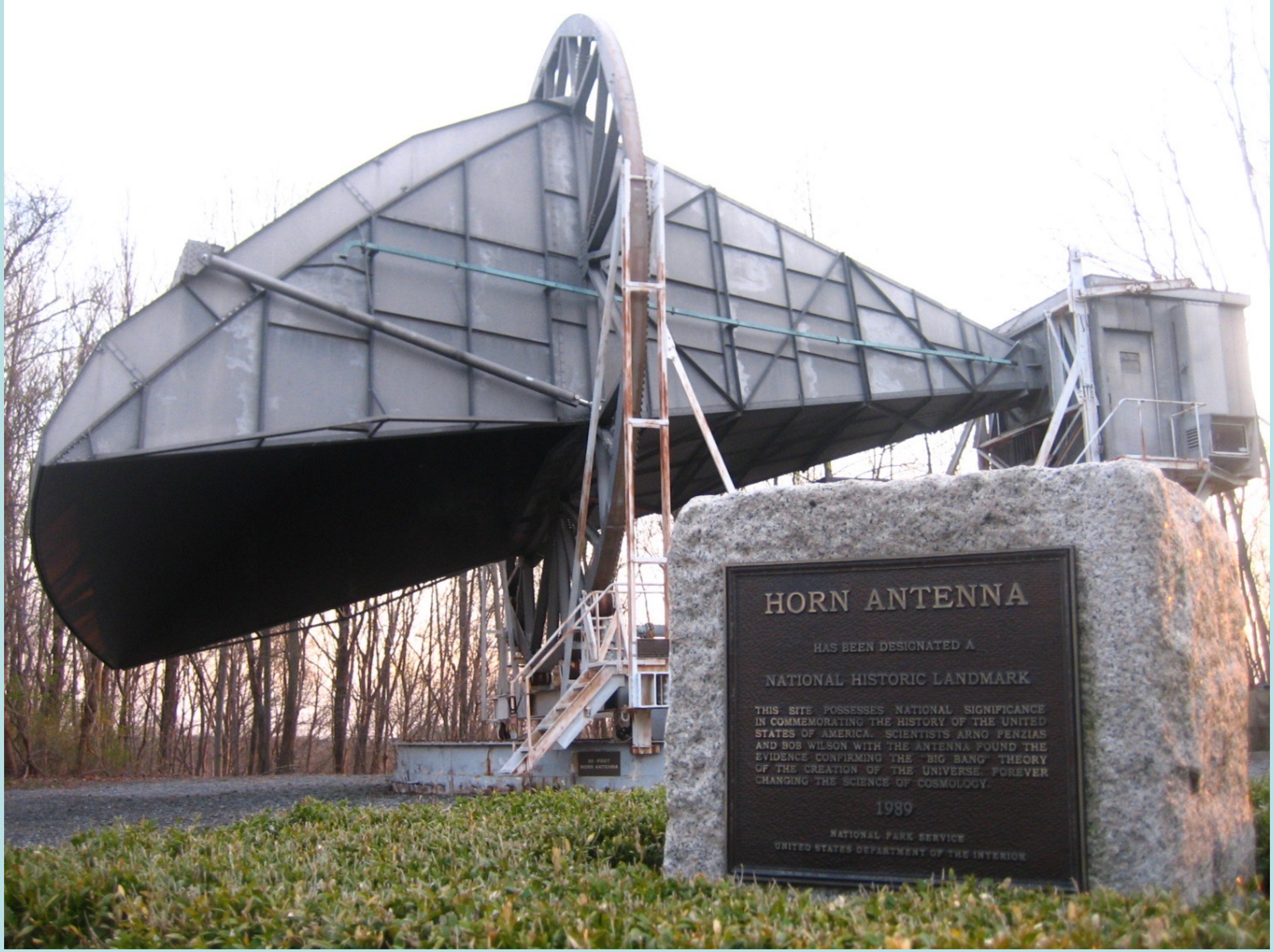
Jon Gertner

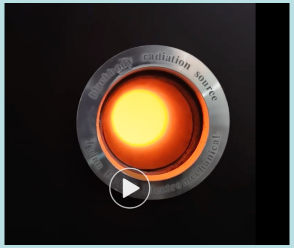


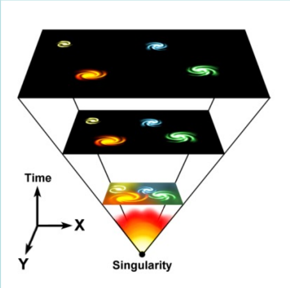
The 15 meter Holmdel horn antenna at Bell Telephone Laboratories in Holmdel, New Jersey was built in 1959 for pioneering work in communication satellites for the NASA ECHO I.

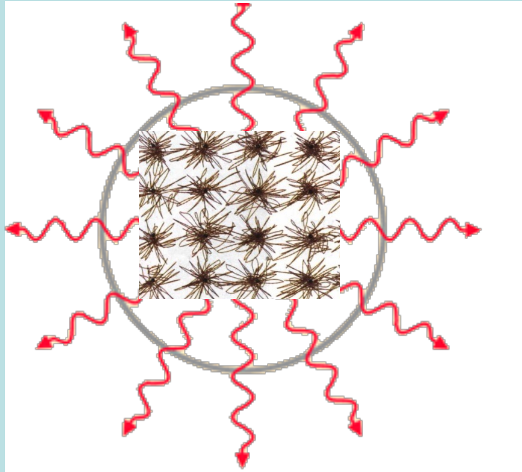
Horn Antenna 觀測到來自宇宙、均勻而同向的微波Microwave。

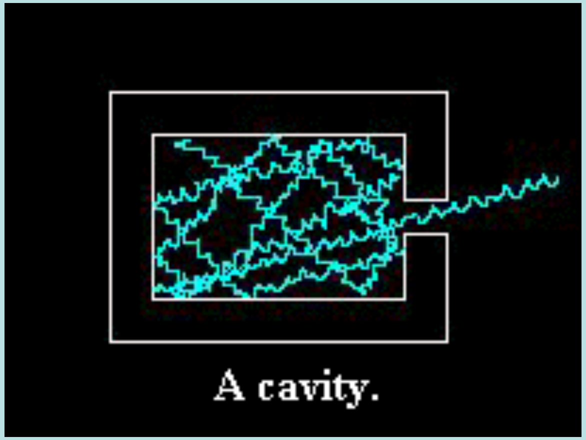
稱為 Cosmic Microwave Background Radiation CMB 宇宙背景輻射。

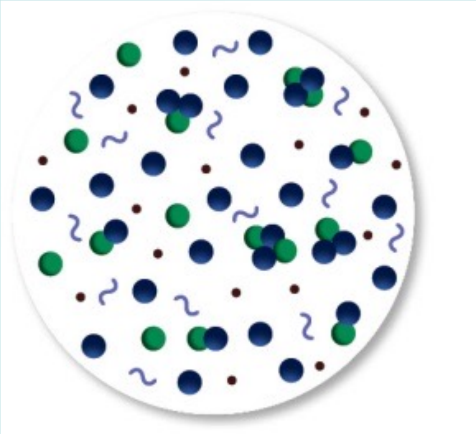






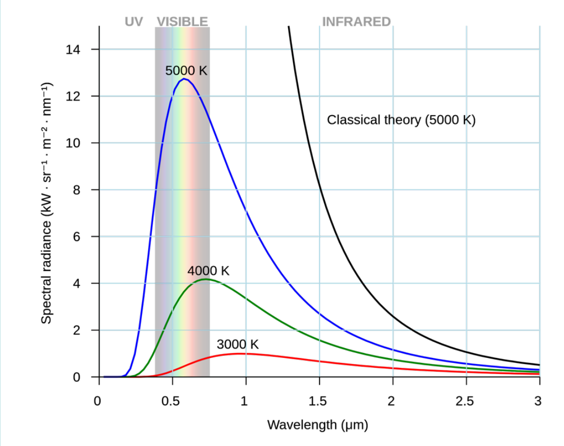






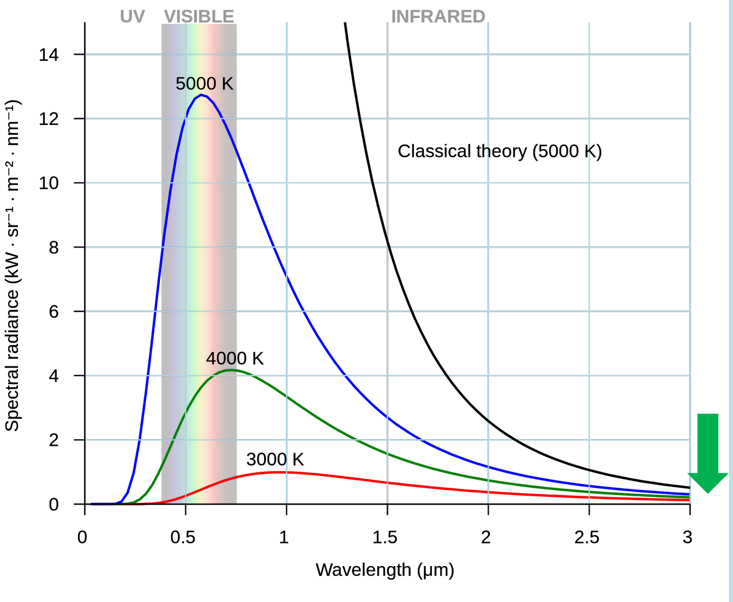
黑體輻射等同於空腔輻射，也等同於電磁波與一群物質一起達成的熱平衡狀態！

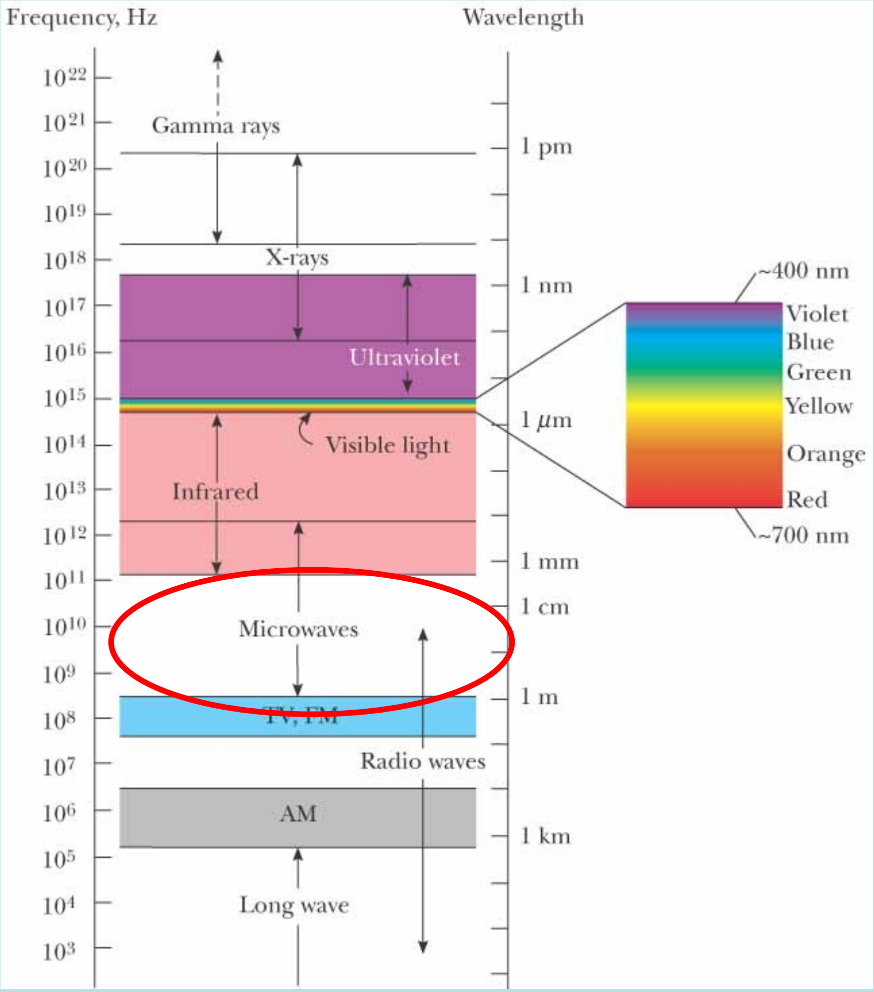
特徵是由溫度完全決定的輻射功率波長分布！測得分布及能推定出溫度！



電磁波以頻率或波長為特徵：

$$\lambda f = c$$

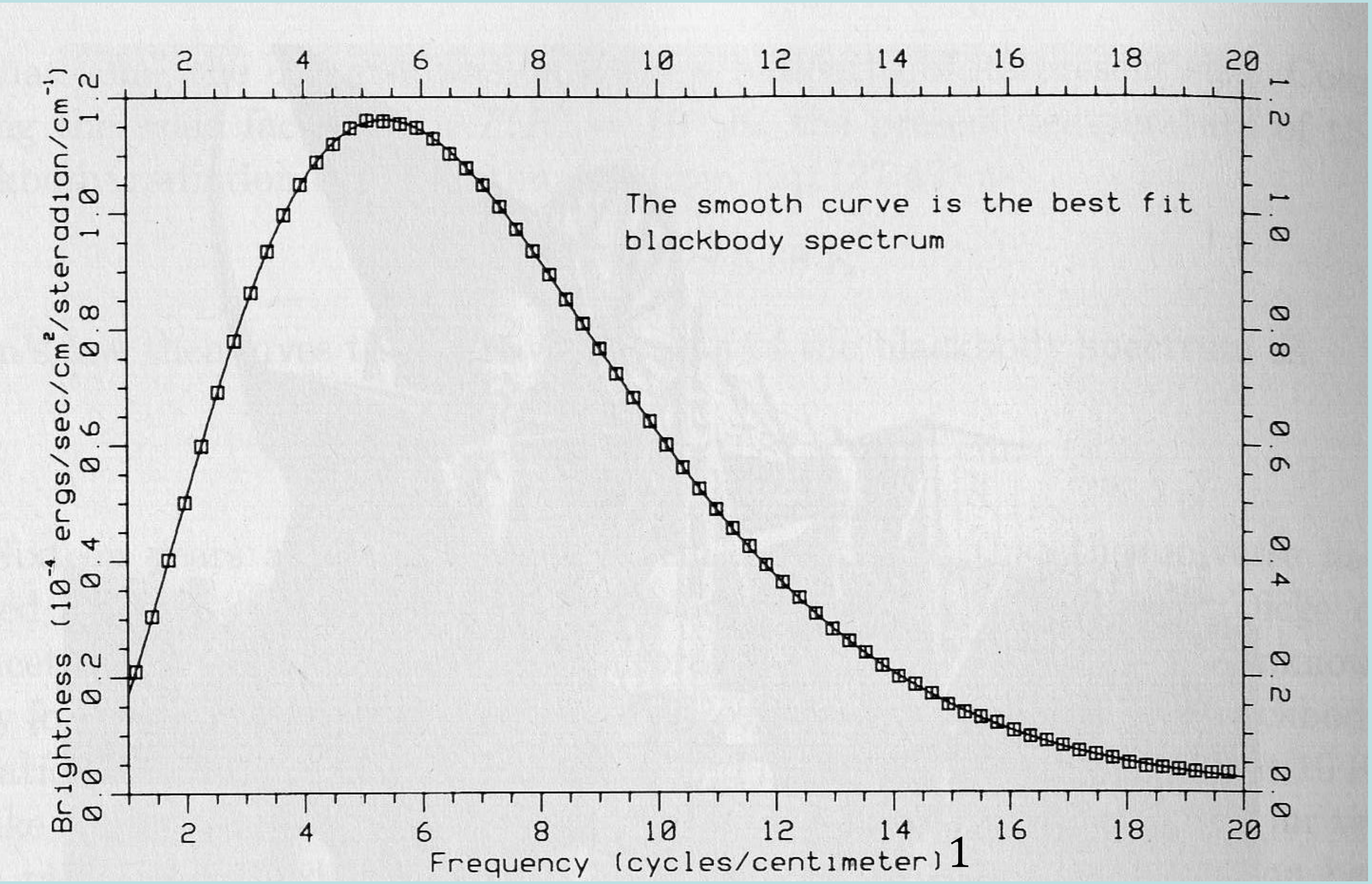




以微波為主的熱輻射非常冷！

CMB is a blackbody radiation at 2.725K。

大部分是微波，很冷。



$\frac{1}{\lambda}$

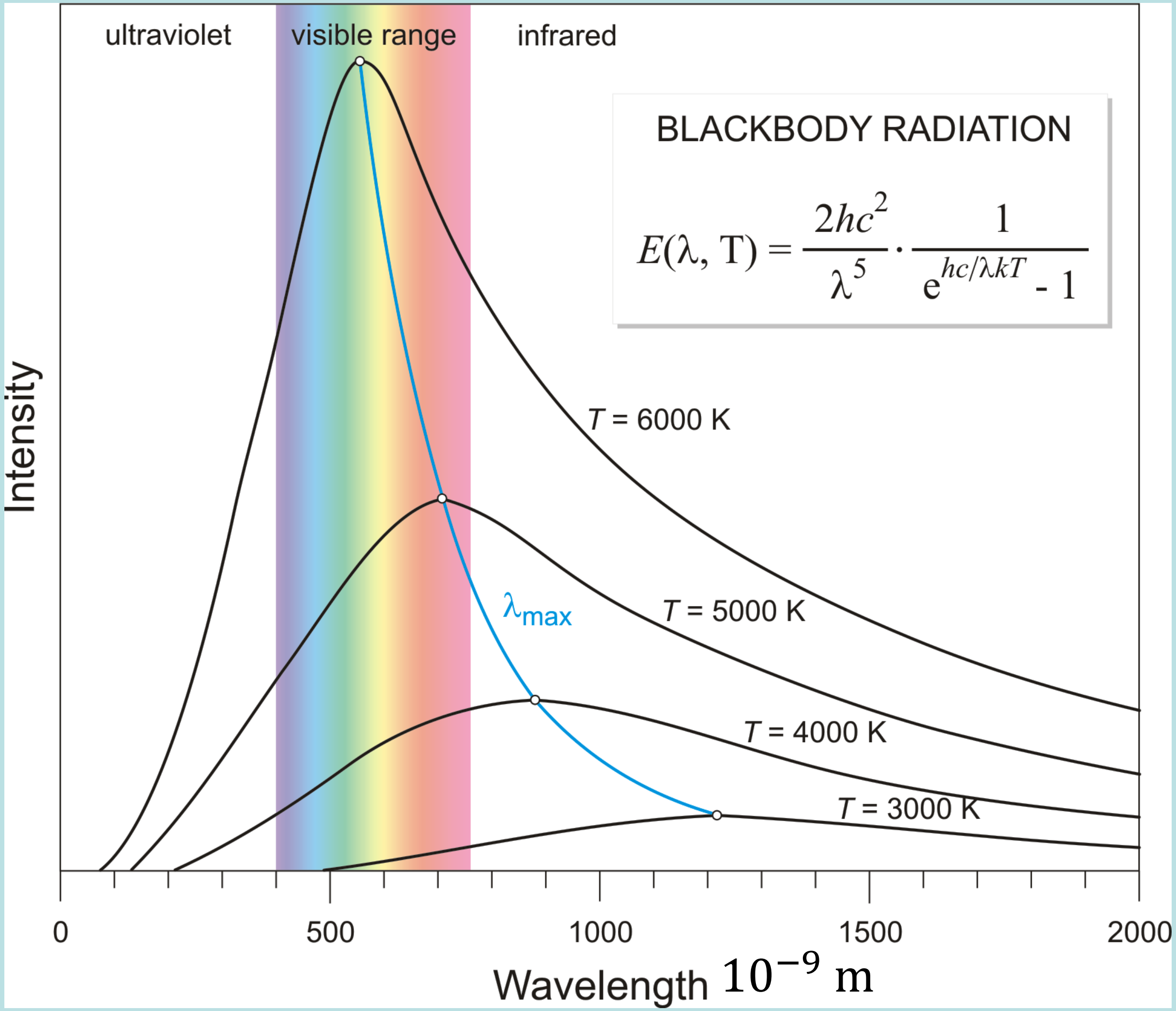
完美的黑體輻射！

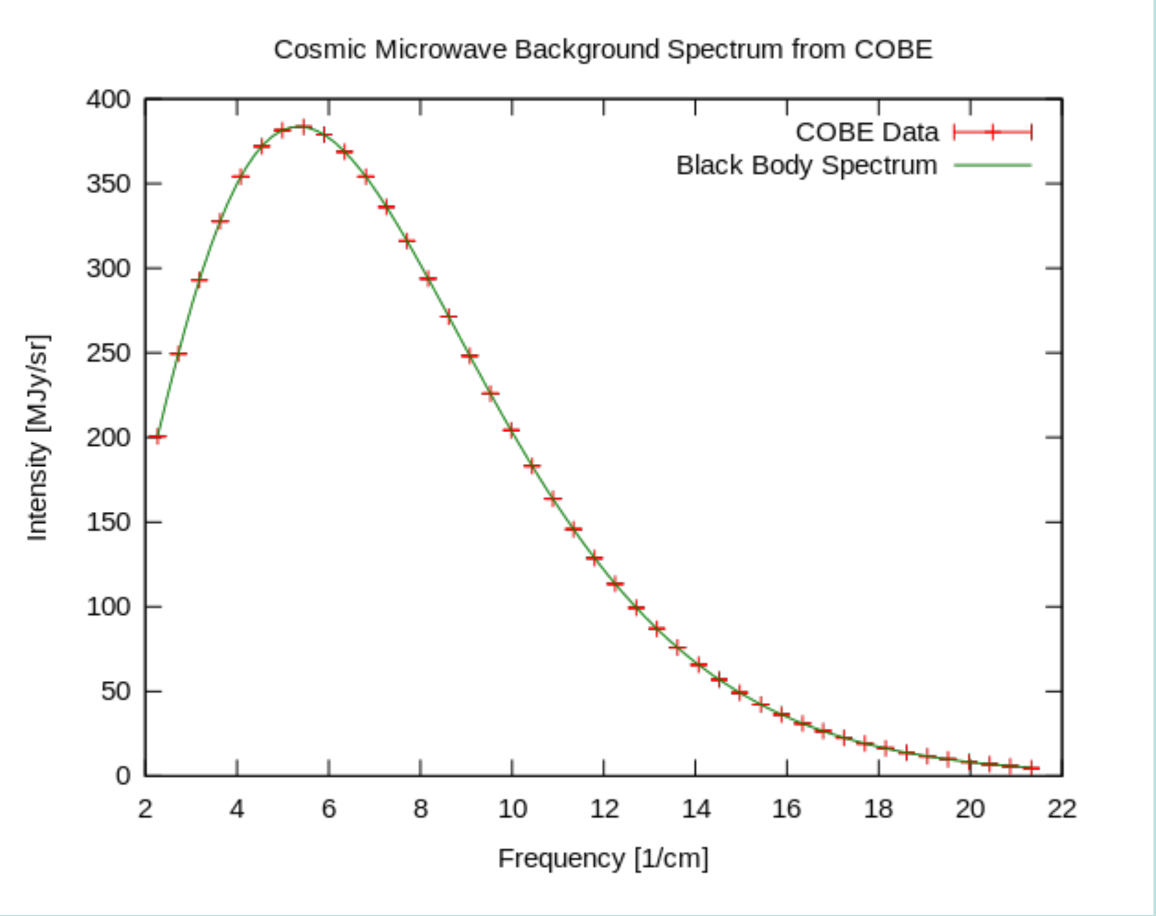
$\lambda_{max} \sim 10^{-3}$m

$\lambda_{\max} \cdot T = 2.898 \times 10^{-3} \mathrm{m} \cdot \mathrm{K}$

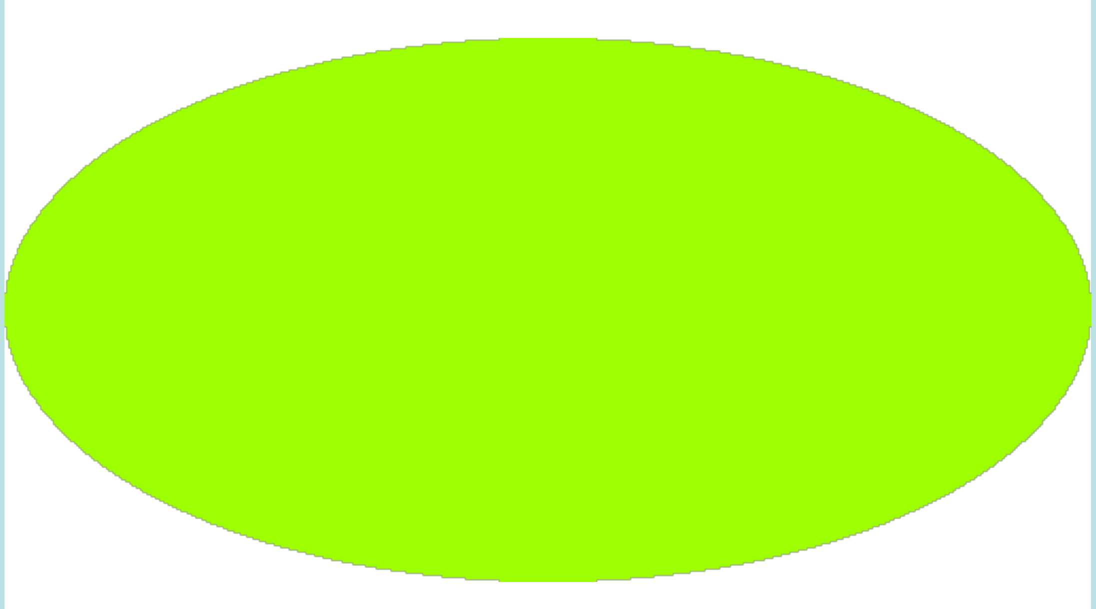
$\lambda_{\max} \sim 10^{-3} \mathrm{m}$

$T \sim 3.0\ \mathrm{K}$




Cosmic Microwave Background Spectrum from COBE
COBE Data
Black Body Spectrum
Intensity [MJy/sr]
Frequency [1/cm]
0
50
100
150
200
250
300
350
400
2
4
6
8
10
12
14
16
18
20
22

CMB 在星空中所有的方向都是 3.0 K！稱為CMB 的同向性 Isotropy。

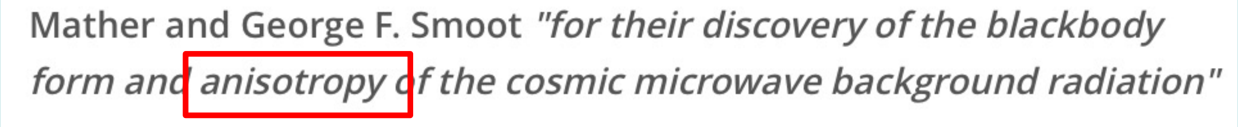


不同角度的微波來自彼此距離非常遙遠的地方。

在廣大的宇宙中，背景輻射如何維持同一溫度呢？

能彼此作用才能達成熱平衡，過去這些電磁波必須彼此很靠近！

沒想到科學家已經早有答案了。



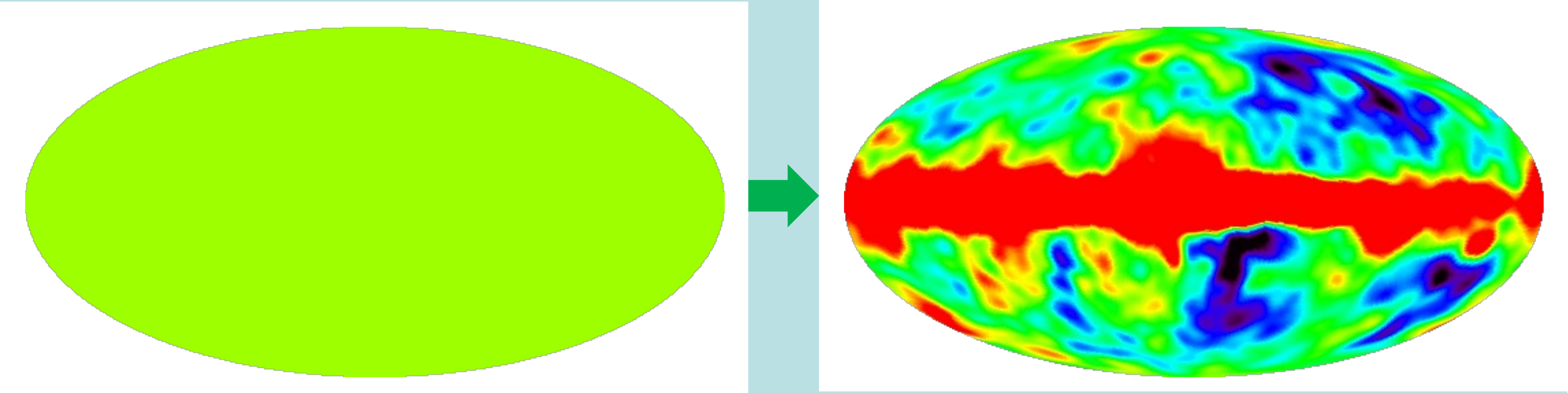
Mather and George F. Smoot *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*

Cobe 還有一個更重要的發現！

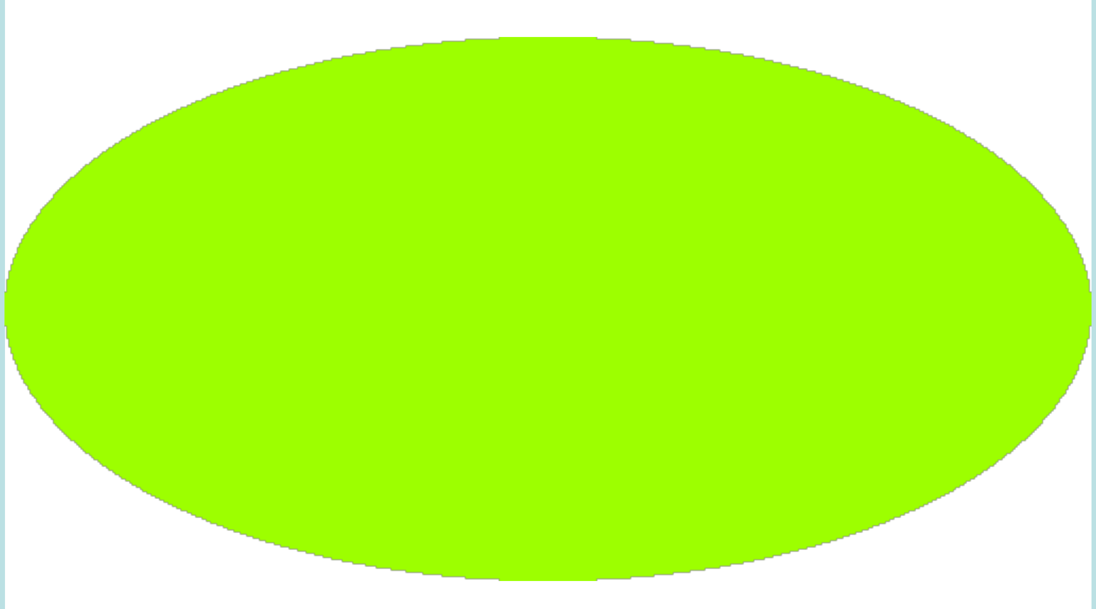
Cobe 同時觀察到大致同向的背景輻射有極微小的非同向性 anisotropy。

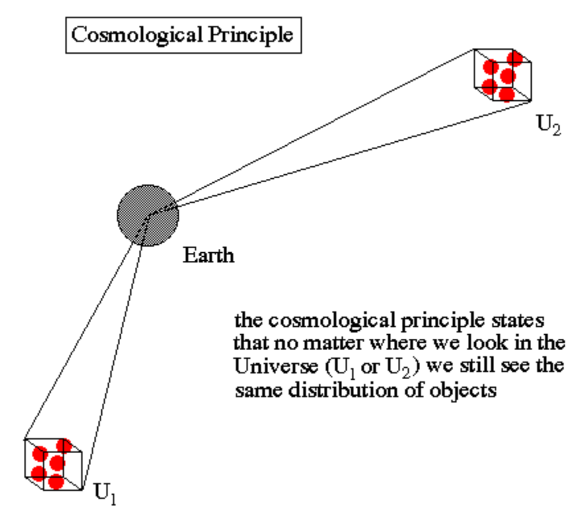
顏色代表冷熱，溫度差距大約是10^{-4}~10^{-5}K。

這是後話。



Cosmological principle



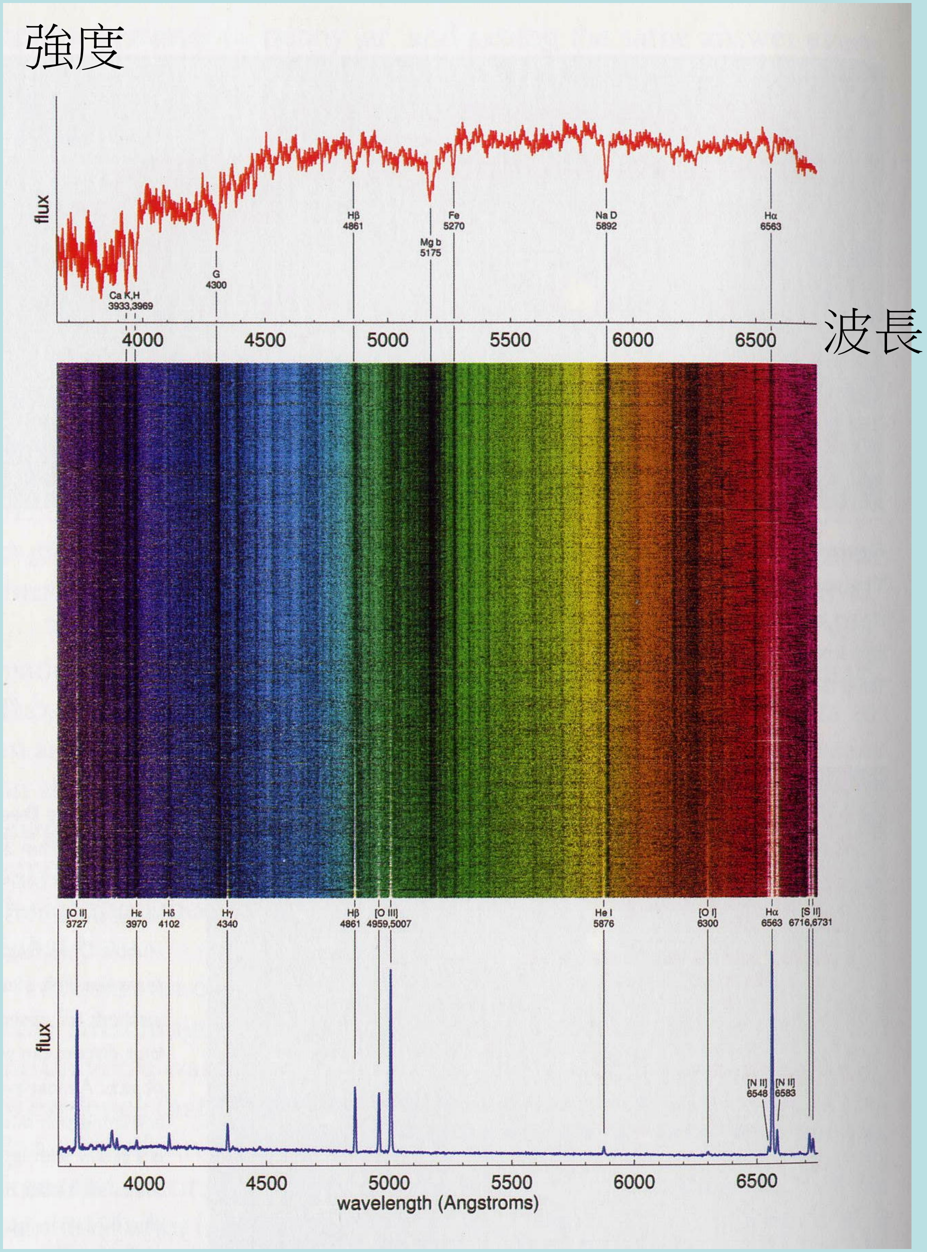


在~100Mpc的尺度，平均來說，宇宙是均勻同相的，

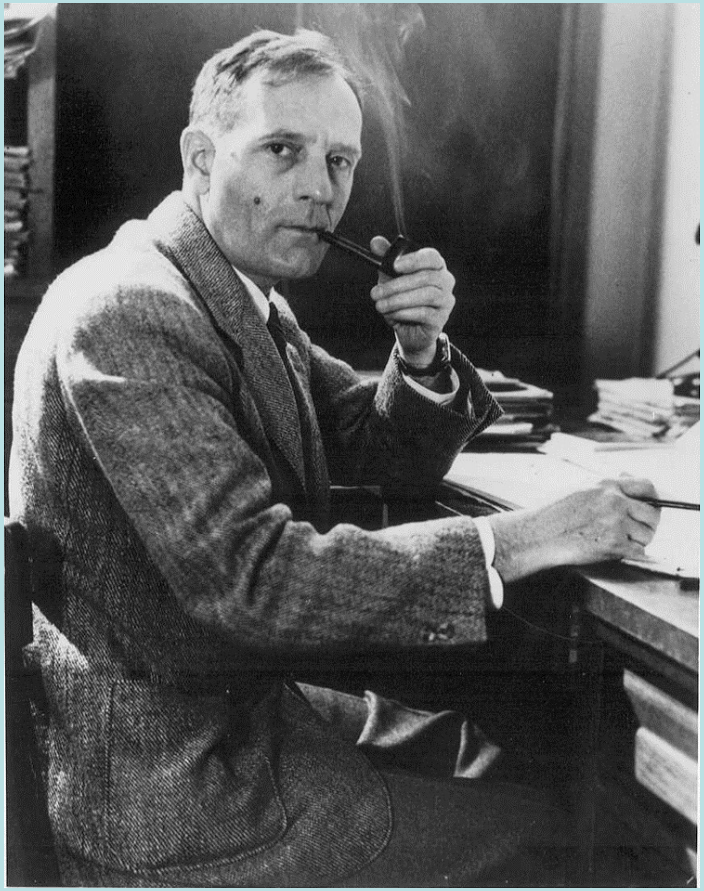
大尺度下均勻的宇宙，星體應該什麼都看不清了，有什麼意思呢？

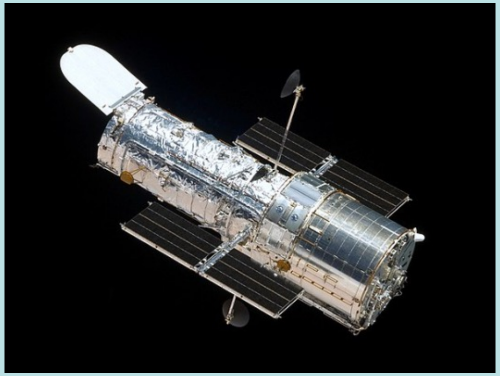
宇宙有大尺度的背景輻射！

天文學家在二十世紀初開始對星光作光譜分析。

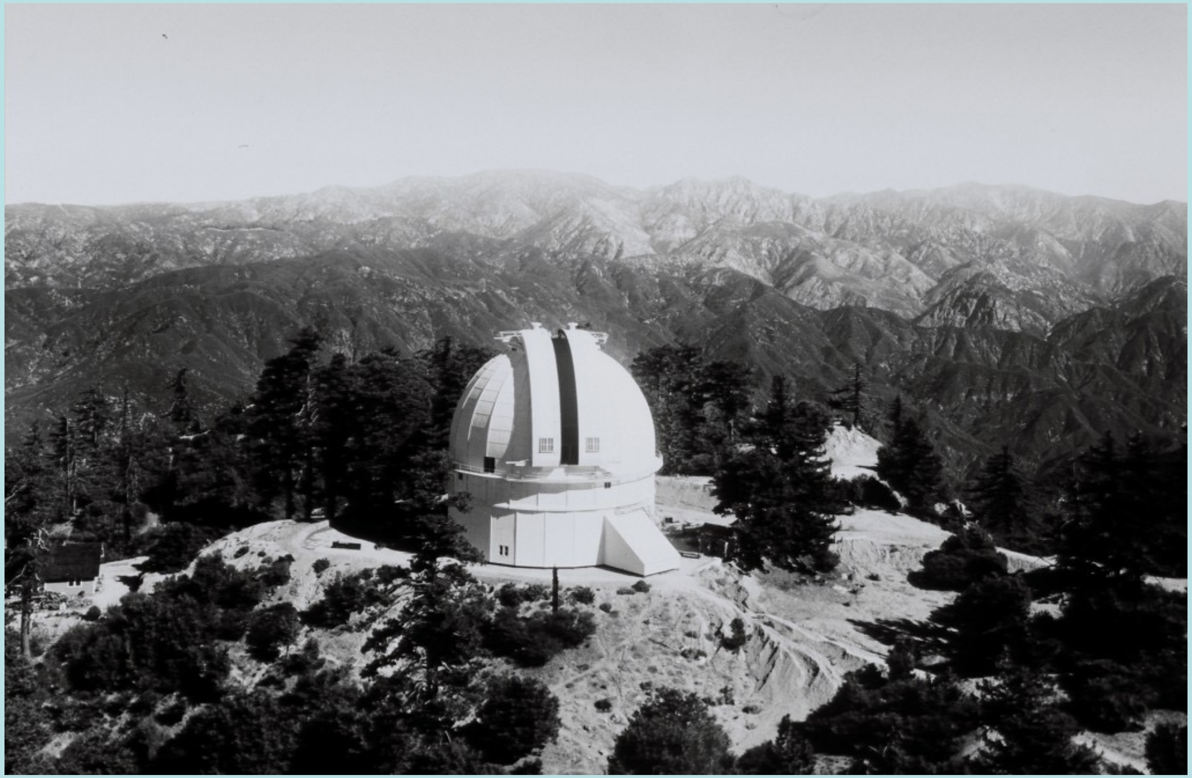


Edwin Hubble 1889-1953

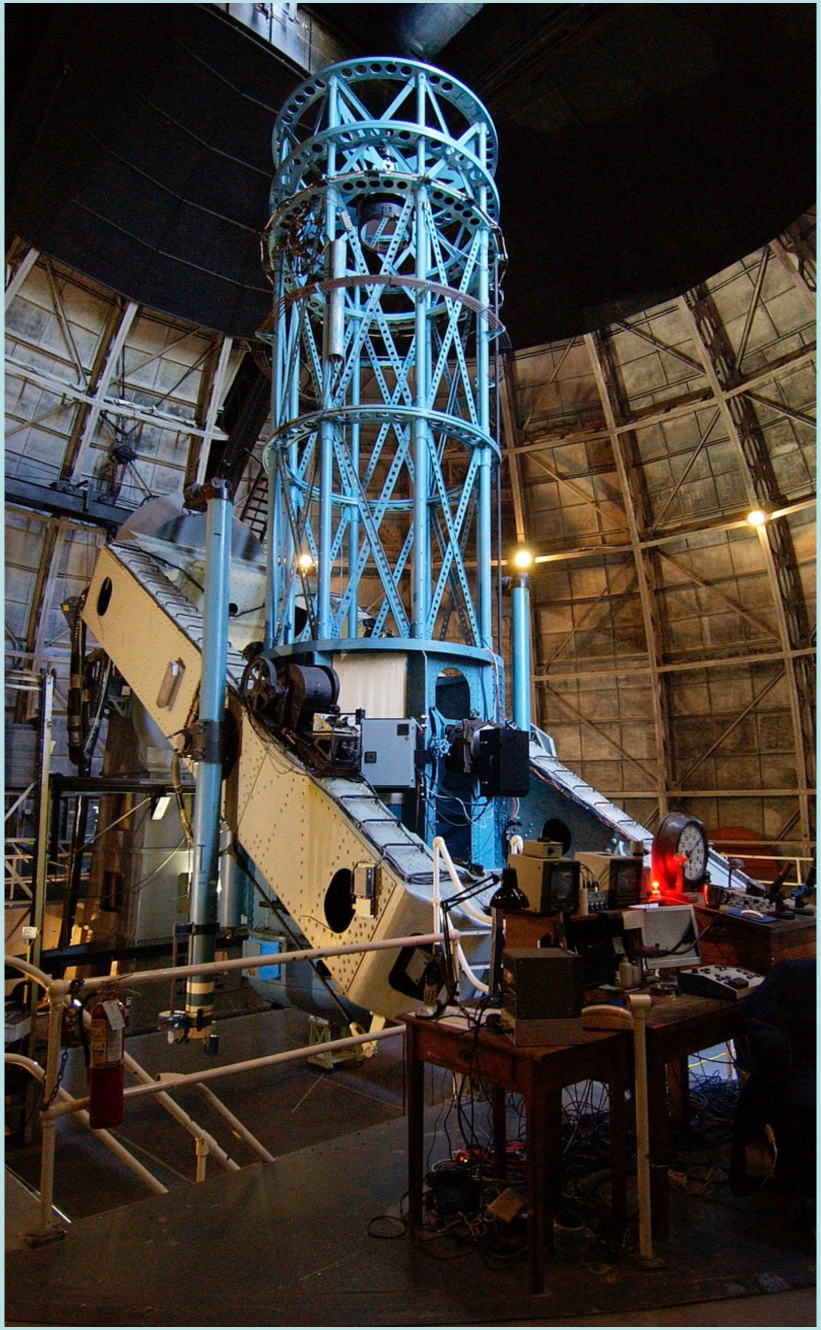




Hubble Telescope

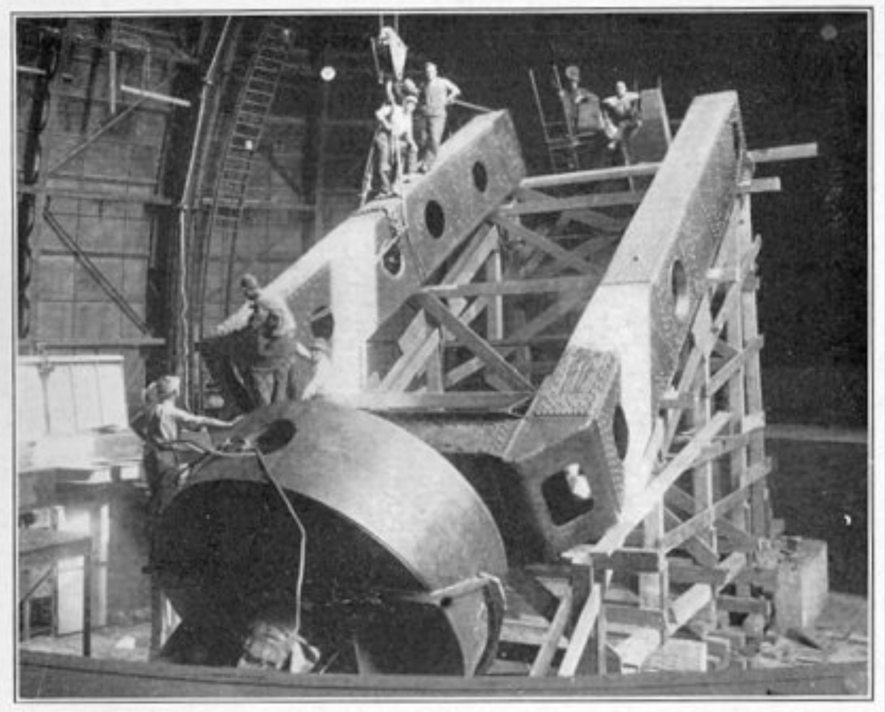


Mount Wilson Observatory 1917

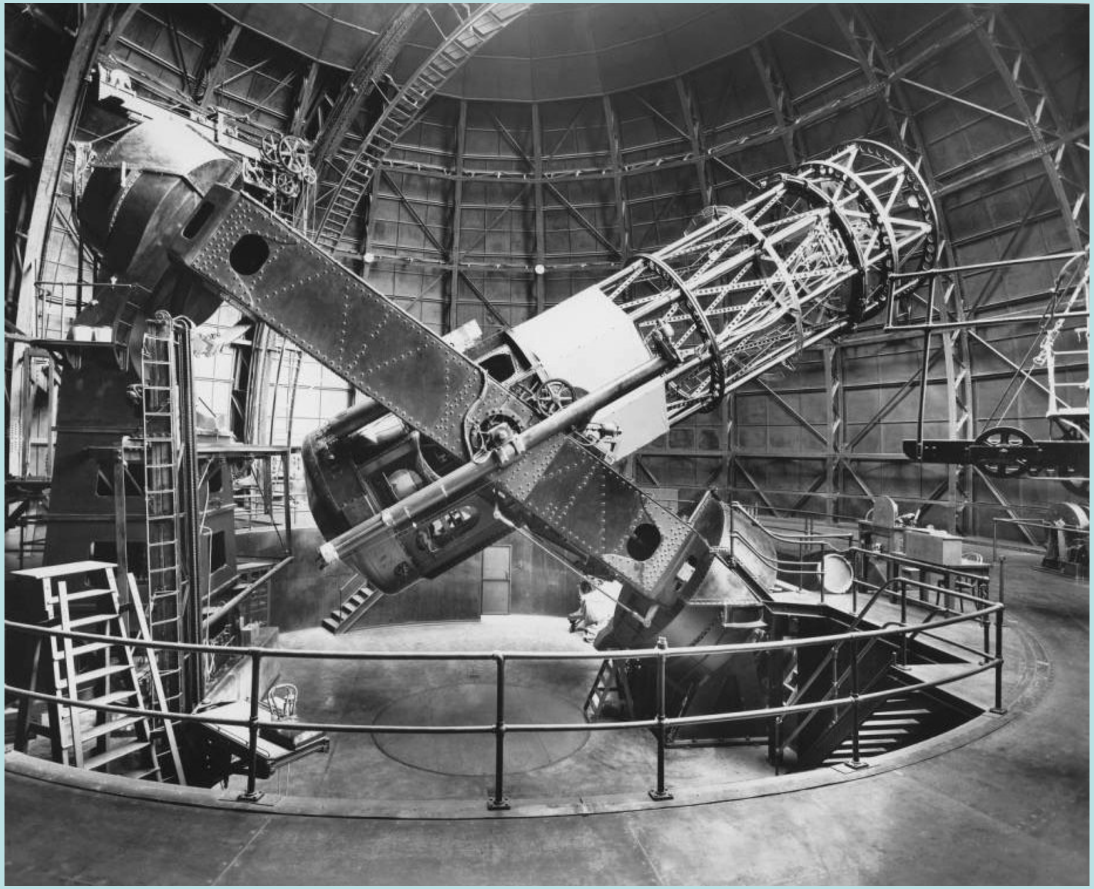


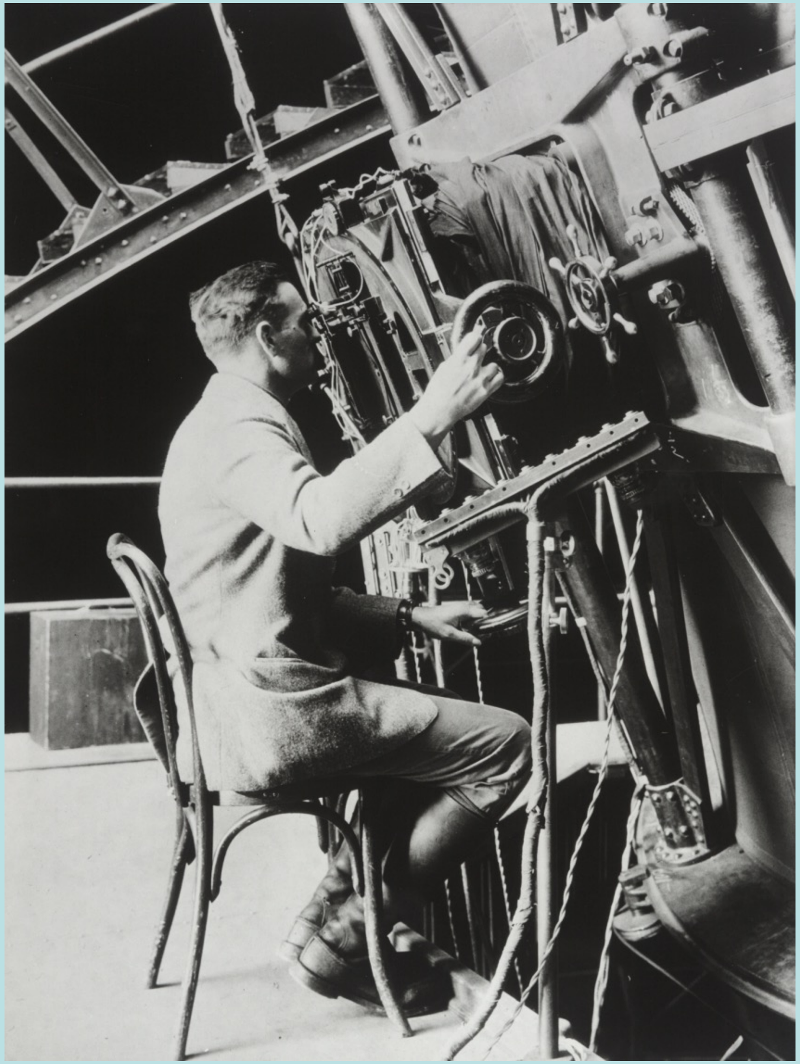
The 100-inch (2.5 m) **Hooker telescope** located at Mount Wilson Observatory, California, was the world's largest telescope from 1917 to 1949.

The mirror of the Hooker telescope on its way up the Mount Wilson Toll Road on a Mack Truck in 1917.

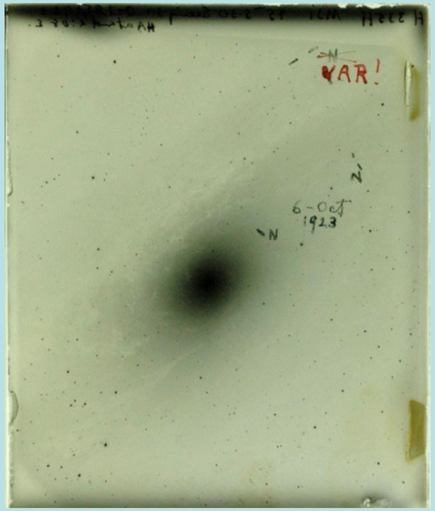


Workmen assembling the polar axis of the Hooker telescope.

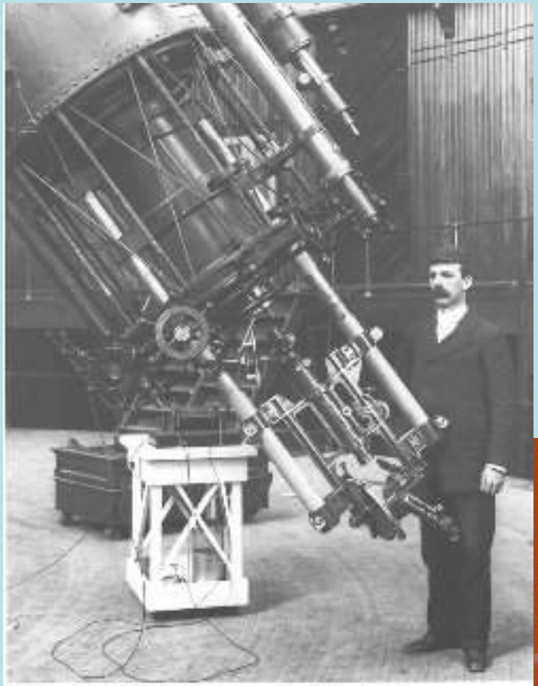




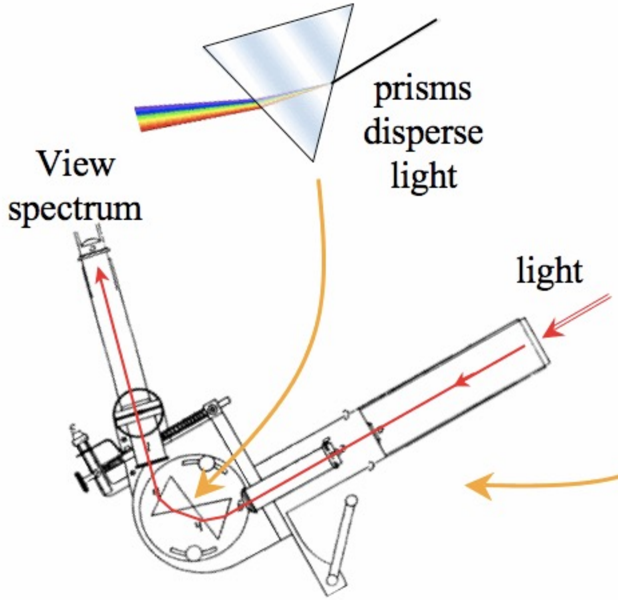
Edwin Hubble Papers/Courtesy of Huntington Library, San Marino, Calif.



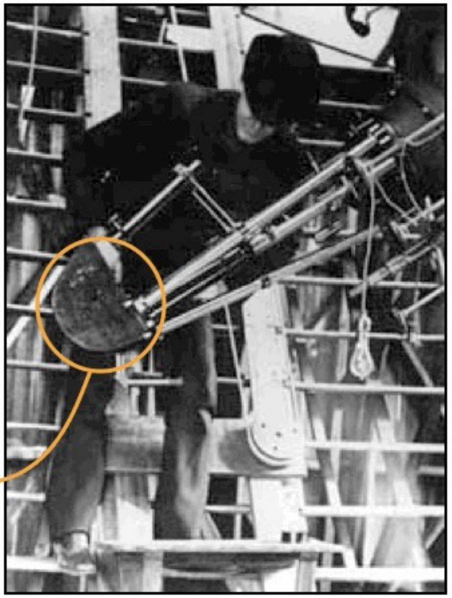
This glass side of a photographic plate shows where Hubble marked novas. The red VAR! in the upper right corner marks his discovery of the first Cepheid variable star — a star that told him the Andromeda galaxy isn't part of our Milky Way.



W. W. Campbell with a 36-inch spectroscope



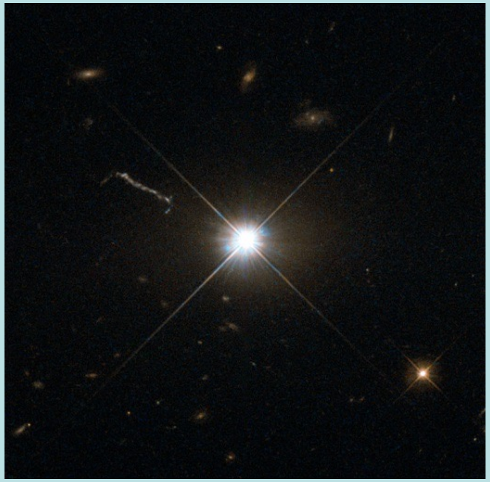
A two-prism spectrograph

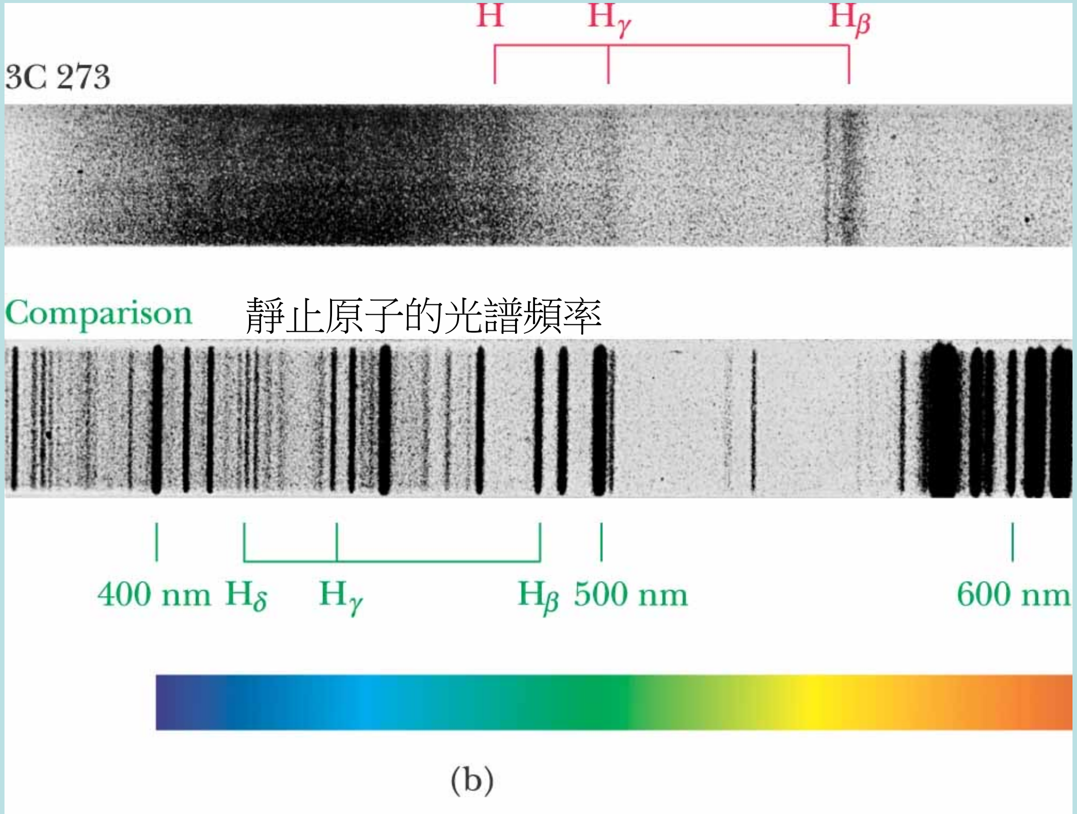


Vesto Slipher & spectrograph

Source: The University of Virginia

Hubble發現遠處星光的紅移現象redshift：星光的光譜頻率低於靜止原子的光譜頻率！

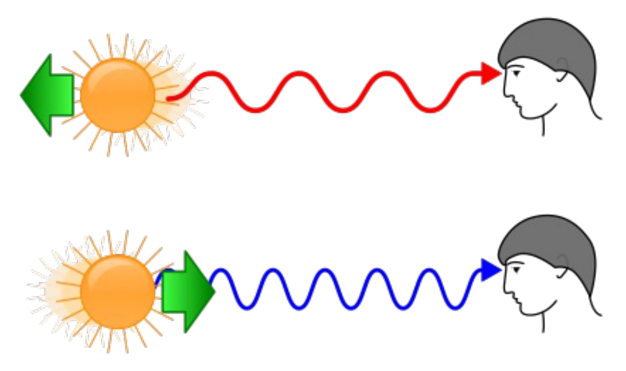




Vesto Slipher
1875-1969

3C 273 is a quasar located in the constellation Virgo. It was the first quasar ever to be identified. It is the optically brightest quasar in our sky and one of the closest with a redshift, *z*, of 0.158.

這是單一星體。第一個發現的Quasar。



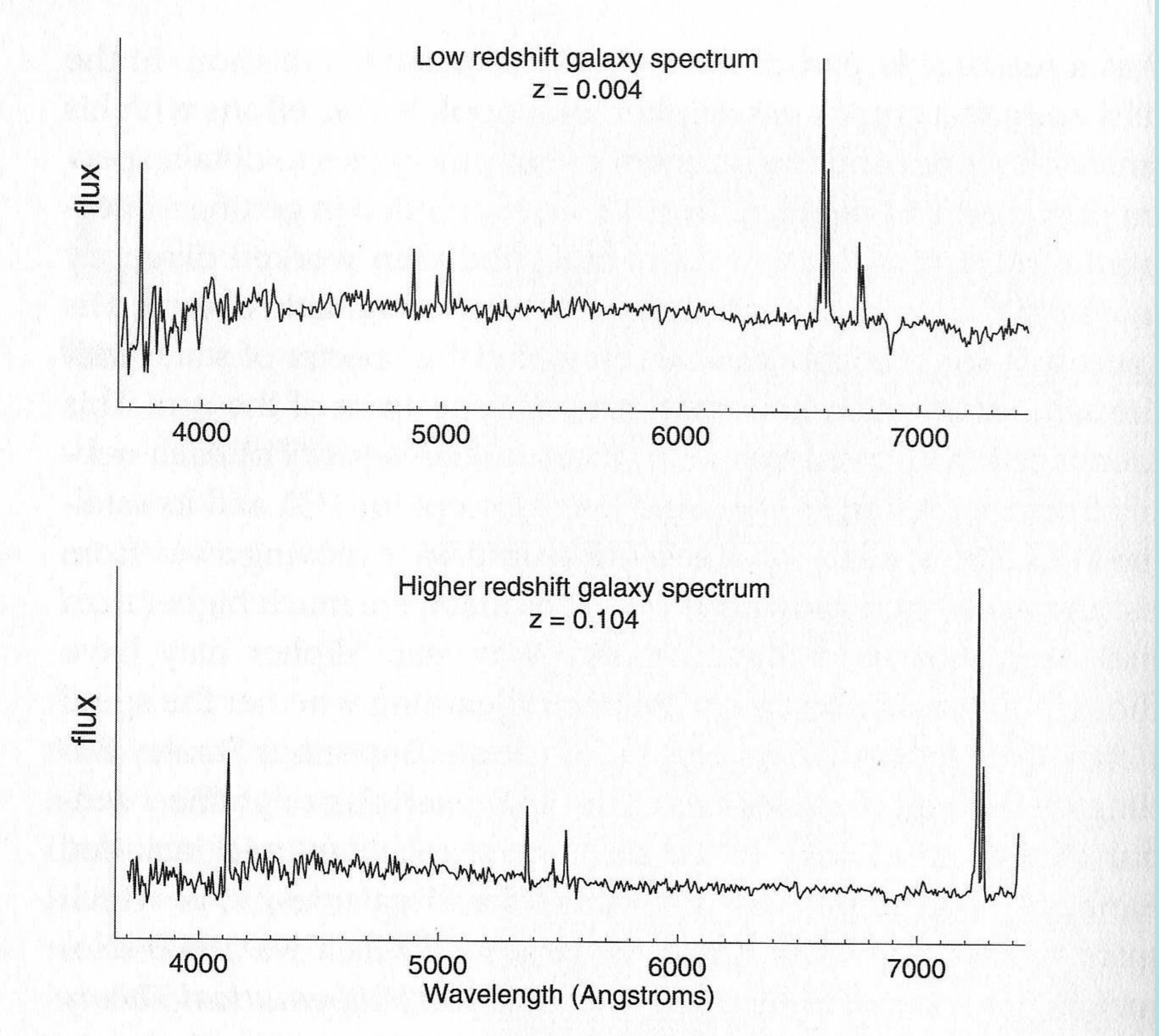
$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}}$$

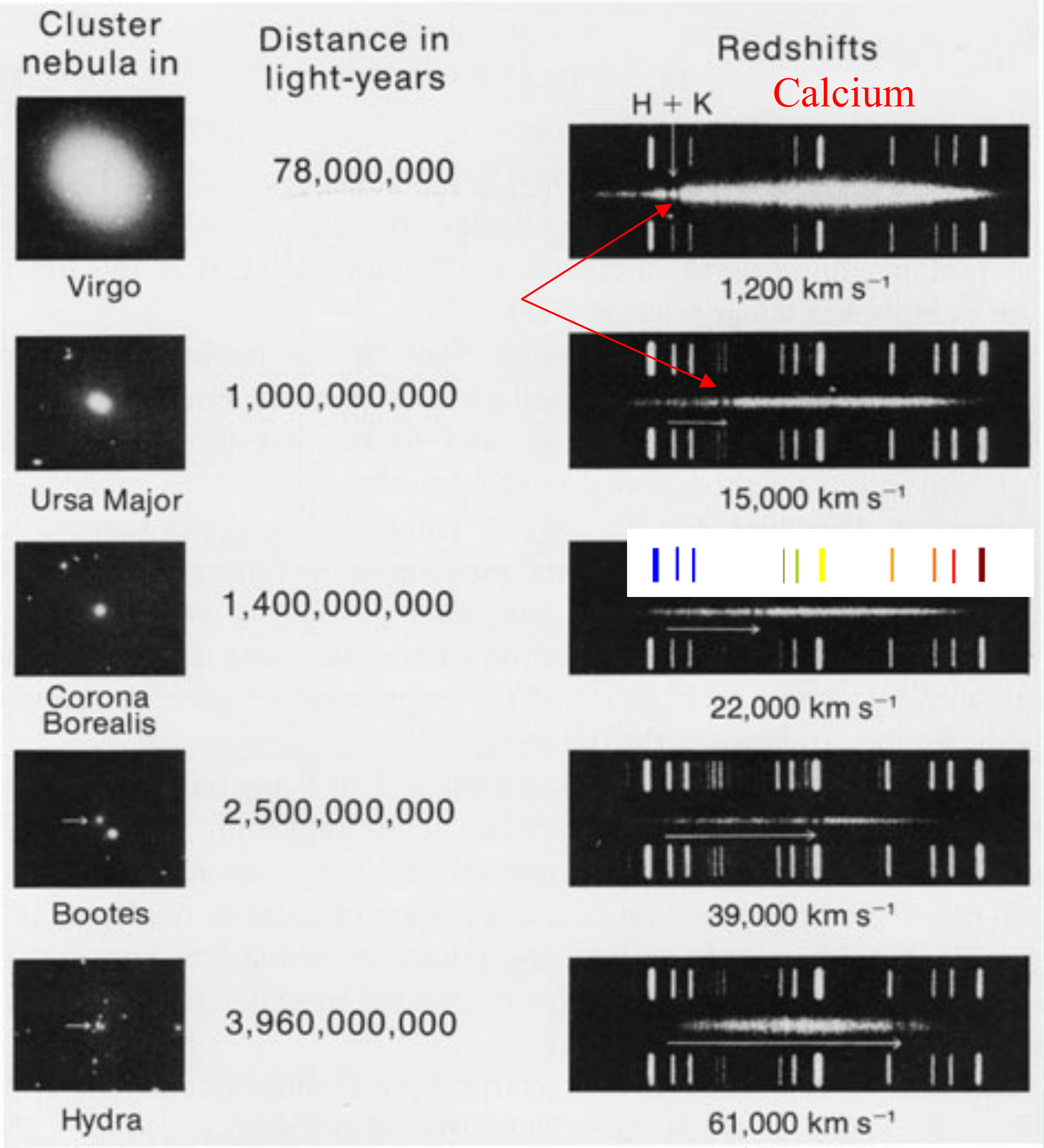
根據都卜勒效應： $z \sim \frac{v}{c}$ 速度遠小於光速時。

測量z就等於測量發光物體遠離的速度v。

z相當方便，就用來表示星體離開我們的速度。

3C 273 is a quasar with a redshift, *z*, of 0.158.遠離速度接近光速的五分之一。


Low redshift galaxy spectrum
z = 0.004
flux
4000
5000
6000
7000
Higher redshift galaxy spectrum
z = 0.104
flux
4000
5000
6000
7000
Wavelength (Angstroms)



早年看到的是星系Galaxy。

處女座

大熊座

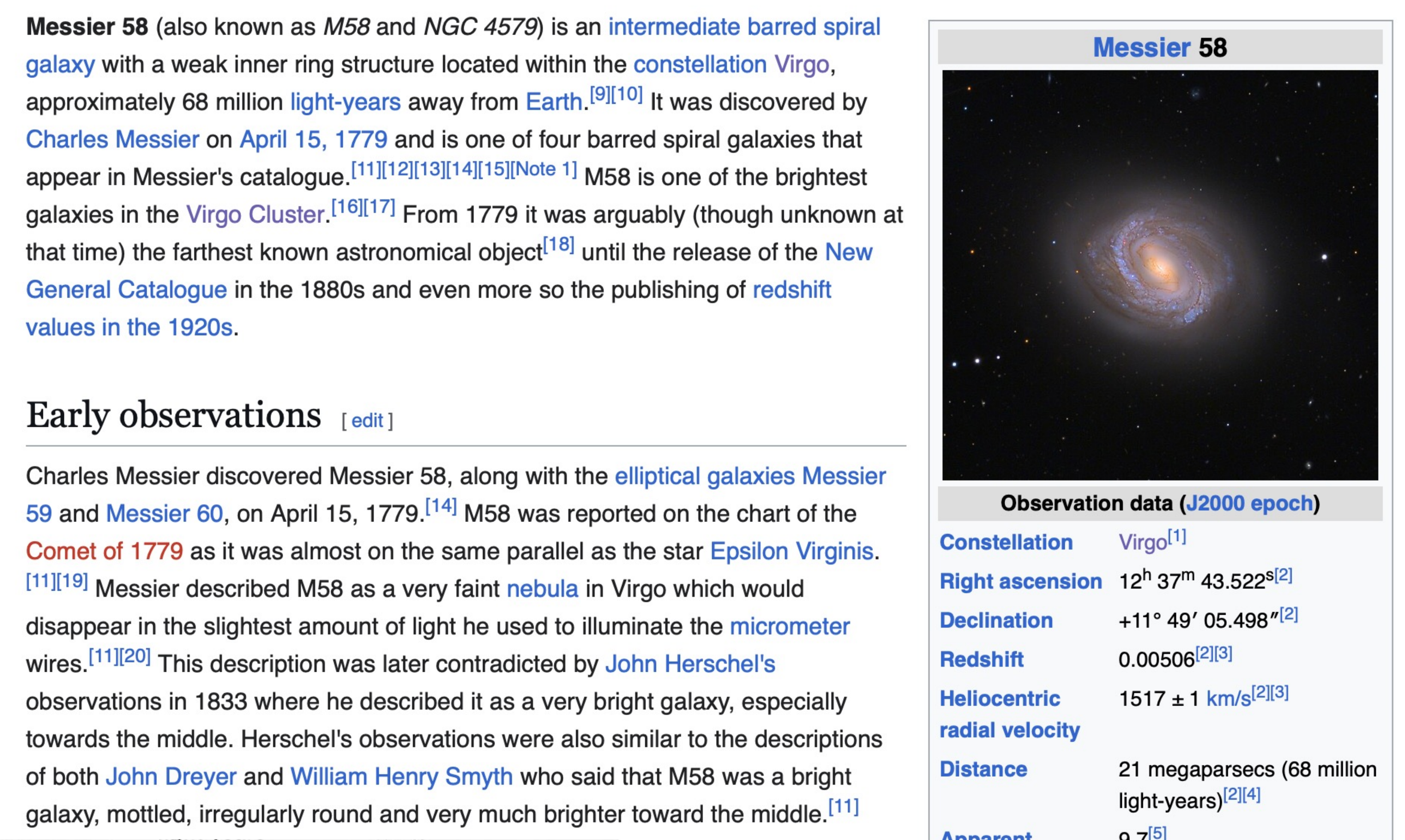
長蛇座

Milton Humason
1891-1971

根據電磁波的都卜勒效應，星體應該是離我們遠去！

遠方的銀河離開的速度似乎與距離相關！

這是上一頁的第一個光譜。



Messier 58 (also known as *M58* and *NGC 4579*) is an intermediate barred spiral galaxy with a weak inner ring structure located within the constellation Virgo, approximately 68 million light-years away from Earth.[9][10] It was discovered by Charles Messier on April 15, 1779 and is one of four barred spiral galaxies that appear in Messier's catalogue.[11][12][13][14][15][Note 1] M58 is one of the brightest galaxies in the Virgo Cluster.[16][17] From 1779 it was arguably (though unknown at that time) the farthest known astronomical object[18] until the release of the New General Catalogue in the 1880s and even more so the publishing of redshift values in the 1920s.

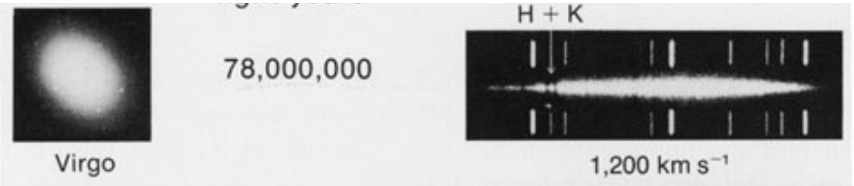
Early observations [edit]

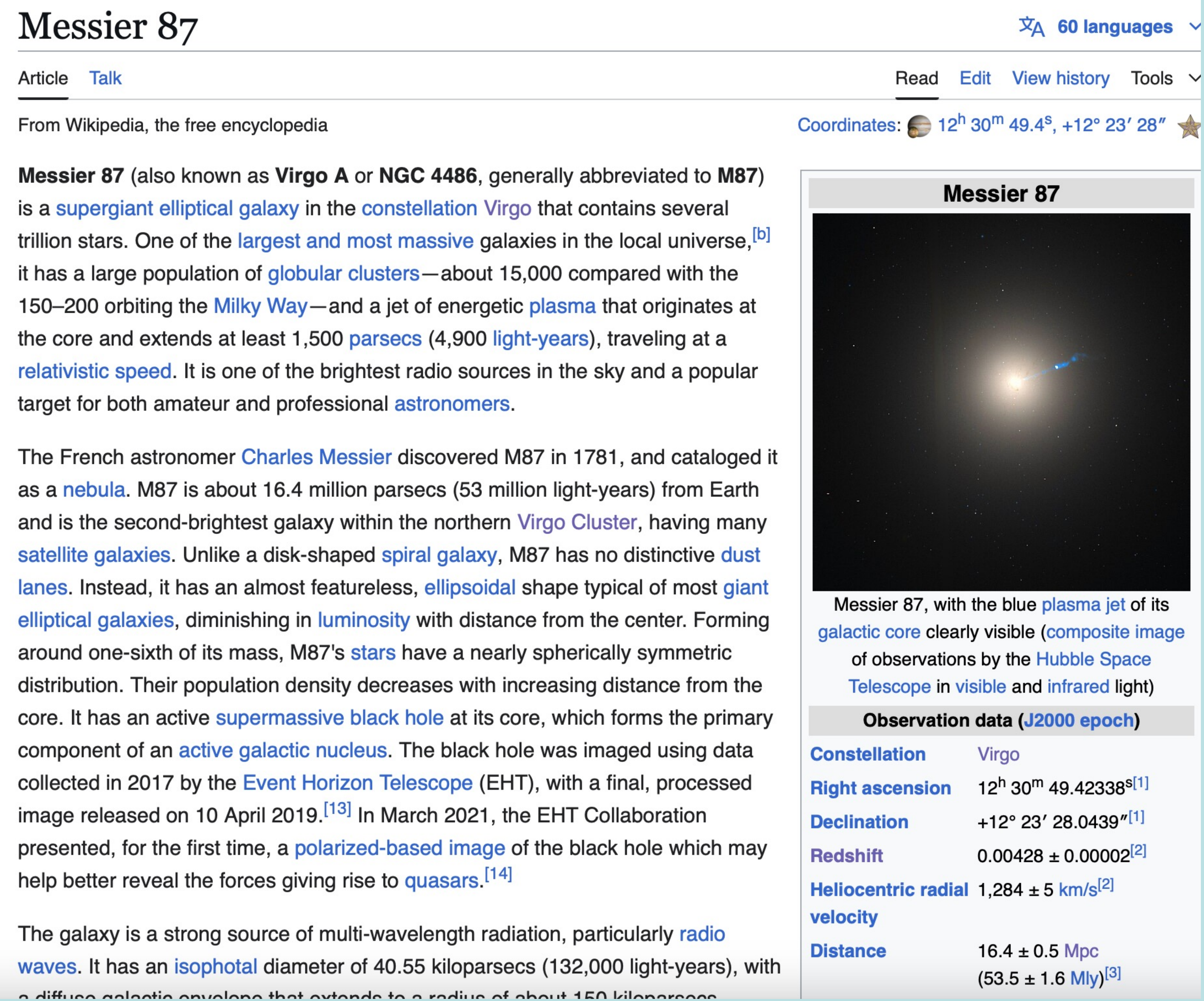
Charles Messier discovered Messier 58, along with the elliptical galaxies Messier 59 and Messier 60, on April 15, 1779.[14] M58 was reported on the chart of the Comet of 1779 as it was almost on the same parallel as the star Epsilon Virginis.[11][19] Messier described M58 as a very faint nebula in Virgo which would disappear in the slightest amount of light he used to illuminate the micrometer wires.[11][20] This description was later contradicted by John Herschel's observations in 1833 where he described it as a very bright galaxy, especially towards the middle. Herschel's observations were also similar to the descriptions of both John Dreyer and William Henry Smyth who said that M58 was a bright galaxy, mottled, irregularly round and very much brighter toward the middle.[11]

Messier 58

Observation data (J2000 epoch)

Constellation	Virgo[1]
Right ascension	$12^h\ 37^m\ 43.522^s$[2]
Declination	+11° 49′ 05.498″[2]
Redshift	0.00506[2][3]
Heliocentric radial velocity	1517 ± 1 km/s[2][3]
Distance	21 megaparsecs (68 million light-years)[2][4]
Apparent magnitude (V)	9.7[5]





Messier 87

From Wikipedia, the free encyclopedia

Coordinates: $12^h\ 30^m\ 49.4^s$, +12° 23′ 28″

Messier 87 (also known as **Virgo A** or **NGC 4486**, generally abbreviated to **M87**) is a supergiant elliptical galaxy in the constellation Virgo that contains several trillion stars. One of the largest and most massive galaxies in the local universe,[b] it has a large population of globular clusters—about 15,000 compared with the 150–200 orbiting the Milky Way—and a jet of energetic plasma that originates at the core and extends at least 1,500 parsecs (4,900 light-years), traveling at a relativistic speed. It is one of the brightest radio sources in the sky and a popular target for both amateur and professional astronomers.

The French astronomer Charles Messier discovered M87 in 1781, and cataloged it as a nebula. M87 is about 16.4 million parsecs (53 million light-years) from Earth and is the second-brightest galaxy within the northern Virgo Cluster, having many satellite galaxies. Unlike a disk-shaped spiral galaxy, M87 has no distinctive dust lanes. Instead, it has an almost featureless, ellipsoidal shape typical of most giant elliptical galaxies, diminishing in luminosity with distance from the center. Forming around one-sixth of its mass, M87's stars have a nearly spherically symmetric distribution. Their population density decreases with increasing distance from the core. It has an active supermassive black hole at its core, which forms the primary component of an active galactic nucleus. The black hole was imaged using data collected in 2017 by the Event Horizon Telescope (EHT), with a final, processed image released on 10 April 2019.[13] In March 2021, the EHT Collaboration presented, for the first time, a polarized-based image of the black hole which may help better reveal the forces giving rise to quasars.[14]

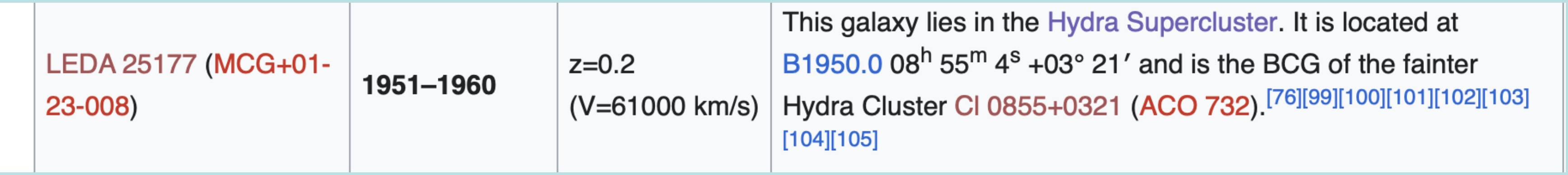
The galaxy is a strong source of multi-wavelength radiation, particularly radio waves. It has an isophotal diameter of 40.55 kiloparsecs (132,000 light-years), with a diffuse galactic envelope that extends to a radius of about 150 kiloparsecs

Messier 87

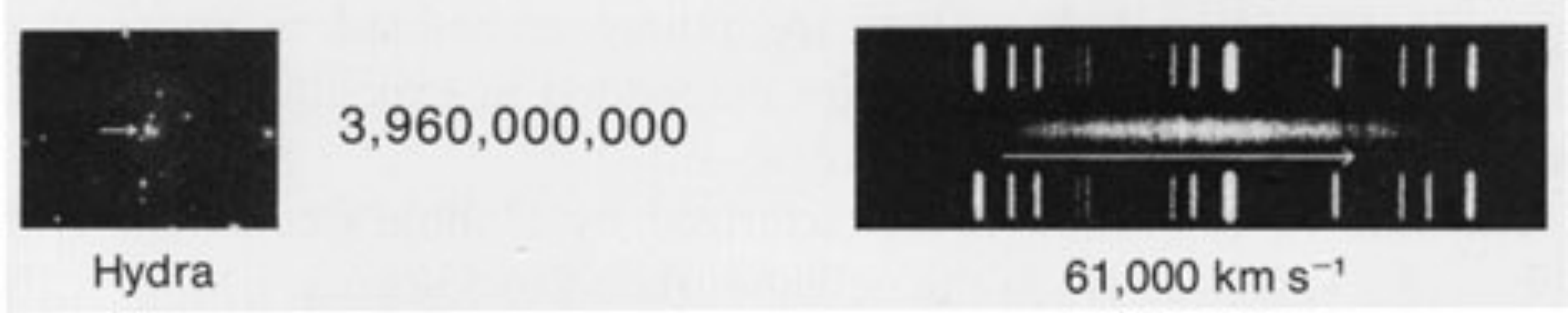
Messier 87, with the blue plasma jet of its galactic core clearly visible (composite image of observations by the Hubble Space Telescope in visible and infrared light)

Observation data (J2000 epoch)	
Constellation	Virgo
Right ascension	$12^h\ 30^m\ 49.42338^s$[1]
Declination	+12° 23′ 28.0439″[1]
Redshift	0.00428 ± 0.00002[2]
Heliocentric radial velocity	1,284 ± 5 km/s[2]
Distance	16.4 ± 0.5 Mpc (53.5 ± 1.6 Mly)[3]

這是上一頁列出的最遠的長蛇座星系。



	LEDA 25177 (MCG+01-23-008)	**1951–1960**	z=0.2 (V=61000 km/s)	This galaxy lies in the Hydra Supercluster. It is located at B1950.0 08^h 55^m 4^s +03° 21′ and is the BCG of the fainter Hydra Cluster Cl 0855+0321 (ACO 732).[76][99][100][101][102][103][104][105]



$v{\sim}0.2c$

Hubble發現銀河離開我們的速率，與該銀河與地球的距離成正比！1929

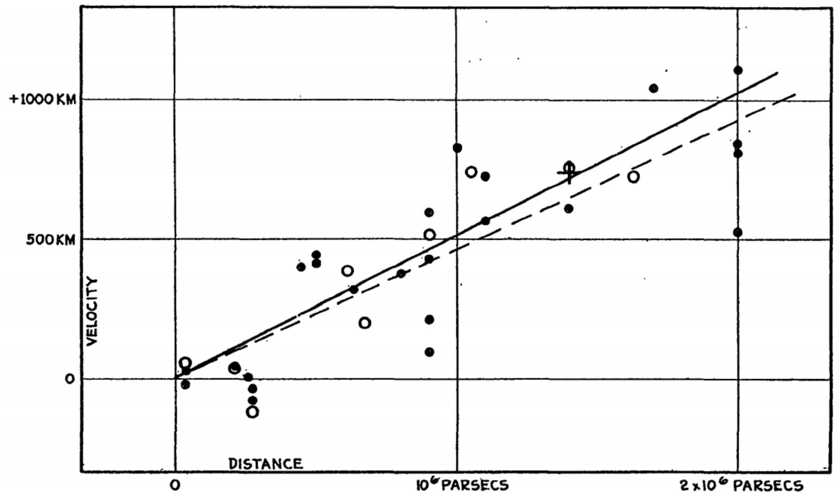
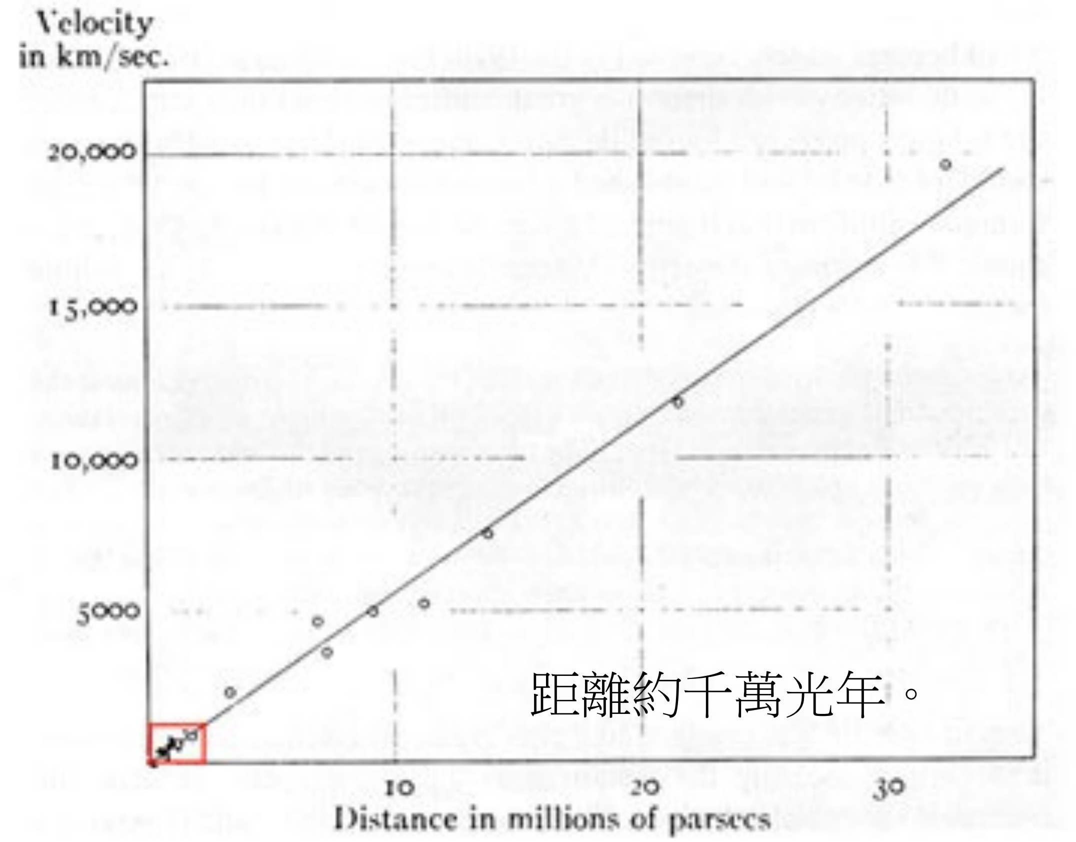


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

距離約百萬光年。

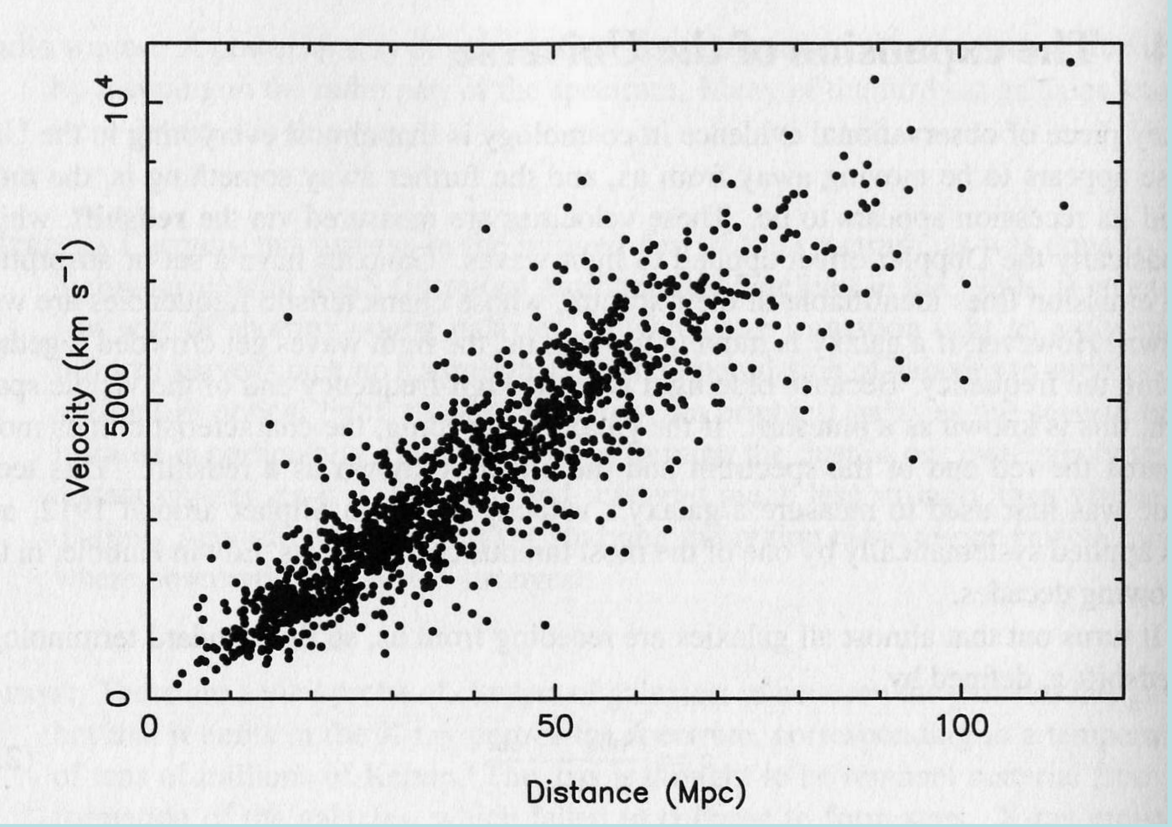


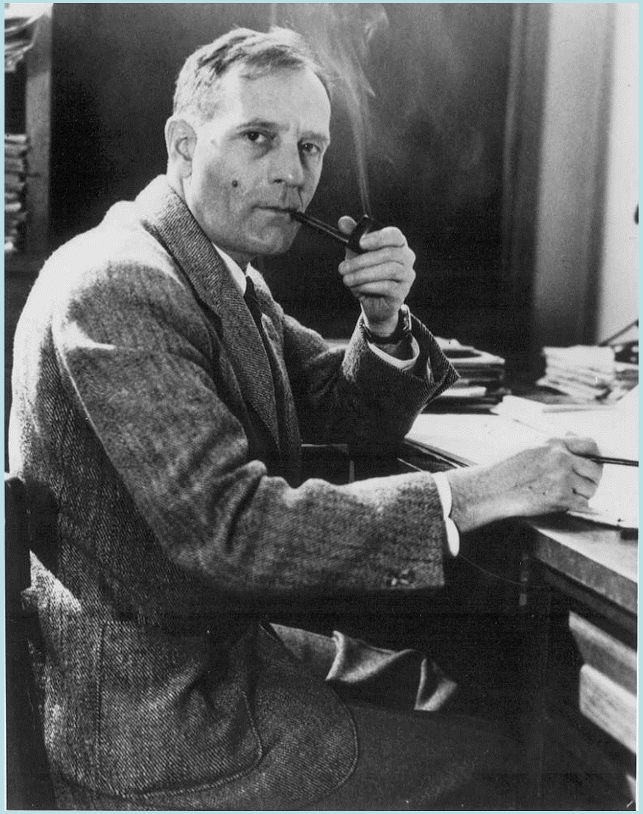
距離約千萬光年。

Galactic redshift vs. distance, plotted by Hubble and Humason (1931); red rectangle in lower left corner encloses data points plotted in 1929 graph above.

得到這個結果的努力中，距離的測量最難！

Edwin Hubble 1889-1953

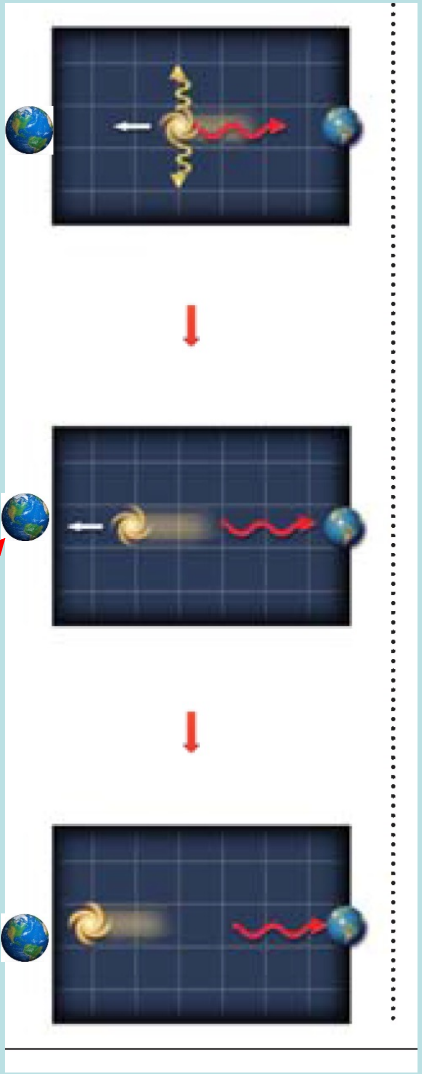




最近的數據，距離已經延伸至億光年。

Hubble發現銀河離開我們的速率，與該銀河與地球的距離成正比！

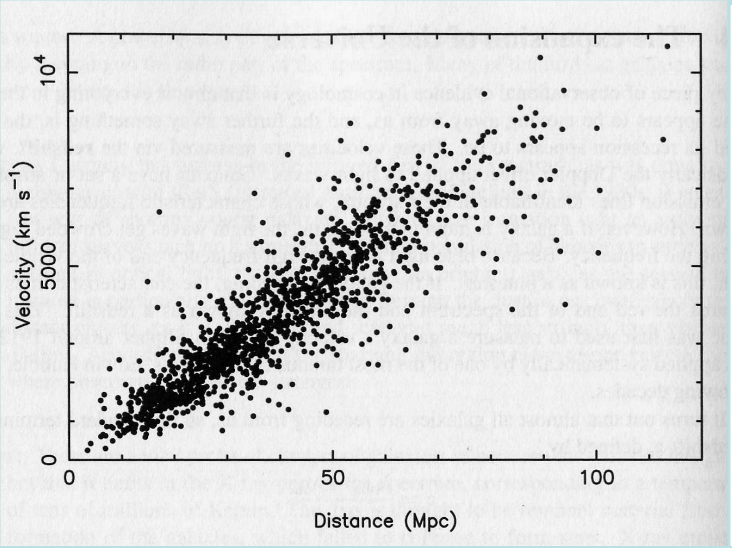
$v = Hr$ Hubble’s Law

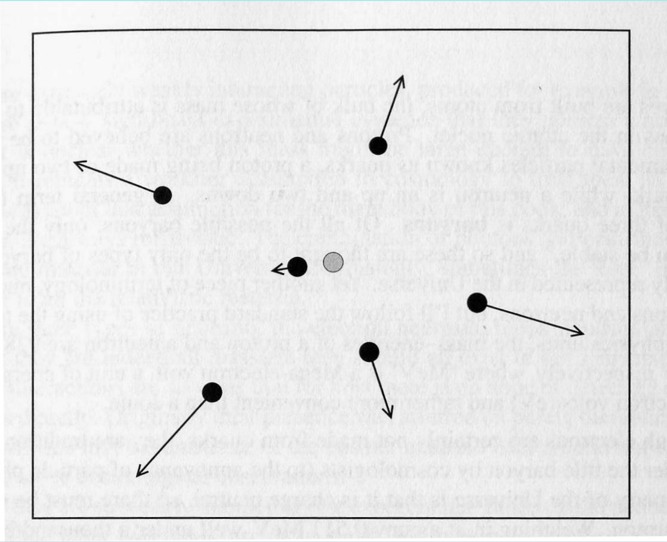


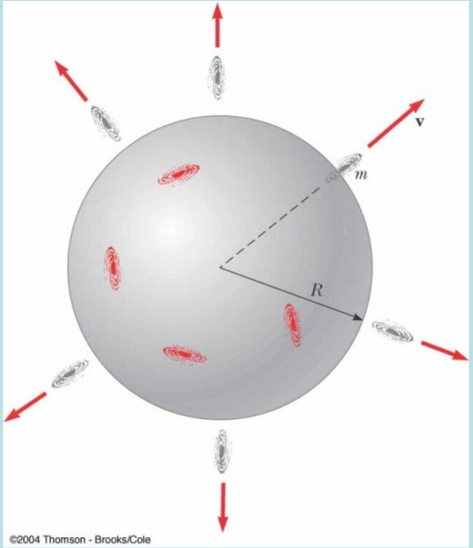
如果紅外移是星團自身在宇宙中移動造成，

另一邊的星球會看到星團靠近，光會發生藍外移，地球上紅移藍移應該大致各半。

在地球上往任何方向都從未看到藍外移。因此紅外移現象並不是來自星團移動。





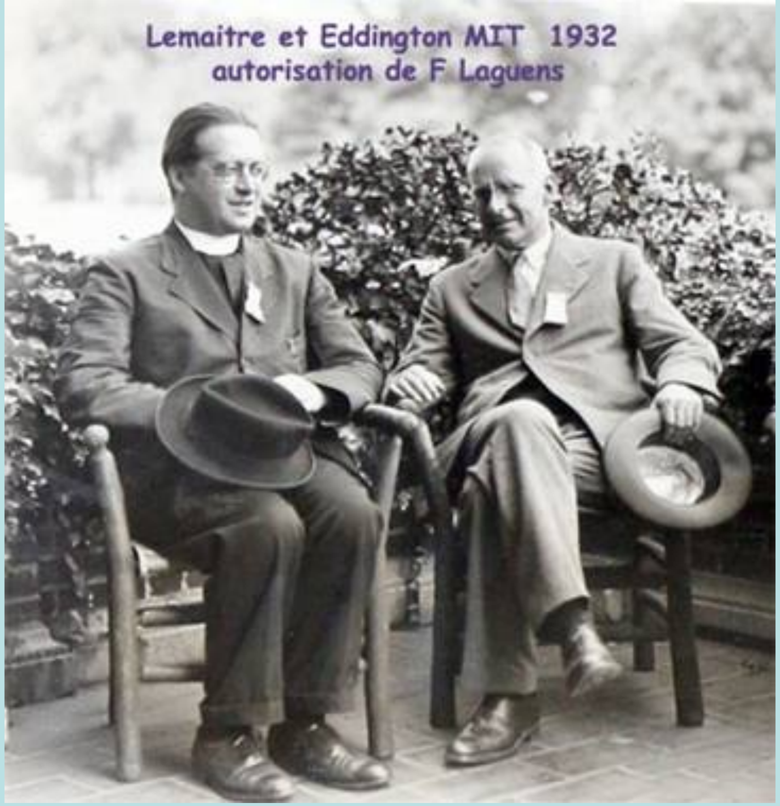


如果所有星系都以遠離地球的方向運動，

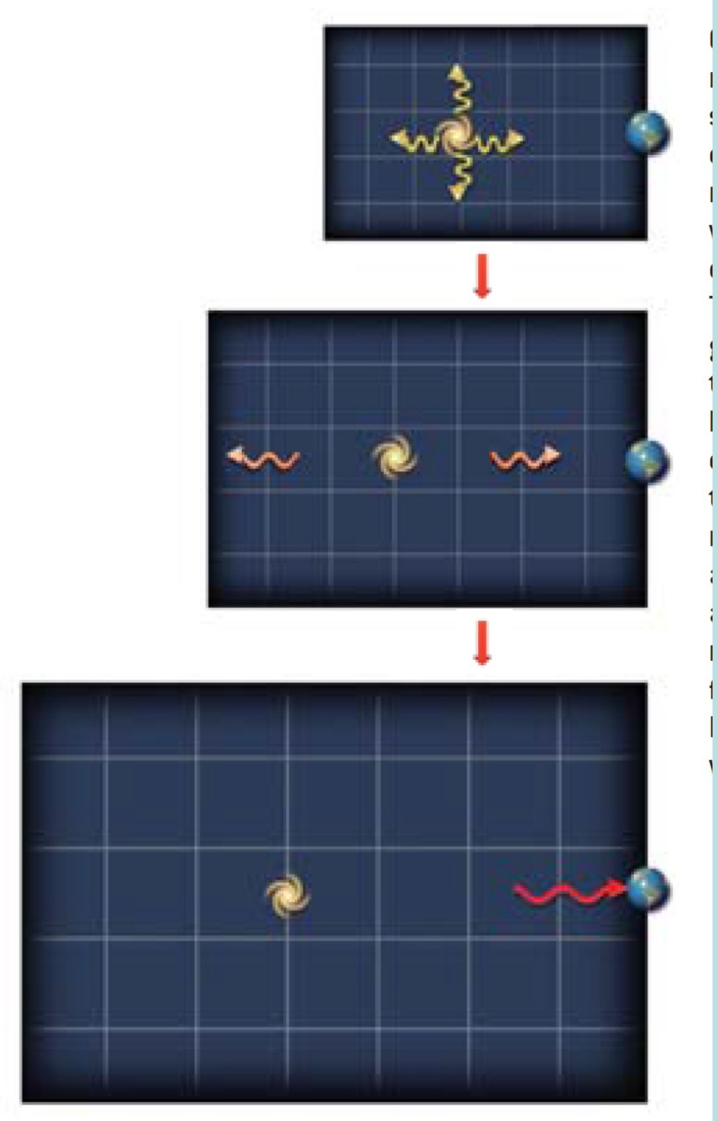
地球似乎應該是宇宙的中心！這太不可能了！

但理論天文物理學家對這個奇異的現象，其實已經有了答案。

Lemaître勒梅特立刻認出這就是他的均勻宇宙膨脹的自然結果！

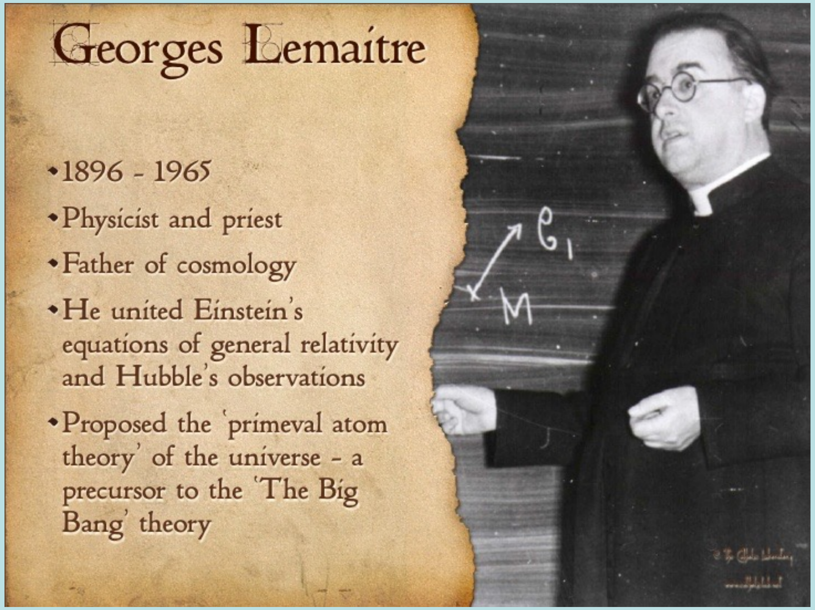


宇宙本身自然的擴張造成星團的遠離！



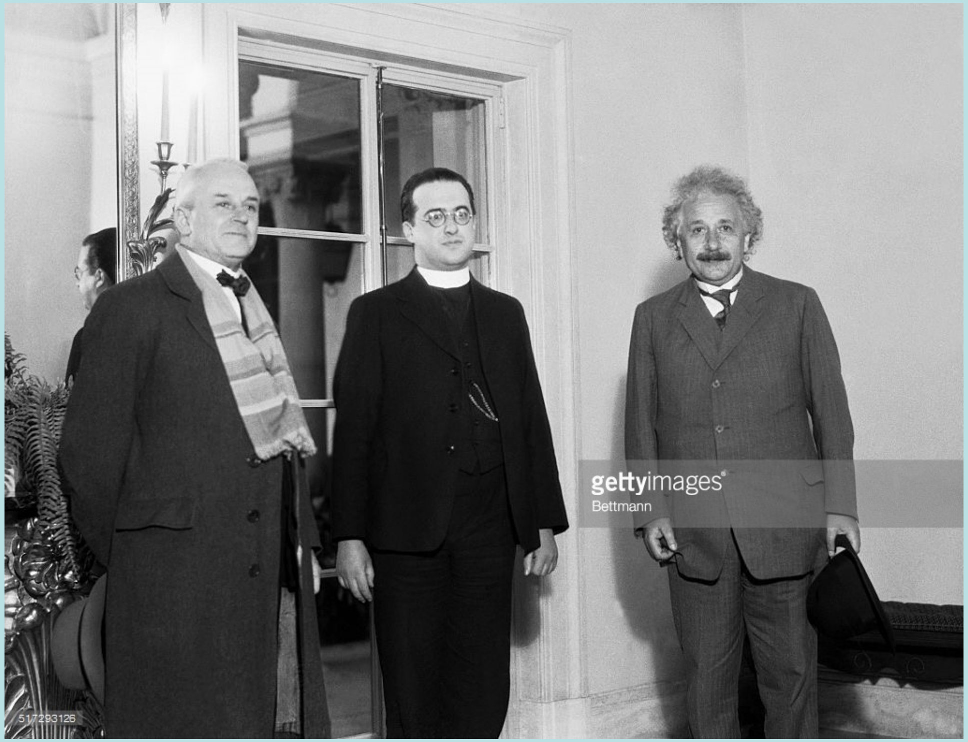
Lemaître勒梅特神父是第一位提出擴張宇宙：Expanding Universe！

Georges Lemaître 1894-1966



Georges Lemaître

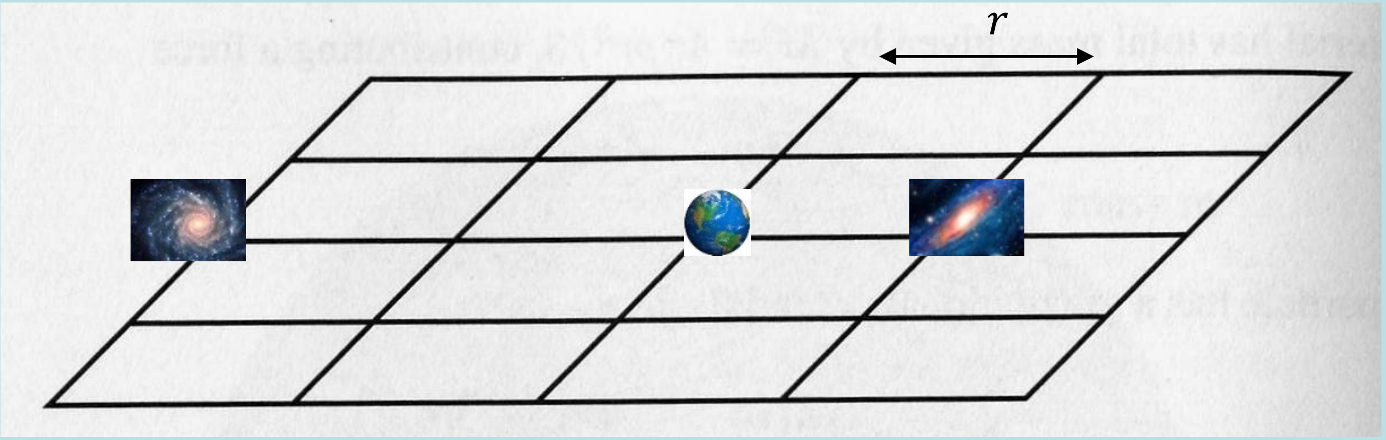
- 1896 - 1965
- Physicist and priest
- Father of cosmology
- He united Einstein's equations of general relativity and Hubble's observations
- Proposed the 'primeval atom theory' of the universe - a precursor to the 'The Big Bang' theory



Lemaître從愛因斯坦的解出發得出：宇宙的尺度是動態的！

宇宙的尺度是自然地隨時間而改變的。

讓我想像我們的宇宙，有一個個的星團。假設彼此相對大致是靜止的。
利用這些星團的位置為標記，可以在宇宙畫出尺格座標。
距離原則上可以事先測量，例如地球與下圖右的星團距離是r。



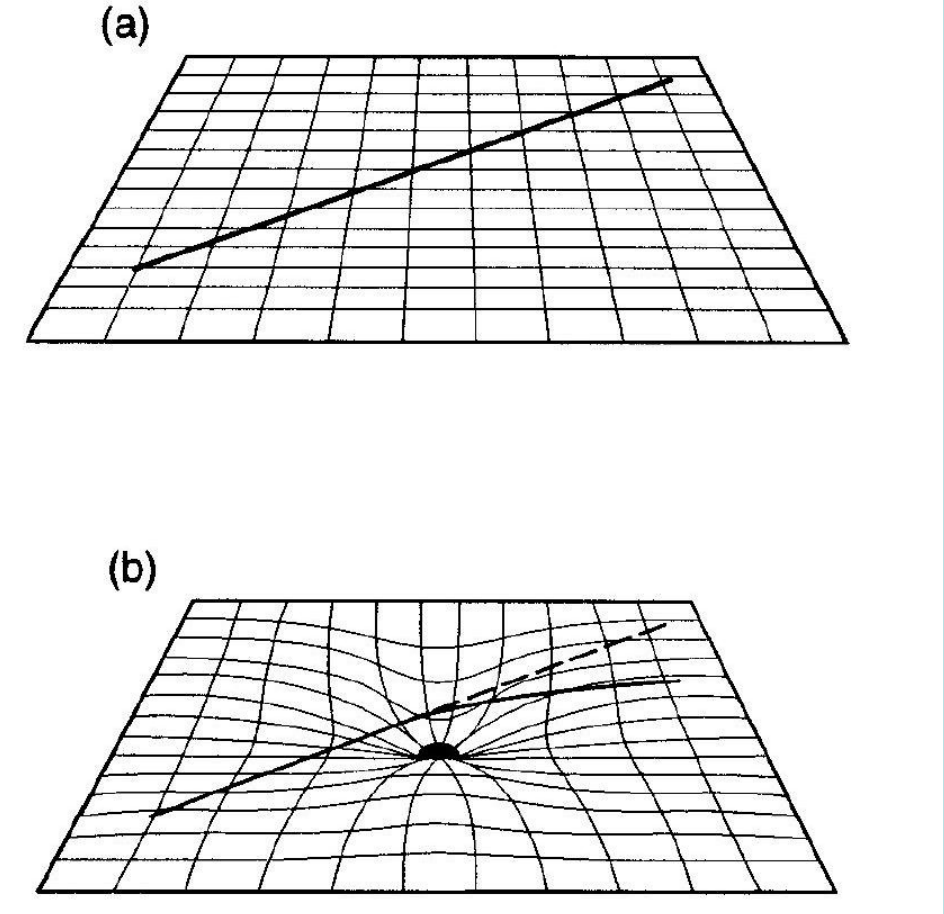
距離在方格上的測量，就統稱為尺度、尺格 Metric。

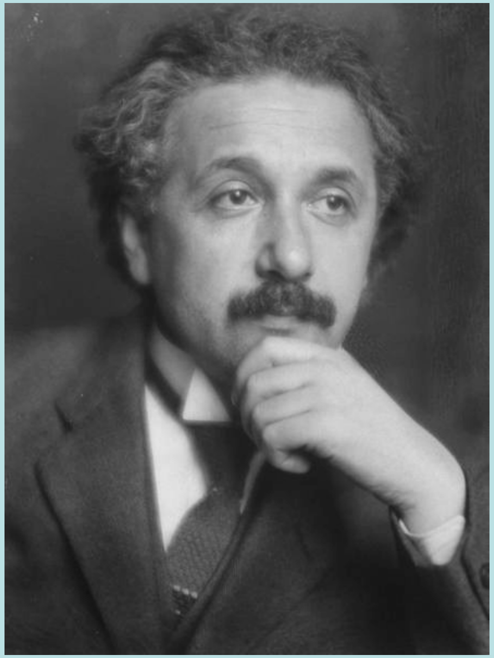
重力根本不是力！

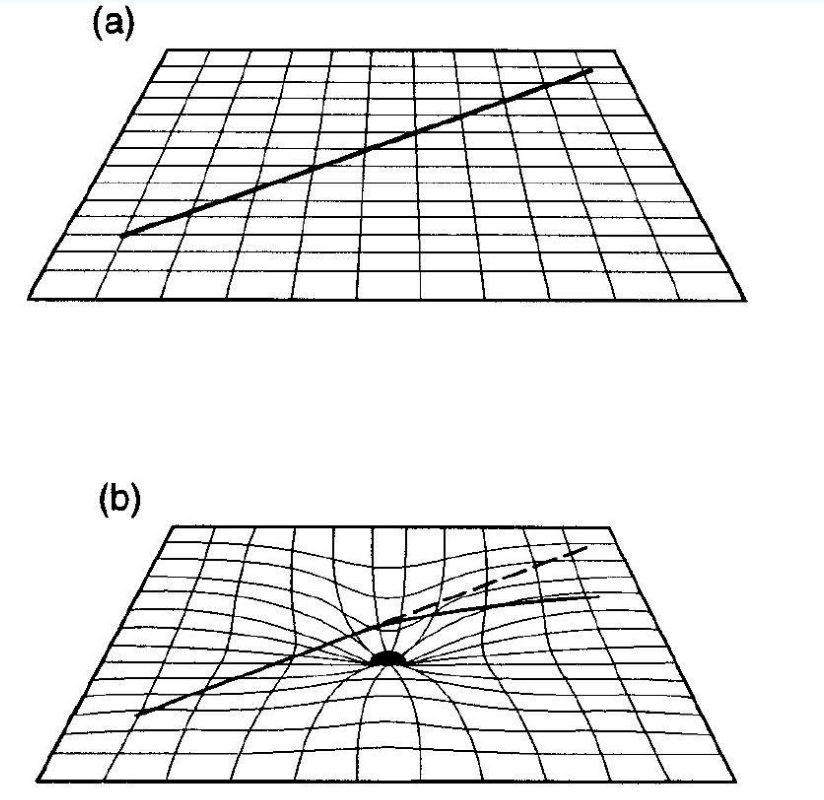
愛因斯坦提出：重力現象是質量造成周圍時空彎曲。

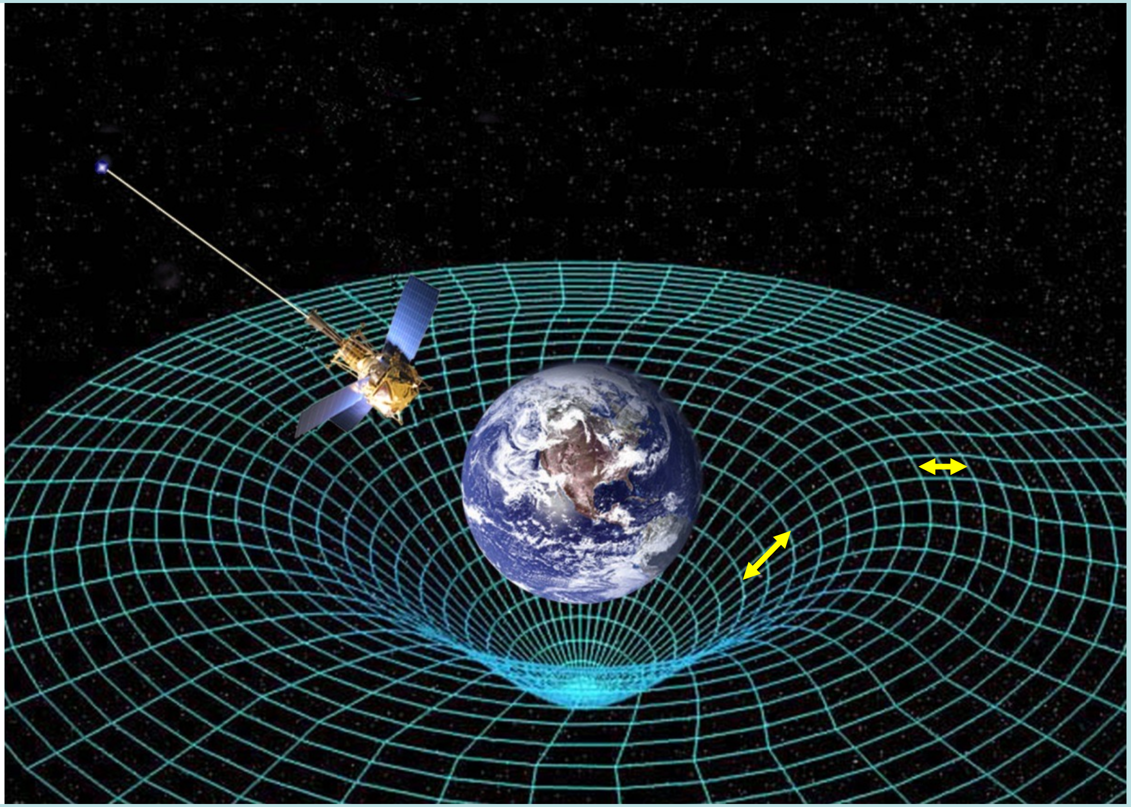
若無其他外力，所有物體都沿此彎曲時空的直線運動。

在彎曲時空中粒子走的直線由遠方看來是一條曲線！



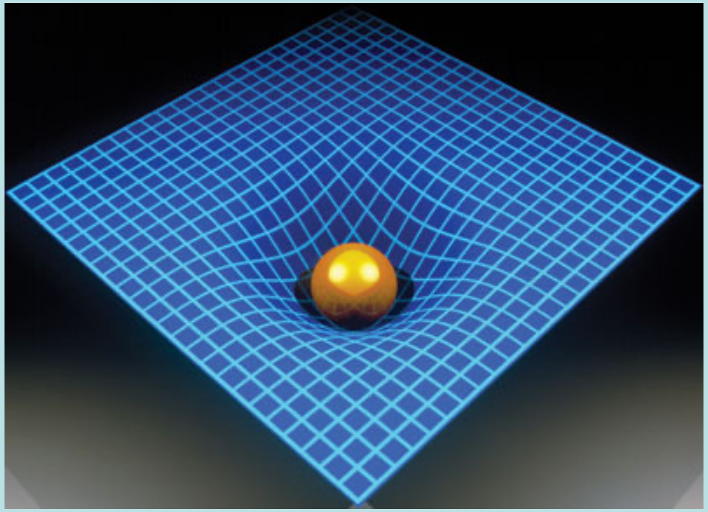






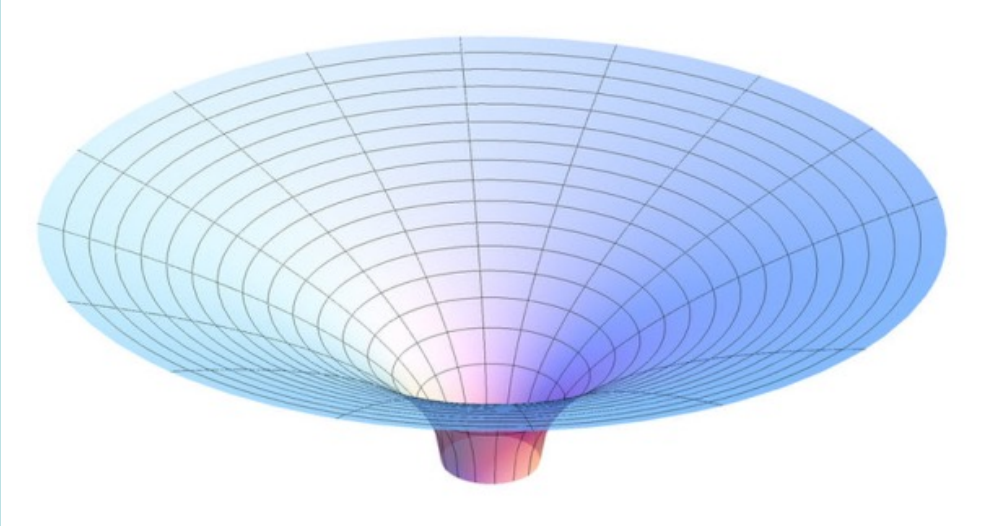
若平坦空間以棋盤狀等距尺格代表，彎曲空間以則扭曲的尺格來描述。

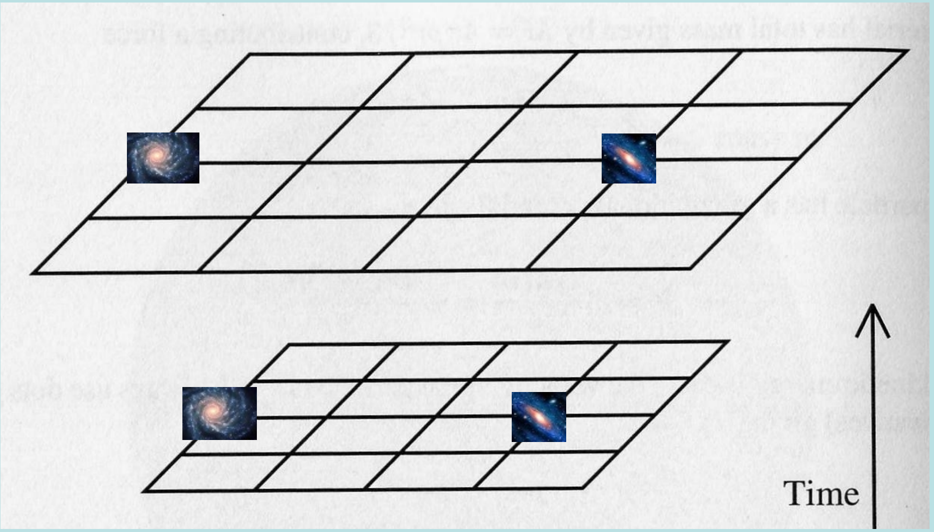
原是平坦時空等距的方格，間距在彎曲時空下有些地方會被拉長或有些壓縮。



如果空間因重物而彎曲是可能的，……
空間像果凍一樣可以變形，那麼……

宇宙果凍會不會動一下就來回搖晃…..

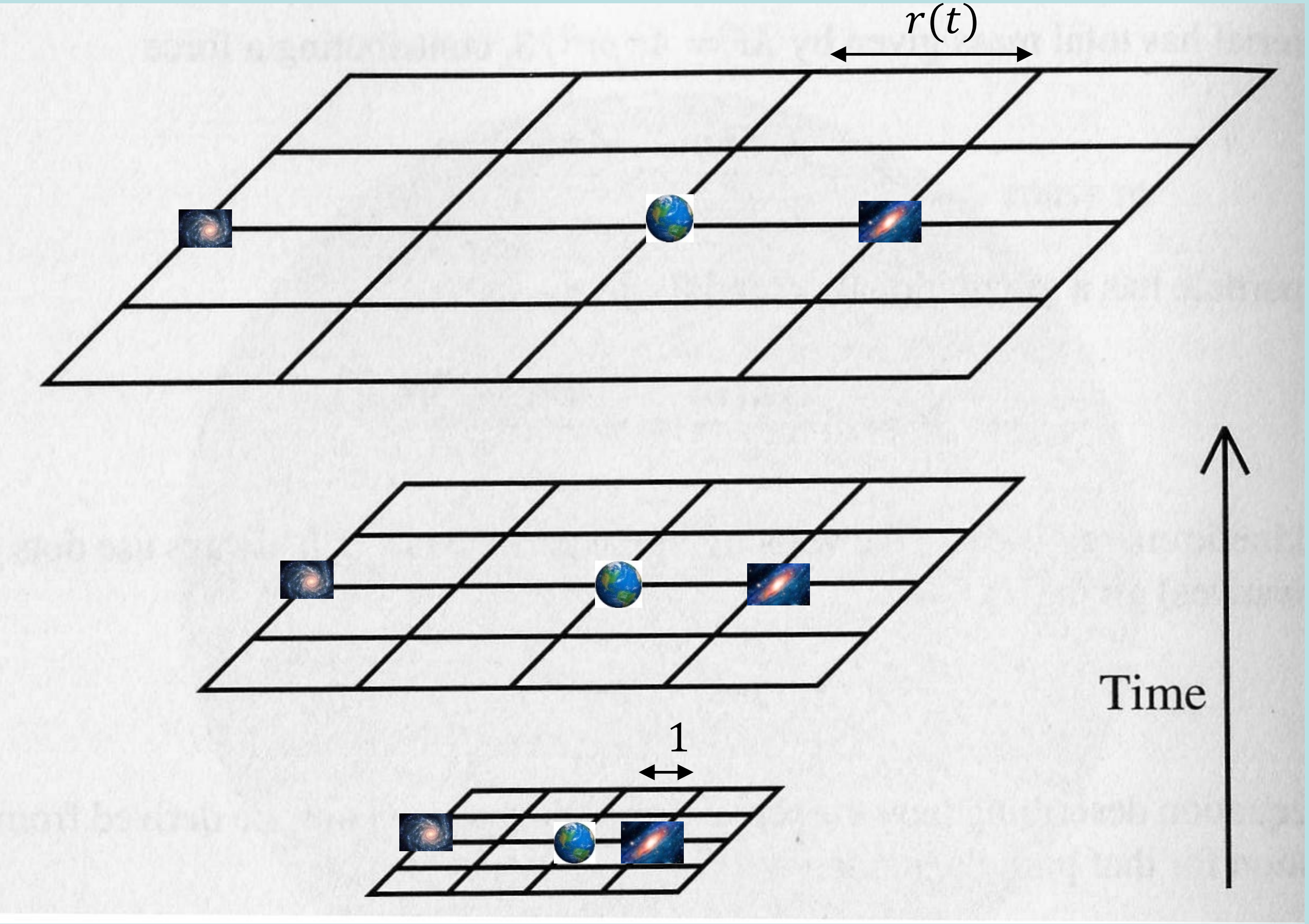




彎曲空間中尺格可以隨空間位置而不同，但時間與空間是分不開的。

因此，尺格也可能會隨時間而變化。

那麼兩個靜止的星系，彼此的距離，測量結果也可能跟時間有關！



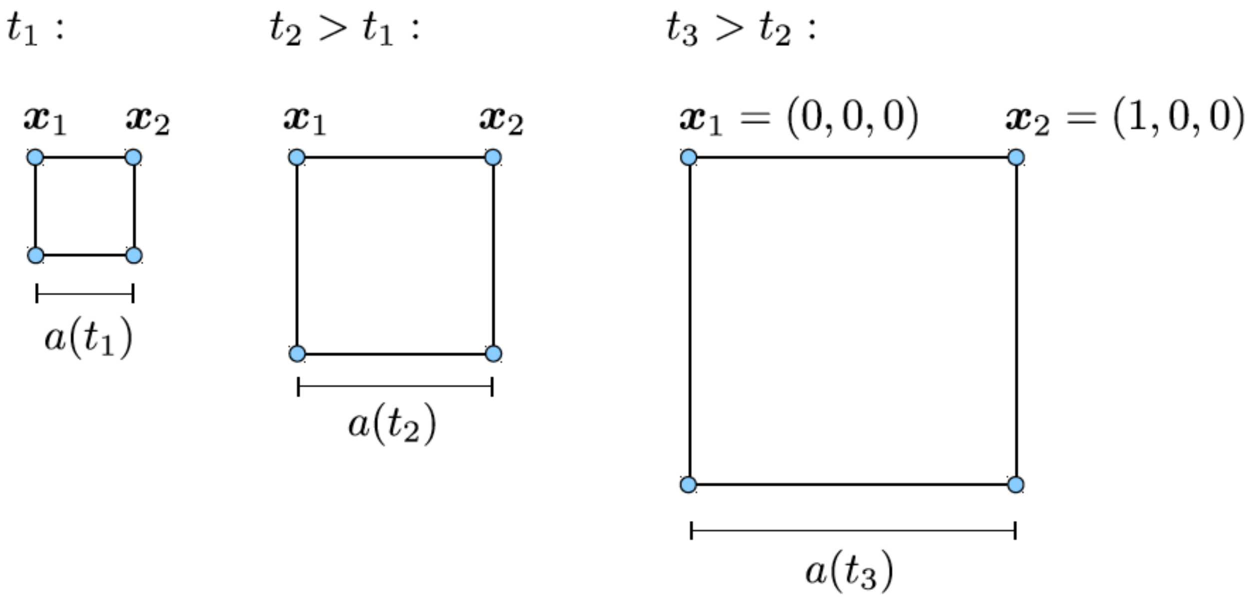
尺格是動態的，靜止星系間的距離就會隨時間改變。

假設在時間為零時取的單位尺格，時間t時，變化為原來的$a(t)$倍。

$$r(t) \equiv a(t)$$

若宇宙是均勻的，所有地方的尺格變化$a(t)$也會是均勻、即與位置無關。

所有的星系之間的距離，會以同樣的放大比例$a(t)$來放大或縮小！



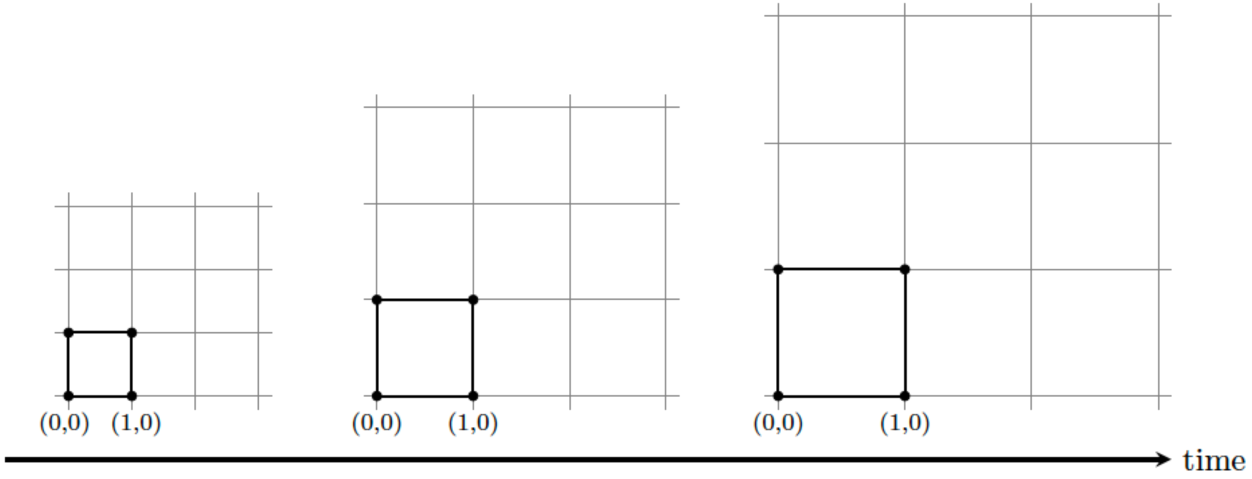
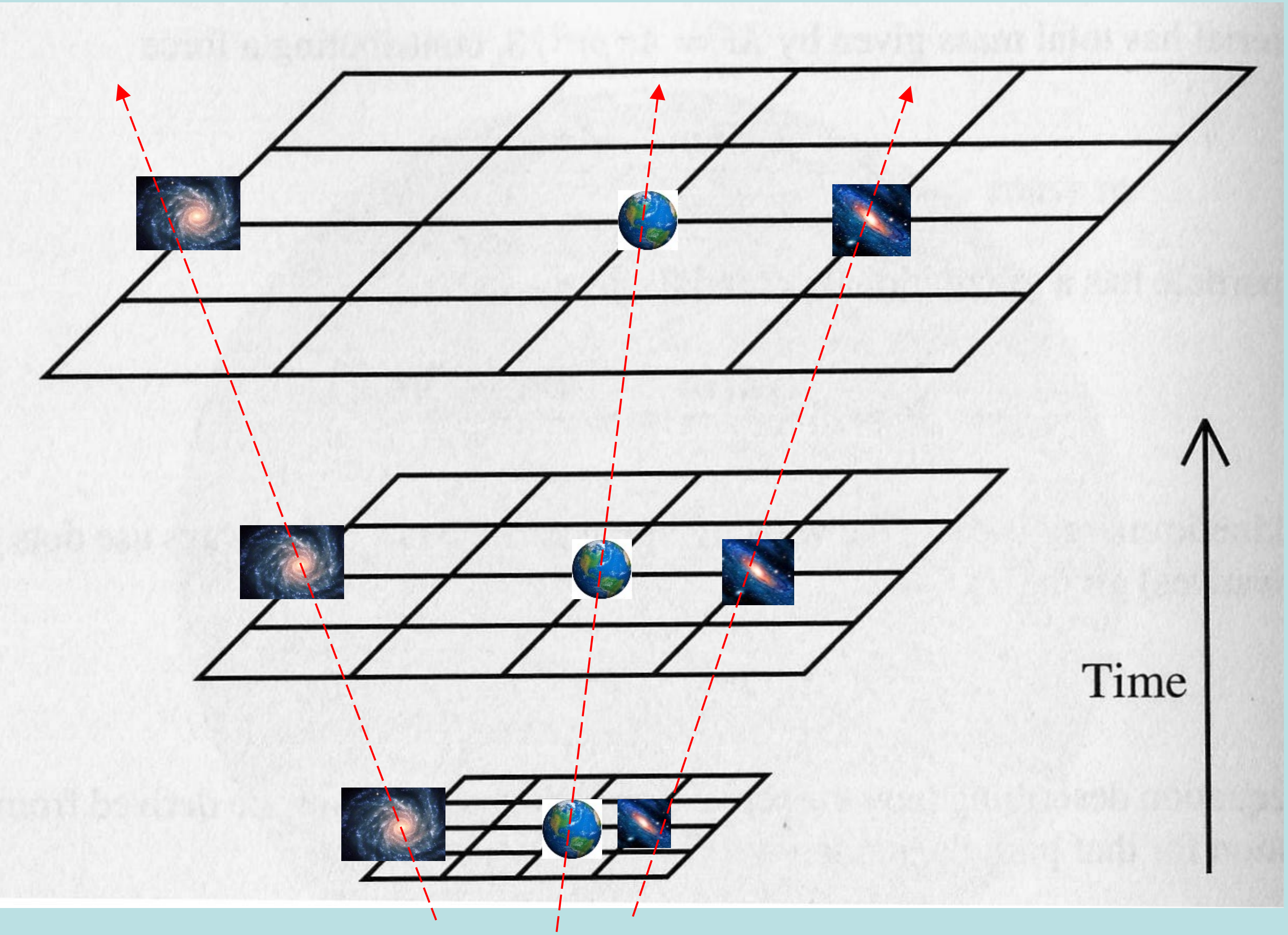


Fig. 2.2 Expansion of the universe. The comoving distance between points on an imaginary coordinate grid remains constant as the universe expands. The physical distance, on the other hand, grows in proportion to the scale factor $a(t)$.



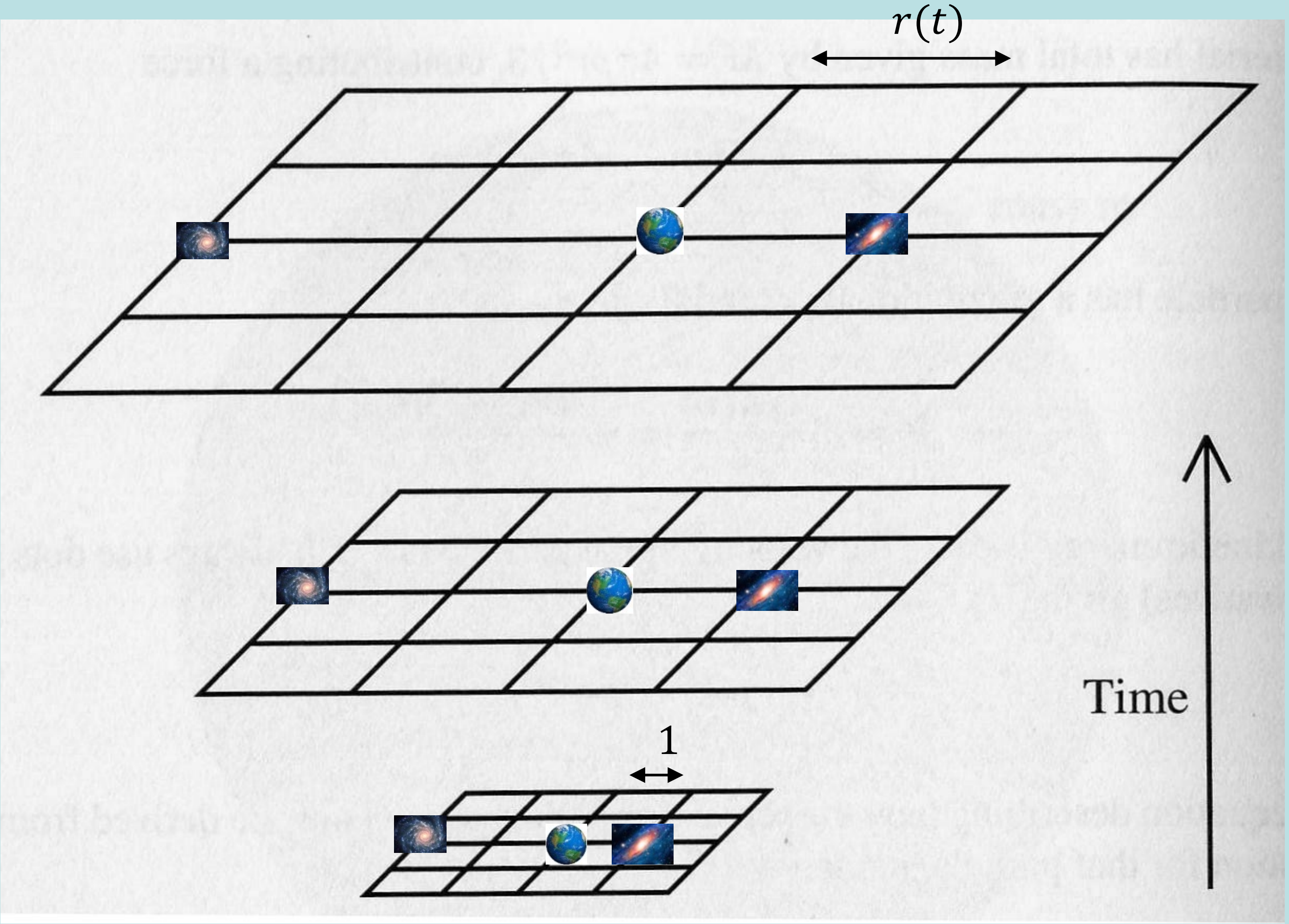
若所有的星系之間的距離，以同樣的放大比例$a(t)$來放大！ $a(t) > 1$

那麼越遠的星系，自然遠離我們的速率越快！ $v = H \cdot r$

上圖左星系離我們的距離增加率，自然是上圖右星系距離增加率的兩倍。

簡言之，宇宙是均勻在擴張之中！

精細的計算：



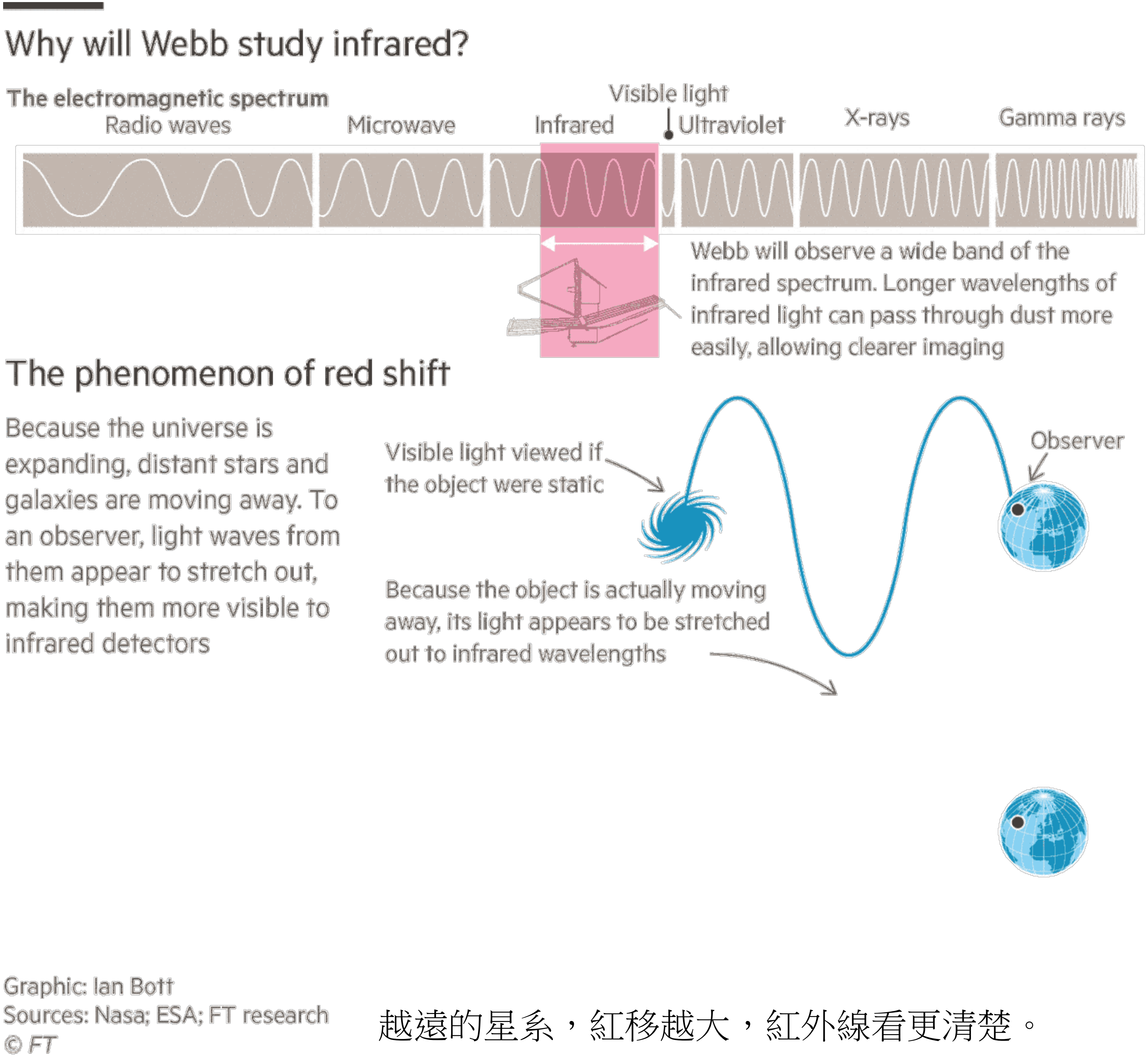
若宇宙是均勻的，所有地方的尺度變化$a(t)$也會是均勻而與位置無關。

$$r(t) \equiv a(t)$$

$$H = \frac{1}{a}\frac{da}{dt}$$

$$v = \frac{dr}{dt} = \frac{d}{dt}a(t) = H \cdot a(t) = H \cdot r$$

$$v = H \cdot r$$



Why will Webb study infrared?

Webb will observe a wide band of the infrared spectrum. Longer wavelengths of infrared light can pass through dust more easily, allowing clearer imaging

The phenomenon of red shift

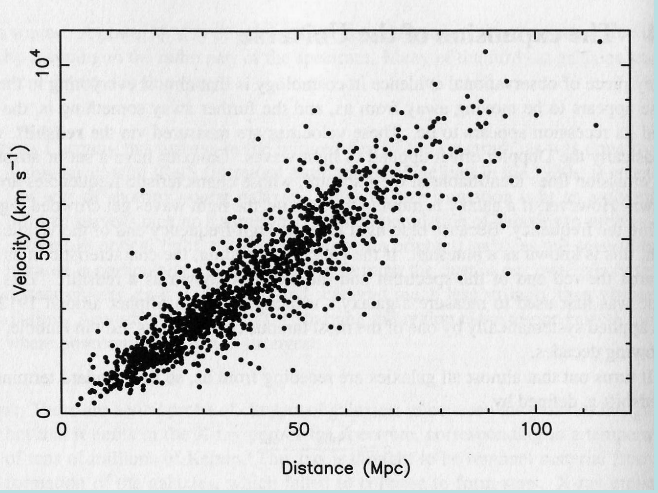
Because the universe is expanding, distant stars and galaxies are moving away. To an observer, light waves from them appear to stretch out, making them more visible to infrared detectors

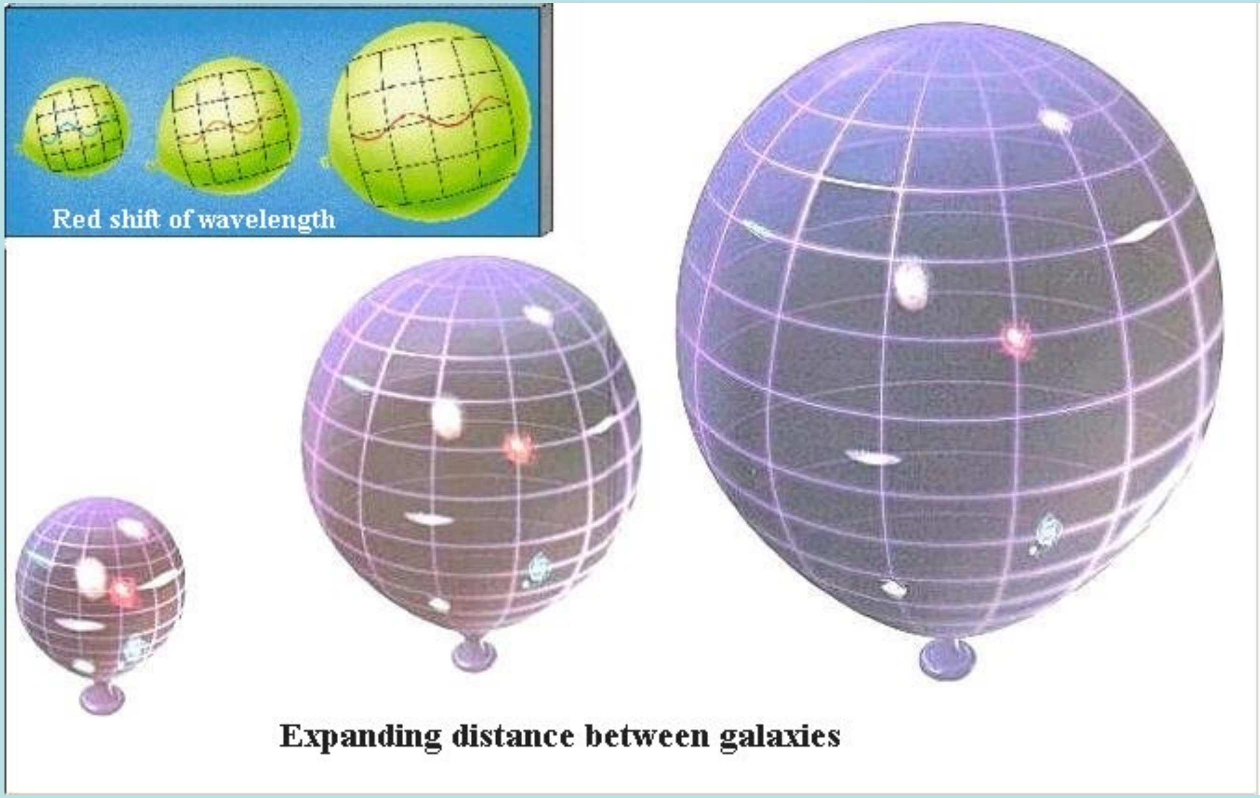
Visible light viewed if the object were static

Because the object is actually moving away, its light appears to be stretched out to infrared wavelengths

Graphic: Ian Bott
Sources: Nasa; ESA; FT research

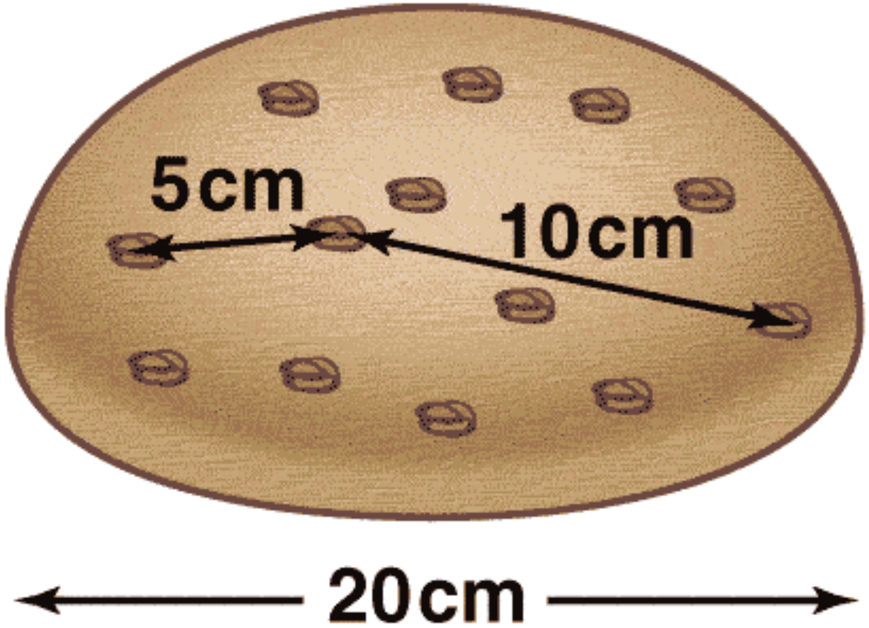
越遠的星系，紅移越大，紅外線看更清楚。





哈伯定律可能顯示：宇宙正在擴張或膨脹之中，尺度放大比例在增加之中：

Expansion of the universe $a(t)\uparrow$

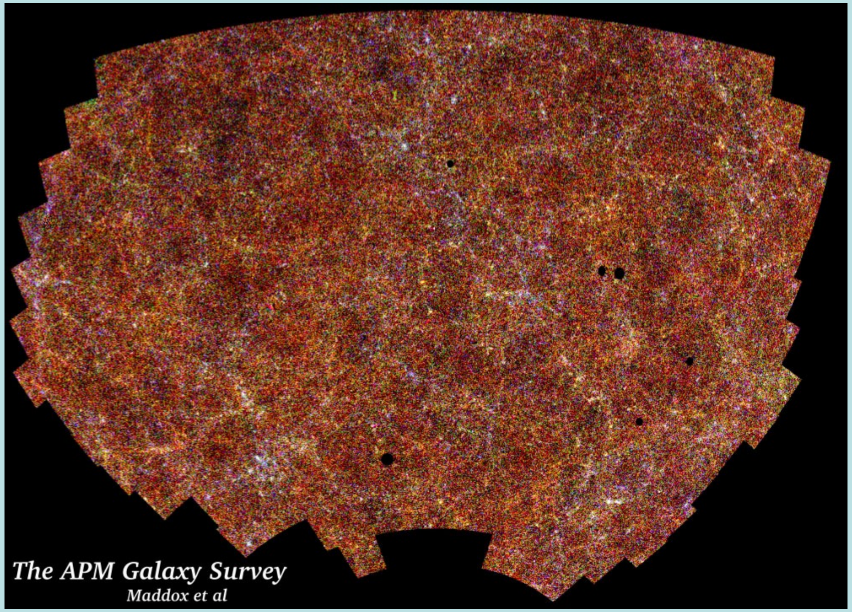


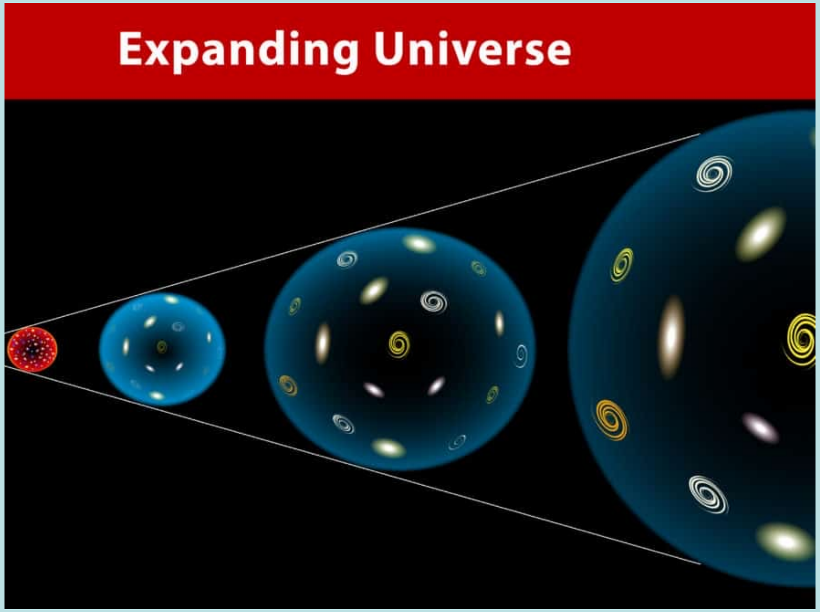
MAP990404

宇宙真得像果凍.......或麵包

$a(t)\uparrow$

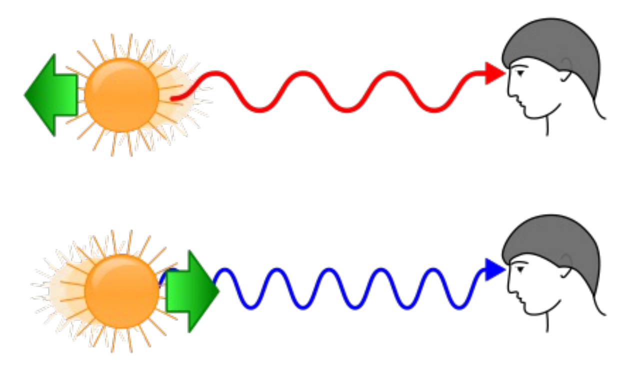
Cosmological principle





大尺度下均勻的宇宙，星體應該什麼都看不清了，有什麼意思呢？

宇宙有大尺度的擴張 Expanding！



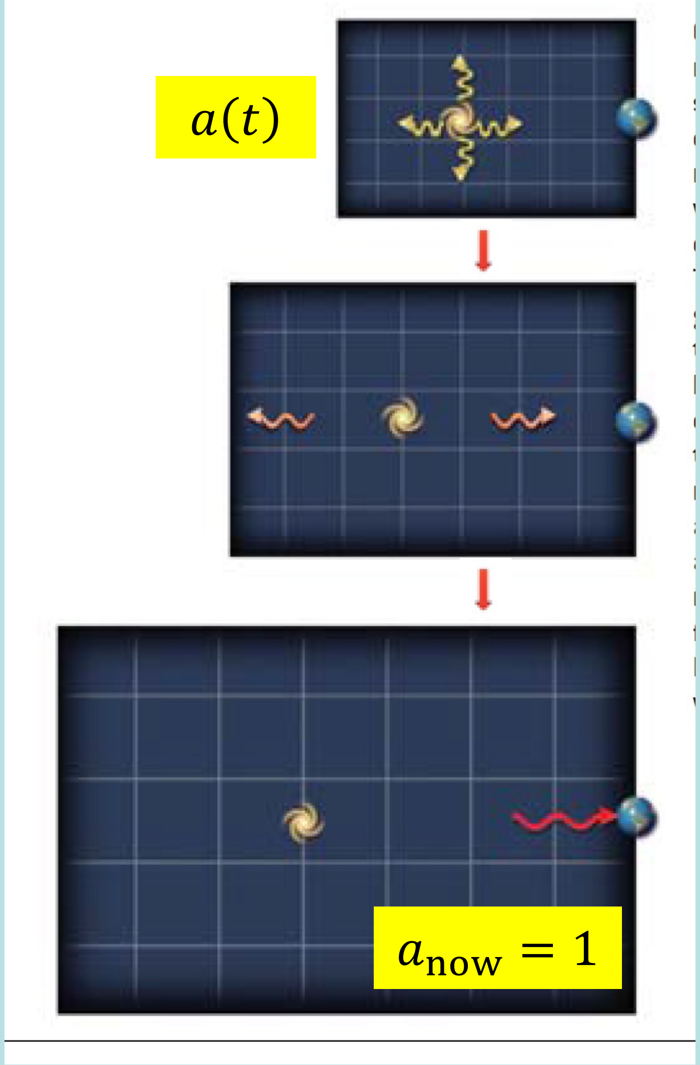
根據都卜勒效應：

$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = 1 + \frac{v}{c}$$

嚴格來說，都卜勒效應的推導只適用於較近的銀河。

較嚴格的推導：

廣義相對論的宇宙論紅移 cosmological redshift



現在被觀測的光來自過去，設距今時間為t。

那時的尺規$a(t)$較小。

發送與觀測時波長的比例是兩個時間的$a(t)$的比：

設現在的尺度為一：$a(0) = 1$

$$1 + z = \frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = \frac{1}{a(t)}$$

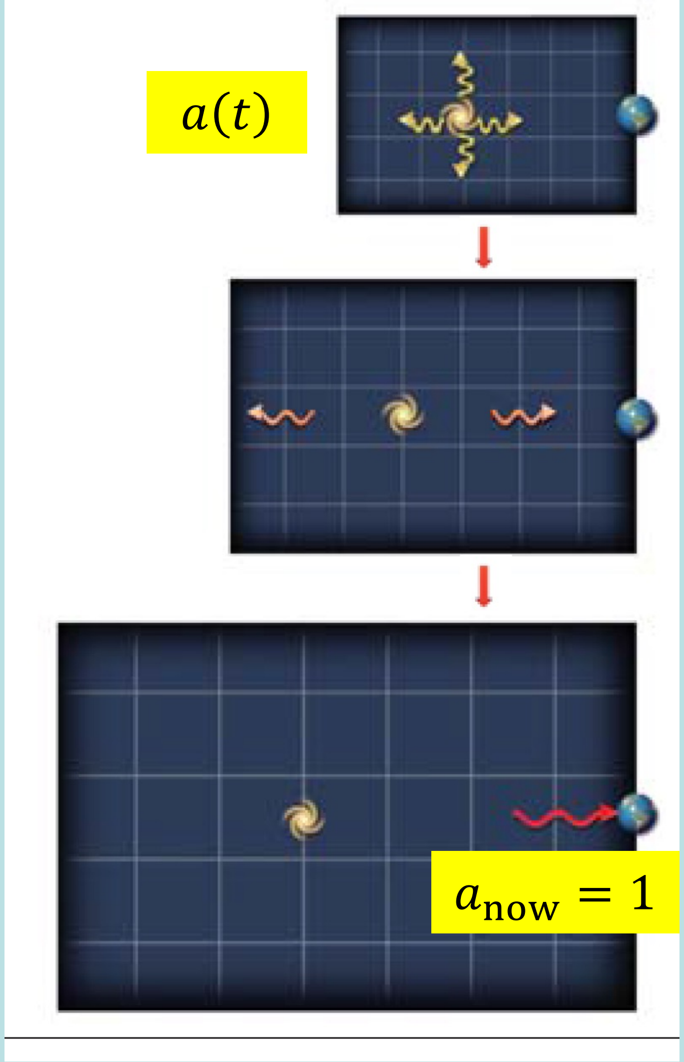
z值越大，$a(t)$越小，越是久遠，

對近處的銀河 $z < 1$ $a(t)$可以對時間展開：

$$a(t) \sim 1 - tH \qquad \frac{1}{1 - tH} \sim 1 + tH = 1 + \frac{v}{c}$$

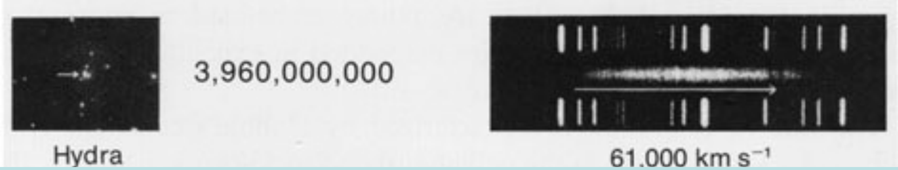
代入即得到哈伯定律。

$$tH = \frac{v}{c} \qquad v = H \cdot ct = Hr$$



$$1 + z = \frac{1}{a(t)}$$

此式也適用於極遠的銀河



LEDA 25177 (MCG+01-23-008)	**1951–1960**	z=0.2 (V=61000 km/s)

z值可以直接取代了宇宙歷史的紀年t。

z值越大，$a(t)$越小，越是久遠，

因為距離極遠，這些光多半來自宇宙誕生初期，

所以韋伯不只是一個望遠鏡，還是一個時間機器呢，以紅移z紀年。

對這些光仔細研究，將讓我們可以看透整個宇宙的歷史。

節目 知識好好玩

【物理好好玩S2EP08】馬克思威爾的彩虹與韋伯望遠鏡的深空照片

主持人｜張嘉泓

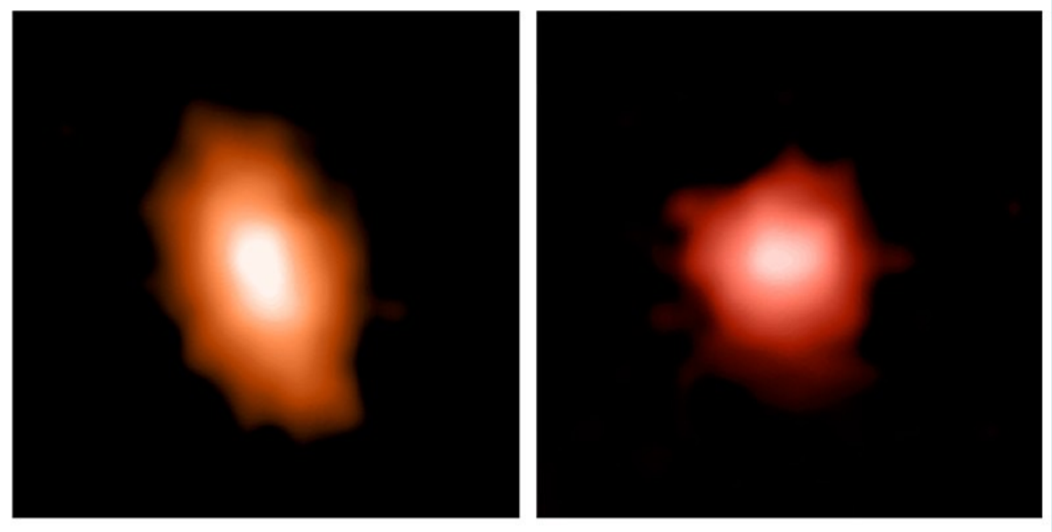
單曲長度｜00:25:22　發布時間｜2022-08-09

#張嘉泓 #物理好好玩 #黑洞 #彩虹 #韋伯望遠鏡 #紅外線 #電磁波 #馬克思威爾 #深空照片 #伽馬射線

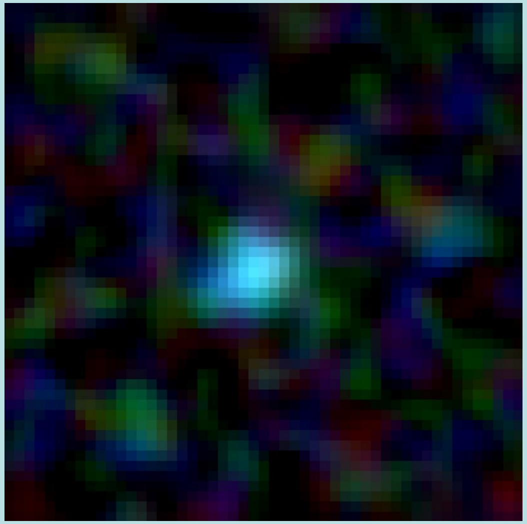
張嘉泓

專長是理論粒子物理，畢業於台大物理系，在美國哈佛大學取得博士學位後，曾在清華大學進行研究，現在...

第一張韋伯深空區照片，包含上千個星系，每個星系又有上億顆恆星，是宇宙至今最深、最清晰的紅外線影像。照片前景中，大部分星系是屬於星系團SMACS 0723，距離我們大約50億光年。而更顯眼、正要緊的是許多後方更加極度遙遠的星系，它們發出的光先經過SMACS 0723才到地球。被SMACS 0723極大的重力影響，光是彎著走的，所以它們影像好像經過了透鏡，被扭曲、放大成奇怪的形狀，有的看似毛筆隨意的一筆，有的像一段圓弧，有的甚至像是被壓扁了的麵疙瘩。這是典型的重力透鏡效應，



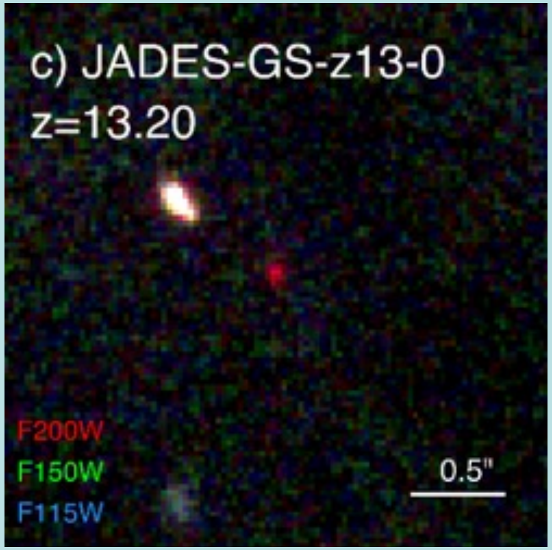
Astronomers found these two distant galaxies in the same small part of the sky. They estimate that the one on the right is from 300 million years after the Big Bang.

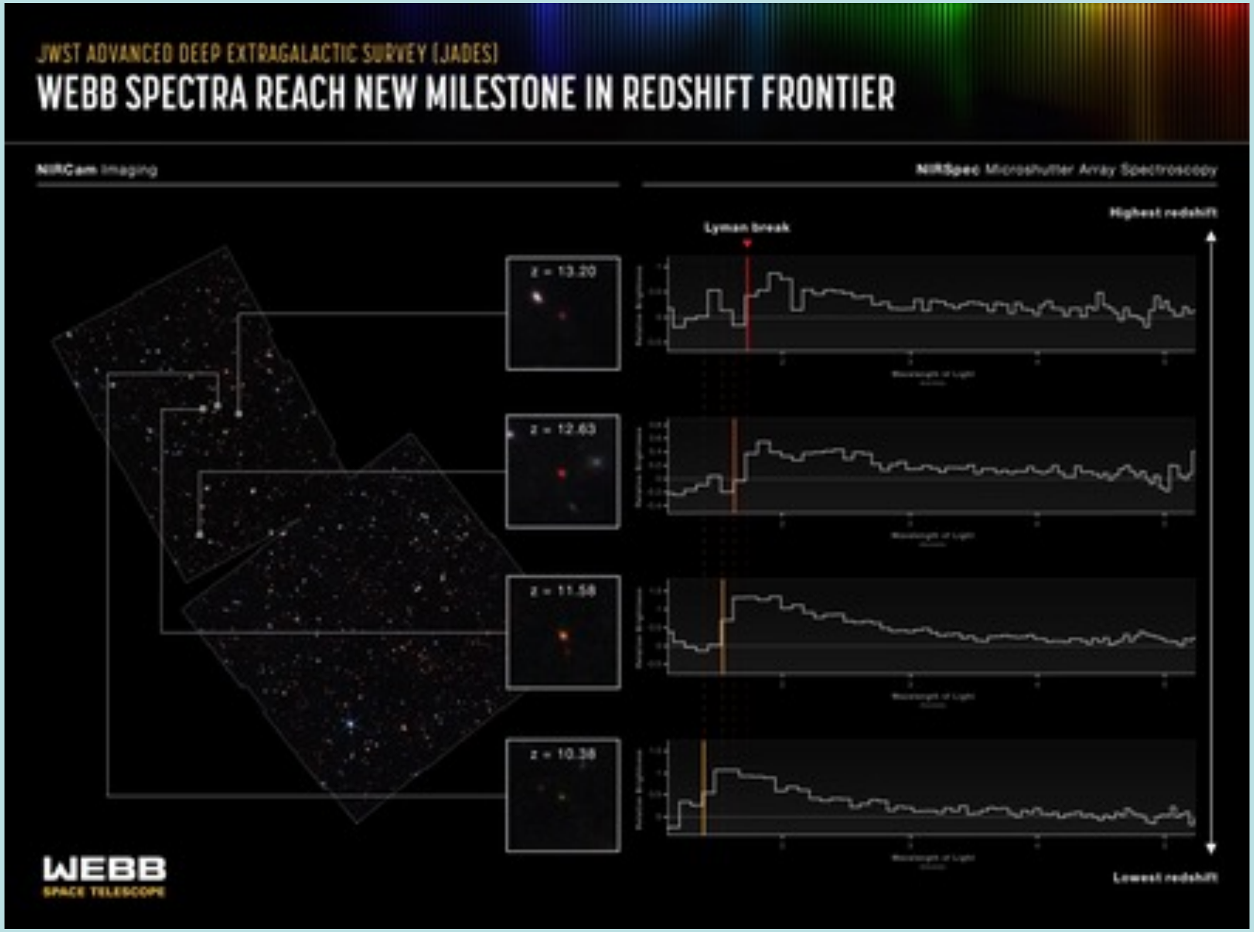


Maisie's Galaxy: Astronomer Steven Finkelstein nicknamed this distant galaxy after his daughter. He estimates that it is from 280 million years after the Big Bang.

The JADES Deep Field uses observations taken by NASA’s James Webb Space Telescope (JWST) as part of the JADES (JWST Advanced Deep Extragalactic Survey) program. A team of astronomers studying JADES data identified about 80 objects that changed in brightness over time. Most of these objects, known as transients, are the result of exploding stars or supernovae. Prior to this survey, only a handful of supernovae had been found above a redshift of 2, which corresponds to when the universe was only 3.3 billion years old — just 25% of its current age. The JADES sample contains many supernovae that exploded even further in the past, when the universe was less than 2 billion years old. It includes the farthest one ever spectroscopically confirmed, at a redshift of 3.6. Its progenitor star exploded when the universe was only 1.8 billion years old.

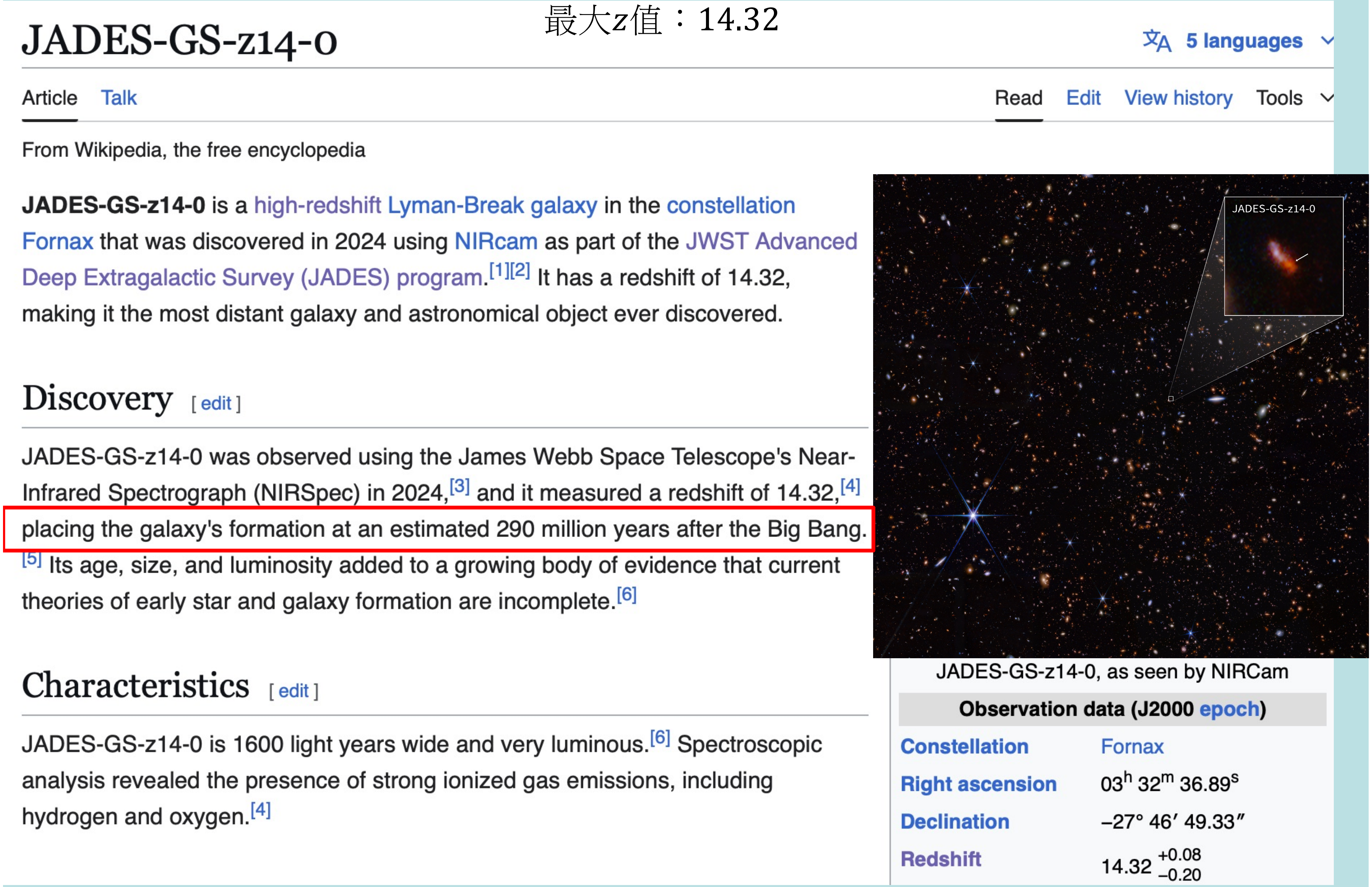
NASA, ESA, CSA, STScI, JADES Collaboration





Of the four, the most distant is one with the somewhat unwieldy name JADES-GS-z13-0. It has a redshift value of 13.2, meaning we are seeing the galaxy as it appeared just 320 million years after the big bang. That high redshift makes JADES-GS-z13-0 the most distant currently known in the universe

最大z值：14.32



JADES-GS-z14-0

From Wikipedia, the free encyclopedia

JADES-GS-z14-0 is a high-redshift Lyman-Break galaxy in the constellation Fornax that was discovered in 2024 using NIRcam as part of the JWST Advanced Deep Extragalactic Survey (JADES) program.[1][2] It has a redshift of 14.32, making it the most distant galaxy and astronomical object ever discovered.

Discovery [edit]

JADES-GS-z14-0 was observed using the James Webb Space Telescope's Near-Infrared Spectrograph (NIRSpec) in 2024,[3] and it measured a redshift of 14.32,[4] placing the galaxy's formation at an estimated 290 million years after the Big Bang.[5] Its age, size, and luminosity added to a growing body of evidence that current theories of early star and galaxy formation are incomplete.[6]

Characteristics [edit]

JADES-GS-z14-0 is 1600 light years wide and very luminous.[6] Spectroscopic analysis revealed the presence of strong ionized gas emissions, including hydrogen and oxygen.[4]

JADES-GS-z14-0, as seen by NIRCam

Observation data (J2000 epoch)	
Constellation	Fornax
Right ascension	$03^h\ 32^m\ 36.89^s$
Declination	−27° 46′ 49.33″
Redshift	$14.32\ ^{+0.08}_{-0.20}$

我們怎麼知道放大比例$a(t)$呢？

Alexander Friedmann 1888-1925

Friedmann 在1922 發現，尺度函數$a(t)$可以由廣義相對論預測計算。

$a(t)$滿足一個很簡單的微分方程式。

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} \Rightarrow \left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

Friedmann Equation

Cosmology的起點

尺度的變化率由當時宇宙的能量密度ρ、以及宇宙的曲度K決定！

驚人的，宇宙中的物質除了小範圍扭曲空間，造成重力效應。

也會合起來，積小成大，大範圍的拉動空間尺格，使其隨時間變化。

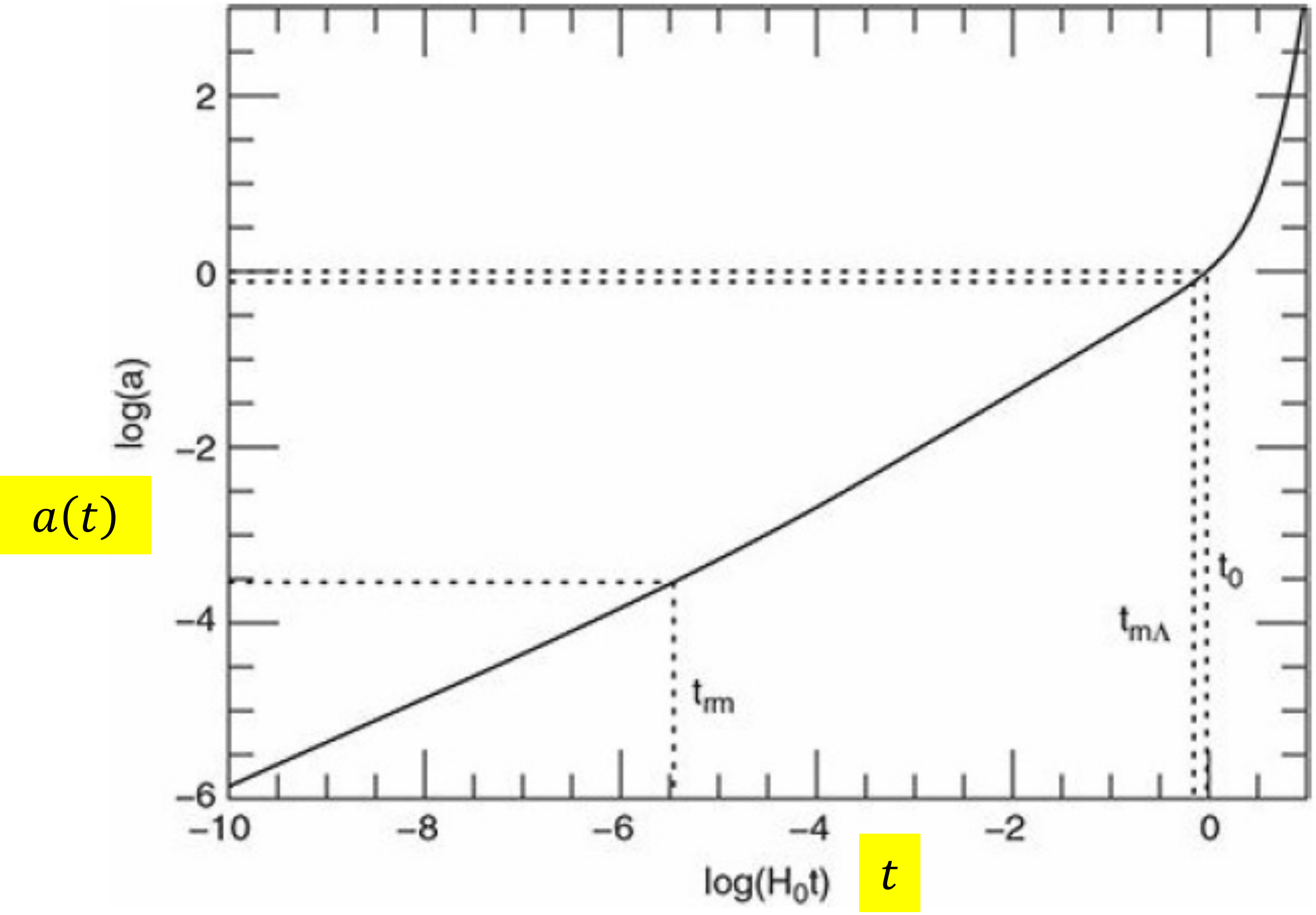


Figure 5.8 The scale factor a as a function of time t (measured in units of the Hubble time), computed for the Benchmark Model. The dotted lines indicate the time of radiation–matter equality, $a_{rm} = 2.9 \times 10^{-4}$, the time of matter–lambda equality, $a_{m\Lambda} = 0.77$, and the present moment, $a_0 = 1$.

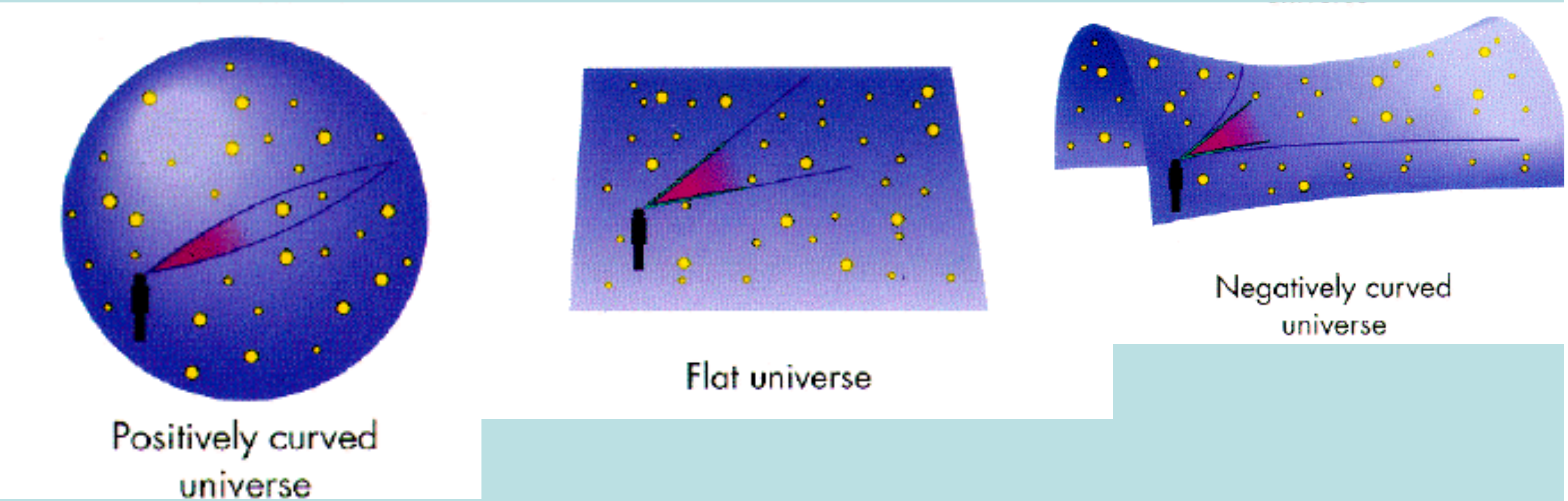
由Friedman Eq. 可以得到尺度放大比例與時間的關係：$a(t)$

比較奇妙的是，在廣義相對論下，空間還可以有一個自己的均勻彎曲度，

均勻的彎曲度也會影響尺度的變化率！

On the curvature of space

凸的 平的 凹的



Positively curved universe

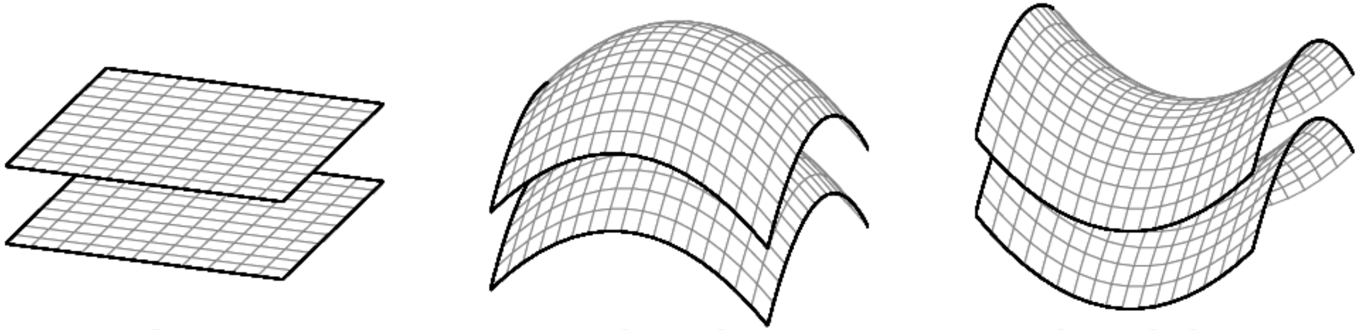
Flat universe

Negatively curved universe

不同的彎曲度，它的效應可以以一曲度常數K: $+1, 0, -1$表示。

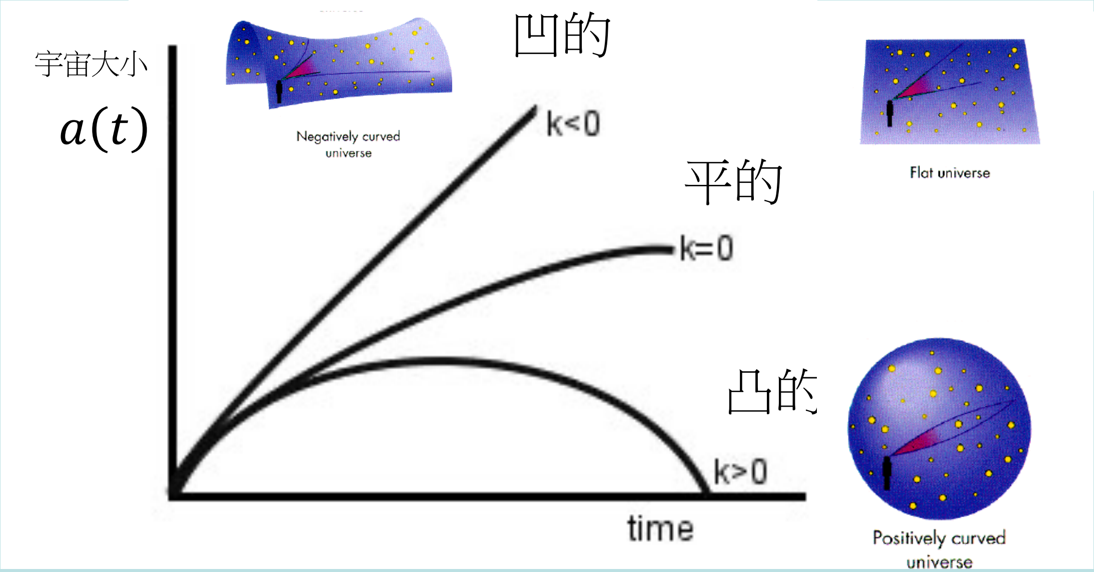
$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2}$$

現在暫時的測量結果是平的。

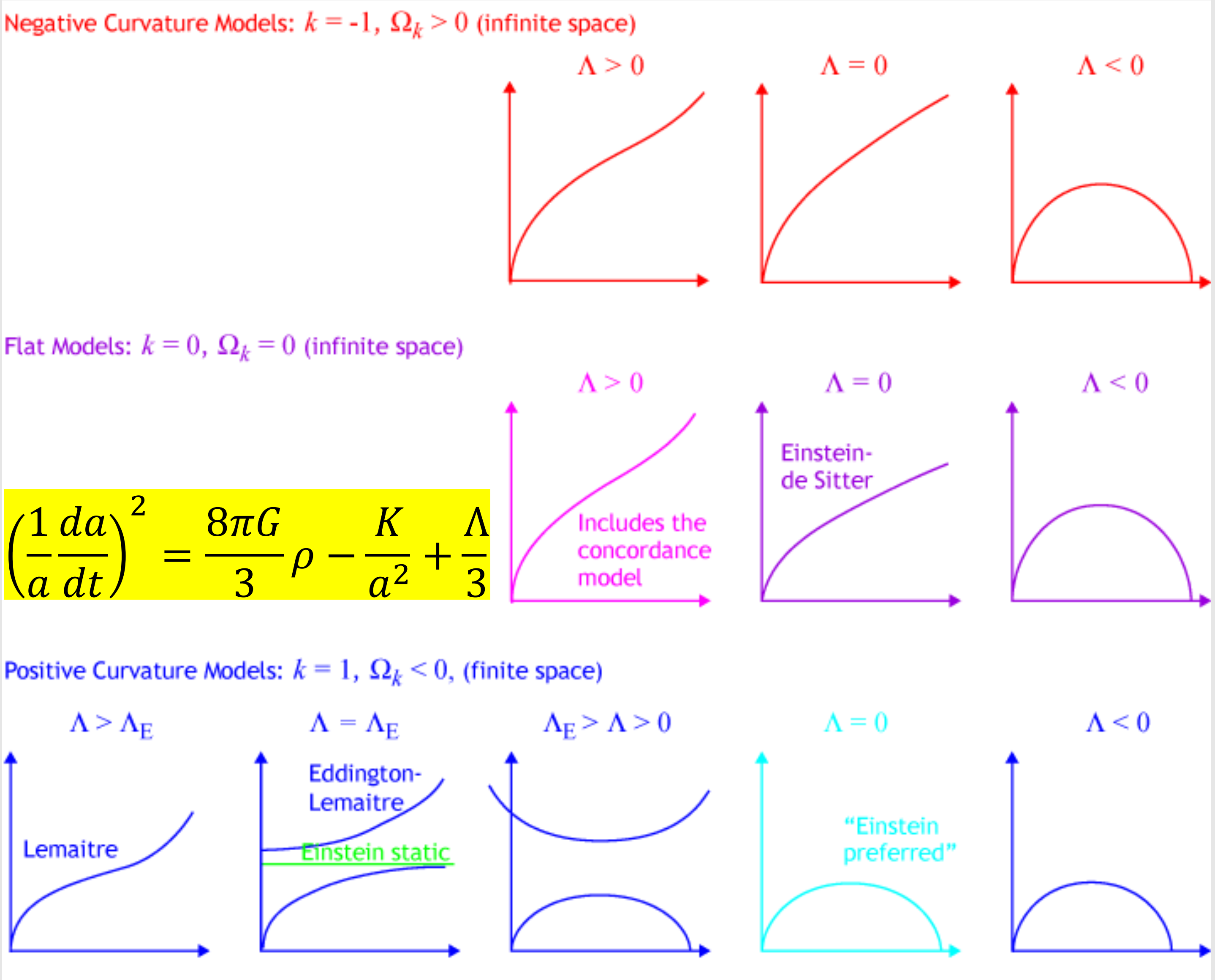


flat spherical hyperbolic

The spacetime of the universe can be foliated into flat, spherical (positively-curved) or hyperbolic (negatively-curved) spatial hypersurfaces.



不同的彎曲度會造成宇宙不同的演化，擁有完全不同的未來！

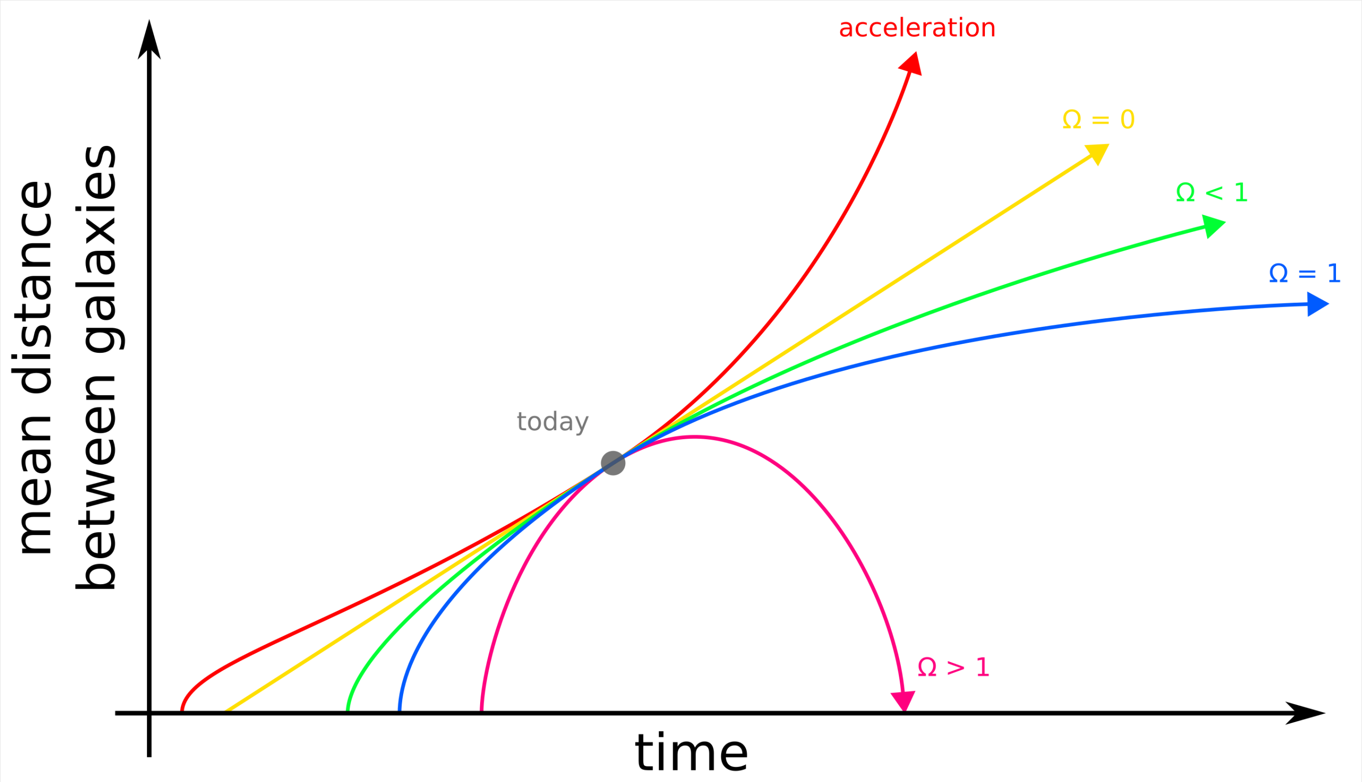


$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho - \frac{K}{a^2} + \frac{\Lambda}{3}$$

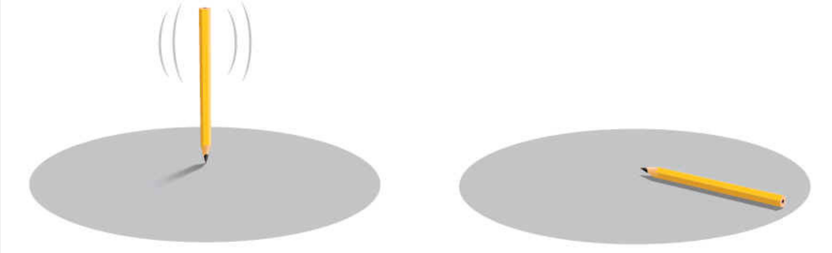
Classification of Friedmann Models

考慮物質含量及宇宙常數Λ的話，可能性就更多了。

重點是在所有可能性之中，幾乎沒有維持不變的的可能！ $a(t) \neq$ 常數



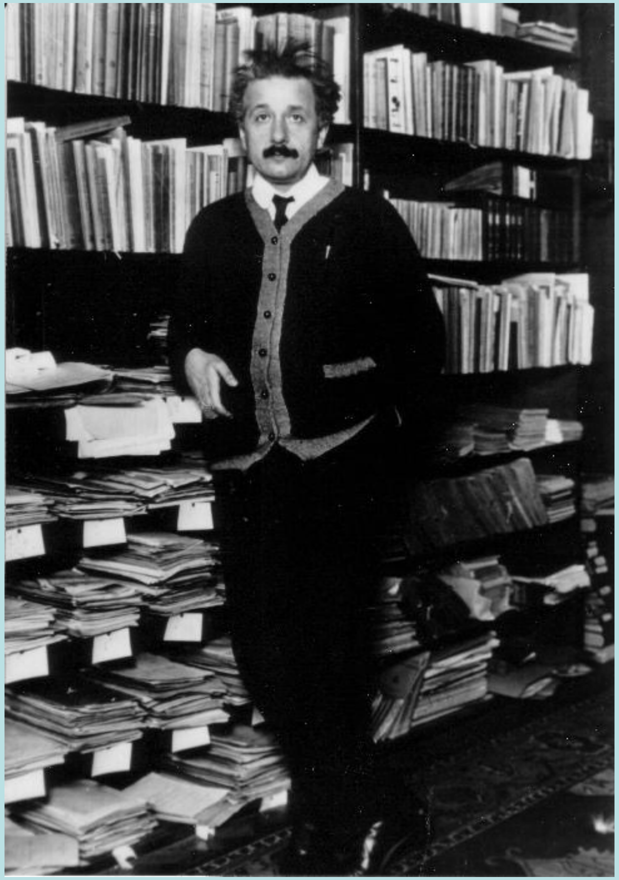
除非曲度常數正好為零，宇宙常數與能量密度正好抵消。



廣義相對論預測動態宇宙是非常自然的！所有星團距離都等比例變化。

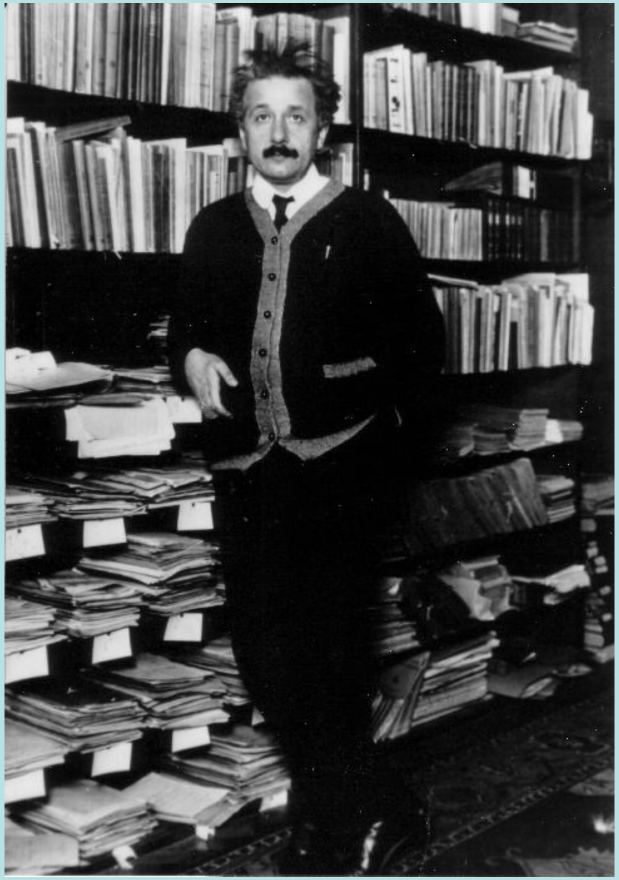
放大比例$a(t) =$ 常數的情況極為罕見，靜態宇宙是不自然且不穩定的！

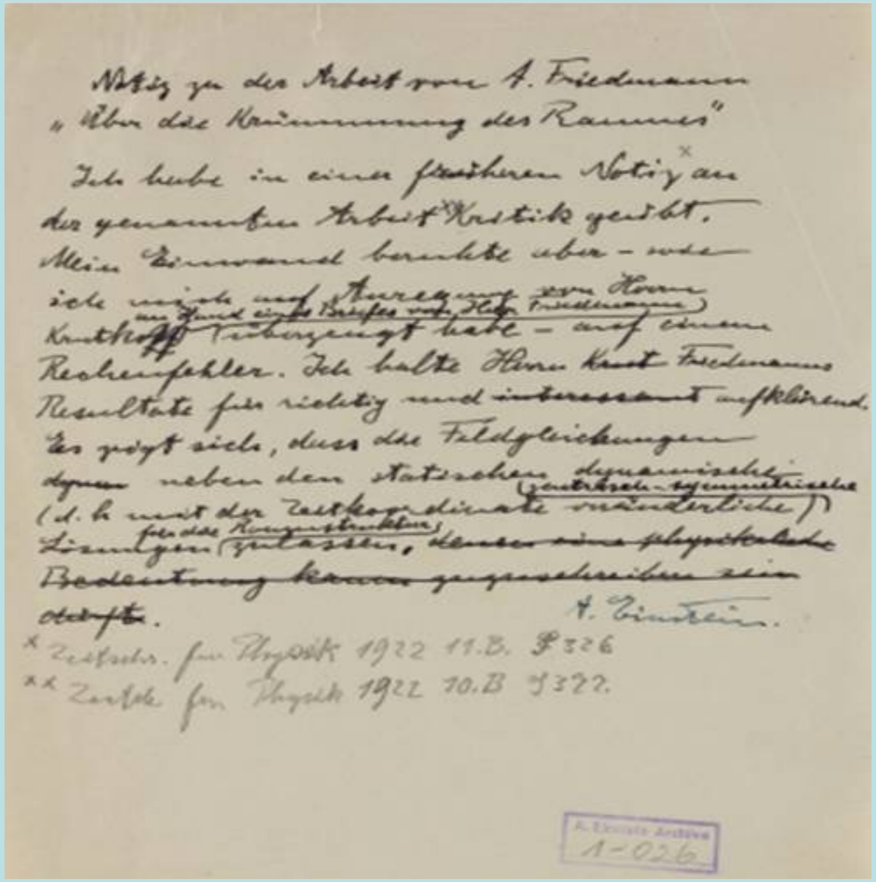
這樣的想法是愛因斯坦無法接受的！



The results concerning the non-stationary world, contained in Friedmann’s paper, appear to me suspicious 可疑. In fact, it turns out the solution given in it does not satisfy the equation of GR. 在這篇論文中的解釋不滿足廣義相對論的！

作為數學家的Friedmann 自然無法接受！立刻回信反駁。





Notiz zu der Arbeit von A. Friedmann
„Über die Krümmung des Raumes“

Ich habe in einer früheren Notiz[x] an
der genannten Arbeit[xx] Kritik geübt.
Mein Einwand beruhte aber – wie
ich ~~mich auf Anregung von Herrn~~ an Hand eines Briefes von Herrn Friedmann
~~Krutkoff~~ überzeugt habe – auf einem
Rechenfehler. Ich halte Herrn ~~Kurt~~ Friedmanns
Resultate für richtig und ~~interessant~~ aufklärend.
Es zeigt sich, dass die Feldgleichungen
~~dyn~~ neben den statischen dynamische zentrisch-symmetrische
(d. h. mit der Zeitkoordinate veränderliche)
Lösungen für die Raumstruktur zulassen, ~~denen eine physikalische~~
~~Bedeutung kaum zuzuschreiben sein~~
~~dürfte~~.

A. Einstein.

[x] Zeitschr. für Physik 1922 11. B. S. 326
[xx] Zeitschr. für Physik 1922 10. B S. 377.

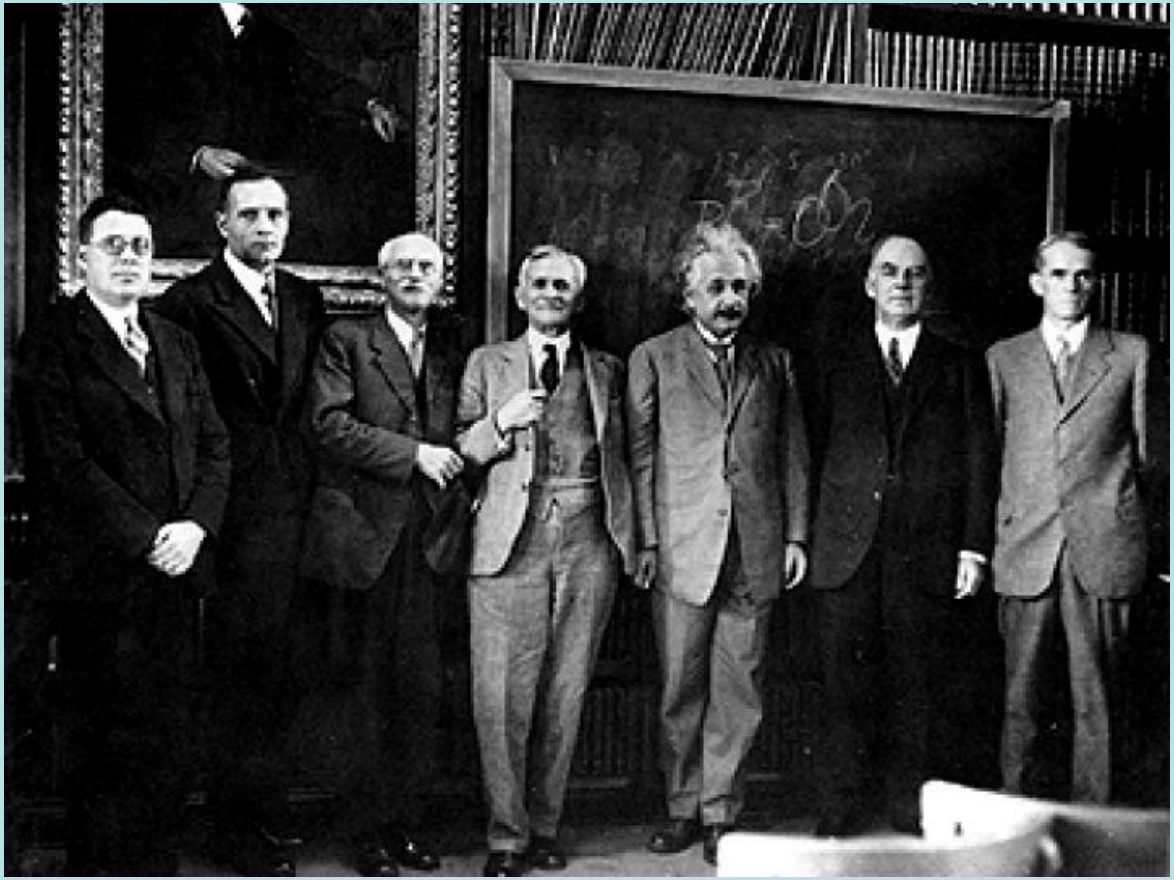
愛因斯坦後來承認自己的錯誤: I am convinced that Mr. Friedmann's result are both correct and clarifying.

但愛因斯坦堅持他的偏見，在他的澄清信函的草稿中，還留有以下：”a physical relevance can hardly be ascribed （很難看出與物理現實有甚麼關聯）” 這樣的字句。後來刪去了。

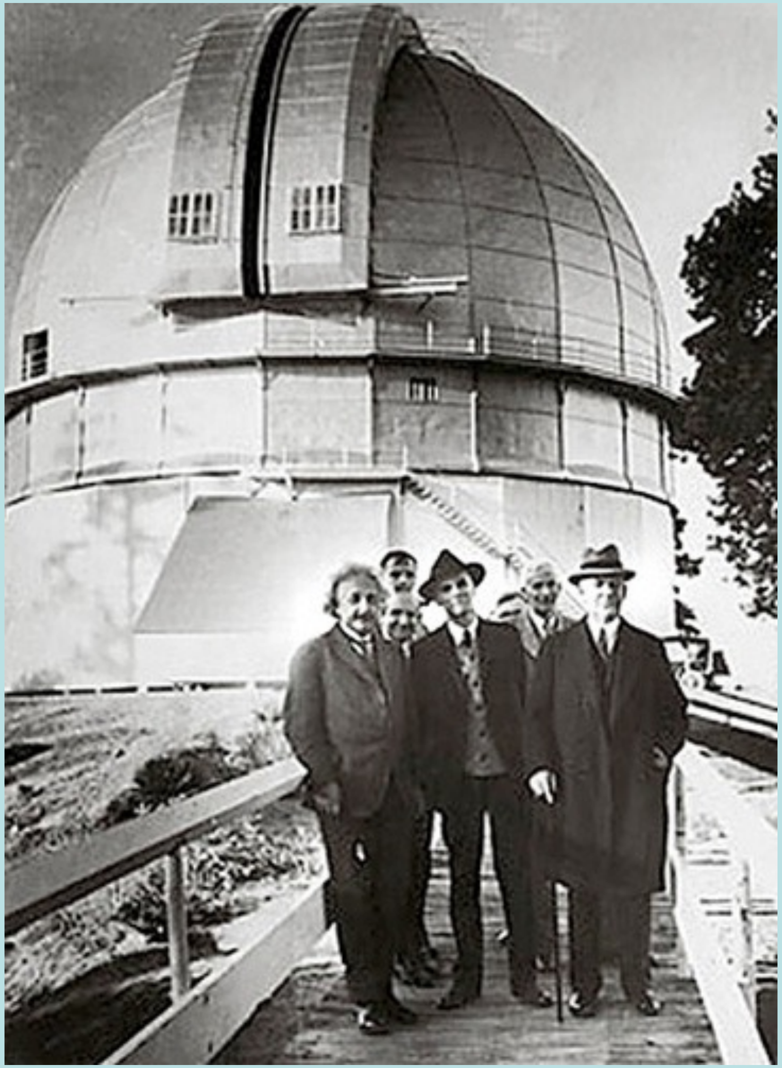
但因為愛因斯坦的意見，Friedmann的文章有十年完全被忽視。

當勒梅特在1927年告訴愛因斯坦他的動態宇宙的結果，

愛因斯坦回答：從物理的角度，這個理論在他看來十分abominable（disgusting 令人厭惡的）他還無法忘記他對靜態宇宙的偏見。



Albert A. Michelson (center) with (left to right) M.L. Humason, Edwin Hubble, C.E. St. John, Albert Einstein, W.W. Campbell, and W.S. Adams in the library of the Mount Wilson Observatory, Pasadena, California, in early 1931.



On a visit to the Mount Wilson Observatory near Pasadena in 1931：

愛因斯坦最後在證據之前，才接受宇宙是動態的事實！

Big Bang 宇宙大霹靂

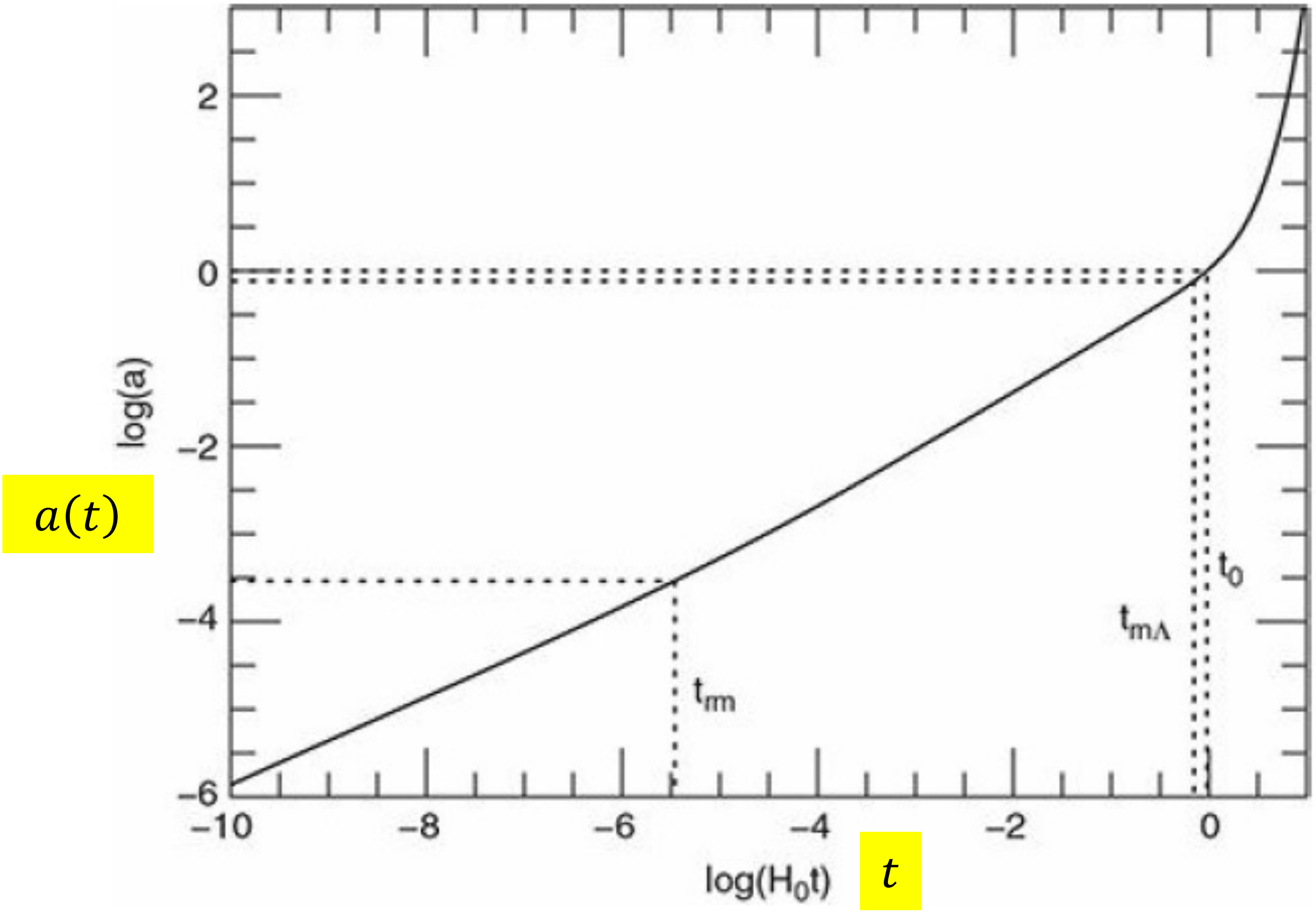


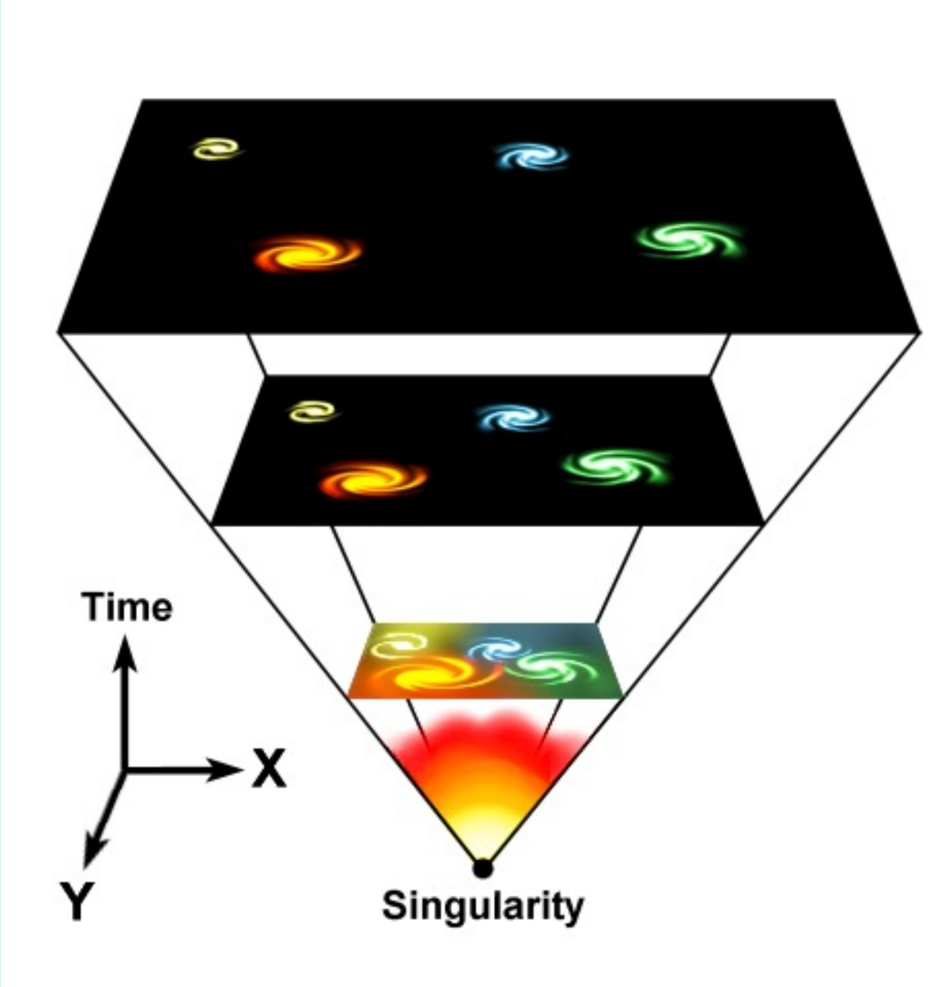
Figure 5.8 The scale factor *a* as a function of time *t* (measured in units of the Hubble time), computed for the Benchmark Model. The dotted lines indicate the time of radiation–matter equality, $a_{rm} = 2.9 \times 10^{-4}$, the time of matter–lambda equality, $a_{m\Lambda} = 0.77$, and the present moment, $a_0 = 1$.

由Friedman Eq. 可以得到尺度放大比例與時間的關係：$a(t)$

宇宙正在擴張之中，這事實確立之後：

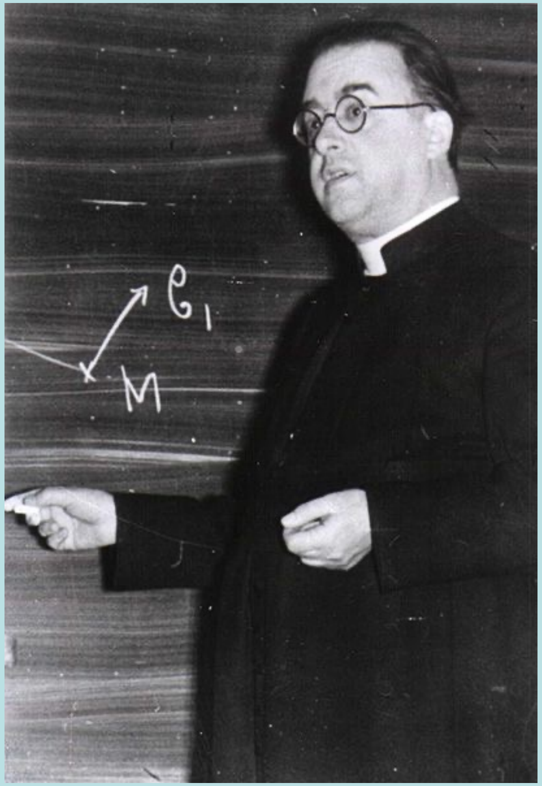
往過去看，宇宙自然就是越來越限縮，

能量限縮在越來越小的範圍，因此一定是越來越熱！



Hot Big Bang 大霹靂

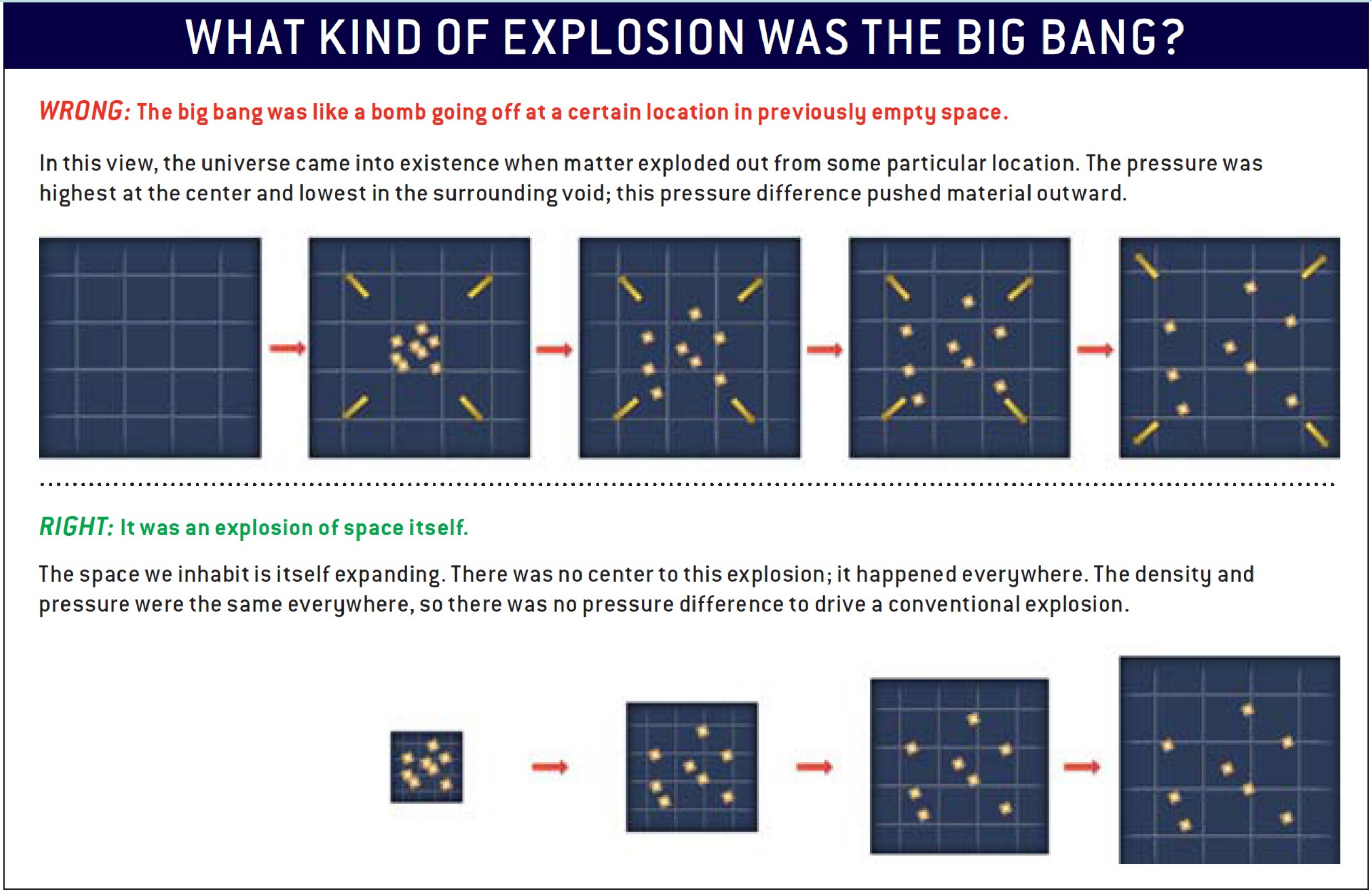
越是過去，宇宙越密，溫度越高



Georges Lemaître
1894-1966 Belgium

George Gamow
1904-1968 Russia, US

the Cosmic Egg exploding at the moment of the creation



WHAT KIND OF EXPLOSION WAS THE BIG BANG?

WRONG: The big bang was like a bomb going off at a certain location in previously empty space.

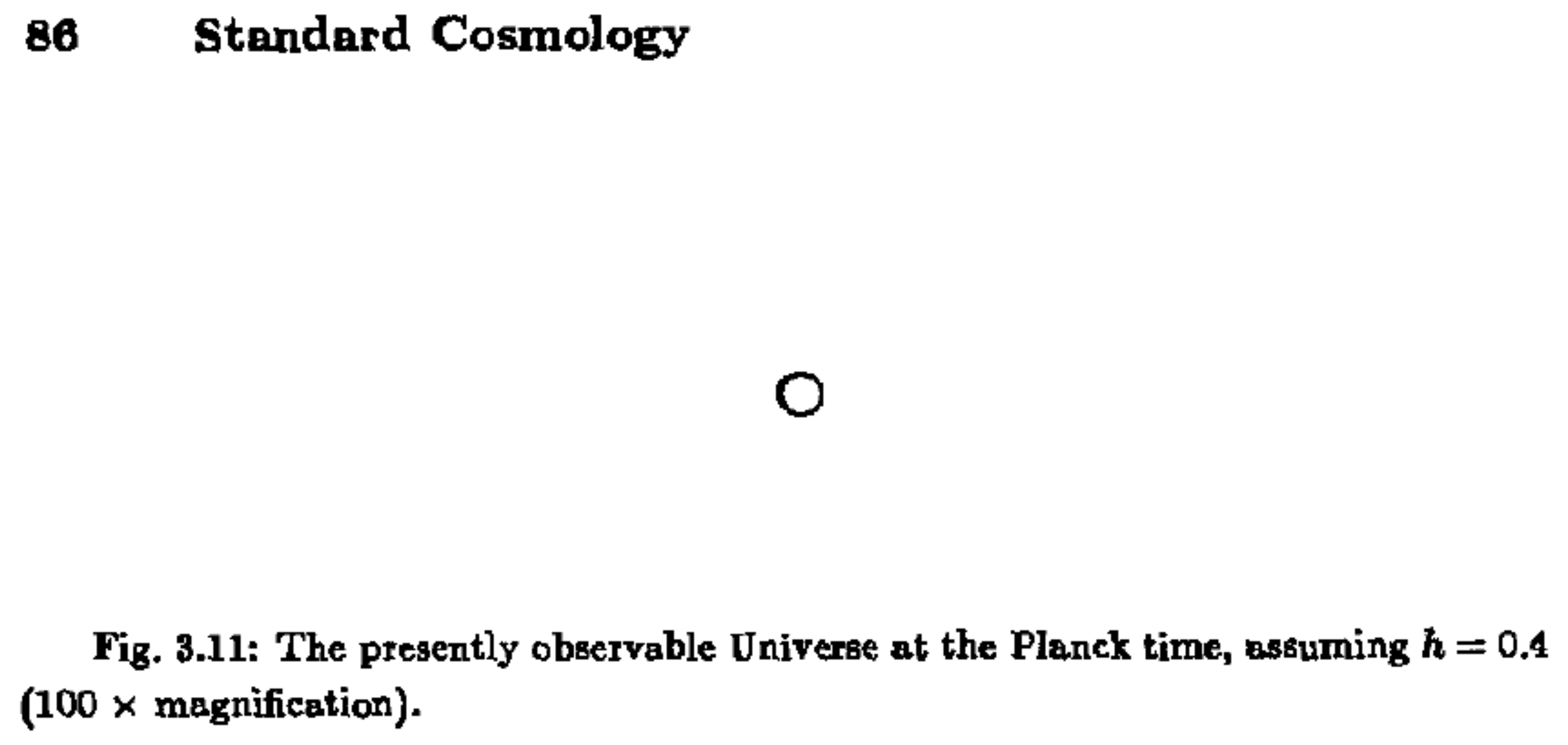
In this view, the universe came into existence when matter exploded out from some particular location. The pressure was highest at the center and lowest in the surrounding void; this pressure difference pushed material outward.

RIGHT: It was an explosion of space itself.

The space we inhabit is itself expanding. There was no center to this explosion; it happened everywhere. The density and pressure were the same everywhere, so there was no pressure difference to drive a conventional explosion.

大霹靂不是一個爆炸，因為沒有一個爆炸中心點。

大霹靂是一個均勻的宇宙擴張，因為早期宇宙能量密度極高，稱大霹靂。

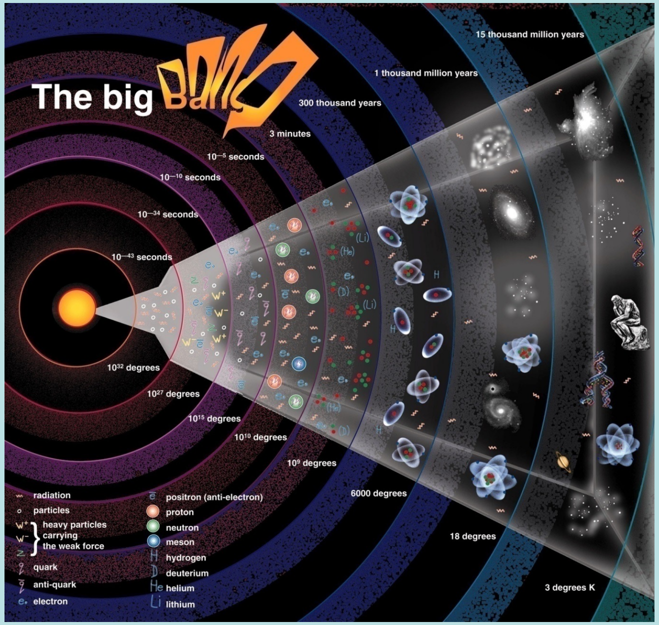


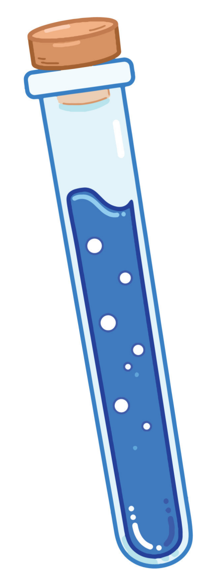
86 **Standard Cosmology**

Fig. 3.11: The presently observable Universe at the Planck time, assuming $h = 0.4$ (100 × magnification).

早期宇宙只有這麼大！$a(t)$非常小！

因為沒有外面，大小並不重要，但與現在比，極度擁擠，因此激烈作用！





當溫度極高，激烈熱運動的碰撞會將物質的組成成分撞擊分開，

早期宇宙是一個如試管的、擁擠的、激烈的反應物！

幸運的是對這一管反應物，我們非常了解它的成分與反應。

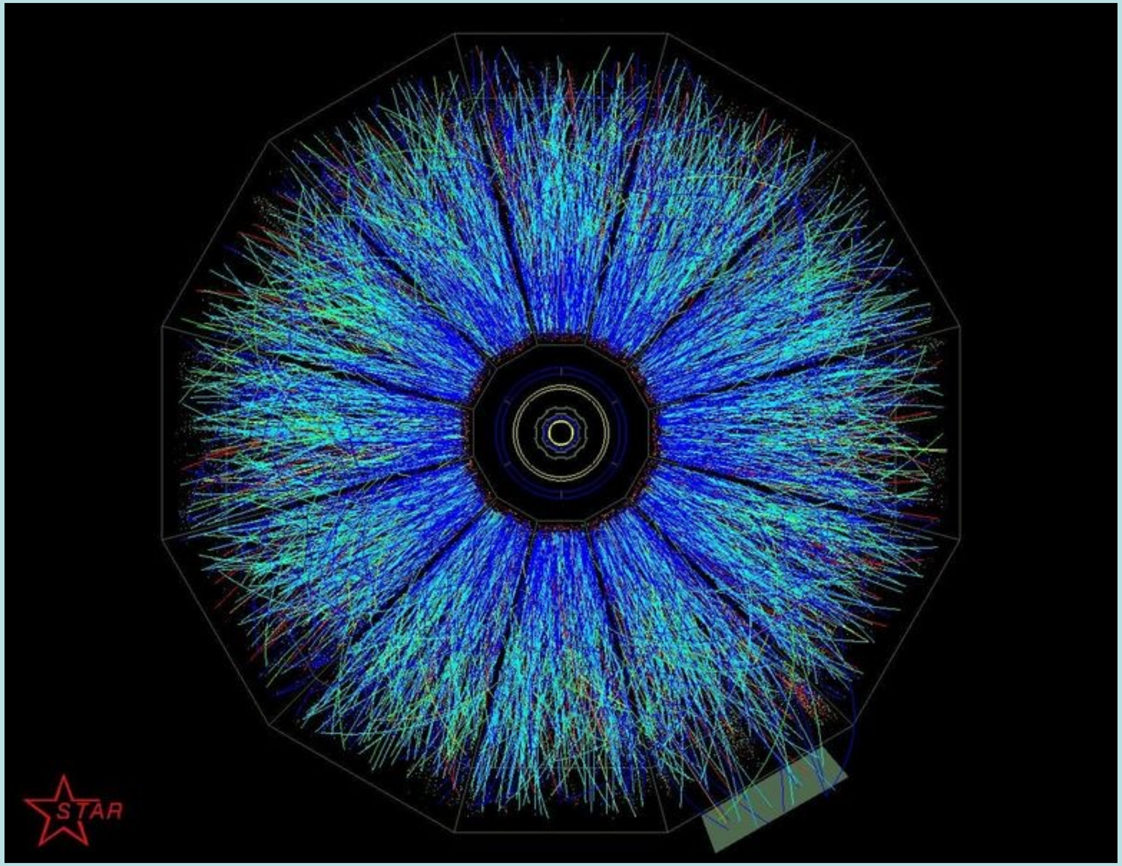
如同在特定溫度下，我們了解理想氣體的速度分布。

原子核內的質子與中子，甚至其內的夸克也無法再束縛在一起。

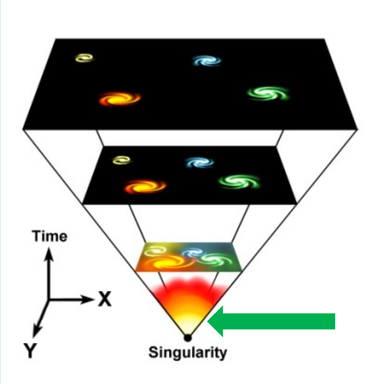
和電子形成湯一樣密度很高的帶電漿體。

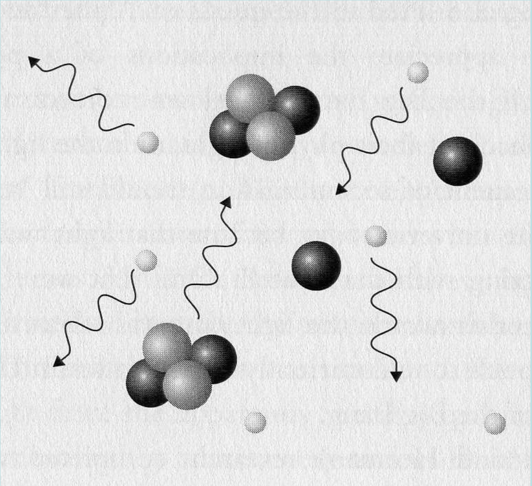
這樣的漿體的性質，竟然如理想氣體，可根據統計力學原則，由溫度完全決定！

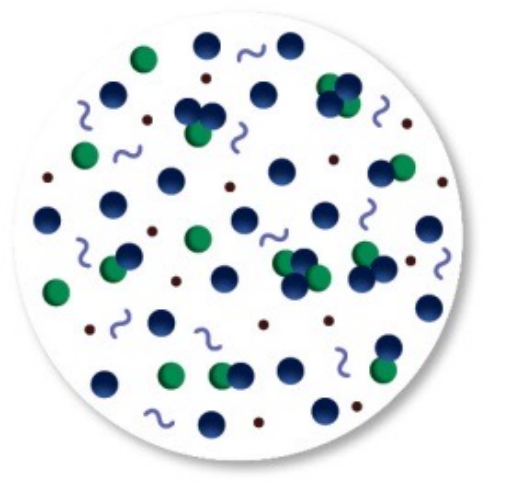
原始電漿 Primordial Plasma

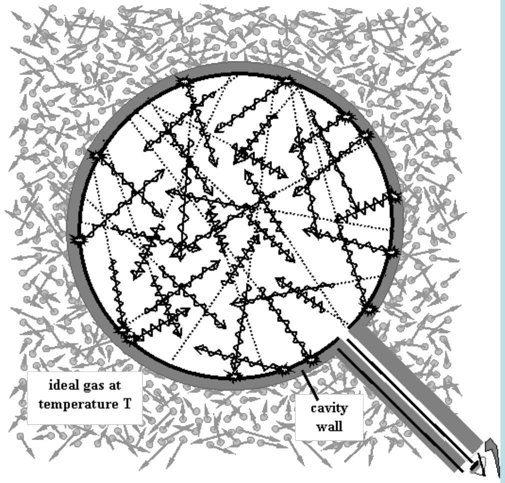


Light and matter are coupled









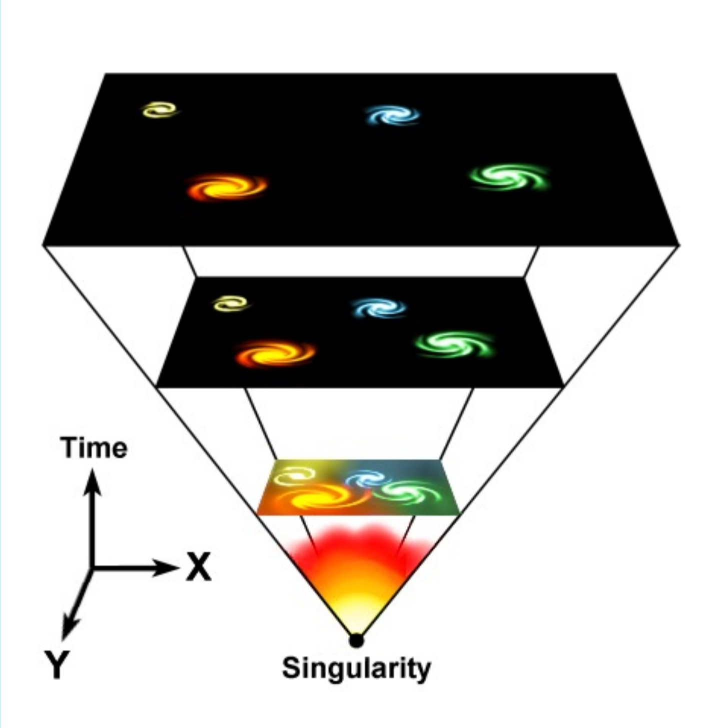
原始電漿因為帶電，會放出黑體輻射！

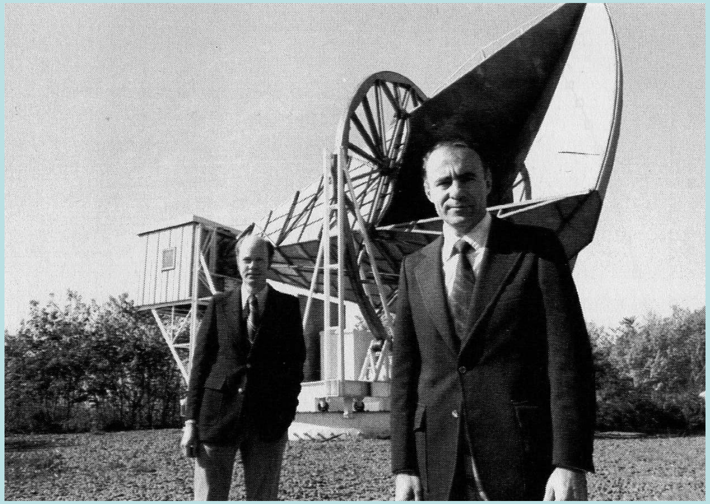
輻射與物質湯電漿不斷碰撞交互作用，如空腔輻射與空腔的器壁，一直維持熱平衡。

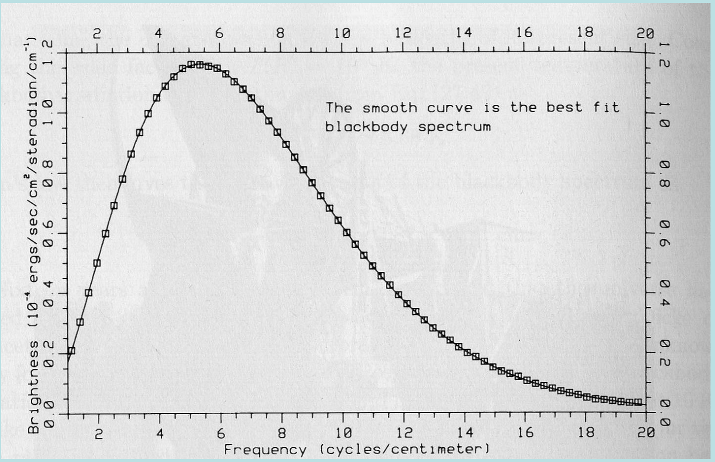
所以在接近大霹靂時，宇宙中的熱輻射會維持黑體輻射的樣式，

輻射的溫度就是電漿的溫度。

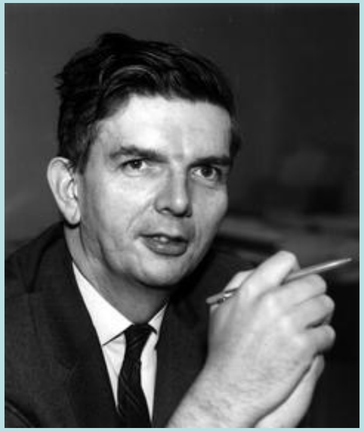
因為物質湯是均勻的、意思是與位置無關，因此輻射也是均勻而同向。







Alpher, 1948



Dicke 1964

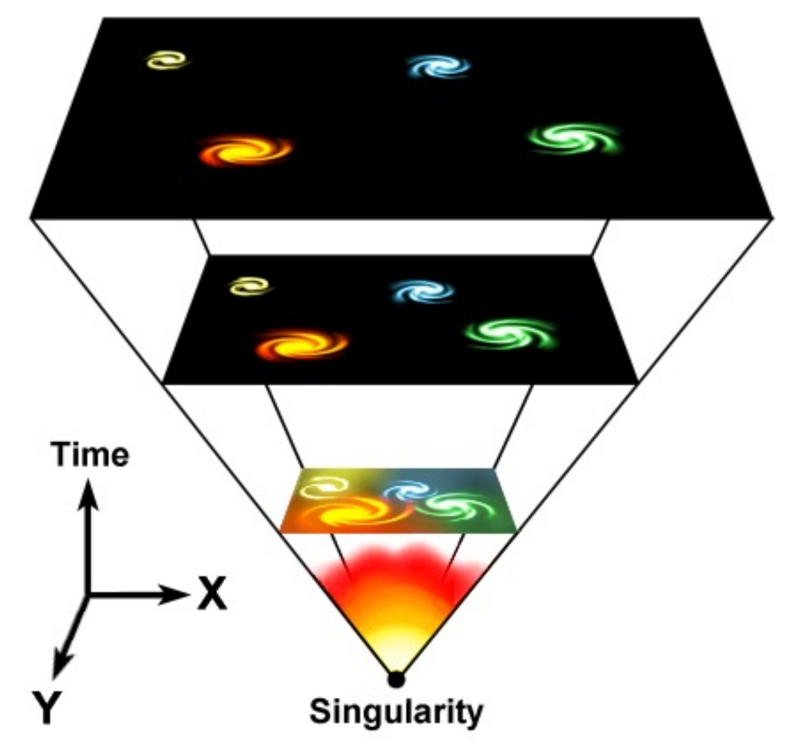
物理學家猜測，早期宇宙黑體輻射會在現在留下可以觀測的痕跡。

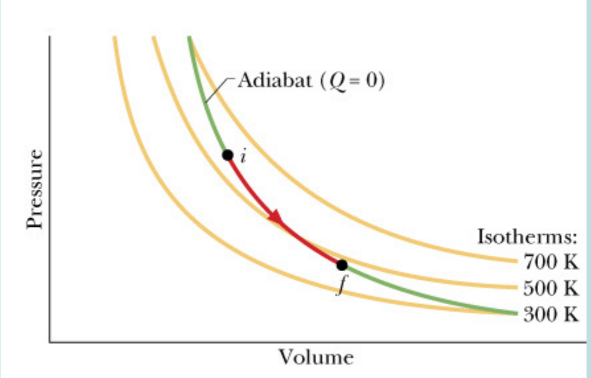
宇宙背景輻射一觀測到，立刻被猜到這就是早期宇宙物質湯的黑體輻射的遺跡。

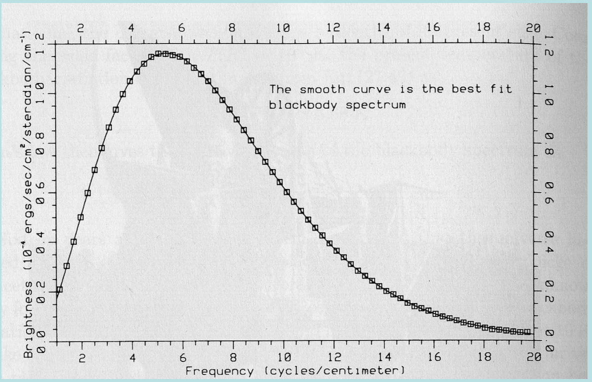
背景輻射隨著宇宙的擴張漸漸冷卻，類似絕熱膨脹，到今天只剩 2.725K。

嚴格說這是一個等熵過程 $\Delta S = 0$ 。因為擴張是一個均匀同向的過程，。

絕熱膨脹後現在的背景輻射依舊維持接近大霹靂時的均匀同向及黑體的特性。

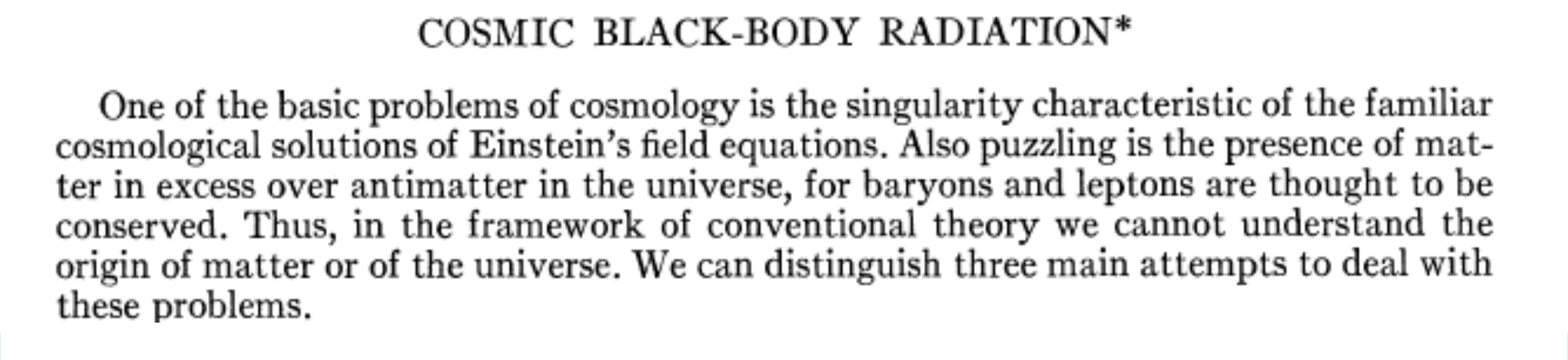






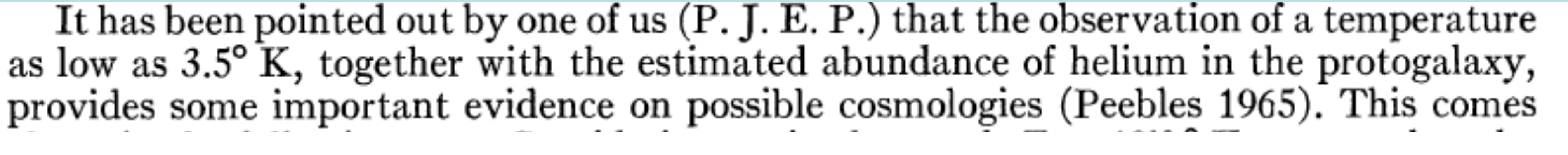
背景輻射的同向性可以以大霹靂理論解釋！

背景輻射成為大霹靂理論最重要的直接證據！

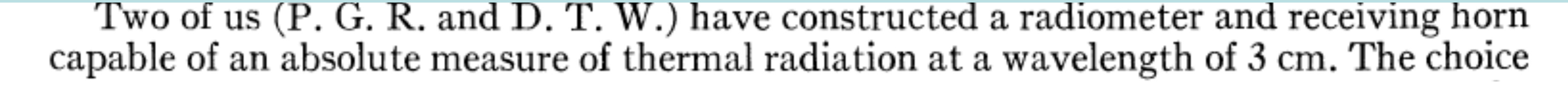


COSMIC BLACK-BODY RADIATION*

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.



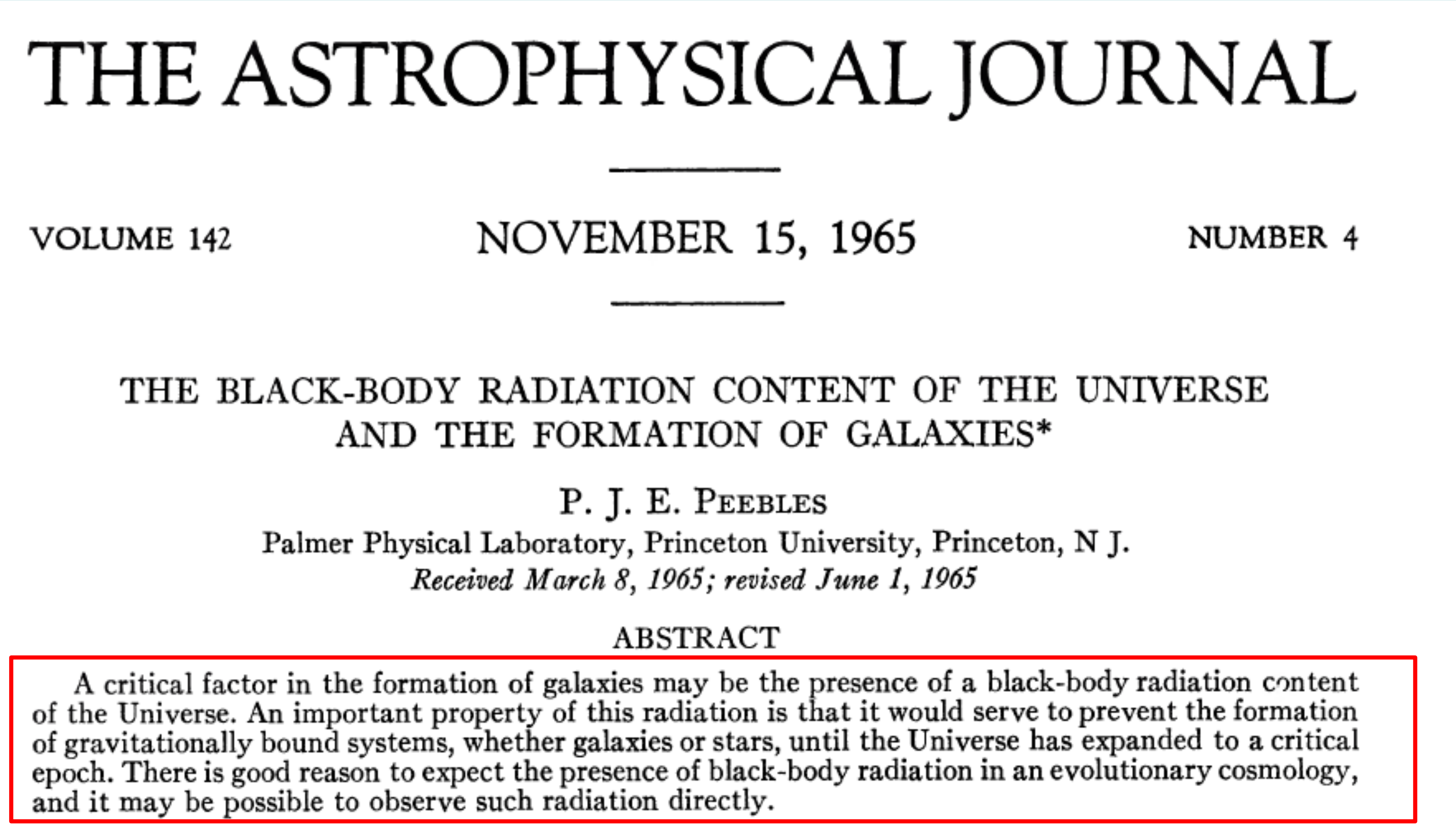
It has been pointed out by one of us (P. J. E. P.) that the observation of a temperature as low as 3.5° K, together with the estimated abundance of helium in the protogalaxy, provides some important evidence on possible cosmologies (Peebles 1965). This comes



Two of us (P. G. R. and D. T. W.) have constructed a radiometer and receiving horn capable of an absolute measure of thermal radiation at a wavelength of 3 cm. The choice

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey



THE ASTROPHYSICAL JOURNAL

VOLUME 142 NOVEMBER 15, 1965 NUMBER 4

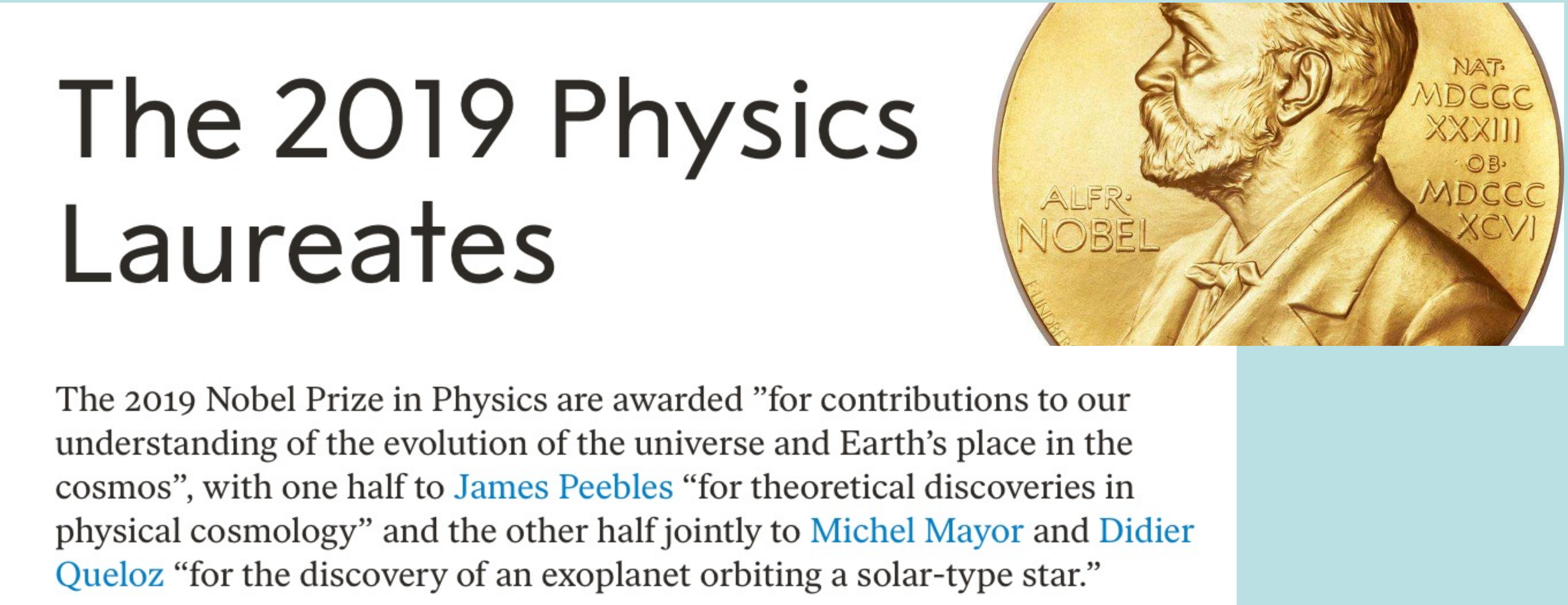
THE BLACK-BODY RADIATION CONTENT OF THE UNIVERSE AND THE FORMATION OF GALAXIES*

P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University, Princeton, N J.

Received March 8, 1965; revised June 1, 1965

ABSTRACT

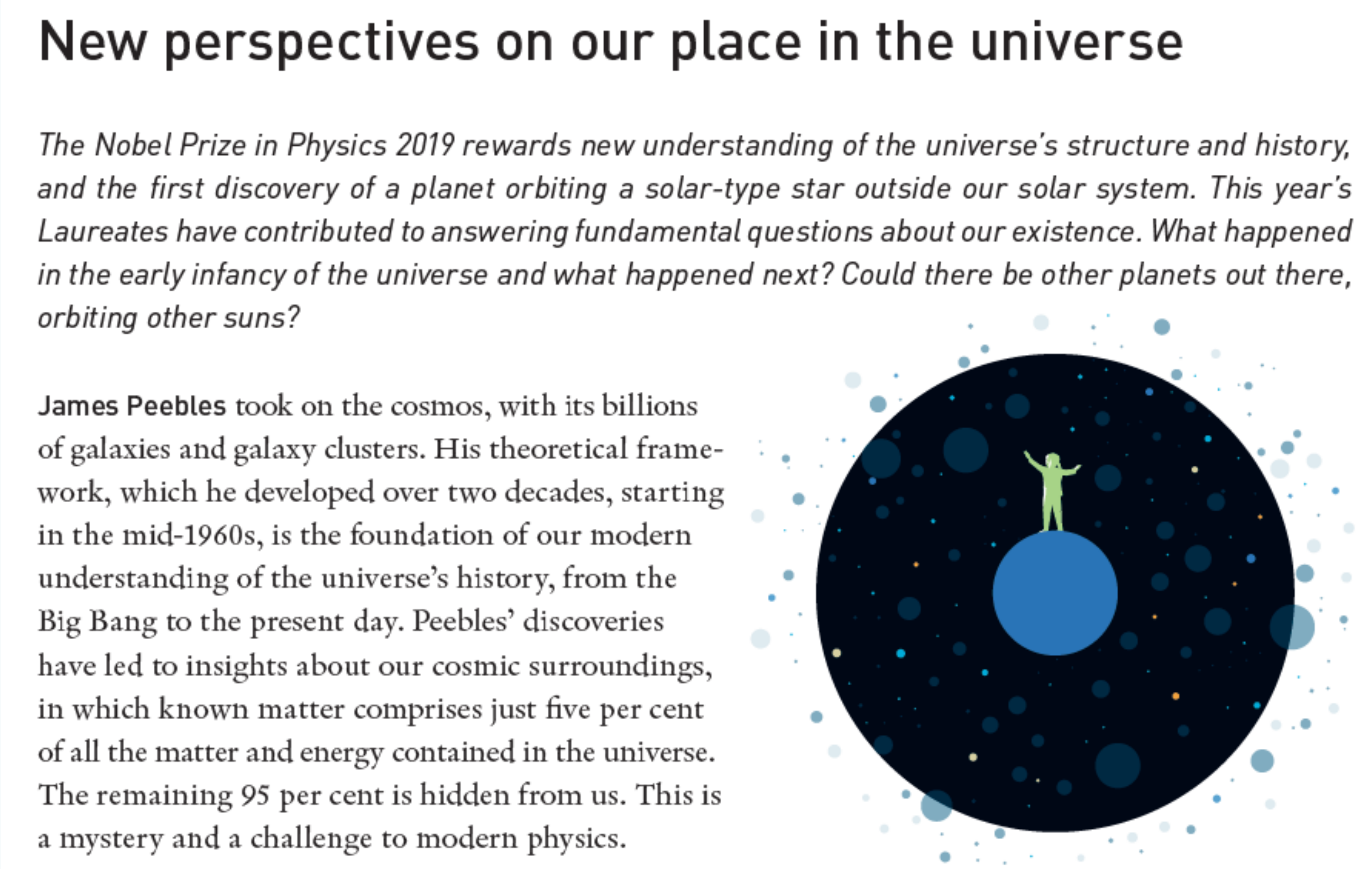
A critical factor in the formation of galaxies may be the presence of a black-body radiation content of the Universe. An important property of this radiation is that it would serve to prevent the formation of gravitationally bound systems, whether galaxies or stars, until the Universe has expanded to a critical epoch. There is good reason to expect the presence of black-body radiation in an evolutionary cosmology, and it may be possible to observe such radiation directly.



The 2019 Physics Laureates

The 2019 Nobel Prize in Physics are awarded ”for contributions to our understanding of the evolution of the universe and Earth’s place in the cosmos”, with one half to James Peebles “for theoretical discoveries in physical cosmology” and the other half jointly to Michel Mayor and Didier Queloz “for the discovery of an exoplanet orbiting a solar-type star.”

Images tweeted by @NobelPrize



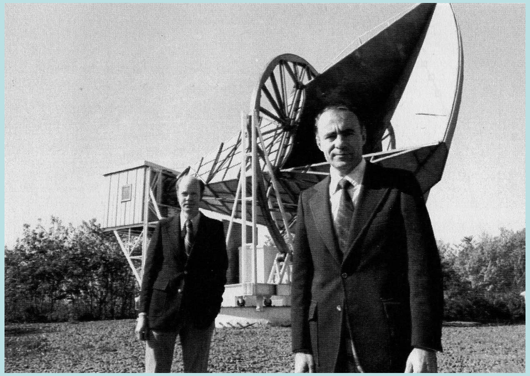
New perspectives on our place in the universe

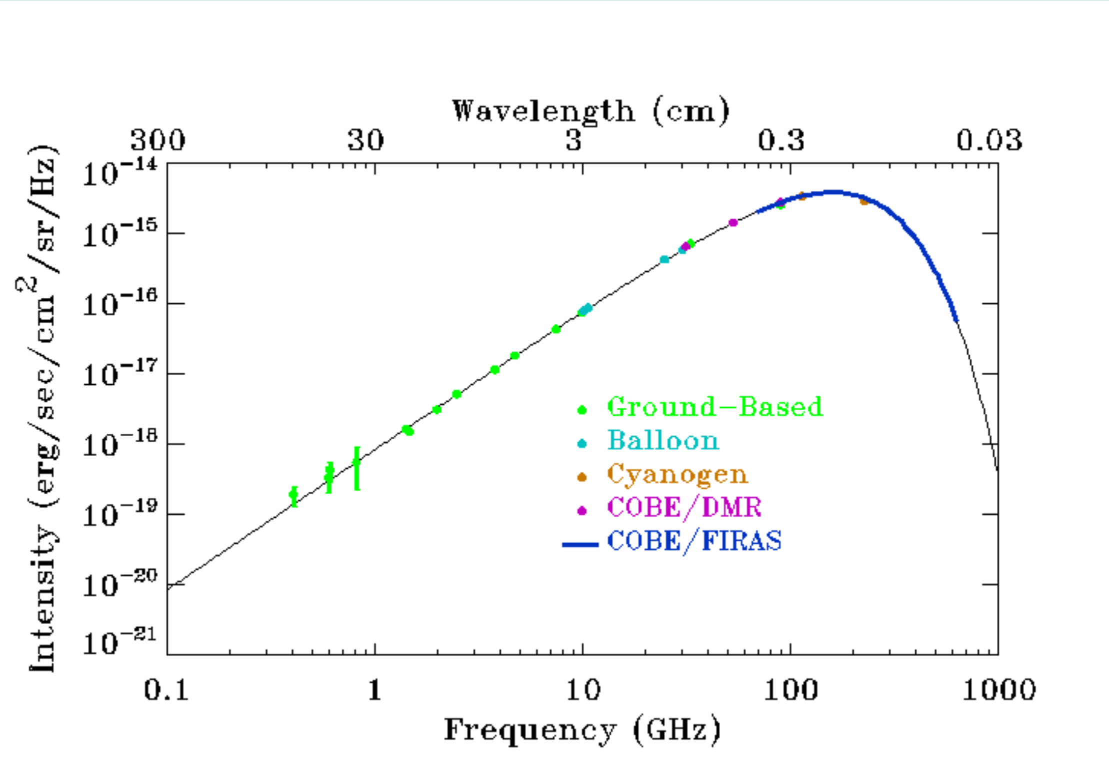
The Nobel Prize in Physics 2019 rewards new understanding of the universe's structure and history, and the first discovery of a planet orbiting a solar-type star outside our solar system. This year's Laureates have contributed to answering fundamental questions about our existence. What happened in the early infancy of the universe and what happened next? Could there be other planets out there, orbiting other suns?

James Peebles took on the cosmos, with its billions of galaxies and galaxy clusters. His theoretical framework, which he developed over two decades, starting in the mid-1960s, is the foundation of our modern understanding of the universe's history, from the Big Bang to the present day. Peebles' discoveries have led to insights about our cosmic surroundings, in which known matter comprises just five per cent of all the matter and energy contained in the universe. The remaining 95 per cent is hidden from us. This is a mystery and a challenge to modern physics.

對於人在宇宙中的地位之嶄新觀點

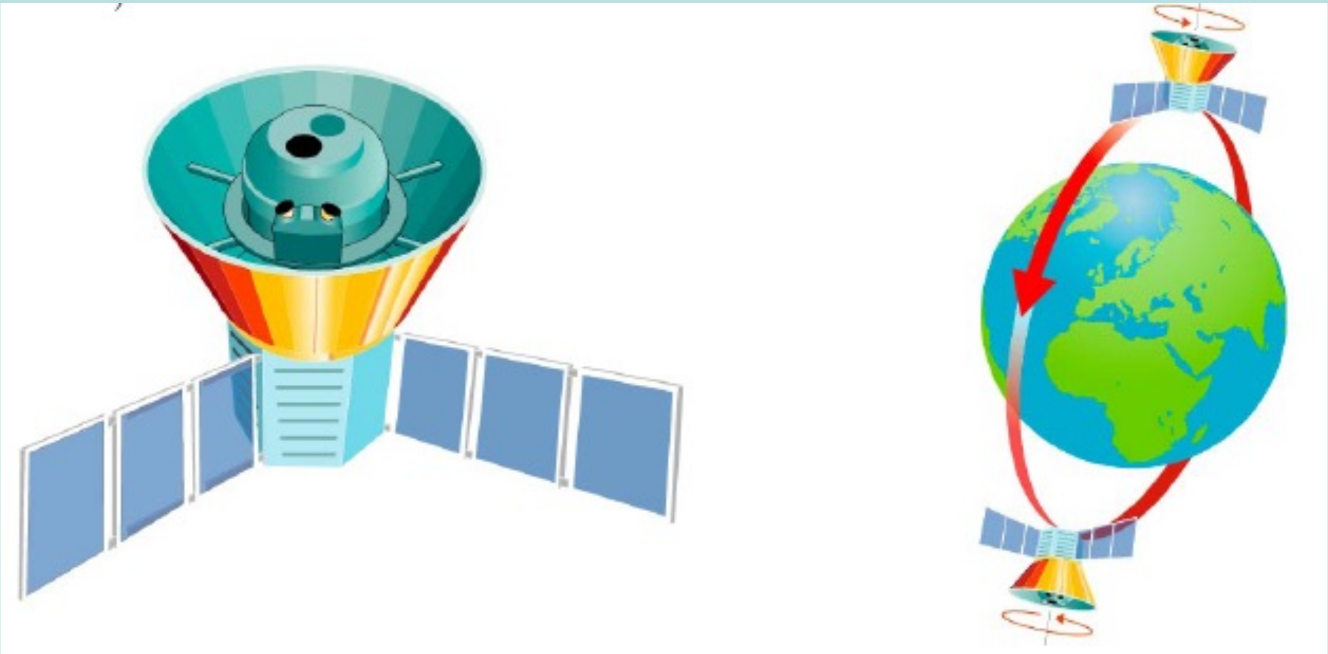
Penzias and Wilson 的測量因大氣吸收微波，十分不精確

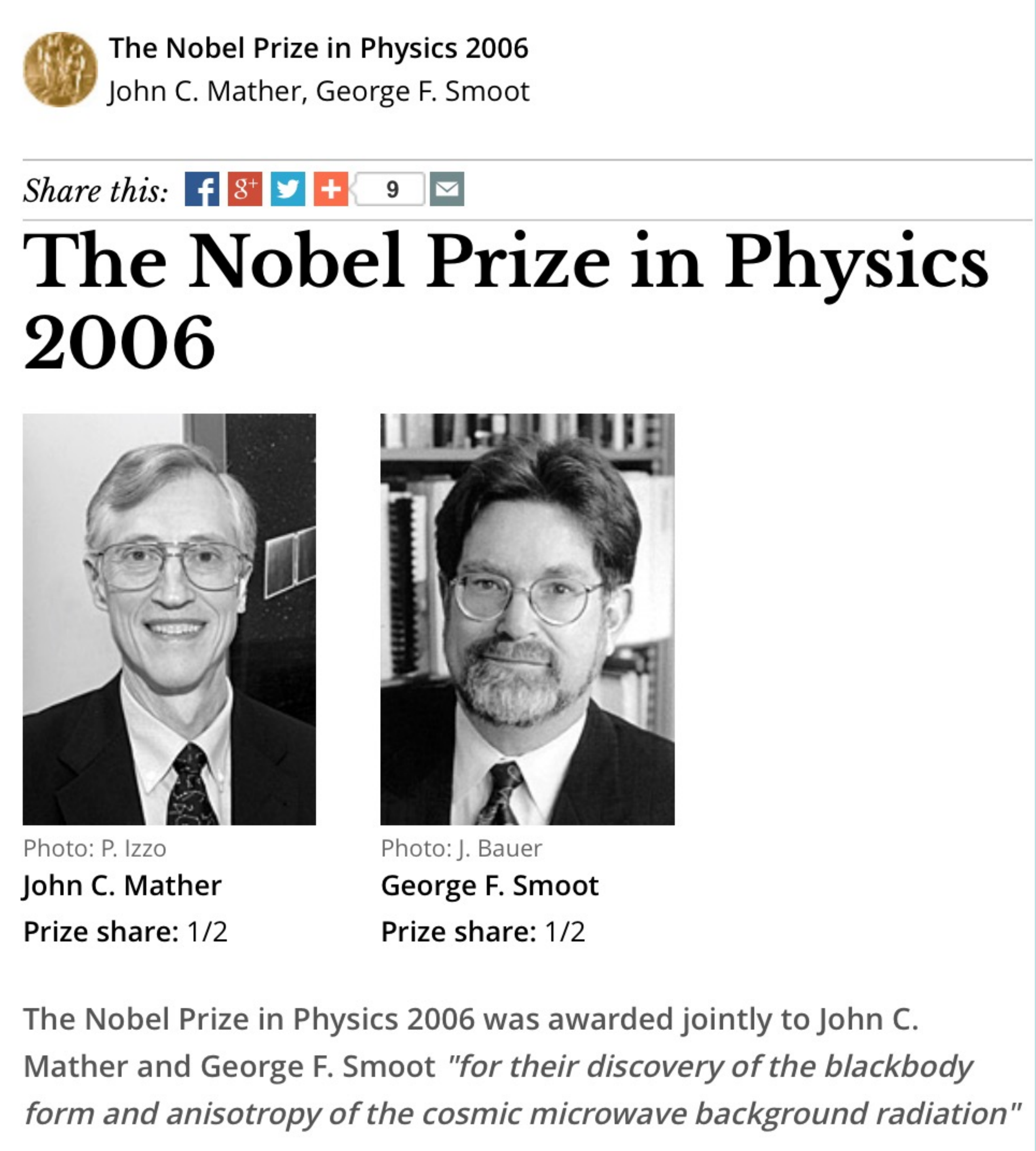




Cobe (COsmic Background Explorer)

CMB大部分是微波，空氣可吸收，所以精密的測量必須在大氣層外進行





The Nobel Prize in Physics 2006
John C. Mather, George F. Smoot

The Nobel Prize in Physics 2006

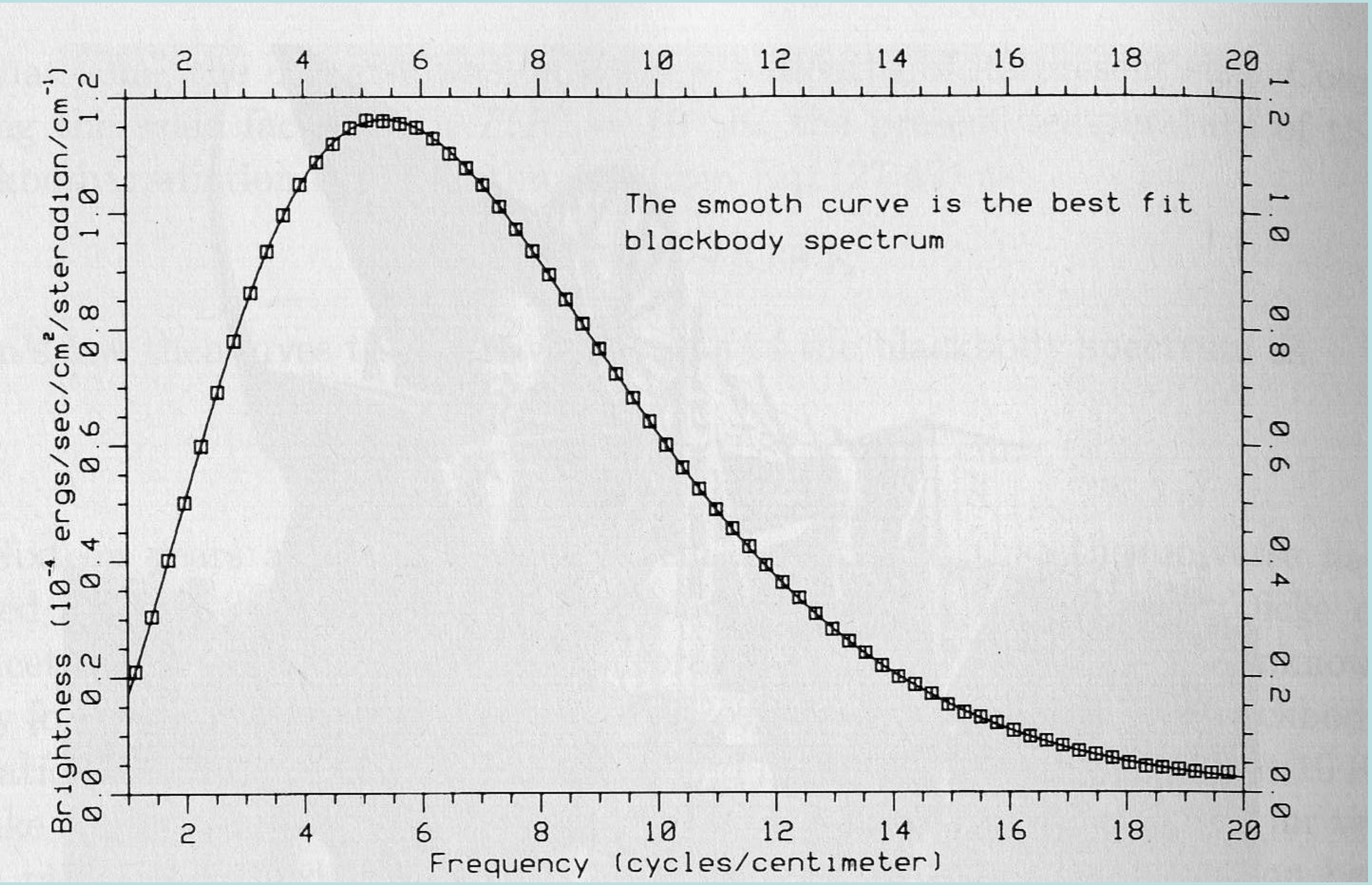
Photo: P. Izzo
John C. Mather
Prize share: 1/2

Photo: J. Bauer
George F. Smoot
Prize share: 1/2

The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*

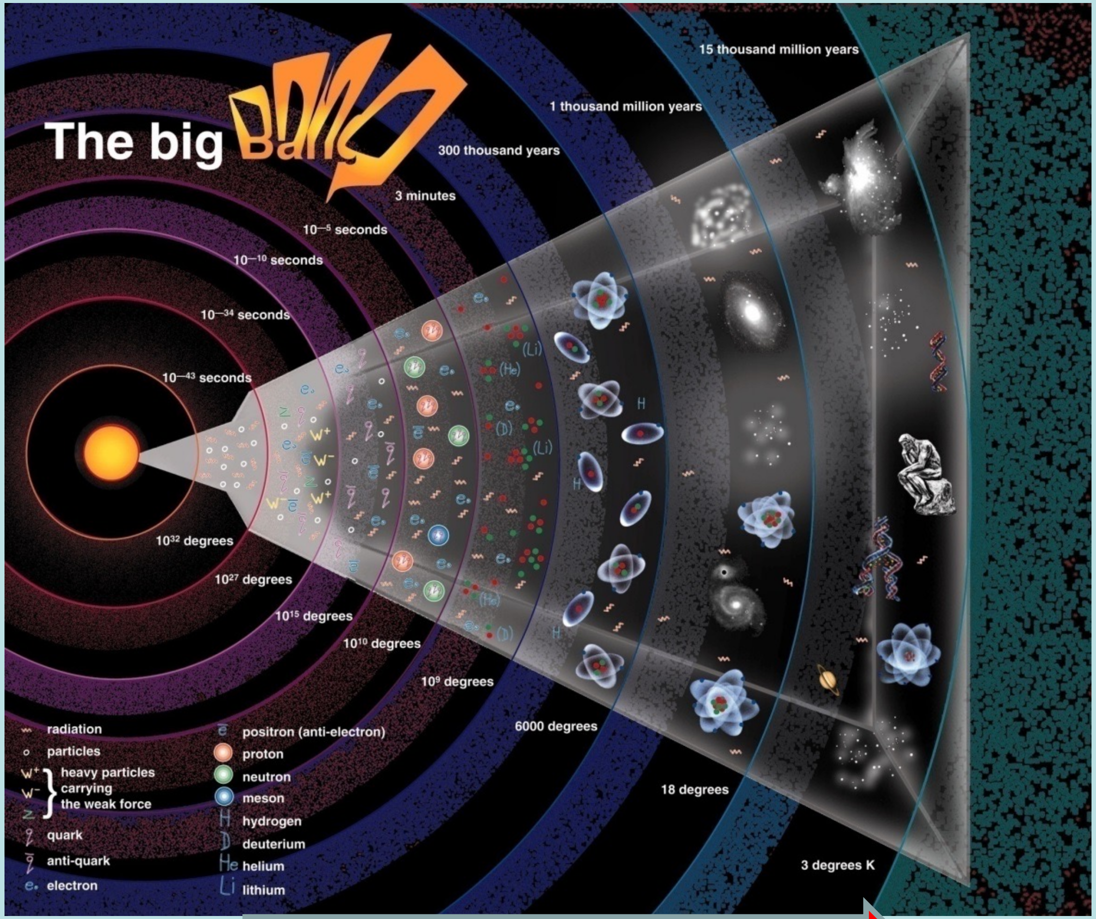
Mather and George F. Smoot *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*

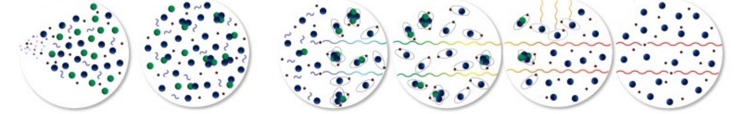
2.72548±0.00057 K

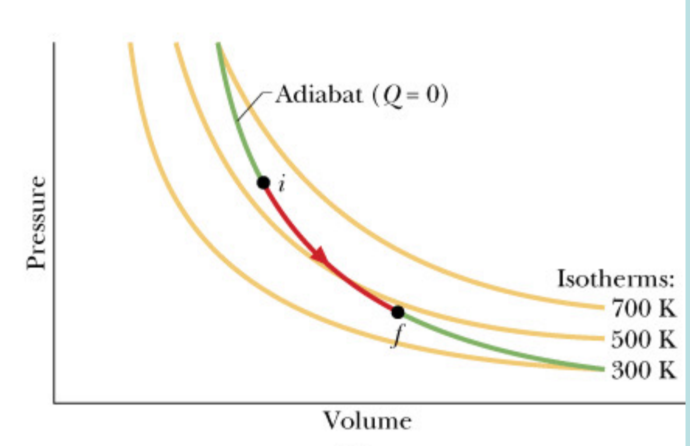


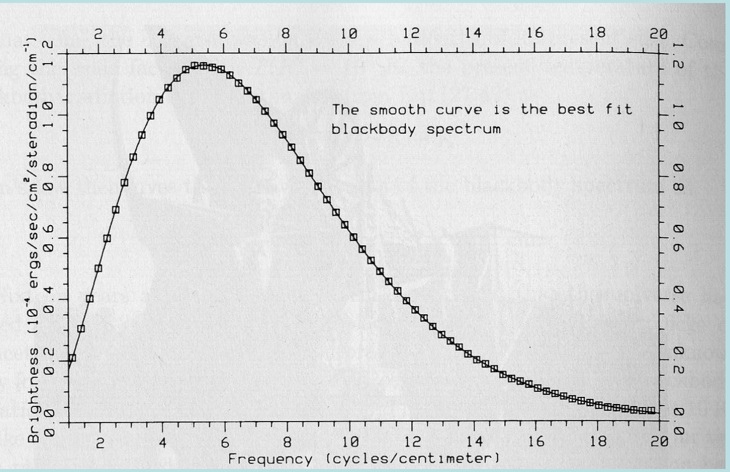
宇宙背景輻射是均勻同向的完美的黑體，成為大霹靂理論最重要的直接證據！

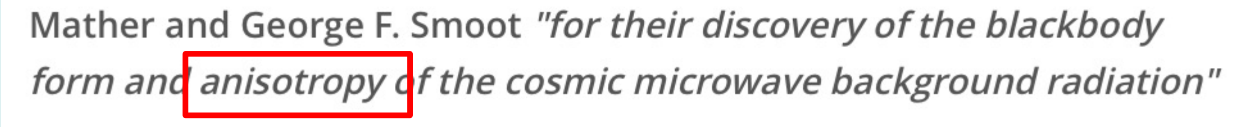
也證實了從大霹靂到今天，近似是一個獨立的等熵冷卻的過程，不需要外力干預。











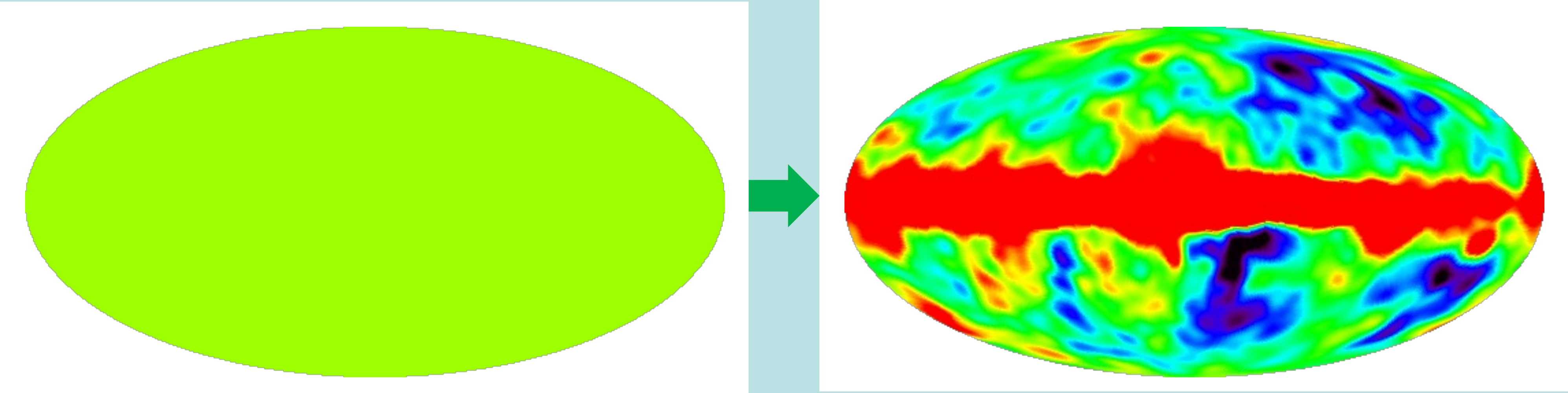
Mather and George F. Smoot *"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"*

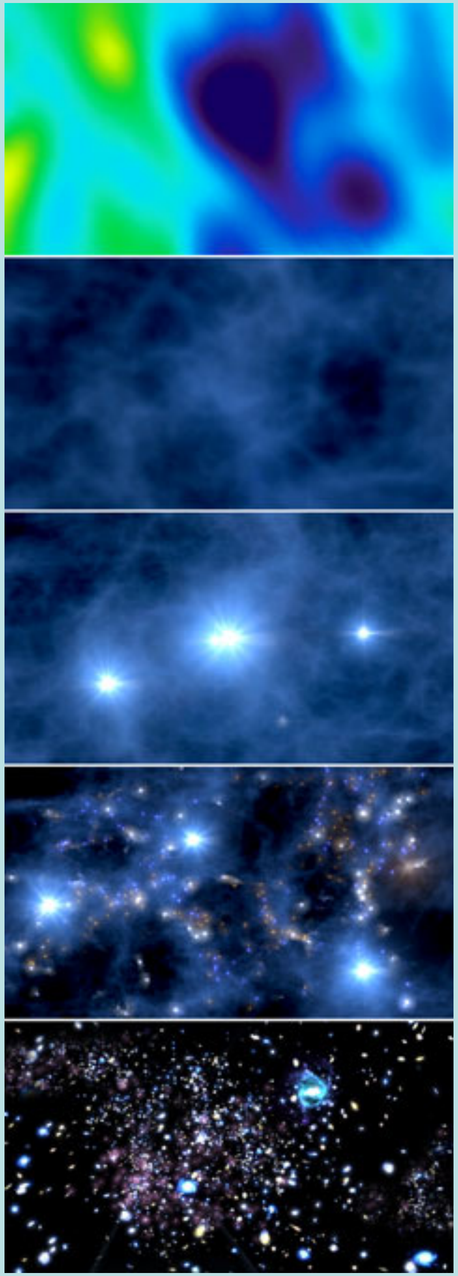
Cobe 還有一個更重要的發現！

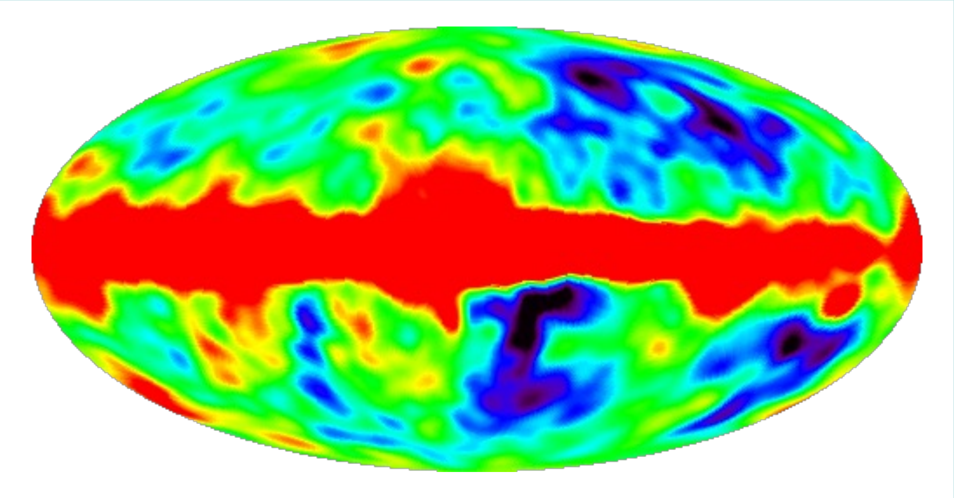
Cobe 同時觀察到大致同向的背景輻射有極微小的非同向性 anisotropy。

顏色代表冷熱，溫度差距大約是10^{-4}~10^{-5}K。

這個現象科學家也猜到了！



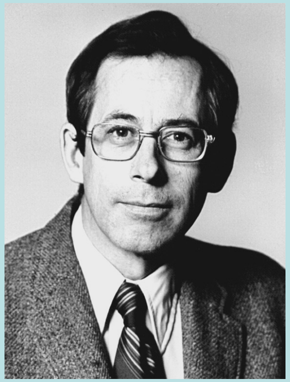




現在宇宙物質分布並不均勻，星團與星團之間是空的。

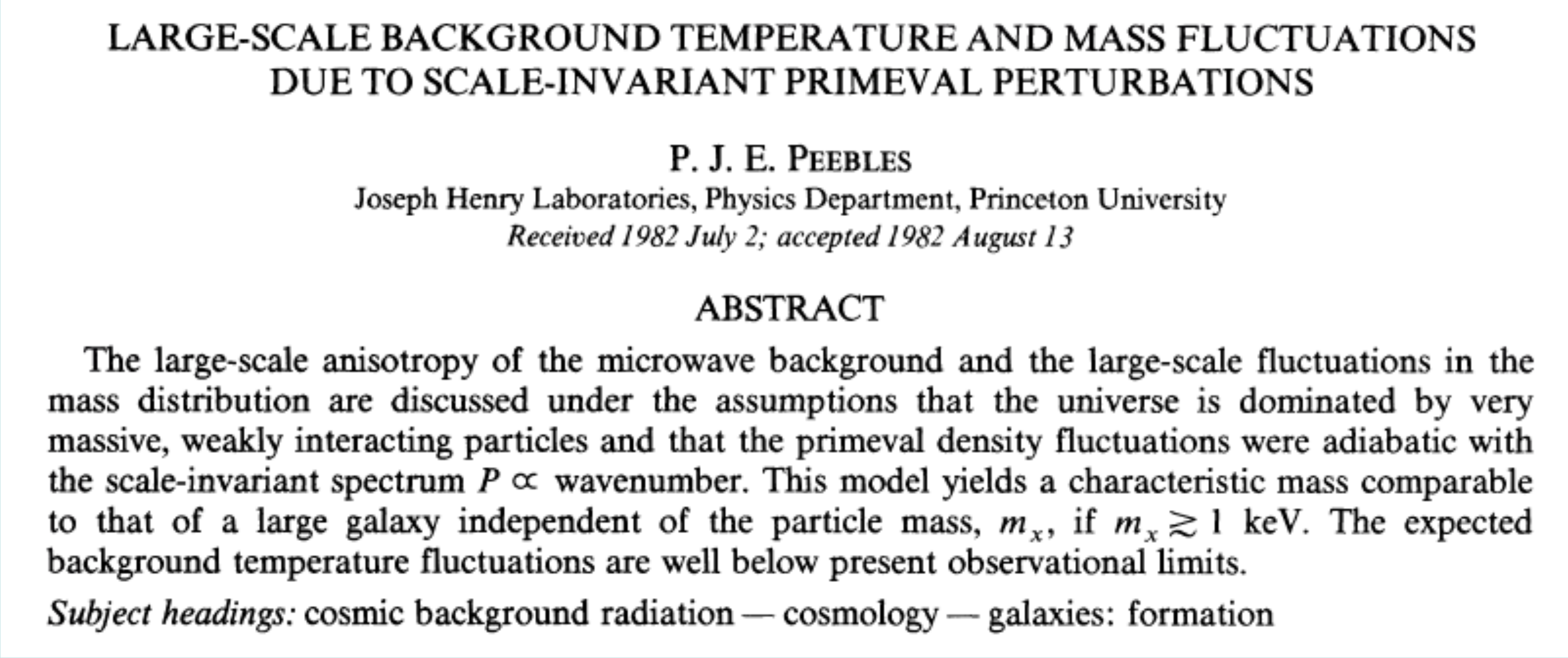
這應該起源於早期宇宙物質分布極微小的不均勻。

那背景輻射的溫度也應該會被影響而有微小的不均勻！



Peebles 1970

Zel'dovich 1970



LARGE-SCALE BACKGROUND TEMPERATURE AND MASS FLUCTUATIONS DUE TO SCALE-INVARIANT PRIMEVAL PERTURBATIONS

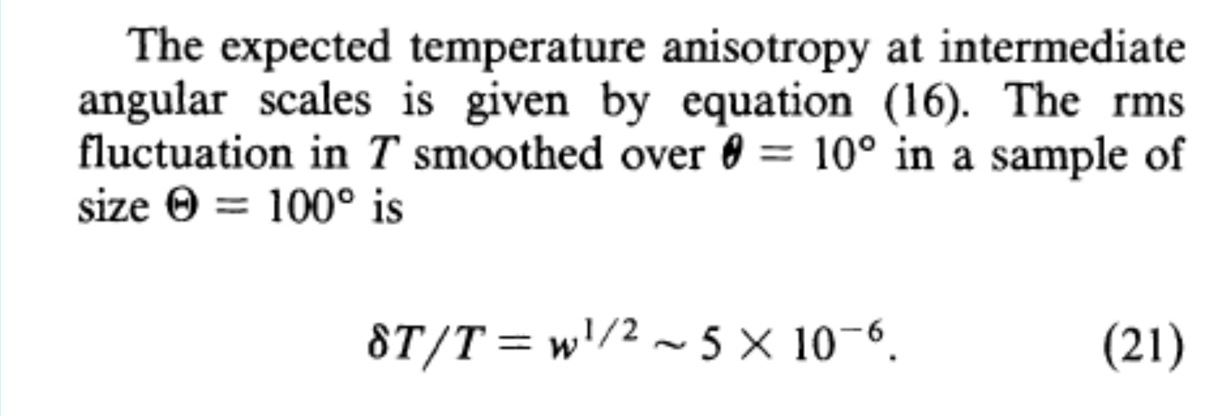
P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University

Received 1982 July 2; accepted 1982 August 13

ABSTRACT

The large-scale anisotropy of the microwave background and the large-scale fluctuations in the mass distribution are discussed under the assumptions that the universe is dominated by very massive, weakly interacting particles and that the primeval density fluctuations were adiabatic with the scale-invariant spectrum $P \propto$ wavenumber. This model yields a characteristic mass comparable to that of a large galaxy independent of the particle mass, m_x, if $m_x \gtrsim 1$ keV. The expected background temperature fluctuations are well below present observational limits.

Subject headings: cosmic background radiation — cosmology — galaxies: formation



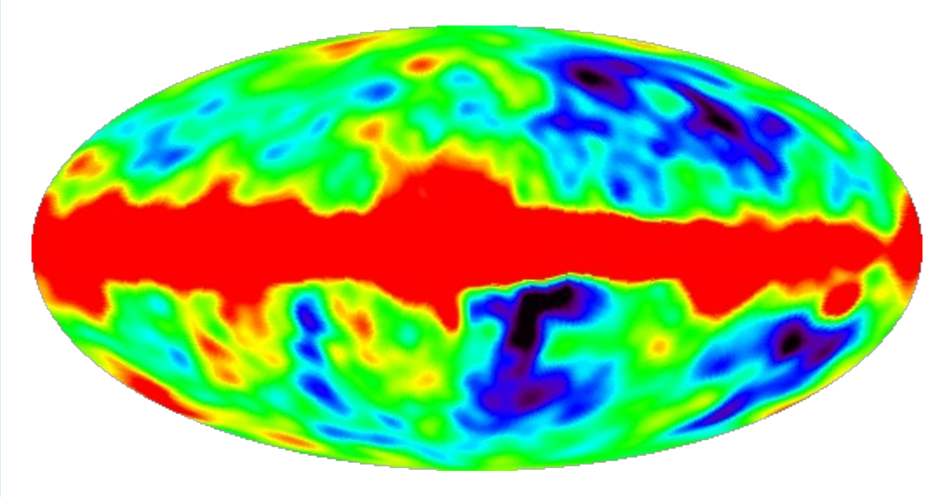
The expected temperature anisotropy at intermediate angular scales is given by equation (16). The rms fluctuation in T smoothed over $\theta = 10°$ in a sample of size $\Theta = 100°$ is

$$\delta T/T = w^{1/2} \sim 5 \times 10^{-6}. \qquad (21)$$

由現在物質分布推算，背景輻射溫度不均勻度大約是10^{-5}K。
正好與觀測結果相近。

宇宙的熱歷史

Thermal History of Universe



具體來說，背景輻射微小的不均勻是怎麼產生的呢？

為了回答這個問題，我們必須了解宇宙擴張的熱歷史！

宇宙是有溫度的！

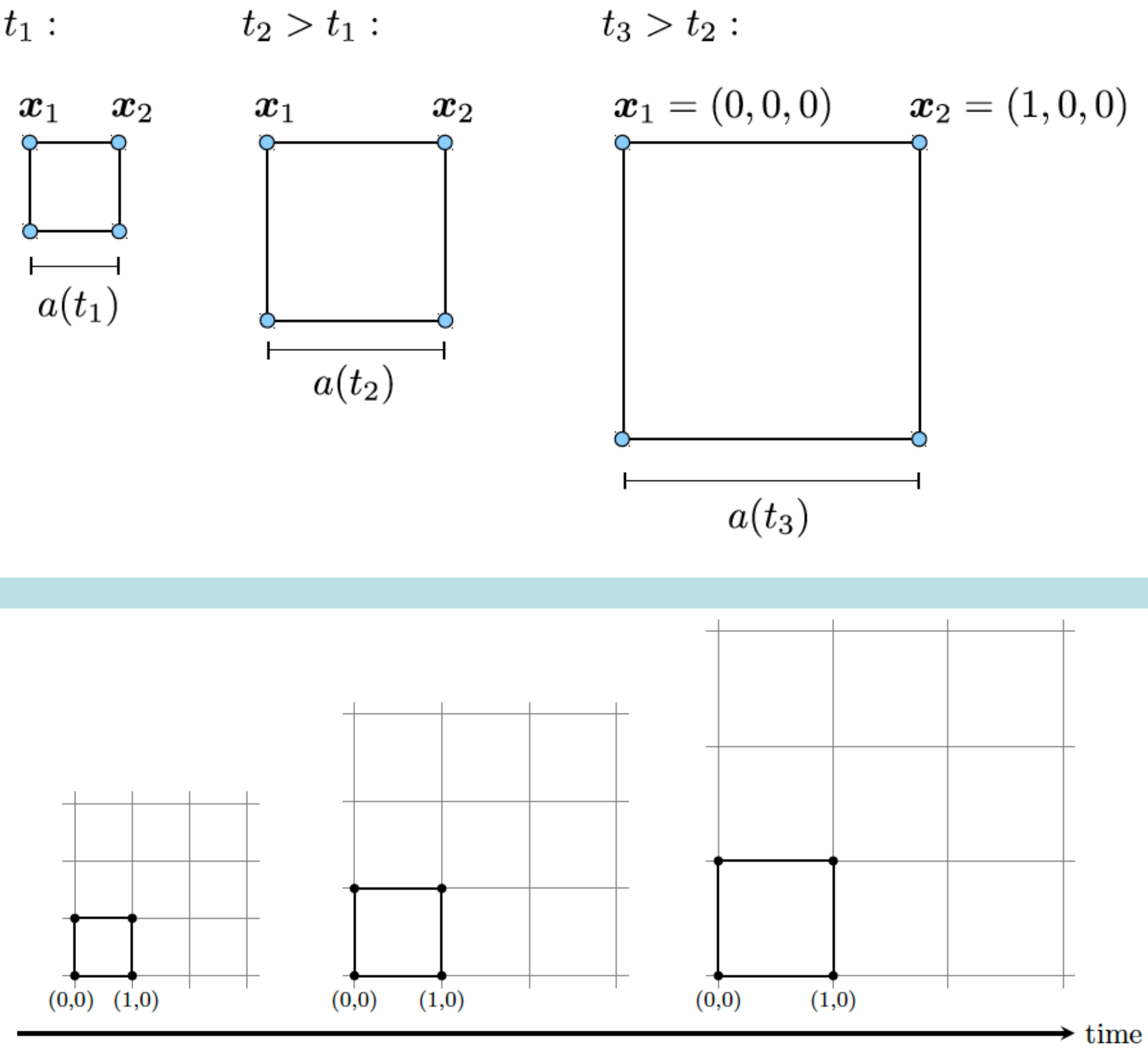


Fig. 2.2 Expansion of the universe. The comoving distance between points on an imaginary coordinate grid remains constant as the universe expands. The physical distance, on the other hand, grows in proportion to the scale factor $a(t)$.

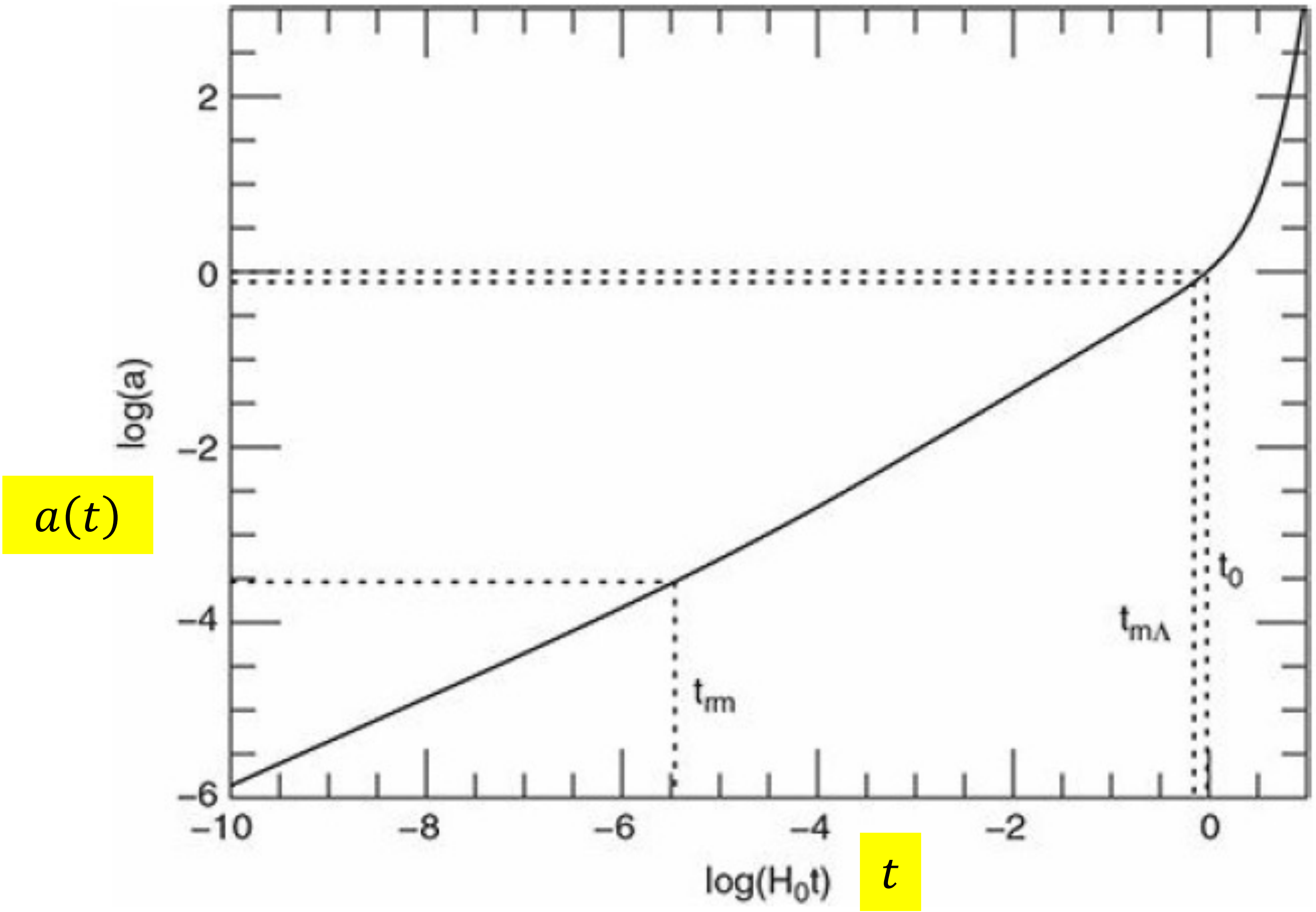


Figure 5.8 The scale factor a as a function of time t (measured in units of the Hubble time), computed for the Benchmark Model. The dotted lines indicate the time of radiation–matter equality, $a_{rm} = 2.9 \times 10^{-4}$, the time of matter–lambda equality, $a_{m\Lambda} = 0.77$, and the present moment, $a_0 = 1$.

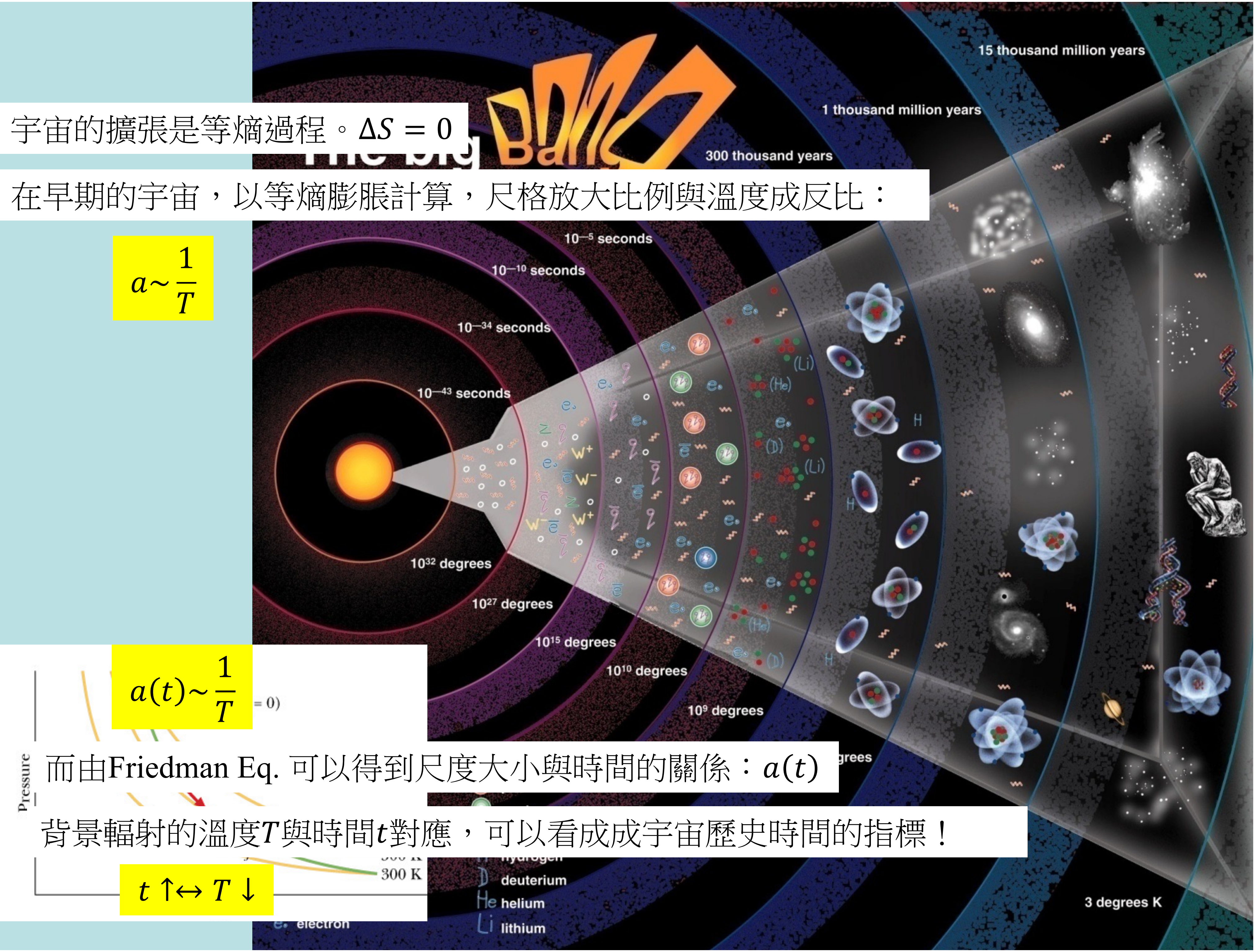
由Friedman Eq. 可以得到尺度放大比例與時間的關係：$a(t)$

從現在起，時間t是從大霹靂起算的宇宙時間，

宇宙的擴張是等熵過程。$\Delta S = 0$

在早期的宇宙，以等熵膨脹計算，尺格放大比例與溫度成反比：

$$a \sim \frac{1}{T}$$



$$a(t) \sim \frac{1}{T}$$

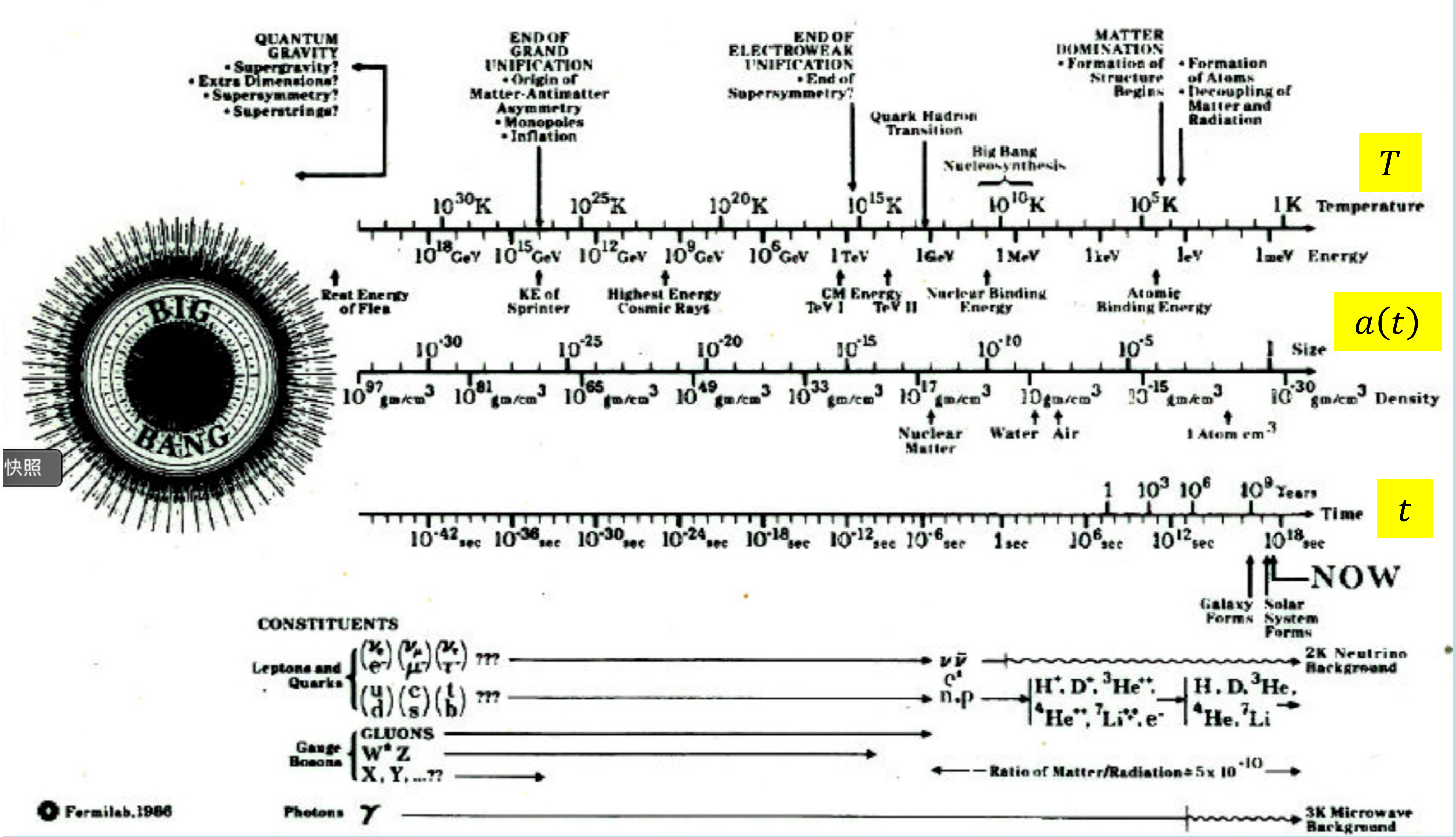
而由Friedman Eq. 可以得到尺度大小與時間的關係：$a(t)$

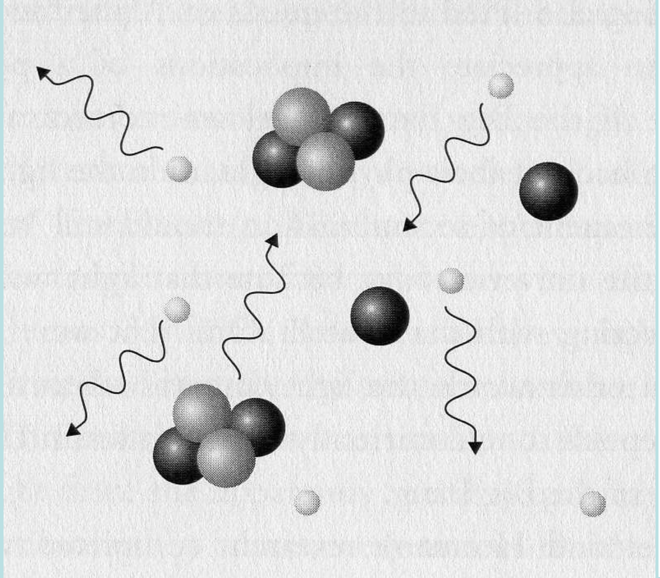
背景輻射的溫度T與時間t對應，可以看成成宇宙歷史時間的指標！

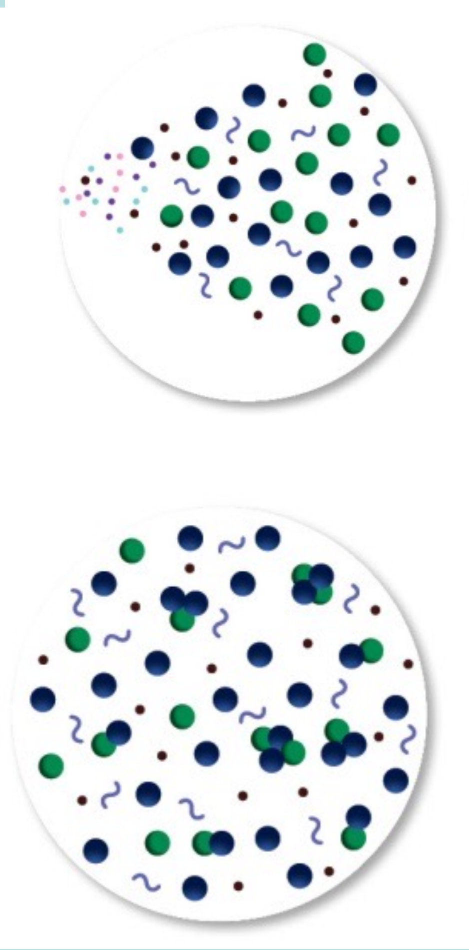
$$t \uparrow \leftrightarrow T \downarrow$$

$t\uparrow \leftrightarrow T\downarrow \leftrightarrow a\uparrow$

Thermal History of Universe 而溫度決定了宇宙中物質的狀態！





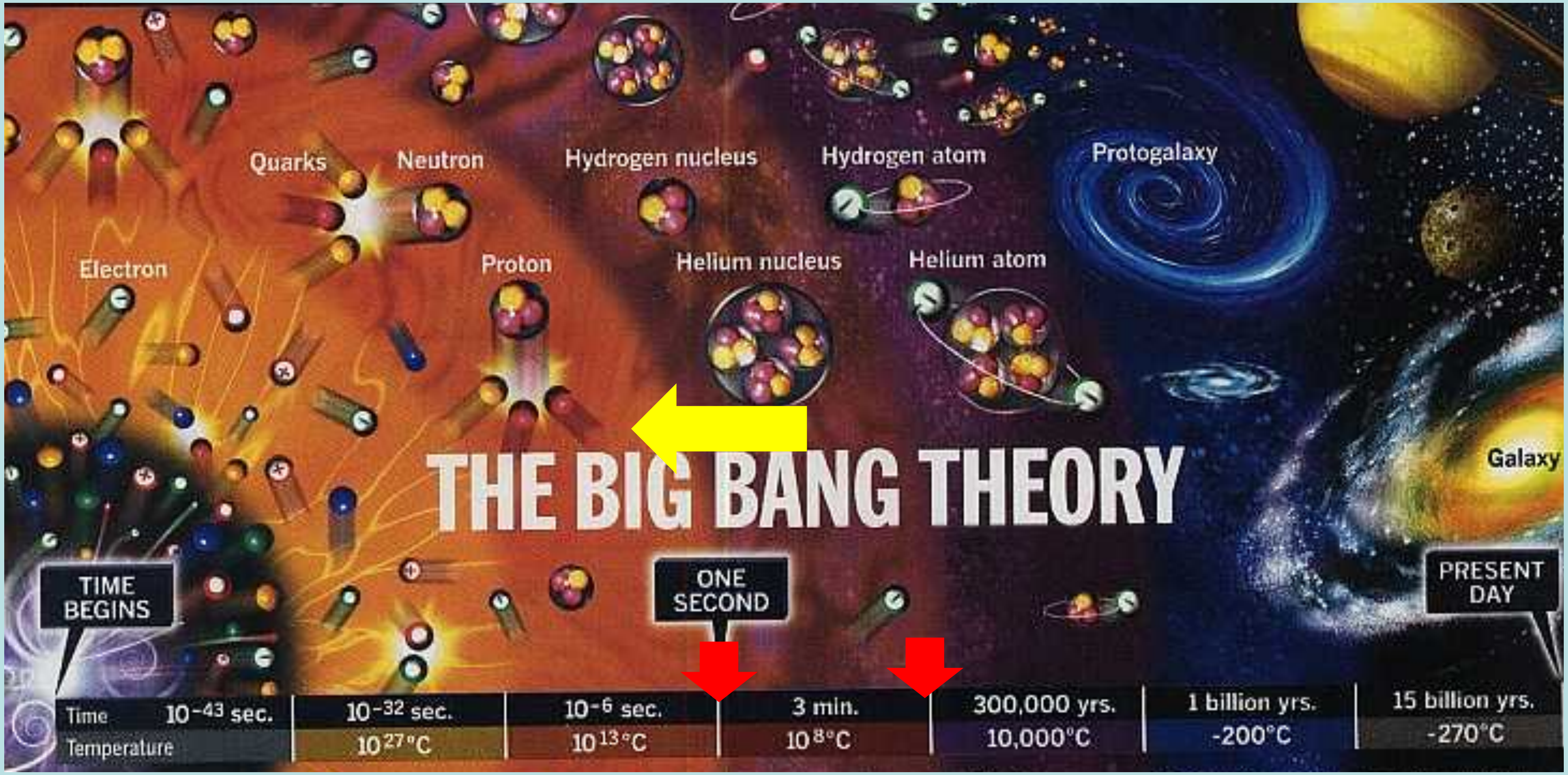


接近大霹靂時的黑體輻射與帶電的物質湯不斷碰撞作用，兩者一直維持熱平衡，

物質湯中的粒子一直放出熱輻射，也一直吸收熱輻射。此平衡時輻射就是黑體輻射。

早期宇宙的能量以黑體輻射為主，物質猶如泡在一大巨鍋熱湯Heat Bath 內。

物質的溫度就是黑體輻射的溫度，也就是宇宙的溫度！



有了如此紀年方法，如果我們往回追朔，溫度T越來越高。 $t\downarrow \quad T\uparrow$

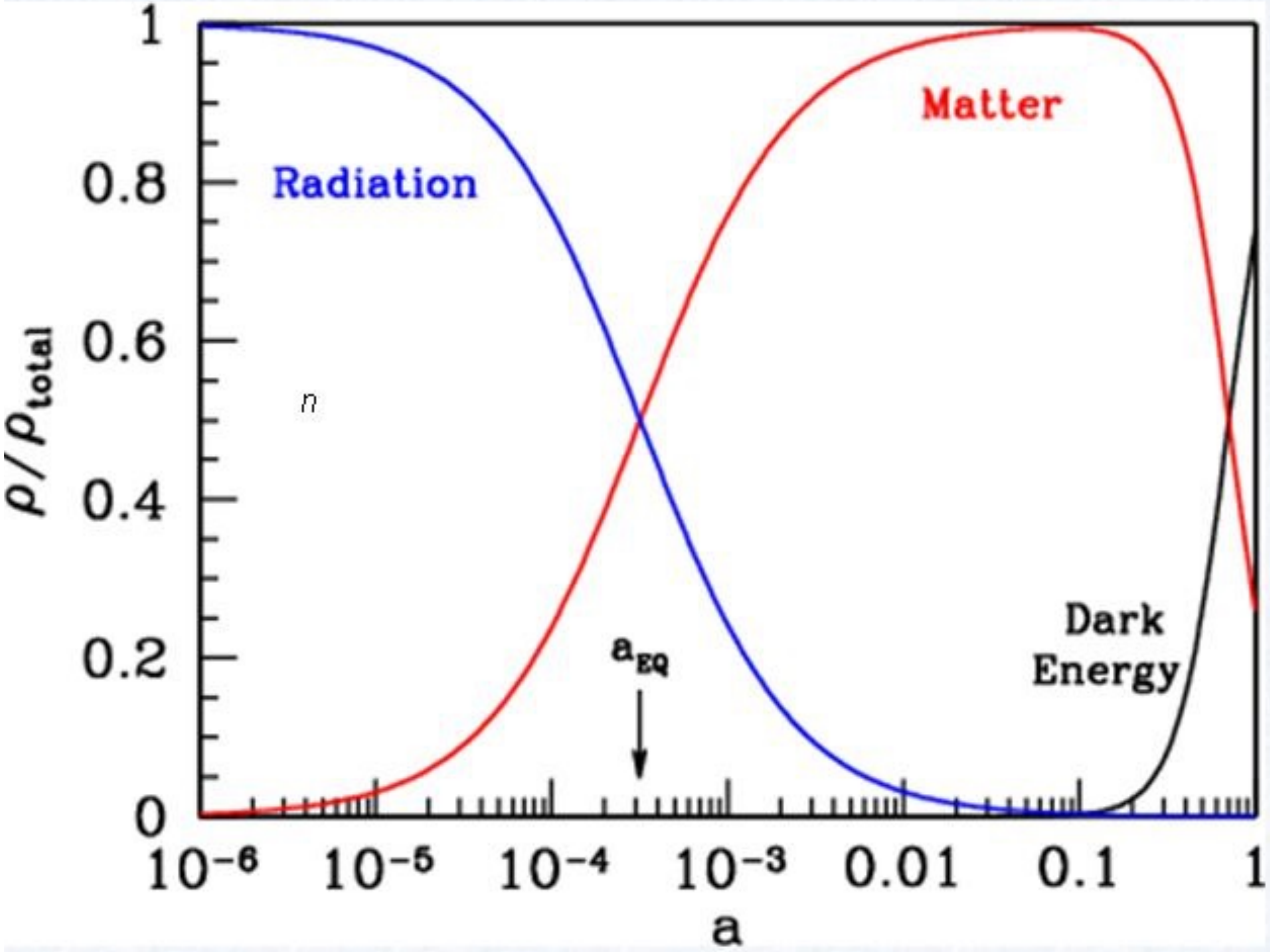
當溫度T足夠高時，熱運動的碰撞會將物質的組成成分撞擊分開。

例如溫度高於10^4K~1eV，電子會從原子中被撞擊與原子核分離。

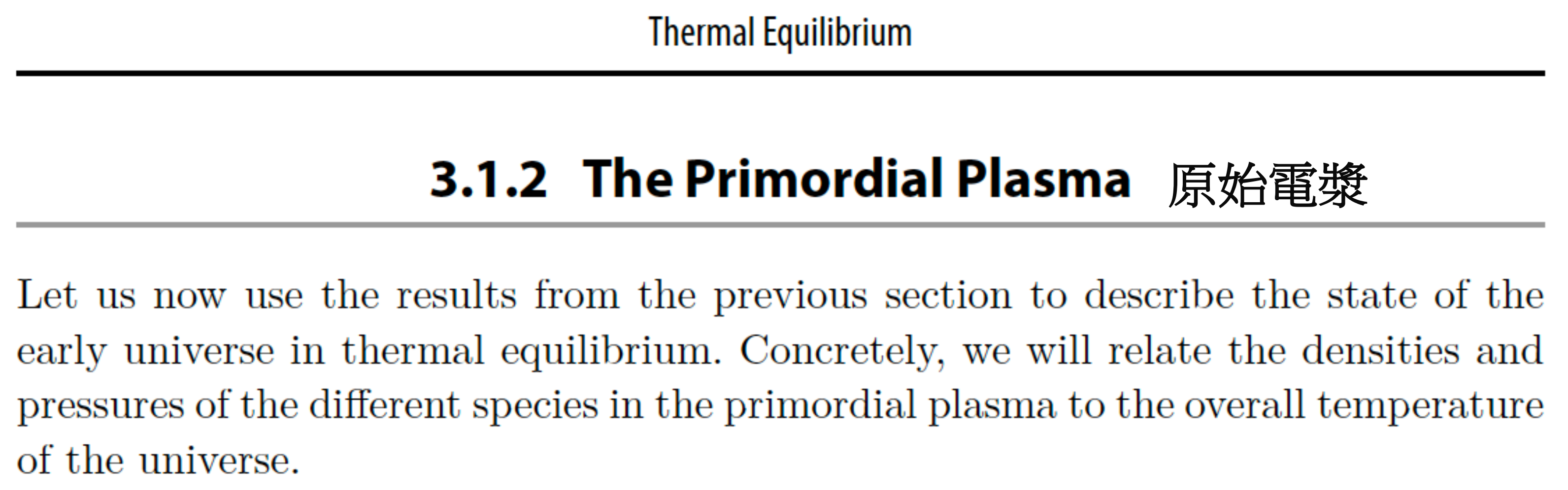
溫度高於10^{10}K~1MeV，原子核中的質子和中子都無法束縛在一起。

因此每一段時間，宇宙物質的組成會不同，這就構成了宇宙的歷史！

Thermal History of the Universe



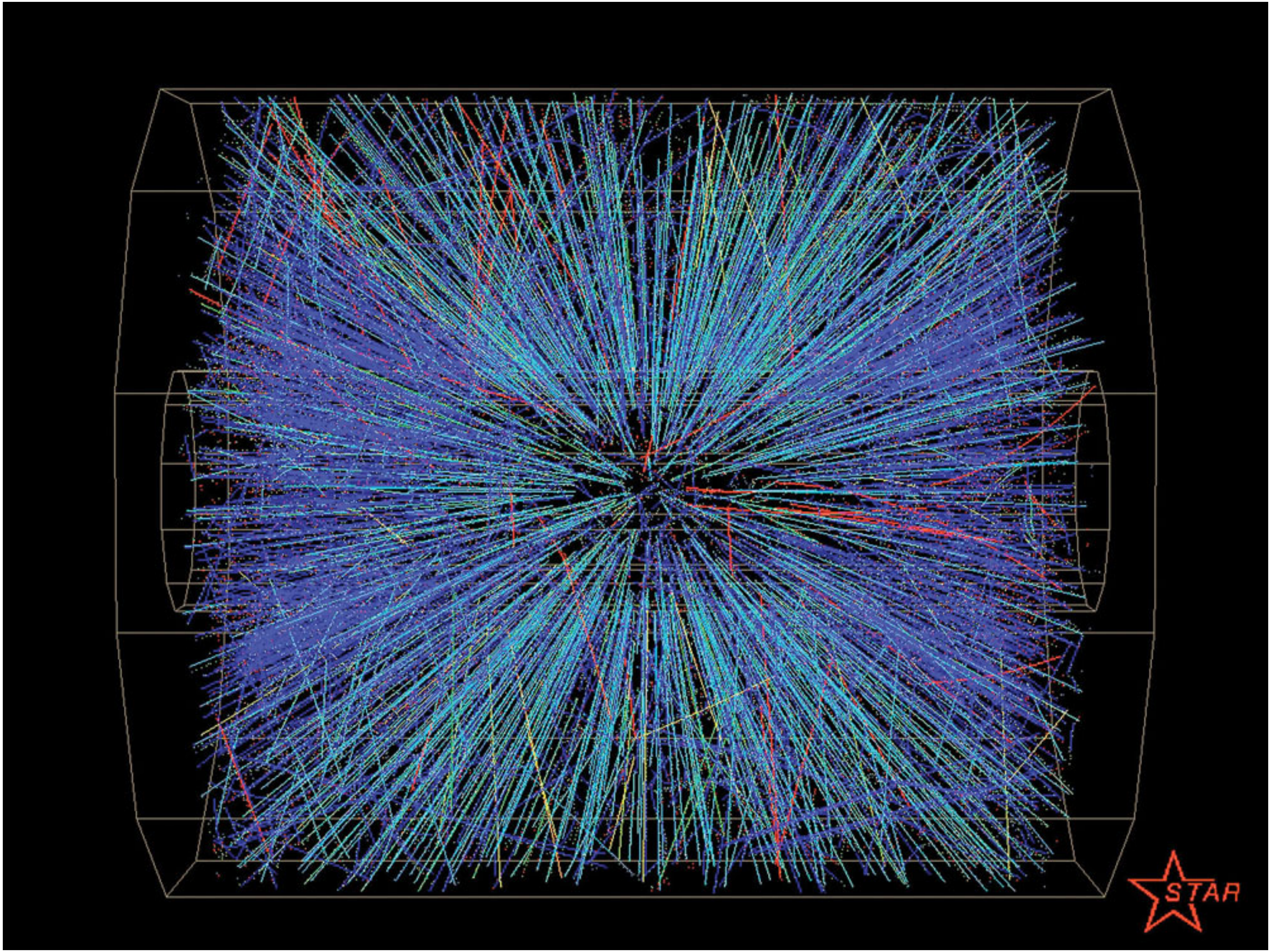
輻射能量與物質能量隨時間演化不一樣，後者會越來越重要！

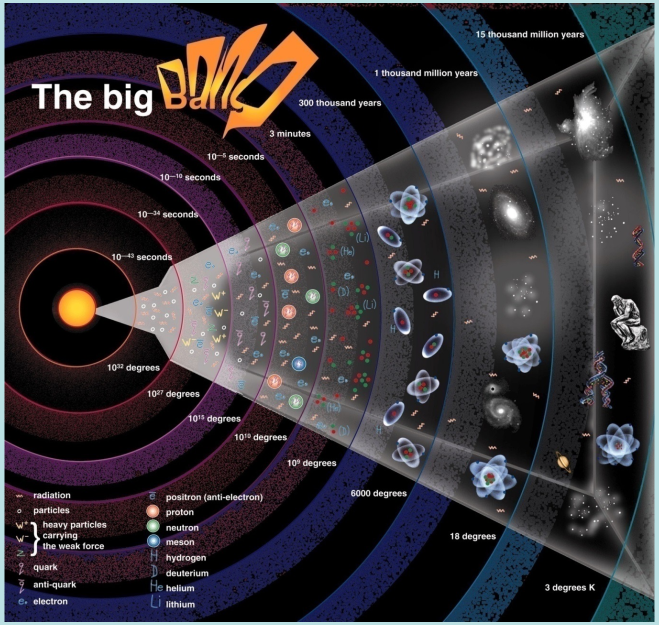


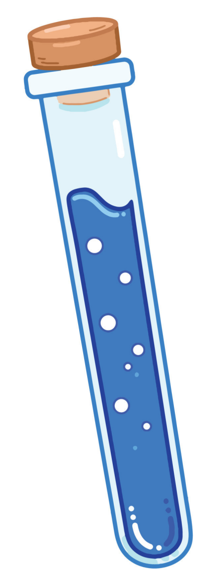
Thermal Equilibrium

3.1.2 The Primordial Plasma 原始電漿

Let us now use the results from the previous section to describe the state of the early universe in thermal equilibrium. Concretely, we will relate the densities and pressures of the different species in the primordial plasma to the overall temperature of the universe.


STAR





早期宇宙如在試管中擁擠激烈的反應物！

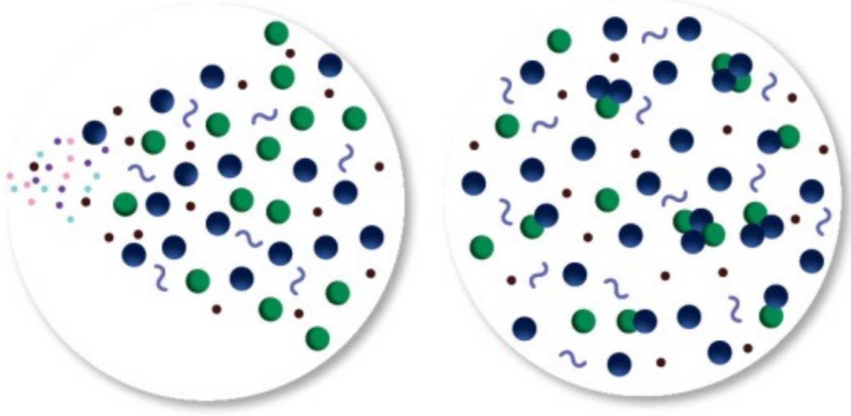
幸運的是對這一管反應物，我們非常了解它的成分與反應的細節。

如同在特定溫度下，我們了解理想氣體的速度分布。

早期宇宙如同一個化學反應實驗！

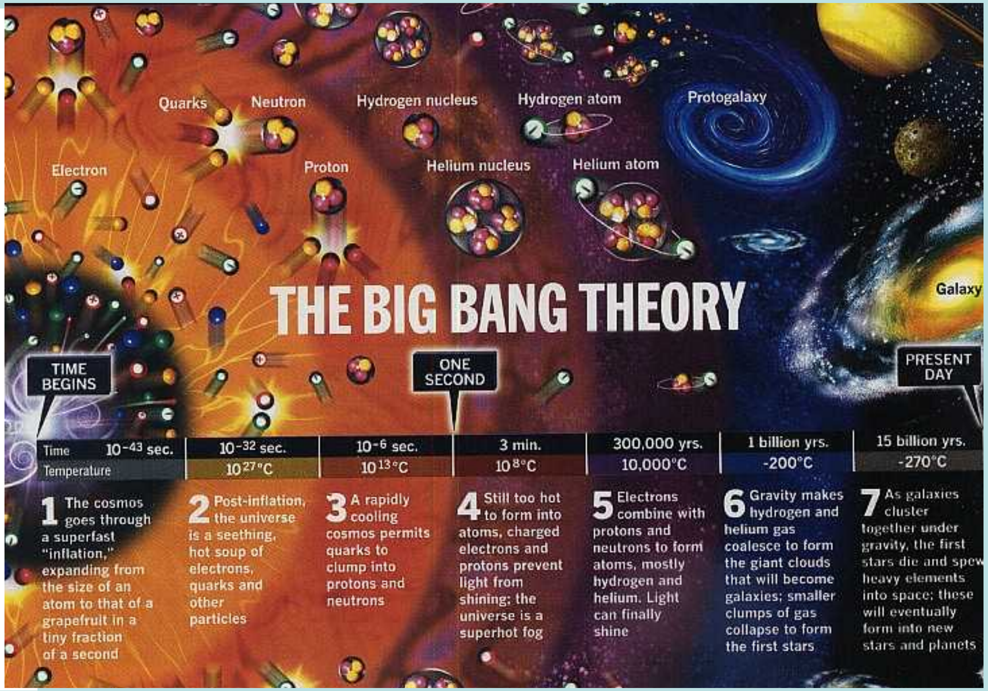
早期宇宙是一團極濃的量子理想氣體！

雖然極濃，但因為溫度極高，粒子交互作用影響不大。



Frequent collisions between normal matter and light

As the Universe expands, particles collide less frequently



Time 10-43 sec.	10-32 sec.	10-6 sec.	3 min.	300,000 yrs.	1 billion yrs.	15 billion yrs.
Temperature	10^{27}°C	10^{13}°C	10^{8}°C	10,000°C	-200°C	-270°C

1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second

2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles

3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons

4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog

5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine

6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars

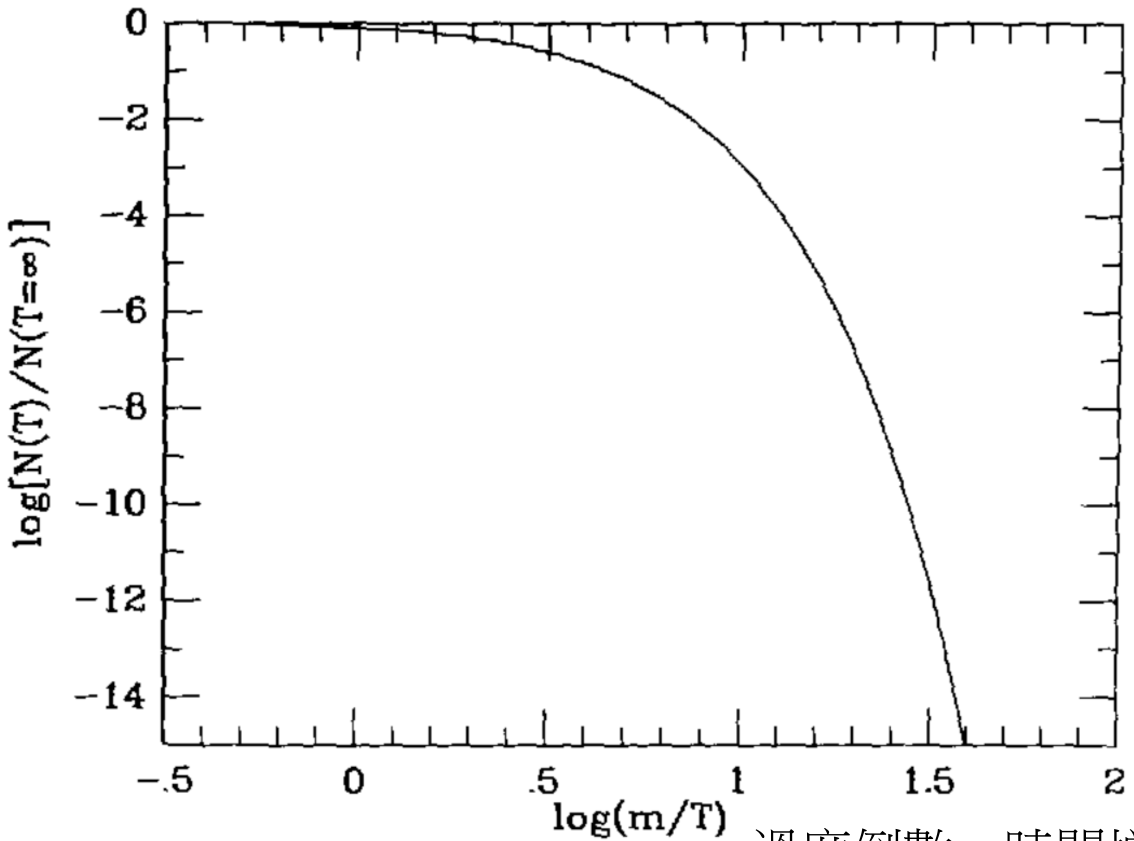
7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

宇宙是處於熱平衡狀態！黑體輻射能量完全由溫度控制！

根據統計力學，各式粒子的數目也完全由溫度控制，可以計算出來。

早期宇宙是單面向的，非常簡單而容易預測！我們對它的成分一清二楚！

Bose-Einstein and Fermi-Dirac Distribution

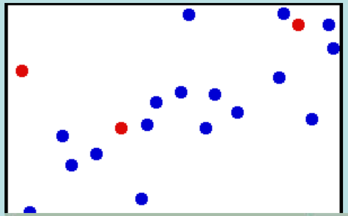


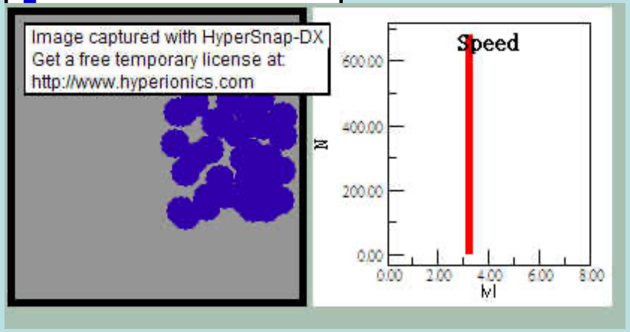
溫度倒數，時間增加

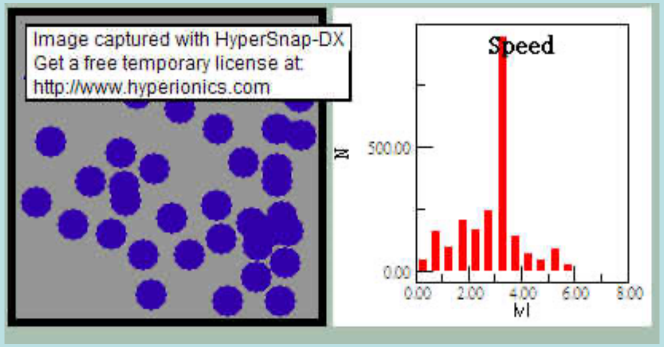
Fig. 3.6: The equilibrium abundance of a species in a comoving volume element, $N = n/s$. Since both n_γ and s vary as T^3, N is also proportional to n/n_γ.

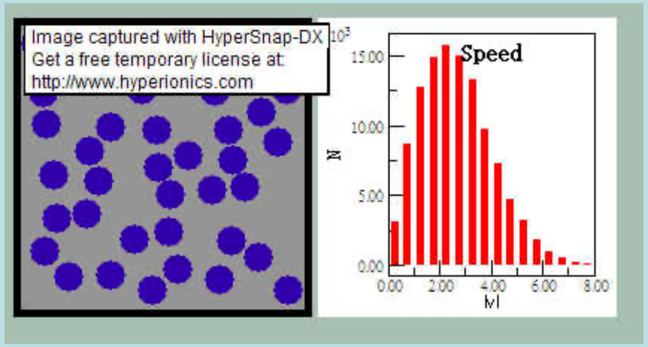
粒子平衡時的數目，完全由溫度決定（此圖適用於黑體輻射以外的粒子）。

$$n_i(T) \sim g_i \left(\frac{m_i kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_i c^2 + \mu_i}{kT}\right)$$









粒子的碰撞推動了平衡態的達成！

碰撞將狀態搞亂，到達平衡態後，巨觀不再改變，雖然微觀下，繼續碰撞。

不斷地被弄亂之下如何能夠維持不變、不亂？

已經足夠亂的狀態就不怕越來越亂了！

平衡態就是足夠亂而碰撞無法使之更亂的狀態。

亂是有強制性的，亂強迫粒子的數目必須服從！

亂是控制力極強的！

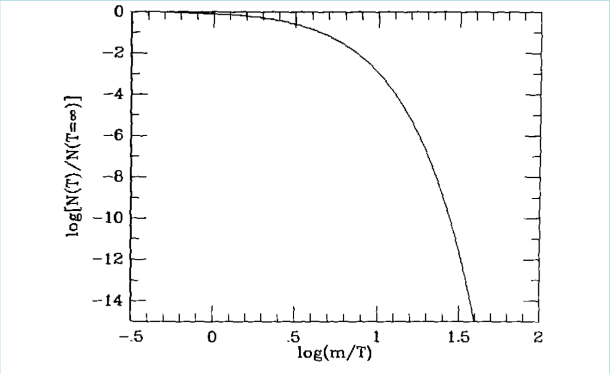
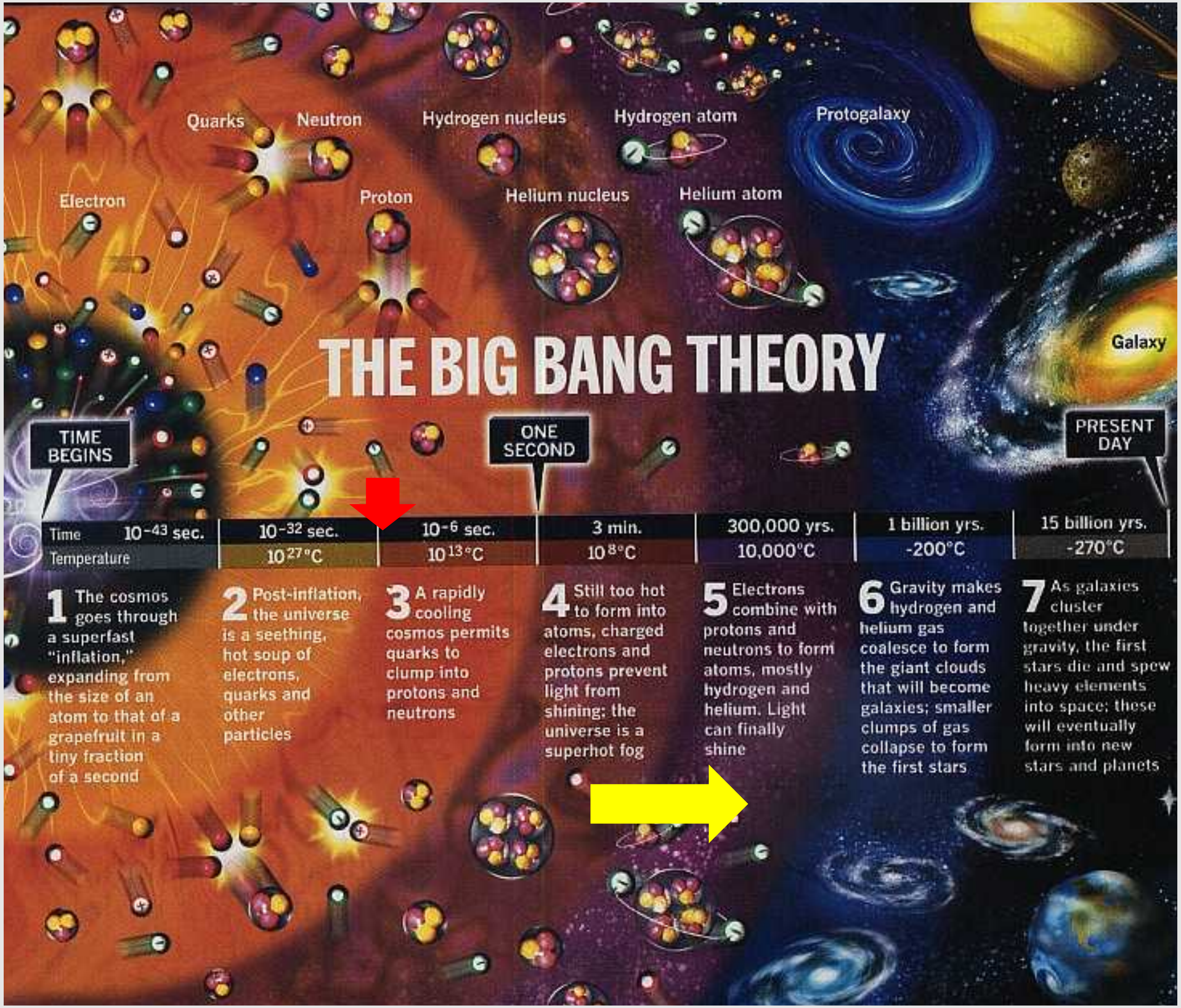


Fig. 3.6: The equilibrium abundance of a species in a comoving volume element, $N = n/s$. Since both n_γ and s vary as T^3, N is also proportional to n/n_γ.



1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second

2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles

3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons

4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog

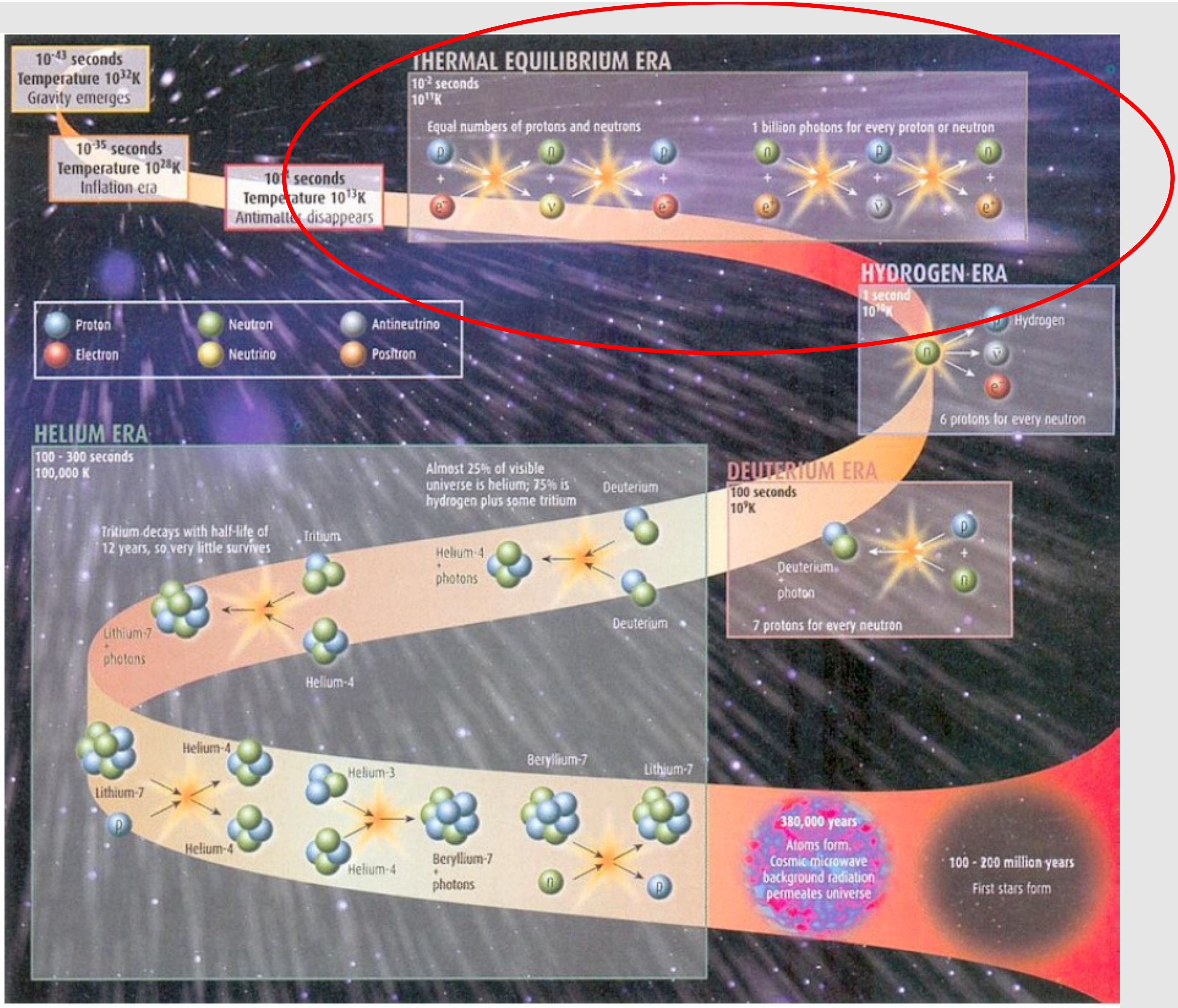
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine

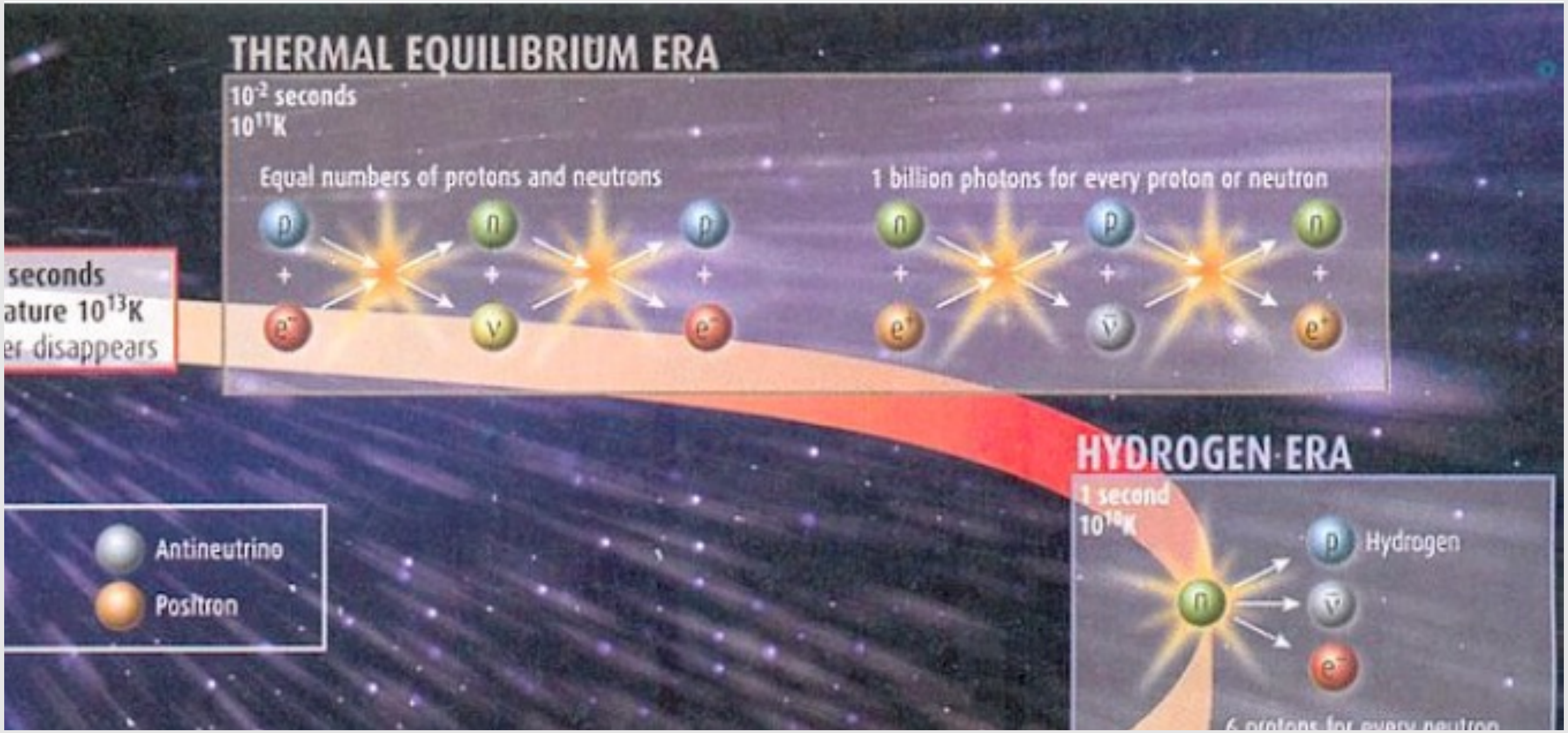
6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars

7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

現在順著歷史，時間增加，溫度下降，物質湯開始凝結。 $t\uparrow$ $T\downarrow$

到了10^{-6}s,10^{13} K時，夸克開始組合成質子中子。熱能已不夠將其拆散。

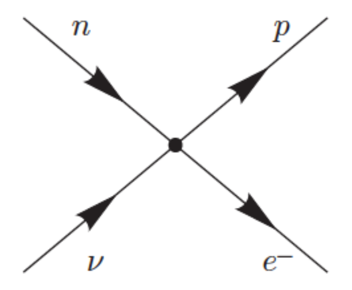

10^{-43} seconds
Temperature 10^{32}K
Gravity emerges
10^{-35} seconds
Temperature 10^{28}K
Inflation era
10[illegible] seconds
Temperature 10^{13}K
Antimatter disappears
THERMAL EQUILIBRIUM ERA
10^{-2} seconds
10^{11}K
Equal numbers of protons and neutrons
1 billion photons for every proton or neutron
p
n
e^-
ν
e^+
$\bar{\nu}$
HYDROGEN ERA
1 second
10^{10}K
Hydrogen
6 protons for every neutron
Proton
Electron
Neutron
Neutrino
Antineutrino
Positron
HELIUM ERA
100 - 300 seconds
100,000 K
Almost 25% of visible universe is helium; 75% is hydrogen plus some tritium
Tritium decays with half-life of 12 years, so very little survives
Tritium
Deuterium
Helium-4 + photons
Lithium-7 + photons
Helium-4
Lithium-7
Helium-3
Beryllium-7
Beryllium-7 + photons
Lithium-7
DEUTERIUM ERA
100 seconds
10^9K
Deuterium + photon
7 protons for every neutron
380,000 years
Atoms form.
Cosmic microwave background radiation permeates universe
100 - 200 million years
First stars form



一開始，溫度高時，由夸克生成的質子與中子的數量大致相等：$n_n \sim n_p$

溫度漸漸降低，夸克不再出現。中子質子不再由夸克生成。

質子與中子會透過與電子及微中子的反應互相轉換！



$n + \nu \leftrightarrows p + e^-$

這個反應現在會繼續保持質子與中子處於熱平衡狀態！

$n+\nu \leftrightharpoons p+e^-$ $\mu_e \sim \mu_\nu \sim 0$ $\mu_n \sim \mu_p$

這個反應會保持質子與中子處於熱平衡狀態！

$$n_n \sim 2\left(\frac{m_n kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_n c^2}{kT}\right) \qquad n_p \sim 2\left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_p c^2}{kT}\right)$$

$$\frac{n_n}{n_p} \sim \exp\left[\frac{-(m_n-m_p)c^2}{kT}\right] = \exp\left(\frac{-Q}{kT}\right) \sim \exp\left(\frac{-1.29\mathrm{MeV}}{kT}\right)$$

向右反應會放熱，

溫度下降，傾向向右反應：$n_n \downarrow$

直到$t\sim 1\mathrm{s}$，$kT\sim 0.8\mathrm{MeV}$：

$$\tau(n+\nu \leftrightharpoons p+e^-) \ll \frac{1}{H}$$

空間擴張太快，此反應無法發生，

質子與中子數目凍結！

$$\frac{n_n}{n_p} \sim \exp\left(\frac{-1.29\mathrm{MeV}}{0.8\mathrm{MeV}}\right) \sim \frac{1}{5} = 0.2$$

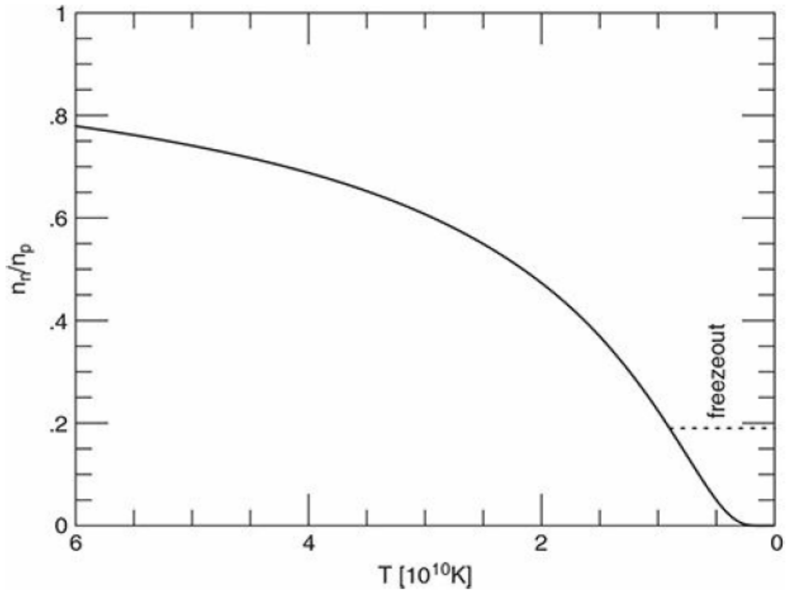


Figure 9.2 Neutron-to-proton ratio in the early universe. The solid line assumes equilibrium; the dotted line gives the value after freezeout. Temperature decreases, and thus time increases, from left to right.

Neutron Freeze Out or Neutrino Decoupling

根據比較精確的計算，這是發生在$t\sim 20$ s，$T\sim 1.3\times 10^9$ K。

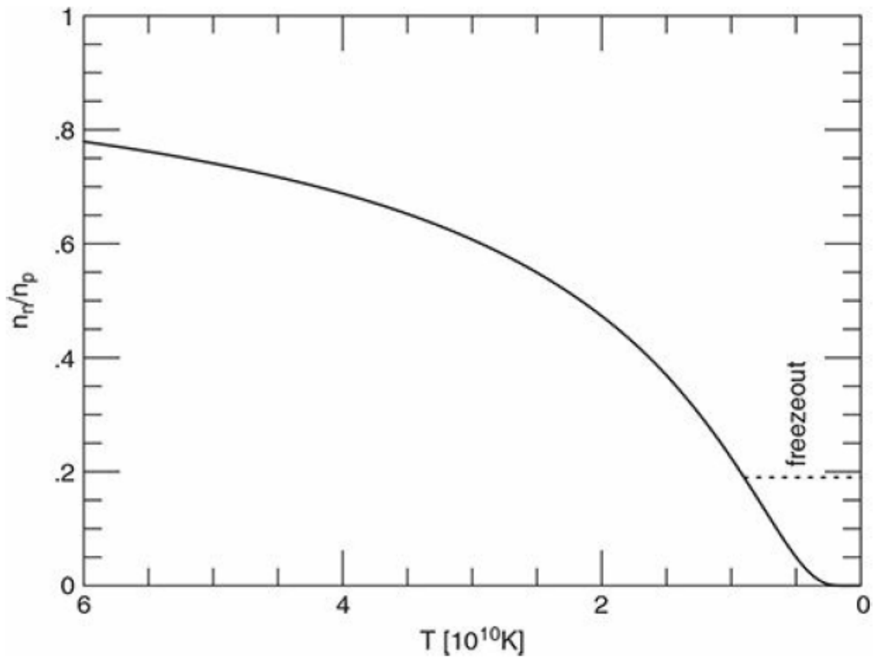


Figure 9.2 Neutron-to-proton ratio in the early universe. The solid line assumes equilibrium; the dotted line gives the value after freezeout. Temperature decreases, and thus time increases, from left to right.

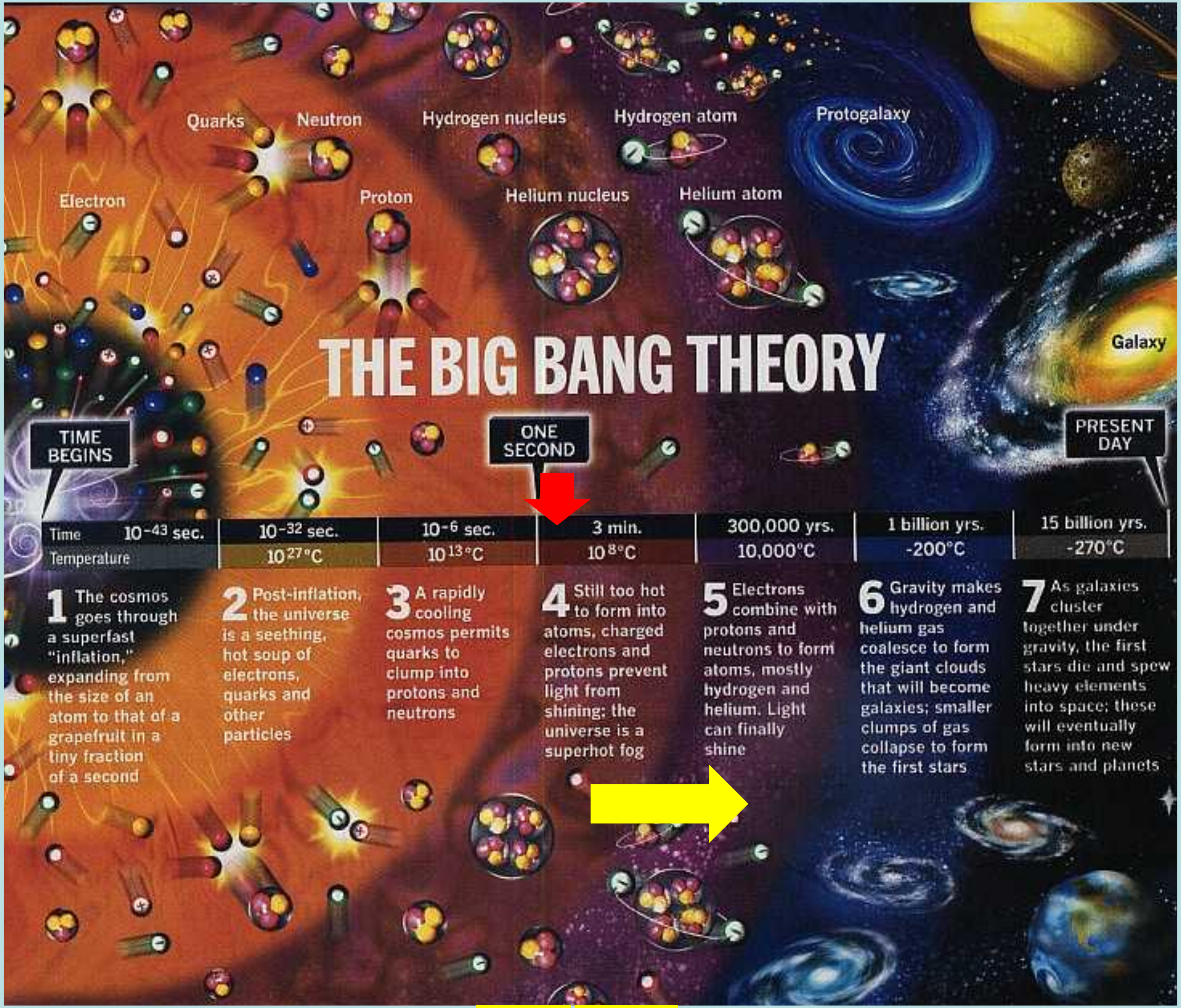
根據精確的計算，在t~20 s，T~1.3×10^{9} K時：

質子與中子數目凍結！注意中子少於質子！

$$\frac{n_n}{n_p}\sim\exp\left(\frac{-1.29\mathrm{MeV}}{0.8\mathrm{MeV}}\right)\sim\frac{1}{5}=0.2$$

Neutron Freeze Out or Neutrino Decoupling

Big Bang Nucleosynthesis核合成



Time	10^{-43} sec.	10^{-32} sec.	10^{-6} sec.	3 min.	300,000 yrs.	1 billion yrs.	15 billion yrs.
Temperature		10^{27}°C	10^{13}°C	10^{8}°C	10,000°C	-200°C	-270°C

1 The cosmos goes through a superfast "inflation," expanding from the size of an atom to that of a grapefruit in a tiny fraction of a second

2 Post-inflation, the universe is a seething, hot soup of electrons, quarks and other particles

3 A rapidly cooling cosmos permits quarks to clump into protons and neutrons

4 Still too hot to form into atoms, charged electrons and protons prevent light from shining; the universe is a superhot fog

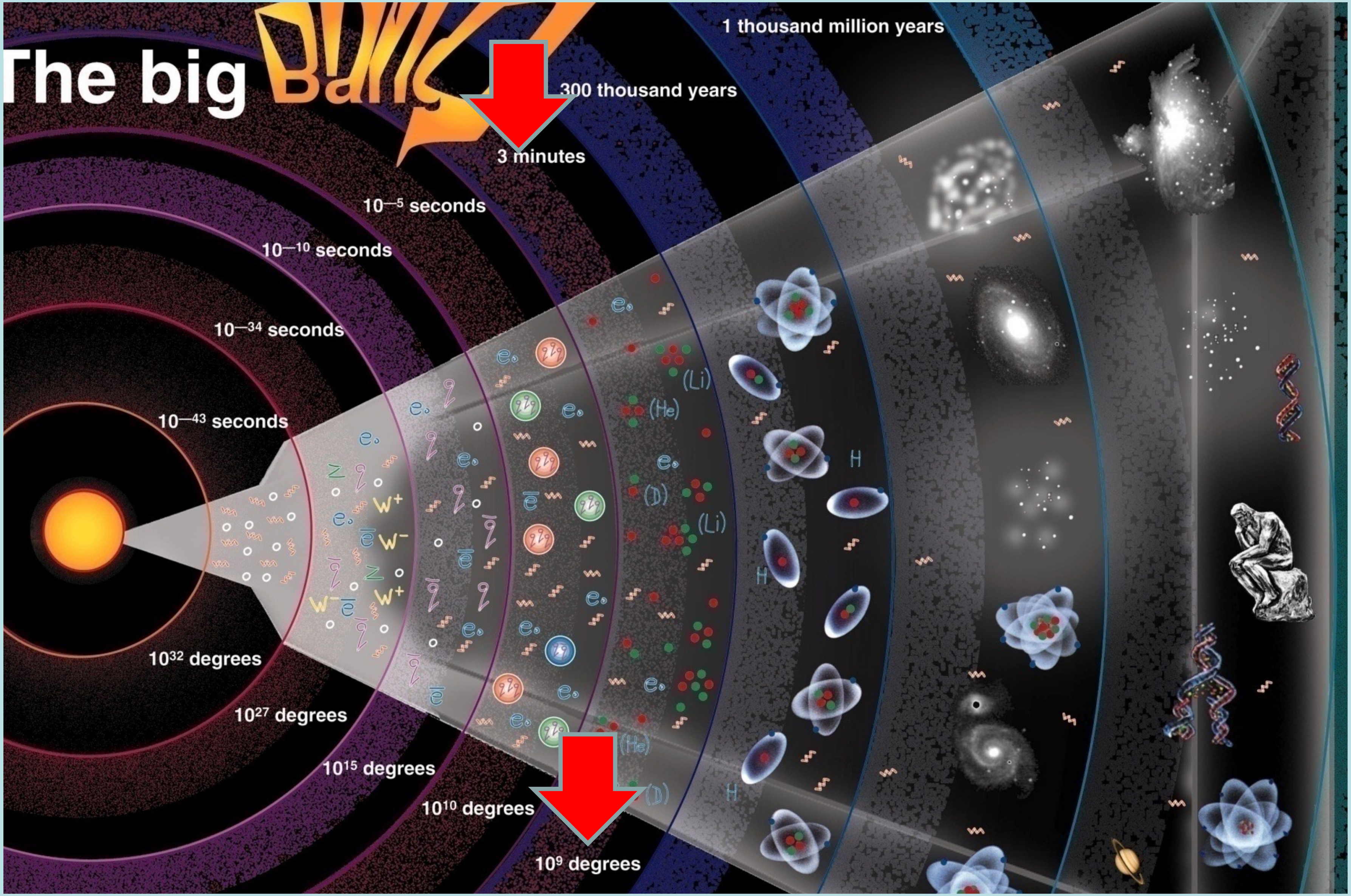
5 Electrons combine with protons and neutrons to form atoms, mostly hydrogen and helium. Light can finally shine

6 Gravity makes hydrogen and helium gas coalesce to form the giant clouds that will become galaxies; smaller clumps of gas collapse to form the first stars

7 As galaxies cluster together under gravity, the first stars die and spew heavy elements into space; these will eventually form into new stars and planets

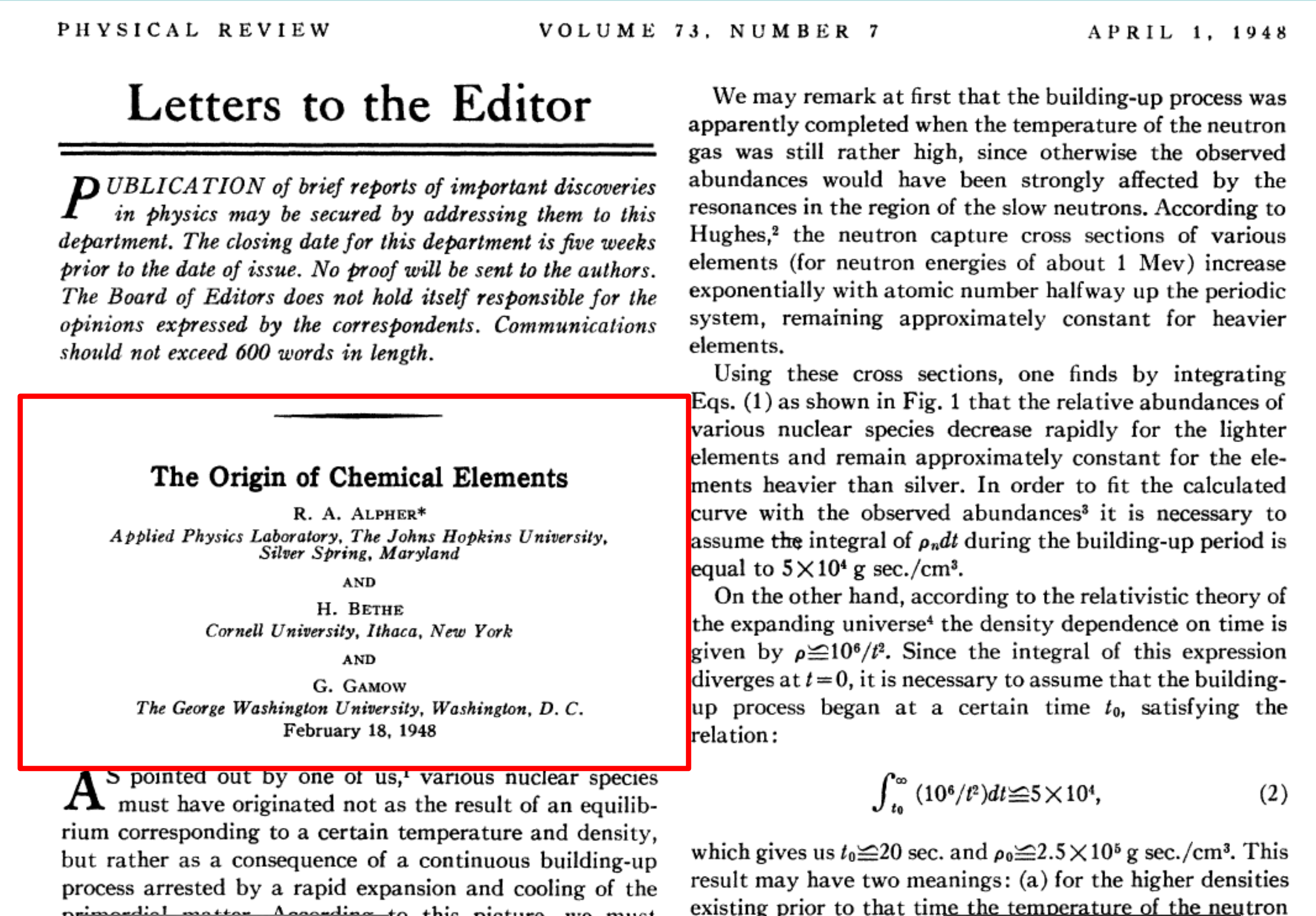
時間增加，溫度下降。 $t\uparrow$ $T\downarrow$

到了$1\text{s}-3\text{ min},10^{8}\text{ K}$時，質子中子開始組成氦原子核。這是極重要的時刻。



宇宙誕生三分鐘左右，熱能~1 – 0.1 MeV，質子與中子開始形成原子核。

核合成 Big Bang Nucleosynthesis BBN 就開始了。



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 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

in … er as a highly c

ne … ral nuclear flu

st … nd electrons wh

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:

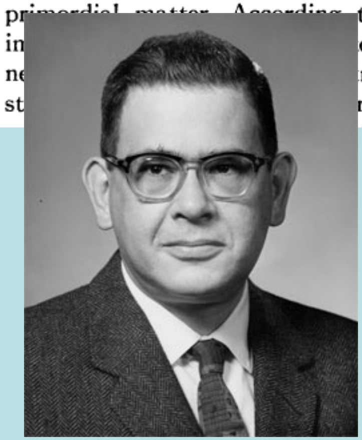
$$\int_{t_0}^{\infty}(10^6/t^2)dt \cong 5\times10^4, \qquad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5\times10^5$ g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron

gh that no … , (b)

of the uni … alue

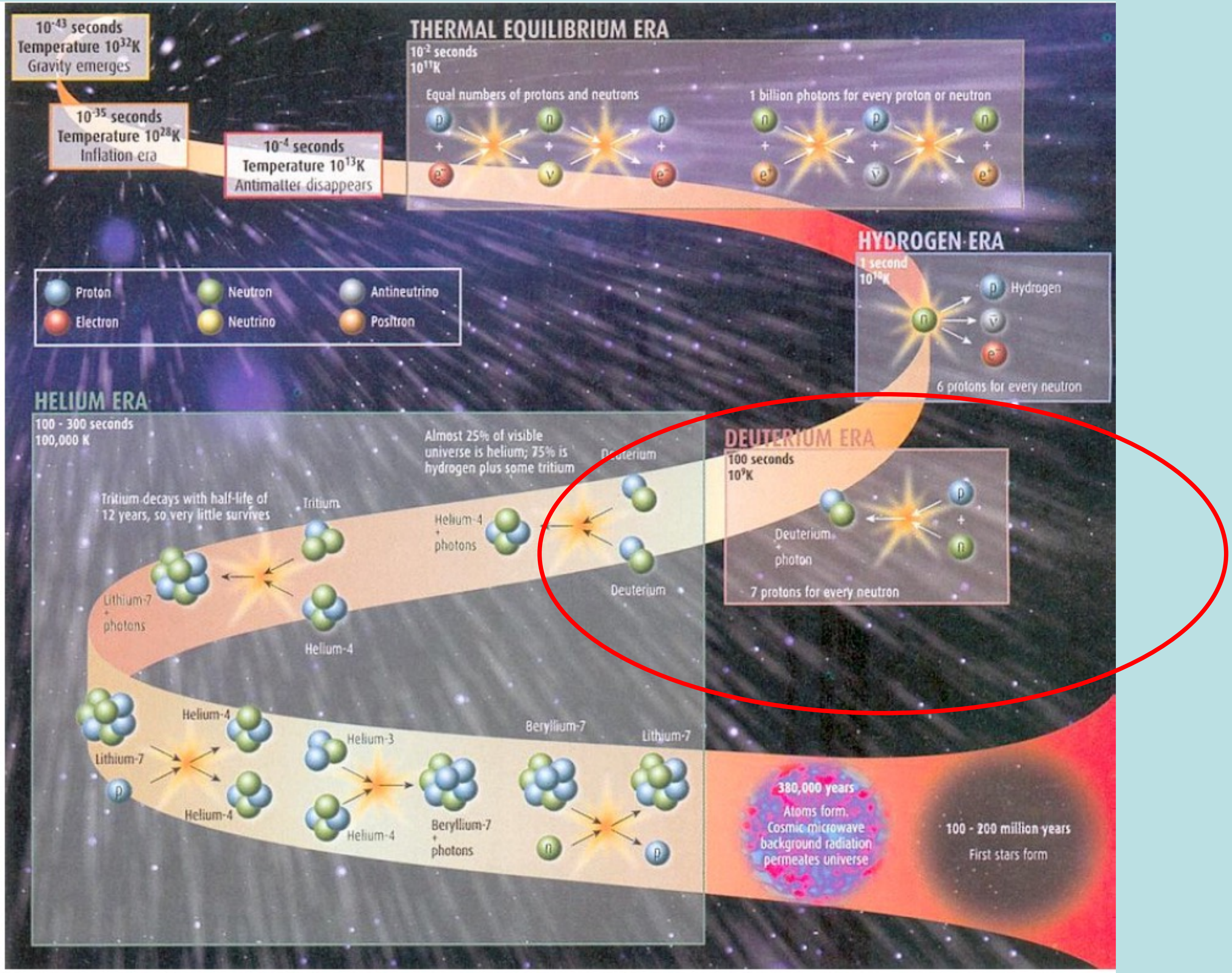
./cm³ which … if we



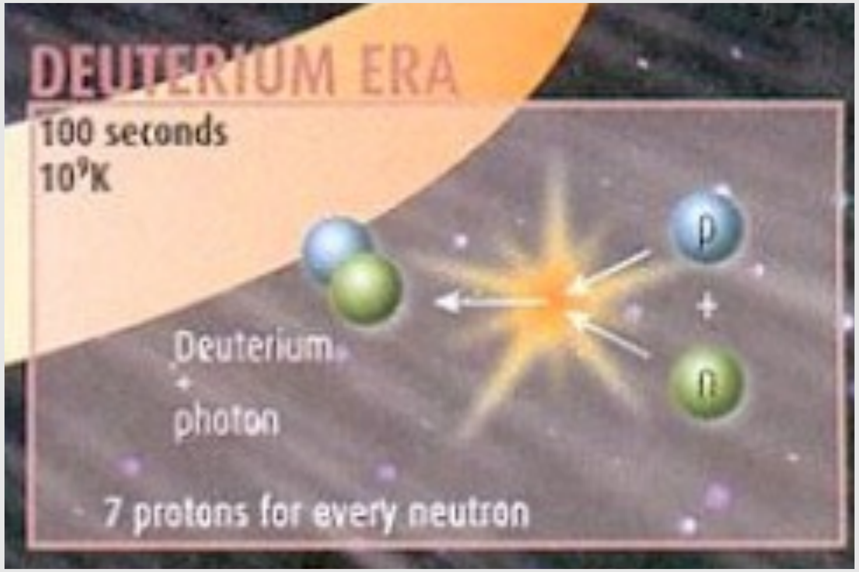
R. A. Alpher α

H. Bethe β

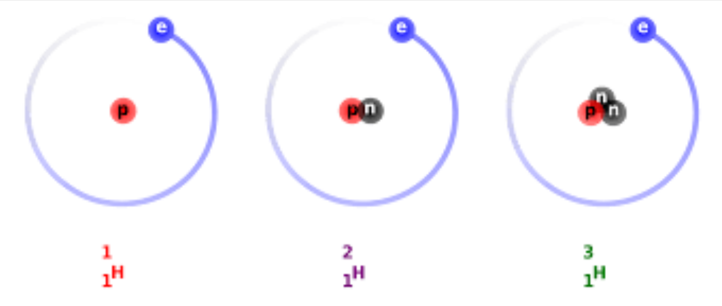
G. Gamow γ



質子與中子首先產生氫的同位素：氘 Deuterium的原子核。宇宙的首原子核！



$$p + n \leftrightarrows D + \gamma$$



氘 Deuterium　氚 Tritium

這個生成反應如同一個化學反應！

宇宙猶如一個化學實驗的大熔爐！那就將化學反應的熱學直接移植過來即可！

$$\mu_p + \mu_n = \mu_D$$ 化學平衡的條件！

由此條件可以得到氘的數目n_D，它是隨溫度而變化的，溫度越低，n_D數目越多：

$$\frac{n_D}{n_p n_n} \propto T^{-\frac{3}{2}} \cdot e^{\frac{B_D}{T}}$$

$p + n \leftrightarrows D + \gamma$ $\mu_p + \mu_n = \mu_D$ 化學平衡的條件！

$$n_D \sim g_D \left(\frac{m_D kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_D c^2 + \mu_D}{kT}\right)$$

此時這些粒子依舊處於熱平衡。

$$n_n \sim g_N \left(\frac{m_n kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_n c^2 + \mu_n}{kT}\right)$$

$$n_p \sim g_p \left(\frac{m_p kT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{-m_p c^2 + \mu_p}{kT}\right)$$

代入上三式計算$\frac{n_D}{n_p n_n}$，根據化學平衡條件，化學能μ_i正好全部消去！

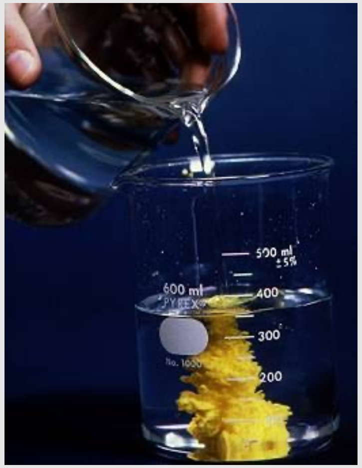
$$\frac{n_D}{n_p n_n} \propto T^{-\frac{3}{2}} \cdot e^{\frac{(m_p+m_n-m_D)c^2}{kT}} = T^{-\frac{3}{2}} \cdot e^{\frac{B_D}{kT}}$$

$B_D \equiv (m_p + m_n - m_D)c^2 \sim 2.23\ \text{MeV}$ 氘的束縛能，也就是反應的放熱！

當$T \gg B_D$，$n_D \sim 0$。 當$T \ll B_D$，$n_D \gg n_{p,n}$。

當熱能大於束縛能時，向左反應遠大於向右，束縛態氘就無法形成。

當熱能小於束縛能時，向左反應遠小於向右，束縛態氘會大量形成。



定溫定壓下的化學反應

定溫定壓的化學反應中，各氣體的分壓會隨隨反應進行而改變。

$$\mathrm{N_2} + 3\mathrm{H_2} \rightarrow 2\mathrm{NH_3}$$

$\Delta G = 0$ 平衡條件 $-\mu_{\mathrm{N_2}} - 3\mu_{\mathrm{H_2}} + 2\mu_{\mathrm{NH_3}} = 0$

$$-1\left(\mu_{\mathrm{N_2}0} + RT\ln\frac{P_{\mathrm{N_2}}}{P_0}\right) - 3\left(\mu_{\mathrm{H_2}0} + RT\ln\frac{P_{\mathrm{H_2}}}{P_0}\right) + 2\left(\mu_{\mathrm{NH_3}0} + RT\ln\frac{P_{\mathrm{NH_3}}}{P_0}\right) = 0$$

$$\ln\frac{P_{\mathrm{H_2}}^3 P_{\mathrm{N_2}}}{P_{\mathrm{NH_3}}^2 P_0^2} = \frac{1}{RT}\left(2\mu_{\mathrm{NH_3}0} - \mu_{\mathrm{N_2}0} - 3\mu_{\mathrm{N_2}0}\right) \equiv \frac{\Delta G_0}{RT}$$

$$\frac{P_{\mathrm{NH_3}}^2 P_0^2}{P_{\mathrm{H_2}}^3 P_{\mathrm{N_2}}} = e^{-\frac{\Delta G_0}{RT}}$$

這個條件決定了平衡時各個成分的分壓與分子數：

$$\frac{n_{\mathrm{NH_3}}^2 n^2}{n_{\mathrm{H_2}}^3 n_{\mathrm{N_2}}} \cdot \frac{P_0^2}{P^2} = e^{-\frac{\Delta G_0}{RT}}$$

$$\frac{n_{\mathrm{NH_3}}^2 n^2}{n_{\mathrm{H_2}}^3 n_{\mathrm{N_2}}} = e^{-\frac{\Delta G_0}{RT}}$$

$$\frac{n_D n_N}{n_p n_n} \propto T^{-\frac{3}{2}} \cdot e^{\frac{B_D}{T}}$$

ΔG_0越大，溫度越低，越往右反應

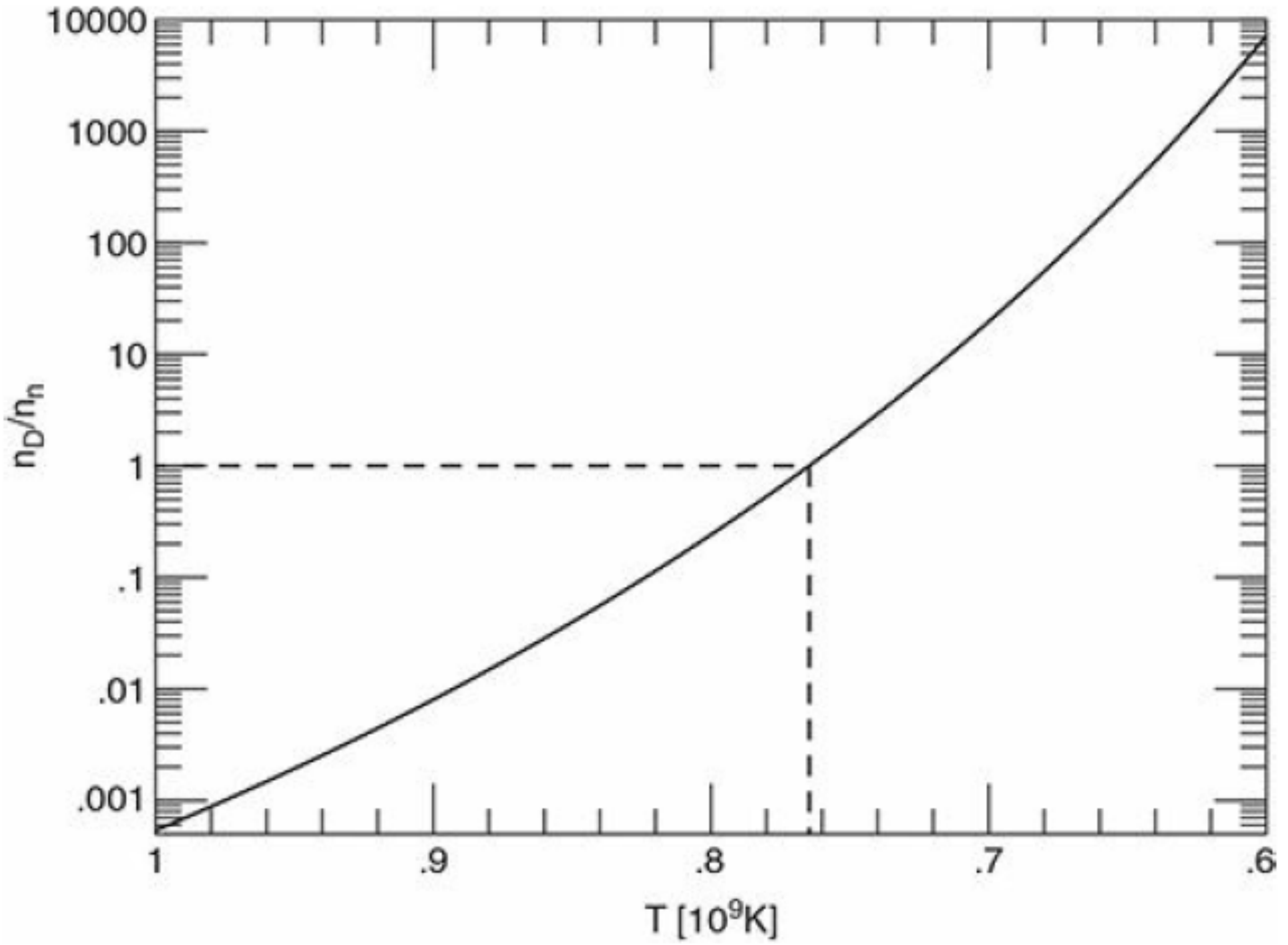
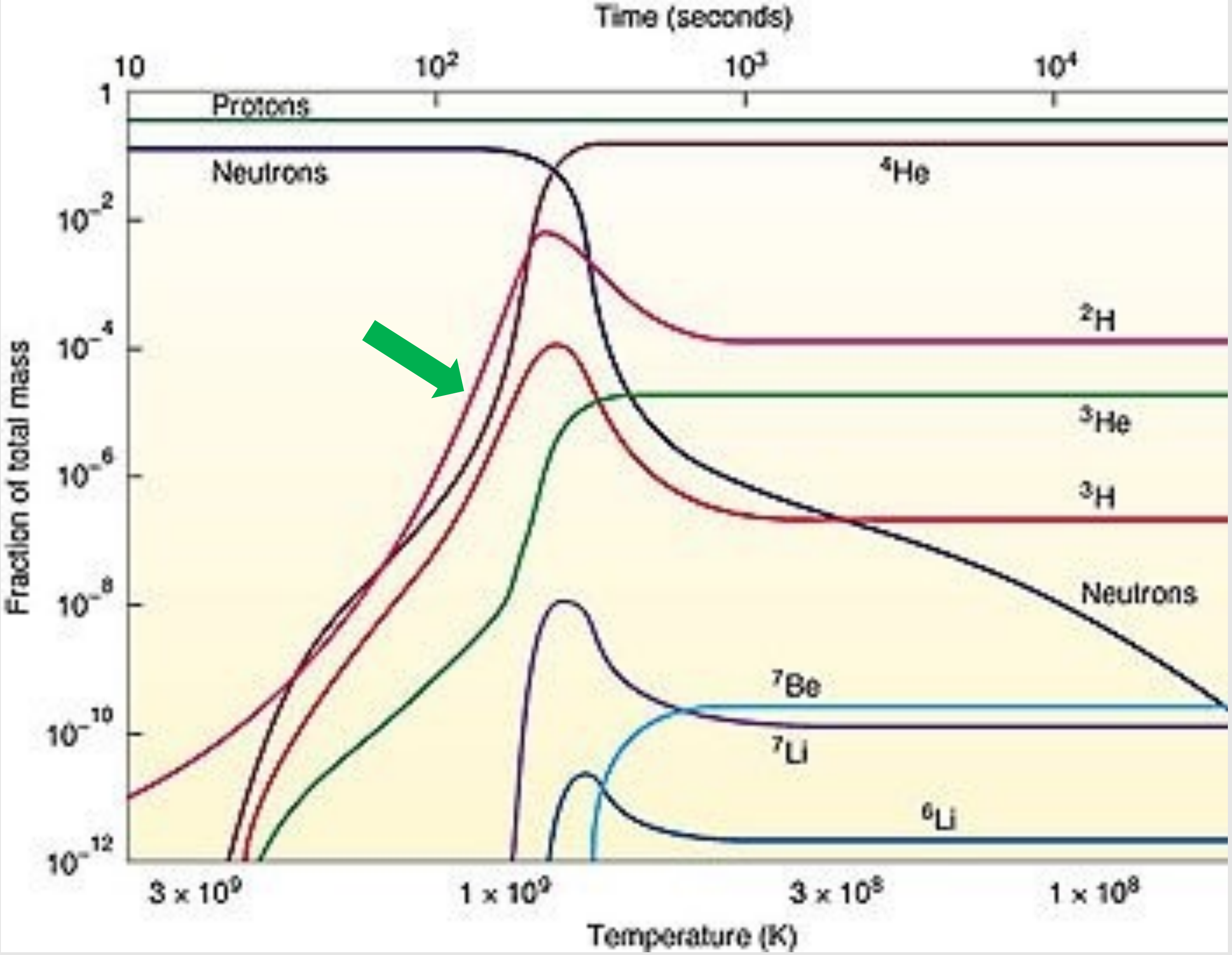


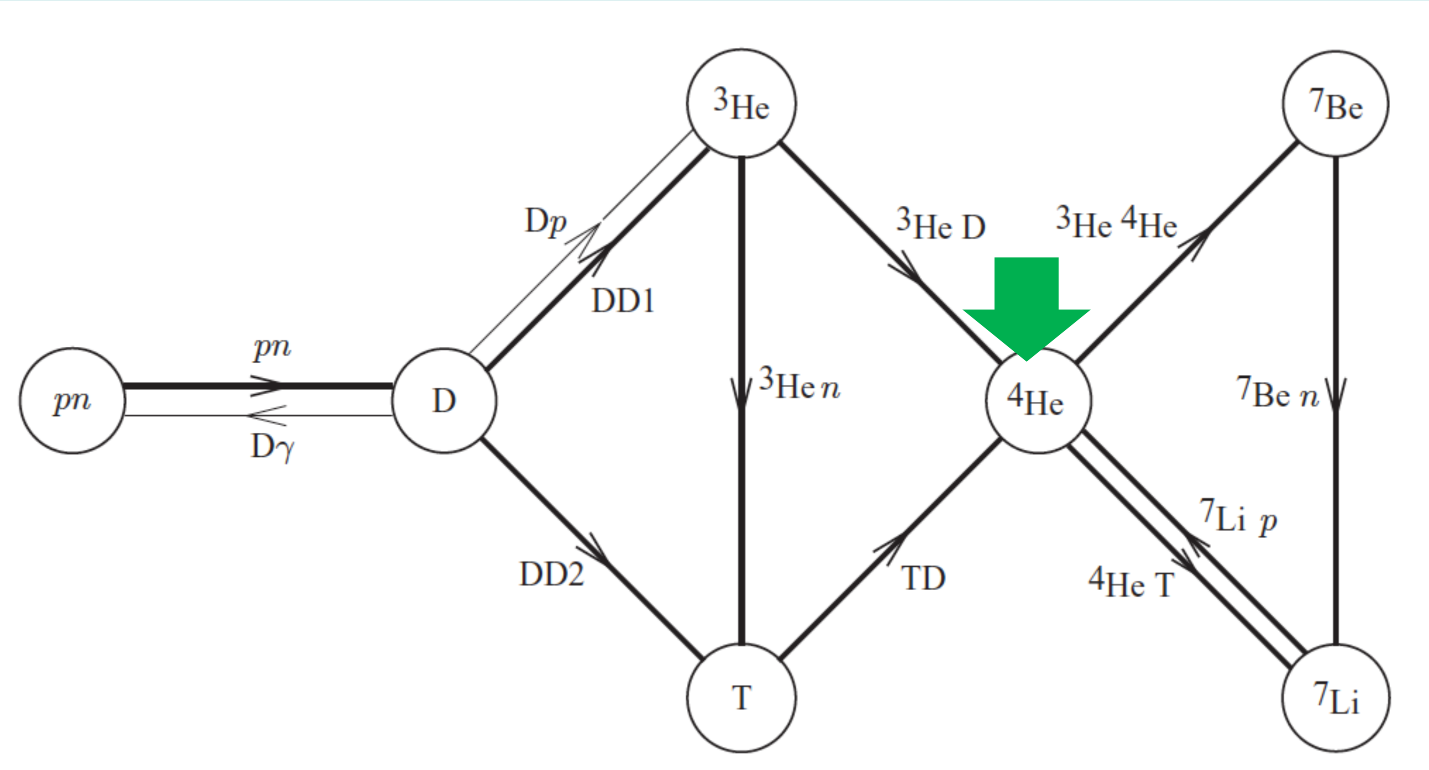
Figure 9.3 The deuteron-to-neutron ratio during the epoch of deuterium synthesis. The

$$\frac{n_D}{n_p n_n} \propto T^{-\frac{3}{2}} \cdot e^{\frac{B_D}{T}}$$

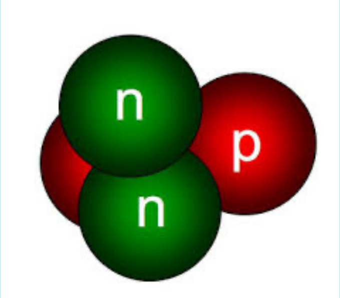
大約$t \sim 200$ s，$T \sim 0.76 \times 10^9$ K，就有相當足夠的氘生成了！



Time (seconds)
10
10^2
10^3
10^4
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
Fraction of total mass
Protons
Neutrons
4He
2H
3He
3H
Neutrons
7Be
7Li
6Li
3 × 10^9
1 × 10^9
3 × 10^8
1 × 10^8
Temperature (K)



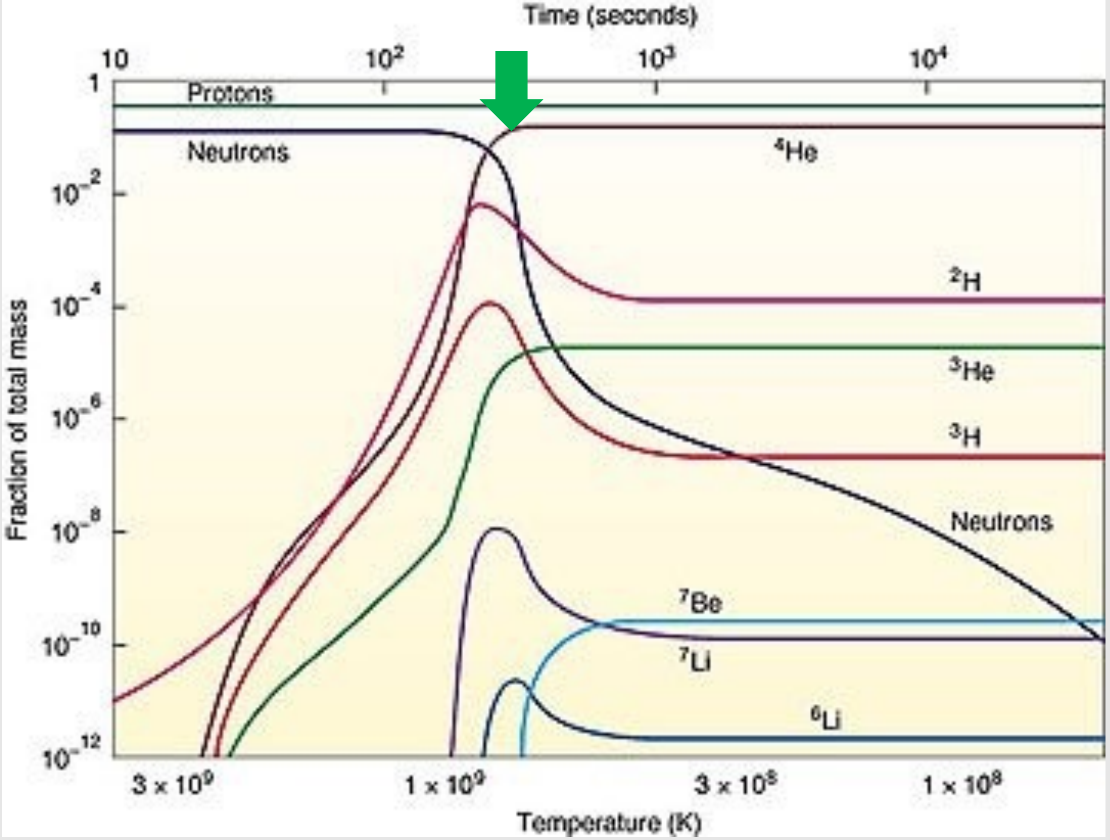
氦原子核 ^{4}He

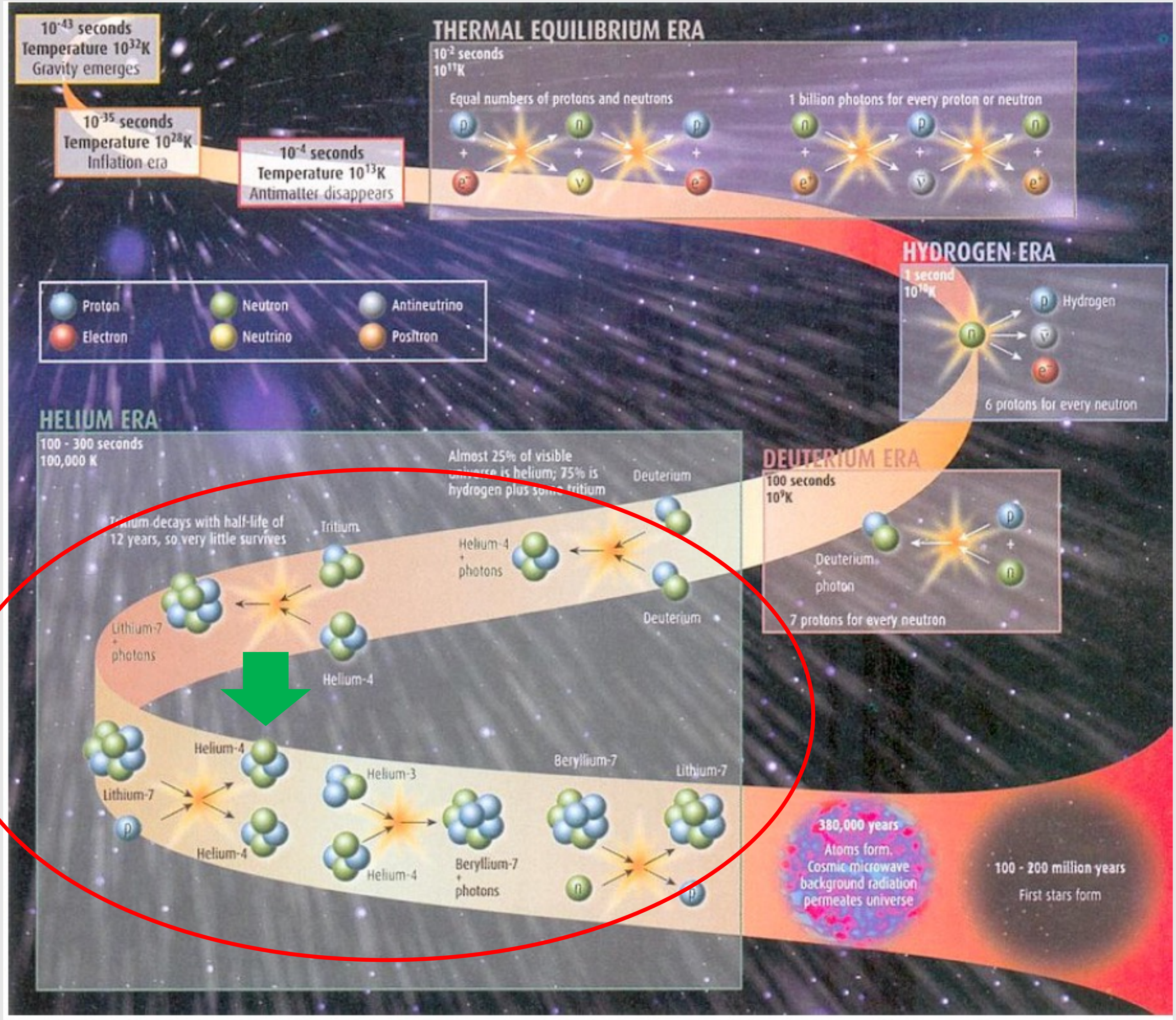


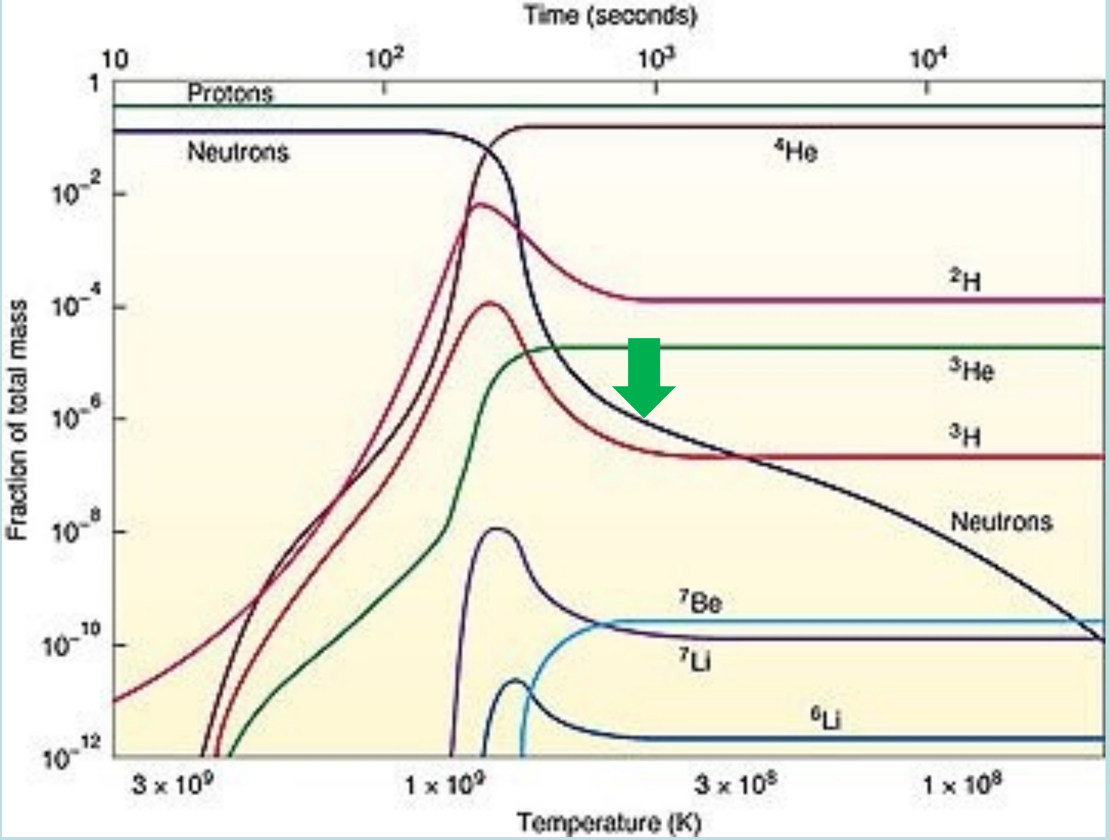
氘一產生後，會非常快速地再合成其他的原子核，最後會停頓在氦原子核 ^{4}He：

氦原子核 ^{4}He比較穩定，很快地大部分的氘、氚及氦同位素 ^{3}He都轉化為氦 ^{4}He！

氦 ^{4}He再進一步製造更重的原子核就困難許多，量也很少！


Time (seconds)
10
10^2
10^3
10^4
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Fraction of total mass
Protons
Neutrons
^{4}He
^{2}H
^{3}He
^{3}H
Neutrons
^{7}Be
^{7}Li
^{6}Li
3×10^9
1×10^9
3×10^8
1×10^8
Temperature (K)


10^{-43} seconds
Temperature 10^{32}K
Gravity emerges
10^{-35} seconds
Temperature 10^{28}K
Inflation era
10^{-4} seconds
Temperature 10^{13}K
Antimatter disappears
THERMAL EQUILIBRIUM ERA
10^{-2} seconds
10^{11}K
Equal numbers of protons and neutrons
1 billion photons for every proton or neutron
p
n
e⁻
ν
e⁺
ν̄
+
HYDROGEN ERA
1 second
10^{10}K
Hydrogen
6 protons for every neutron
Proton
Electron
Neutron
Neutrino
Antineutrino
Positron
DEUTERIUM ERA
100 seconds
10^{9}K
Deuterium
photon
7 protons for every neutron
HELIUM ERA
100 - 300 seconds
100,000 K
Almost 25% of visible universe is helium; 75% is hydrogen plus some tritium
Deuterium
Deuterium
Helium-4
+
photons
Tritium decays with half-life of 12 years, so very little survives
Tritium
Helium-4
Lithium-7
+
photons
Helium-4
Lithium-7
Helium-4
Helium-3
Helium-4
Beryllium-7
+
photons
Beryllium-7
Lithium-7
380,000 years
Atoms form.
Cosmic microwave background radiation permeates universe
100 - 200 million years
First stars form



^{4}He會一直製造直到中子用盡為止！此時 Nucleosynthesis核合成就停止了。

^{4}He產生很快，一般就以氘生成時間大約t~200 s來標定核合成的時間！

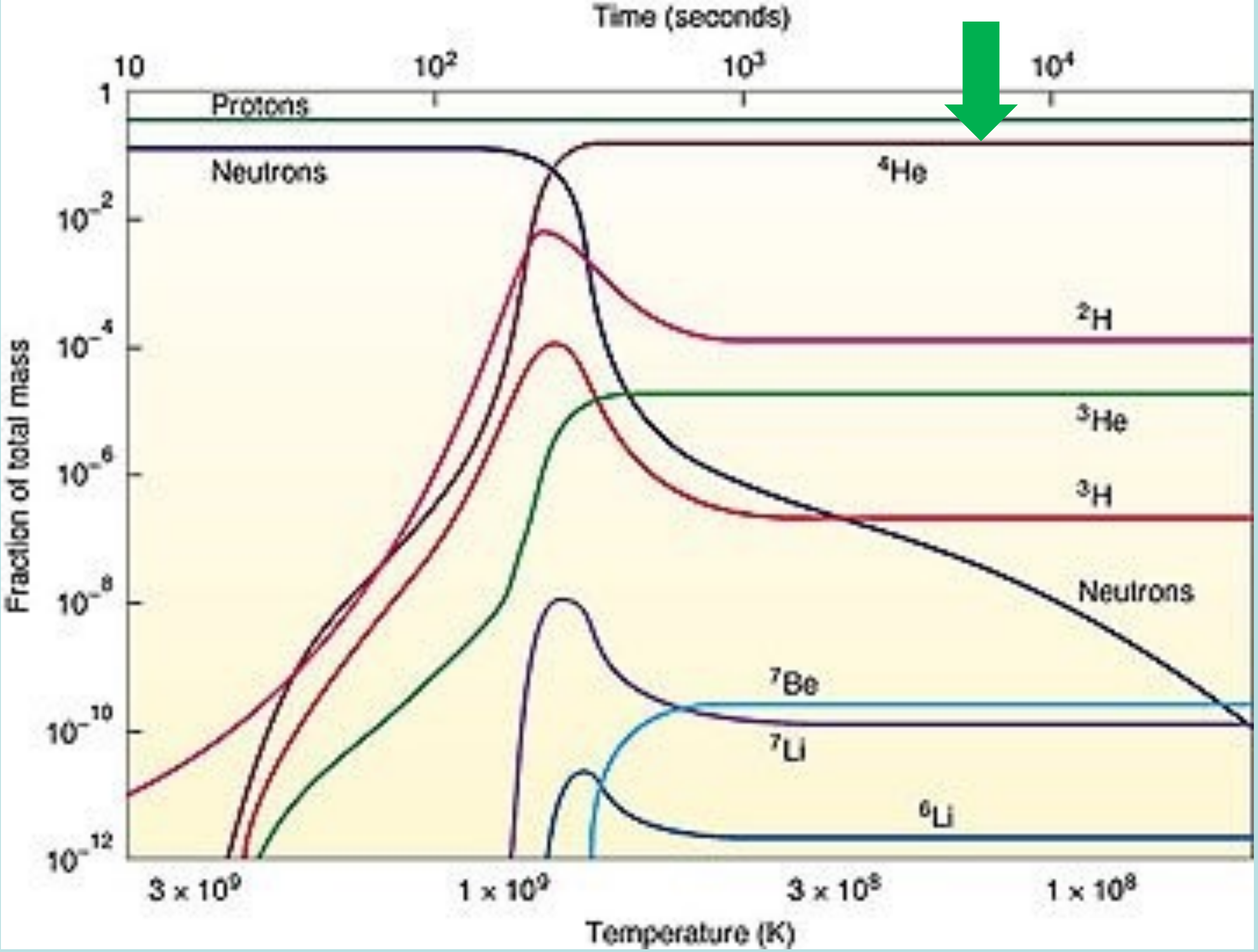
因為氦原子核很穩定，絕大部分中子會進入 ^{4}He ，

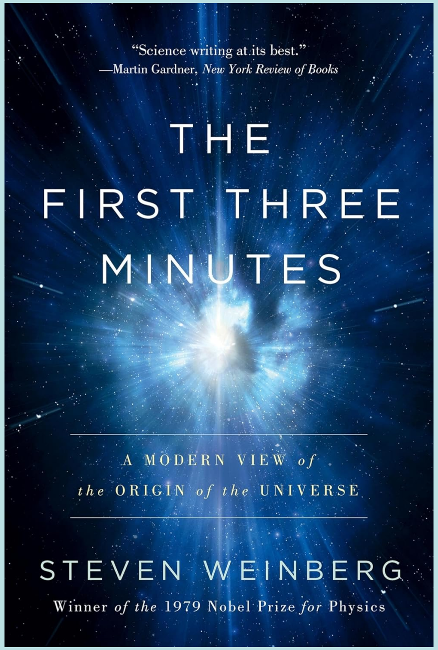
我們可以由凍結的中子質子比，簡單估計可以形成的 ^{4}He數量：

$$\frac{n_n}{n_p} \sim \frac{1}{5} \Rightarrow \frac{n_{^4\mathrm{He}}}{n_N} \sim \frac{0.5}{6} \quad \frac{m_{^4\mathrm{He}}}{m_N} \sim \frac{4 \cdot 0.5}{6} \sim \frac{1}{3}$$

非常接近觀察結果：$\frac{m_{^4\mathrm{He}}}{m_N} \sim 0.25$

考慮中子的衰變，此值的預測可以下修到：0.27。





"Science writing at its best."
—Martin Gardner, *New York Review of Books*

THE
FIRST THREE
MINUTES

A MODERN VIEW *of*
the ORIGIN *of the* UNIVERSE

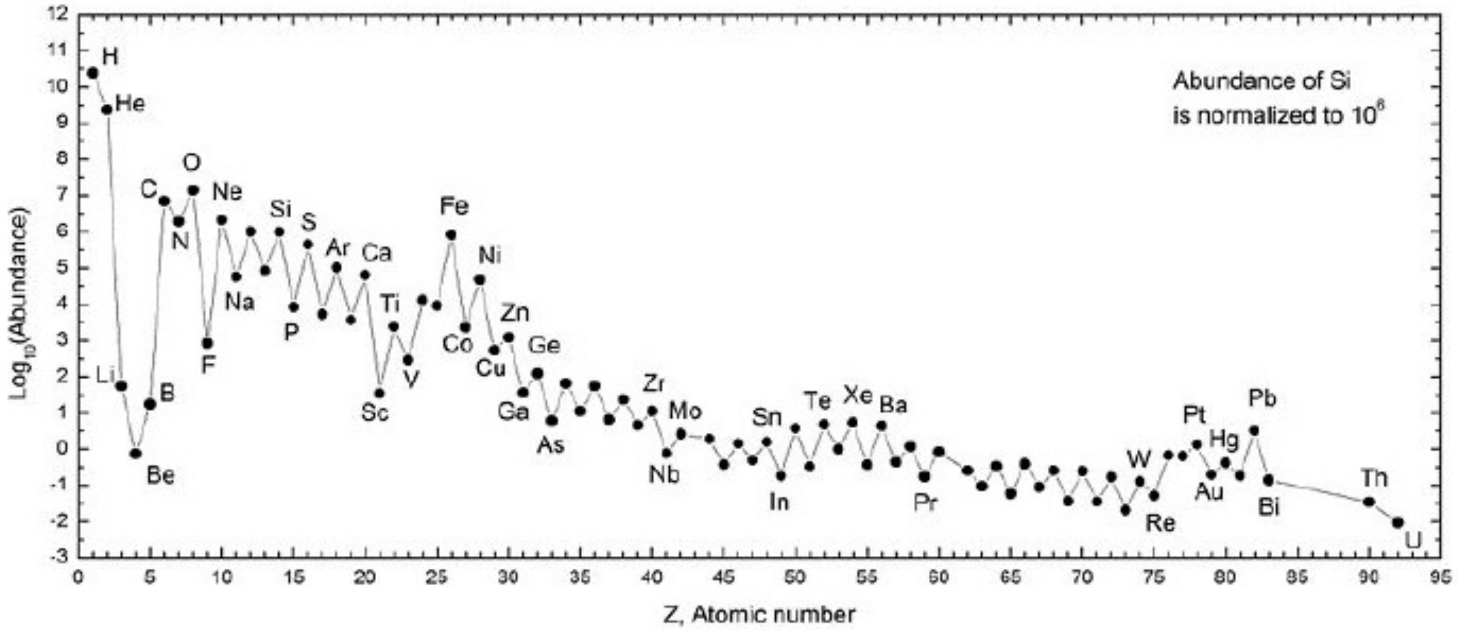
STEVEN WEINBERG
Winner *of the* 1979 Nobel Prize *for* Physics

真實的模型要複雜得多！但可以數值模擬計算！

中子耗盡後，核反應完全中斷，原子核不再與背景輻射達到熱平衡，

原子核種類數量固定直到現在。但在宇宙誕生三分鐘就決定了！

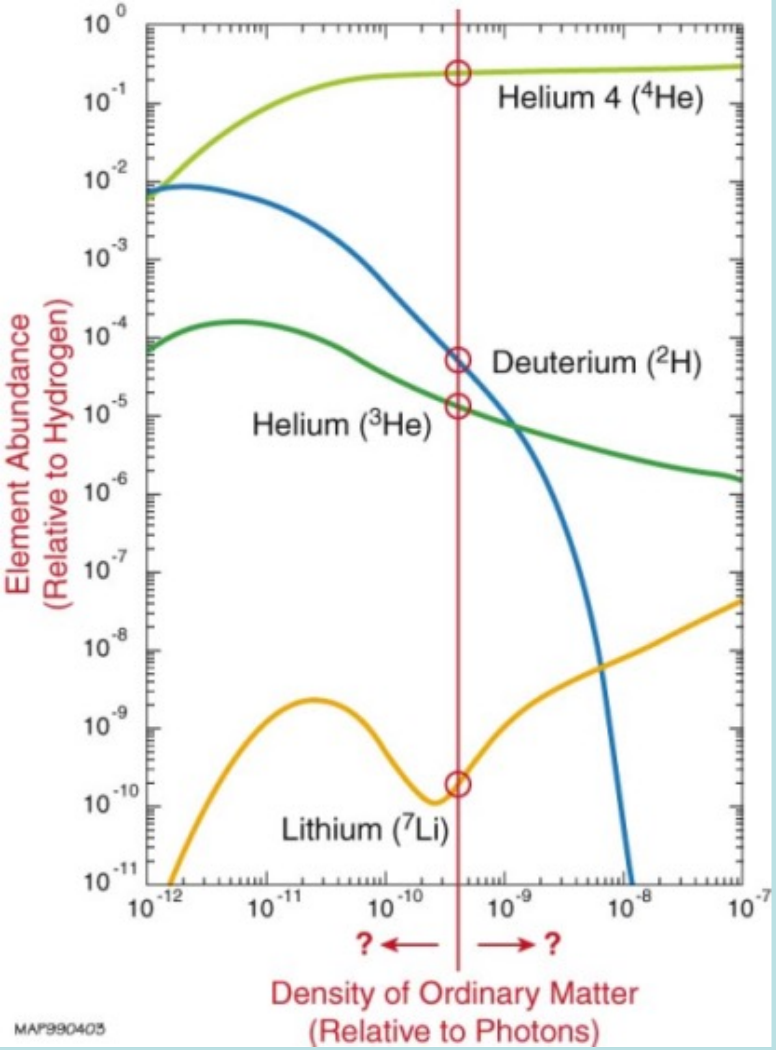
亂是有強制性的，宇宙前三分鐘極亂，這個亂強迫元素的數目必須服從！



source: wikipedia

亂是有強制性的，宇宙前三分鐘極亂，這個亂強迫元素的數目必須服從！

現在原子核種類數量對早期宇宙核子的絕對總數量非常敏感！



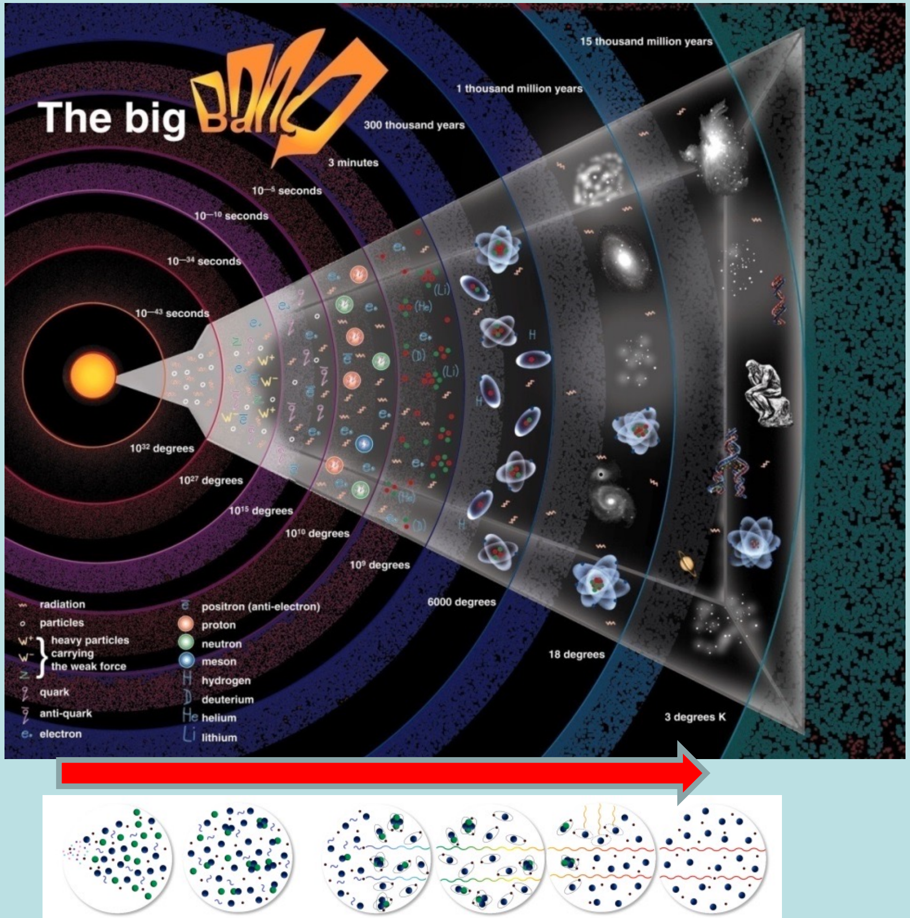
Big Bang Nucleosynthesis BBN 與觀察符合，成為大霹靂另一個有力證據

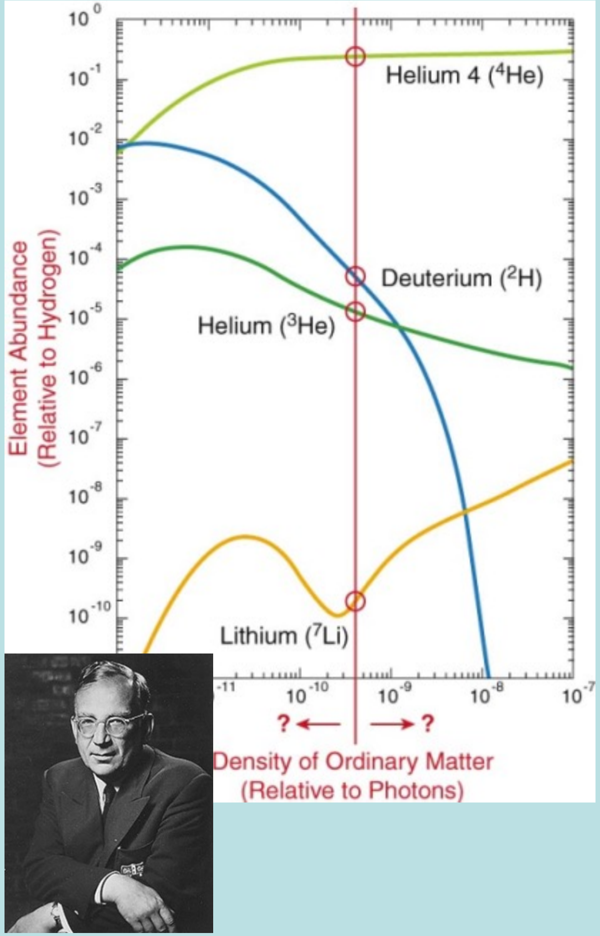
Essentially all of the elements that are heavier than lithium and beryllium were created much later, by stellar nucleosynthesis in evolving and exploding stars

BBN的預測成為大霹靂理論最重要的直接證據！

BBN能作如此簡單而精確的預測，是因為早期宇宙中，物質是處於熱平衡狀態！

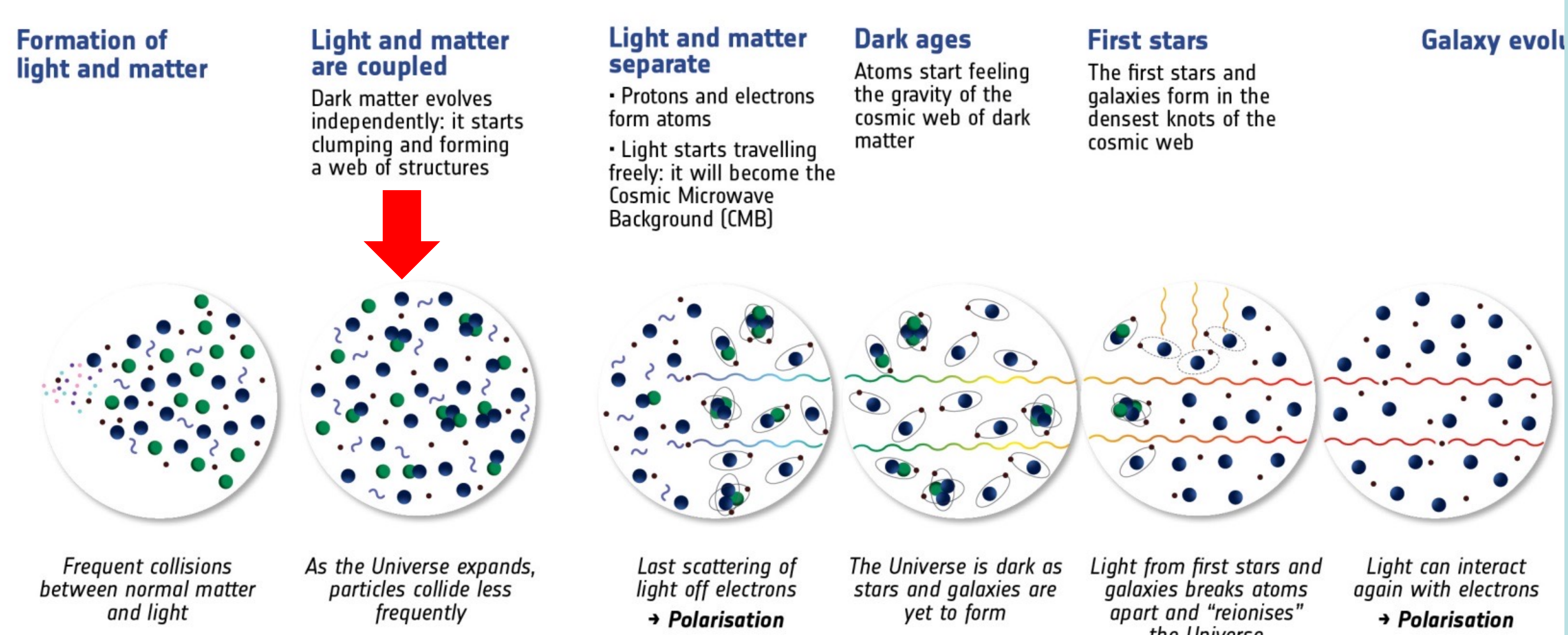
這個預測，沒有被宇宙後來的演化破壞，也證實了從大霹靂到今天140億年間宇宙的擴張近似地是一個獨立的等熵的過程，不需要外力干預。





Recombination

宇宙中物質與宇宙背景輻射之間的熱平衡關係，並不是永久的。



Formation of light and matter

Frequent collisions between normal matter and light

Light and matter are coupled

Dark matter evolves independently: it starts clumping and forming a web of structures

As the Universe expands, particles collide less frequently

Light and matter separate

- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Last scattering of light off electrons
→ Polarisation

Dark ages

Atoms start feeling the gravity of the cosmic web of dark matter

The Universe is dark as stars and galaxies are yet to form

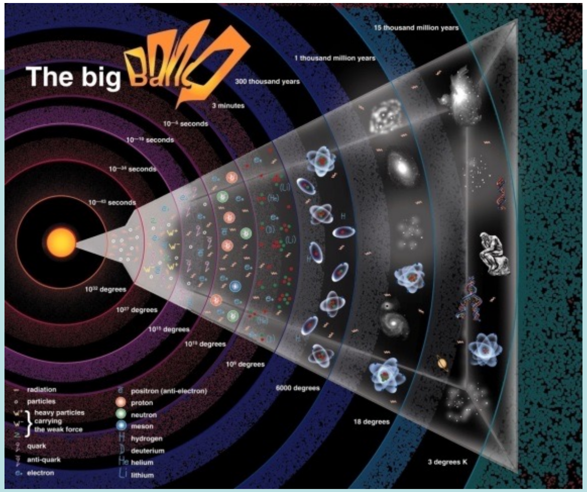
First stars

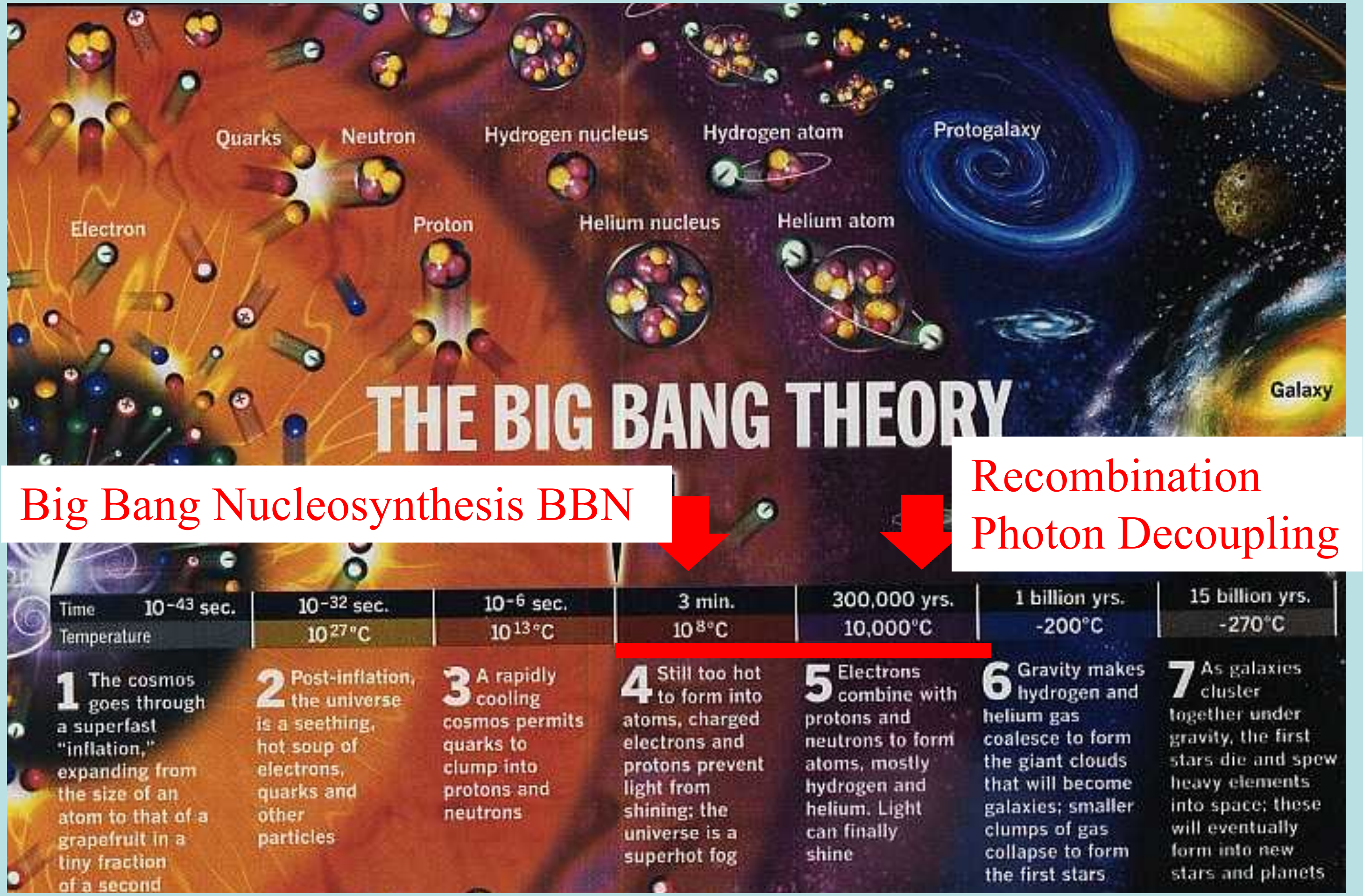
The first stars and galaxies form in the densest knots of the cosmic web

Light from first stars and galaxies breaks atoms apart and "reionises" the Universe

Galaxy evolu

Light can interact again with electrons
→ Polarisation





Big Bang Nucleosynthesis BBN

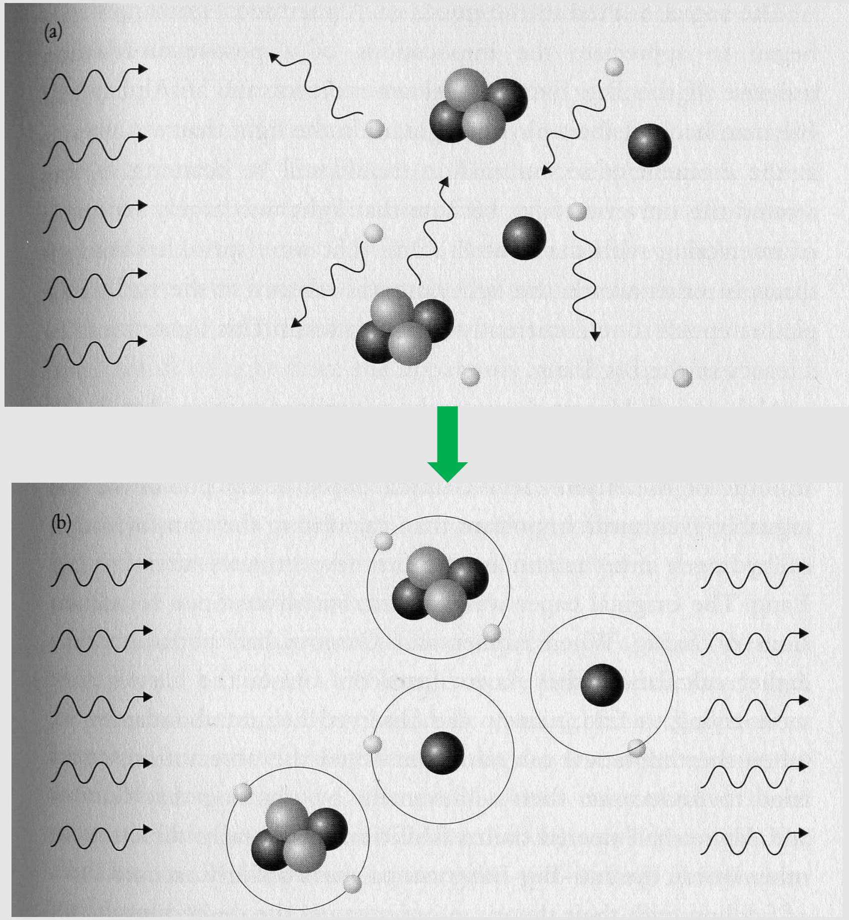
Recombination
Photon Decoupling

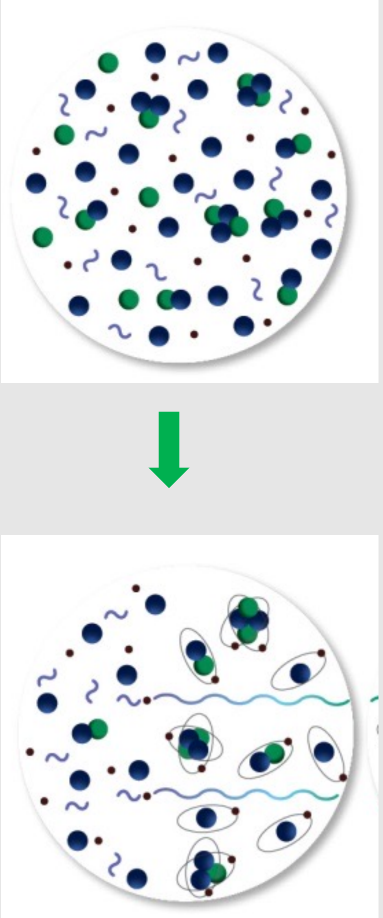
大霹靂後約三十萬年，質子開始捕捉電子，形成原子

氫原子的束縛能大約~10eV

當熱能低於束縛能，氫原子就開始形成，而且無法拆散。

這又是一個宇宙歷史的里程碑。





大霹靂後約三十萬年，質子開始捕捉電子，形成原子，稱為Recombination。

$p + e^- \leftrightarrows H + \gamma$ 捕捉的同時，拆散也還在進行，這是一個典型的化學平衡。

$$\frac{n_H}{n_p n_e} \propto T^{-\frac{3}{2}} \cdot e^{\frac{B_H}{kT}}$$

$$B_H \equiv m_p + m_e - m_H \sim 13.6\ \text{eV}$$

當熱能kT小於束縛能B_H時，向左反應遠小於向右，氫原子會大量形成。這時：

$T_{\text{rec}} \sim 0.3\text{eV} \sim 3600\text{K}$ $t_{\text{rec}} \sim 288000\text{yr}$

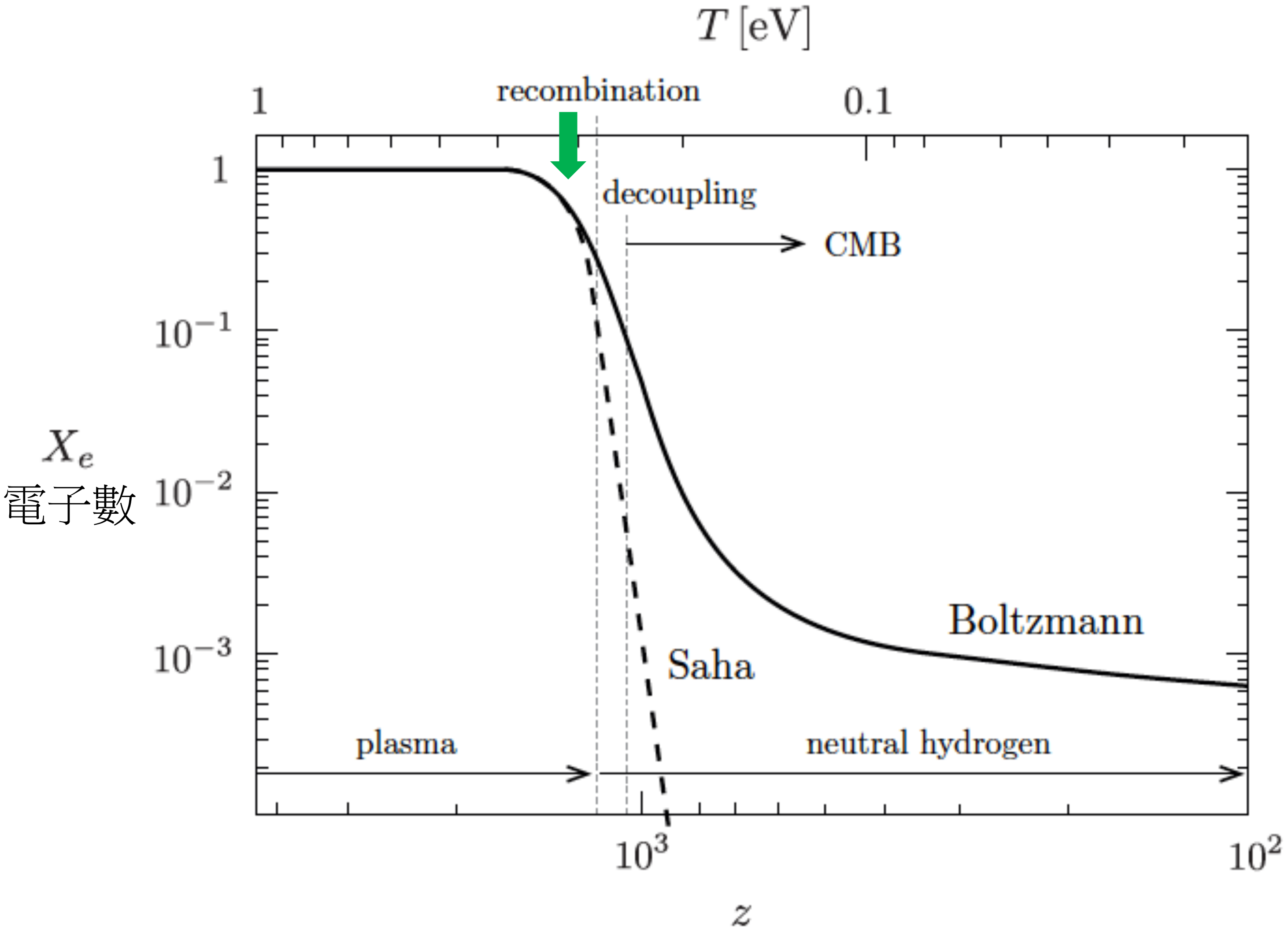


Figure 3.8: *Free electron fraction as a function of redshift.*

Recombination之後，電子數量急速降低↓！

$p + e^- \leftrightarrows H + \gamma$ Recombination之後，向右反應遠快於向左！

電子密度急速降低！電中性的氫原子取而代之。

背景輻射與現在量較多的電中性的氫原子作用很小，

光子與電子的散射碰撞： $e^- + \gamma \leftrightarrows e^- + \gamma$

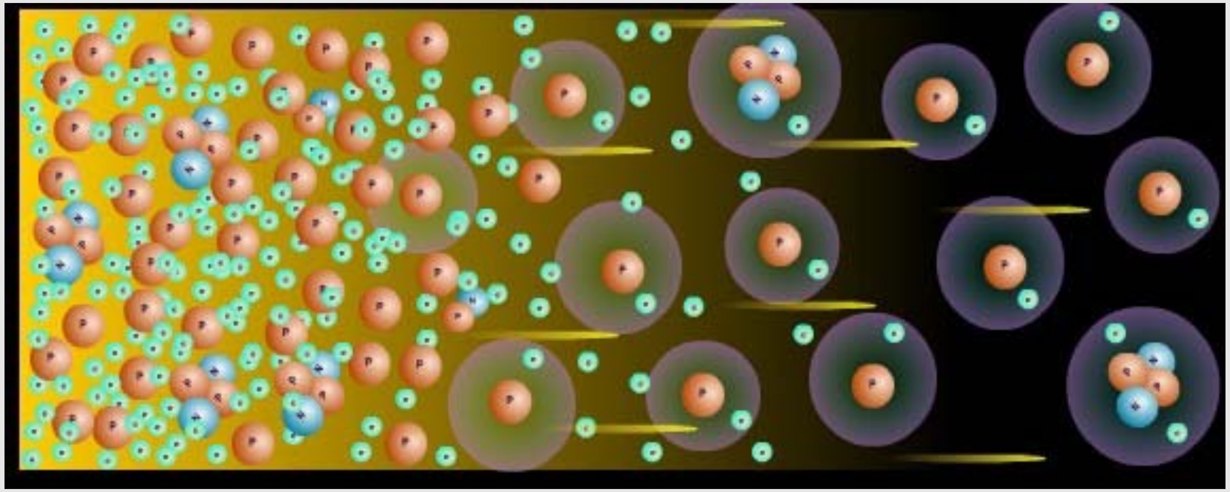
碰撞發生越來越趕不上宇宙擴張的速度： $\tau \gg \frac{1}{H}$

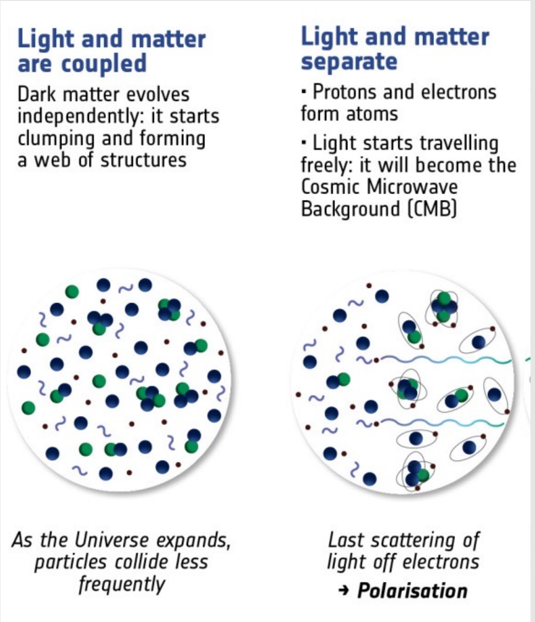
不久之後，光與物質便彼此獨立發展，稱為Photon Decoupling。

光在宇宙中幾乎自由行走，宇宙由模糊變透明。

從此，輻射的溫度不再是物質的溫度。這時：

$T_{\mathrm{D}} \sim 0.27\mathrm{eV} \sim 3240\mathrm{K}$ $t_{\mathrm{D}} \sim 380000\mathrm{yr}$





Light and matter are coupled

Dark matter evolves independently: it starts clumping and forming a web of structures

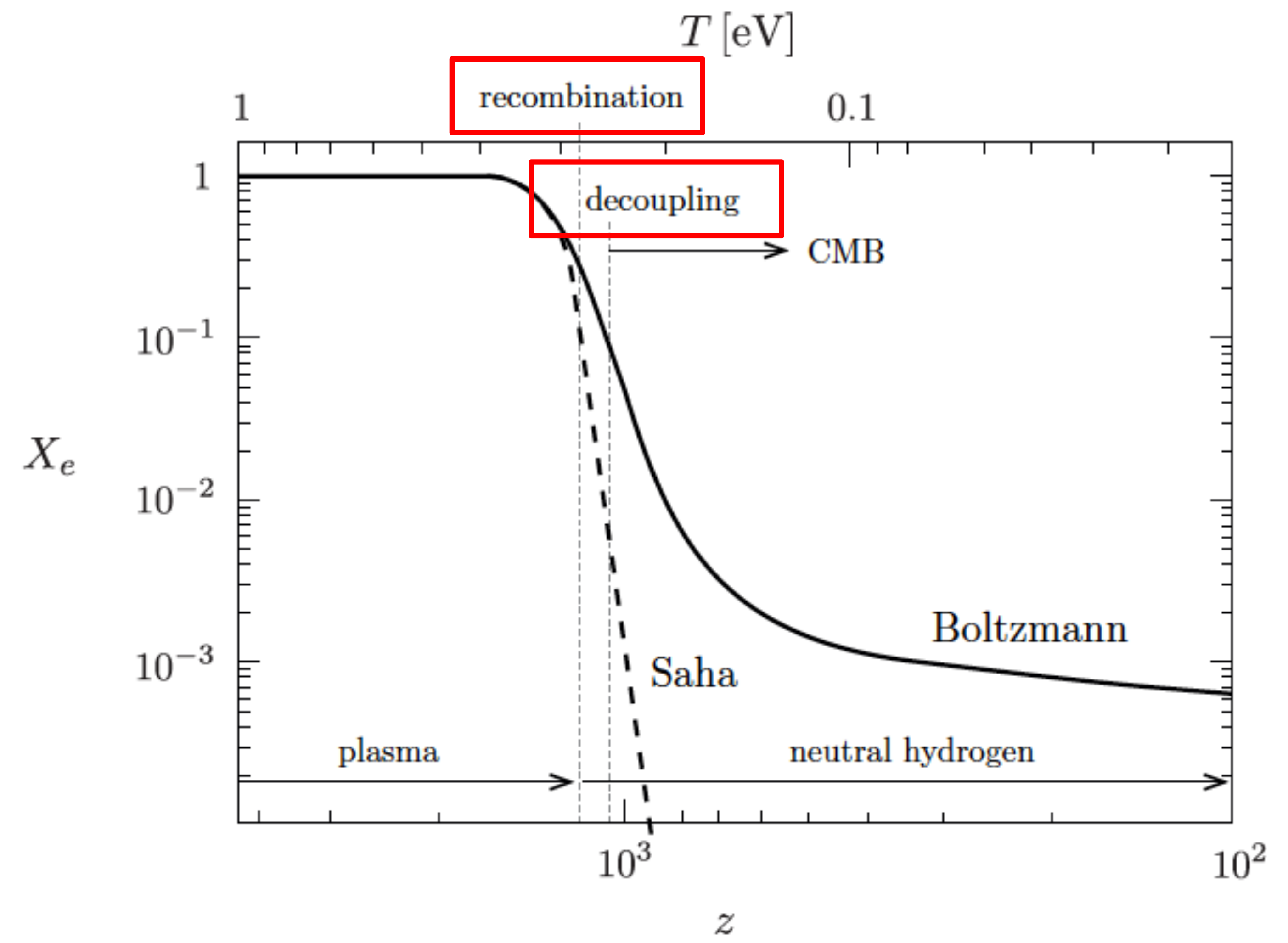
As the Universe expands, particles collide less frequently

Light and matter separate

- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Last scattering of light off electrons

→ ***Polarisation***



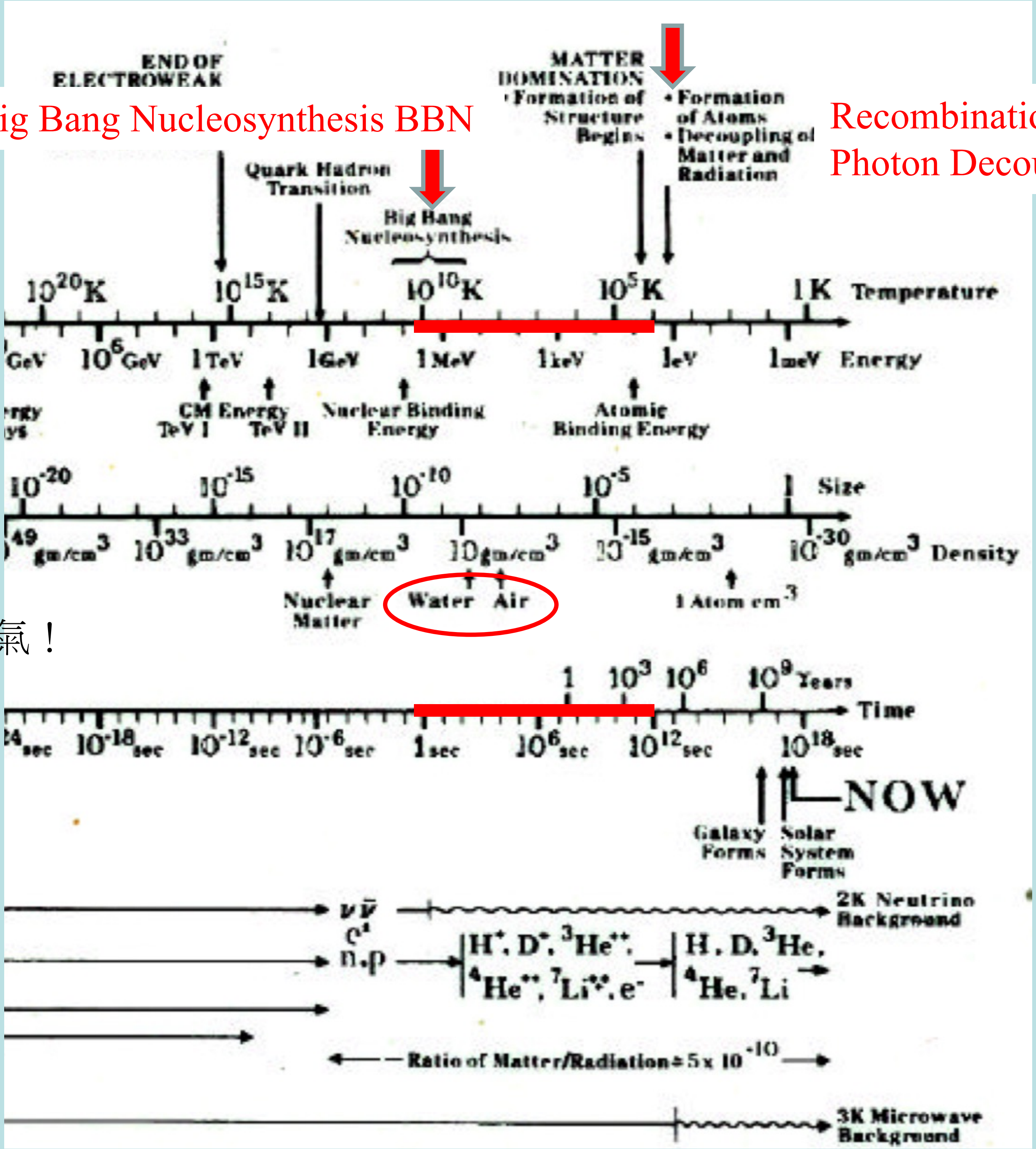
Recombination is followed quickly by Photon Decoupling.

從此物質與背景輻射分道揚鑣，不再處於熱平衡。

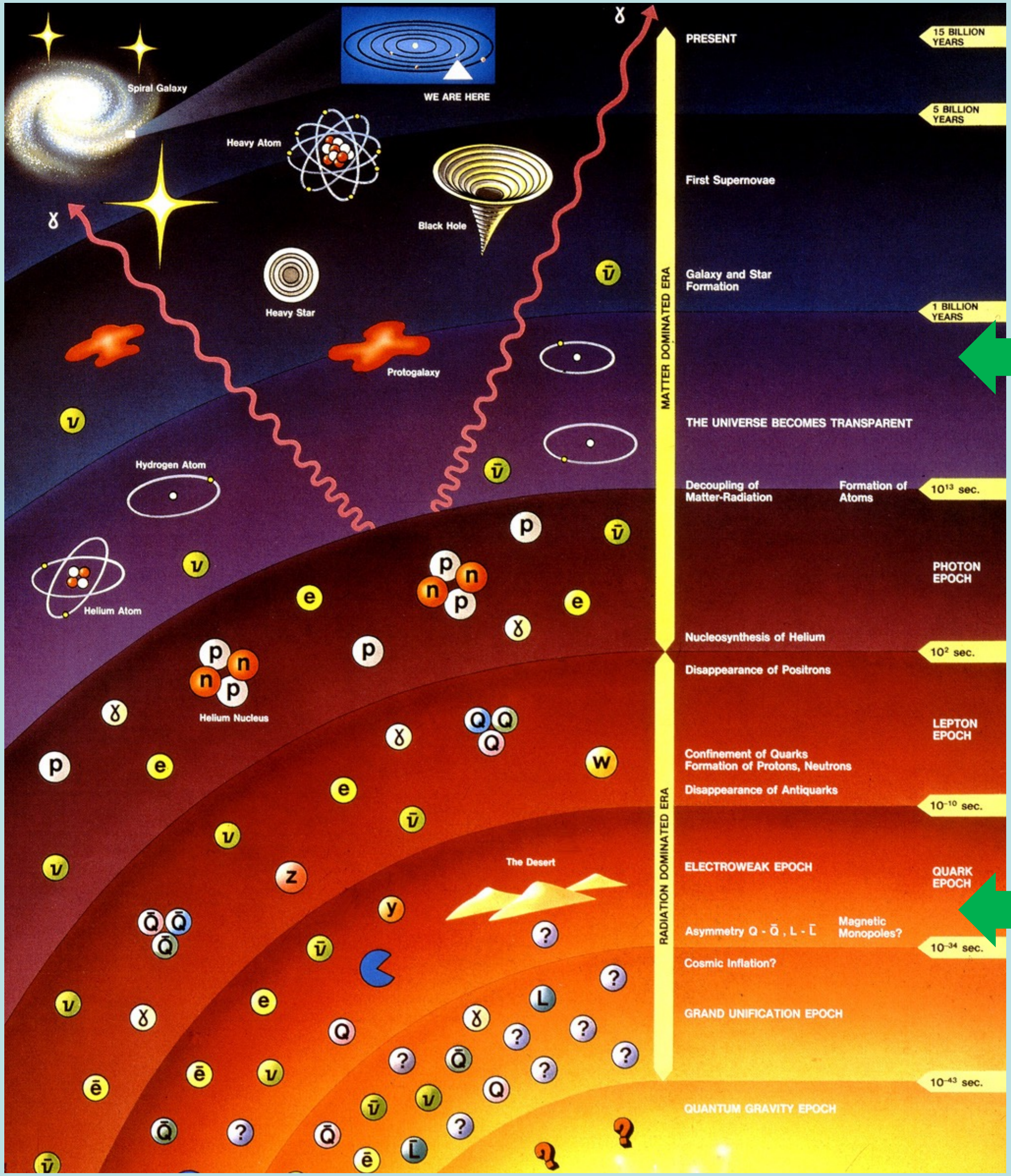
物質與背景輻射會有各自的溫度。各自會有自己的故事。

Big Bang Nucleosynthesis BBN

Recombination
Photon Decoupling

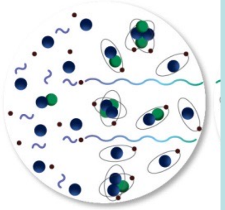


宇宙此時密度如同空氣！



Light and matter separate

- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

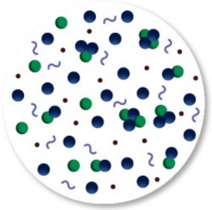


Last scattering of light off electrons

→ ***Polarisation***

Light and matter are coupled

Dark matter evolves independently: it starts clumping and forming a web of structures



As the Universe expands, particles collide less frequently

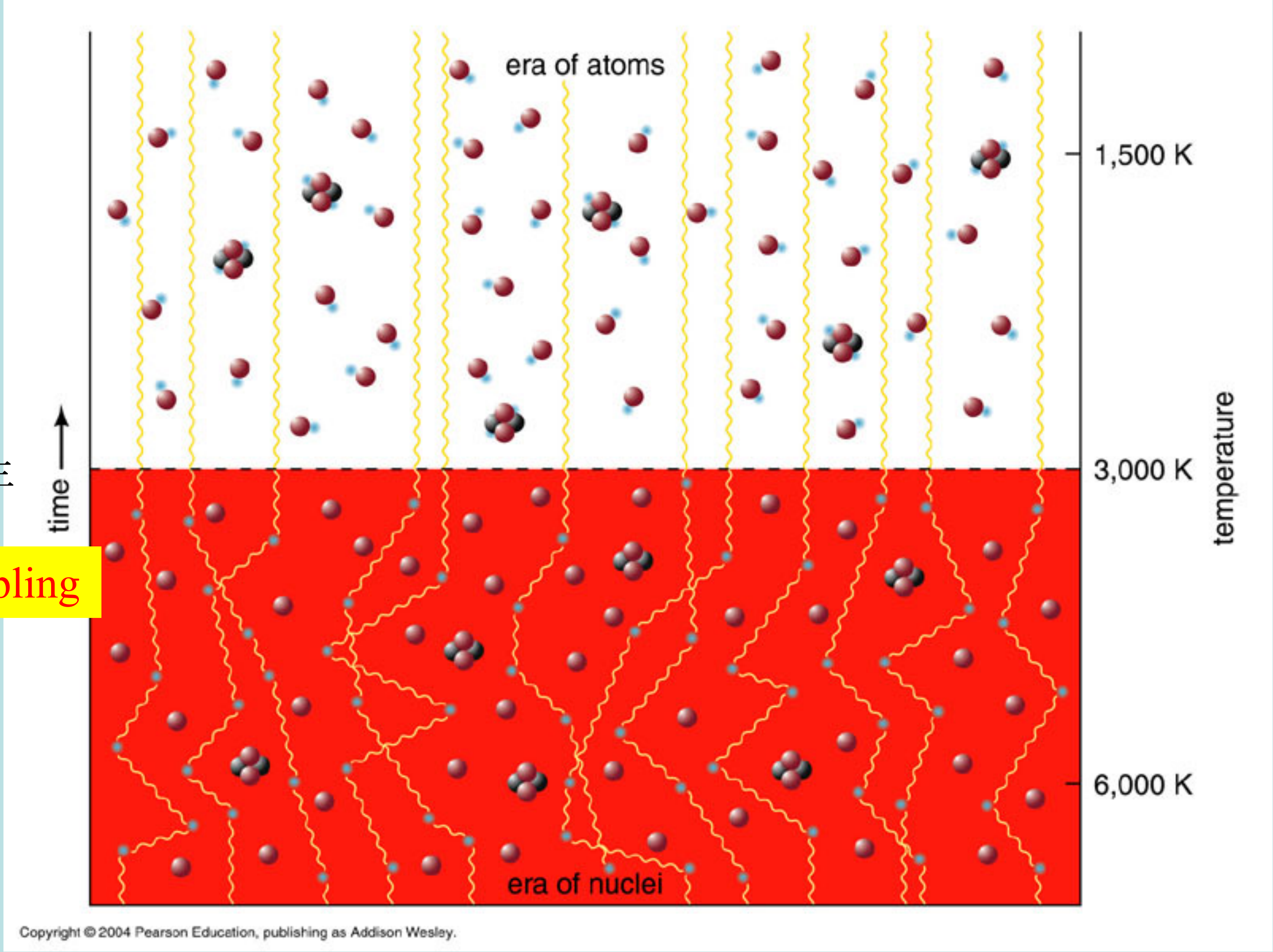
從此物質與背景輻射分道揚鑣，

物質沒有非常均勻的背景輻射的干擾，才能發展出不均勻的分佈。

若是沒有decoupling，現在整個宇宙還是一鍋均勻但稀疏的湯！

38萬年

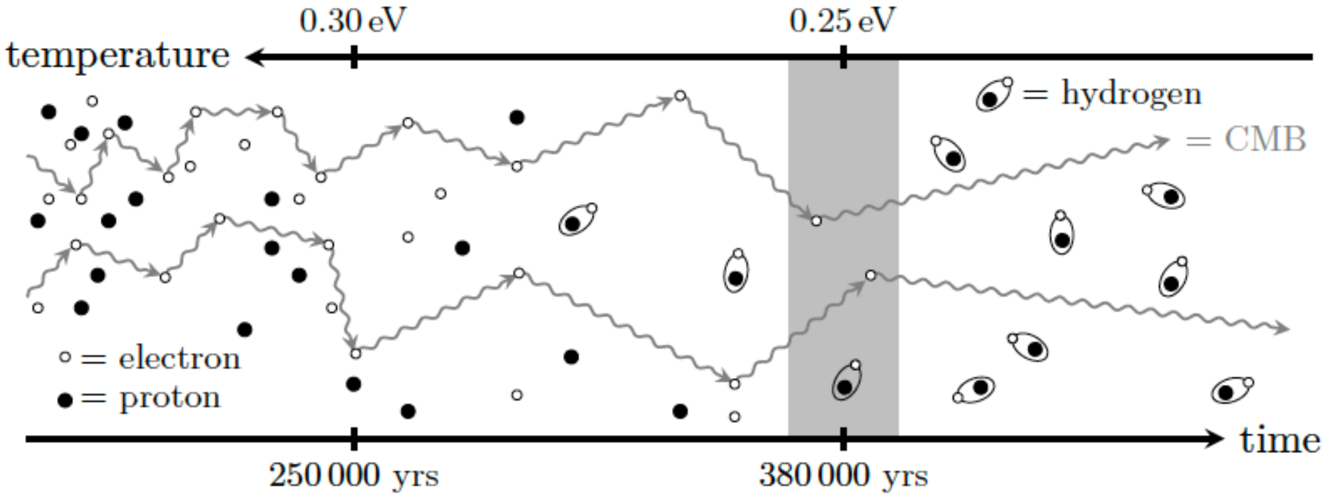
Photon Decoupling



Photon Decoupling之前，背景輻射不斷被電子散射，宇宙是模糊的。

之後，背景輻射不再被散射而直進，宇宙由模糊變透明。

透明的宇宙對輻射不留下任何痕跡。



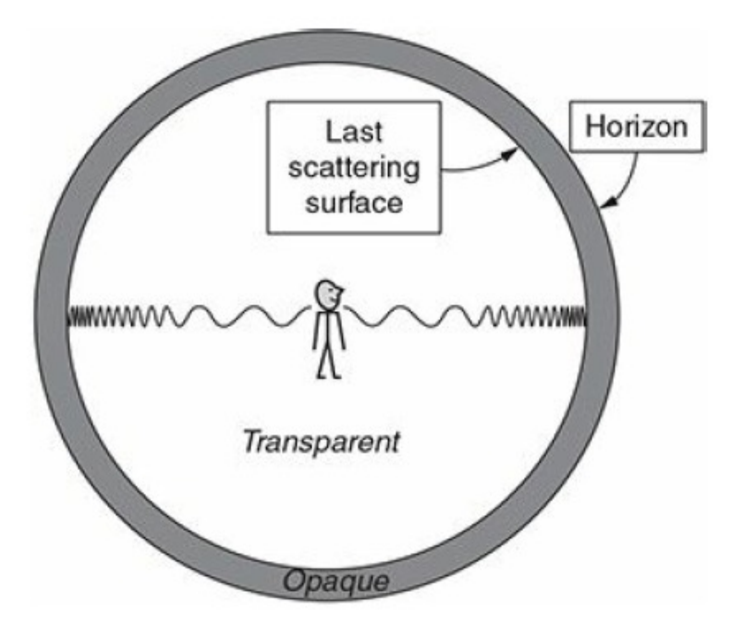
Cartoon of the recombination of protons and electrons into neutral hydrogen atoms and the corresponding decoupling of photons.

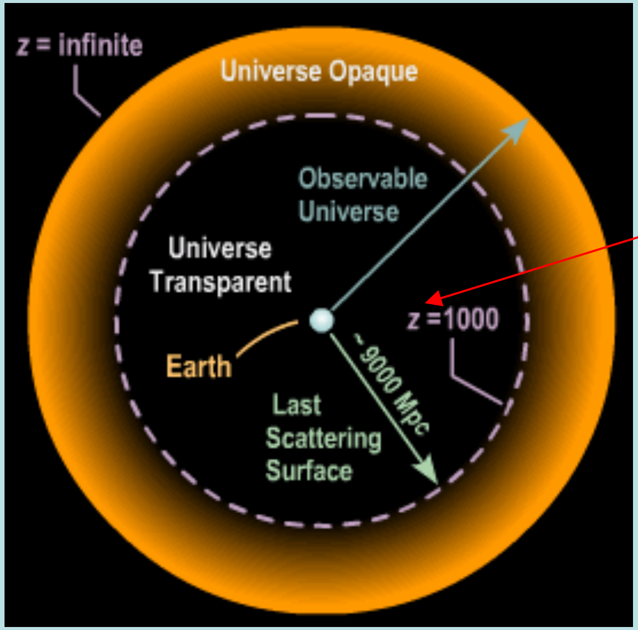
現在觀察到的背景輻射微波，自從宇宙誕生38萬年之後即無散射，而走直線。

它們的最後一次散射就發生在宇宙誕生38萬年時。

地球現在觀察到的微波在當時，分布於一個以地球為球心的球面上。

Surface of last scattering 最後散射面是位置的球面，也是歷史上特定的時間。

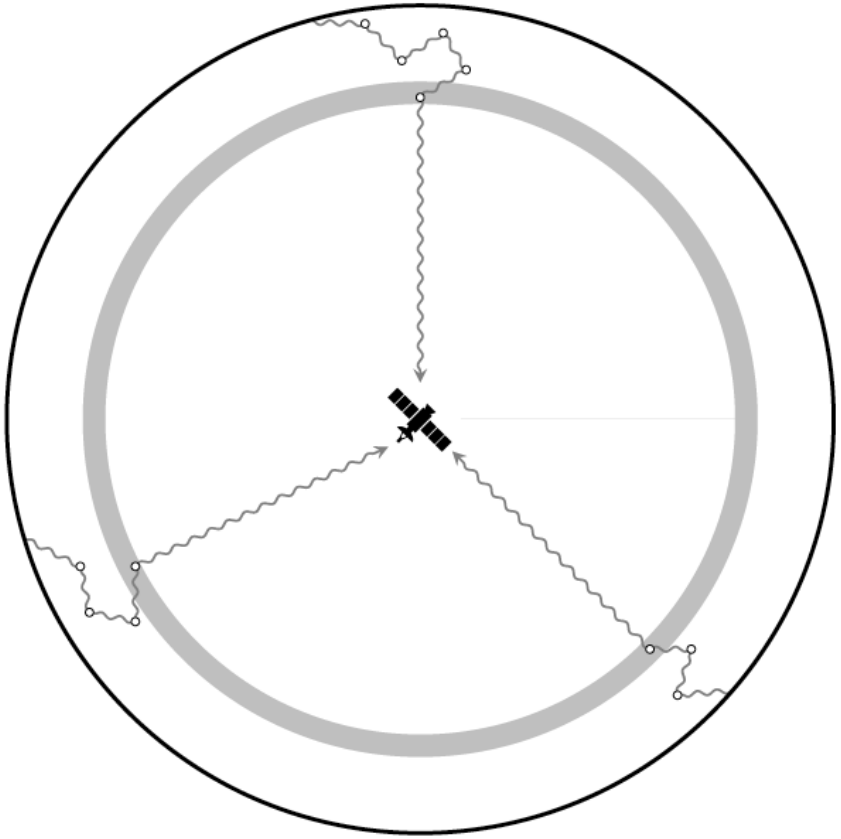




最後散射面對應的z

在這球面上，這些光作了最後一次散射，

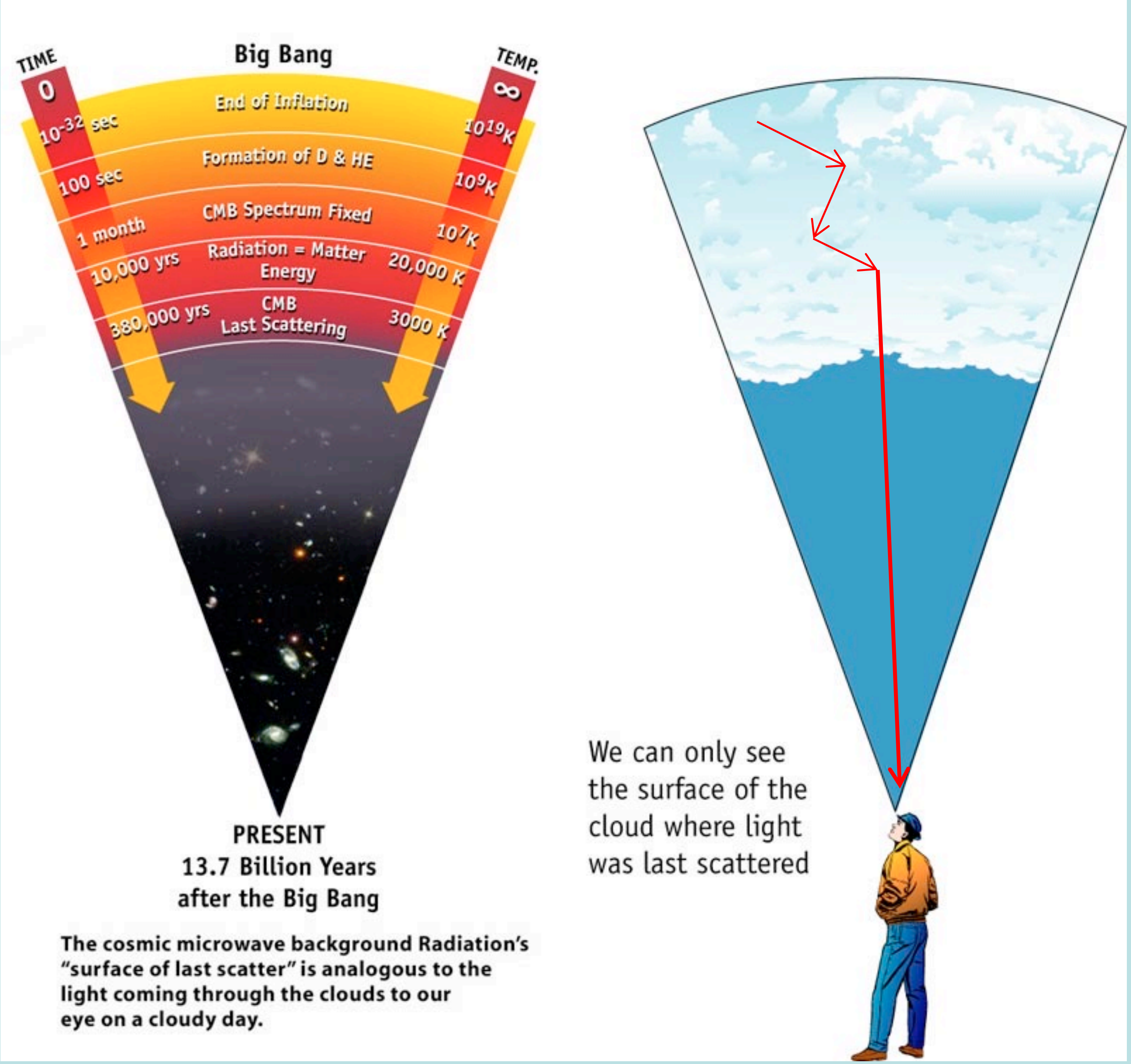
此球面上不同方向的物質分布的不均勻，就印在該角度的宇宙背景輻射微波上。



Cartoon of the last-scattering of CMB photons after recombination. Today we observe the CMB photons from the spherical surface of last-scattering.

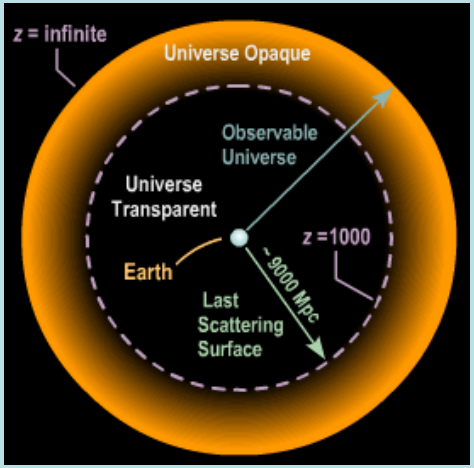
我們現在看到的宇宙背景輻射，猶如穿越雲層後被我們看到的光。

我們看到的光的影像，是雲層的下方表面，也就對應CMB的最後散射面！



We can only see the surface of the cloud where light was last scattered

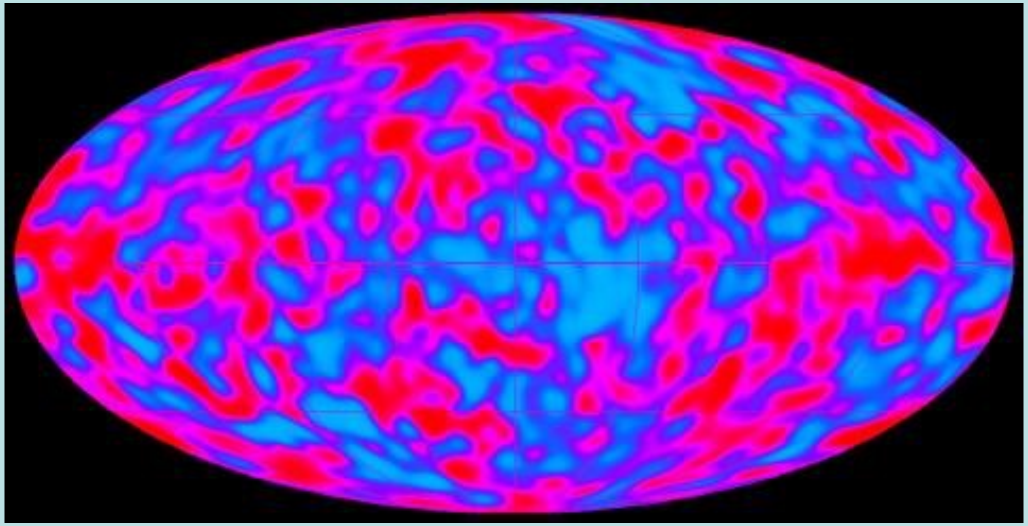
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



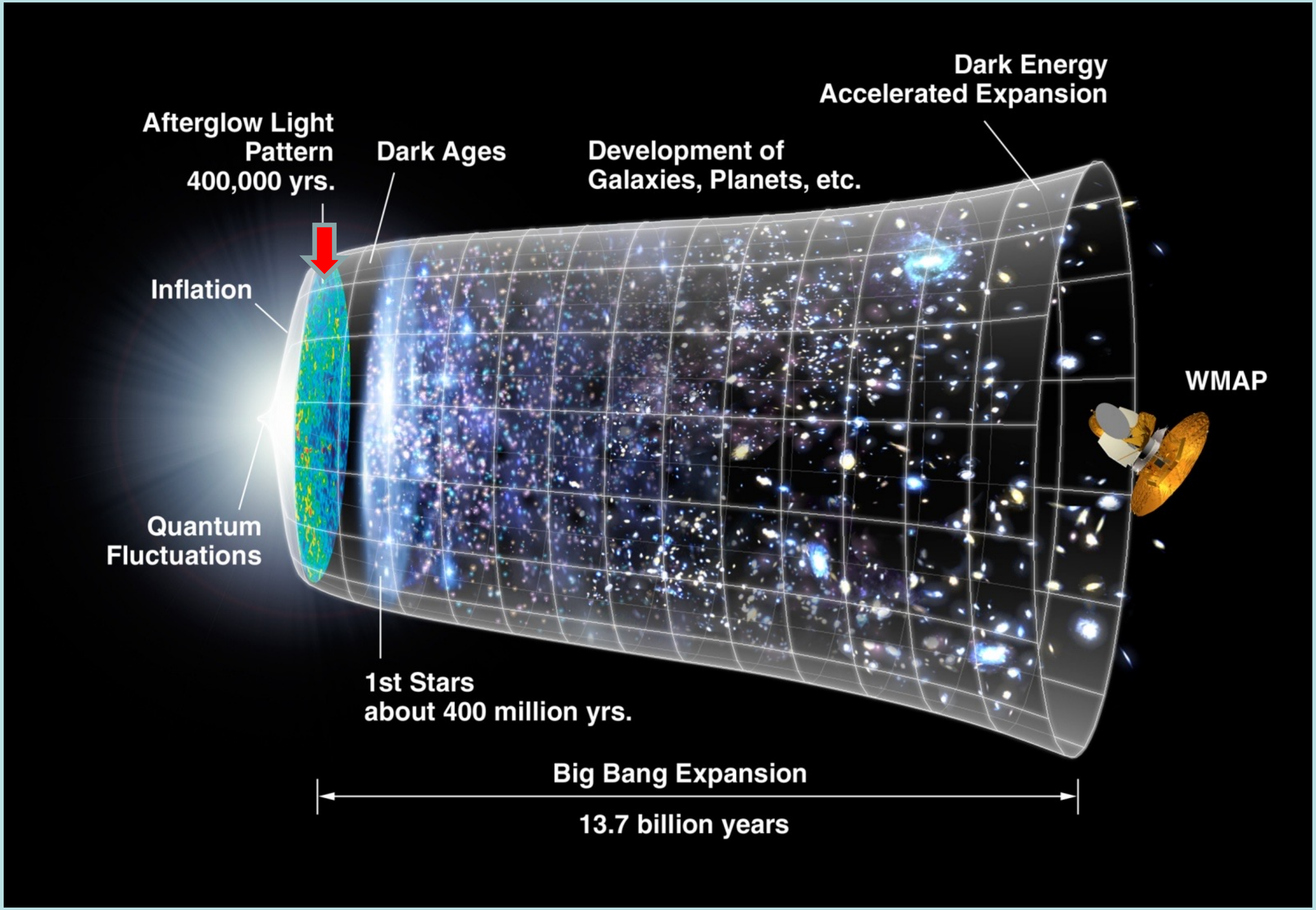
背景輻射極微小的非同向性，就是這個球面上物質的不均勻分布。

CMB的非均勻性，保留了宇宙誕生38萬年時的影像！

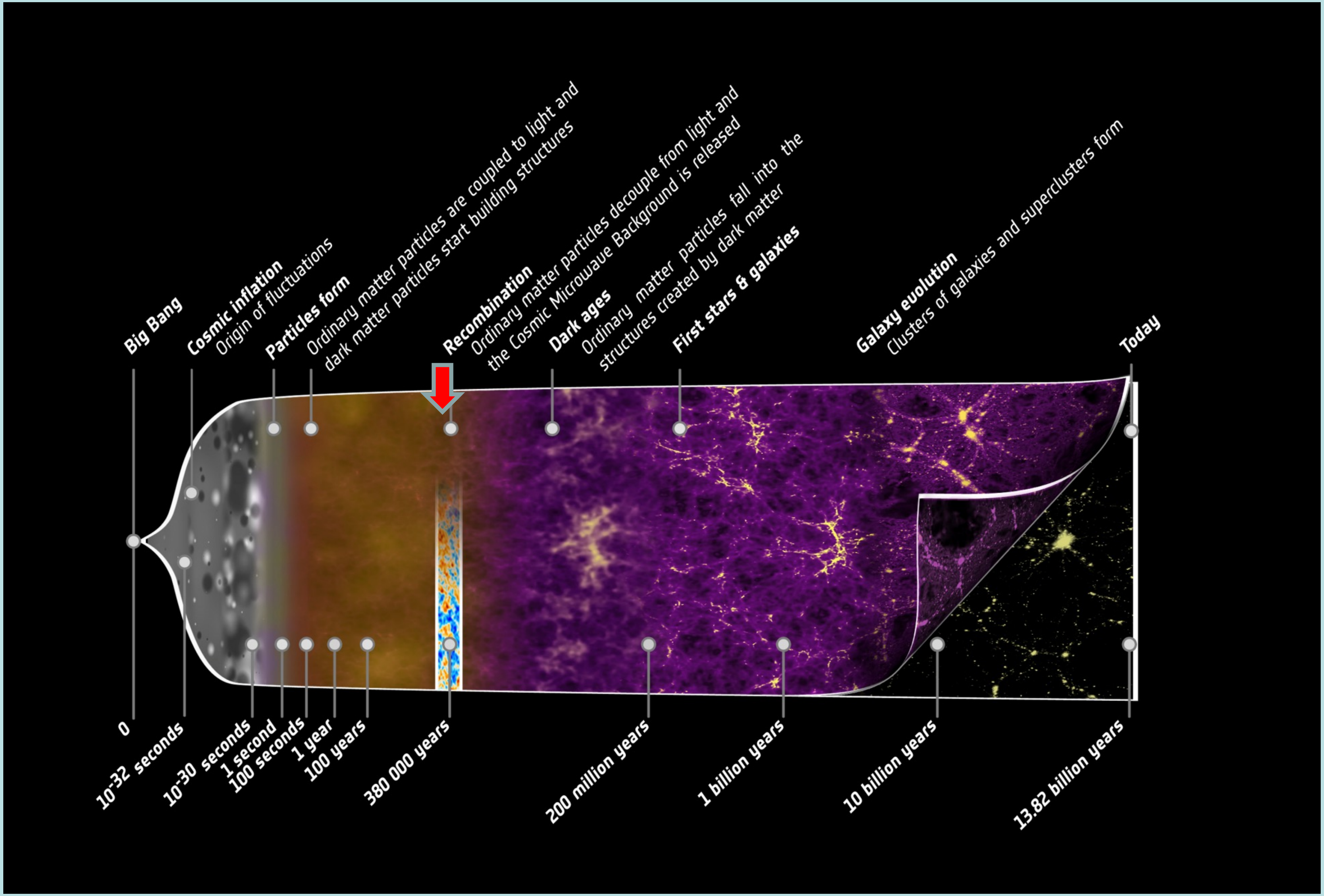
Cobe 1991



宇宙誕生38萬年時，也就是138 億年前的影像！



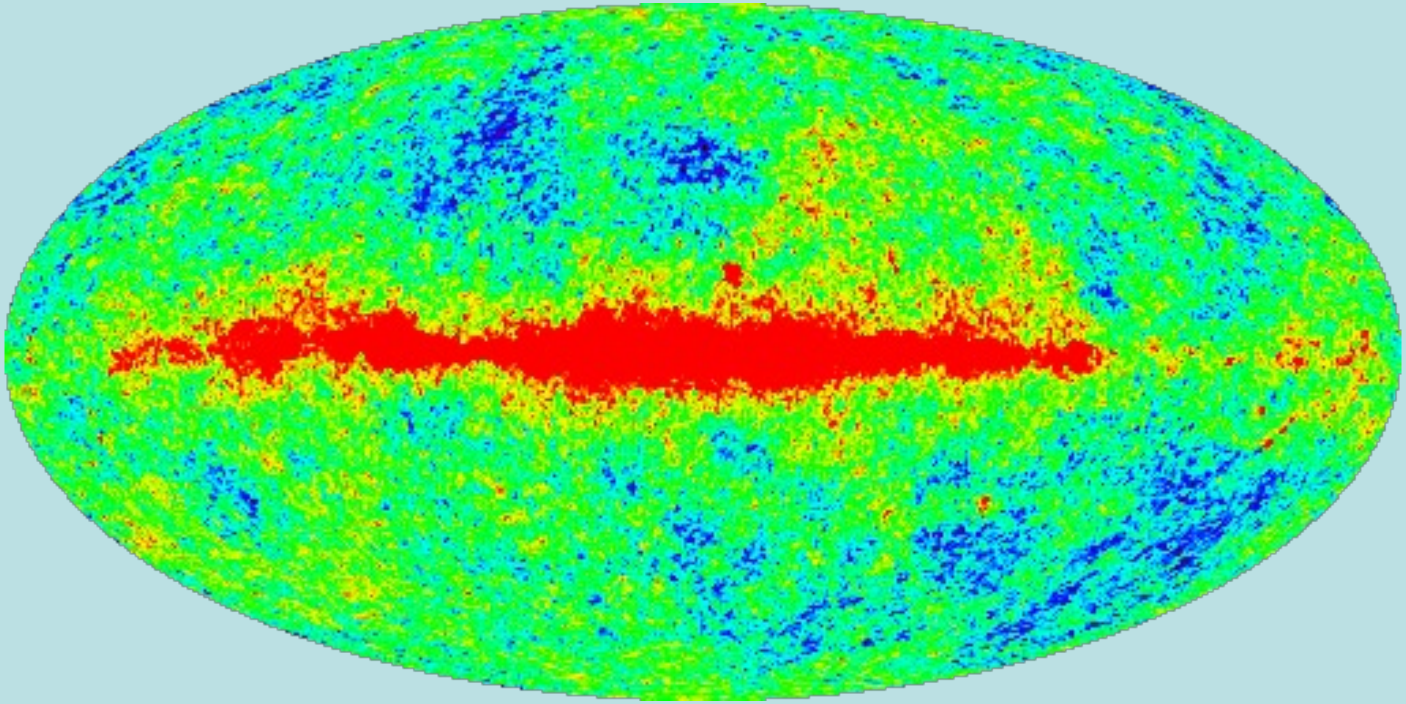
宇宙早期微小的物質分布不均勻，演化到今日形成星球，以及星系分布的不均勻。

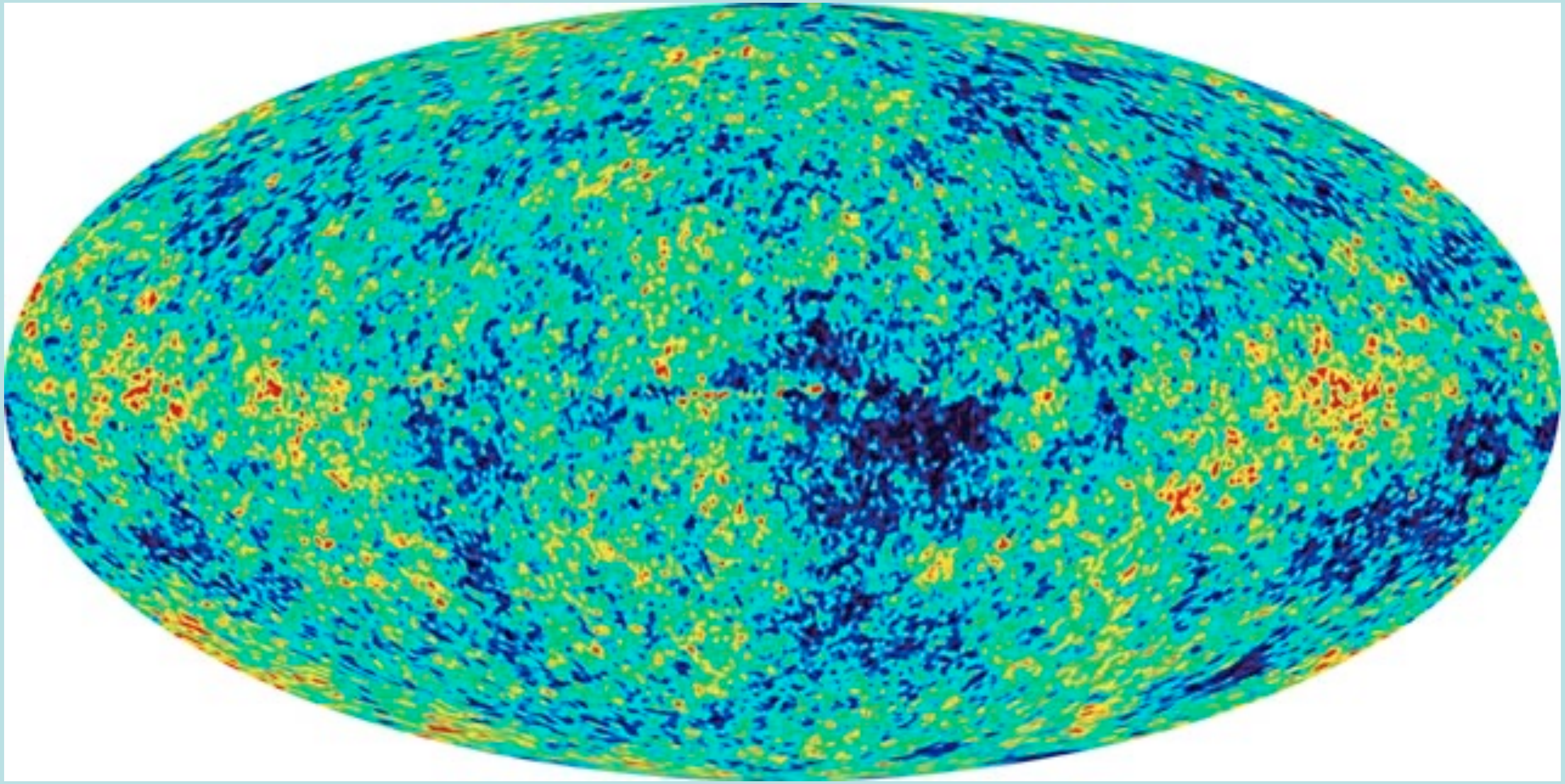


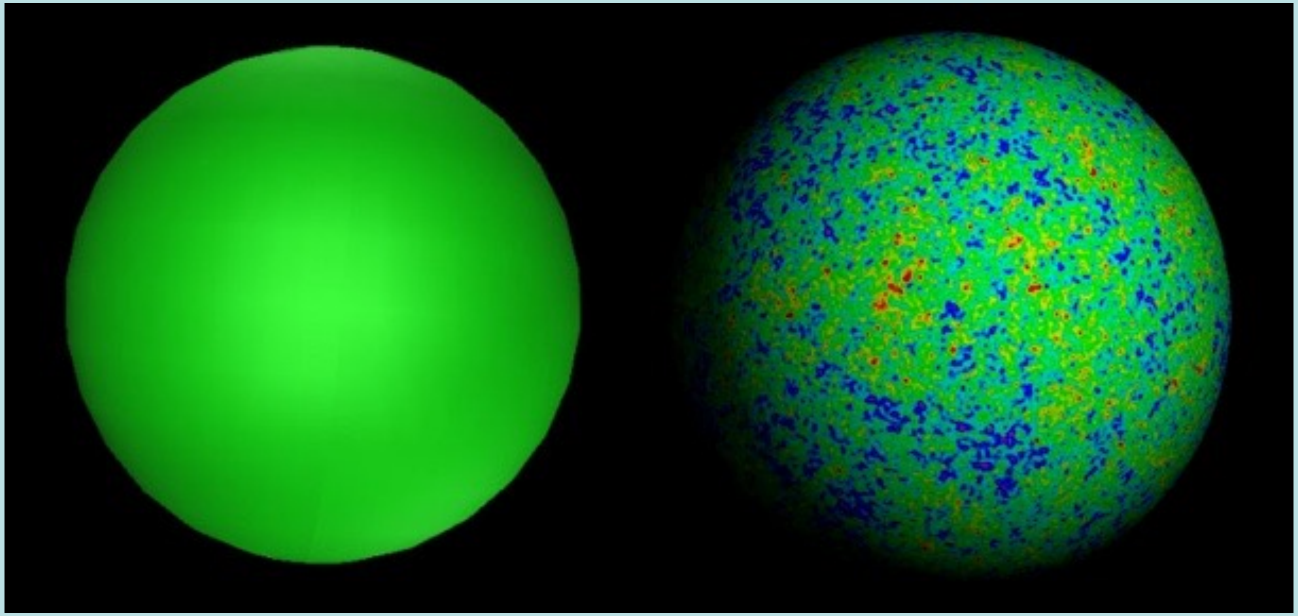
測量CMB非同向性，就是測量宇宙早期能量分布不均性。

宇宙背景輻射非同向性數據

WMAP 2005



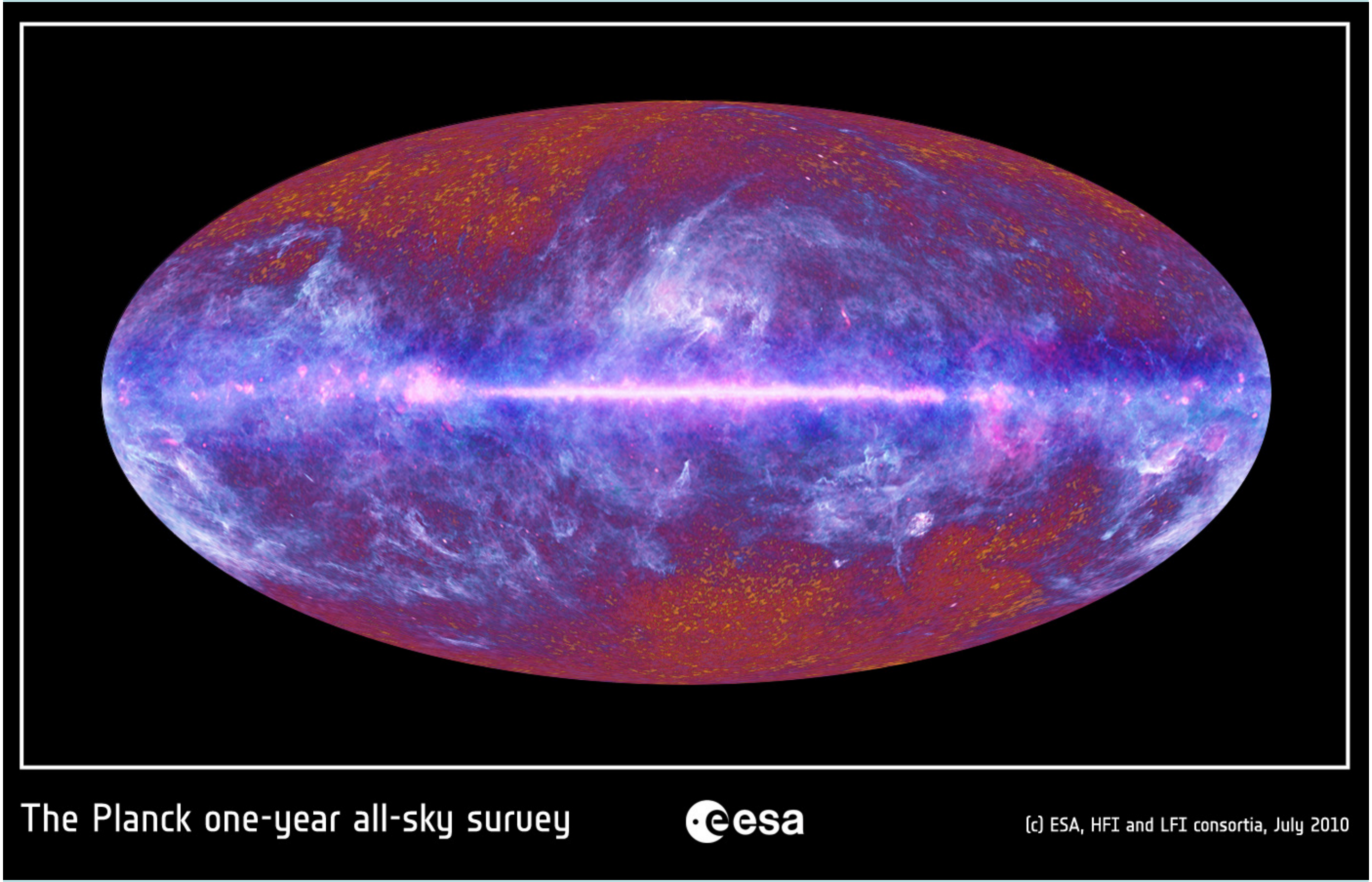




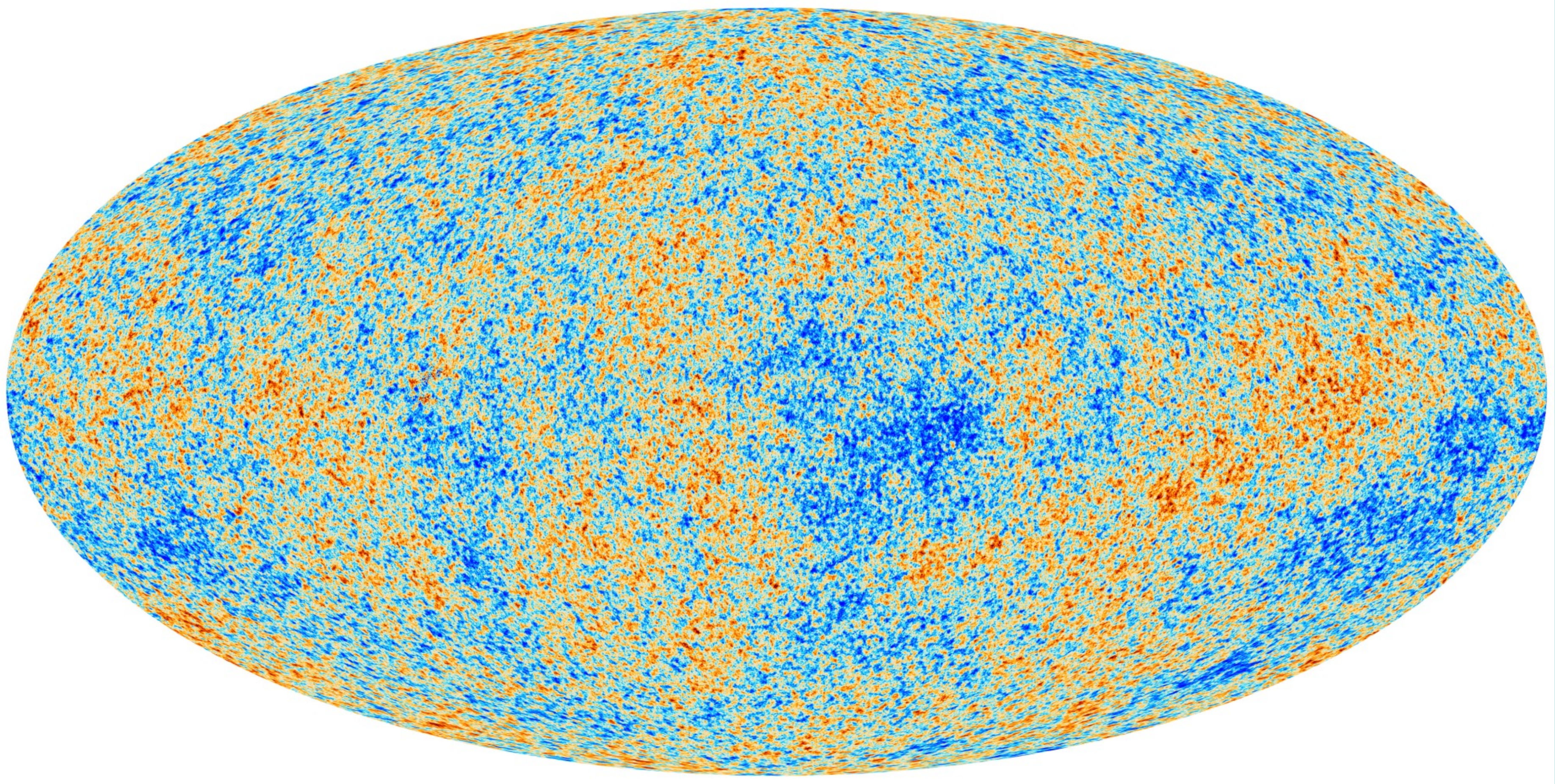

esa

PLANCK

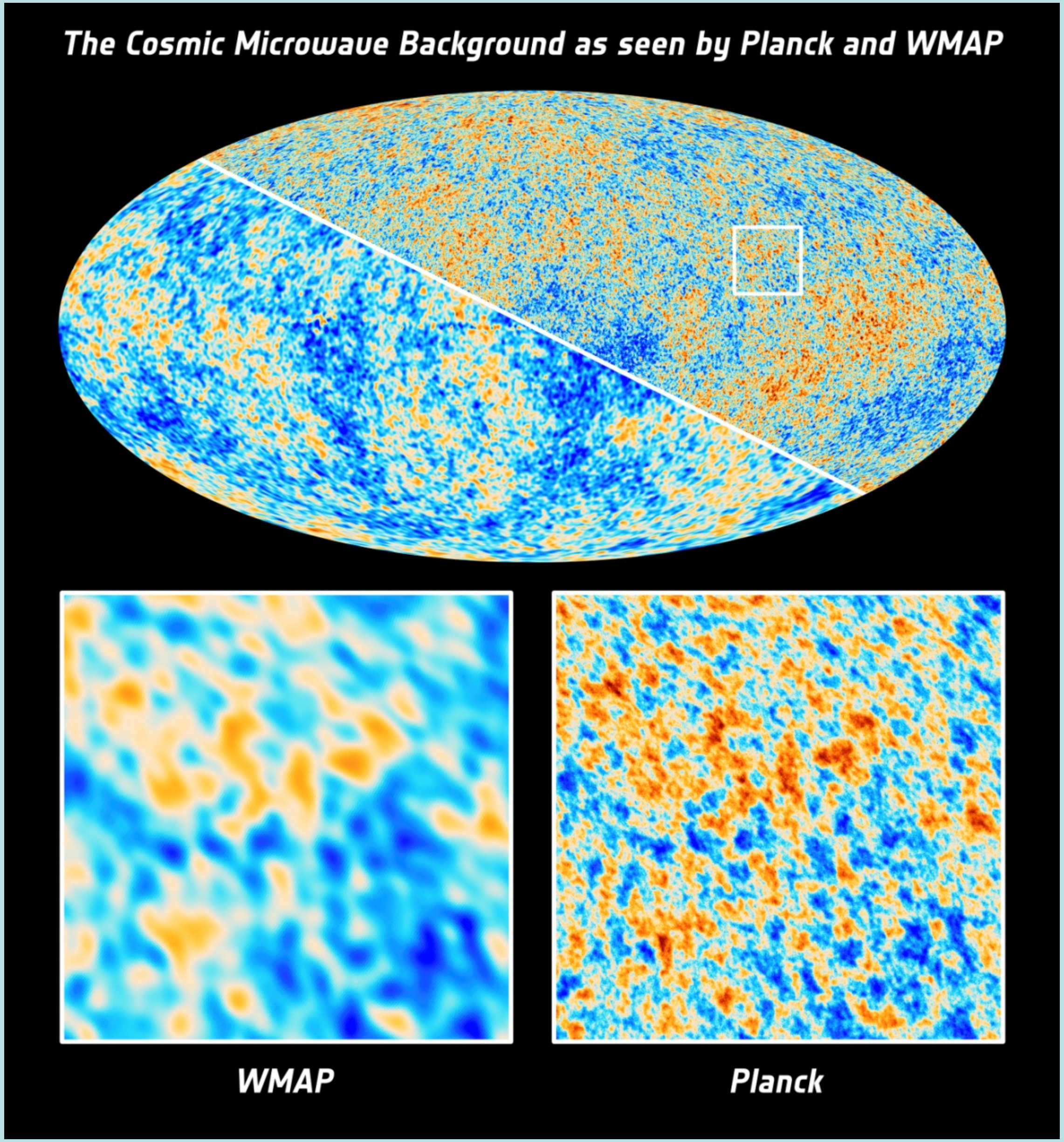
Looking back to the dawn of time



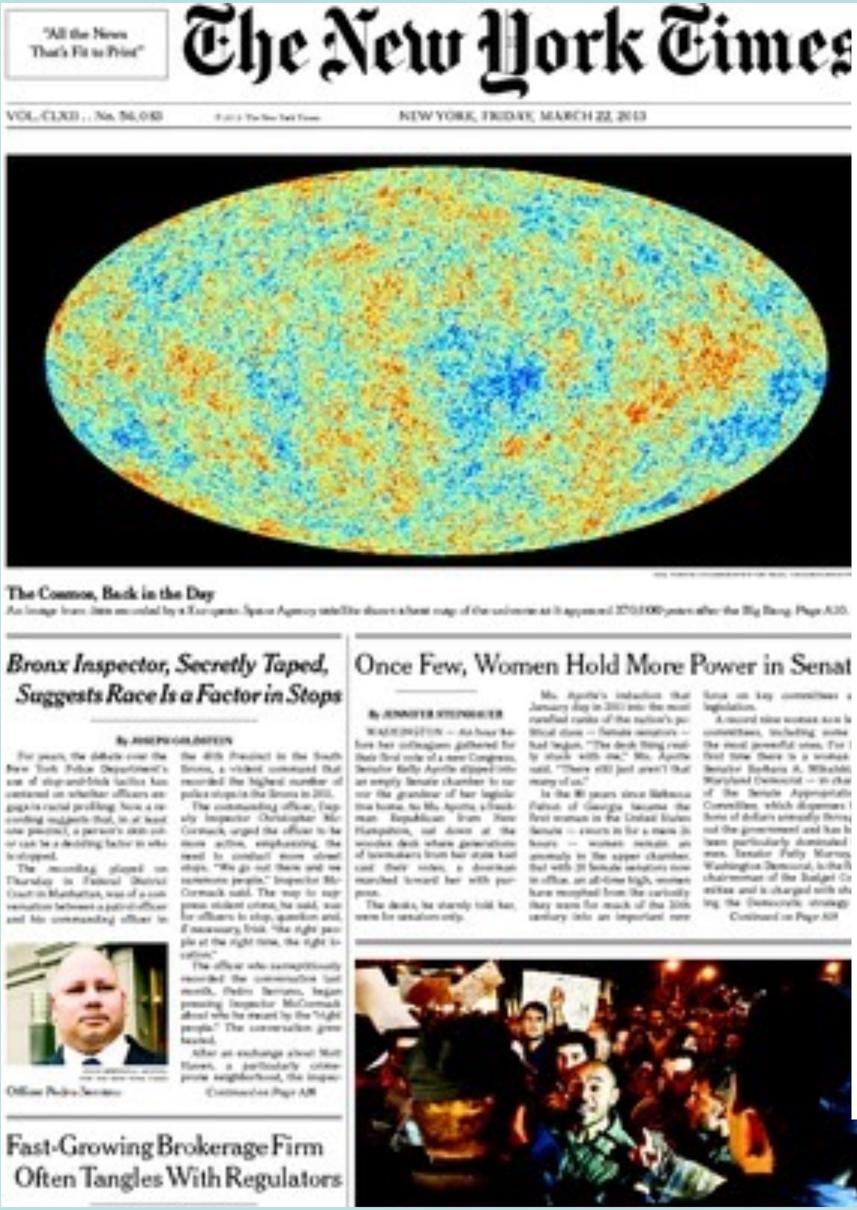
Planck 看到的星光



The anisotropies of the Cosmic Microwave Background (CMB) as observed by Planck 2013.



Planck 非常精密，對角度的解析更好



"All the News That's Fit to Print"

The New York Times

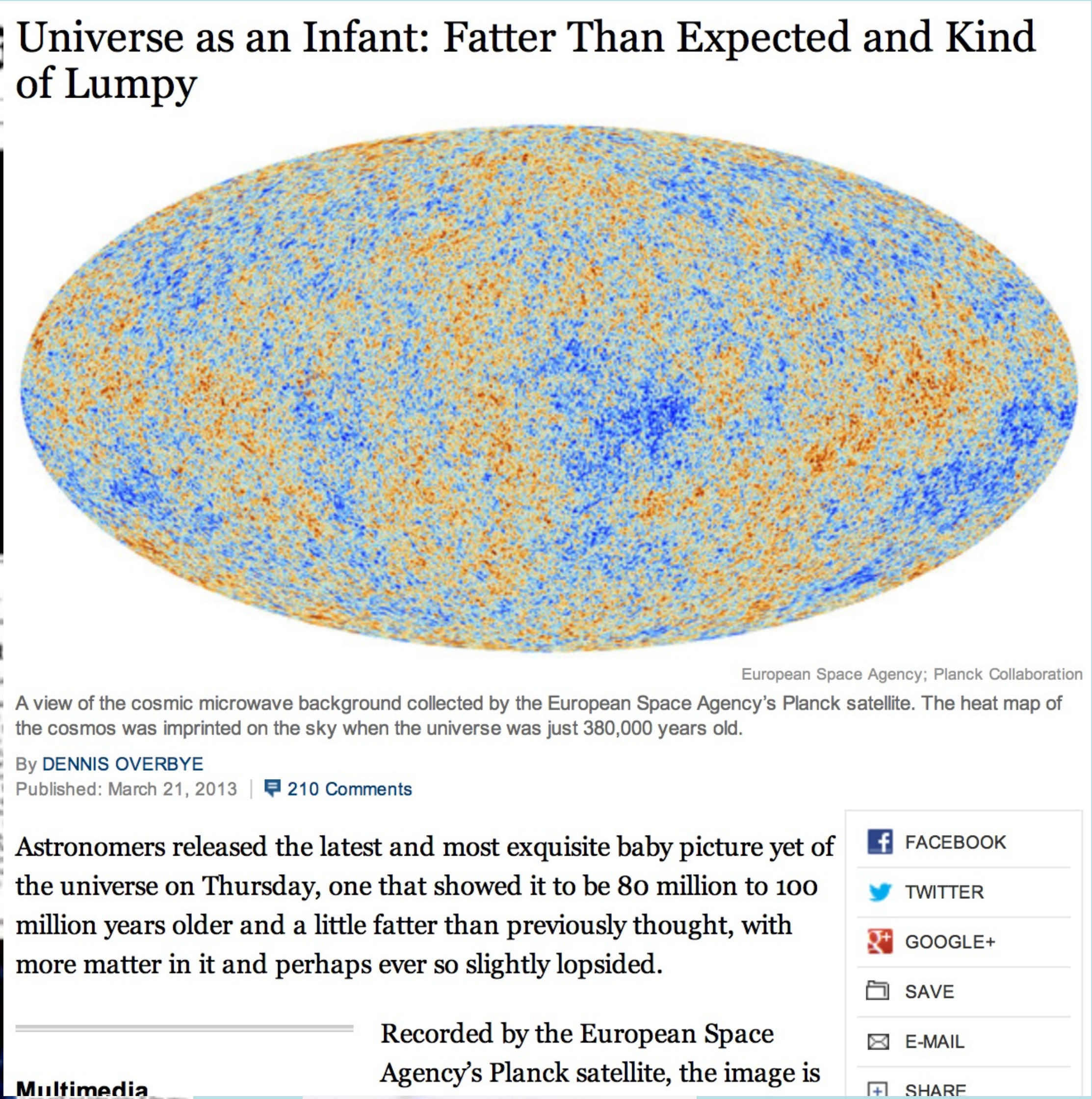
NEW YORK, FRIDAY, MARCH 22, 2013

The Cosmos, Back in the Day

Bronx Inspector, Secretly Taped, Suggests Race Is a Factor in Stops

Once Few, Women Hold More Power in Senat

Fast-Growing Brokerage Firm Often Tangles With Regulators



Universe as an Infant: Fatter Than Expected and Kind of Lumpy

European Space Agency; Planck Collaboration

A view of the cosmic microwave background collected by the European Space Agency's Planck satellite. The heat map of the cosmos was imprinted on the sky when the universe was just 380,000 years old.

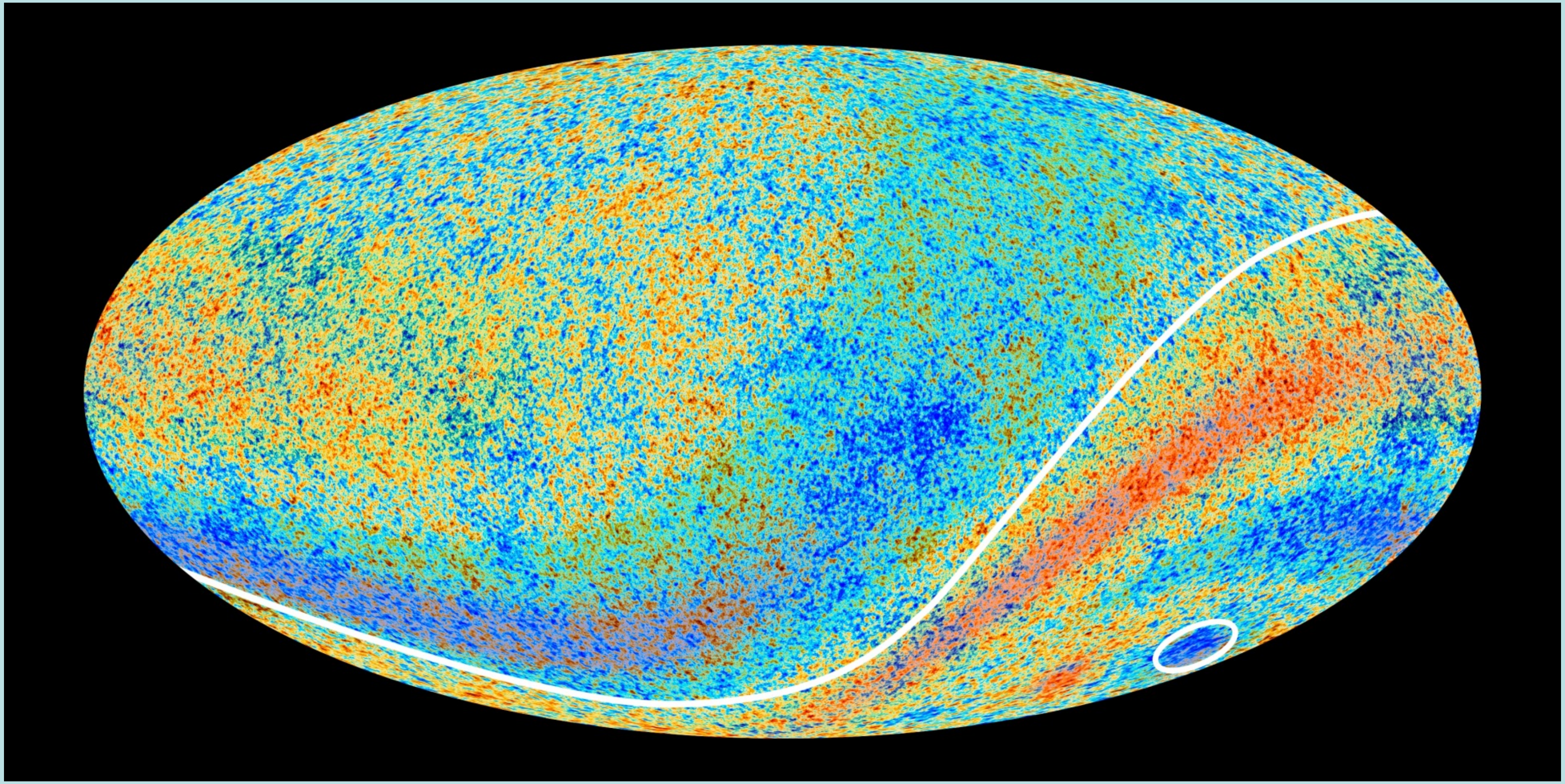
By DENNIS OVERBYE

Published: March 21, 2013 | 210 Comments

Astronomers released the latest and most exquisite baby picture yet of the universe on Thursday, one that showed it to be 80 million to 100 million years older and a little fatter than previously thought, with more matter in it and perhaps ever so slightly lopsided.

Recorded by the European Space Agency's Planck satellite, the image is

Multimedia



Asymmetry in the average temperatures on opposite hemispheres of the sky

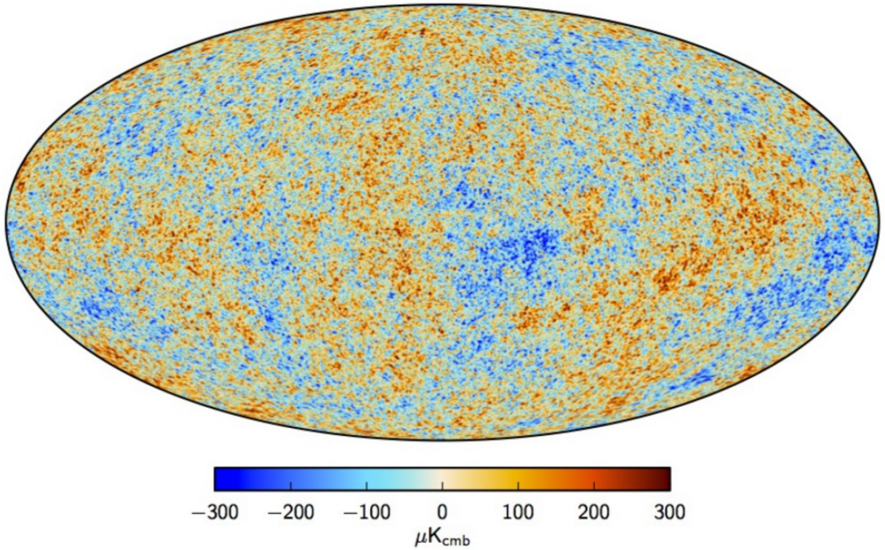


Fig. 7. Maximum posterior CMB intensity map at 5′ resolution derived from the joint baseline analysis of *Planck*, WMAP, and 408 MHz observations. A small strip of the Galactic plane, 1.6 % of the sky, is filled in by a constrained realization that has the same statistical properties as the rest of the sky.

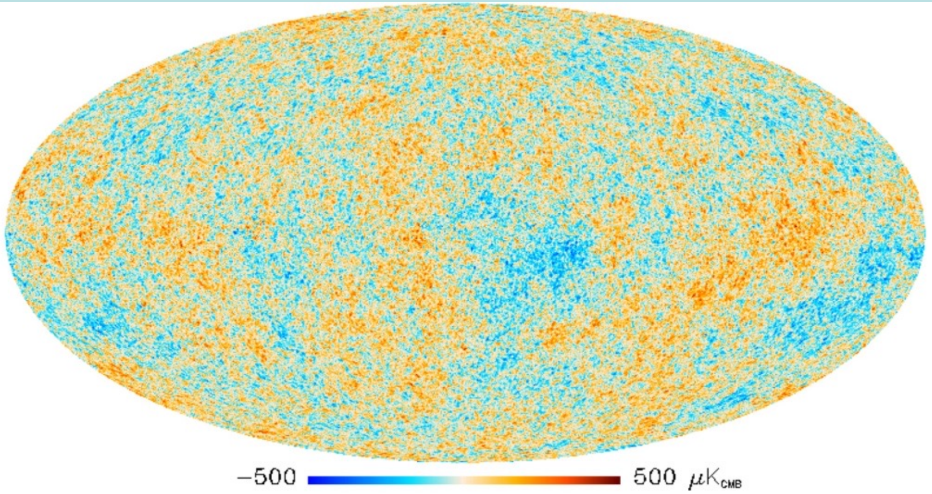
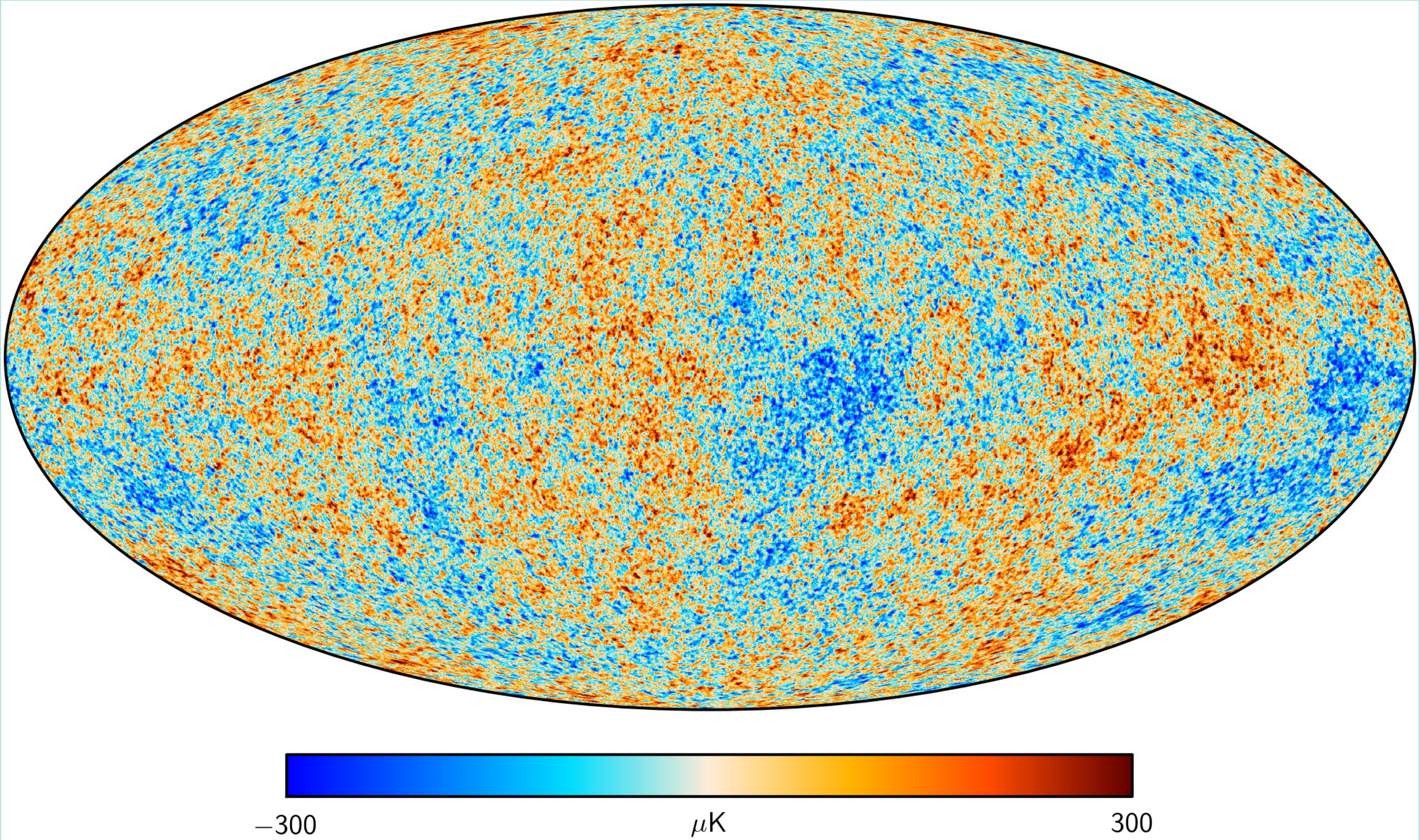


Fig. 14. The SMICA CMB map (with 3 % of the sky replaced by a constrained Gaussian realization).

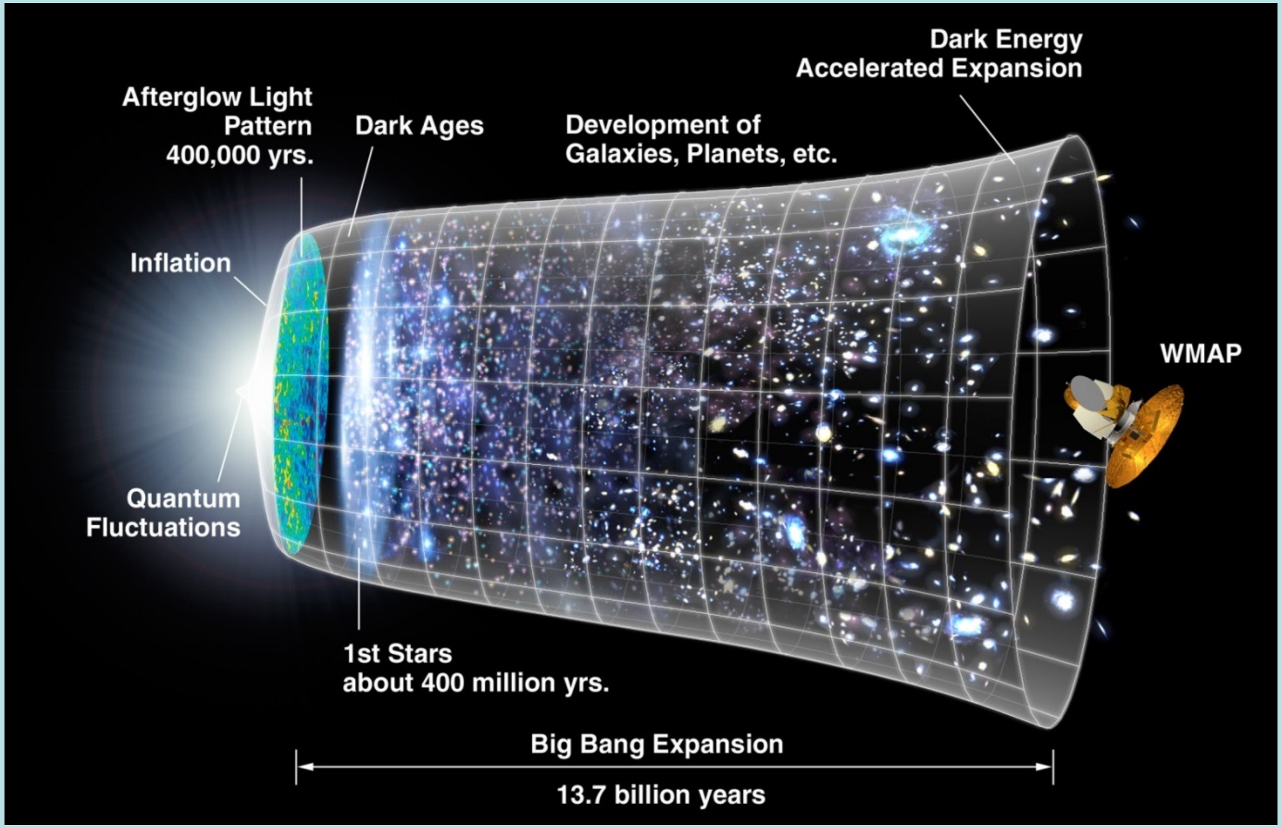
The 2015 *Planck* CMB temperature maps produced by all four methods (see an example in Fig. 7) are significantly more sensitive than those produced in 2013 (by a factor of 1.3).



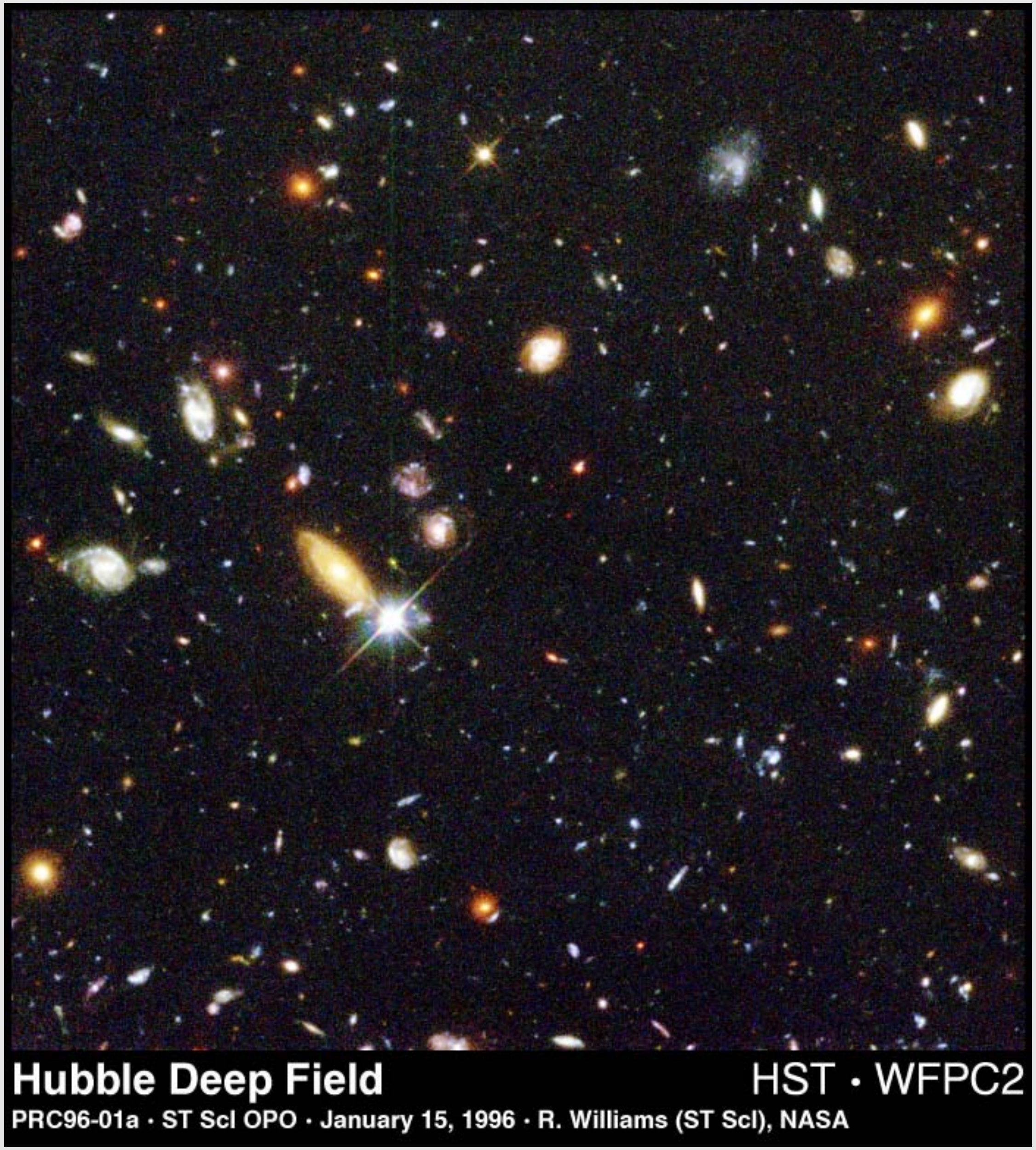
The anisotropies of the Cosmic Microwave Background (CMB) as observed by Planck 2015.

我們會為了一張137億年的老照片 這麼大費周章嗎？

這張照片除了當年的資訊，還包含了中間宇宙演化的歷史！

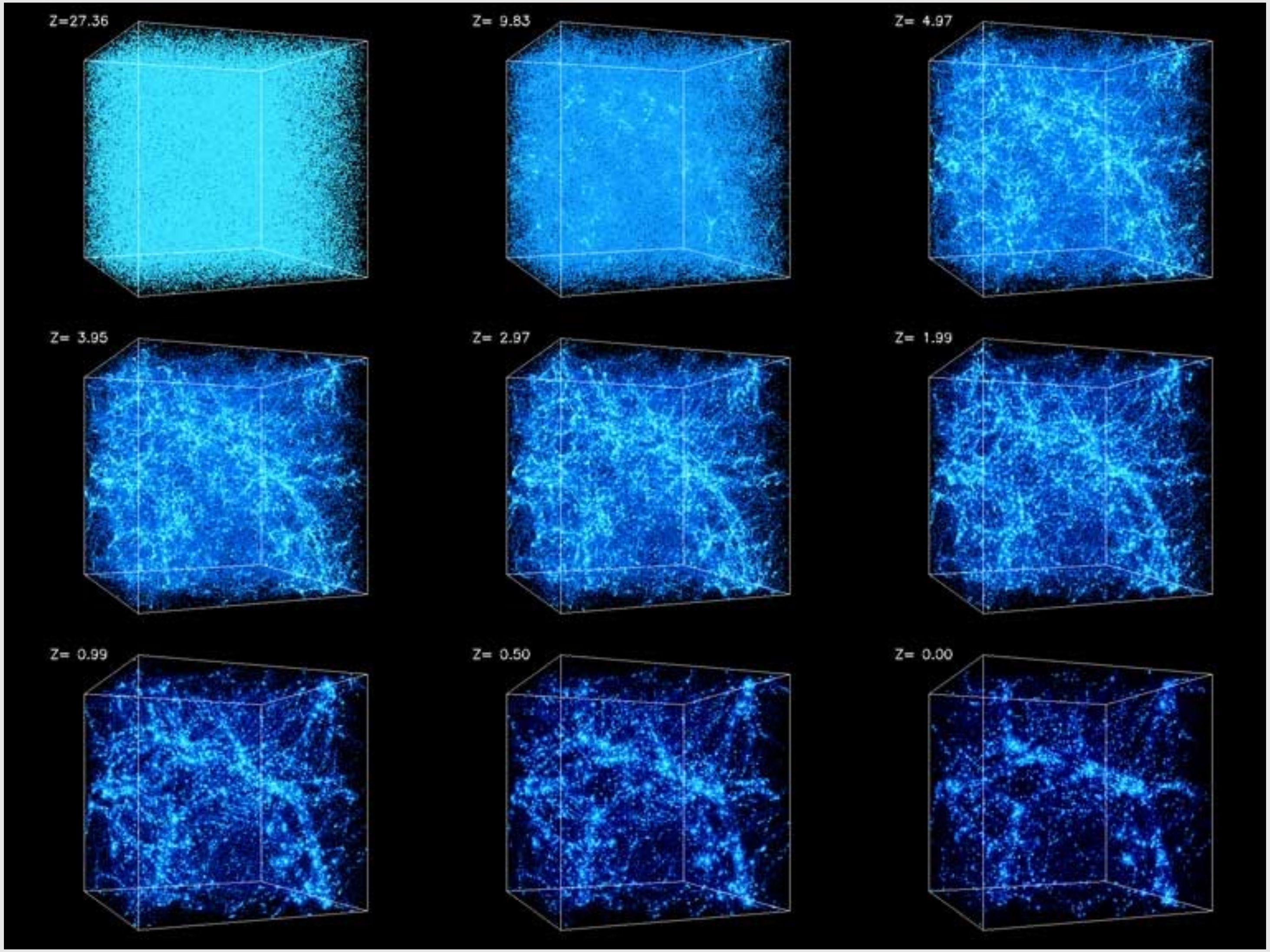


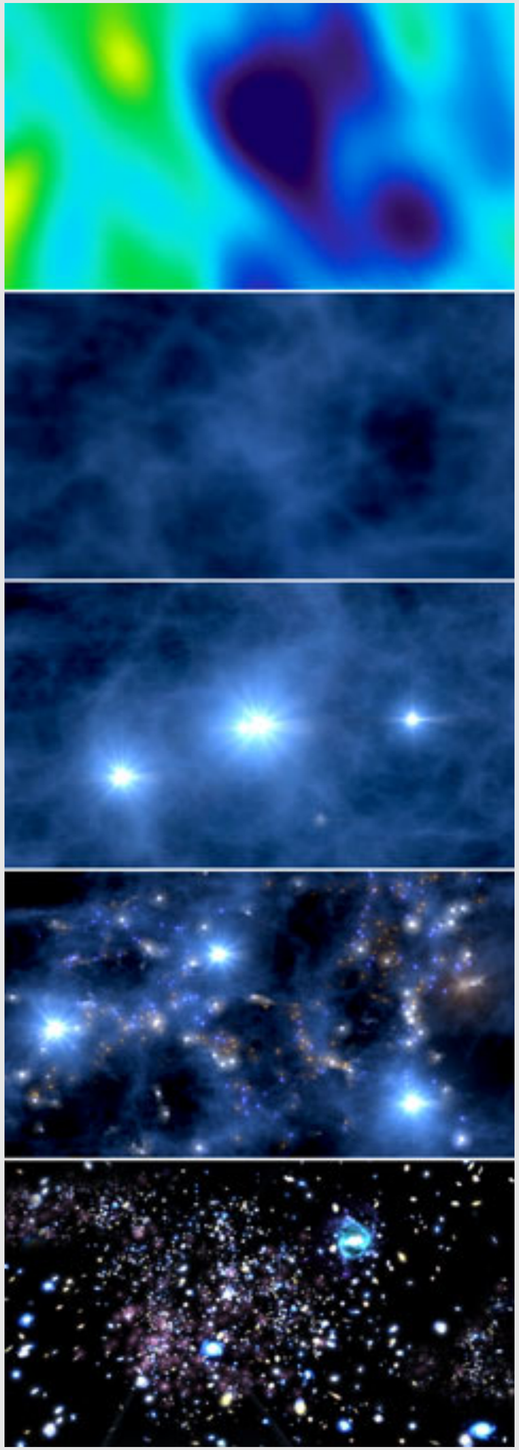
宇宙早期能量分布不均性，在擴張下演化為宇宙中的結構



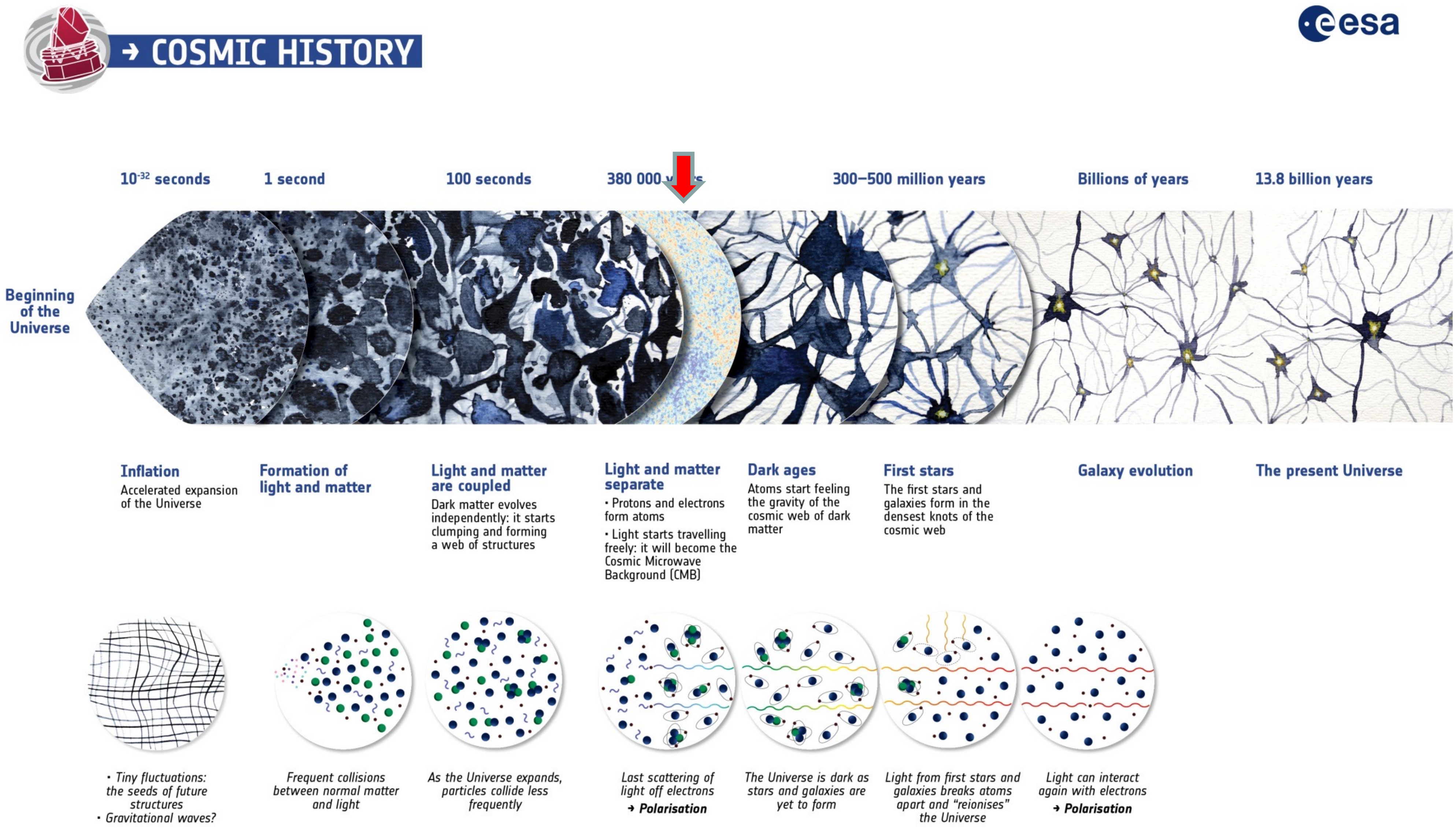
Structure formation

宇宙早期物質密度微小的不均勻，由於引力吸引漸漸形成宇宙中的結構





星球才能形成



我們對此宇宙早期微小的不均勻，有理論可以計算，等待驗證。

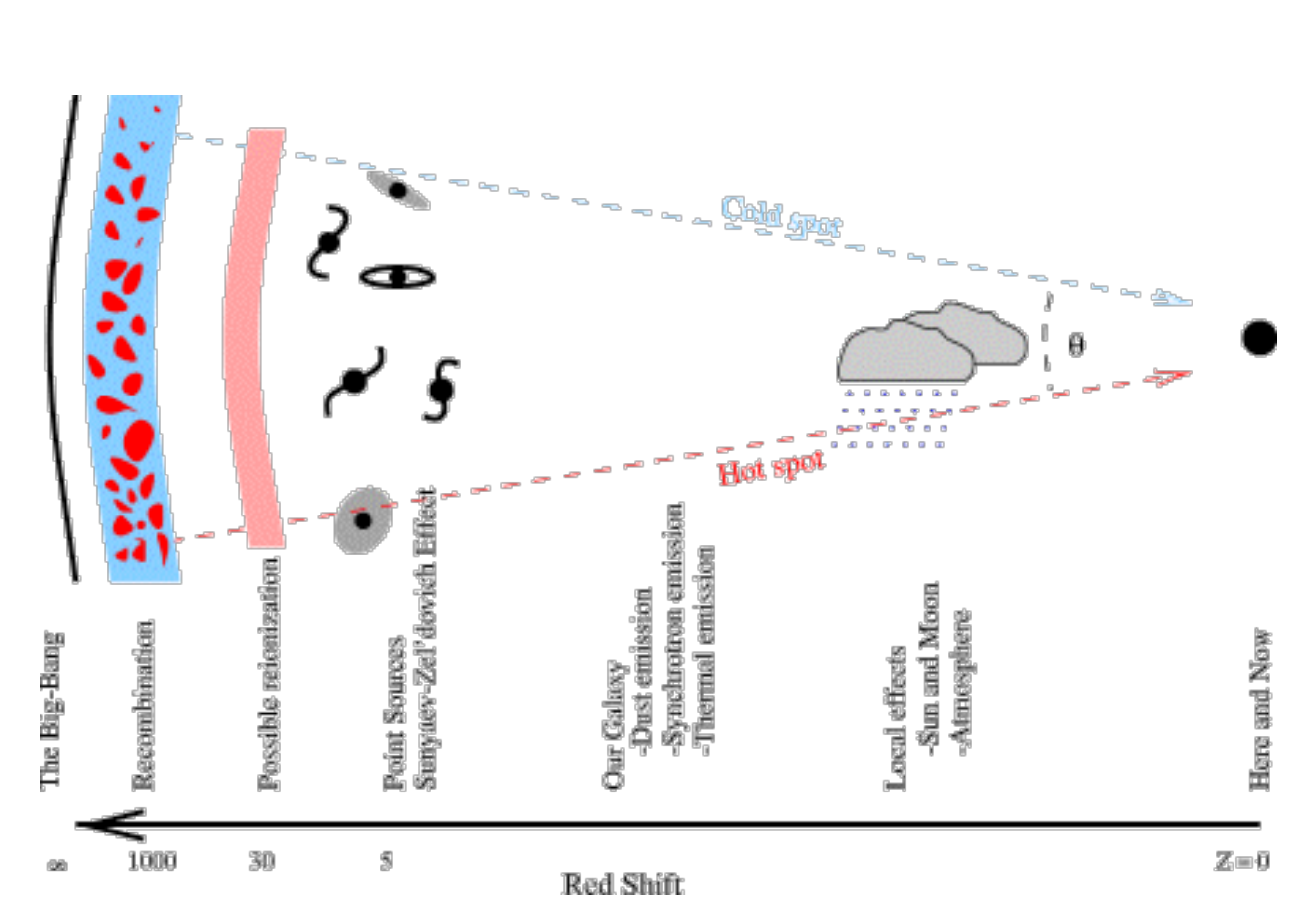
宇宙早期能量分布不均性，在最後散射面烙印於背景輻射之上，產生了CMB非同向性。

精確測量CMB非同向性即有機會驗證理論的計算。

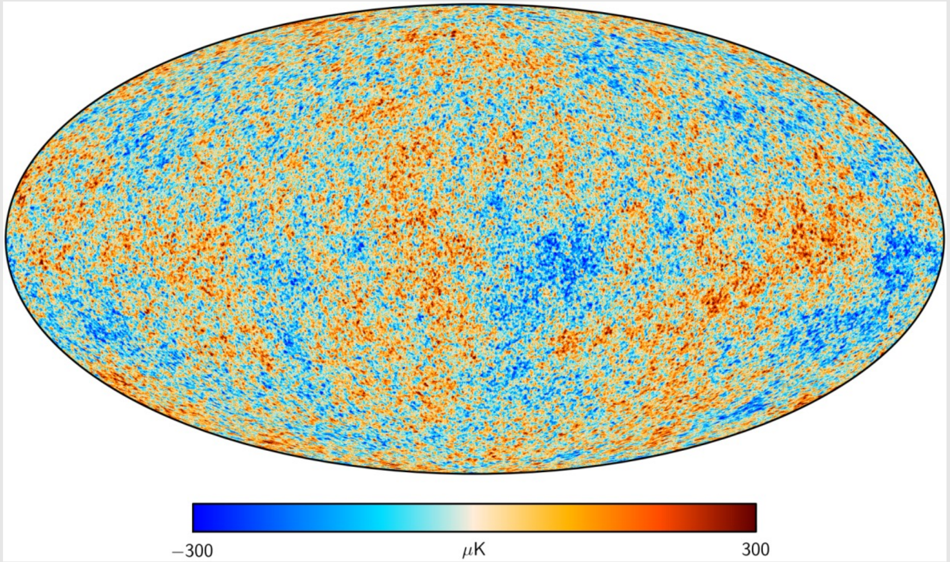
而且CMB由當時傳播到現在、與物質雖無散射，但會受到中間宇宙擴張的影響。

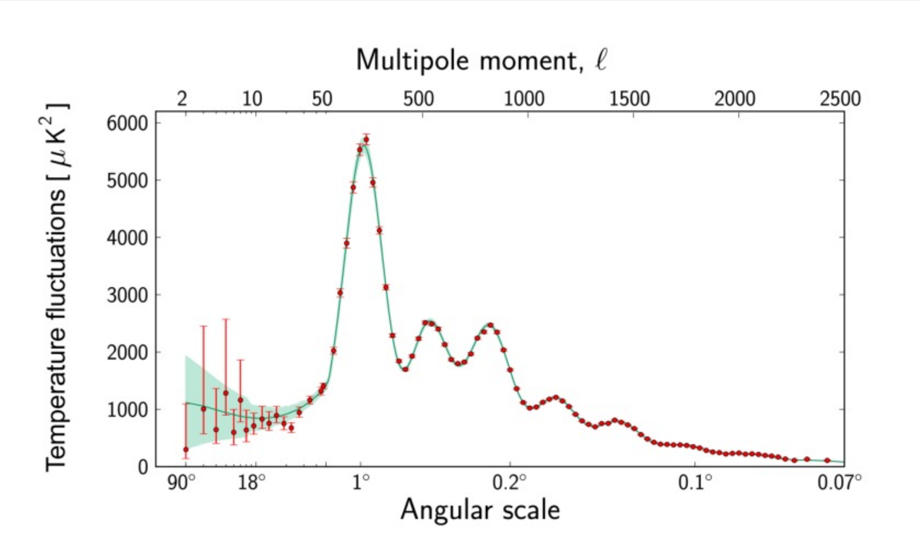
CMB經歷了整個宇宙擴張的歷史。

CMB記錄了最後散射面上的不均勻度，同時包含了當時到現在宇宙演化的歷史，兩者都對宇宙的特性十分敏感。



一般的做法就是設想一系列宇宙擴張的模型與參數，模擬預測出CMB的數據，再與觀測的數據對照，找出能正確預測數據的模型與參數！





例如非同向性的定量數據分析。

專業稱傅立葉分析，將左圖溫度差異對角度的變化作展開，得到右圖。

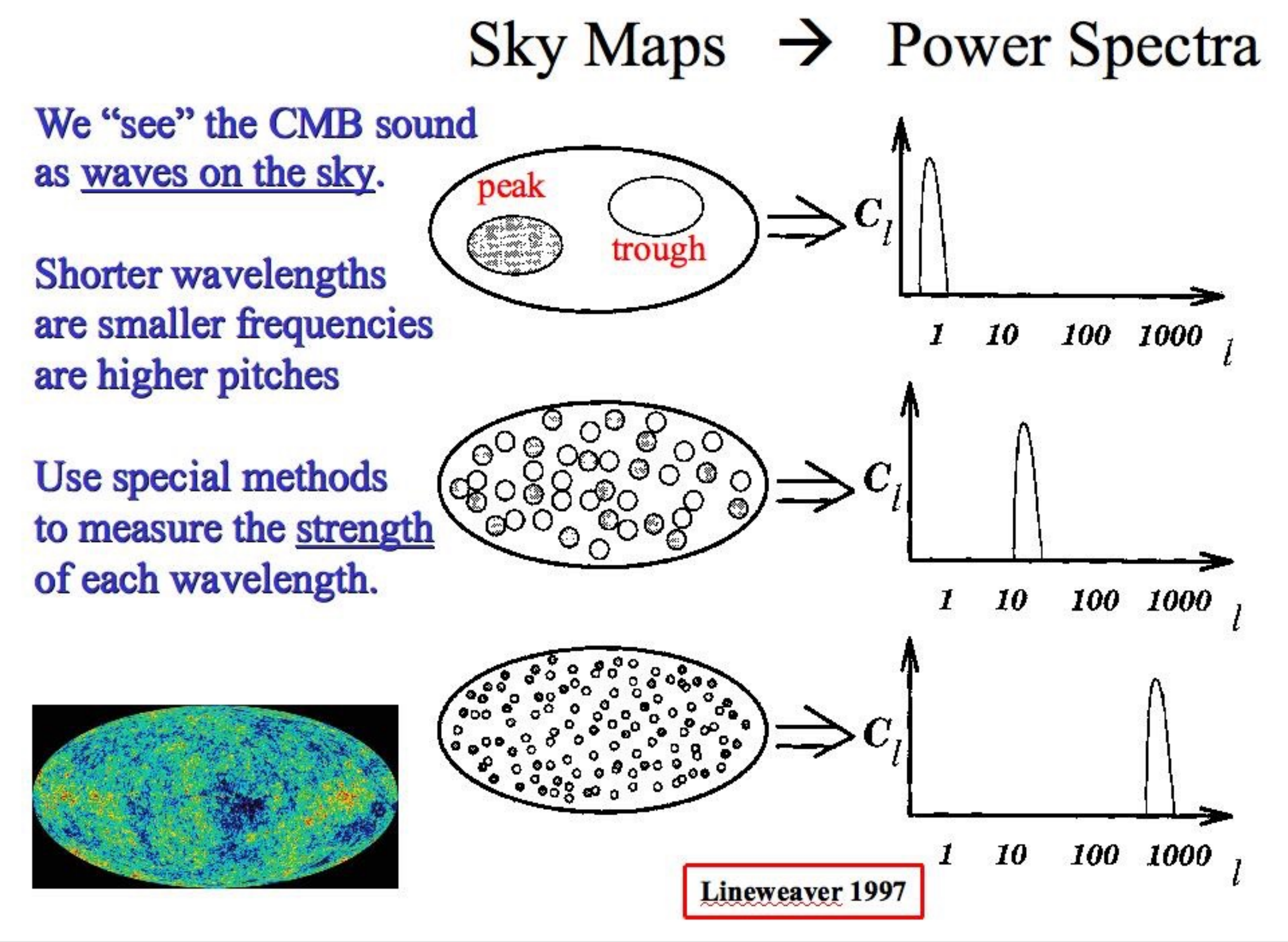
$$\Delta T(\phi) = \sum_{l} a_l \sin(l\phi)$$

意思就是，我們可以問左圖不均勻的顆粒粗細平均是多大。

$$\Delta T(\phi) = \sum_{l} a_l \sin(l\phi)$$ 溫度差異對角度的變化作展開。變化度記為l。

較粗的點表示溫度相對角度變化較小， 變化度l 較小。

較細的點表示溫度相對角度變化較大，變化度l較大。 。



Sky Maps → Power Spectra

We “see” the CMB sound as waves on the sky.

Shorter wavelengths are smaller frequencies are higher pitches

Use special methods to measure the strength of each wavelength.

Lineweaver 1997

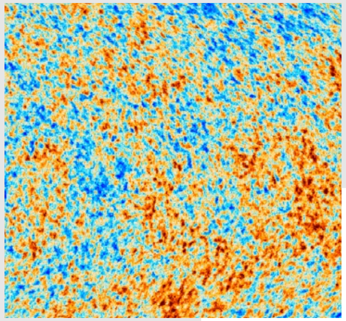
"Credit: Mark Whittle, University of Virginia"

這有點像畫畫：

將圖對色點的粗細做分解。

底色部分隨角度變化小，極粗。

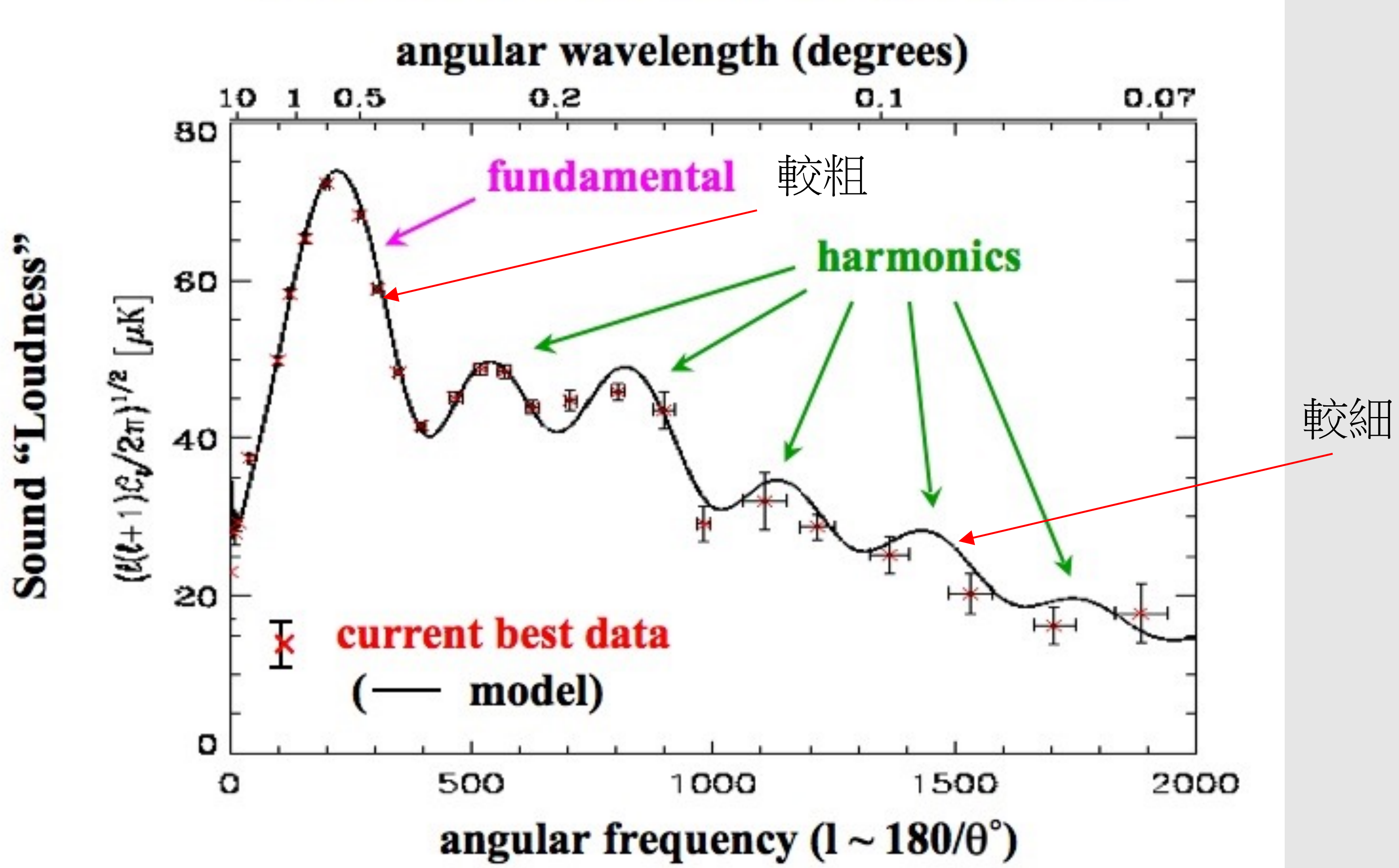
倒影部分隨角度變化大，極細。



將CMB的非同向性分解為粗細的點的疊加：

紀錄不同粗細的點的比重：對角度的傅立葉分析出現明顯的峰值！

The Observed Sound Spectrum



PRIMEVAL ADIABATIC PERTURBATION IN AN EXPANDING UNIVERSE*

P. J. E. PEEBLES†
Joseph Henry Laboratories, Princeton University

AND

J. T. YU‡
Goddard Institute for Space Studies, NASA, New York

Received 1970 January 5; revised 1970 April 1

ABSTRACT

The general qualitative behavior of linear, first-order density perturbations in a Friedmann-Lemaître cosmological model with radiation and matter has been known for some time in the various limiting situations. An exact quantitative calculation which traces the entire history of the density fluctuations is lacking because the usual approximations of a very short photon mean free path before plasma recombination, and a very long mean free path after, are inadequate. We present here results of the direct integration of the collision equation of the photon distribution function, which enable us to treat in detail the complicated regime of plasma recombination. Starting from an assumed initial power spectrum well before recombination, we obtain a final spectrum of density perturbations after recombination. The calculations are carried out for several general-relativity models and one scalar-tensor model. One can identify two characteristic masses in the final power spectrum: one is the mass within the Hubble radius ct at recombination, and the other results from the linear dissipation of the perturbations prior to recombination. Conceivably the first of these numbers is associated with the great rich clusters of galaxies, the second with the large galaxies. We compute also the expected residual irregularity in the radiation from the primeval fireball. If we assume that (1) the rich clusters formed from an initially adiabatic perturbation and (2) the fireball radiation has not been seriously perturbed after the epoch of recombination of the primeval plasma, then with an angular resolution of 1 minute of arc the rms fluctuation in antenna temperature should be at least $\delta T/T = 0.00015$.

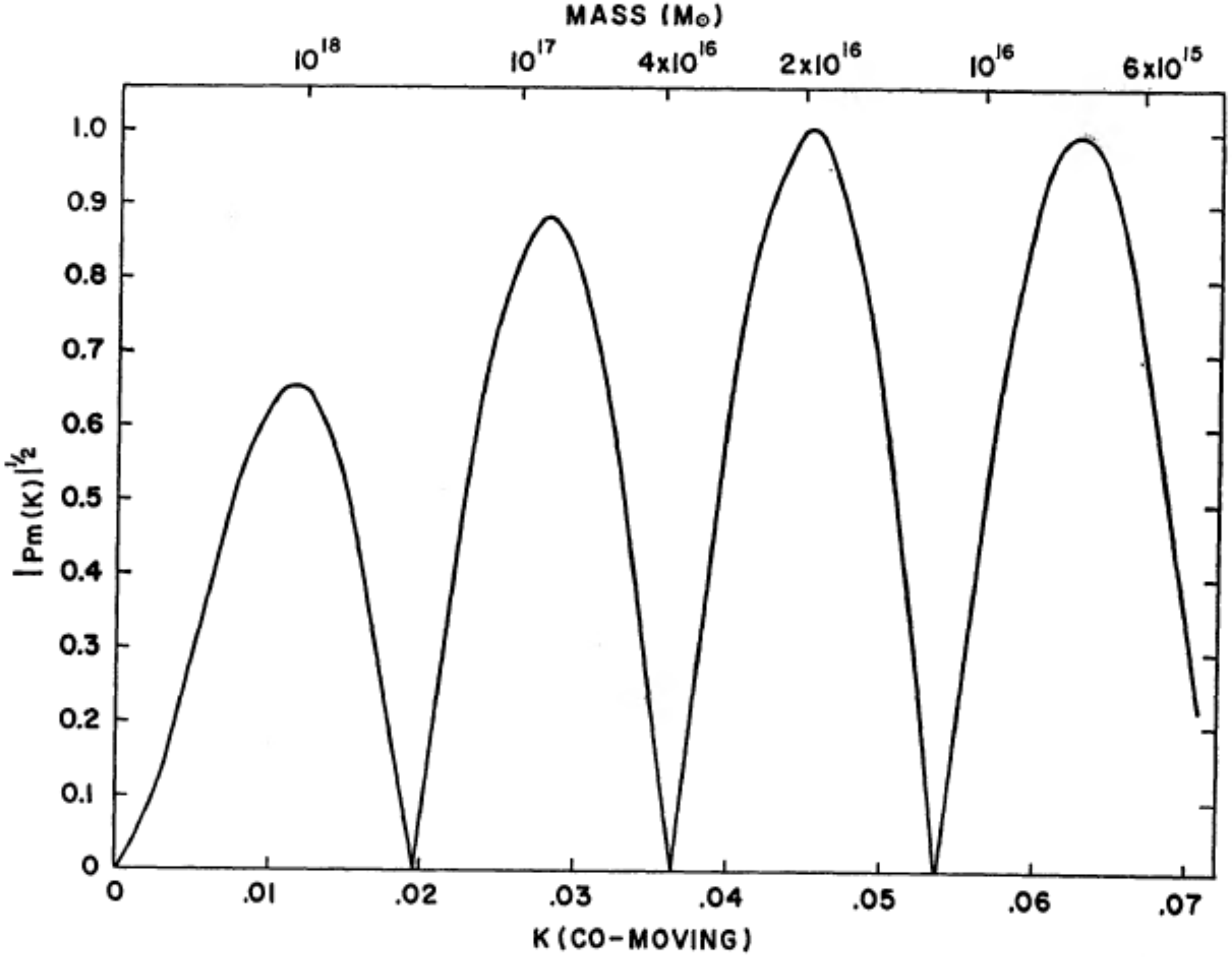
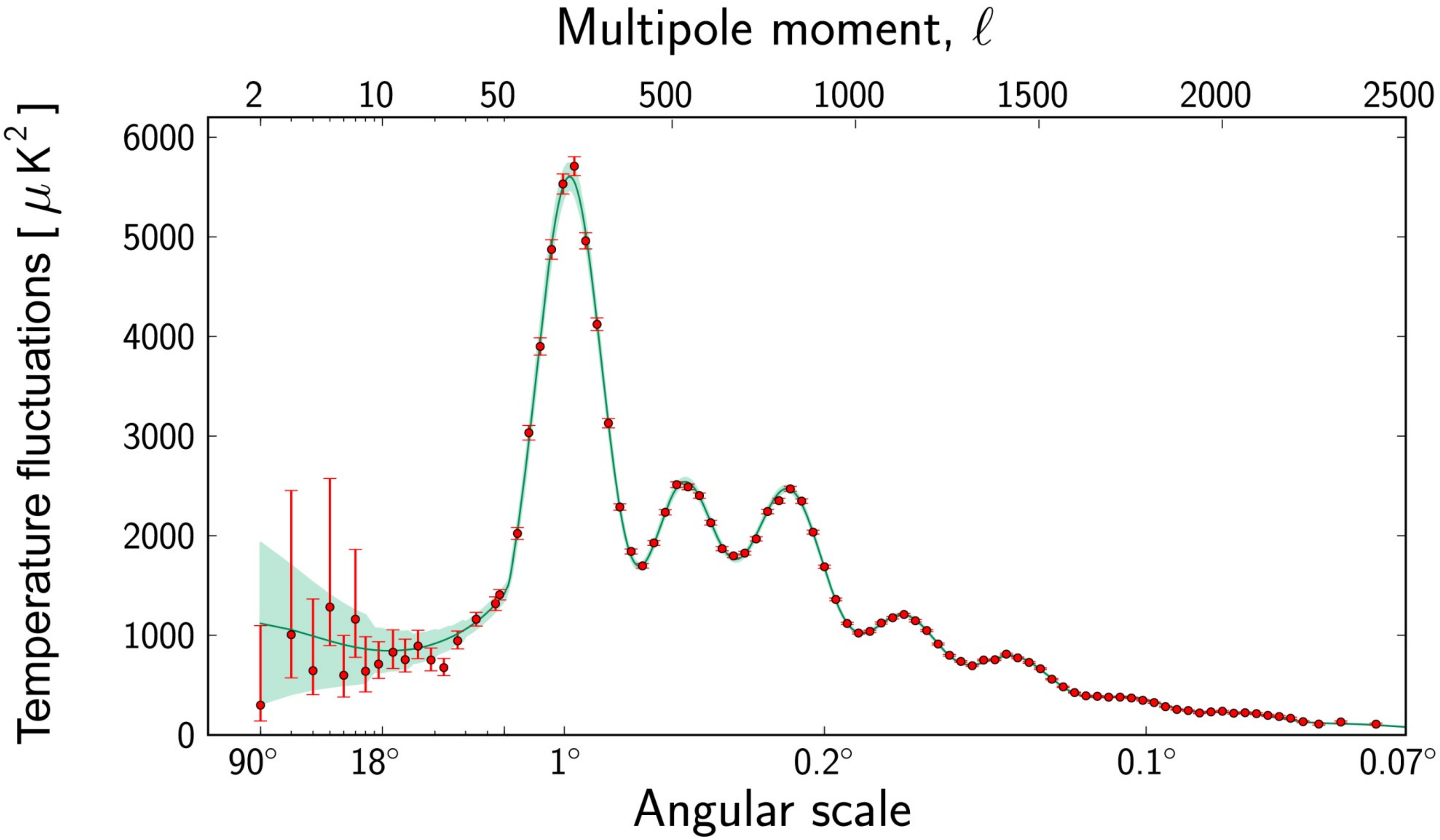


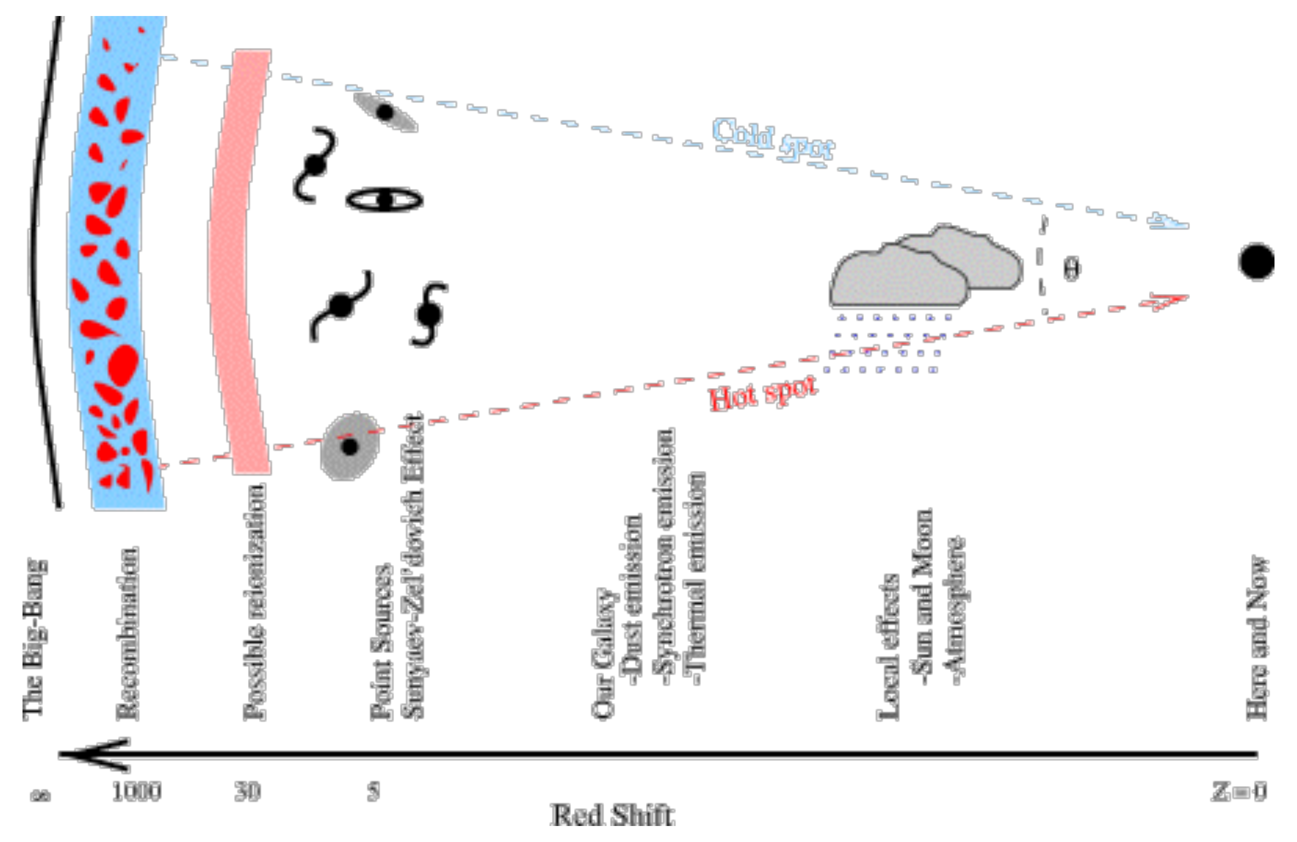
FIG. 4.—The residual mass-fluctuation spectrum $\mathcal{P}_m(k)^{1/2}$ (eq. [72]) in the open general-relativity model, $\rho_0 = 0.03\rho_c$ ($\rho_c = 1.8 \times 10^{-29}$ g cm^{-3}). The curve has been normalized to unity at maximum.



在$l = 220, \theta \sim 1°$左右有一個峯 peak

這表示CMB圖上冷熱之間最典型的角度是1°左右。

這對應最後散射面上能彼此聯絡、達成平衡、達成同溫的角度範圍。



在最後散射面上，宇宙只經歷了時間$t_{\rm ls}$，

在此面上能彼此有影響的區域最快是透過光，

而到此時，光最多只能走$\sim ct_{\rm ls}$，這個範圍稱為 horizon $d_{\rm Hor}(t_{\rm ls})$。

$$\theta \sim \frac{d_{\rm Hor}(t_{\rm ls})}{d_A} \sim \frac{0.251\rm Mpc}{12.8\rm Mpc} \approx 0.020\rm rad \approx 1.1$$

這區域演化傳播到現在地球，就對應到CMB圖上冷熱之間最典型的角度1°左右。

峰的位置、高度，與宇宙的彎曲度，物質密度以及其他宇宙常數有關。
例如宇宙的彎曲度很明顯會影響地球上觀察CMB的視角。

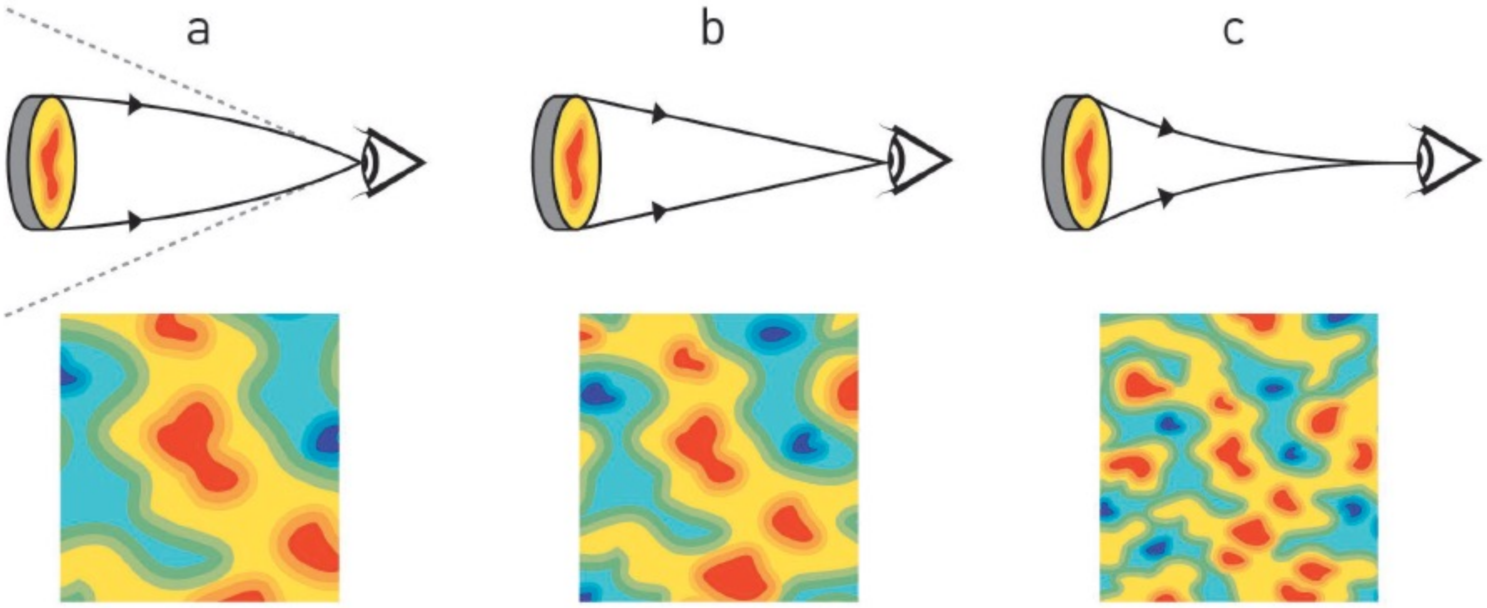
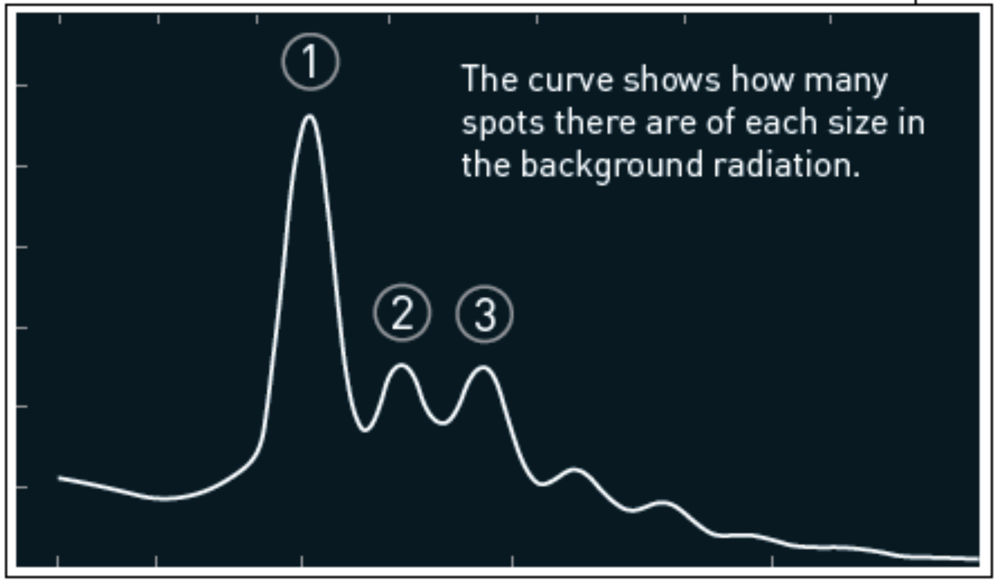


***Figure 5**. The angular size of spots in the CMB are determined by the geometry.*



The curve shows how many spots there are of each size in the background radiation.

① The first peak shows that the universe is geometrically flat, i.e. two parallel lines will never meet.

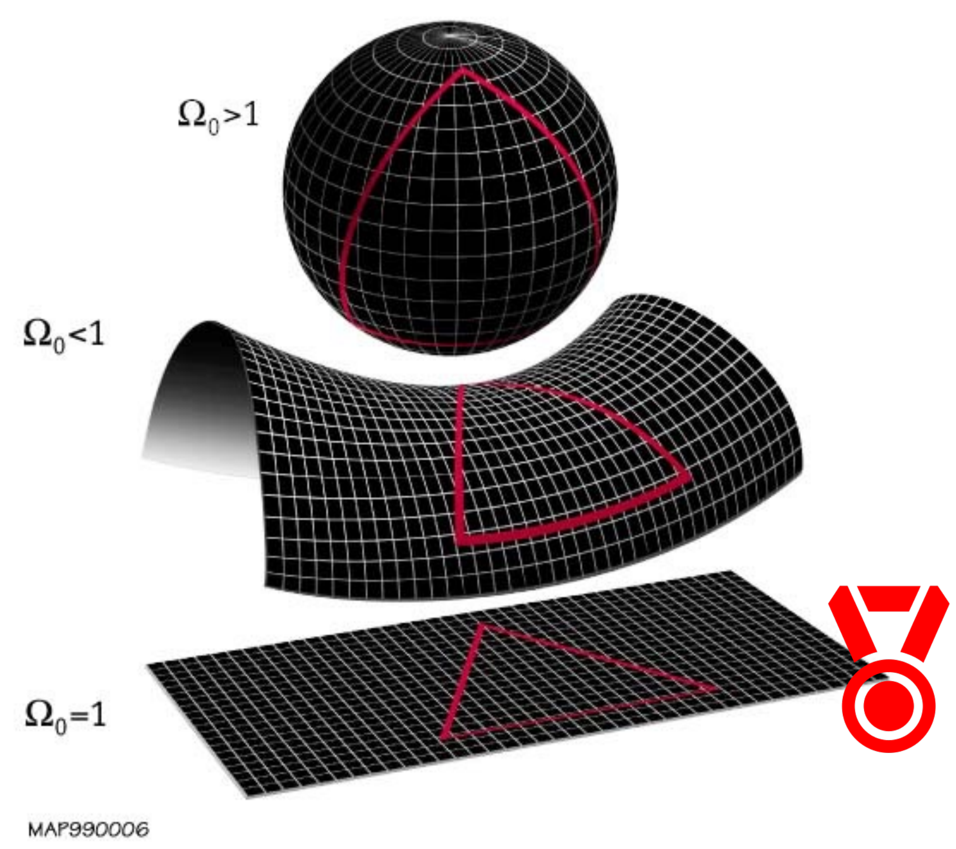
② The second peak shows that ordinary matter is just 5% of the matter and energy in the universe.

③ The third peak shows that 26% of the universe consists of dark matter.

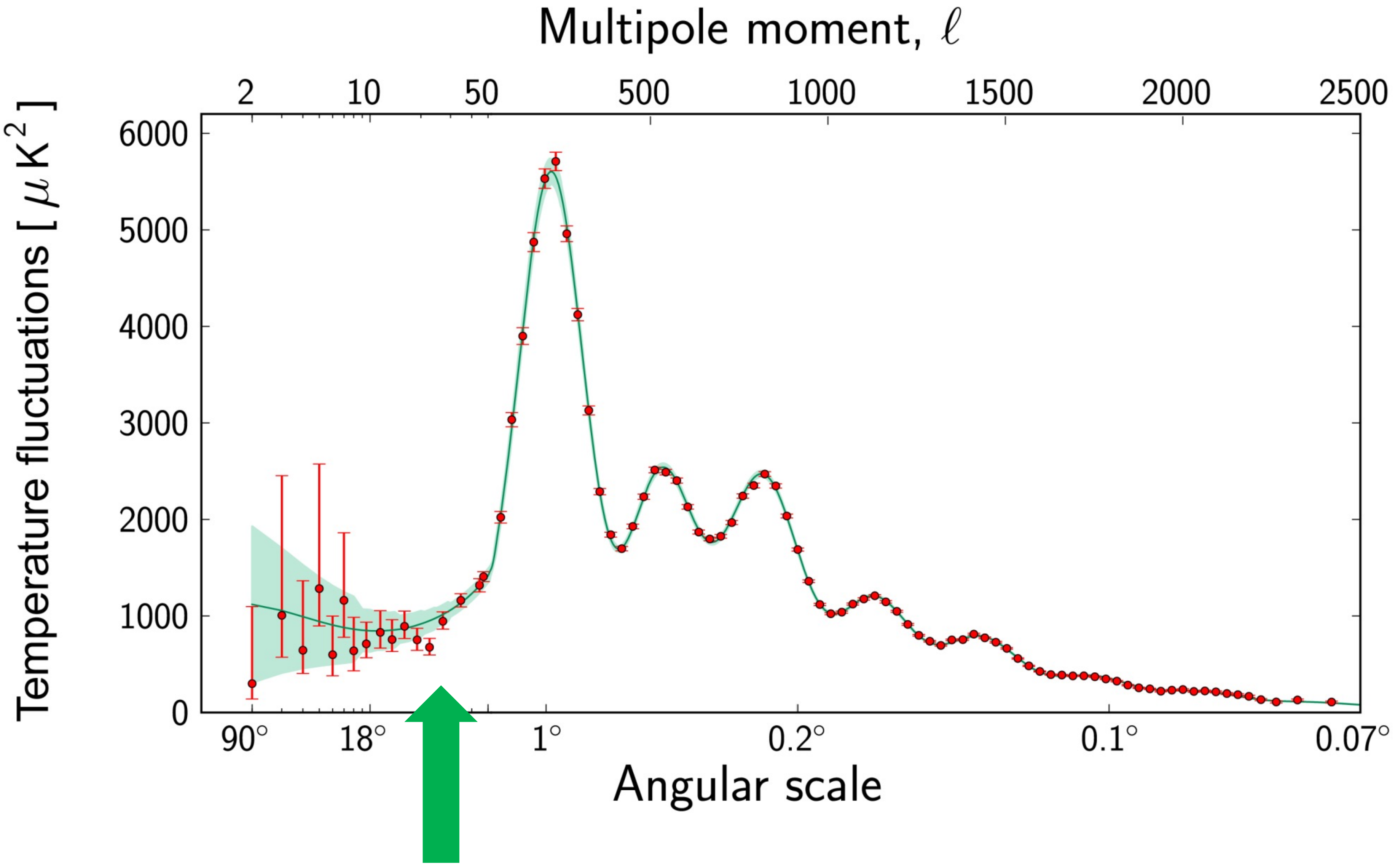
From these three peaks, it is possible to conclude that if 31% (5%+26%) of the universe is composed of matter, then 69% must be dark energy in order to fulfil the requirement for a flat universe.

第一個峰值的位置正好是若宇宙為平的時後，理論計算預期的位置。

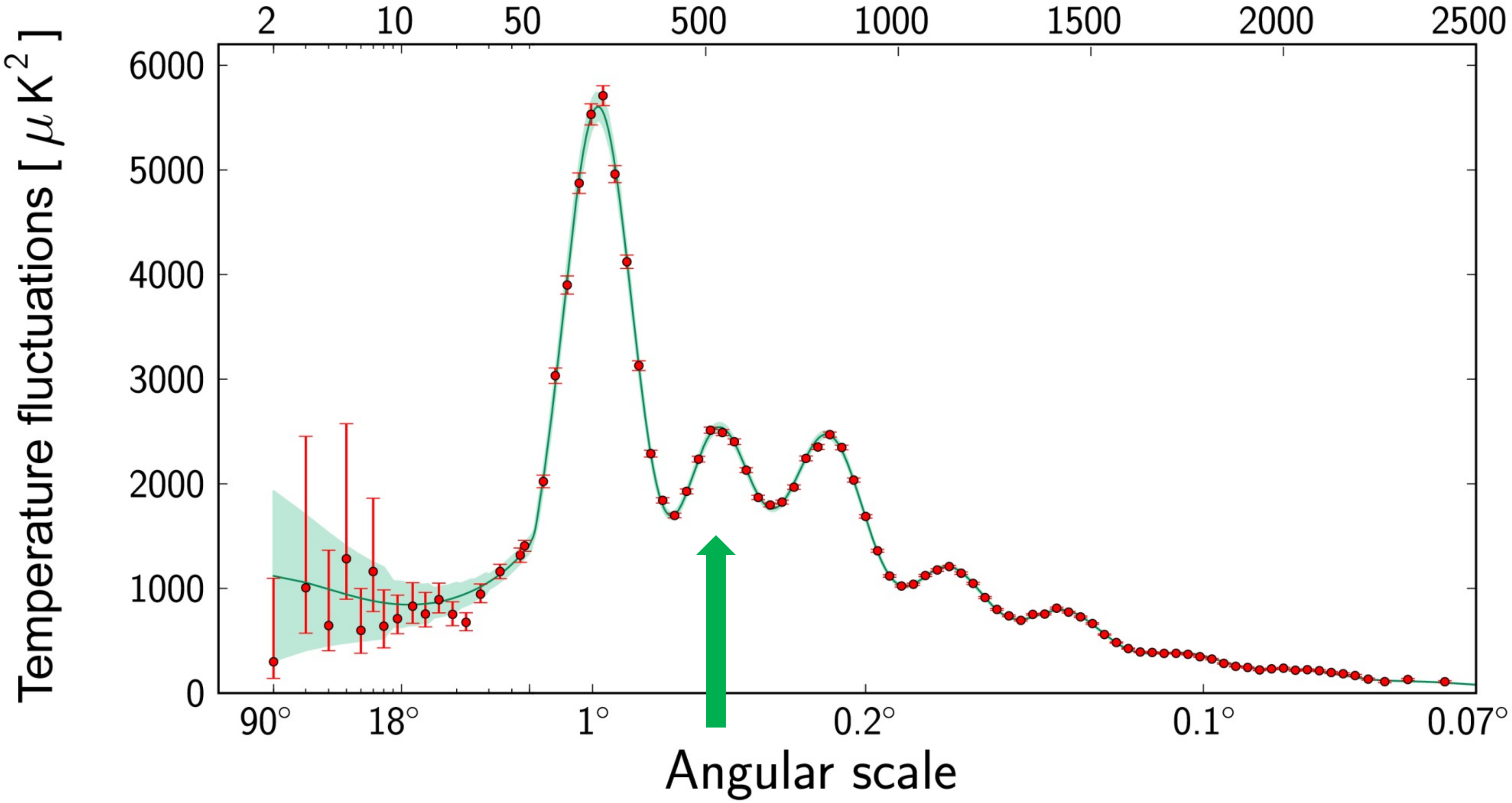
所以根據宇宙背景輻射的非同向性測量數據，宇宙是平的，。



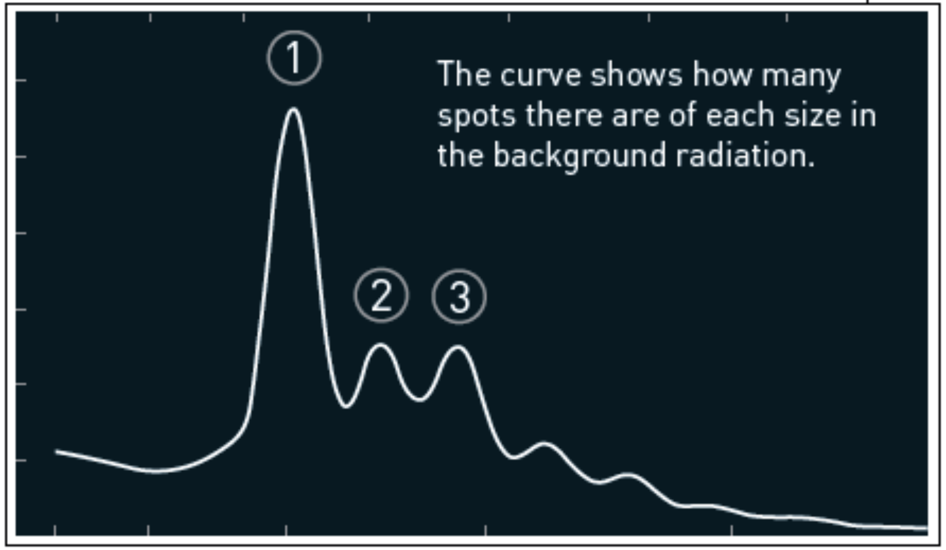
宇宙大尺度是平的！



大角度區ΔT是來自最後散射面上，暗物質分布不均勻所造成的重力位能脹落，進而影響CMB的光子。ΔT基本上是常數，被稱為平台，這是暴脹的特徵。



小角度區ΔT呈現一個個的peak，這是來自最後散射面上，
在暗物質所產生的重力位能不均勻影響下，光子夸克電漿形成如音波般的駐波，
進而影響CMB的光子。因為是駐波所以是一個一個的峰。



The curve shows how many spots there are of each size in the background radiation.

① The first peak shows that the universe is geometrically flat, i.e. two parallel lines will never meet.

② The second peak shows that ordinary matter is just 5% of the matter and energy in the universe.

③ The third peak shows that 26% of the universe consists of dark matter.

From these three peaks, it is possible to conclude that if 31% (5%+26%) of the universe is composed of matter, then 69% must be dark energy in order to fulfil the requirement for a flat universe.

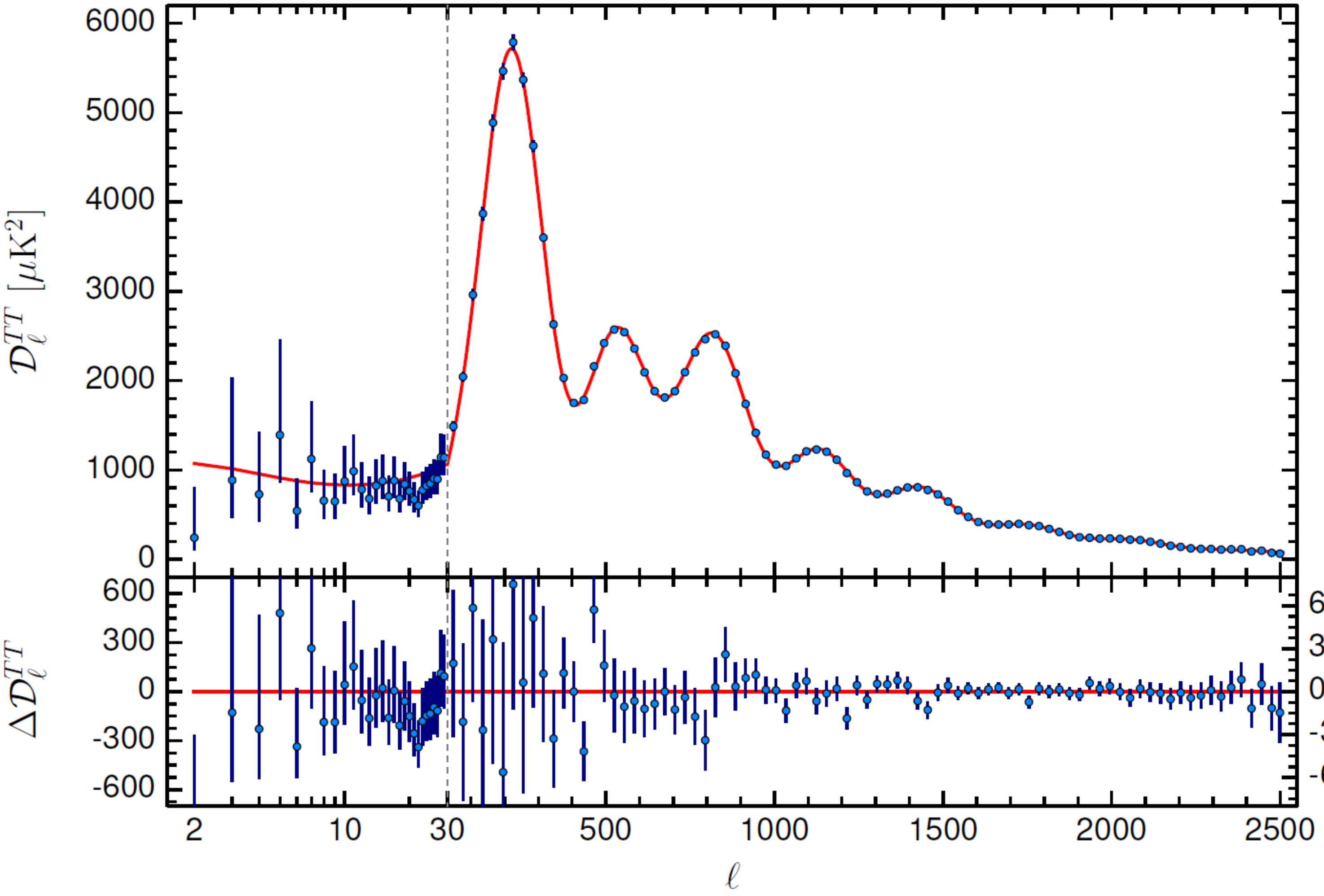
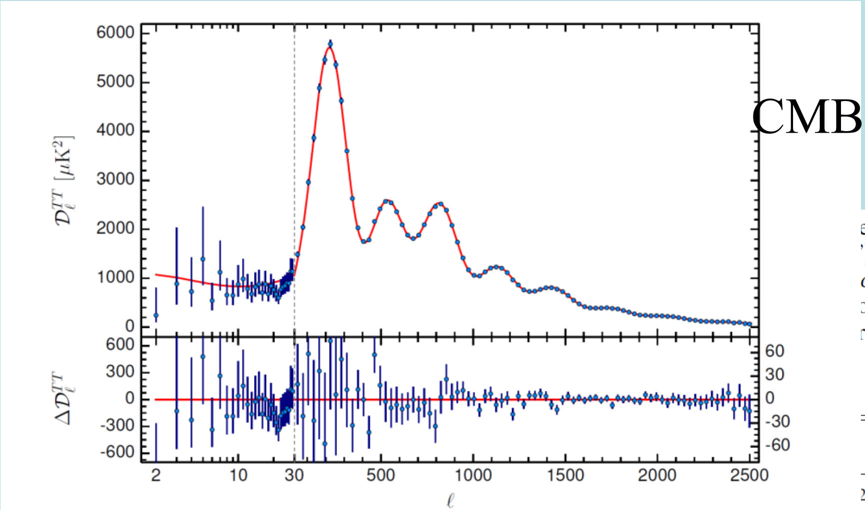
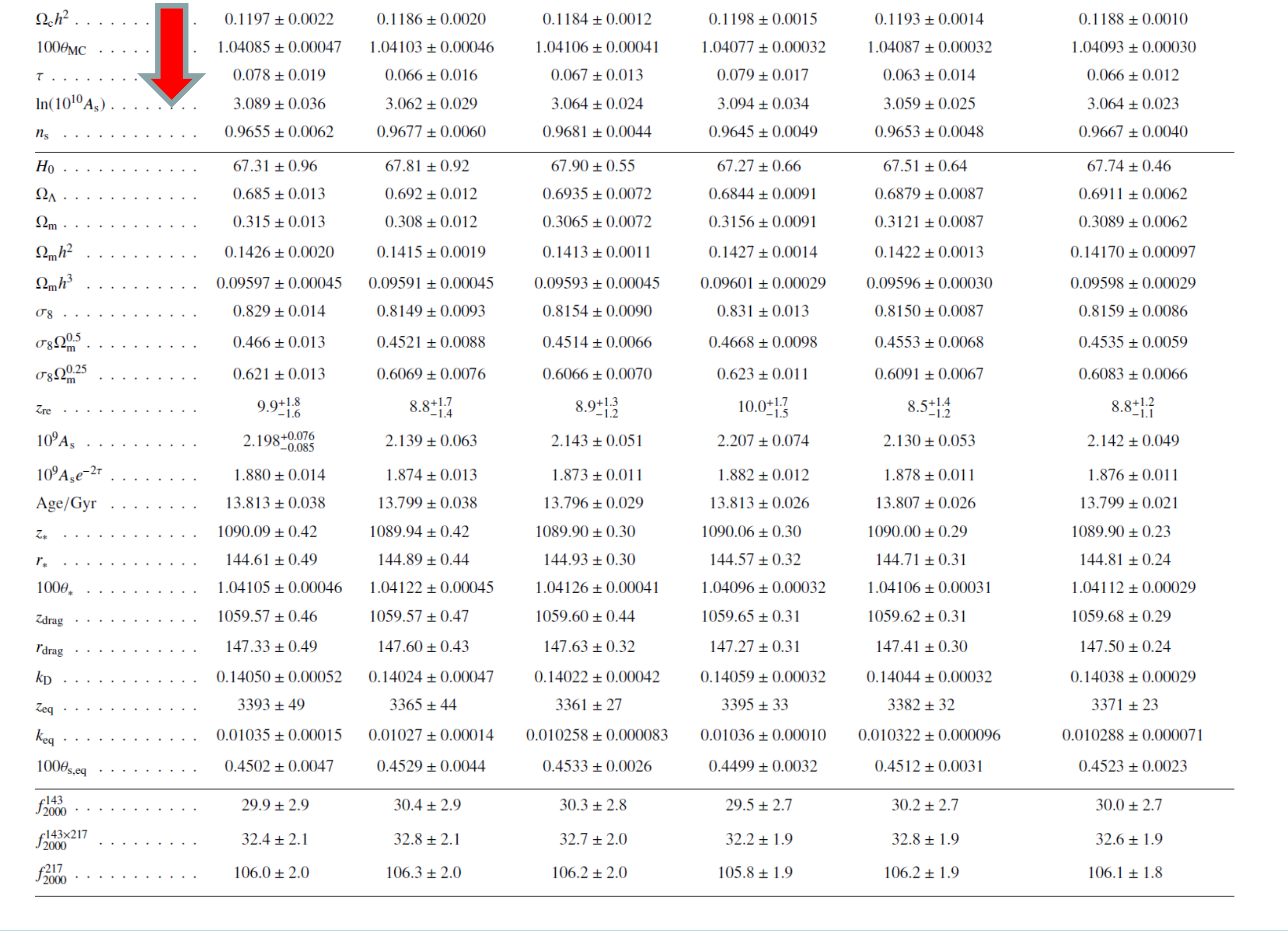


Fig. 1. The *Planck* 2015 temperature power spectrum. At multipoles $\ell \geq 30$ we show the maximum likelihood frequency averaged temperature spectrum computed from the `Plik` cross-half-mission likelihood with foreground and other nuisance parameters determined from the MCMC analysis of the base ΛCDM cosmology. In the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum estimates from the `Commander` component-separation algorithm computed over 94% of the sky. The best-fit base ΛCDM theoretical spectrum fitted to the *Planck* TT+lowP likelihood is plotted in the upper panel. Residuals with respect to this model are shown in the lower panel. The error bars show $\pm 1\,\sigma$ uncertainties.

CMB的數據分析可以告訴我們宇宙的基本特性（參數）



ence limits for the base ΛCDM model from *Planck* CMB power spectra, in combination with
’) and external data (“ext,” BAO+JLA+H_0). Nuisance parameters are not listed for brevity (they
cy *Archive* tables), but the last three parameters give a summary measure of the total foreground
or the three high-ℓ temperature spectra used by the likelihood. In all cases the helium mass fraction
rior mean $Y_P \approx 0.2453$, with theoretical uncertainties in the BBN predictions dominating over the



		TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
	23	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10}A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8\Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8\Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

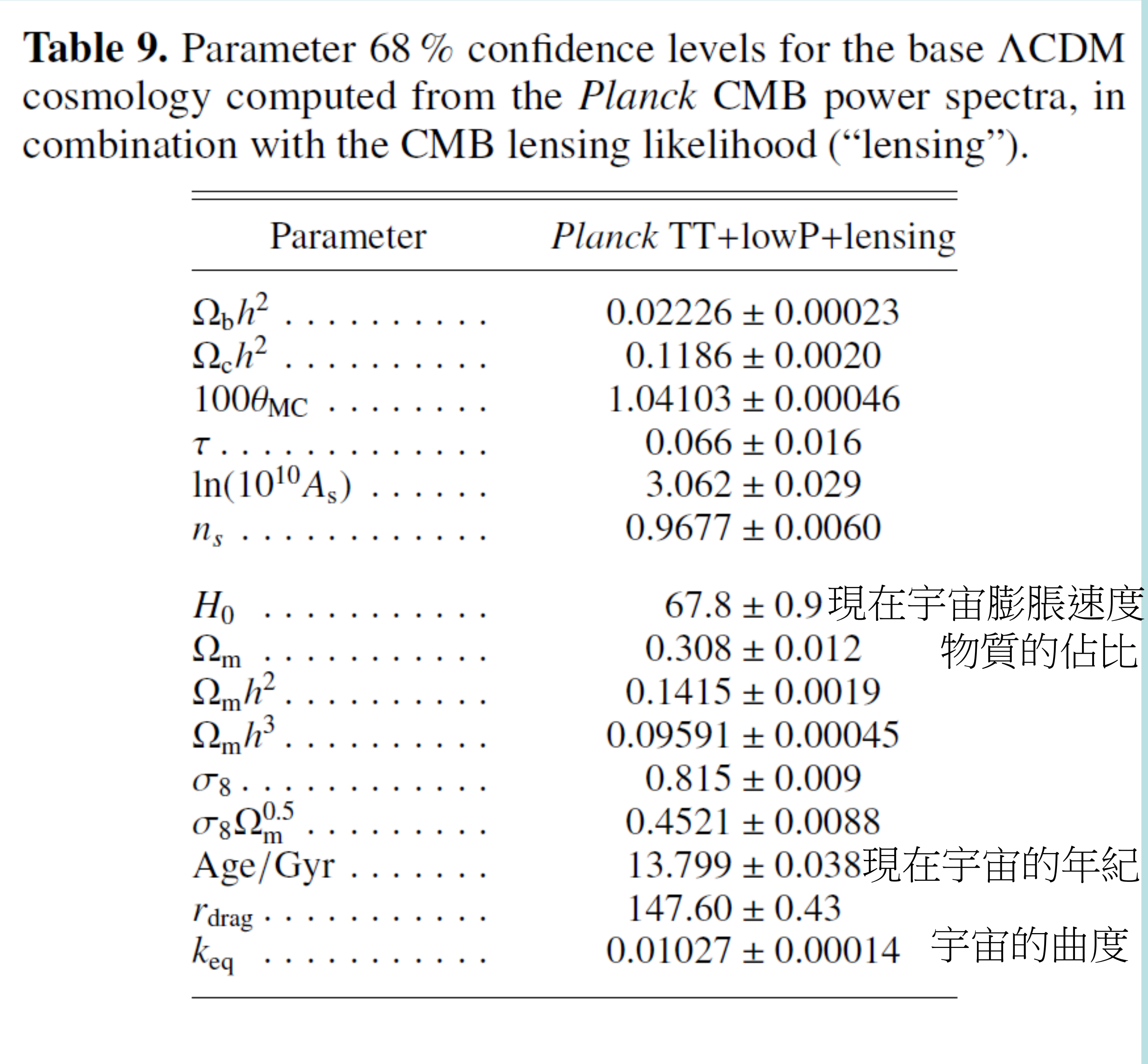


Table 9. Parameter 68 % confidence levels for the base ΛCDM cosmology computed from the *Planck* CMB power spectra, in combination with the CMB lensing likelihood (“lensing”).

Parameter	*Planck* TT+lowP+lensing	
$\Omega_b h^2$	0.02226 ± 0.00023	
$\Omega_c h^2$	0.1186 ± 0.0020	
$100\theta_{MC}$	1.04103 ± 0.00046	
τ	0.066 ± 0.016	
$\ln(10^{10} A_s)$	3.062 ± 0.029	
n_s	0.9677 ± 0.0060	
H_0	67.8 ± 0.9	現在宇宙膨脹速度
Ω_m	0.308 ± 0.012	物質的佔比
$\Omega_m h^2$	0.1415 ± 0.0019	
$\Omega_m h^3$	0.09591 ± 0.00045	
σ_8	0.815 ± 0.009	
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088	
Age/Gyr	13.799 ± 0.038	現在宇宙的年紀
r_{drag}	147.60 ± 0.43	
k_{eq}	0.01027 ± 0.00014	宇宙的曲度

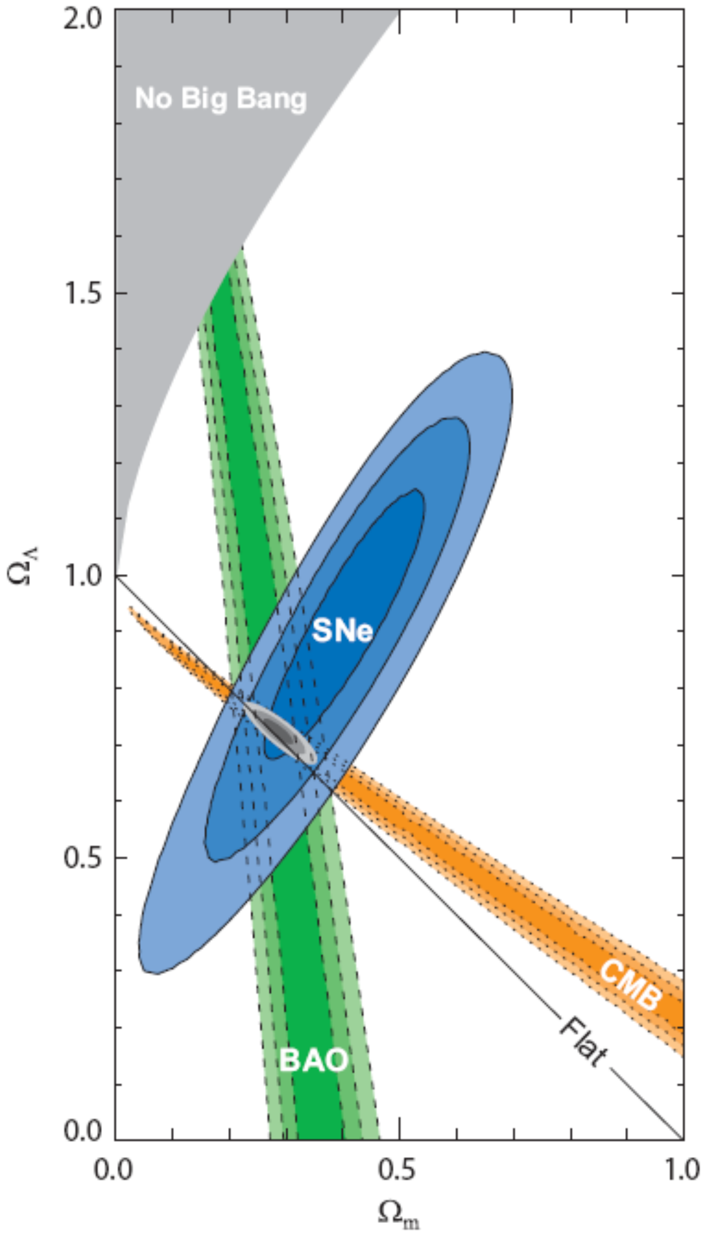


Figure 21.1: Confidence level contours of 68.3%, 95.4% and 99.7% in the Ω_Λ–Ω_m plane from the Cosmic Microwave Background, Baryonic Acoustic Oscillations and the Union SNe Ia set, as well as their combination (assuming $w = -1$). Courtesy of Kowalski *et al.* [22]

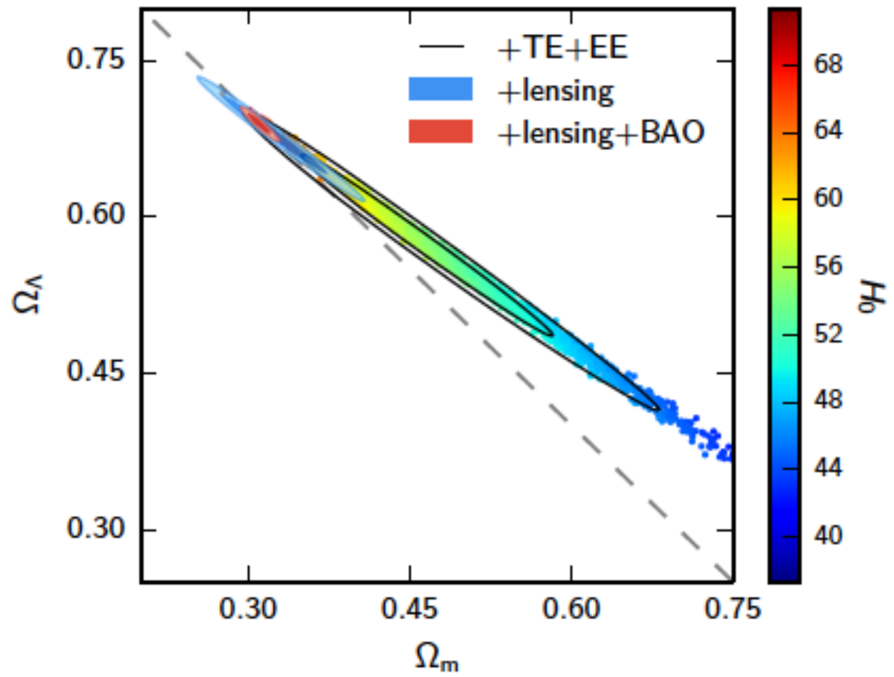
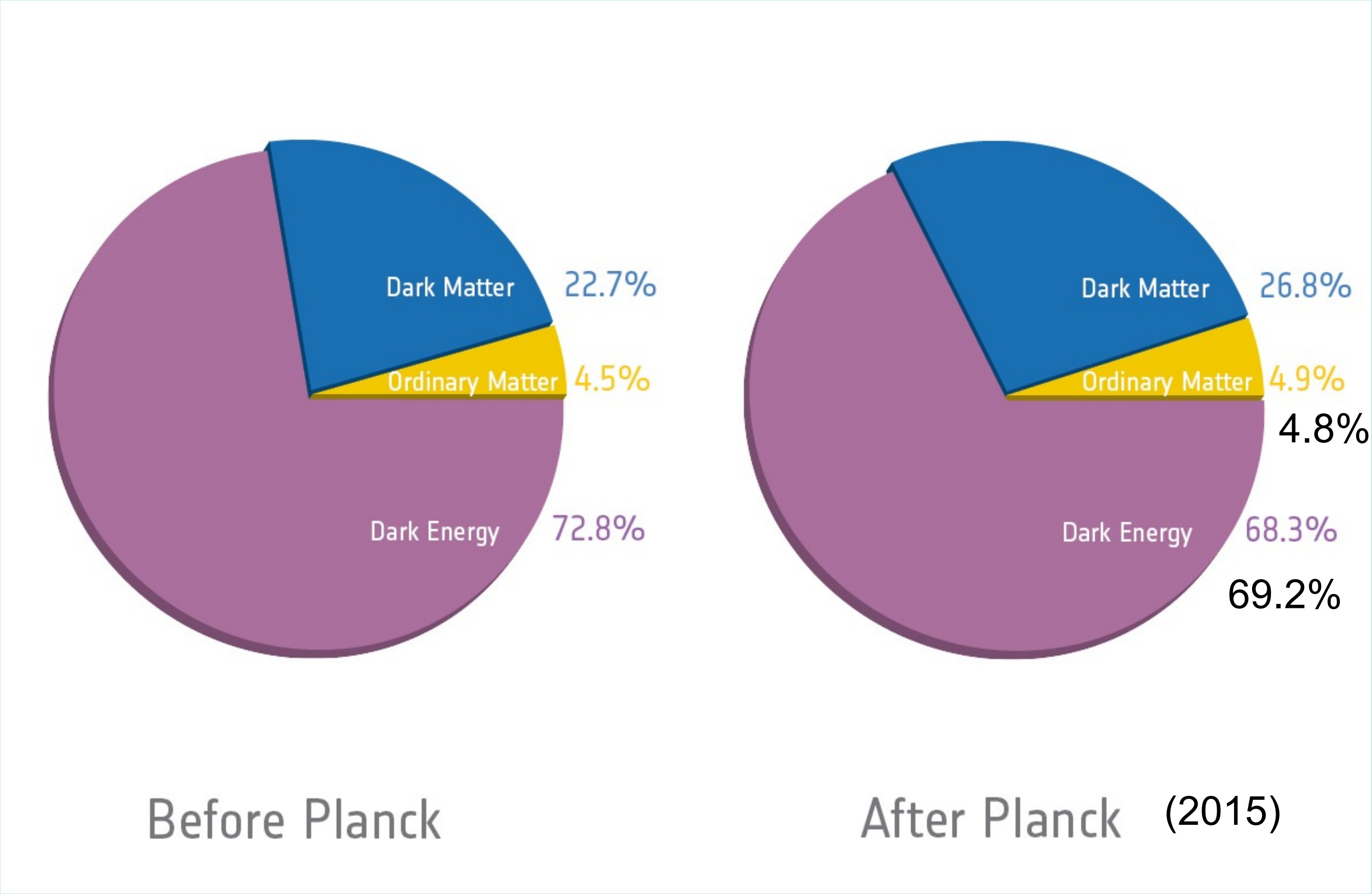


Fig. 26. Constraints in the Ω_m–Ω_Λ plane from the *Planck* TT+lowP data (samples; colour-coded by the value of H_0) and *Planck* TT,TE,EE+lowP (solid contours). The geometric degeneracy between Ω_m and Ω_Λ is partially broken because of the effect of lensing on the temperature and polarization power spectra. These limits are improved significantly by the inclusion of the *Planck* lensing reconstruction (blue contours) and BAO (solid red contours). The red contours tightly constrain the geometry of our Universe to be nearly flat.



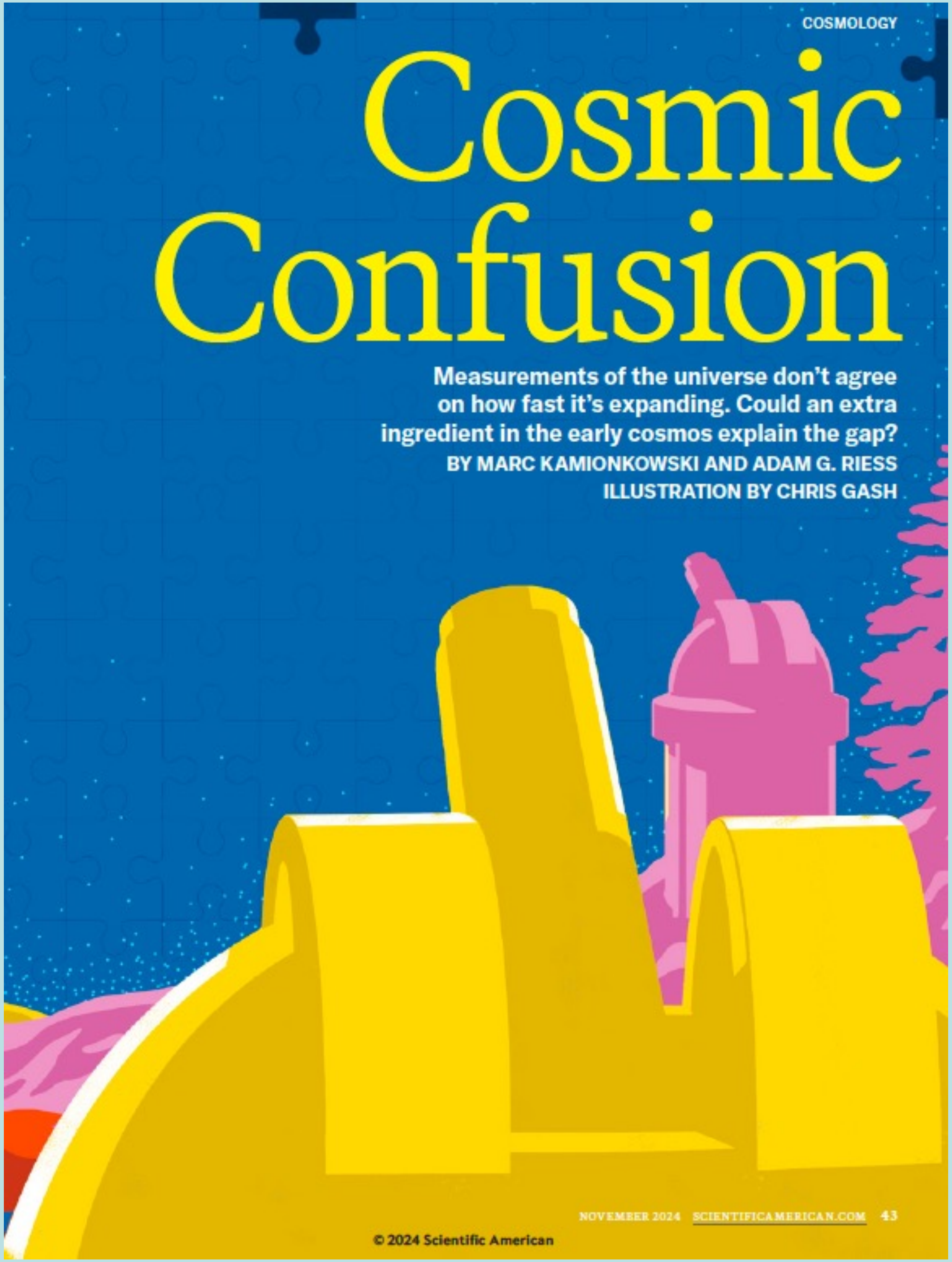
背景輻射的圖像其實預測宇宙的總能量與質量中，有26%的黑暗物質，70%的黑暗能量，這兩個成分科學家都還完全不清楚它們究竟是什麼。所以我們所了解的部分，只佔宇宙總量的4%。所以有位教授是這樣說的：這場宇宙學的考試，科學家的得分只有四分，顯然是不及格的。但也顯示我們還處在科學發展的西部開墾時代，前方還有廣闊的知識土地，等待我們去探索。

Cosmic Confusion

Measurements of the universe don't agree on how fast it's expanding. Could an extra ingredient in the early cosmos explain the gap?

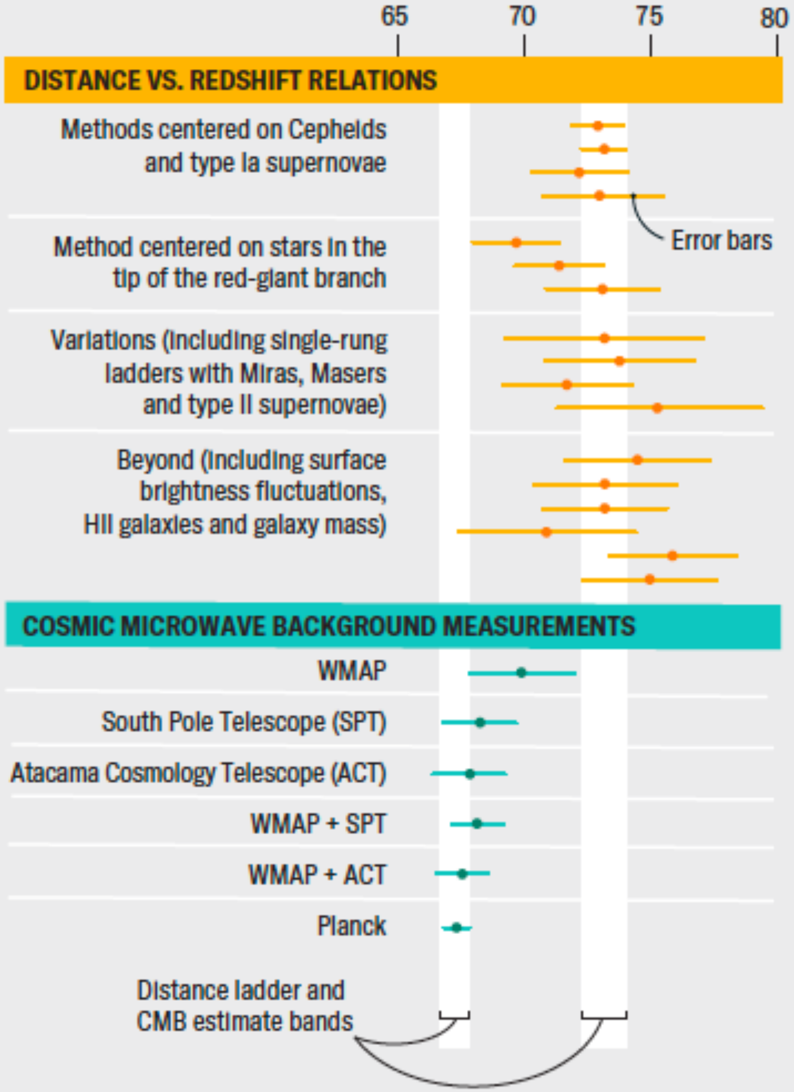
BY MARC KAMIONKOWSKI AND ADAM G. RIESS

ILLUSTRATION BY CHRIS GASH



A Sampling of Hubble Constant Estimates, Organized by Measuring Method

Kilometers per second per 3.26 million light-years



RESULTS

Over the years the distance ladder measurements of the Hubble constant have converged at a value of 73 ± 1 kilometers per second per megaparsec (km/s/Mpc). The CMB method, on the other hand, gives an estimate of 67.5 ± 0.5 km/s/Mpc. The two values are too far apart to explain. Perhaps there is some overlooked error in the methods, or maybe they are telling us our cosmological model is incomplete.

The Dark Energy Spectroscopic Instrument (DESI) will spend five years creating a 3D map of the universe that will help reveal the nature of the dark energy driving cosmic expansion. The project's first six months of data show slivers of the universe that represent just 1 percent of the survey's ultimate volume of space. The colors represent different types of galaxies, including nearby bright galaxies in yellow, luminous red galaxies in magenta and galaxies with supermassive black holes in turquoise.

Credit: Source: "The Early Data Release of the Dark Energy Spectroscopic Instrument," by DESI Collaboration et al.; 2023 (data)

The Most Shocking Discovery in Astrophysics Is 25 Years Old

A quarter of a century after detecting dark energy, scientists are still trying to figure out what it is

By Richard Panek | December 1, 2023

One afternoon in early 1994 a couple of astronomers sitting in an air-conditioned computer room at an observatory headquarters in the coastal town of La Serena, Chile, got to talking. Nicholas Suntzeff, an associate astronomer at the Cerro Tololo Inter--American Observatory, and Brian Schmidt, who had recently completed his doctoral

Exotic black hole stars could explain the mystery of Little Red Dots

Astronomers are racing to understand mysterious ancient objects that pepper James Webb Space Telescope images

BY REBECCA BOYLE EDITED BY CLARA MOSKOWITZ