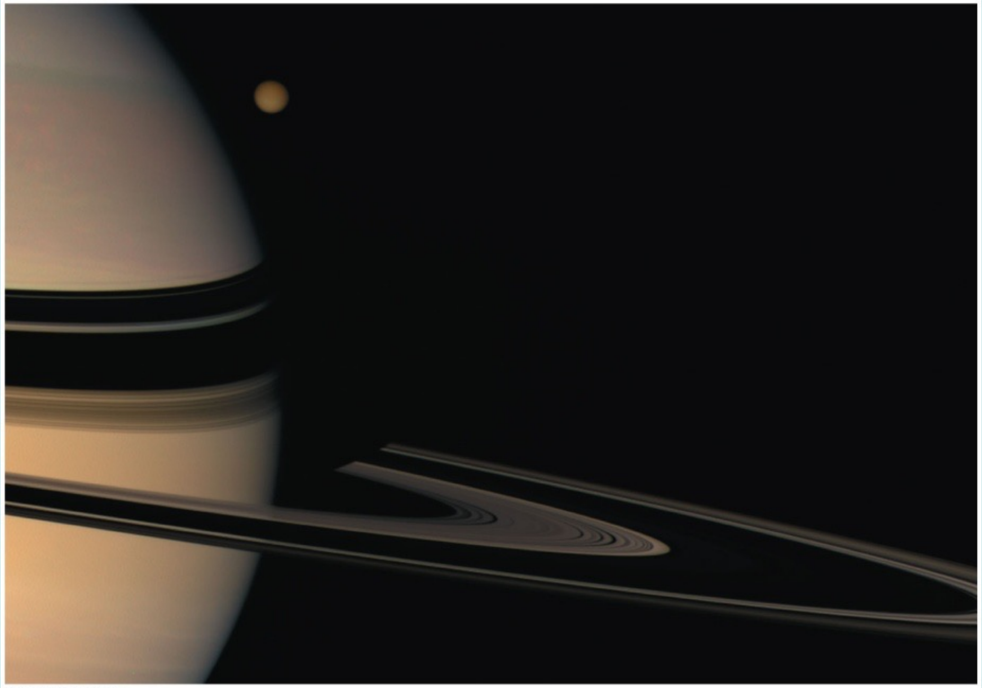
我們在地球上發現的物理定律，將適用於看得到的整個宇宙。

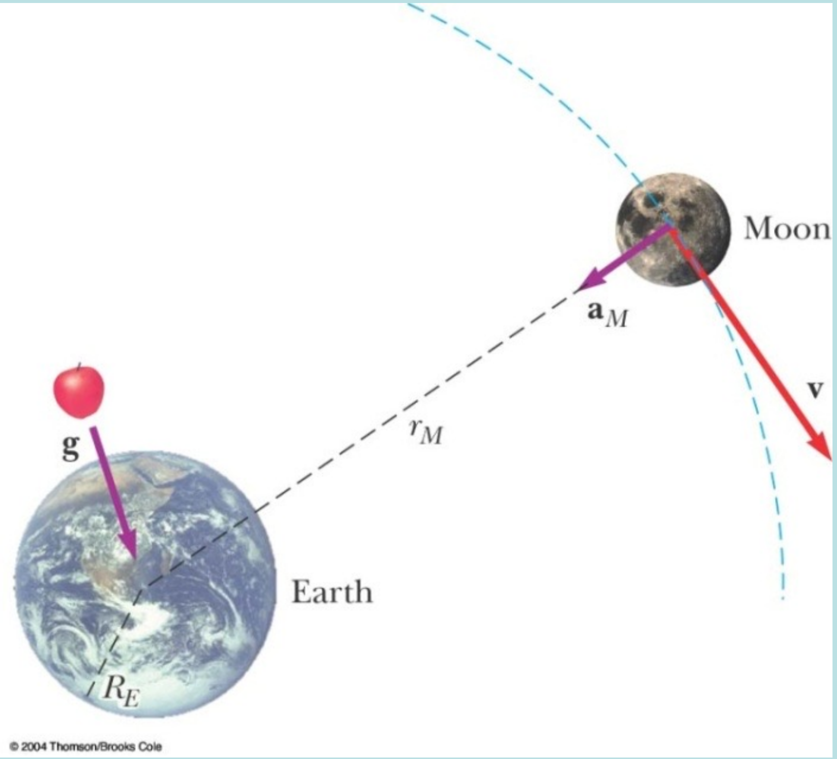
Einstein 接下來將相對論應用到更神祕的現象：重力！

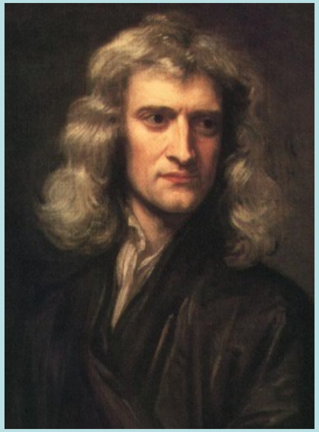


Einstein 自己覺得狹義相對論不算什麼革命性的創舉，

但接下來的廣義相對論真的是十分令人驚嘆的創見。

牛頓提出的萬有引力同時描述了地球周圍蘋果與月球的運動！



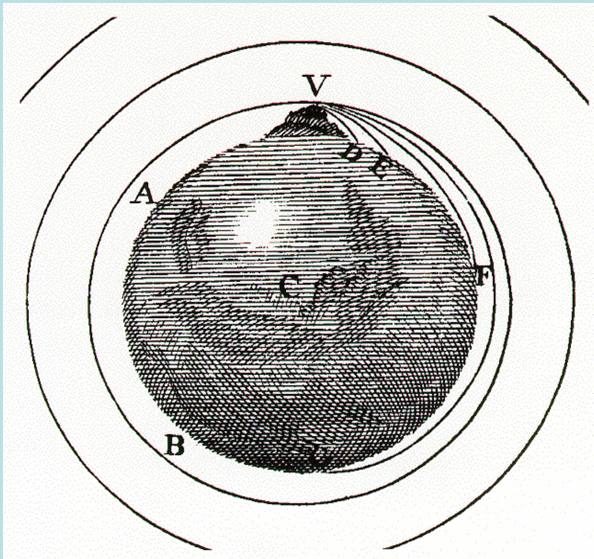


在當時這是非常顛覆常識的想法！

=

塵世的物體可以成為神聖的天體！

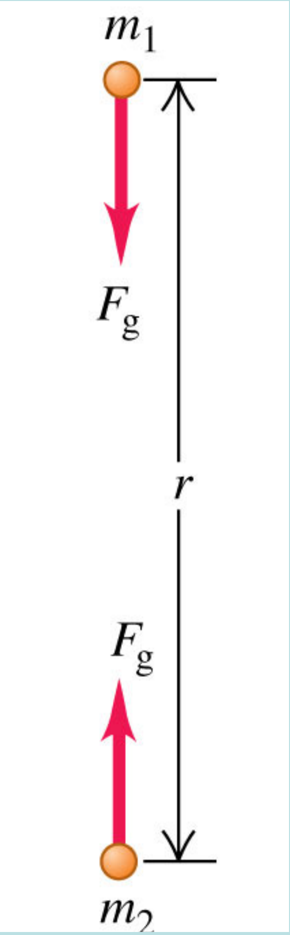
天體與地面物體本質上是平等的！



萬有引力定律

$$F = \frac{GMm}{r^2}$$

$$F(t) = \frac{GMm}{r(t)^2}$$



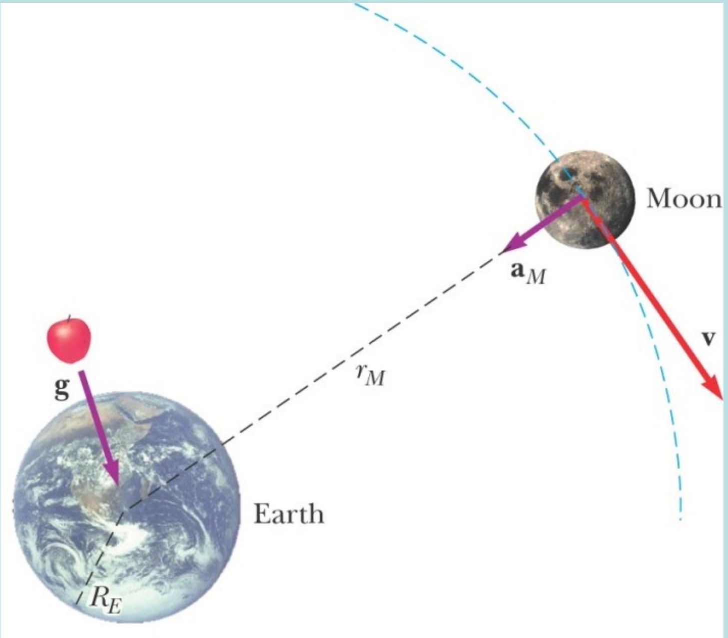
萬有引力與距離平方成反比

什麼時候的距離？

牛頓認為是力作用**當時t**的距離！

但**當時**是根據施力者的時鐘還是受力者（運動中）的時鐘？

萬有引力與當時距離平方成反比，因此是超距力。



地球若被彗星撞歪了，月亮什麼時候會知道？

若引力是超距力，月亮會由當時引力大小立刻知道！

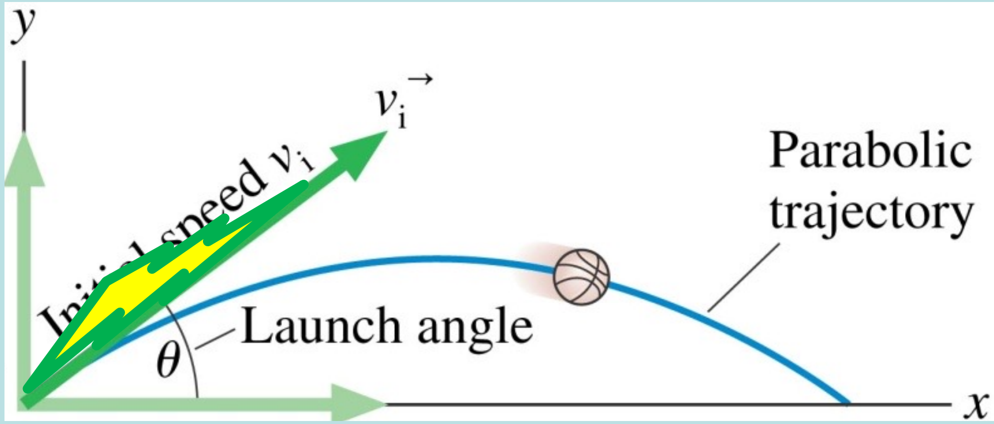
但訊息的傳遞不能快於光速！

超距力是一個不成立的概念！

牛頓的萬有引力定律必須修正！

在重力下，物體會被偏折而作曲線的拋體運動。

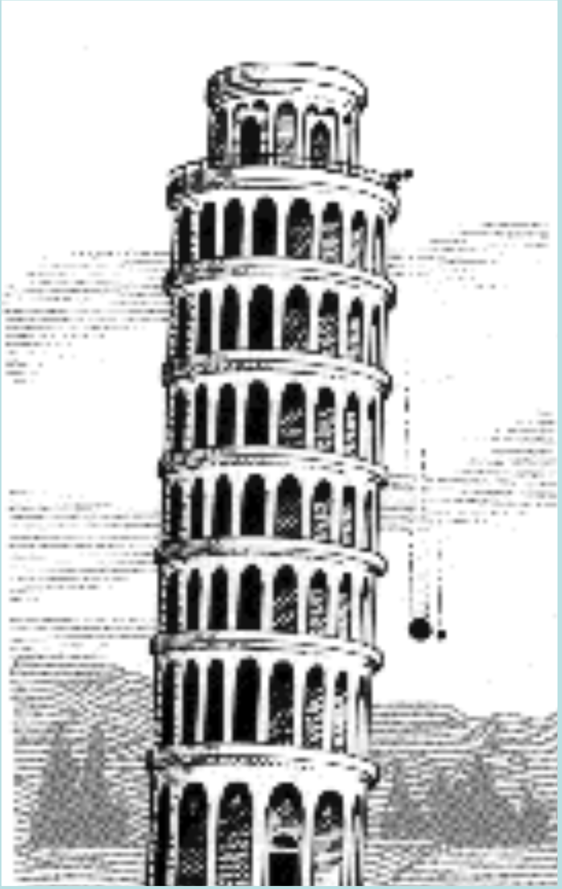
一道光在重力下會不會被偏折？

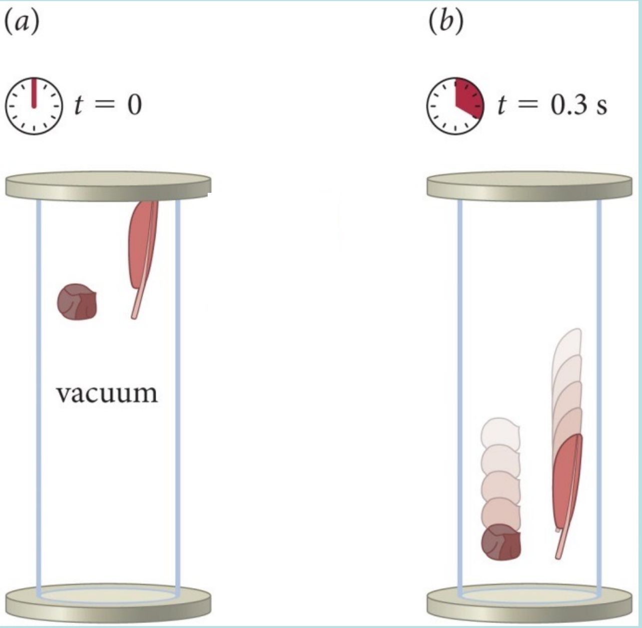


$$F = \frac{GMm}{r^2}$$

電磁波是真空中的波動現象，根本不是物質。

它會有萬有引力嗎？萬有引力定律適用於光嗎？





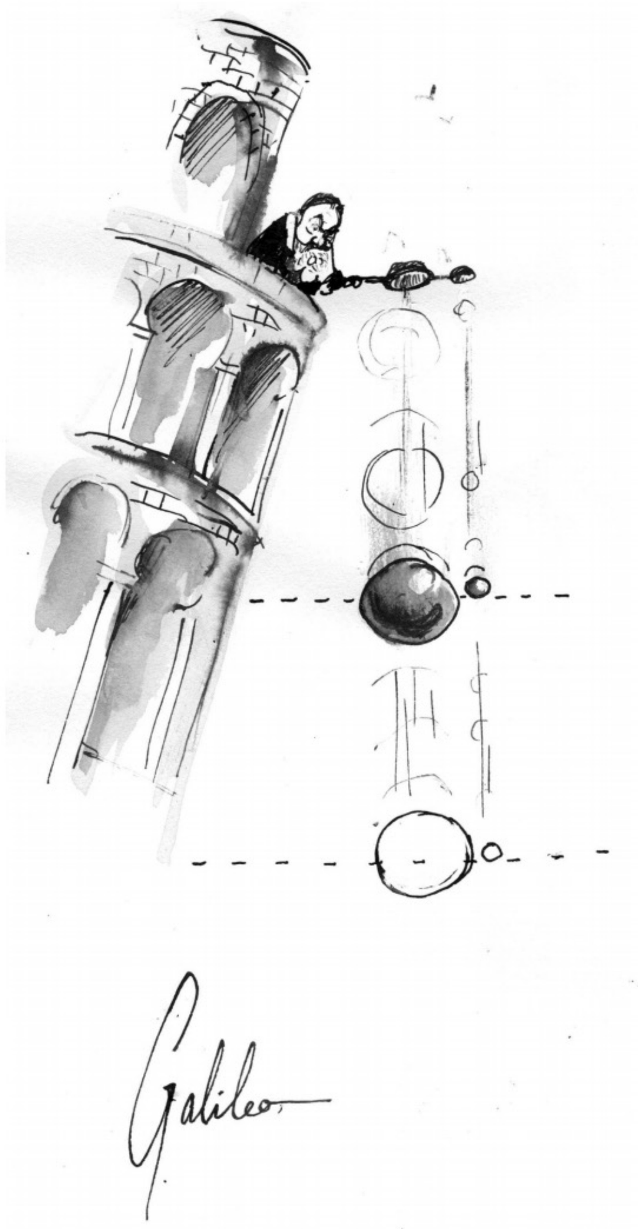
愛因斯坦注意到，當年伽利略所指出來，重力很特別的一個性質！

如果沒有空氣，所有物體，無論輕重，落地時間相同。

就如特殊相對論由光速恆定現象出發，整個廣義相對論就由以上觀察出發！

On one day in 1907, I was sitting in a chair in the patent office at Bern, when all of a sudden, a thought occurred to me.....

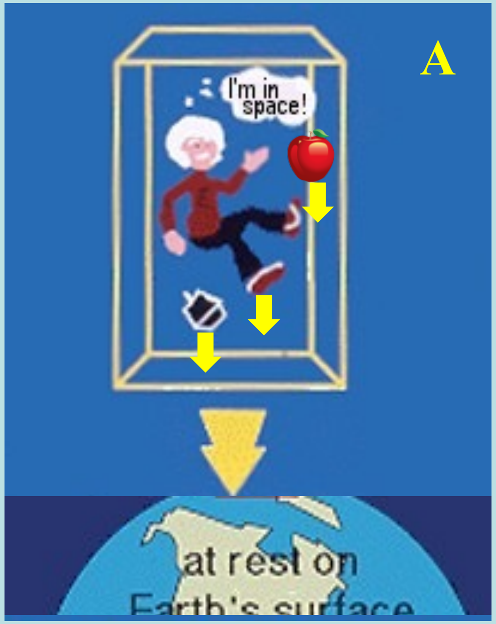
"the happiest thought of my life"　我一生最快樂的想法！



They all fall in the
same time!

如果，所有物體，在重力影響下下落的方式都一樣……

那麼.......



＝

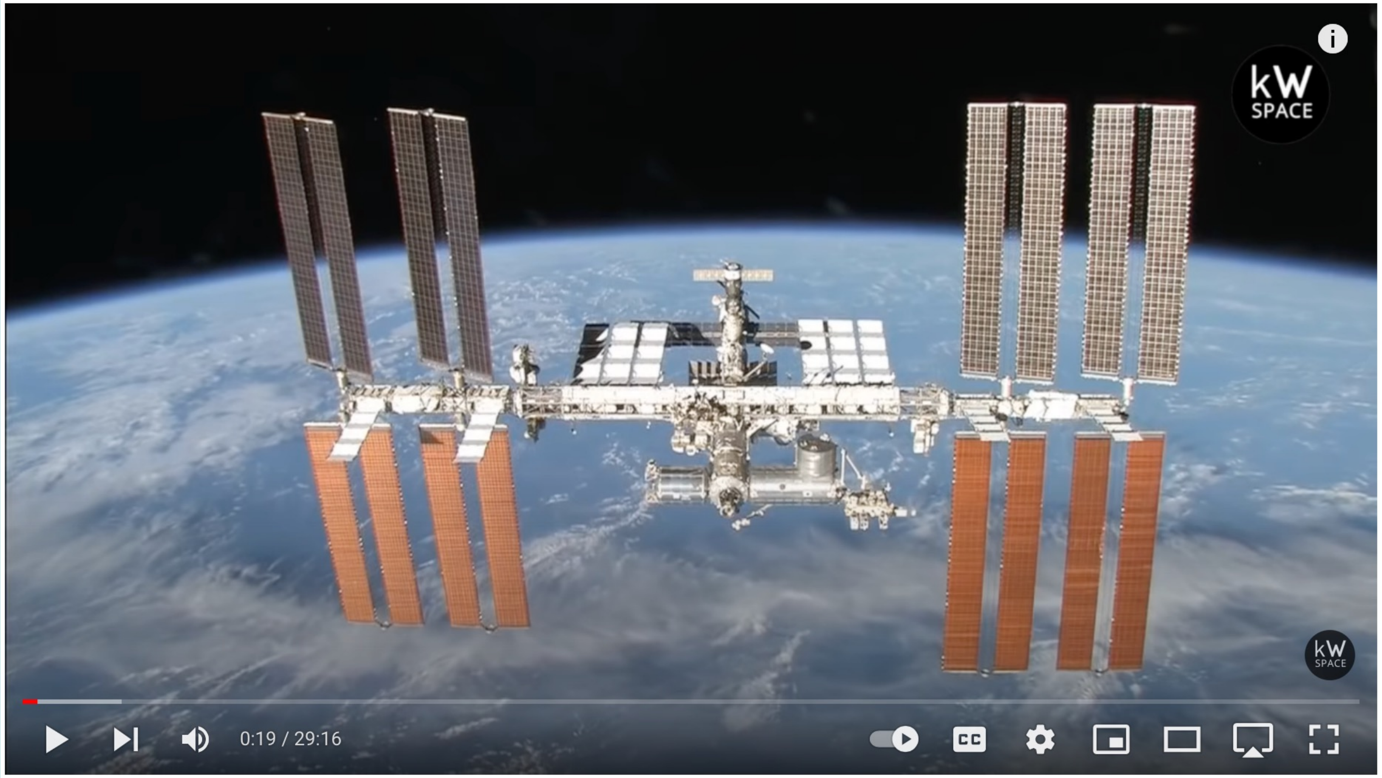
在地表自由下落的觀察者，會觀察到周圍一起下落的物體都是靜止或等速的。

這和他在無重力的太空看到的會是一樣的！彷彿重力消失了。

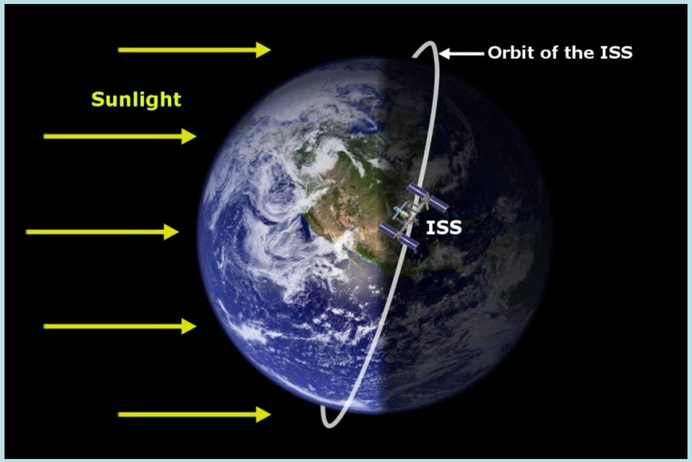
"If a person falls freely, he will not feel his own weight!"

"一個自由下落的人，不會感覺到自己的重量！"

在重力下自由下落者**A**所觀察的現象，與無重力時靜止者所觀察的現象相同。



ISS - International Space Station - Inside ISS - Tour - Q&A - HD

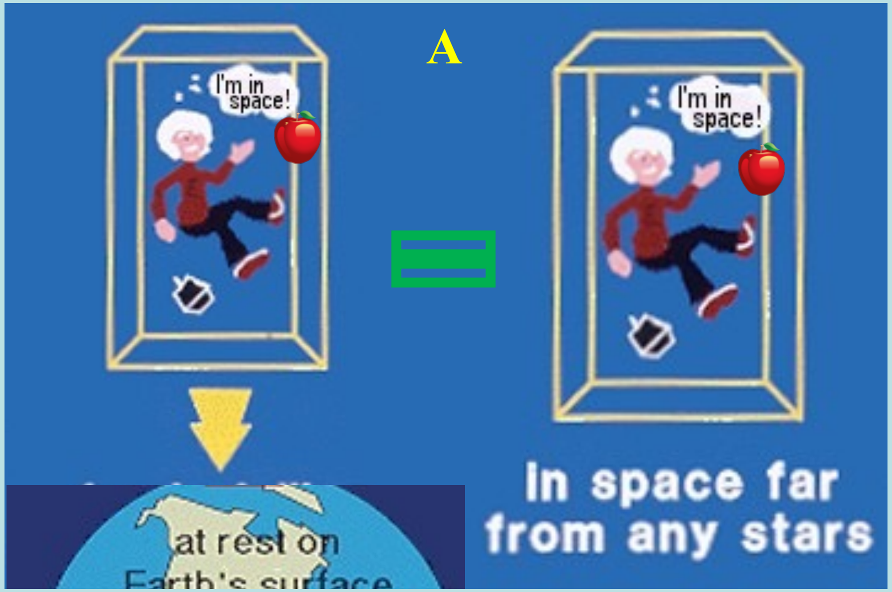


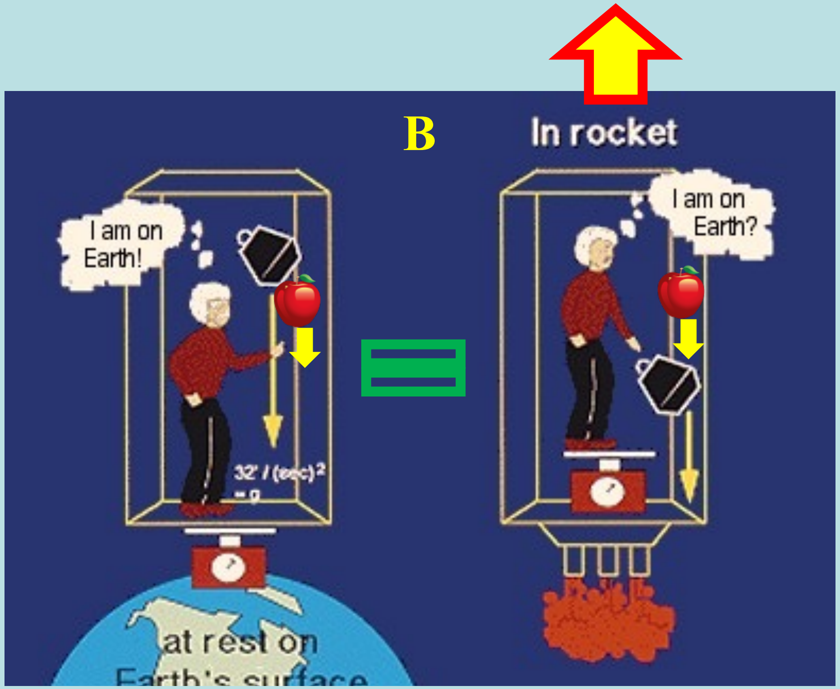
地表上自由下落**A**所觀察的現象，與無重力下靜止觀察者所觀察的現象相同。

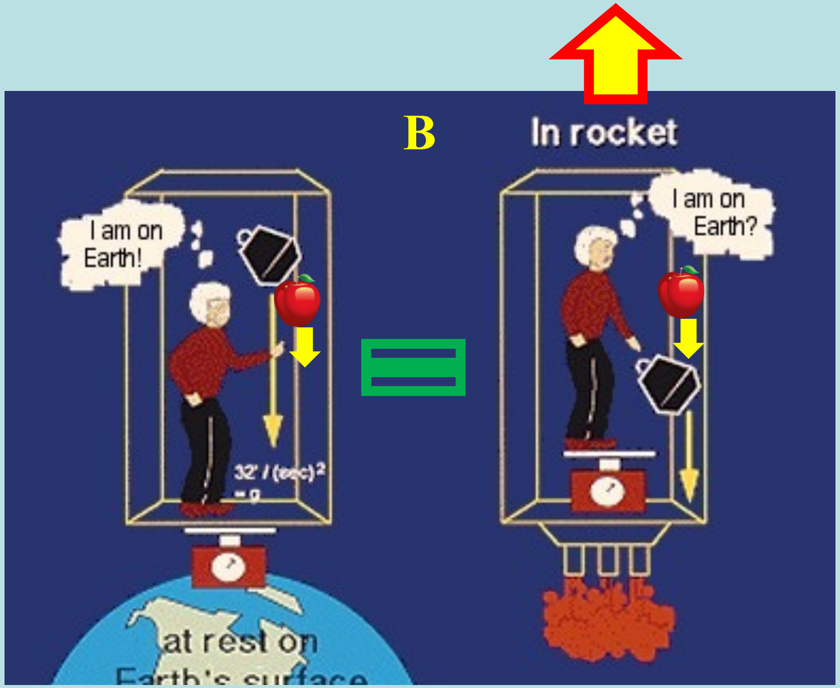
同樣的兩個場景：

但考慮地表上還有一個靜止的觀察者**B**（**B**相對於自由下落的**A**是往上加速運動！）

他與一個太空中另一個往上加速的觀察者，兩者也會看到一模一樣的現象才對。







左圖中的觀察者感覺到周圍物體受到地球的重力而作自由下落等加速度運動。

而右圖太空中加速火箭上的另一個觀察者，在他看來，

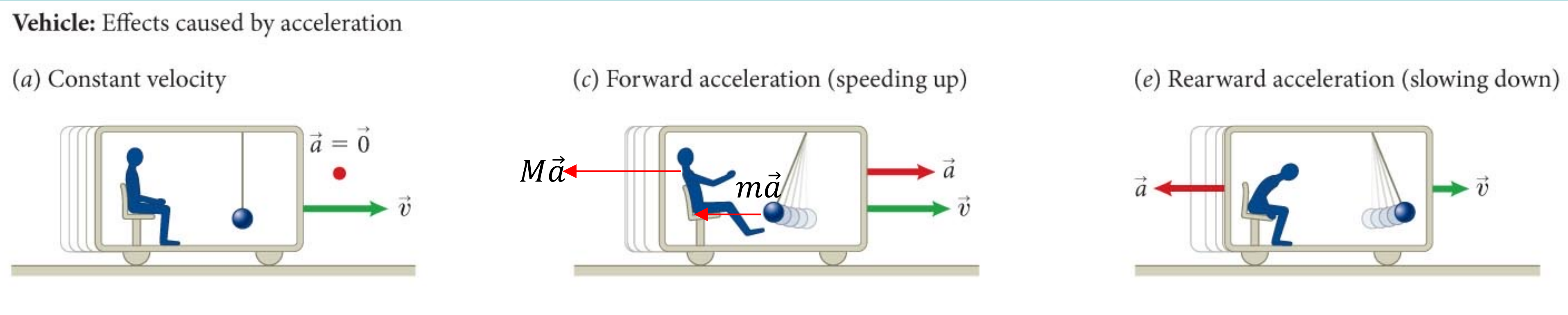
所有物體，因為慣性，也會往反方向作等加速運動！好像都受一個力的作用。

問題是：你無法分辨你是在重力影響之下，還是在無重力處的加速火箭上！

結論是：假力猶如重力，假力與重力等效。假力與重力無法分辨。

加速觀察者會觀察到一個假力！

他感覺的力沒有來源，因此稱為假力。

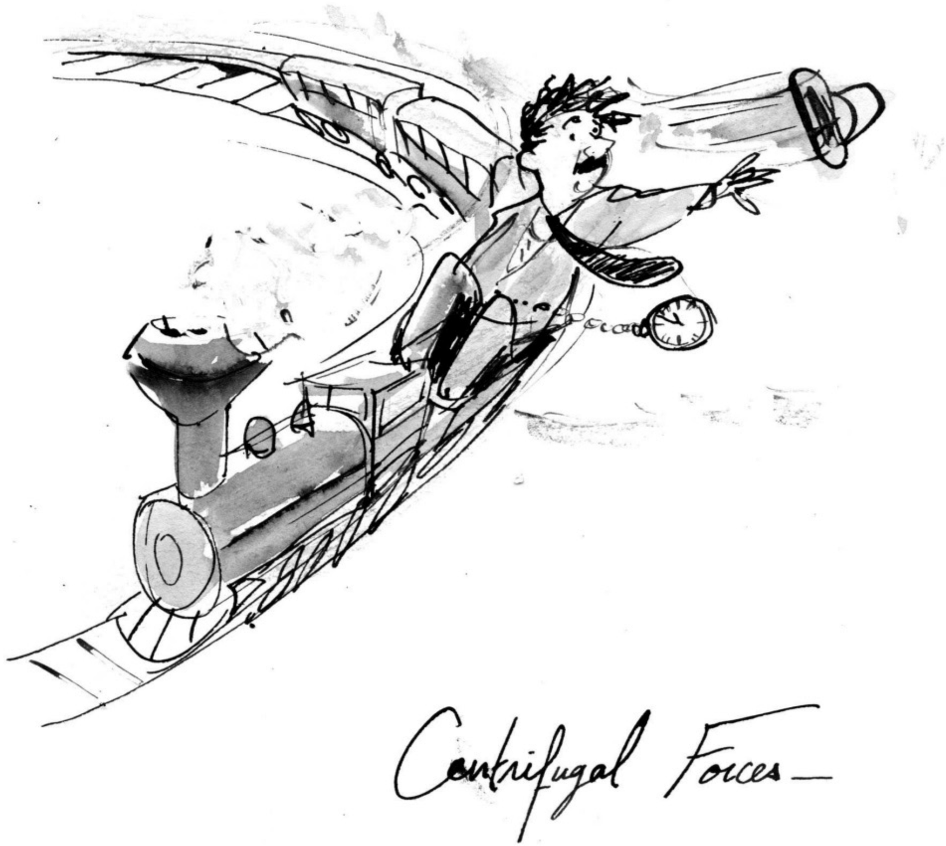


因為慣性，物體並不會如加速觀察者一 起加速。

對以 $\vec{a}$ 加速的觀察者，所有物體會出現一反向，似乎由假力造成的加速度 $-\vec{a}$ 。

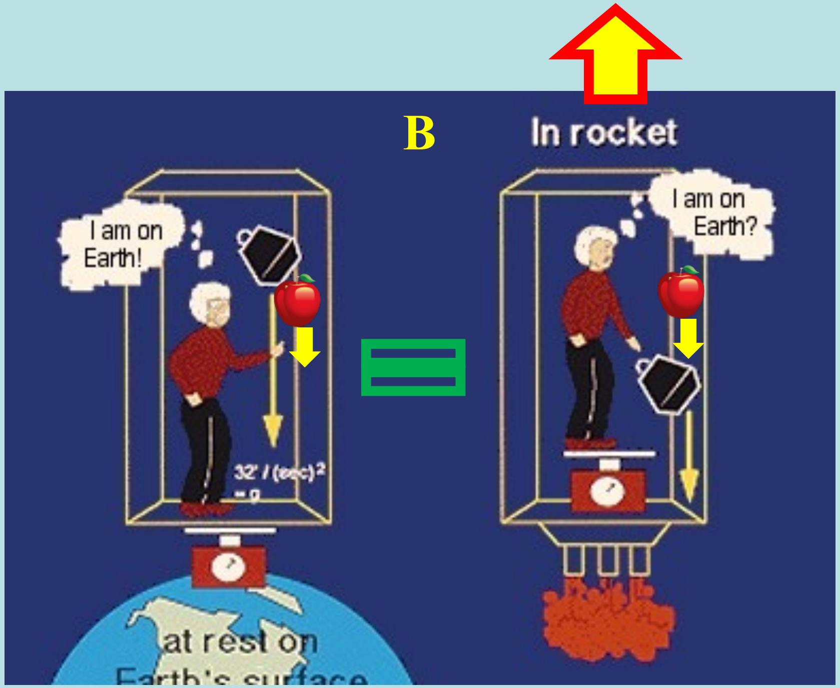
所有物體，無論輕重，假力加速度$-\vec{a}$是一樣的！

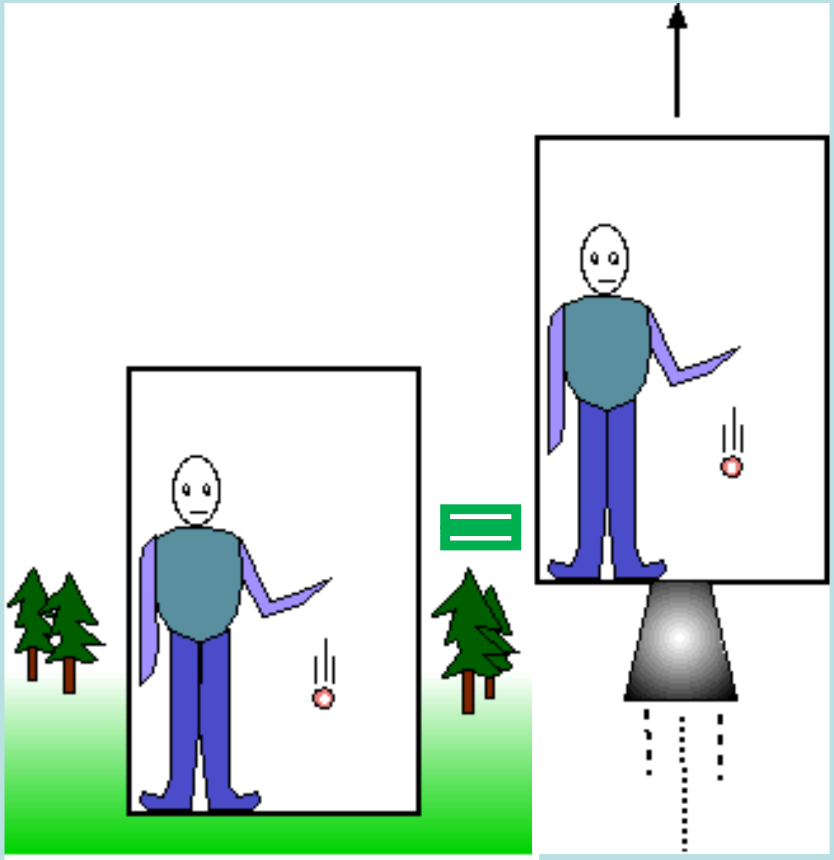
因此物體所受假力與其質量成正比： $-m\vec{a}$，這與重力完全一致。



A “fictitious” force makes it difficult for Einstein to keep his hat on.

假力與重力特徵一致，上圖就好似多了一個水平的重力！

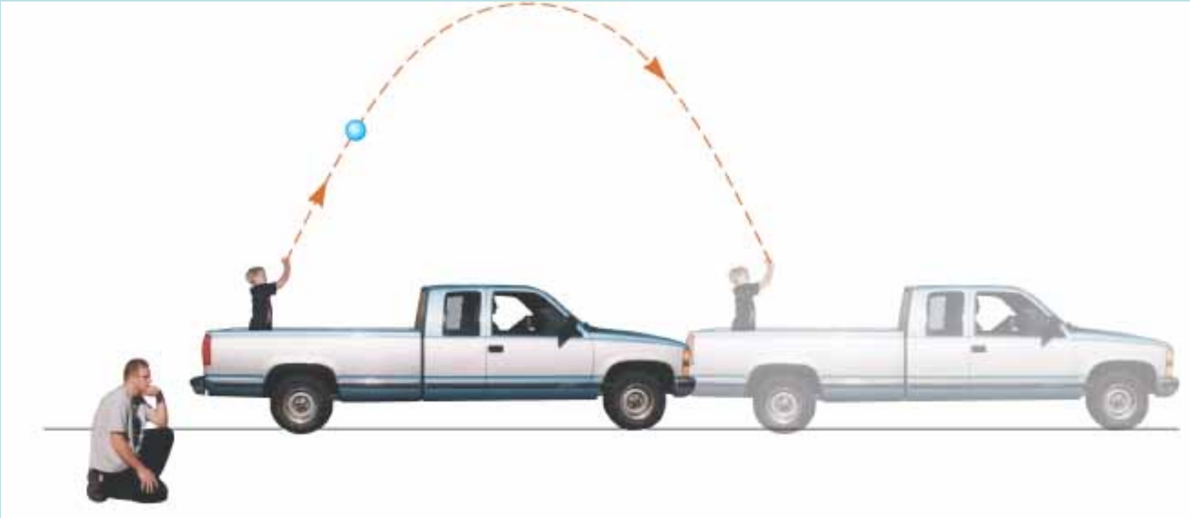


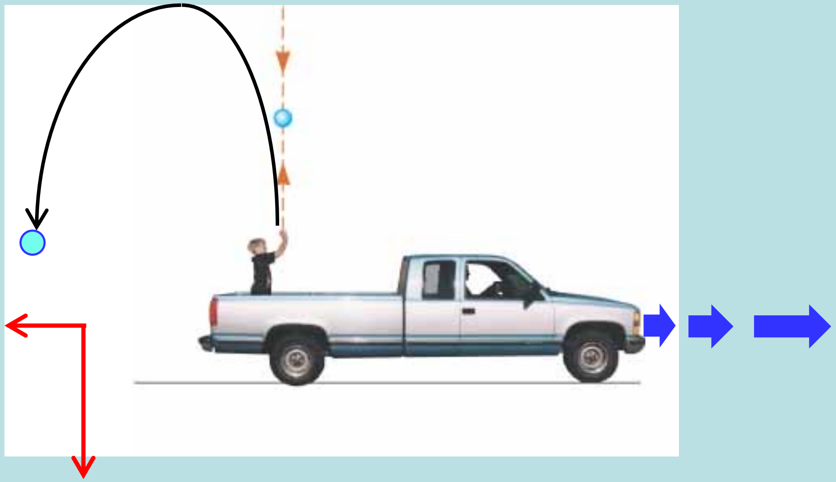


愛因斯坦指之：樂觀看待此事：那麼靜止觀察者所看到的重力的效應，
與無重力狀態下，加速的觀察者所觀察到的假力的效應相同！無法分辨。

透過了解加速座標系，就可以了解重力。

等效原則 Equivalence Principle





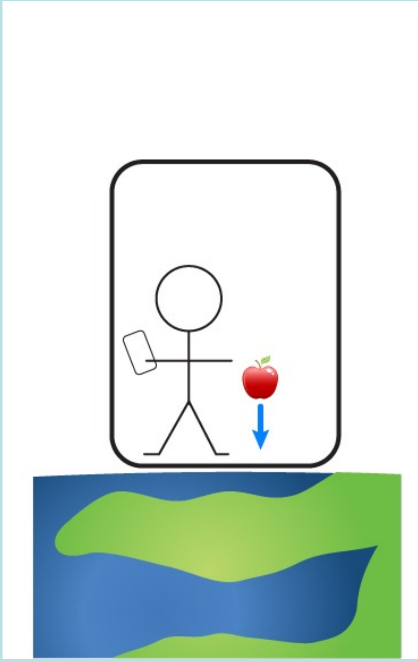
新的重力

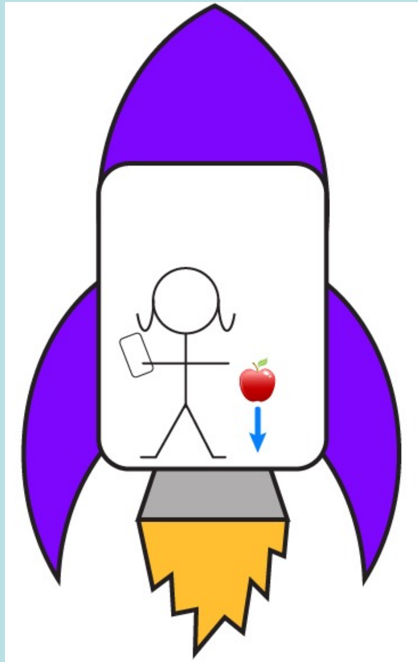
特殊相對論的相對性原則指出我們無法分辨等速運動及靜止的座標系！

加速或任意的座標系會有假力，似乎可以被分辨出來。

但等效原則指出你依舊無法分辨此假加速度效應是來自加速座標或是重力。

物理的現象與定律是無關於你所選定的觀察者（只要你考慮適當的重力效應）。





等效原則 Equivalence Principle

有重力下的靜止觀察者，與無重力下的加速觀察者，是等效的。

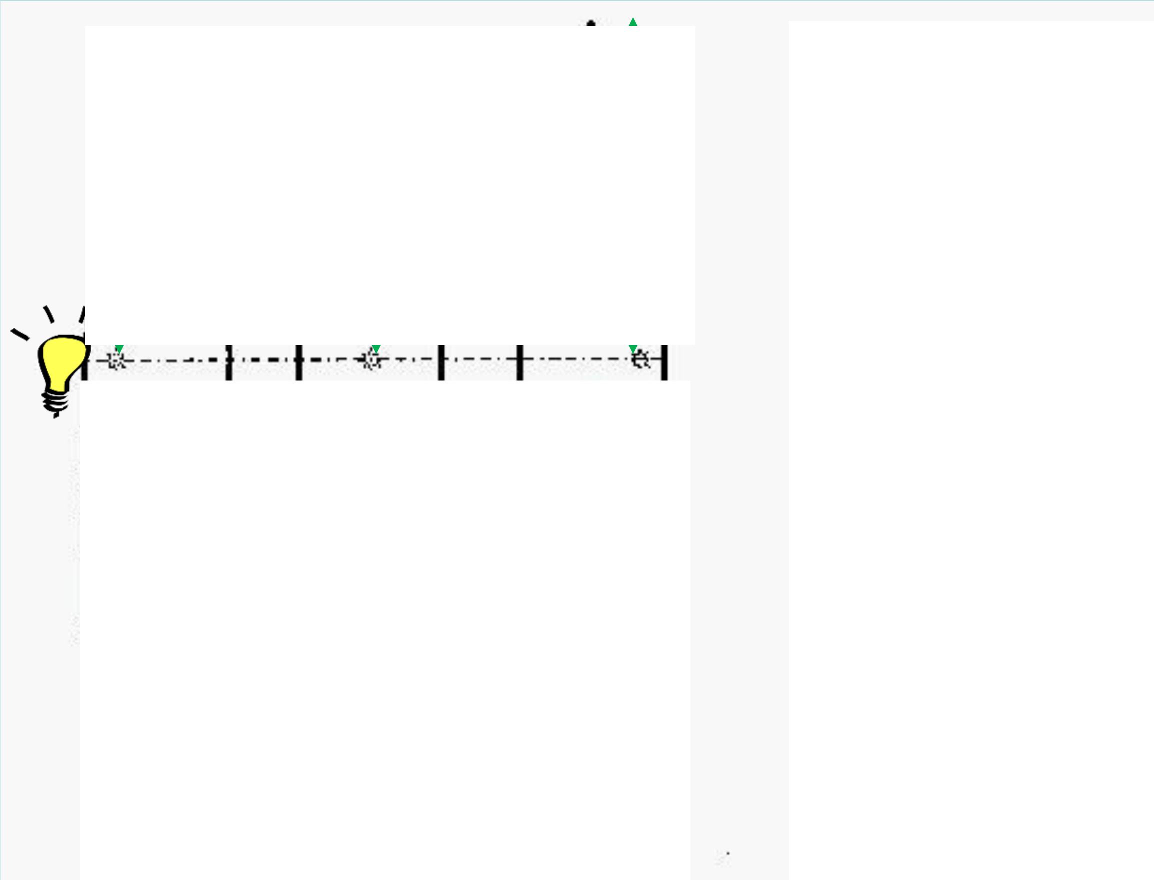
以上是從力學及日常經驗得到的結論：

愛因斯坦進一步推論這樣的對應關係適用於任何物理現象，包括光的傳播！

透過了解加速座標系，就可以了解重力。

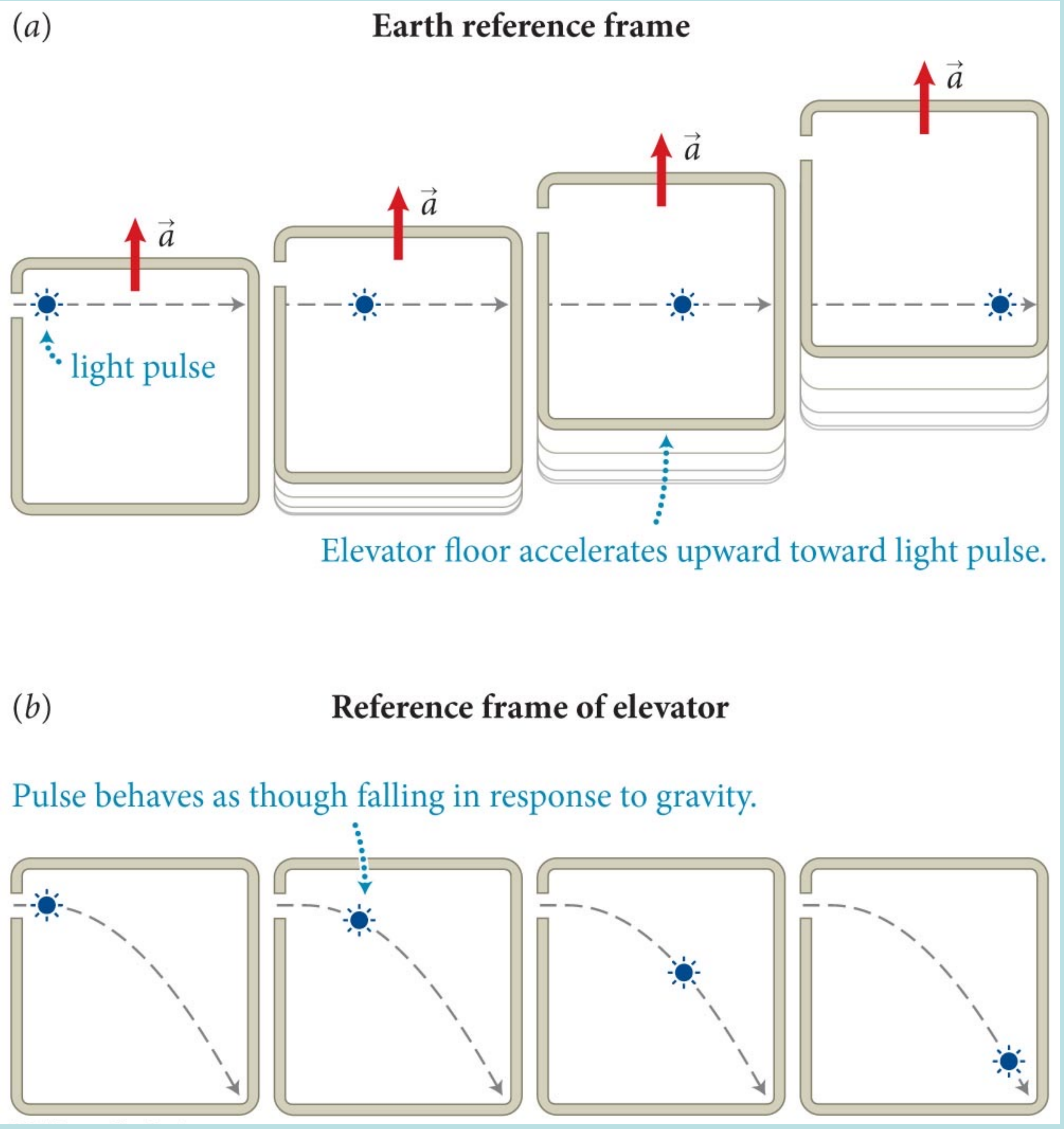
因此要研究在重力下光是否會偏轉，

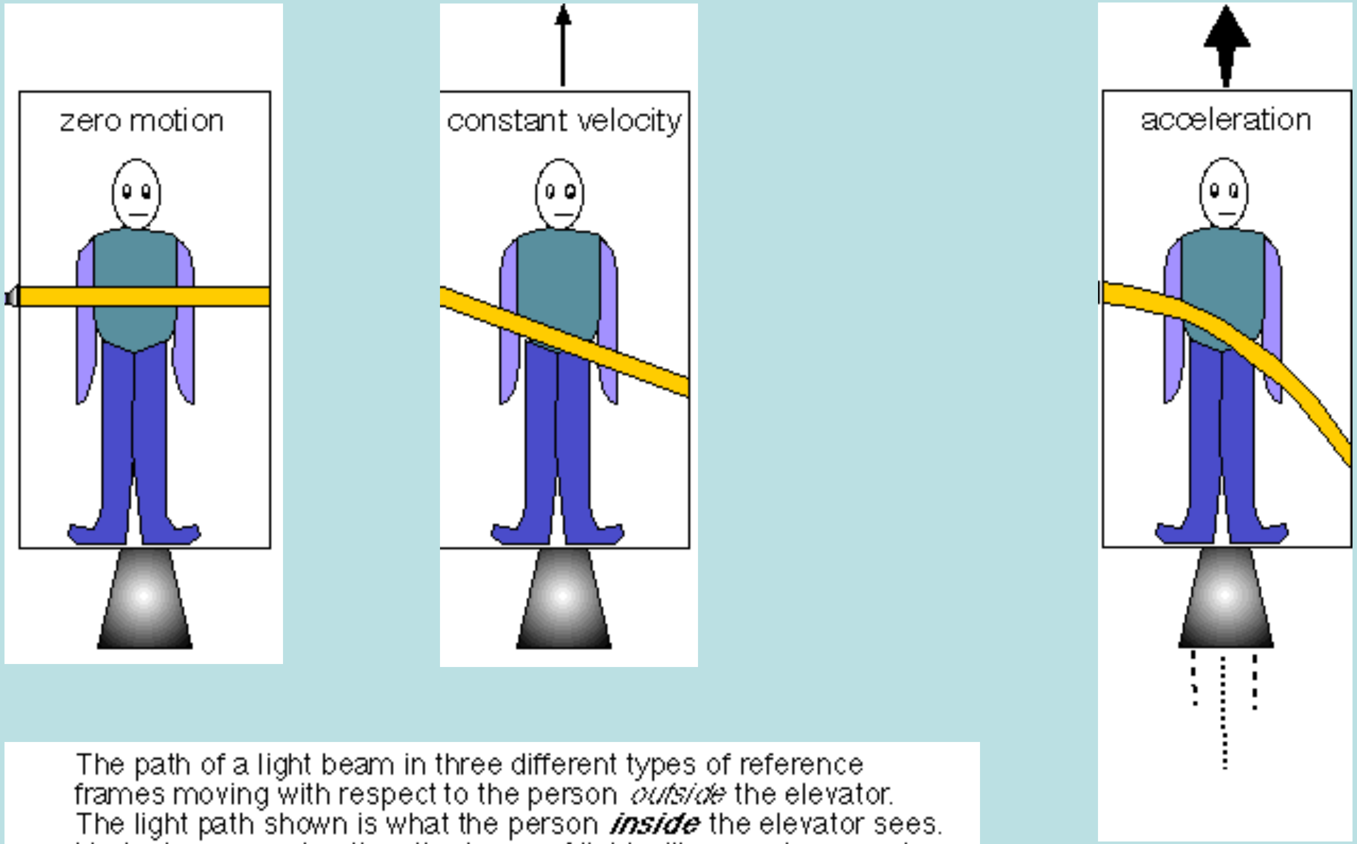
就考慮在無重力下的加速觀察者看來，一道光會不會偏轉就知道了。



從外界看來，光是走直線。但同時火箭加速運動！

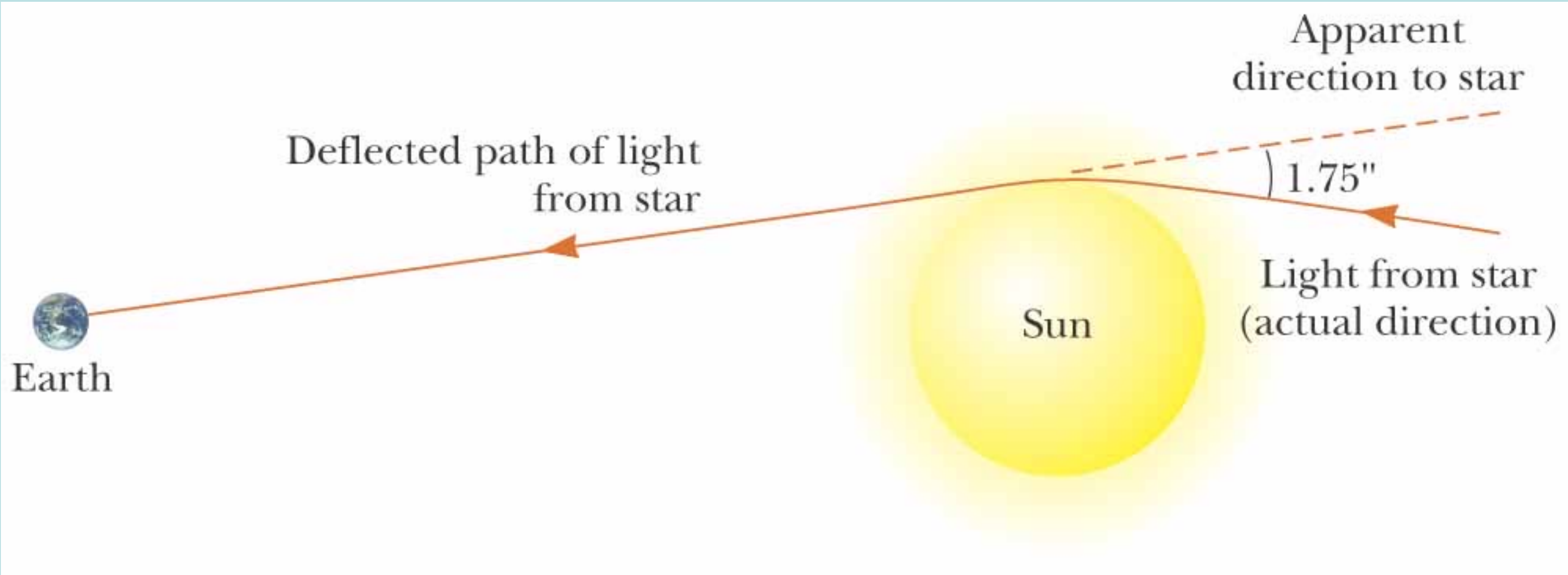
從火箭上的觀察者看來，光會向下偏轉。如同重力下的拋體。


(a)
Earth reference frame
$\vec{a}$
light pulse
Elevator floor accelerates upward toward light pulse.
(b)
Reference frame of elevator
Pulse behaves as though falling in response to gravity.

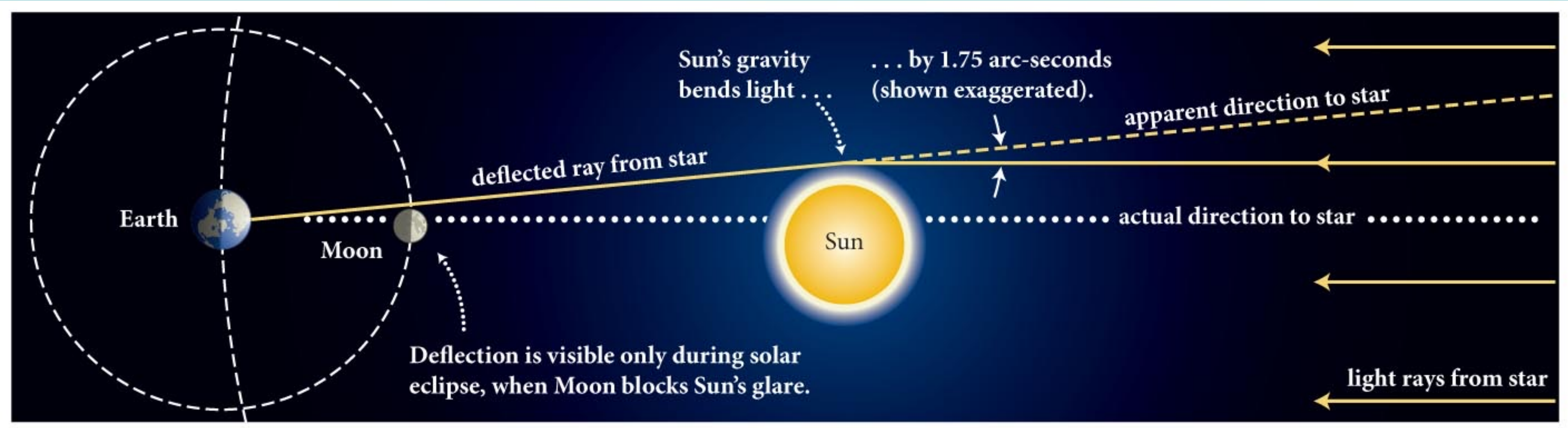


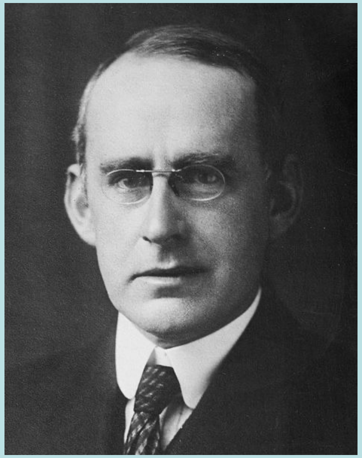
The path of a light beam in three different types of reference frames moving with respect to the person *outside* the elevator. The light path shown is what the person ***inside*** the elevator sees. Under large acceleration, the beam of light will curve downward. It should also do that in a region of strong gravity.

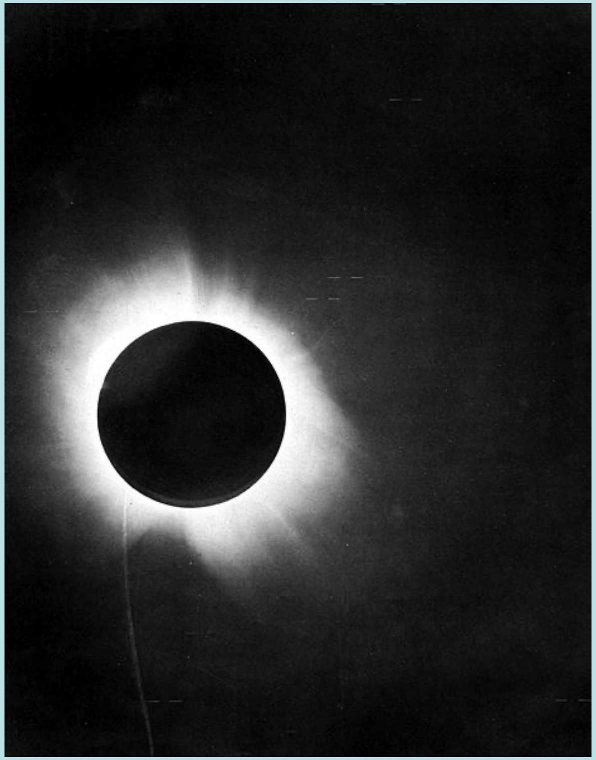
光即使沒有質量，還是會受到重力的作用而彎曲其路徑。

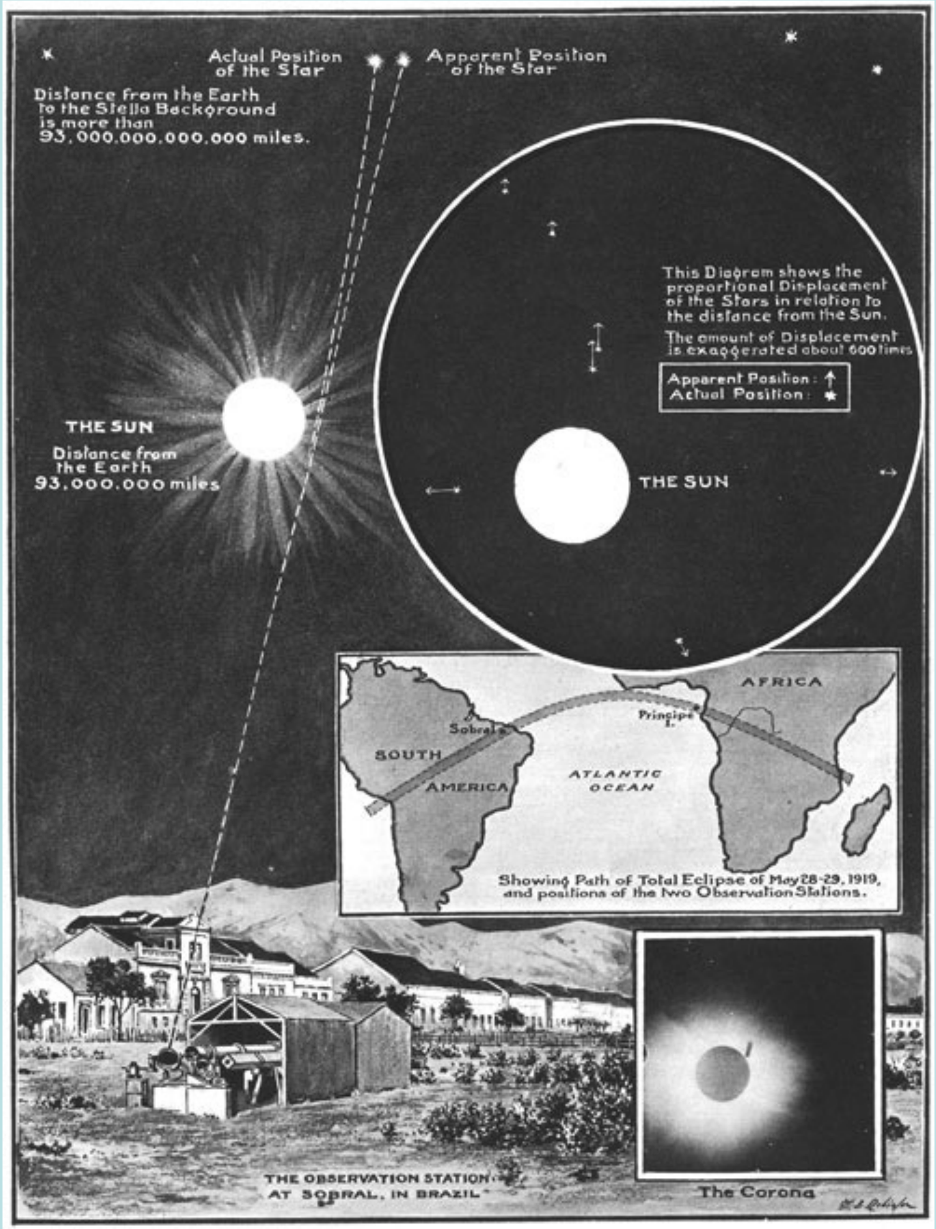


利用日蝕，觀察星光受太陽質量重力的偏折：

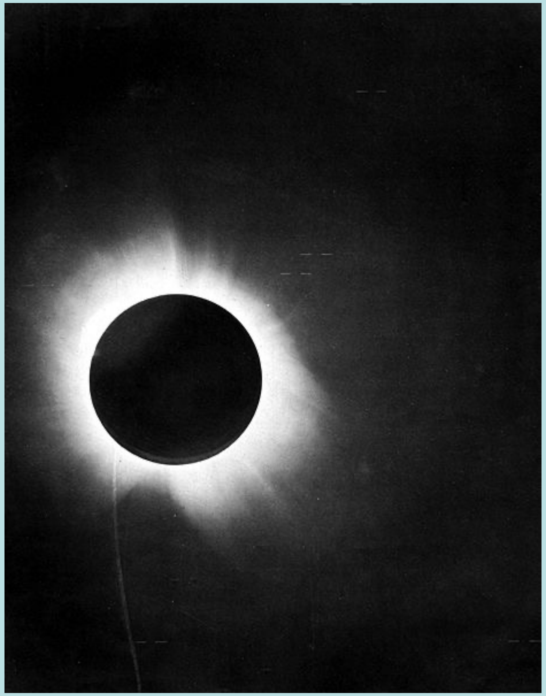


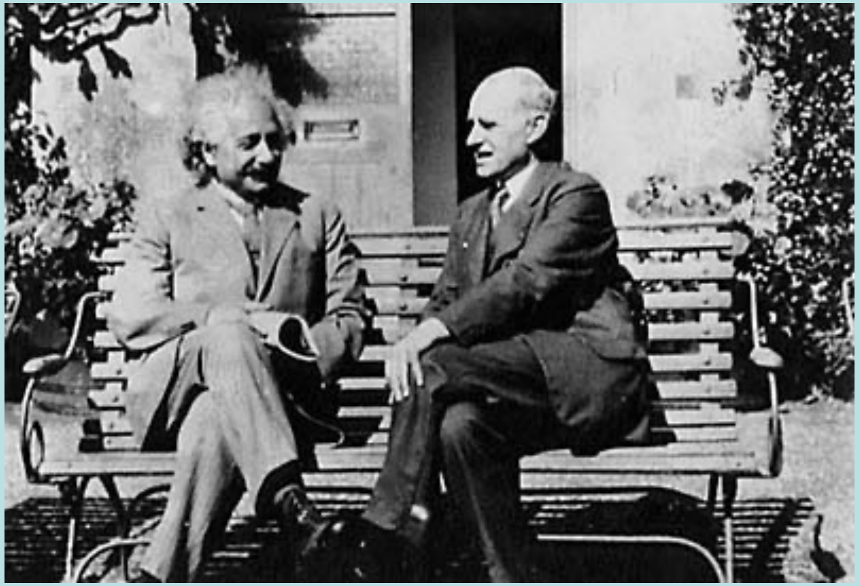






One of Eddington's photographs of the total solar eclipse of 29 May 1919, presented in his 1920 paper announcing its success, confirming Einstein's theory that light bends





LIGHTS ALL ASKEW IN THE HEAVENS
Special Cable to THE NEW YORK TIMES.
New York Times 1857; Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
pg. 17

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

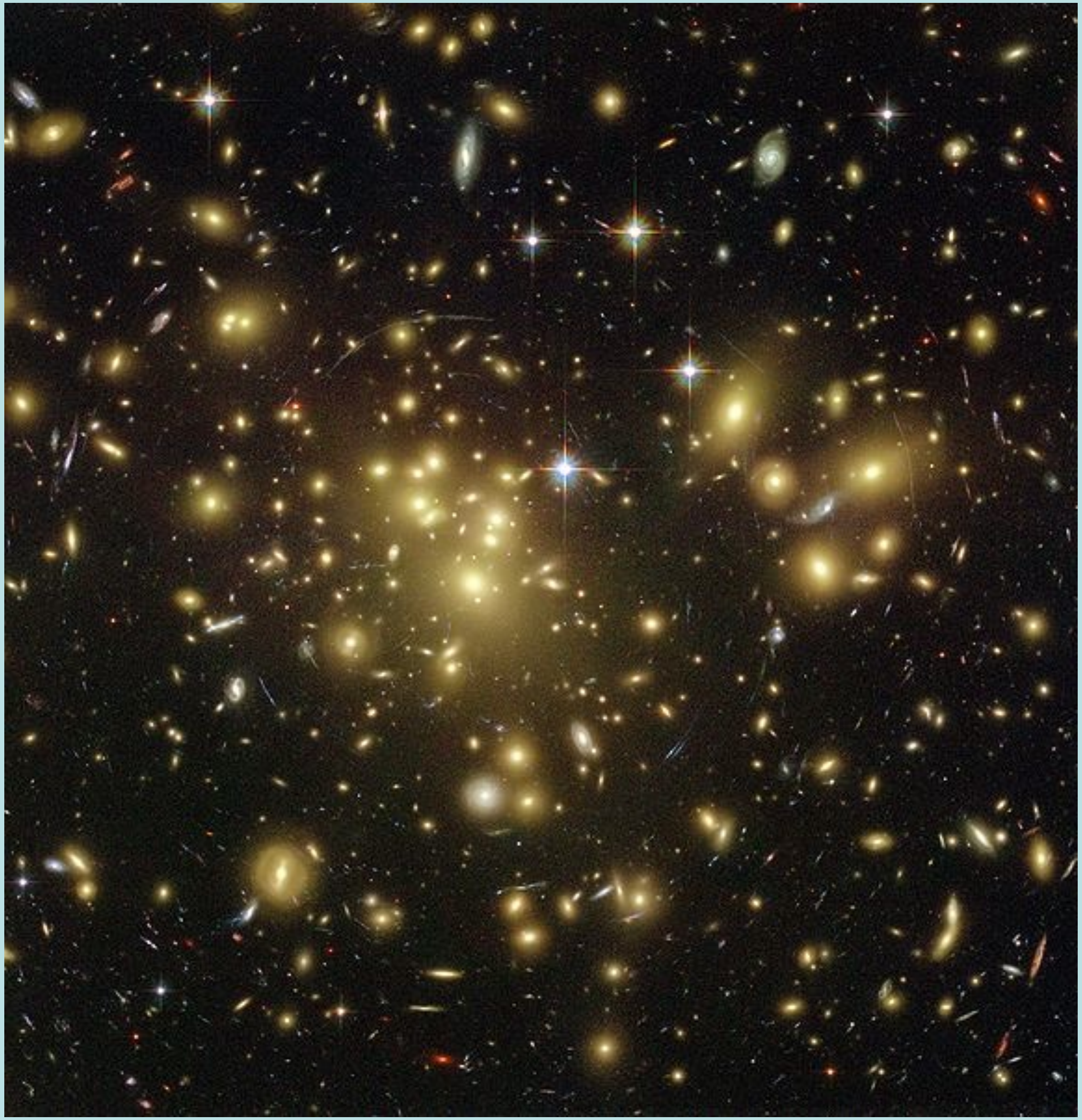
A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

NY Times, Nov 10, 1919

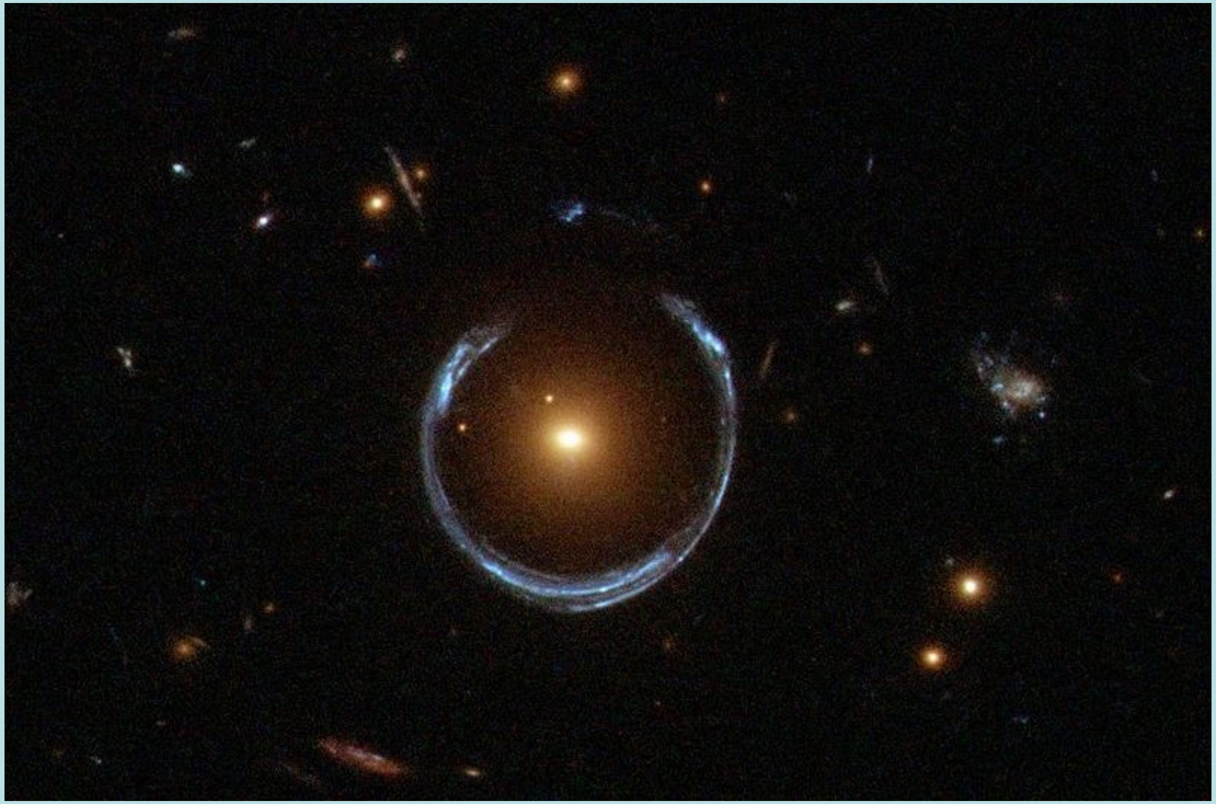
重力透鏡

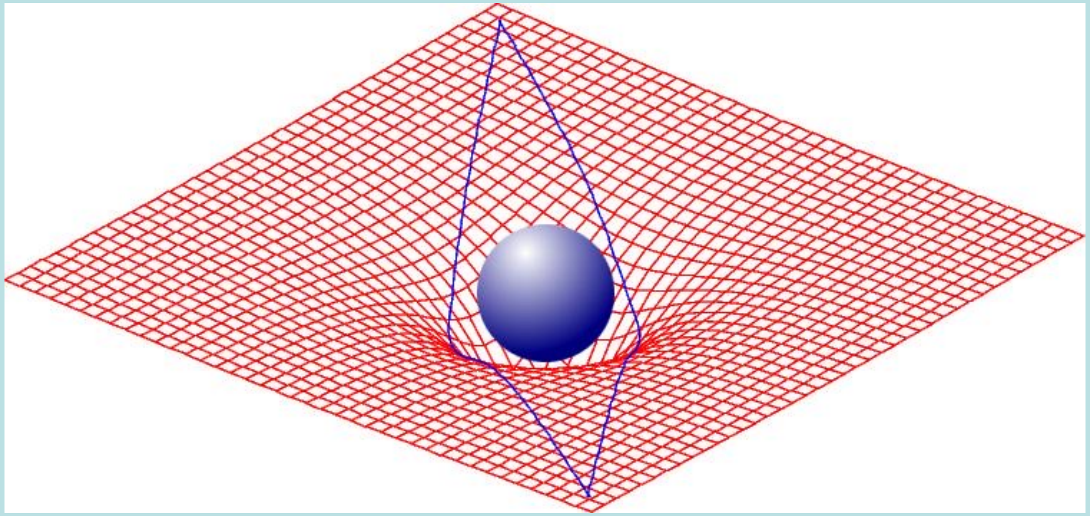
在天文觀測中也驗證了這個結果



照片 中弧形若是星體，將有好幾萬光年長，所以是扭曲的影像。

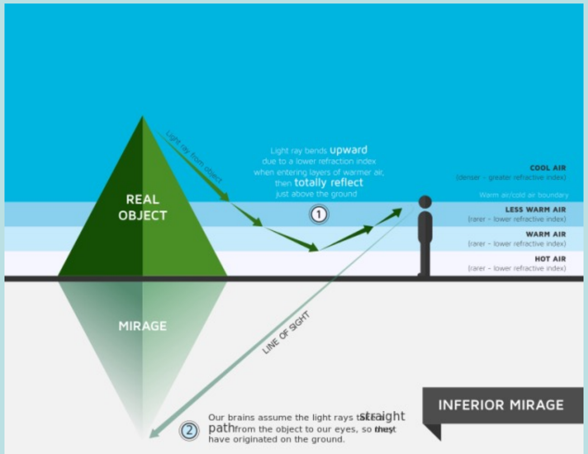
Einstein Ring 這是光線偏折的結果。

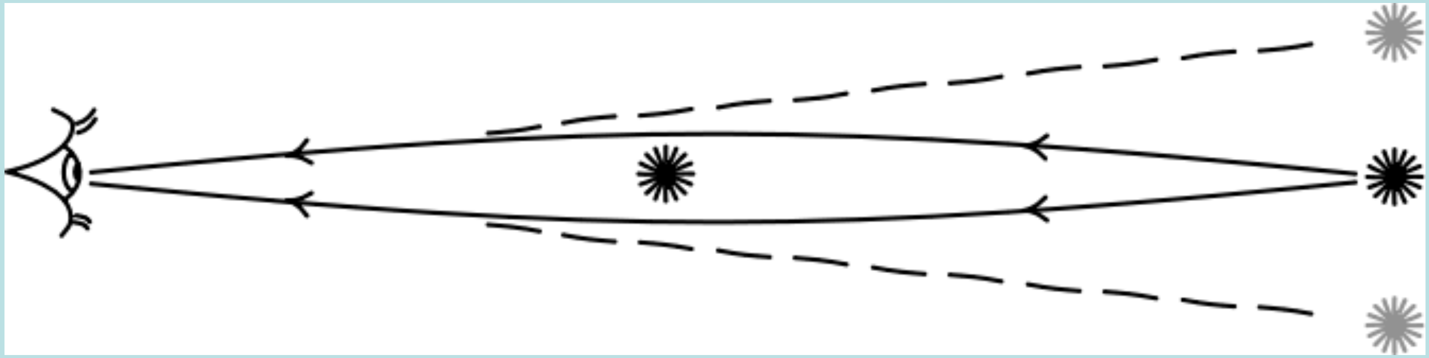


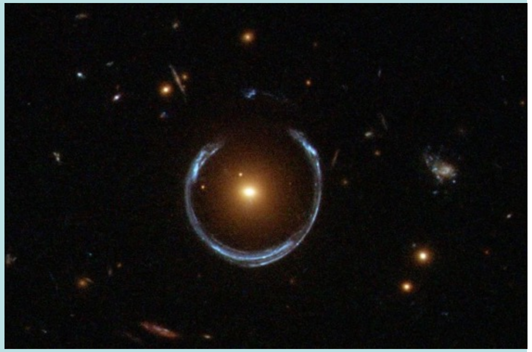


海市蜃樓 Mirage

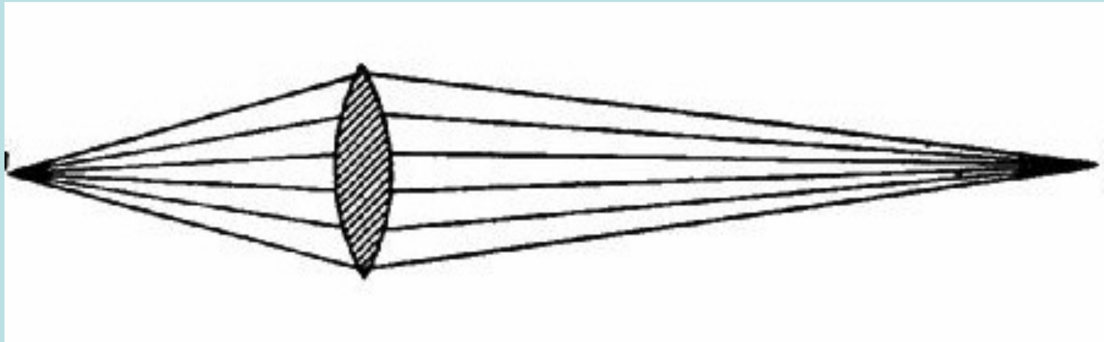
光走彎曲路線時，所看到的幻象。



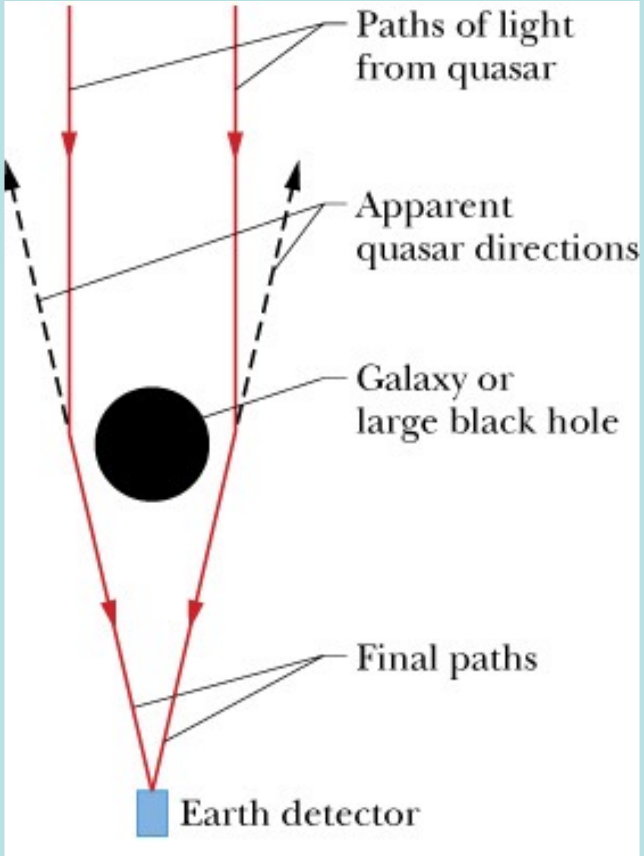


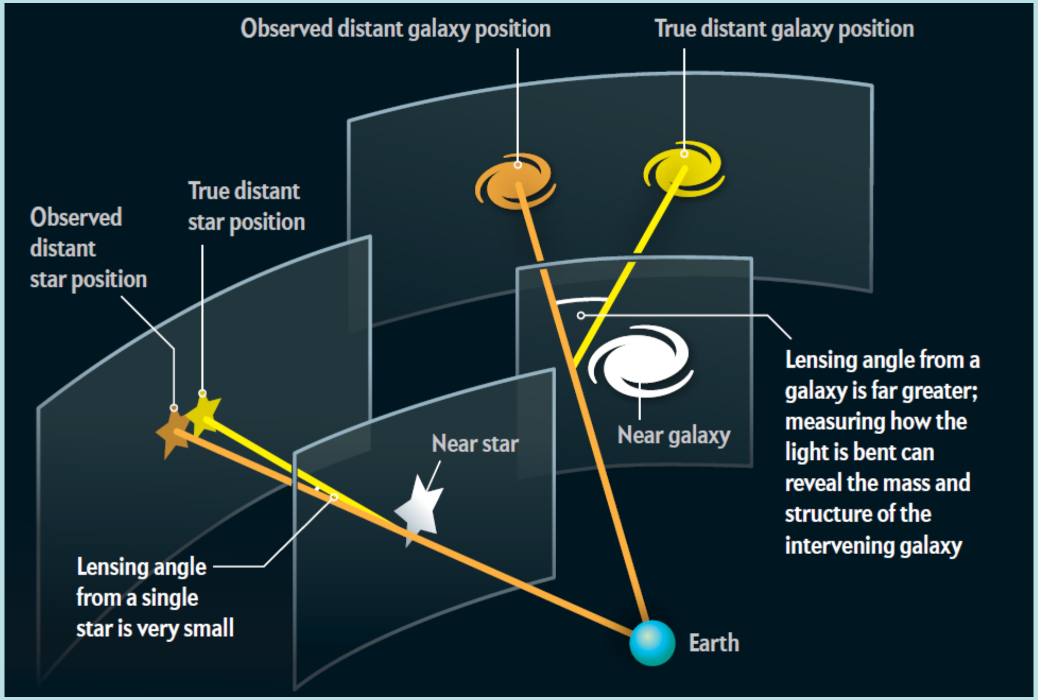


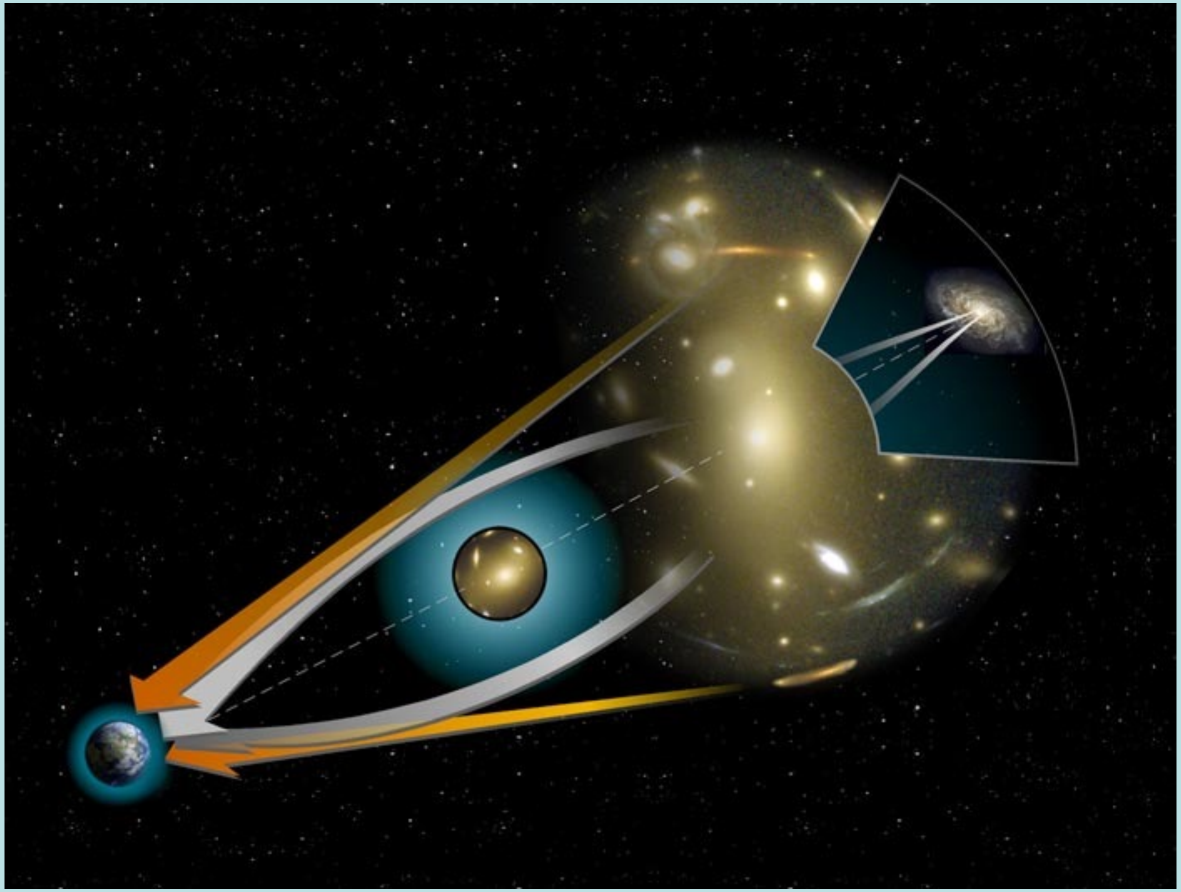
被近處星團遮蔽的遠方星團，所發出的光，其路徑會被近處星團彎曲。
在地球被看到時，看來會是位於偏離原來的星團的位置。
這樣的影像在近處星團周圍都會發生，因此遠處星團看來成了一個環！

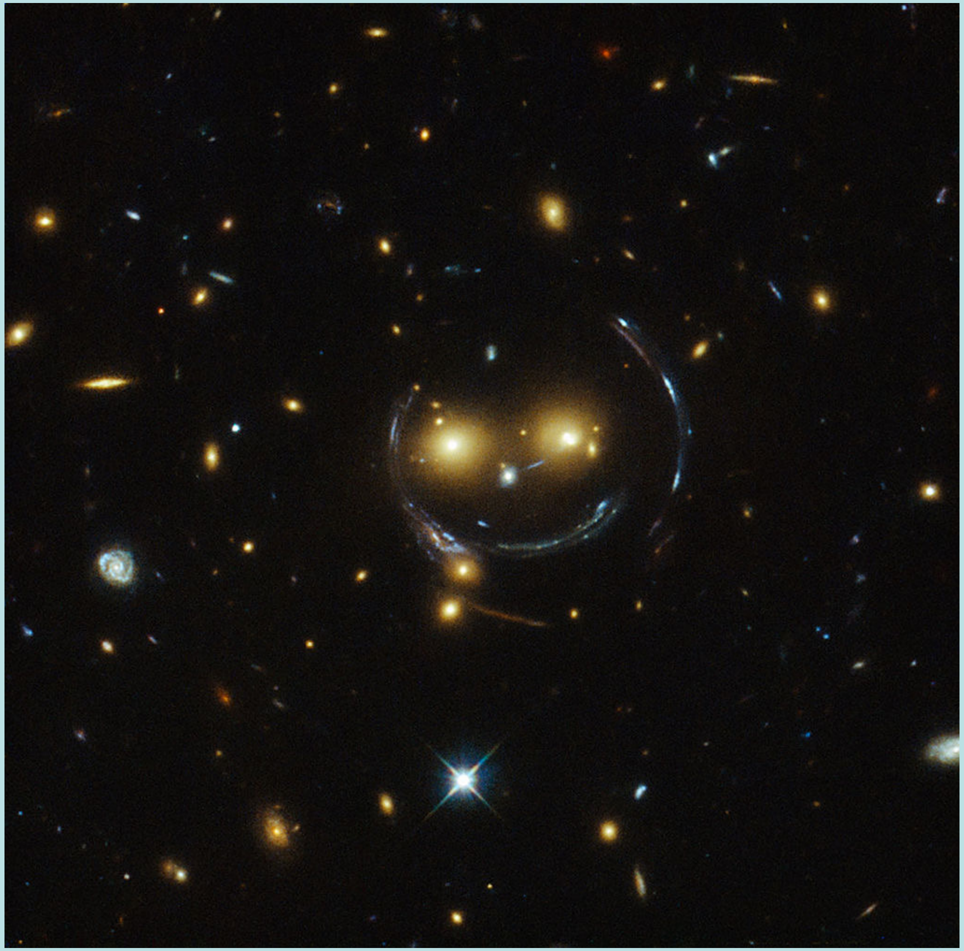


這個現象就稱為重力透鏡：Gravitational Lenses

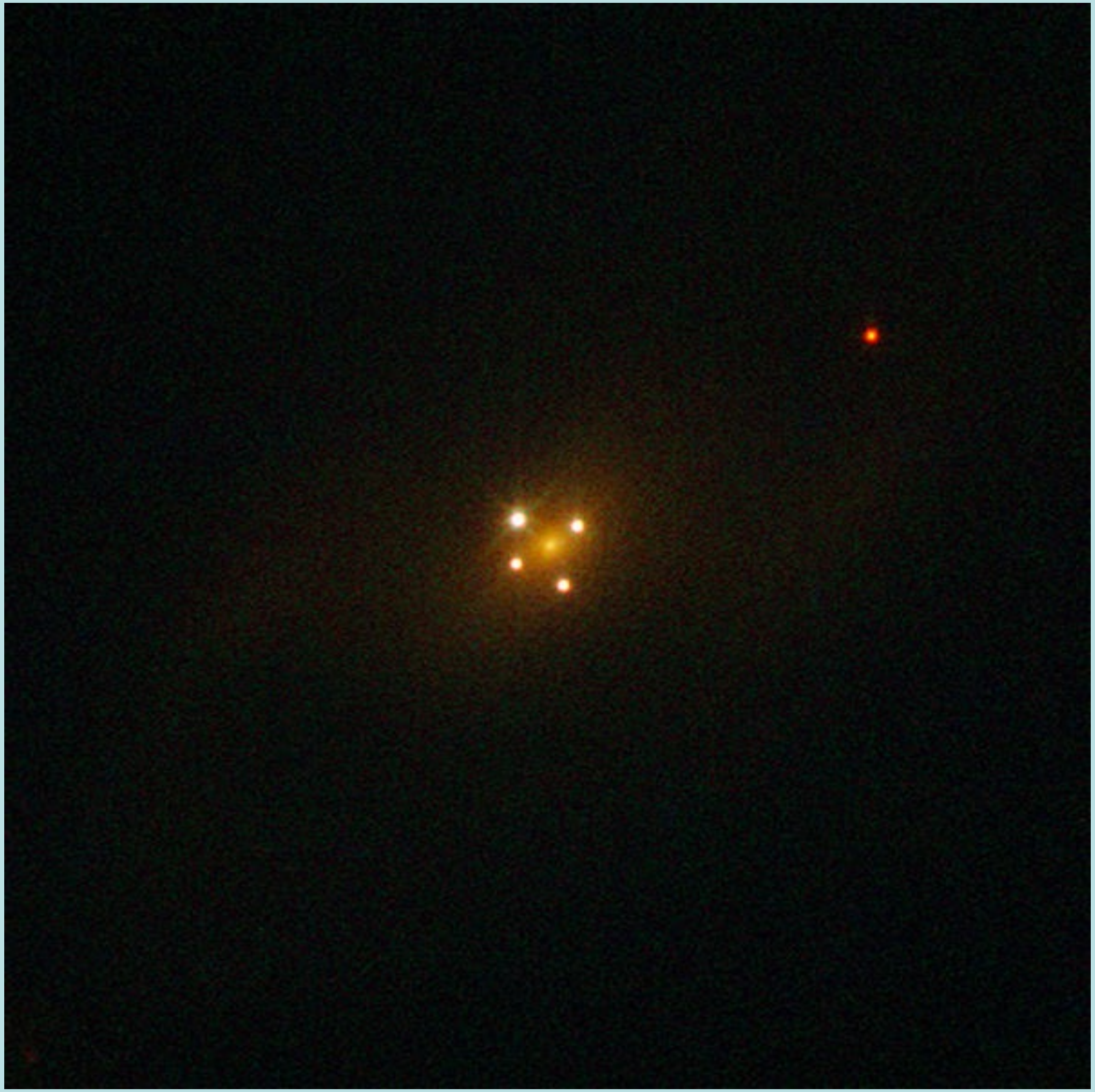

Paths of light
from quasar
Apparent
quasar directions
Galaxy or
large black hole
Final paths
Earth detector

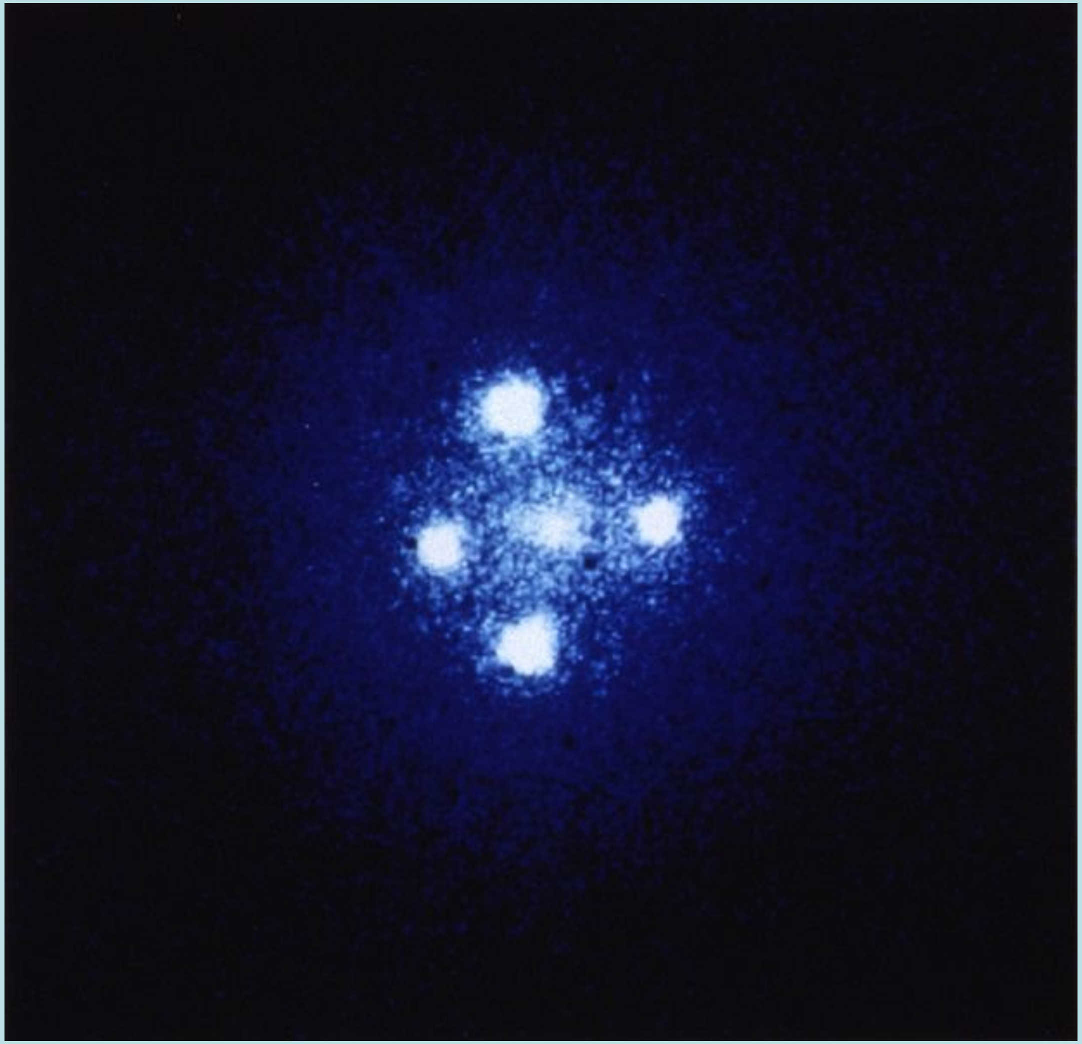

Observed distant galaxy position
True distant galaxy position
Observed
distant
star position
True distant
star position
Near star
Near galaxy
Lensing angle from a
galaxy is far greater;
measuring how the
light is bent can
reveal the mass and
structure of the
intervening galaxy
Lensing angle
from a single
star is very small
Earth

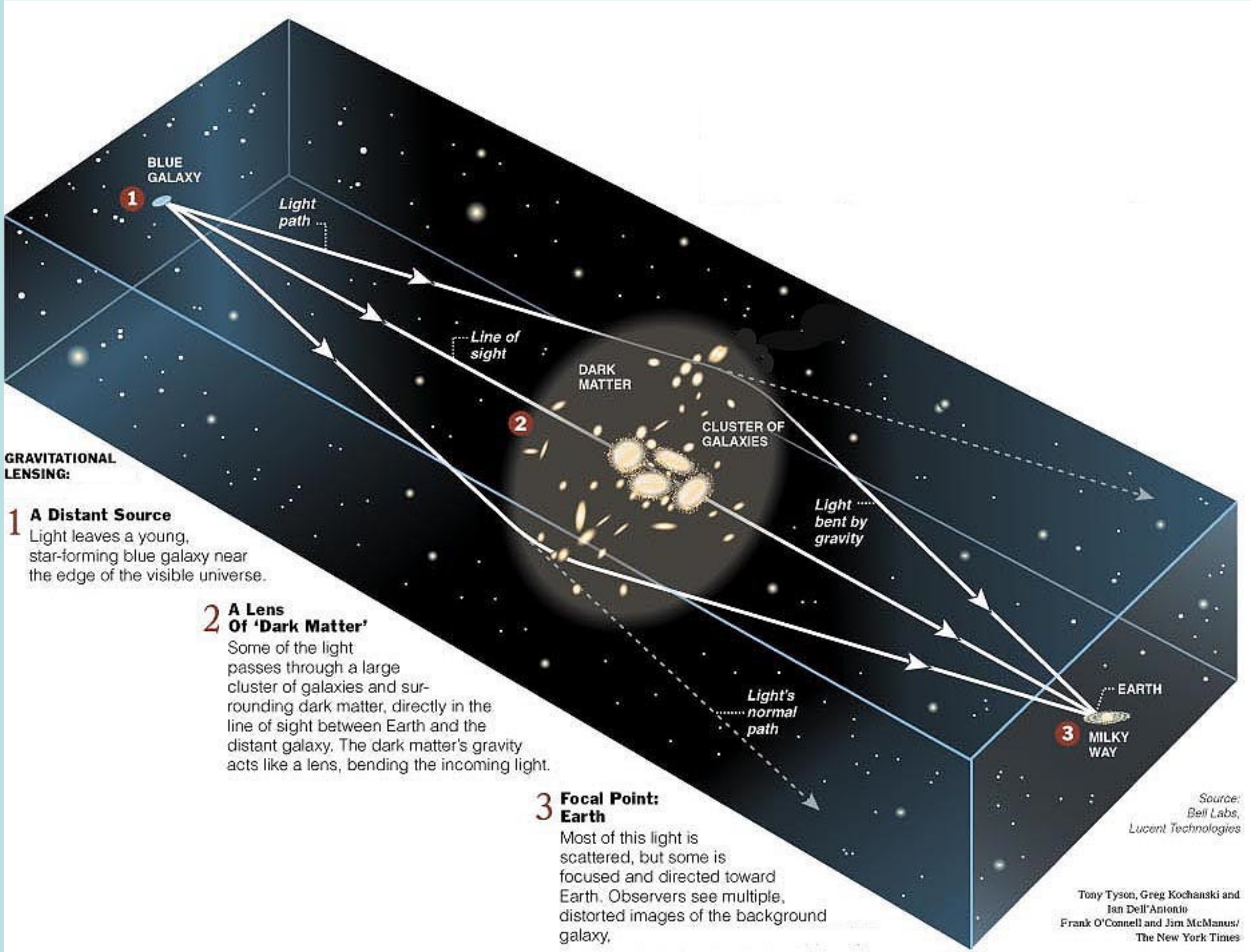




Einstein Cross

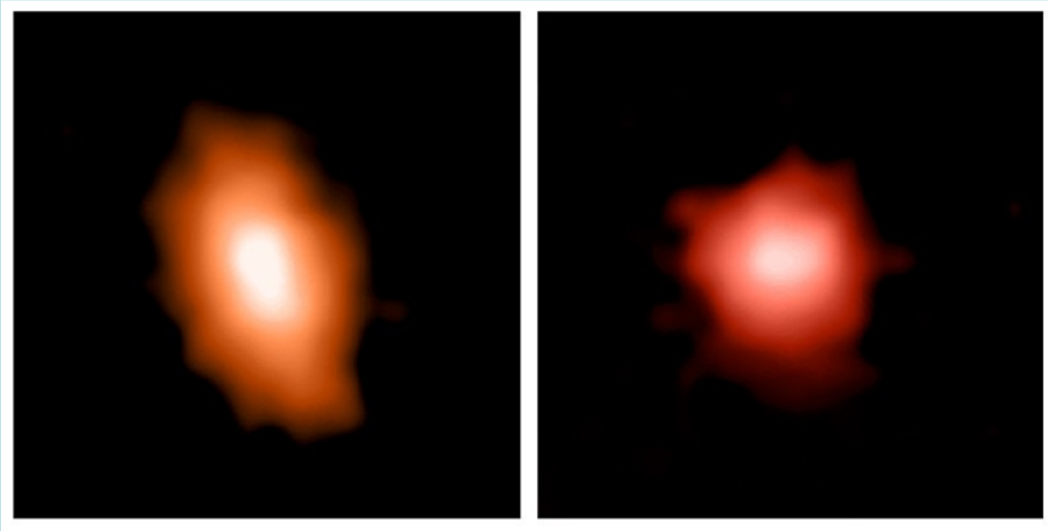




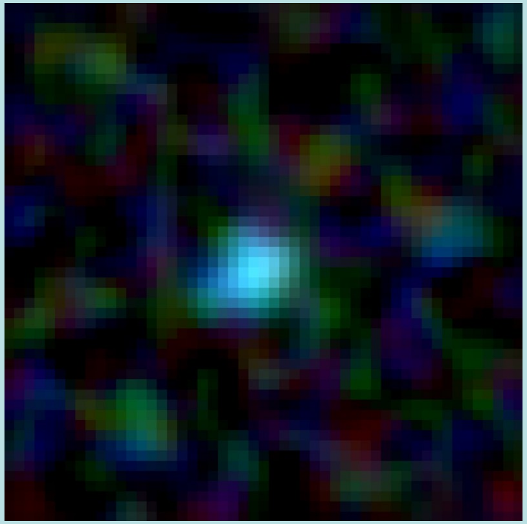

BLUE GALAXY
1
Light path
Line of sight
DARK MATTER
2
CLUSTER OF GALAXIES
Light bent by gravity
Light's normal path
EARTH
3
MILKY WAY
GRAVITATIONAL LENSING:
1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.
2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.
3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.
Source: Bell Labs, Lucent Technologies
Tony Tyson, Greg Kochanski and Ian Dell'Antonio
Frank O'Connell and Jim McManus/ The New York Times

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，

這是典型的重力透鏡效應，韋伯望遠鏡使他們細微結構清晰可見。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，對這些光仔細研究，將讓我們可以看透整個宇宙的歷史。



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.

This image from NASA's James Webb Space Telescope shows a massive galaxy cluster called WHL0137-08, and at the right, an inset of the most strongly magnified galaxy known in the universe's first billion years: the Sunrise Arc. Within that galaxy is the most distant star ever detected, first discovered by the Hubble Space Telescope.

Webb's NIRCam (Near-Infrared Camera) instrument reveals the star, nicknamed Earendel, to be a massive B-type star more than twice as hot as our Sun, and about a million times more luminous. Stars of this mass often have companions. Astronomers did not expect Webb to reveal any companions of Earendel since they would be so close together and indistinguishable on the sky. However, based solely on the colors of Earendel detected by Webb, astronomers think they see hints of a cooler companion star.

First Supernova 超新星 Einstein Cross

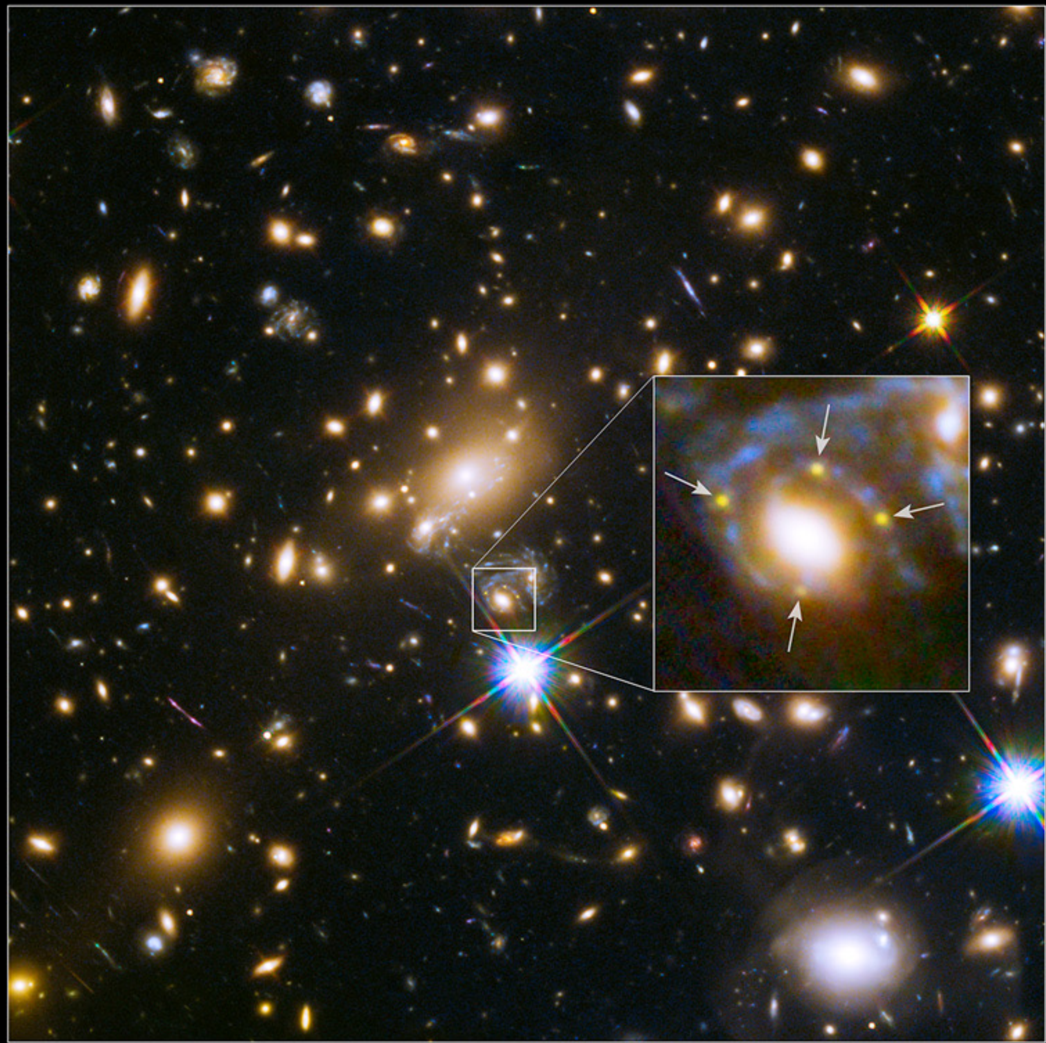
超新星是爆炸的恆星，在一定時段發光。

REPORTS

ASTROPHYSICS

Multiple images of a highly magnified supernova formed by an early-type cluster galaxy lens

Patrick L. Kelly,[1*] Steven A. Rodney,[2] Tommaso Treu,[3] Ryan J. Foley,[4,5] Gabriel Brammer,[6] Kasper B. Schmidt,[7] Adi Zitrin,[8] Alessandro Sonnenfeld,[3,7] Louis-Gregory Strolger,[6,9] Or Graur,[10,11] Alexei V. Filippenko,[1] Saurabh W. Jha,[12] Adam G. Riess,[2,6] Marusa Bradac,[13] Benjamin J. Weiner,[14] Daniel Scolnic,[15,16] Matthew A. Malkan,[3] Anja von der Linden,[17,18] Michele Trenti,[19] Jens Hjorth,[17] Raphael Gavazzi,[20] Adriano Fontana,[21] Julian C. Merten,[8] Curtis McCully,[7,22] Tucker Jones,[7] Marc Postman,[6] Alan Dressler,[23] Brandon Patel,[12] S. Bradley Cenko,[24,25] Melissa L. Graham,[1] Bradley E. Tucker[1,26]



Supernova Refsdal ▪ Galaxy Cluster MACS J1149.5+2223

Hubble Space Telescope ▪ ACS/WFC ▪ WFC3/IR

NASA and ESA

STScI-PRC15-08a

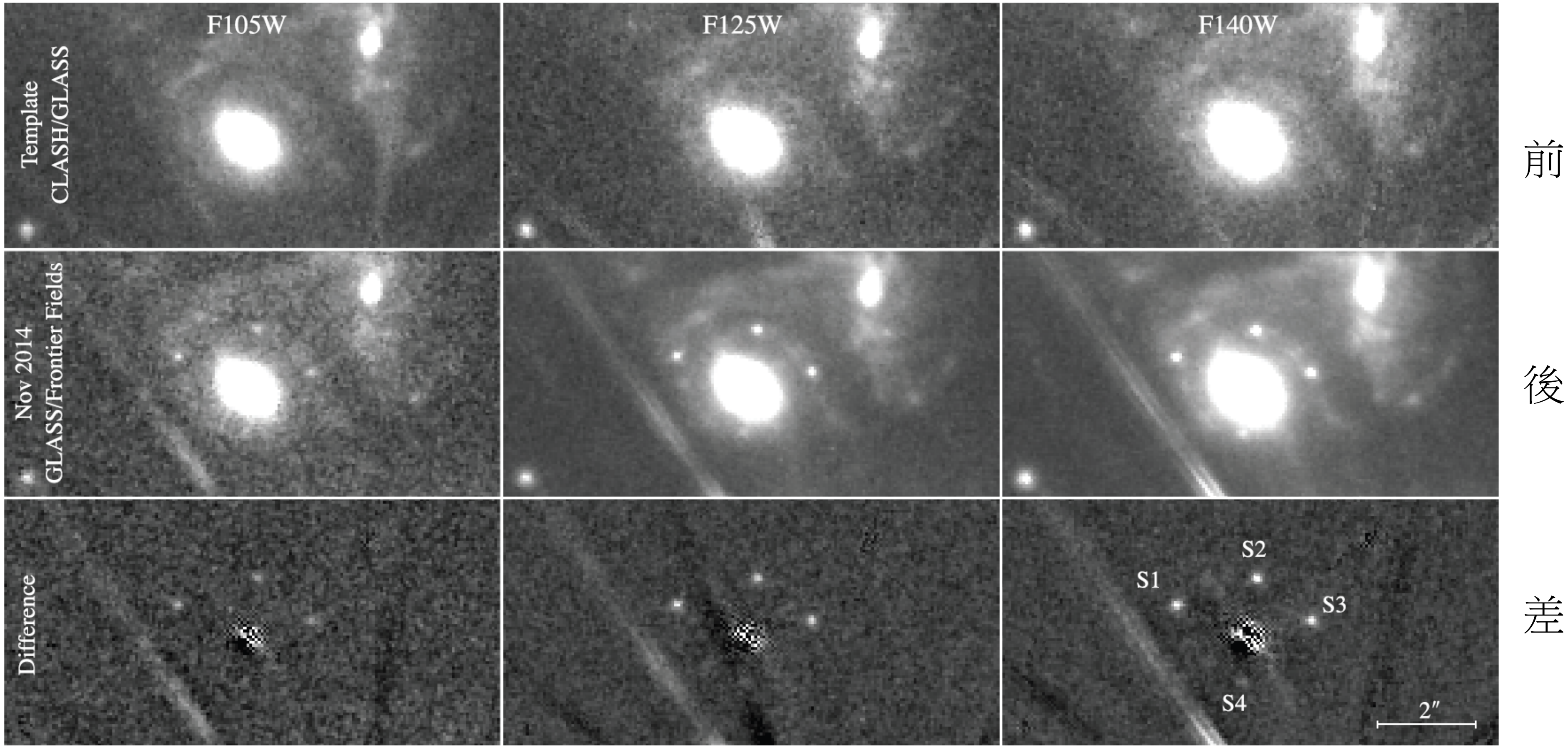
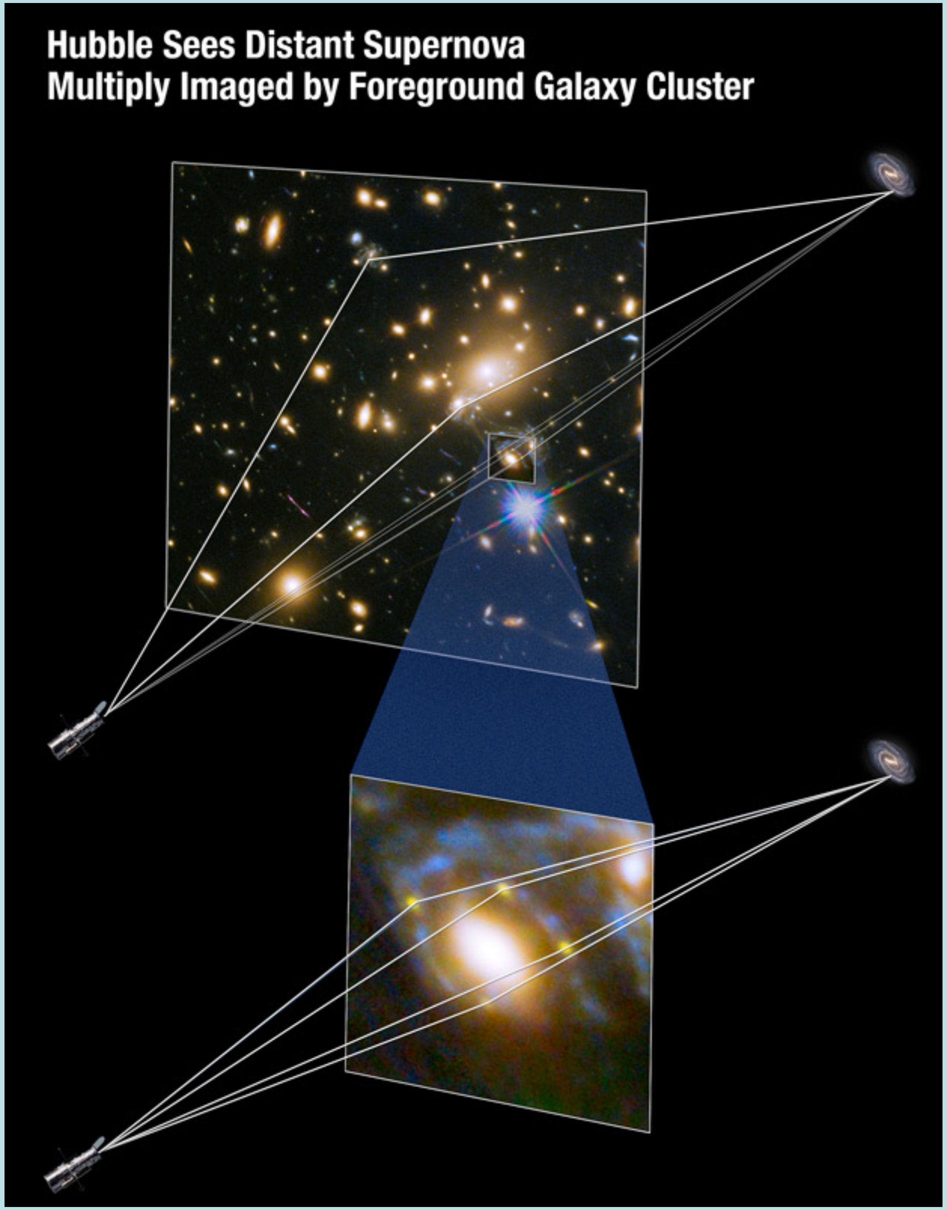
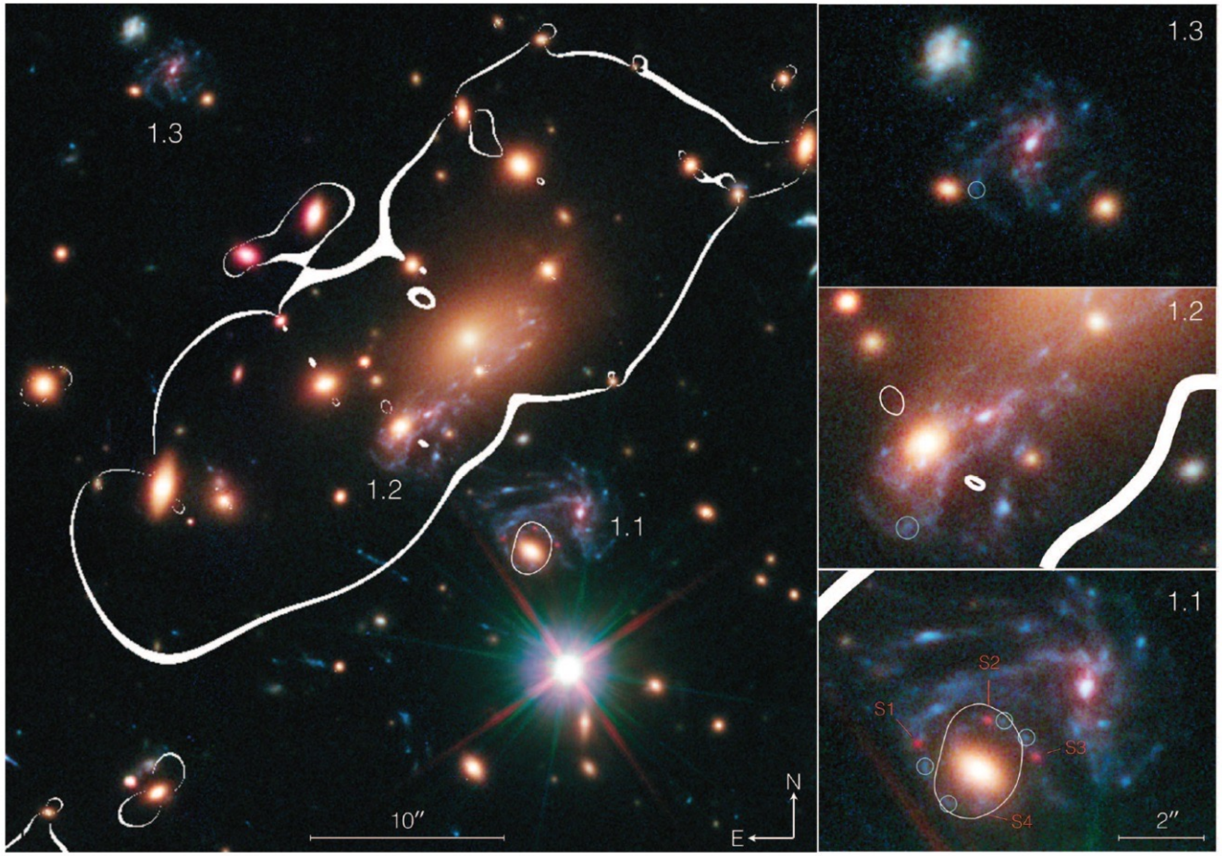


Fig. 1. HST WFC3-IR images showing the simultaneous appearance of four point sources around a cluster member galaxy. From left to right, the columns show imaging in the F105W filter (*Y* band), F125W (*J*), and F140W (*JH*). From top to bottom, the rows show archival imaging from the Cluster Lensing And Supernova survey with Hubble (CLASH, GO-12068; PI M.P.) program, discovery epoch images from GLASS and the Hubble Frontier Fields programs, and the difference images. The template images in the top row comprise all available archival WFC3-IR imaging in these filters, collected from 5 December 2010 through 10 March 2011. The images in the middle row are the composite of all available HST imaging collected between 3 November and 11 November 2014 (for F105W, left), on 20 November 2014 (F125W, middle), and between 10 November and 20 November 2014 (F140W, right). The sources S1, S2, S3, and S4, which form an Einstein cross, are absent from all images obtained at earlier epochs but are clearly detected in the difference images along the bottom row. The line segments below S4 and in the lower right corner are diffraction spikes from a nearby bright star in the foreground.



計算發現光還有其他路徑會被彎曲到達地球，有得早，有得晚。

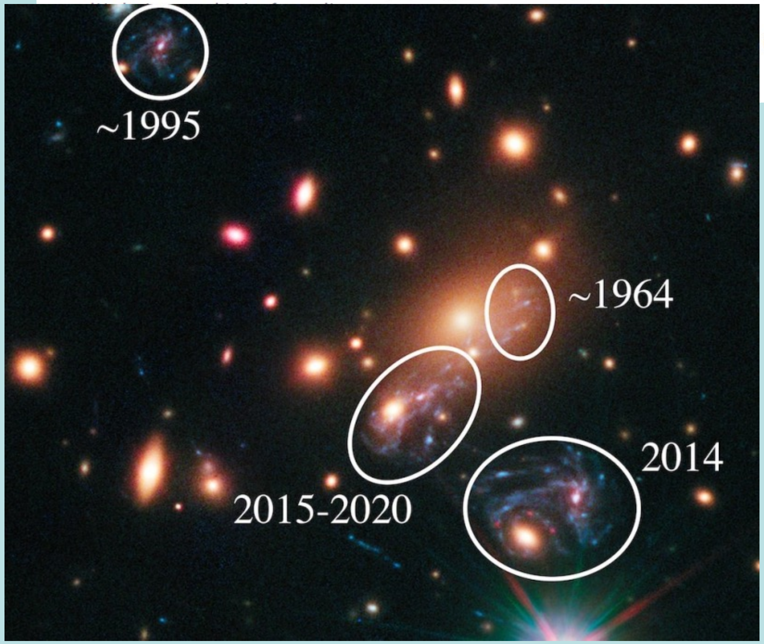
Fig. 2. Color-composite image of the galaxy cluster MACSJ1149.6+2223, with critical curves for sources at the $z = 1.49$ redshift of the host galaxy overlaid. Three images of the host galaxy formed by the cluster are marked with white labels (1.1, 1.2, and 1.3) in the left panel, and each is enlarged at right. The four current images of SN Refsdal that we detected (labeled S1 to S4 in red) appear as red point sources in image 1.1. Our model indicates that an image of the SN appeared in the past in image 1.3 and that one will appear in the near future in image 1.2. The extreme red hue of the SN may be somewhat exaggerated, because the blue and green channels include only data taken before the SN erupted. In image 1.1, both a single bright blue knot (cyan circles) and SN Refsdal are



過去

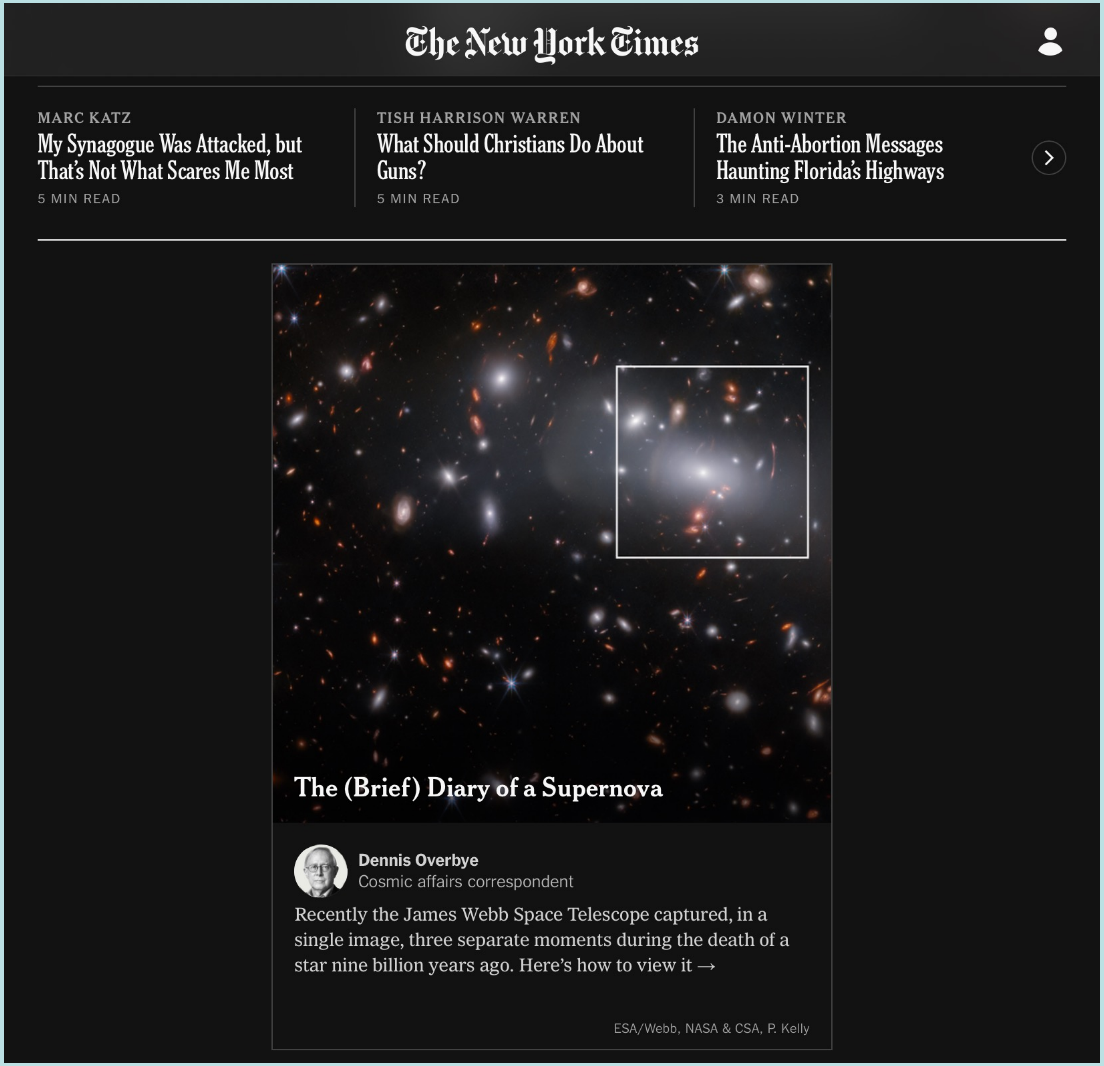
未來

偵測到的



data from the Frontier Fields and GLASS programs, along with images from the

Seeing Triple 2023



The New York Times

MARC KATZ
My Synagogue Was Attacked, but That's Not What Scares Me Most
5 MIN READ

TISH HARRISON WARREN
What Should Christians Do About Guns?
5 MIN READ

DAMON WINTER
The Anti-Abortion Messages Haunting Florida's Highways
3 MIN READ

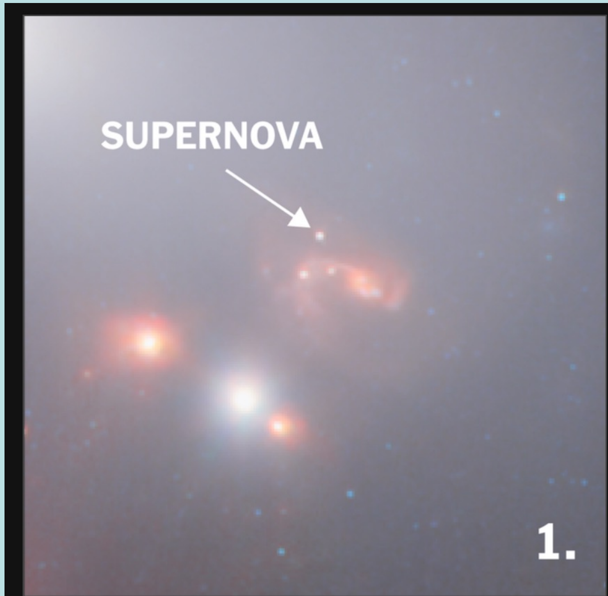
The (Brief) Diary of a Supernova

Dennis Overbye
Cosmic affairs correspondent

Recently the James Webb Space Telescope captured, in a single image, three separate moments during the death of a star nine billion years ago. Here's how to view it →

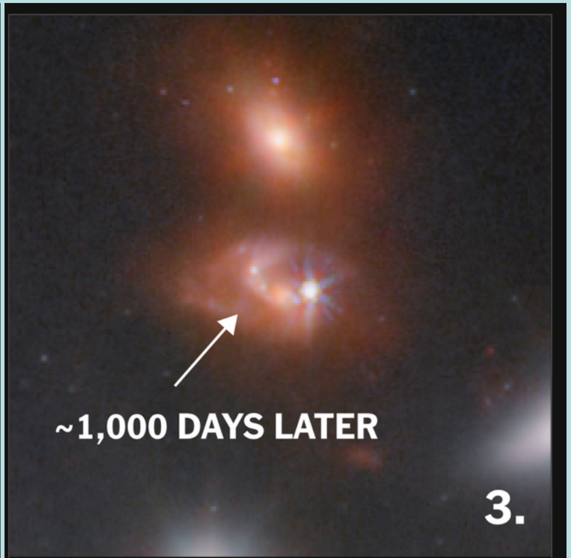
ESA/Webb, NASA & CSA, P. Kelly

The star and its galaxy (a hook-shaped blob) lie behind a galaxy cluster that has warped space into a lens. As the explosion unfolded, its light found three paths of different lengths through the warp, creating this time-lapse.

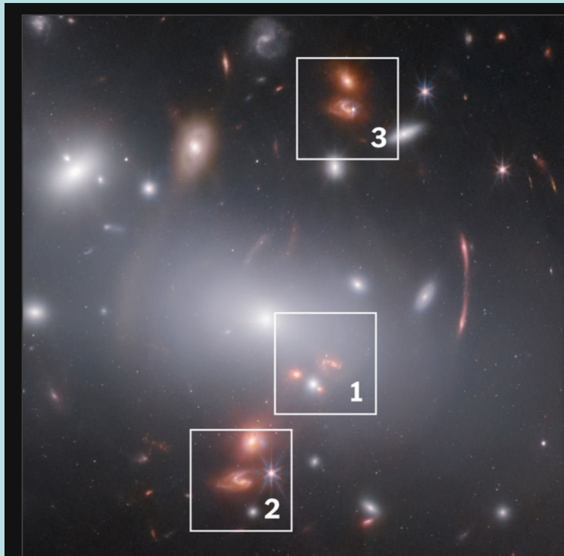


Supernova explosions are among the rarest and most cataclysmic events in the universe. This one begins as a bright dot just above the arc of the galaxy.

Almost a year later, Earth time, the supernova is no longer easily visible. Shock waves, gas and radiation spread out across the galaxy. Behind the cover of distance, time and darkness, the galactic chaos has barely begun.



After roughly 1,000 days, the supernova has faded from view. Astronomers have tentatively identified it as a Type 1A, which can be used as a “standard candle” to calibrate the size of the universe and how fast it is expanding.



The star and its galaxy (a hook-shaped blob) lie behind a galaxy cluster that has warped space into a lens. As the explosion unfolded, its light found three paths of different lengths through the warp, creating this time-lapse.

下午11:14 4月23日 週日

49%

The New York Times

MARC KATZ
My Synagogue Was Attacked, but That's Not What Scares Me Most
5 MIN READ

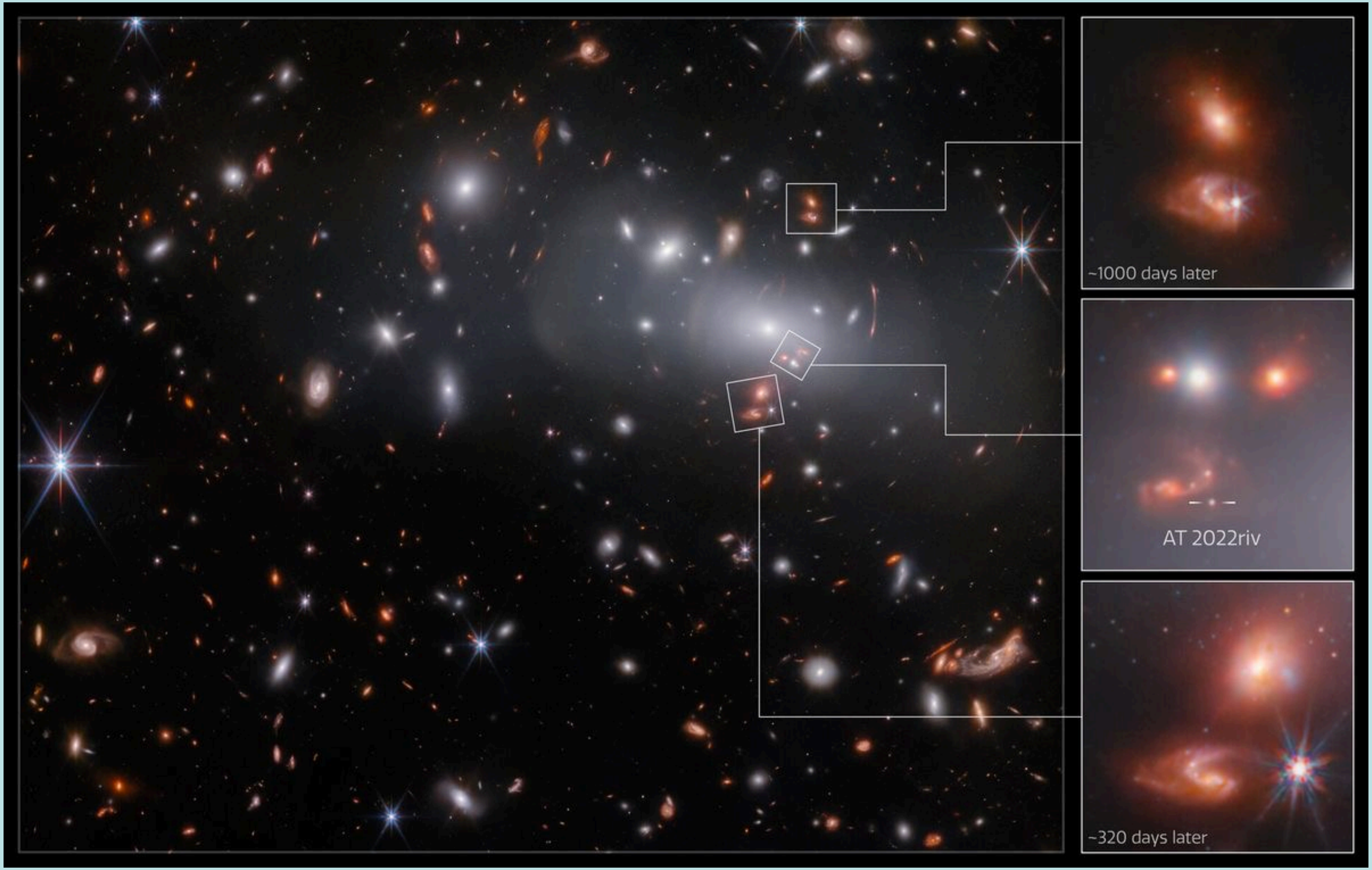
TISH HARRISON WARREN
What Should Christians Do About Guns?
5 MIN READ

DAMON WINTER
The Anti-Abortion Messages Haunting Florida's Highways
3 MIN READ

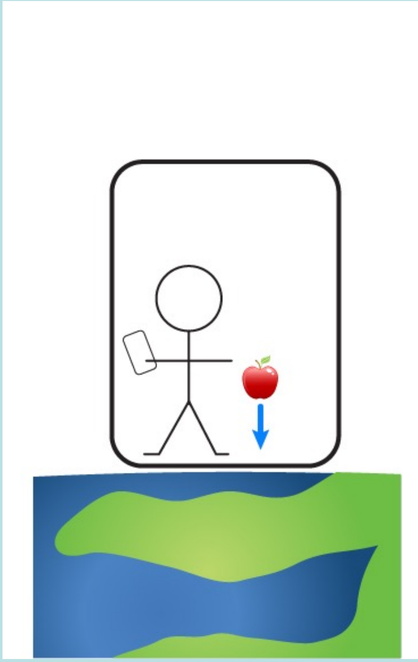
This triple feature was discovered last year by Patrick Kelly of the University of Minnesota, using first the Hubble Space Telescope and then the James Webb Space Telescope.

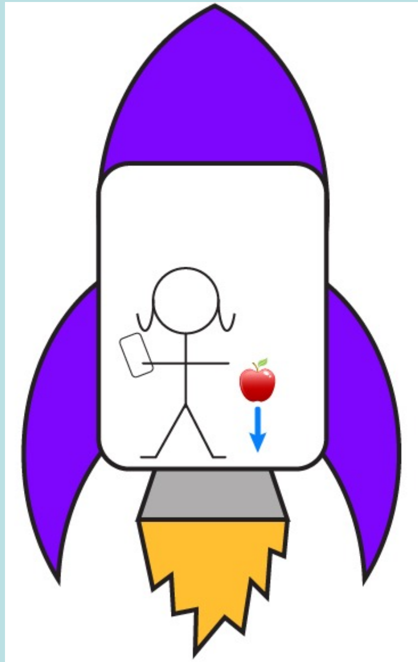
Records like these help astronomers refine their calculations to find out where we came from, where we are going and how soon we might get there — if we ever do.

ESA/Webb, NASA & CSA, P. Kelly


~1000 days later
AT 2022riv
~320 days later

彎曲時空



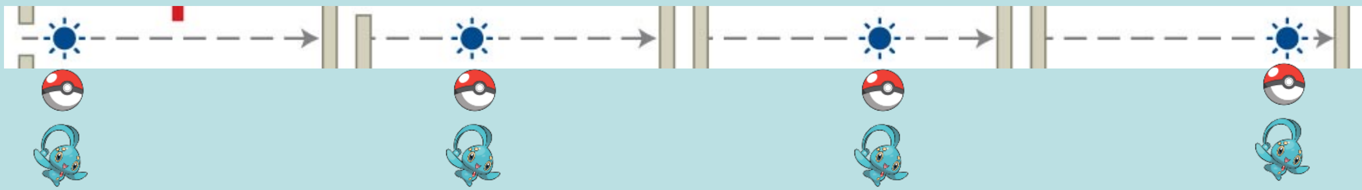


等效原則 Equivalence Principle

有重力下的靜止觀察者，與無重力下的加速觀察者，是等效的。

透過了解加速座標系，就可以了解重力。

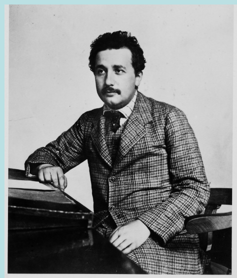
這還是非常不容易，但後來愛因斯坦抓到一個突破點！

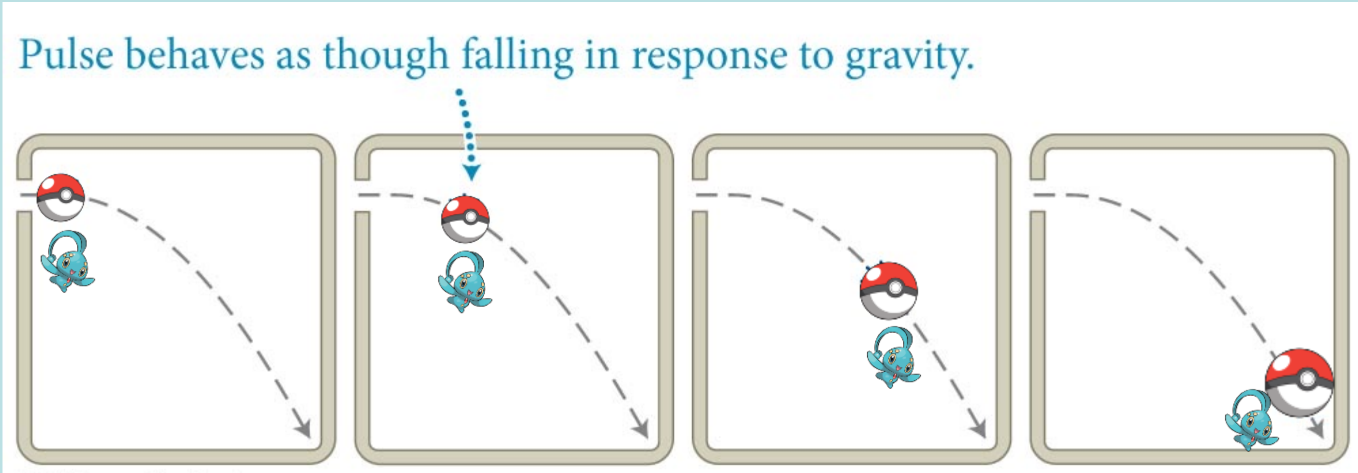


未受力的任何物體，其運動所沿的直線是同一條！

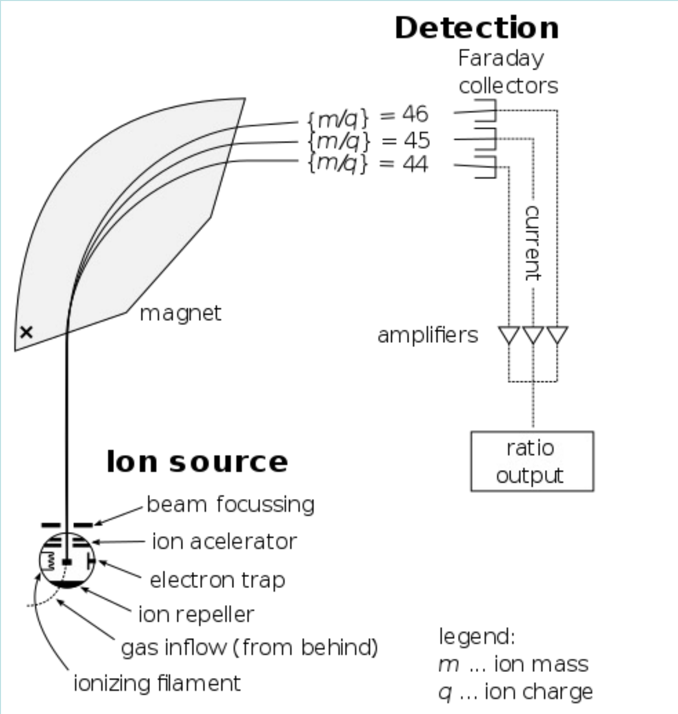
這條直線路徑，與物體性質無關，不屬於個別物體，是公共的，

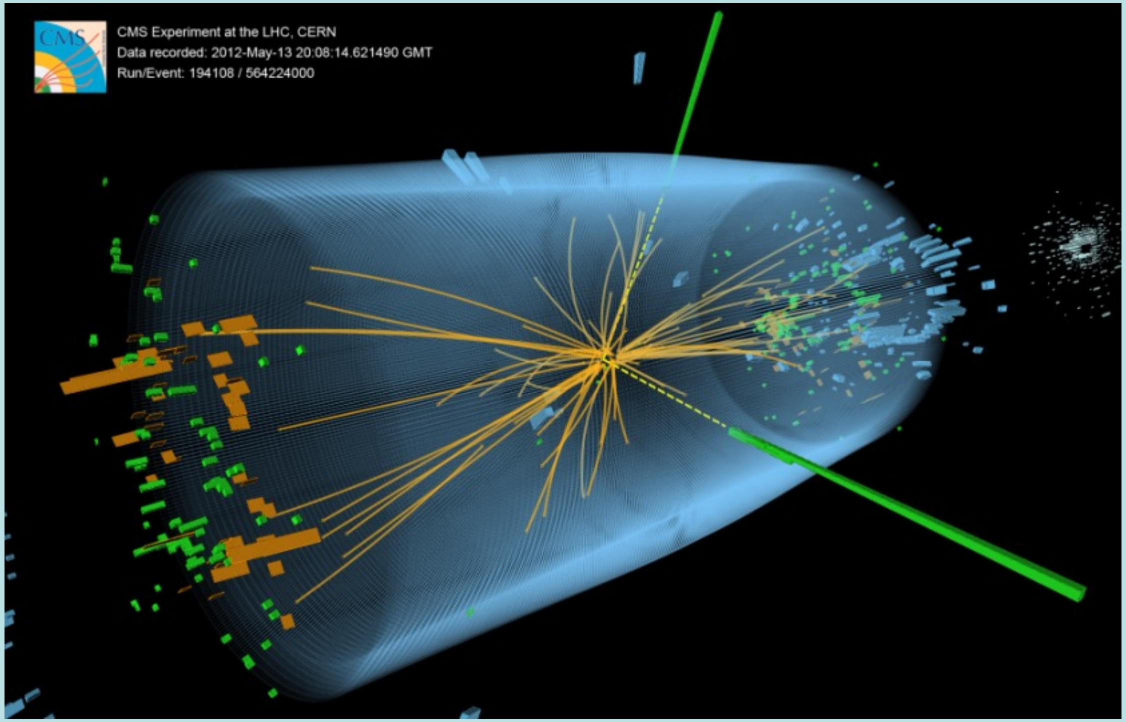
直線是空間的性質。





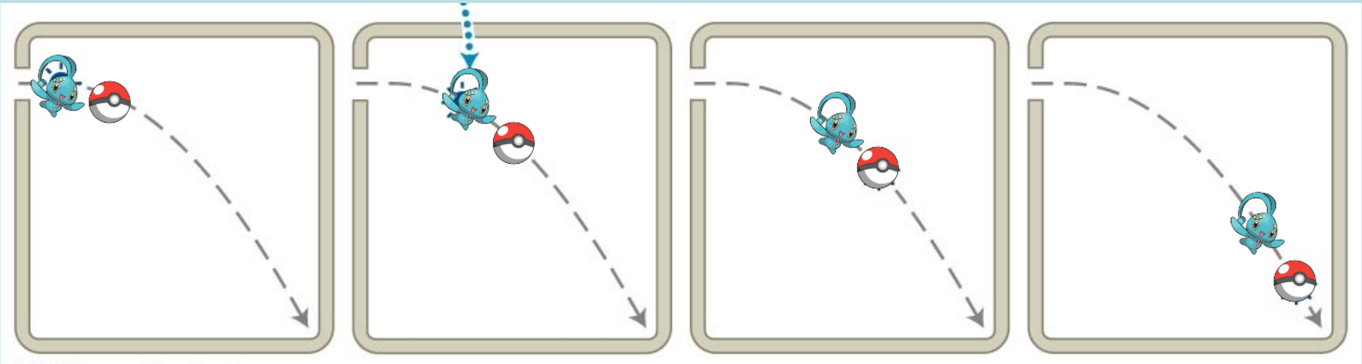
現在，在重力作用下，所有物體仍沿同一彎曲路徑運動，與物體性質無關。





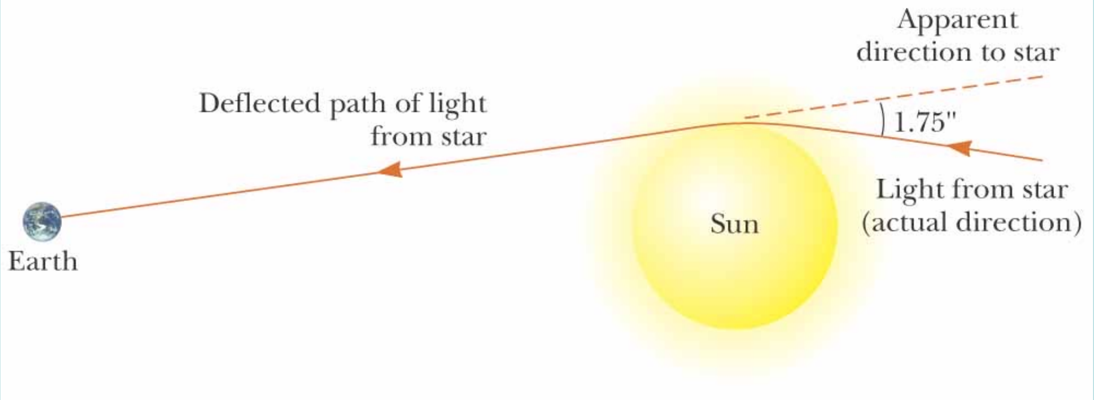
若物體受其他的力的作用，一般來說，不同質量的物體會走不同的路徑。

這就是質譜儀的原理。



如果等效原則正確，重力作用下，所有物體沿同一彎曲路徑運動，與其性質無關。

這條彎曲的路徑是公共的。



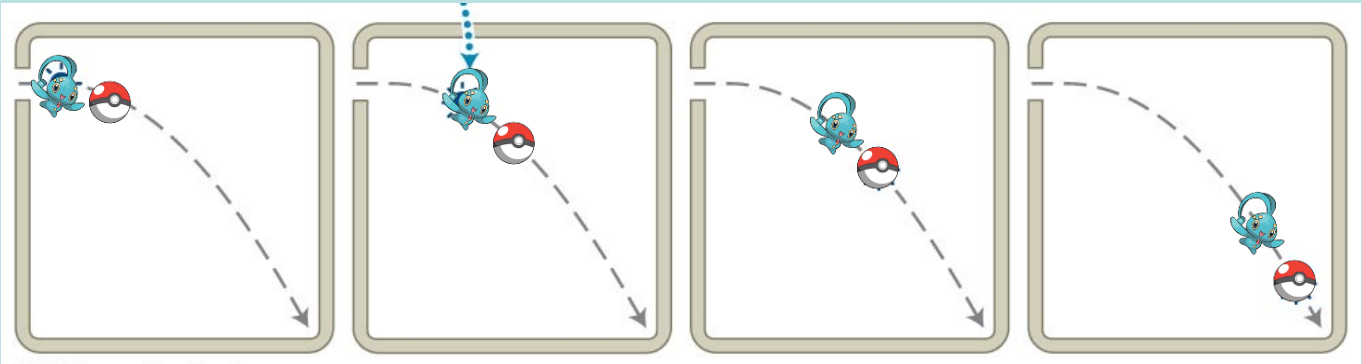
在重力作用下，光也會被偏折。

這是不是代表有重力作用時，空間是被彎曲的？不再是平坦的？

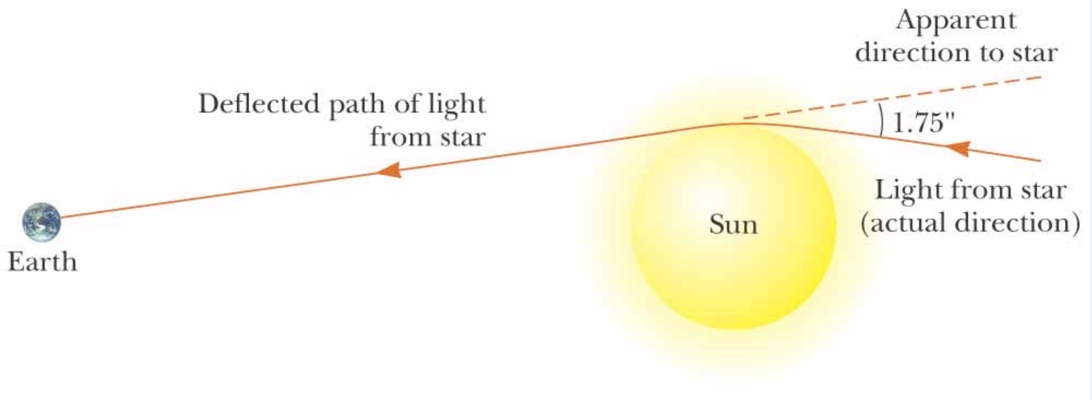
在不是平坦的空間，公共的直線，可能就是彎曲的！

空間中的直線卻是彎曲的！這在彎曲空間中，是非常典型的情況。

沿著地球表面，所有自由物體的運動，都會沿兩點間最短距離的唯一直線，在遠處看來卻是曲線，稱為測地線，這是直線比較精確的名稱。



在重力作用下，所有物體仍沿共同的一彎曲路徑運動，與物體性質無關。



在重力作用下，光也會被偏折。

重力作用下彎曲的路徑，不屬於個別物體，是公共的，是大家共享的！

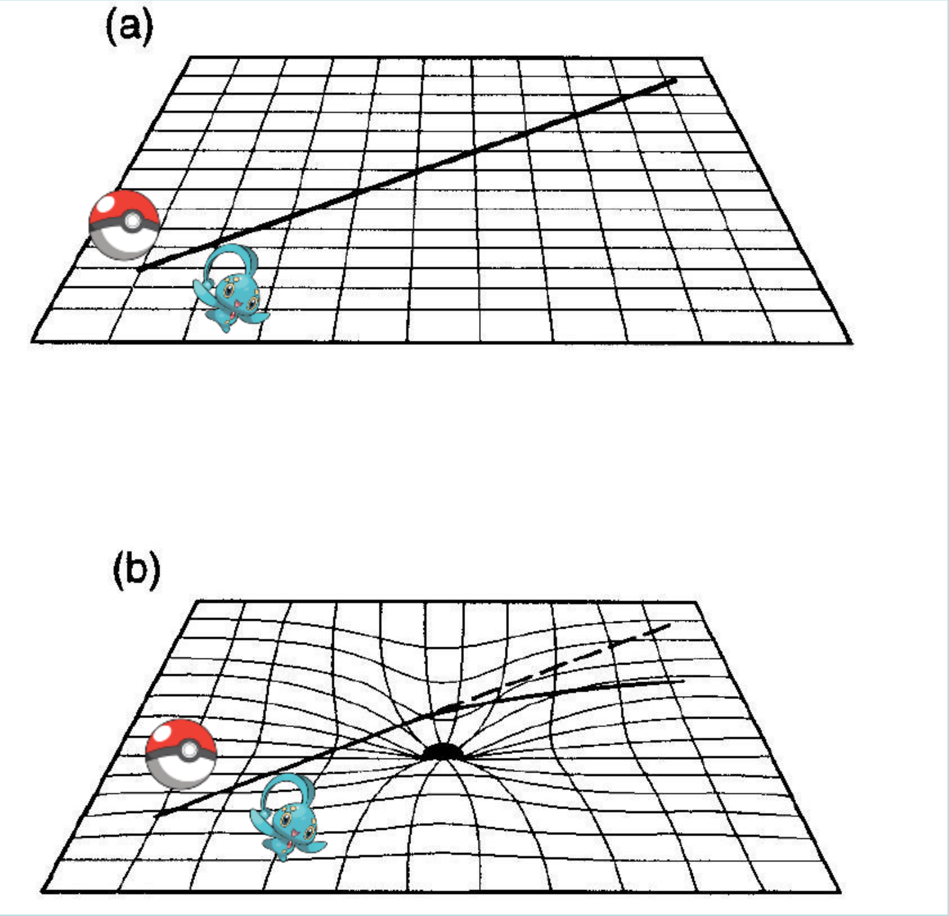
愛因斯坦頓悟：這一條彎曲的路徑，就是重力作用下該處彎曲空間的直線！

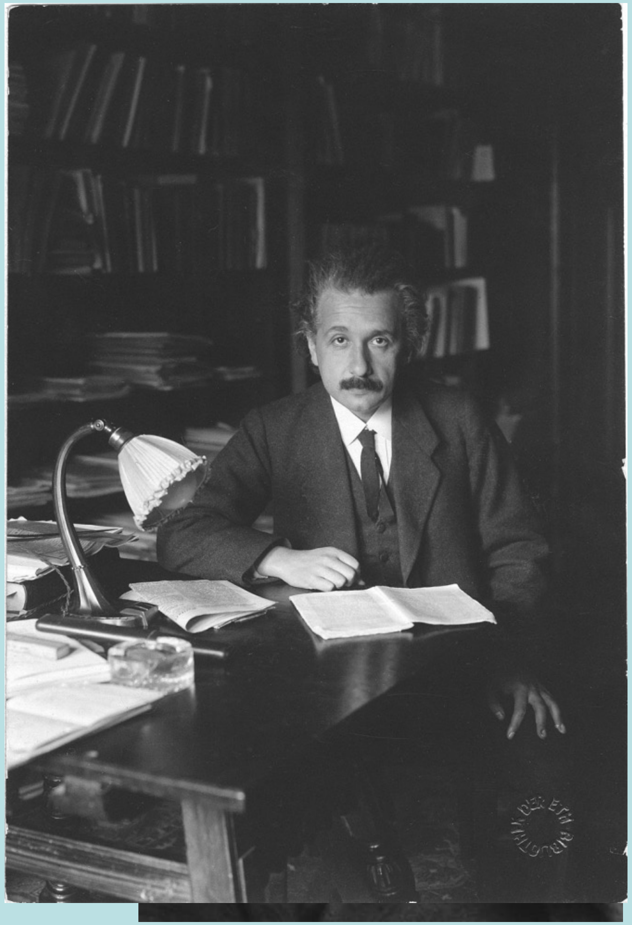
重力根本不是力！

愛因斯坦提出：重力現象是質量造成周圍時空彎曲。（時空不可分！）

若無其他外力，所有物體都沿此彎曲時空的直線（即測地線）運動。

在彎曲時空中粒子走的直線由遠方看來是一條曲線！



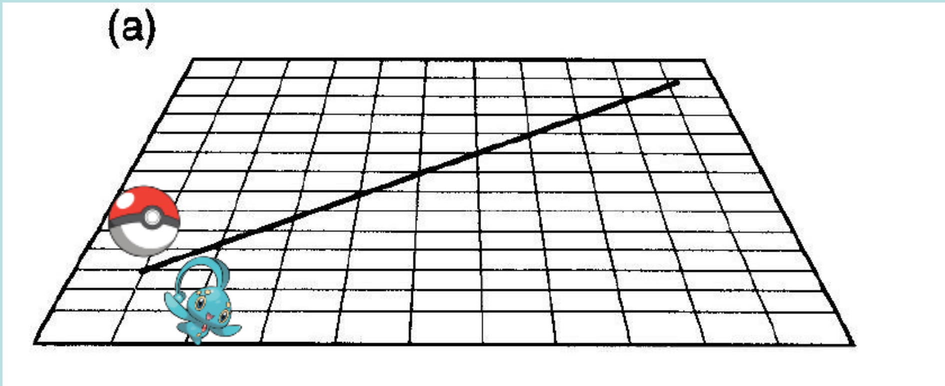


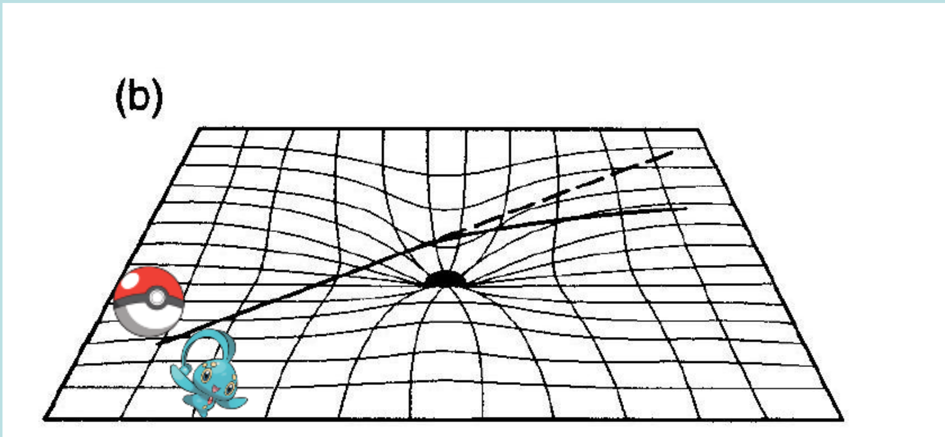
我們可以運用直進的光為空間畫出一條條等距的直線作為座標尺格。

在重力影響下，同樣的畫座標的動作，得到的卻是偏折的曲線。

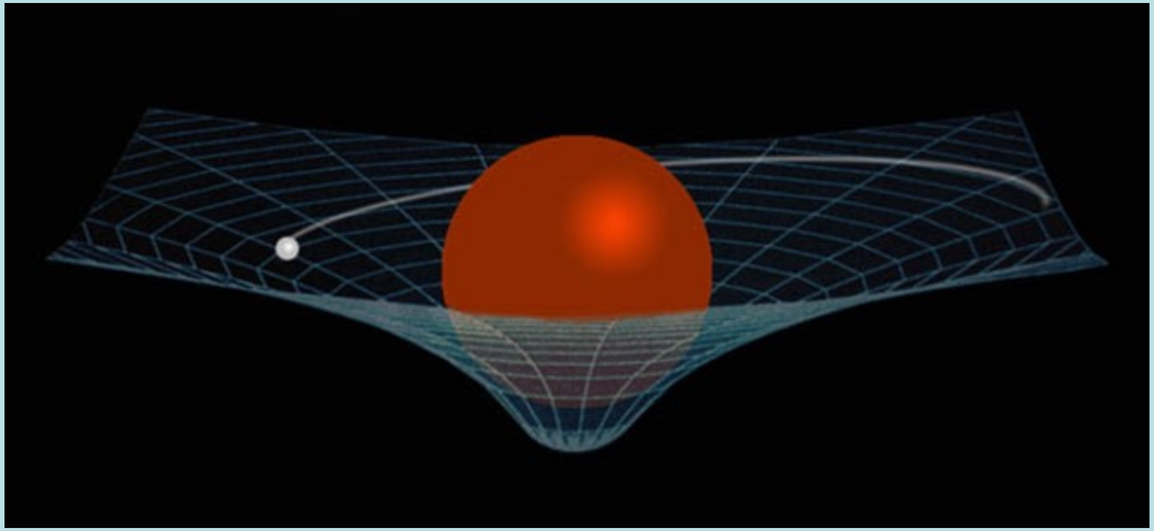
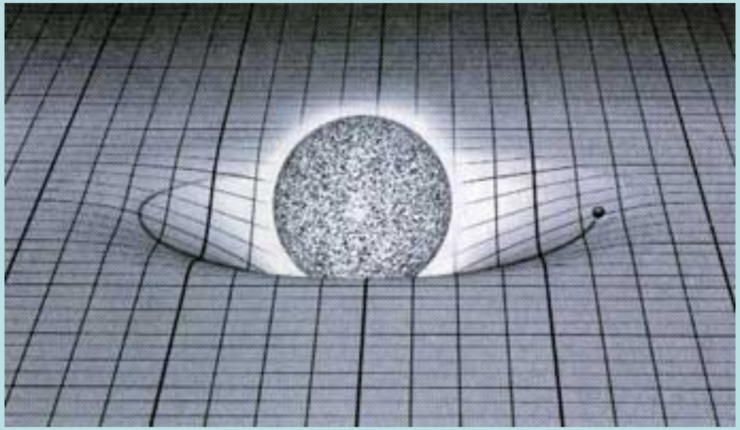
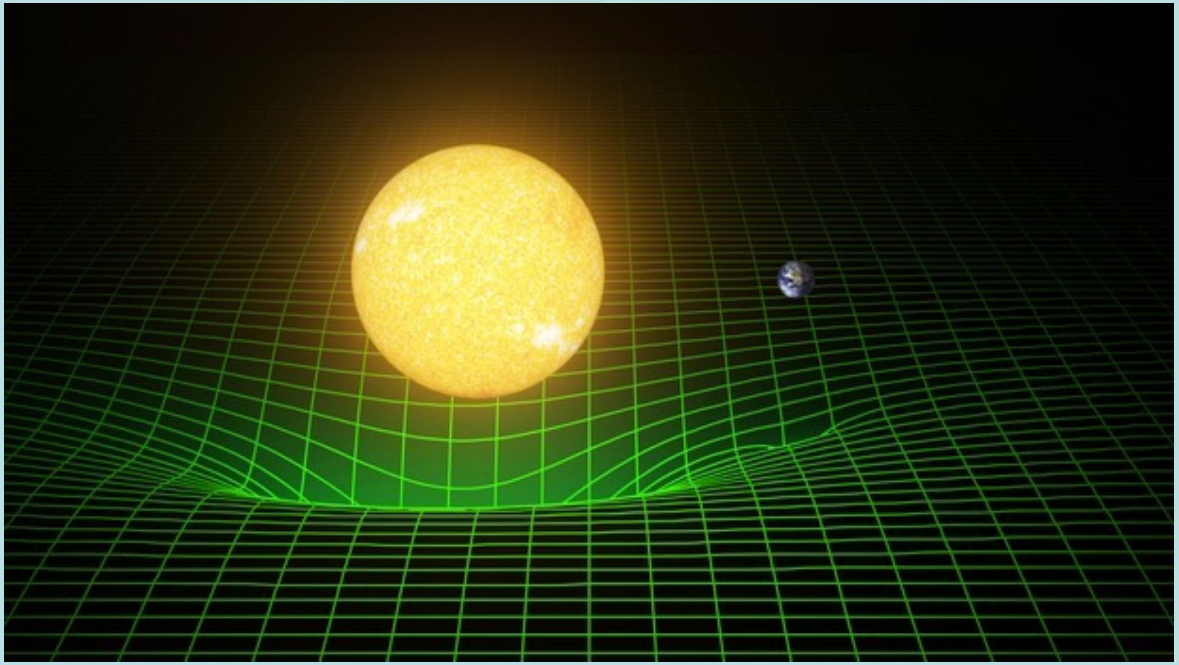
但在真空中這是唯一畫座標尺格的方法，

這些線就是重力下的座標尺格！可見空間是彎曲的！



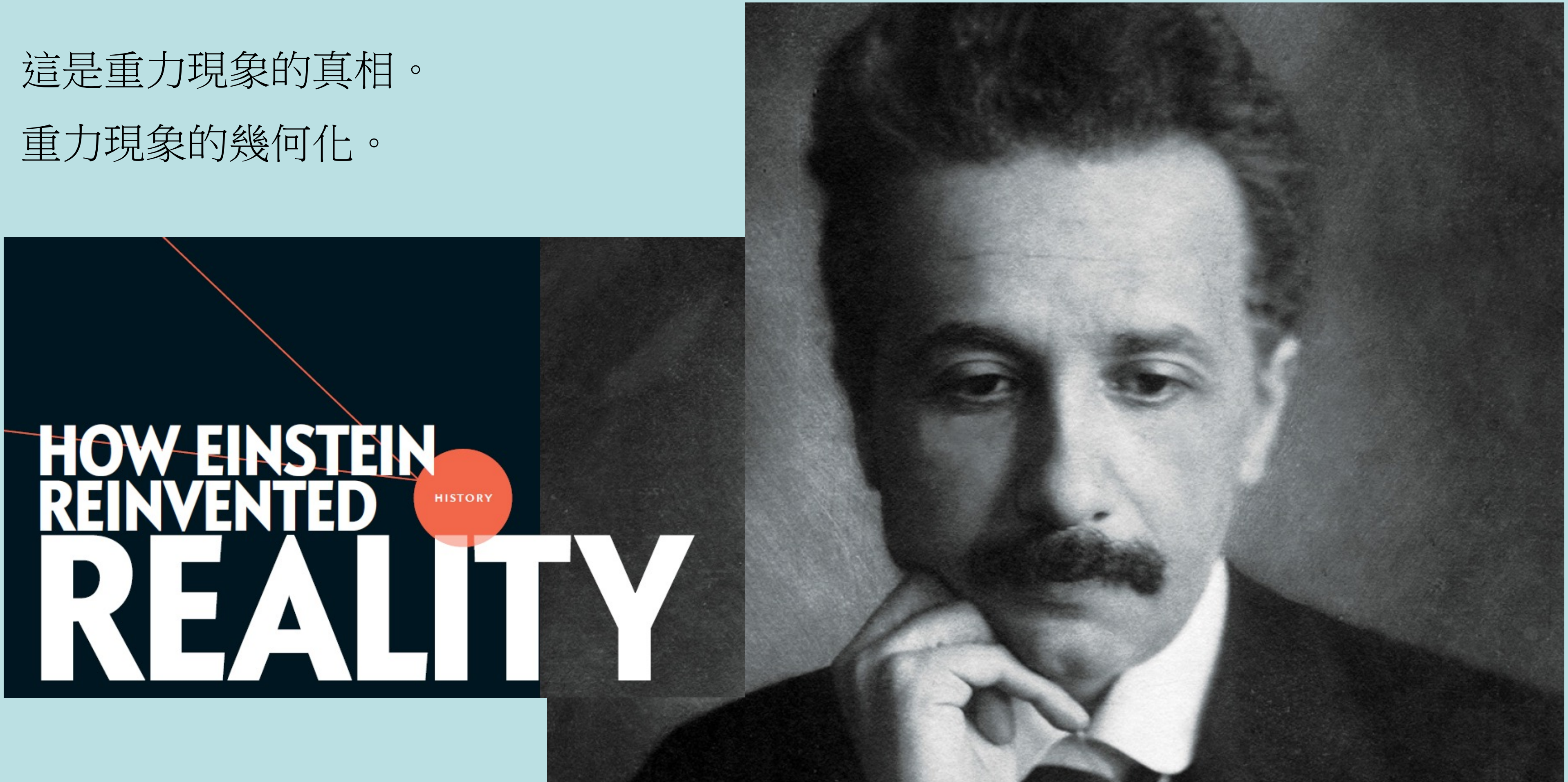


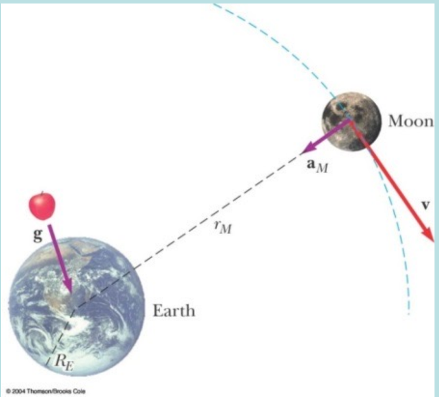
在此彎曲空間，所以物體走同樣一條彎曲的路徑！

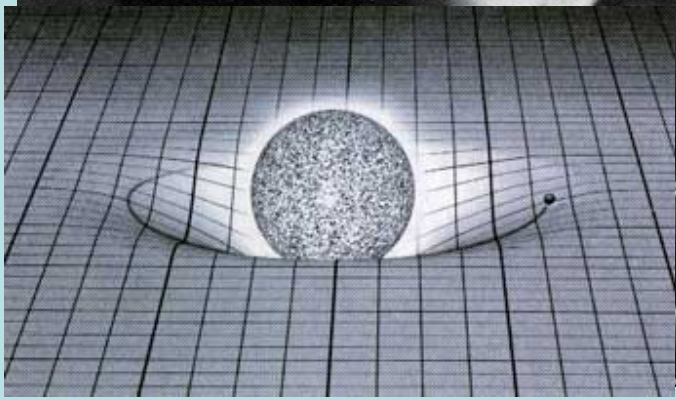




這是重力現象的真相。

重力現象的幾何化。

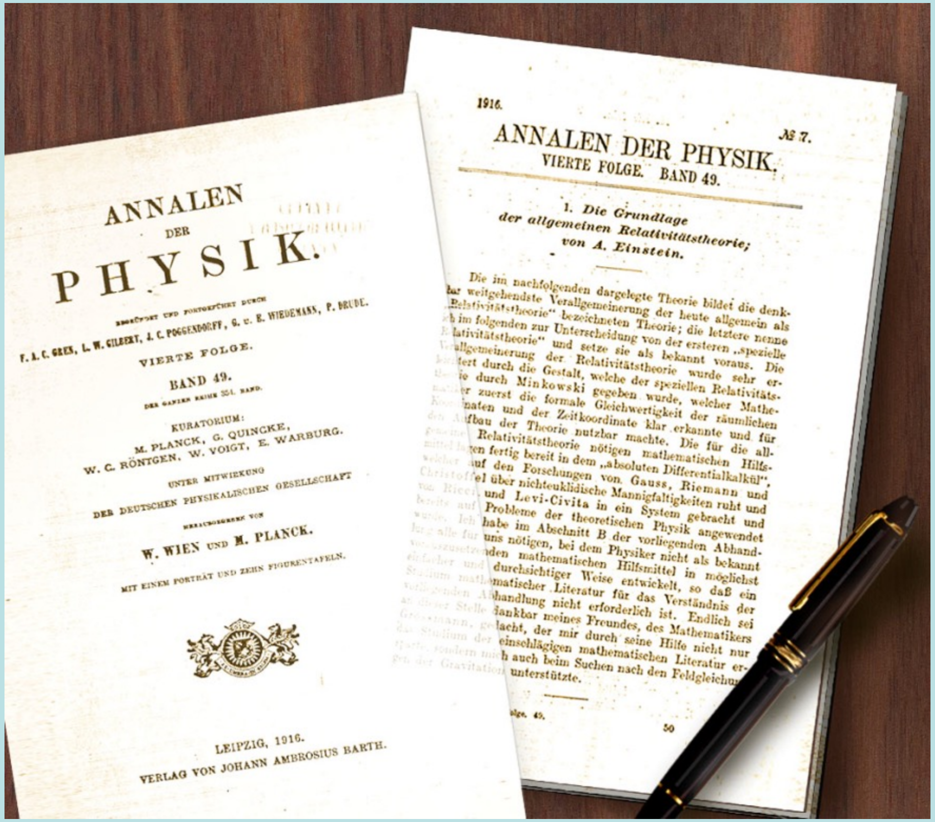


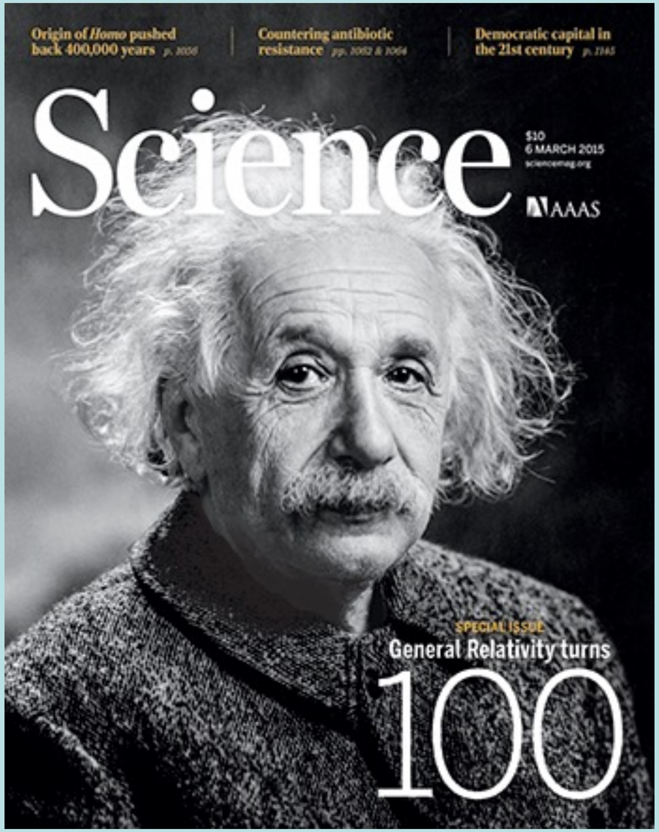




在日常生活已成為常識，我們以為是真實的萬有引力，其實不是真實的。

廣義相對論 1915-1916





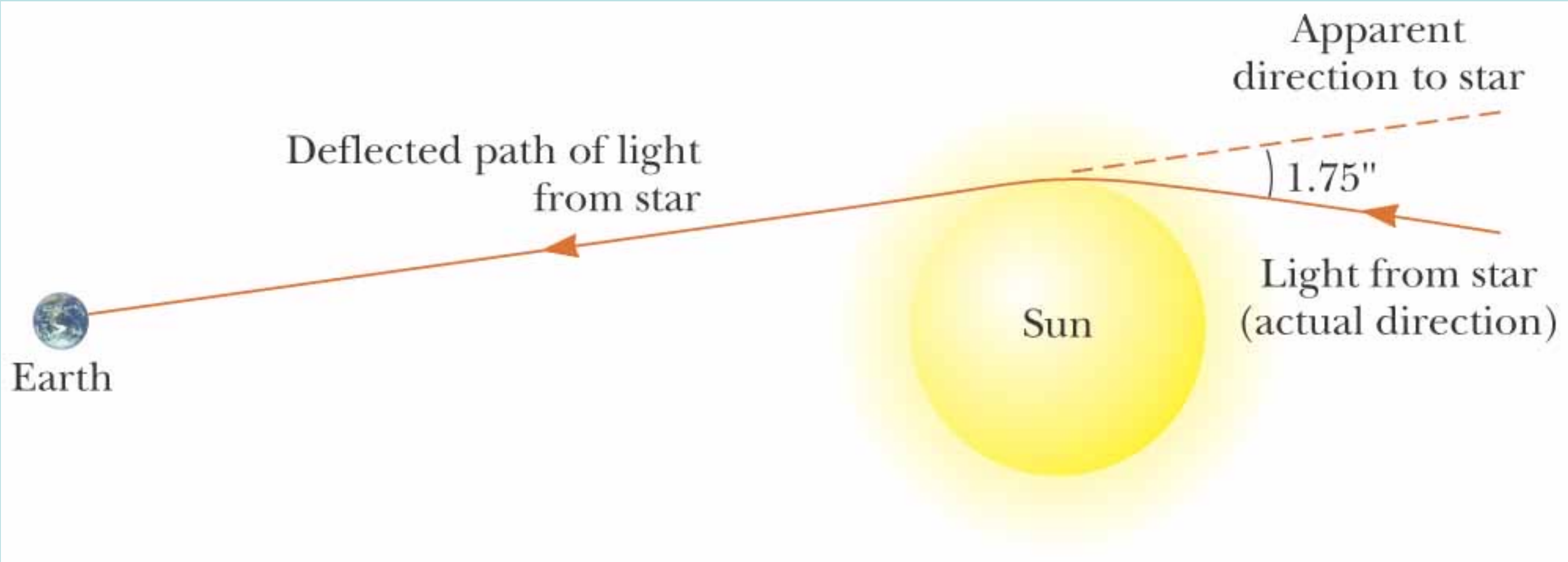
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

愛因斯坦方程式

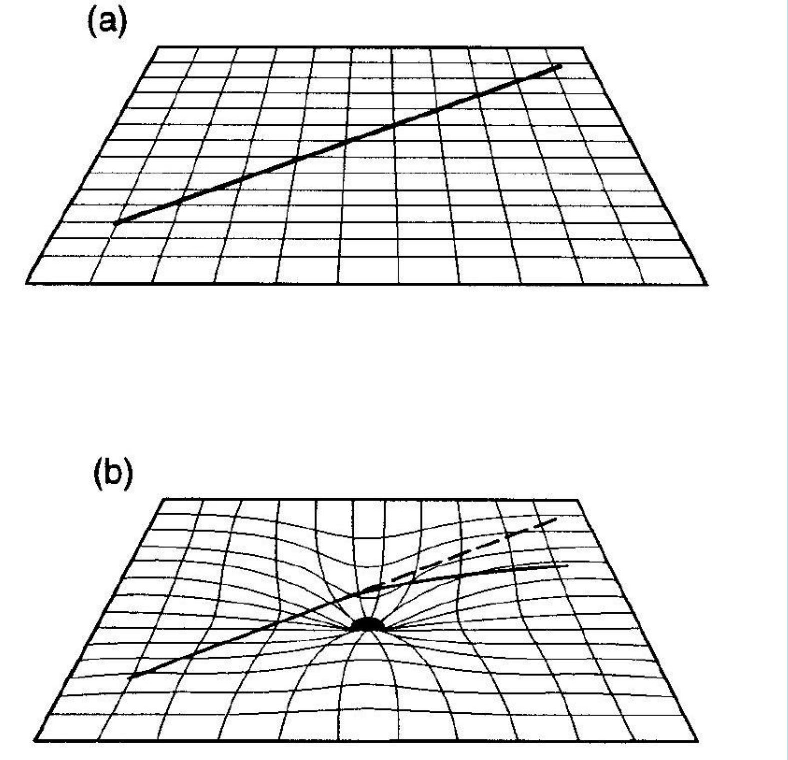
時空的彎曲曲率　　　　　當地的能量（質量）

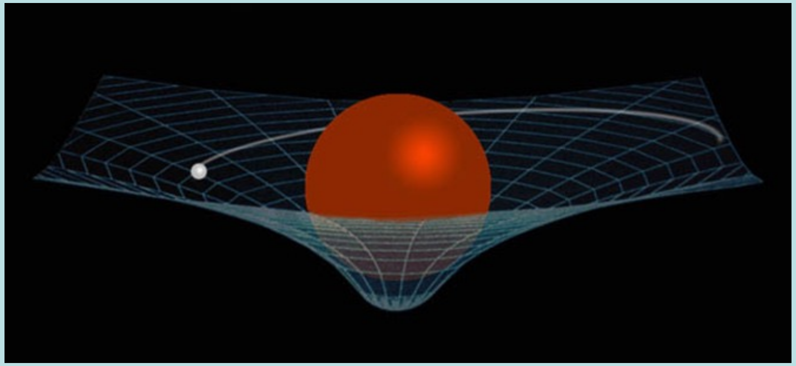
質量決定時空怎麼彎，時空再決定帶質量的粒子怎麼走！

Photo: Orren Jack Turner, Prints & Photographs Division, Library of Congress, LC-USZ62-60242



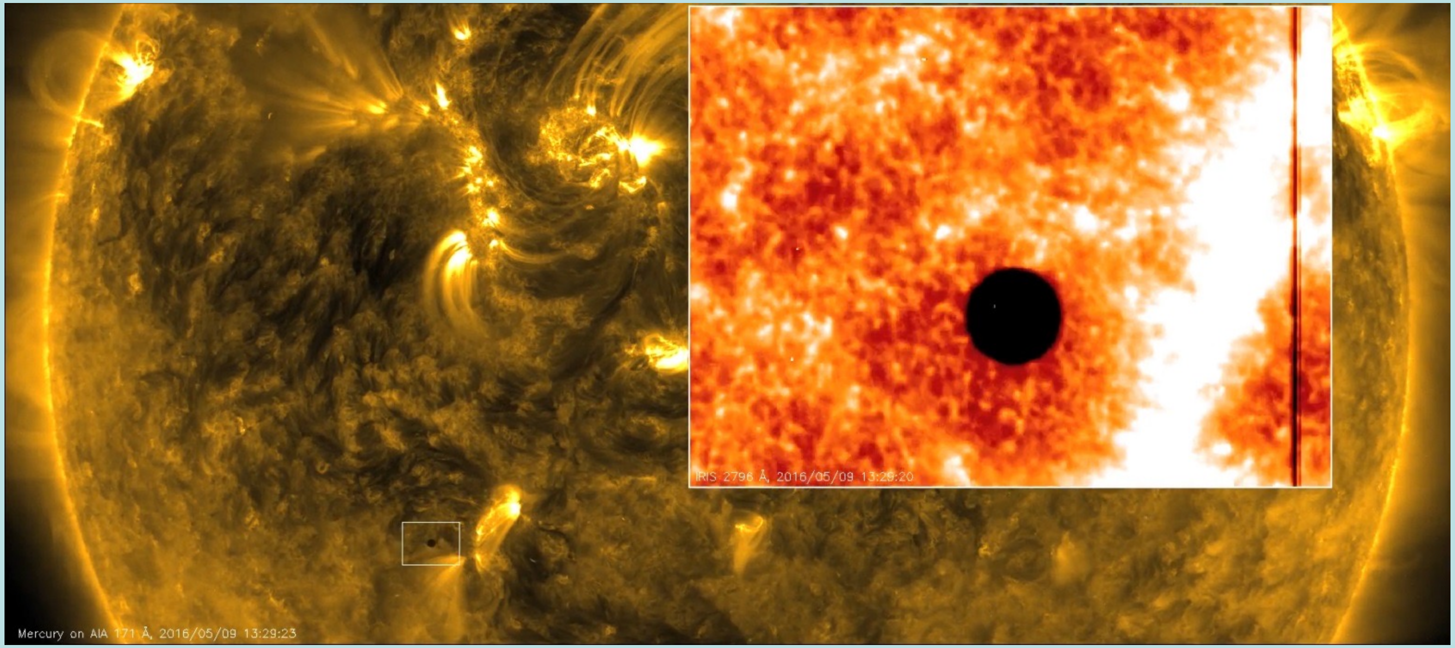
能量（質量）造成周圍時空彎曲，所有物體都沿此彎曲時空的直線運動！





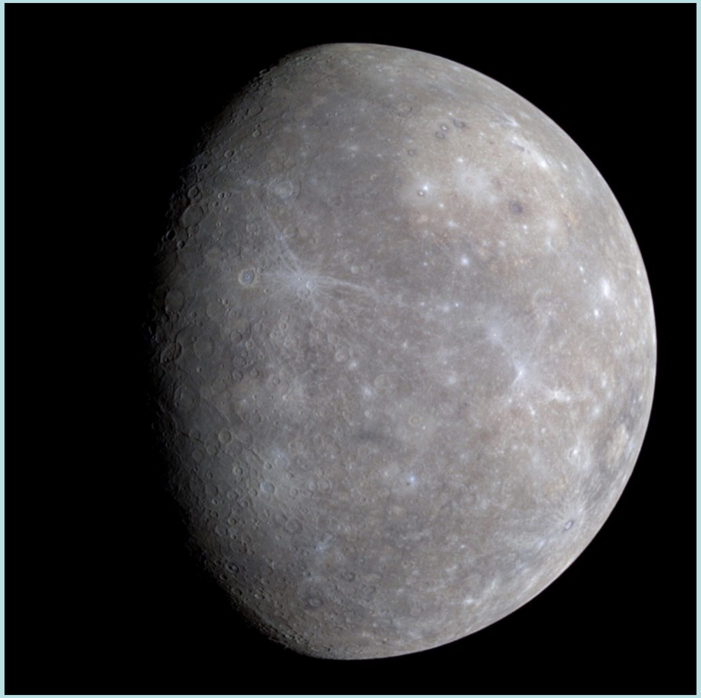
請注意，這些新穎的想法都還是猜測，等效原則不一定對，而物理是實驗的科學。

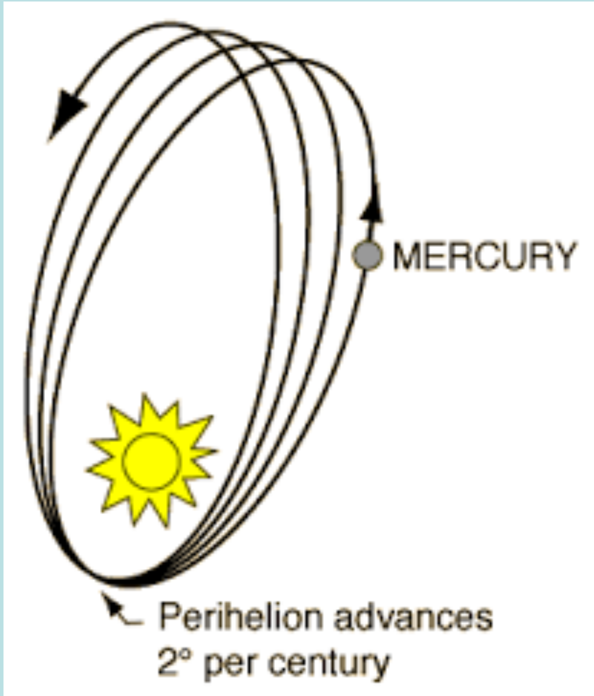
彎曲時空的重力效應對行星軌道的預測，與牛頓萬有引力是有可觀測的差距的。

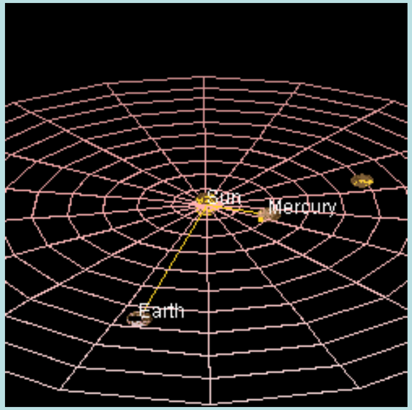


The planet Mercury is seen in silhouette, lower third of image, as it transits across the face of the sun Monday, May 9, 2016.

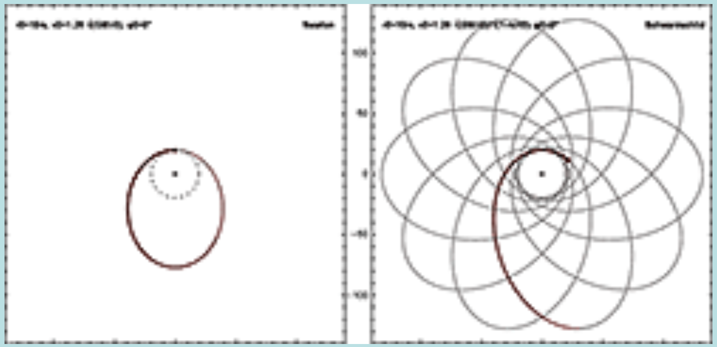
The anomalous rate of precession of the perihelion of Mercury's orbit was first recognized in 1859 as a problem in celestial mechanics, by Urbain Le Verrier. His re-analysis of available timed observations of transits of Mercury over the Sun's disk from 1697 to 1848 showed that the actual rate of the precession disagreed from that predicted from Newton's theory by 38" (arc seconds) per century (later re-estimated at 43")



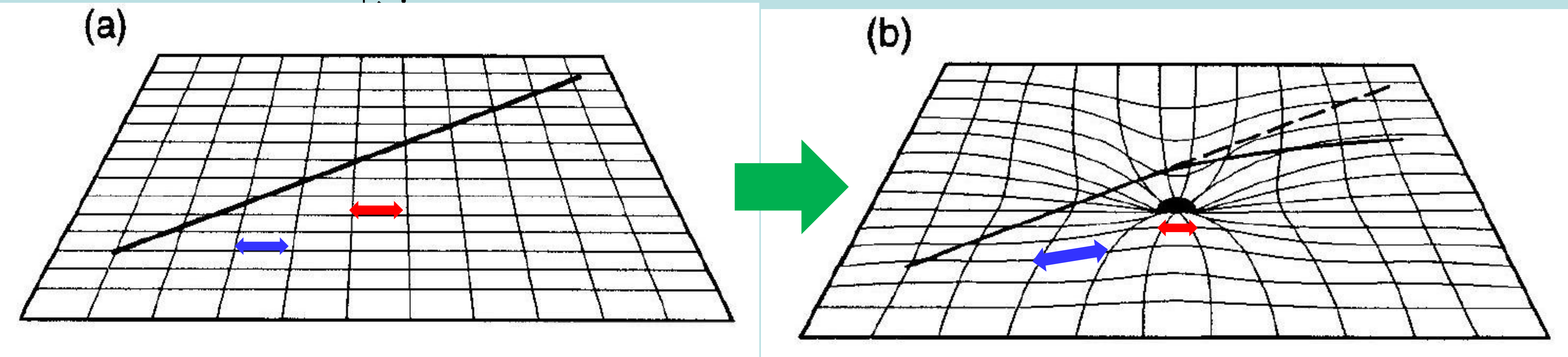




廣義相對論證實是正確的。



如何表現與描述 Curved Space-time 彎曲時空？

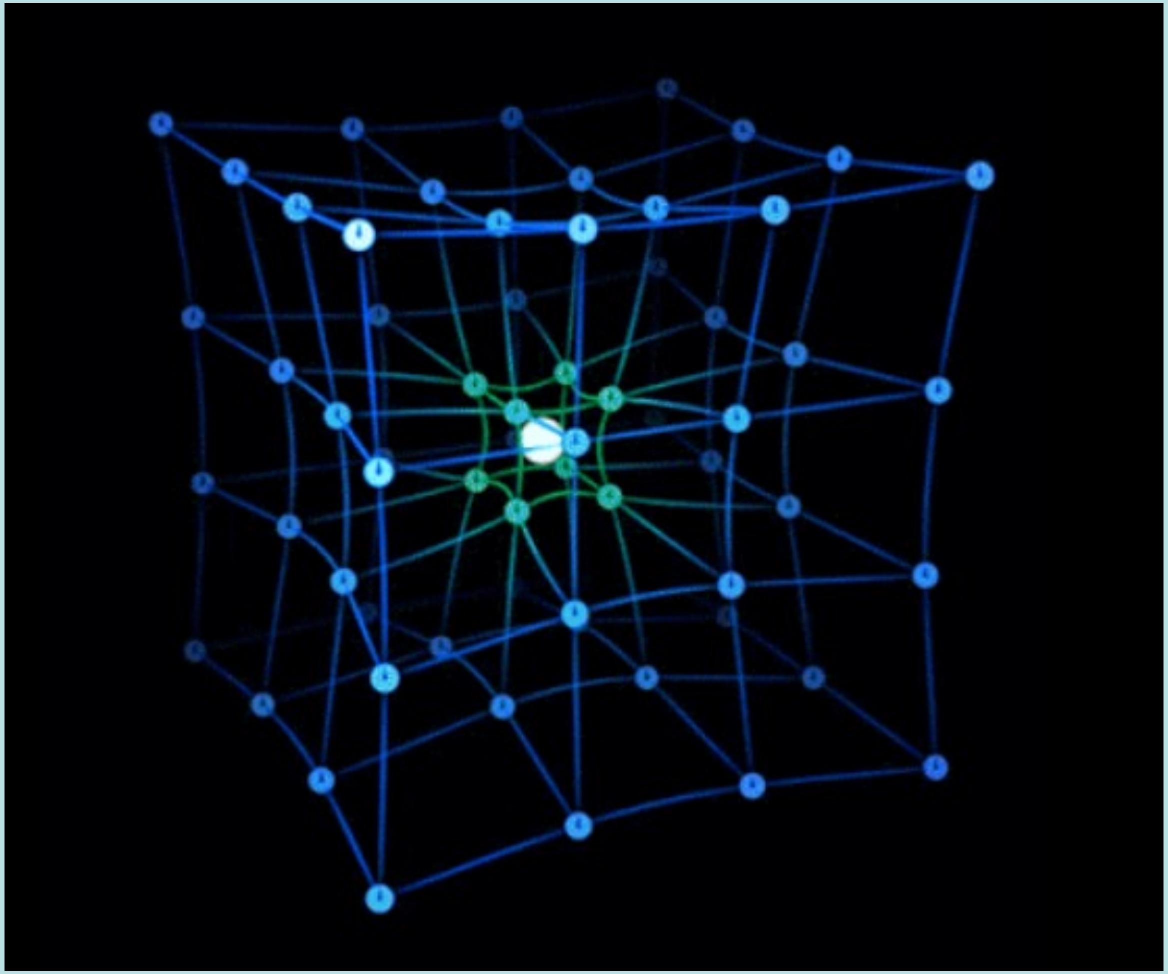


平坦空間一般可以以棋盤狀的等距座標尺格(用等距的光畫訂)來描述，

彎曲之後，尺格自然就會變得扭曲！如右圖。

意思是：原來在平坦時空是等距的格子，其間距在扭曲後必定會被拉長或壓縮。

原來等間距的座標尺格，現在測量發現被拉長或壓縮，這就彎曲空間的特徵！



原來在平坦時空時，間距相等的尺格，在彎曲之後就會有的較大，有的較小。

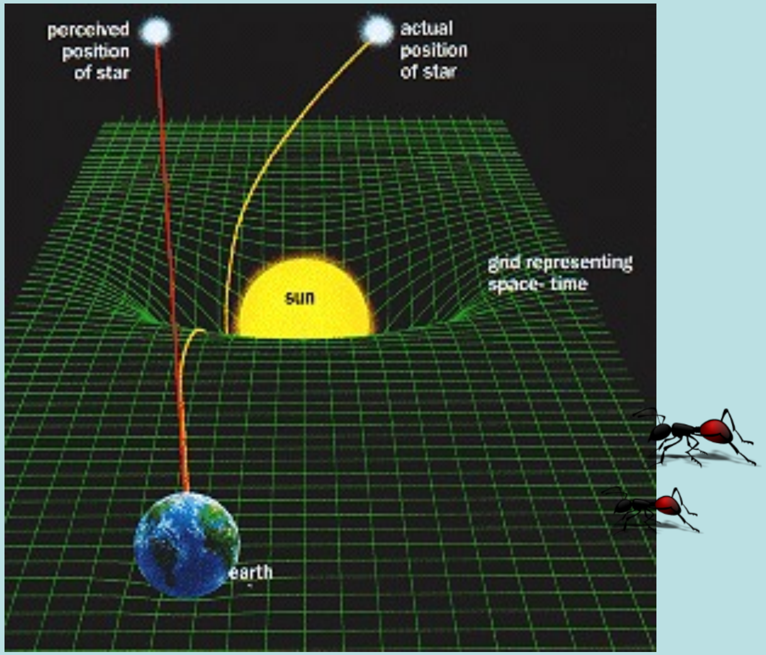
兩維曲面很容易畫，但真實世界是三度空間（加上時間）都是彎曲的。

我們一般就那就把三維彎曲空間先忽略其中一維空間。

剩餘的二維真實空間的曲度，與示意圖上的二維曲面的曲度相同。

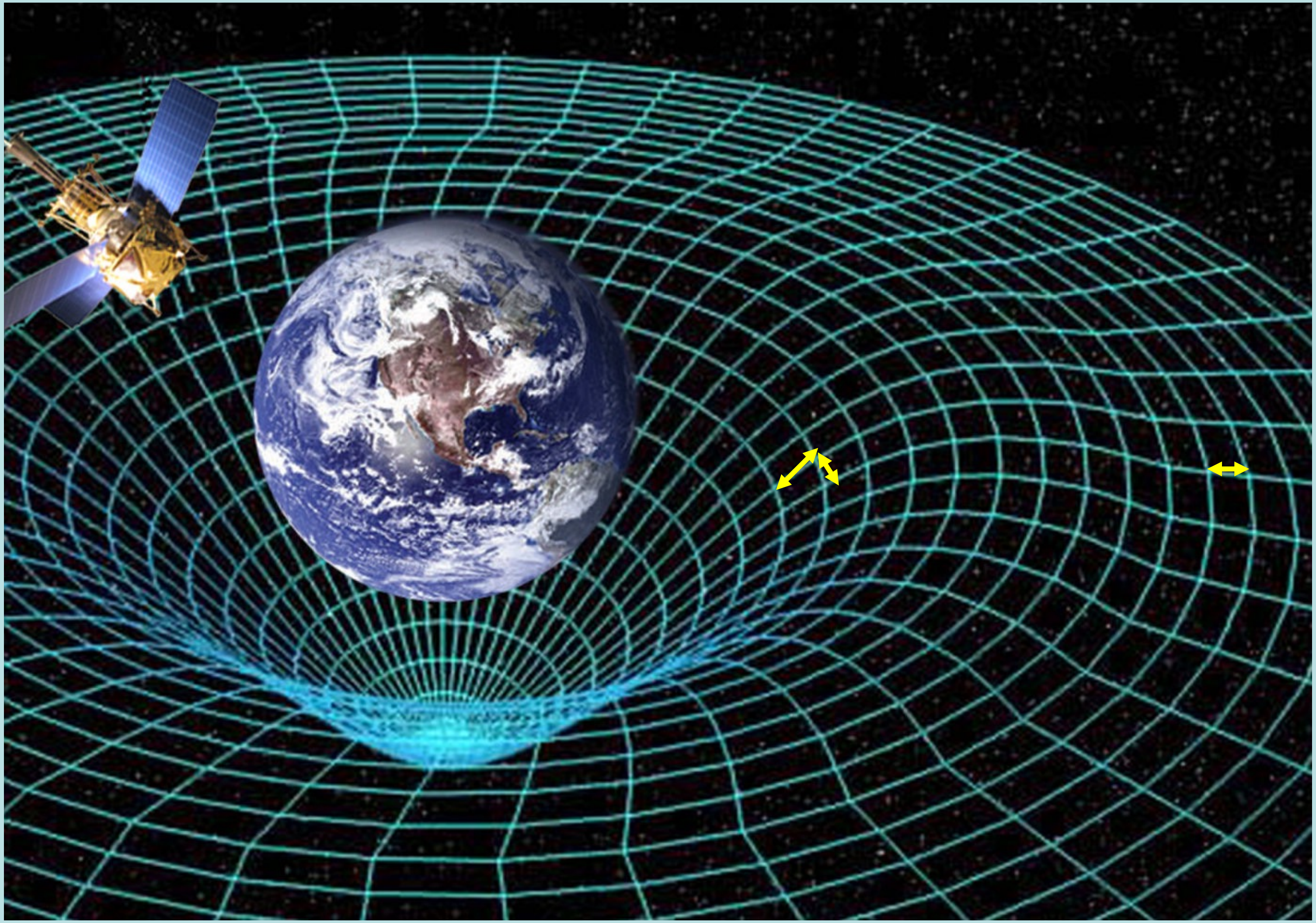
但示意圖上，額外的垂直空間是不存在的，不是真實的，

完全只是為了表現描繪出曲面的彎曲程度而加上去的。



很好的辦法就是想像觀察者是只能在曲面上運動的螞蟻：

螞蟻所觀察到的就是：原本等距的尺格，現在間距都不相等了。



在各處，測量固定座標尺格的間隔距離，記為g_{ij}。

例如$g_{xx}(\vec{r},t)$就是在位置為$\vec{r}$，時間為t時量到，沿x方向，一公分的格子，現在多長。

原來在平坦時，間距相等$g_{xx}=1$的座標，在彎曲時空下就會有的較大，有的較小。

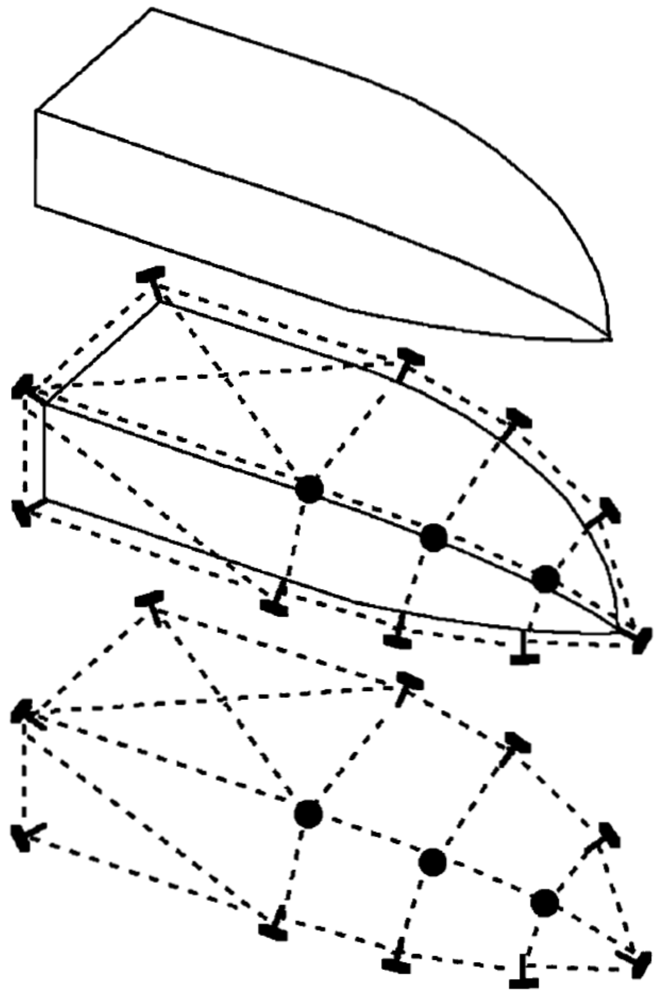


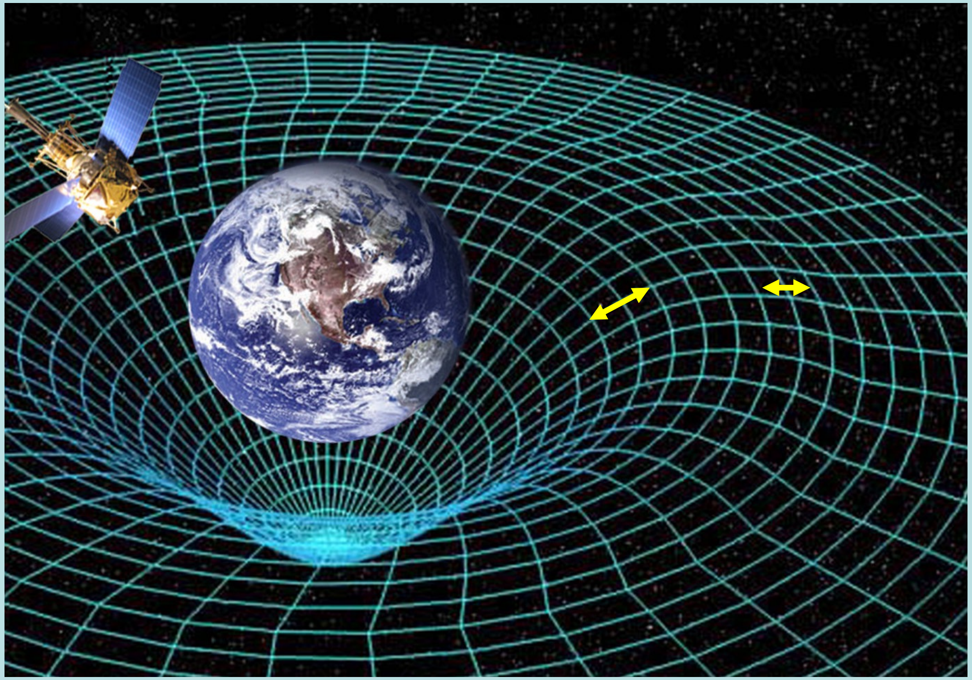
Figure 1 Reproducing the shape of an overturned rowboat (top) by driving nails around its perimeter, then stretching strings between each nail and every nearby nail (middle) The shape of the rowboat can be reconstructed (bottom) using only the lengths of string segments—the distances between nails. To increase the precision of reproduction, increase the number of nails, the number of string segments, the table of distances

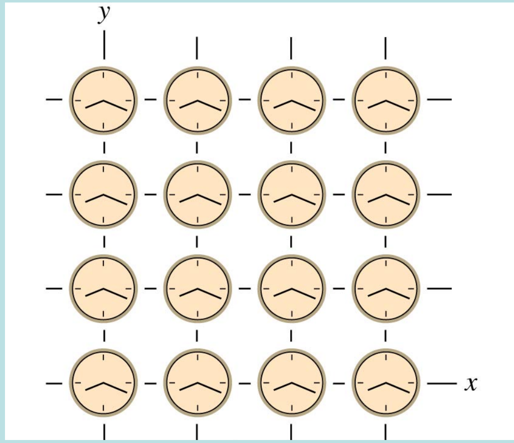
這很像要記錄一個曲面，例如翻過來的船身，

最方便的辦法，可以在船身釘上固定的釘子作為座標，

然後測量紀錄所有釘子間彼此的距離。

由此資訊將來就能重建整個船身的曲面！



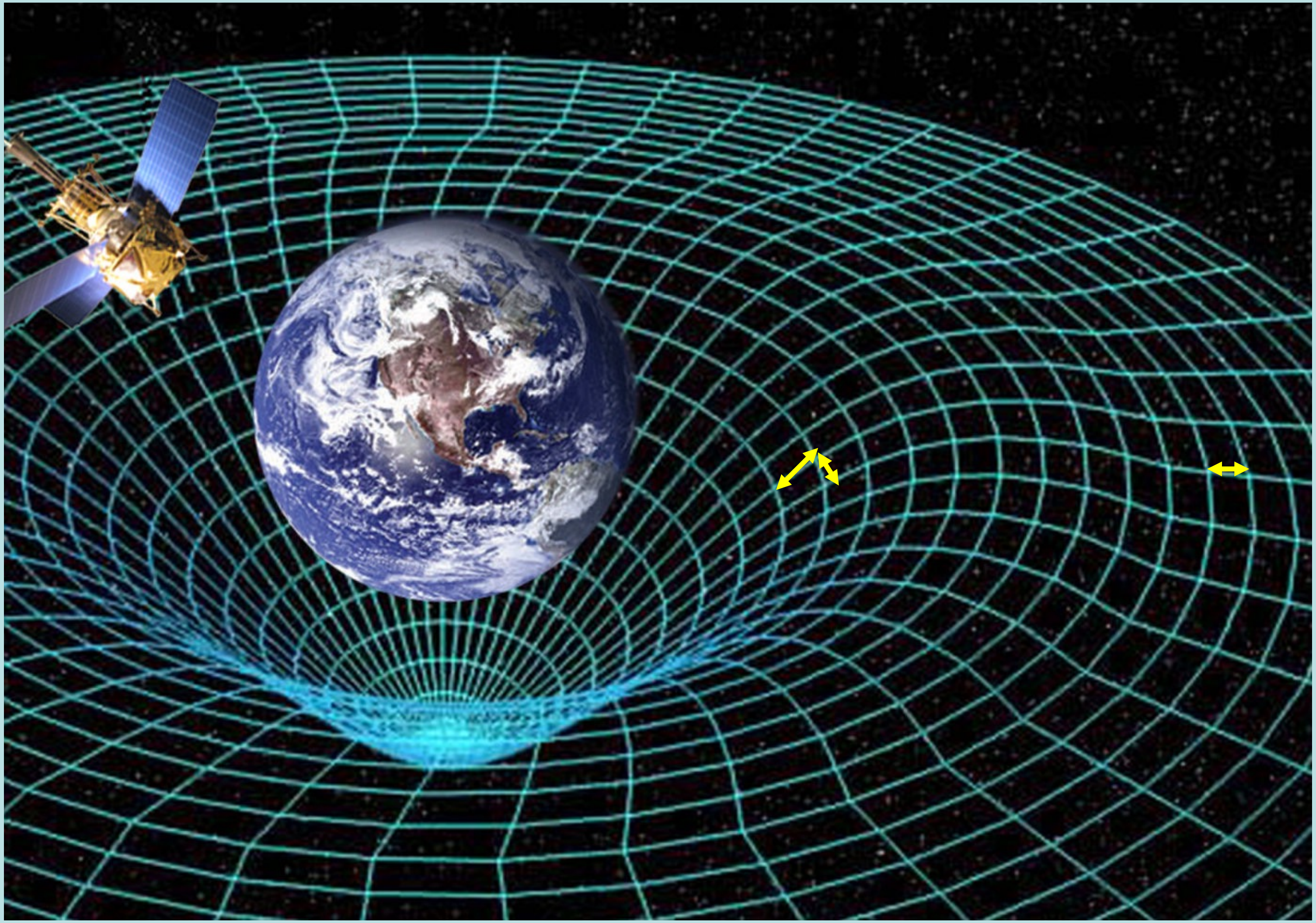


別忘了時鐘事實上也是一個時間座標尺格，

時間$g_{tt}(\vec{r},t)$就是原來校準的、間隔一秒的時鐘，現在量起來的時間差。

可以發出一道光比較各處個的時鐘的快慢！

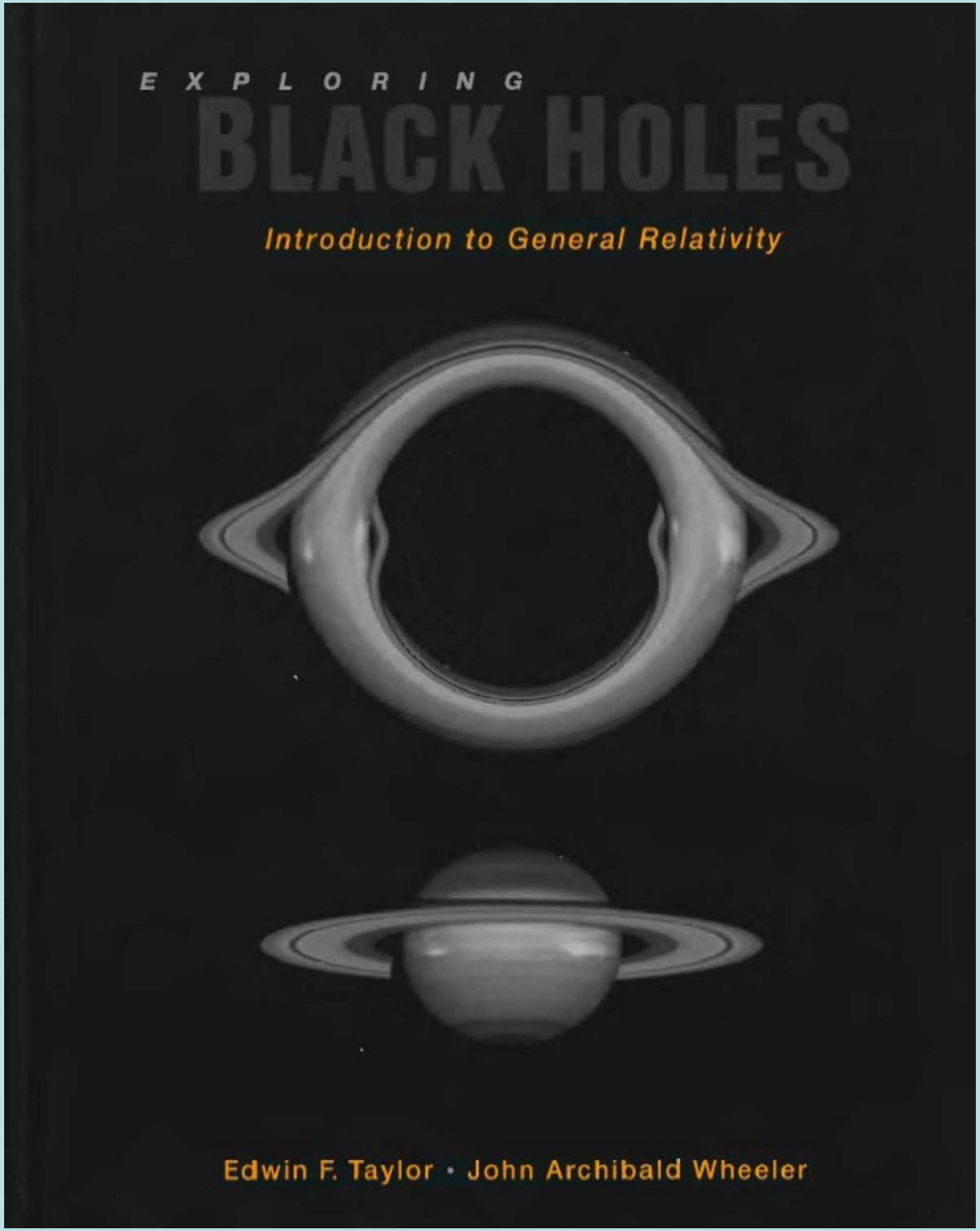
以上這些資料的總和，稱為度規或尺規：Metric $g_{\mu\nu}(\vec{r},t)$。

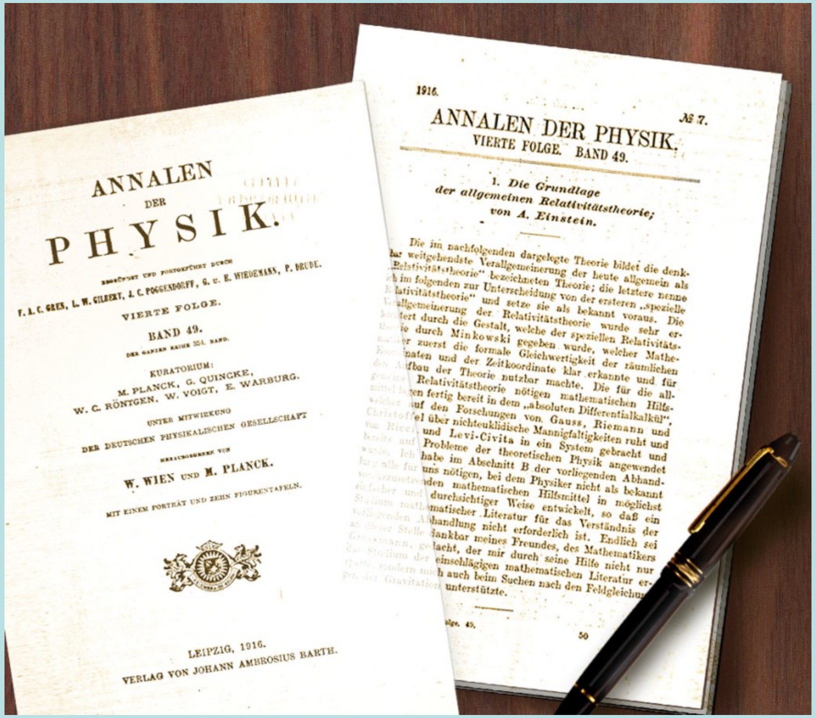


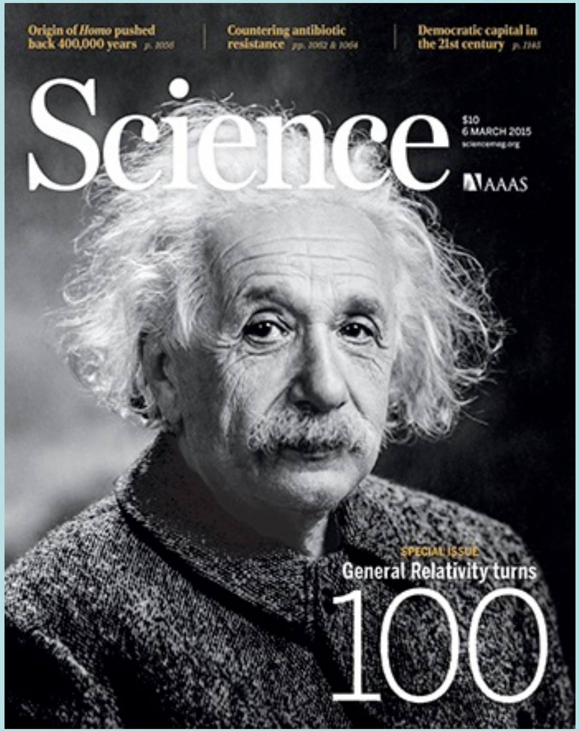
收集各處時空間距的變化，即是度規的資訊$g_{\mu\nu}$，就可以唯一描述時空的彎曲。

時空彎曲的資訊遍佈空間各處且隨時間變化。

這些資訊的總和：$g_{\mu\nu}(\vec{r},t)$，可以說是一個重力場。


EXPLORING
BLACK HOLES
Introduction to General Relativity
Edwin F. Taylor · John Archibald Wheeler

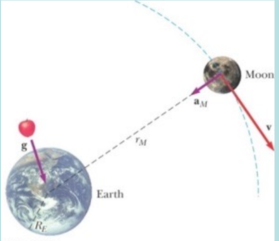




$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

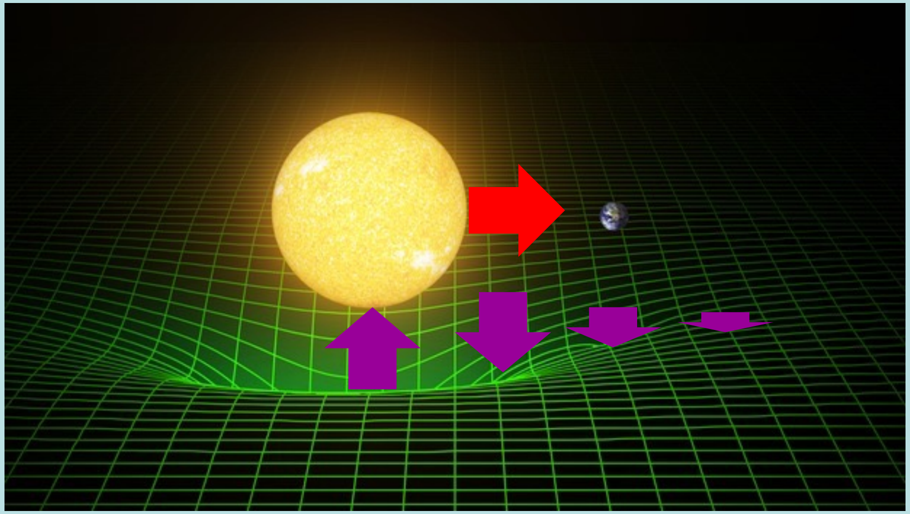
愛因斯坦方程式左邊的時空的彎曲曲率就是由$g_{\mu\nu}(\vec{r},t)$計算出來的。

愛因斯坦方程式就是$g_{\mu\nu}(\vec{r},t)$需要滿足的方程式。



重力的資訊，也就是時空彎曲的尺格遍佈空間各處且隨時間變化。

地球若被彗星撞歪了，月亮什麼時候會知道？



地球突然被撞歪偏右了，地球右邊近處的尺格立刻被彎曲得更厲害！

也就是尺格立刻被拉得比原來長！

想像時空的尺格，如水面一樣有彈性，

稍遠處的尺格又會因近處尺格被拉長而跟著被拉長。

如此撞歪的地球造成尺格度規的擾動，如同平坦的海面突然落下一個物體，

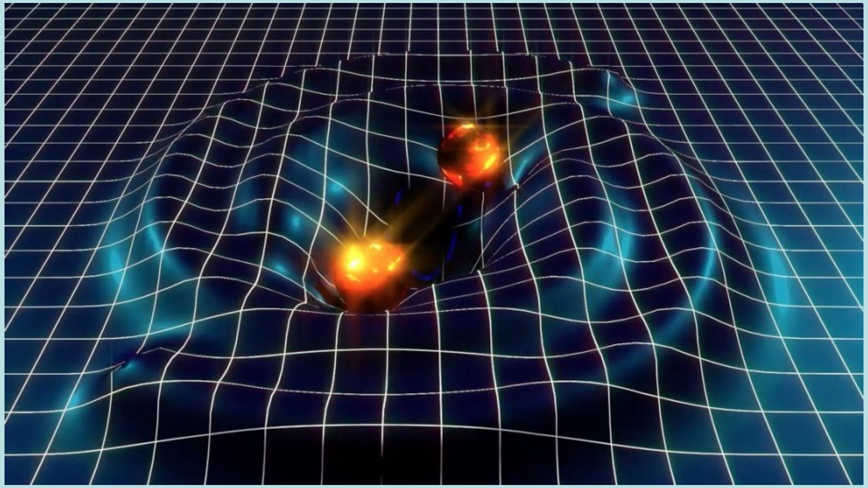
物體激起的水波需要時間才能傳播到遠方！

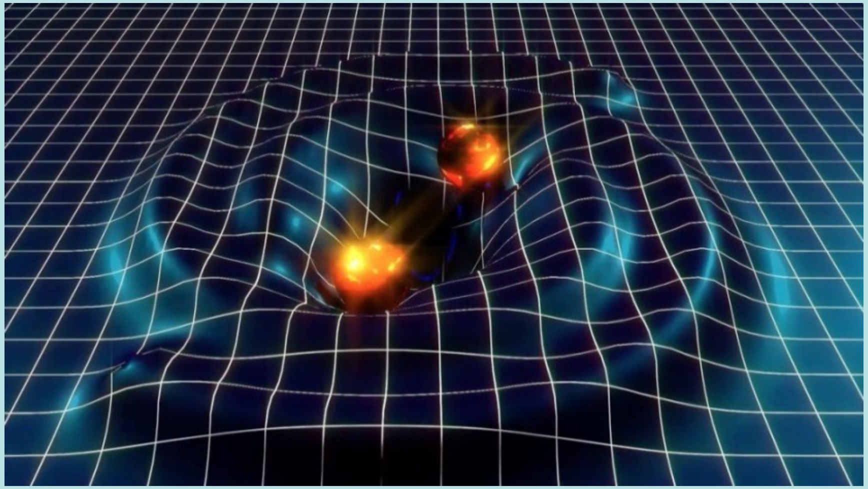
時空彎曲會以重力波的形式傳播。

這就如同加速的電荷會產生電磁波，突然加速的巨大質量會產生重力波。

可以推導重力波傳播的波速洽為光速！**地球被彗星撞歪的訊息以光速傳播。**

真空中的尺格與時空彎曲扮演了如介質般的角色，使重力不再是超距力！





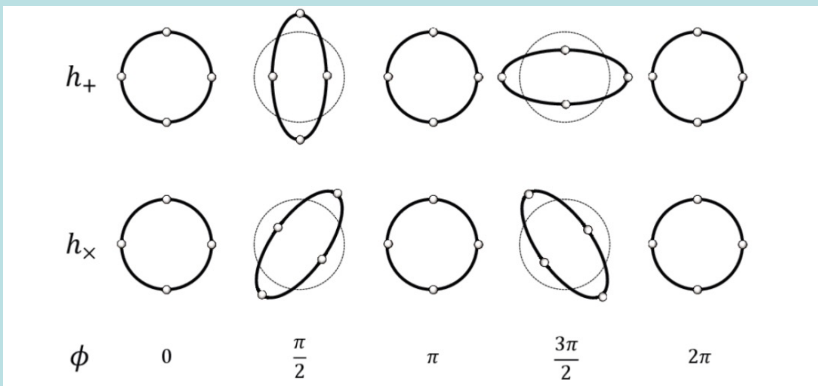
如同水面波會把水面的起伏傳播至遠方，

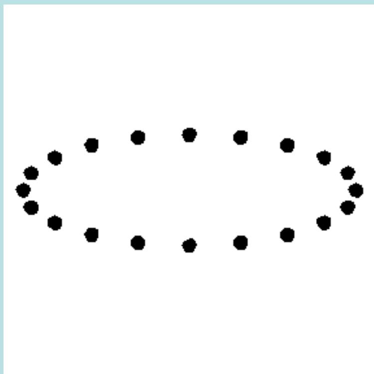
重力波也會傳遞時空的彎曲、也就尺格的拉長與壓縮至遠方，

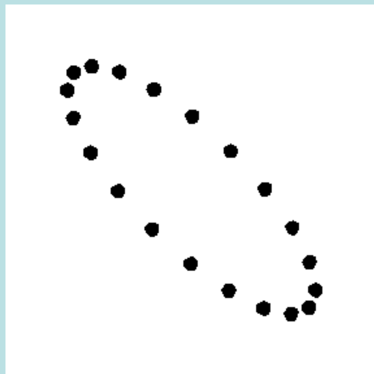
重力波經過時，兩點間測得的間距會如波動現象，而反覆拉長或縮短。

也就是：測量一物體長度得到的結果會有反覆變化：$\Delta L \sim \cos \omega t$。

經過計算，尺格的扭曲，沿一個軸被拉長，在垂直的軸就被壓縮。







重力波

重力波到2015年才觀測到。

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

VOL. CLXV . . . No. 57,140 + © 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016 $2.50

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by bashing his past criticism of President Obama — a remark that Mr. Sanders called a "low blow."

With tensions between the two Democrats becoming increasingly obvious, the debate was full of new lines of attack from Mrs. Clinton, who faces pressure to puncture Mr. Sanders's growing popularity before the next nominating contests in Nevada and

CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most foreboding (and unwelcome) part of his theory.

Long in Clinton's Corner, Blacks Notice Sanders

Courted Hard in South Carolina, Loyalists Listen Closely

By RICHARD FAUSSET

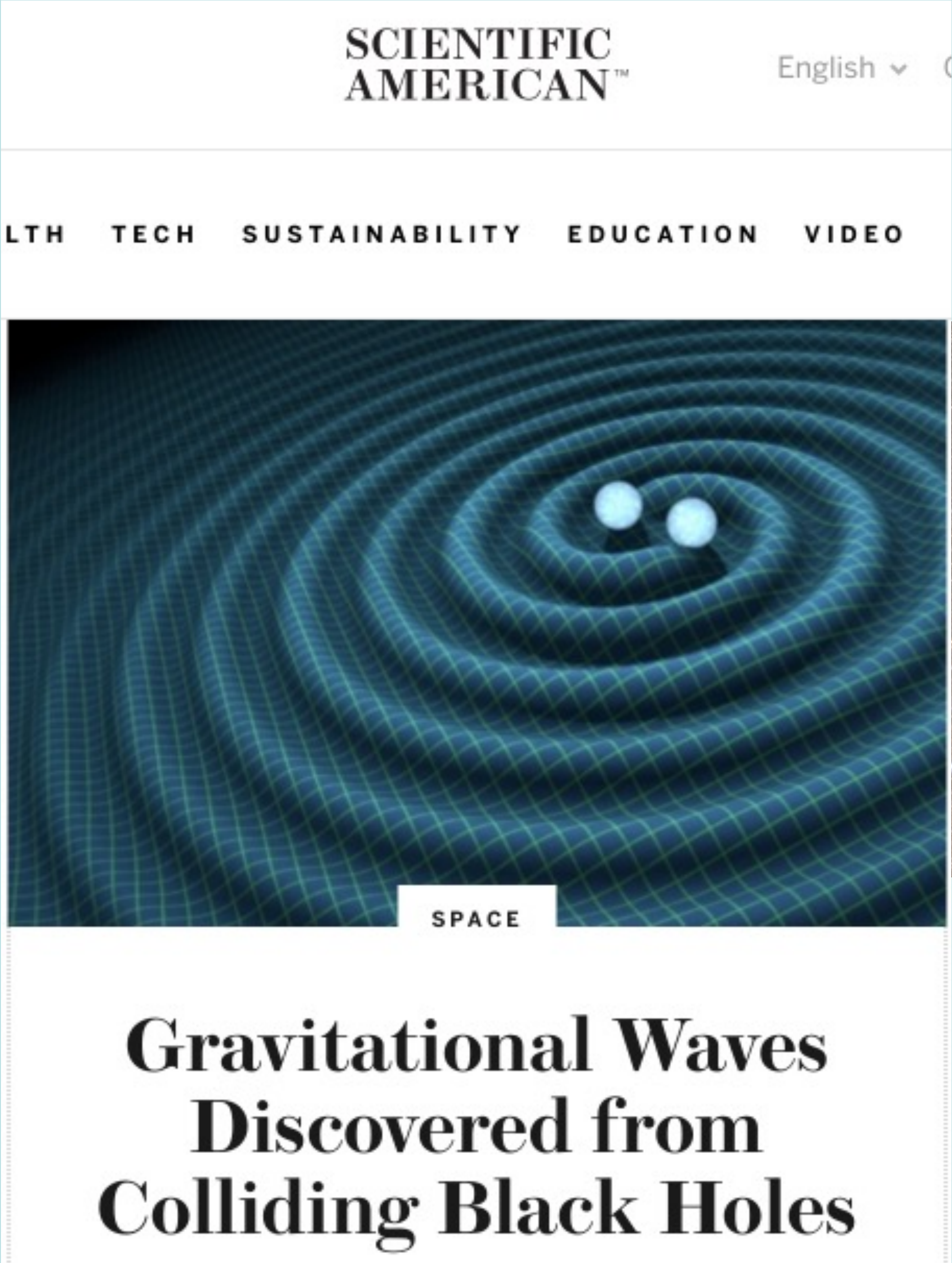
ORANGEBURG, S.C. — When Helen Duley was asked whom she would vote for in the South Carolina primary, she answered

candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an undecided voter and planned to do some homework on Mr. Sanders.

Last Occupier In Rural Oregon Is Coaxed Out

This article is by Dave Semi-

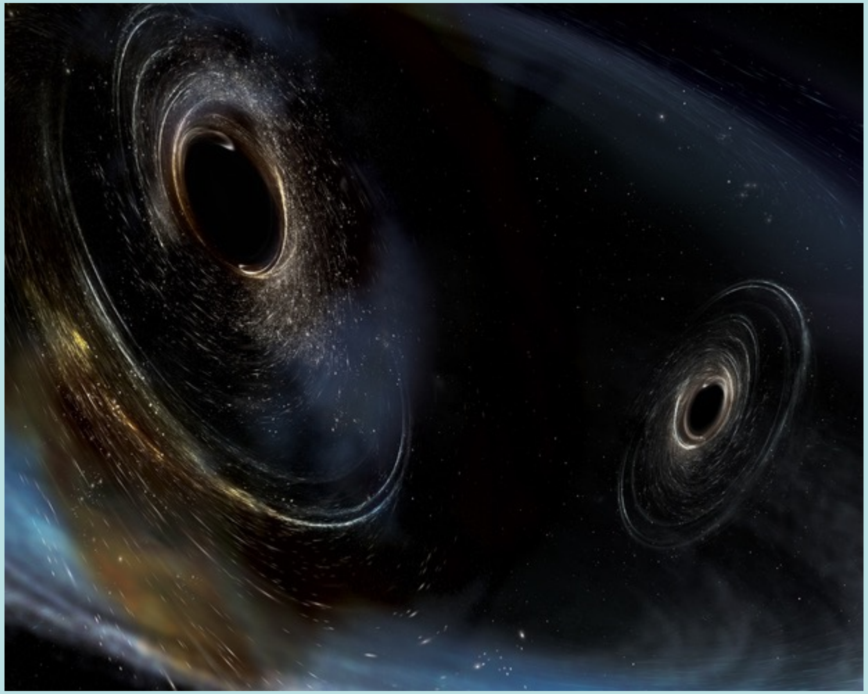
2015 發現由黑洞撞擊產生的重力波



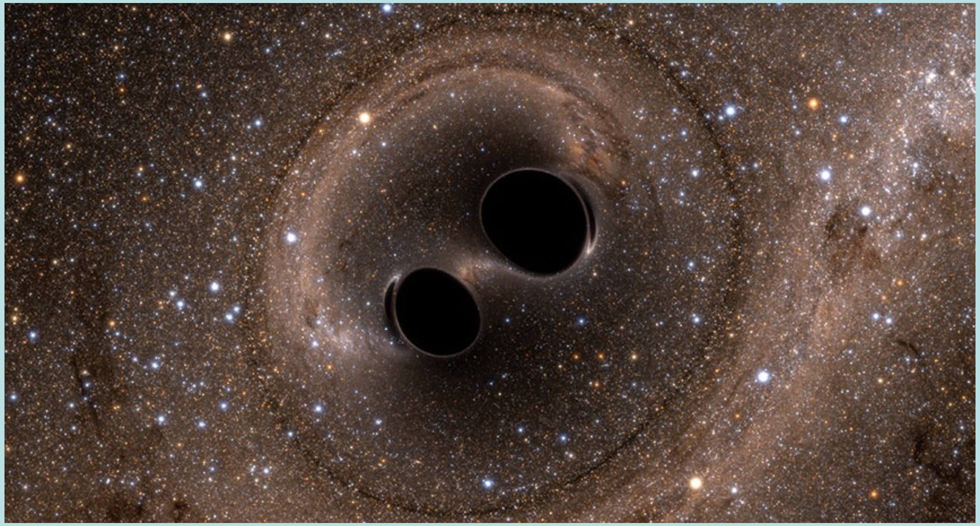
Observation of Gravitational Waves from a Binary Black Hole Merger

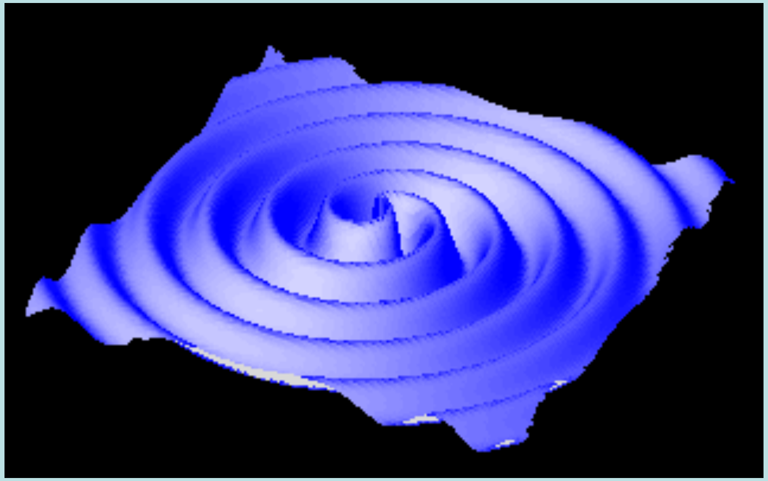
B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.



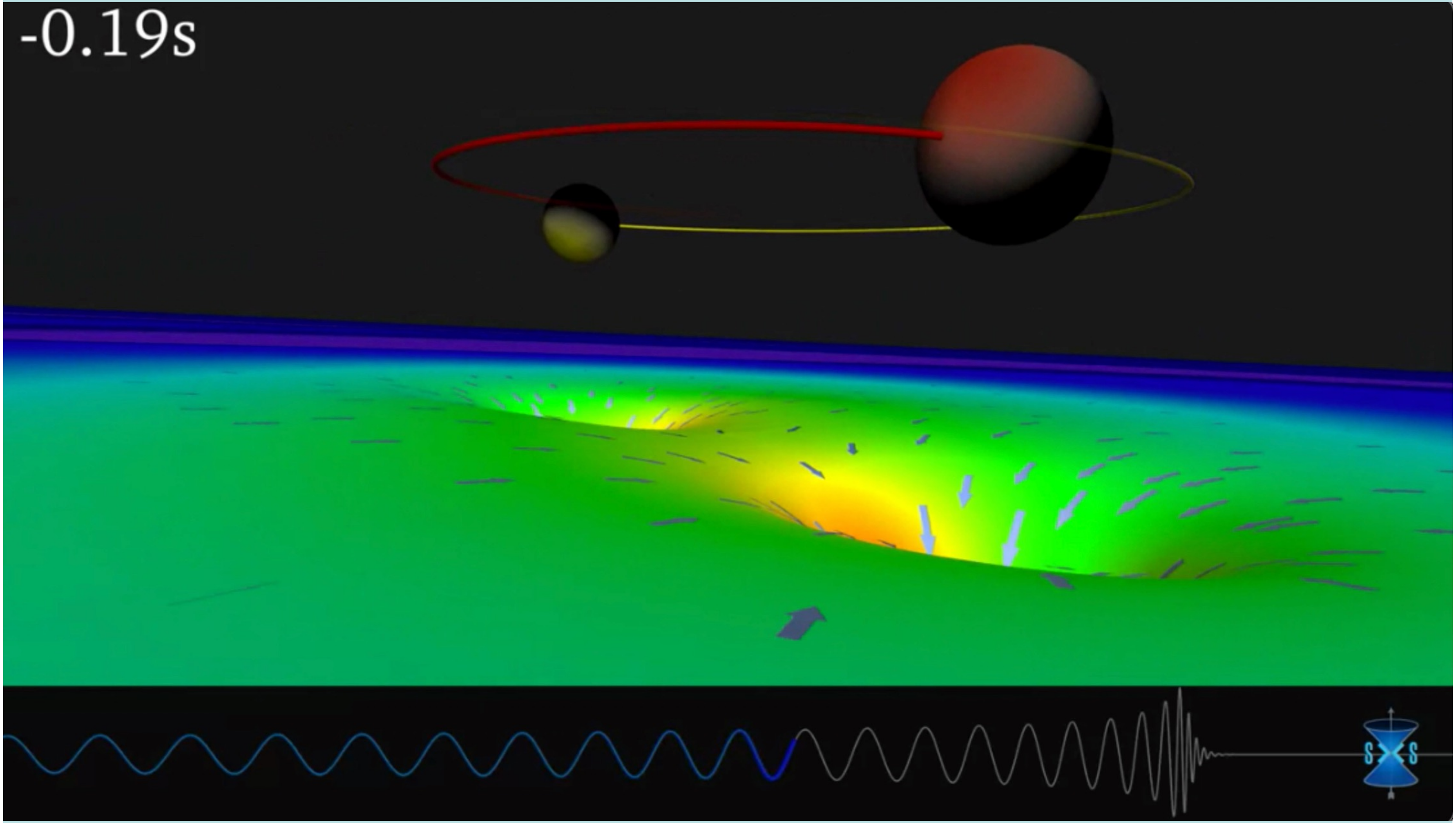
兩個黑洞撞擊，形成一個黑洞所產生的重力波。





Two Black Holes Merge into One

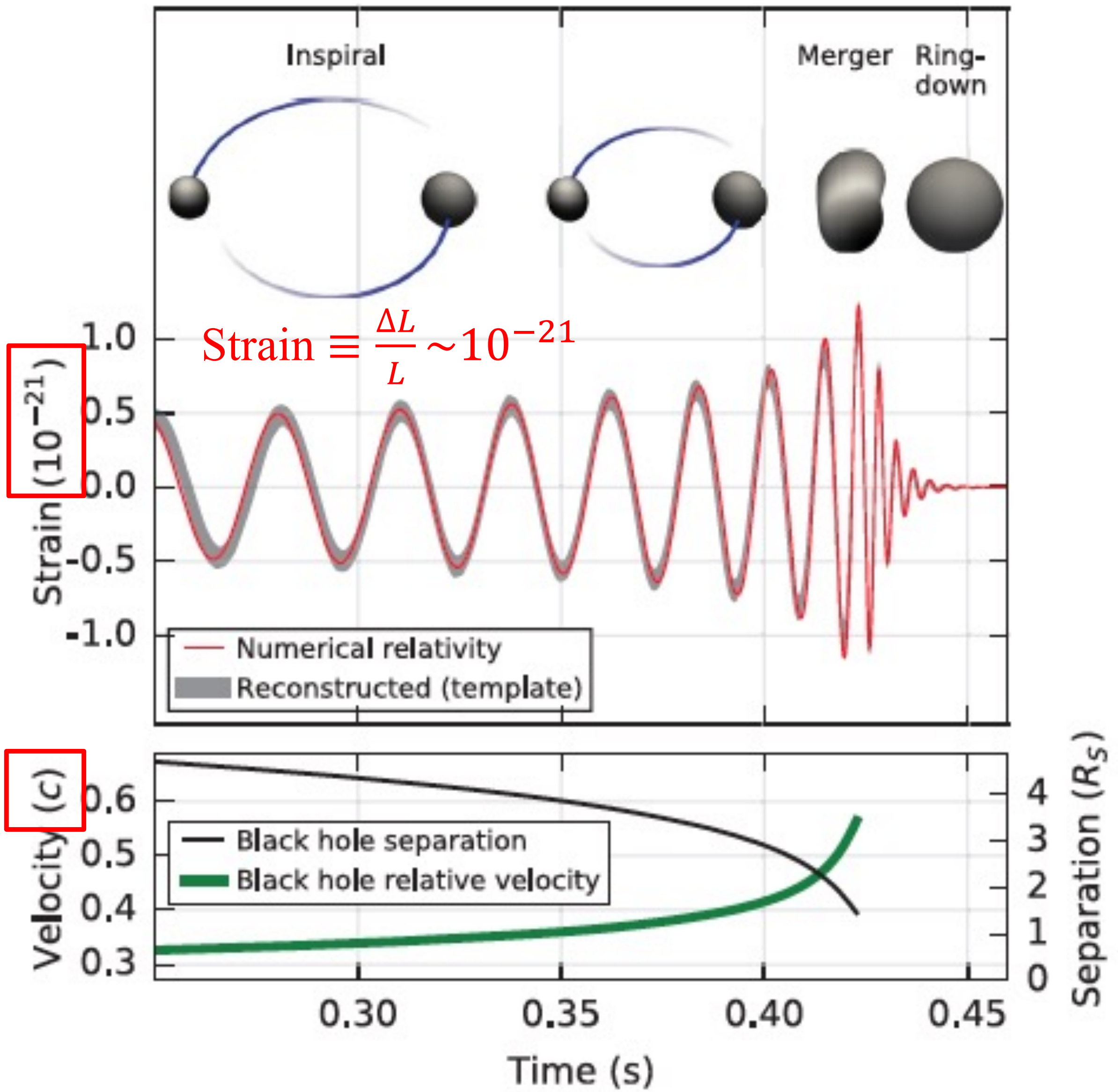
兩個黑洞撞擊，形成一個黑洞的數值模擬。

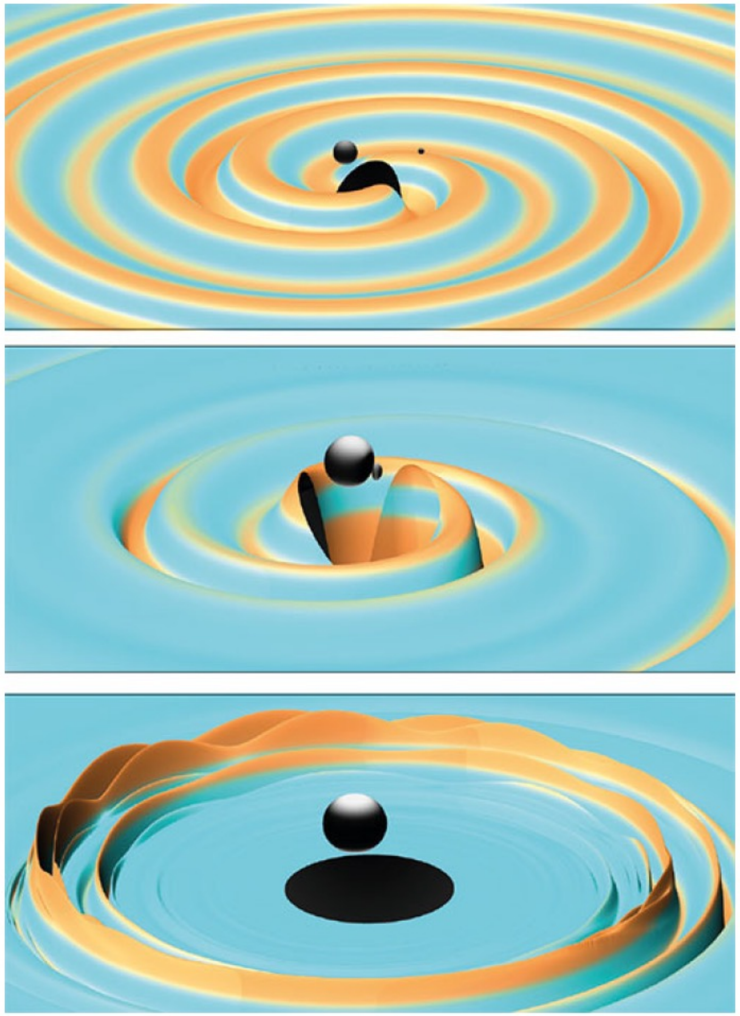


GR-1-3 GW simulation


L
I
G
O
LIGO stands for the Laser
Interferometer Gravitational
Settings
0:00 / 5:26

測量重力波經過時的一段長度的變化：ΔL。

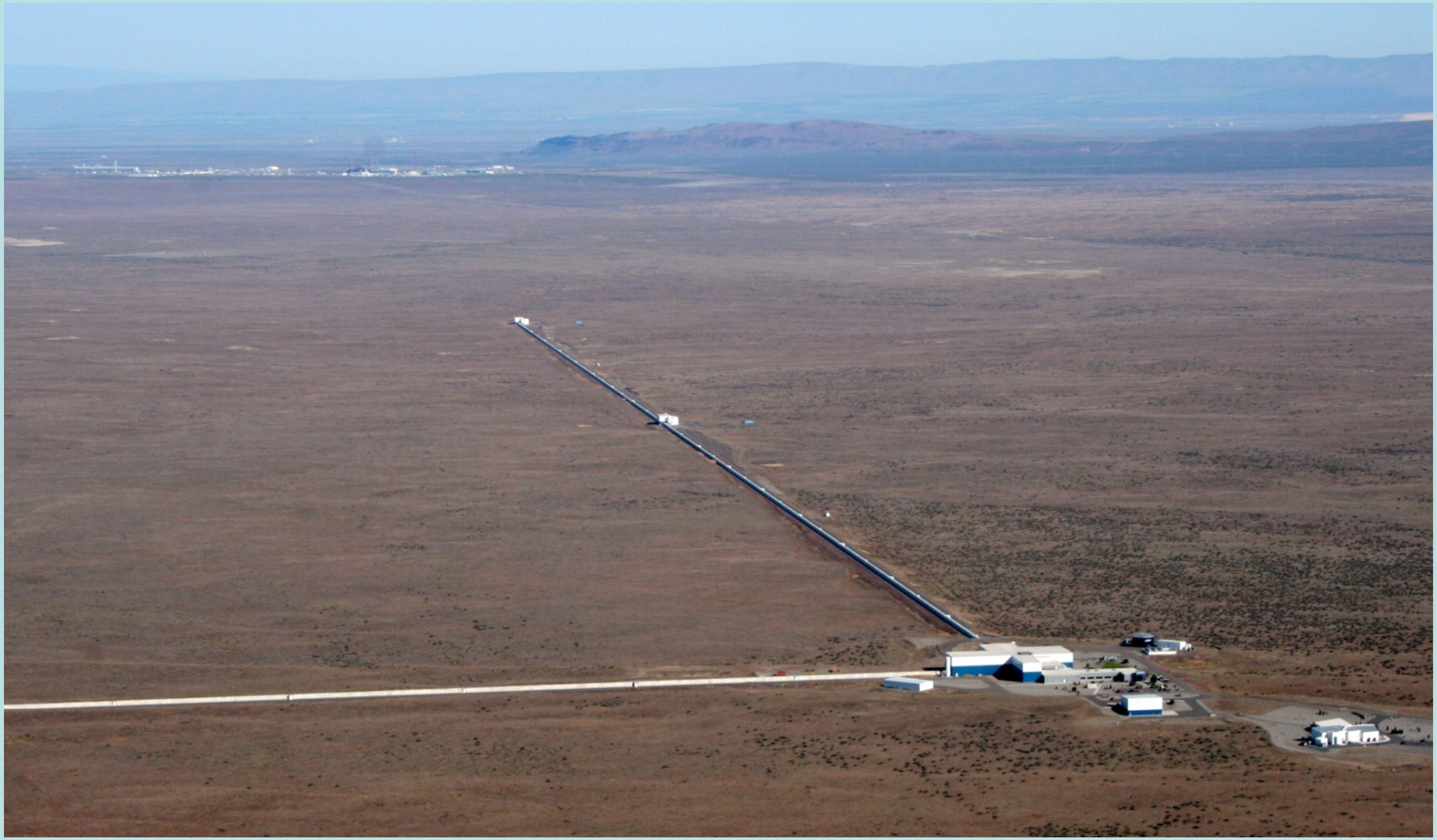




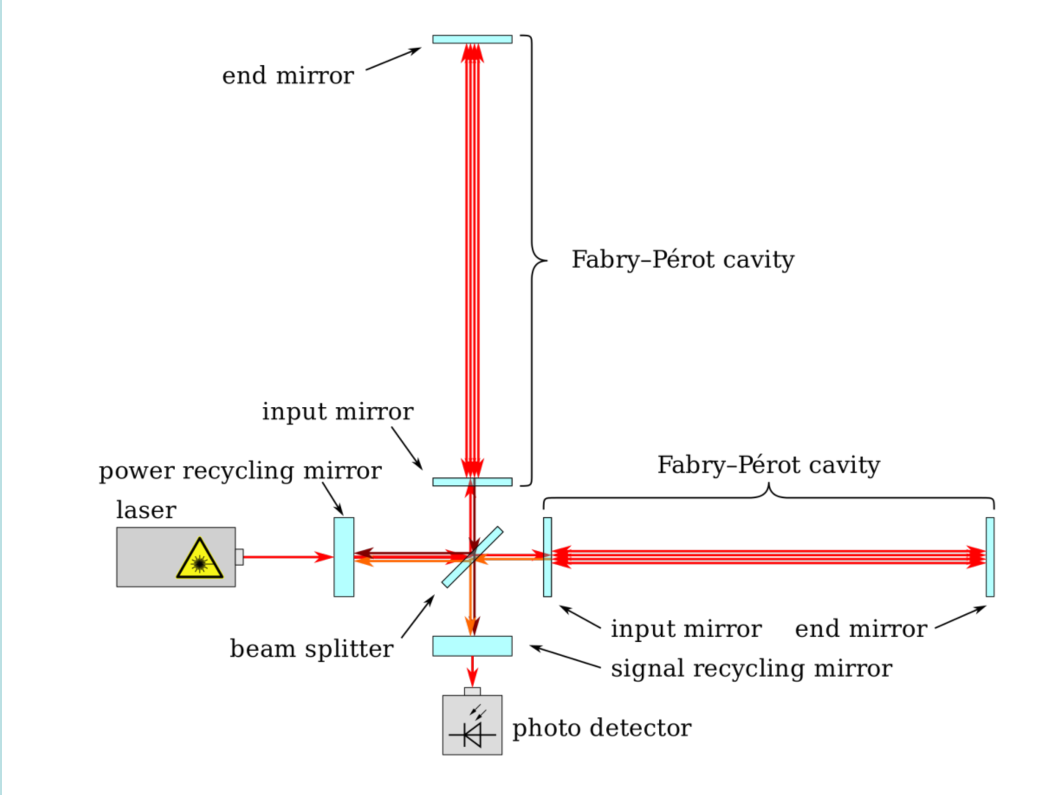
對於黑洞撞擊產生的重力波的樣式，我們已得到蠻清楚的預測。

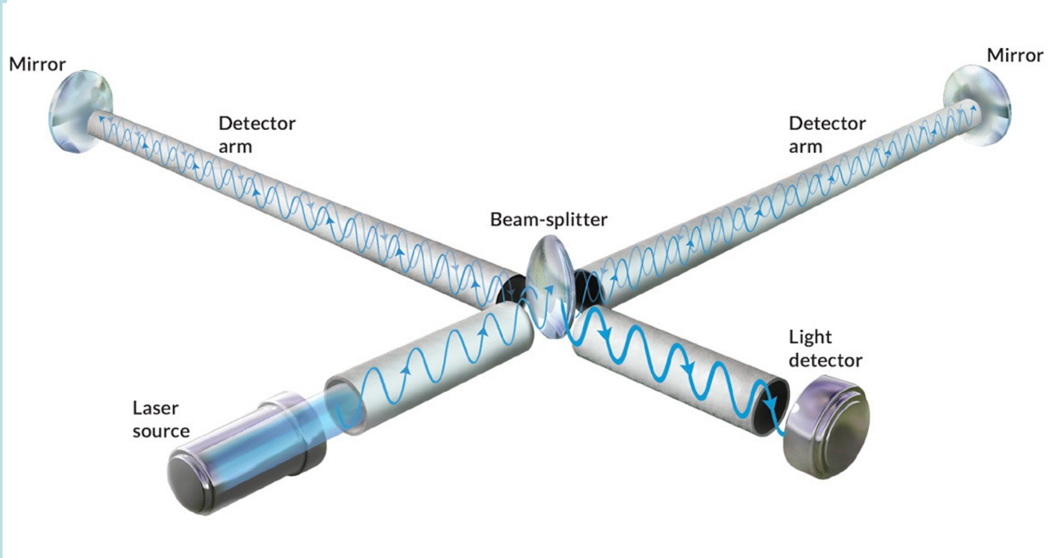
L越大，ΔL就越大！

Laser Interferometer Gravitational-Wave Observatory (LIGO)

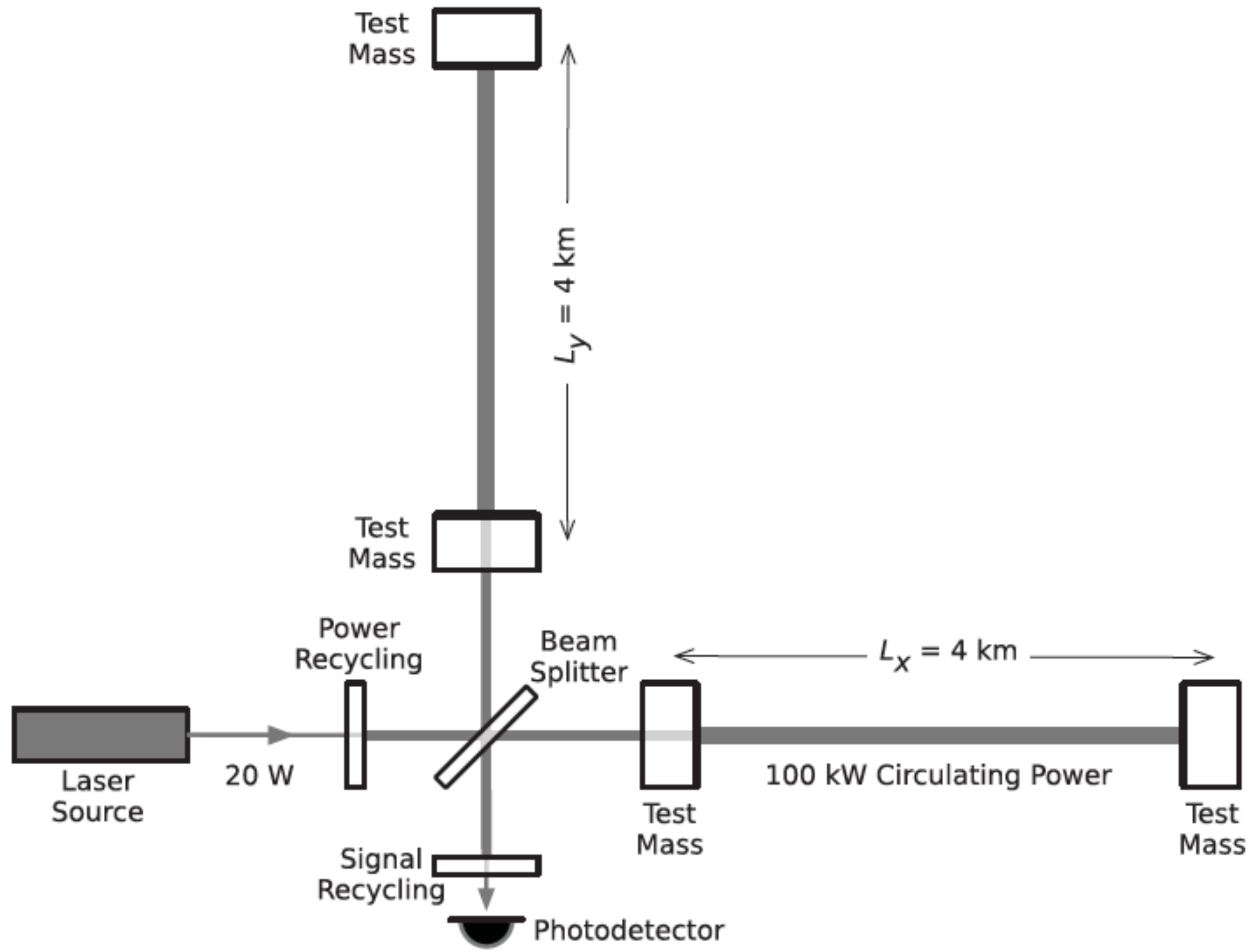


Western leg of LIGO interferometer on Hanford Reservation

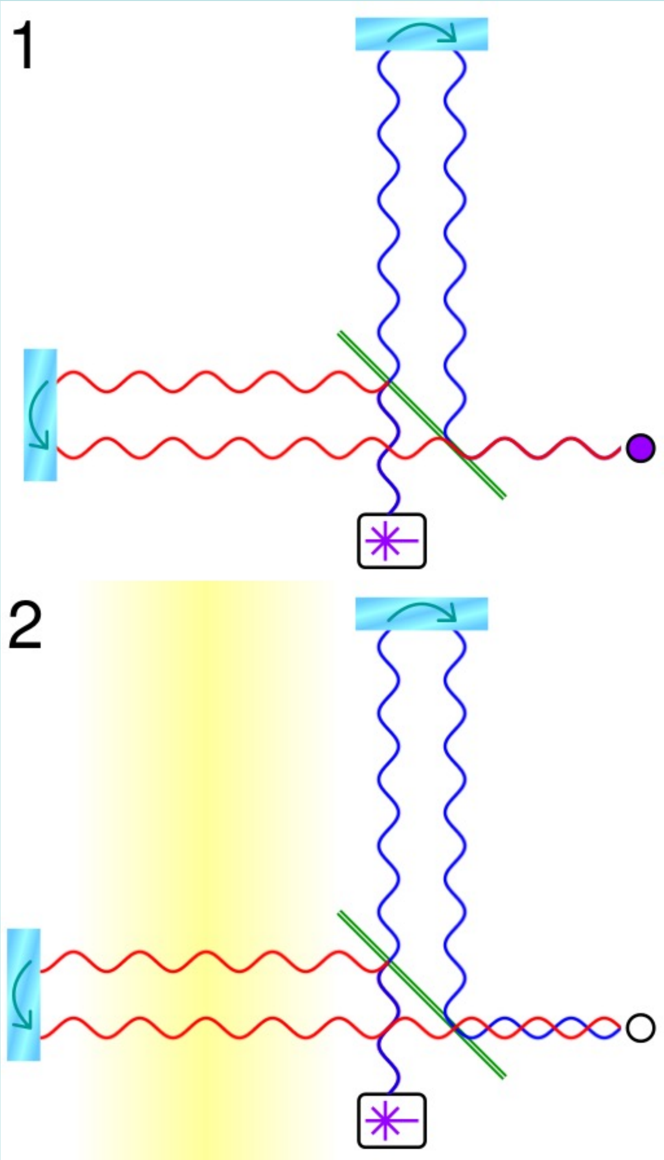




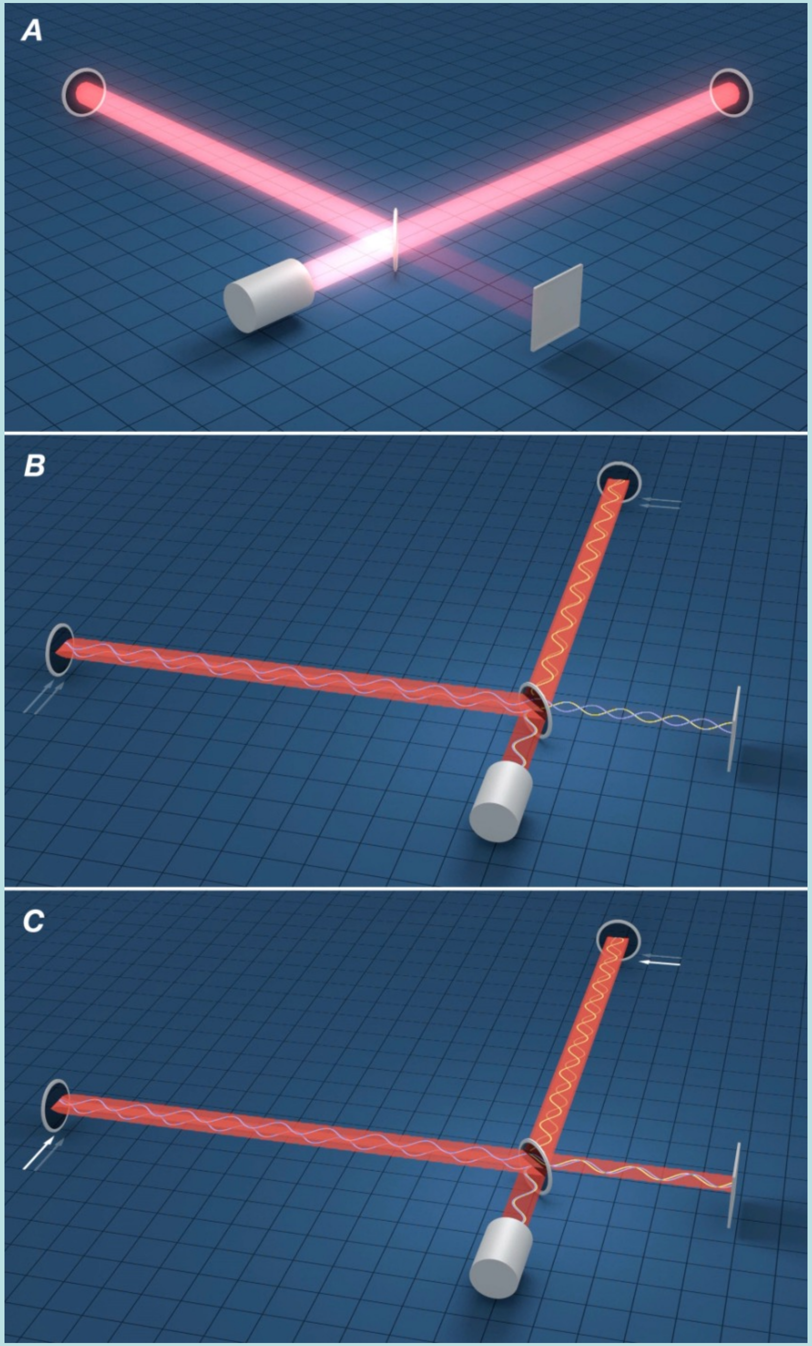
重力波經過時光走的路徑的長度會有變化。


Test
Mass
Ly = 4 km
Test
Mass
Power
Recycling
Beam
Splitter
Lx = 4 km
Laser
Source
20 W
100 kW Circulating Power
Test
Mass
Test
Mass
Signal
Recycling
Photodetector

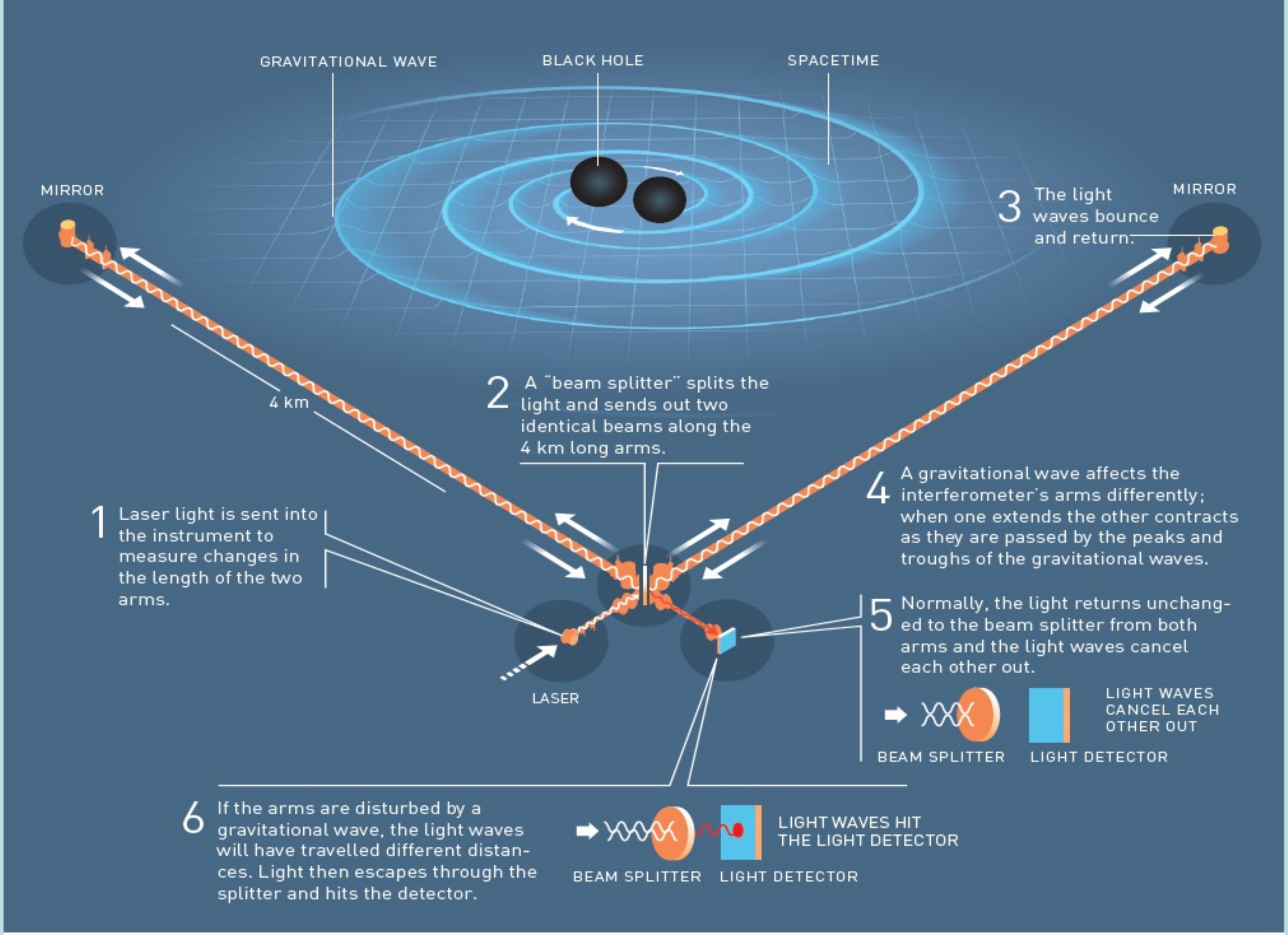
Most Precise Ruler Ever Constructed



利用光的干涉測量路徑長度的差。



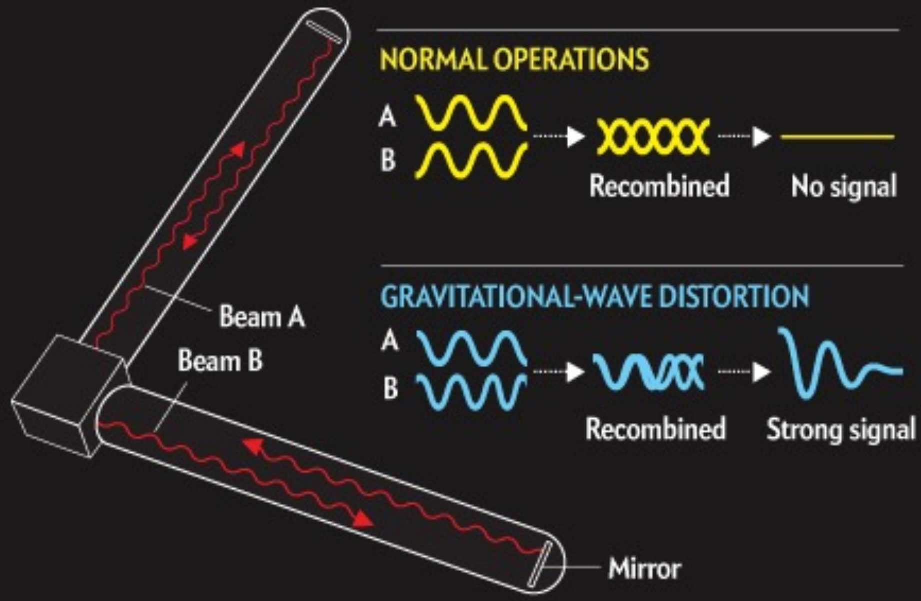
LIGO – A GIGANTIC INTERFEROMETER

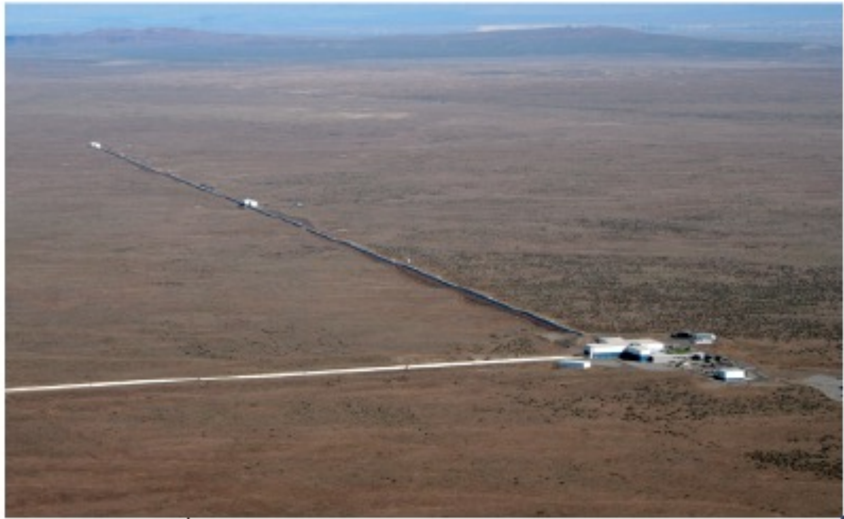


HOW IT WORKS

The Laser Interferometer Gravitational Observatory (LIGO)

The LIGO experiment uses two L-shaped detectors, one in Washington State and one in Louisiana, to search for gravitational waves. Each detector bounces laser light between mirrors down two perpendicular four-kilometer legs. LIGO splits the light so that the wave traveling through the first leg, Beam A, is out of phase with that in the other, Beam B. When the beams recombine (yellow), the waves should cancel each other out, rendering the resulting beam dark. If, however, a gravitational wave passes through Earth and changes the relative length of the legs (blue), the waves will not match up and the combined beams will reveal telltale beats. The effect is tiny, however—a nearby collision of two black holes will change the length of LIGO's legs by less than the diameter of a proton.





The Hanford facility is on the steppes of the northwest USA, outside Hanford.

Courtesy Caltech MIT/Ligo Laboratory

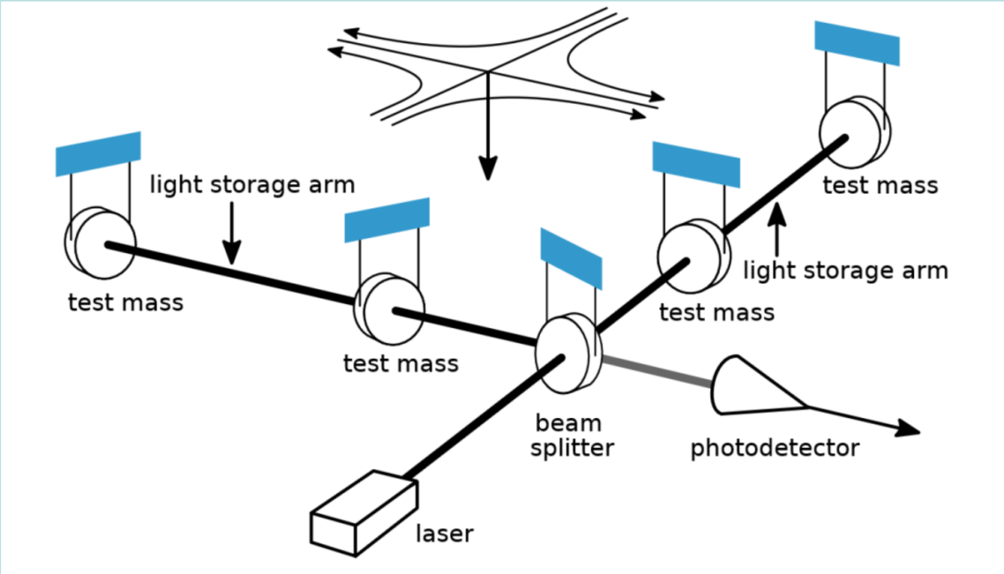
The Livingston facility is in Livingston in the southern swampland of Louisiana.

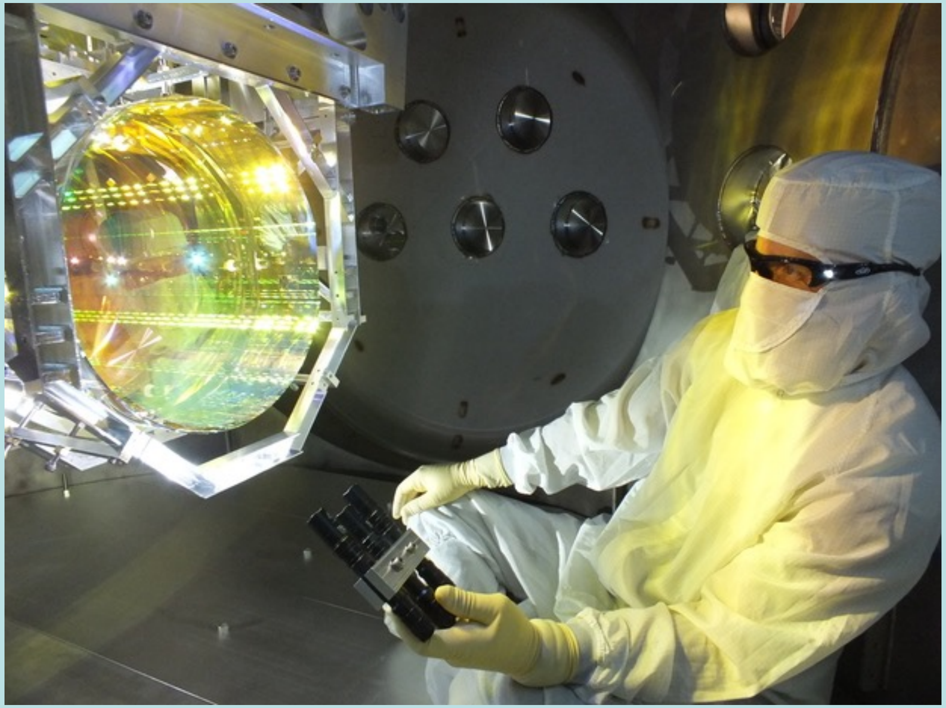
Courtesy Caltech MIT/Ligo Laboratory

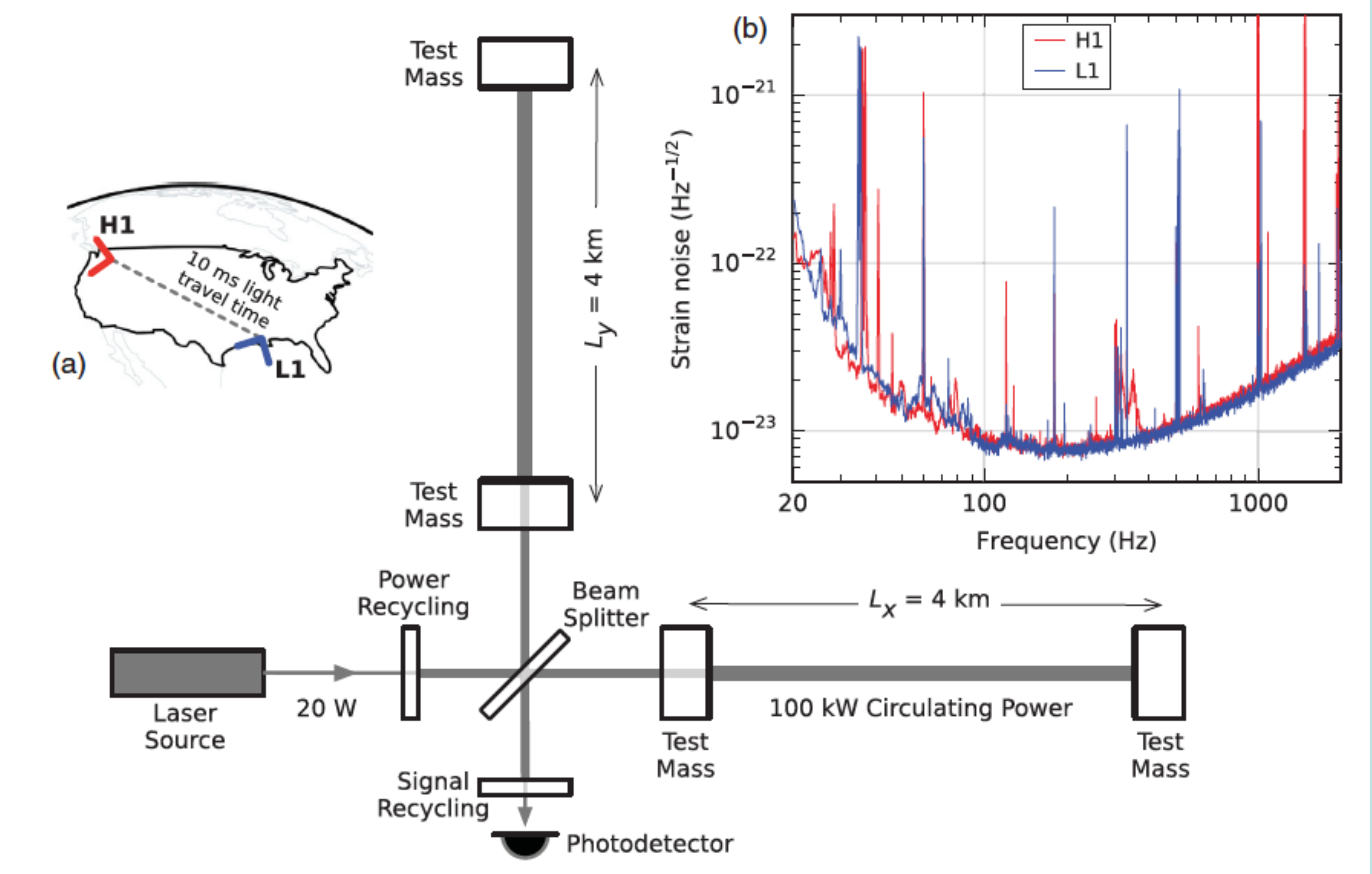
Figure 4. LIGO consists of two gigantic identical interferometers. The gravitational wave first hit the interferometer in Livingston and then passed its twin in Hanford, just over 3,000 km away, 7 milliseconds later. The signals were almost identical, and were a good match with the predicted signal for a gravitational wave. Using the signals, an area in the southern skies could also be identified as the area the waves came from.


Livingston
Hanford

如何控制懸吊的反射鏡的熱擾動，







Simplified diagram of an Advanced LIGO detector (not to scale). A gravitational wave propagating orthogonally to the detector plane and linearly polarized parallel to the 4-km optical cavities will have the effect of lengthening one 4-km arm and shortening the other during one half-cycle of the wave; these length changes are reversed during the other half-cycle. The output photodetector records these differential cavity length variations. While a detector's directional response is maximal for this case, it is still significant for most other angles of incidence or polarizations (gravitational waves propagate freely through the Earth). Inset (a): Location and orientation of the LIGO detectors at Hanford, WA (H1) and Livingston, LA (L1). Inset (b): The instrument noise for each detector near the time of the signal detection; this is an amplitude spectral density, expressed in terms of equivalent gravitational-wave strain amplitude. The sensitivity is limited by photon shot noise at frequencies above 150 Hz, and by a superposition of other noise sources at lower frequencies [47]. Narrow-band features include calibration lines (33–38, 330, and 1080 Hz), vibrational modes of suspension fibers (500 Hz and harmonics), and 60 Hz electric power grid harmonics.

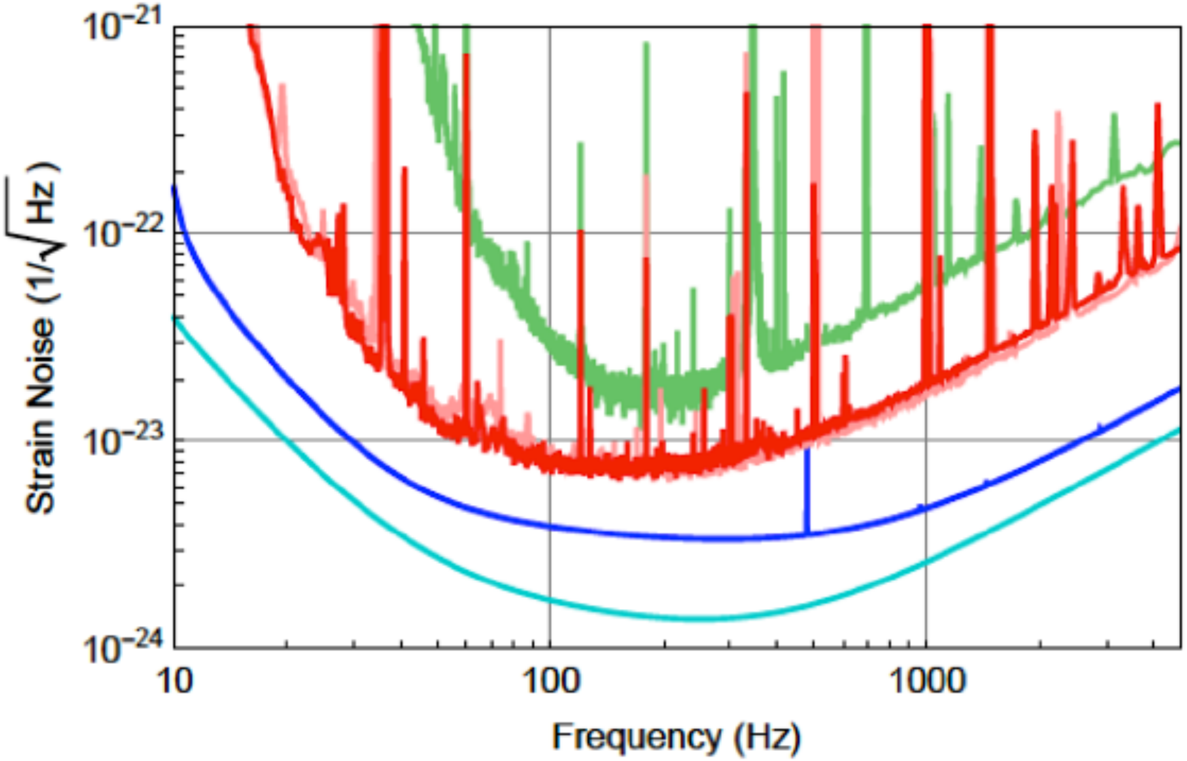


Figure 3: The strain sensitivity of the Advanced LIGO detectors during the first observation run in 2015 (red) and the last science run of the Initial LIGO detectors (green). The improvement in sensitivity is a factor of 3-4 in the most sensitive frequency band 100-300 Hz, and nearly a factor 100 at 50 Hz. The Advanced LIGO design sensitivity, which has not been reached yet, is shown in dark blue, and a possible future upgrade – in light blue. The narrow features include calibration lines, vibrational modes of suspension fibres and 60-Hz power grid harmonics (figure from [37]).

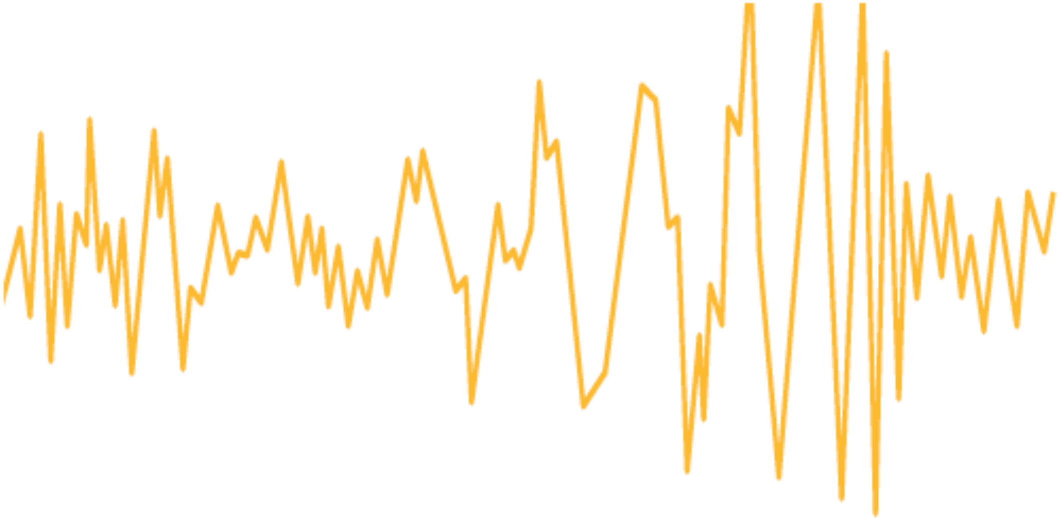


Figure 1. The first gravitational wave ever detected.

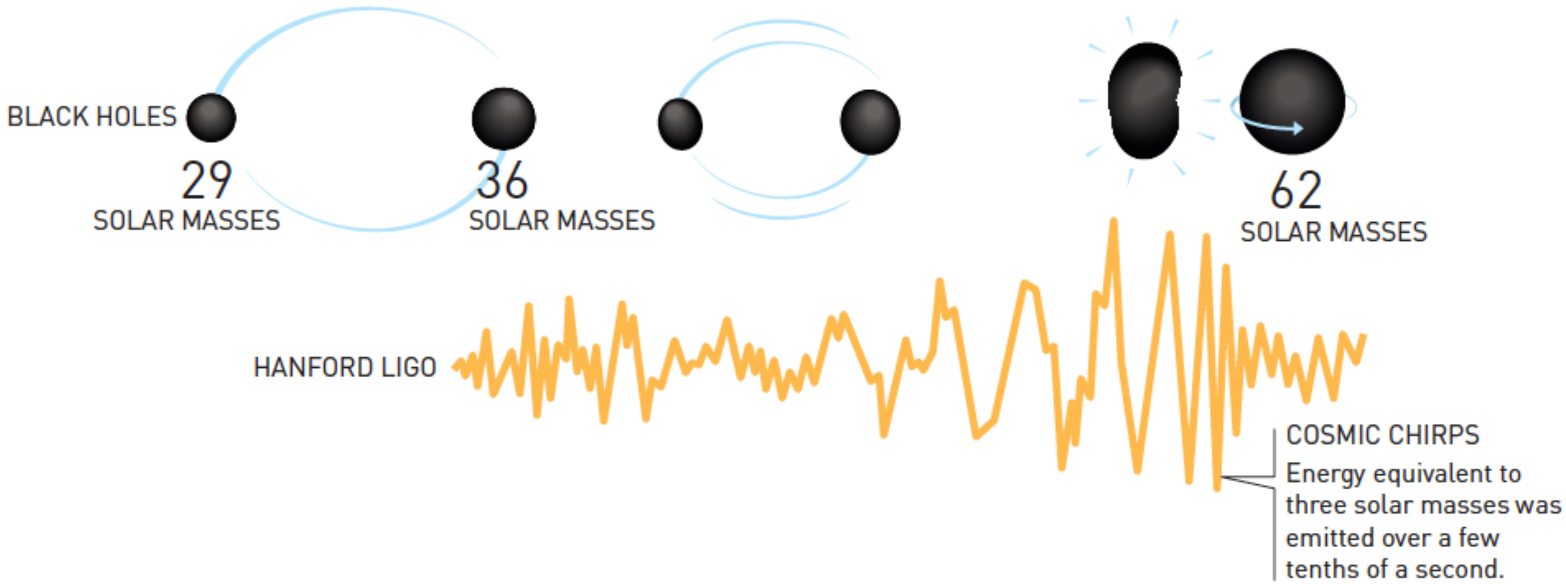
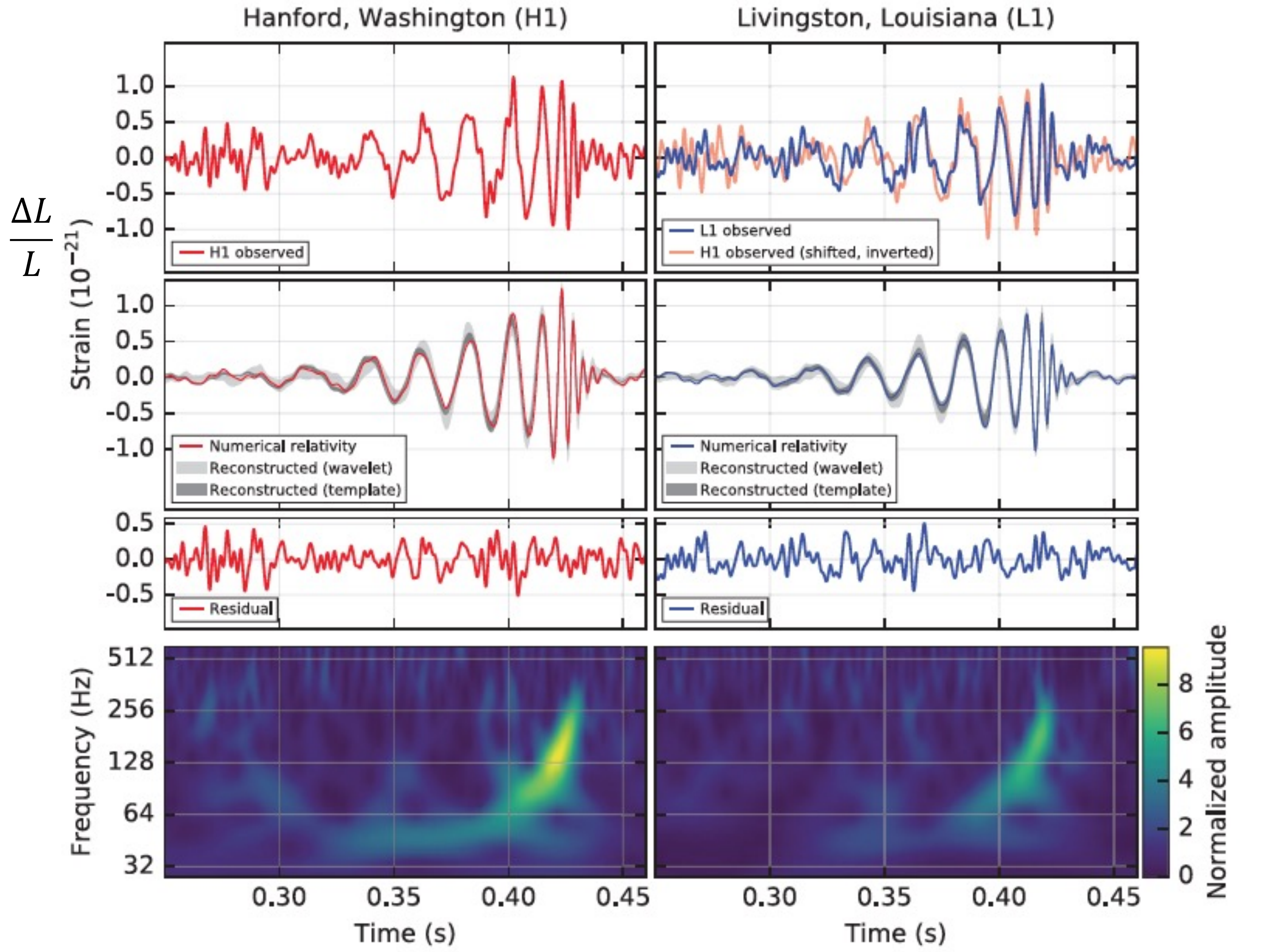
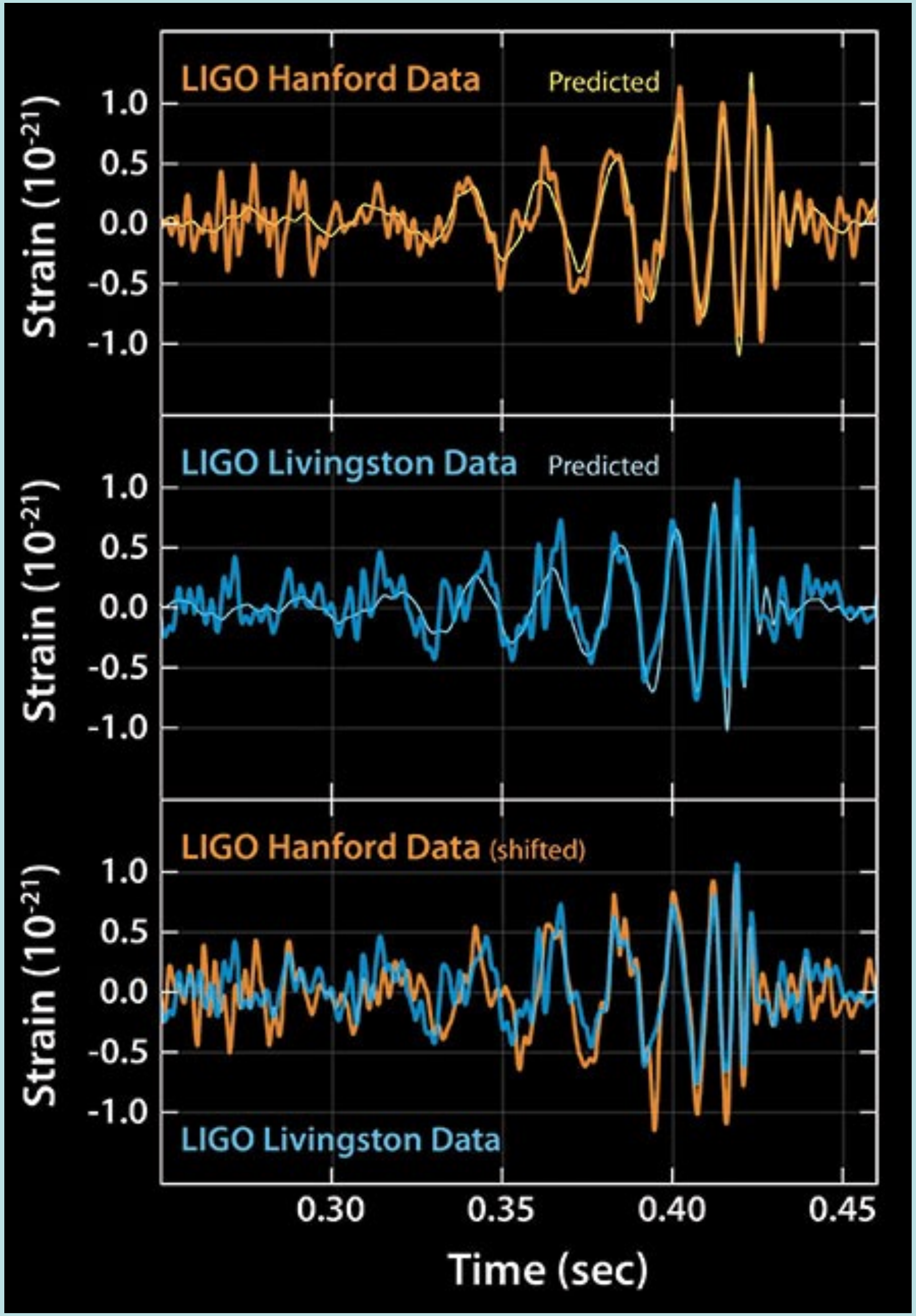


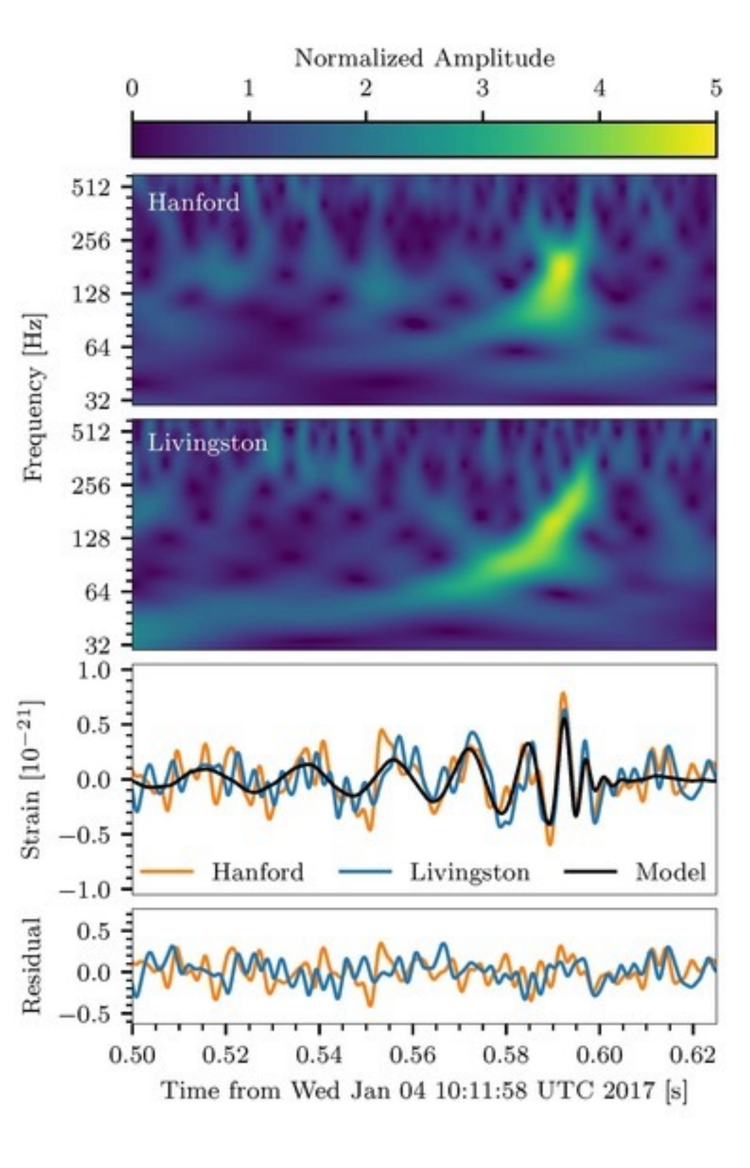
Figure 2. The two black holes emitted gravitational waves for many million years as they rotated around each other. They got closer and closer, before merging to become one black hole in a few tenths of a second. The waves then reached a crescendo which, to us on Earth, 1.3 billion lightyears away, sounded like cosmic chirps that came to an abrupt stop.



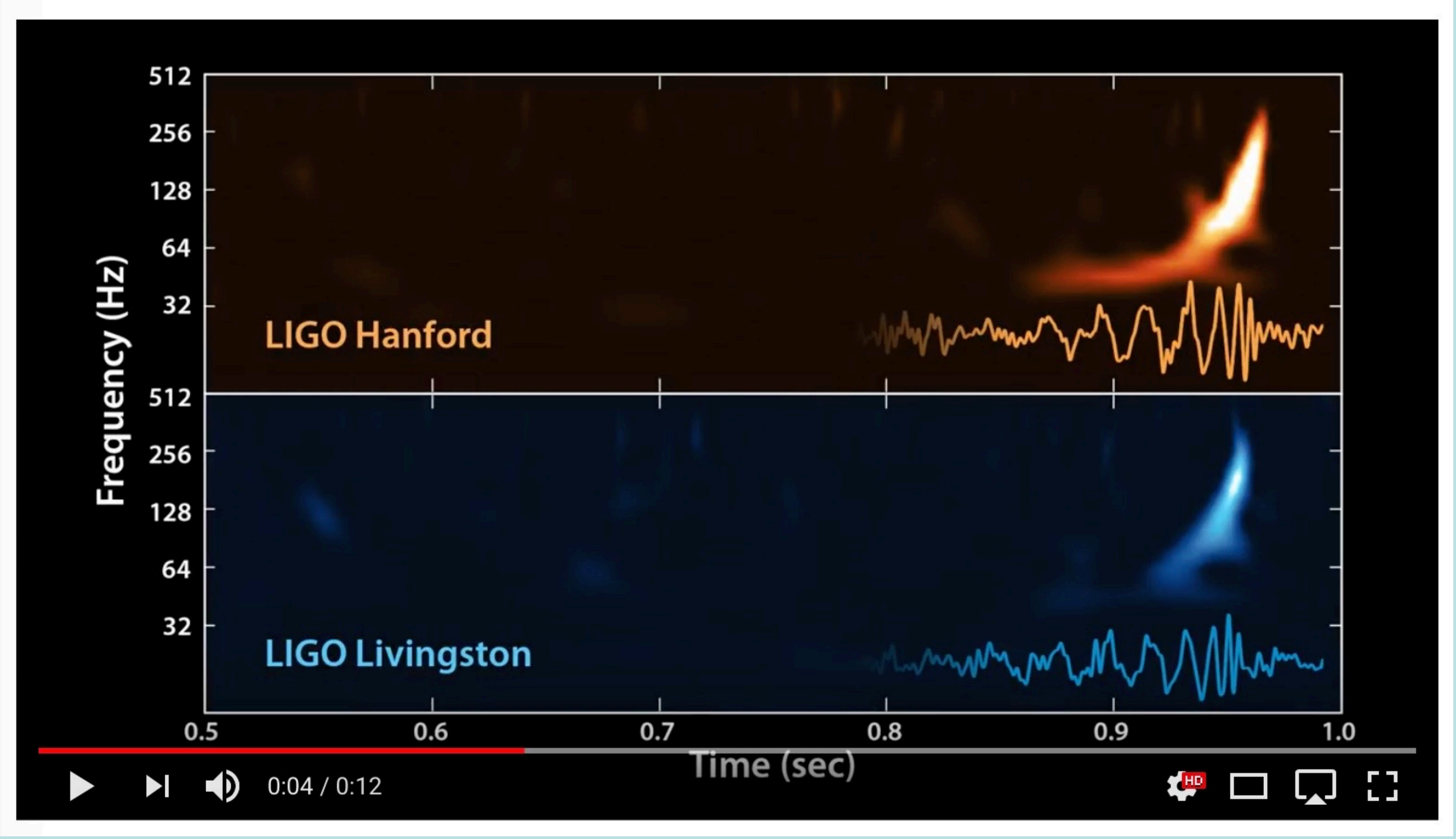
Hanford, Washington (H1)
Livingston, Louisiana (L1)
$\frac{\Delta L}{L}$
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Time (s)
Normalized amplitude
1.0
0.5
0.0
-0.5
-1.0
512
256
128
64
32
0.30
0.35
0.40
0.45
0
2
4
6
8


LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10^-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

LIGO

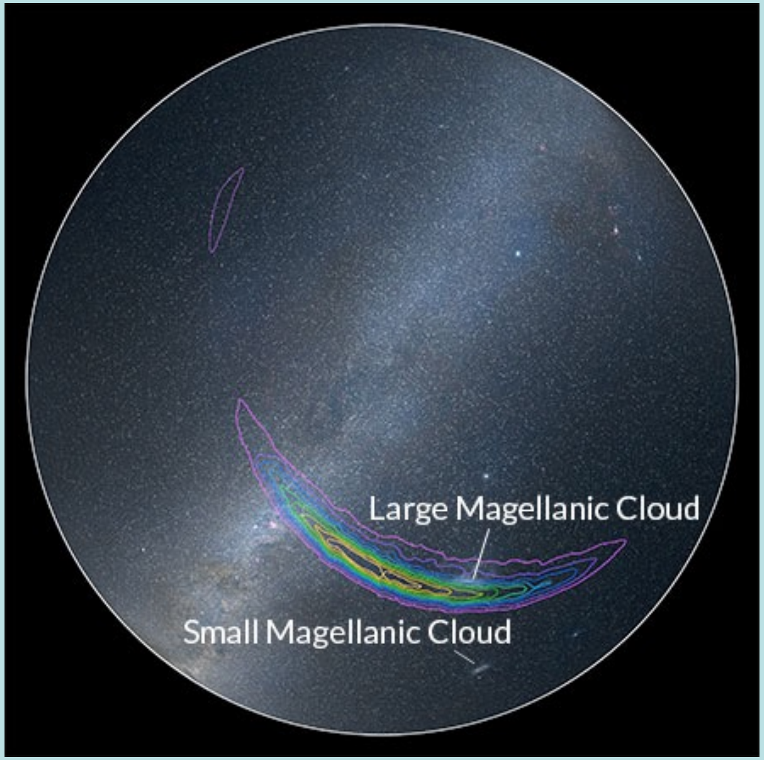


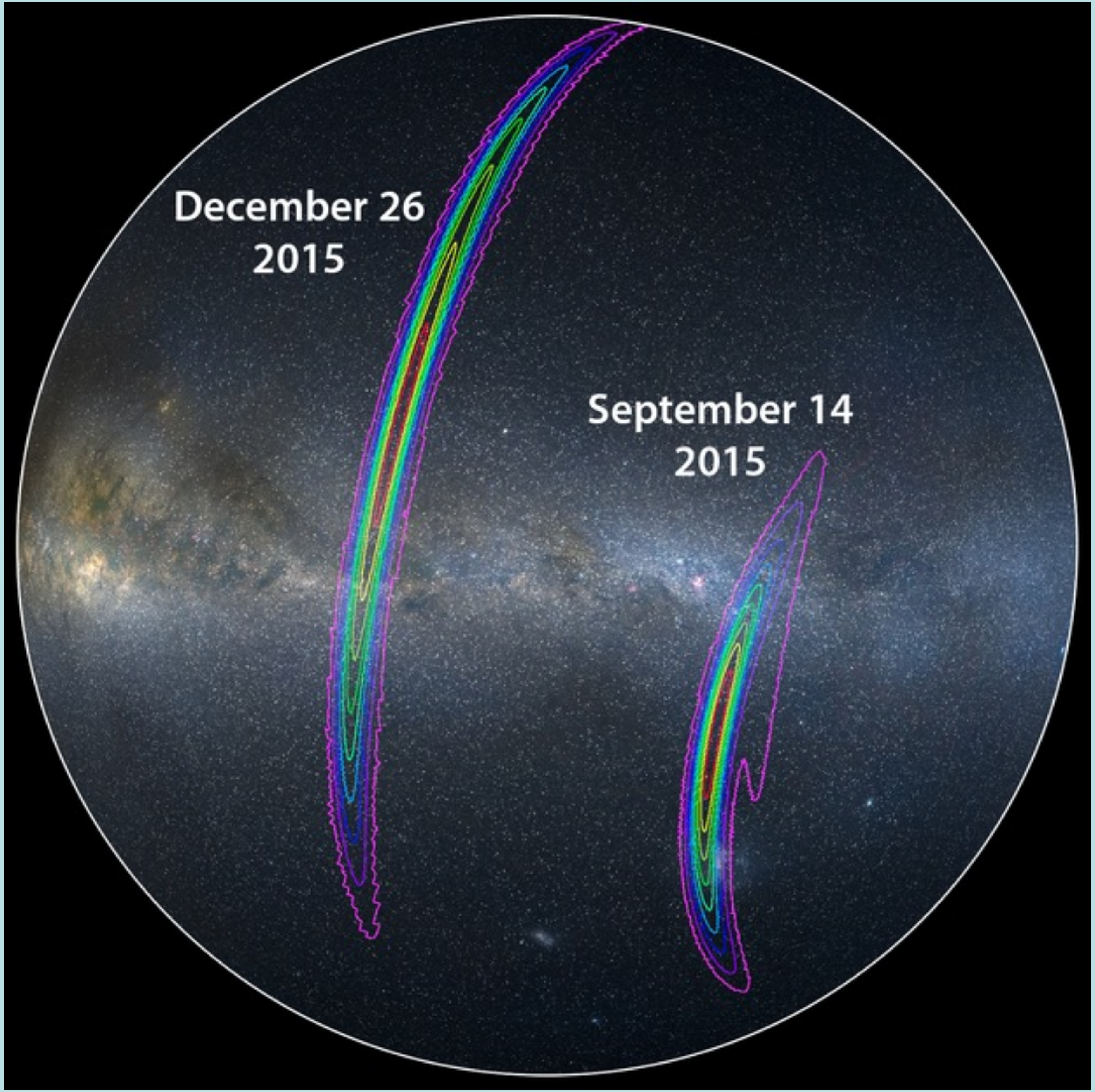
These plots show the strain in the detector, which indicates that a gravitational wave from colliding black holes was detected by LIGO on January 4th, 2017.



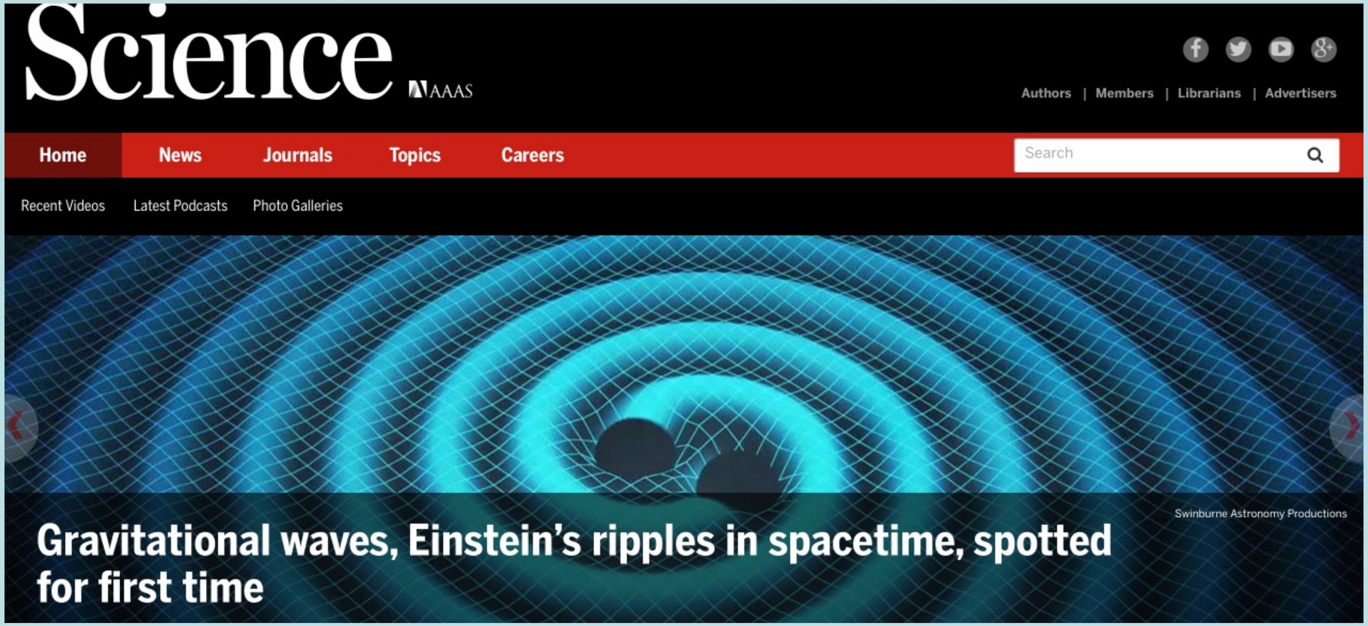
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)
0:04 / 0:12
HD

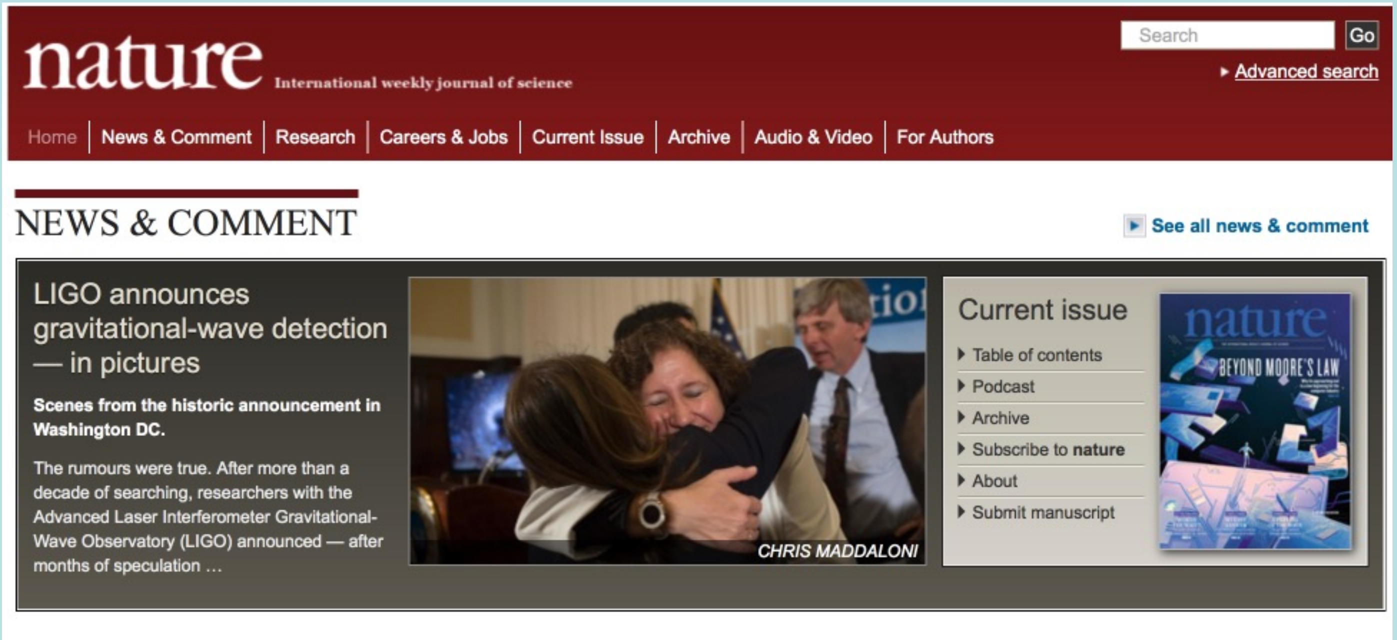
撞擊的位置與距離可以大致知道！



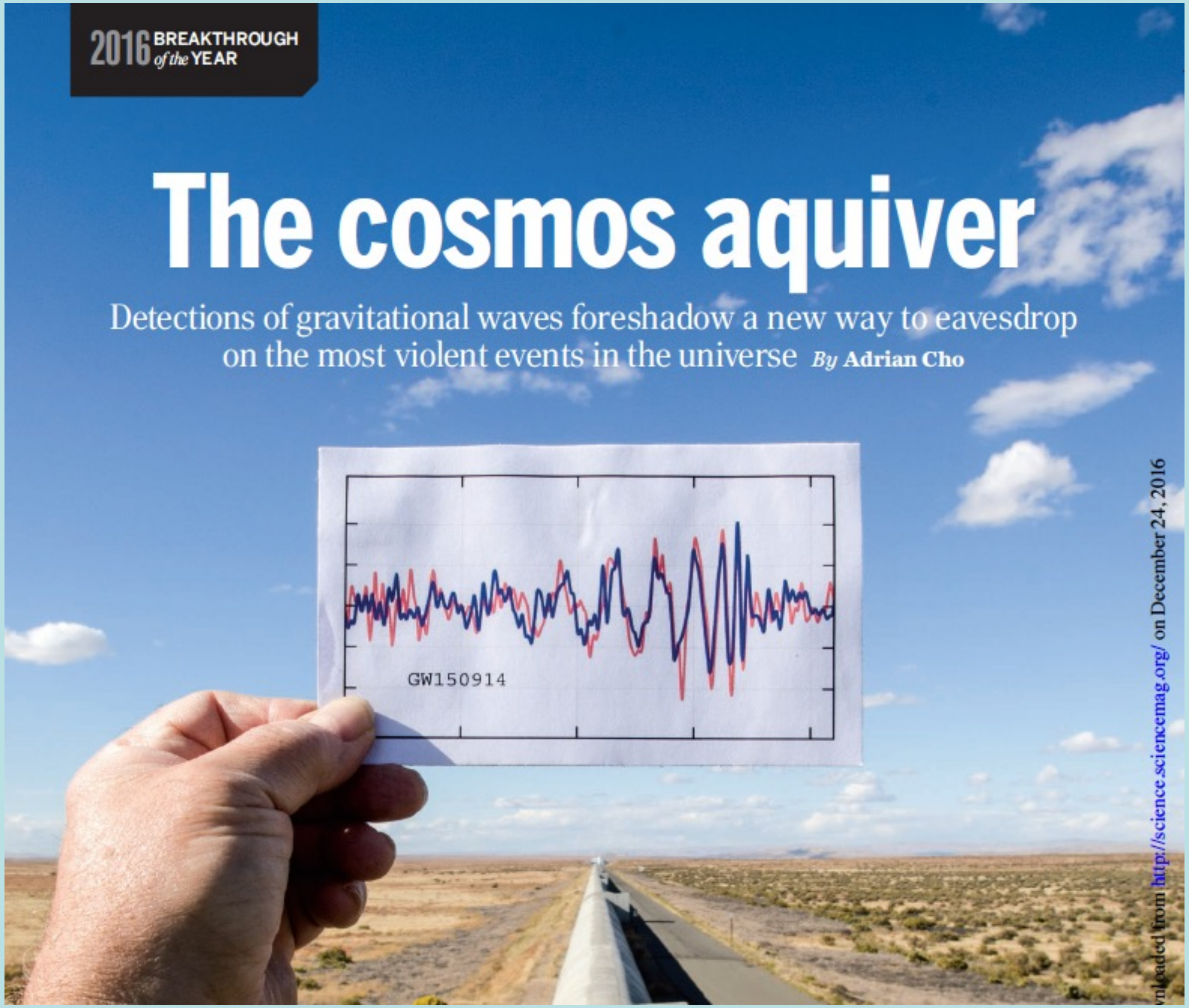

December 26
2015
September 14
2015

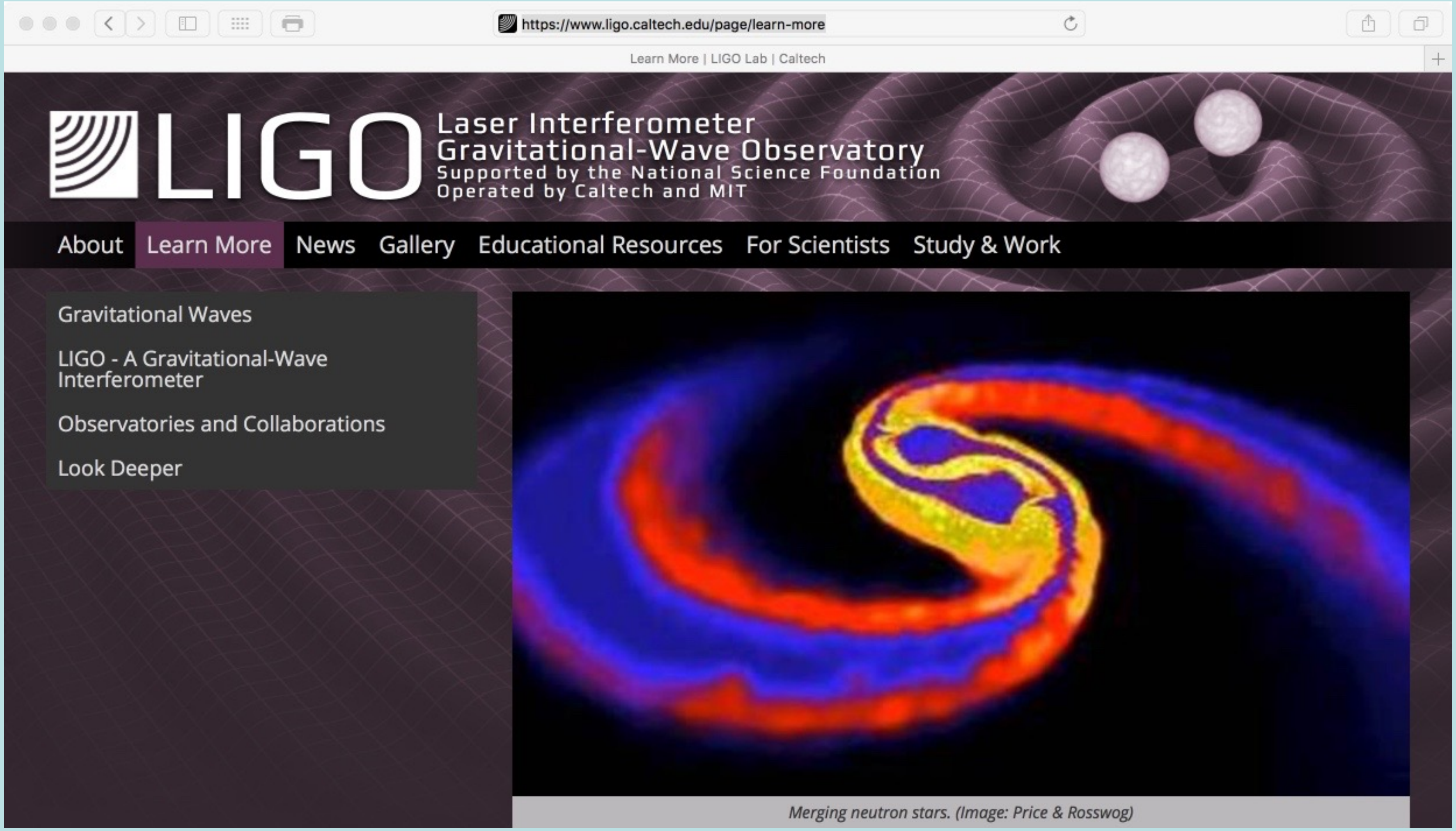
LIGO co-founder Kip Thorne (R), speaks alongside LIGO co-founder Rainer Weiss (2nd R), Gabriela Gonzalez, LIGO spokesperson (2nd L) and David Reitze (L), executive director of LIGO, as they announce that scientists have observed the ripples in the fabric of spacetime called gravitational waves for the first time, confirming a prediction of Albert Einstein's theory of relativity, during a press conference at the National Press Club in Washington, DC, February 11, 2016.


Science
AAAS
Authors | Members | Librarians | Advertisers
Home
News
Journals
Topics
Careers
Search
Recent Videos
Latest Podcasts
Photo Galleries
Swinburne Astronomy Productions
Gravitational waves, Einstein's ripples in spacetime, spotted for first time


nature
International weekly journal of science
Search
Go
Advanced search
Home
News & Comment
Research
Careers & Jobs
Current Issue
Archive
Audio & Video
For Authors
NEWS & COMMENT
See all news & comment
LIGO announces gravitational-wave detection — in pictures
Scenes from the historic announcement in Washington DC.
The rumours were true. After more than a decade of searching, researchers with the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) announced — after months of speculation …
CHRIS MADDALONI
Current issue
Table of contents
Podcast
Archive
Subscribe to nature
About
Submit manuscript
nature
BEYOND MOORE'S LAW


Watching bacteriorhodopsin pump protons p. 1552
Boron nitride paves a path to propylene p. 1570
Trillions of insects migrate over our heads p. 1584
Science
$15
23 DECEMBER 2016
sciencemag.org
AAAS
2016
BREAKTHROUGH of the YEAR


2016 BREAKTHROUGH of the YEAR
The cosmos aquiver
Detections of gravitational waves foreshadow a new way to eavesdrop on the most violent events in the universe By Adrian Cho
GW150914
Downloaded from http://science.sciencemag.org/ on December 24, 2016



LIGO Website

PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

$$36 + 29 - 62 = 3.0$$

3.0個太陽的能量，在最後的0.2s內，被以重力波釋放，這是太陽亮度的10^{22}倍。

幾乎是整個宇宙發光的總亮度（每秒通過單位面積的能量）。

這樣的亮度即使在約13億光年遠的地球，幾乎就是滿月的亮度。

但重力太弱了，這樣能量造成的長度差比只有約10^{-21}。

對4km的LIGO，只有0.1%個質子的半徑！

GW150914: FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds. Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

緊接著有三次重力波訊號

Working in concert with the two LIGO detectors, the Virgo detector (above) can pinpoint the sources of gravitational waves on the sky.

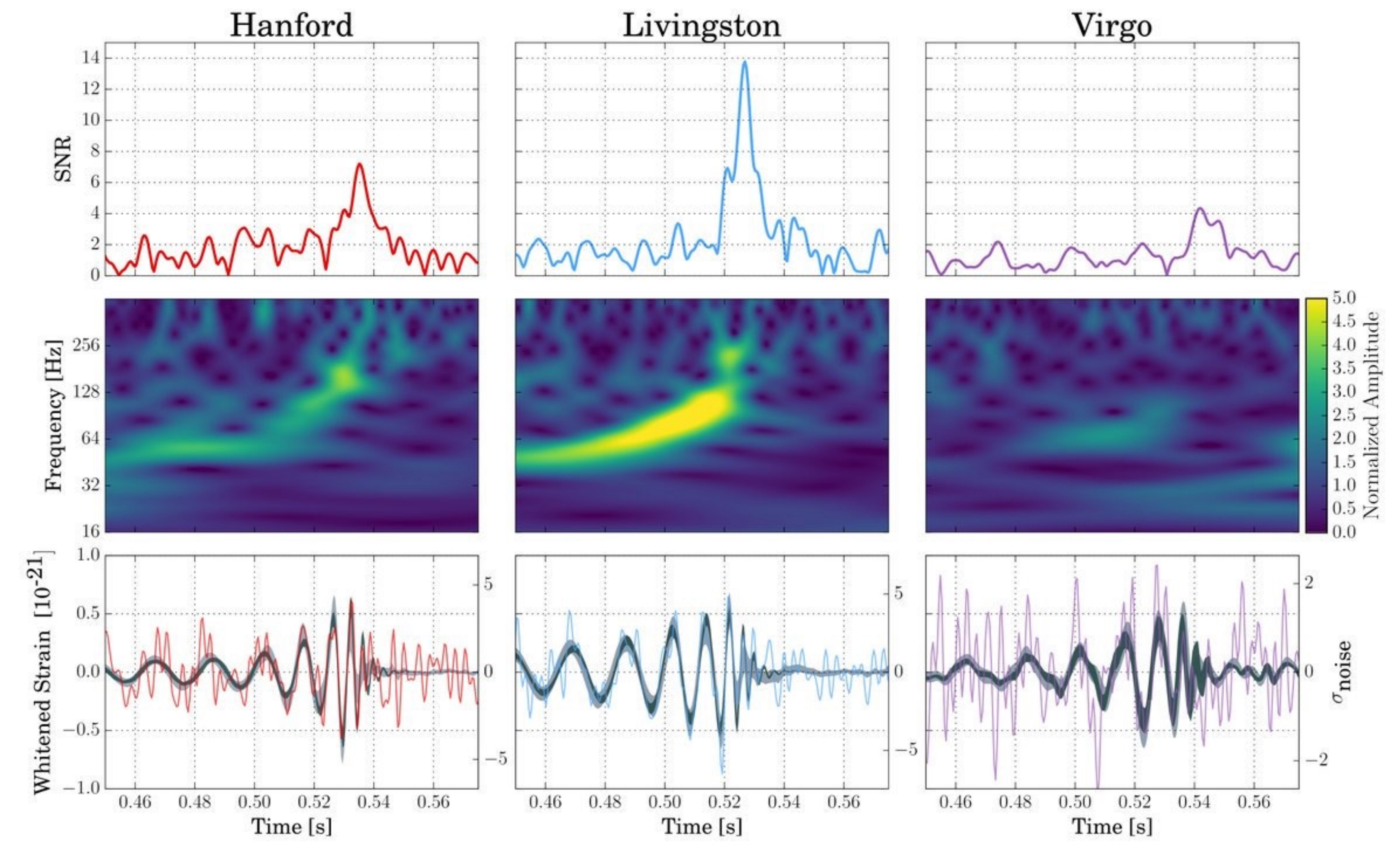
N. Baldocchi/The Virgo Collaboration

Trio of detectors homes in on black hole sources of gravitational waves

By **Adrian Cho** | Sep. 27, 2017 , 12:30 PM

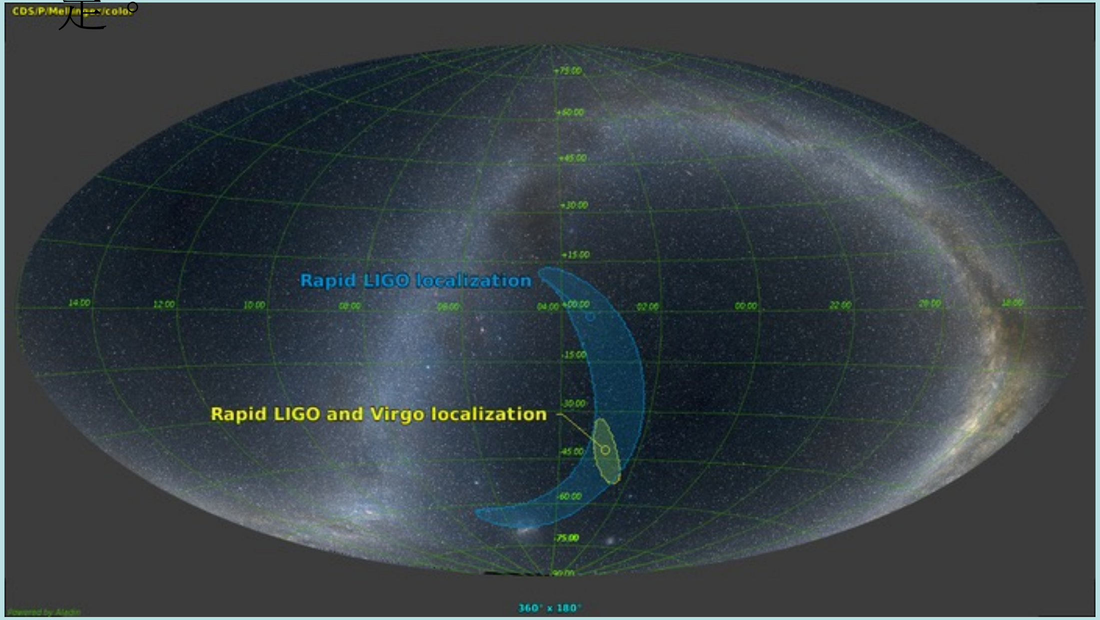
現在LIGO的觀測由獨立的Virgo所驗證！三組探測器同時測得重力波。

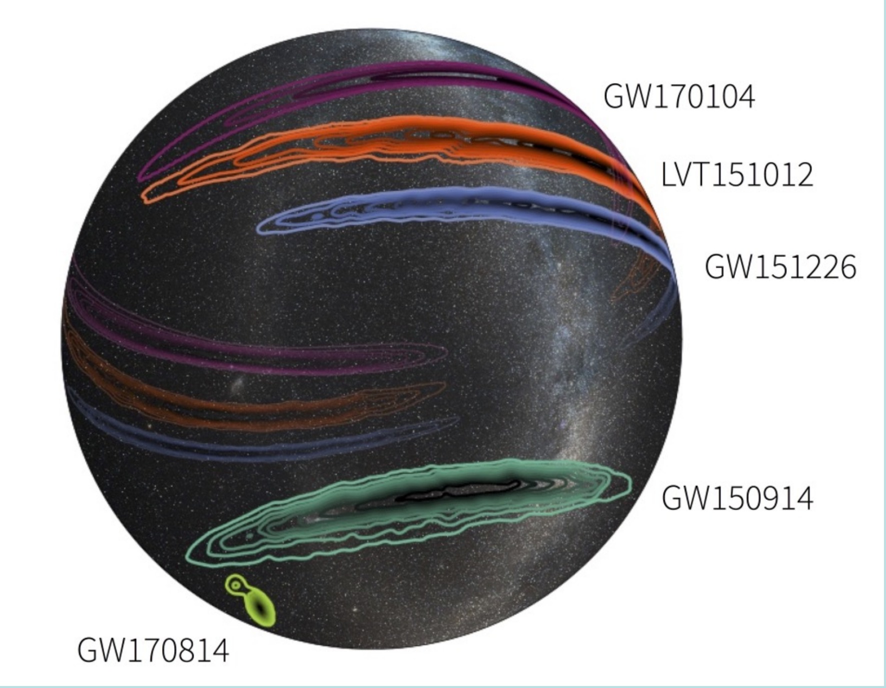
義大利 Virgo



Hanford
Livingston
Virgo
SNR
Frequency [Hz]
Normalized Amplitude
Whitened Strain [10^-21]
σ noise
Time [s]

有三個探測點，黑洞位置可以更精確標定。





The Nobel Prize in Physics 2017
Rainer Weiss, Barry C. Barish, Kip S. Thorne

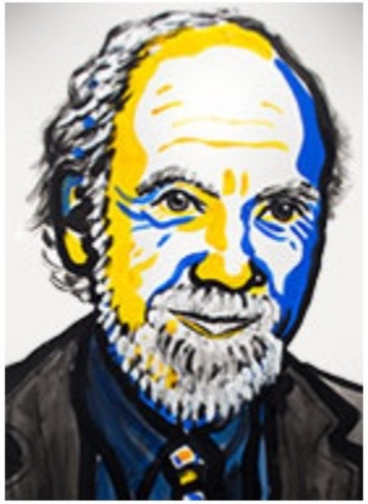
Share this: 929

The Nobel Prize in Physics 2017

© Nobel Media. Ill. N. Elmehed

Rainer Weiss

Prize share: 1/2



© Nobel Media. Ill. N. Elmehed

Barry C. Barish

Prize share: 1/4

© Nobel Media. Ill. N. Elmehed

Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

The Nobel Prize in Physics 2017
Rainer Weiss, Barry C. Barish, Kip S. Thorne

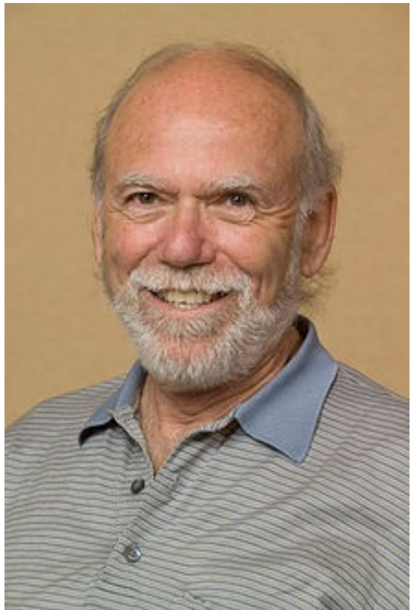
Share this: 929

The Nobel Prize in Physics 2017


© Nobel Media. Ill. N. Elmehed

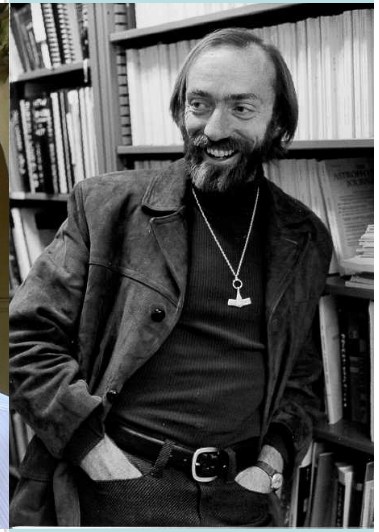
Rainer Weiss

Prize share: 1/2


© Nobel Media. Ill. N. Elmehed

Barry C. Barish

Prize share: 1/4



© Nobel Media. Ill. N. Elmehed

Kip S. Thorne

Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

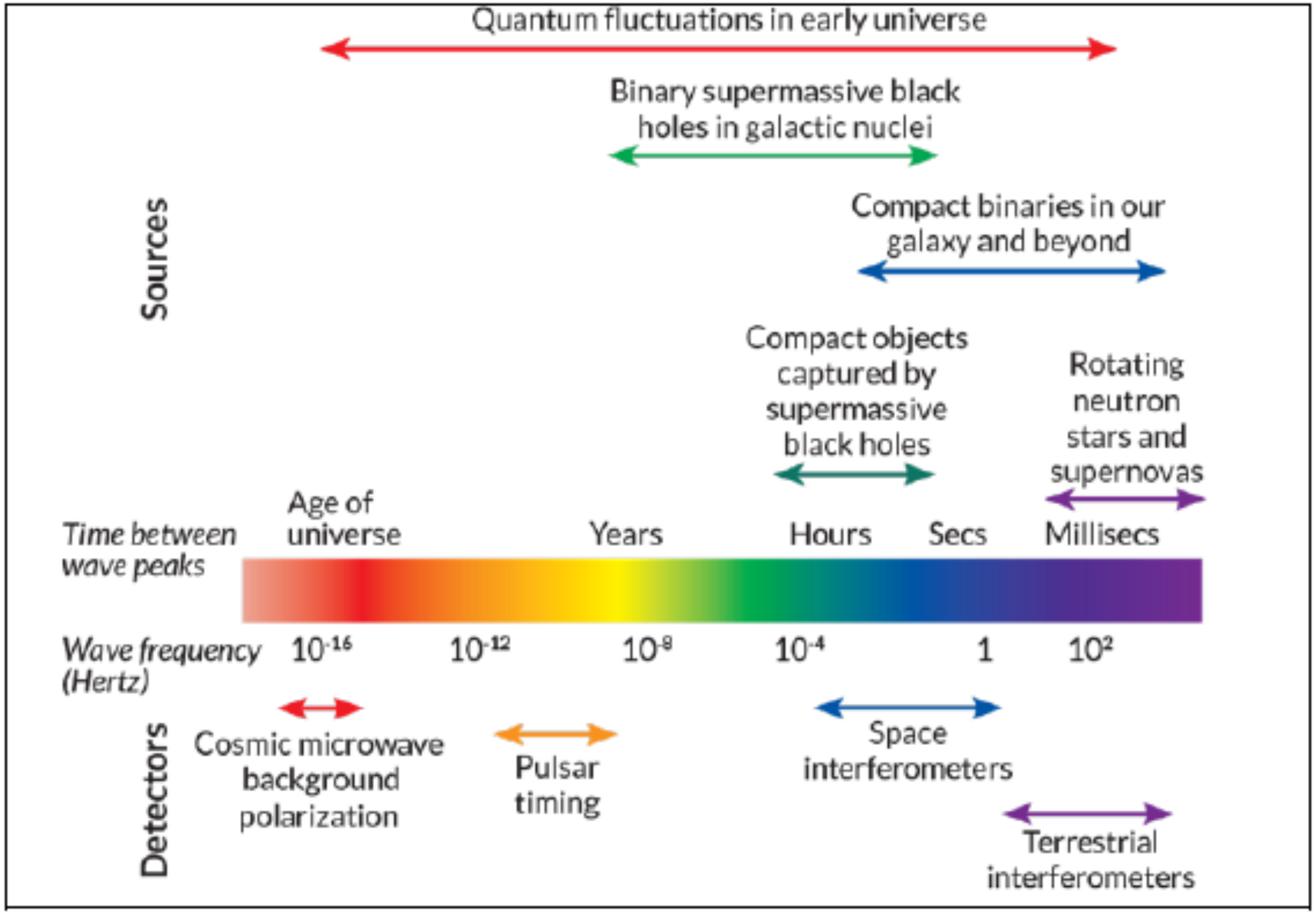
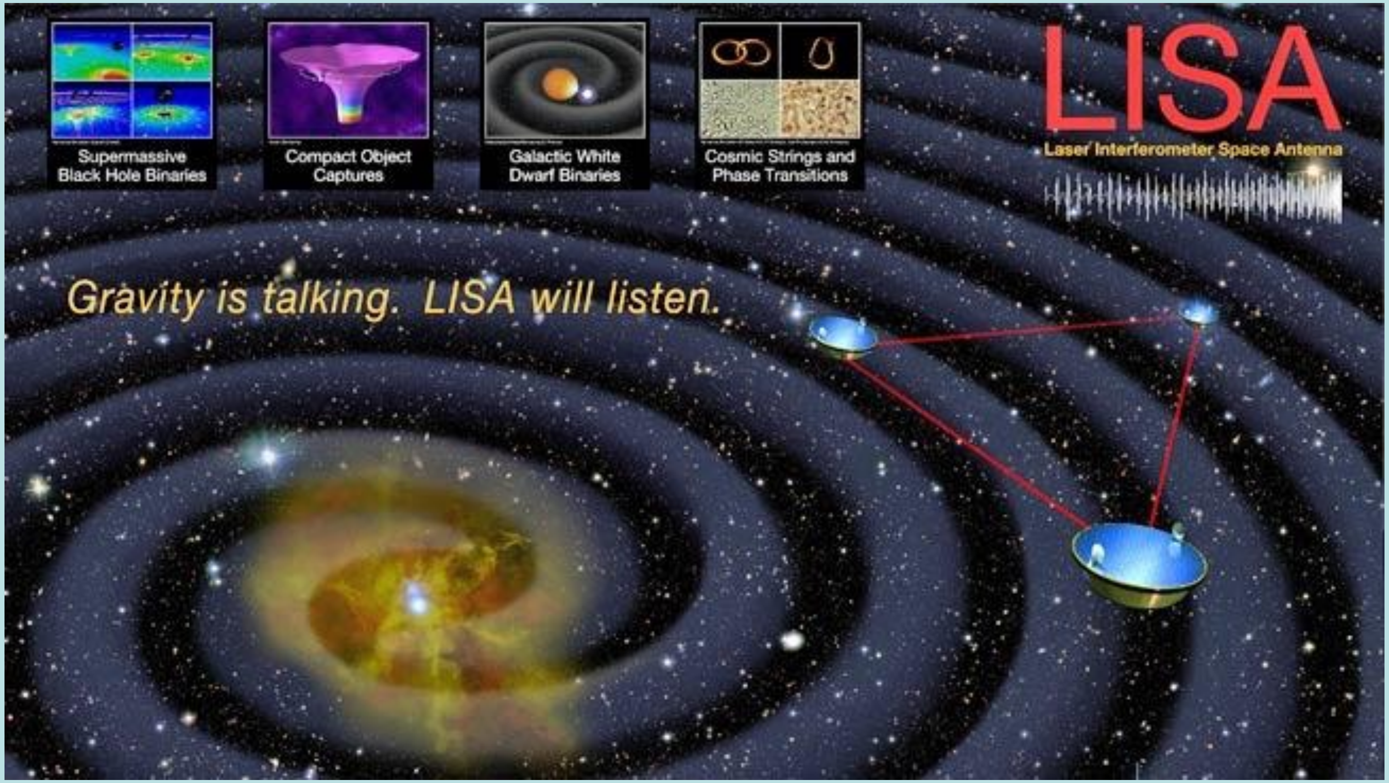
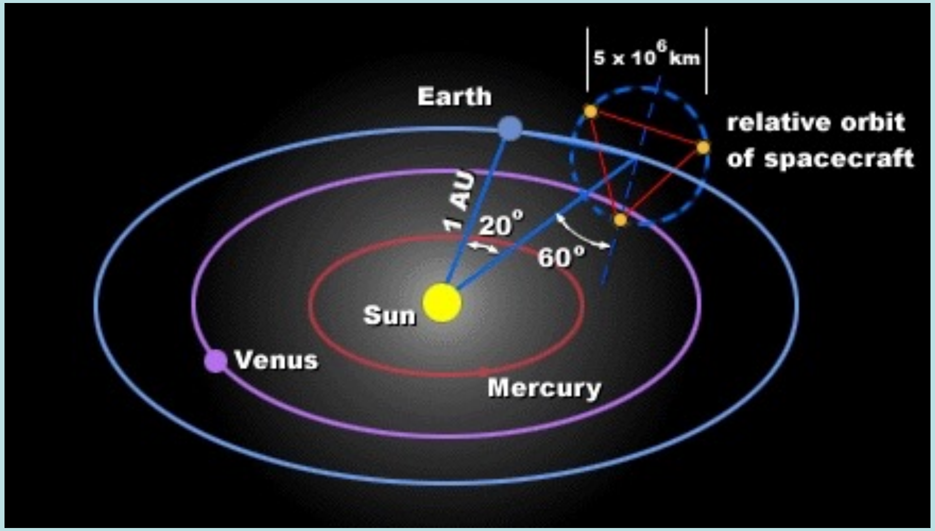


Figure 1: Gravitational-wave spectrum (credit: NASA)


Supermassive Black Hole Binaries
Compact Object Captures
Galactic White Dwarf Binaries
Cosmic Strings and Phase Transitions
LISA
Laser Interferometer Space Antenna
Gravity is talking. LISA will listen.


5 x 10^6 km
Earth
relative orbit of spacecraft
1 AU
20°
60°
Sun
Venus
Mercury

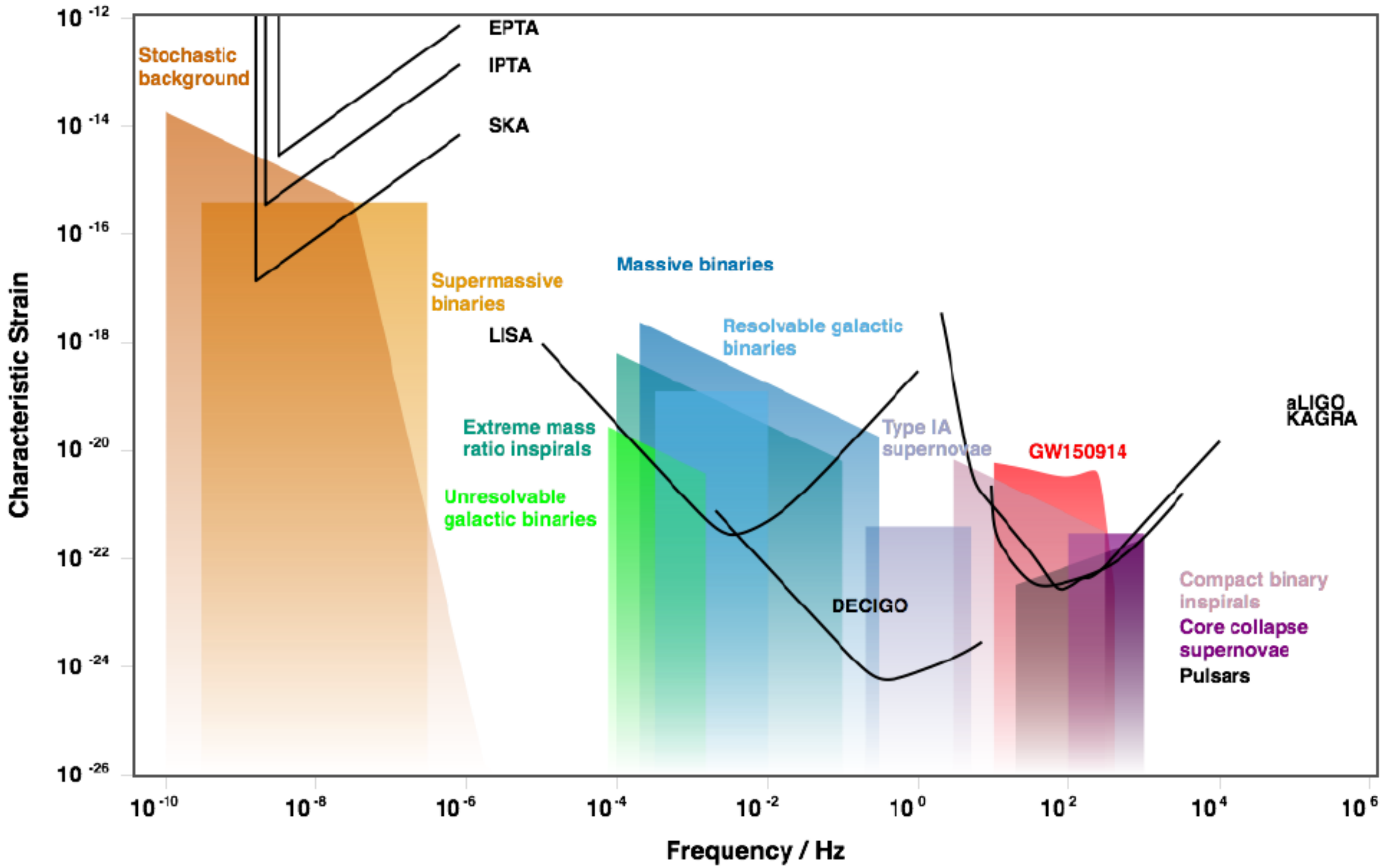
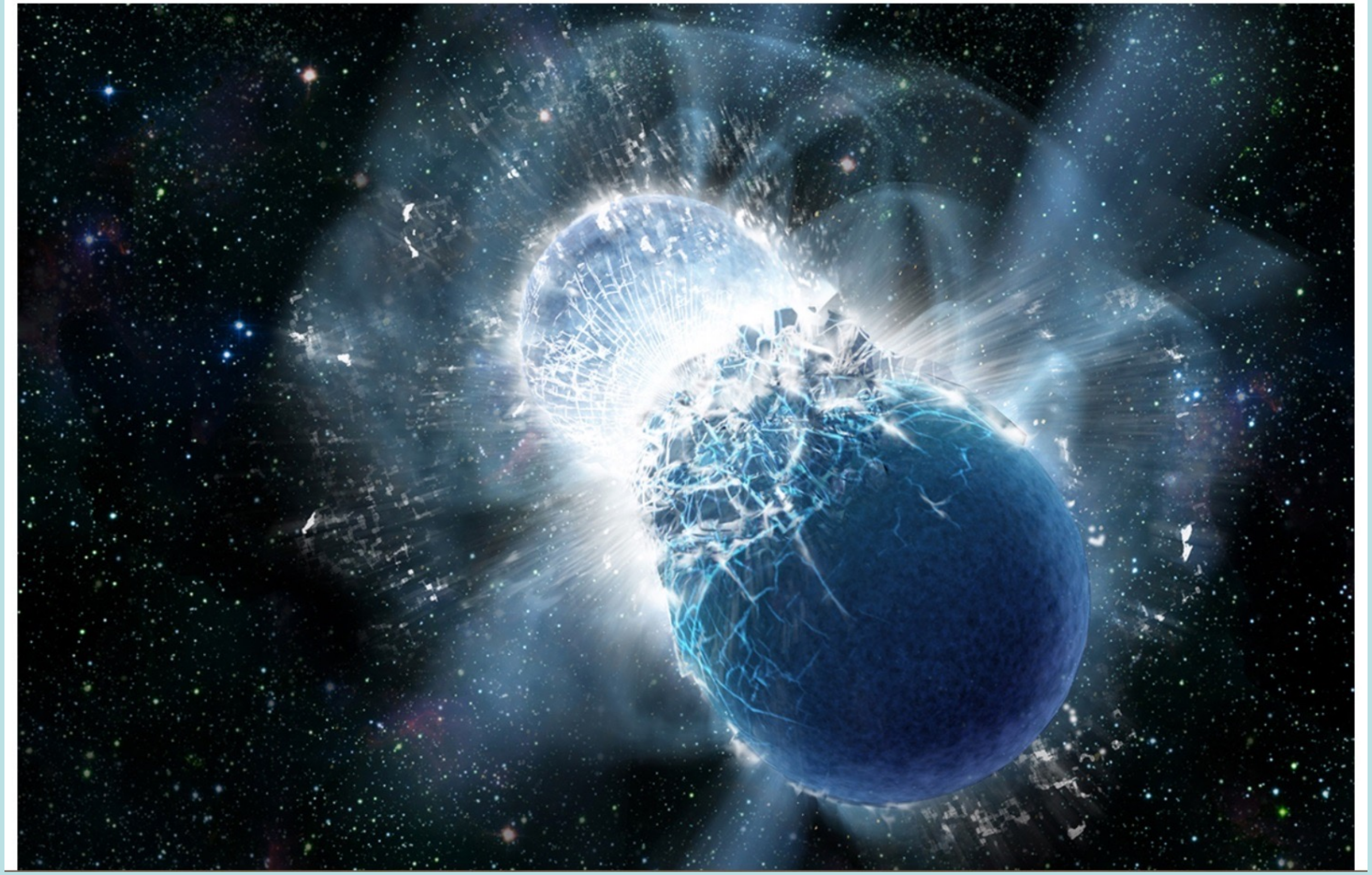


Figure 6: The expected performance of future detectors in terms of strain and frequency [35].

2017年一次嶄新的天體撞擊重力波訊號，開啟了新的時代！

DAILY NEWS 23 August 2017, updated 23 August 2017

Exclusive: We may have detected a new kind of gravitational wave



By **Mika McKinnon**

Have we detected a new flavour of gravitational wave? Speculation is swelling that researchers have spotted the subtle warping of the fabric of space resulting from the cataclysmic collision of two neutron stars.

Now optical telescopes – including the Hubble Space Telescope – are scrambling to point at the source of the possible wave: an elliptical galaxy hundreds of millions of light years away.

Gravitational waves are markers of the most violent events in our universe, generated when dense objects such as black holes or neutron stars crash together with tremendous energy. Two experiments – LIGO in the US and VIRGO in Europe – set out to detect minuscule changes in the path of laser beams caused by passing gravitational waves.

Read more: Gravitational waves – Your cheat sheet on the find of the decade

LIGO has discovered three gravitational wave sources to date, all of them colliding black holes. The two observatories have been coordinating data collection since November, increasing their sensitivity. That collaboration may be about to pay off.

Neutron stars

Over the weekend, astronomer J. Craig Wheeler of the University of Texas at Austin launched speculation over a potential new LIGO detection by tweeting: "New LIGO. Source with optical counterpart. Blow your sox off!"

By optical counterpart, he probably means that astronomers could observe light emitted by the gravitational wave source. This suggests the source is neutron stars as, unlike black holes, they can be seen in visible wavelengths. LIGO researchers have long-anticipated this possibility, setting up partnerships with optical observatories to rapidly follow-up on potential signals prior to formally announcing a discovery.

LIGO spokesperson David Shoemaker dodged confirming or denying the rumours, saying only "A very exciting O2 Observing run is drawing to a close August 25. We look forward to posting a top-level update at that time."

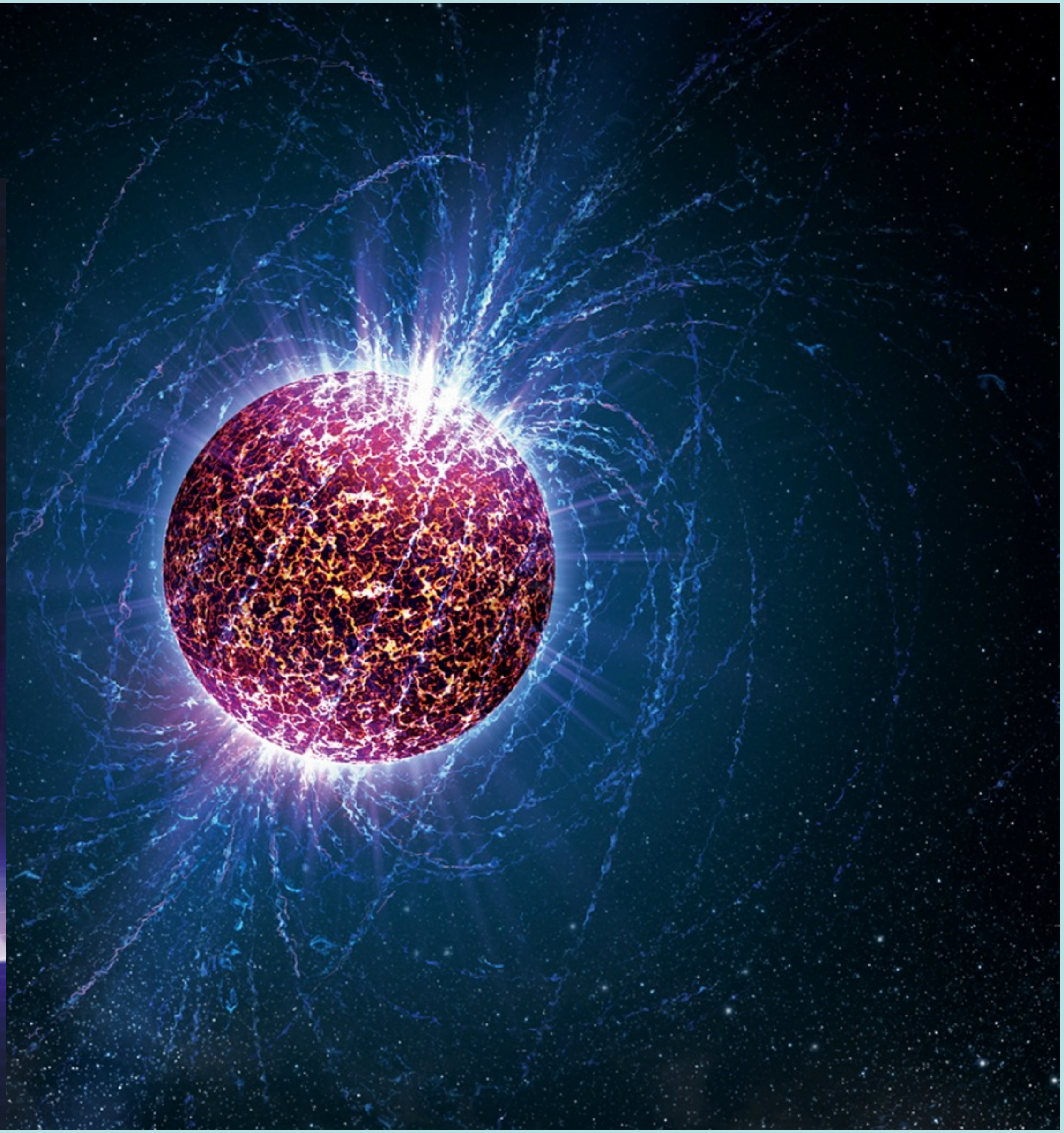

LIGO
Laser Interferometer
Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT
About
Learn More
News
Gallery
Educational Resources
For Scientists
Study & Work
1 2 3 4 5 6
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars
Press release • October 16, 2017
For the first time, scientists have directly detected gravitational waves — ripples in space and time — in addition to light from the spectacular collision of two neutron stars. This marks the first time that a cosmic event has been viewed in both gravitational waves and light.

LIGO Detects Fierce Collision of Neutron Stars for the First Time

By **DENNIS OVERBYE** OCT. 16, 2017

[NYT article](#) [NYT Video](#)

Neutron Star



中子星 [編輯]

維基百科，自由的百科全書
（已重新導向自 Neutron star）

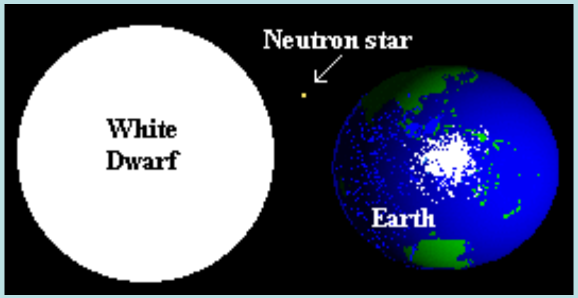
中子星（英語：neutron star），是恆星演化到末期，經由重力坍縮發生超新星爆炸之後，可能成為的少數終點之一。恆星在核心的氫、氦、碳等元素於核融合反應中耗盡，當它們最終轉變成鐵元素時便無法從核融合中獲得能量。失去熱輻射壓力支撐的外圍物質受重力牽引會急速向核心墜落，有可能導致外殼的動能轉化為熱能向外爆發產生超新星爆炸，或者根據恆星質量的不同，恆星的內部區域被壓縮成白矮星、中子星或黑洞。白矮星被壓縮成中子星的過程中恆星遭受劇烈的壓縮使其組成物質中的電子併入質子轉化成中子，直徑大約只有十餘公里，但上面一立方厘米的物質便可重達十億噸，且旋轉速度極快。由於其磁軸和自轉軸並不重合，磁場旋轉時所產生的無線電波等各種輻射可能會以一明一滅的方式傳到地球，有如人眨眼，此時稱作脈衝星。

脈衝星PSR B1509−58的輻射，一個快速旋轉的中子星，使得周邊氣體X射線發光（金色，來自錢德拉）並且照亮星雲的其他部分，這裡以紅外線可見（藍色與紅色，來自WISE）。

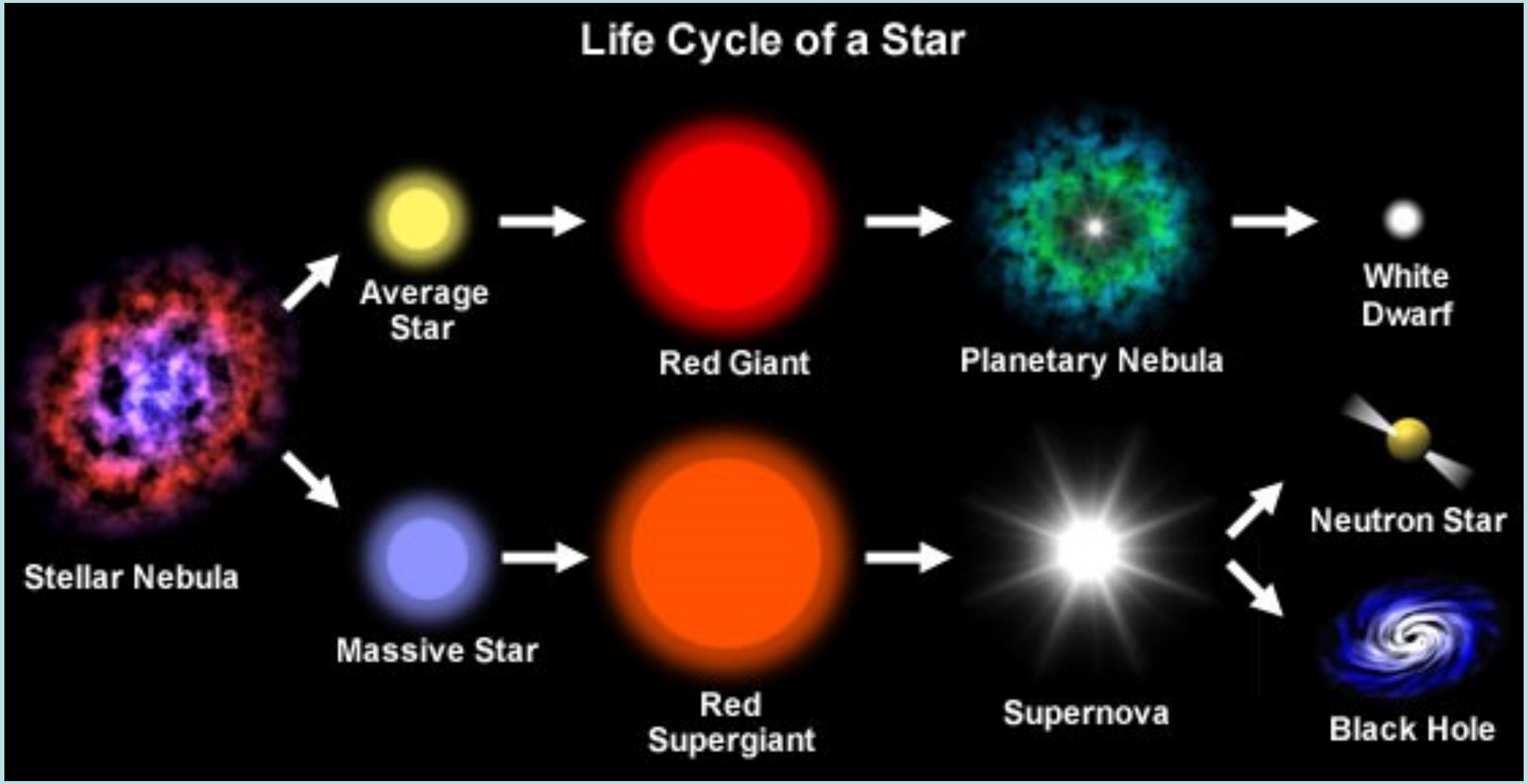
一顆典型的中子星質量介於太陽質量的1.35到2.1倍，半徑則在10至20公里之間（質量越大半徑收縮得越小），也就是太陽半徑的30,000至70,000分之一。因此，中子星的密度在每立方公分8×10^{13}克至2×10^{15}克間，此密度大約是原子核的密度[1]。

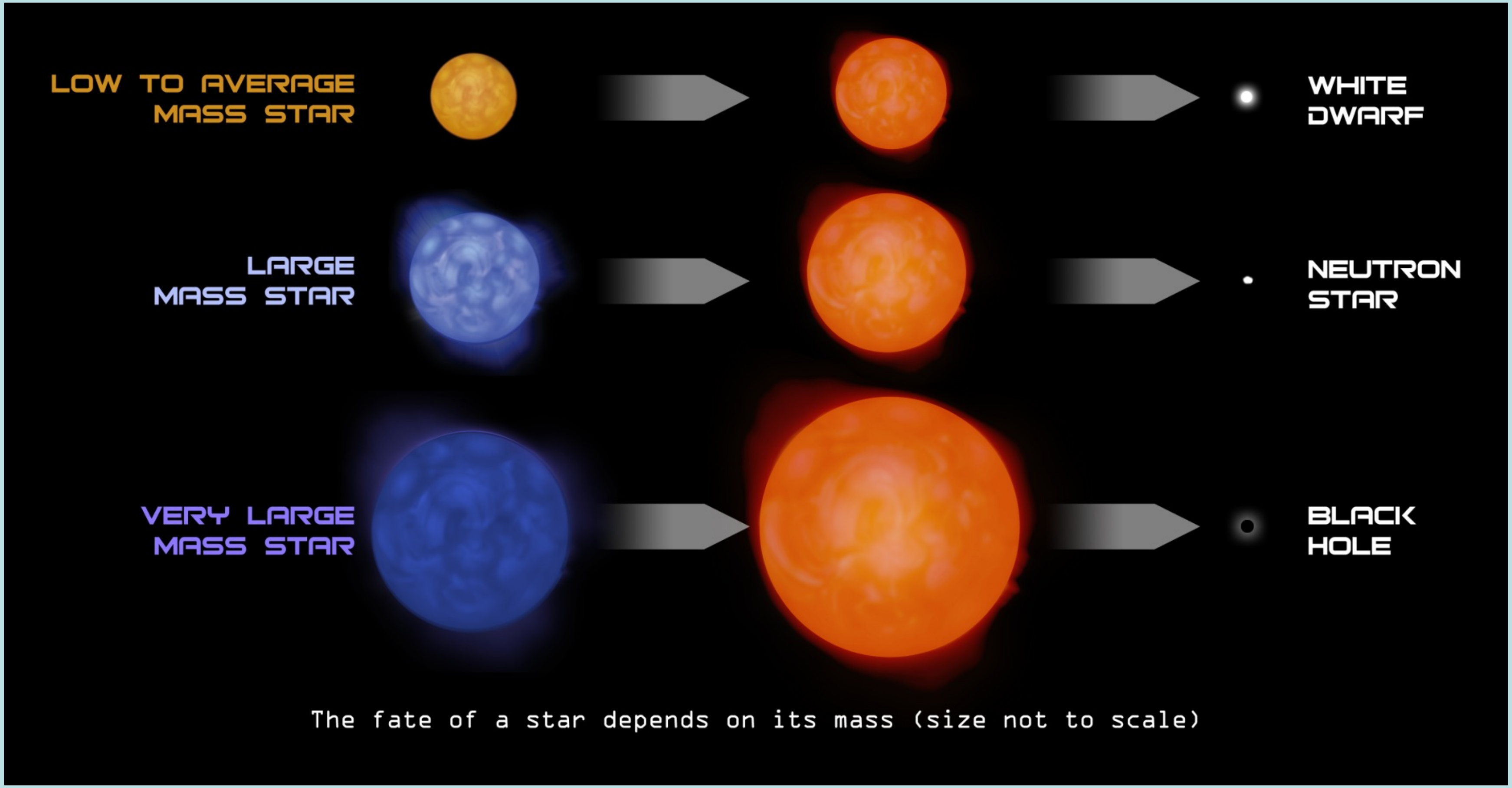
緻密恆星的質量低於1.44倍太陽質量，則可能是白矮星，但質量大於奧本海默–沃爾可夫極限（3.2倍太陽質量）的恆星會繼續發生重力坍縮，則無可避免的將產生黑洞。

由於中子星保留母恆星大部分的角動量，但半徑只是母恆星極微小的量，轉動慣量的減少導致轉速迅速的增加，產生非常高的自轉速率，周期從毫秒脈衝星的700分之一秒到30秒都有。中子星的高密度也使它有強大的表面重力，強度是地球的2×10^{11}到3×10^{12}倍。逃逸速度是將物體由重力場移動至無窮遠的距離所需要的速度，是測量重力的一項指標。一顆中子星的逃逸速度大約在10,000至150,000公里／秒之間，也就是可以達到光速的一半。換言之，物體落至中子星表面的速度也將達到150,000公里／秒。更具體的說明，如果一個普通體重（70公斤）的人遇到中子星，他撞擊到中子星表面的能量將相當於二億噸TNT當量的威力（四倍於全球最巨大的核彈大沙皇的威力）[2]。

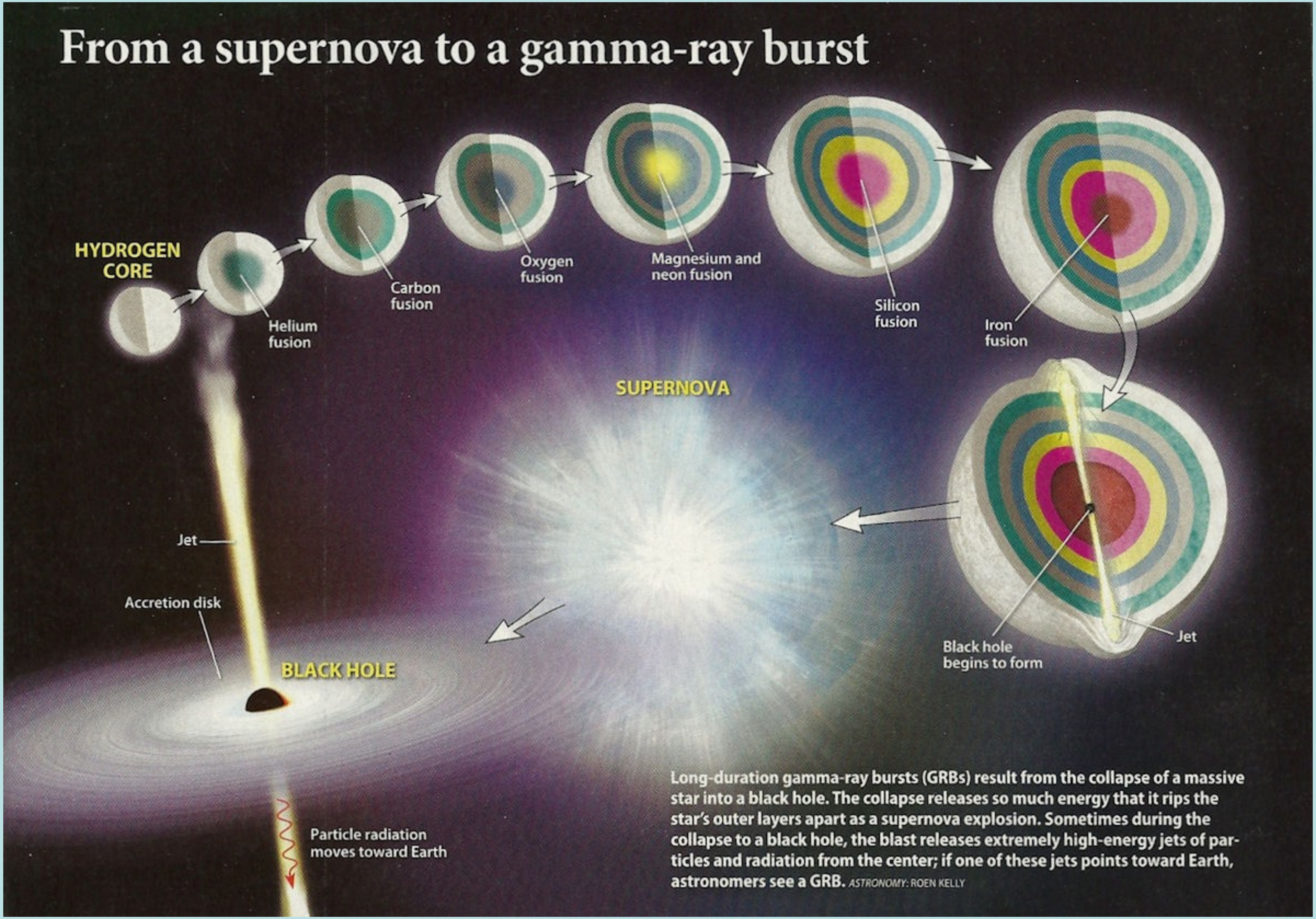

Neutron star
White
Dwarf
Earth

中子星是星球演化的可能終點之一！

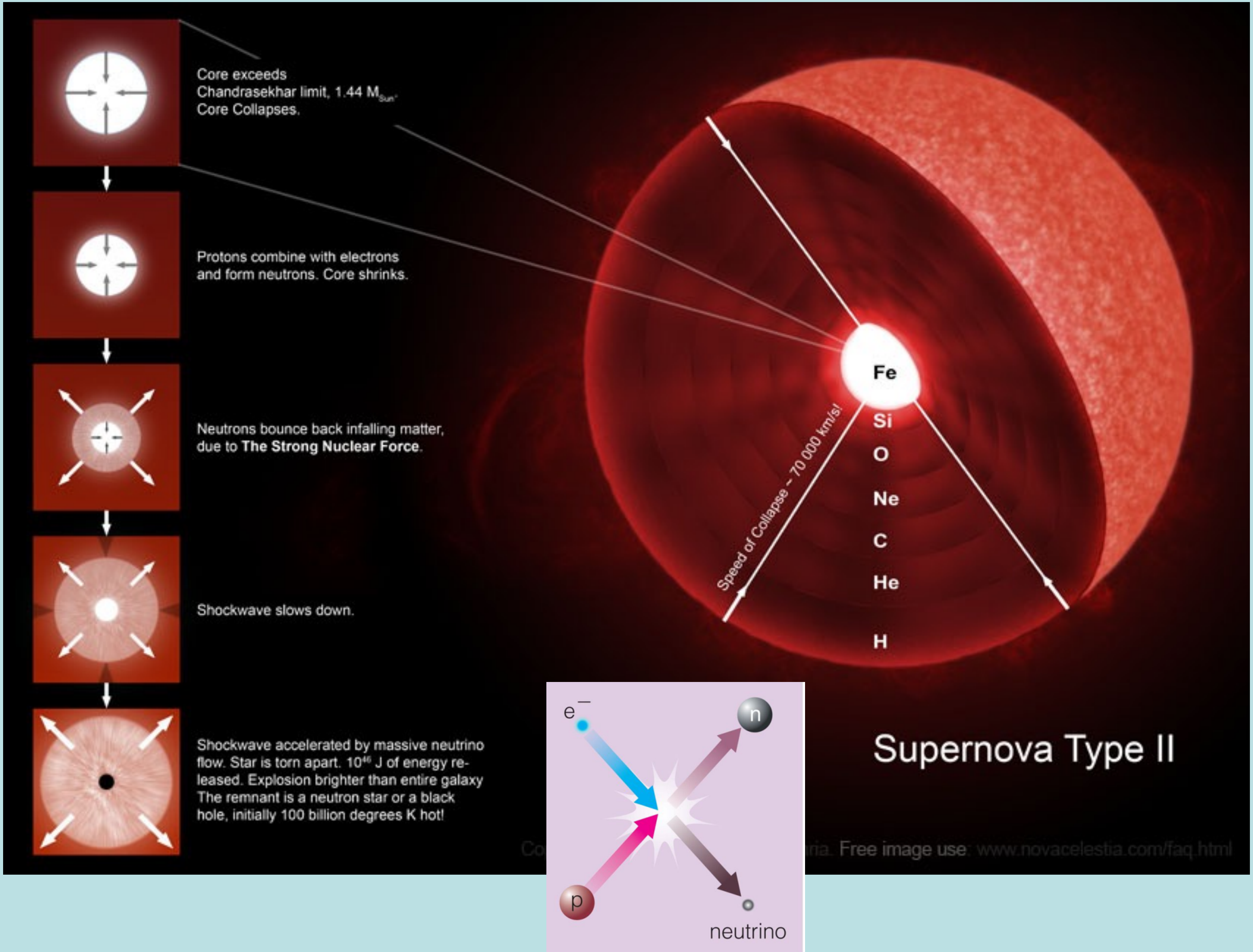




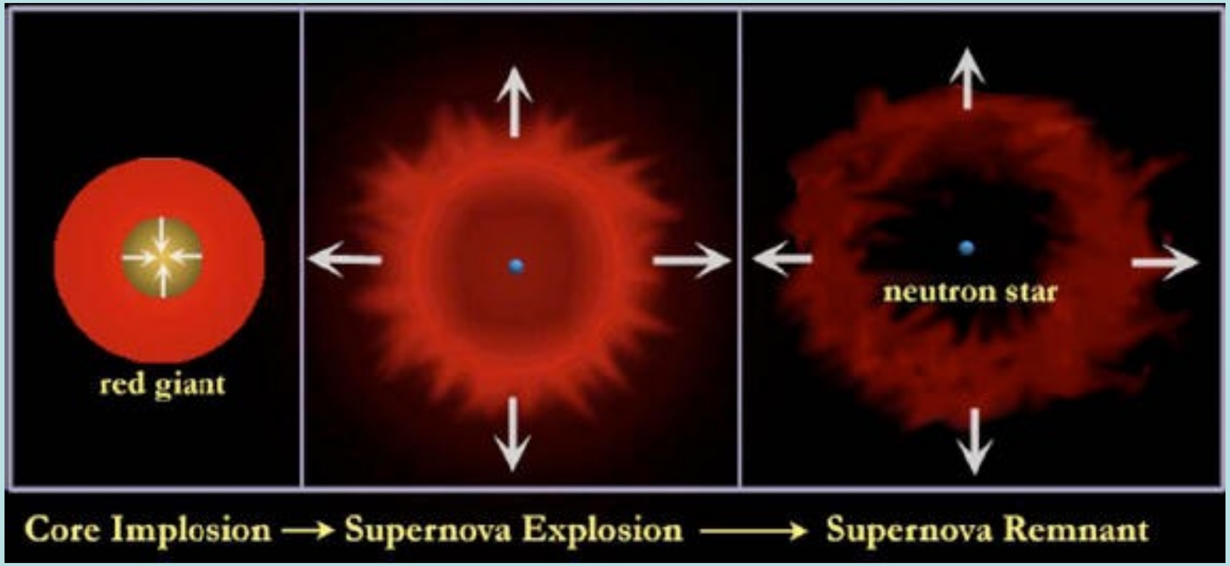
核融合燃燒產生的能量支撐引力使星球不崩潰！　　燃料耗盡，就得有其他支撐。



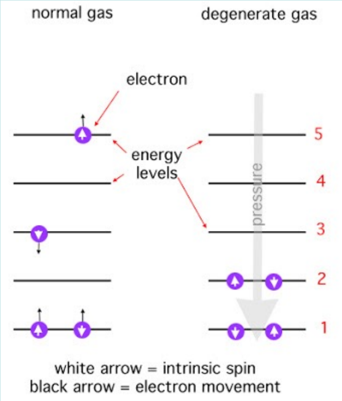
Long-duration gamma-ray bursts (GRBs) result from the collapse of a massive star into a black hole. The collapse releases so much energy that it rips the star's outer layers apart as a supernova explosion. Sometimes during the collapse to a black hole, the blast releases extremely high-energy jets of particles and radiation from the center; if one of these jets points toward Earth, astronomers see a GRB. *ASTRONOMY:* ROEN KELLY


Core exceeds
Chandrasekhar limit, 1.44 M_{Sun}.
Core Collapses.
Protons combine with electrons
and form neutrons. Core shrinks.
Neutrons bounce back infalling matter,
due to **The Strong Nuclear Force**.
Shockwave slows down.
Shockwave accelerated by massive neutrino flow. Star is torn apart. 10^{46} J of energy released. Explosion brighter than entire galaxy The remnant is a neutron star or a black hole, initially 100 billion degrees K hot!
Fe
Si
O
Ne
C
He
H
Speed of Collapse ~ 70 000 km/s!
Supernova Type II
Free image use: www.novacelestia.com/faq.html
e^-
n
p
neutrino

超新星爆炸後的殘餘！


red giant
neutron star
Core Implosion → Supernova Explosion → Supernova Remnant

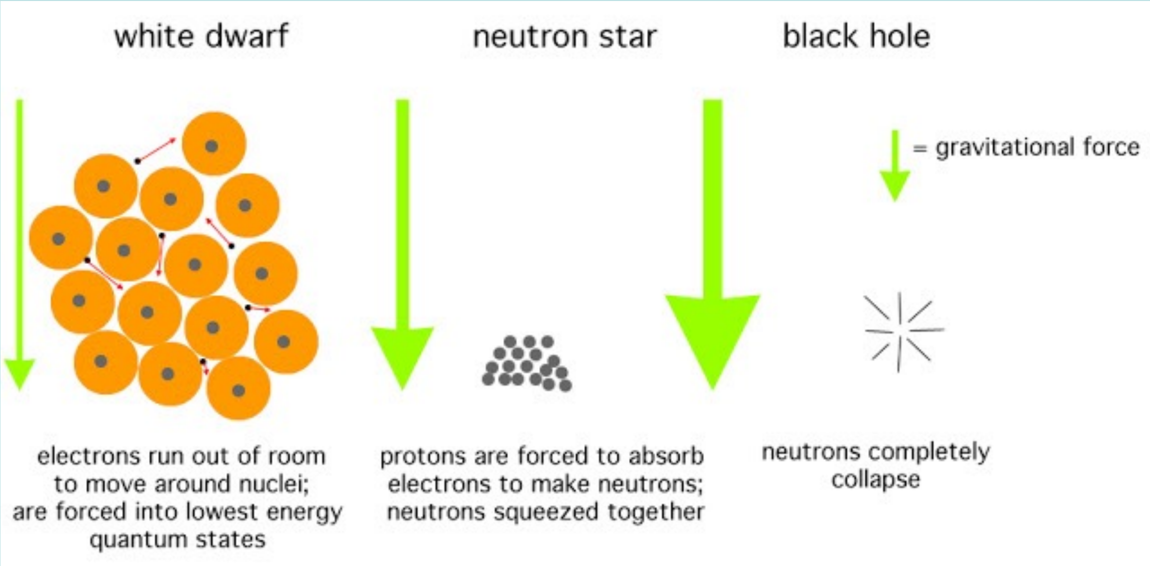
燃料耗盡，就得有其他支撐。

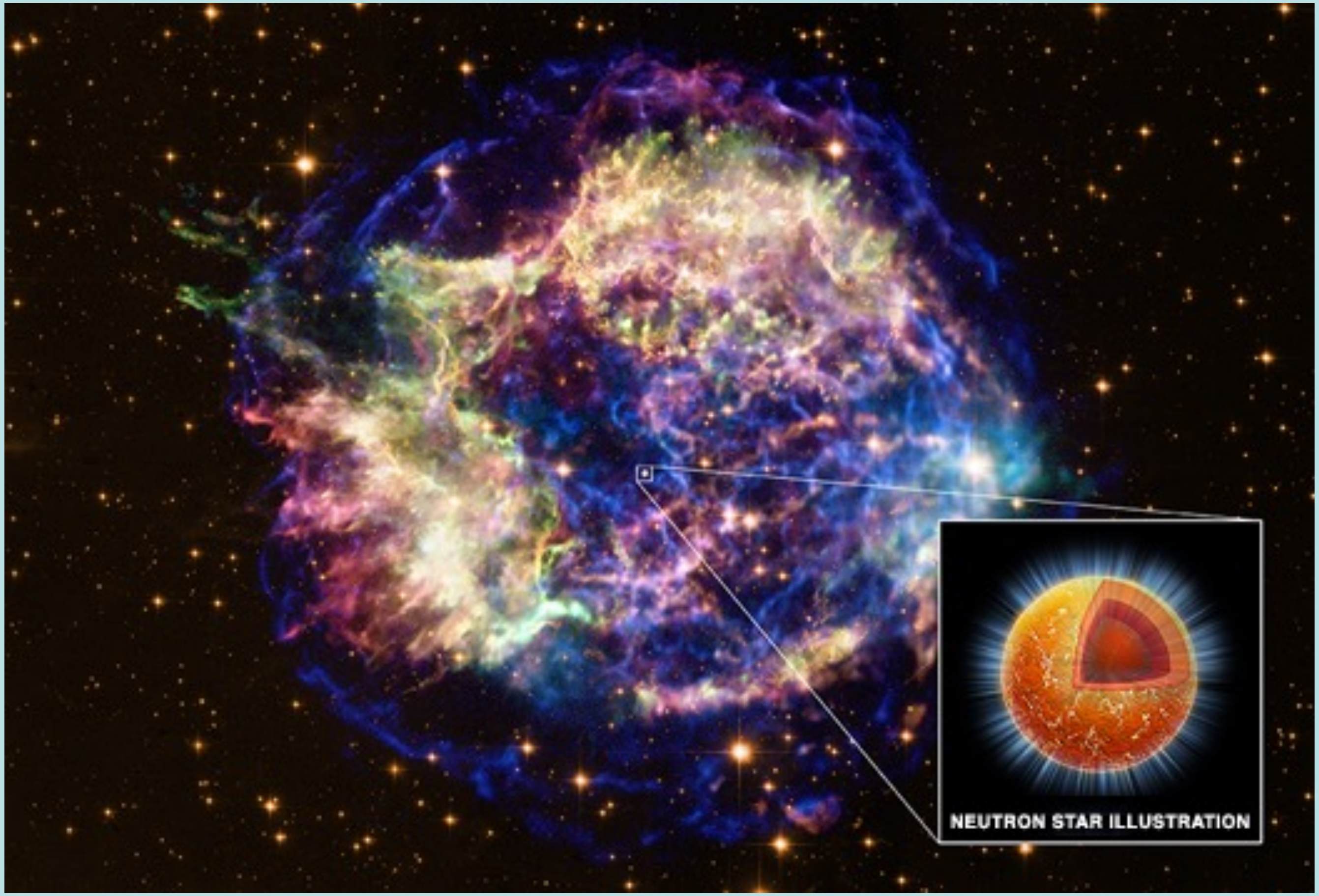


兩顆電子與中子都不能留在一樣的量子態中！

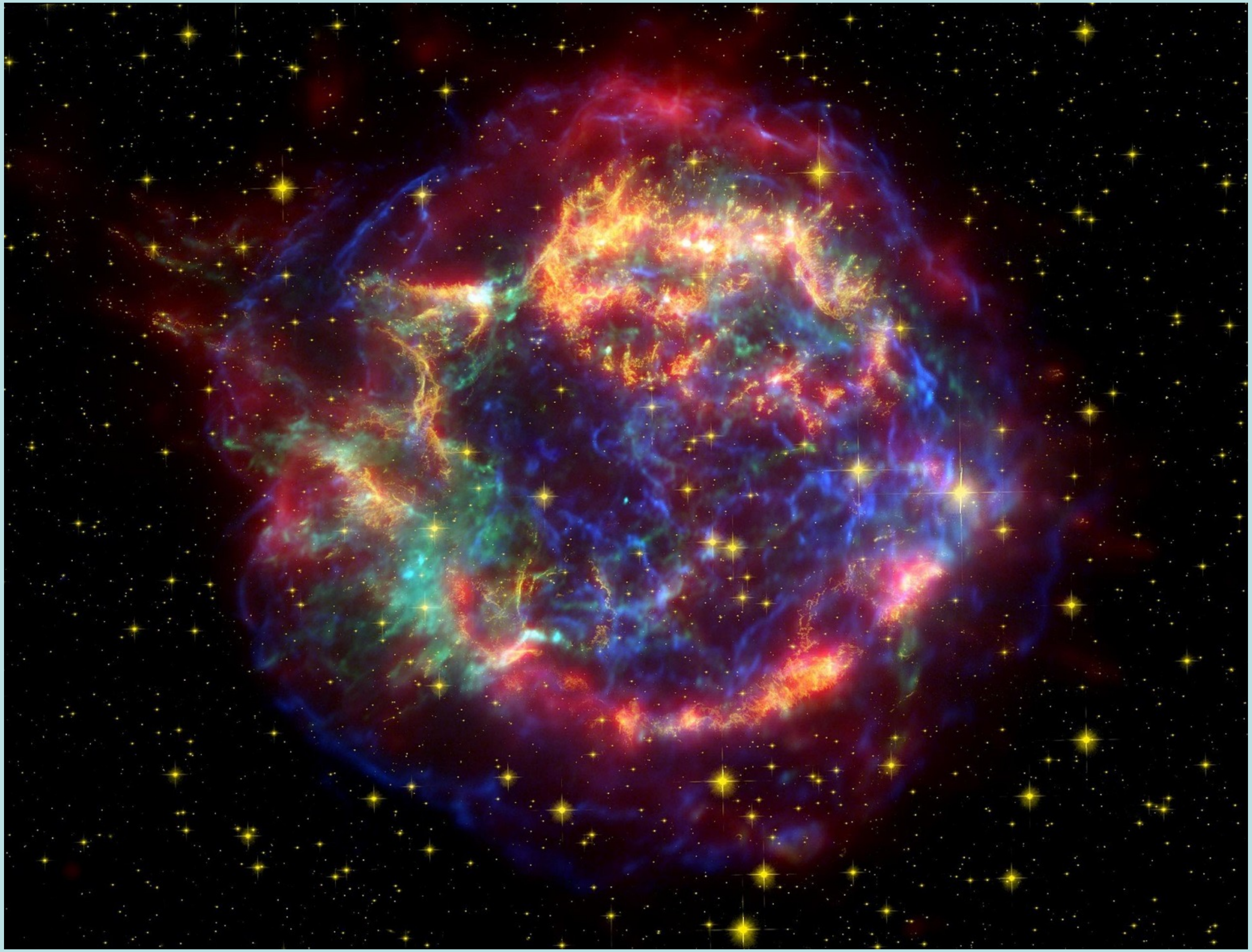
殘骸內電子（中子）彼此的排斥會形成向外的壓力抵抗重力向內的擠壓！

形成（暫時）穩定的 Compact Objects。





仙后座 Cassiopeia A



A false color image composited of data from three sources. Red is infrared data from the Spitzer Space Telescope, orange is visible data from the Hubble Space Telescope, and blue and green are data from the Chandra X-ray Observatory. The cyan dot just off-center is the remnant of the star's core.

WHY WE BELIEVE CONSPIRACY THEORIES PAGE 58
SCIENTIFIC AMERICAN
THE INNER LIVES OF NEUTRON STARS
Inside the densest objects in the universe
PLUS
TOOL USE IN MONKEYS
Archaeology's surprising finds PAGE 64
UNDISCOVERED ILLNESS
The opposite of depression PAGE 36
WEATHER AMPLIFIER
Weird atmospheric waves cause heat waves and floods PAGE 42
© 2019 Scientific American
MARCH 2019
ScientificAmerican.com

ASTROPHYSICS

THE INNER LIVES OF NEUTRON STARS

The insides of neutron stars—the densest form of matter in the universe—have long been a mystery, but it is one that scientists are starting to crack

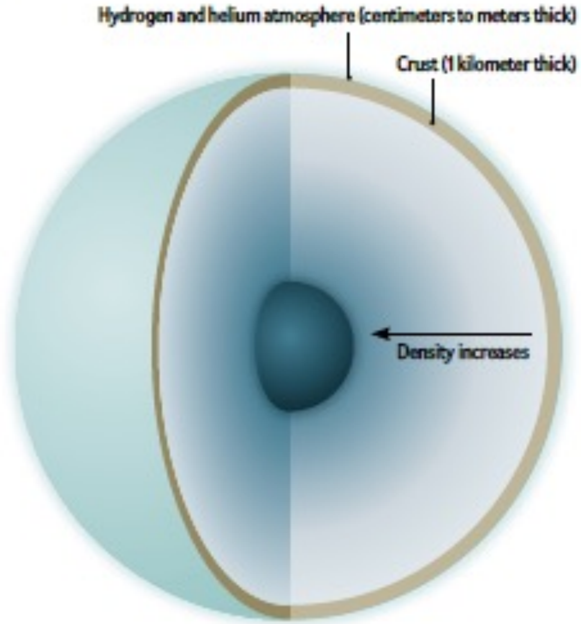
By Clara Moskowitz

Illustration by FOREAL

CASSIOPEIA A is the remnant of an ancient supernova. At its center is a neutron star whose core may contain "superfluid."

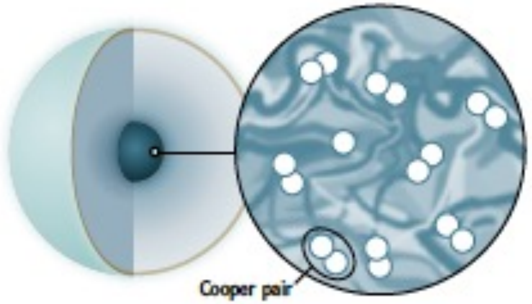
Inside a Neutron Star

Neutron stars are a puzzle. Scientists know they have a slight gaseous atmosphere above a thin crust layer made of heavy atomic nuclei and some floating electrons. But inside these outer layers lies the core—an unknown substance that is likely mostly neutrons. But what form these neutrons take and whether they break down into their ingredients, quarks and gluons, inside the densest inner core is an open question.



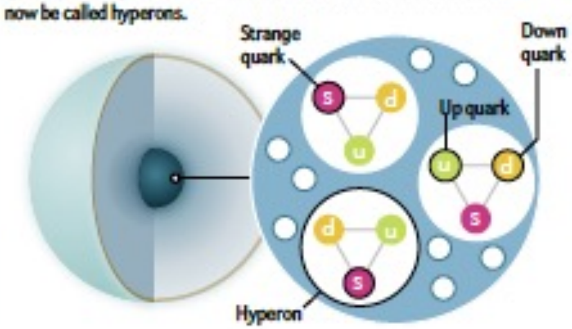
Core Hypothesis 1: Superfluid Seas

One possibility is that particles in the inner core are squeezed in so tight that some of them join to form new particles, called Cooper pairs. This can happen with protons, neutrons or, if these particles have dissolved, quarks. The new particles create a "superfluid" that flows without resistance.

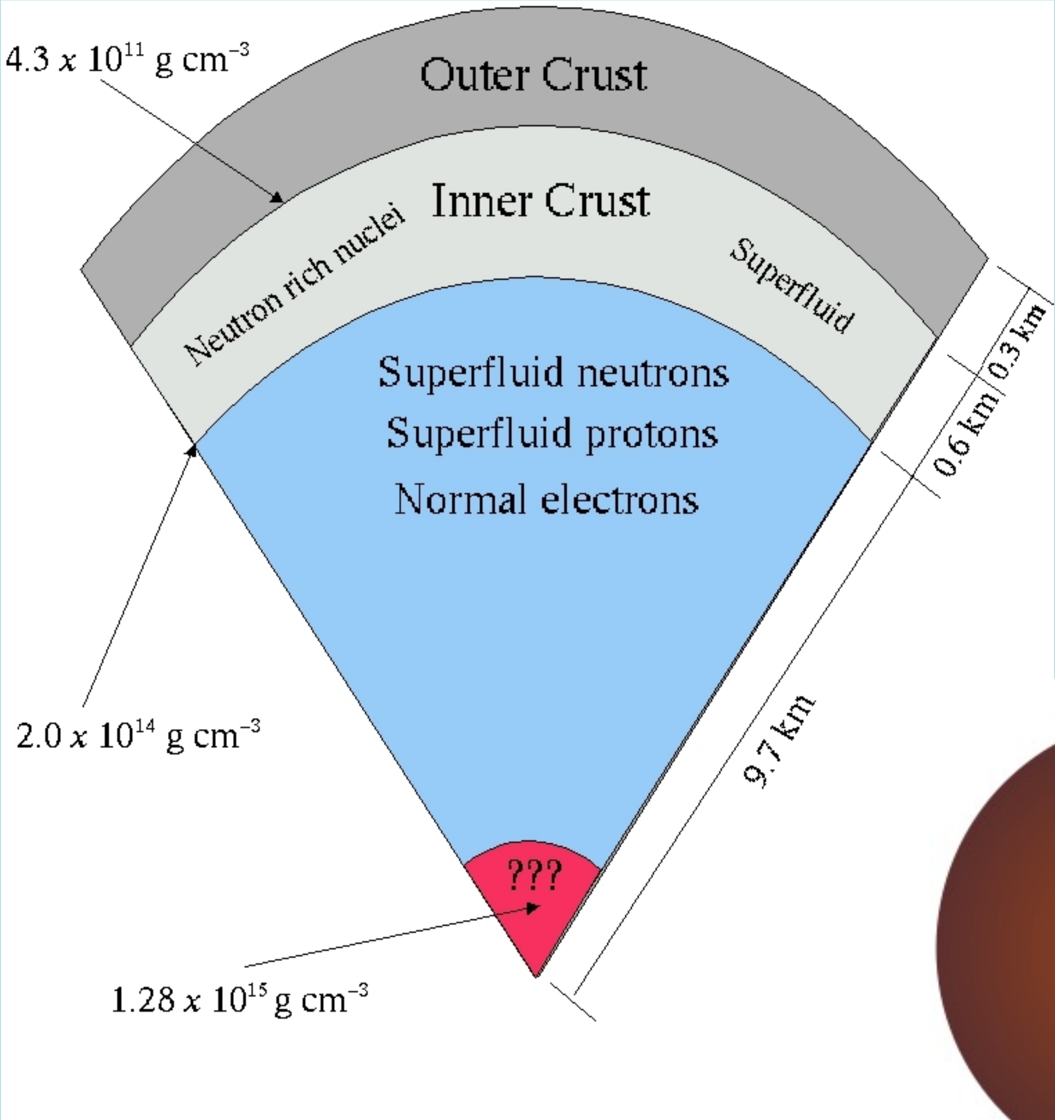


Core Hypothesis 2: Weird Quarks

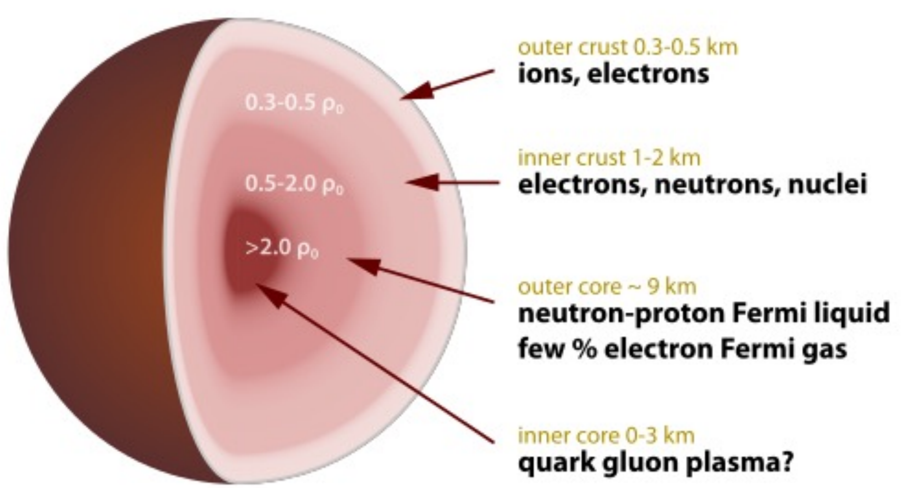
The incredible density could also prompt quarks in the inner core to transform from their usual type, "up" or "down," into exotic "strange quarks." If the quarks are still inside neutrons, these neutrons would now be called hyperons.

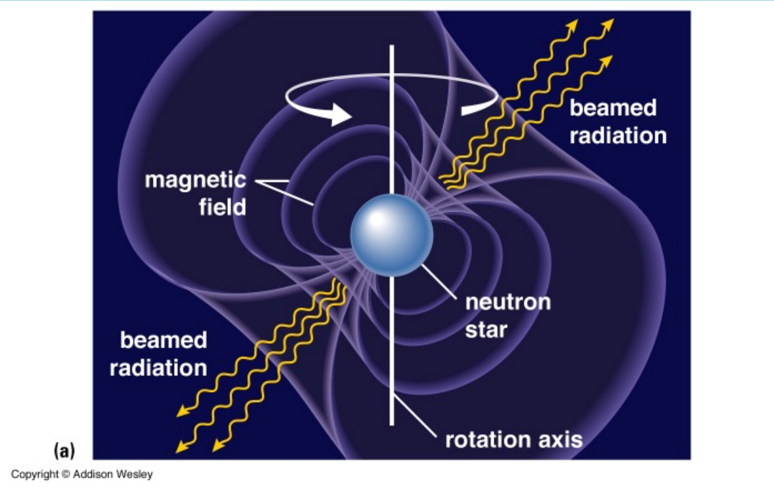


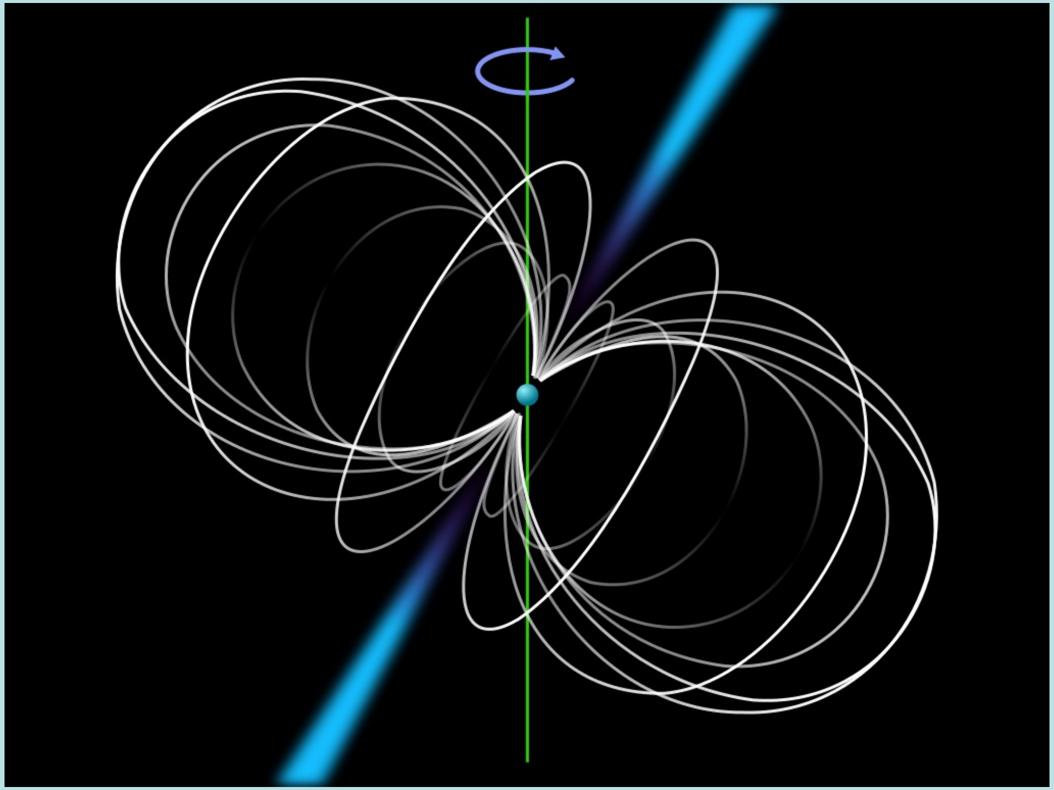
Inside Neutron Star



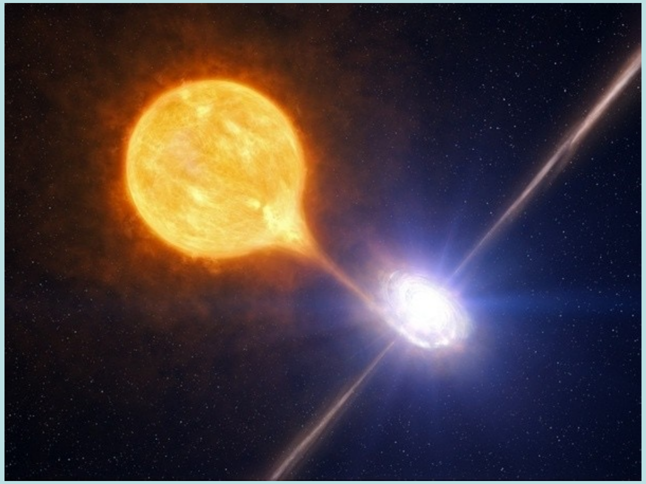
Neutron Star Pizza

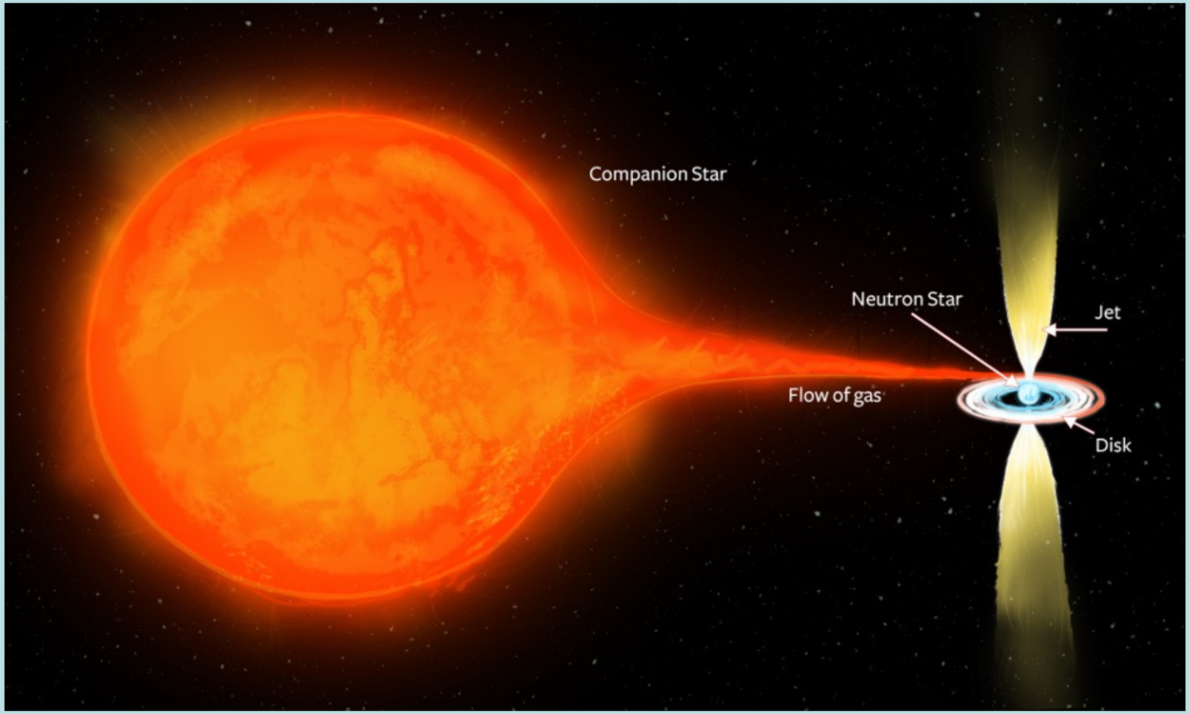




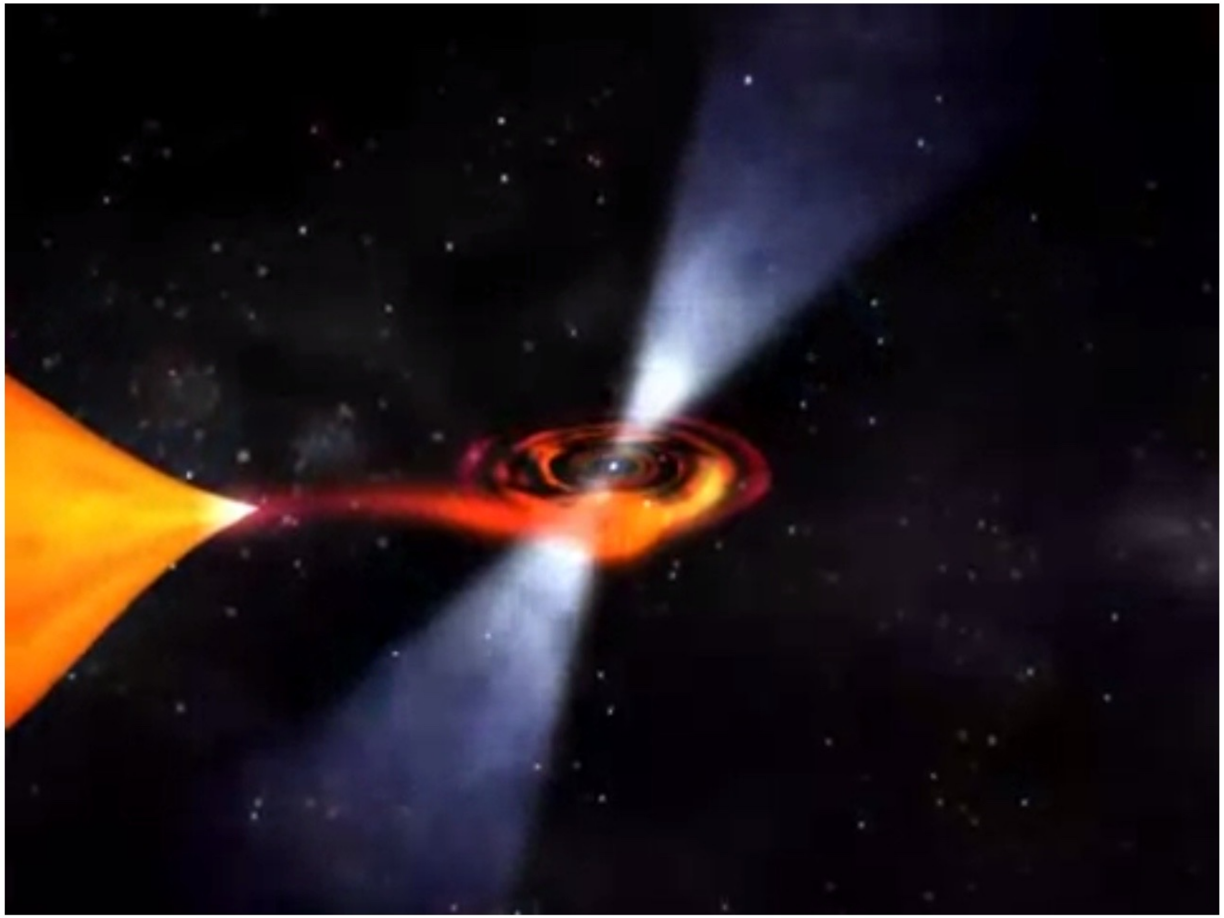


中子星一般是有自轉以及極強的磁場，一般會形成噴流。





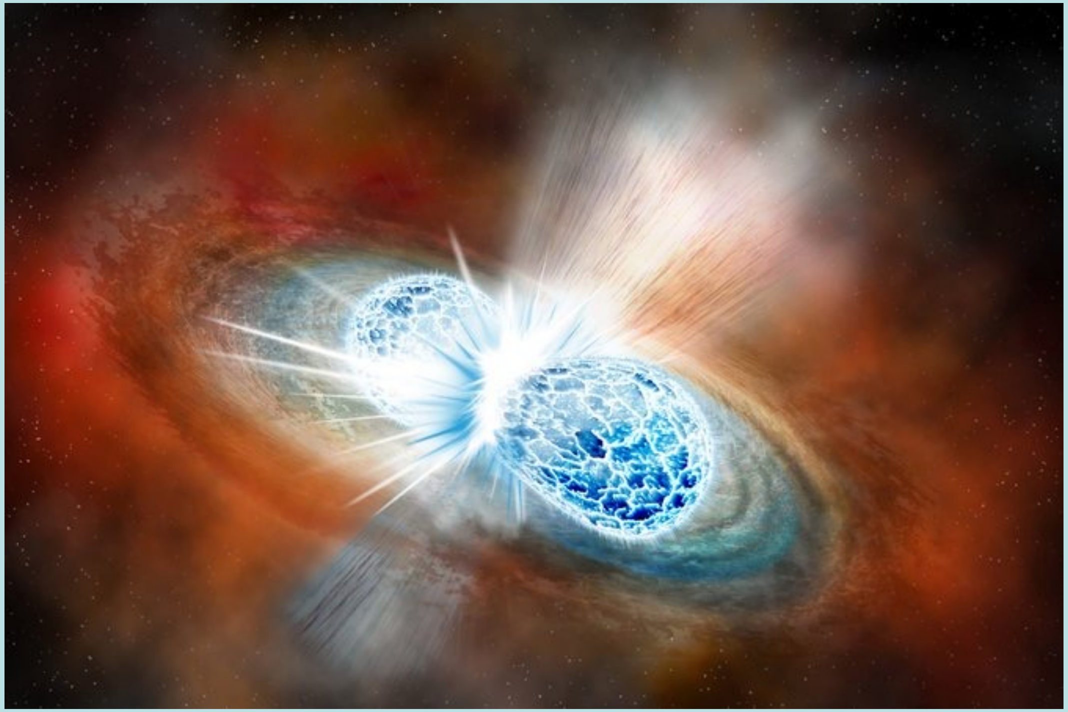
中子星不發光，但從伴侶抽取的物質落入中子星強大的重力，就會發光。



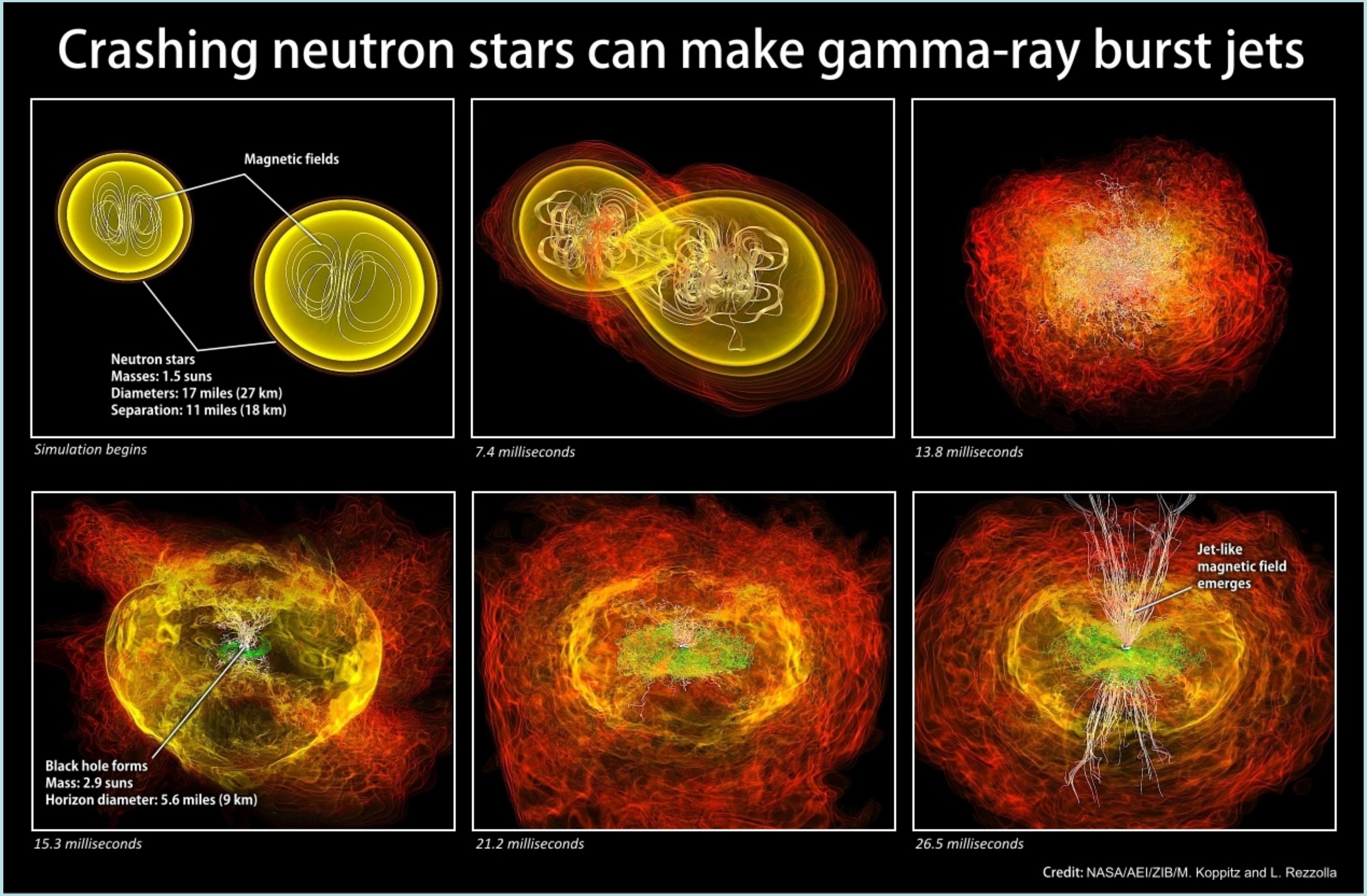
No higher resolution available

Composite optical/X-ray image of the Crab Nebula, showing synchrotron emission in the surrounding pulsar wind nebula, powered by injection of magnetic fields and particles from the central pulsar.

Neutron Star Collision

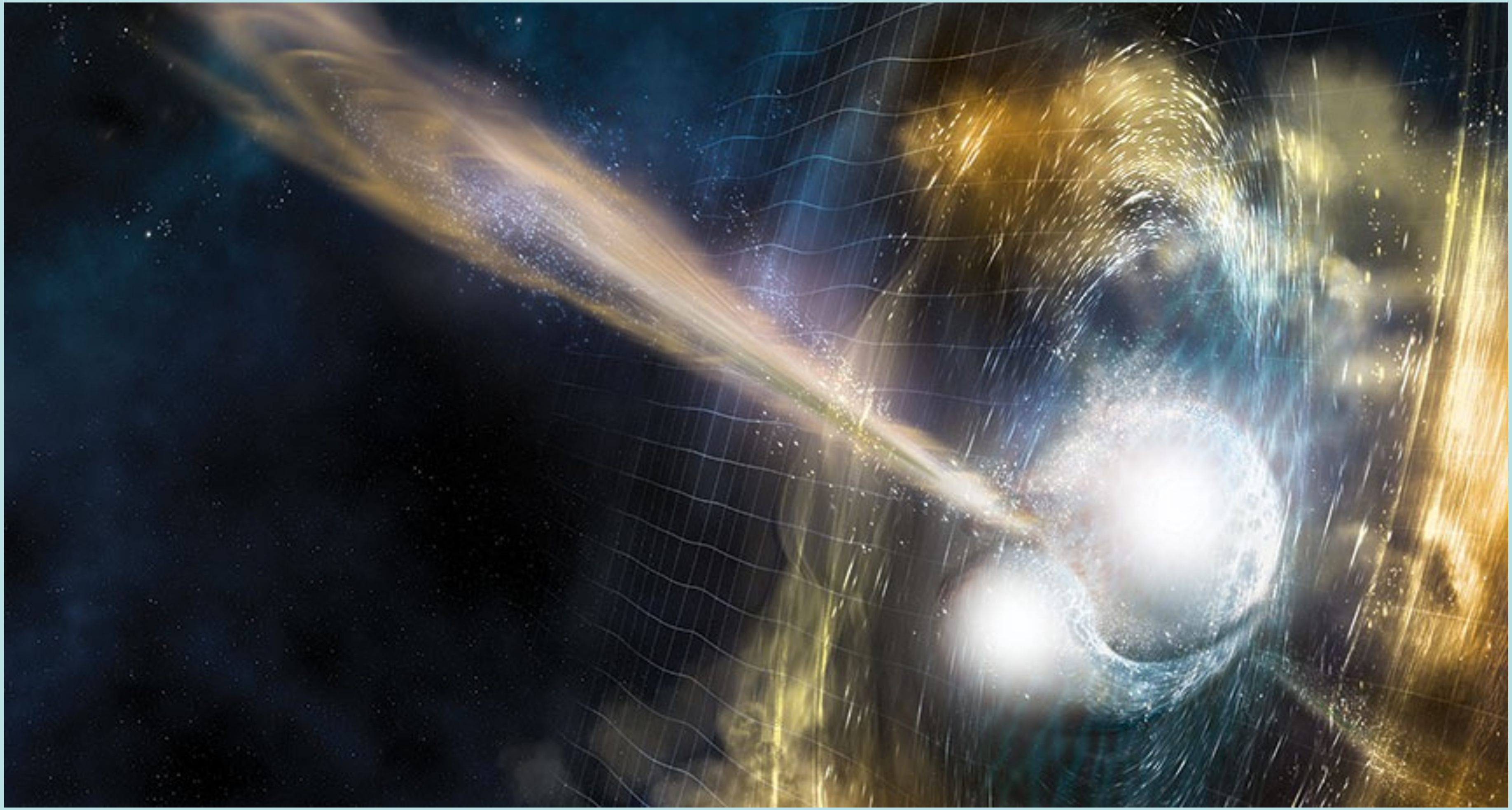


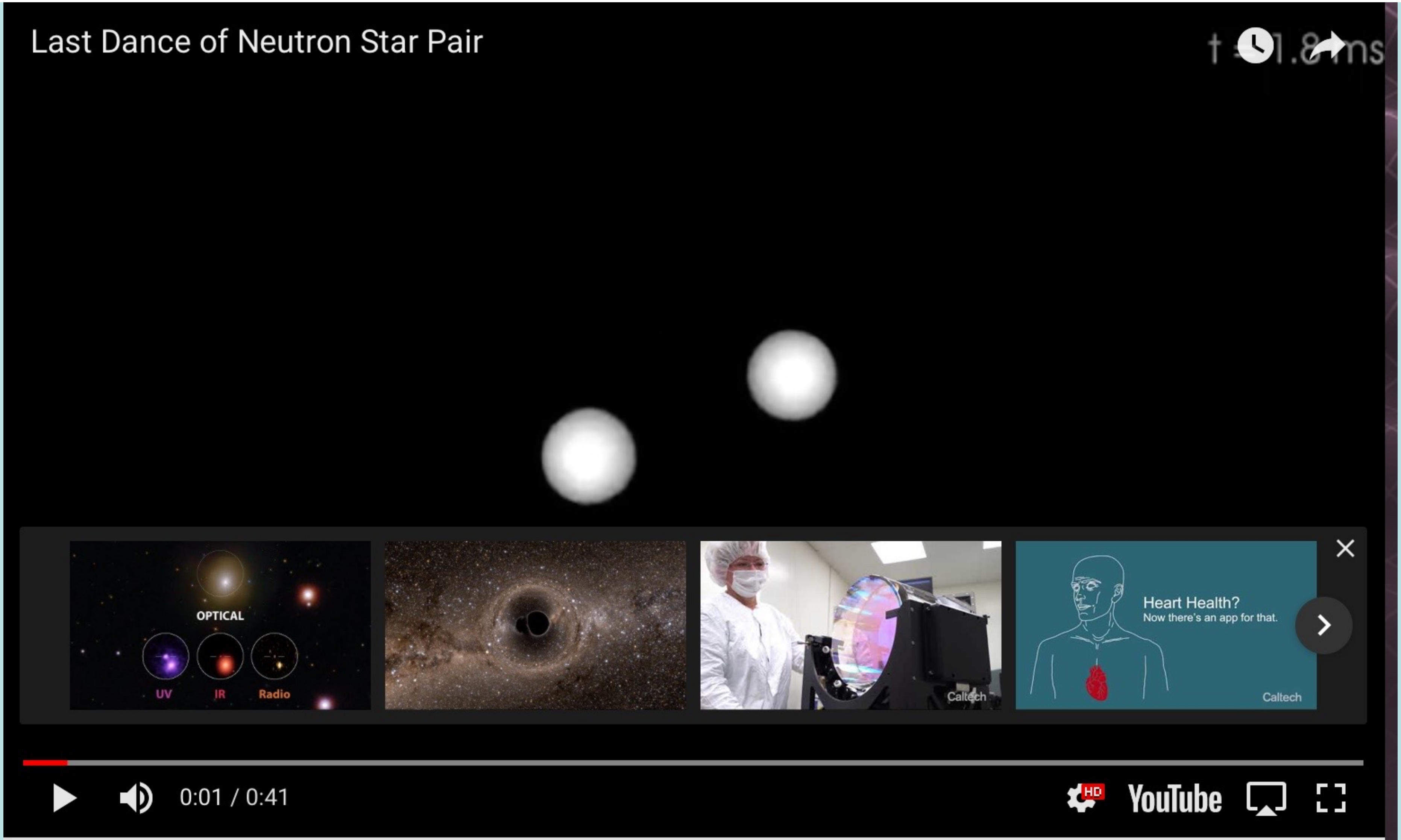
中子星撞擊會發光！



Crashing neutron stars can make gamma-ray burst jets
Magnetic fields
Neutron stars
Masses: 1.5 suns
Diameters: 17 miles (27 km)
Separation: 11 miles (18 km)
Simulation begins
7.4 milliseconds
13.8 milliseconds
Black hole forms
Mass: 2.9 suns
Horizon diameter: 5.6 miles (9 km)
15.3 milliseconds
21.2 milliseconds
Jet-like
magnetic field
emerges
26.5 milliseconds
Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

kilonova

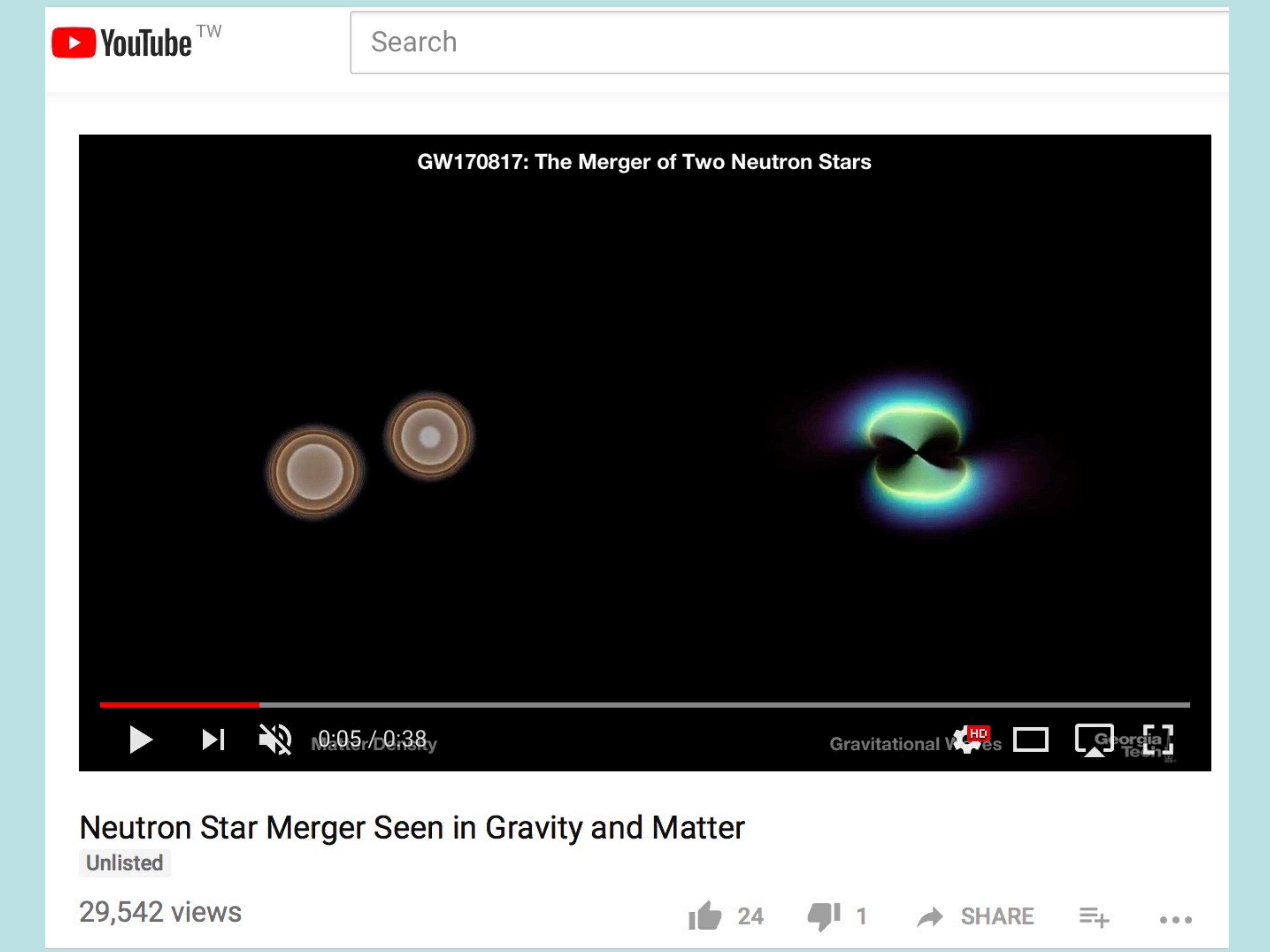


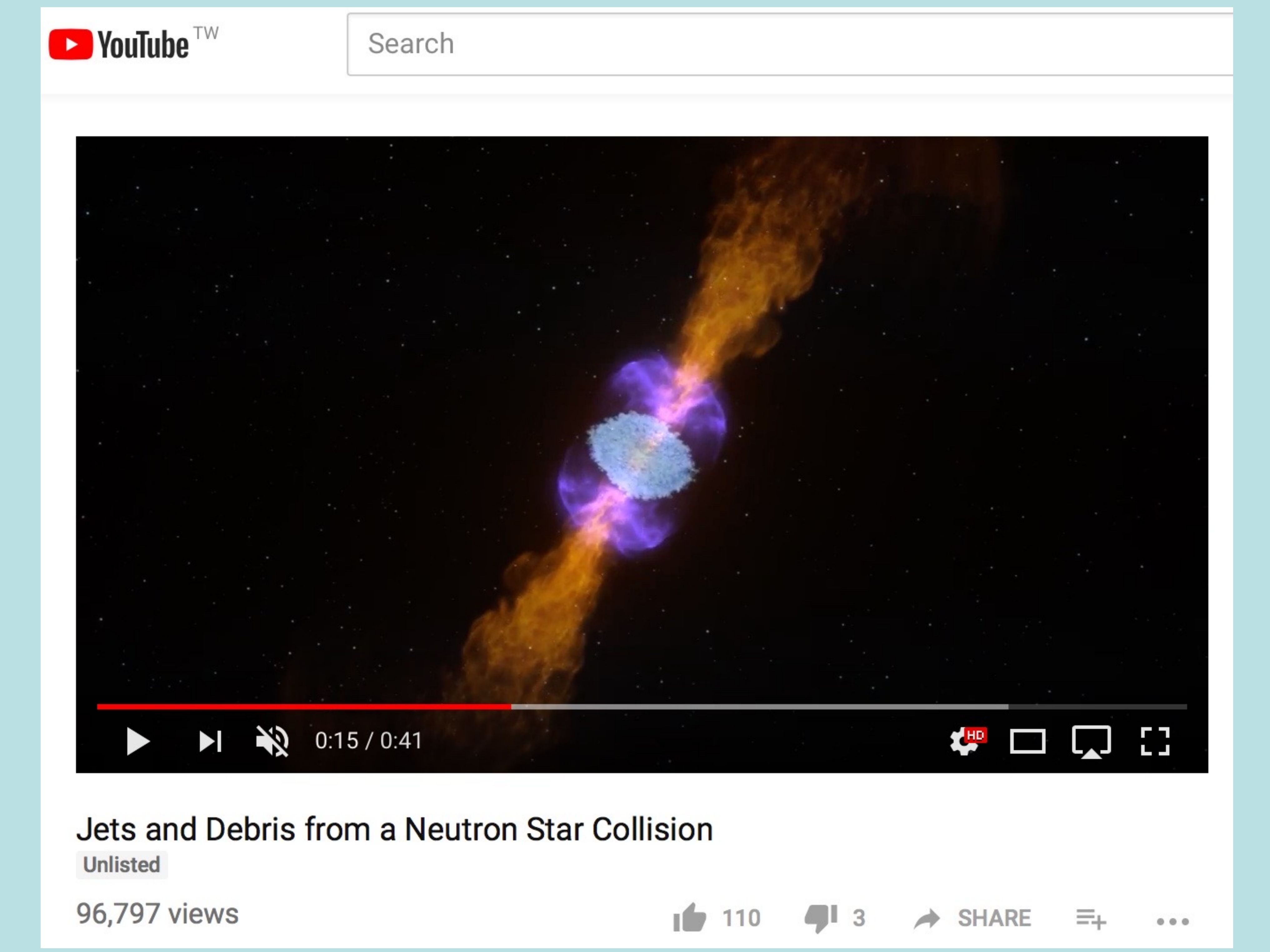


Last Dance of Neutron Star Pair

This simulation shows the final stages of the merging of two neutron stars. The merger shown in the simulation is happening much faster in reality, within less than a hundredth of a second, and produces strong gravitational waves. This illustrates one of the possible scenarios for the merger event GW170817, detected by the LIGO-Virgo gravitational-wave network. The result of the merger could have been a neutron star or a black hole, the latter of which is shown here.

Credit: W. Kastaun/T. Kawamura/B. Giacomazzo/R. Ciolfi/A. Endrizzi


YouTube TW
Search
GW170817: The Merger of Two Neutron Stars
0:05 / 0:38
Gravitational
HD
Neutron Star Merger Seen in Gravity and Matter
Unlisted
29,542 views
24
1
SHARE

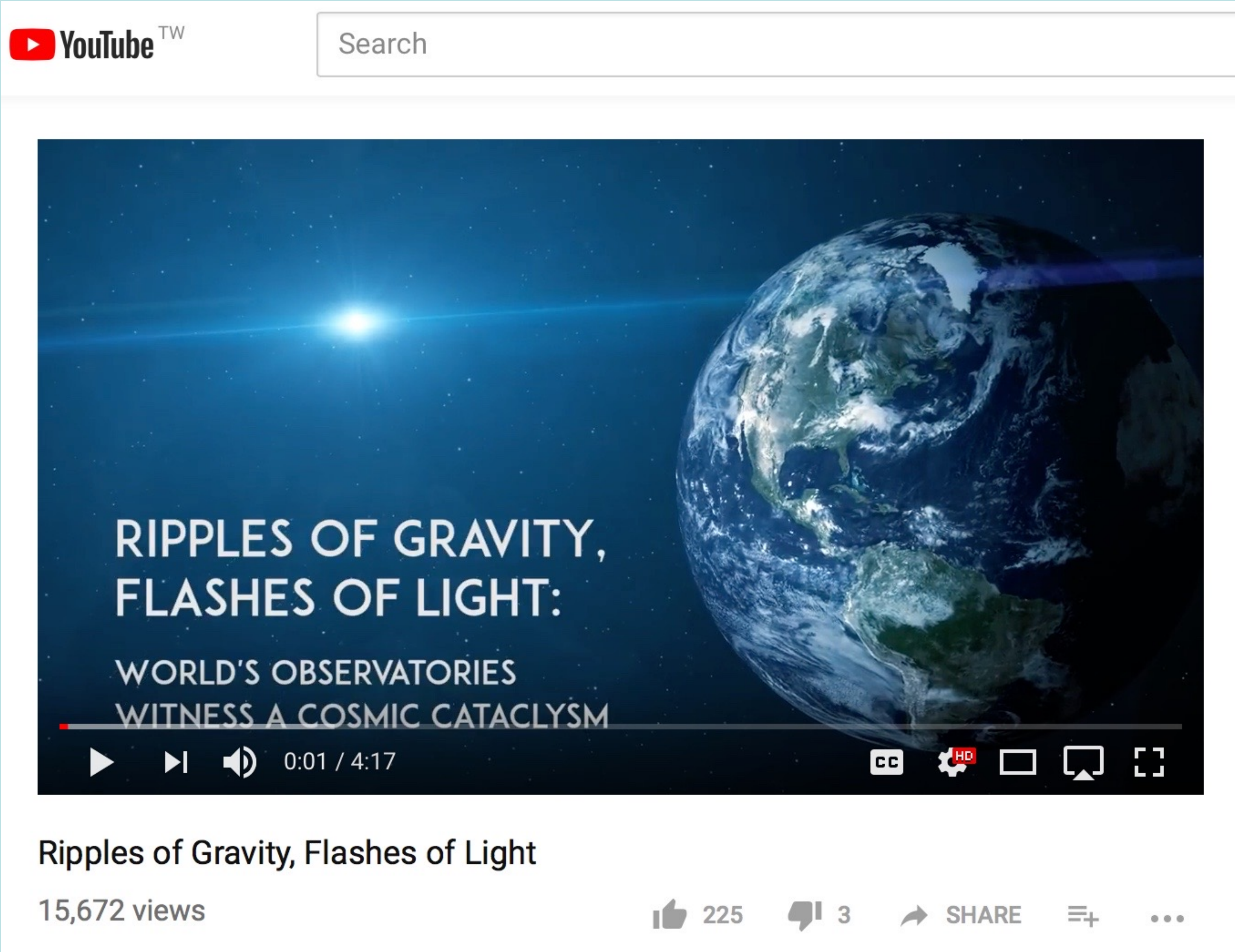

YouTube TW
Search
0:15 / 0:41
HD
Jets and Debris from a Neutron Star Collision
Unlisted
96,797 views
110
3
SHARE


LIGO
Laser Interferometer
Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT
About
Learn More
News
Gallery
Educational Resources
For Scientists
Study & Work
1 2 3 4 5 6
LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars
Press release • October 16, 2017
For the first time, scientists have directly detected gravitational waves — ripples in space and time — in addition to light from the spectacular collision of two neutron stars. This marks the first time that a cosmic event has been viewed in both gravitational waves and light.

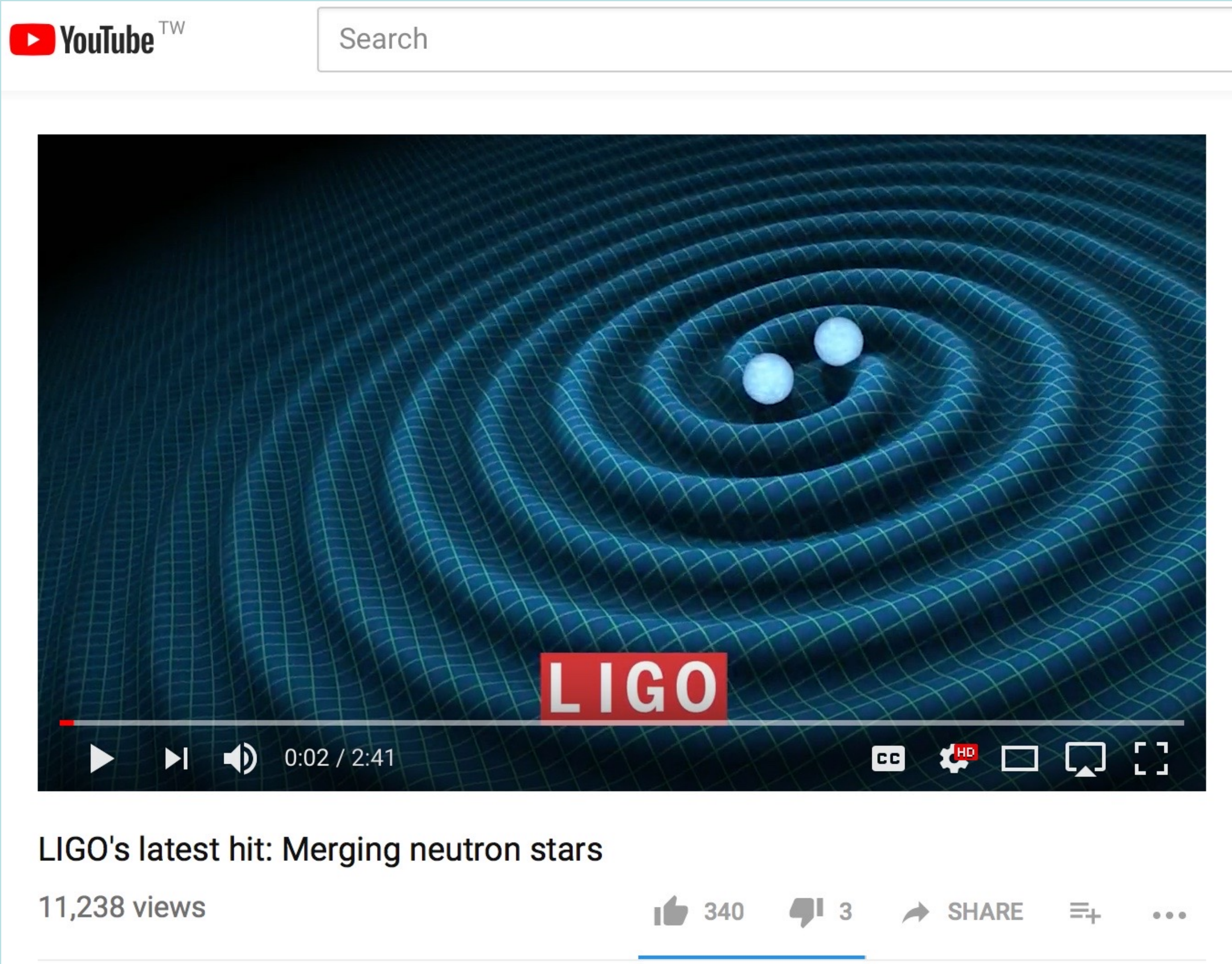
LIGO Detects Fierce Collision of Neutron Stars for the First Time

By DENNIS OVERBYE OCT. 16, 2017

NYT article NYT Video



Caltech Video



[Science Video]

發現中子星碰撞重力波 黃金成因有解

2017-10-16 23:53 聯合報 編譯王麗娟／綜合報導

美國的LIGO（雷射干涉重力波偵測站，Laser Interferometer Gravitational-Wave Observatory）與全球七十個天文台十六日召開記者會，宣布再有重力波新發現。科學家去年首次發現兩個黑洞相撞產生的重力波，此次新觀察到的重力波，則由兩顆中子星相撞產生，有助於學界了解黃金這類貴金屬的來源。

這次發現是物理學家首次能在可見光下，直接觀測到重力波。

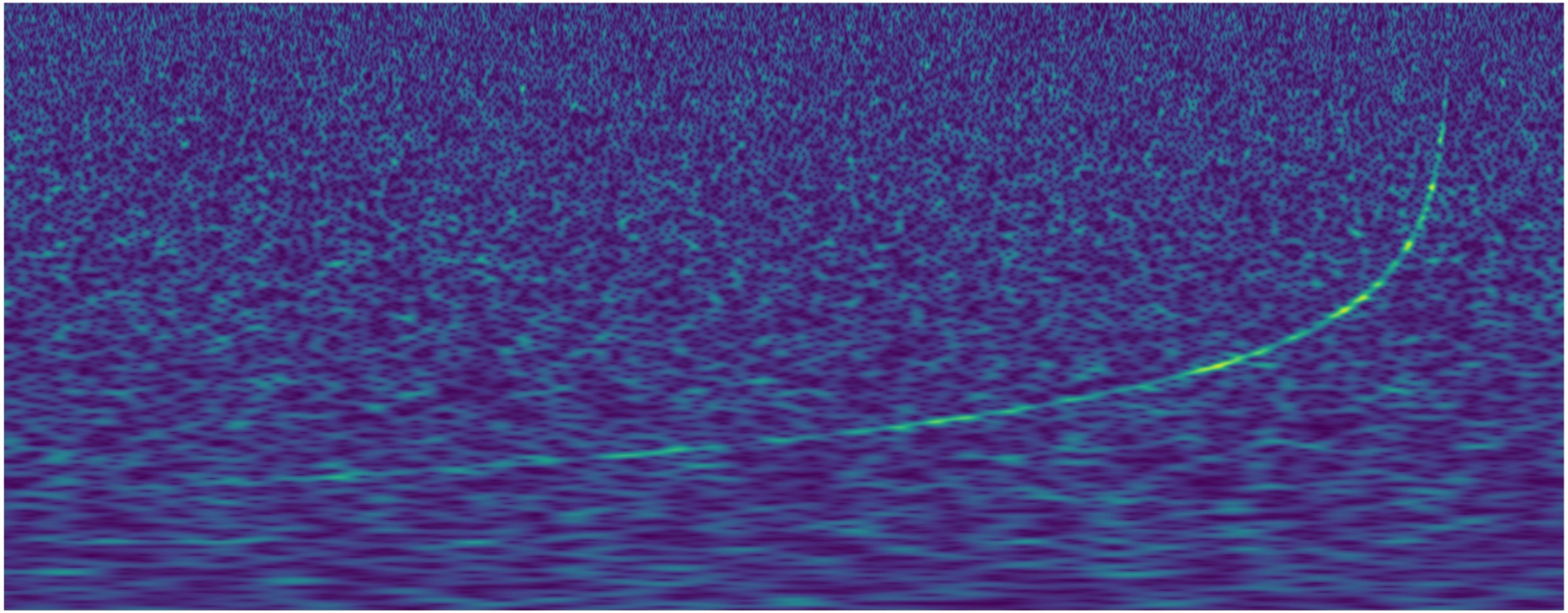
新發現將為物理界提供一種研究宇宙、解開暗能量等謎團的新途徑，包括了解黃金、白金、鈾從何而來。科學家指出，重力波為人類打開一扇觀測宇宙、了解黑洞和中子星等神秘天體的新大門。了解這些天文現象，將有助人類理解宇宙的起源。

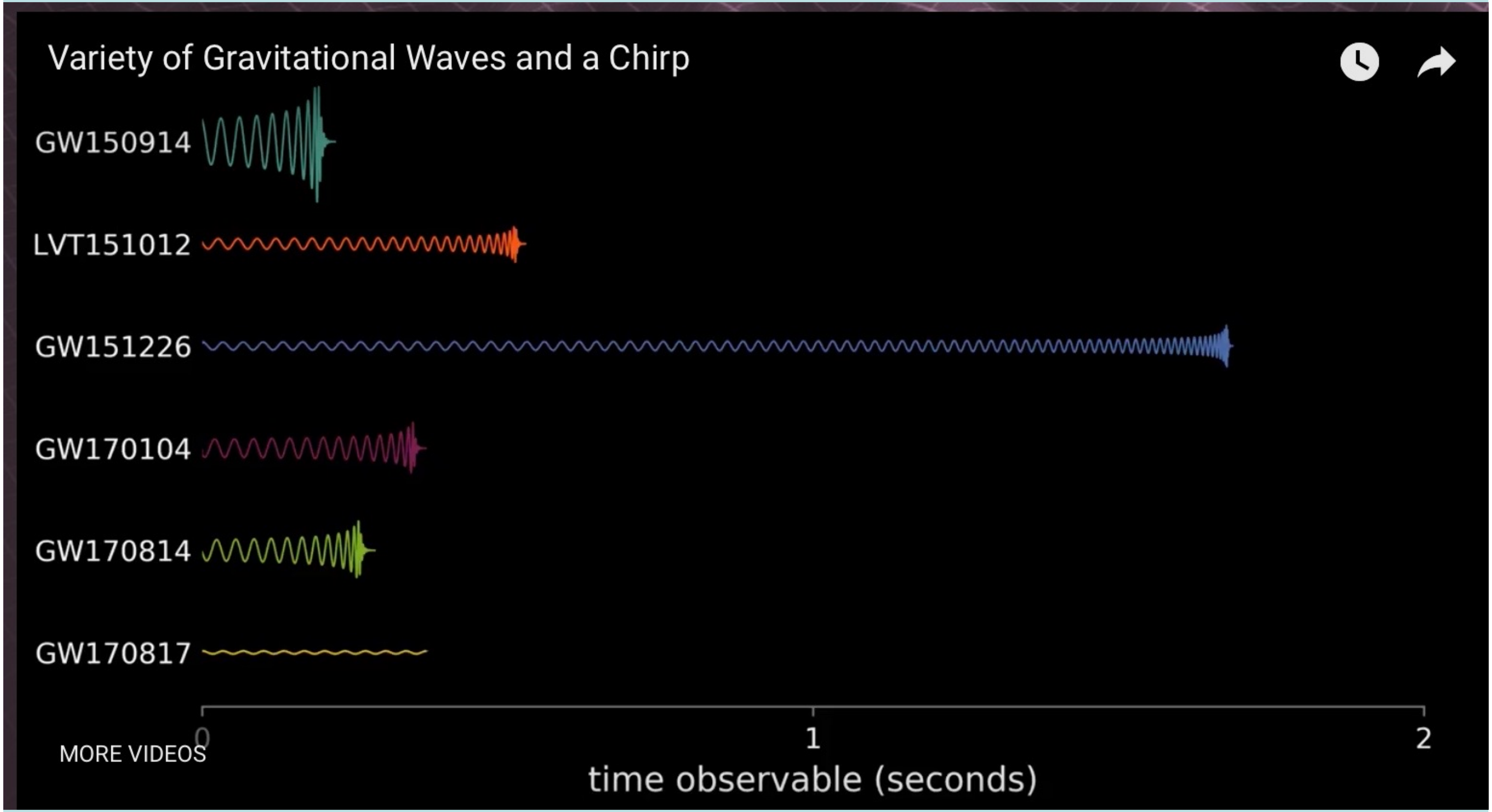
美聯社報導，最新發現的中子星碰撞，噴發出亮藍色高熱殘骸，密度極高且很不穩定。這些殘骸部分形成重元素，如金、白金和鈾。科學家過去就認為這類碰撞可產生足夠能量創造較重的元素，但直到實際觀測到才得以確認。

LIGO的三位科學家剛因他們發現重力波的貢獻，獲得二〇一七年諾貝爾物理學獎，三人分別是八十五歲的魏斯、七十七歲的索恩、八十一歲的巴利許。

LIGO天文台為全球最大的重力波觀測天文台，之前已記錄了四次由劇烈爆炸產生的引力波。四次的重力波均是黑洞相撞產生。第四次發現重力波「GW170814」是美國的LIGO物理實驗團隊與歐洲處女座（Virgo）干涉儀天文台的合作成果。雙方合作提高探測敏感度後，兩周內就發現了第四個重力波。

黑洞產生的重力波無法在可見光波段進行觀測 ，但中子星相撞會釋出可見光。科學家將望遠鏡對準位於長蛇座中一處名為NGC 4993的星系，距地球約一點三億光年，進行觀測。此一星系中有兩顆成對的中子星，科學家從它們的相撞，發現新型的重力波。



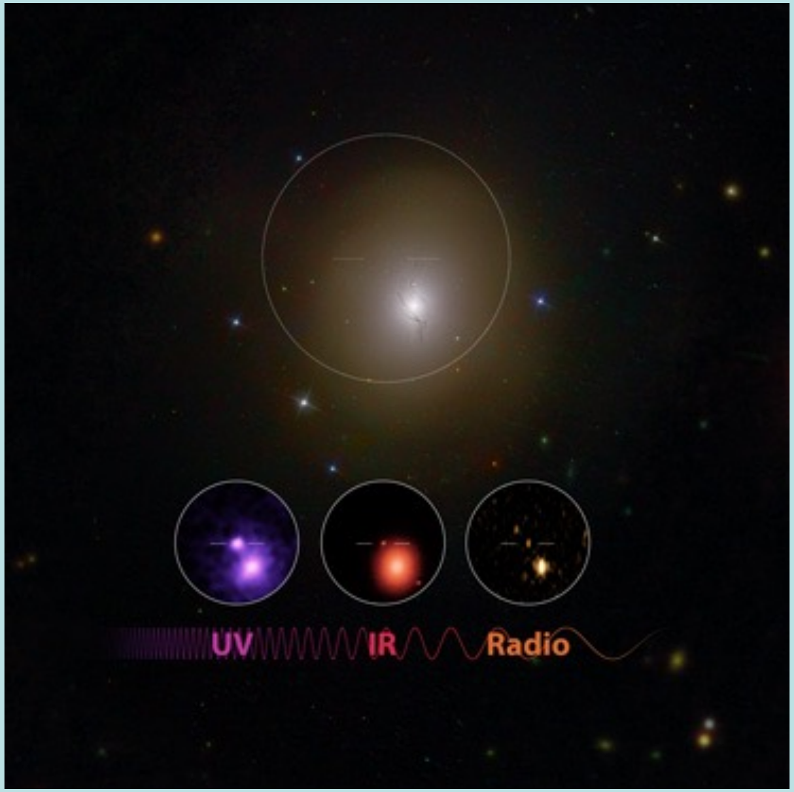


Variety of Gravitational Waves and a Chirp
GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
MORE VIDEOS


First Cosmic Event Observed in
Gravitational Waves and Light
LIGO
Georgia Tech
Center for Relativistic Astrophysics

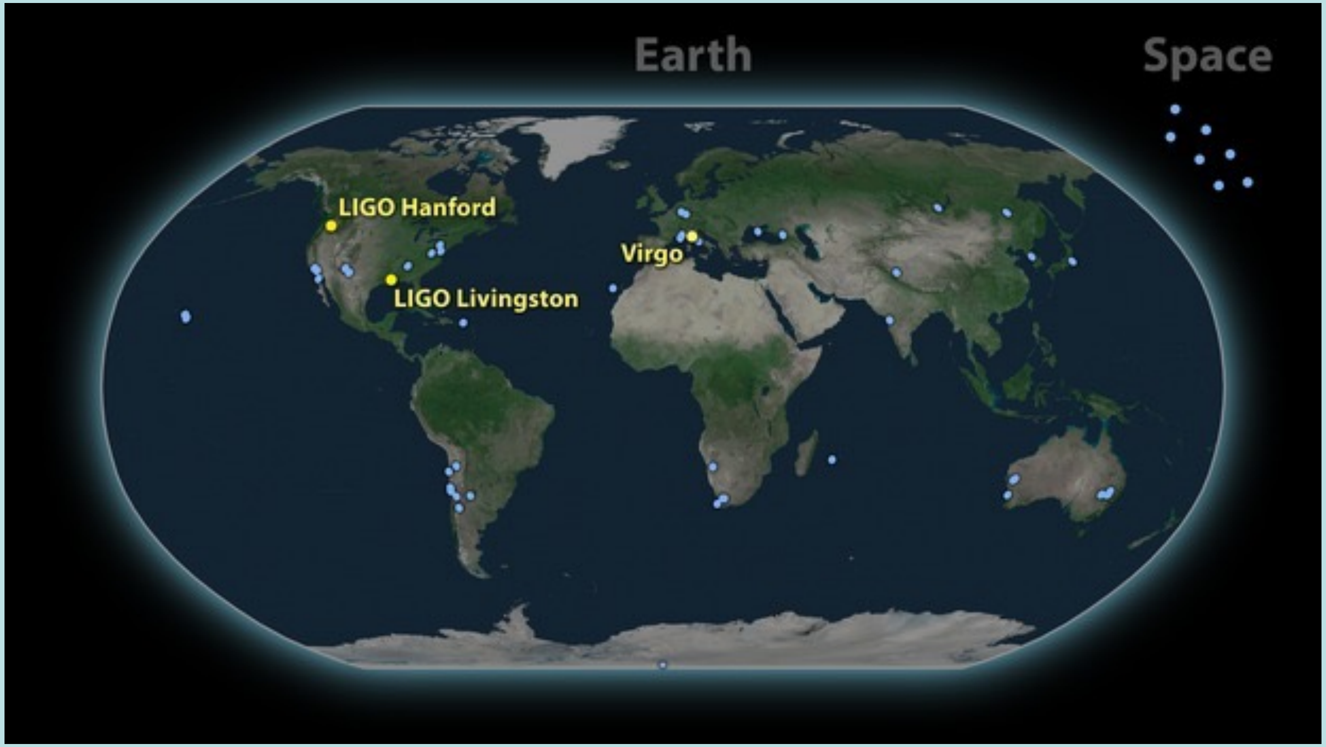

FGST
FERMI GAMMA-RAY SPACE TELESCOPE

NGC4993, the galaxy that played host to the first binary neutron star merger ever detected by human beings. The galaxy is 130 million light years away from the Earth. Credit: ESA/Hubble



各個波長的電磁波都被觀測
到。

multimessenger astronomy

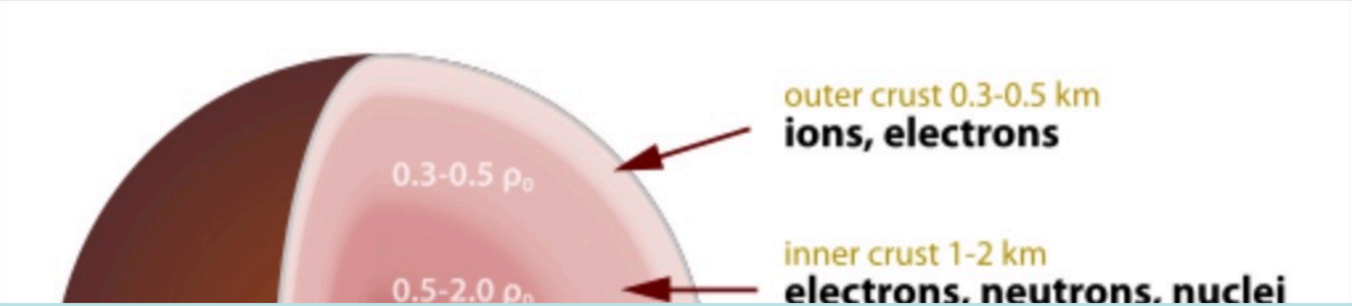


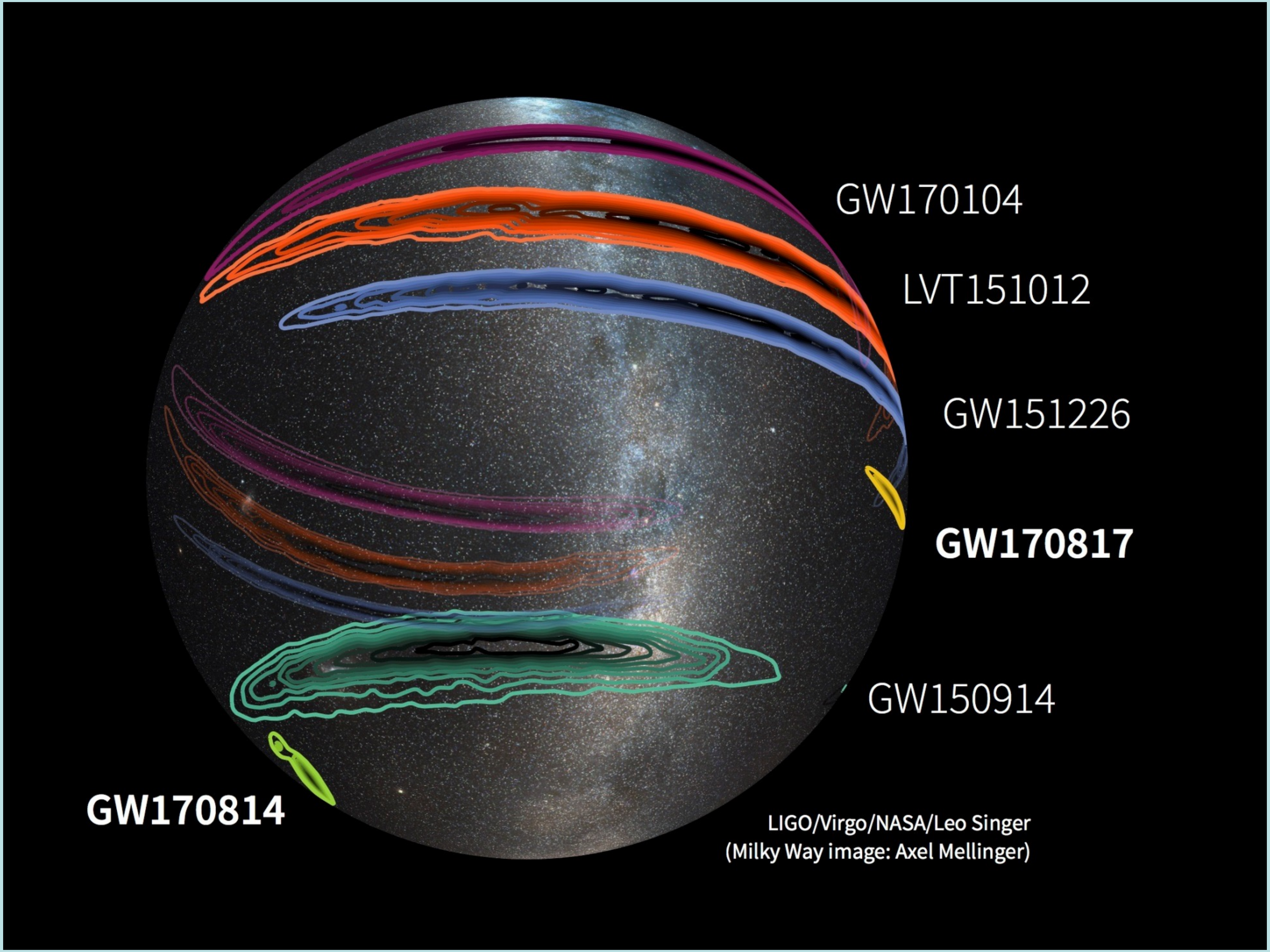
GW+EM Observatories Map: A map of the approximately 70 light-based observatories that detected the gravitational-wave event called GW170817. On August 17, the LIGO and Virgo detectors spotted gravitational waves from two colliding neutron stars. Light-based telescopes around the globe observed the aftermath of the collision in the hours, days, and weeks following. They helped pinpoint the location of the neutron stars and identified signs of heavy elements, such as gold, in the collision's ejected material.

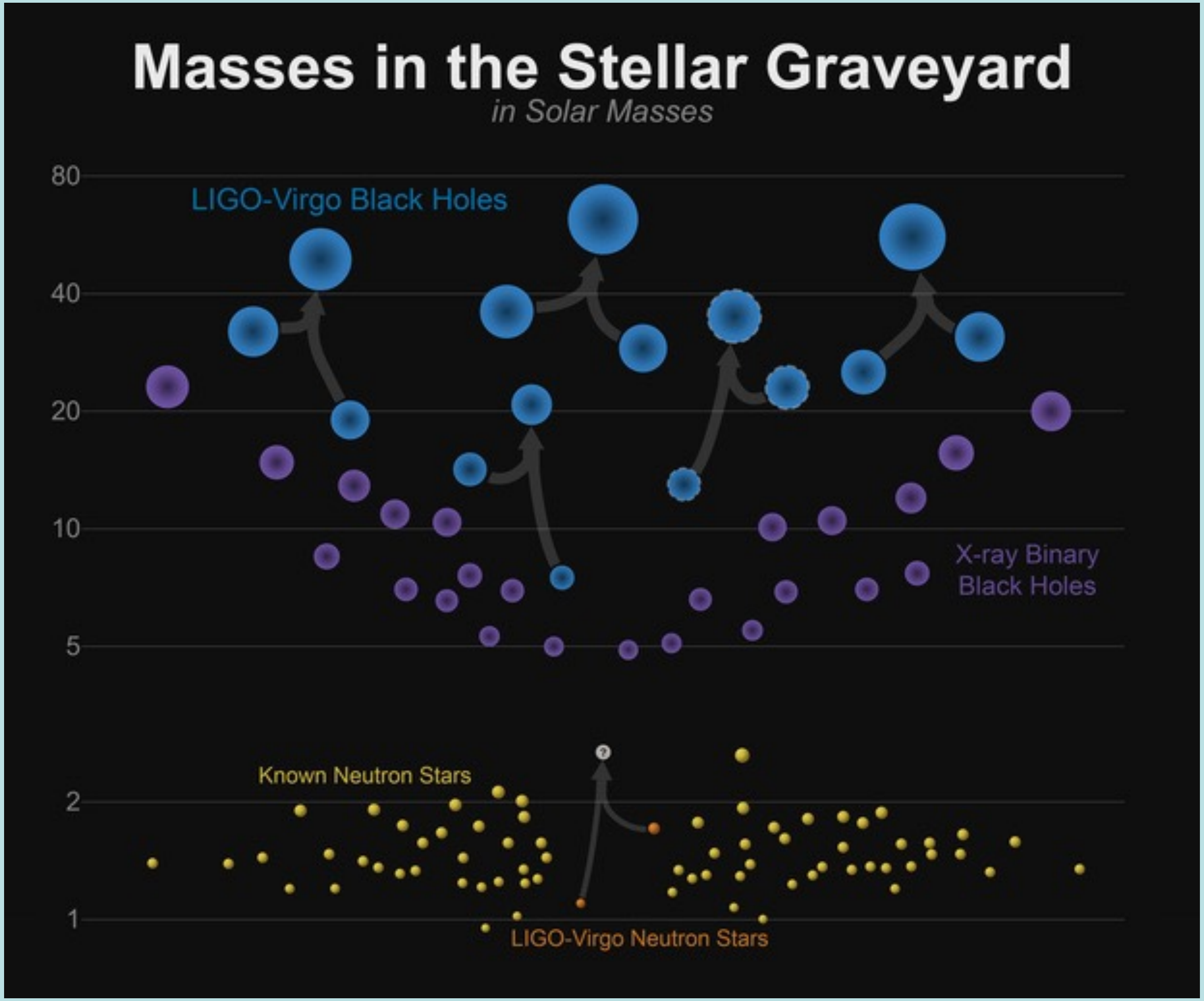
Why all the Excitement?

Up until that day in August, LIGO's detections had all been gravitational waves caused by merging black holes. While there's no doubt that those discoveries have been monumental, the scope and magnitude of this discovery would prove unprecedented. The LIGO and Virgo detection has become probably the most widely studied astronomical event in human history. Within days, this object was being examined by nearly one-third of the world's electromagnetic (EM) astronomers. The fact that EM astronomers were able to observe the phenomenon alongside GW astronomers is what truly elevated this event to history-making levels. LIGO's previous detections of merging black holes did not result in such widespread study because, by their very nature, black holes are believed not to emit electromagnetic waves (i.e., light of any wavelength). No amount of searching by astronomers using telescopes designed to observe EM radiation has revealed anything. Only gravitational wave observatories like LIGO and Virgo can 'observe' black holes colliding.

Neutron stars are different, however. Unlike black holes, neutron stars are made up of actual matter, including copious amounts of neutrons (hence their moniker), and when you accelerate or slam matter together you get electromagnetic radiation (again, not something one expects to detect from colliding black holes).

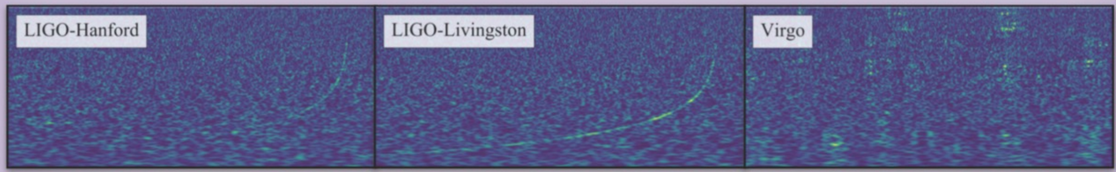



GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)



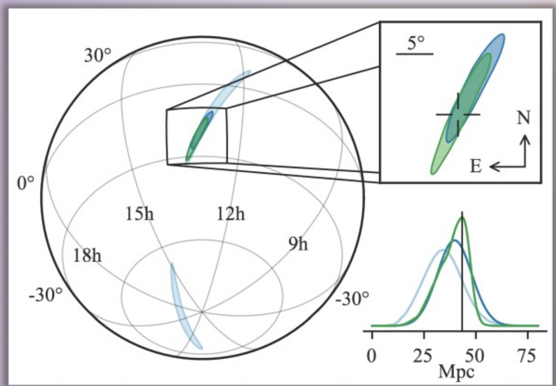
Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars

GW170817 FACTSHEET



observed by	H, L, V
source type	binary neutron star (NS)
date	17 August 2017
time of merger	12:41:04 UTC
signal-to-noise ratio	32.4
false alarm rate	< 1 in 80 000 years
distance	85 to 160 million light-years
total mass	2.73 to 3.29 $M_\odot$
primary NS mass	1.36 to 2.26 $M_\odot$
secondary NS mass	0.86 to 1.36 $M_\odot$
mass ratio	0.4 to 1.0
radiated GW energy	> 0.025 $M_\odot c^2$
radius of a 1.4 $M_\odot$ NS	likely ≲ 14 km
effective spin parameter	-0.01 to 0.17
effective precession spin parameter	unconstrained
GW speed deviation from speed of light	< few parts in 10^{15}

inferred duration from 30 Hz to 2048 Hz**	~ 60 s
inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
initial astronomer alert latency*	27 min
HLV sky map alert latency*	5 hrs 14 min
HLV sky area†	28 deg^2
# of EM observatories that followed the trigger	~ 70
also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
host galaxy	NGC 4993
source RA, Dec	$13^h09^m48^s$, $-23°22'53''$
sky location	in Hydra constellation
viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}



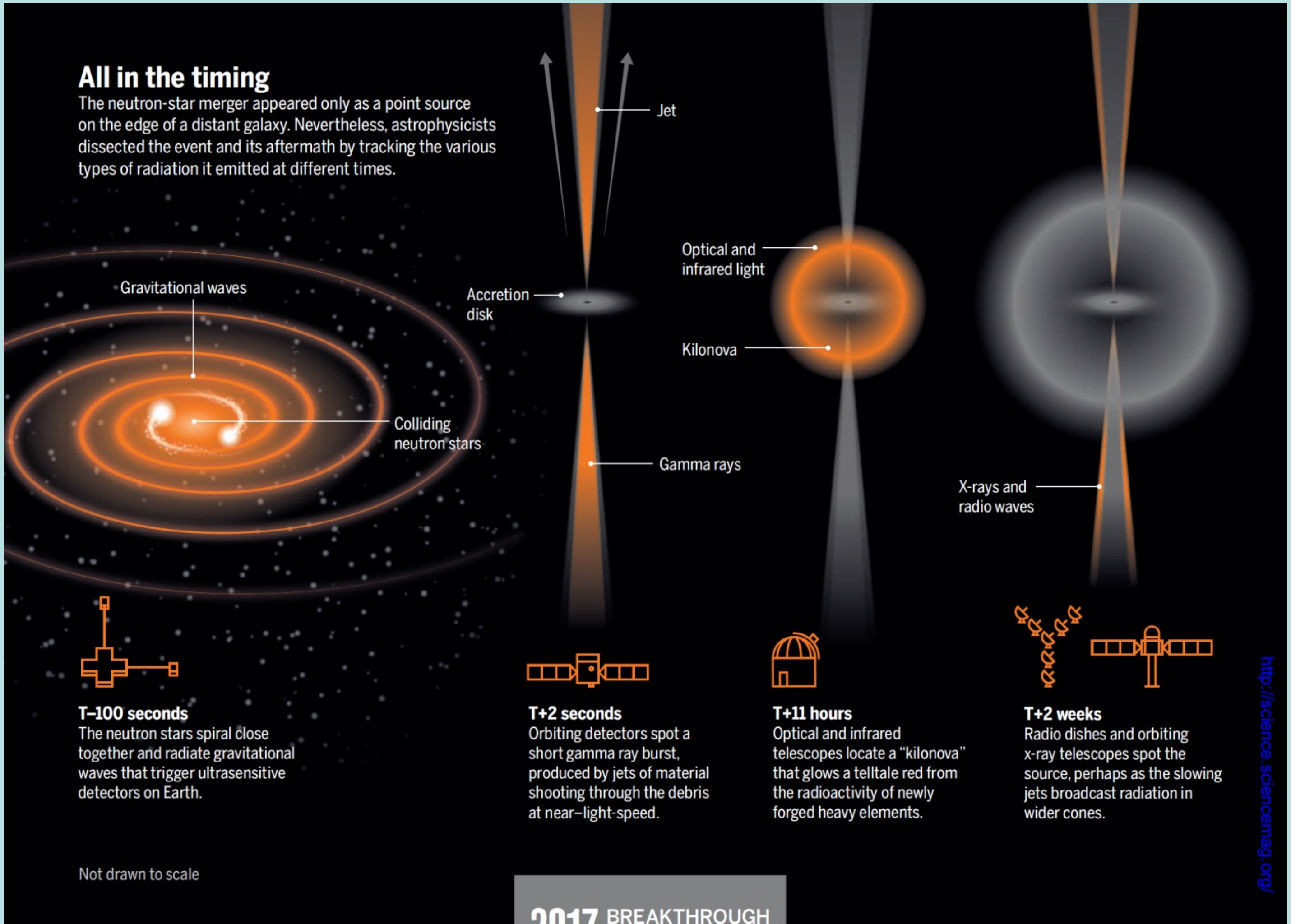
Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2×10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region

Great Waves (The LIGO Gravitational Wave Song)


How will AI impact jobs and the economy?
The catalog of New World plants
Minor recurrent infections and colitis
Science
$15
22 DECEMBER 2017
AAAS
2017
BREAKTHROUGH
of the YEAR



http://science.sciencemag.org/

December 21, 2017

2017 BREAKTHROUGH *of the* YEAR

COSMIC CONVERGENCE

The merger of two neutron stars captivated thousands of observers and fulfilled multiple astrophysical predictions

By **Adrian Cho**

Artist conception of the moment two neutron stars collide.

LIGO Celebrates One-Year Anniversary of Historic Binary Neutron Star Merger Detection

News Release • August 17, 2018

Today LIGO commemorates the one-year anniversary of its most important discovery to-date: The detection of a merging pair of neutron stars, aka a BNS (binary neutron star) merger.

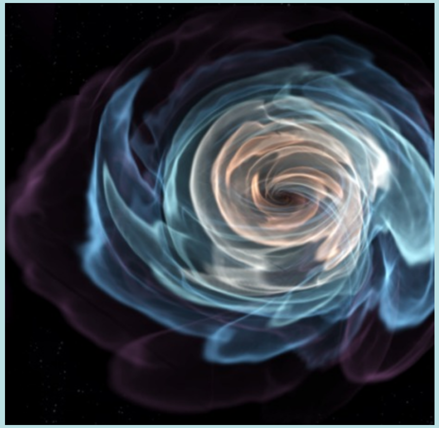
After a 130 million year journey, the gravitational waves generated by these exotic stars arrived at LIGO's Hanford and Livingston detectors in the United States, and the Virgo detector in Italy on August 17th, 2017. Dubbed a 'kilonova' (a term coined in 2010 in **a paper** wherein it was theorized that a pair of merging neutron stars would emit light about 1000 times brighter than a **classical nova**), the detection also led to a massive explosion of multimessenger astronomy results gathered by astronomers from all around the globe. LIGO **announced the discovery to the world** with papers published on October 16th.

How important was this detection? Well, on the day of the announcement, **84 scientific papers were published** about it.

Today, an internet search for "GW170817" will yield over 110,000 results, all related to this one event that captured the world scientific community's attention (incidentally, a search for "GW150914", LIGO's first detection, yields a mere 80,000 hits).

How important was this detection? Well, on the day of the announcement, **84 scientific papers were published** about it.

84 papers were published about this event on the day LIGO announced the discovery

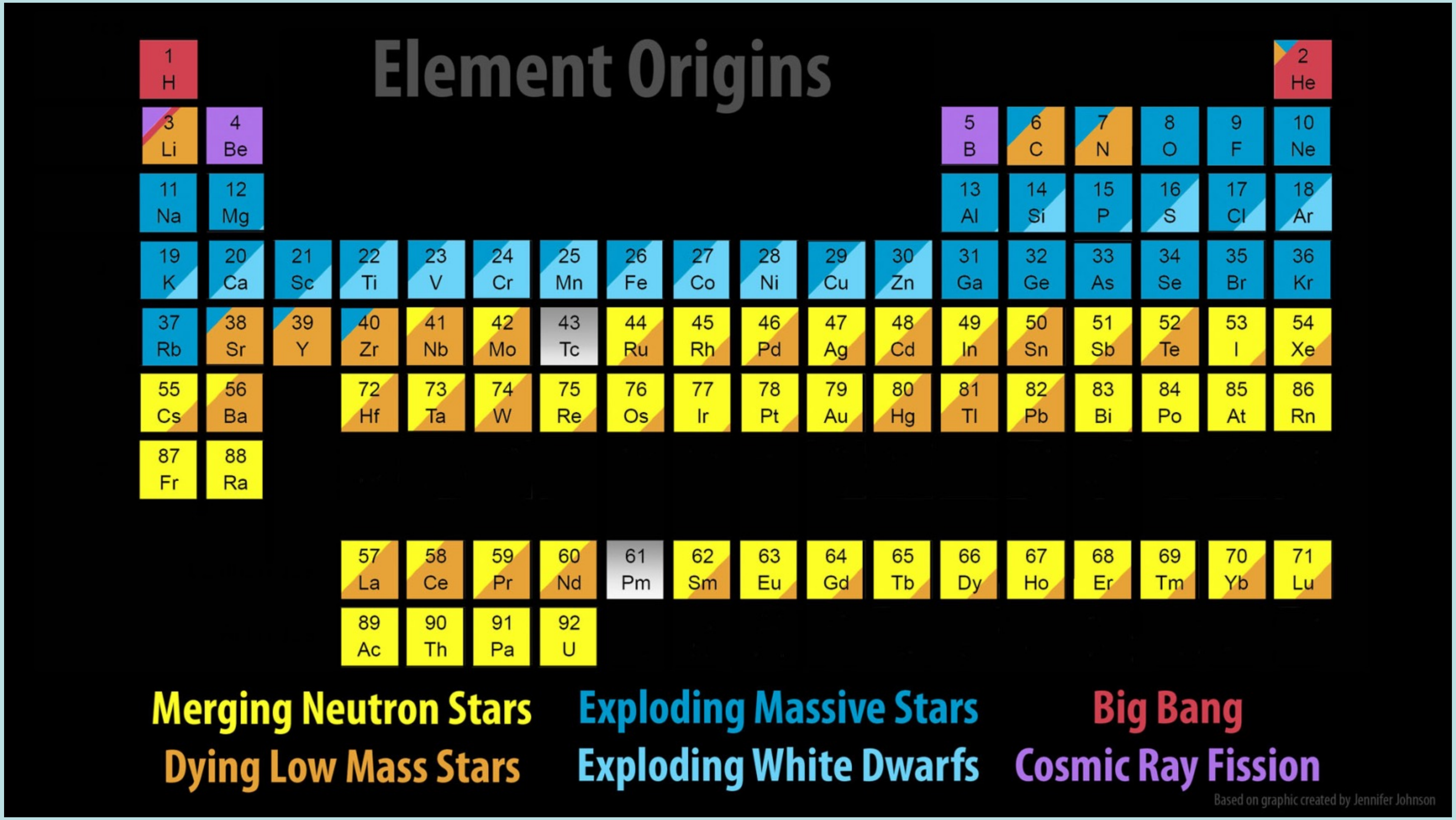


The object resulting from the merger is about 2.7 times the mass of the Sun. As the object continues to be studied, evidence is mounting that what was created in the process was a low-mass black hole (if true, this would represent yet another new class of black holes discovered by LIGO). Continued observations over the next several years may confirm or refute this notion.

Mystery of short Gamma Ray Bursts at least partly solved: With our unprecedented knowledge of the progenitor (i.e., pre-merger) masses, studies have confirmed that binary neutron star (BNS) mergers are the source of at least some (if not all) short Gamma Ray Bursts (sGRBs), a phenomenon often seen in satellite-borne detectors, but only speculated to be associated with coalescences.

Gravitational waves travel at the speed of light! “Multimessenger” observations have confirmed that the speed of gravitational waves and electromagnetic (i.e. light) waves is equivalent, to a very high precision. This unequivocally confirms a basic assumption of General Relativity (the gift to science that keeps on giving!)

Our understanding of the origin of elements in the periodic table changed nearly overnight. Electromagnetic (EM) follow-up observations — possible because LIGO and Virgo's observations pin-pointed the location on the sky — have now confirmed a long-standing supposition that binary neutron star mergers generate a large fraction of the universe’s heavier-than-iron elements, including familiar ones like gold and platinum, to more exotic things such as thorium and uranium.



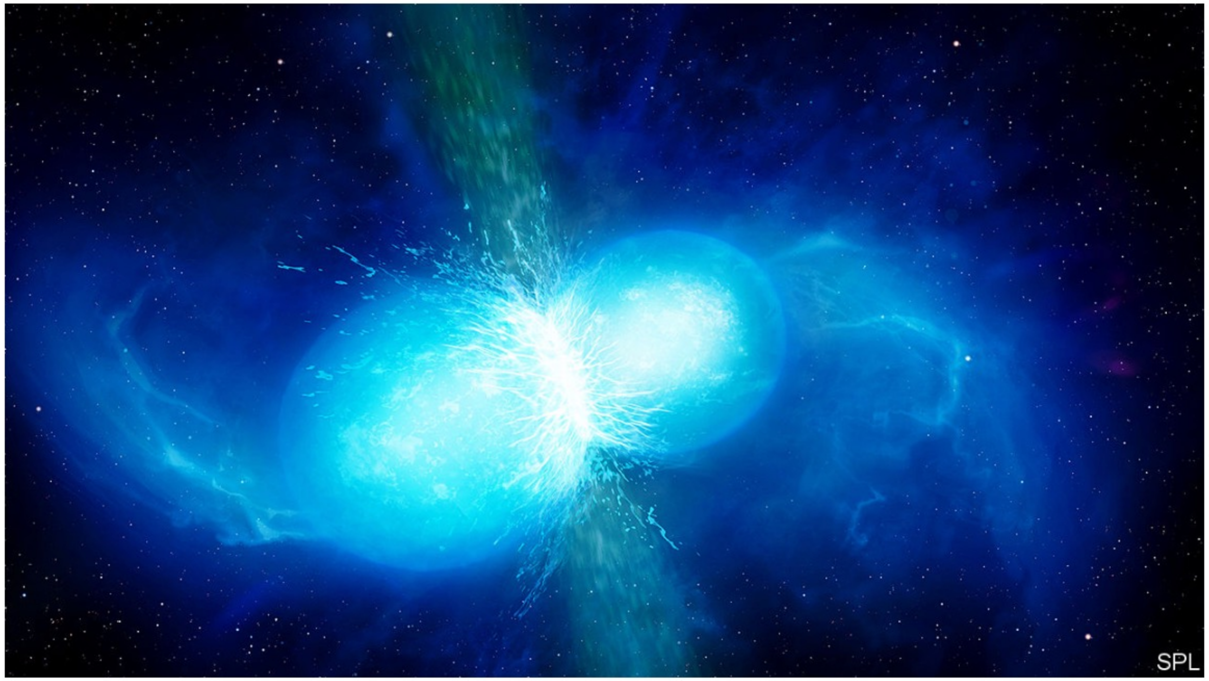
The Economist Topics Current edition More

螢幕快照

How heavy elements were made

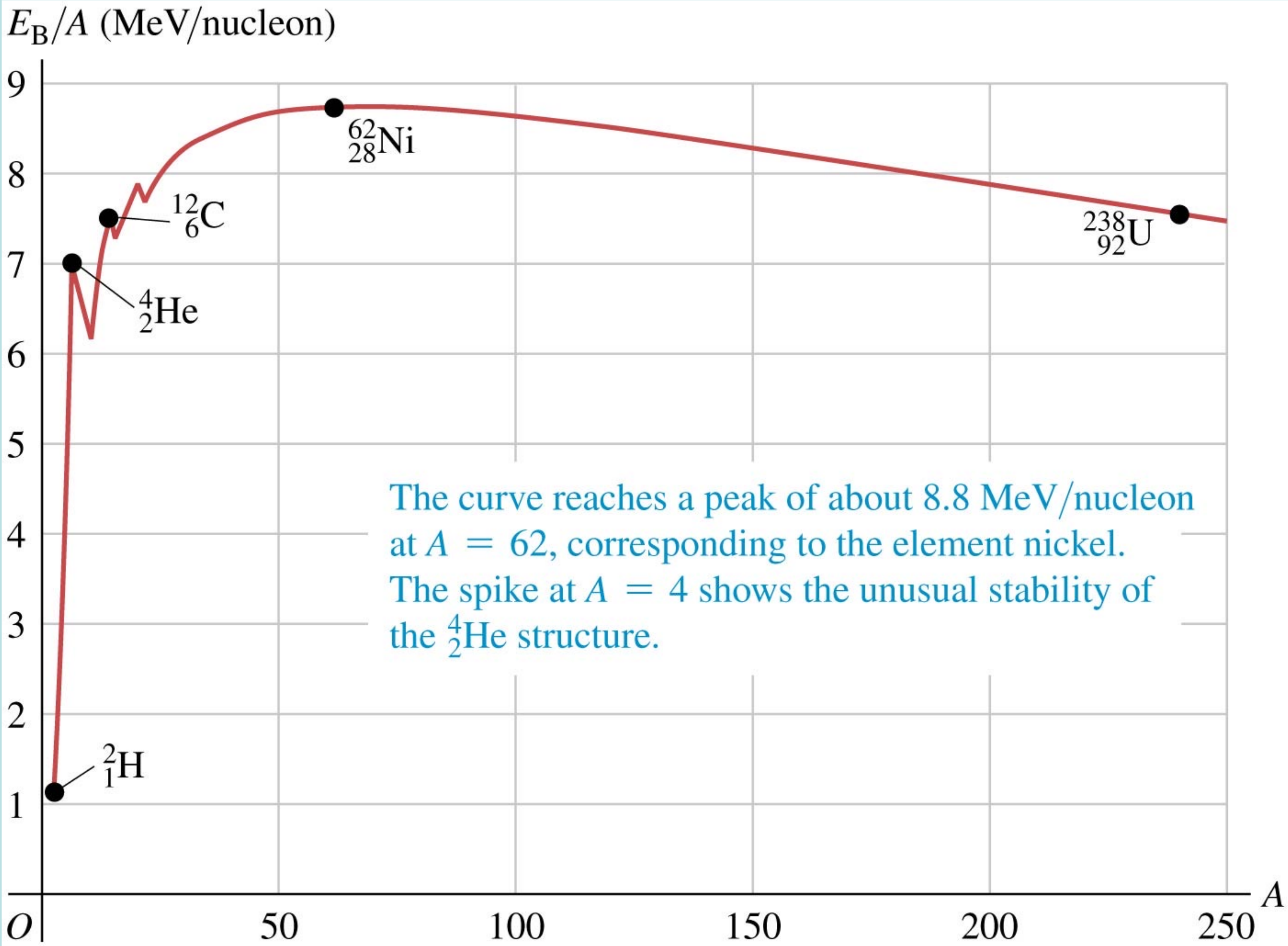
A lot of the periodic table is a result of neutron stars colliding

Such collisions are the ultimate nuclear reactor


SPL

Print edition | Science and technology ›

Feb 21st 2019 | WASHINGTON, DC

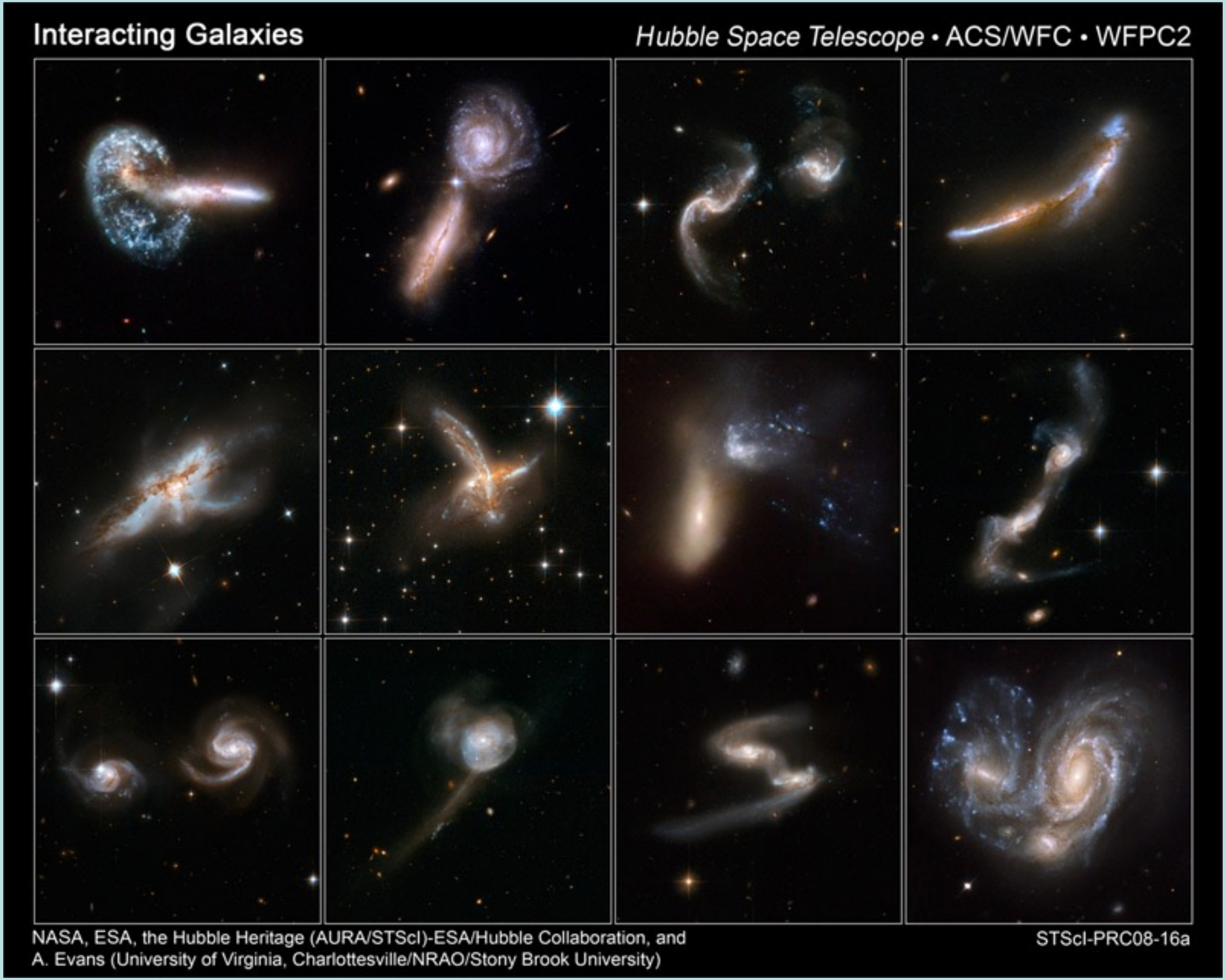


E_B/A (MeV/nucleon)
9
8
7
6
5
4
3
2
1
O
50
100
150
200
250
A
$^{62}_{28}Ni$
$^{12}_{6}C$
$^{4}_{2}He$
$^{238}_{92}U$
$^{2}_{1}H$
The curve reaches a peak of about 8.8 MeV/nucleon at $A = 62$, corresponding to the element nickel. The spike at $A = 4$ shows the unusual stability of the $^{4}_{2}He$ structure.

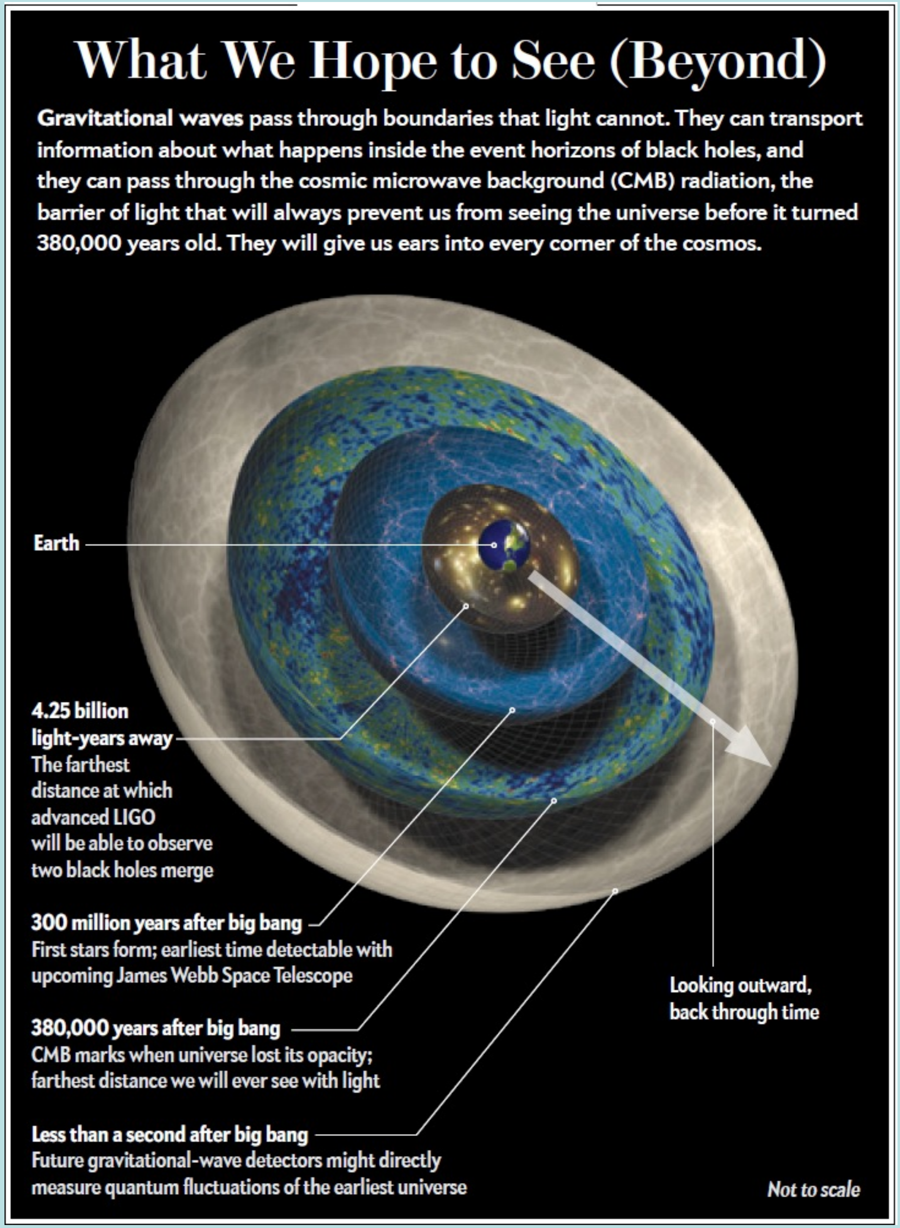
為什麼重力波如此重要而有趣？

NASA’s NuSTAR telescope

The real monster black hole is revealed in this new image from NASA's Nuclear Spectroscopic Telescope Array of colliding galaxies Arp 299. In the center panel, the NuSTAR high-energy X-ray data appear in various colors overlaid on a visible-light image from NASA's Hubble Space Telescope. The panel on the left shows the NuSTAR data alone, while the visible-light image is on the far right.Before NuSTAR, astronomers knew that the each of the two galaxies in Arp 299 held a supermassive black hole at its heart, but they weren't sure if one or both were actively chomping on gas in a process called accretion. The new high-energy X-ray data reveal that the supermassive black hole in the galaxy on the right is indeed the hungry one, releasing energetic X-rays as it consumes gas.In this image, X-rays with energies of 4 to 6 kiloelectron volts are red, energies of 6 to 12 kiloelectron volts are green, and 12 to 25 kiloelectron volts are blue.


Interacting Galaxies
Hubble Space Telescope • ACS/WFC • WFPC2
NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)
STScI-PRC08-16a

為什麼重力波如此重要而有趣？



宇宙在第四十萬年生日之前是模糊的，因此靠電磁波無法觀察，
但宇宙早期的重力波會保留宇宙早期的痕跡。