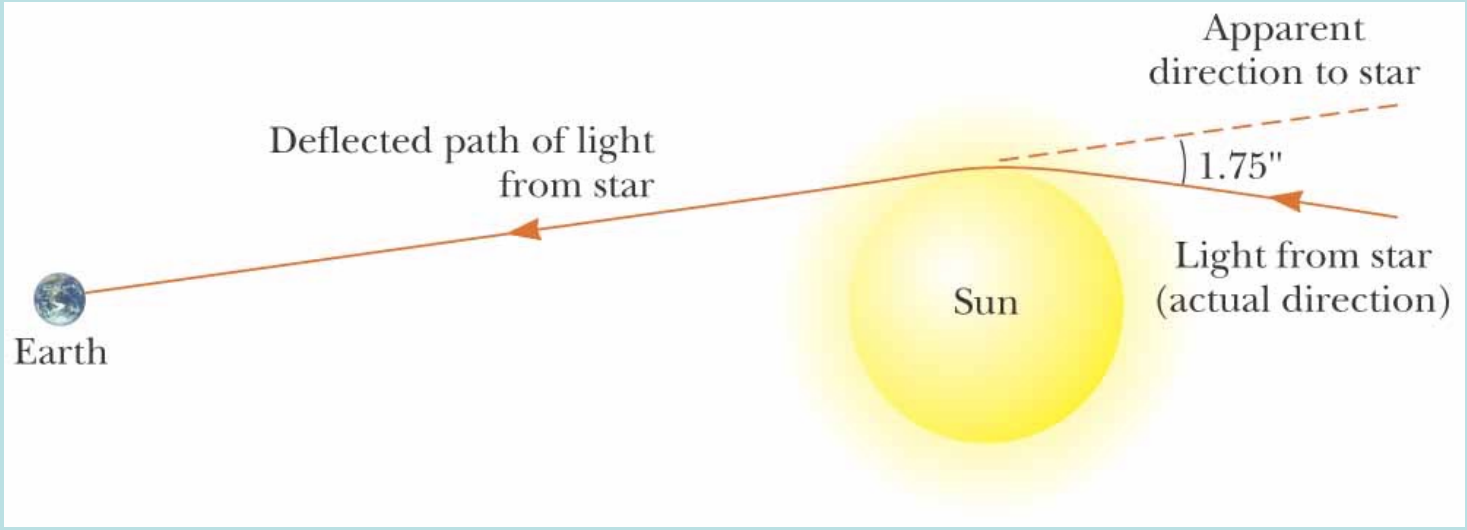
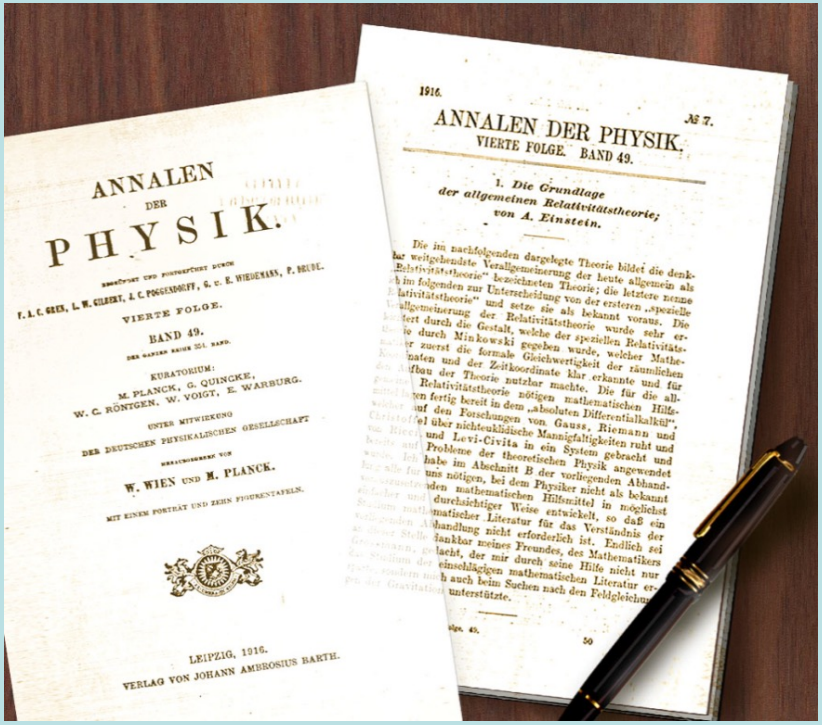
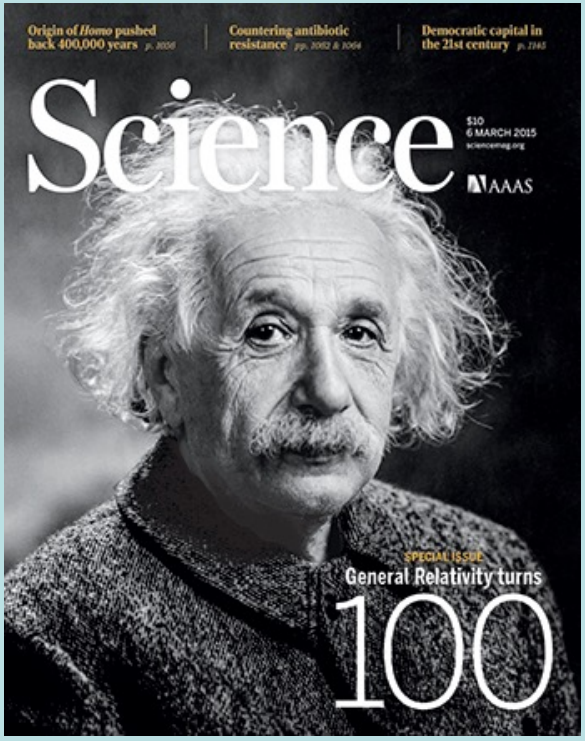


能量（質量）造成周圍時空彎曲，所有物體都沿此彎曲時空的直線運動！

廣義相對論 1915-1916







重力不是力！

重力現象是能量（質量）造成周圍時空彎曲。

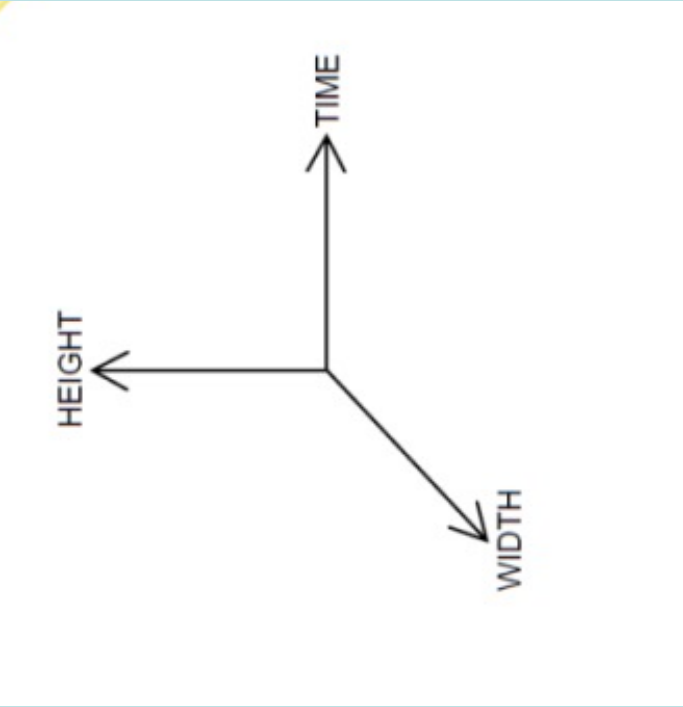
彎曲時空如何描述最簡單的自由落體呢？

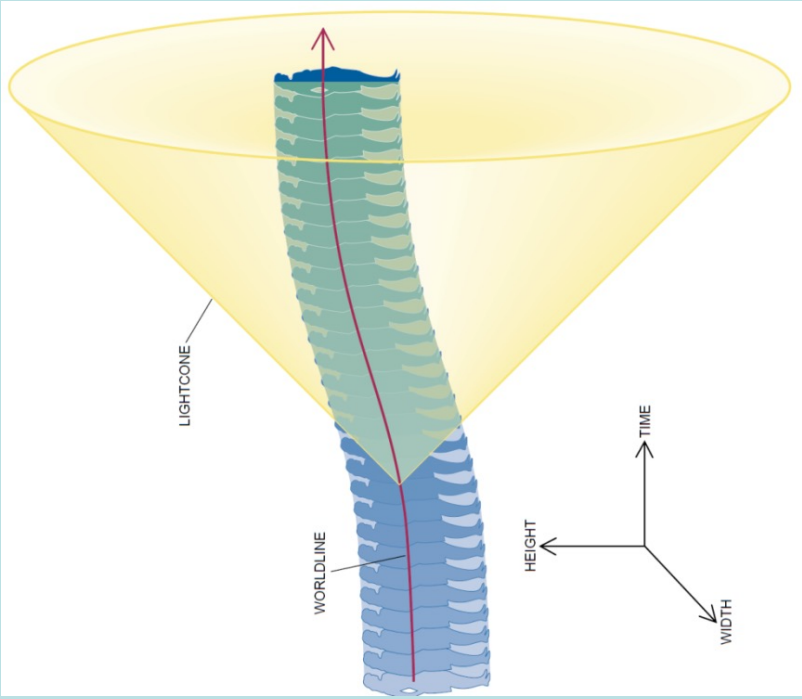
先讓我們介紹一個很有用的工具：光錐。

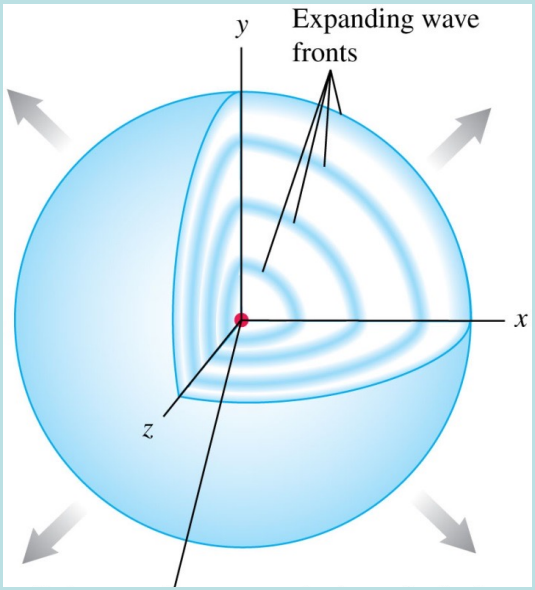
時間與空間是絕對無法分割的，因此必須合併討論，稱為時空 Space-time。

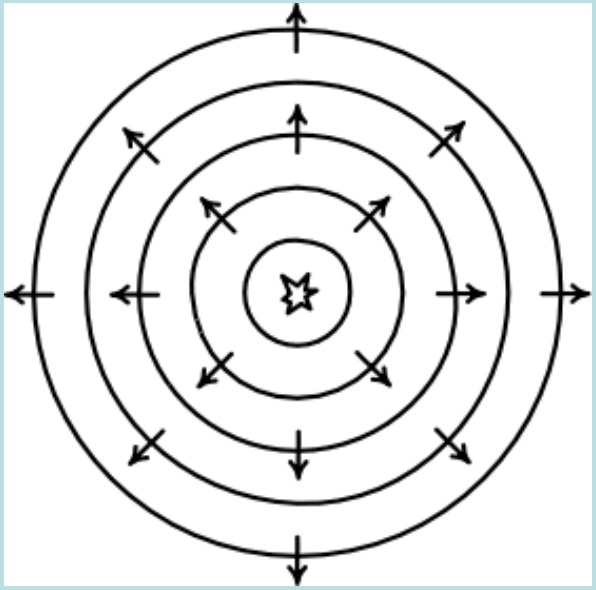
一般會把時間與空間畫在同一圖上，稱為時空圖，注意：空間就要少畫一維。

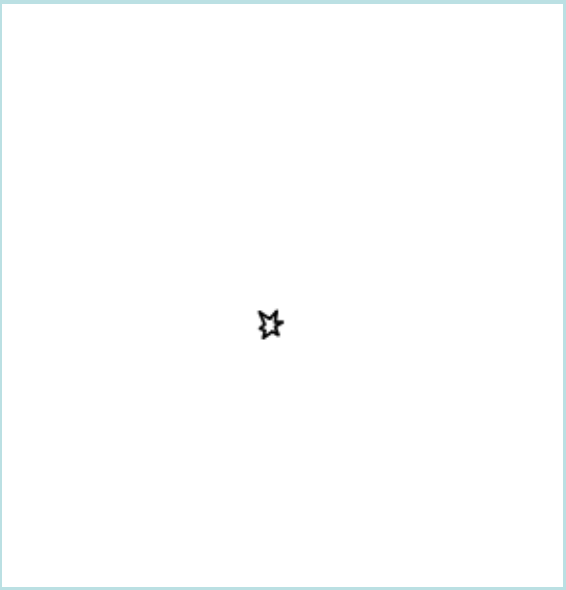
一個物體的歷史在時空圖上就形成一條彎曲的線，稱為世界線。

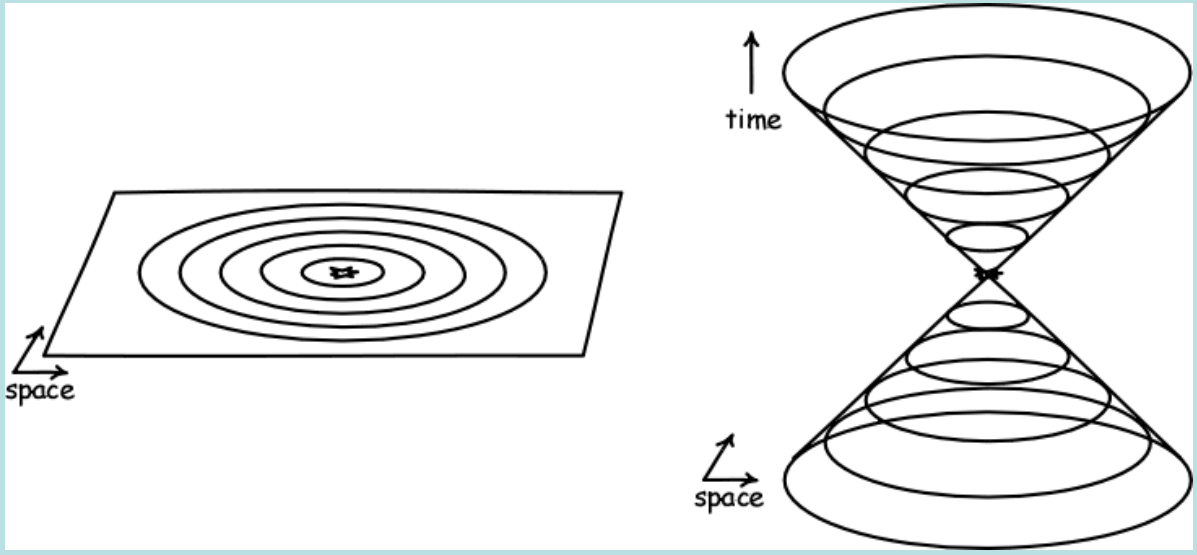








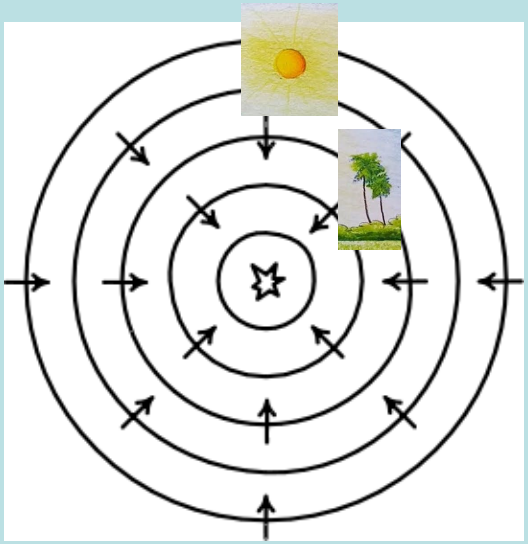


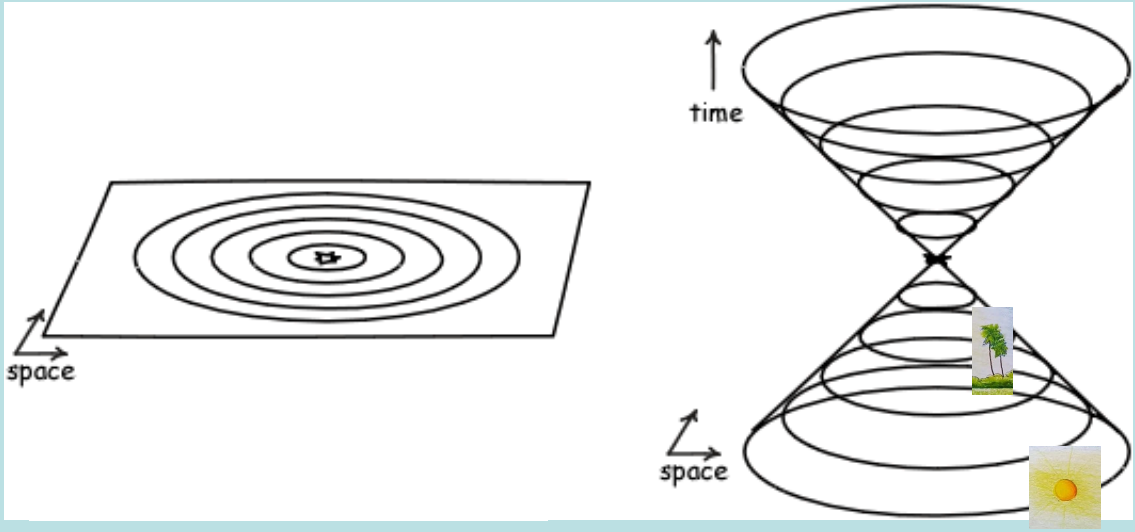


考慮在原點的觀察者，向四面放出光脈衝。光傳播會形成一個逐漸加大的球殼。

在時空圖上，忽略一維空間後，球殼則簡化為逐漸加大的圓。

因此，在時空圖上，這脈衝光會形成一個以原點為頂點的圓錐，稱為光錐。





現在，如果在原點的觀察者收到一脈衝光。

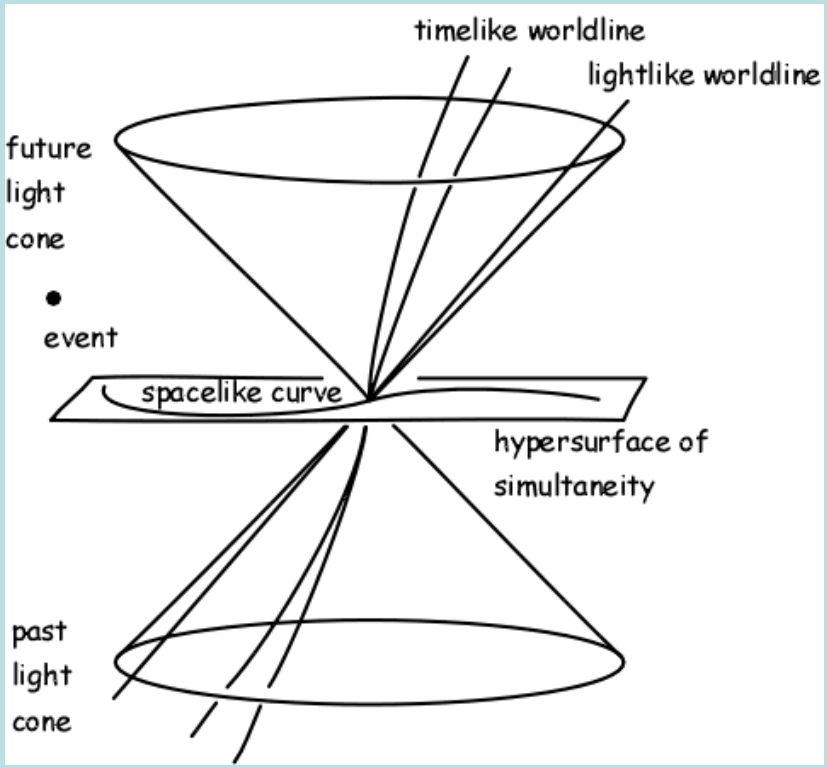
我們可以根據它的方向，回溯這道光可能的過去的軌跡，

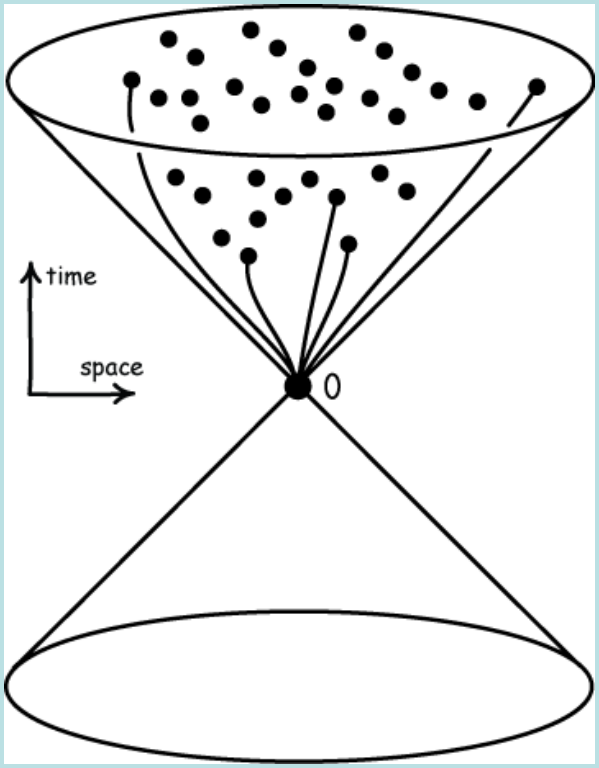
集合所有可能的軌跡即形成一以原點為頂點，向過去延伸的錐體。稱為過去光錐！

其實這就相當於你向四面觀看時所看到的景象。那是你所能看到的過去！

注意比較遠的影像來自比較久以前的過去。





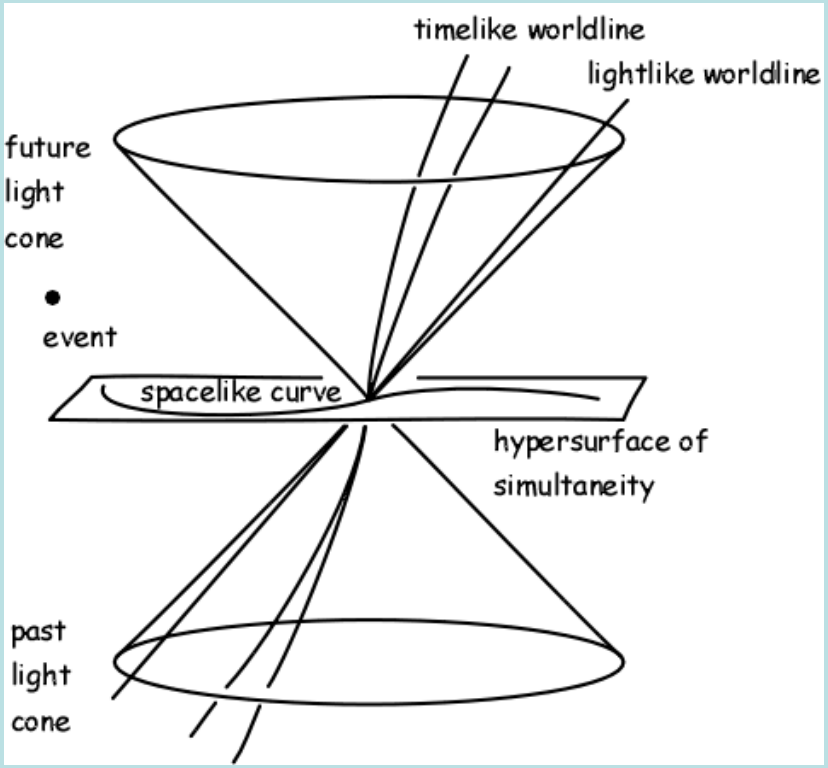


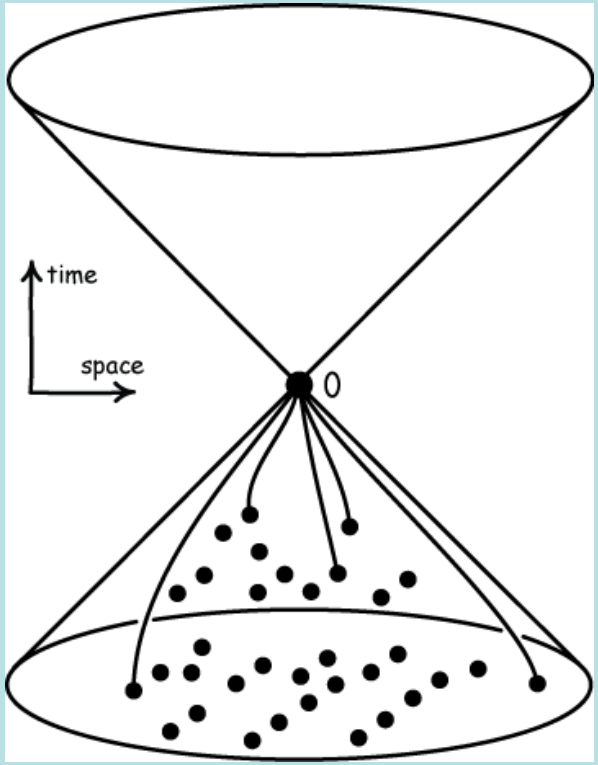
任何物體的運動不能快過光速，通過原點的世界線只能落在未來光錐之內！

因爲通過原點的世界線若要落在未來光錐之外，速度得快過光速！

位於原點的觀察者能影響的、有因果關係的事件一定落在光錐之內！

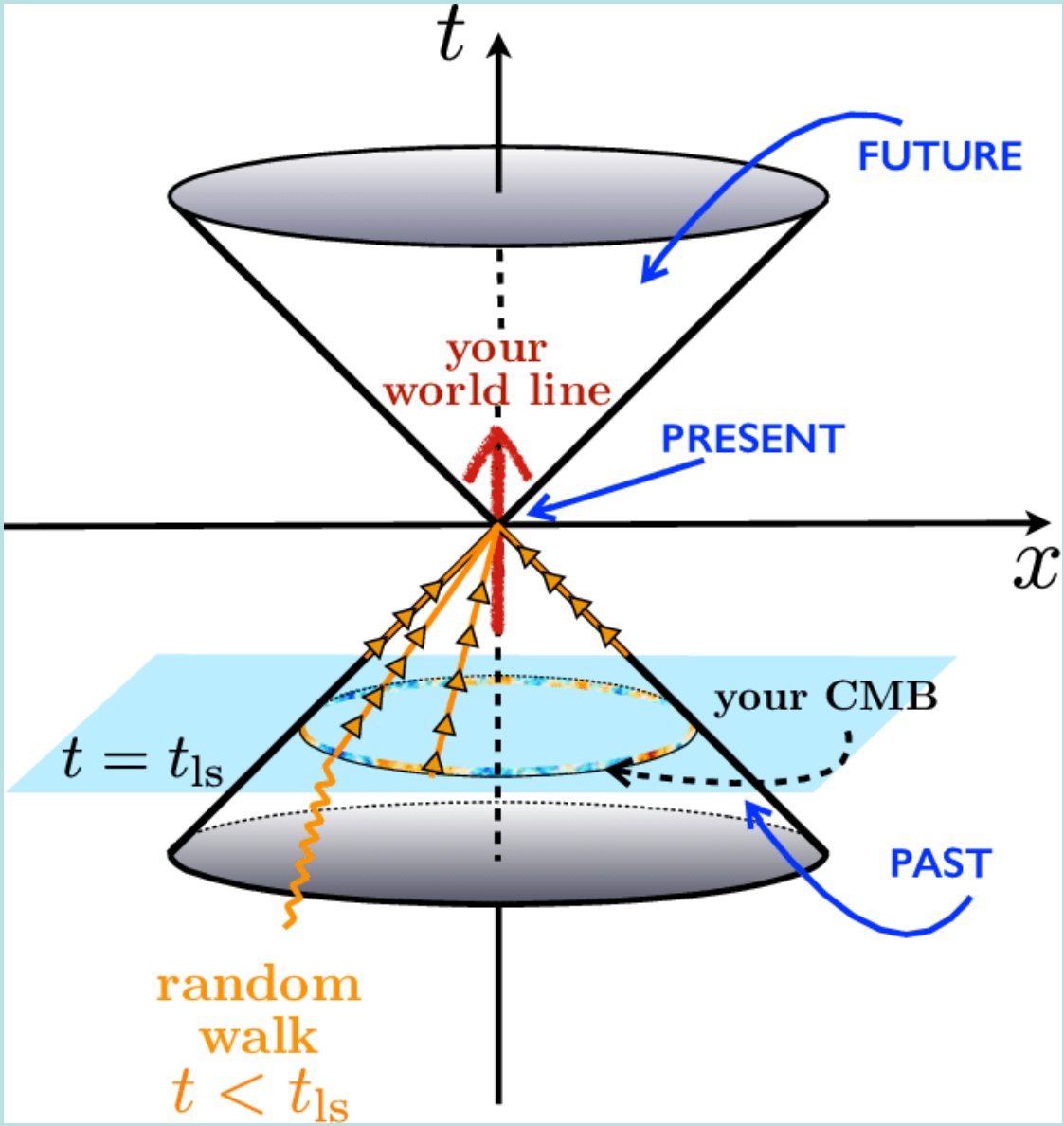
未來光錐，代表觀察者可能的未來！



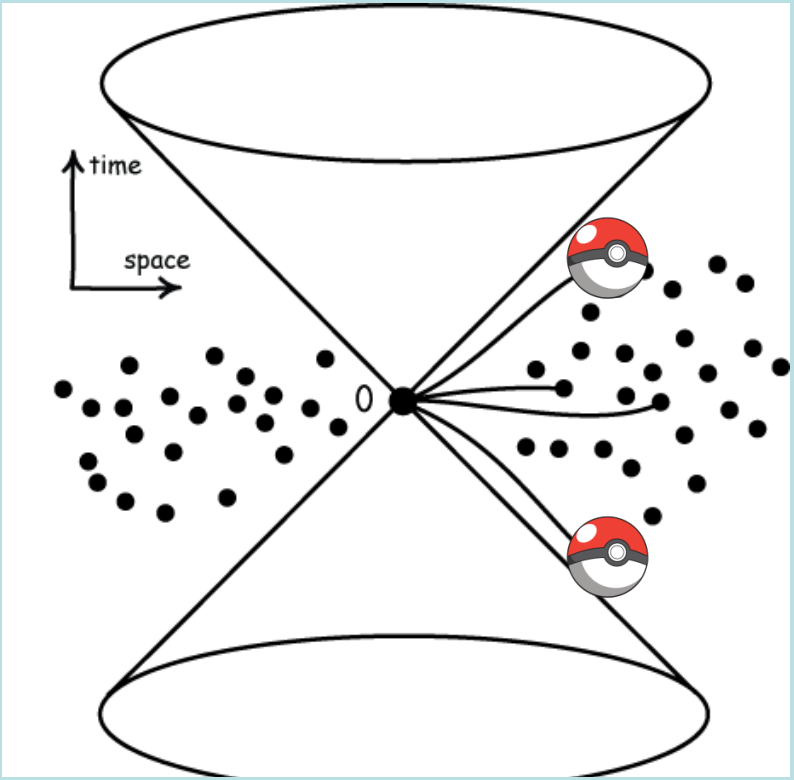


同理，所有能影響原點的觀察者、有因果關係的事件一定落在過去光錐內，

過去光錐代表觀察者可能有關係的過去。



前光錐是未來，後光錐是過去，因此光錐構成了可以與現在有關的宇宙的邊界.....

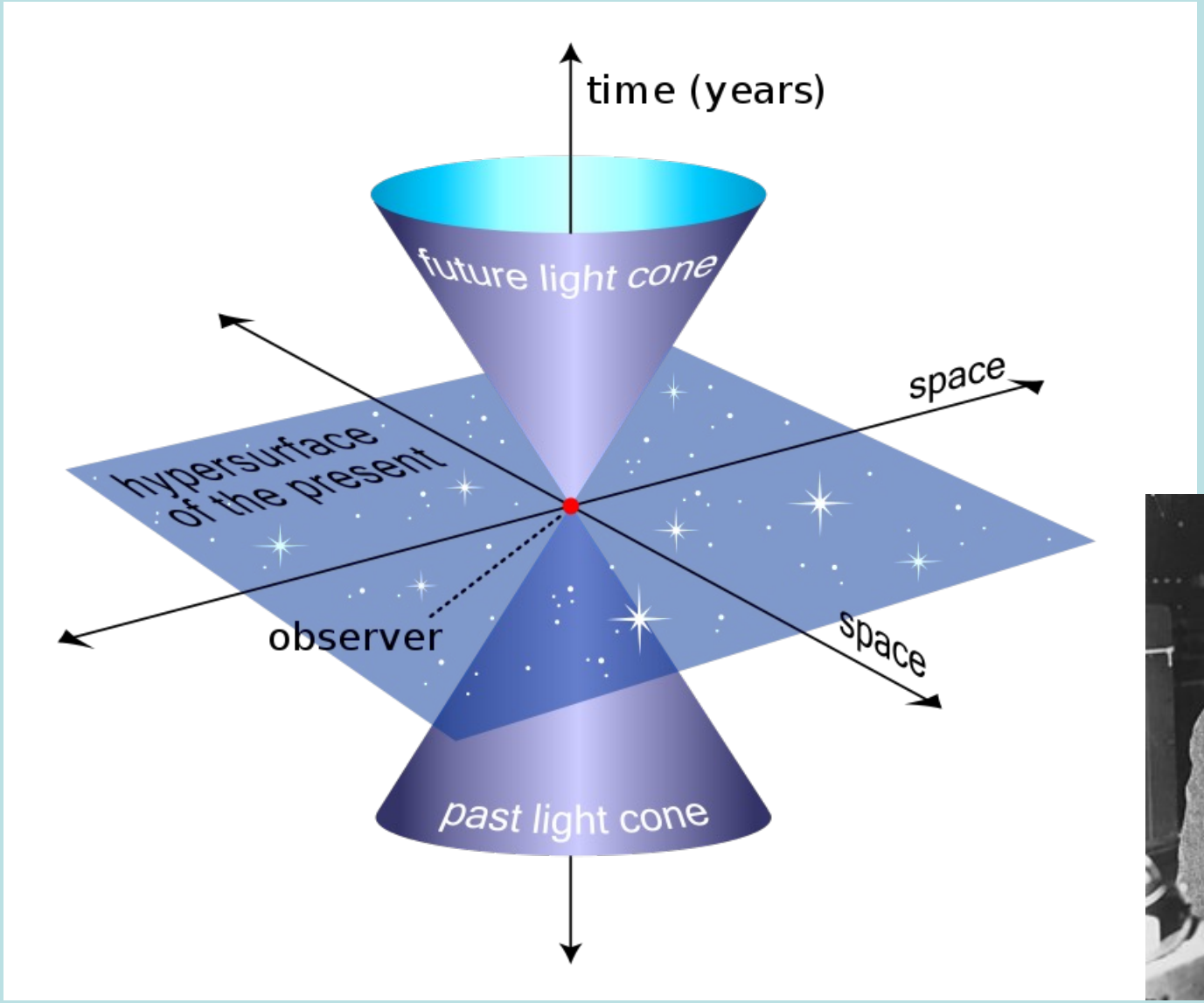


注意：發生於光錐之外的事件，

若要與原點的觀察者發生關係，

此關係的發生必須以超越光速的速度傳遞！

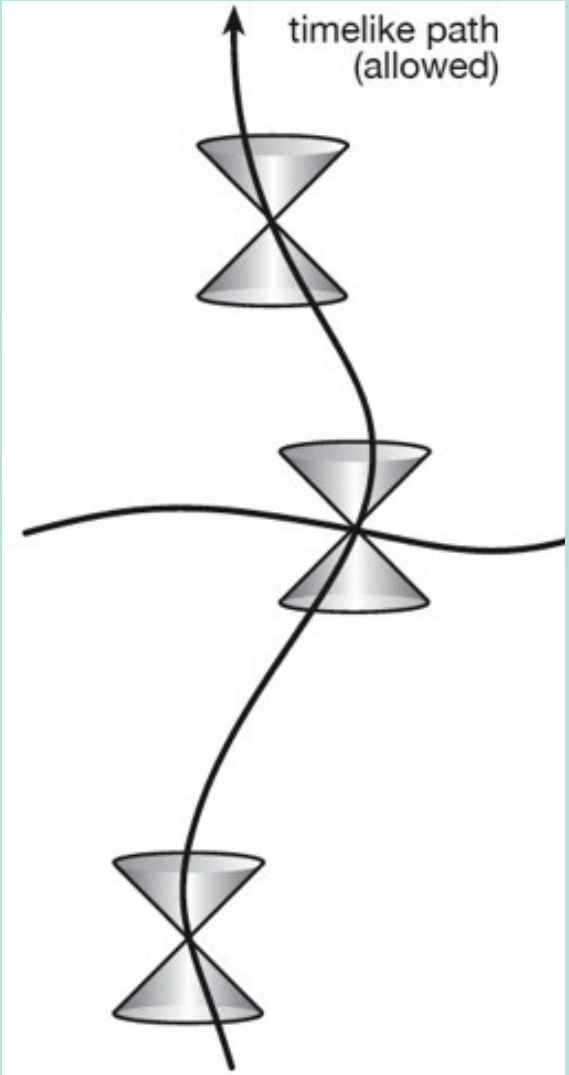
因此發生於光錐之外的事件，不能與原點的觀察者有關。

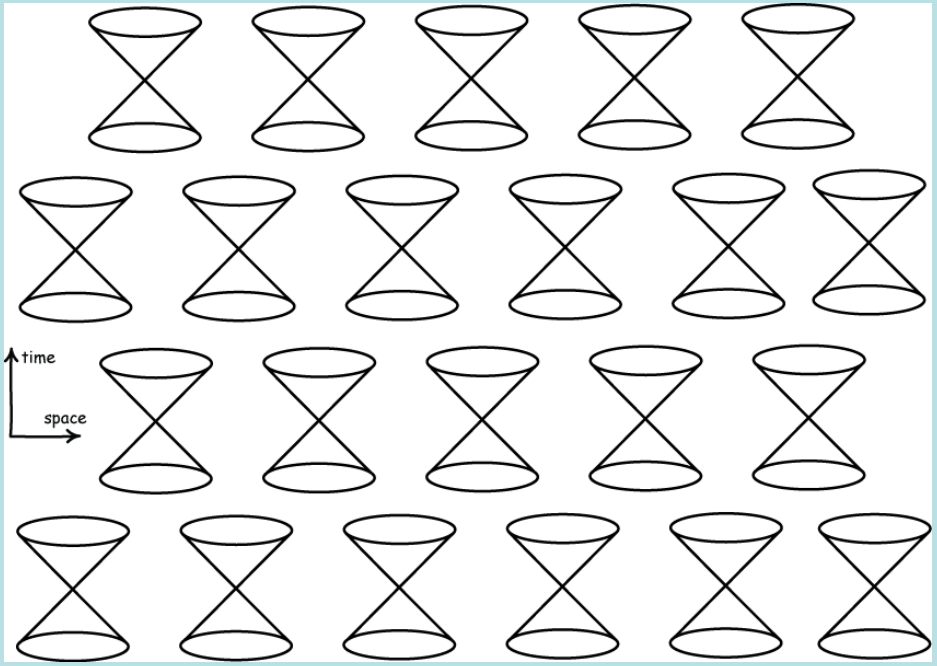




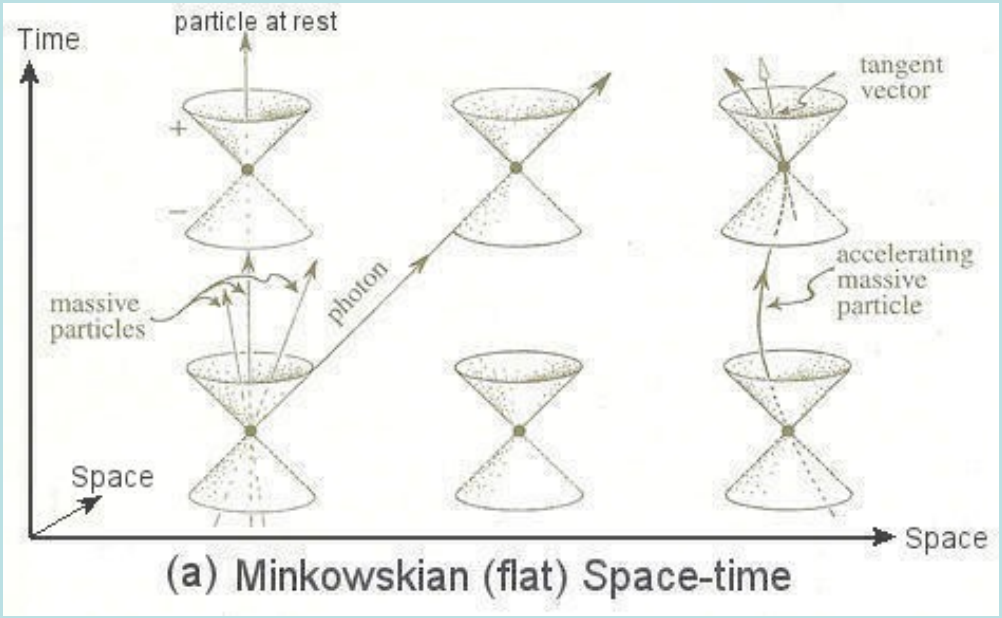
時空以因果關係被切成了三個區域！

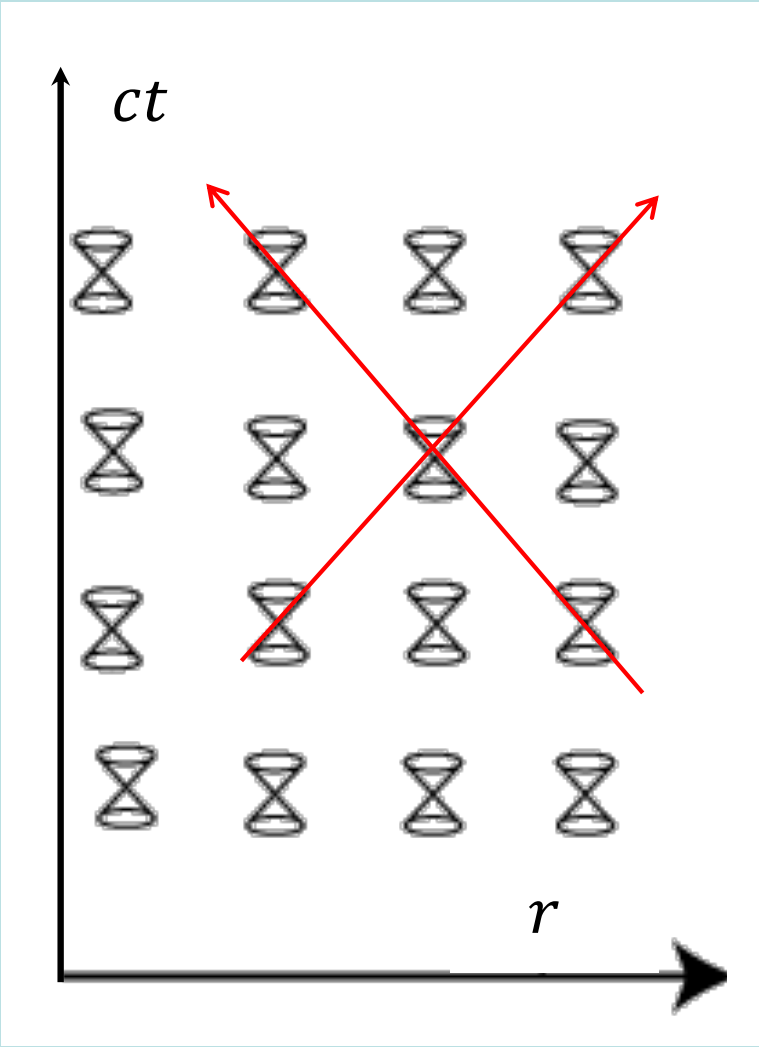
物體的運動路徑，將落在沿著路徑的光錐之內！





時空中每一點都有一個光錐





在星體旁的物理，可以取 ct為縱軸，半徑r為橫軸來討論。

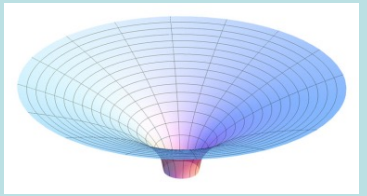
若是平坦的時空，則光總是沿45°角運動，因此各地光錐是平行的。

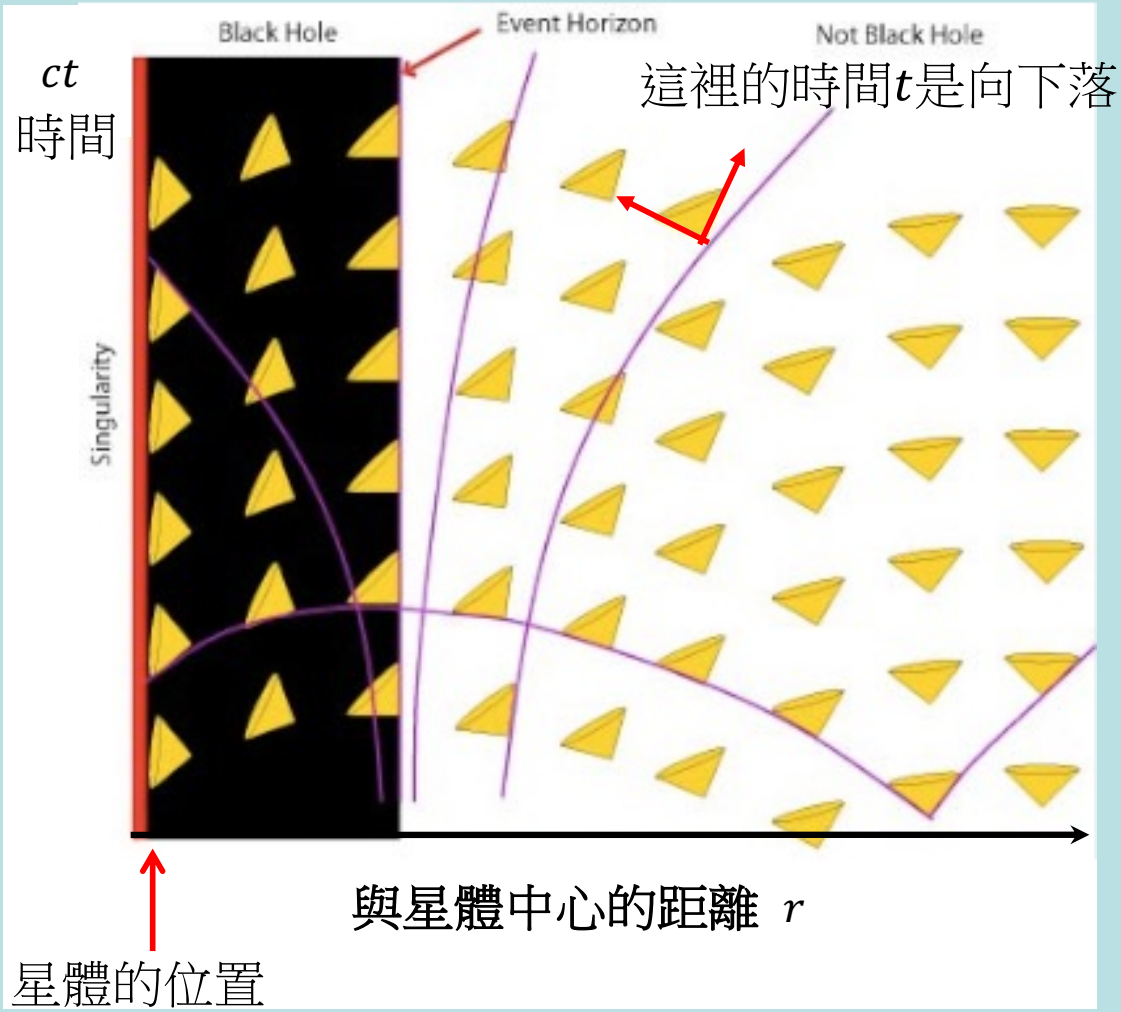
在星體的周圍，時空會被彎曲為史瓦西度規，

光會被星體重力所加速，向星體的光快於離星體的光。

因此時空中各點的光錐，會向星體的中心傾斜的。

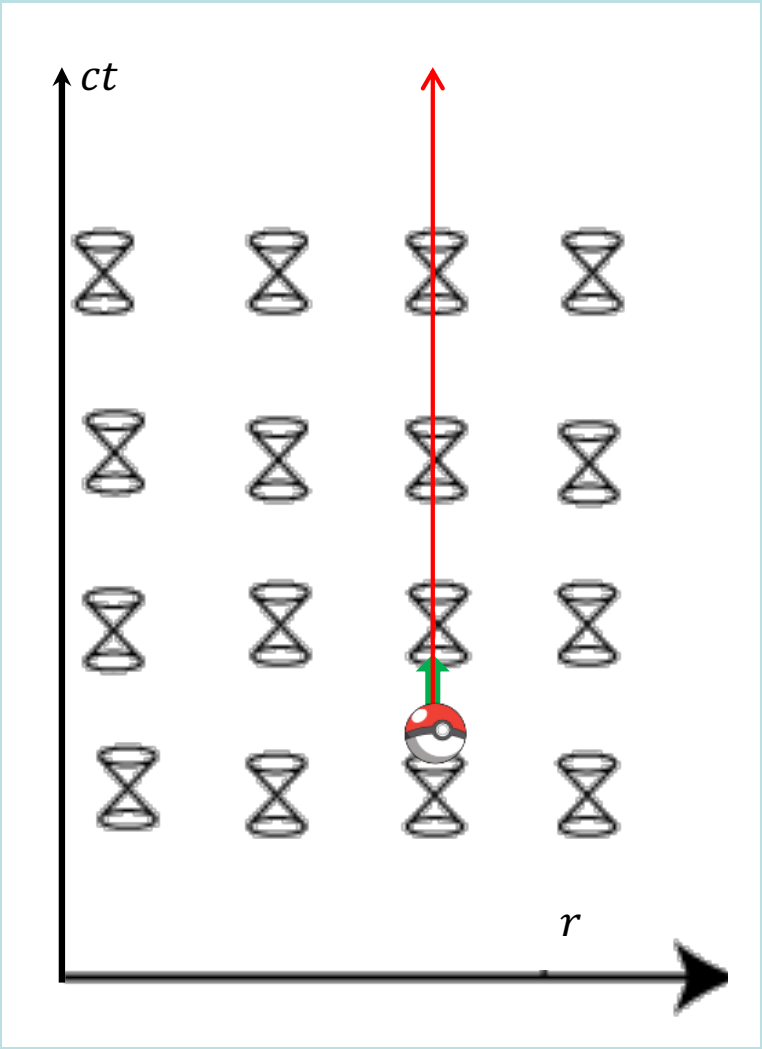
愈靠近星體，傾斜越厲害。



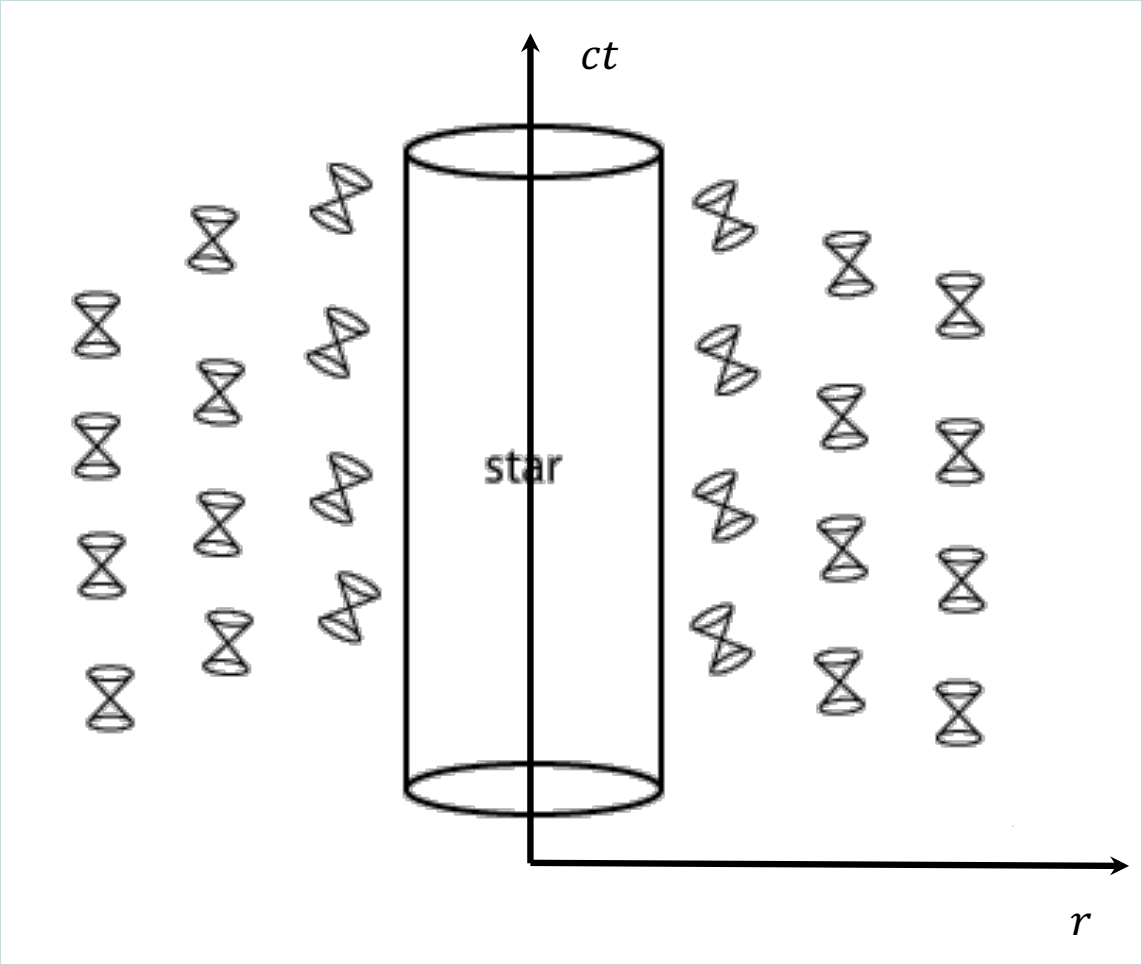


這裡的時間t是向下落的雨滴帶的表的時間。

在平坦的時空中，不受力的靜止的物體，其時空軌跡為沿時間軸的直線。







一個球型星體會使各地的光錐往內傾斜

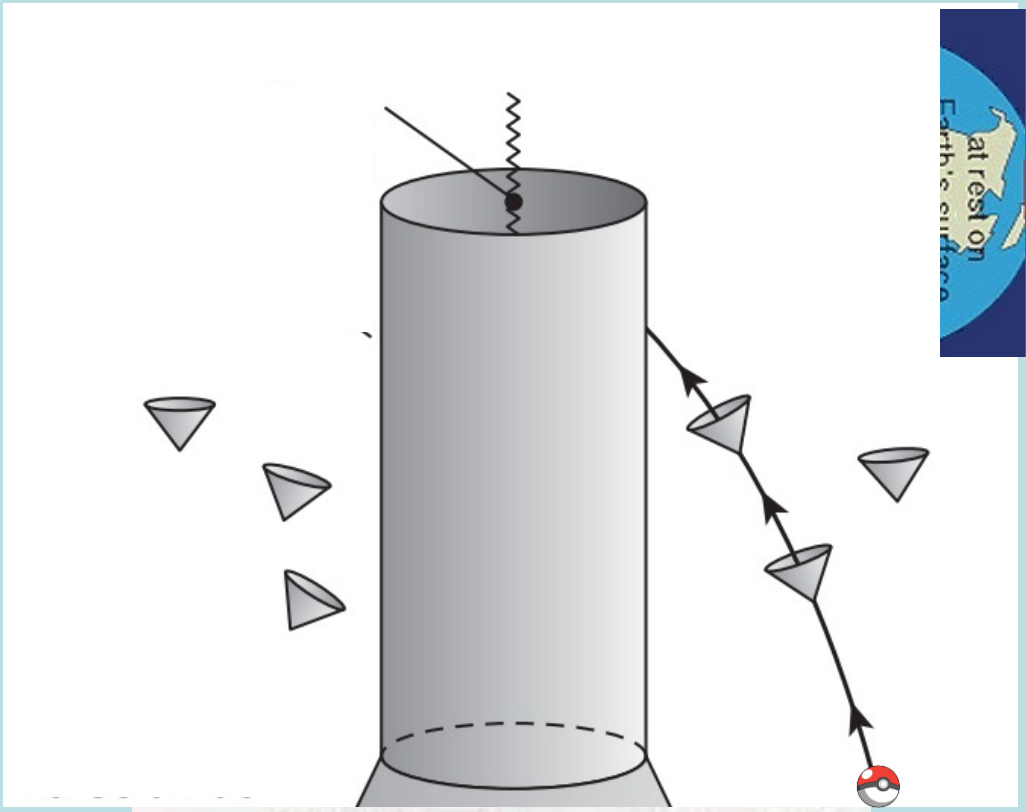
越靠近星體傾斜越大。

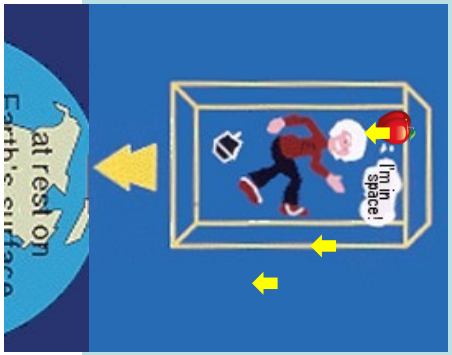
在星體周圍的彎曲時空中：

不受力的”靜止”物體，隨著光錐的傾斜，其世界線也會朝向球心偏移。

從物體自己的觀點看來，它是靜止的，此世界線就是他的時間的流動。

從遠處看來，物體的運動路徑就是一個自由落體的加速運動！





這就是廣義相對論史瓦西度規描述自由落體的方式！

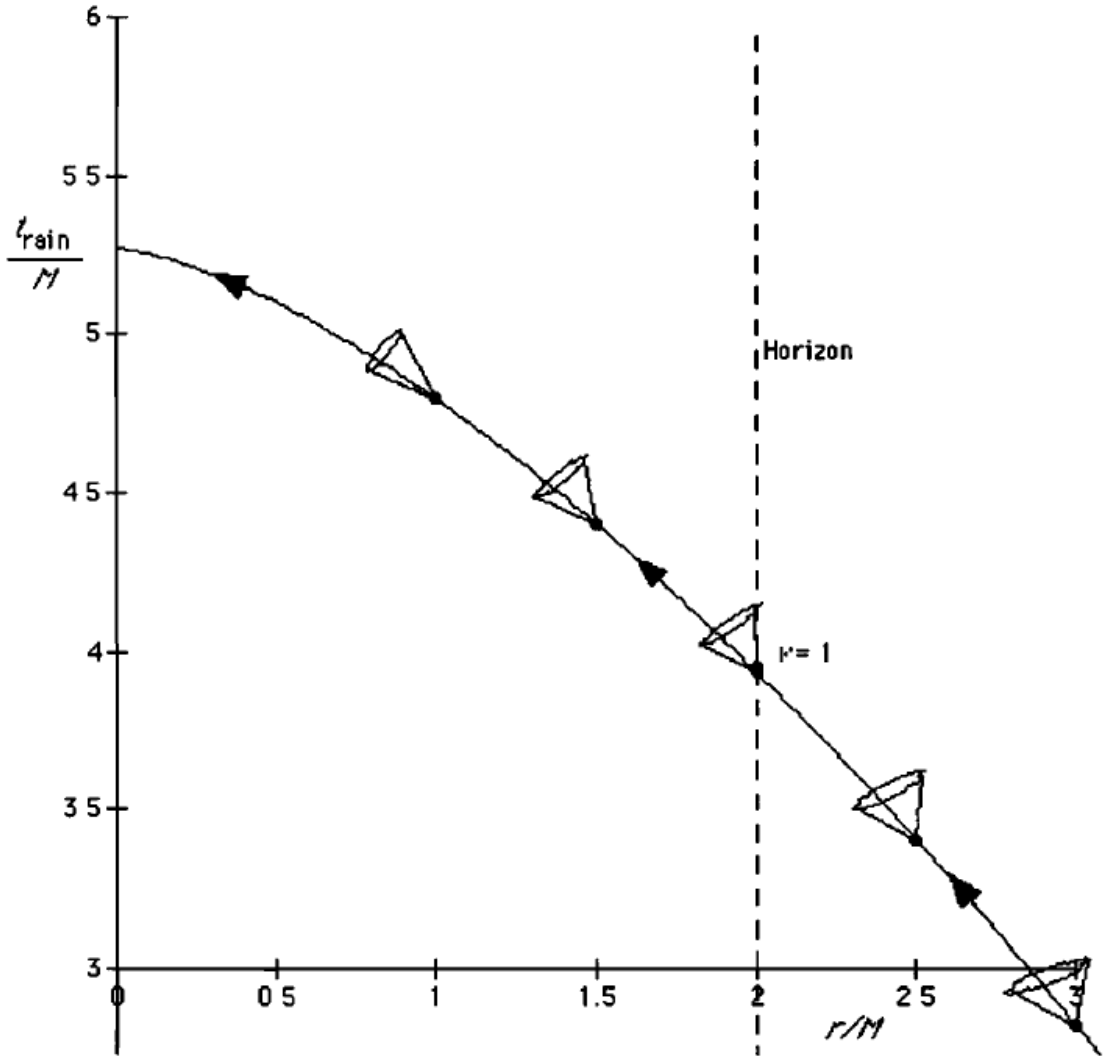
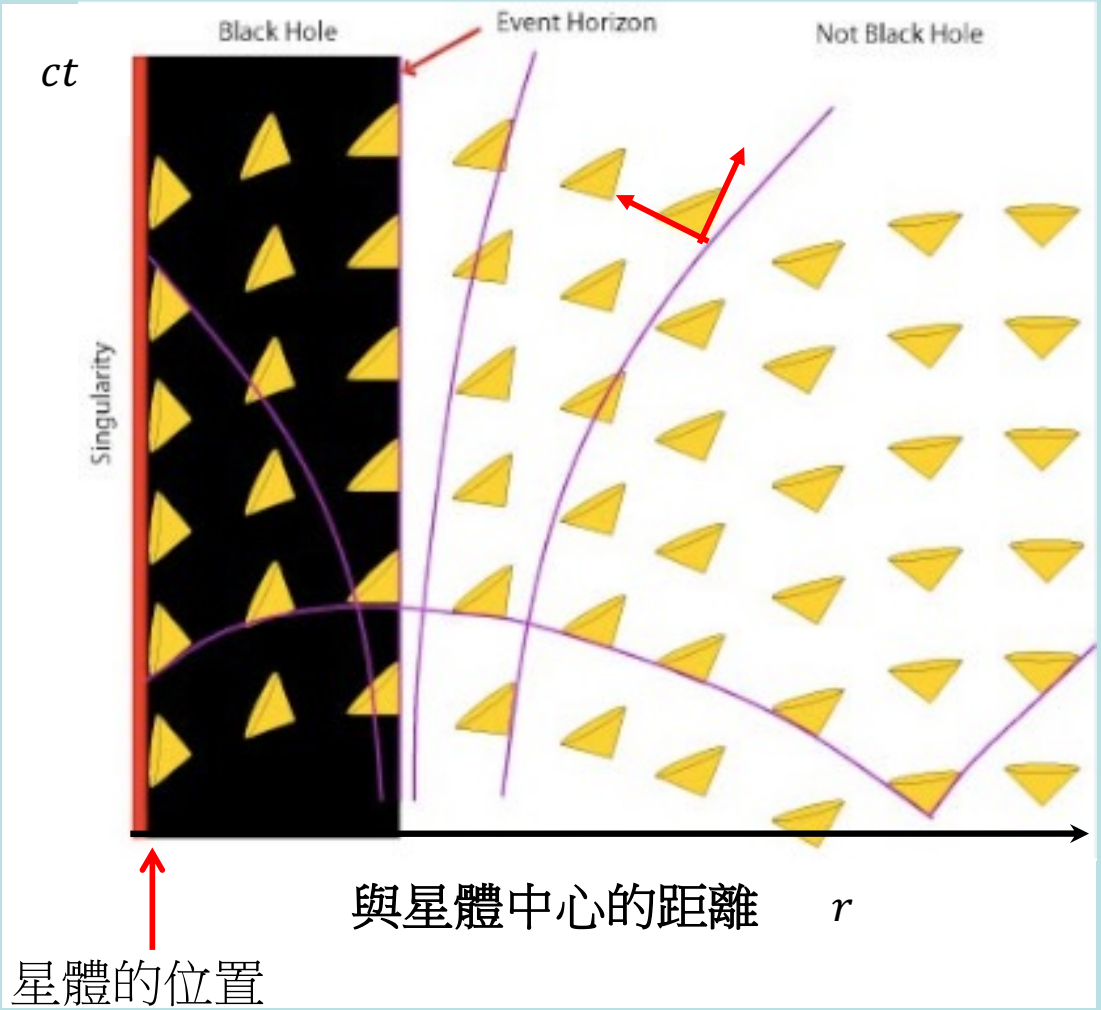


Figure 5 *Computer plot· Worldline of a raindrop emitting flashes as it passes inward through the horizon of a black hole Arrowheads show the direction of motion of the raindrop along its worldline Little cones represent light spreading out in all directions from flash emissions along the worldline The lower line segment leaving each dot represents the initial motion of the portion of the flash sent inward (minus sign chosen in equation [17]) The upper line segment represents the initial motion of the portion of the flash aimed radially outward (plus sign chosen in equation [17]) Inside the horizon even the portion of the flash aimed radially outward moves inward, toward the center Note that the figure shows only the initial motion of these light flashes For an example of a full trajectory of light, see Figure 7, page B-19.*

一個自由落體向四周發光所形成的光錐。

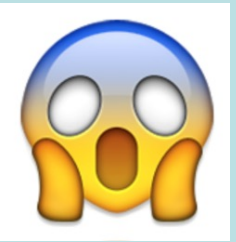
Schwarzschild metric 史瓦西度規中各點的光錐



一個球型星體會使各地的光錐往內傾斜

越接近球心，光錐傾斜越厲害。

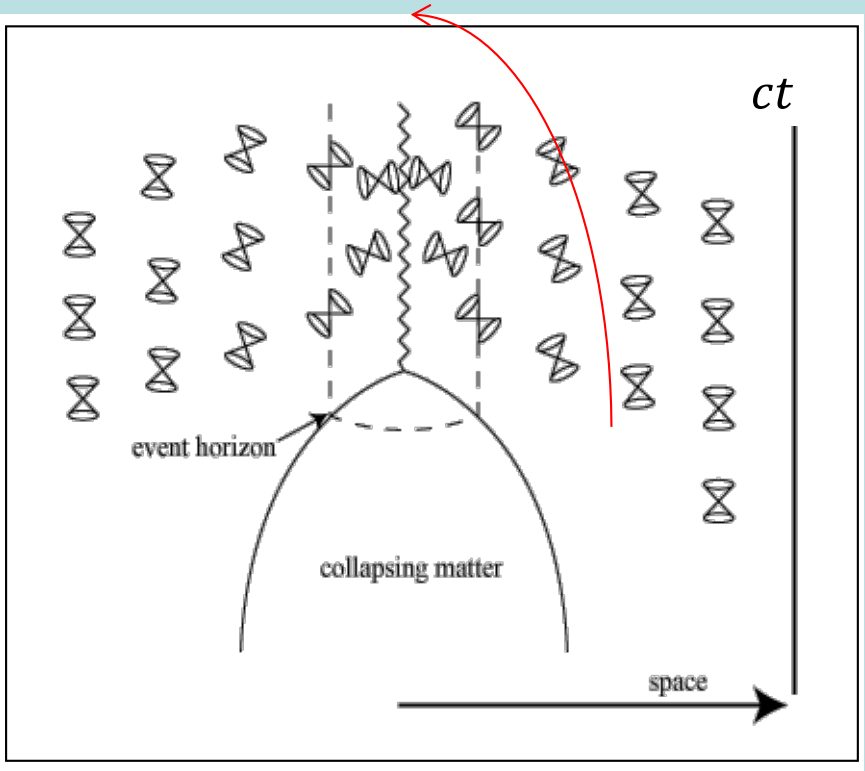
史瓦西度規同時預測$r < \frac{2GM}{c^2}$時光錐會傾斜超過45°!

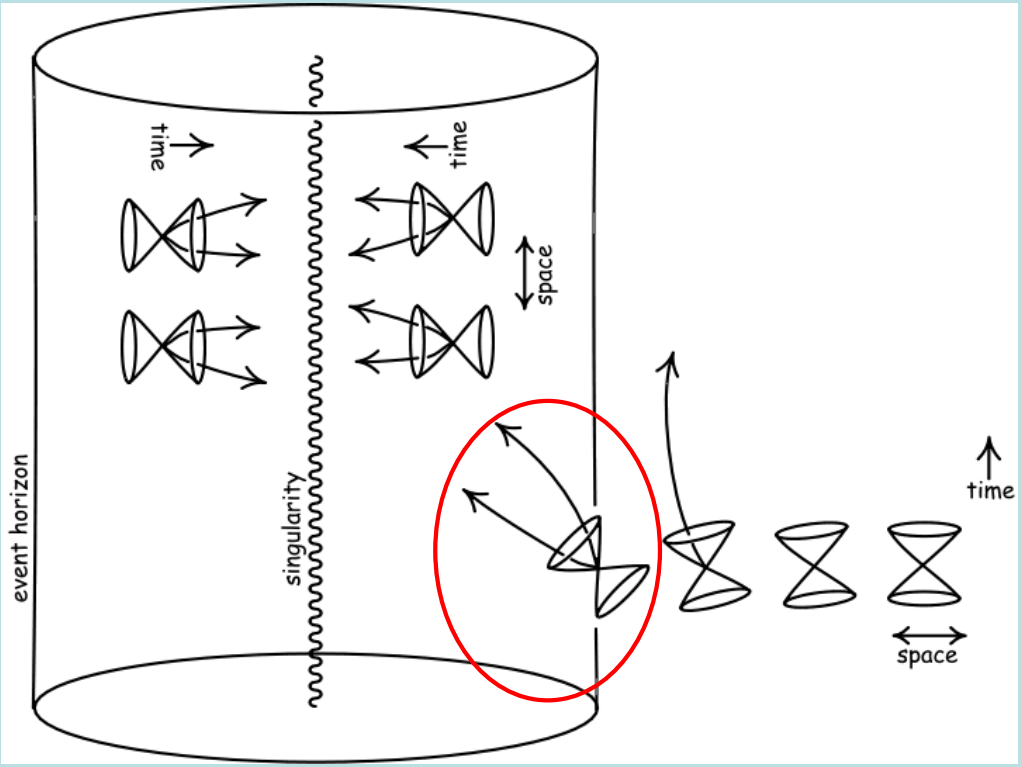


$r = \frac{2GM}{c^2}$時光錐會傾斜超過45°！

物體只能在光錐內移動，因此進入這個範圍內的物體，r只能減少，無法增加！

進入這個範圍內的物體就永遠無法遠離星體了！





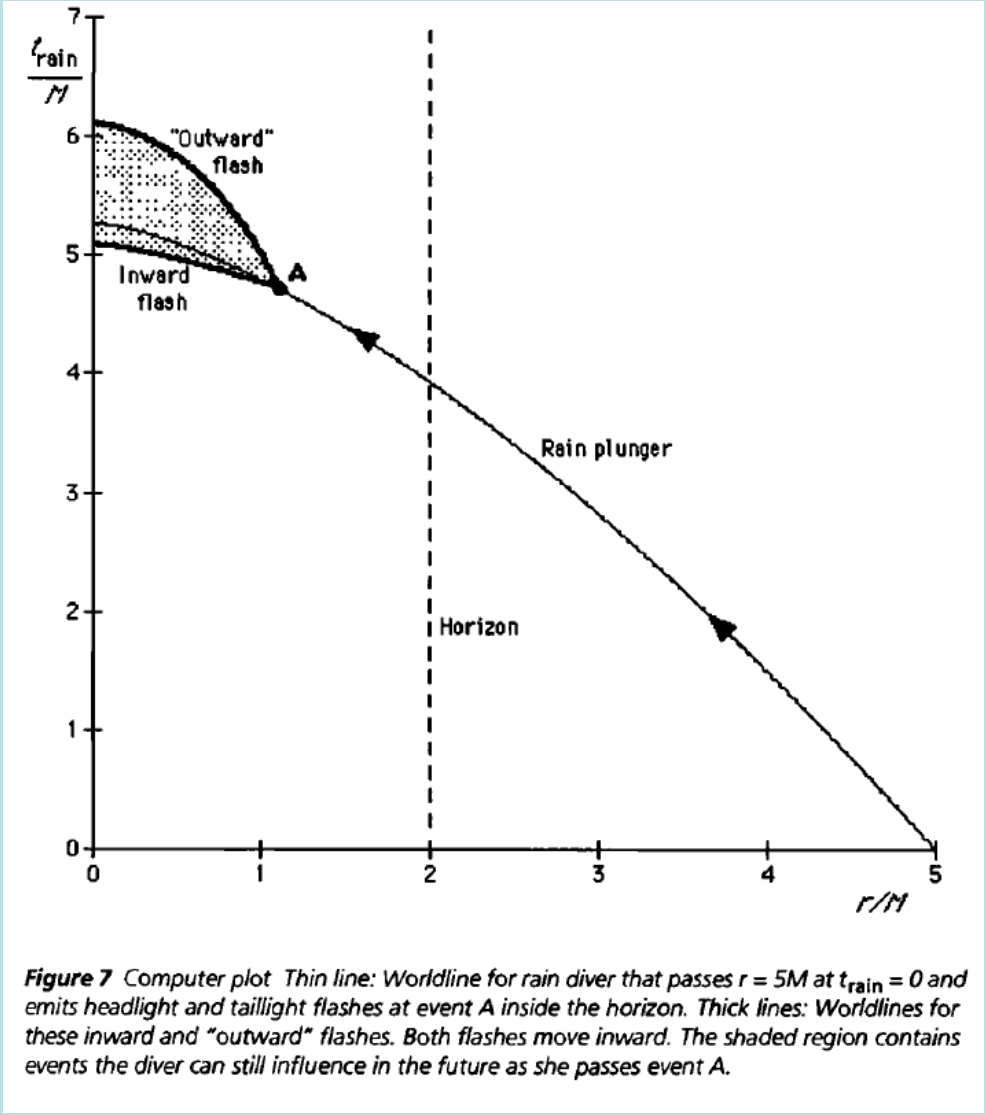
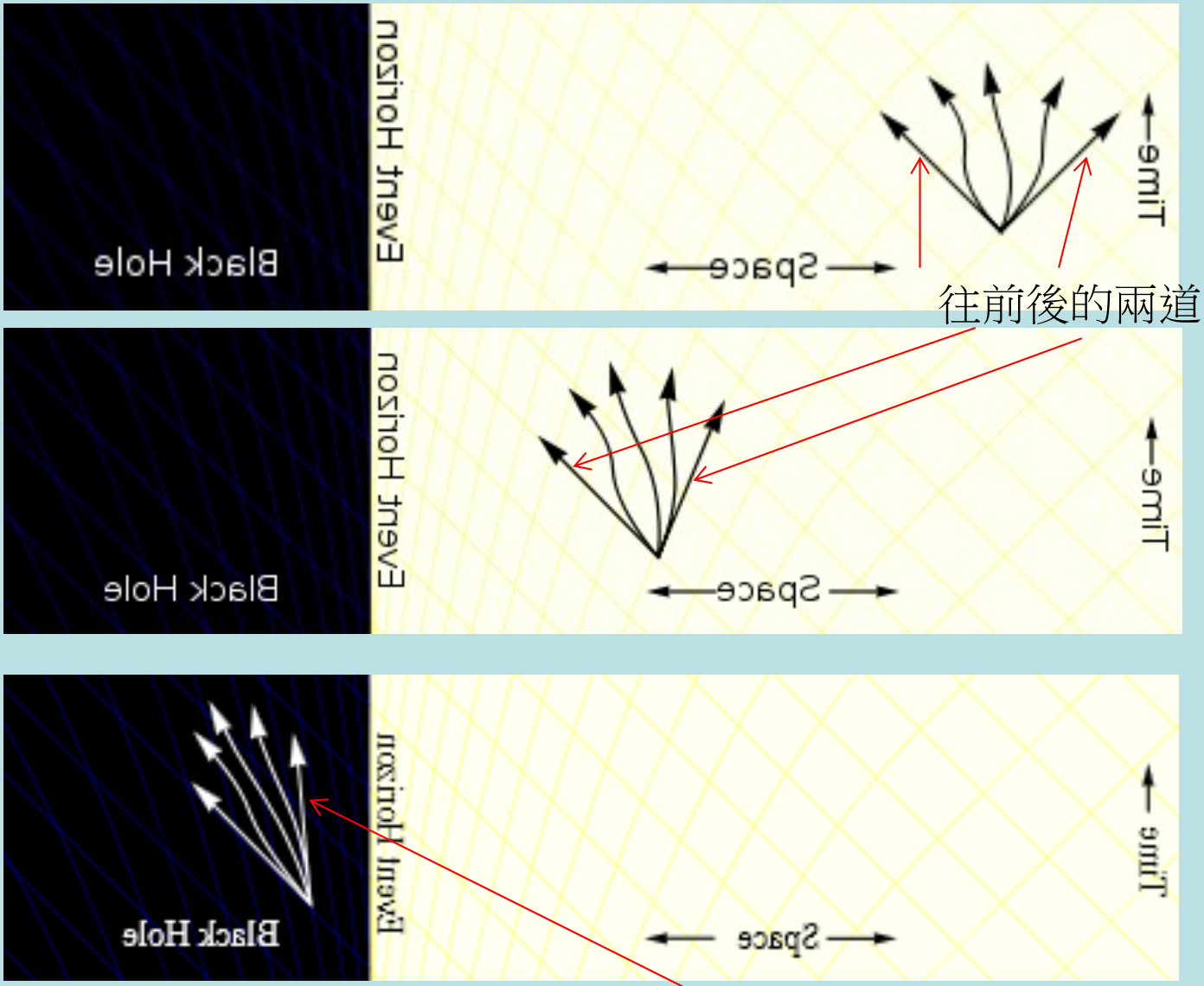


Figure 7 *Computer plot Thin line: Worldline for rain diver that passes r = 5M at* $t_{rain} = 0$ *and emits headlight and taillight flashes at event A inside the horizon. Thick lines: Worldlines for these inward and "outward" flashes. Both flashes move inward. The shaded region contains events the diver can still influence in the future as she passes event A.*

即使向外發射的光，也被吸近星體，

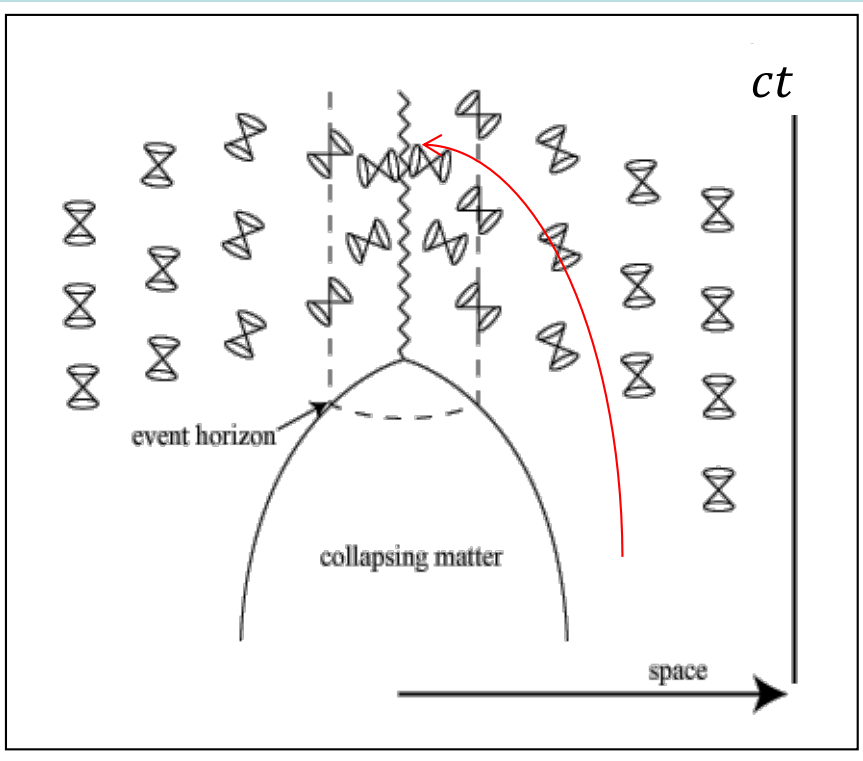
在A點向外發射的光，也是朝半徑減少的方向移動，也就是接近星體的方向。

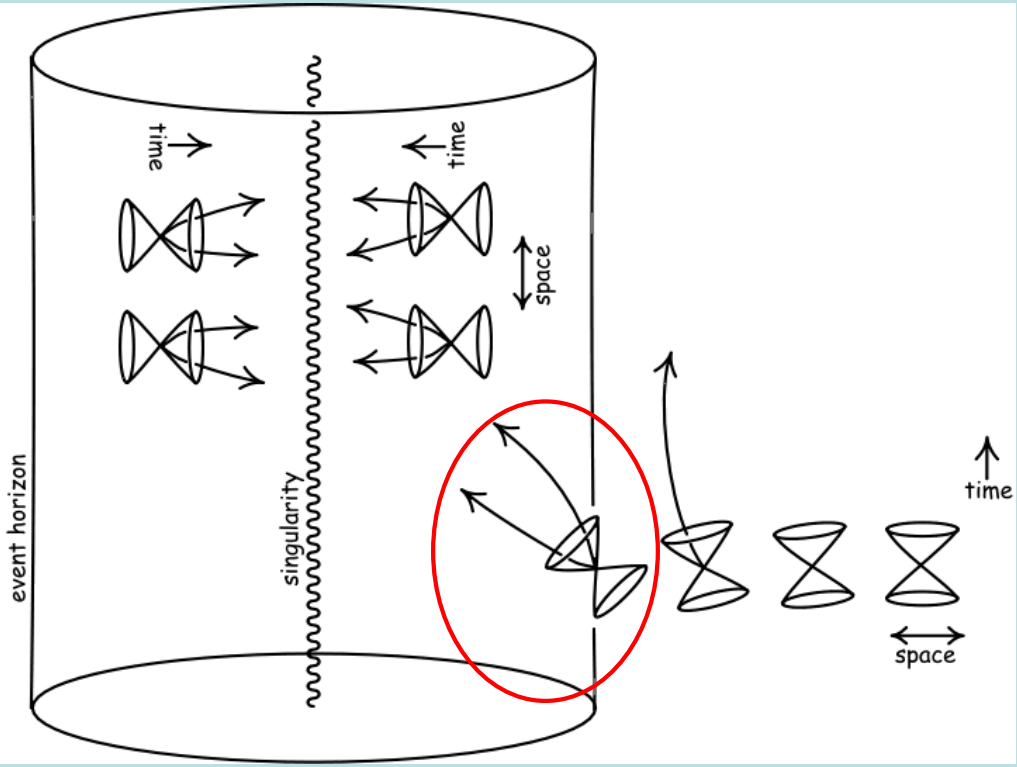

Black Hole
Event Horizon
Space
Time
往前後的兩道光！
Black Hole
Event Horizon
Space
Time
Black Hole
Event Horizon
Space
Time
進入Horizon後的光是無法離開的！

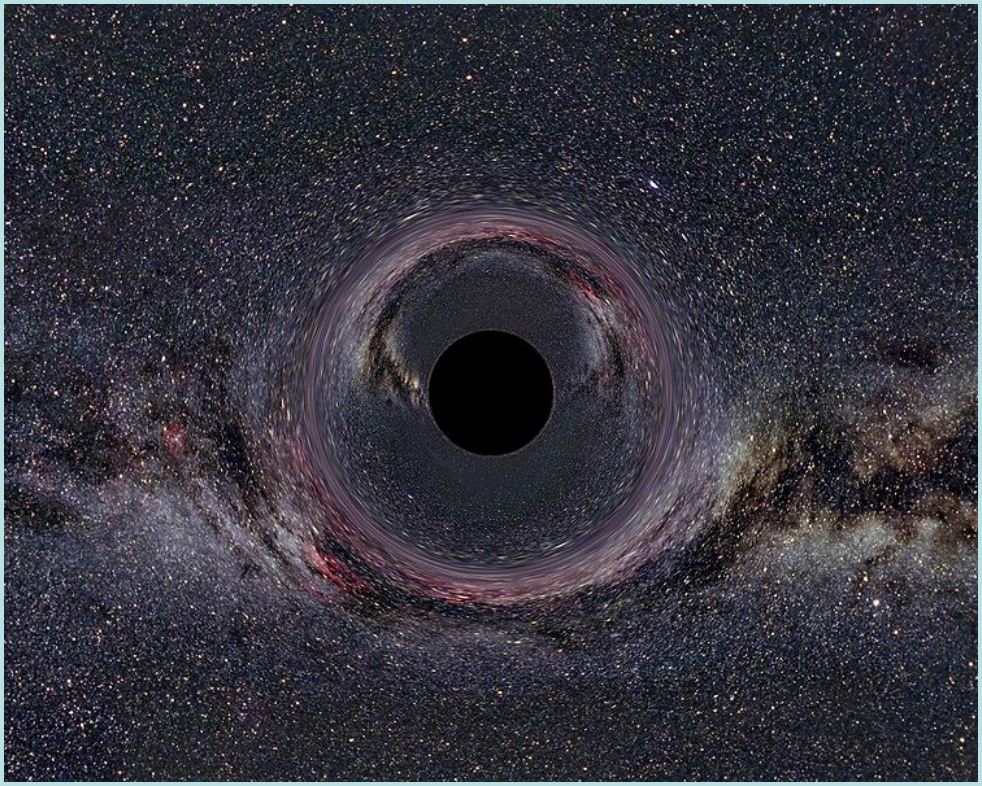
在這個範圍內的任何物體、光都永遠無法脫離這個範圍！

這個範圍的邊界，稱為 Horizon 地平線，其半徑稱為史瓦希半徑 $r_s = \frac{2GM}{c^2}$

無論用什麼辦法，我們都看不見範圍裡面。

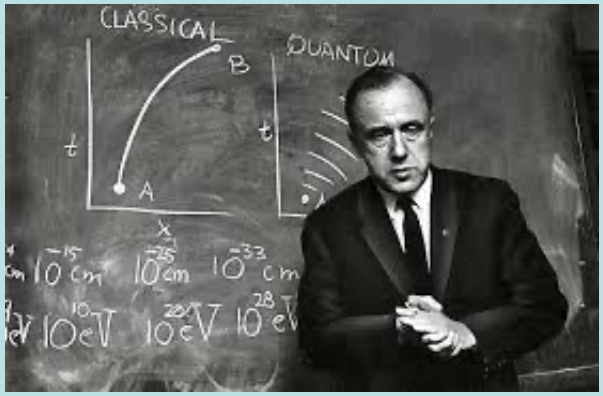




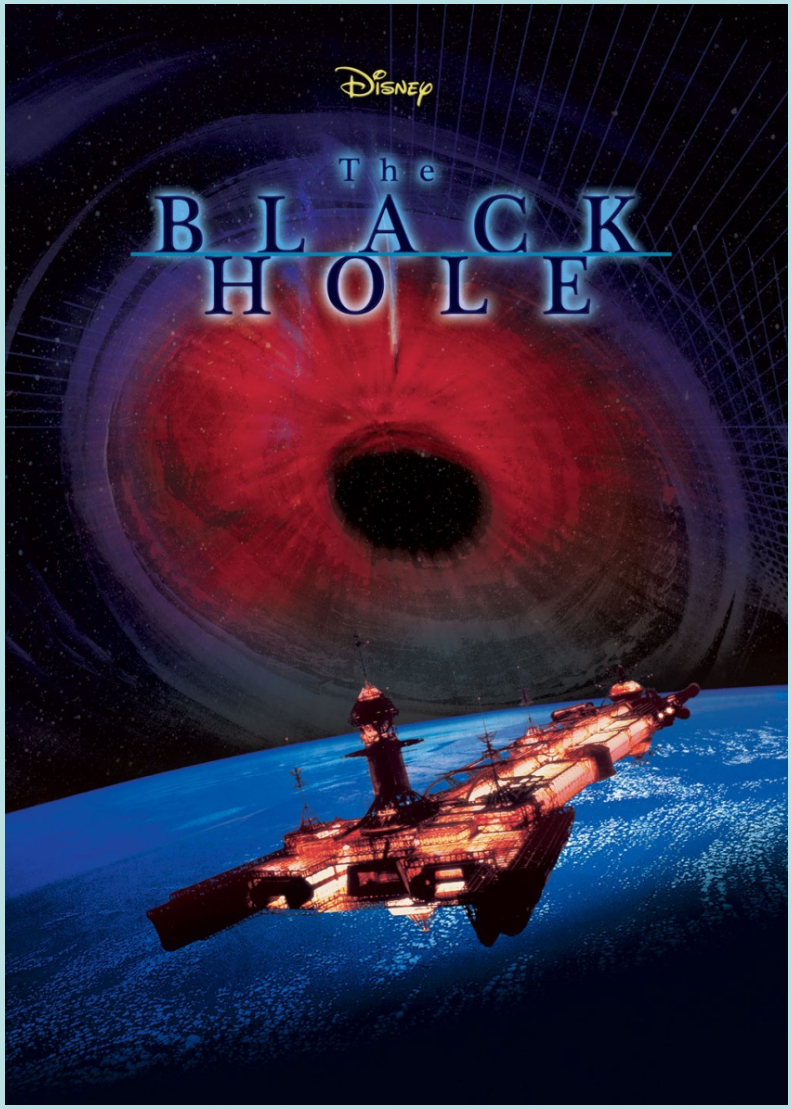


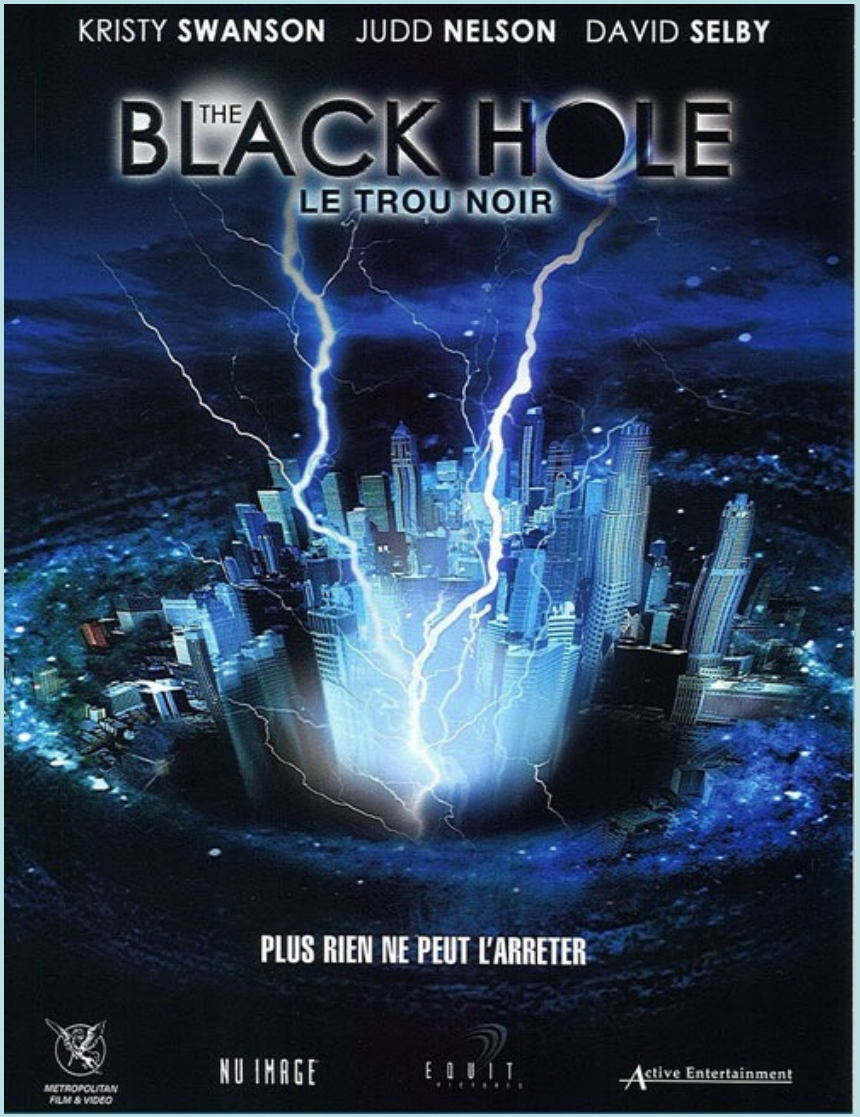
通過 Horizon 後即使光都無法脫離！內外完全被隔離！

黑洞 Black hole 1967

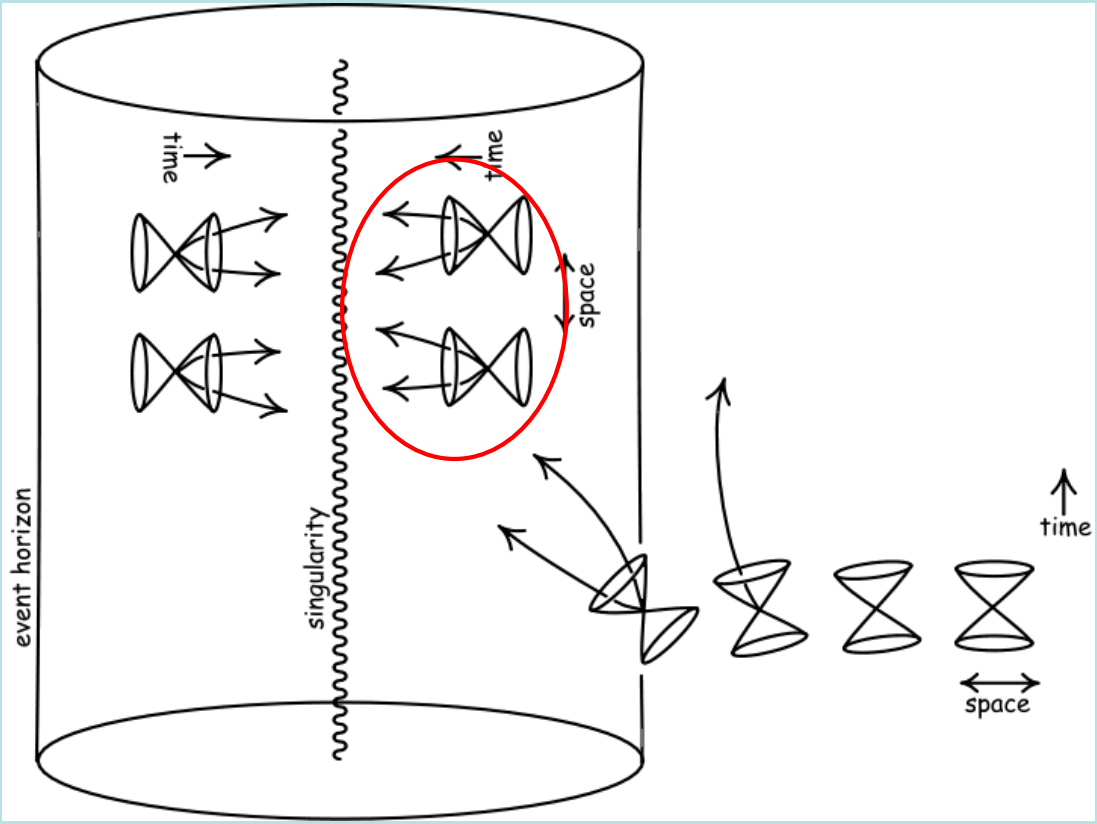


John Archibald Wheeler


Disney
The
BLACK
HOLE


KRISTY SWANSON
JUDD NELSON
DAVID SELBY
THE BLACK HOLE
LE TROU NOIR
PLUS RIEN NE PEUT L'ARRETER
METROPOLITAN FILM & VIDEO
NU IMAGE
EQUIT
Active Entertainment





黑洞，質量極大的星體，足以扭曲時間與空間

在Horizon內，光錐可以幾乎是水平！

光錐是該時空的未來，進入Horizon後，所有的未來都是指向星體！

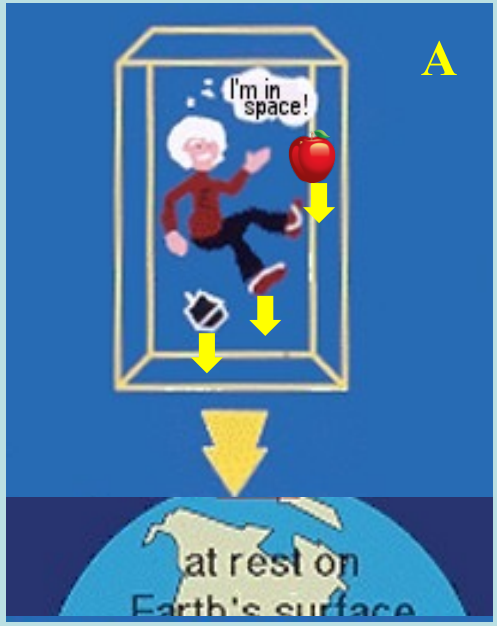
進入這個範圍內的物體就永遠無法遠離星體了！就如同我們現在不能回到過去。

進入Horizon內的運動者的時間，在外界觀察者看來，是空間的方向！

時間不能後退，從外界看，實驗者只能一直落入黑洞之中，而不能離開！







=

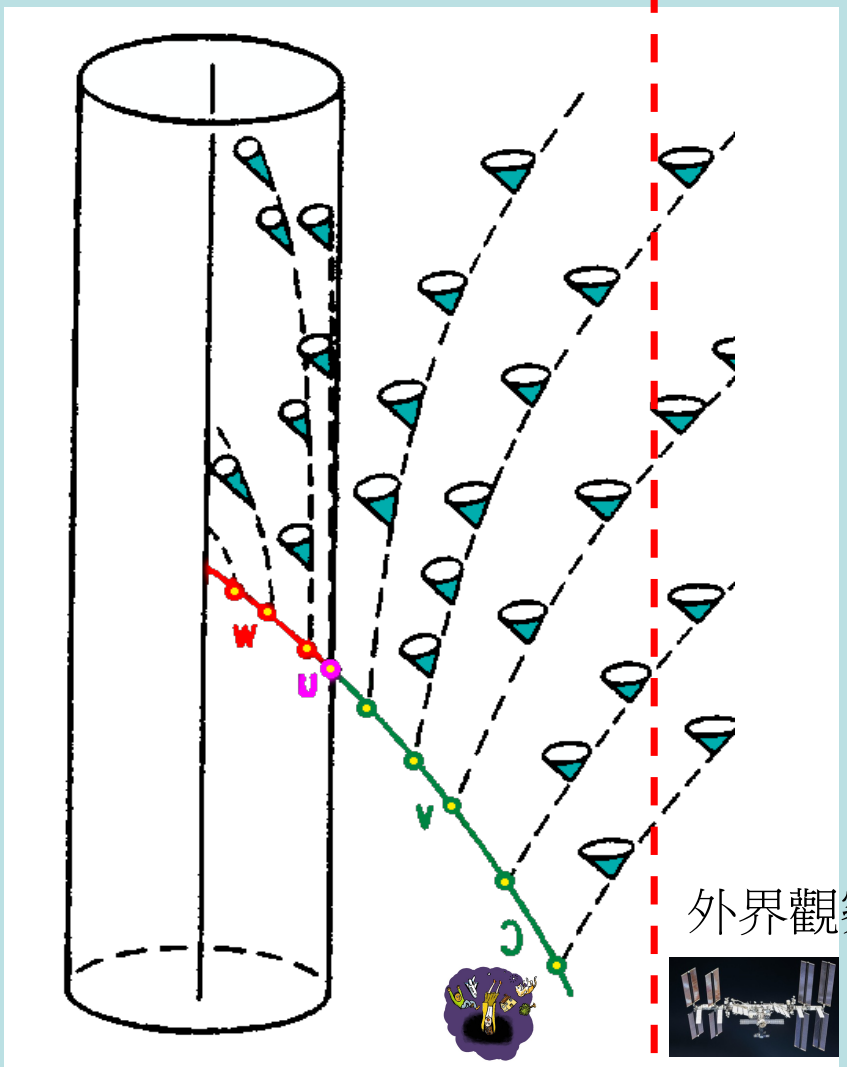


但一個自由下落的人，不會感覺到自己的重量！

而落入黑洞的人，覺得自己是靜止的，只會覺得日子照舊。

計算結果顯示：地平線處的重力並不是無限大。（球心是無限大）

落入黑洞的人，覺得自己靜止，只會覺得日子照舊。但外界從此永遠失去聯絡！





外界觀察者的軌跡

自由下落者的軌跡

從外界看來：落入黑洞實驗者所發出的電磁波信號週期會拉長！

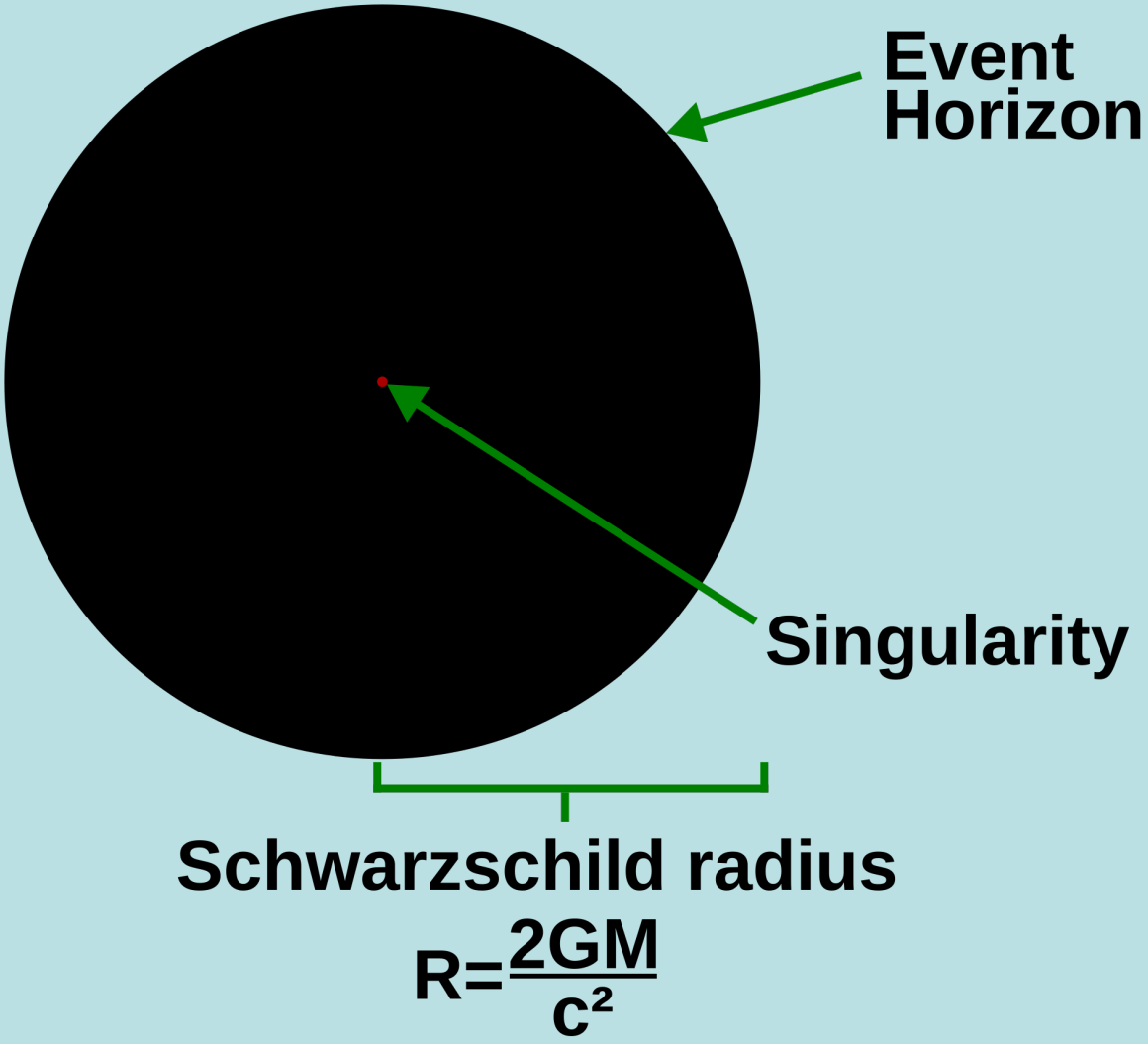
到了地平線上發出的信號週期是無限大。等於這個信號永遠無法到達外界。

黑洞等於把空間分成兩塊，而且地平線內永遠無法回到外界，掉入黑洞是一條不歸路！



https://www.mirrorvoice.com.tw/podcasts/78/1567

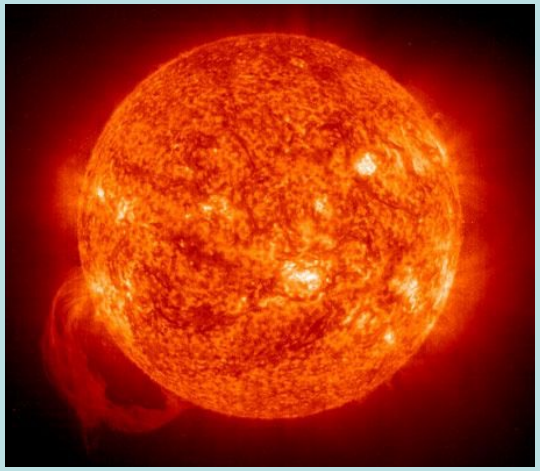
宇宙中的黑洞


Event
Horizon
Singularity
Schwarzschild radius
$R=\frac{2GM}{c^2}$

只要是球對稱的質量分布，就有地平線：地球也有！

$$r_s = \frac{2GM}{c^2}$$





$$r_s = \frac{2GM}{c^2} \sim \frac{10^{-11} \cdot 10^{24}}{10^{16}} \sim 8.9\times10^{-3}\text{m} < 1\text{cm}$$

$r_s \sim 2.9\times10^{3}\text{m}$

進入地球內部後，外圍的球殼對重力無貢獻

質量減少，史瓦希半徑也跟著變小！

太陽半徑$\sim 7\times10^{8}\text{m}$

越往地平線靠近，地平線反而越來越遠。所以地心內並沒有黑洞。

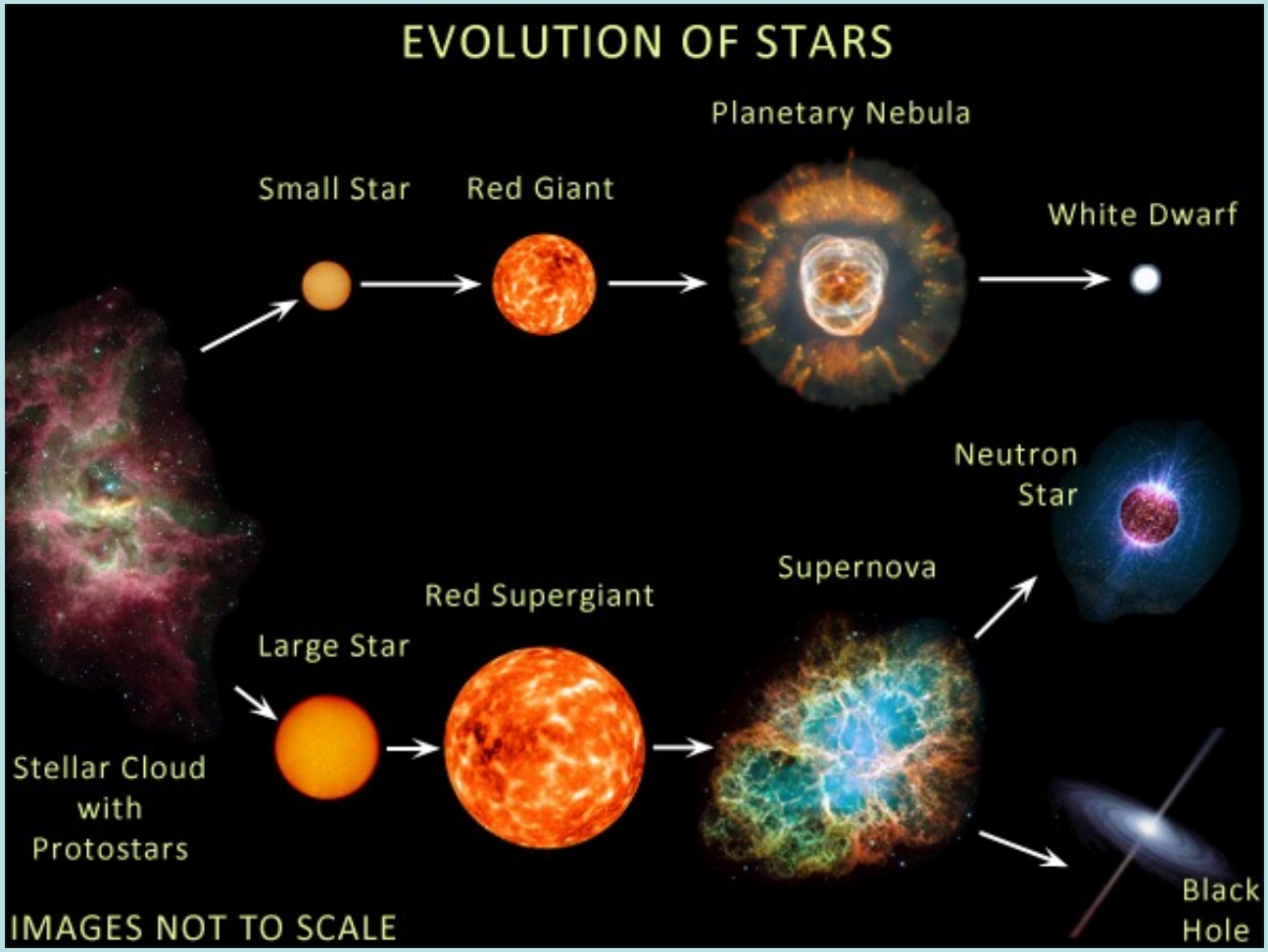
有很長時間，大部分物理學家以為星體大小不可能小於其史瓦西半徑。

黑洞是不存在的！

但後來天文學家發現，宇宙中有許多極重的星體，而且星體是有歷史演化的。

恆星燃料燒盡塌陷後，質量會集中在很小的空間中！

對於極緻密的質量，地平線就會裸露！黑洞是可能存在的。



恆星燃料燒盡塌陷後形成的黑洞稱為Stellar Black Hole！

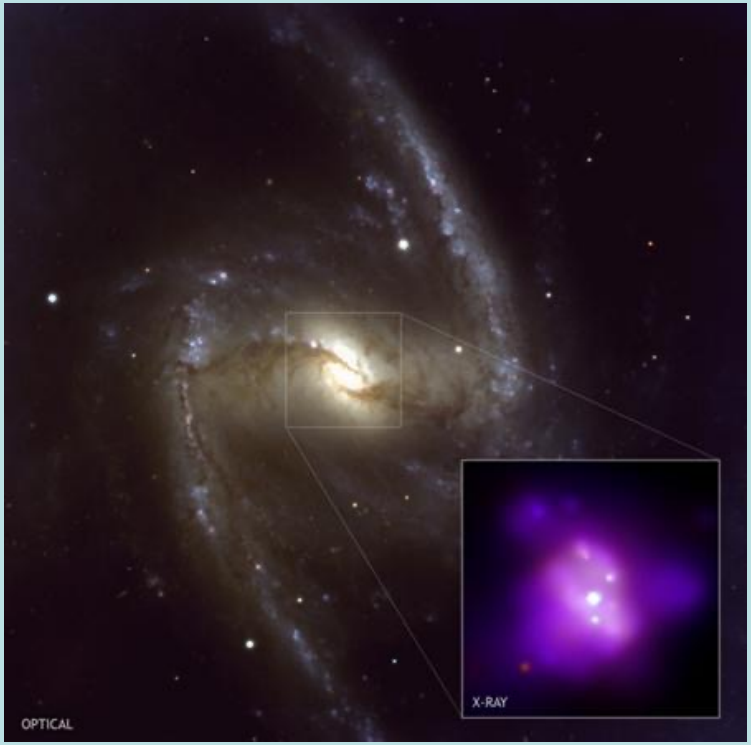
估計銀河系就有10^8個黑洞，而恆星總數約為10^{11}。



銀河系的中央也是一個巨大的黑洞，質量是太陽的10^6倍！

這麼重的黑洞顯然不只是單純死亡恆星造成，稱Supermassive BH。

r_s~0.1AU~10^{10}m，我們也相信它的地平線是裸露的！



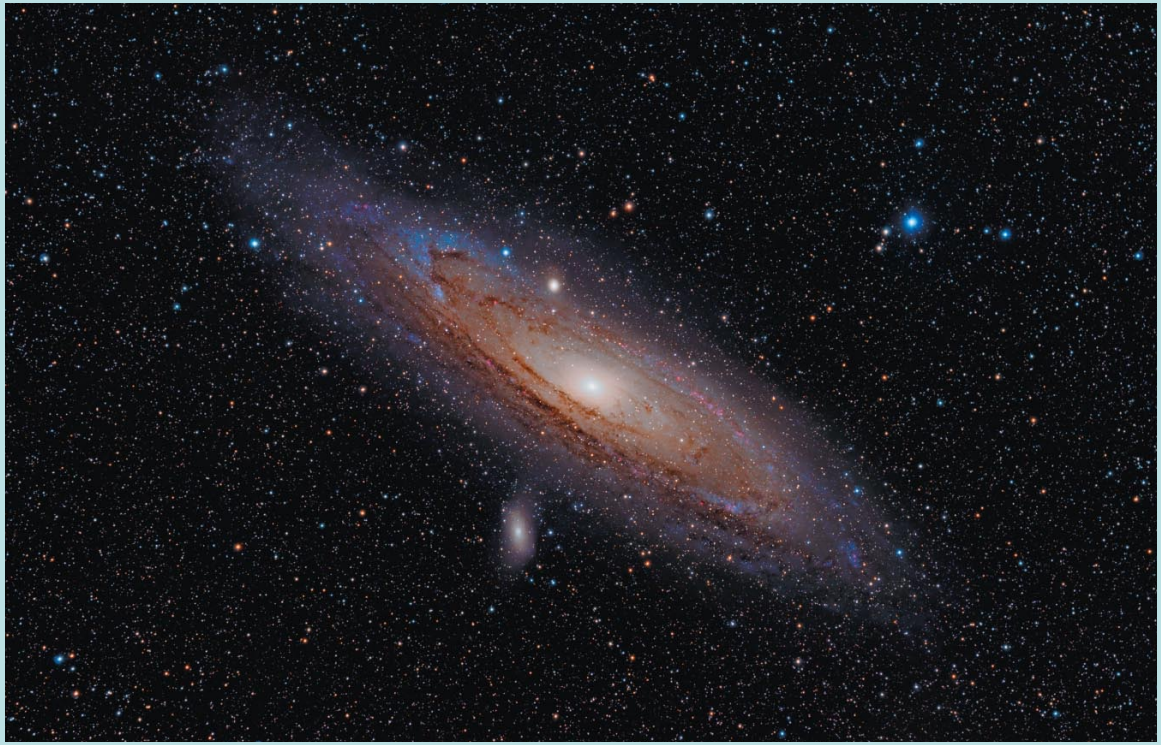
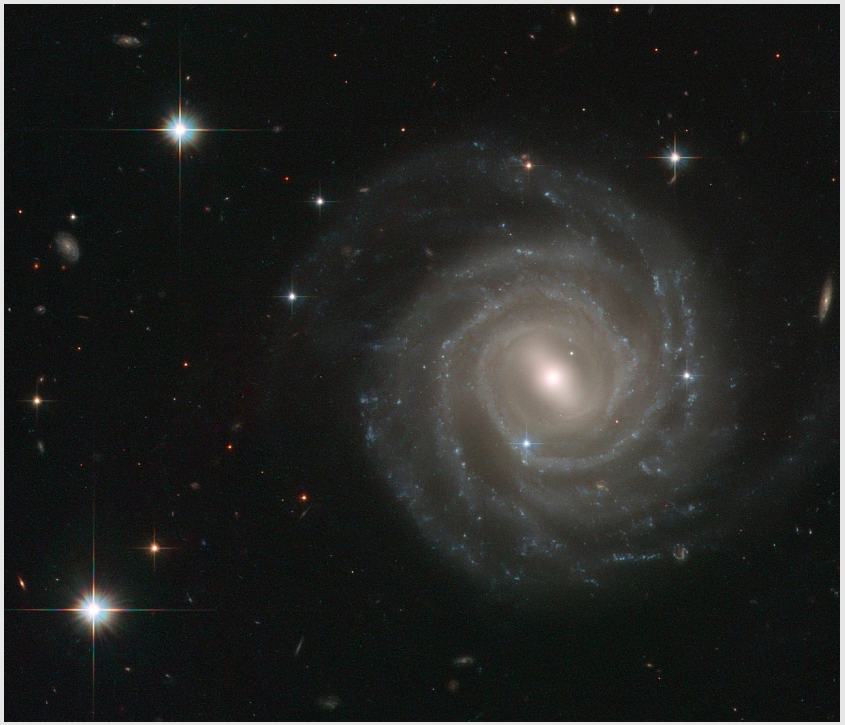


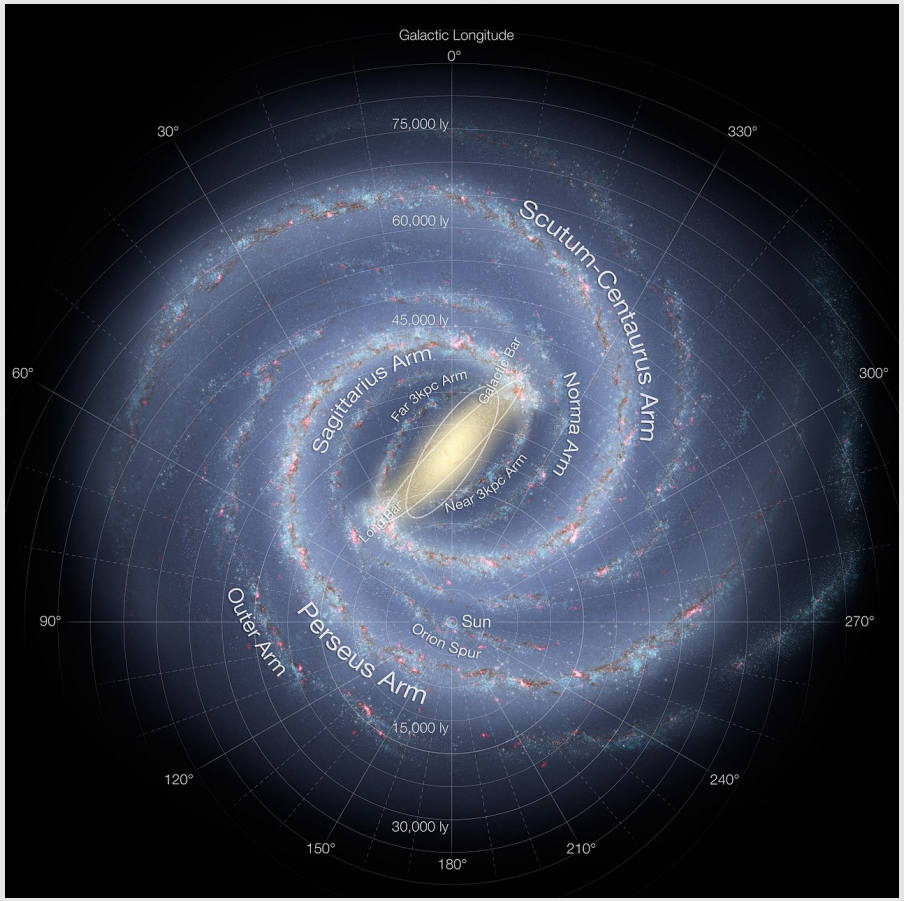


Image of the night sky above Paranal, Chile on 21 July 2007, taken by ESO astronomer Yuri Beletsky. A wide band of stars and dust clouds, spanning more than 100 degrees on the sky, is seen. This is the Milky Way, the galaxy to which we belong. At the centre of the image, two bright objects are visible. The brightest is the planet Jupiter, while the other is the star Antares. Three of the four 8.2-m telescopes forming ESO's VLT are seen, with a laser beaming out from Yepun, Unit Telescope number 4. The laser points directly at the Galactic Centre. Also visible are three of the 1.8-m Auxiliary Telescopes used for interferometry. They show small light beams which are diodes located on the domes. The exposure time is 5 minutes and because the tracking was made on the stars, the telescopes are slightly blurred.



The Milky Way arching at a high inclination across the night sky, (this composited panorama was taken at Paranal Observatory in northern Chile), the bright object is Jupiter in the constellation Sagittarius, and the Magellanic Clouds can be seen on the left; galactic north is downward.





A HST image of galaxy UGC 12158, which is thought to resemble the Milky Way in appearance


Artist's_impression_of_the_Milky_Way.ogv
ESO
www.eso.org
0:02
CC
VP9 360P
MENU



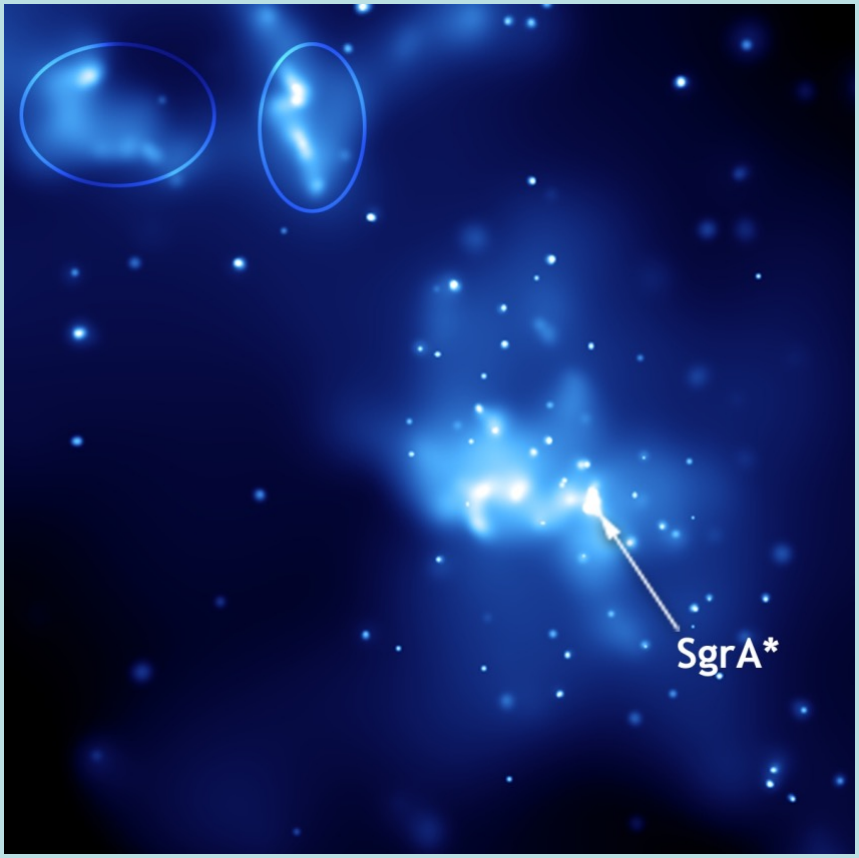


A view of the Milky Way toward the constellation Sagittarius (including the Galactic Center), as seen from a dark site with little light pollution (the Black Rock Desert, Nevada), the bright object on the lower right is Jupiter, just above Antares



This image of the center of the Milky Way galaxy was taken by the Chandra X-ray Observatory. Image Credit: NASA/CXC/MIT/F.K. Baganoff et al.

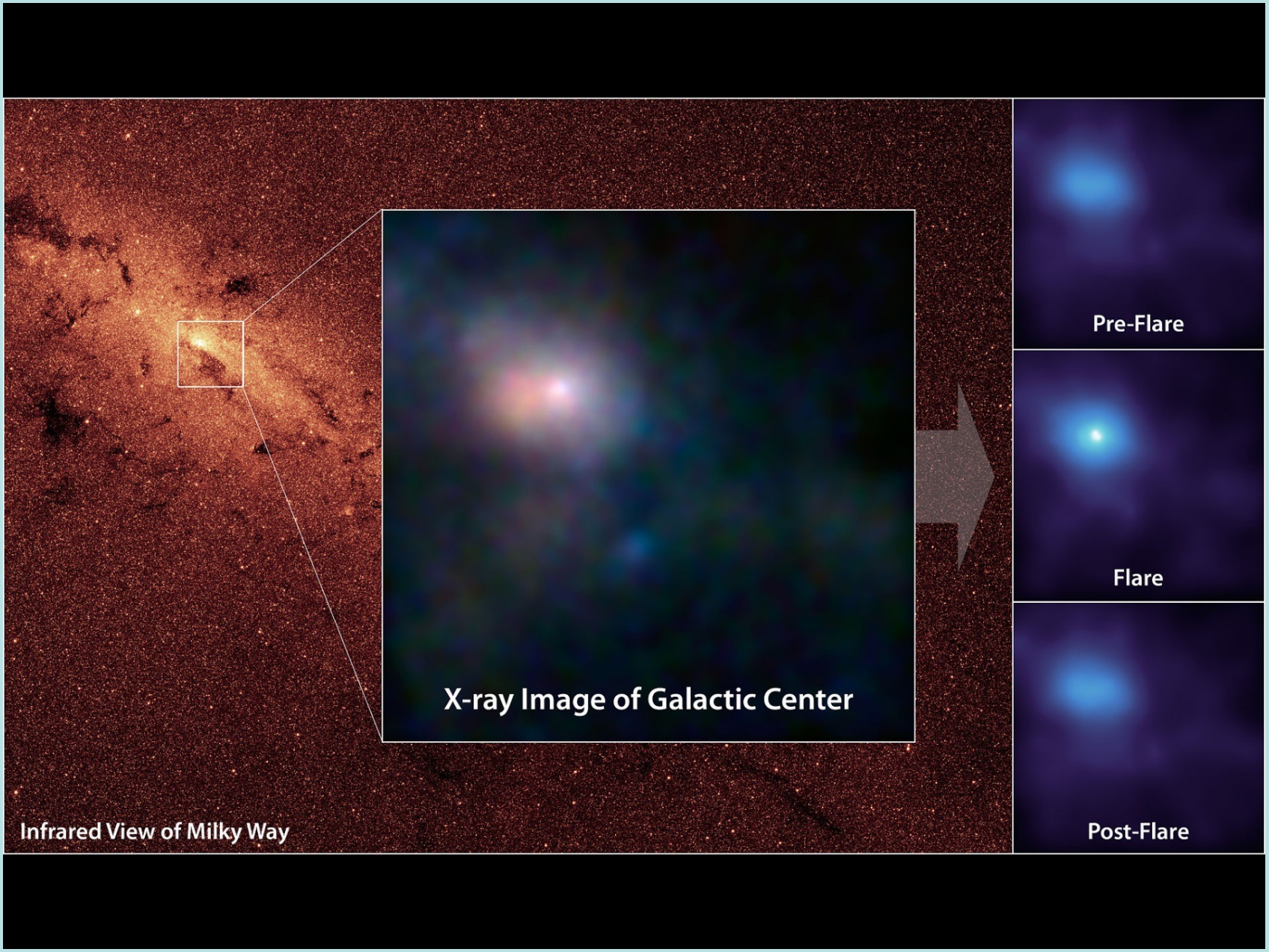
人馬座A* Sagittarius A*



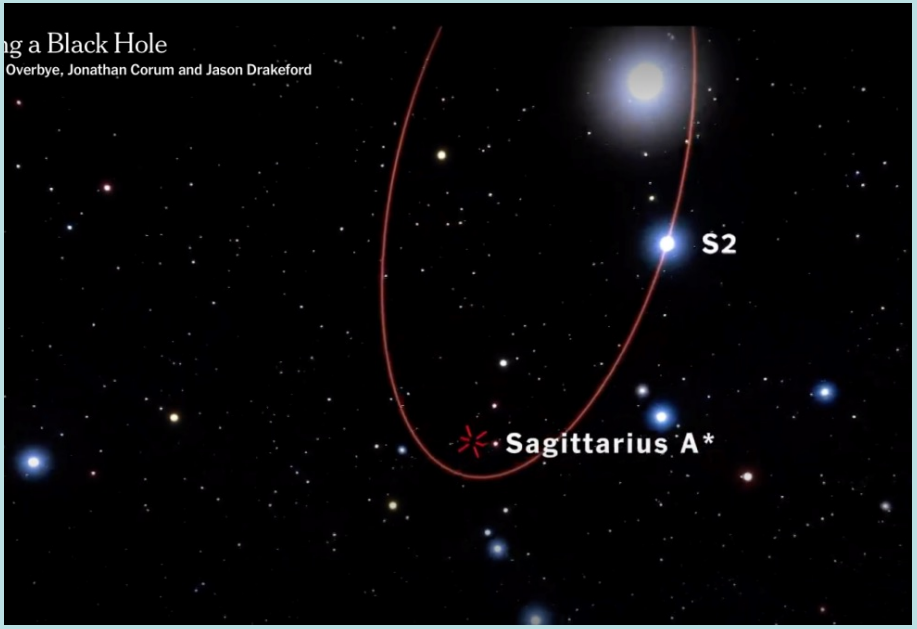


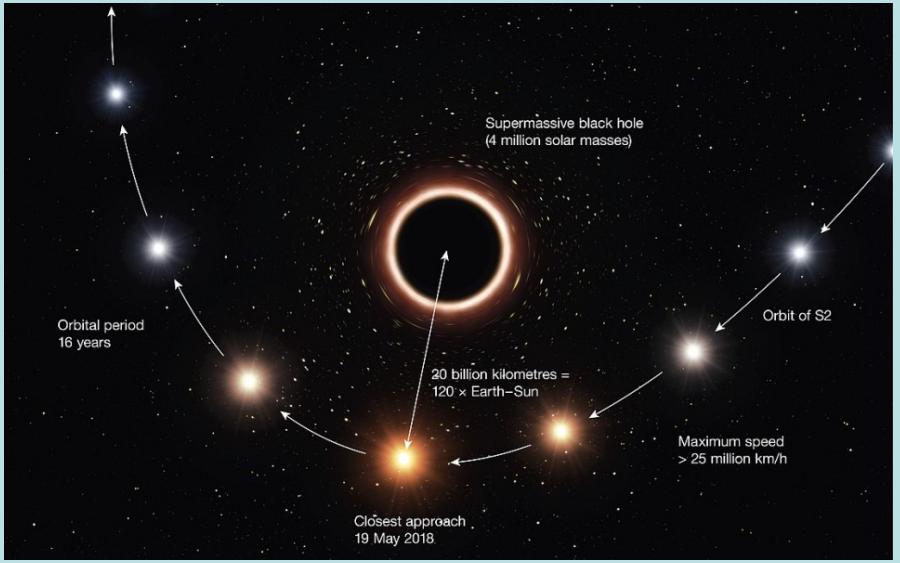
Mass $(4.31 \pm 0.38) \times 10^6 M_\odot$

Distance $8178 \pm 13(\text{stat.}) \pm 22(\text{sys.})$ pc

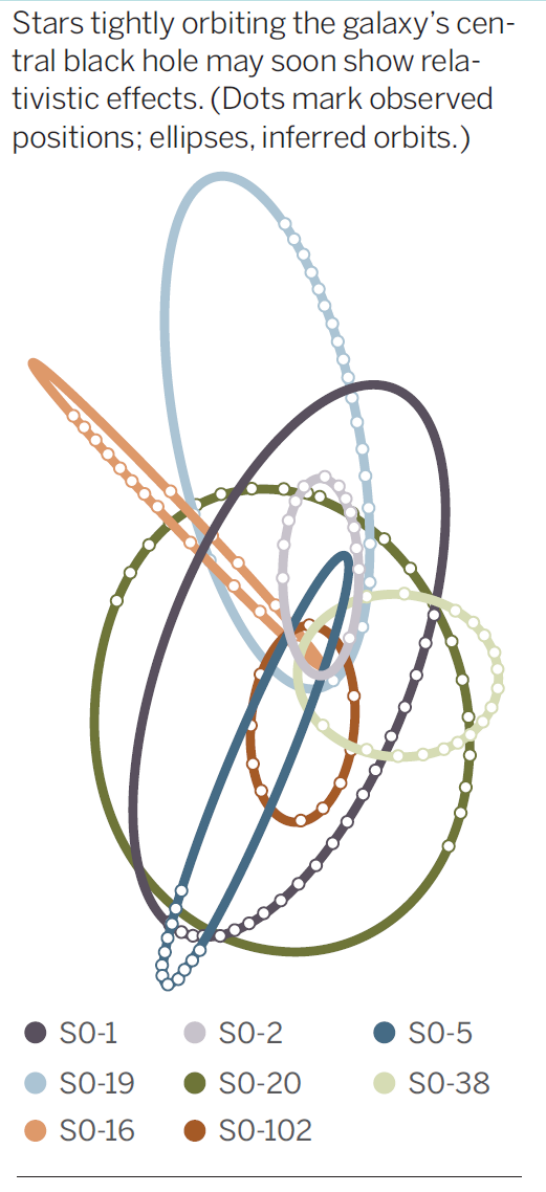

Infrared View of Milky Way
X-ray Image of Galactic Center
Pre-Flare
Flare
Post-Flare

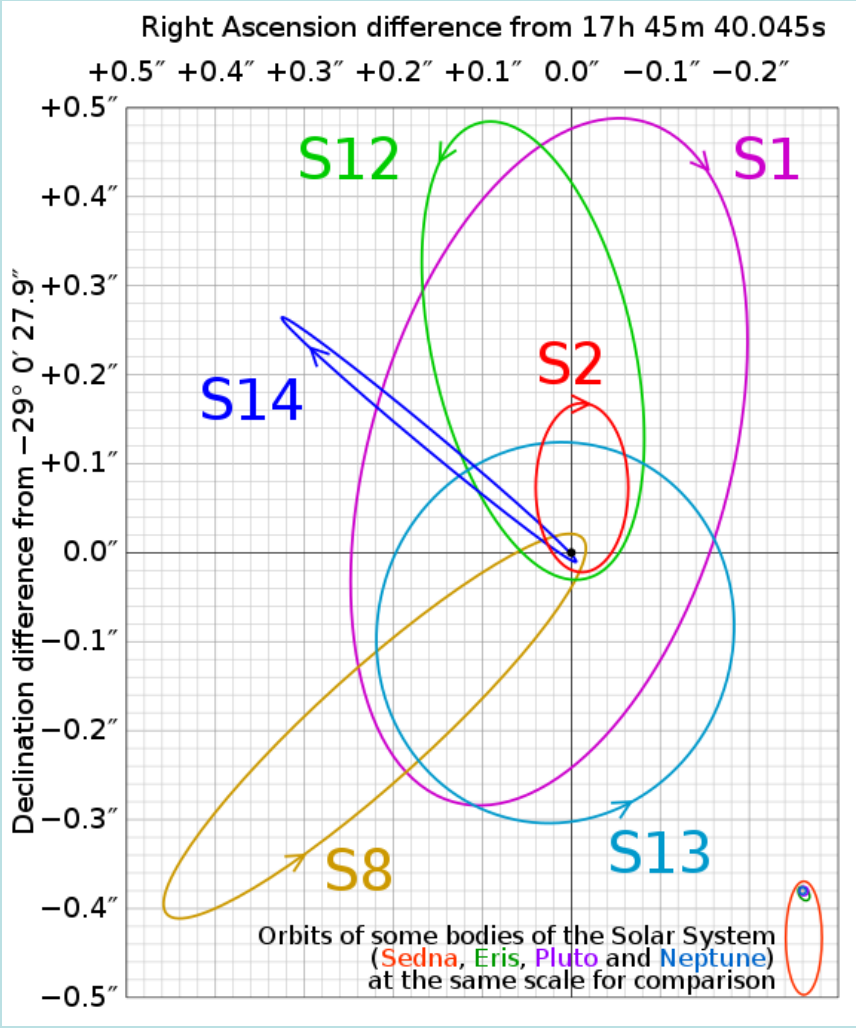
人馬座A*


g a Black Hole
Overbye, Jonathan Corum and Jason Drakeford
S2
Sagittarius A*

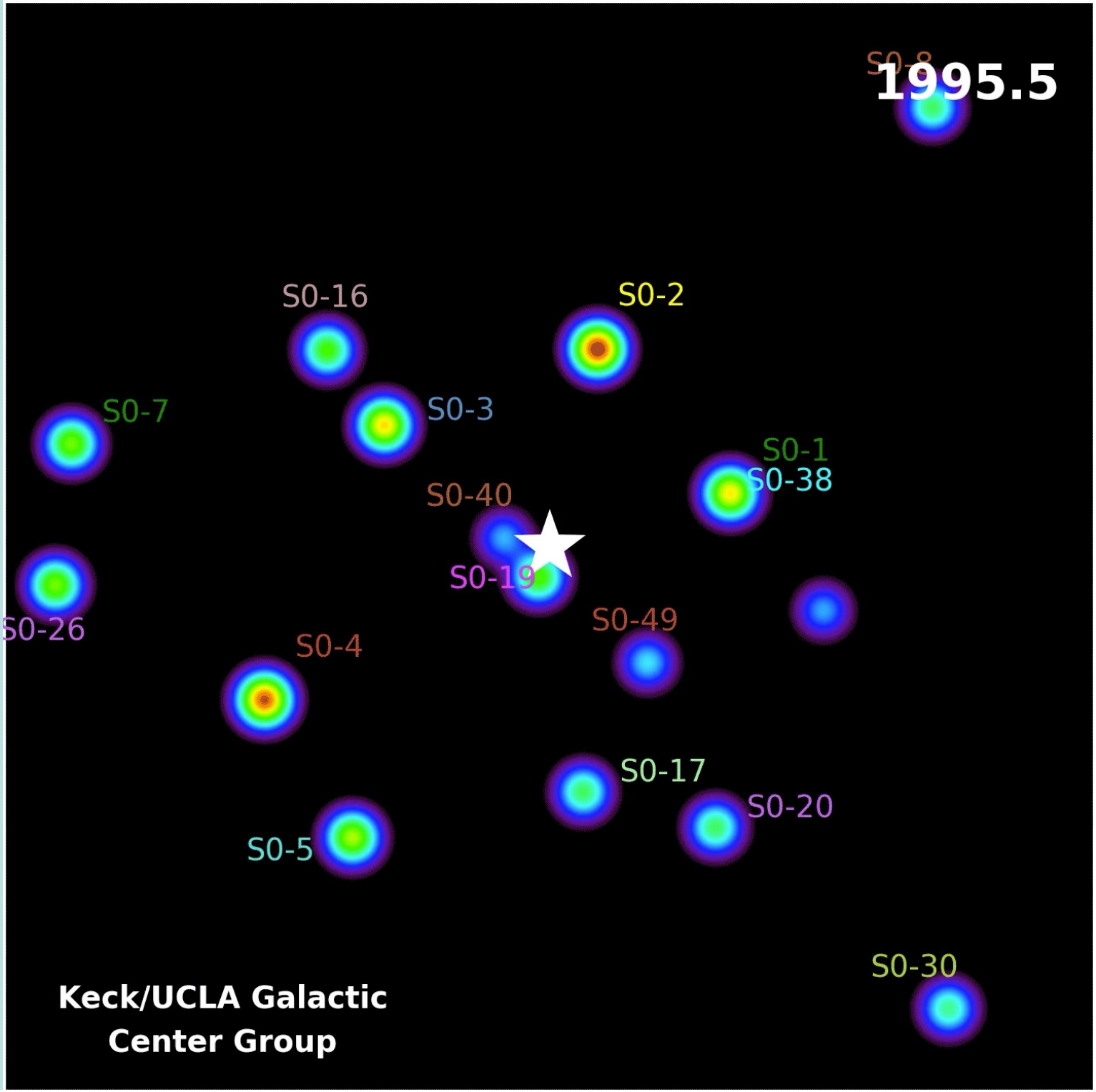

Supermassive black hole
(4 million solar masses)
Orbital period
16 years
Orbit of S2
20 billion kilometres =
120 × Earth–Sun
Maximum speed
> 25 million km/h
Closest approach
19 May 2018


Circling a Black Hole
By Dennis Overbye, Jonathan Corum and Jason Drakeford
S2
Sagittarius A*





現在一般相信在每一個銀河的中心都是一個極重的黑洞。


1995.5
S0-8
S0-16
S0-2
S0-7
S0-3
S0-1
S0-38
S0-40
S0-19
S0-26
S0-49
S0-4
S0-17
S0-20
S0-5
S0-30
Keck/UCLA Galactic
Center Group


Circling a Black Hole
By Dennis Overbye, Jonathan Corum and Jason Drakeford

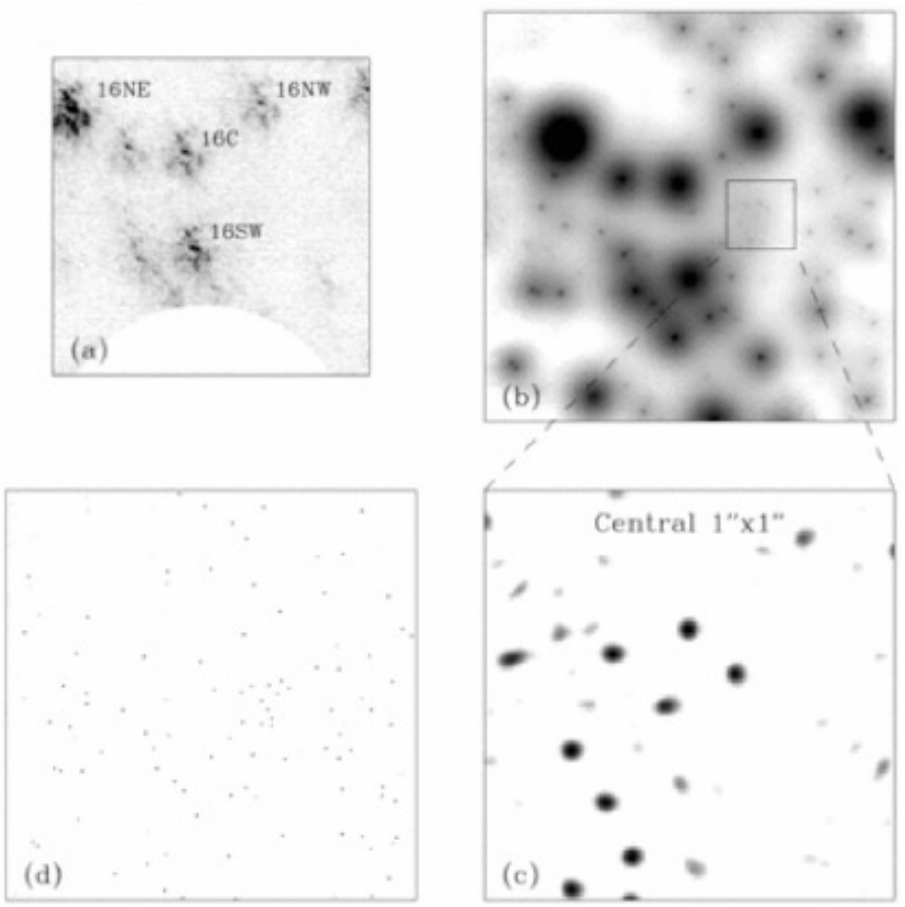


Figure 4. *(a) One of the many short (t_{exp} = 0.13 s) exposures of the stellar cluster surrounding the Galactic centre using the Keck-I 10-m telescope showing the speckle pattern, dominated by one bright speckle. (b) The individual frames are shifted to the same location using a bright reference source. (c) The resulting positions of the stars are shown. (d) The diffraction-limited central 1"x1" stellar region surrounding the compact object. From Ghez et al. (1998).*

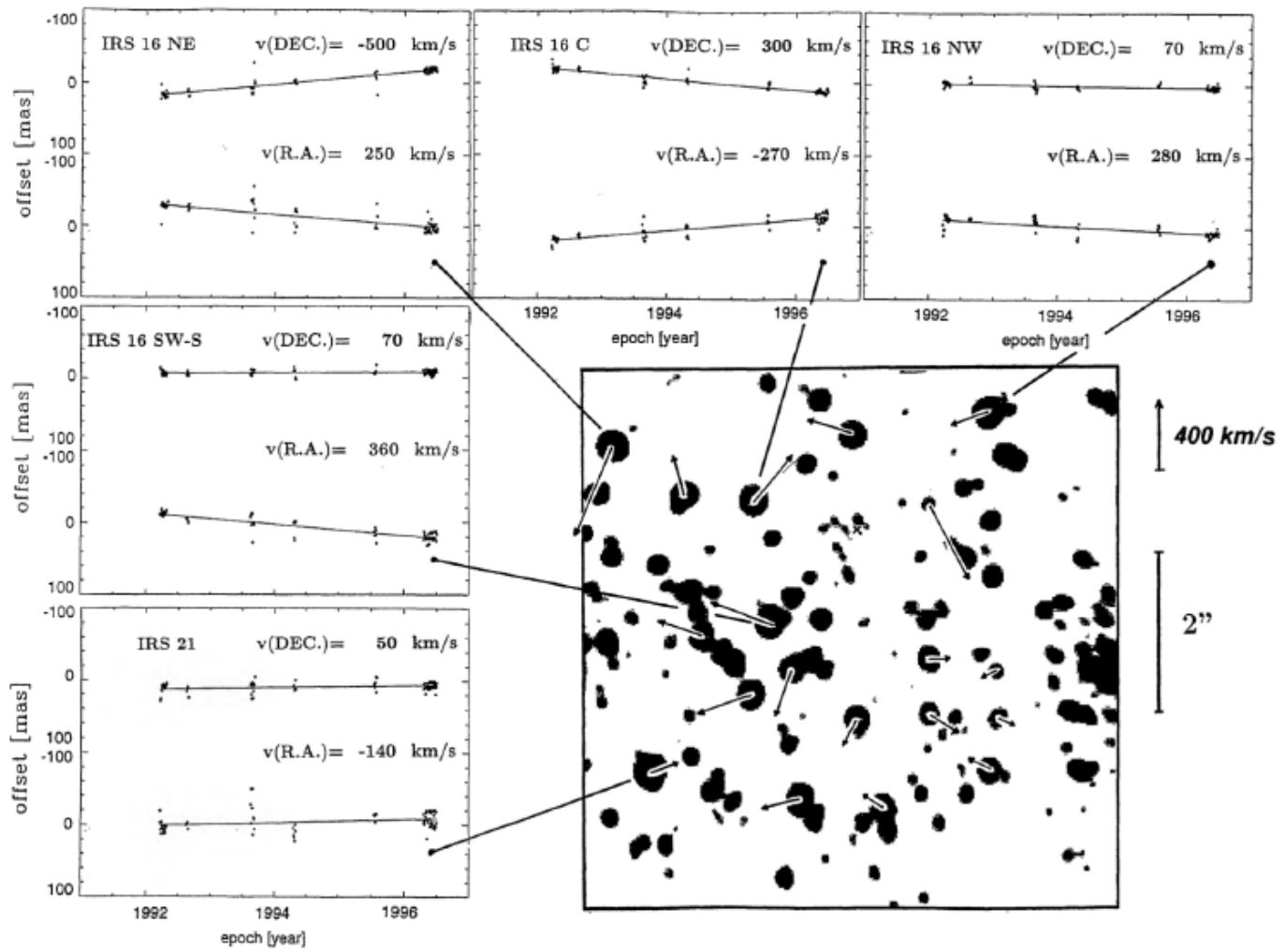


Figure 5. *Proper motions and vectors of selected stars surrounding the central compact radio source Sgr A*, marked with a cross. The measurements were carried out over four years and the offsets were determined with respect to the base epoch in 1994. From Eckart & Genzel (1997).*

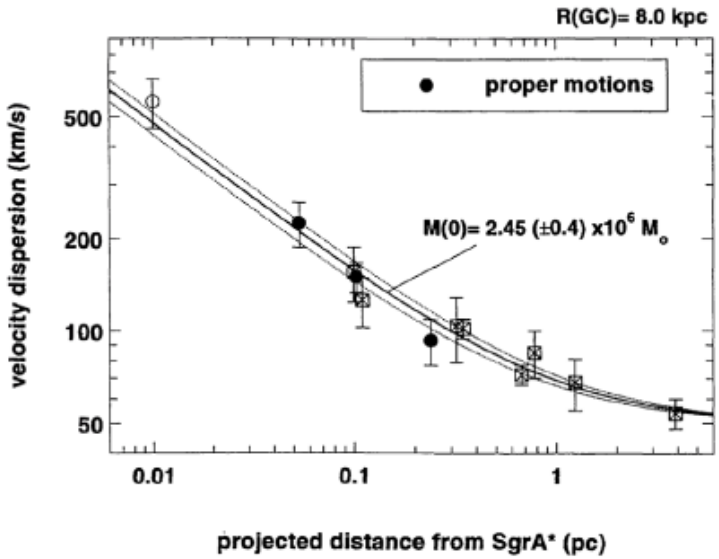


Figure 6. *Projected stellar velocity dispersion as a function of projected distance from Sgr A* from a set of measurements, culminating with the innermost points within 0.2 parsec (circles) obtained from measurements with the SHARP camera on the ESO 3.5-m NTT. The curves indicate the expectations from a supermassive black hole with ~2.5 million solar masses. Adding more recent data from VLT and Keck the mass estimate increased to over 4 million solar masses. From Eckart & Genzel (1997).*

$$m\frac{v^2}{r} = m\frac{GM}{r^2}$$

$$v \propto \sqrt{r}$$

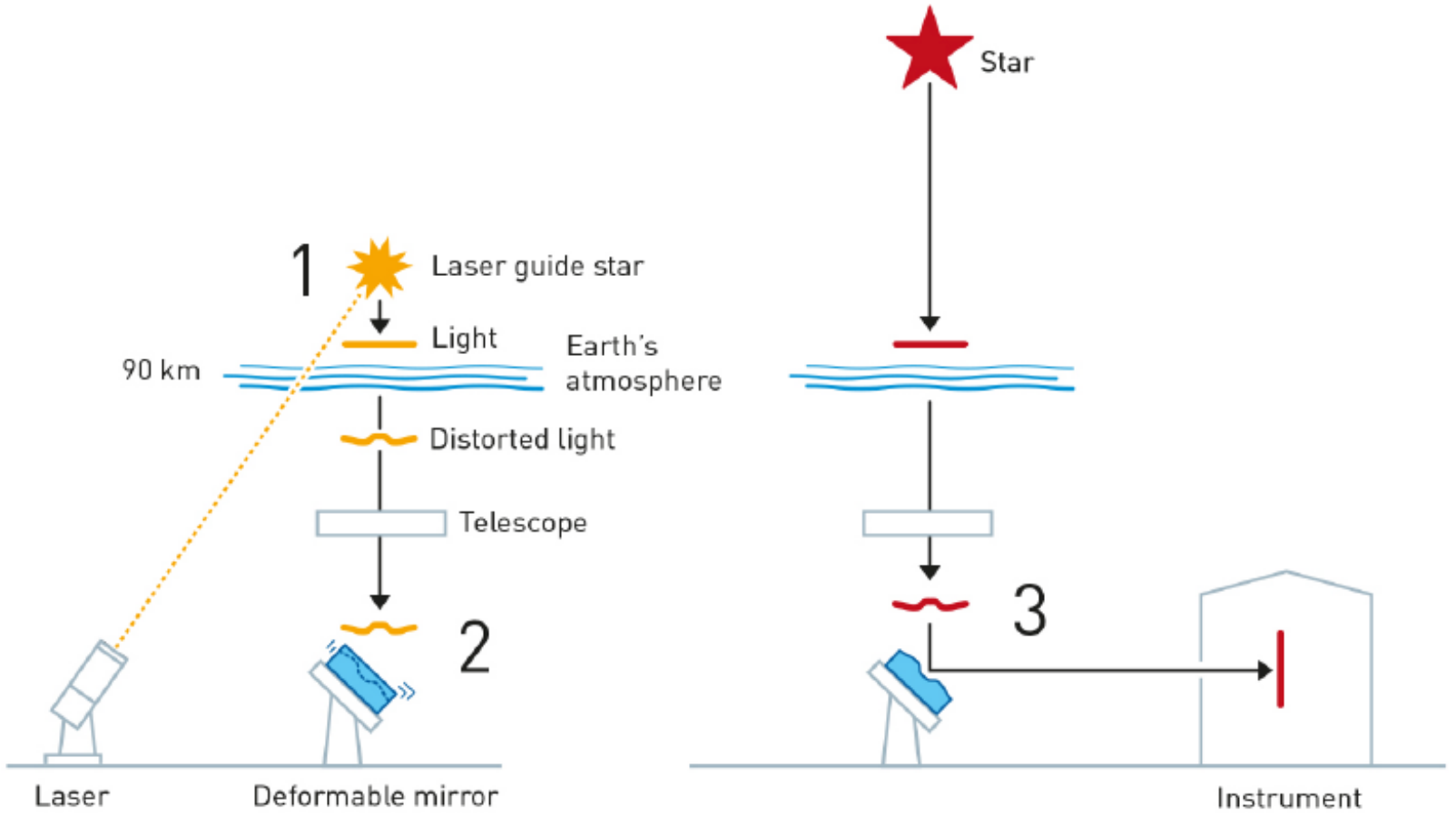


Figure 7. *The principle of adaptive optics. A laser system is used to make artificial guide stars that sense the blurring in the Earth's atmosphere. The images of the bright spots generated by the laser [1] are used in a feedback loop to introduce fast deformations of a secondary mirror [2] that effectively correct for the atmospheric turbulence in the science images [3].*

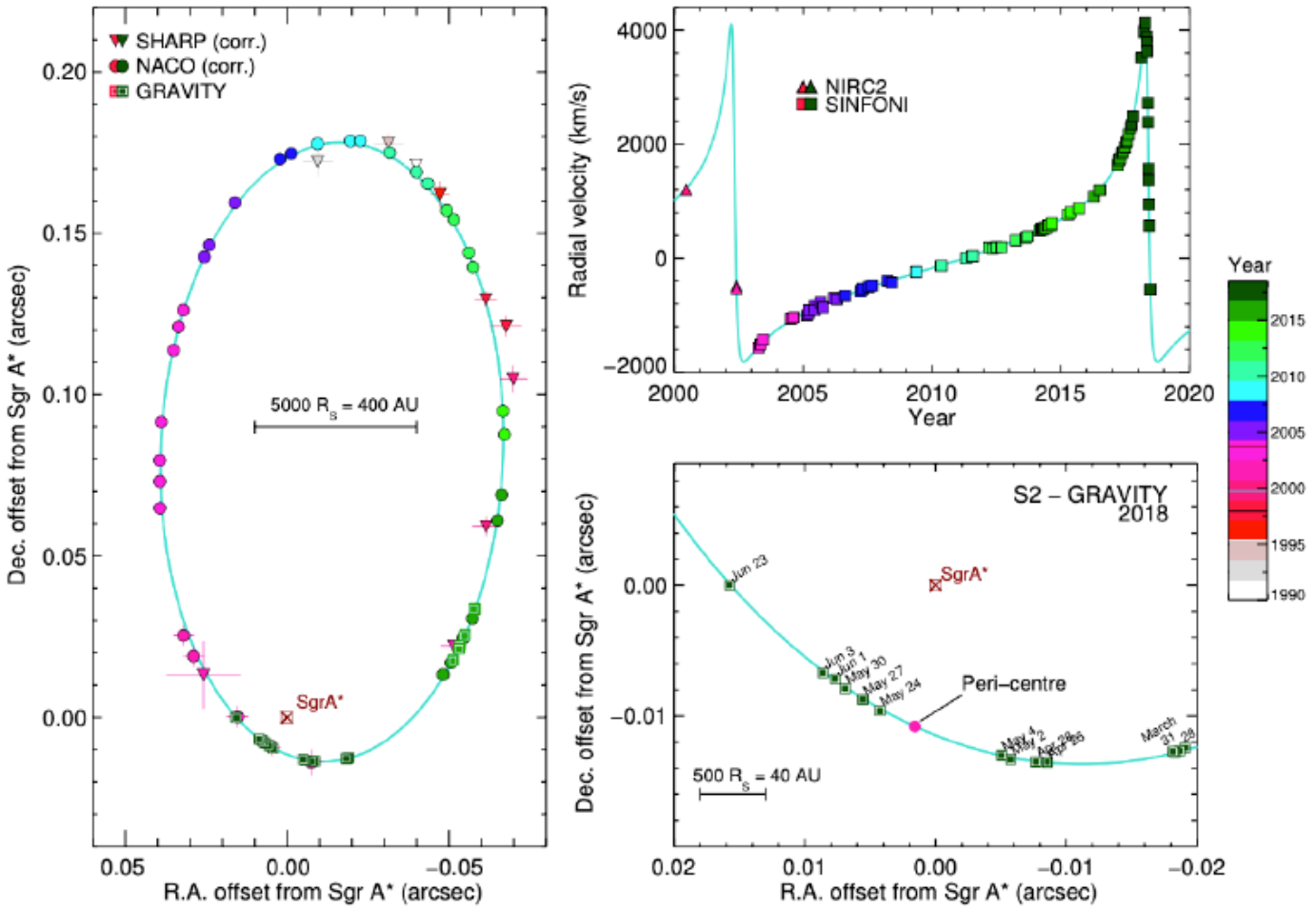


Figure 9. *Summary of the observational results of monitoring the S2–Sgr A* orbit from 1992 to 2018. Left: Projected orbit of the star S2 on the sky (J2000) relative to the position of the compact radio source Sgr A* (brown crossed square at the origin). Triangles and circles (and 1 σ uncertainties) denote the position measurements with SHARP at the NTT and NACO at the VLT, color-coded for time (colour bar on the right side). The cyan curve shows the best-fitting S2 orbit to all these data, including the effects of general and special relativity. The bottom right panel shows a zoom-in around pericentre in 2018. Upper right: Radial velocity of S2 as a function of time (squares: SINFONI/NACO at the VLT; triangles: NIRC2 at Keck). S2 reached pericentre of its orbit at the end of April 2002, and then again on 19 May 2018. The cyan curve shows the best-fitting S2 orbit to all these data, including the effects of General and Special Relativity. From Abuter et al. (2018).*

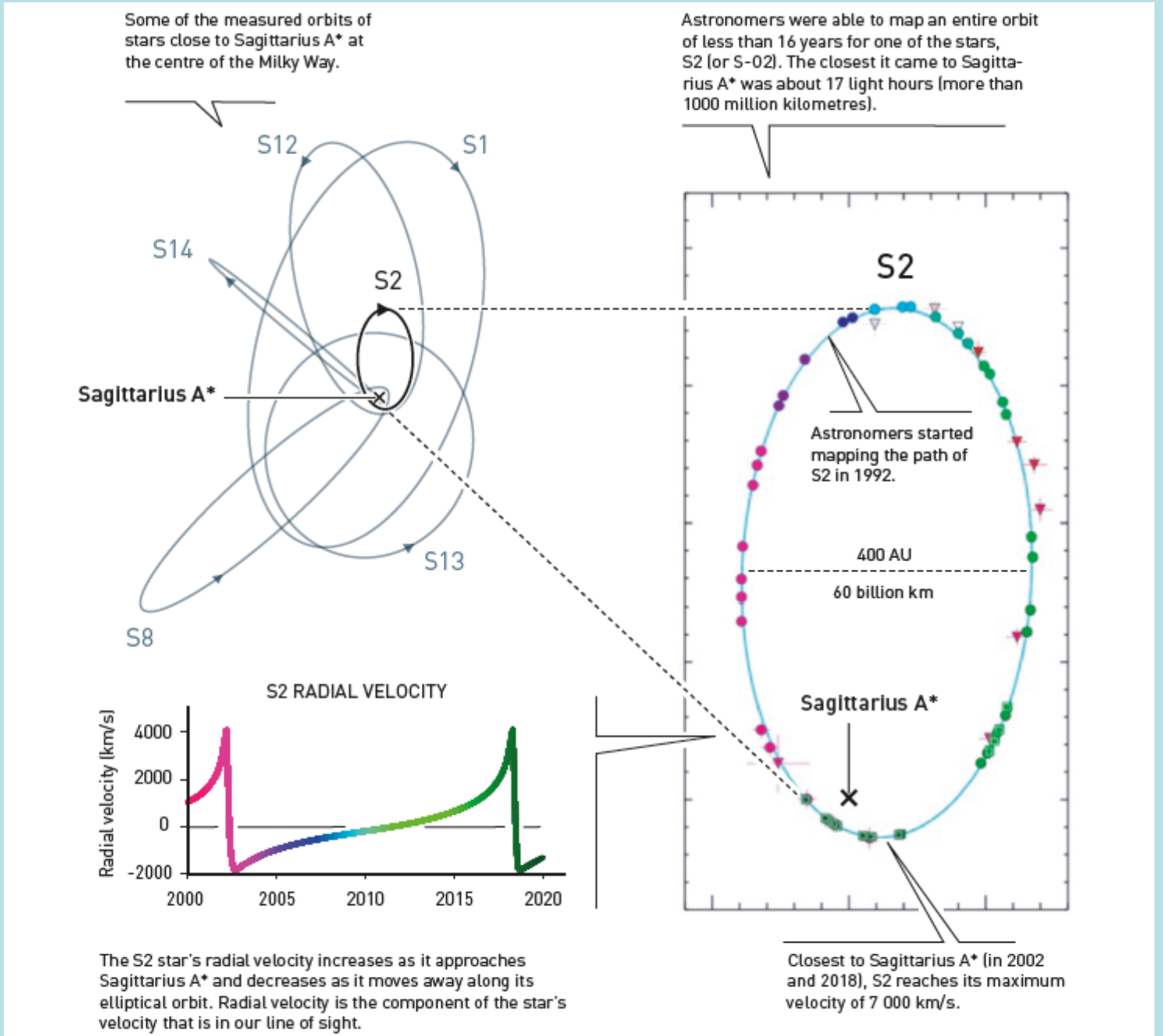
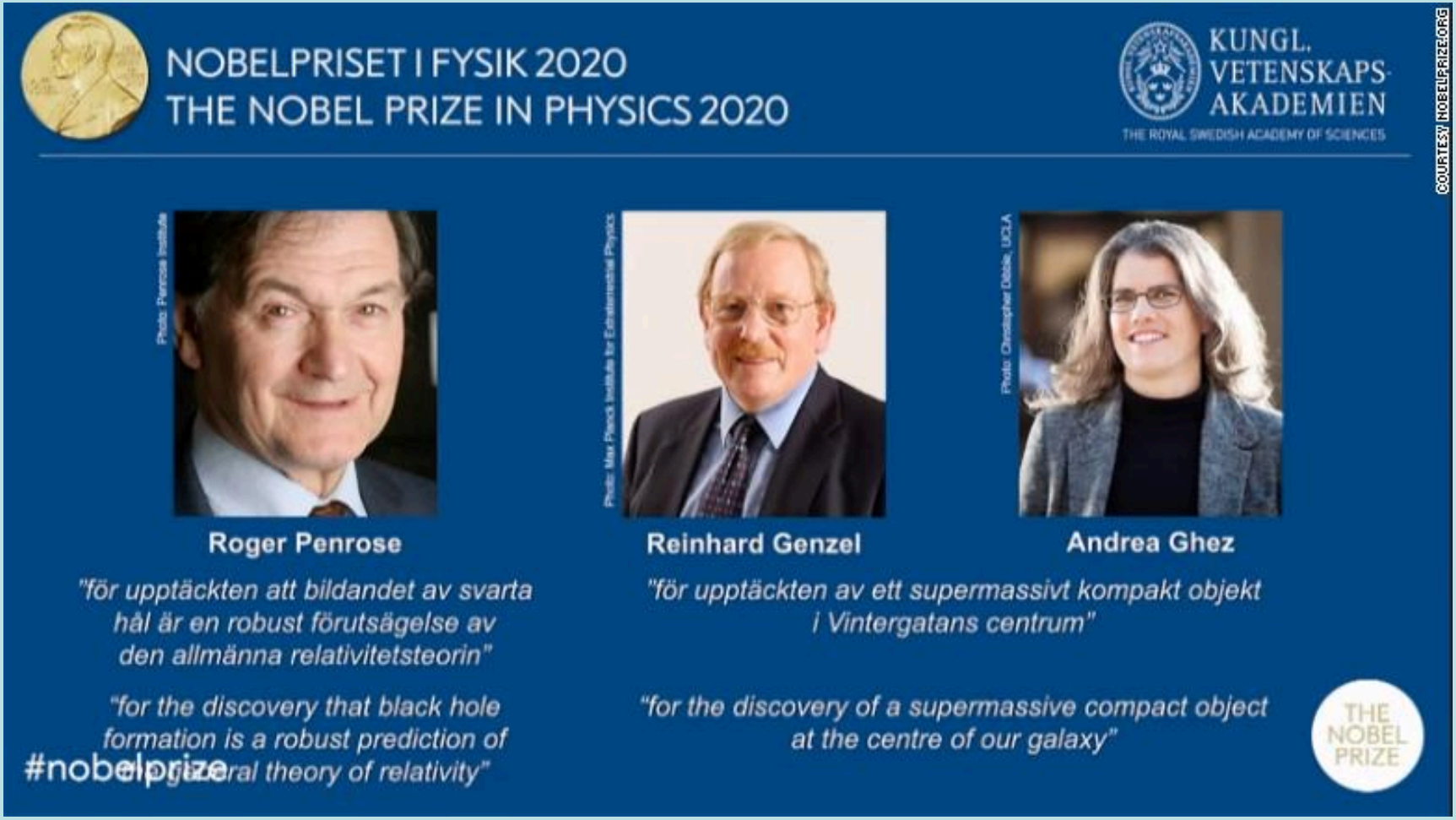


Figure 4. The stars' orbits revealed that something invisible and heavy governed their paths at the heart of the Milky Way.


NOBELPRISET I FYSIK 2020
THE NOBEL PRIZE IN PHYSICS 2020
KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES
COURTESY NOBELPRIZE.ORG
Roger Penrose
"för upptäckten att bildandet av svarta hål är en robust förutsägelse av den allmänna relativitetsteorin"
"for the discovery that black hole formation is a robust prediction of the general theory of relativity"
Reinhard Genzel
Andrea Ghez
"för upptäckten av ett supermassivt kompakt objekt i Vintergatans centrum"
"for the discovery of a supermassive compact object at the centre of our galaxy"
THE NOBEL PRIZE
#nobelprize

Roger Penrose, Reinhard Genzel and Andrea Ghez share 10m Swedish kronor award



▲ From left: Richard Penrose, Andrea Ghez and Reinhard Genzel, winners of the Nobel prize in physics. Composite:

The Nobel Prize in Physics 2020

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2020

with one half to

Roger Penrose

University of Oxford, UK

"for the discovery that black hole formation is a robust prediction of the general theory of relativity"

and the other half jointly to

Reinhard Genzel

Max Planck Institute for Extraterrestrial Physics, Garching, Germany and University of California, Berkeley, USA

Andrea Ghez

University of California, Los Angeles, USA

"for the discovery of a supermassive compact object at the centre of our galaxy"

Black holes and the Milky Way's darkest secret

Andrea Ghez
Facts



Andrea Ghez
The Nobel Prize in Physics 2020

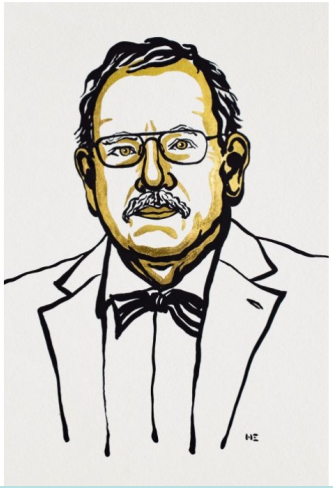
Born: 1965, New York, NY, USA

Affiliation at the time of the award: University of California, Los Angeles, CA, USA

Prize motivation: "for the discovery of a supermassive compact object at the centre of our galaxy."

Prize share: 1/4

Reinhard Genzel
Facts



Reinhard Genzel
The Nobel Prize in Ph

Born: 24 March 1952,

Affiliation at the time
Berkeley, CA, USA, M
Physics, Garching, Ge

Prize motivation: "for
compact object at the

Prize share: 1/4



TYPES OF BLACK HOLES:

- **Stellar-mass Black Holes:**

  Stellar-mass black holes are created when massive stars explode, leaving behind a black hole with the mass of just a few suns.

- **Supermassive Black Holes:**

  Supermassive black holes exist in the hearts of galaxies and usually contain the mass equivalent to millions and billions of suns.

- **Intermediate Black Holes:**

  Such bodies could form when stars collide in a chain reactions and usually contain the mass equivalent to hundreds and thousands of suns.





?



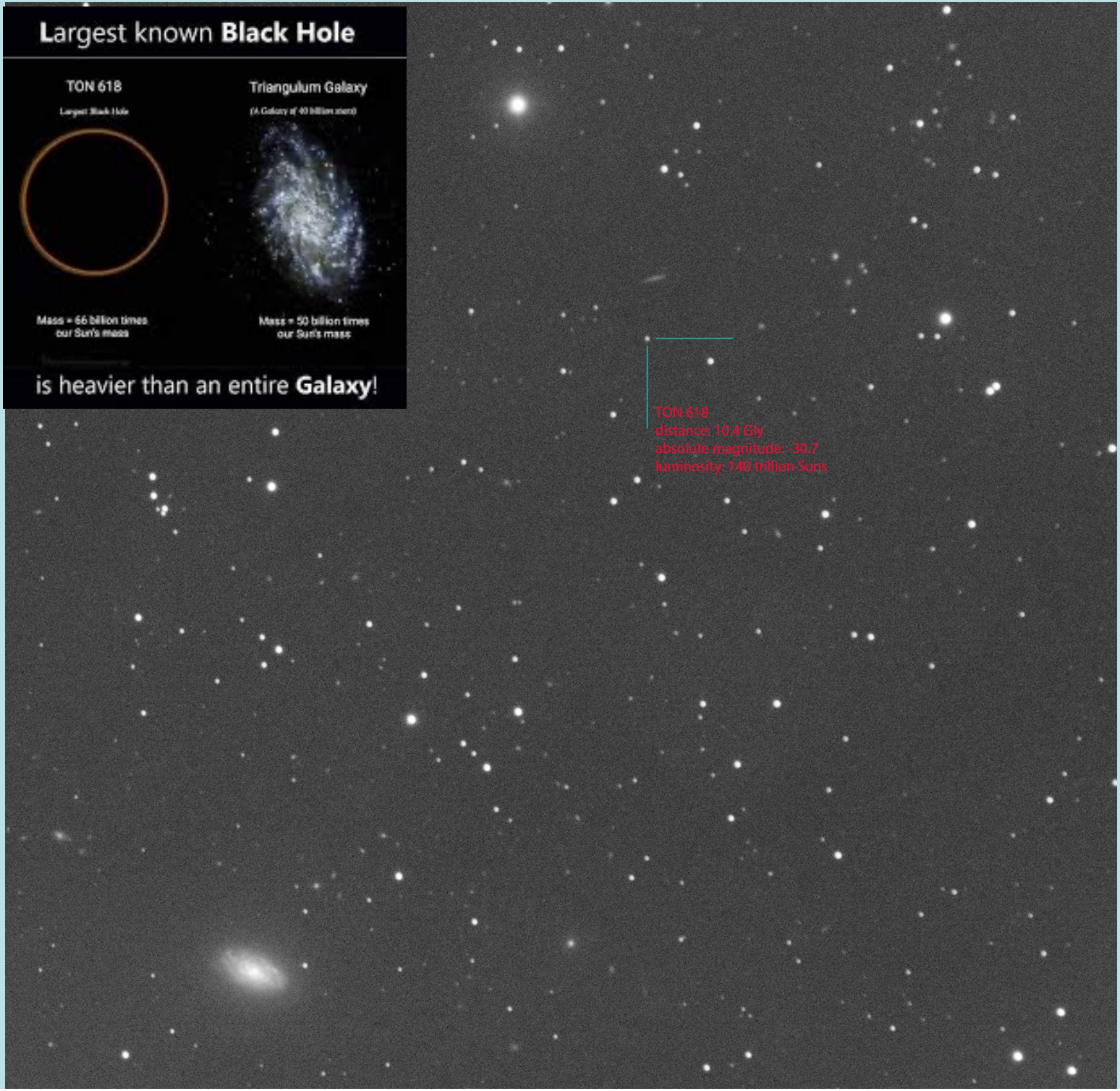
Stellar Black Hole

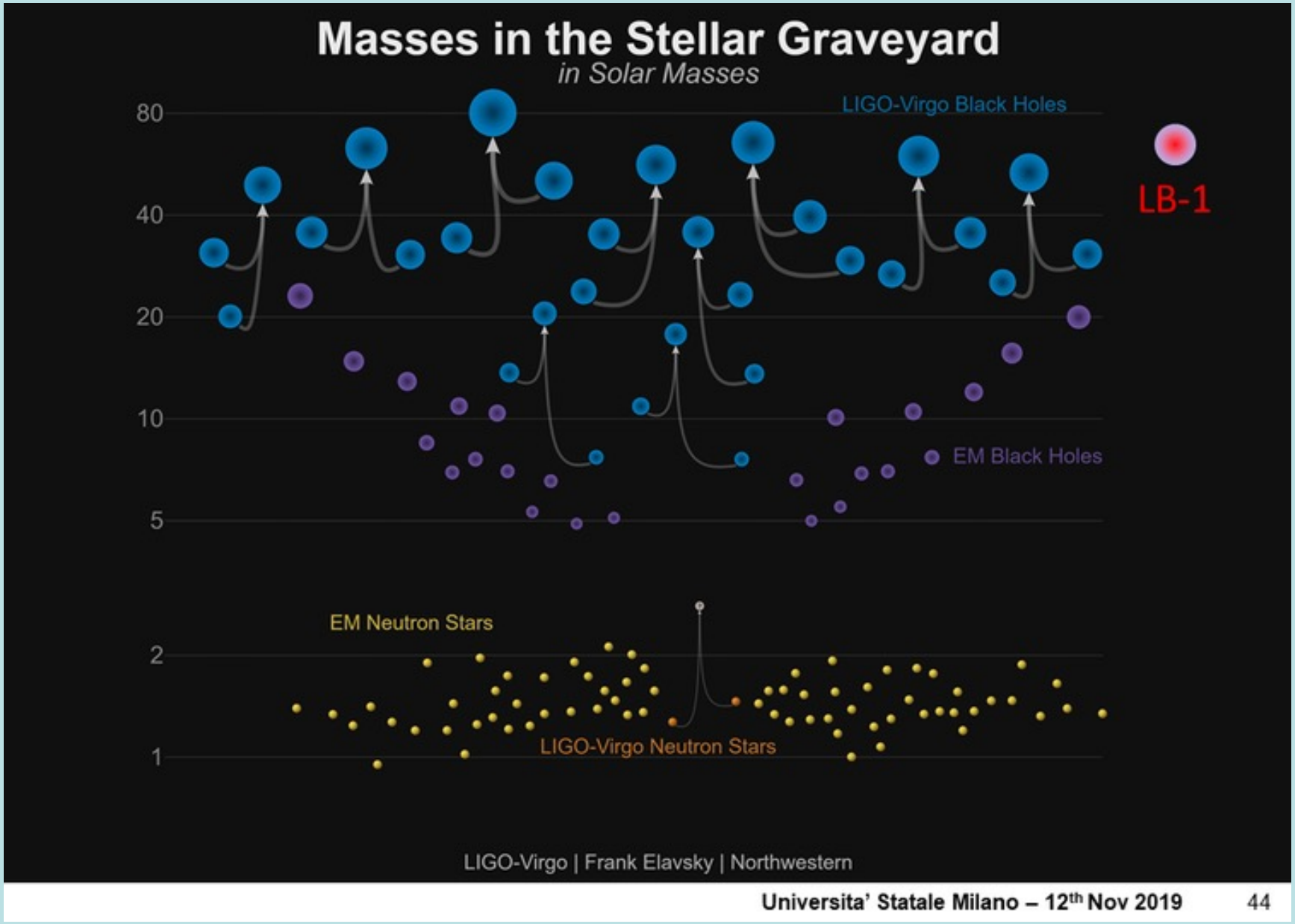
Intermediate Mass Black Hole

Supermassive Black Hole

1 10 100 1,000 10,000 100,000 1,000,000 ...

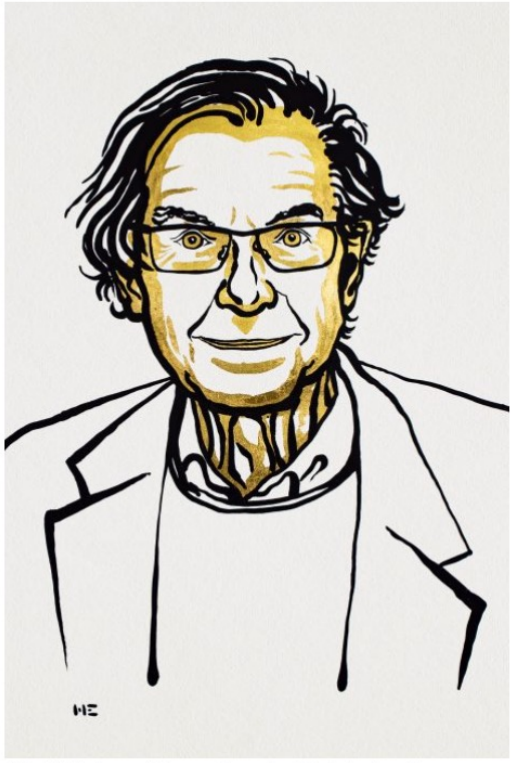
Object Mass
(Relative to the Sun)


Largest known Black Hole
TON 618
Largest Black Hole
Triangulum Galaxy
(A Galaxy of 40 billion stars)
Mass = 66 billion times our Sun's mass
Mass = 50 billion times our Sun's mass
is heavier than an entire Galaxy!
TON 618
distance: 10.4 Gly
absolute magnitude: -30.7
luminosity: 140 trillion Suns



LIGO測到的黑洞質量幾乎都在Stellar BH質量分佈的上緣。

Roger Penrose
Facts



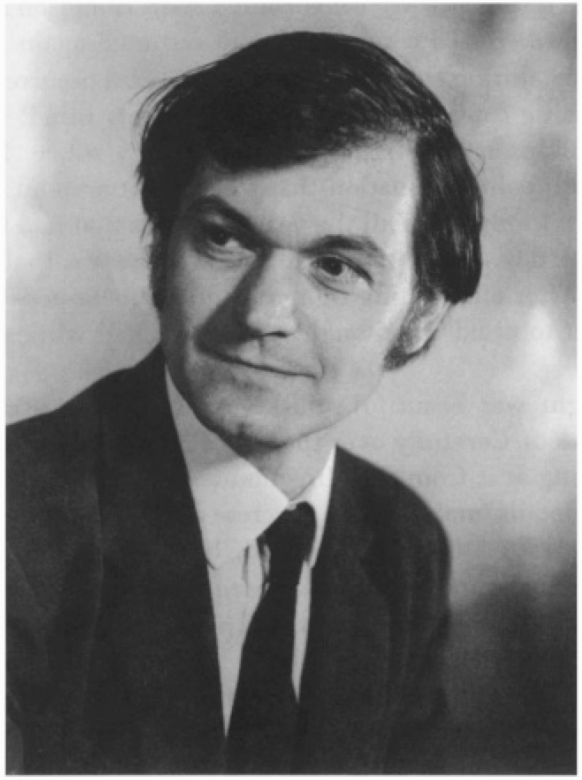
Roger Penrose
The Nobel Prize in Physics 2020

Born: 1931, Colchester, United Kingdom

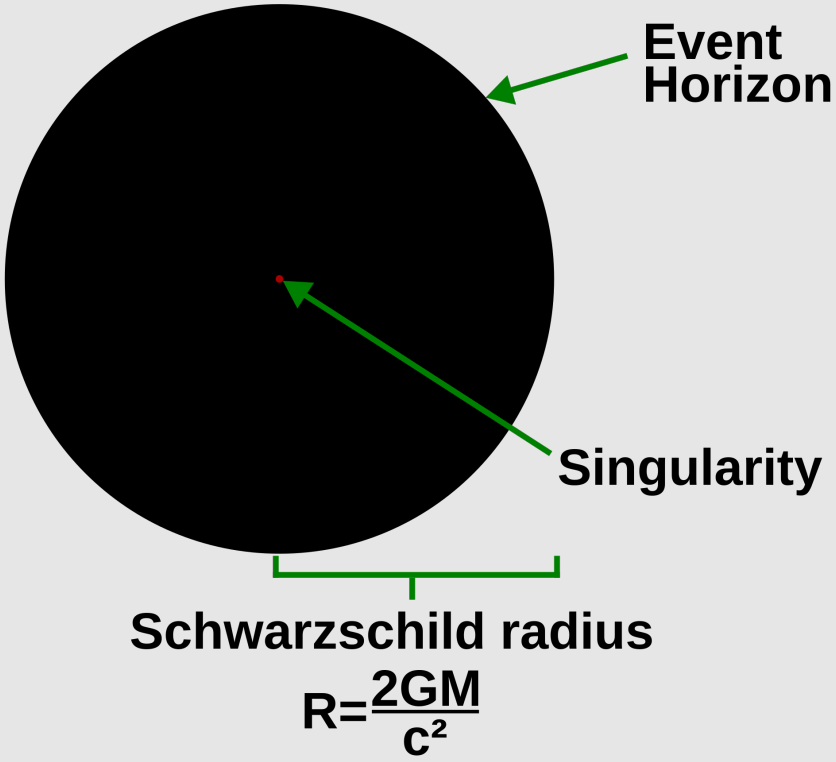
Affiliation at the time of the award: University of Oxford, Oxford, United Kingdom

Prize motivation: "for the discovery that black hole formation is a robust prediction of the general theory of relativity."

Prize share: 1/2



Roger Penrose, ca. 1964. [Photo by Godfrey Argent for the National Portrait Gallery of Britain and the Royal Society of London; courtesy Godfrey Argent.]



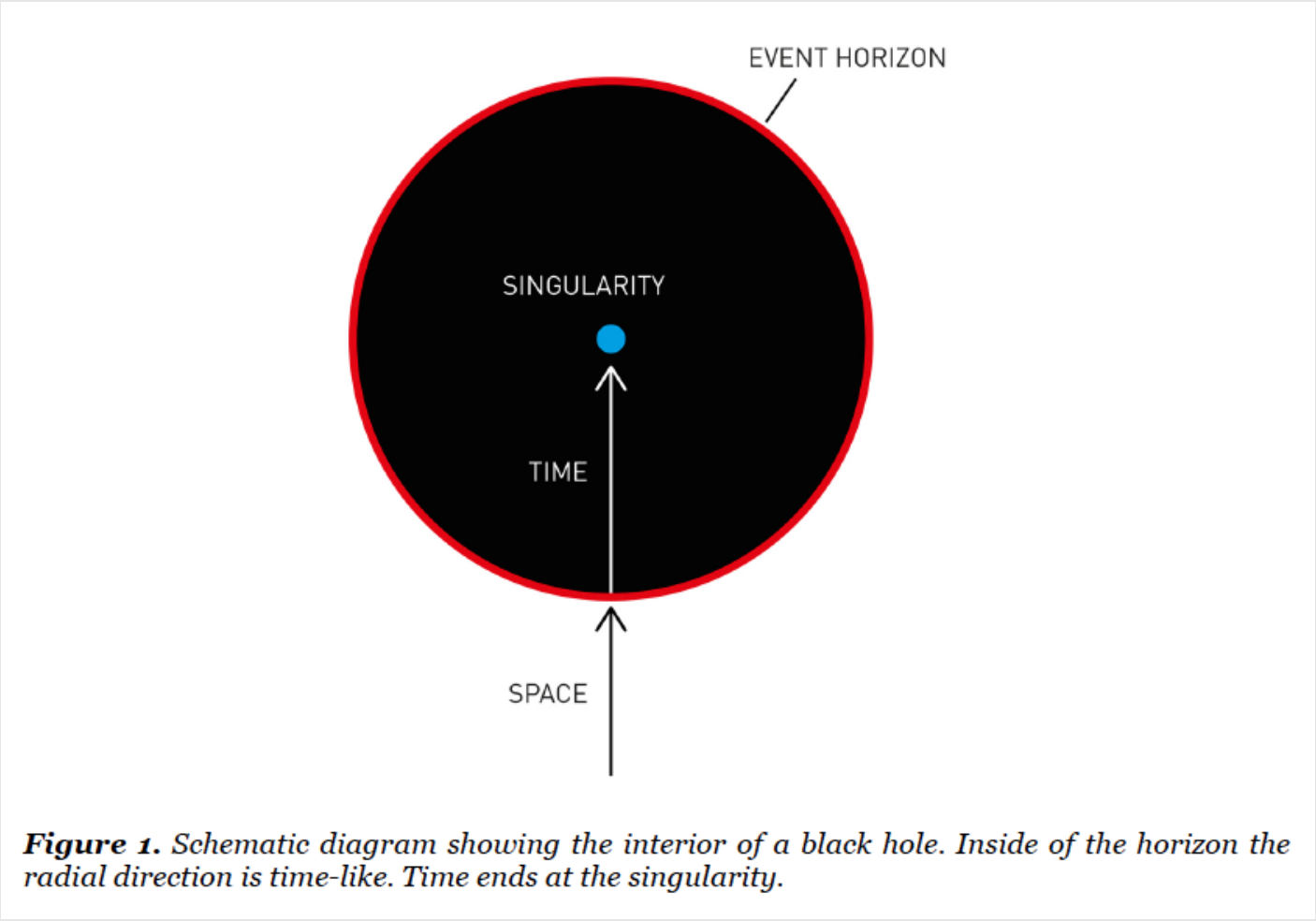


Figure 1. *Schematic diagram showing the interior of a black hole. Inside of the horizon the radial direction is time-like. Time ends at the singularity.*

在黑洞的球心處，重力產生的曲率，因此物質受到的扭力是無限大。此處是數學稱的奇異點 Singularity。落入黑洞的物質會停止於該處。

How Eating Meat Contributes to Global Warming (*page 72*)

SCIENTIFIC AMERICAN

Nanomedicine
Revolutionizing the Fight against Disease
page 44

February 2009 www.SciAm.com

Black holes may have even stranger siblings that violate known laws of physics

NAKED SINGULARITIES

Fold the Brain
How Forces That Shape It Link to Autism and More

Submarine Lava
The Mysterious, Red-Hot Origins of the Ocean Floor

Electric Rockets
Efficient Travel to Deep Space

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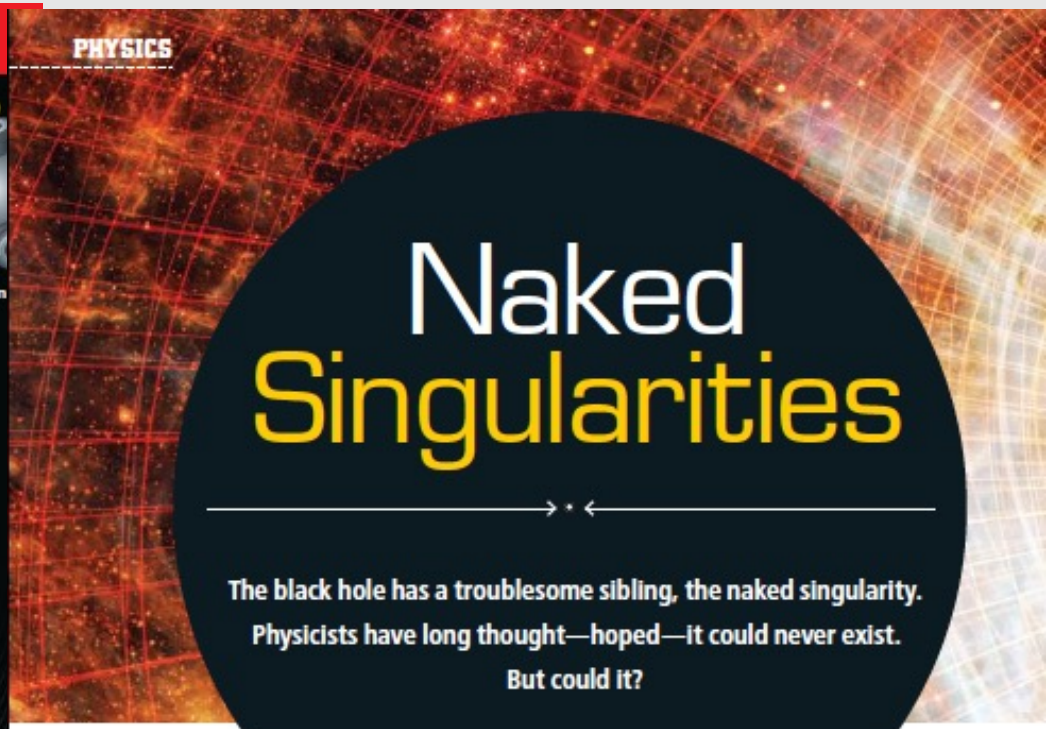

PHYSICS

Naked Singularities

The black hole has a troublesome sibling, the naked singularity. Physicists have long thought—hoped—it could never exist. But could it?

BY PANKAJ S. JOSHI

KEY CONCEPTS

- Conventional wisdom has it that a large star eventually collapses to a black hole, but some theoretical models suggest it might instead become a so-called naked singularity [*see box on opposite page for definition*]. Sorting out what happens is one of the most important unresolved problems in astrophysics.
- The discovery of naked singularities would transform the search for a unified theory of physics, not least by providing direct observational tests of such a theory.

—*The Editors*

Modern science has introduced the world to plenty of strange ideas, but surely one of the strangest is the fate of a massive star that has reached the end of its life. Having exhausted the fuel that sustained it for millions of years, the star is no longer able to hold itself up under its own weight, and it starts collapsing catastrophically. Modest stars like the sun also collapse, but they stabilize again at a smaller size. Whereas if a star is massive enough, its gravity overwhelms all the forces that might halt the collapse. From a size of millions of kilometers across, the star crumples to a pinprick smaller than the dot on an "i."

Most physicists and astronomers think the result is a black hole, a body with such intense gravity that nothing can escape from its immediate vicinity. A black hole has two parts. At its core is a singularity, the infinitesimal point into which all the matter of the star gets crushed. Surrounding the singularity is the region of space from which escape is impossible, the perimeter of which is called the event horizon. Once something enters the event horizon, it loses all hope of exiting. Whatever light the falling body gives off is trapped, too, so an outside observer never sees it again. It ultimately crashes into the singularity.

But is this picture really true? The known laws of physics are clear that a singularity forms,

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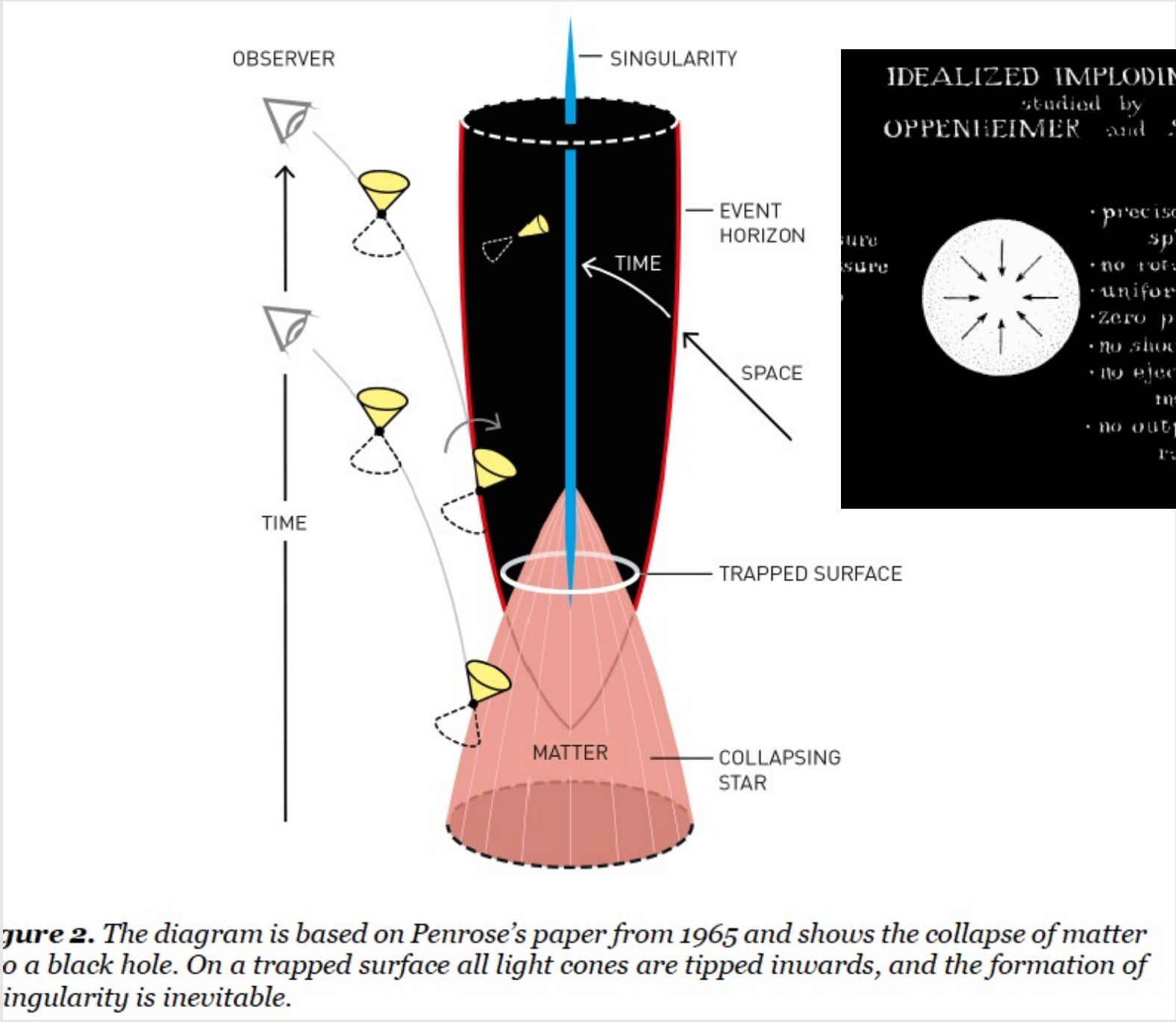
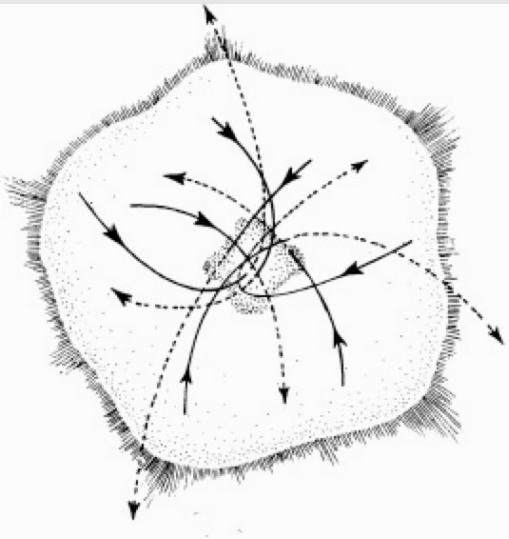
本來大家以為奇異點會永遠被Horizon遮蓋住。



***gure 2.** The diagram is based on Penrose's paper from 1965 and shows the collapse of matter o a black hole. On a trapped surface all light cones are tipped inwards, and the formation of ingularity is inevitable.*

但塌陷下去的黑洞物質，似乎也會堆在奇異點上！



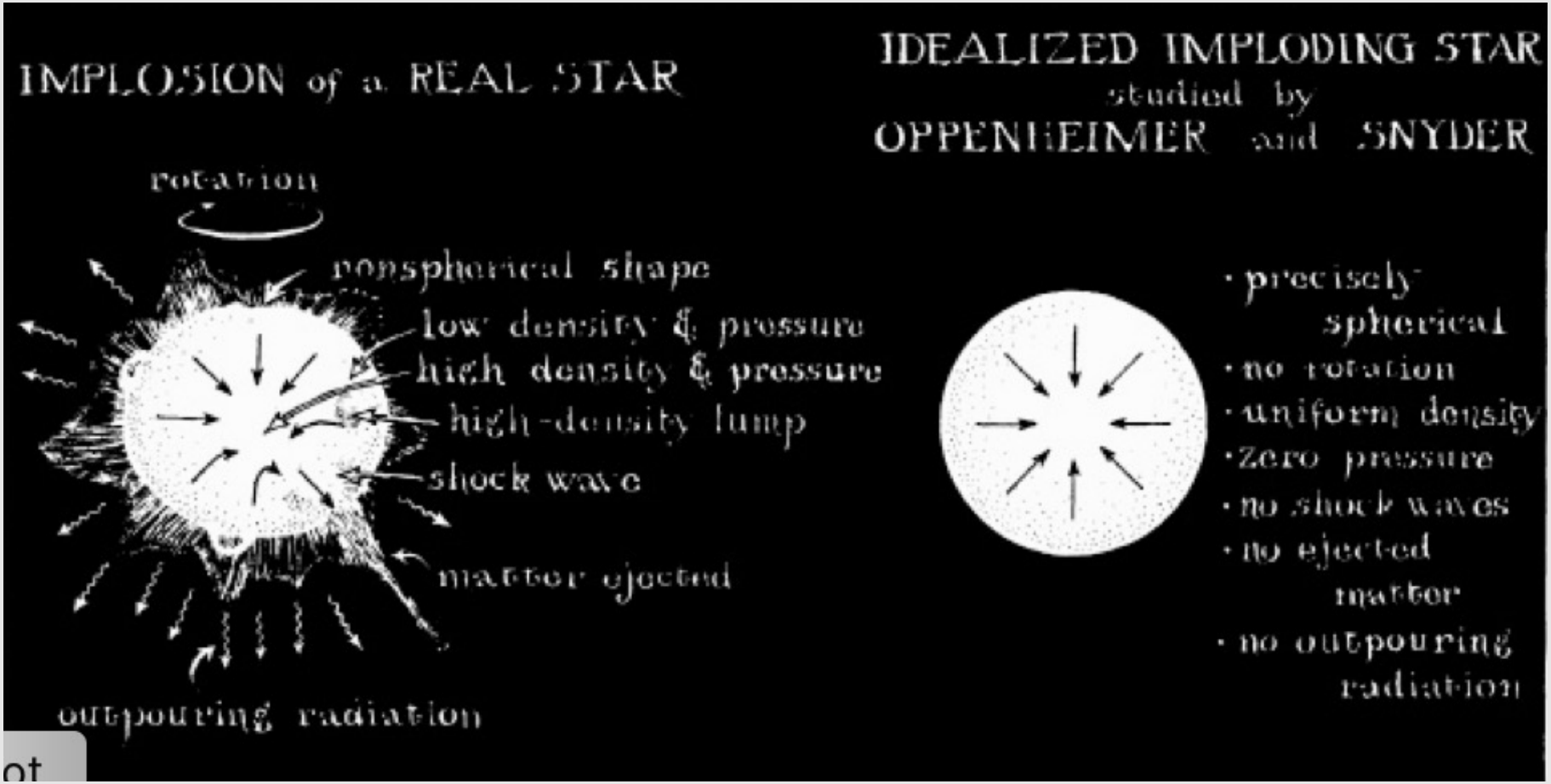
13.3 One mechanism for converting a star's implosion into an explosion, when gravity is weak enough that Newton's laws are accurate, and when internal pressure is weak enough to be unimportant. If the imploding star is slightly deformed ("perturbed"), its atoms implode toward slightly different points, swing around each other, and then fly back out.

史瓦西度規假設球對稱。

如果星體物質有一點變形，不完全是球對稱。

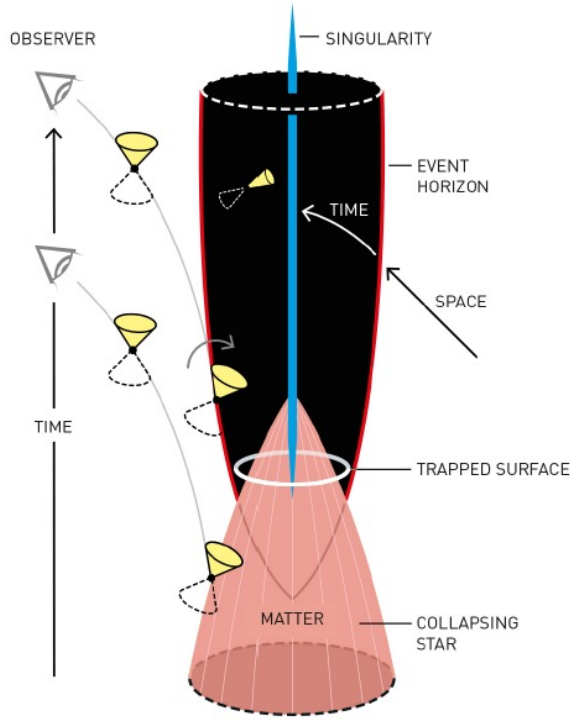
塌陷的物質有沒有可能錯過球心，擴大了不對稱。

甚至可不可能因此造成horizon也變形甚至打開？



塌陷下去的黑洞物質，會不會重新爆炸？

Penrose's theorem said *roughly* this: Suppose that a star—any kind of star whatsoever—implodes so far that its gravity becomes strong enough to form an *apparent horizon*, that is, strong enough to pull outgoing light rays back inward (Box 12.1). After this happens, nothing can prevent the gravity from growing so strong that it creates a singularity. Consequently (since black holes always have apparent horizons), *every black hole must have a singularity inside itself.*



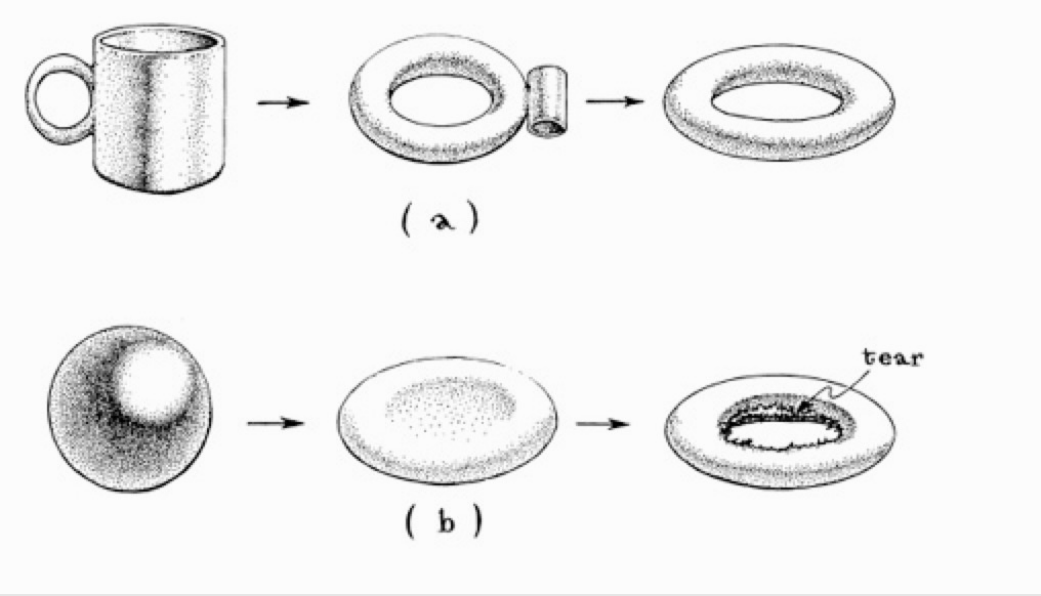
gure 2. *The diagram is based on Penrose's paper from 1965 and shows the collapse of matter o a black hole. On a trapped surface all light cones are tipped inwards, and the formation of ingularity is inevitable.*

Penrose's singularity theorem acquired its amazing power from a new mathematical tool that he used in its proof, a tool that no physicist had ever before used in calculations about curved spacetime, that is, in general relativistic calculations: *topology*.

Topology is a branch of mathematics that deals with the qualitative ways in which things are connected to each other or to themselves. For example, a coffee cup and a doughnut "have the same topology" because (if they are both made from putty) we can smoothly and continuously deform one into the other without tearing it, that is, without changing any connections (Figure 13.5a). By contrast, a sphere has a different topology from a doughnut; to deform a sphere into a doughnut, we must tear a hole in it, thereby changing how it is connected to itself (Figure 13.5b).

Topology cares *only* about connections, and *not* about shapes or sizes or curvatures. For example, the doughnut and the coffee cup have very different shapes and curvatures, but they have the same topology.

We physicists, before Penrose's singularity theorem, ignored topology because we were fixated on the fact that spacetime *curvature* is the central concept of general relativity, and topology cannot tell us anything about curvature. (Indeed, because Penrose's theorem was



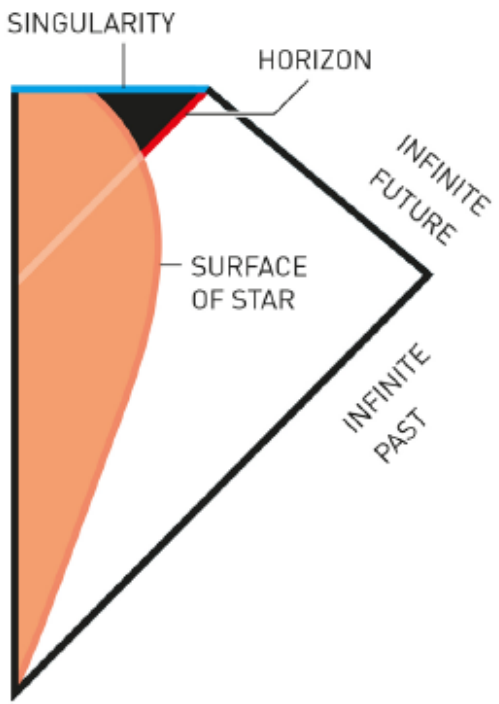


Figure 3. *A Penrose diagram of a star that collapses into a black hole. Time runs upwards and light rays are inclined at 45 degrees.*

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BLACK HOLES & TIME WARPS

EINSTEIN'S OUTRAGEOUS LEGACY



WINNER OF THE NOBEL PRIZE IN PHYSICS

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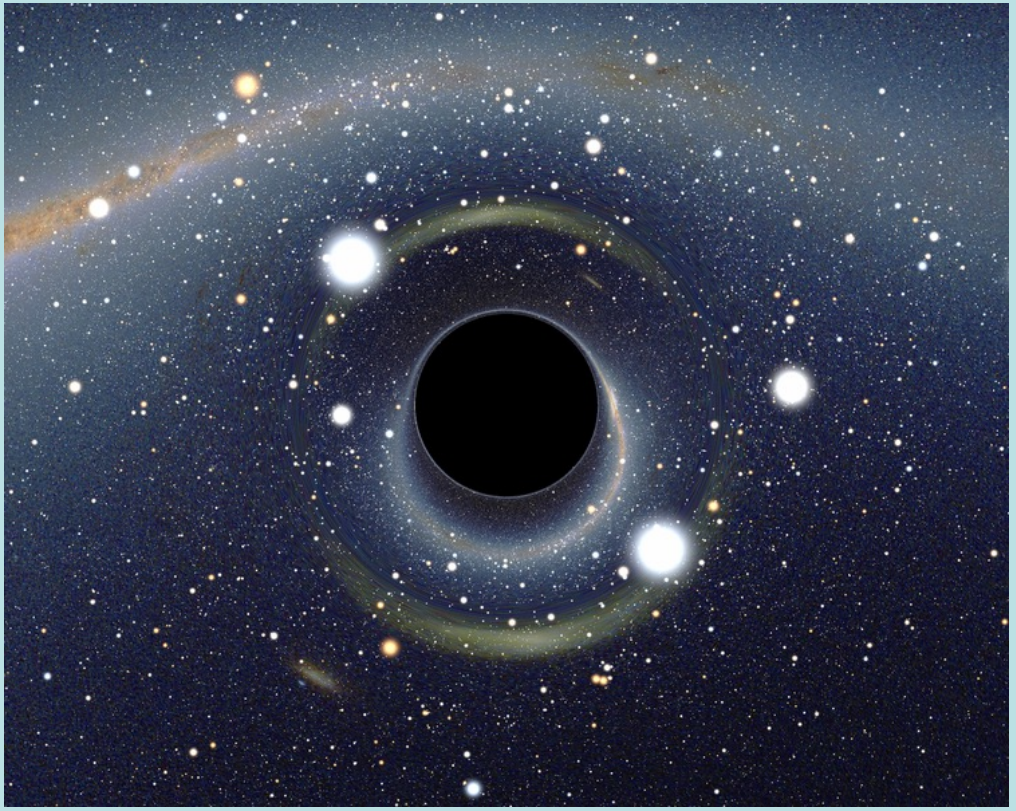
FOREWORD BY STEPHEN HAWKING

"Deeply satisfying. . . . [An] engrossing blend of theory, history, and anecdote." —*WALL STREET JOURNAL*

黑洞看起來如何？



黑洞自然是黑的，

但對背景的星星有重力透鏡的效果。

Simulated view of a black hole (center) in front of the Large Magellanic Cloud. Note the gravitational lensing effect, which produces two enlarged but highly distorted views of the Cloud. Across the top, the Milky Way disk appears distorted into an arc.



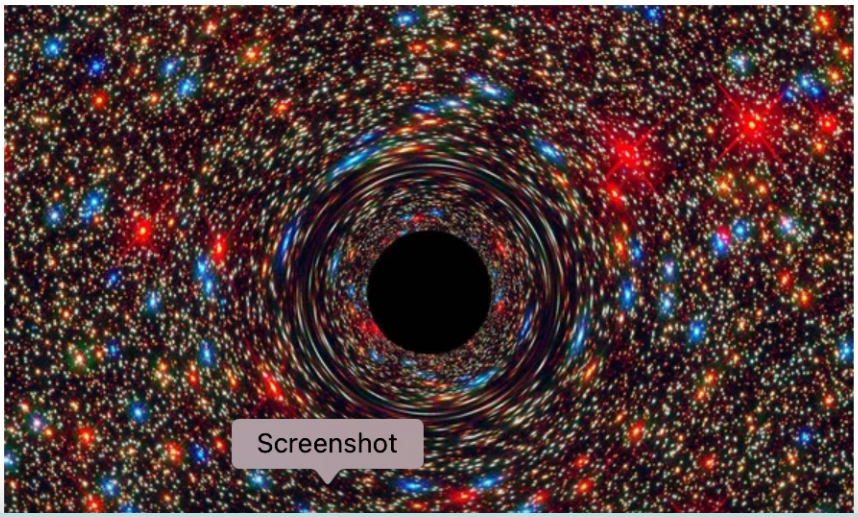
Lensing by a black hole. Animated simulation of gravitational lensing caused by a Schwarzschild black hole going past a background galaxy. A secondary image of the galaxy can be seen within the black hole Einstein ring on the opposite direction of that of the galaxy. The secondary image grows (remaining within the Einstein ring) as the primary image approaches the black hole. The surface brightness of the two images remain constant, but their angular size vary, hence producing an amplification of the galaxy luminosity as seen from a distant observer. The maximum amplification occurs when the background galaxy (or in the present case a bright part of it) is exactly behind the black hole.

BLACK HOLES

Astronomers Find First Ever Rogue Black Hole Adrift in the Milky Way

Weighing in at seven times the mass of our sun, the dark object is by far the best-yet candidate for a free-floating stellar-mass black hole

By Jonathan O'Callaghan on February 3, 2022



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Shredded Stars Offer New View of

An Isolated Stellar-Mass Black Hole Detected Through Astrometric Microlensing*

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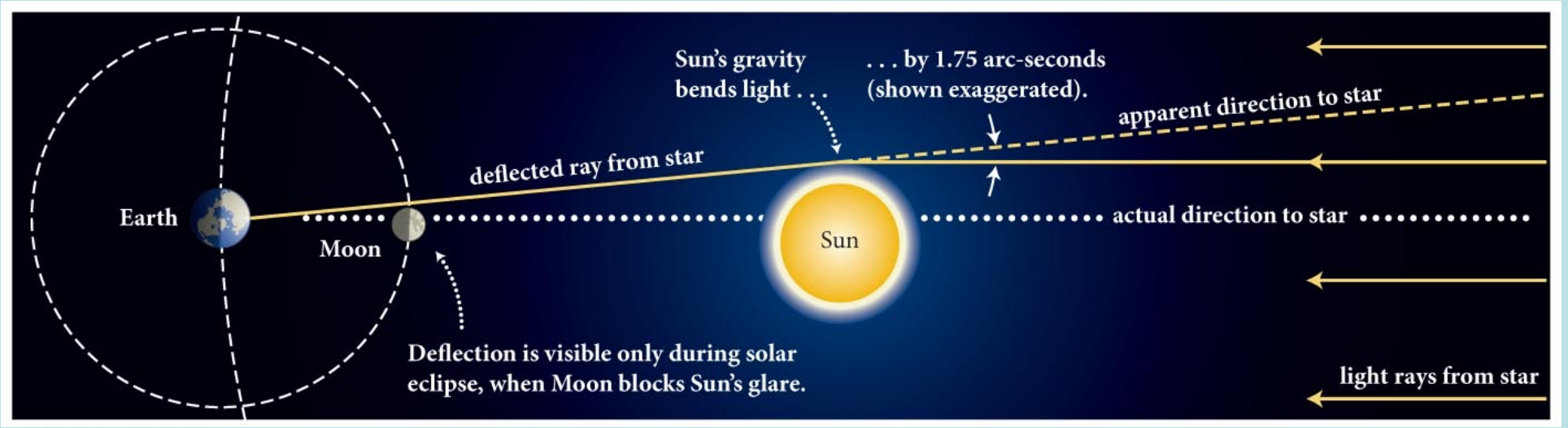
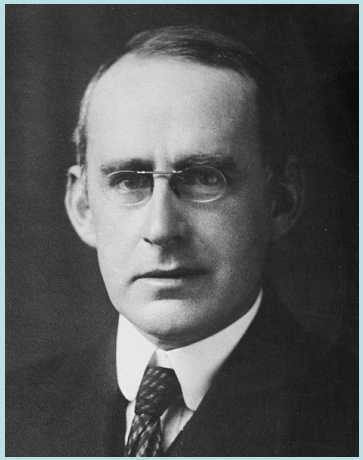
ABSTRACT

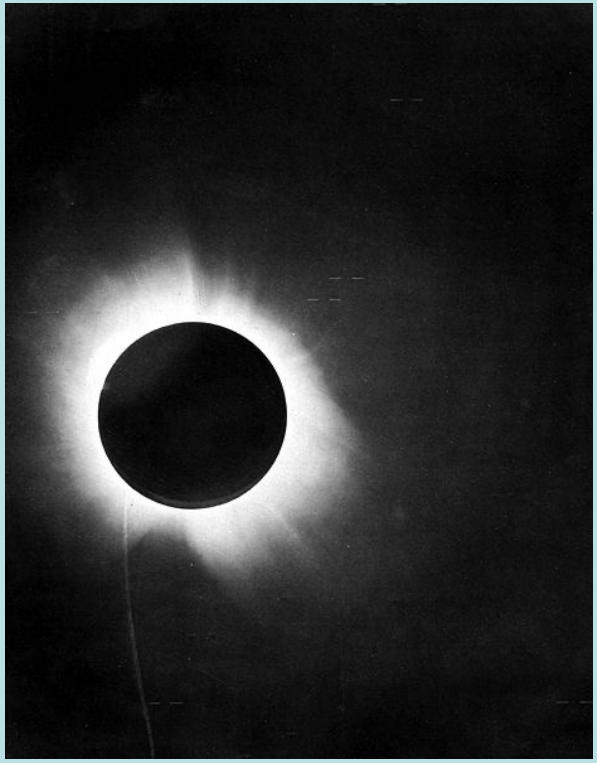
We report the first unambiguous detection and mass measurement of an isolated stellar-mass black hole (BH). We used the *Hubble Space Telescope* (*HST*) to carry out precise astrometry of the source star of the long-duration ($t_{\rm E} \simeq 270$ days), high-magnification microlensing event MOA-2011-BLG-191/OGLE-2011-BLG-0462, in the direction of the Galactic bulge. *HST* imaging, conducted at eight epochs over an interval of six years, reveals a clear relativistic astrometric deflection of the background star's apparent position. Ground-based photometry shows a parallactic signature of the effect of the Earth's motion on the microlensing light curve. Combining the *HST* astrometry with the ground-based light curve and the derived parallax, we obtain a lens mass of $7.1 \pm 1.3\,M_\odot$ and a distance of 1.58 ± 0.18 kpc. We show that the lens emits no detectable light, which, along with having a mass higher than is possible for a white dwarf or neutron star, confirms its BH nature. Our analysis also

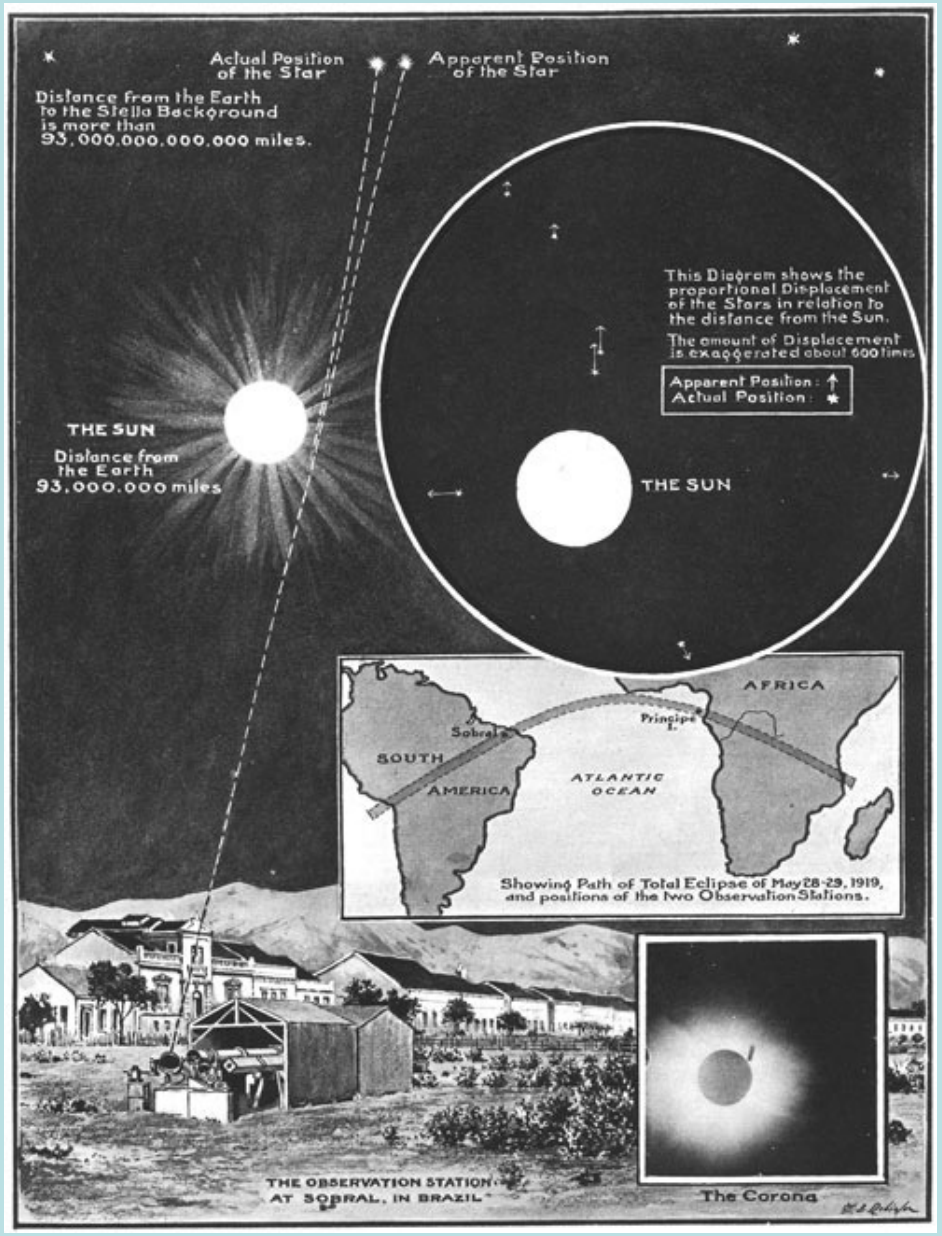
利用日蝕，觀察星光受太陽質量重力的偏折：

若是黑洞就直接觀察星光受黑洞質量重力的偏折: Lensing！

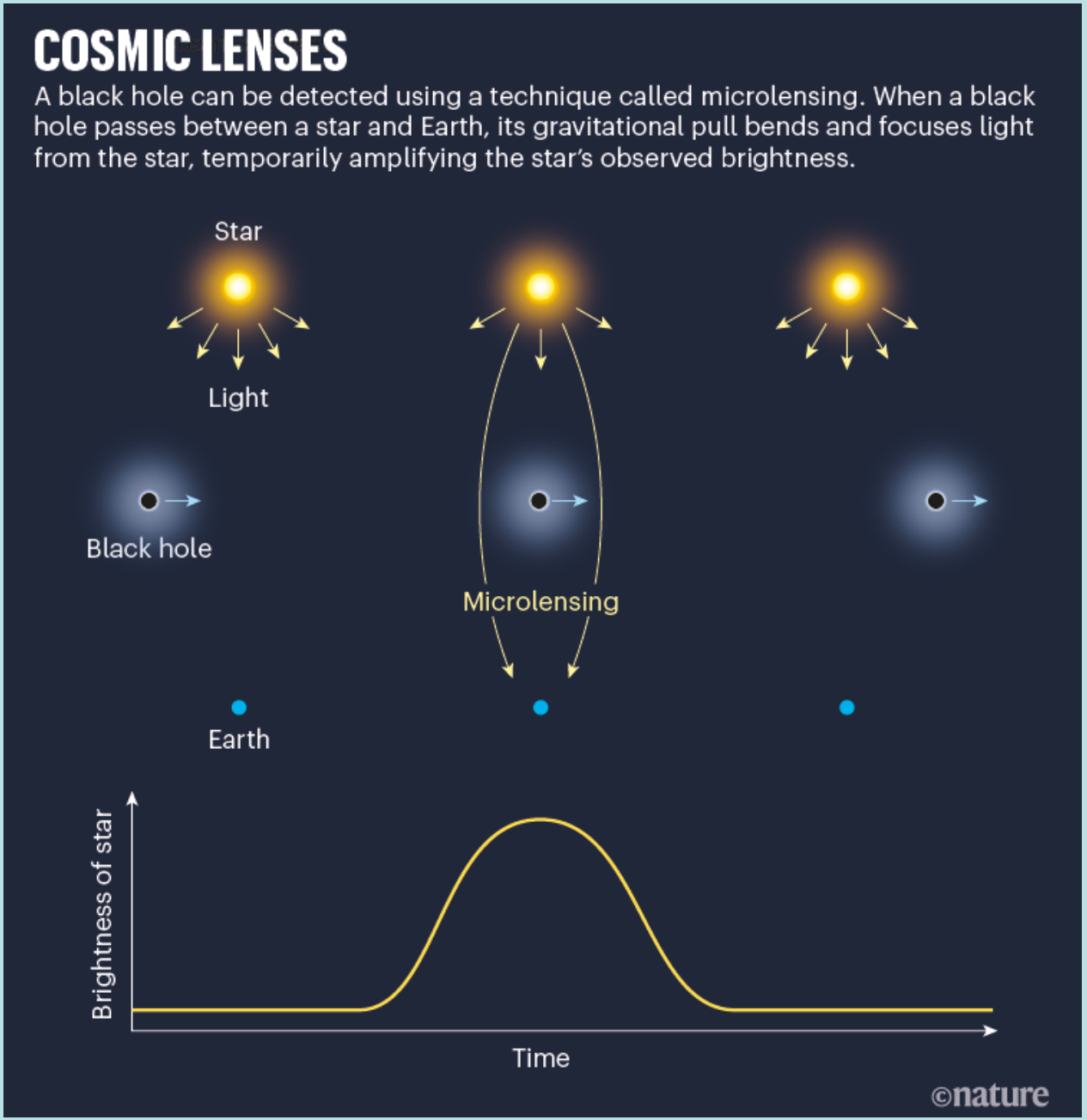








One of Eddington's photographs of the total solar eclipse of 29 May 1919, presented in his 1920 paper announcing its success, confirming Einstein's theory that light bends


COSMIC LENSES
A black hole can be detected using a technique called microlensing. When a black hole passes between a star and Earth, its gravitational pull bends and focuses light from the star, temporarily amplifying the star's observed brightness.
Star
Light
Black hole
Microlensing
Earth
Brightness of star
Time
©nature

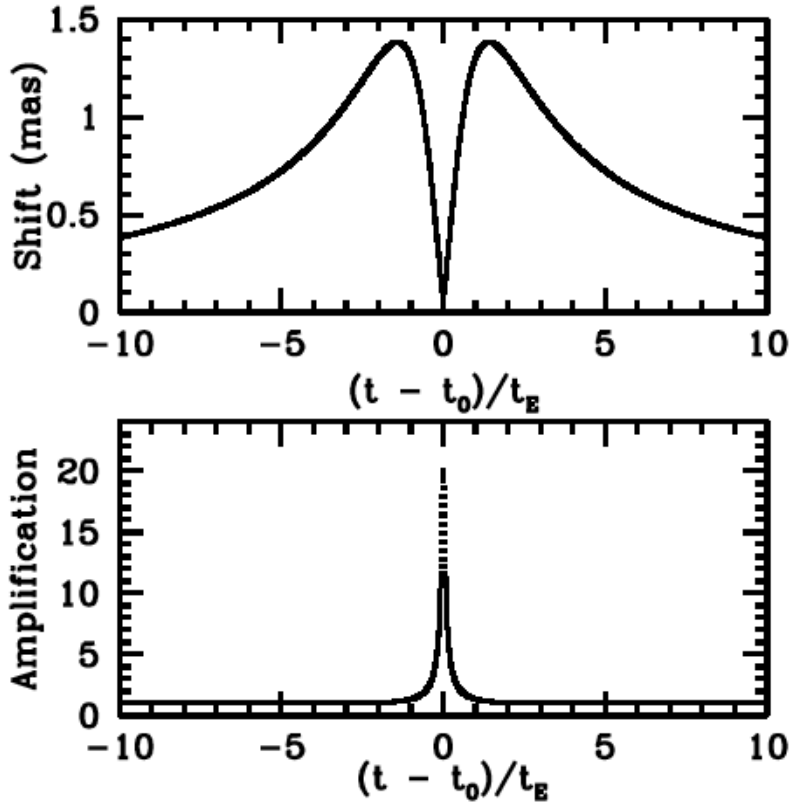


Figure 1. Astrometric shift (top panel) and light magnification (bottom panel) for a microlensing event produced by a $5\,M_{\odot}$ black hole at a distance of 2 kpc passing in front of a background star at 8 kpc. The assumed minimum impact parameter $u_0 = 0.05$. The maximum astrometric shift of the source is $\sim$1.4 mas, at $u = \sqrt{2}$, and the maximum magnification is $\sim$20, at the time of closest angular approach. Note the much longer duration for the astrometric shift, compared to that of the light magnification.

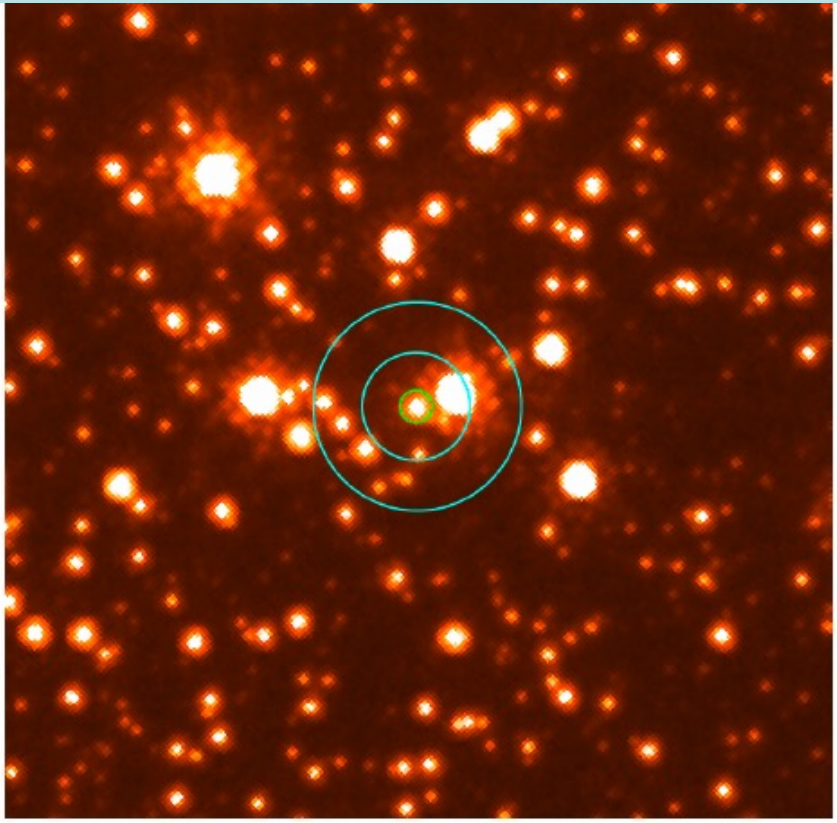


Figure 3. *HST* image in the F814W (I-band) filter of an $8'' \times 8''$ region centered on MOA-11-191/OGLE-11-0462, obtained at our final epoch in 2017 August. North is at the top, east on the left. Encircled in green is the source star, now returned to baseline luminosity. The site is resolved into the source, a much brighter neighboring star $0\farcs4$ to the WNW, and several nearby fainter stars. The inner cyan circle has a diameter of $1''$, corresponding to the typical best seeing in ground-based microlensing survey images; the outer cyan circle's diameter is $2''$, which is not unusual seeing. The source, bright neighbor, and several fainter stars are generally blended in ground-based frames, and the blending increases with seeing.

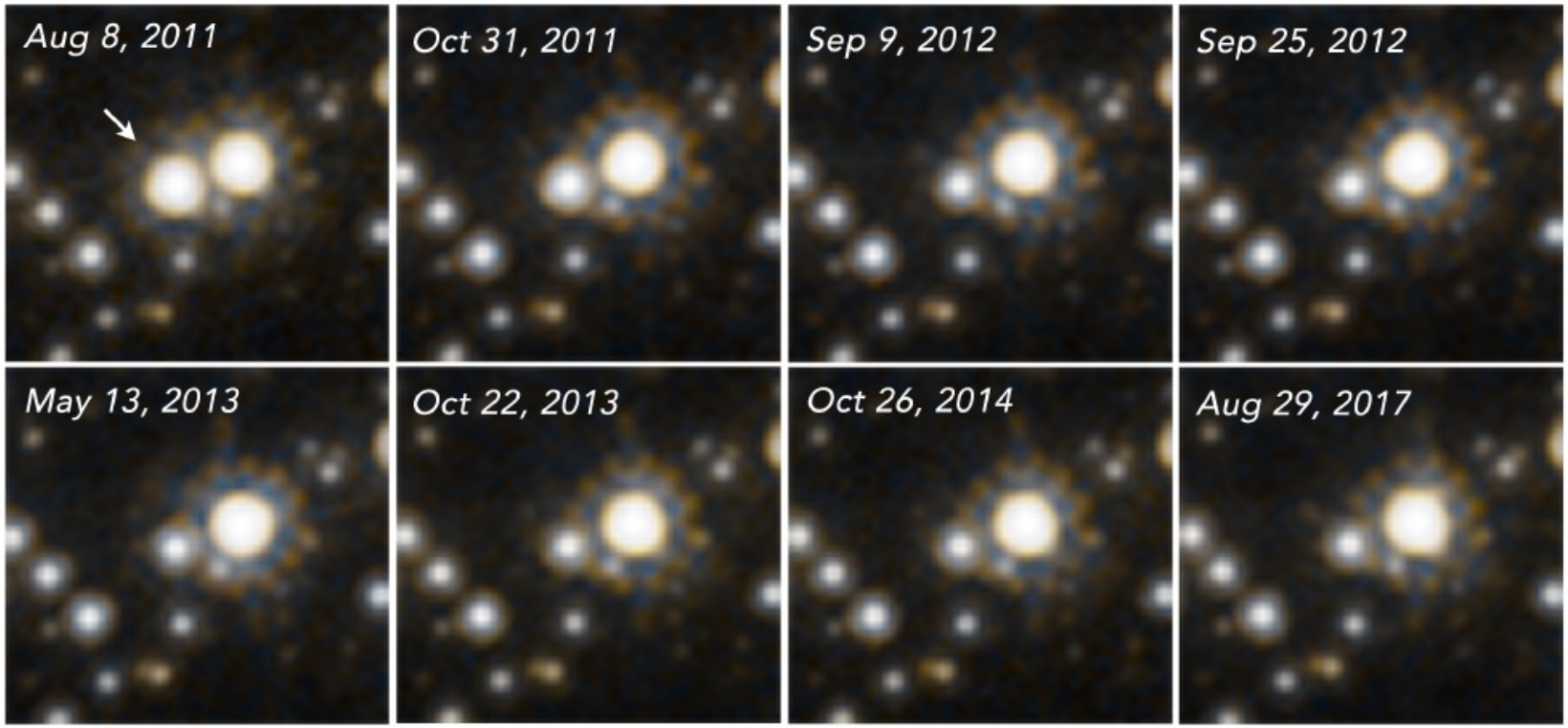


Figure 4. 2.″1 × 2.″0 cutouts around MOA-11-191/OGLE-11-0462 as observed by *HST* at all 8 epochs. Exposures were taken in F606W and F814W from 2011 to 2017; see Table 2 for details. The source star is marked by an arrow in the first-epoch (top left) image. At this epoch, on 2011 August 8, the magnification was a factor of ∼12. The maximum astrometric deflection occurred at Epochs 3 and 4, when the photometric magnification was only about 10%. In 2017, the source had returned very close to its unmagnified brightness and undeflected position.

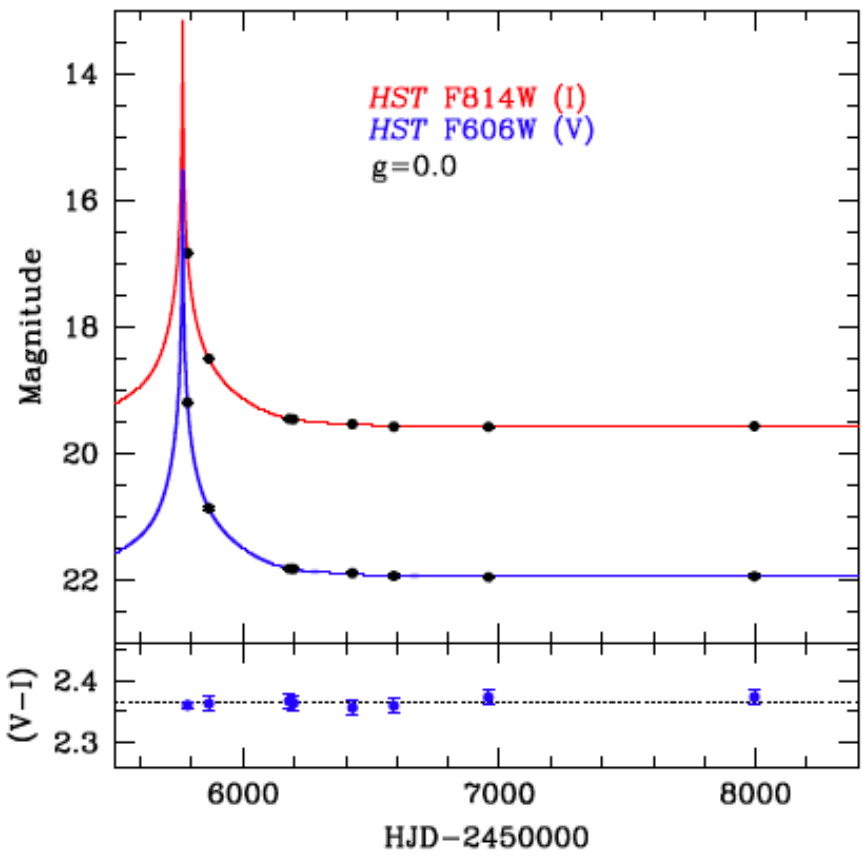


Figure 12. Photometry of MOA-11-191/OGLE-11-0462 obtained with *HST* over 6 years at 8 epochs in the F606W (blue) and F814W (red) filters. To fit the observations, we used the microlensing parameters (u_0, t_E, t_0, and π_E) derived from ground-based observations as described in §8, and baseline magnitudes derived from the late-epoch *HST* observations. The light curve fits best with the blending parameter $g = 0$ in both filters, consistent with no light contribution from the lens. The bottom panel shows the observed values of $(F606W - F814W)$, which clearly shows that the color of the source has remained constant to within 0.01 mag during the entire duration of ∼6 years of *HST* observations.

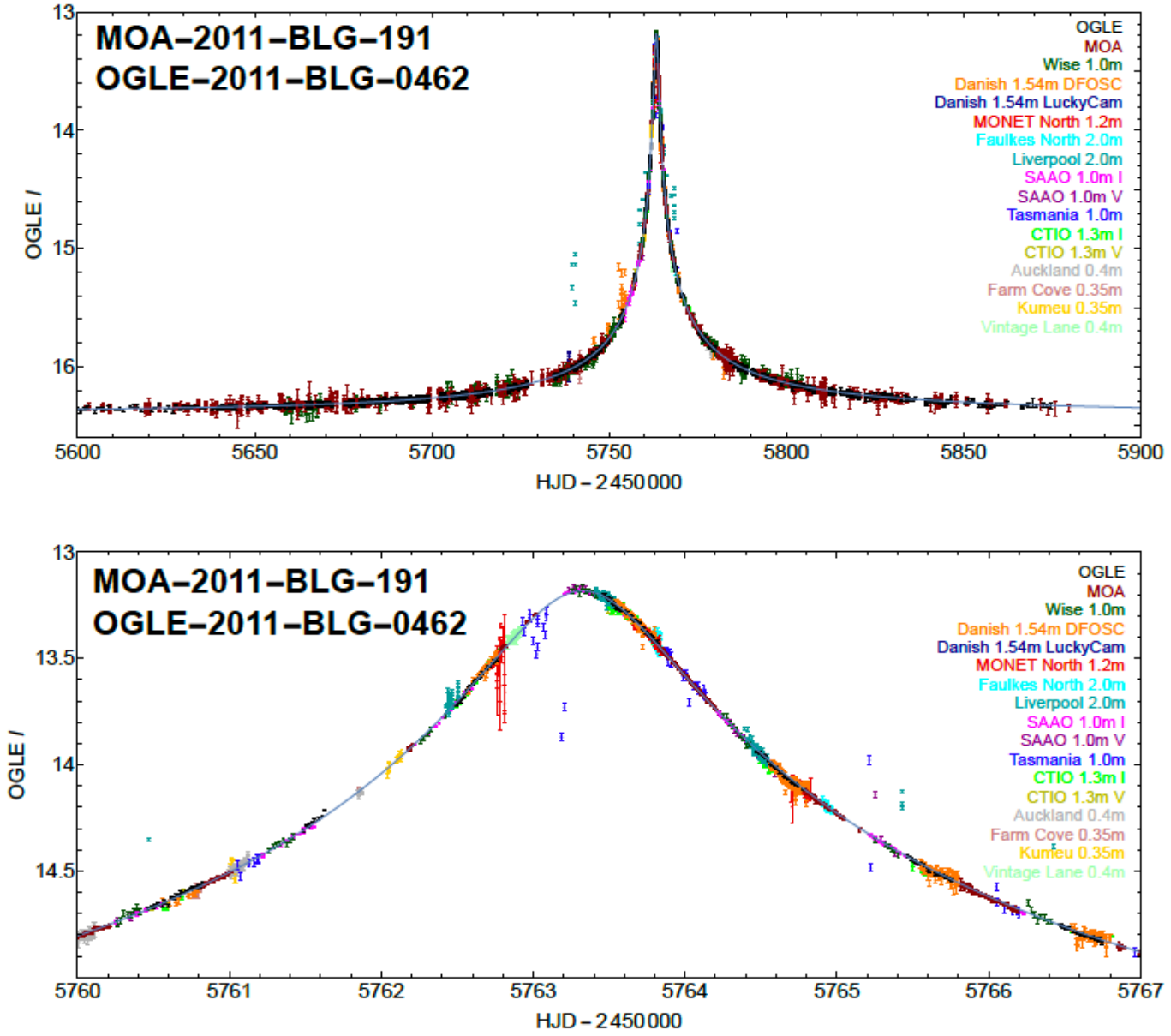
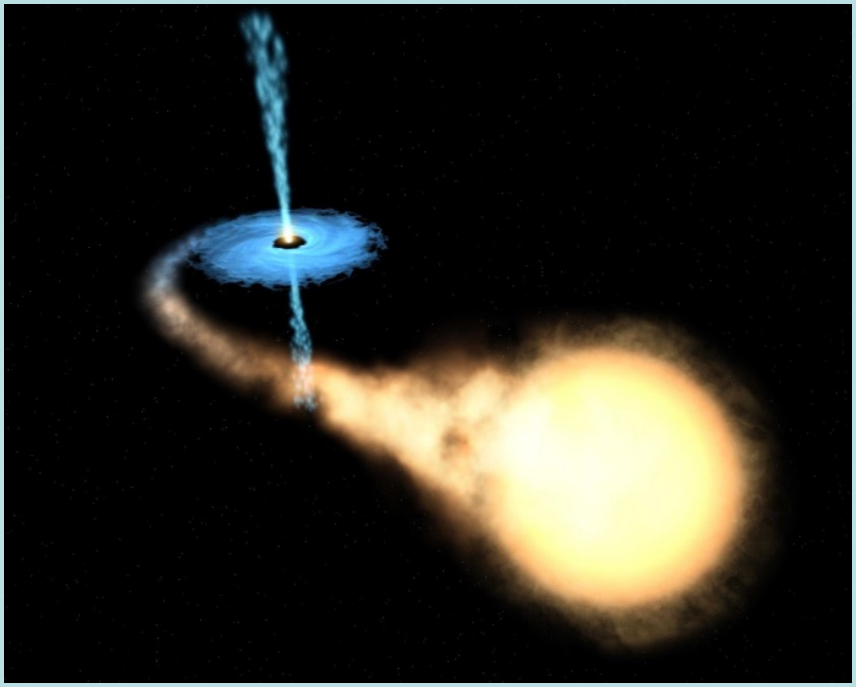


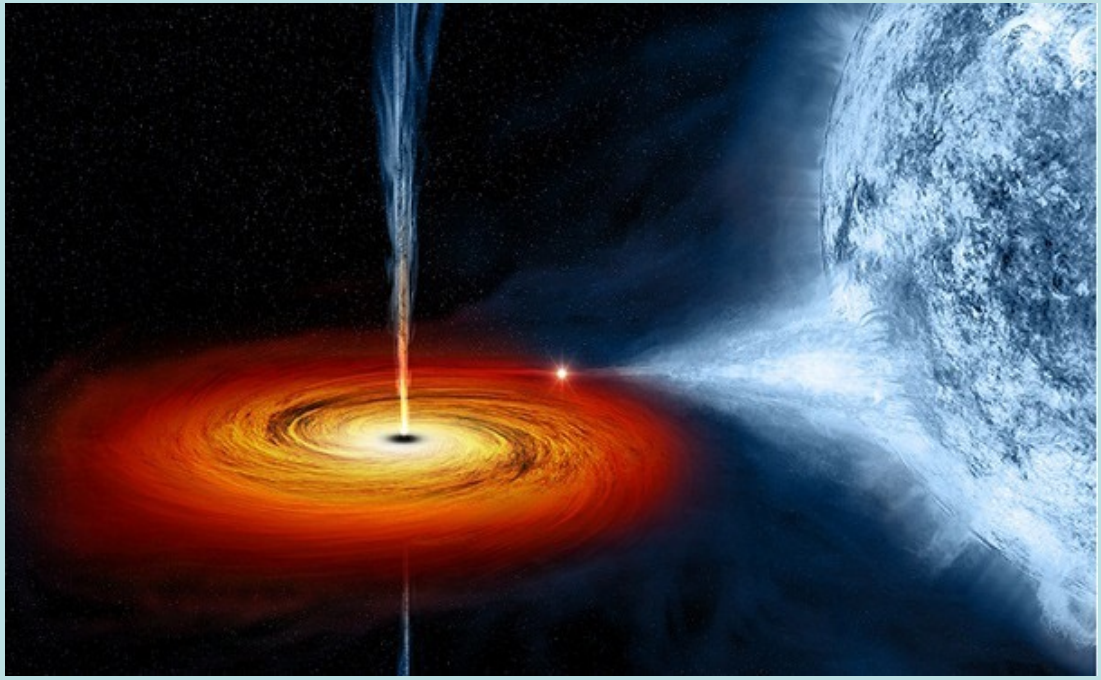
Figure 13. Ground-based photometric observations of MOA-11-191/OGLE-11-0462, along with a best-fitting model light curve, shown over a 300-day interval in the upper panel and over a zoomed-in region covering seven days around peak magnification in the bottom panel. All data have been transformed to OGLE magnitudes according to the inferred baseline magnitudes and blend ratio from the common model.

但有一些黑洞就非常顯眼！

這一般發生在steller黑洞與一顆恆星形成的雙星系統。

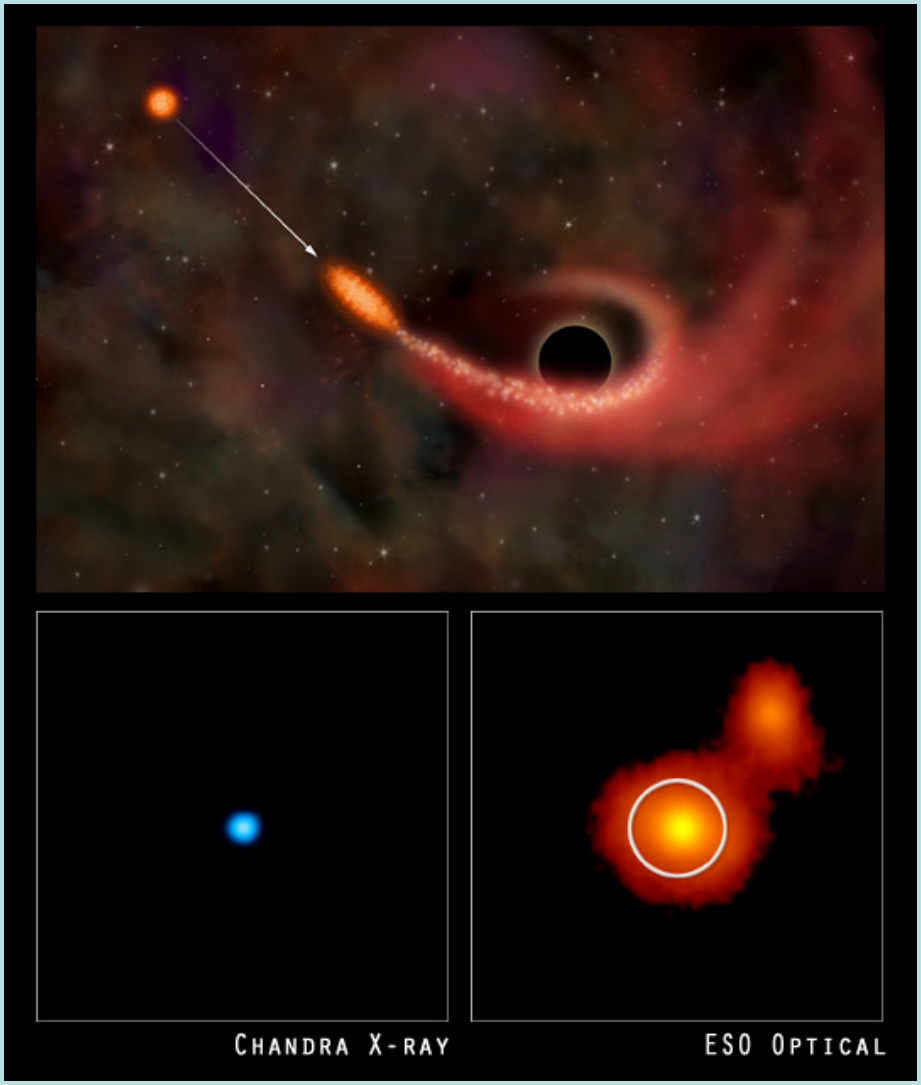
黑洞會將伴星的物質吸收過來。





或是銀河中心的巨大黑洞，把周圍的物質吸收過來。

Supermassive黑洞也會吸收整顆恆星



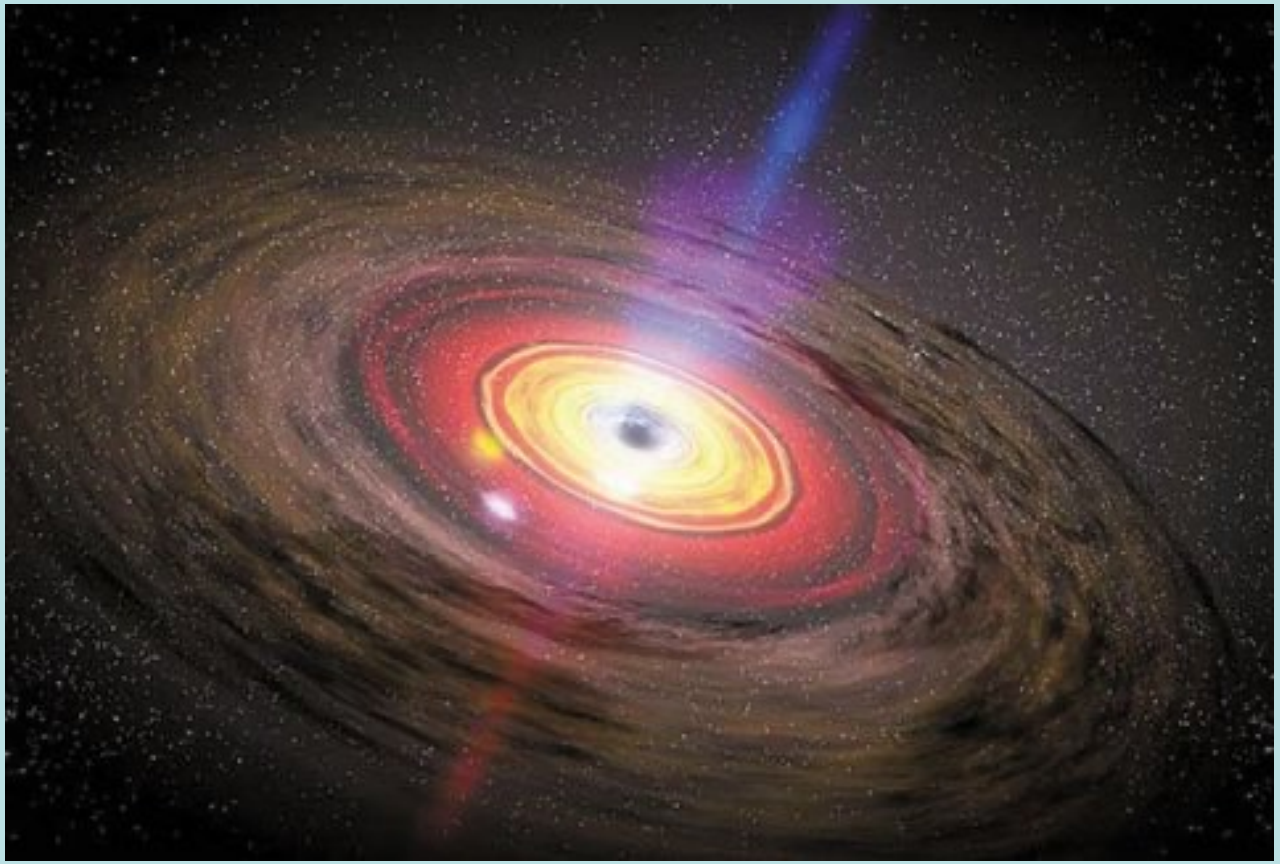
Artist's impression of a supermassive black hole tearing apart a star. Below: supermassive black hole devouring a star in galaxy RX J1242-11 – X-ray (left) and optical (right)

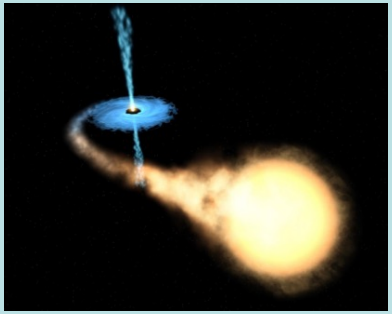
這些物質不一定會直接掉進去黑洞！

因為角動量守恆，被黑洞吸引的物質，會繞著黑洞作圓周運動。

若是來自伴星的物質，必須維持在兩星間的軌道平面上，會形成碟狀：

稱為 Accretion disk 吸積盤。





Artist's impression of the accretion disk around the supermassive black hole at the center of an active galaxy.
Image credit: NASA / Dana Berry, SkyWorks Digital

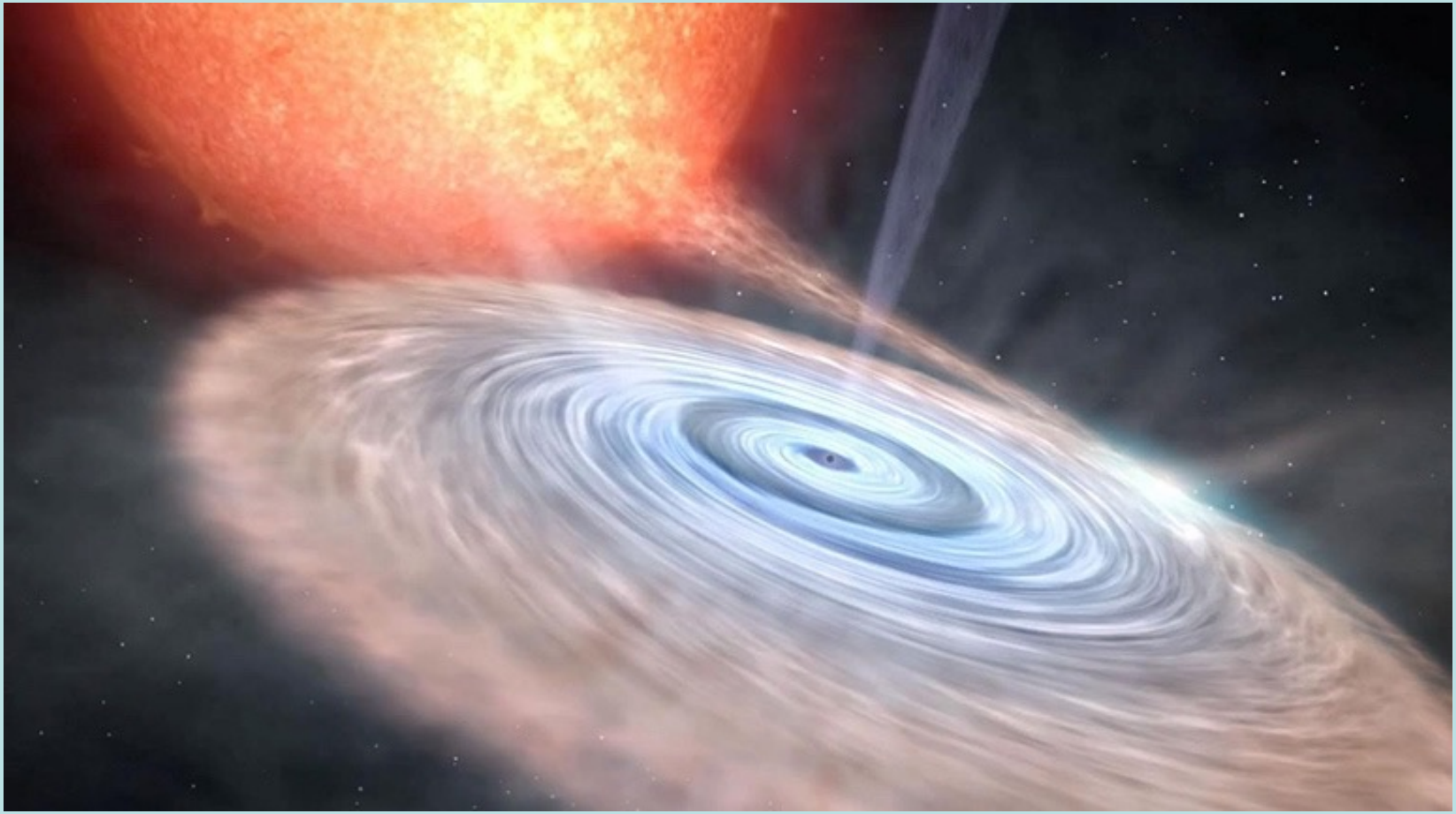
Accretion disk 吸積盤上的物質會彼此摩擦，溫度越來越高。

極熱的 disk 便開始發出強光！

發光會帶走能量，盤內的物質的能量漸漸會降低，

距離降低至最靠近穩定軌道後，就掉入黑洞。

因此吸積盤發光區域的內緣，就是最靠近穩定軌道~$3r_S$。

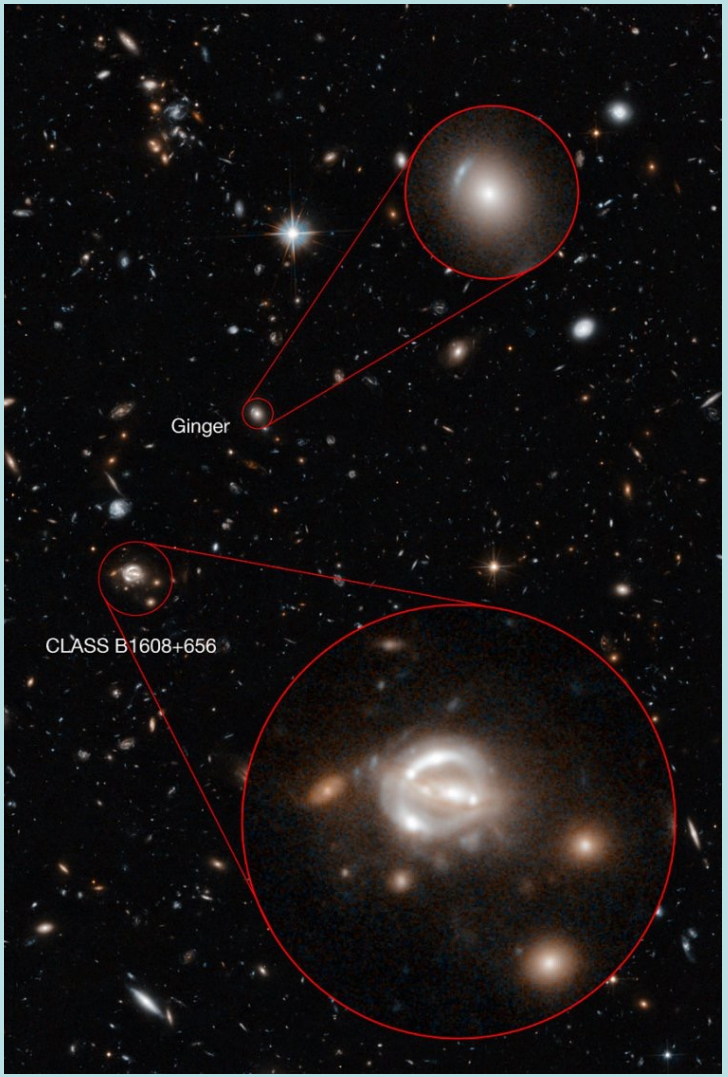


因此觀察上，黑洞可以是非常亮的發光者！



Quasar是極遠極亮的單一星體，據信就是由黑洞構成：





QSO-160913+653228

behind CLASS B1608+656

9 billion light years away

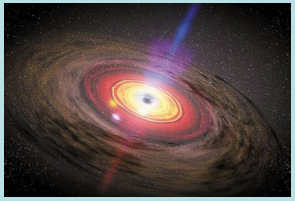
One of the lens systems visible here is called CLASS B1608+656, which appears as a small loop in the centre of the image. It features two foreground galaxies distorting and amplifying the light of a distant quasar the known as QSO-160913+653228. The light from this bright disc of matter, which is currently falling into a black hole, has taken nine billion years to reach us — two thirds of the age of the Universe.

A quasar is a compact region in the center of a massive galaxy surrounding a central supermassive black hole. Its size is 10–10,000 times the Schwarzschild radius of the enclosed black hole. The energy emitted by a quasar derives from mass falling onto the accretion disc around the black hole.

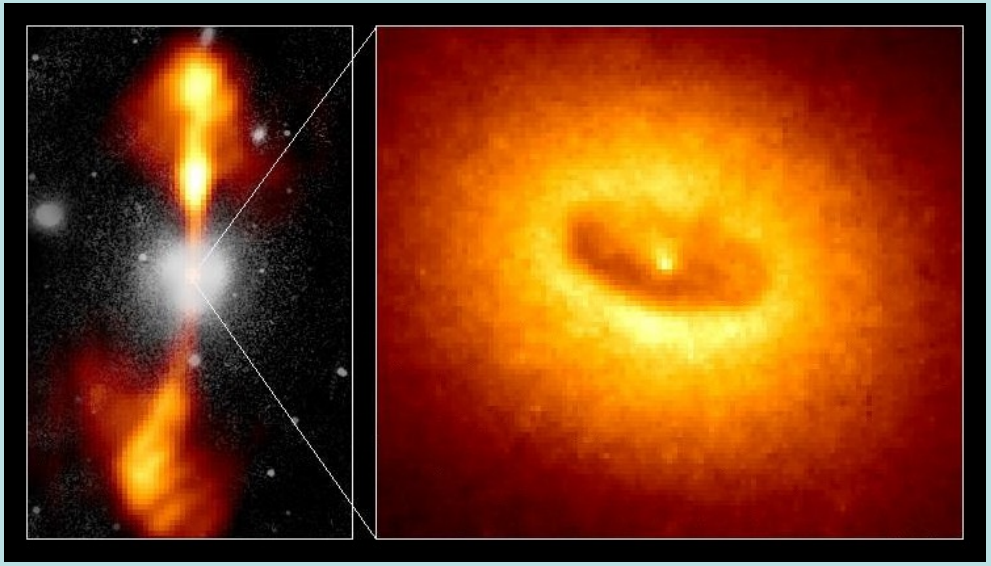


繞著黑洞在地平線外旋轉的物質會形成盤狀結構

Accretion disc



gas accreting onto a black hole in elliptical galaxy NGC 4261

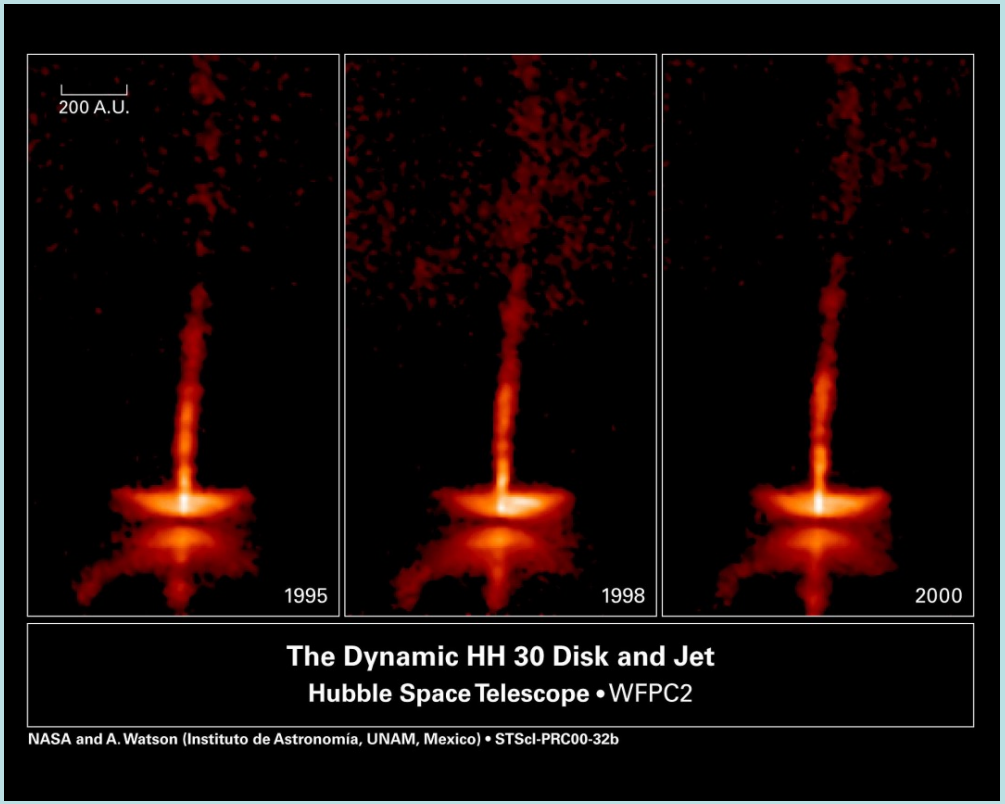


NGC 4261 is an elliptical galaxy located around 100 million light-years away in the constellation Virgo. The active galactic nucleus (AGN) contains a 400-million-solar mass supermassive black hole (SMBH) with an 800-light-year-wide spiral-shaped disk of dust fueling it. The galaxy is estimated to be about 60 thousand light-years across, and a jet emanating from it is estimated to span about 88 thousand light-years.

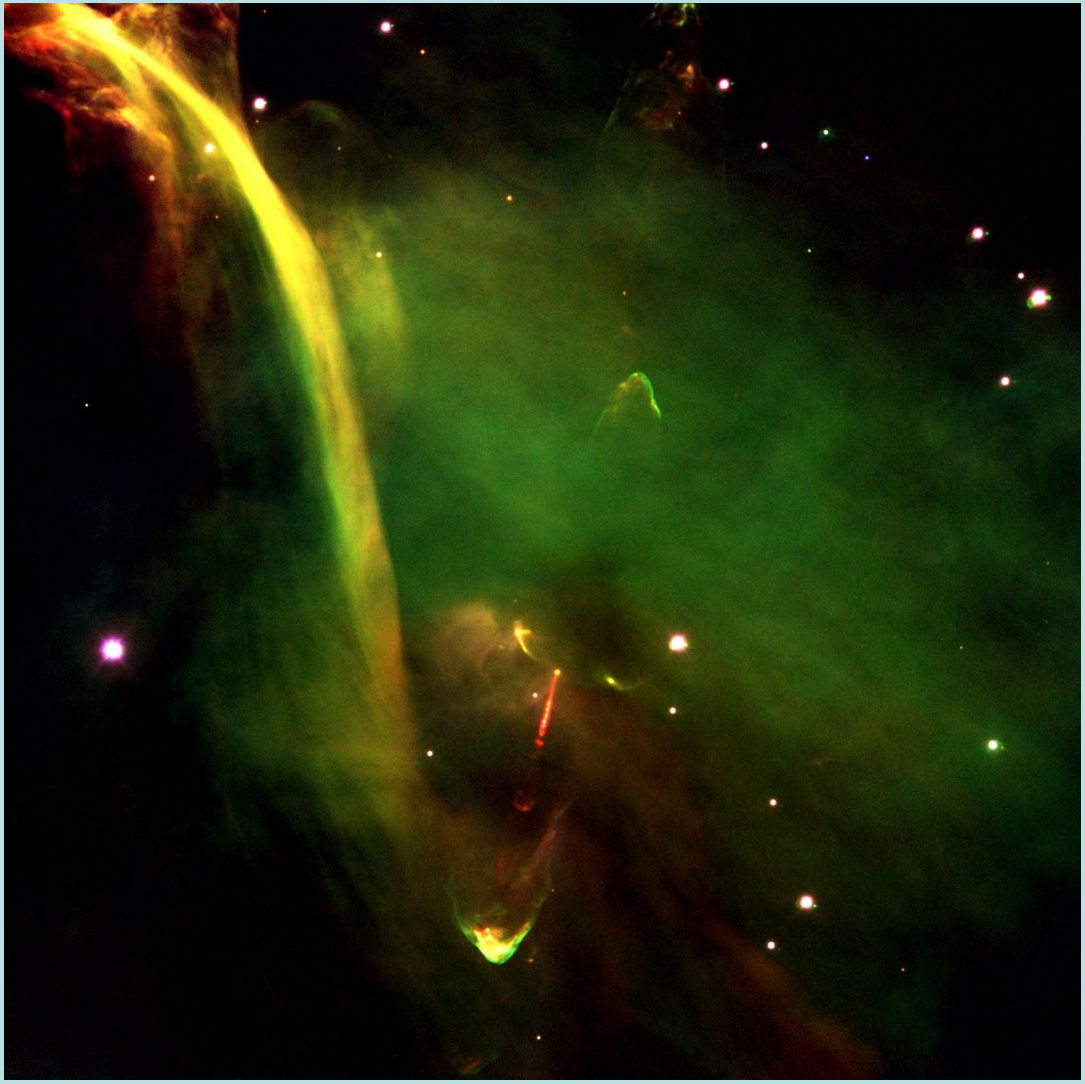


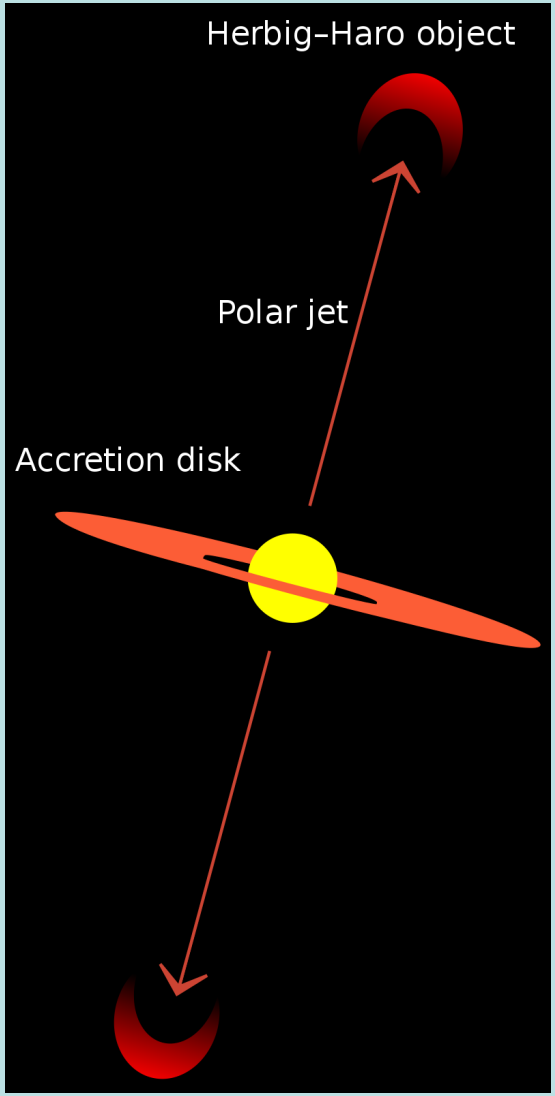
HH-30, a Herbig–Haro object
(New Born star behind nebula)
surrounded by an accretion disc

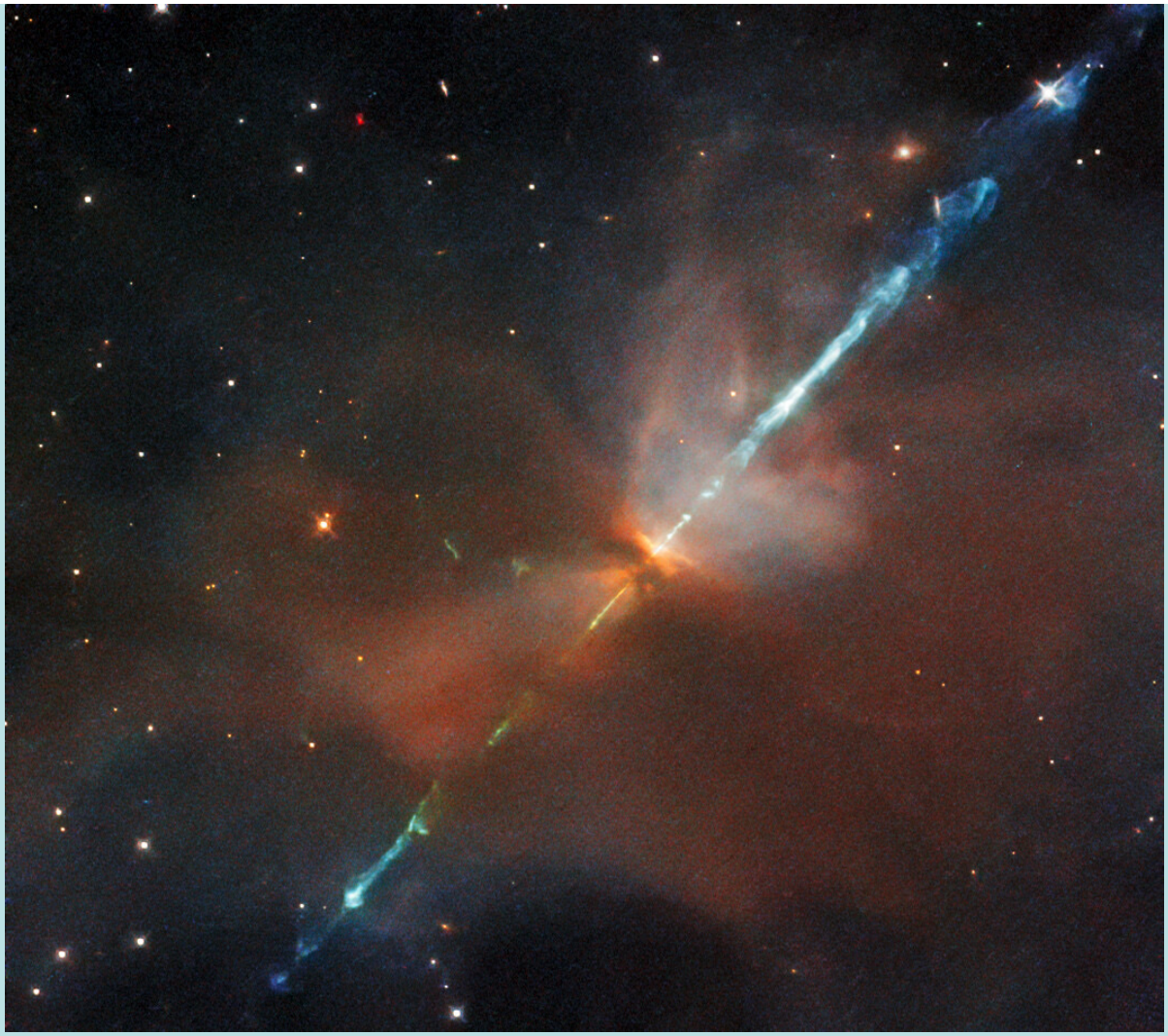




This view of a protostellar object called HH-30 reveals an edge-on disk of dust encircling a newly forming star. Light from the forming star illuminates the top and bottom surfaces of the disk, making them visible, while the star itself is hidden behind the densest parts of the disk. The reddish jet emanates from the inner region of the disk, and possibly directly from the star itself.
Hubble's detailed view shows, for the first time, that the jet expands for several billion miles from the star, but then stays confined to a narrow beam. The protostar is 450 light-years away in the constellation Taurus.



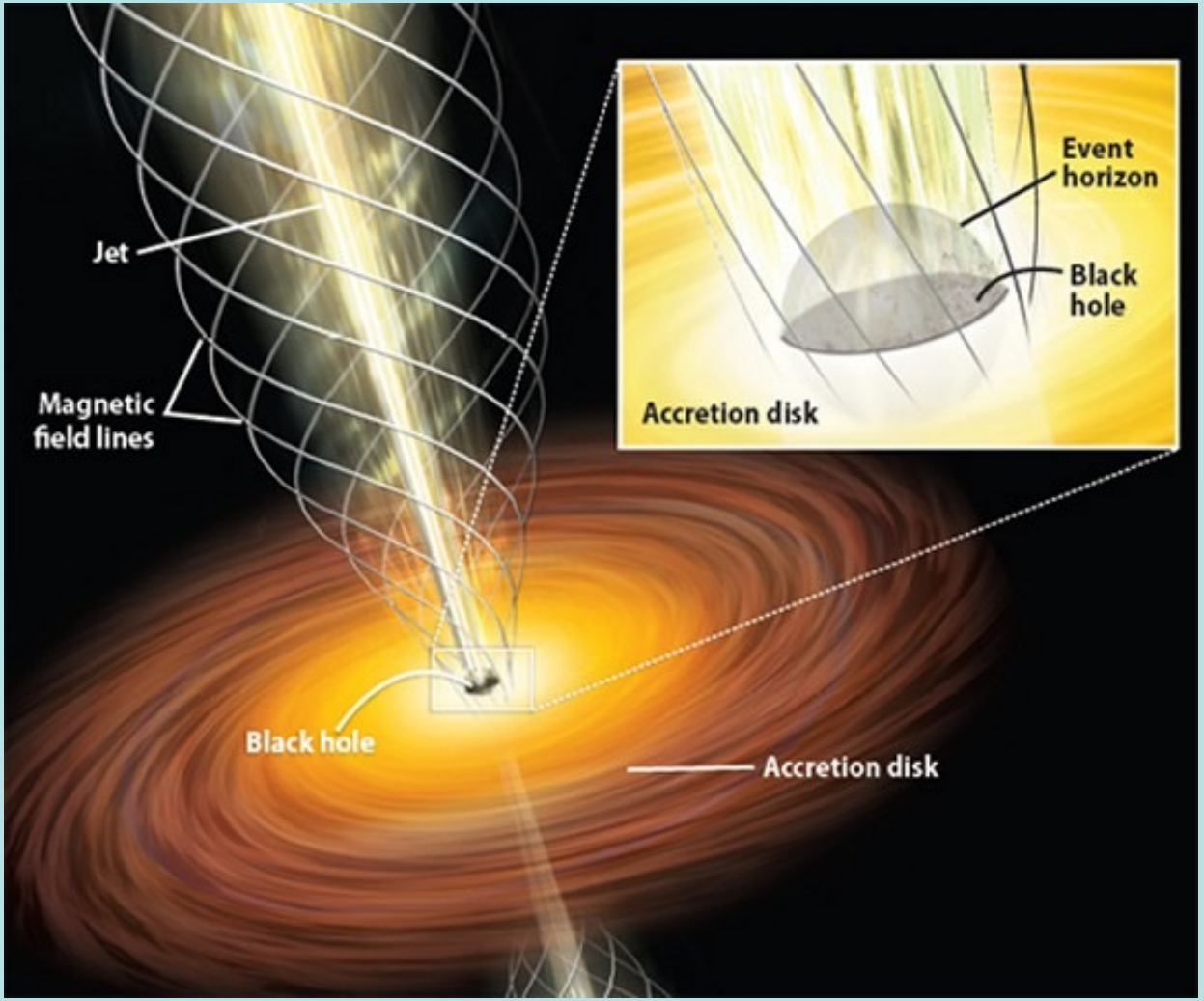

Herbig–Haro object
Polar jet
Accretion disk



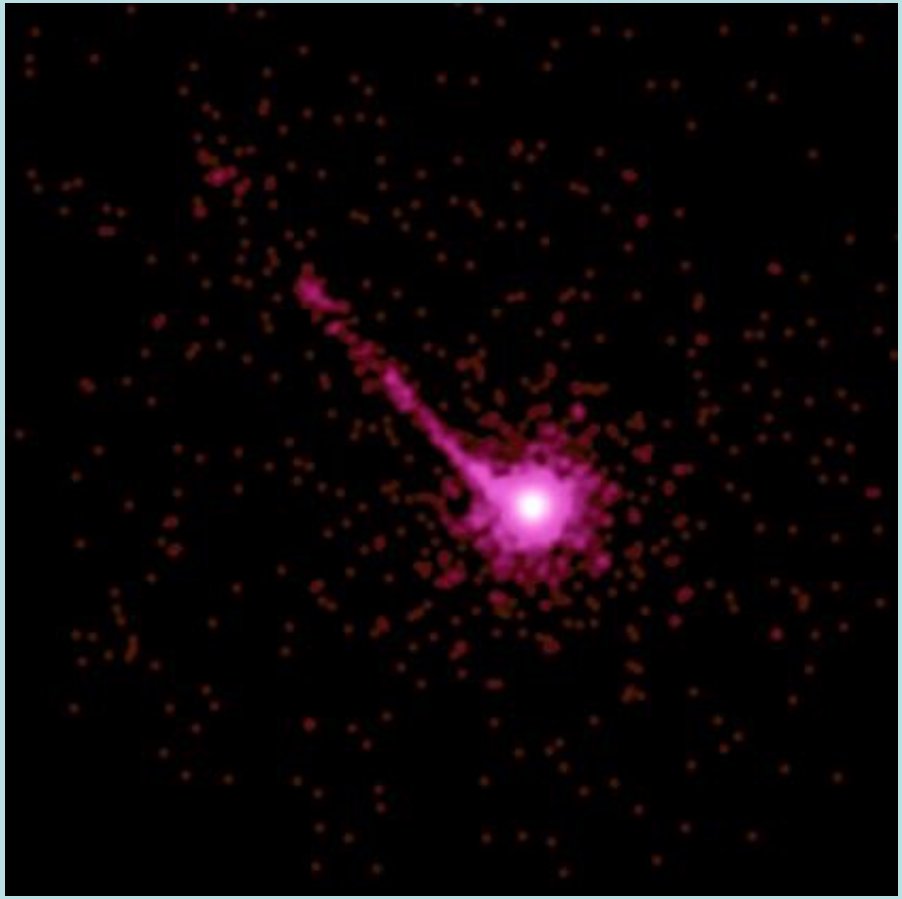
This striking image features a relatively rare celestial phenomenon known as a Herbig–Haro object. This particular Herbig–Haro object is named HH111, and was imaged by Hubble's Wide Field Camera 3 (WFC3). These spectacular objects are formed under very specific circumstances. Newly formed stars are often very active, and in some cases they expel very narrow jets of rapidly moving ionised gas — gas that is so hot that its molecules and atoms have lost their electrons, making the gas highly charged. The streams of ionised gas then collide with the clouds of gas and dust surrounding newly-formed stars at speeds of hundreds of kilometres per second. It is these energetic collisions that create Herbig–Haro objects such as HH111.

旋轉的黑洞一般會有磁場，會帶動落入黑洞的物質，沿旋轉軸的方向噴出，噴出的帶電離子形成速度極快的噴流！

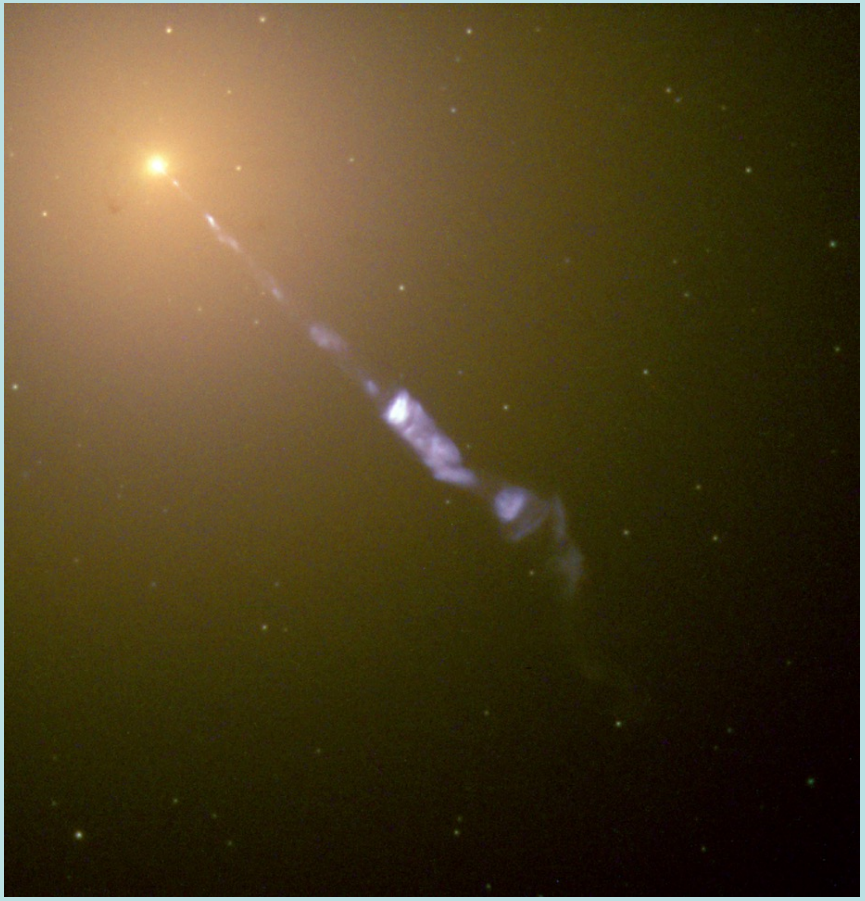
Astrophysical Jets　展開角度很小，放出能量極高。



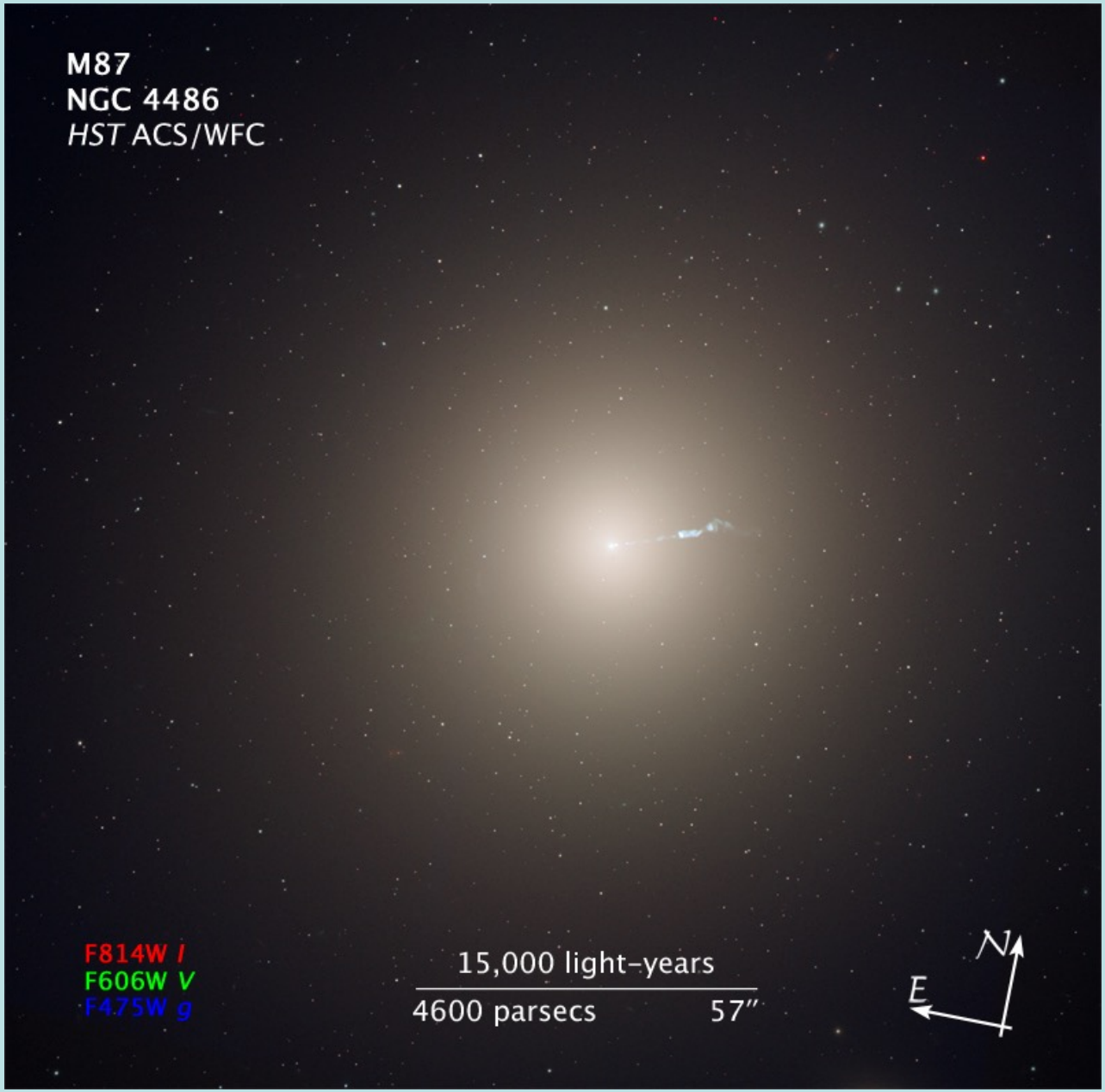


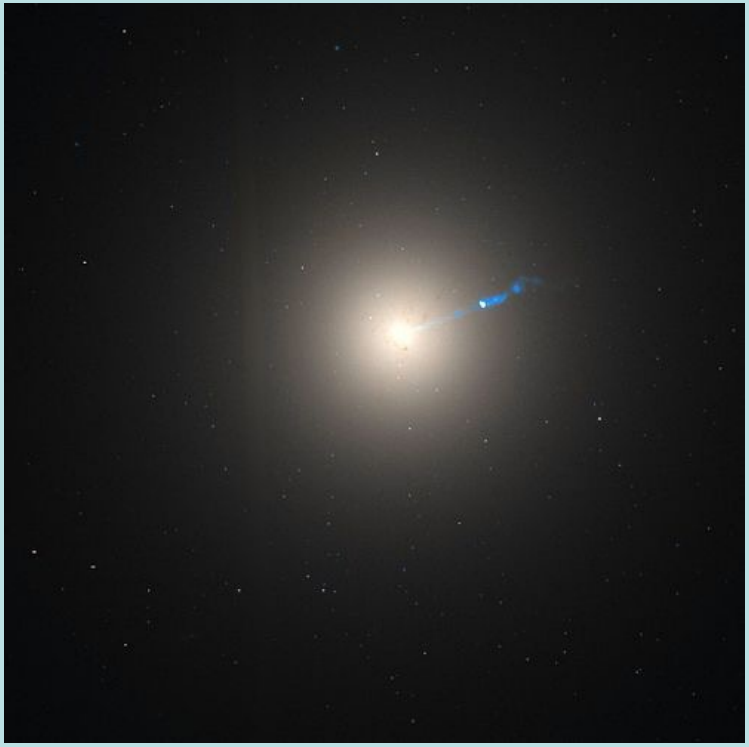


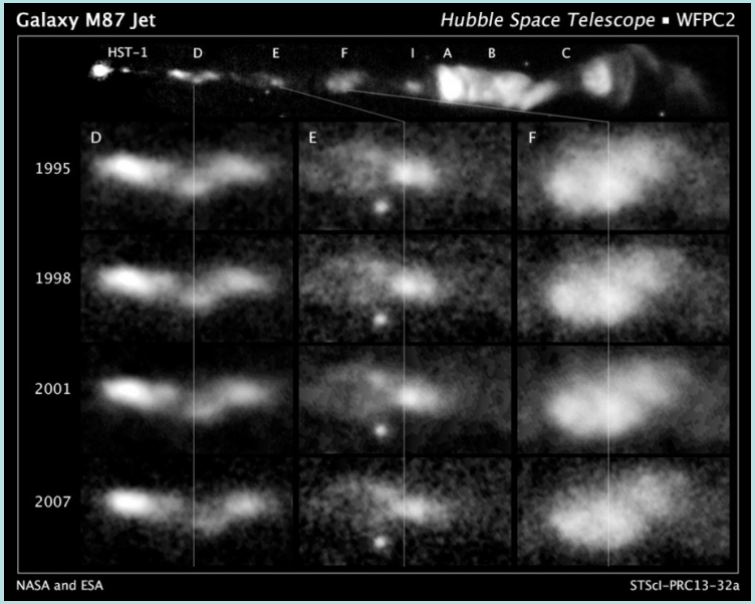
The Chandra X-ray image is of the quasar PKS 1127-145, a highly luminous source of X-rays and visible light about 10 billion light years from Earth. An enormous X-ray jet extends at least **a million light years** from the quasar.



Elliptical galaxy M87 emitting a relativistic jet. The jet is **5000 light years** long!


M87
NGC 4486
HST ACS/WFC
F814W *I*
F606W *V*
F475W *g*
15,000 light-years
4600 parsecs
57″
N
E



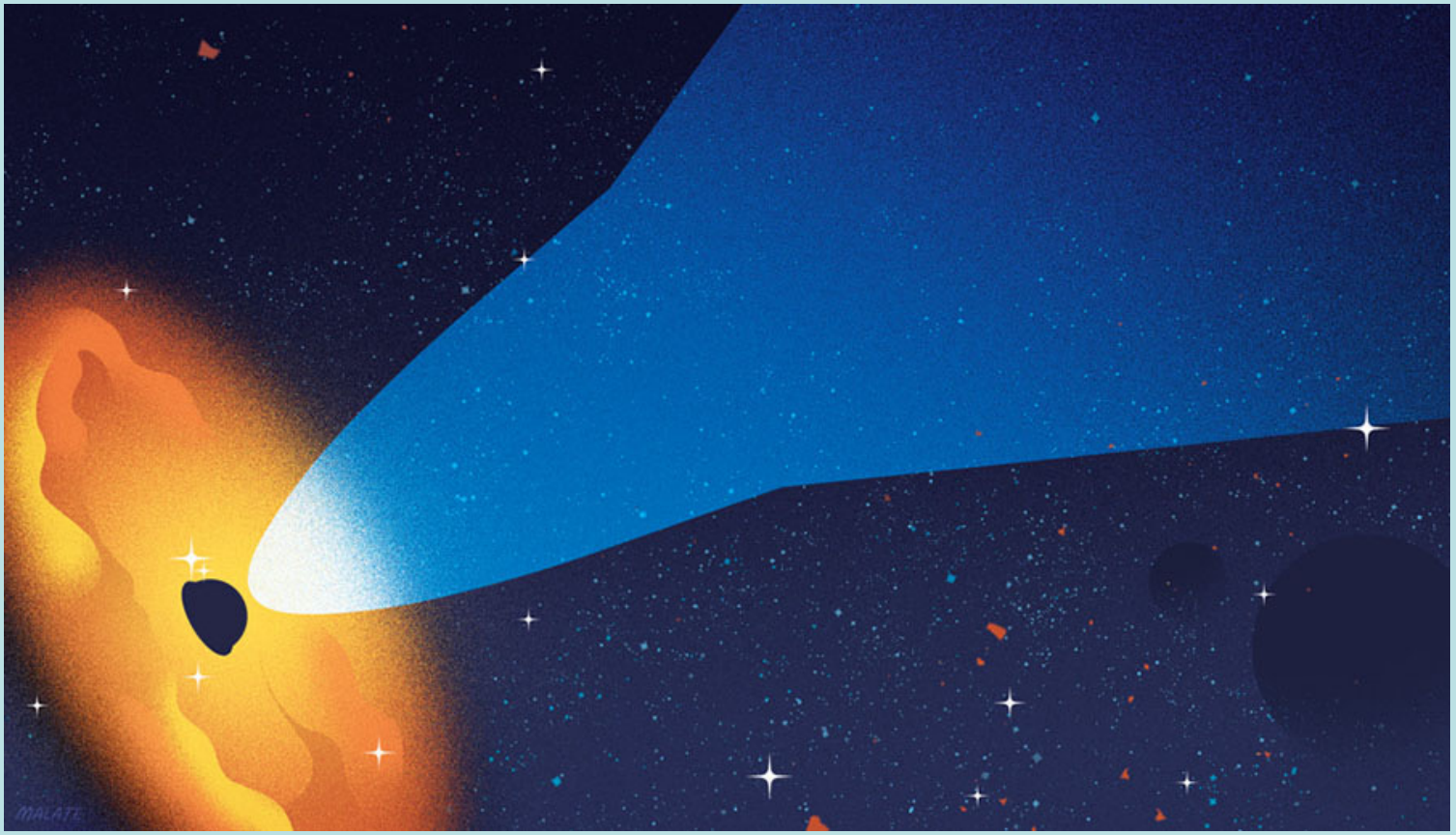


Messier 87 (also known as Virgo A or NGC 4486, generally abbreviated to M87) is a supergiant elliptical galaxy in the constellation Virgo. M87 is about 16.4 million parsecs (53 million light-years) from Earth and is the second-brightest galaxy within the northern Virgo Cluster, having many satellite galaxies. One of the most massive galaxies in the observable universe, it has a large population of globular clusters—about 12,000 compared with the 150–200 orbiting the Milky Way—and a jet of energetic plasma that originates at the core and extends at least 1,500 parsecs (4,900 light-years), traveling at relativistic speed. It is one of the brightest radio sources in the sky and a popular target for both amateur and professional astronomers.

M87位在室女座，是巨大的橢圓星系



In this X-ray (Chandra) and radio (VLA) composite image, hot matter (blue in X-ray) from the Virgo cluster falls toward the core of M87 and cools, where it is met by the relativistic jet (orange in radio), producing shock waves in the galaxy's interstellar medium

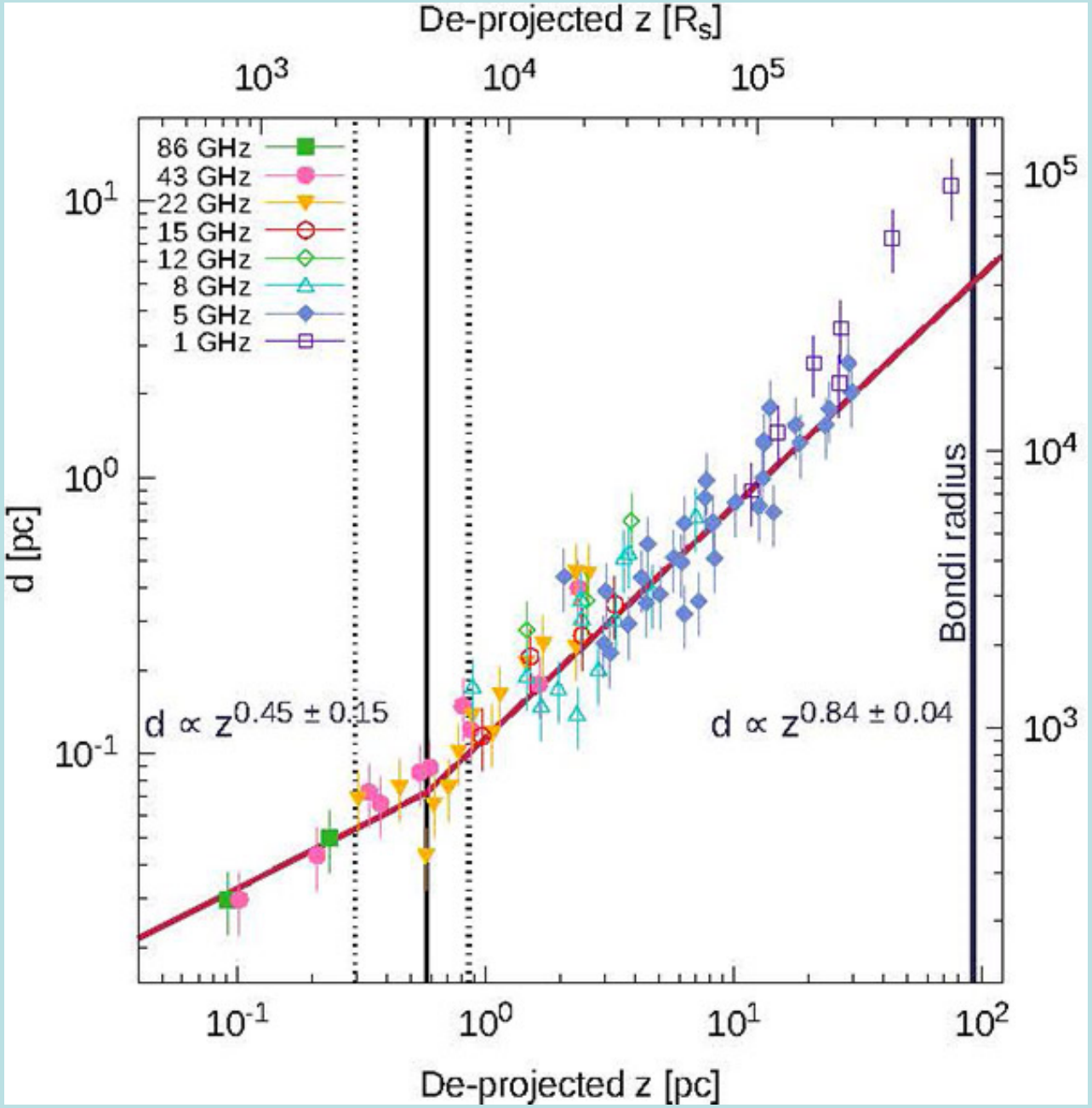


the jets have both parabolic and conical components

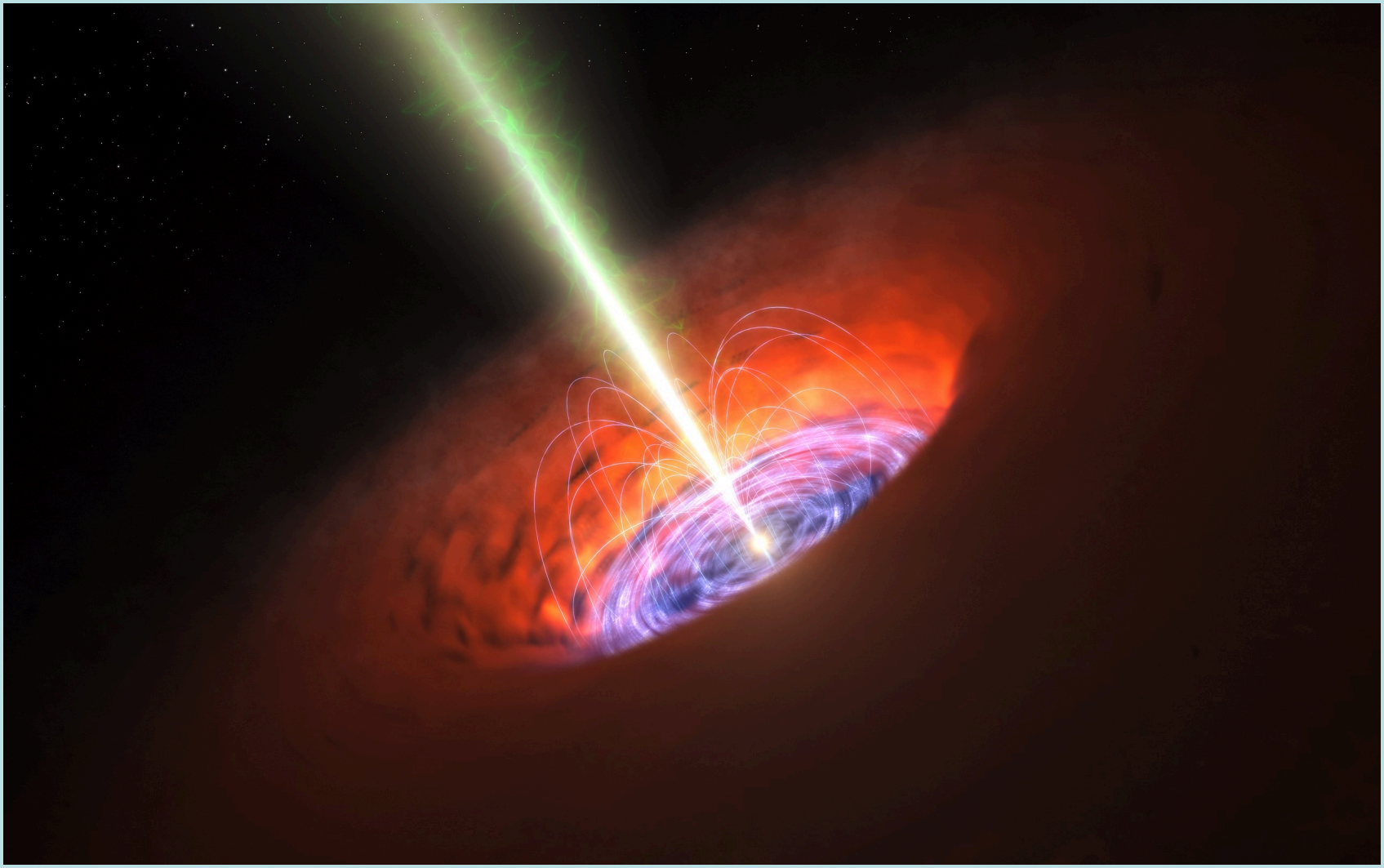
一開始像鍋子，接下來像漏斗！

交接處在萬個r_s左右，大概就是該處銀河的大小。

推測就是黑洞的影響漸漸被整個銀河的影響取代的過度。


De-projected z [R_s]
10^3
10^4
10^5
86 GHz
43 GHz
22 GHz
15 GHz
12 GHz
8 GHz
5 GHz
1 GHz
10^1
10^0
10^{-1}
d [pc]
10^5
10^4
10^3
Bondi radius
$d \propto z^{0.45 \pm 0.15}$
$d \propto z^{0.84 \pm 0.04}$
10^{-1}
10^0
10^1
10^2
De-projected z [pc]

Disk and Jet 就是黑洞看起來的樣子！



Disk and Jet 就是黑洞看起來的樣子！



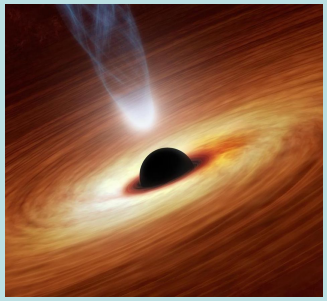
但如果細看：

碟的發光也會被黑洞的重力透鏡所偏轉！

背後的Disk會因Gravitational Lenses被看到。



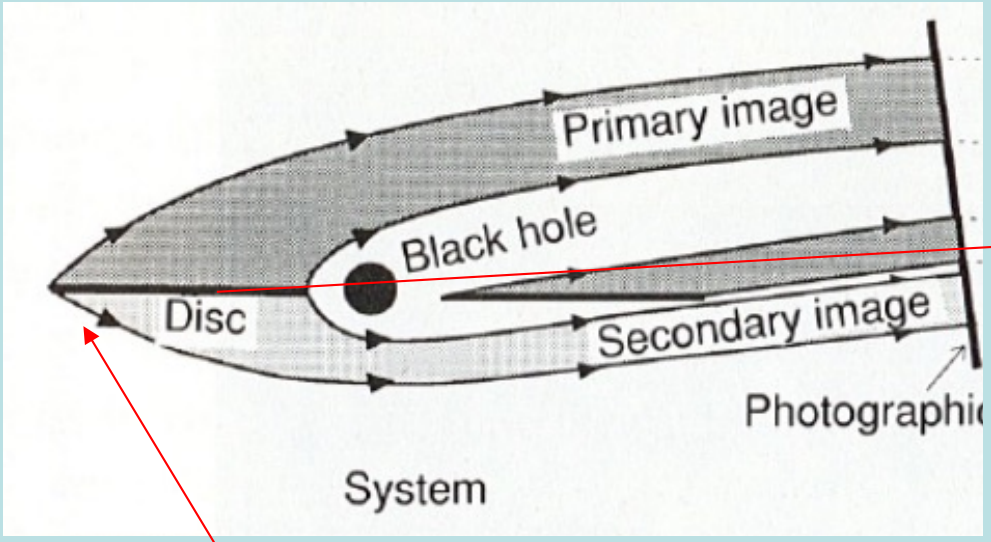


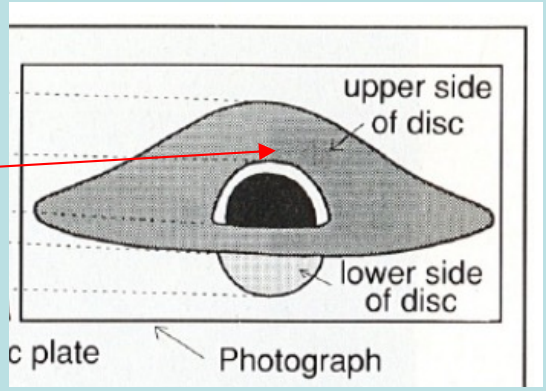


碟的發光會被黑洞的重力透鏡所偏轉！

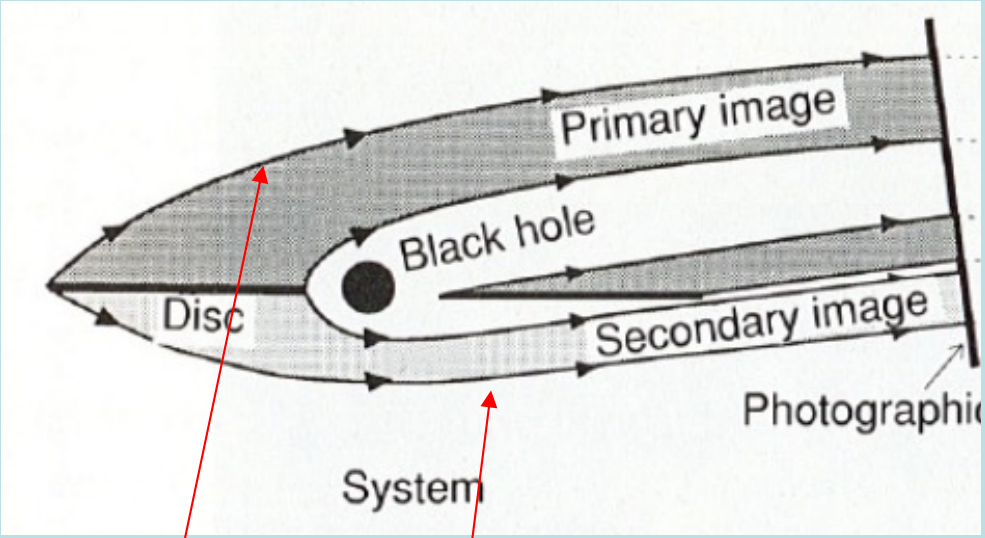
碟上被擋住的部分發光會被看到！

觀察者



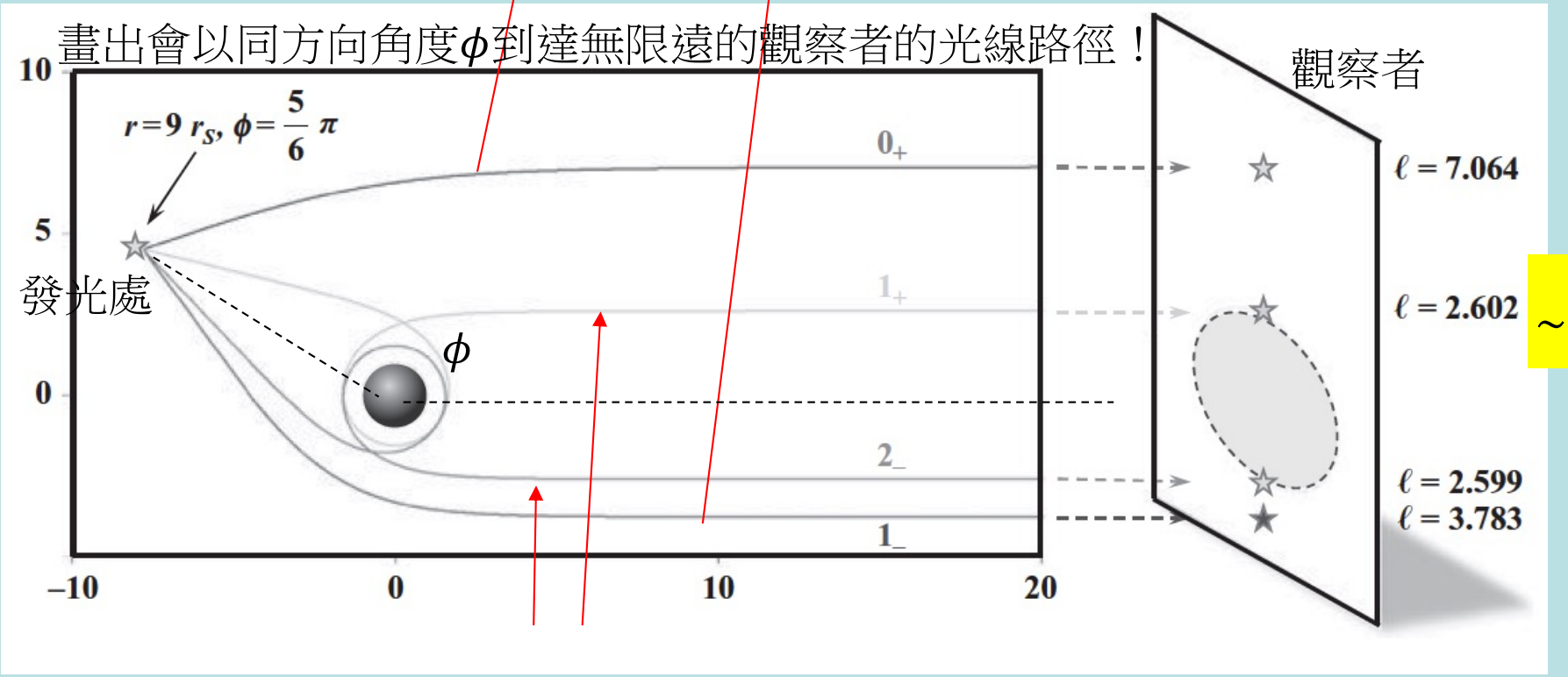


注意：碟子底部竟然也能看到！



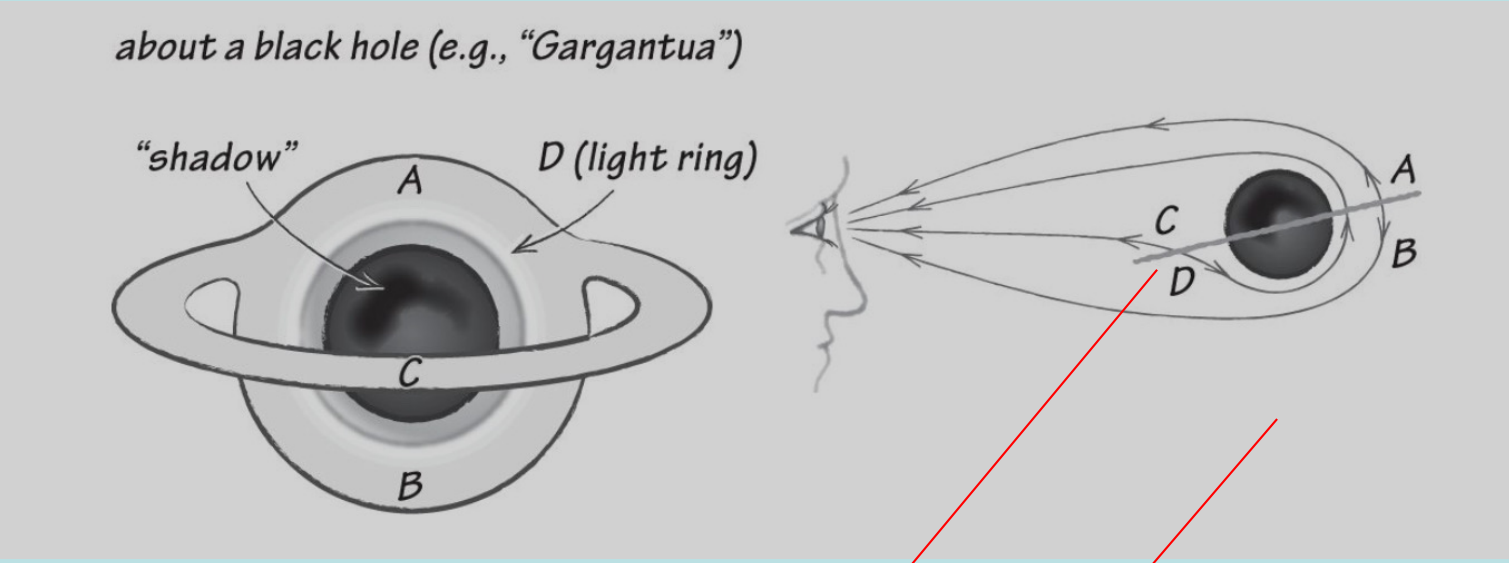
觀察者

畫出會以同方向角度ϕ到達無限遠的觀察者的光線路徑！



碟的發光甚至會被黑洞的重力透鏡所偏轉，而繞行星體一圈後才離開！

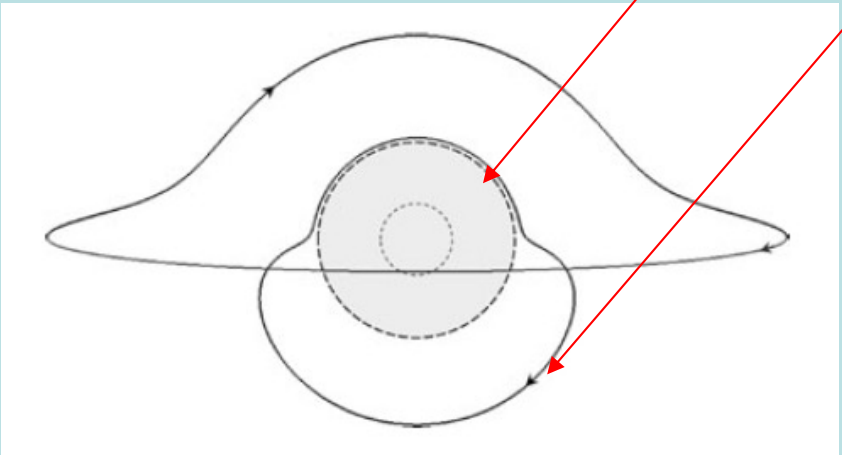
發出的光若繞行一圈以上，落點會與球心投影幾乎等距，影像會形成一個環。

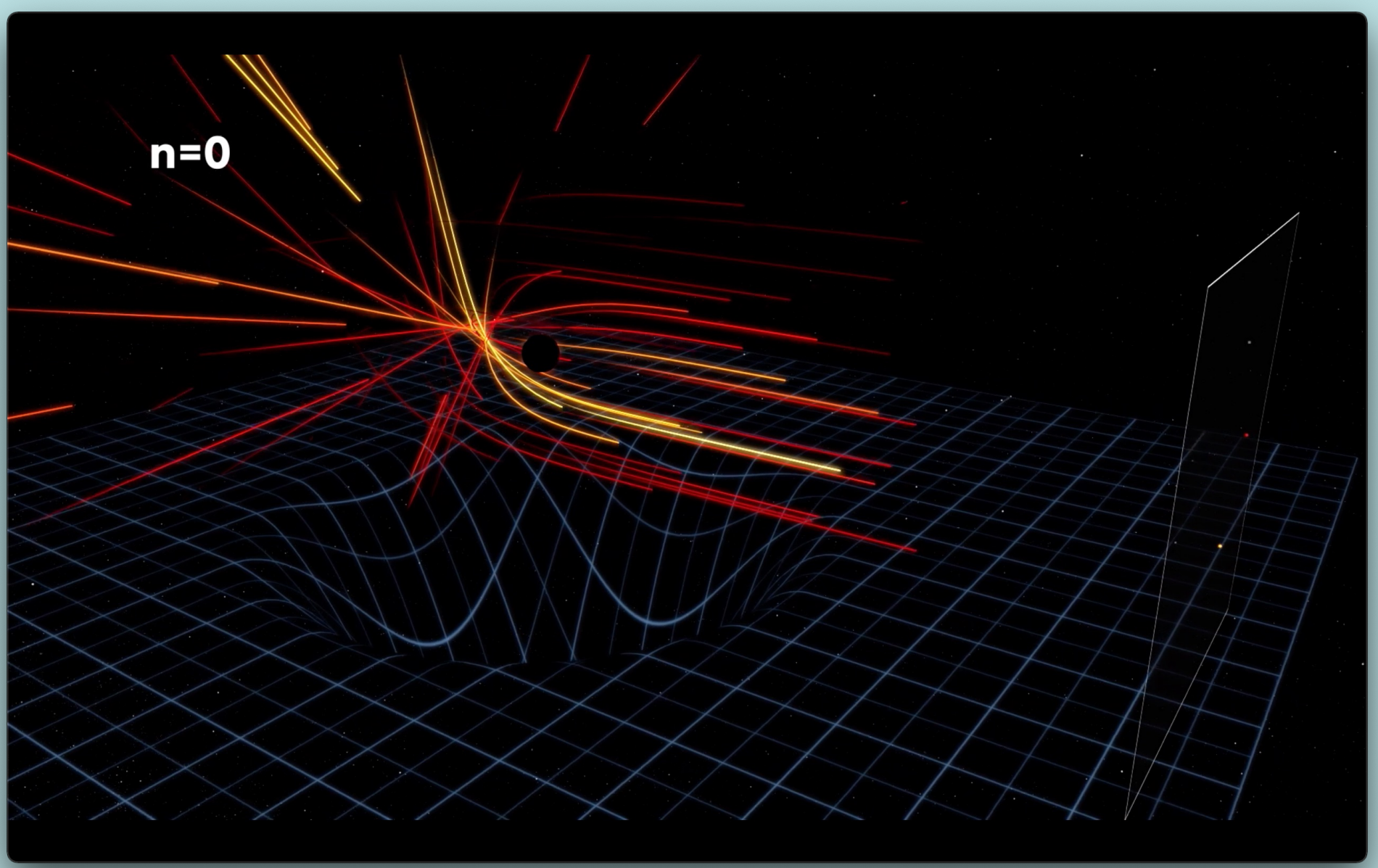


黑洞碟的底部B,D發出的光，原本會被擋住，

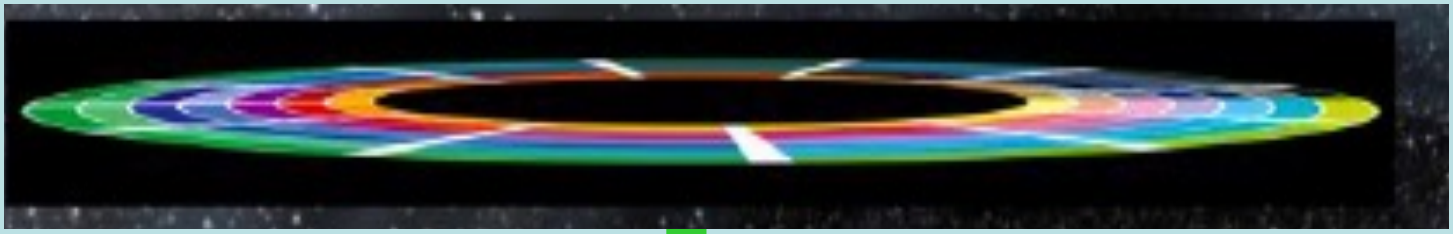
因為黑洞的重力透鏡效應，也會被看見，

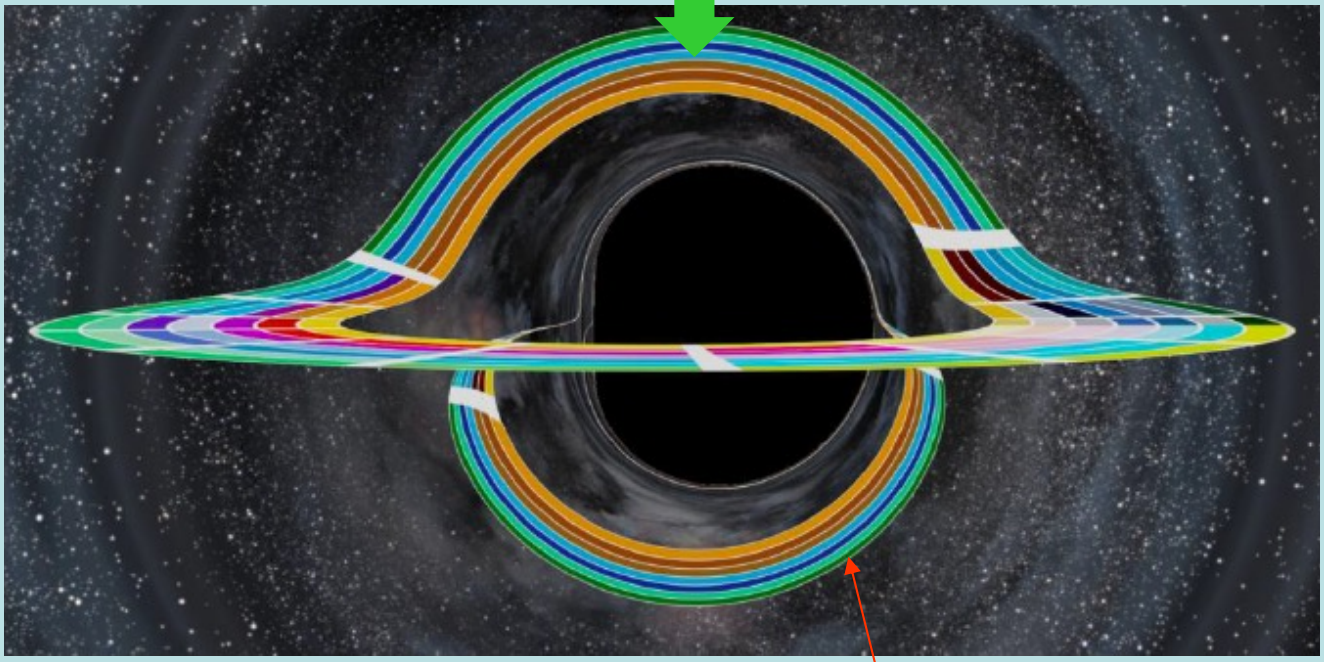
B出現於下方， D發出的光繞行一圈，影像則形成一個環。



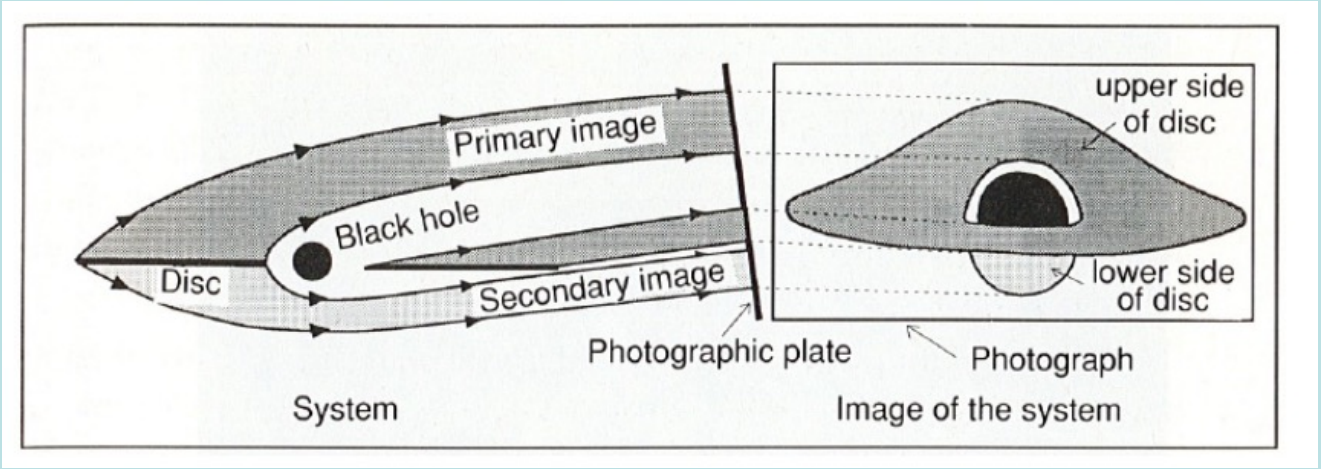


光的測地線





這一圈是盤的底部！


Primary image
Black hole
Disc
Secondary image
Photographic plate
System
upper side of disc
lower side of disc
Photograph
Image of the system

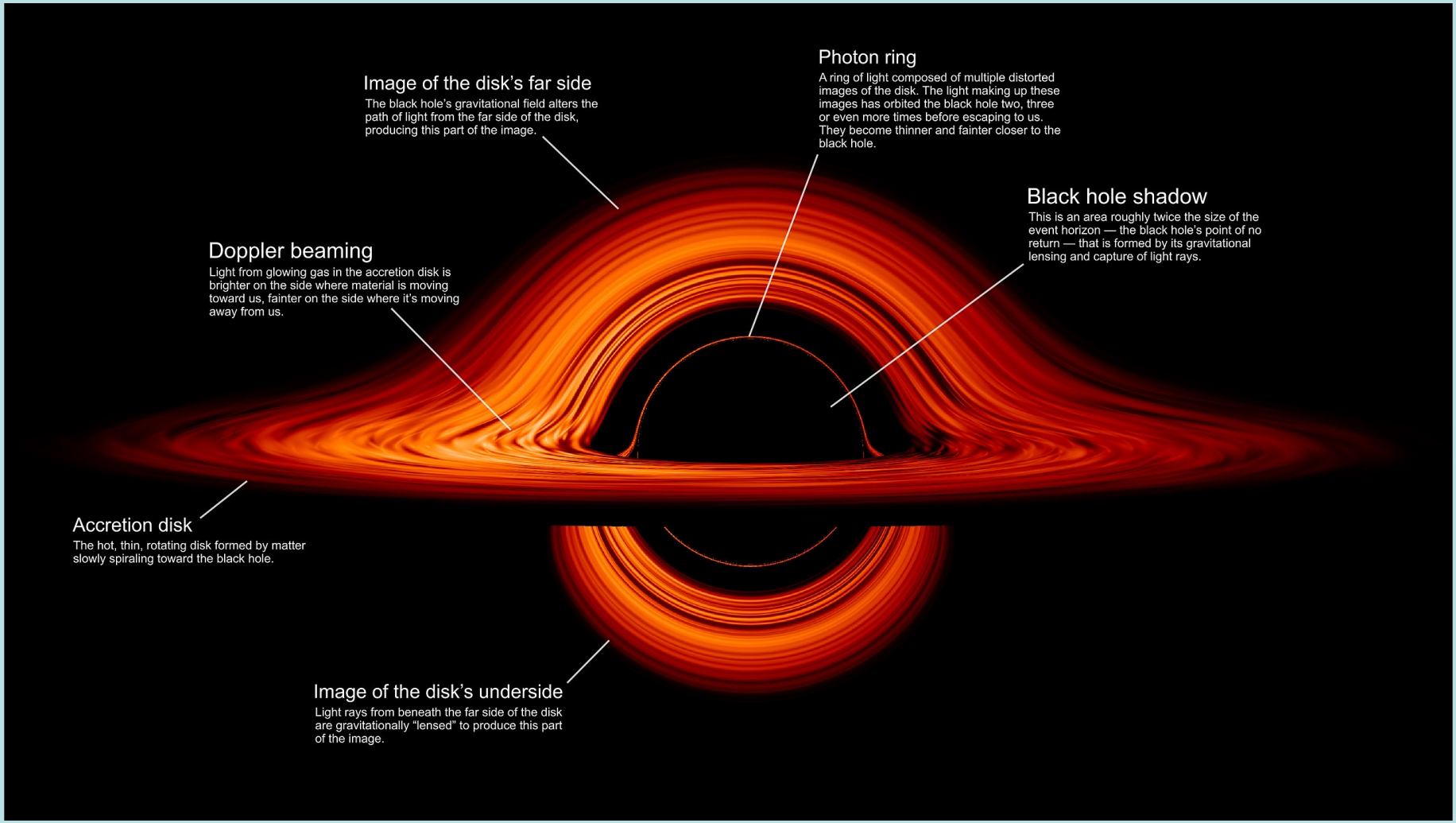
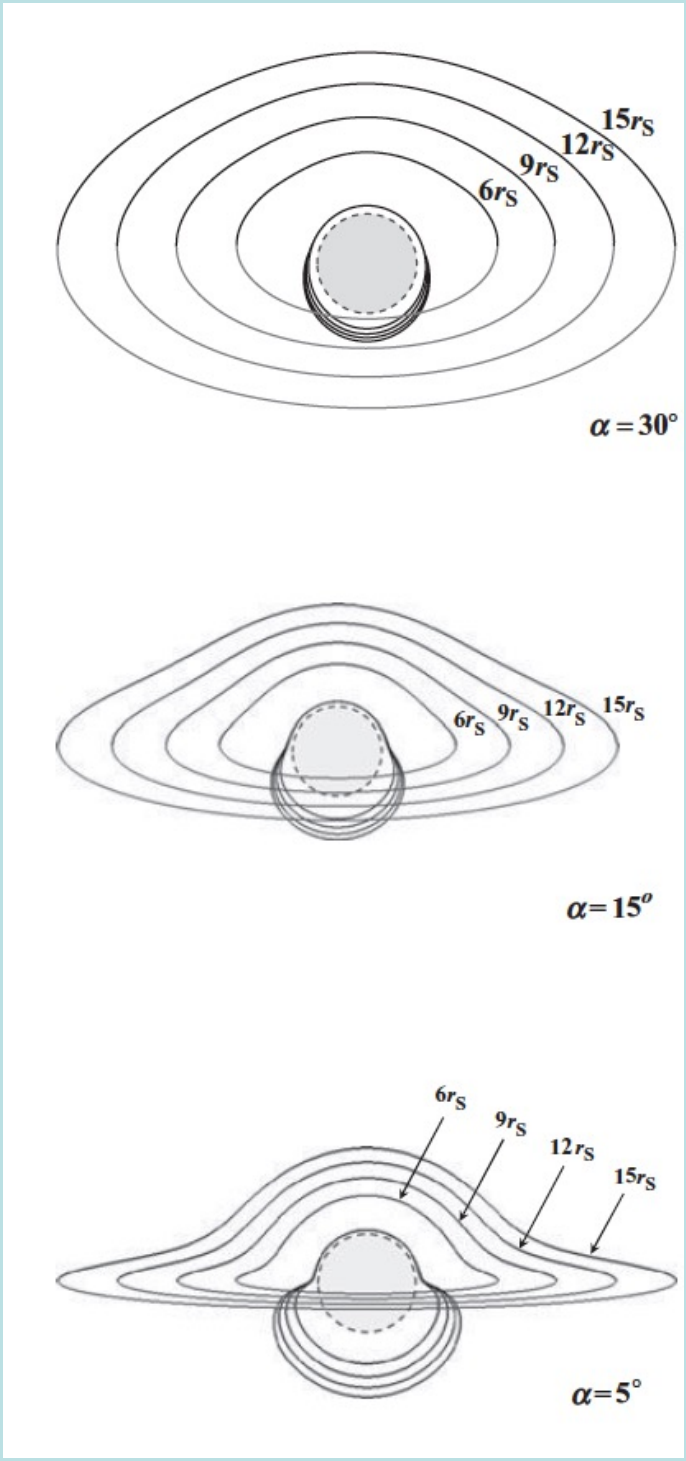
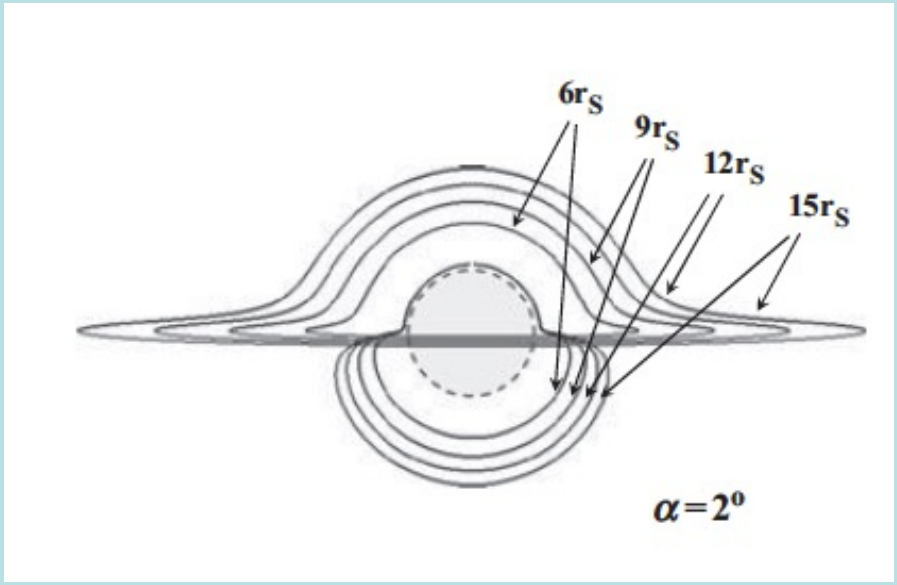
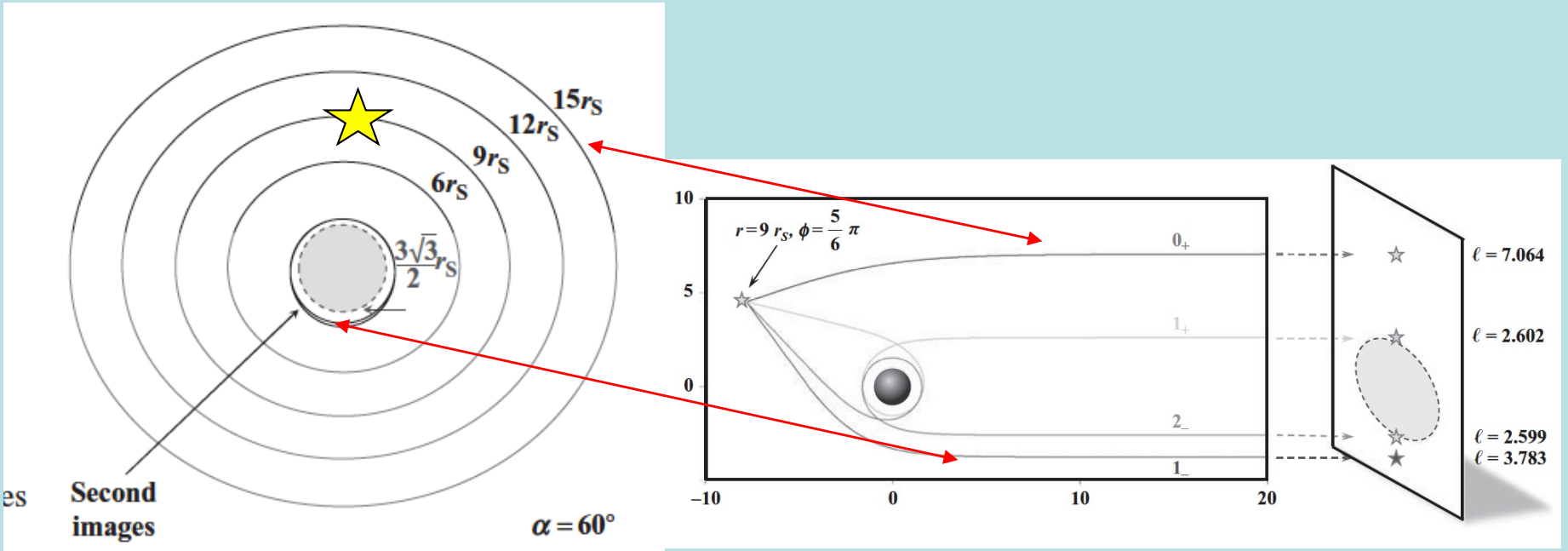


Image of the disk's far side
The black hole's gravitational field alters the path of light from the far side of the disk, producing this part of the image.
Photon ring
A ring of light composed of multiple distorted images of the disk. The light making up these images has orbited the black hole two, three or even more times before escaping to us. They become thinner and fainter closer to the black hole.
Black hole shadow
This is an area roughly twice the size of the event horizon — the black hole's point of no return — that is formed by its gravitational lensing and capture of light rays.
Doppler beaming
Light from glowing gas in the accretion disk is brighter on the side where material is moving toward us, fainter on the side where it's moving away from us.
Accretion disk
The hot, thin, rotating disk formed by matter slowly spiraling toward the black hole.
Image of the disk's underside
Light rays from beneath the far side of the disk are gravitationally "lensed" to produce this part of the image.

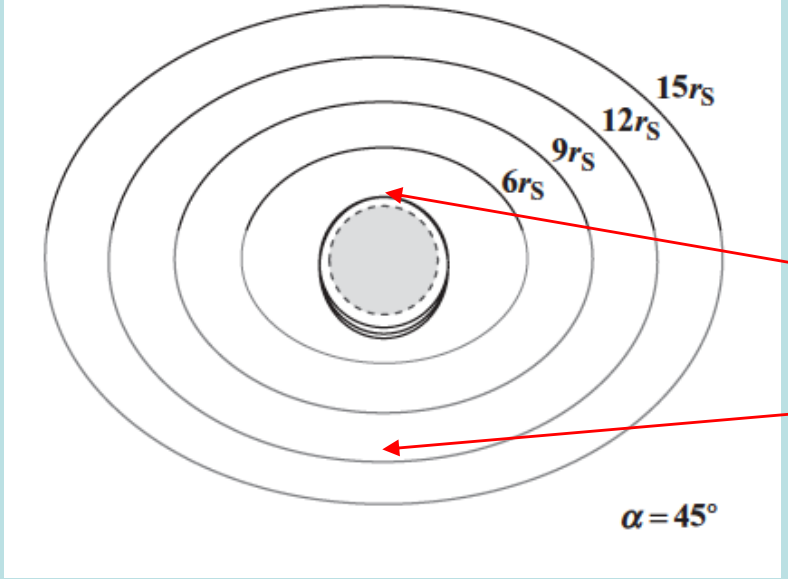




這下半圈是來自上半片碟的下方

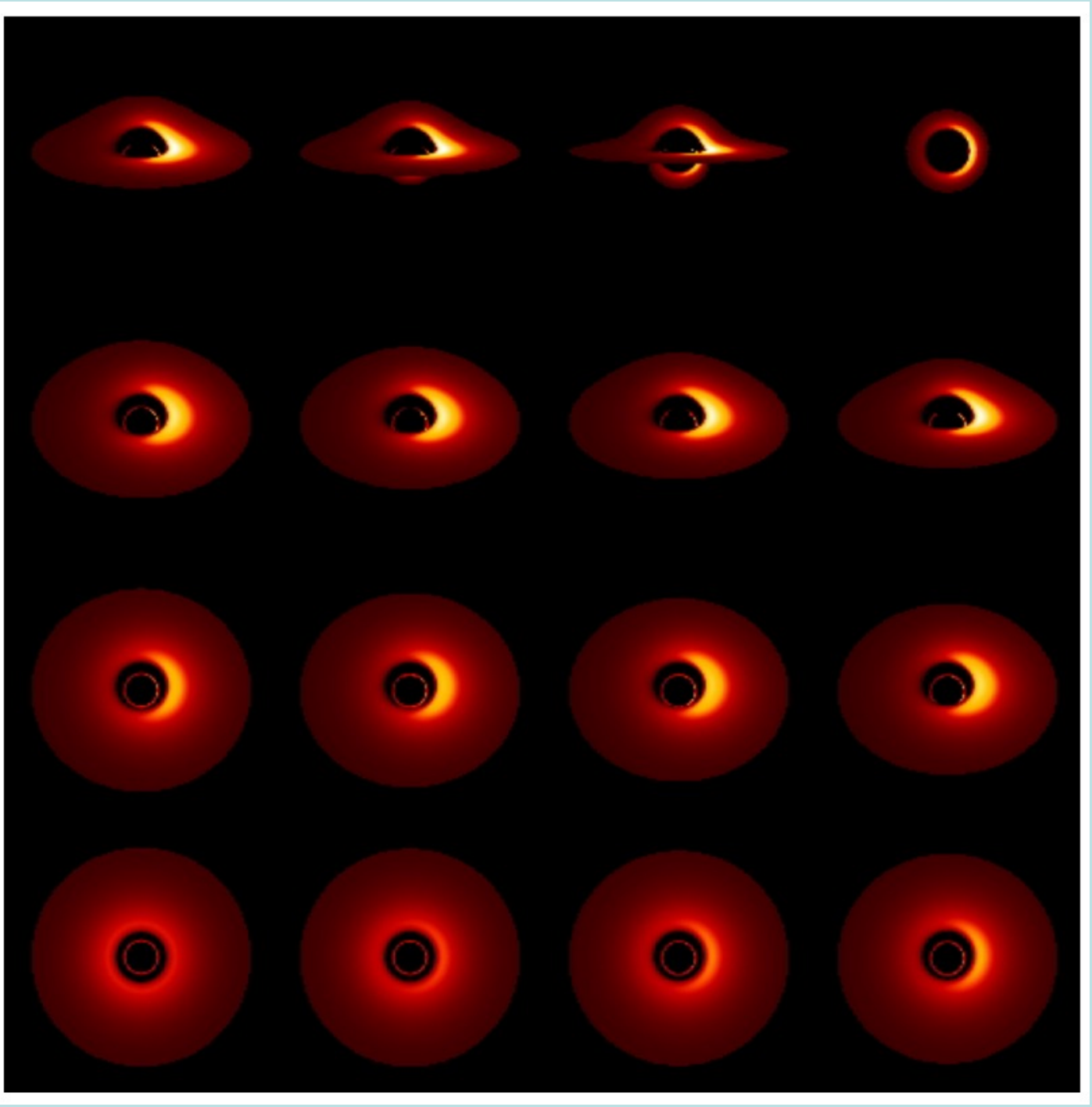


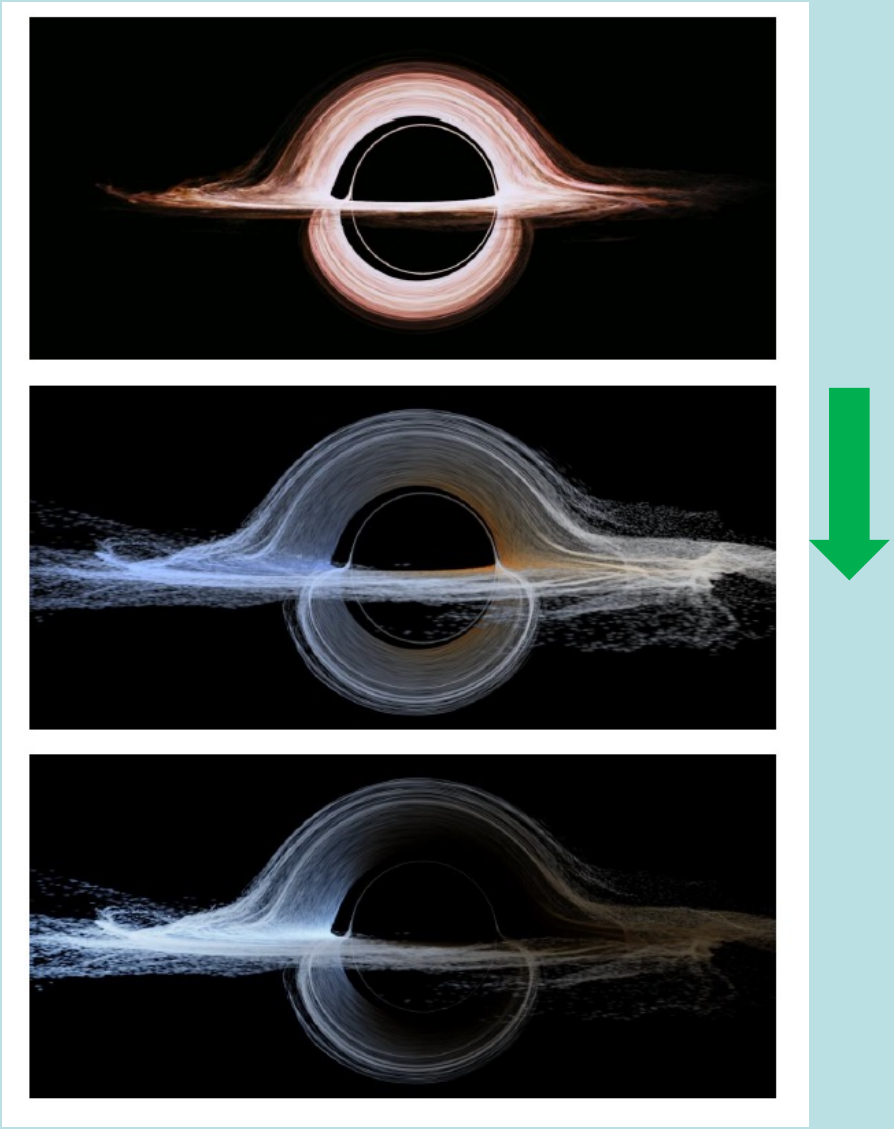
這下半圈的環是來自上半片碟的下方。



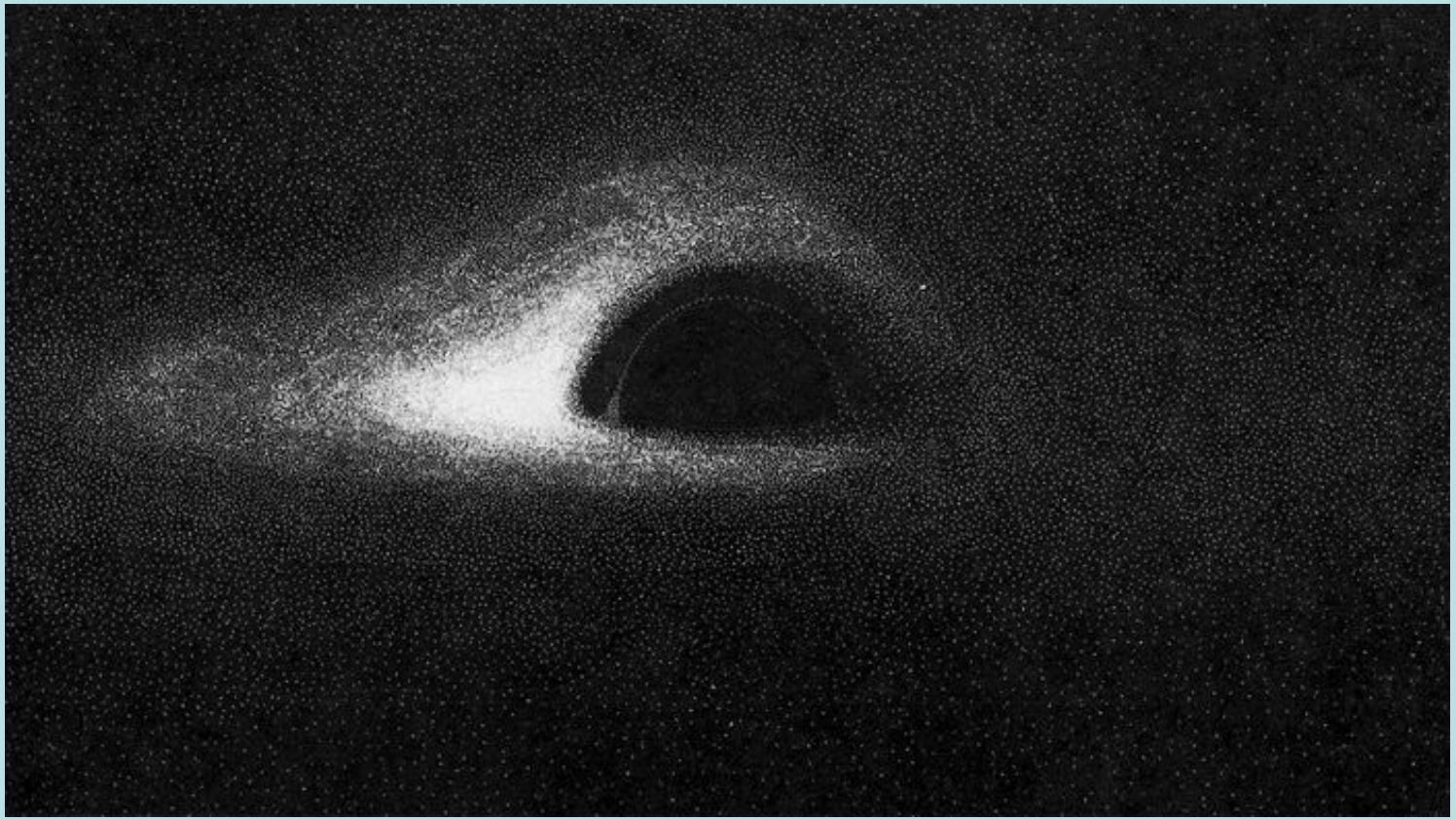
同理，這上半圈的環是來自

這下半片碟的下方。

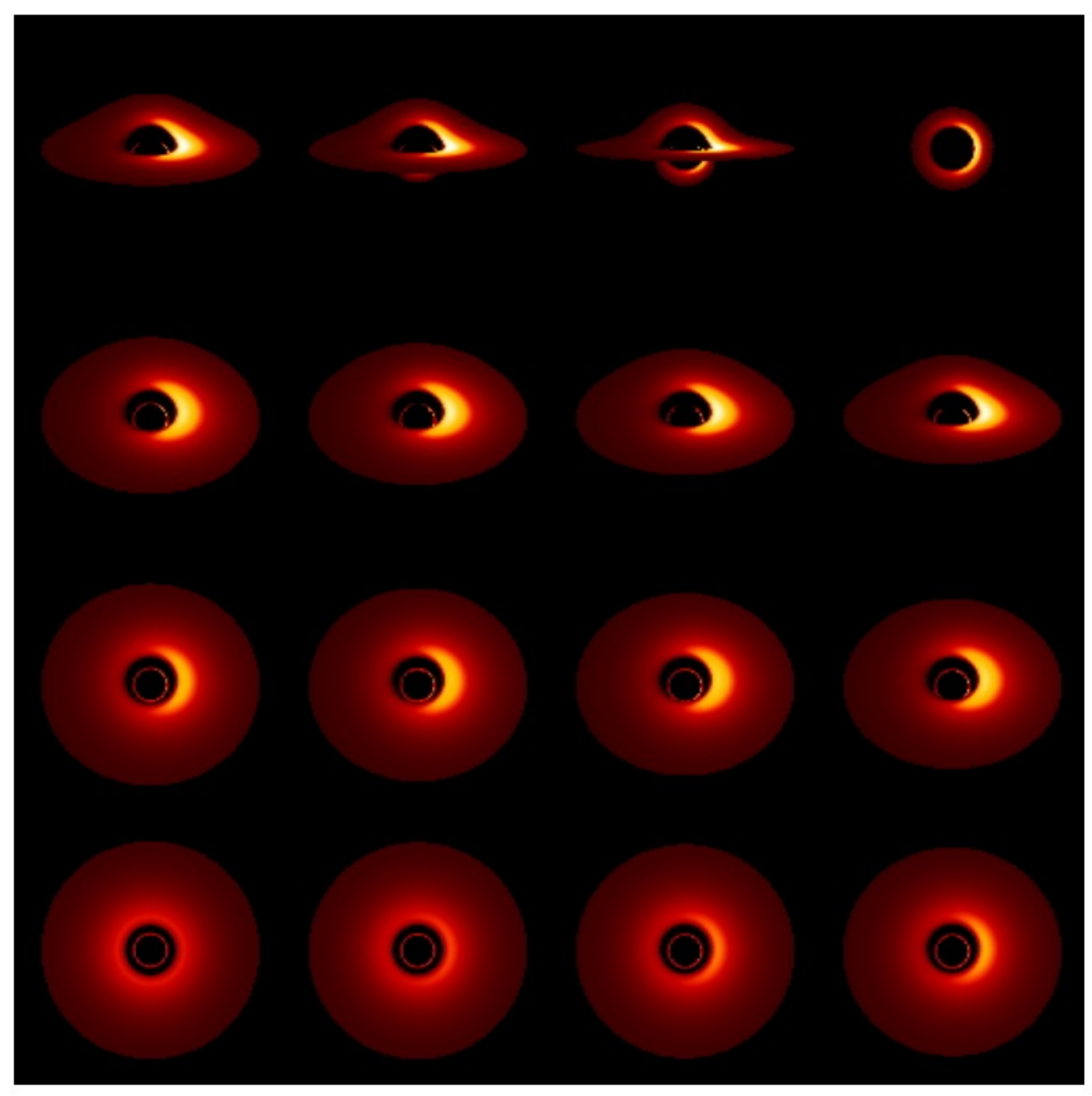


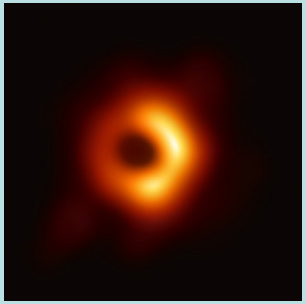


最後，不要忘了碟有旋轉方向，物質向妳運動的那部分會較亮。



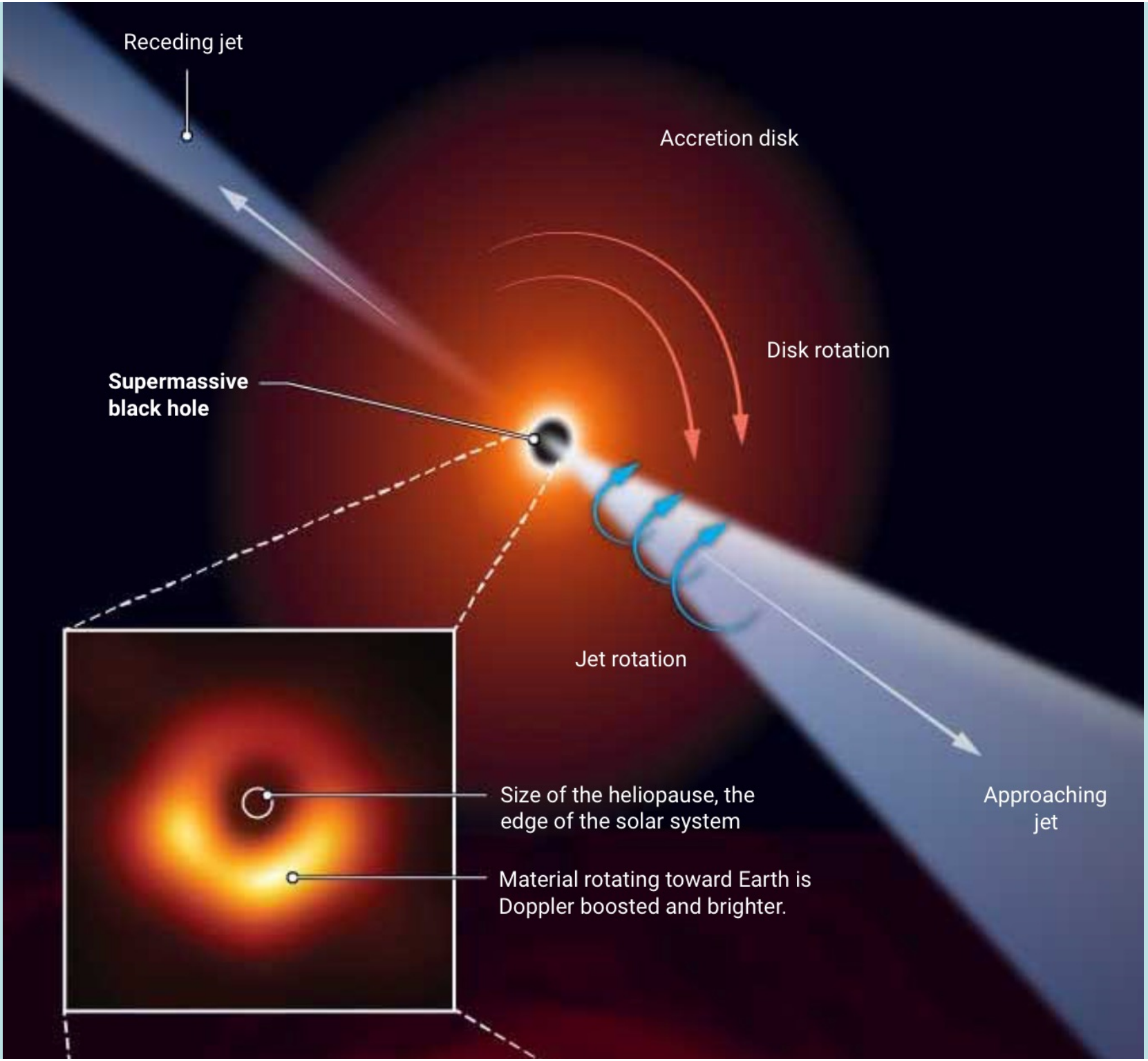
Jean-Pierre Luminet's 1979 black hole visualization. Using computer data, he drew several thousand black dots on a white sheet by hand and took a photographic negative to get the final image. Gas racing around the black hole toward us is brighter from a Doppler boost. The part of the gas disk behind the black hole is visible above it, because its light has been bent by the black hole's gravity.





順時鐘方向的旋轉，使吸積盤的一測較亮。

黑洞本身會在發光的盤的中間形成黑影：Black Hole Shadow


Receding jet
Accretion disk
Disk rotation
Supermassive black hole
Jet rotation
Size of the heliopause, the edge of the solar system
Material rotating toward Earth is Doppler boosted and brighter.
Approaching jet

To see Blackhole

Event Horizon Telescope

Home | About EHT | Science | Technology | Press & Media Resources | For Astronomers

The Event Horizon Telescope is an international collaboration aiming to capture the first image of a black hole by creating a virtual Earth-sized telescope.




Event Horizon Telescope Animated M...

Organization

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Project Scientist	Dimitrios Psaltis
Project Manager	Remo Tilanus

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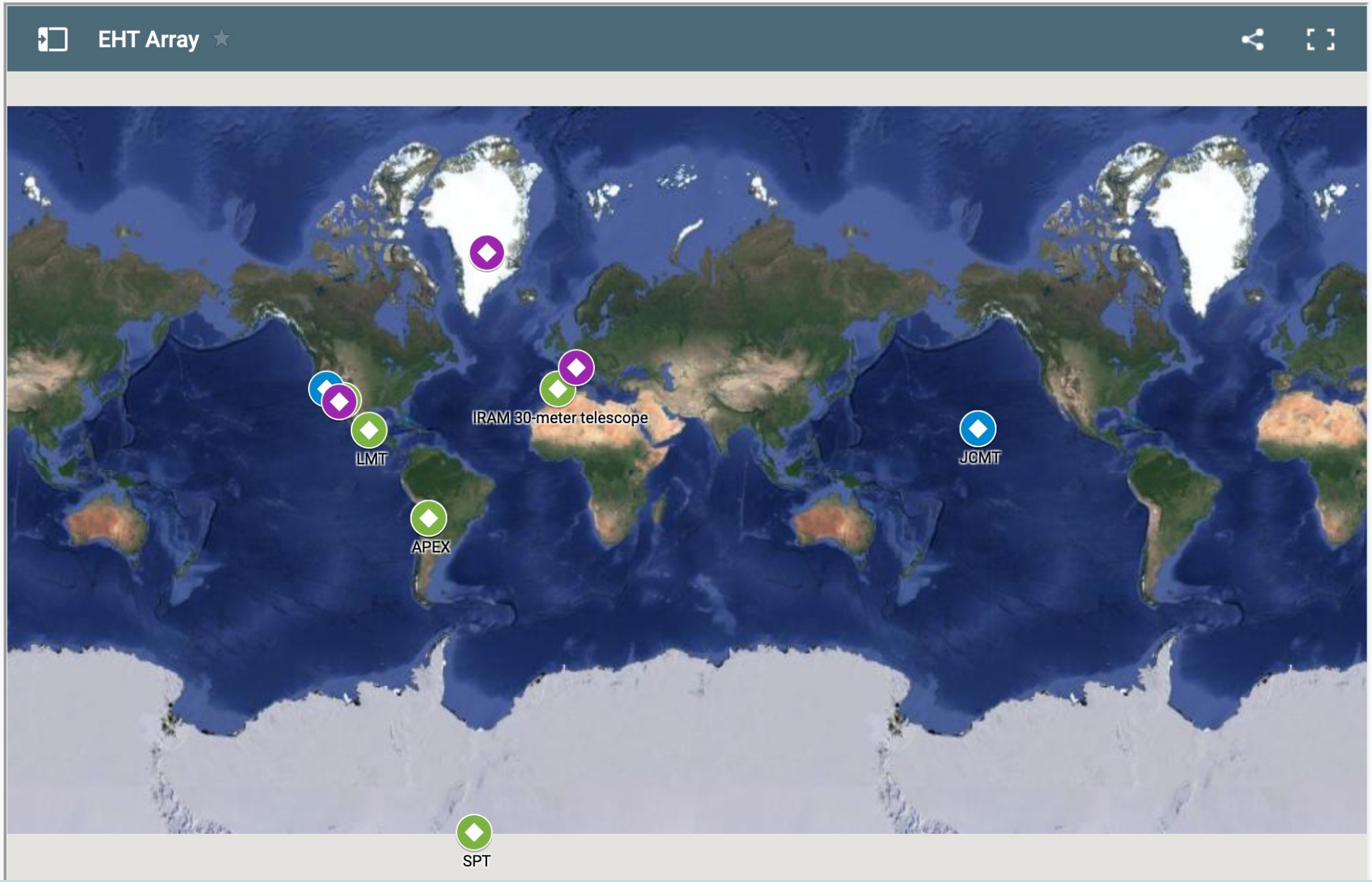
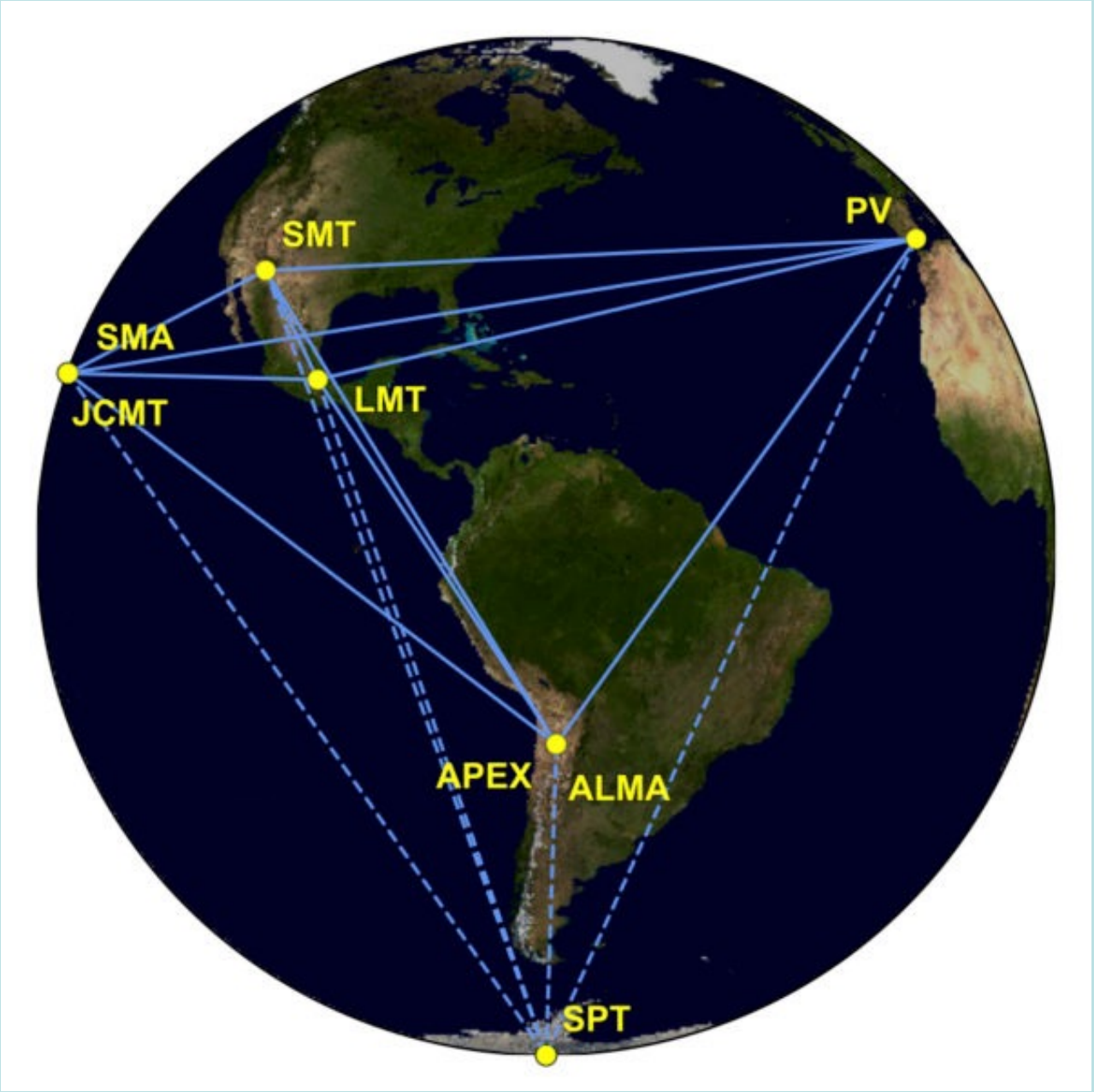
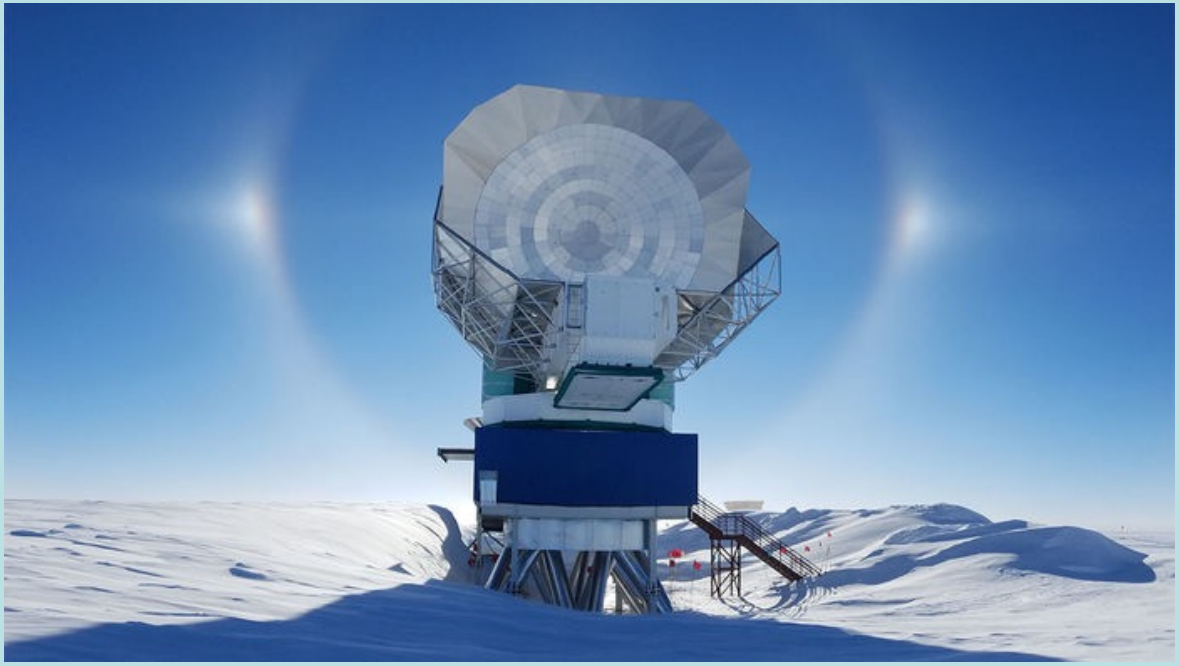

EHT Array
IRAM 30-meter telescope
LMT
JCMT
APEX
SPT


SMT
PV
SMA
JCMT
LMT
APEX
ALMA
SPT

SPT Auroras



South Pole Telescope



LMT Sunrise



The Large Millimeter Telescope Alfonso Serrano (or Gran Telescopio Milimétrico Alfonso Serrano) is the world´s largest single-dish steerable millimetre-wavelength telescope designed specifically for astronomical observations in the wavelength range of 0.85 – 4mm.



Atacama Large Millimeter/submillimeter Array (ALMA) - the largest astronomical project in existence - is a single telescope of revolutionary design, composed of 66 high precision antennas located on the Chajnantor plateau, 5000 meters altitude in northern Chile.



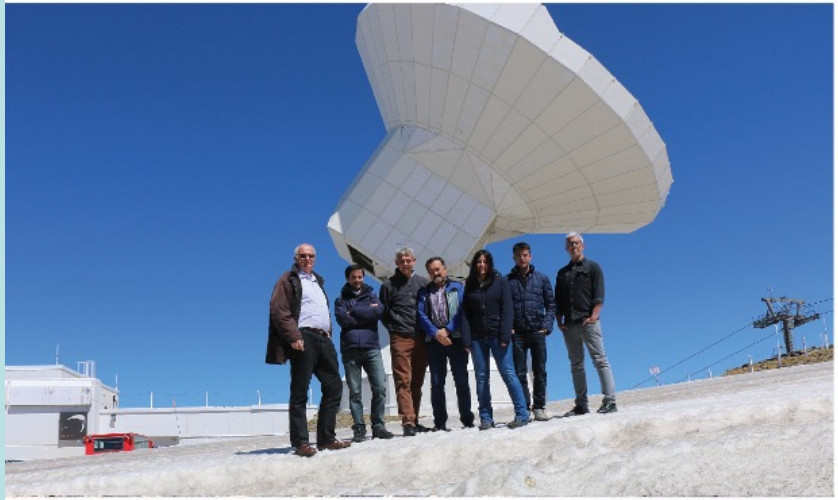
The Atacama Large Millimeter Array in Atacama, Chile, one of several telescopes across the globe that make up the Event Horizon Telescope, below the southern sky.CreditY. Beletsky (LCO)/ESO

Greenland Telescope















中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics

EHT 常見問題集



首頁Home | 報名表Registration | 地圖 Map | › ASIAA Website

中央研究院事件視界望遠鏡（Event Horizon Telescope，EHT）首次成果發表記者會
Academia Sinica Press Conference on First Result from Event Horizon Telescope (EHT)

Email from AS.

We, the GLT/VLBI group, will have the Event Horizon Telescope (EHT) Press Conference, hosted by the AS President Liao, on coming Wednesday, Apr.10, 8:30 PM - 9:30 PM, at the Academia Sinica Headquarter Activity Center:

https://events.asiaa.sinica.edu.tw/conference/20190410/

(you can go from the ASIAA homepage, too)

This will be a world-wide simultaneous press conference, together with the ones in Brussels, Santiago, Shanghai, Tokyo, and Washington D.C.

First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)

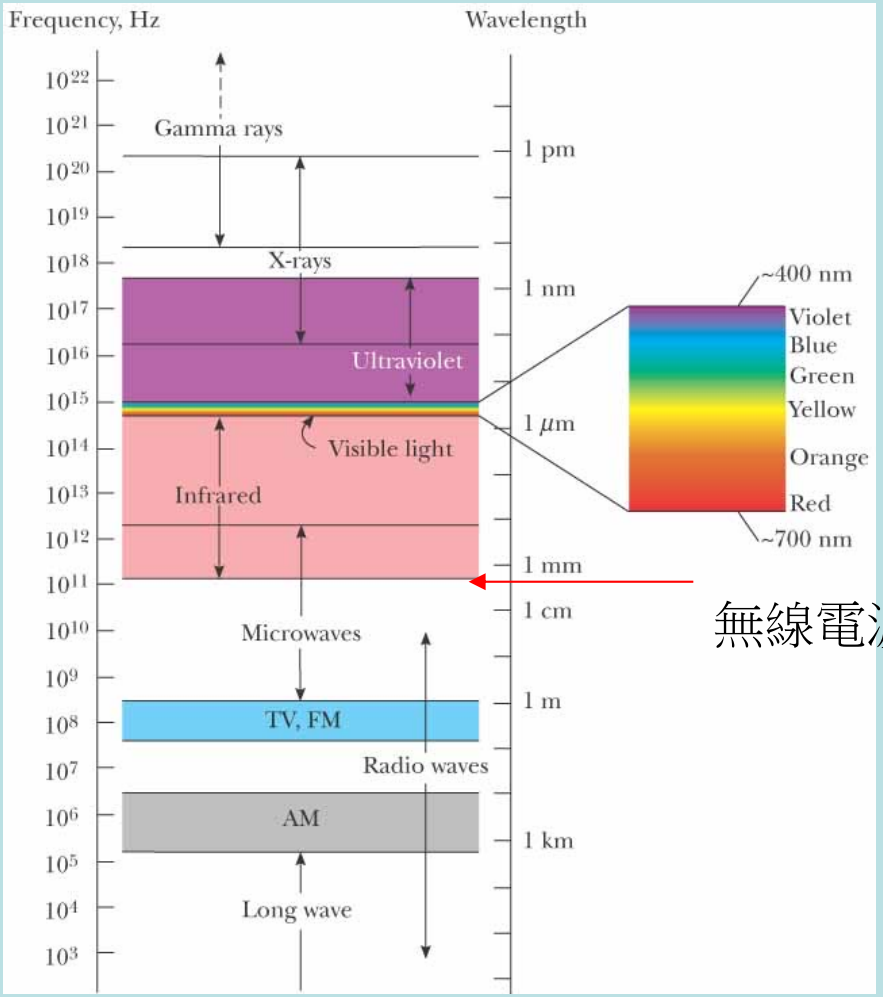
Received 2019 March 1; revised 2019 March 12; accepted 2019 March 12; published 2019 April 10

Abstract

When surrounded by a transparent emission region, black holes are expected to reveal a dark shadow caused by gravitational light bending and photon capture at the event horizon. To image and study this phenomenon, we have assembled the Event Horizon Telescope, a global very long baseline interferometry array observing at a wavelength of 1.3 mm. This allows us to reconstruct event-horizon-scale images of the supermassive black hole candidate in the center of the giant elliptical galaxy M87. We have resolved the central compact radio source as an asymmetric bright emission ring with a diameter of 42 ± 3 μas, which is circular and encompasses a central depression in brightness with a flux ratio $\gtrsim$10:1. The emission ring is recovered using different calibration and imaging schemes, with its diameter and width remaining stable over four different observations carried out in different days. Overall, the observed image is consistent with expectations for the shadow of a Kerr black hole as predicted by general relativity. The asymmetry in brightness in the ring can be explained in terms of relativistic beaming of the emission from a plasma rotating close to the speed of light around a black hole. We compare our images to an extensive library of ray-traced general-relativistic magnetohydrodynamic simulations of black holes and derive a central mass of $M = (6.5 \pm 0.7) \times 10^9\, M_\odot$. Our radio-wave observations thus provide powerful evidence for the presence of supermassive black holes in centers of galaxies and as the central engines of active galactic nuclei. They also present a new tool to explore gravity in its most extreme limit and on a mass scale that was so far not accessible.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: individual (M87) – galaxies: jets – gravitation

所以這是一個無線電波望遠鏡！


Frequency, Hz
Wavelength
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
Gamma rays
X-rays
Ultraviolet
Visible light
Infrared
Microwaves
TV, FM
Radio waves
AM
Long wave
1 pm
1 nm
1 μm
1 mm
1 cm
1 m
1 km
~400 nm
Violet
Blue
Green
Yellow
Orange
Red
~700 nm

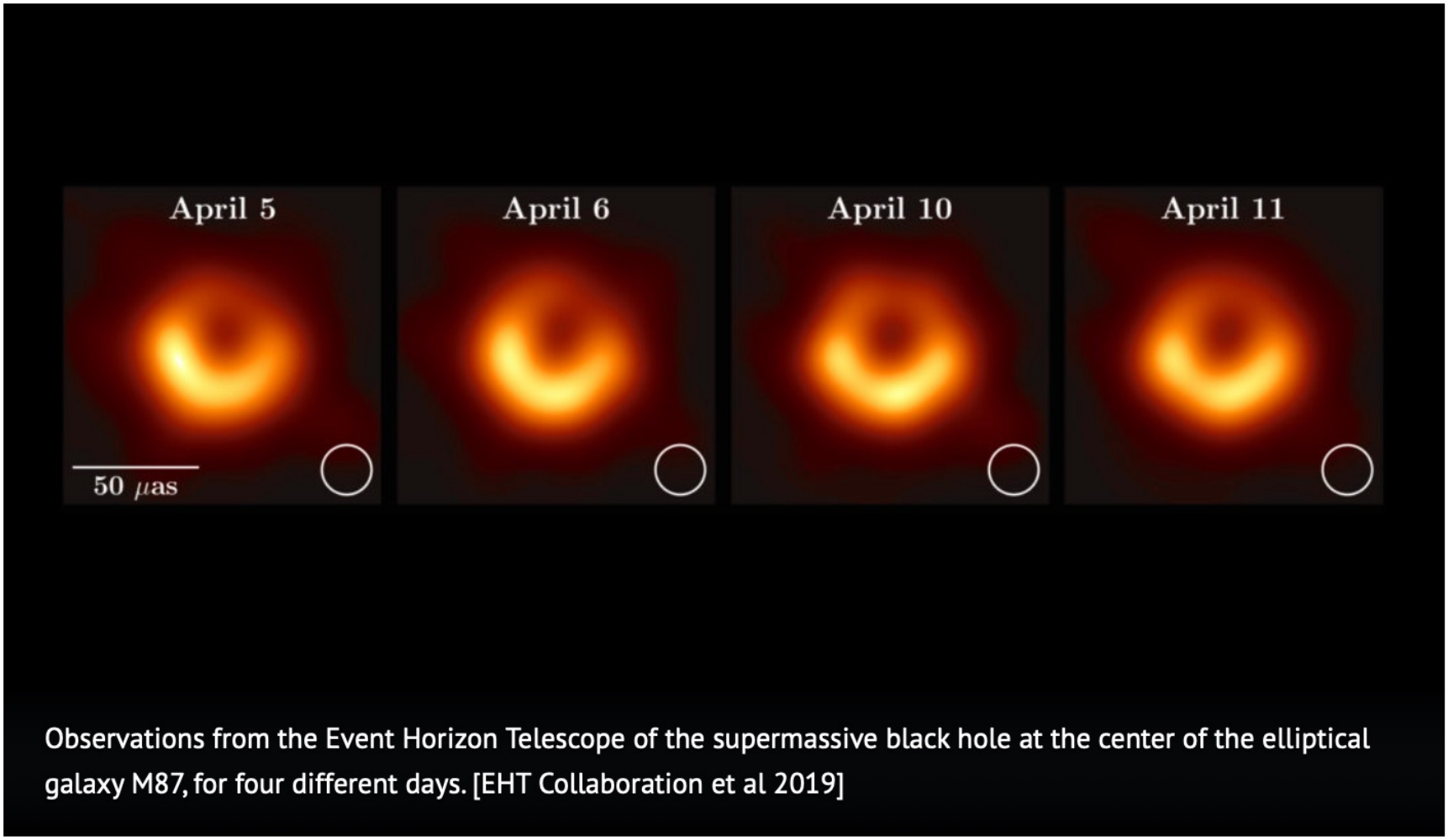
無線電波邊緣！

First Images of a Black Hole from the Event Horizon Telescope

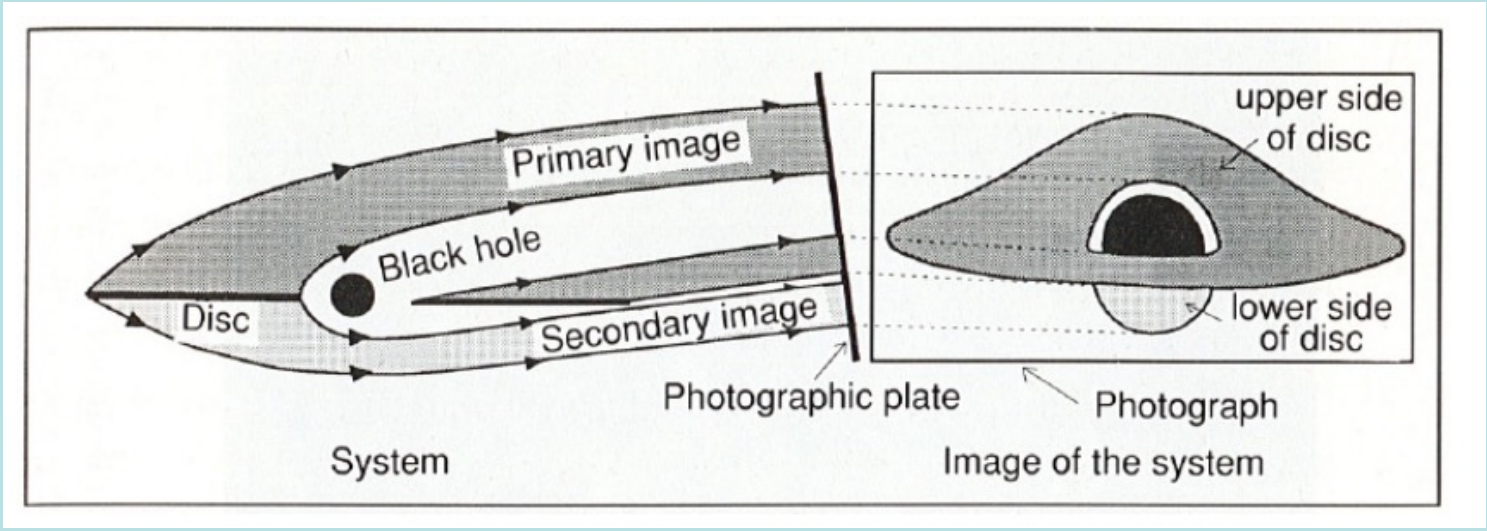
13

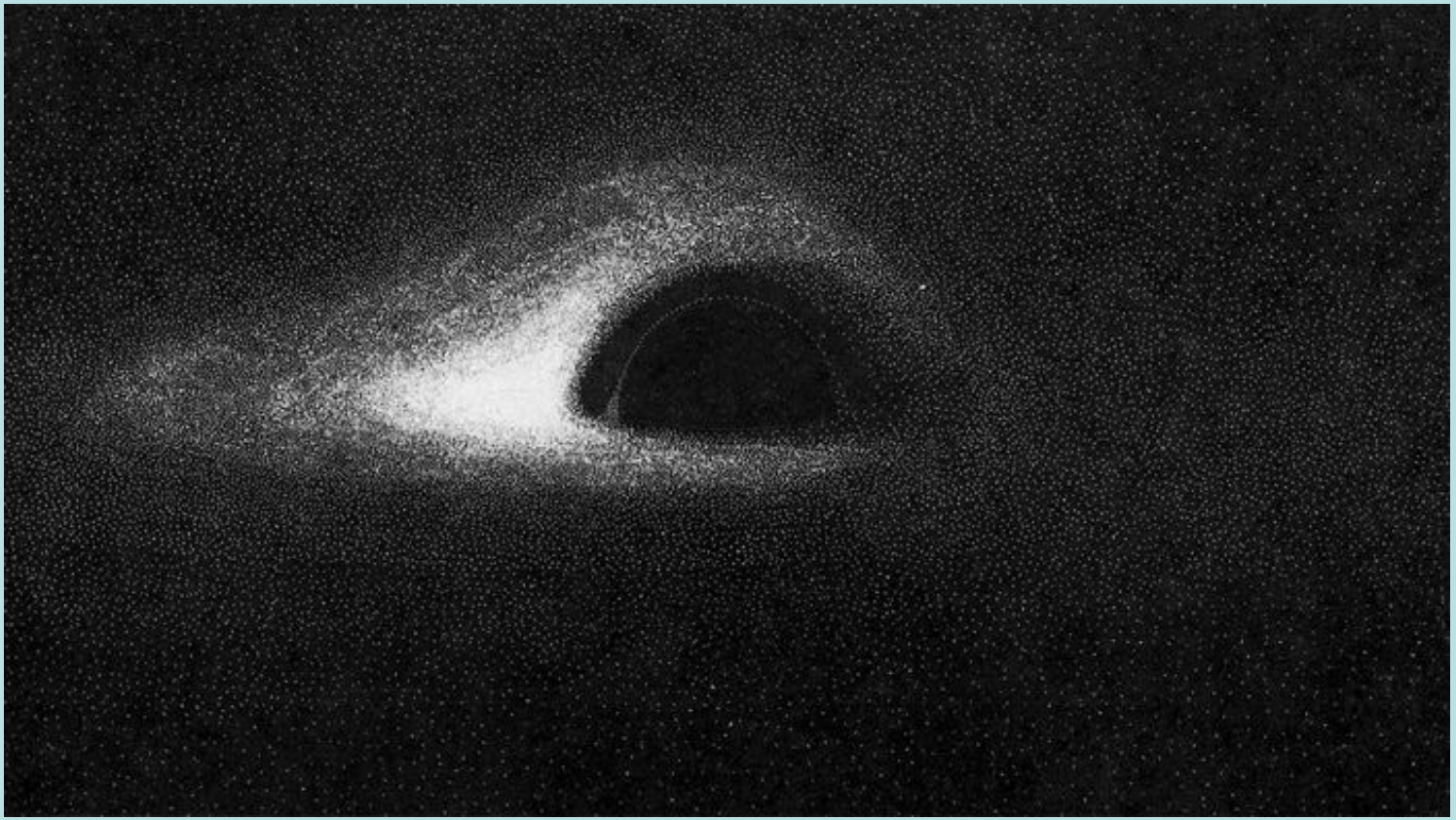
By Susanna Kohler on 10 April 2019 FEATURES

Share:



Observations from the Event Horizon Telescope of the supermassive black hole at the center of the elliptical galaxy M87, for four different days. [EHT Collaboration et al 2019]


Primary image
Black hole
Disc
Secondary image
upper side
of disc
lower side
of disc
Photographic plate
Photograph
System
Image of the system



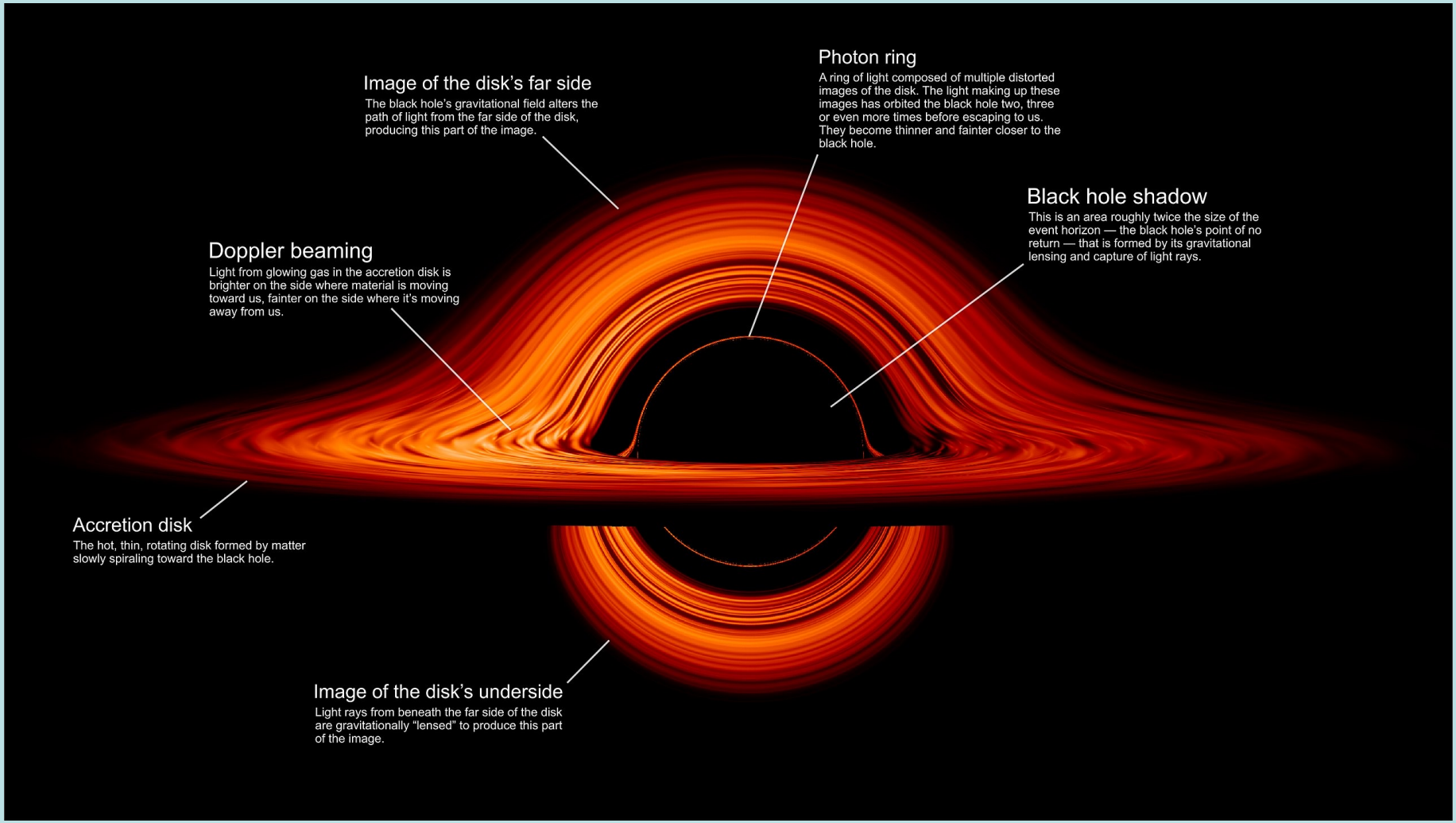
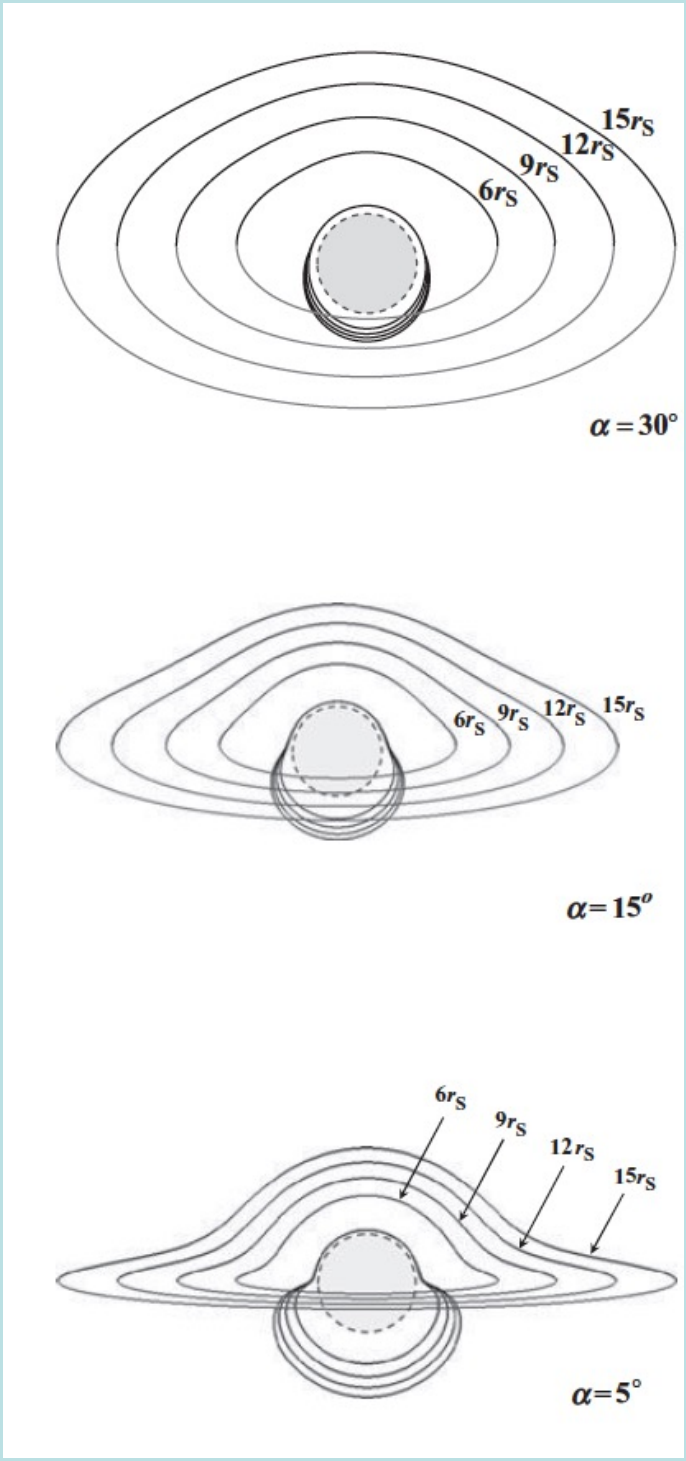
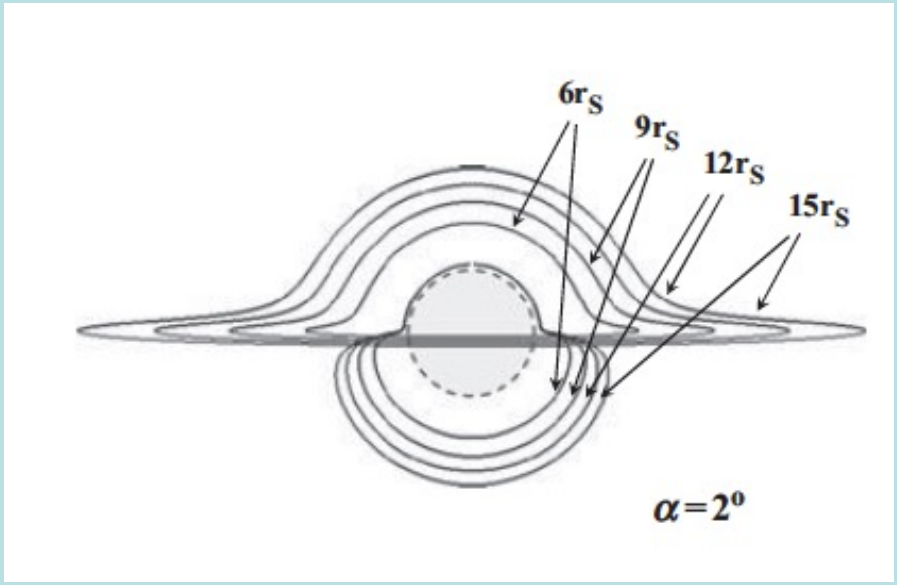
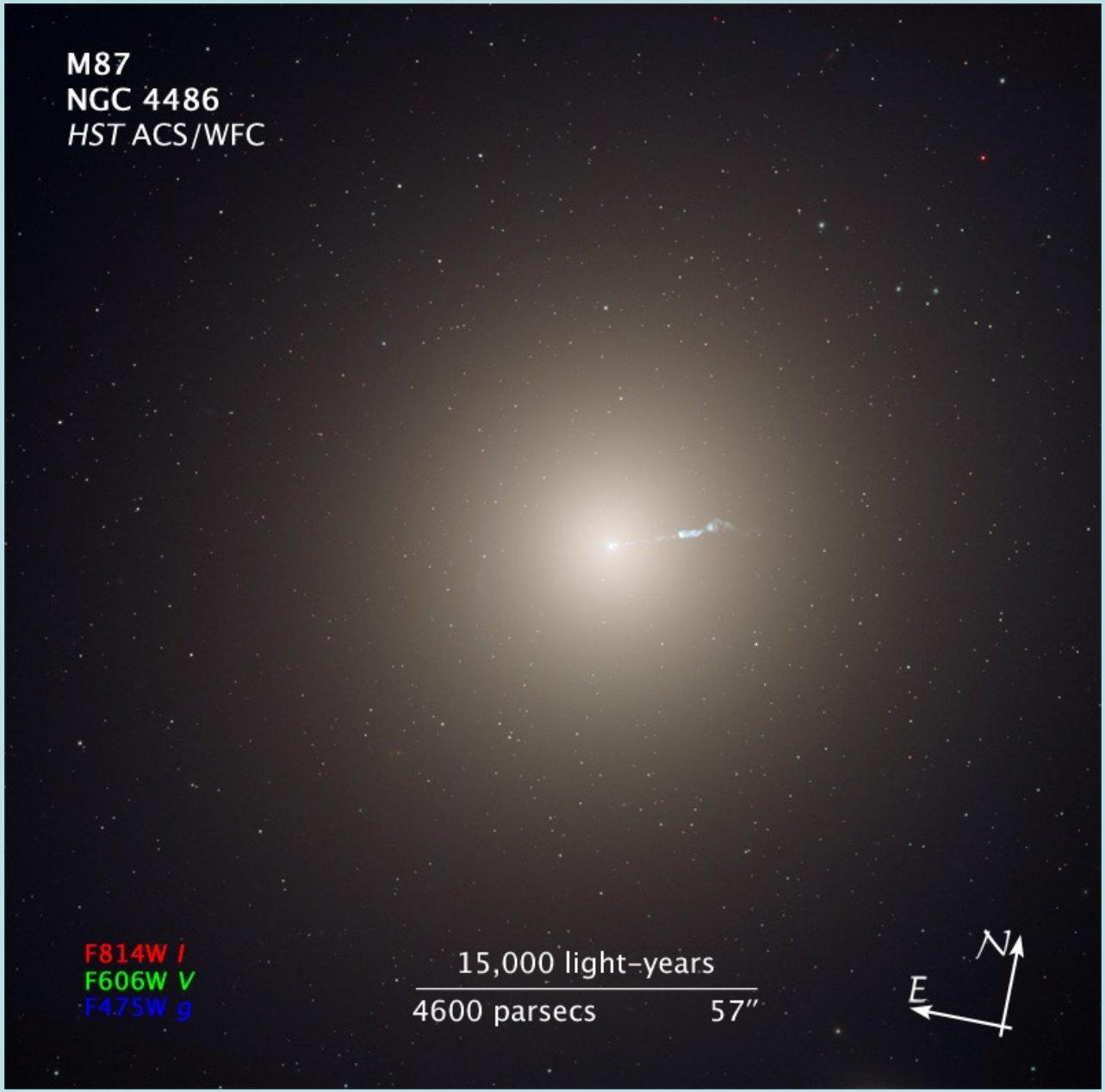
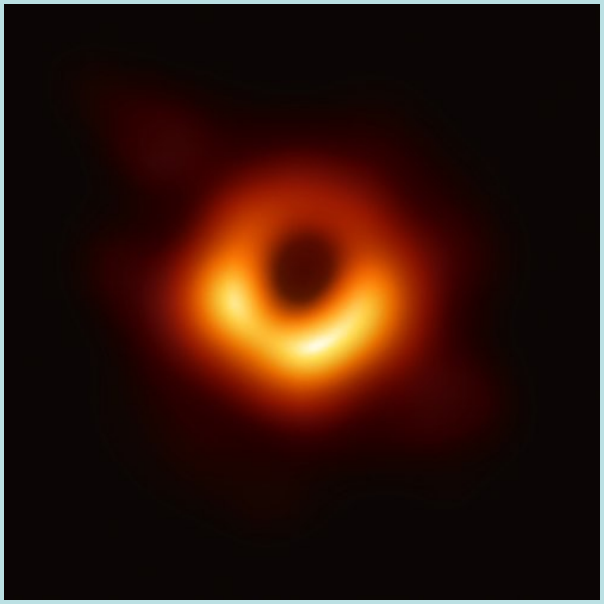


Image of the disk's far side
The black hole's gravitational field alters the path of light from the far side of the disk, producing this part of the image.
Photon ring
A ring of light composed of multiple distorted images of the disk. The light making up these images has orbited the black hole two, three or even more times before escaping to us. They become thinner and fainter closer to the black hole.
Black hole shadow
This is an area roughly twice the size of the event horizon — the black hole's point of no return — that is formed by its gravitational lensing and capture of light rays.
Doppler beaming
Light from glowing gas in the accretion disk is brighter on the side where material is moving toward us, fainter on the side where it's moving away from us.
Accretion disk
The hot, thin, rotating disk formed by matter slowly spiraling toward the black hole.
Image of the disk's underside
Light rays from beneath the far side of the disk are gravitationally "lensed" to produce this part of the image.

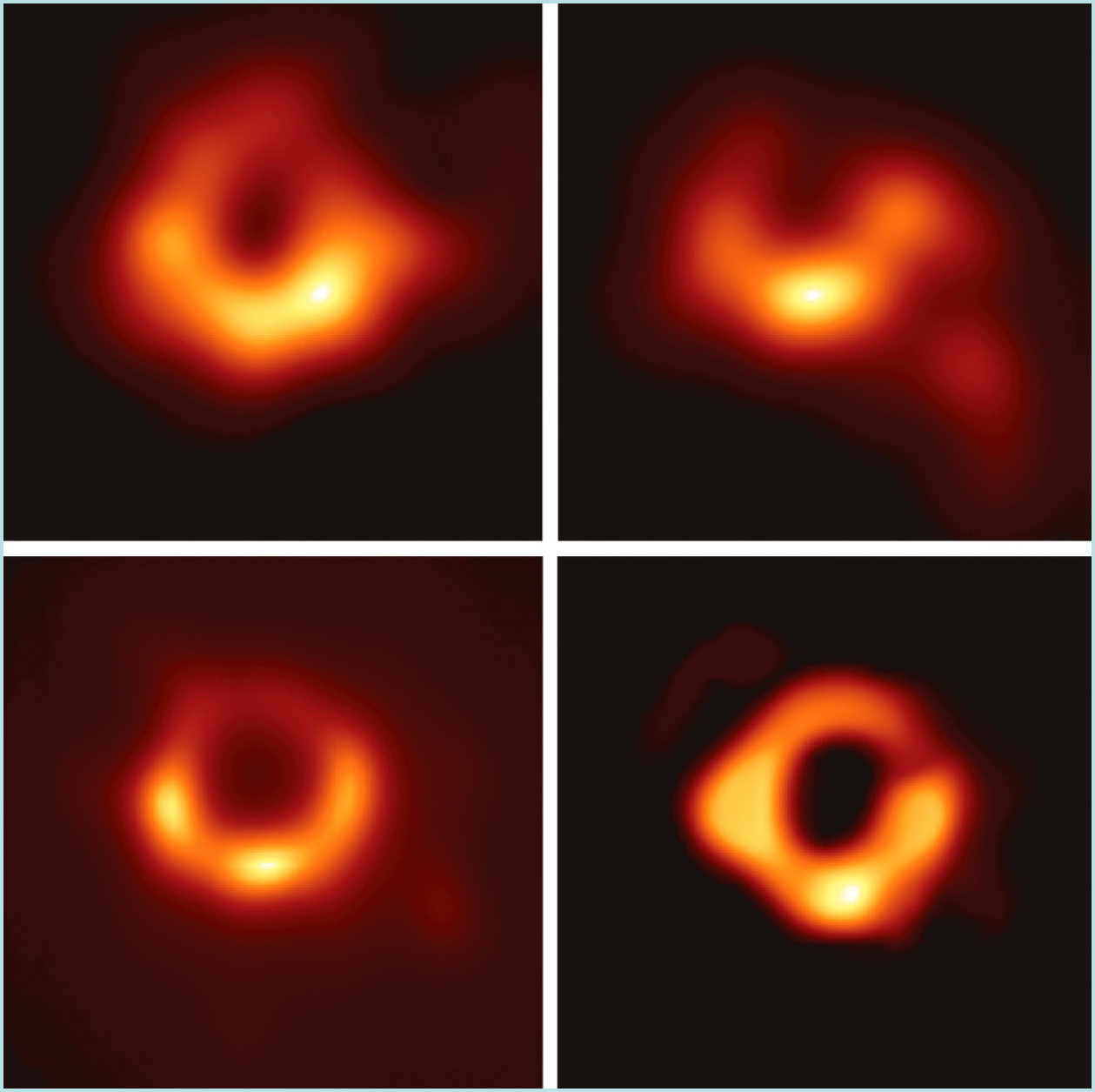

15r_S
12r_S
9r_S
6r_S
$\alpha = 30°$
6r_S
9r_S
12r_S
15r_S
$\alpha = 15^o$
6r_S
9r_S
12r_S
15r_S
$\alpha = 5°$

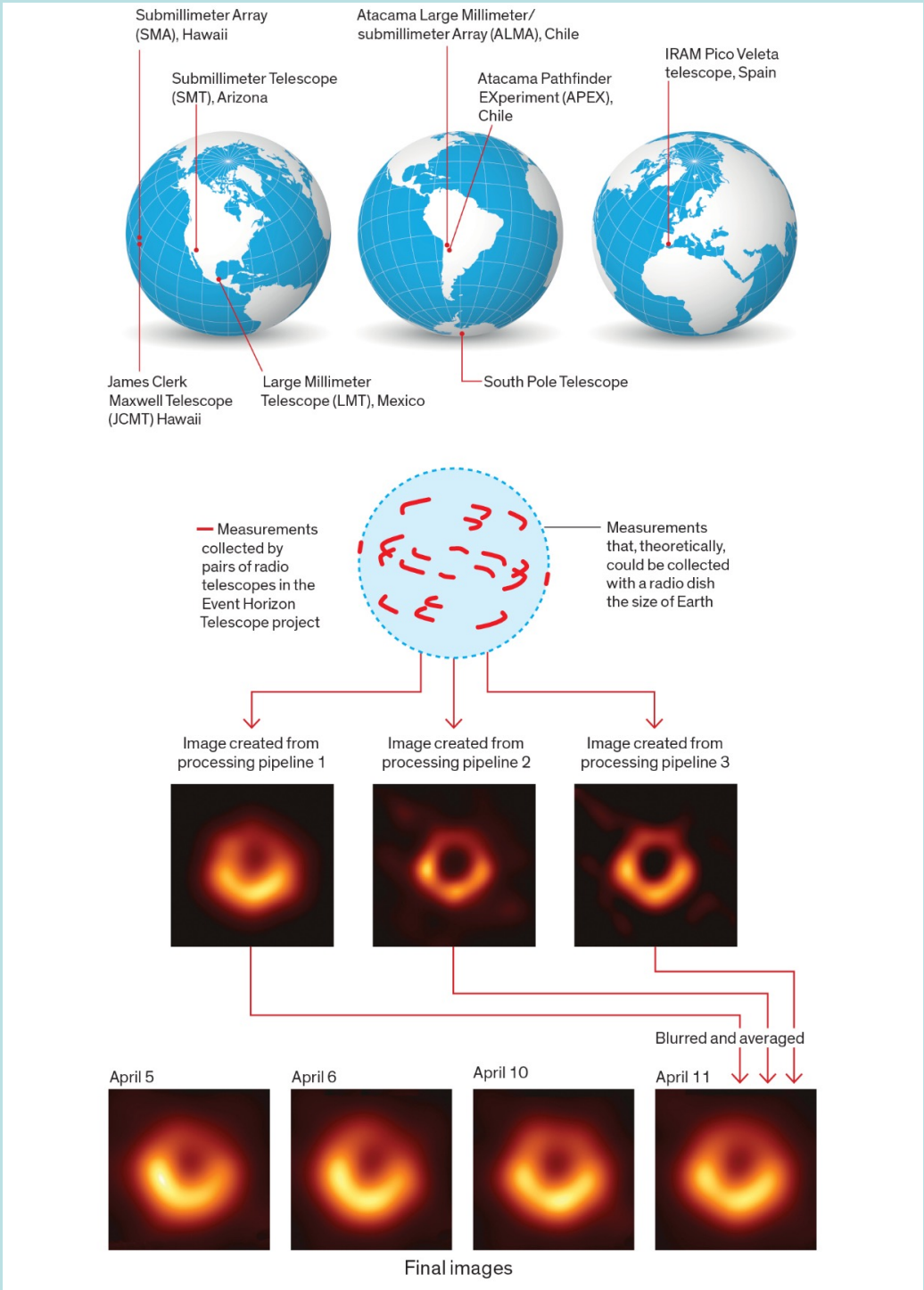

6r_S
9r_S
12r_S
15r_S
$\alpha = 2^o$

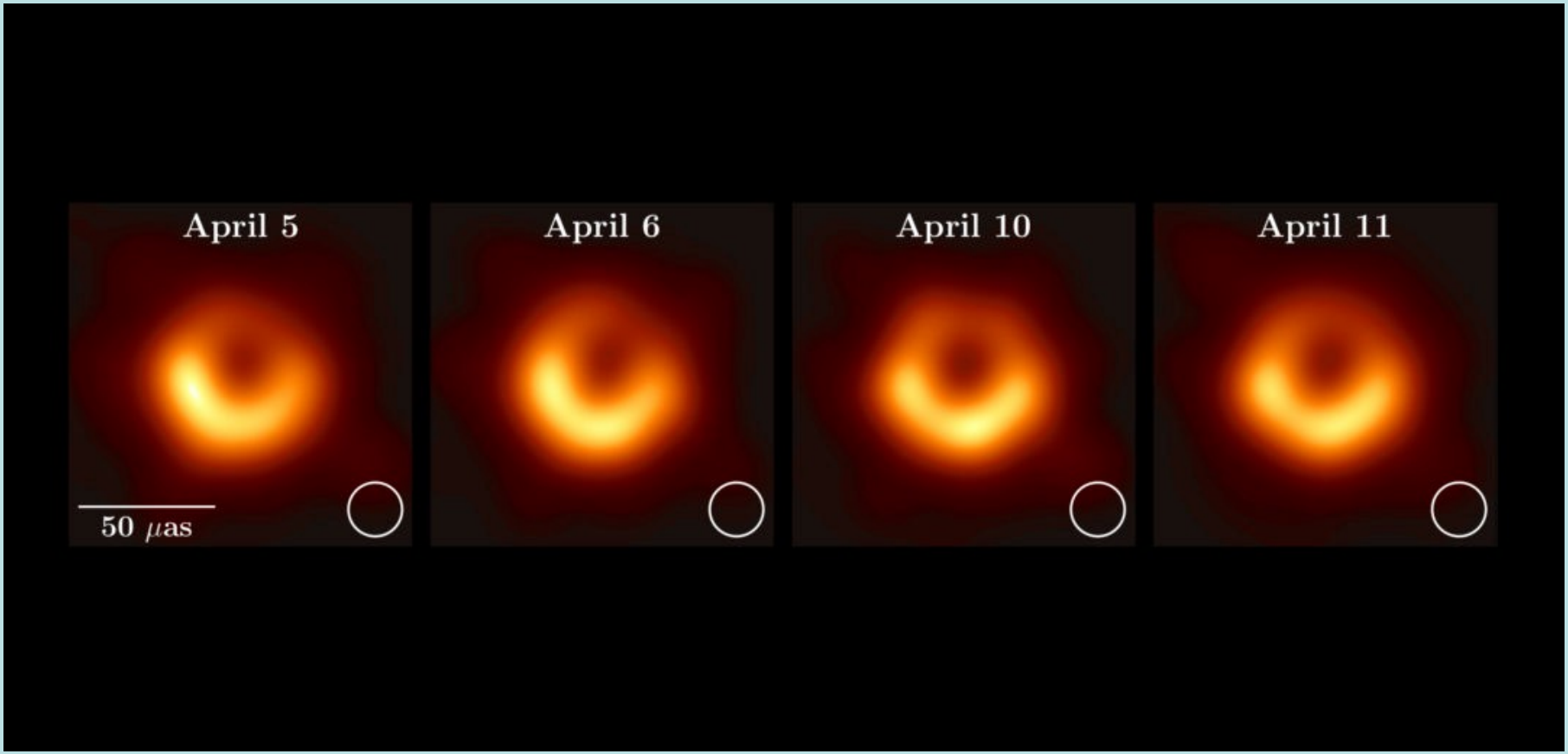

M87
NGC 4486
HST ACS/WFC
F814W *I*
F606W *V*
F475W *g*
15,000 light-years
4600 parsecs
57″
N
E

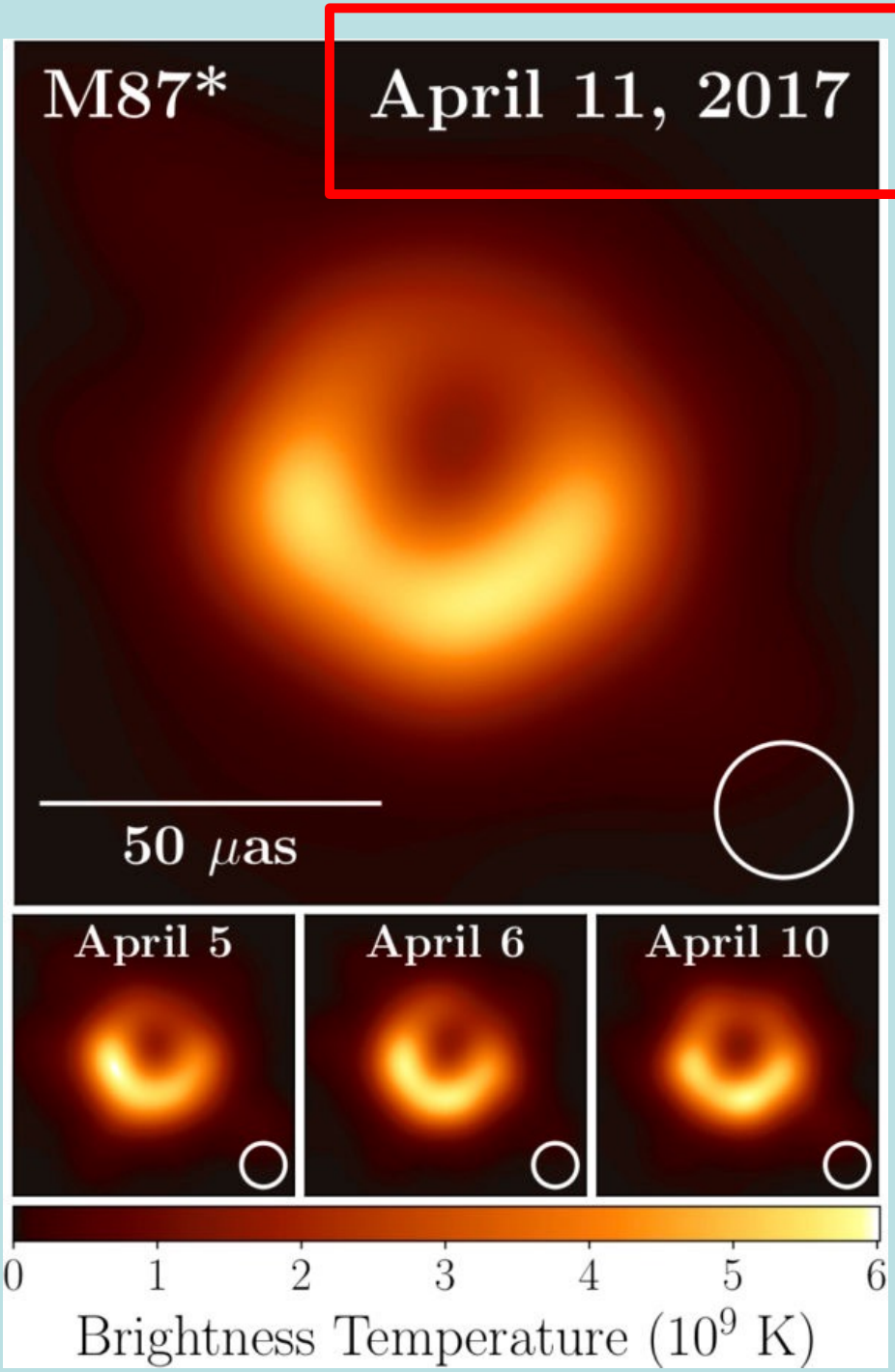


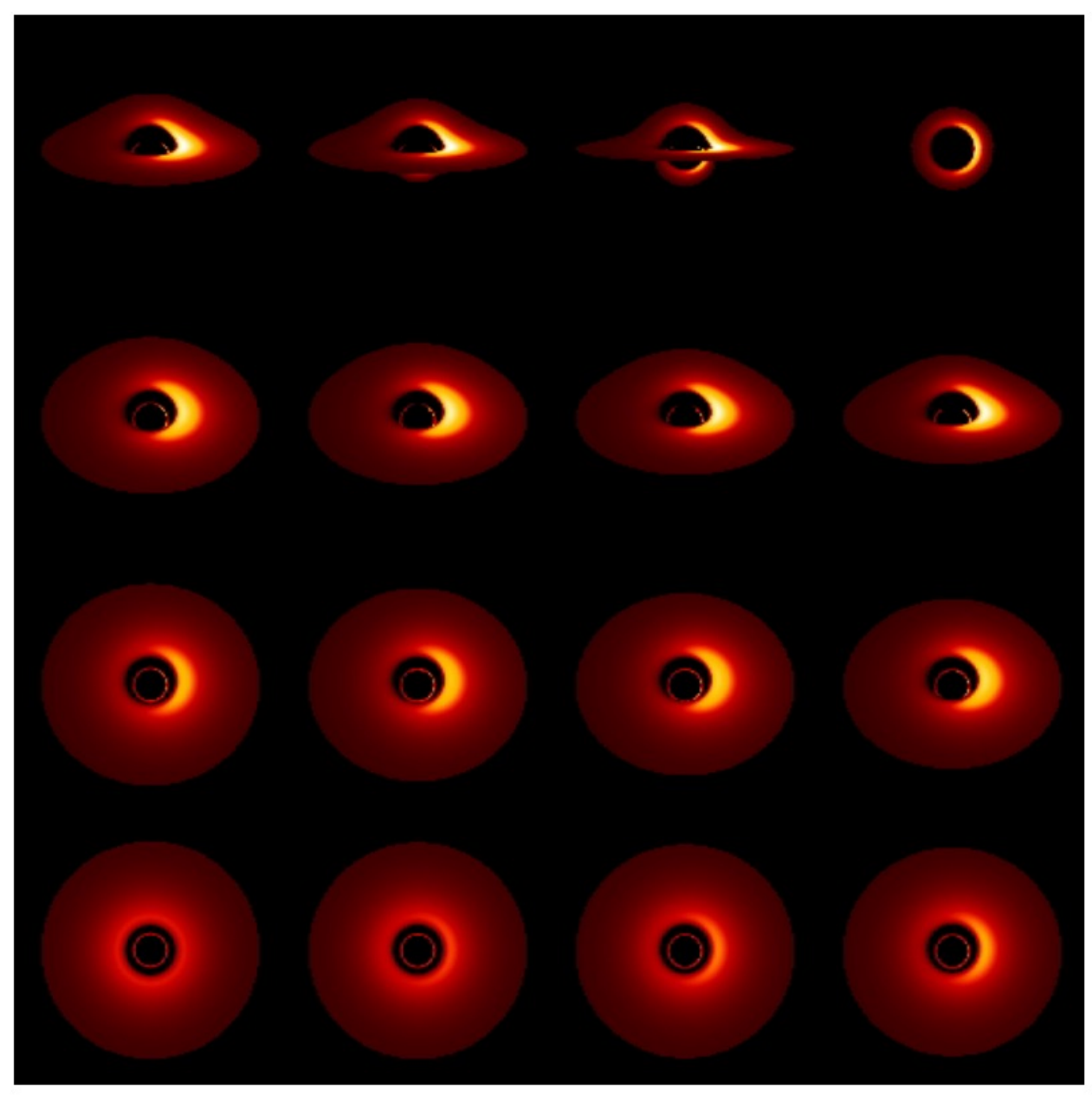
The core of M87 contains a supermassive black hole, designated M87*,whose mass is billions times that of the Earth's Sun; estimates have ranged from $(3.5 \pm 0.8) \times 10^9$ M⊙[67] to $(6.6 \pm 0.4) \times 10^9$M⊙ In April 2019, the Event Horizon Telescope released measurements of the black hole's mass as $(6.5 \pm 0.2\text{stat} \pm 0.7\text{sys}) \times 10^9$M⊙. This is one of the highest known masses for such an object. A rotating disk of ionized gas surrounds the black hole and is roughly perpendicular to the relativistic jet. The disk rotates at velocities of up to roughly 1,000 km/s and spans a maximum diameter of 0.12 parsecs (25,000 AU; 3.7×10^{12} km). By comparison, Pluto averages 39 astronomical units (0.00019 pc; 5.8×10^9 km) from the sun. Gas accretes onto the black hole at an estimated rate of one solar mass every ten years (about 90 Earth masses per day).The Schwarzschild radius of the black hole is 5.9×10^{-4} parsecs (1.9×10^{-3} light-years), which is around 120 times the Earth–Sun distance. Previous observations of the black hole's jet showed that the black hole's spin axis is inclined at an angle of 17° relative to the observer's line of sight. From these two observations, EHT concluded the black hole spins clockwise, as seen from Earth.

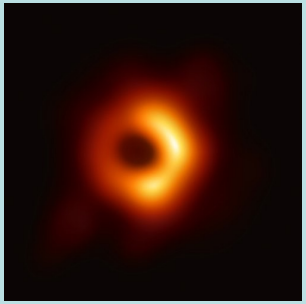



Submillimeter Array (SMA), Hawaii
Submillimeter Telescope (SMT), Arizona
James Clerk Maxwell Telescope (JCMT) Hawaii
Large Millimeter Telescope (LMT), Mexico
Atacama Large Millimeter/ submillimeter Array (ALMA), Chile
Atacama Pathfinder EXperiment (APEX), Chile
South Pole Telescope
IRAM Pico Veleta telescope, Spain
Measurements collected by pairs of radio telescopes in the Event Horizon Telescope project
Measurements that, theoretically, could be collected with a radio dish the size of Earth
Image created from processing pipeline 1
Image created from processing pipeline 2
Image created from processing pipeline 3
Blurred and averaged
April 5
April 6
April 10
April 11
Final images


April 5
April 6
April 10
April 11
50 μas


M87*
April 11, 2017
50 μas
April 5
April 6
April 10
0
1
2
3
4
5
6
Brightness Temperature (10^9 K)





順時鐘方向的旋轉，使吸積盤的一測較亮。

黑洞本身會在發光的盤的中間形成黑影：Black Hole Shadow



Shep Doeleman, director of the Event Horizon Telescope, in 2015 working inside the Large Millimeter Telescope in Pico de Orizaba National Park near Puebla, Mexico


Diversity in emotion language across cultures pp. 1444 & 1517
A crushing approach to redox catalysis pp. 1451 & 1500
Bioscience, law, and being "human" p. 1455
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AAAS
2019
BREAKTHROUGH
of the YEAR

2019 BREAKTHROUGH *of the* YEAR

DARKNESS MADE VISIBLE

An international team of astronomers has produced the first ever image of a black hole

By **Daniel Clery**



The iconic image of galaxy Messier 87's central black hole, showing a ring of photons bent by its gravity.

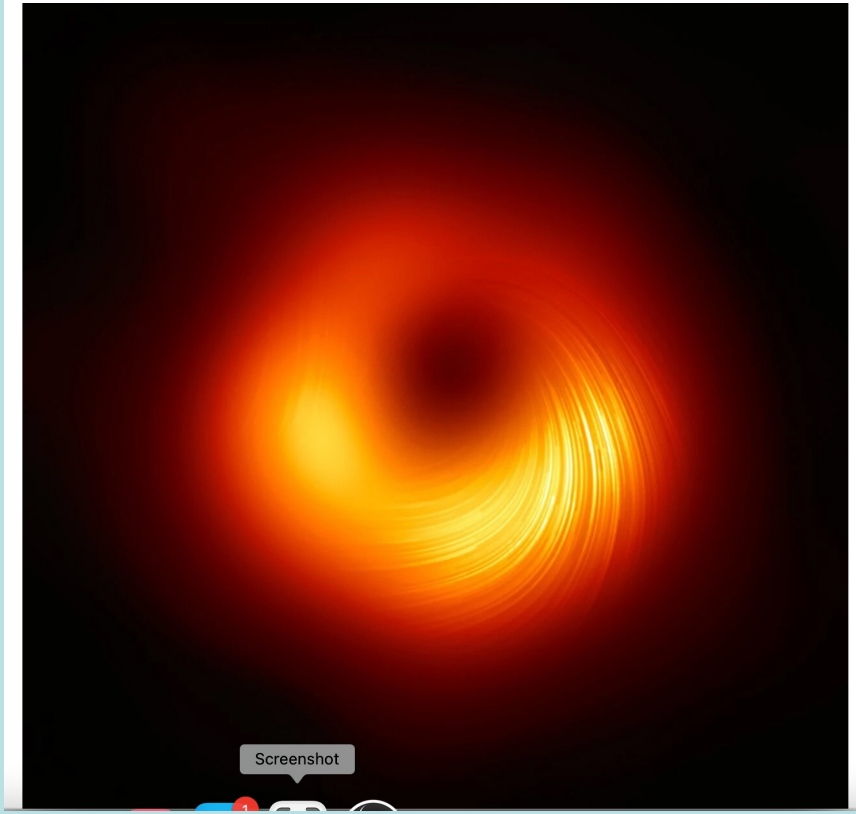
The New York Times

OUT THERE

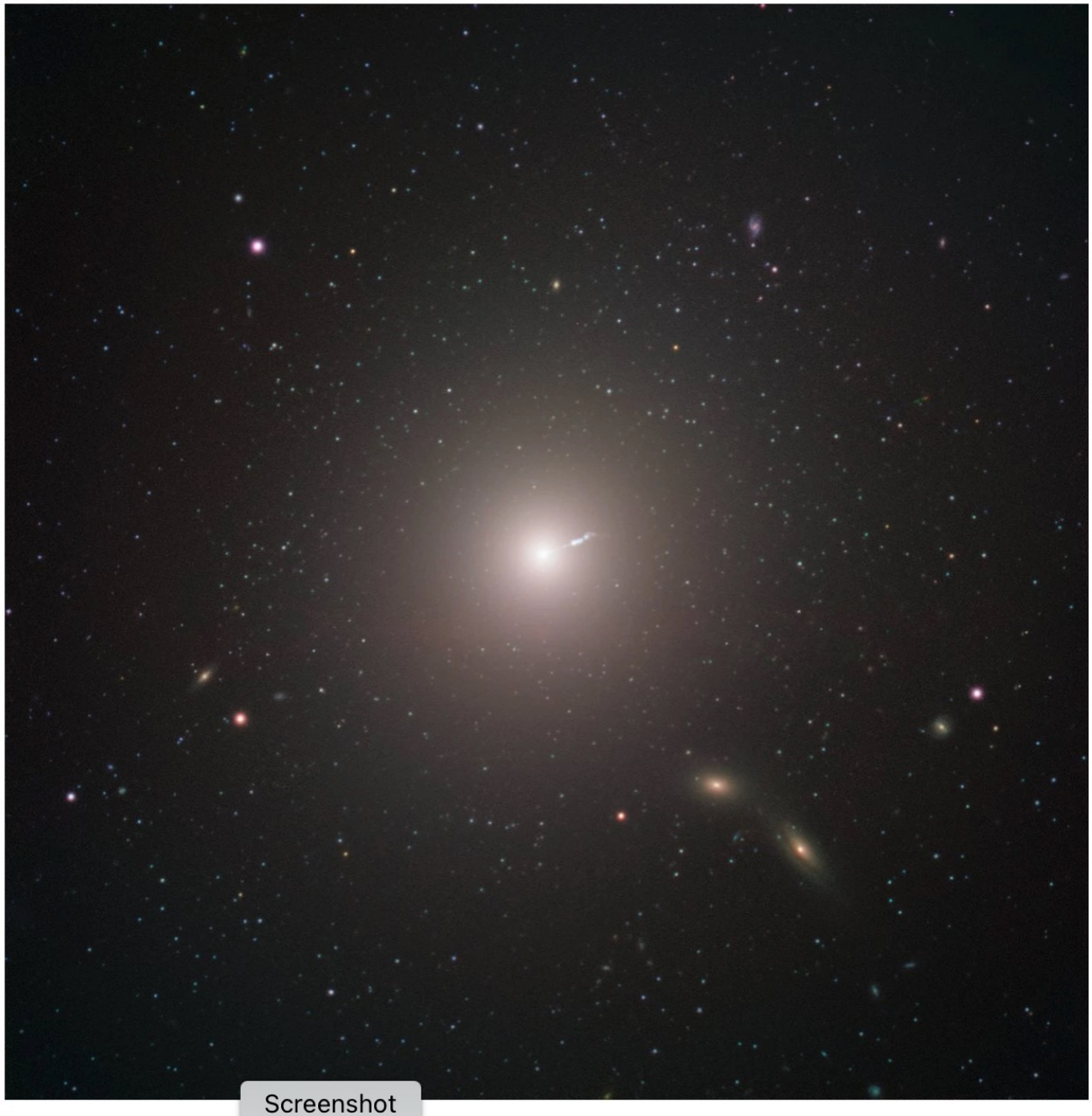
The Most Intimate Portrait Yet of a Black Hole

Two years of analyzing the polarized light from a galaxy's giant black hole has given scientists a glimpse at how quasars might arise.

88



An image of the Messier 87 black hole, showing, for the first time, how it looks in polarized light. The lines mark the orientation of polarization, which is related to the magnetic field around the shadow of the black hole.
Event Horizon Telescope Collaboration

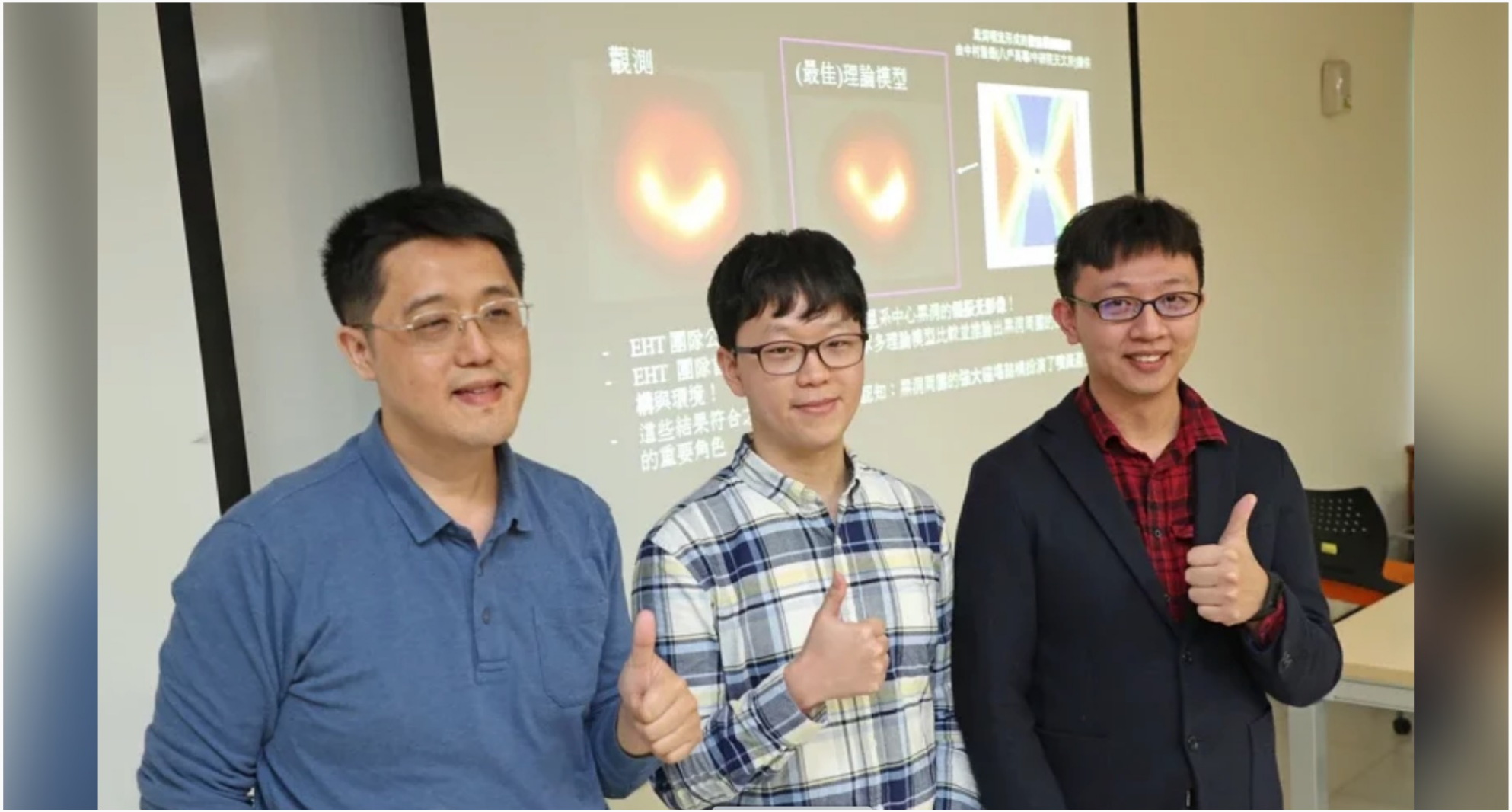


Screenshot

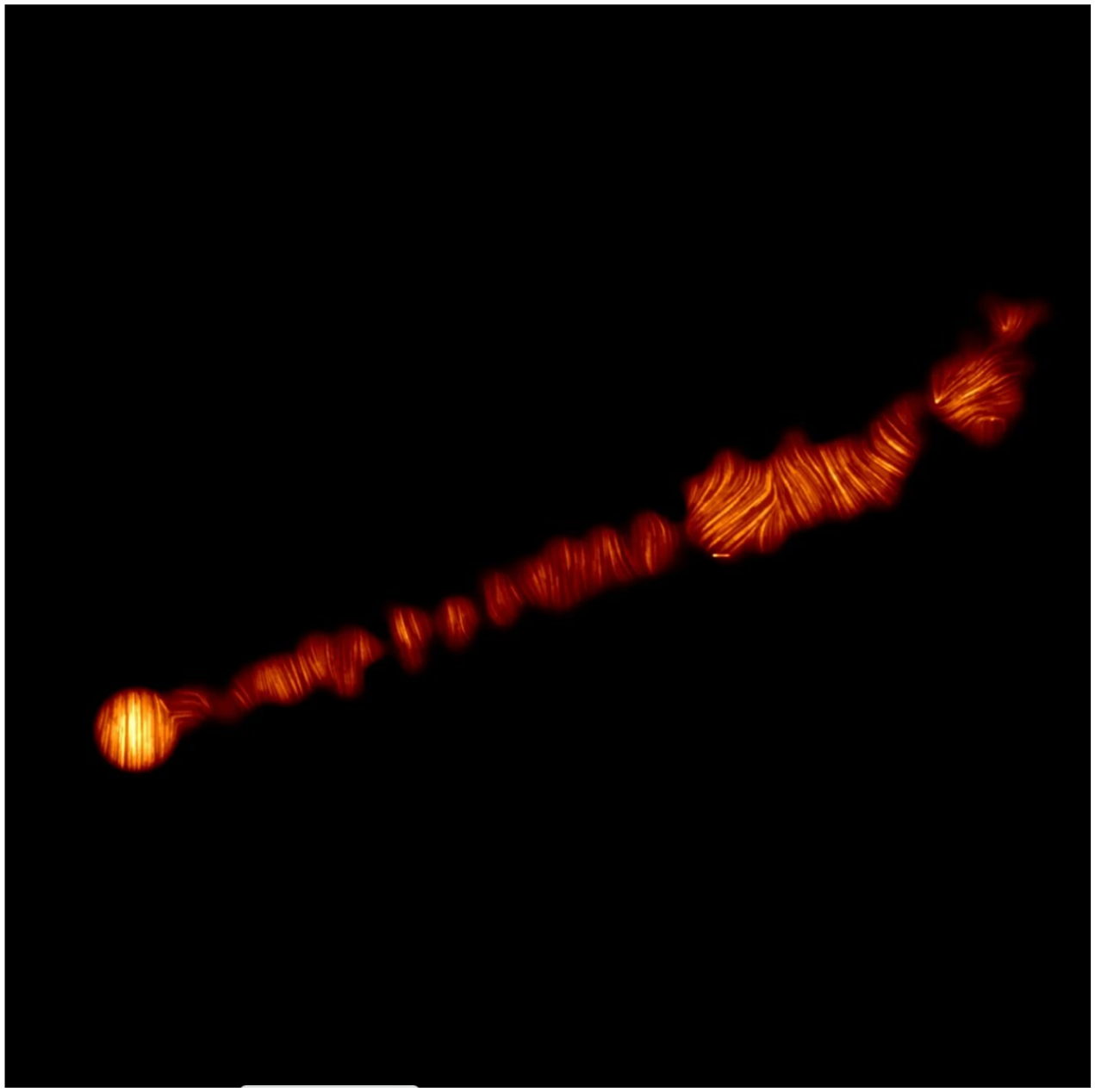
A view of Messier 87, in the constellation Virgo, made by the European Southern Observatory's Very Large Telescope. European Southern Observatory

直擊M87星系偏振光與黑洞磁場

2021-03-26 00:45 聯合報 / 記者葉冠妤／台北報導

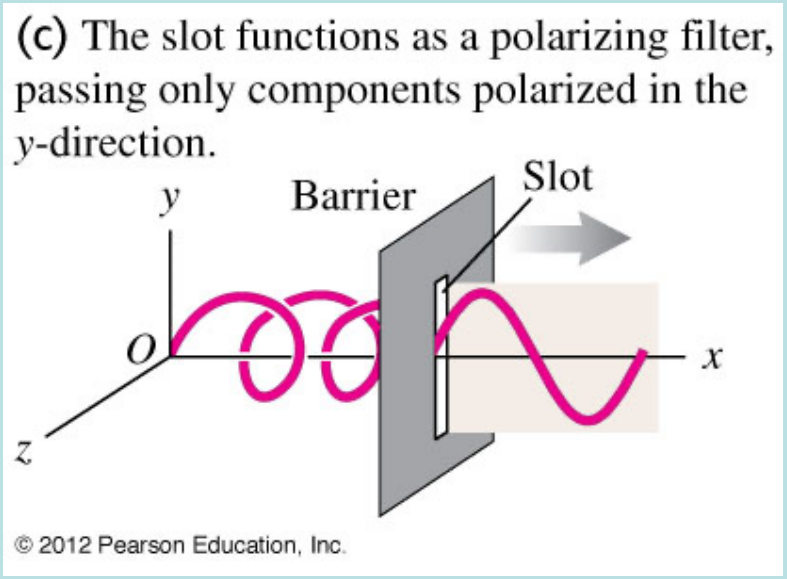


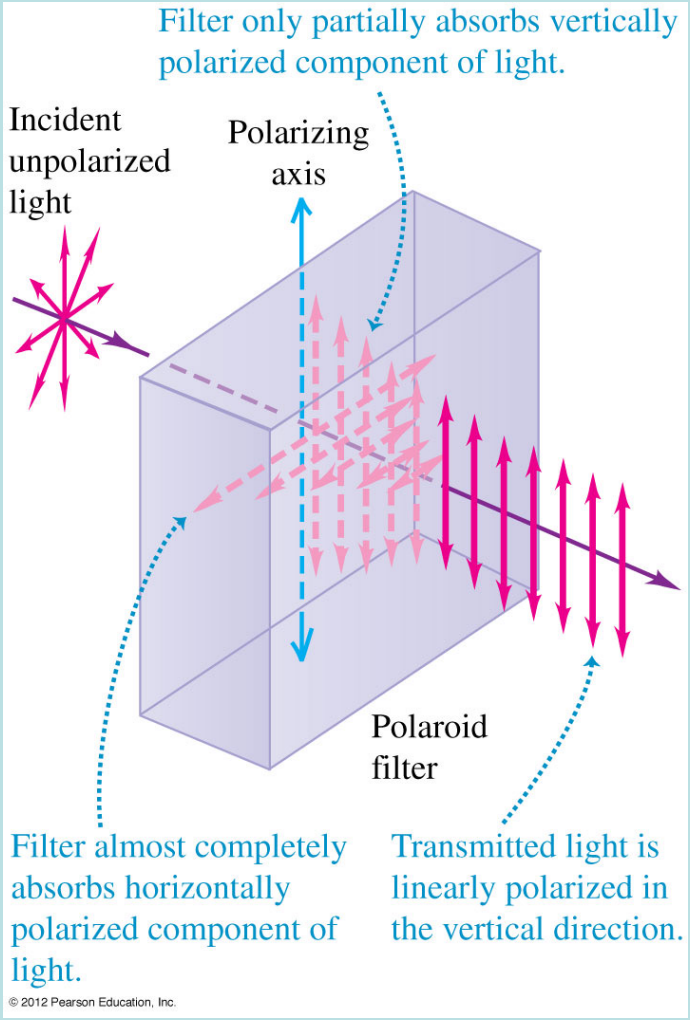
中研院天文所東亞核心觀測聯盟朴鍾浩（中）、師大助理教授卜宏毅（右）及中山大學物理系助理教授郭政育（左）昨出席記者會，公布M87星系偏振光影像。記者潘俊宏／攝影



Part of the jet in Messier 87, 6,000 light-years long, shown in polarized light. ALMA (ESO/NAOJ/NRAO), Goddi et al.

未偏振的光可以以偏振片來偏振化

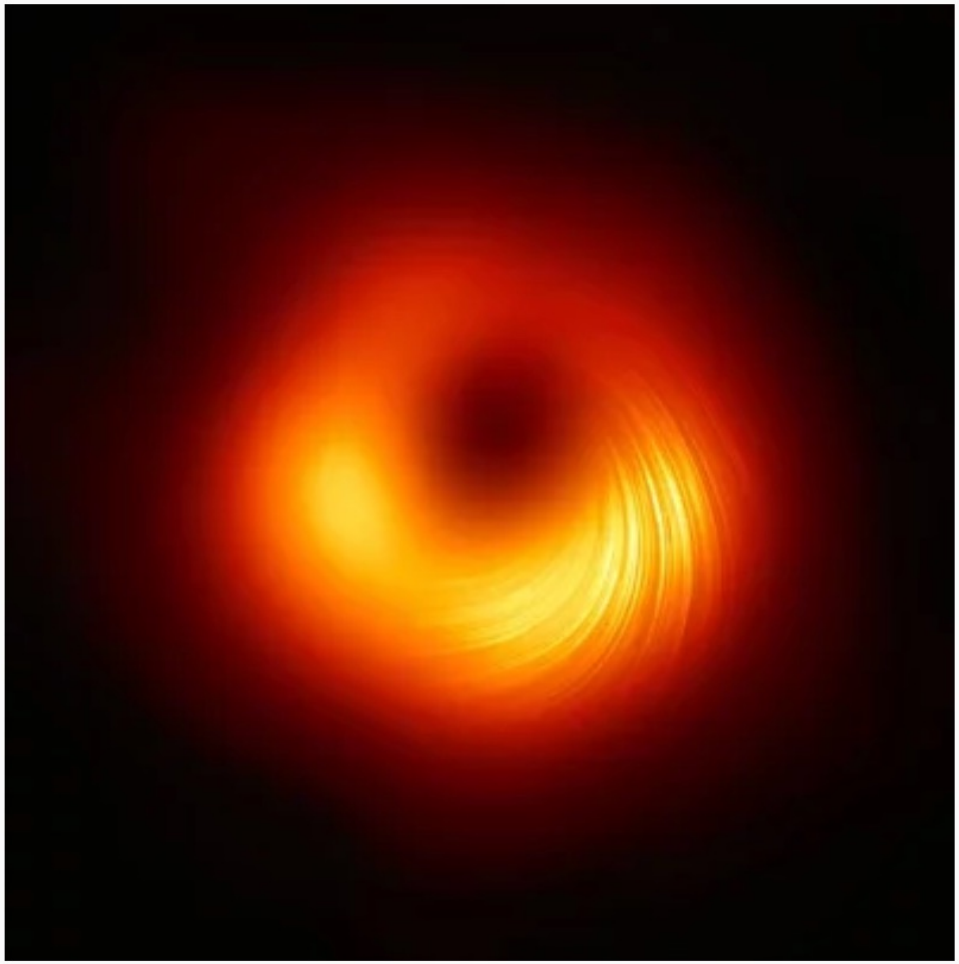




偏振片只容許一特定偏振方向的波通過

中研院指出，「偏振」像是磁場留下的指紋，這次透過觀測偏振光，推論出黑洞周圍磁場分布方式，可進一步解析首張黑洞影像周圍的磁場結構，也可為鄰近黑洞外部磁場結構提供資訊，是重要里程碑，研究成果廿四日發表於「天文物理期刊通訊」。

中研院天文及天文物理所博士後研究人員朴鍾浩指出，天文學家認為磁場在宇宙中無所不在，而黑洞噴流的產生與周圍磁場結構息息相關，透過偏振光原理的觀測，發現黑洞環上偏振光的方向主要順著光環圓弧排列，並推論出黑洞周圍磁場分布方式，進一步與過去眾多理論模型比對，發現符合天文物理界過去的認知，黑洞周圍強大磁場結構，確實扮演了黑洞噴流產生的重要角色。



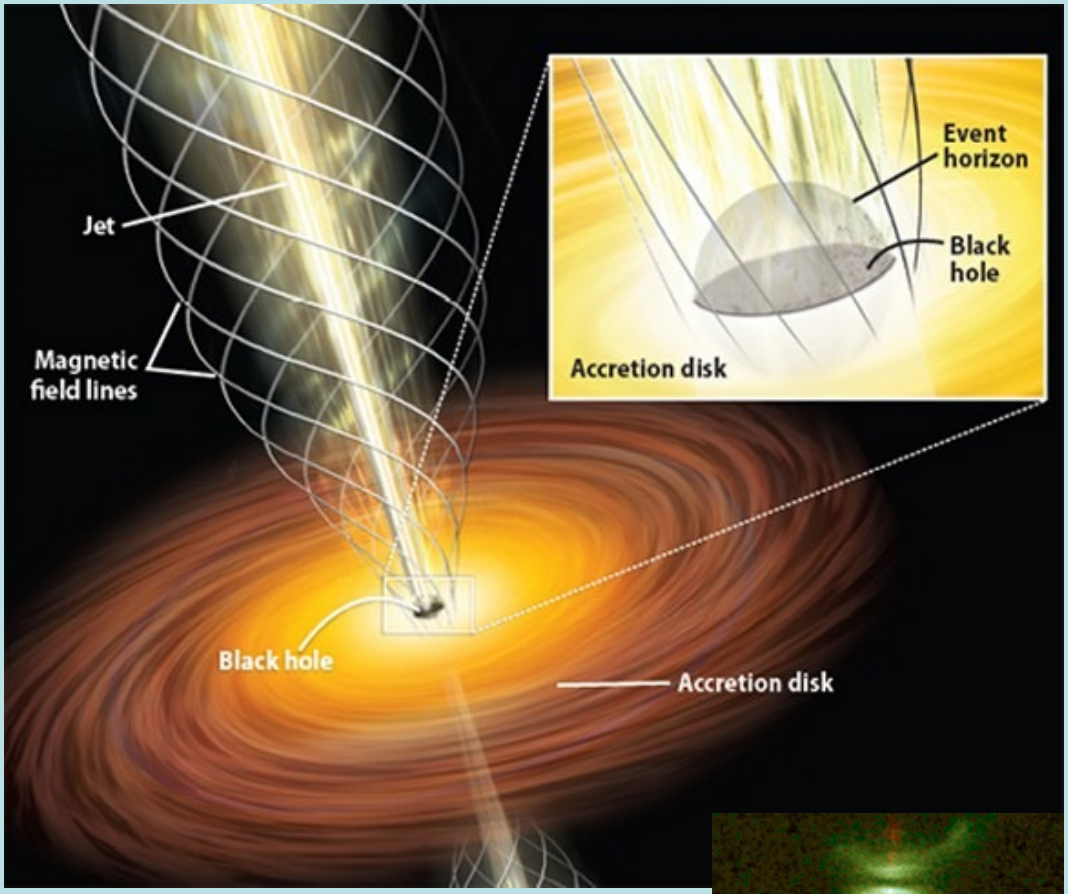
M87星系中心的偏振光影像，線條顯示與黑洞周圍有關的偏振方向。圖／事件視界望遠鏡提供

EHT理論模型工作小組協調人之一、台師大助理教授卜宏毅說，台灣的EHT團隊長期研究物質如何吸積到黑洞和黑洞噴流形

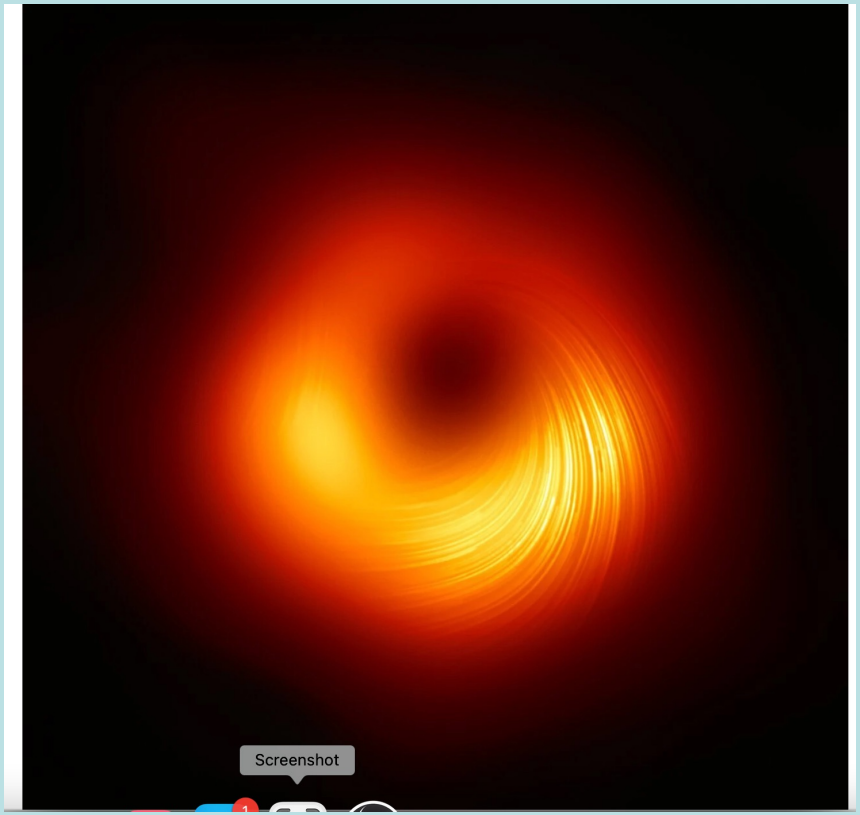
Screenshot

旋轉的黑洞一般會有磁場，會帶動物質形成速度極快的噴流！

Astrophysical Jets









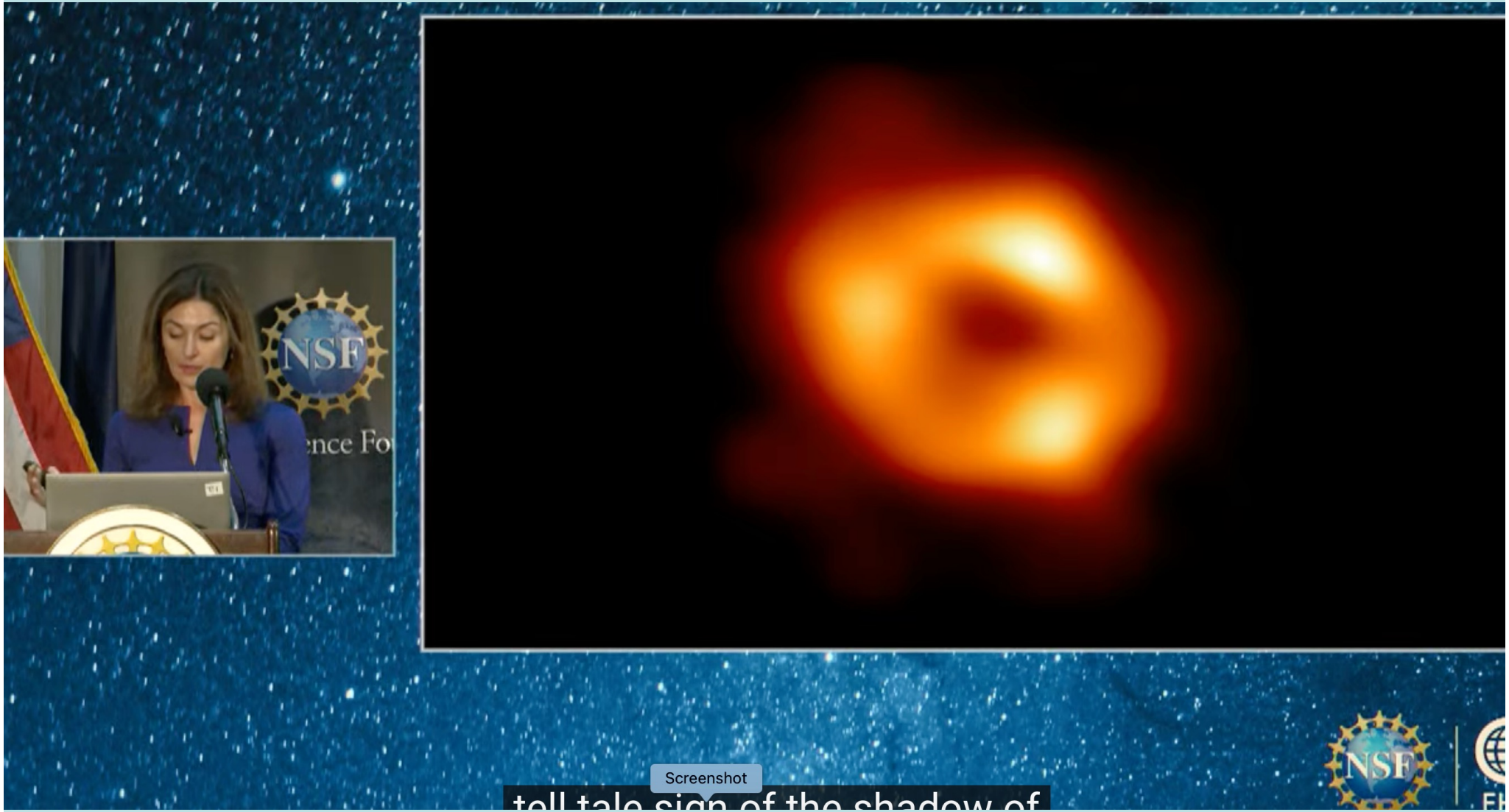
Event Horizon Telescope

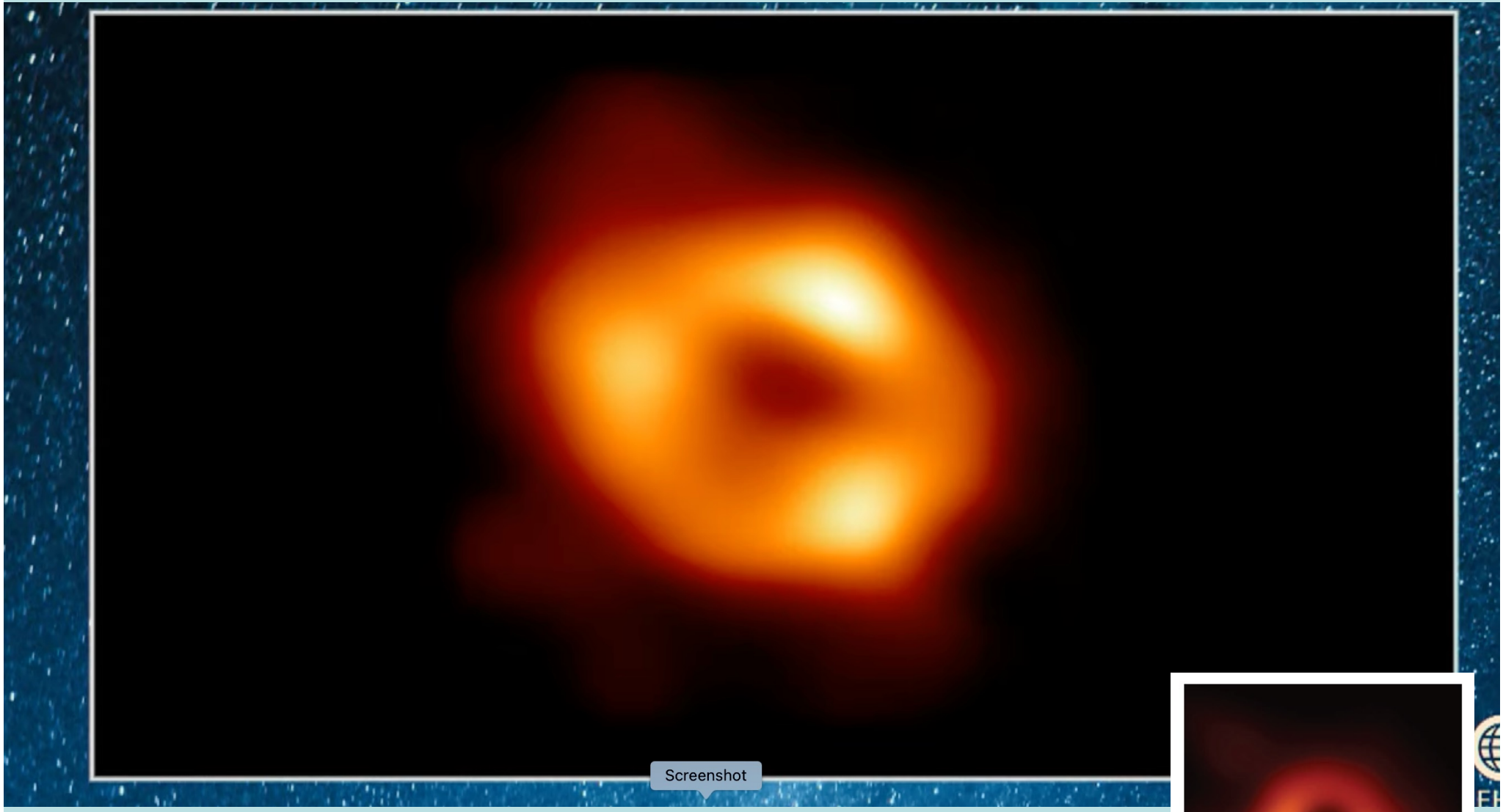
Event Horizon Telescope collaboration to announce groundbreaking Milky Way results on May 12th, 2022, at 13:00 UT

April 29, 2022

Simultaneous press conferences will announce groundbreaking results from the Event Horizon Telescope collaboration, those will be synchronised at 13:00 Universal Time on May 12th, 2022. Those will be held in collaboration with the USA National Science Foundation, the European Southern Observatory, the Joint ALMA Observatory, and other funding agencies and institutions. These events will also be streamed online. A selection of the events is listed, by alphabetical order of location (local times are provided).


中央研究院／科技部
聯合記者會
「事件視界望遠鏡國際合作計畫」全球記者會
【直播】
銀河系中心之重大科學發現
中央研究院
ACADEMIA SINICA
Event Horizon Telescope


NSF
Screenshot
tell tale sign of the shadow of



Screenshot



The iconic image of galaxy Messier 87's central black hole, showing a ring of photons bent by its gravity.

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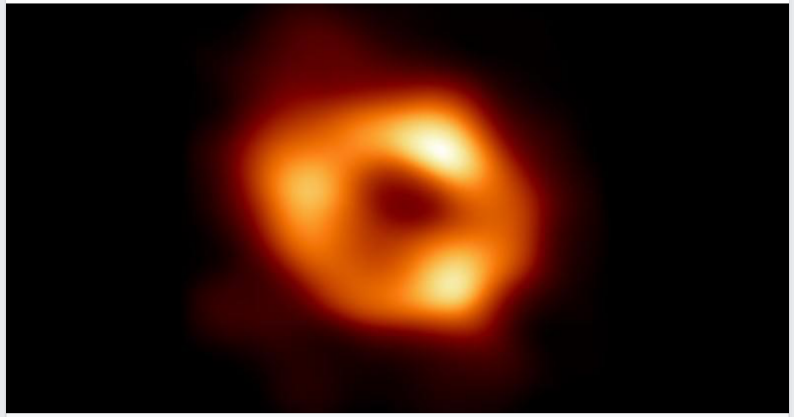
13小時 ·

The astronomers of the Event Horizon Telescope revealed the first image of Sagittarius A*, the supermassive black hole at the center of the Milky Way.



The astronomers of the Event Horizon Telescope revealed the first image of Sagittarius A*, the supermassive black hole at the center of the Milky Way.

rt Has Been Revealed

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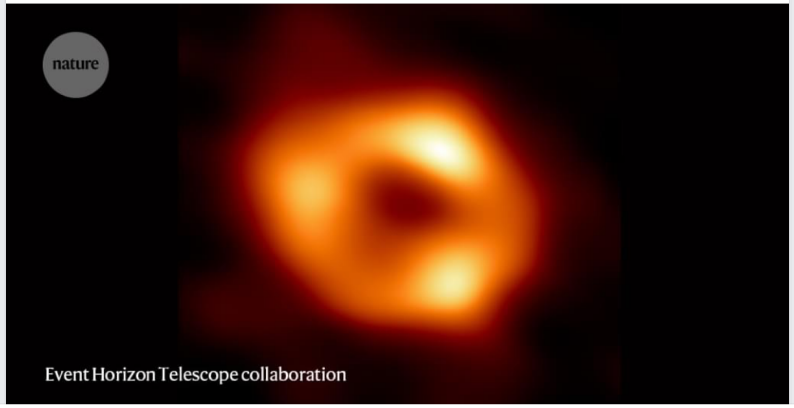
Nature
14小時 ·

The Event Horizon Telescope network has captured the second-ever direct image of a black hole — called Sagittarius A* — at the centre of the Milky Way. Read more about this amazing image



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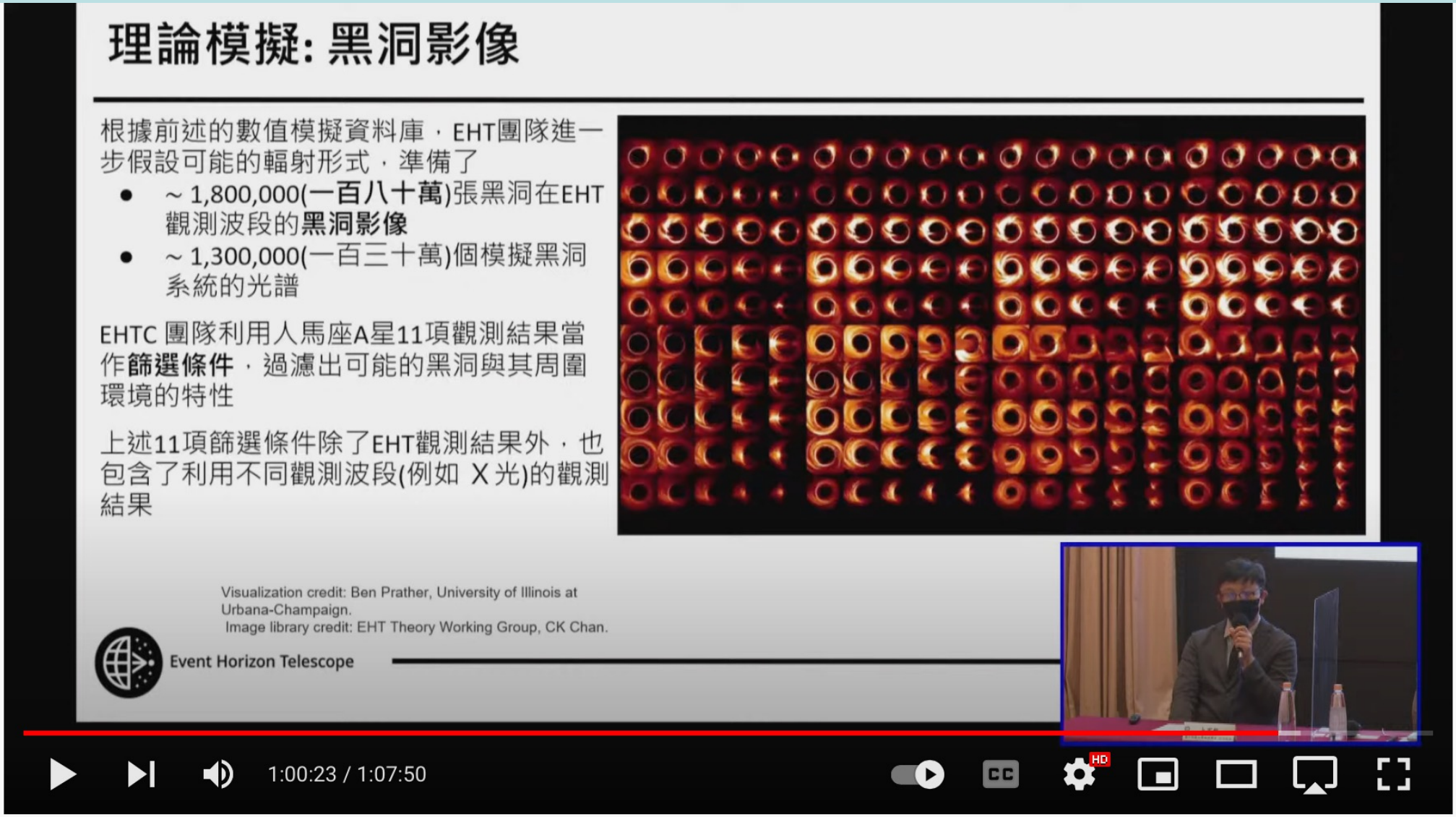

事件視界望遠鏡（Event Horizon Telescope, EHT）全球記者會──關於銀河系中心之重大研究成果發表

99,696 views • Streamed live on May 12, 2022

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First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way

The Event Horizon Telescope Collaboration
(See the end matter for the full list of authors.)
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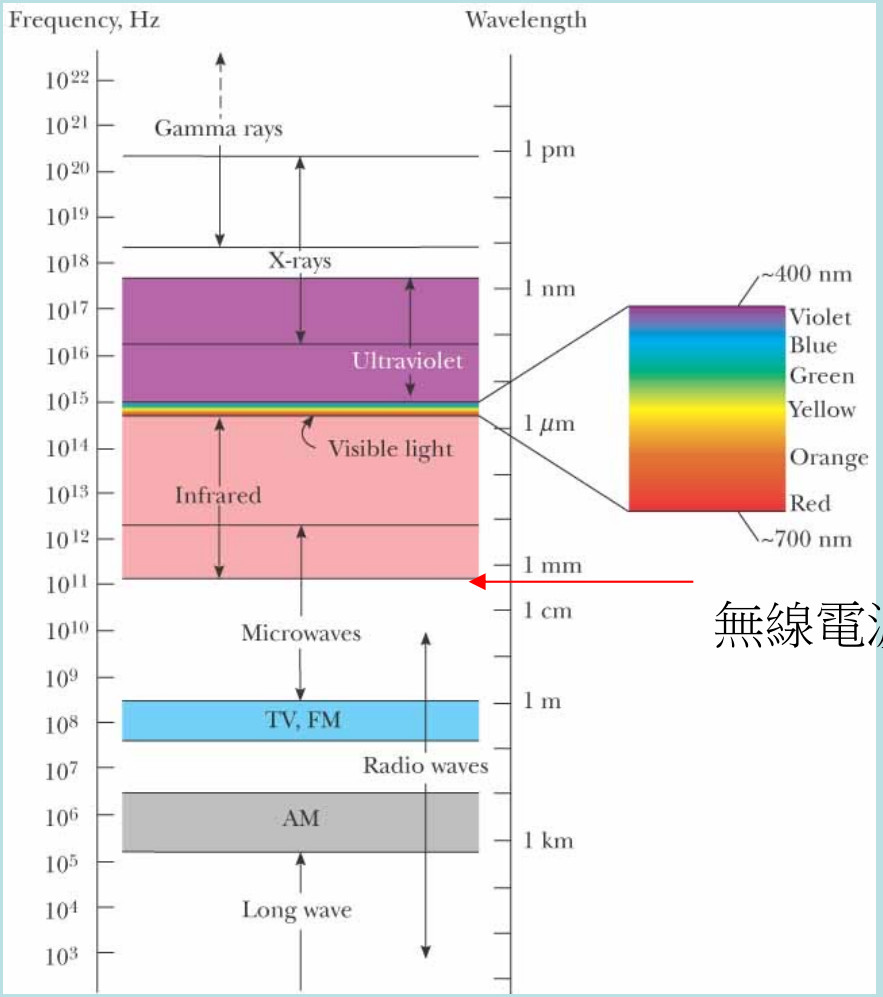
Abstract

We present the first Event Horizon Telescope (EHT) observations of Sagittarius A* (Sgr A*), the Galactic center source associated with a supermassive black hole. These observations were conducted in 2017 using a global interferometric array of eight telescopes operating at a wavelength of $\lambda = 1.3$ mm. The EHT data resolve a compact emission region with intrahour variability. A variety of imaging and modeling analyses all support an image that is dominated by a bright, thick ring with a diameter of 51.8 ± 2.3 μas (68% credible interval). The ring has modest azimuthal brightness asymmetry and a comparatively dim interior. Using a large suite of numerical simulations, we demonstrate that the EHT images of Sgr A* are consistent with the expected appearance of a Kerr black hole with mass $\sim 4 \times 10^6 M_\odot$, which is inferred to exist at this location based on previous infrared observations of individual stellar orbits, as well as maser proper-motion studies. Our model comparisons disfavor scenarios where the black hole is viewed at high inclination ($i > 50°$), as well as nonspinning black holes and those with retrograde accretion disks. Our results provide direct evidence for the presence of a supermassive black hole at the center of the Milky Way, and for the first time we connect the predictions from dynamical measurements of stellar orbits on scales of 10^3–10^5 gravitational radii to event-horizon-scale images and variability. Furthermore, a comparison with the EHT results for the supermassive black hole M87* shows consistency with the predictions of general relativity spanning over three orders of magnitude in central mass.

Unified Astronomy Thesaurus concepts: Black holes (162); Kerr black holes (886); Rotating black holes (1406); Heterodyne interferometry (726); Galactic center (565)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10^{3}
Gamma rays
X-rays
Ultraviolet
Visible light
Infrared
Microwaves
TV, FM
Radio waves
AM
Long wave
1 pm
1 nm
1 μm
1 mm
1 cm
1 m
1 km
~400 nm
Violet
Blue
Green
Yellow
Orange
Red
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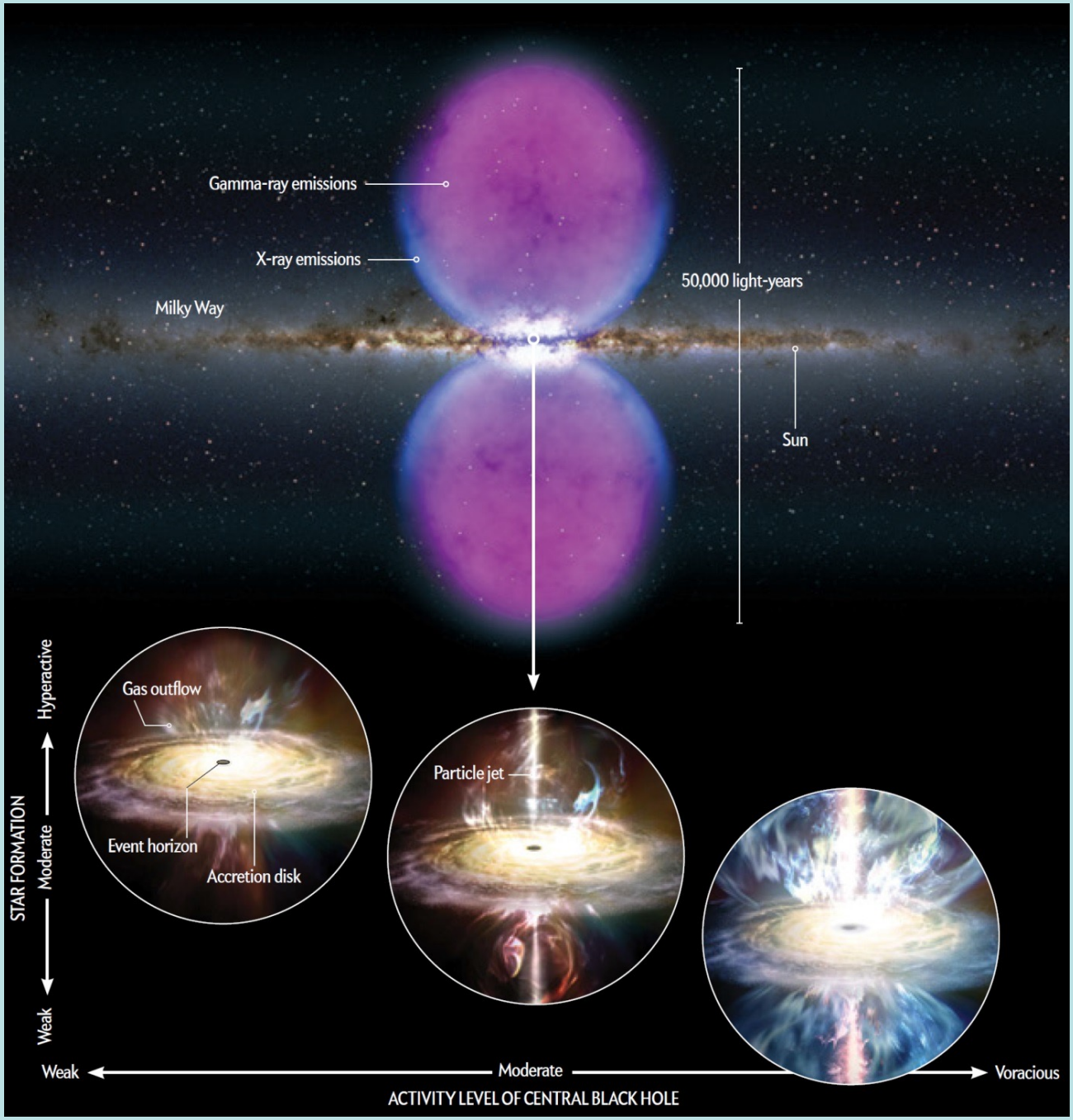
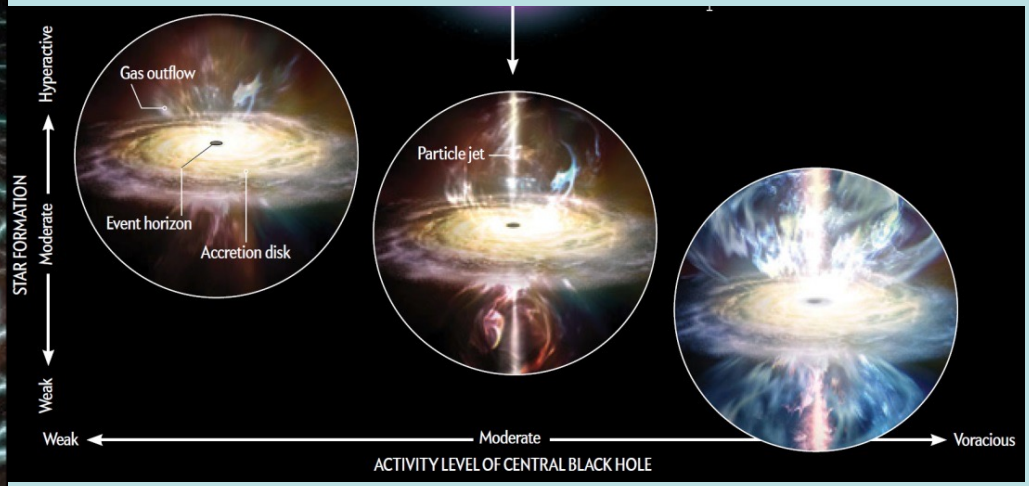
無線電波邊緣！

2010年發現銀河系中央的黑洞也有噴流

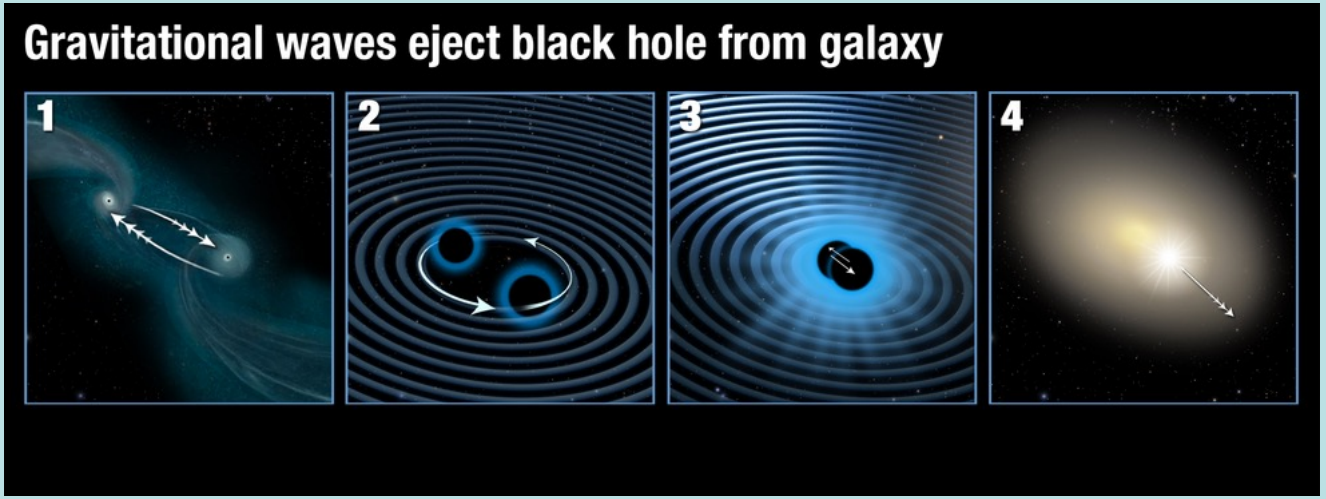


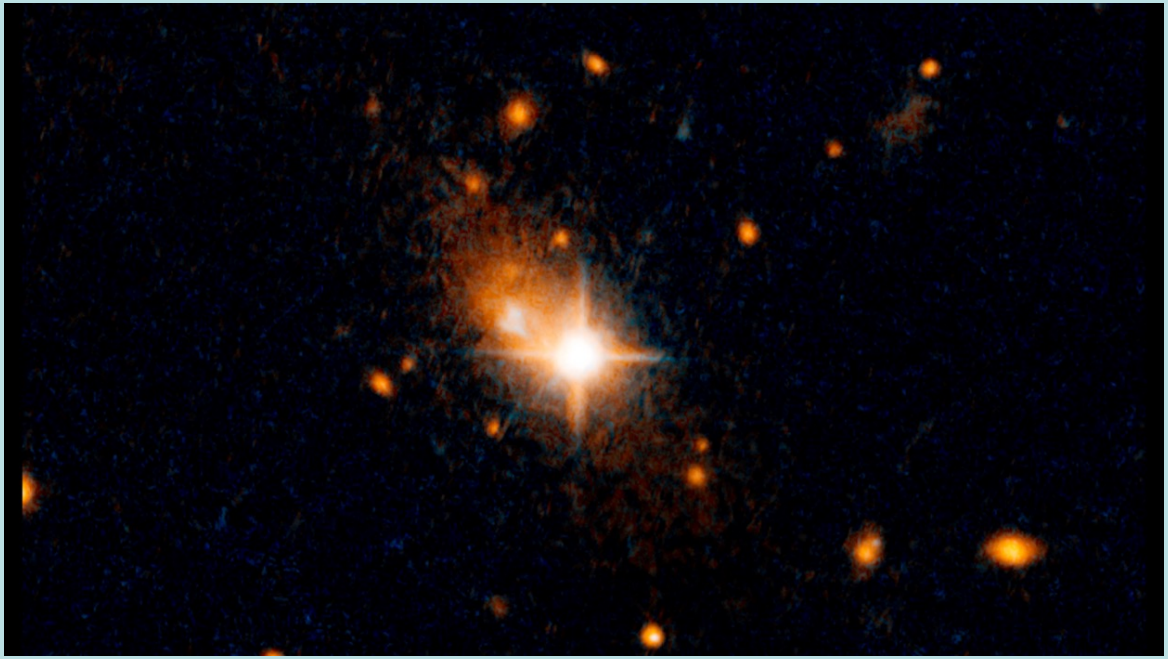
一個銀河中心的黑洞的行為將會劇烈影響整個銀河的生態！

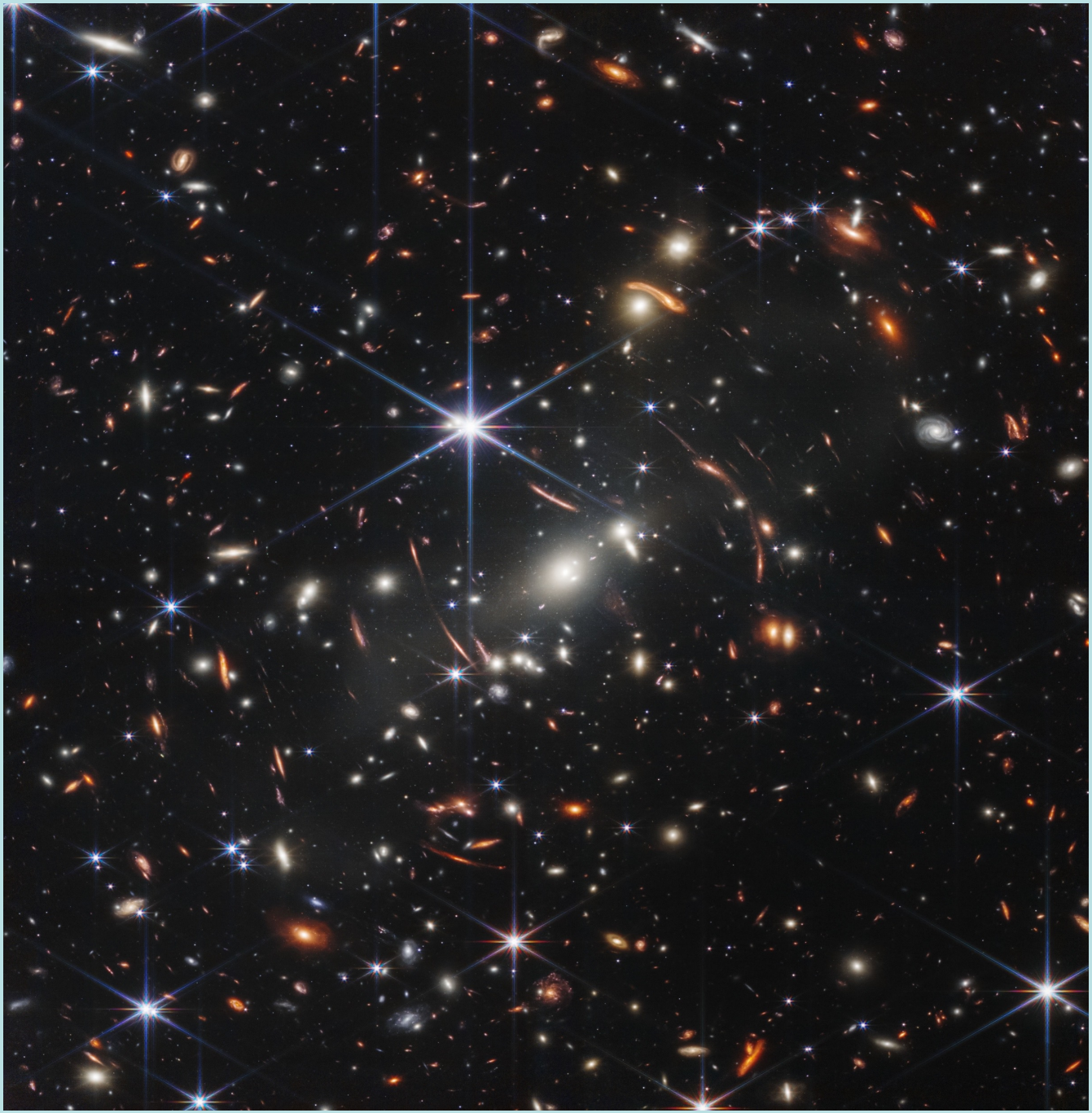




Gravitational Wave Kicks Monster Black Hole Out of Galactic Core







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。





第三張照片 南環星雲NGC 3132，距離2,500光年，星雲的中央有一頻死的恆星，正釋放出大量的塵埃與氣體，韋伯望遠鏡將能更細緻的解析氣體的成分與分佈。

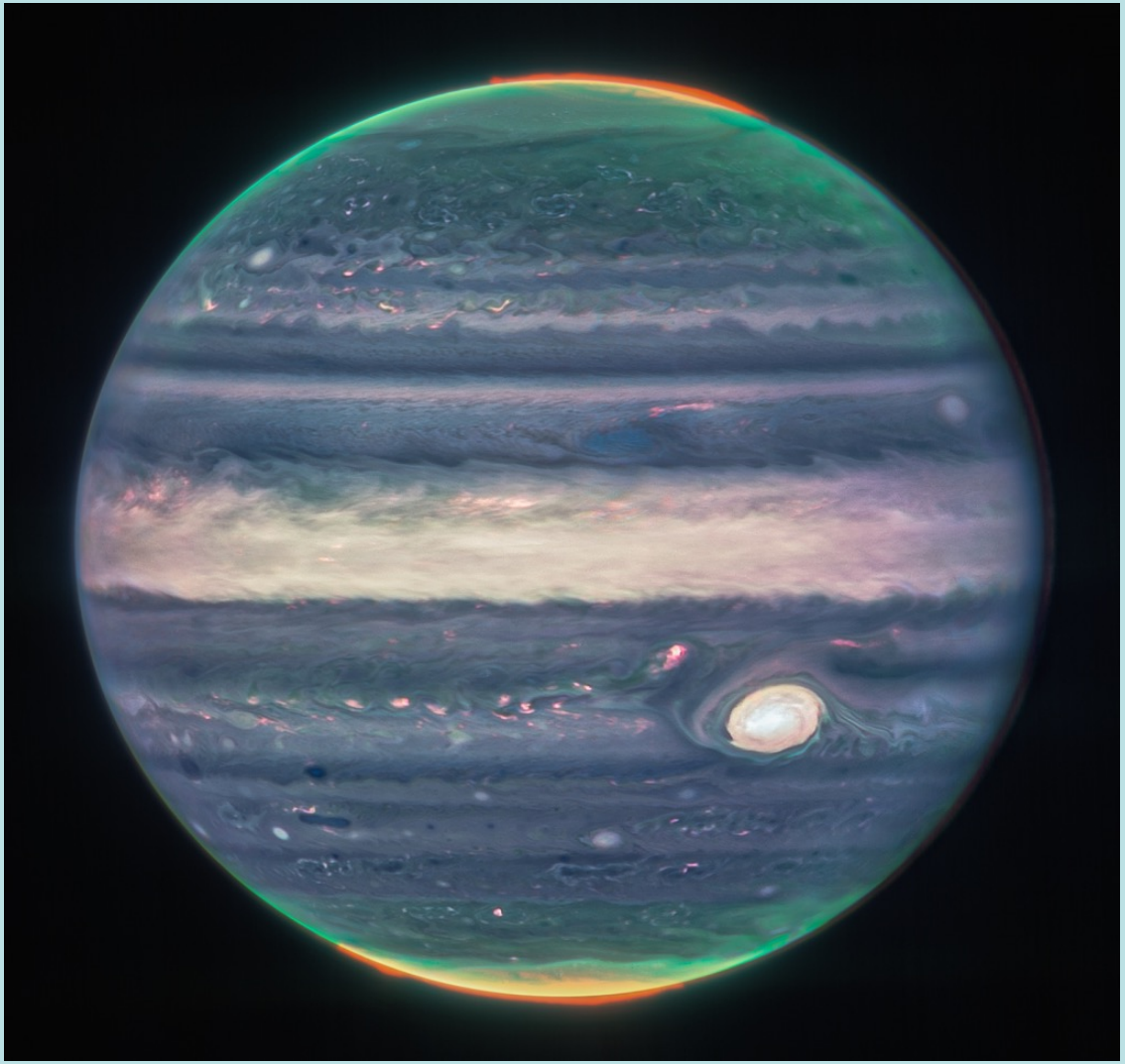


第四張照片史蒂芬五重奏，五個相互吸引的星系，顯示在早期宇宙，星系彼此的作用、碰撞引發星系的演化。韋伯望遠鏡可以解析在星系交會處，出現激烈的恆星生成，以及大量氣體噴發。這張照片是由將近一千張影像拼接而成，是韋伯至今最大的照片。範圍達到滿月半徑的五分之一。

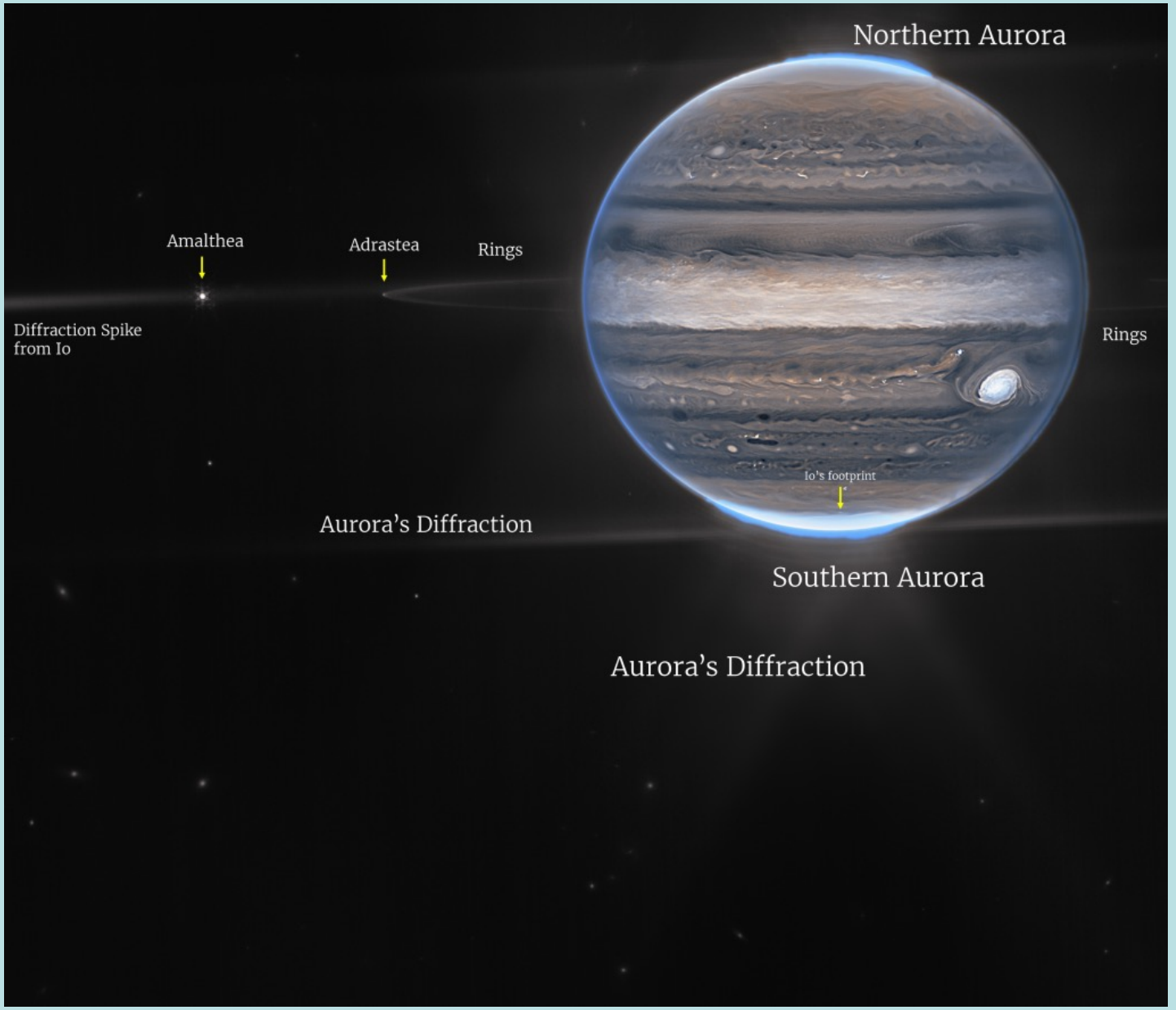


第五張照片：NGC 3324內的船底座星雲，這是大量年輕恆星的誕生地。星雲的邊緣看來如同懸崖，這是由上方圖片外，極重極熱的新生成恆星，所發出的強烈紫外線與星際風，所推擠造成。


Hubble
Webb



Webb NIRCam composite image of Jupiter from three filters – F360M (red), F212N (yellow-green), and F150W2 (cyan) – and alignment due to the planet's rotation. Credit: NASA


Northern Aurora
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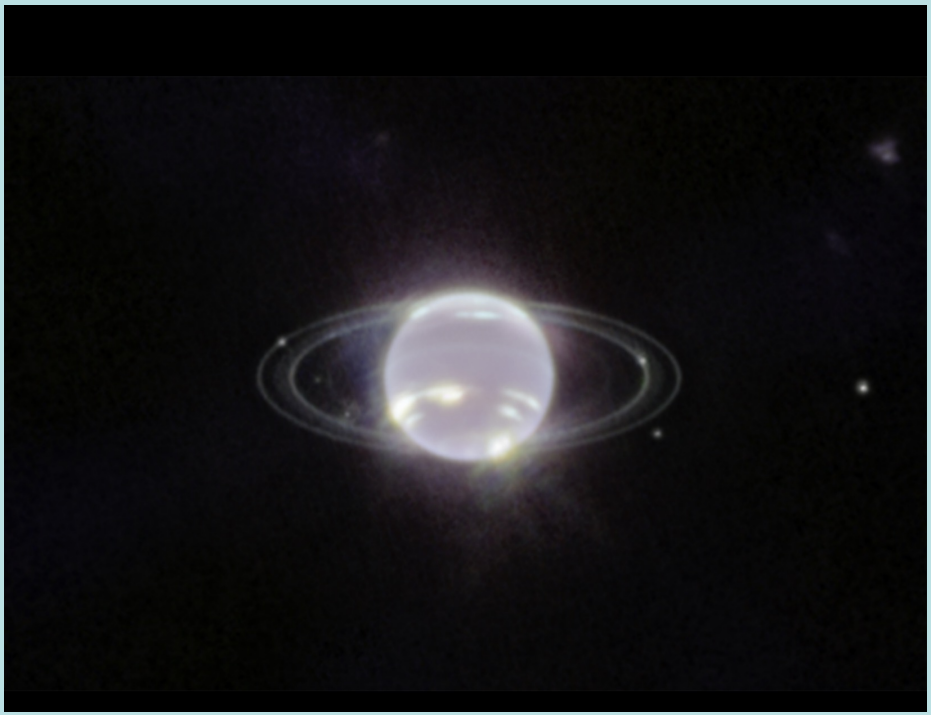
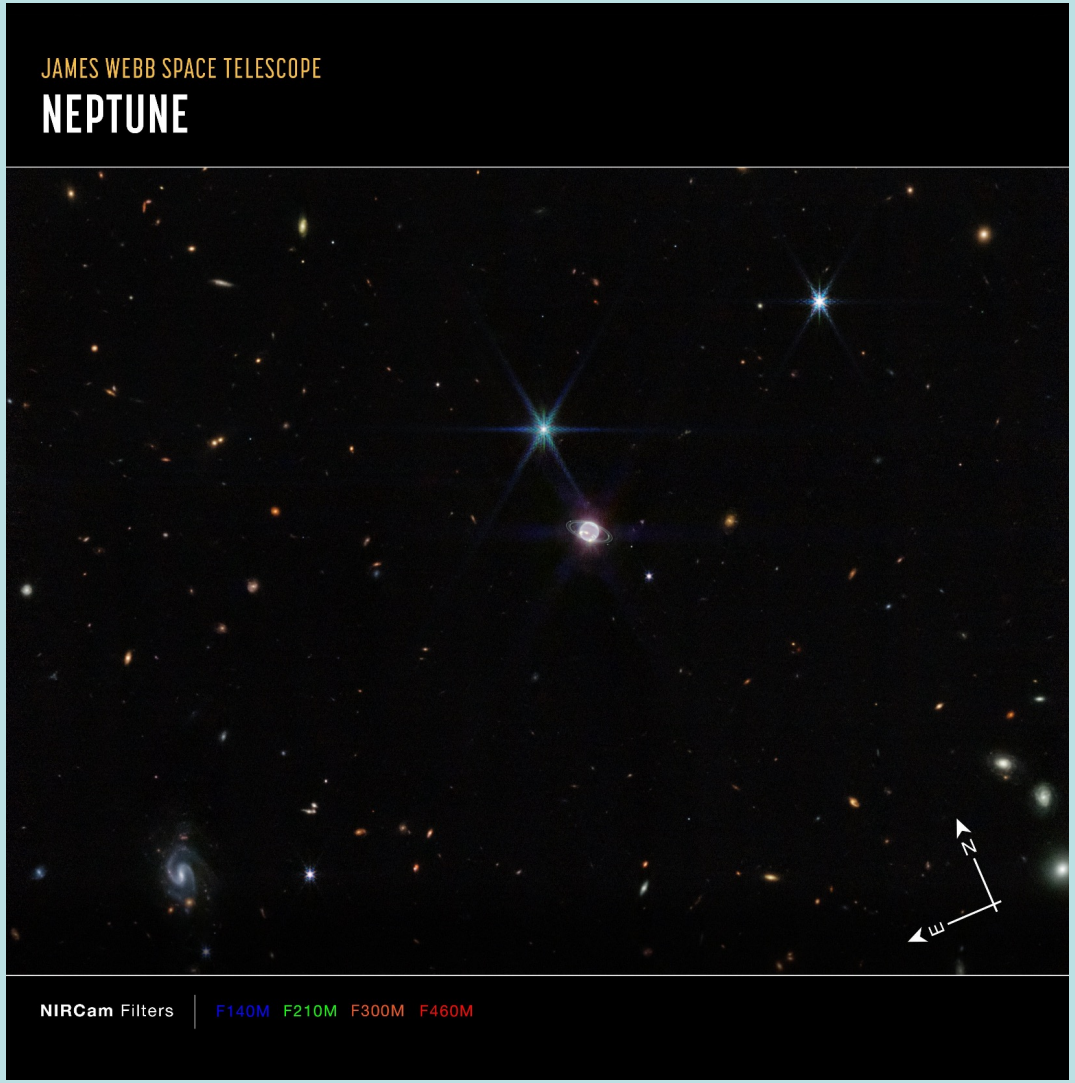
Rings
Diffraction Spike
from Io
Rings
Io's footprint
Aurora's Diffraction
Southern Aurora
Aurora's Diffraction



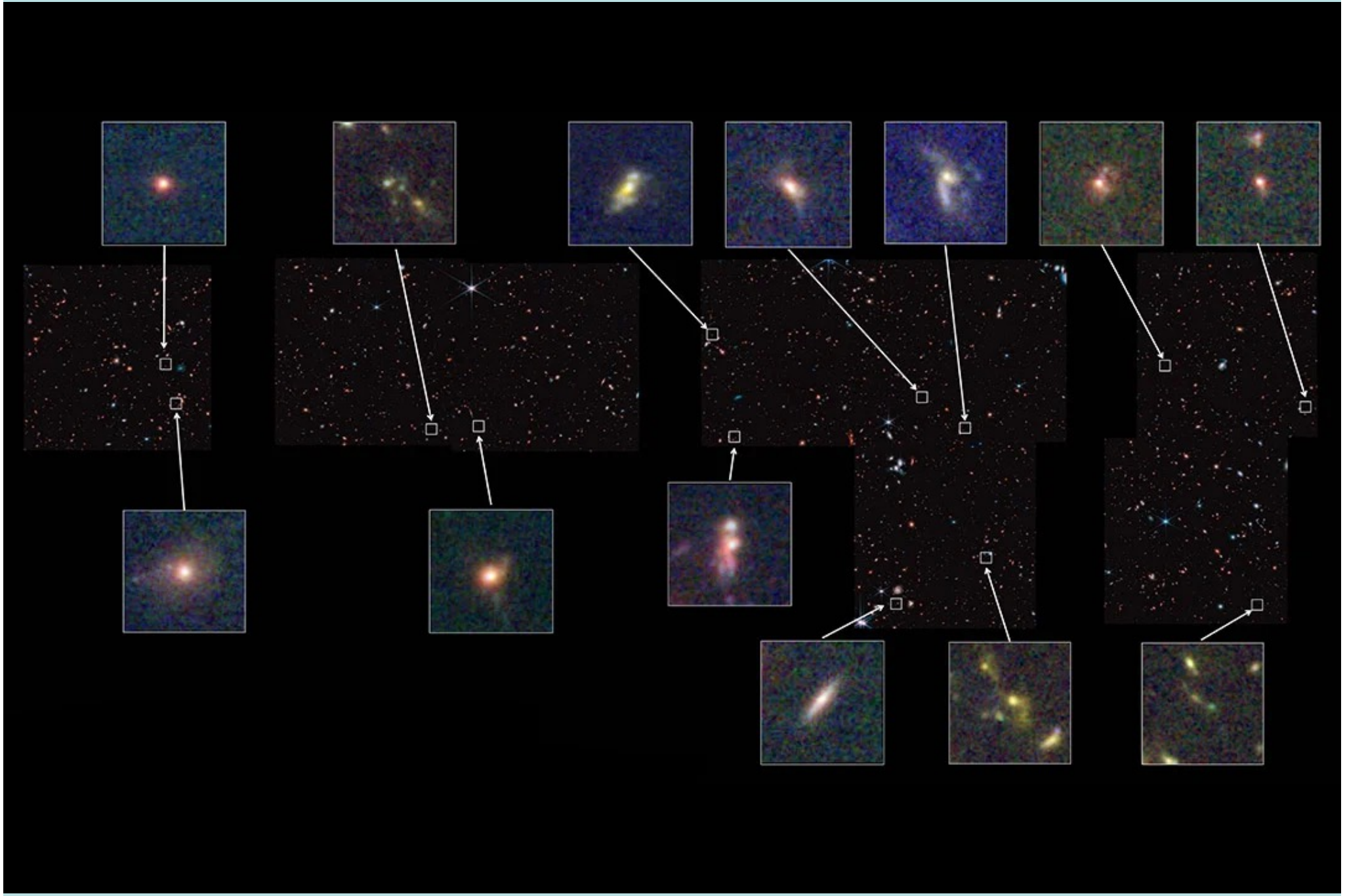
Neptune


JAMES WEBB SPACE TELESCOPE
NEPTUNE
N
E
NIRCam Filters
F140M F210M F300M F460M



週年紀念照

The first anniversary image from NASA's James Webb Space Telescope displays star birth like it's never been seen before, full of detailed, impressionistic texture. The subject is the Rho Ophiuchi cloud complex, the closest star-forming region to Earth. It is a relatively small, quiet stellar nursery, but you'd never know it from Webb's chaotic close-up. Jets bursting from young stars crisscross the image, impacting the surrounding interstellar gas and lighting up molecular hydrogen, shown in red. Some stars display the telltale shadow of a circumstellar disk, the makings of future planetary systems.



JWST's First Glimpses of Early Galaxies Could Break Cosmology

The James Webb Space Telescope's first images of the distant universe shocked astronomers. Is the discovery of unimaginably distant galaxies a mirage or a revolution?

By Jonathan O'Callaghan on September 14, 2022

Astronomers Grapple with JWST's Discovery of Early Galaxies

Researchers are convinced the James Webb Space Telescope has glimpsed an unexpected population of galaxies in the early universe. Now they're trying to decide what this means for our understanding of the cosmos

By Jonathan O'Callaghan on December 6, 2022 أعرض هذا باللغة العربية

JWST's Newfound Galaxies Are the Oldest Ever Seen

We now know that the first galaxies in our universe formed shockingly fast, thanks to the latest results from the James Webb Space Telescope

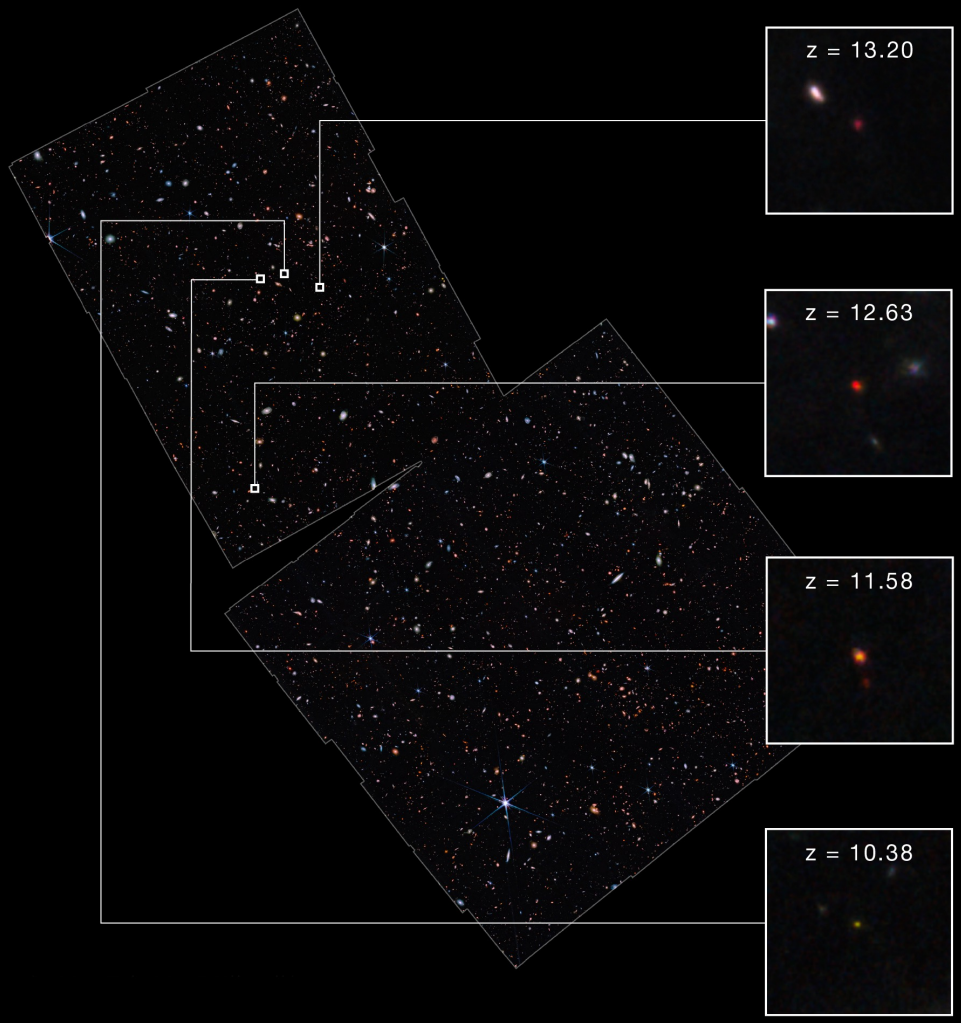
By Jonathan O'Callaghan on April 13, 2023

JWST ADVANCED DEEP EXTRAGALACTIC SURVEY (JADES)

WEBB SPECTRA REACH NEW MILESTONE IN REDSHIFT FRONTIER

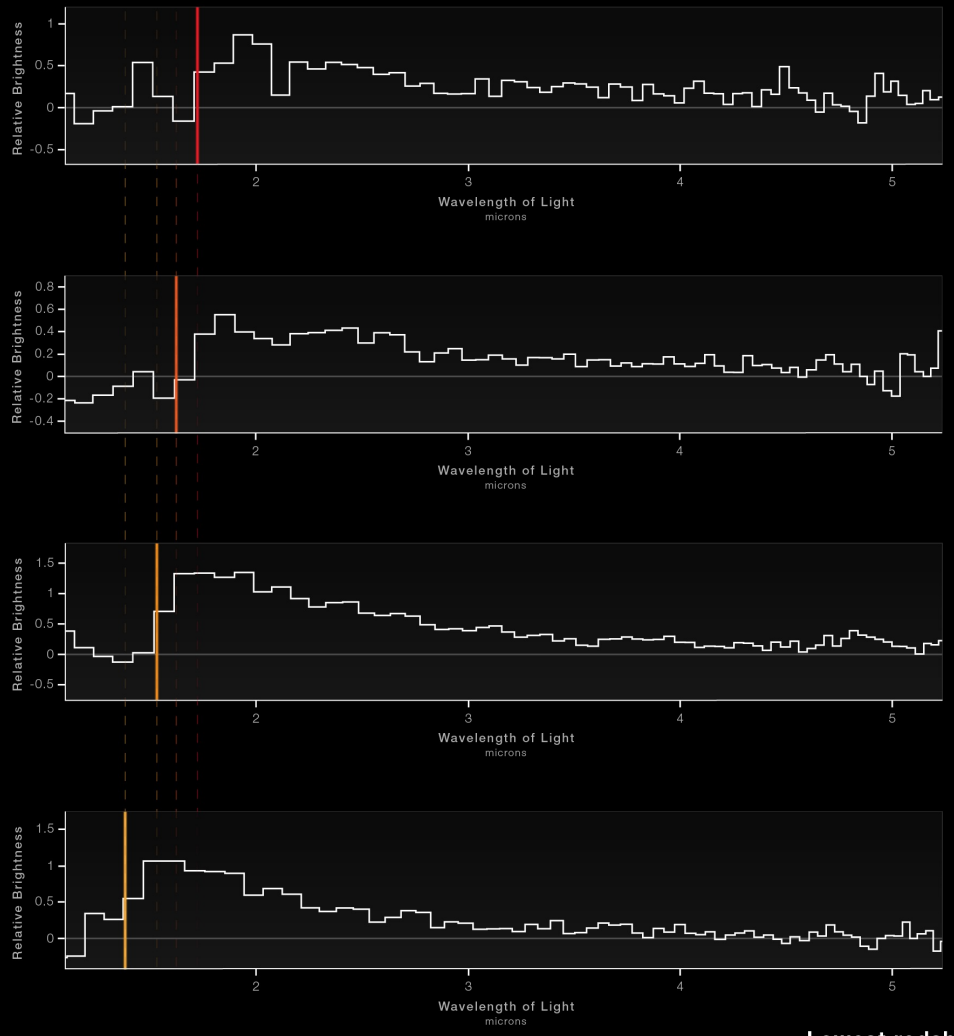
NIRCam Imaging

NIRSpec Microshutter Array Spectroscopy



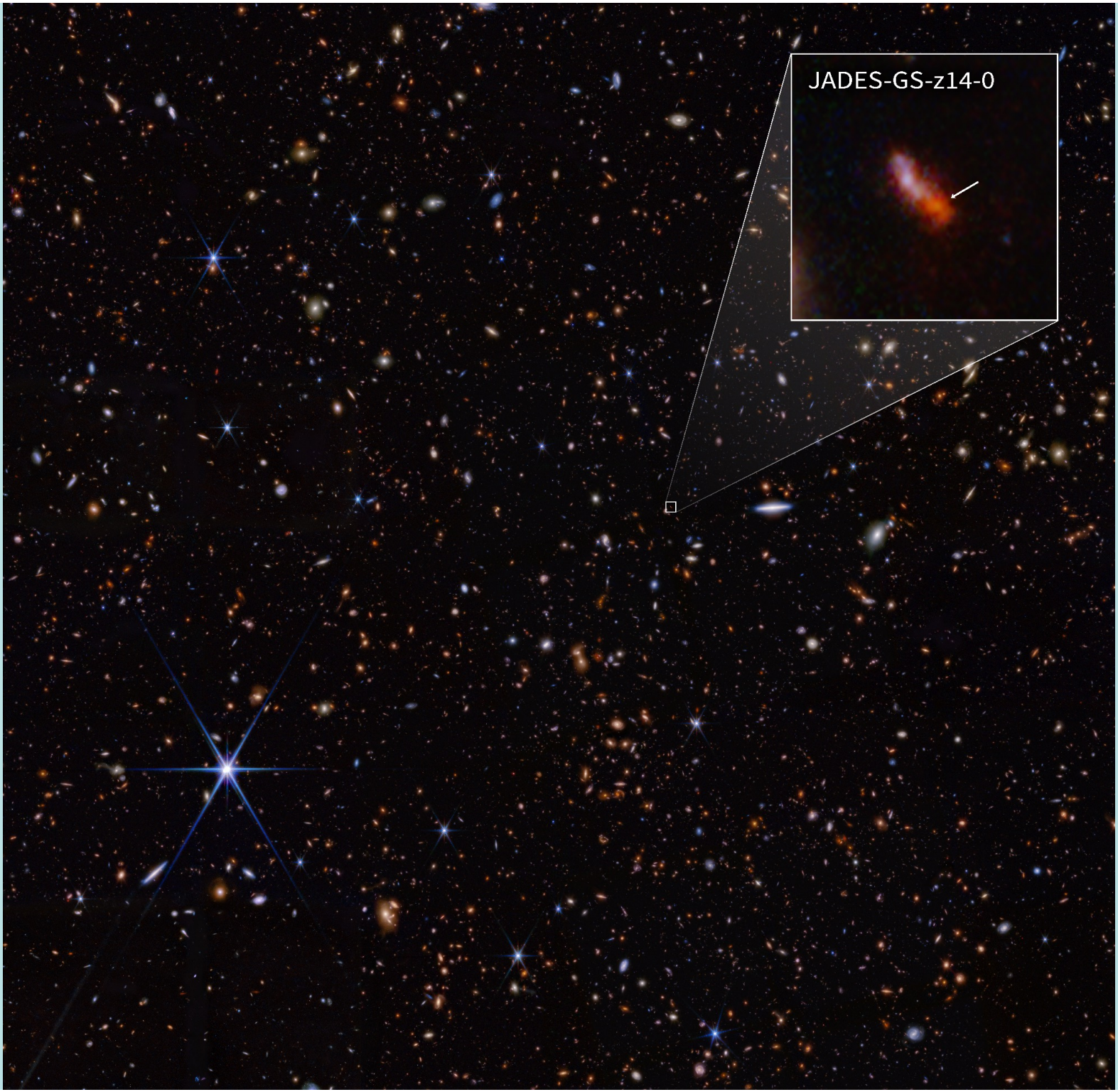
Highest redshift

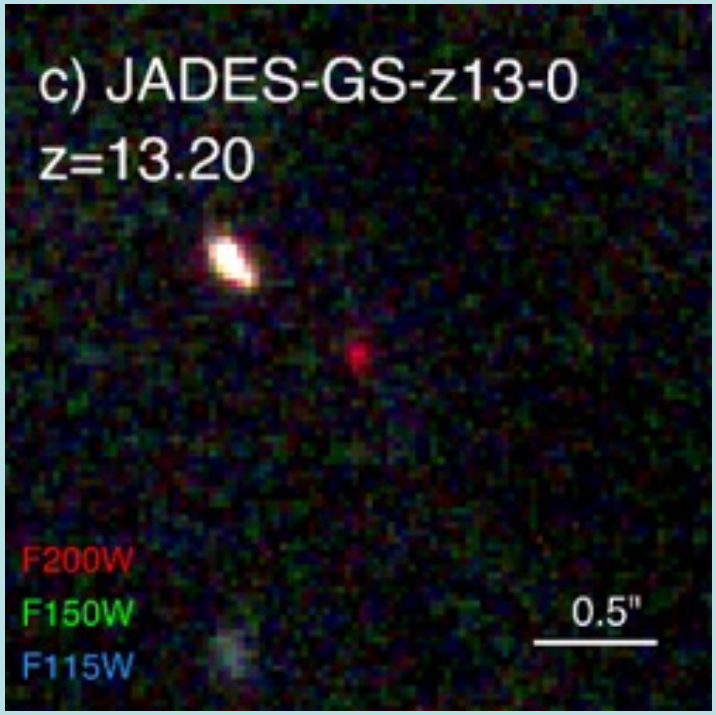
Lyman break



Lowest redshift

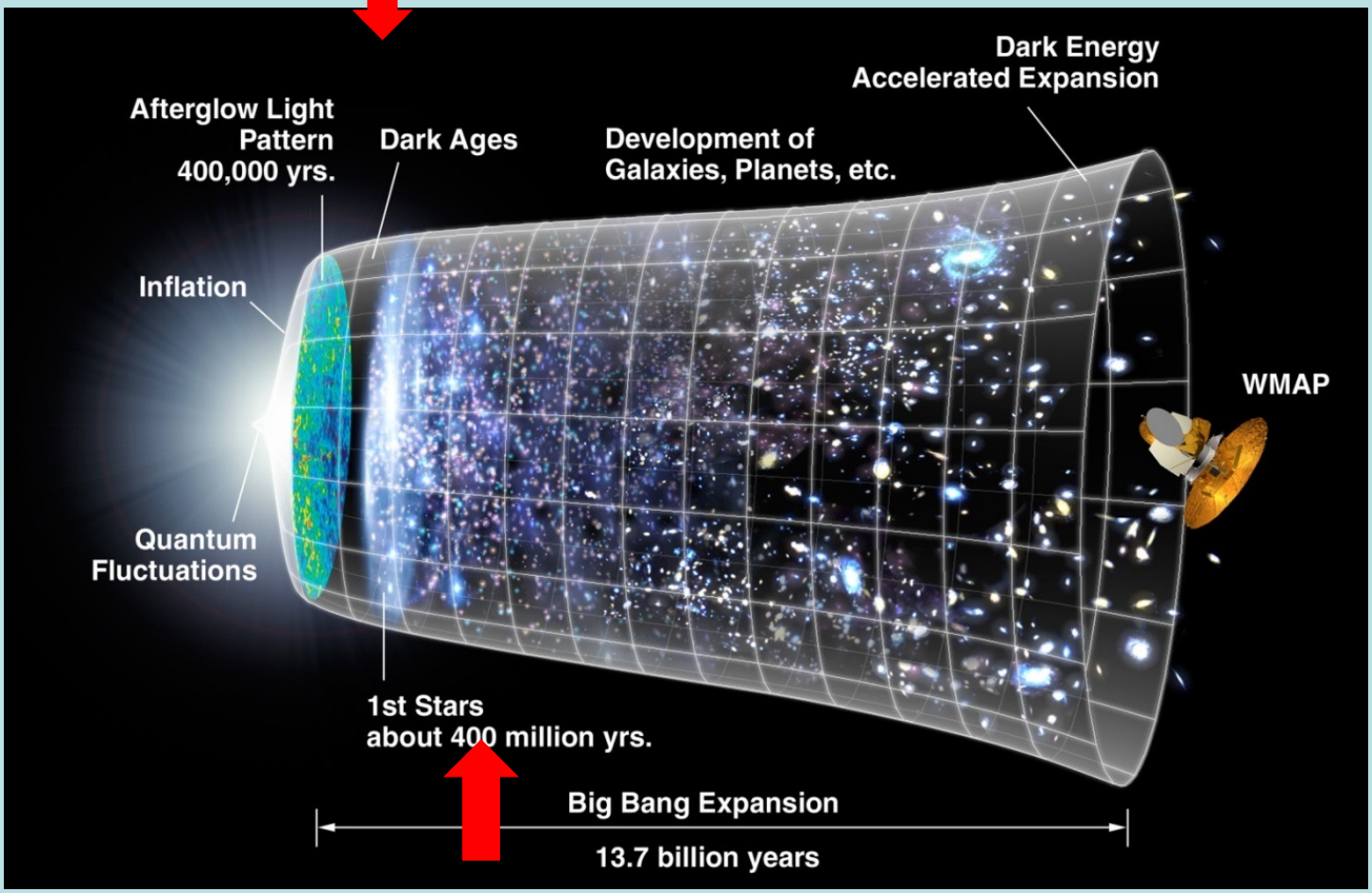
WEBB
SPACE TELESCOPE


JADES-GS-z14-0



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

JADES-GS-z13-0



我們竟然在宇宙論預測第一個恆星生成的霹靂後4億年之前的3億年找到星系。

JWST's First Glimpses of Early Galaxies Could Break Cosmology

3 Years of Science: 10 Cosmic Surprises from NASA's Webb Telescope

Since July 2022, NASA's James Webb Space Telescope has been unwaveringly focused on our universe. With its unprecedented power to detect and analyze otherwise invisible infrared light, Webb is making observations that were once impossible, changing our view of the cosmos from the most distant galaxies to our own solar system.

Webb was built with the promise of revolutionizing astronomy, of rewriting the textbooks. And by any measure, it has more than lived up to the hype — exceeding expectations to a degree that scientists had not dared imagine. Since science operations began, Webb has completed more than 860 scientific programs, with one-quarter of its time dedicated to imaging and three-quarters to spectroscopy. In just three years, it has collected nearly 550 terabytes of data, yielding more than 1,600 research papers, with intriguing results too numerous to list and a host of new questions to answer.

Here are just a few noteworthy examples.

1. The universe evolved significantly faster than we previously thought.

1. The universe evolved significantly faster than we previously thought.

Webb was specifically designed to observe "cosmic dawn," a time during the first billion years of the universe when the first stars and galaxies were forming. What we expected to see were a few faint galaxies, hints of what would become the galaxies we see nearby.

Instead, Webb has revealed surprisingly bright galaxies that developed within 300 million years of the big bang; galaxies with black holes that seem far too massive for their age; and an infant Milky Way-type galaxy that existed when the universe was just 600 million years old. Webb has observed galaxies that already "turned off" and stopped forming stars within a billion years of the big bang, as well as those that developed quickly into modern-looking "grand design" spirals within 1.5 billion years.

Hundreds of millions of years might not seem quick for a growth spurt, but keep in mind that the universe formed in the big bang roughly 13.8 billion years ago. If you were to cram all of cosmic time into one year, the most distant of these galaxies would have matured within the first couple of weeks, rapidly forming multiple generations of stars and enriching the universe with the elements we see today.



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

2. Deep space is scattered with enigmatic “Little Red Dots.”

Webb has revealed a new type of galaxy: a distant population of mysteriously compact, bright, red galaxies dubbed Little Red Dots. What makes Little Red Dots so bright and so red? Are they lit up by dense groupings of unusually bright stars or by gas spiraling into a supermassive black hole, or both? And whatever happened to them? Little Red Dots seem to have appeared in the universe around 600 million years after the big bang (13.2 billion years ago), and rapidly declined in number less than a billion years later. Did they evolve into something else? If so, how? Webb is probing Little Red Dots in more detail to answer these questions.

3. Pulsating stars and a triply lensed supernova are further evidence that the “Hubble Tension” is real.

How fast is the universe expanding? It’s hard to say because different ways of calculating the current expansion rate yield different results — a dilemma known as the Hubble Tension. Are these differences just a result of measurement errors, or is there something weird going on in the universe? So far, Webb data indicates that the Hubble Tension is not caused by measurement errors. Webb was able to distinguish pulsating stars from nearby stars in a crowded field, ensuring that the measurements weren’t contaminated by extra light. Webb also discovered a distant, gravitationally lensed supernova whose image appears in three different locations and at three different times during its explosion. Calculating the expansion rate based on the brightness of the supernova at these three different times provides an independent check on measurements made using other techniques. Until the matter of the Hubble Tension is

OBS

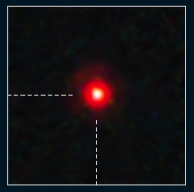
ed, Webb will continue measuring different objects and exploring new methods.

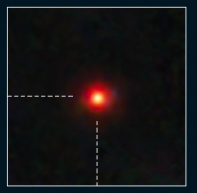
ASTRONOMY

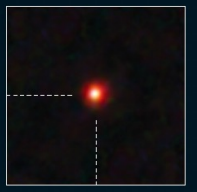
Little Red Dots

Astronomers are racing to understand mysterious ancient objects that pepper images taken by the James Webb Space Telescope BY REBECCA BOYLE













Screenshot

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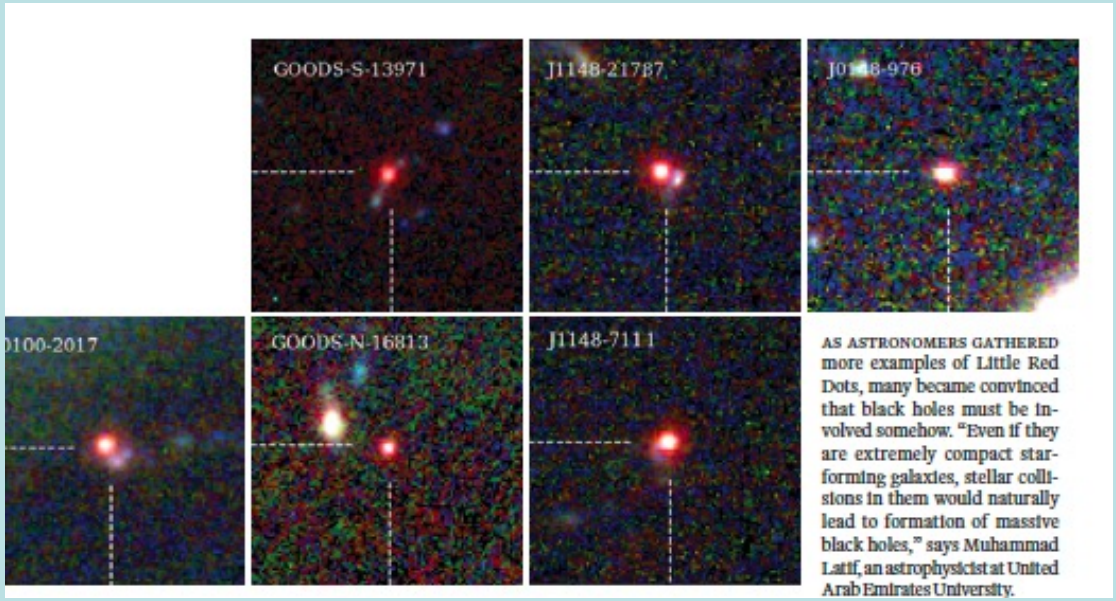
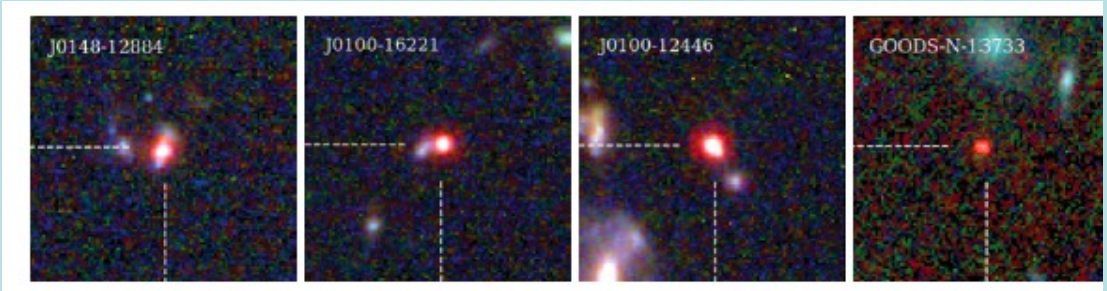
In these James Webb Space Telescope (JWST) images, the black hole star stands out as a little red dot. Such little red dots are extremely common in JWST images.

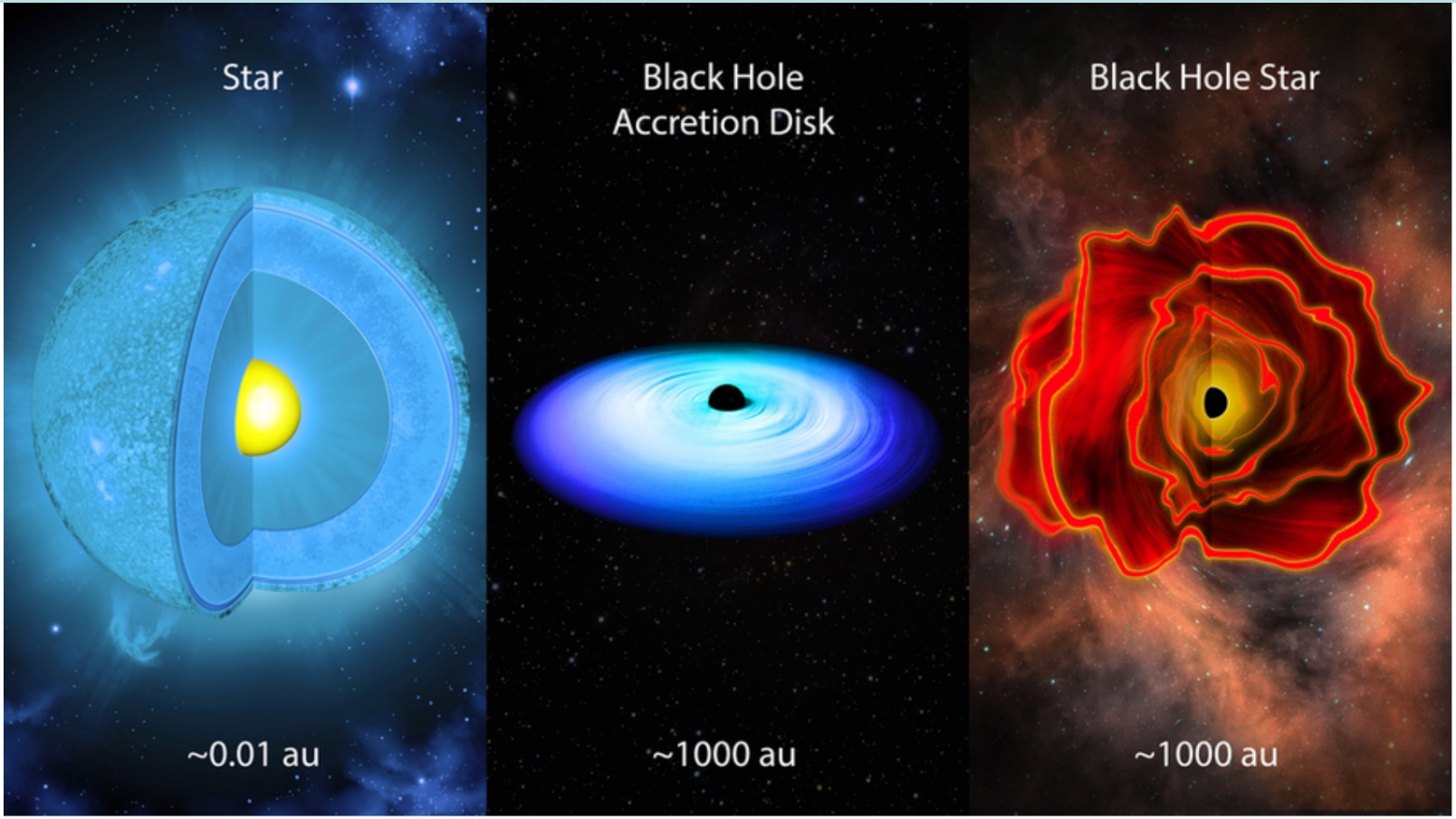
Image: Courtesy of the researchers

Screenshot



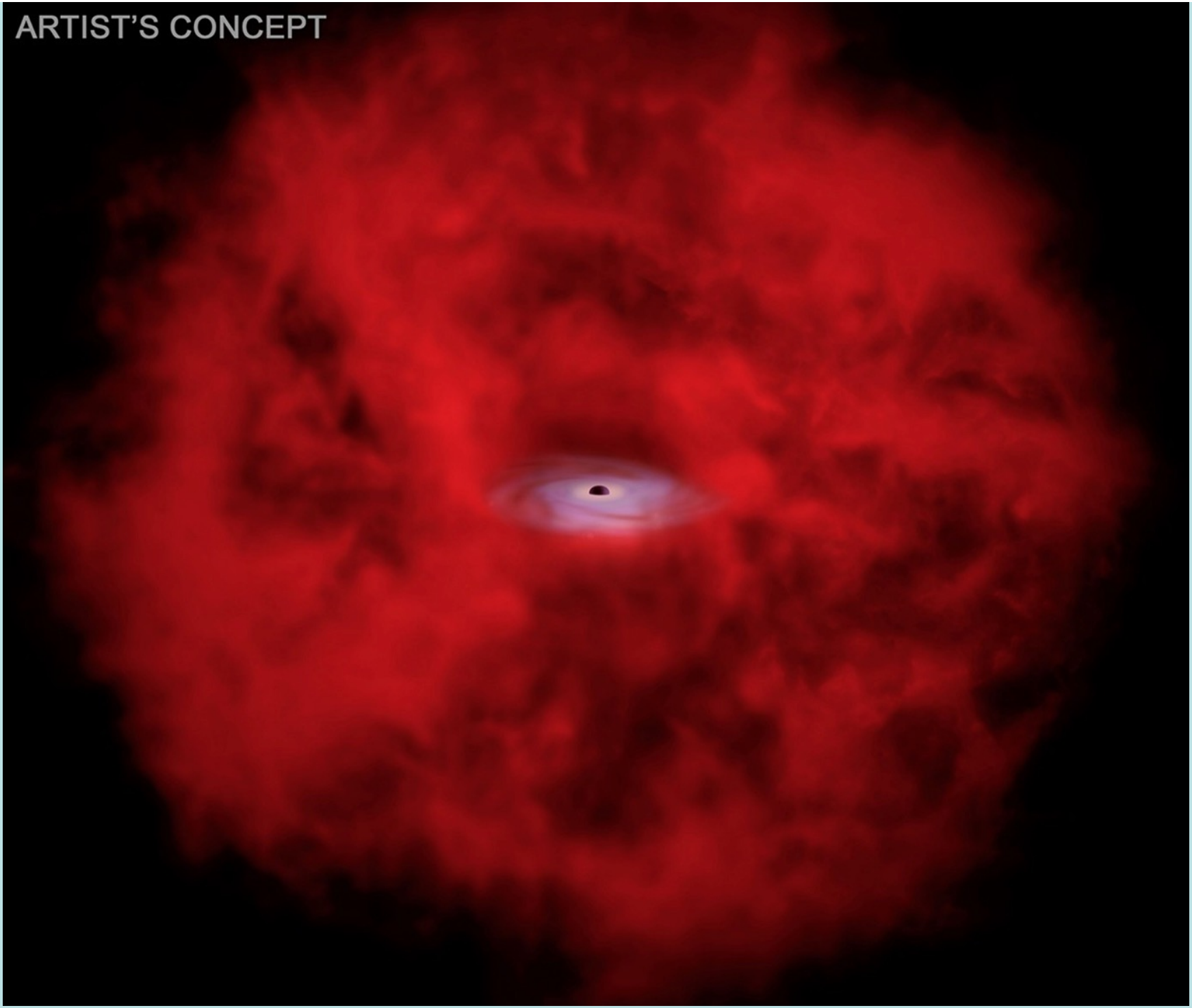
AS ASTRONOMERS GATHERED more examples of Little Red Dots, many became convinced that black holes must be involved somehow. "Even if they are extremely compact star-forming galaxies, stellar collisions in them would naturally lead to formation of massive black holes," says Muhammad Latif, an astrophysicist at United Arab Emirates University.





Stars (left) can be thought of as a dense ball of gas powered by nuclear fusion at their centers. Black holes (center) typically grow by consuming matter via a pancake-like accretion disk. Black hole stars (right) represent a new kind of object — nascent black holes enshrouded in dense gas such that they effectively radiate in a star-like manner. The accreting black hole, as the power source, plays the role of nuclear fusion, and the dense surrounding gas acts similarly to a pseudo photosphere.

Screenshot

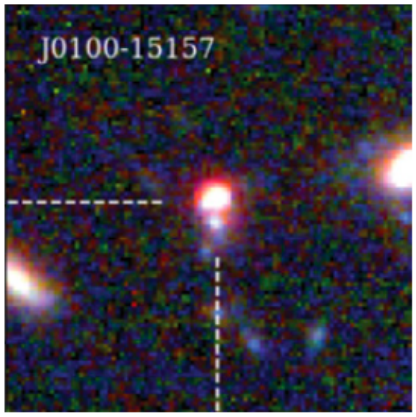

ARTIST'S CONCEPT

WHEN ASTRONOMERS GLIMPSED the first images from the James Webb Space Telescope (JWST) in July 2022, they saw the kind of universe most of them have come to expect. There were dazzling blue bursts of light, glowing trails of stardust, curtains of gas backlit by the birth of stars.

But things got weird very quickly. Almost every new image showed mysterious, tiny red points. The spots were extremely compact, very bright and distinctly red. There were so many of them. Everywhere JWST looked, the telescope found at least one specimen of what are now commonly called Little Red Dots (LRDs).

Astronomers quickly dated the dots to about 600 million years after the big bang, which means their light traveled almost the entire lifetime of the universe before arriving in JWST's honeycomblike hexagonal mirrors. The dots were everywhere, until they were nowhere; about 1.5 billion years after the big bang, they mostly disappear.

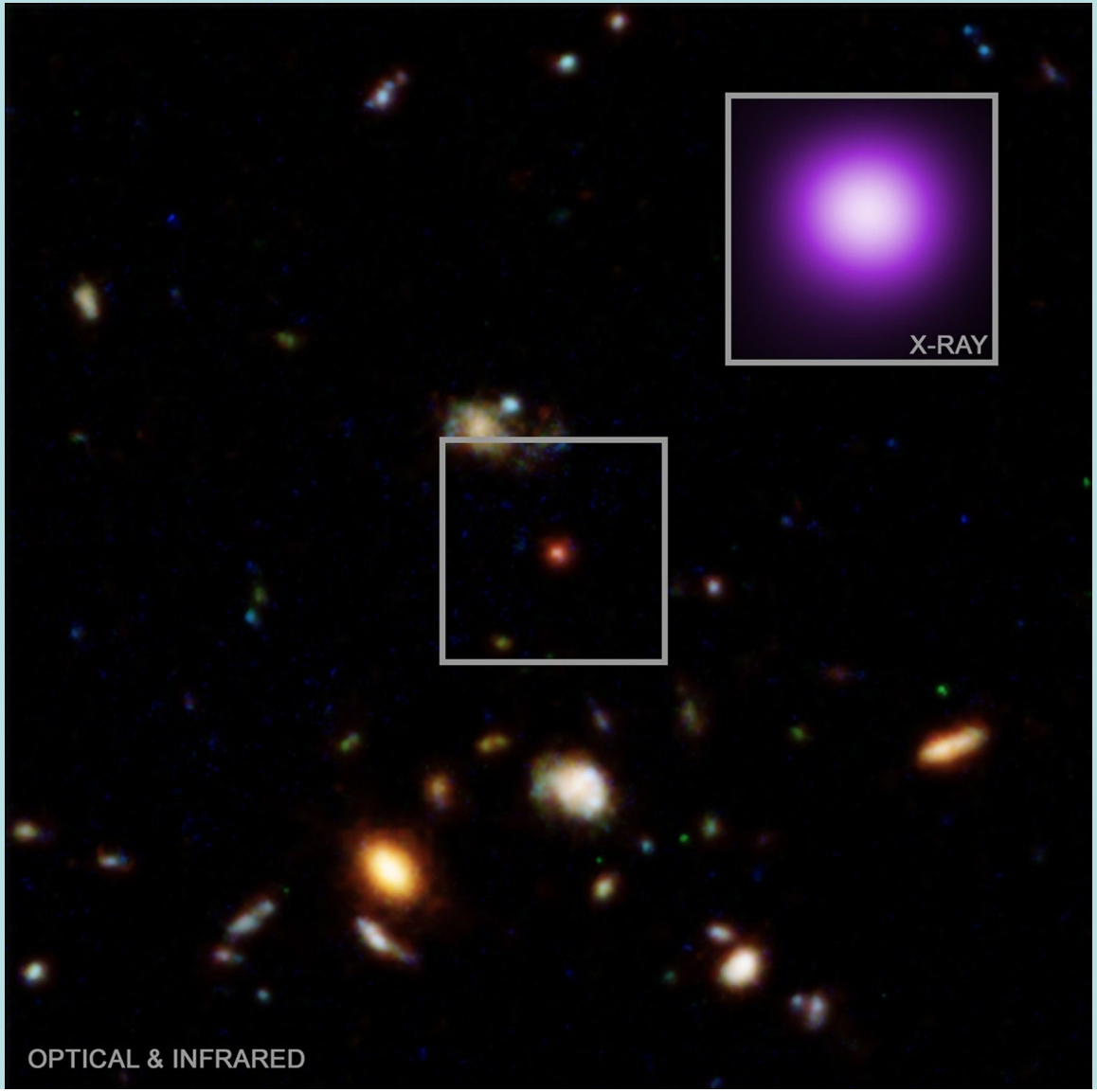
The age, size and sheer number of the Little Red Dots all point to something new, something that JWST is uniquely capable of seeing. "They are in every single image the telescope takes," says Massachusetts Institute of Technology astrophysicist Rohan Naidu. "We have to find out about them if we want to tell a complete story about the early universe."



At first, astrophysicists coalesced around a few theories to explain LRDs, each of which has implications for the evolution of the universe. Little Red Dots might be compact galaxies with brightly belching black holes at their centers. They could represent a never-before-seen stage of the black hole life cycle. They could be dusty starburst galaxies, exploding with new stellar populations like so many popcorn kernels encountering hot oil.

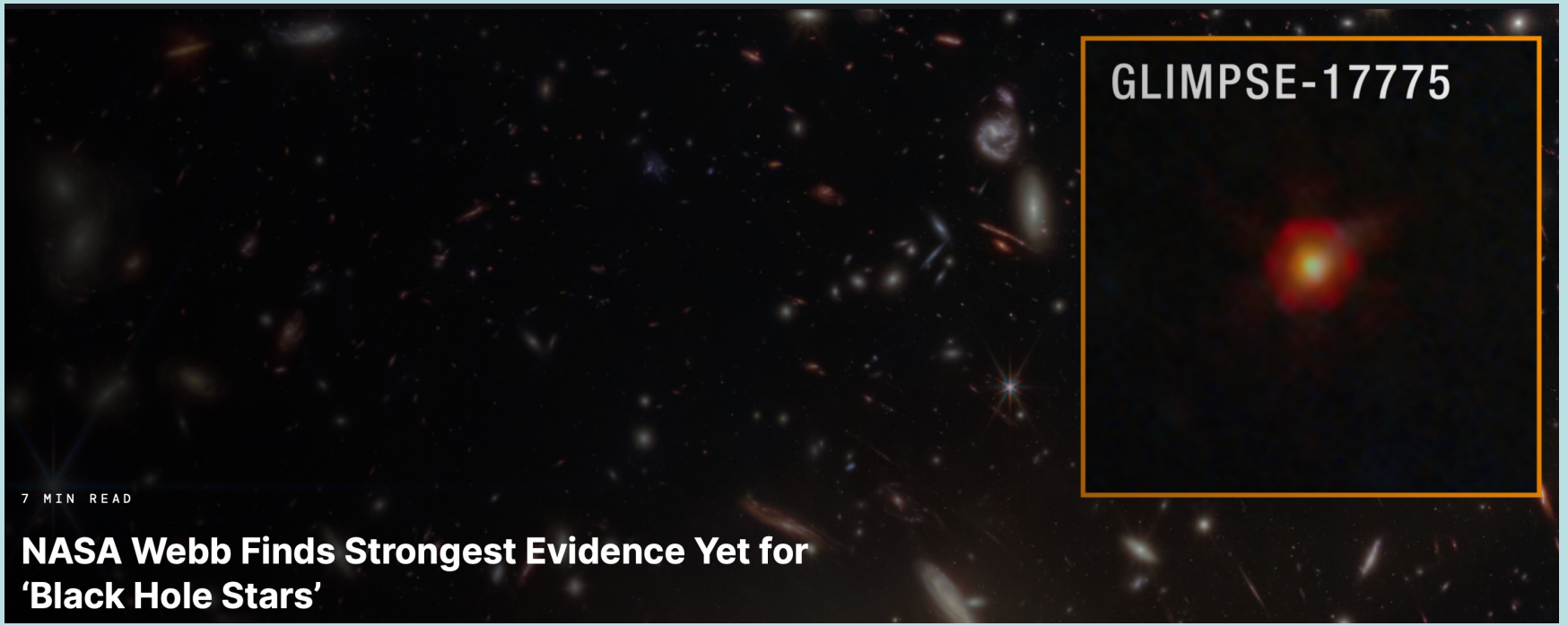
If Little Red Dots are indeed supermassive black holes, their prevalence could help us understand the nature of these weird perversions of gravity. The dots might reveal how black holes evolve and grow so fast and even how galaxy clusters develop. They could help theorists study direct-collapse black holes, a

Rebecca Boyle is a *Scientific American* contributor and an award-winning freelance journalist in Colorado. Her newest book, *Our Moon: How Earth's Celestial Companion Transformed the Planet, Guided Evolution, and Made Us Who We Are* (Random House, 2024), explores Earth's relation with its satellite.



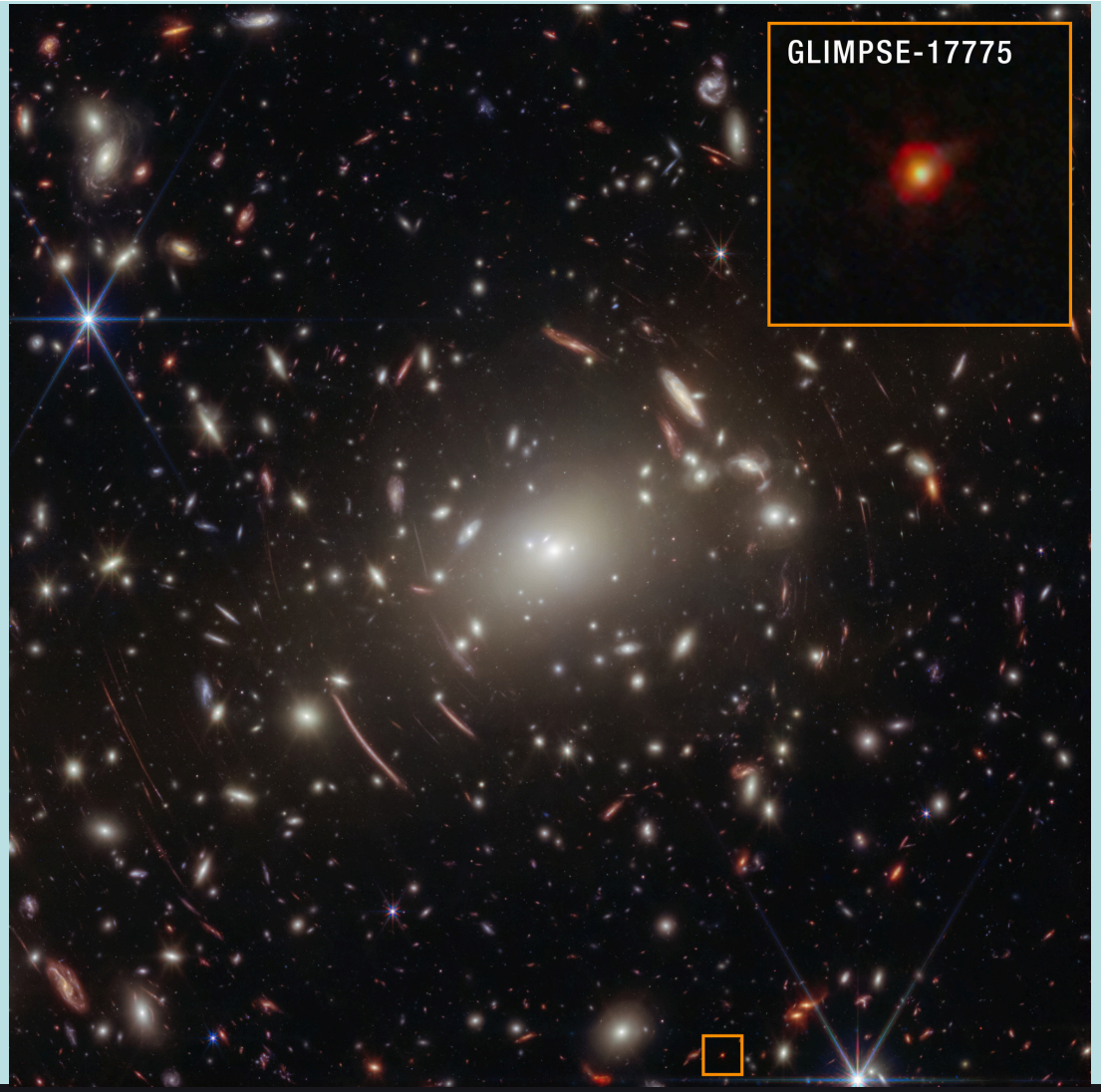
This image of a special object, dubbed the “X-ray dot,” represents a discovery from Chandra that could help explain the nature of a mysterious class of sources in the early Universe. The optical and infrared image from Hubble show the region around the X-ray dot, while the Chandra X-ray image shows the close up. Prior to this discovery, “little red dots” seen by the Webb telescope had not been known to emit X-rays. This one does, which leads researchers to propose that the X-ray dot represents a previously unknown transition phase of growing supermassive black holes.

X-ray: NASA/CXC/Max Plank Inst./R. Hviding et al.; Optical/IR; NASA/ESA/STScI/HST; Image Processing: NASA/CXC/SAO/N. Wolk



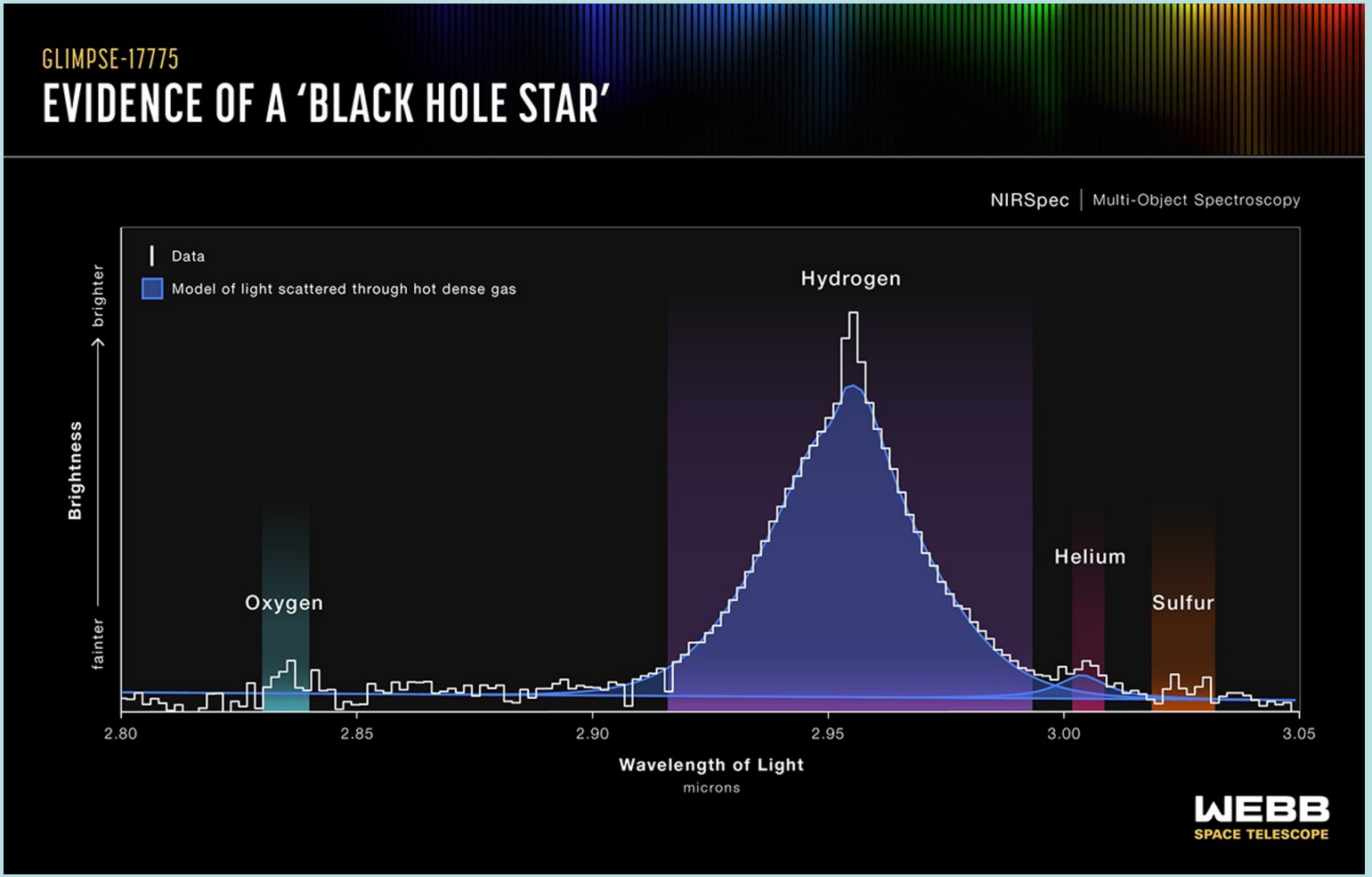
7 MIN READ

NASA Webb Finds Strongest Evidence Yet for ‘Black Hole Stars’



The little red dot that would come to be known as GLIMPSE-17775 was fortunately included in NASA's James Webb Space Telescope's field of view as it was observing galaxy cluster Abell S1063 for a different scientific purpose. GLIMPSE-17775 is located behind the galaxy cluster and has a cosmological redshift of 3.5, meaning it existed about 1.8 billion years after the big bang.

Since galaxy clusters like Abell S1063 are some of the most massive objects in the universe, light emitted by objects farther away can become distorted as it reaches the telescope. This effect is known as gravitational lensing. The combination of Webb's 30 hours of observing time and gravitational lensing enabled scientists to obtain the deepest spectrum to date of a little red dot. The result: the strongest evidence to date of a hot, dense gas cocoon known as a "black hole star."


GLIMPSE-17775
EVIDENCE OF A 'BLACK HOLE STAR'
NIRSpec | Multi-Object Spectroscopy
Data
Model of light scattered through hot dense gas
Hydrogen
Helium
Sulfur
Oxygen
Brightness
brighter
fainter
2.80
2.85
2.90
2.95
3.00
3.05
Wavelength of Light
microns
WEBB
SPACE TELESCOPE

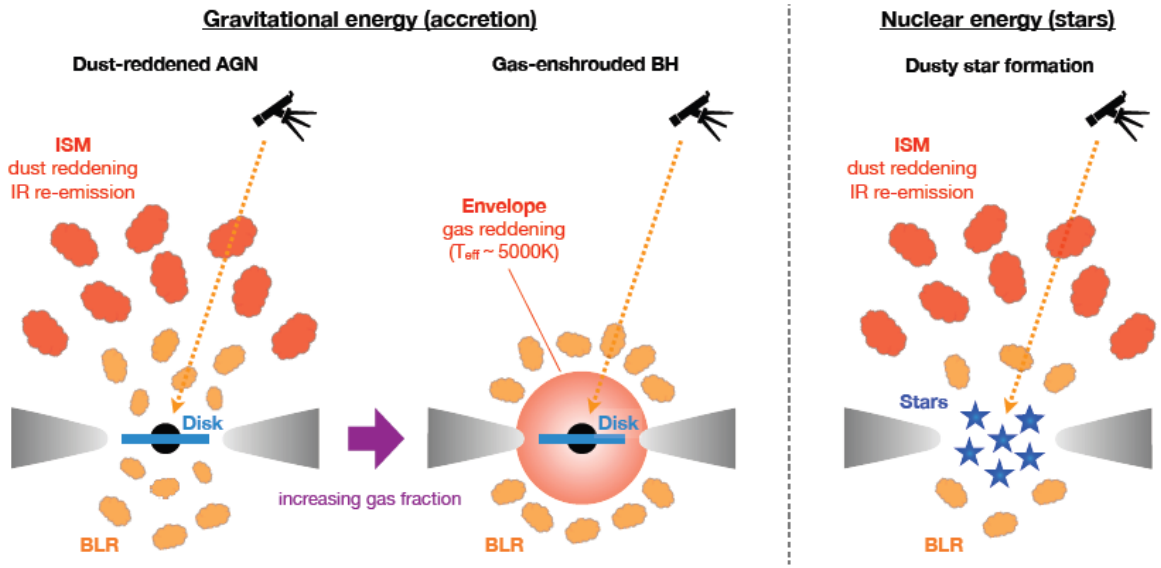
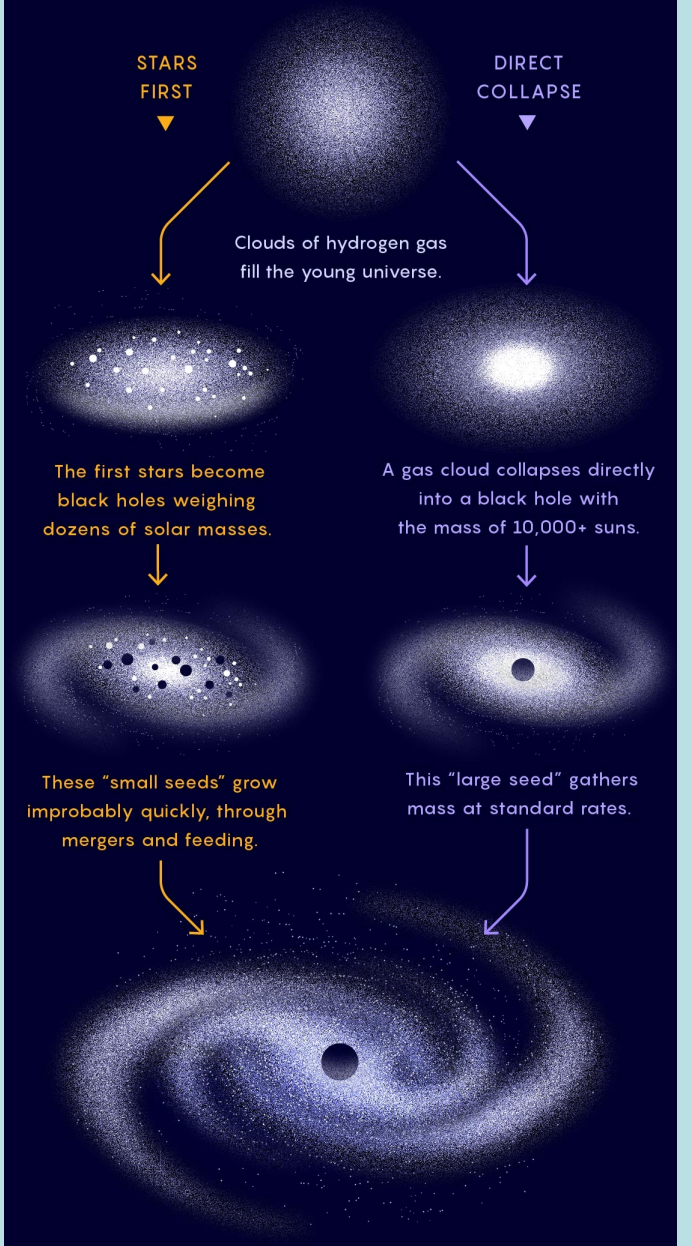


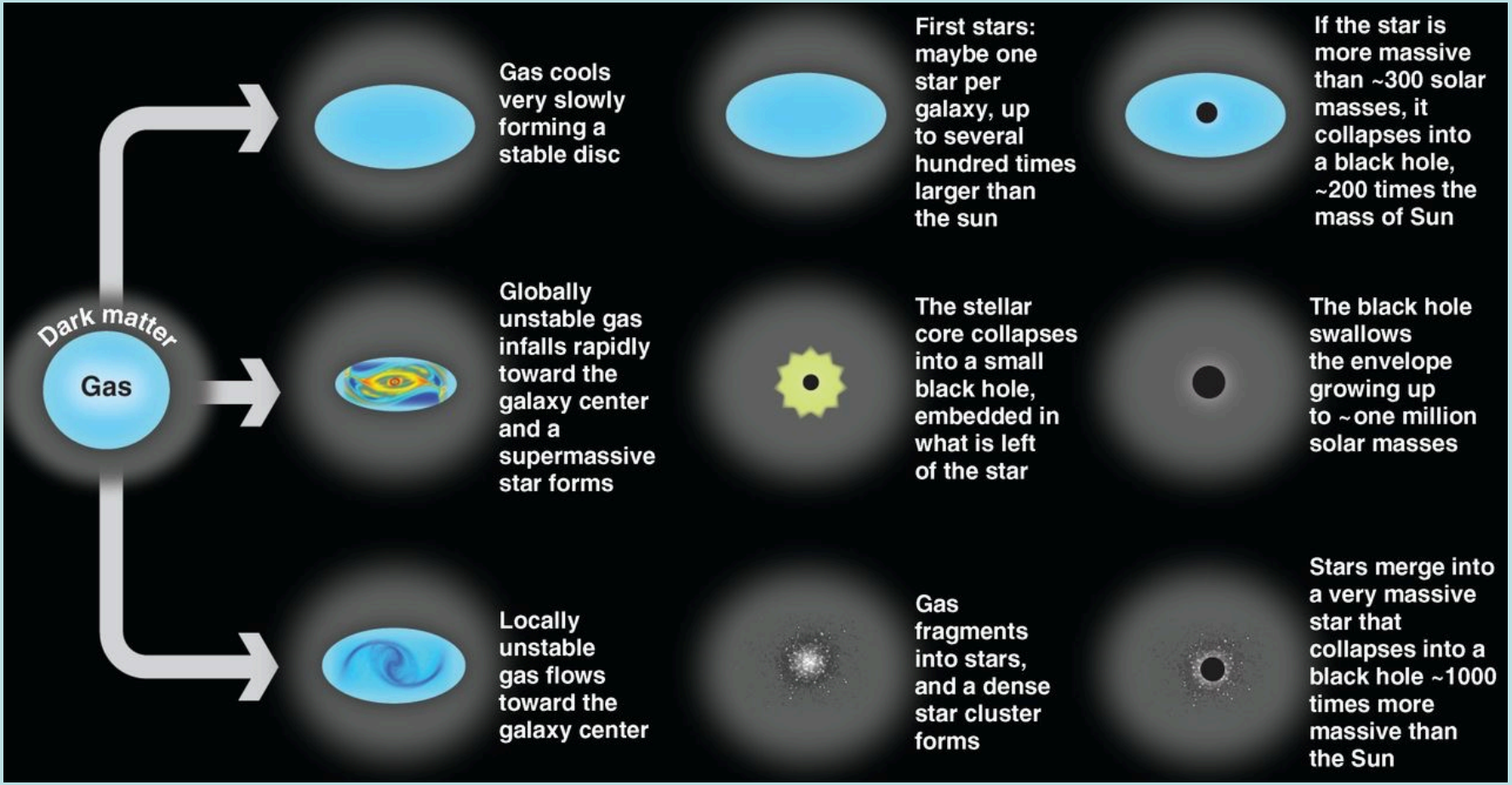
Figure 2. Summary of three proposed scenarios for the energy sources of LRDs. (1) **Dust-reddened AGNs**: broad-line AGNs with moderate dust extinction, explaining their red optical continua. (2) **Gas-enshrouded BHs**: AGNs embedded in dense gas with a high covering fraction, representing the extreme limit of an AGN + dense gas system. (3) **Dusty star formation**: systems where the red colors originate primarily from stellar emission attenuated by dust.

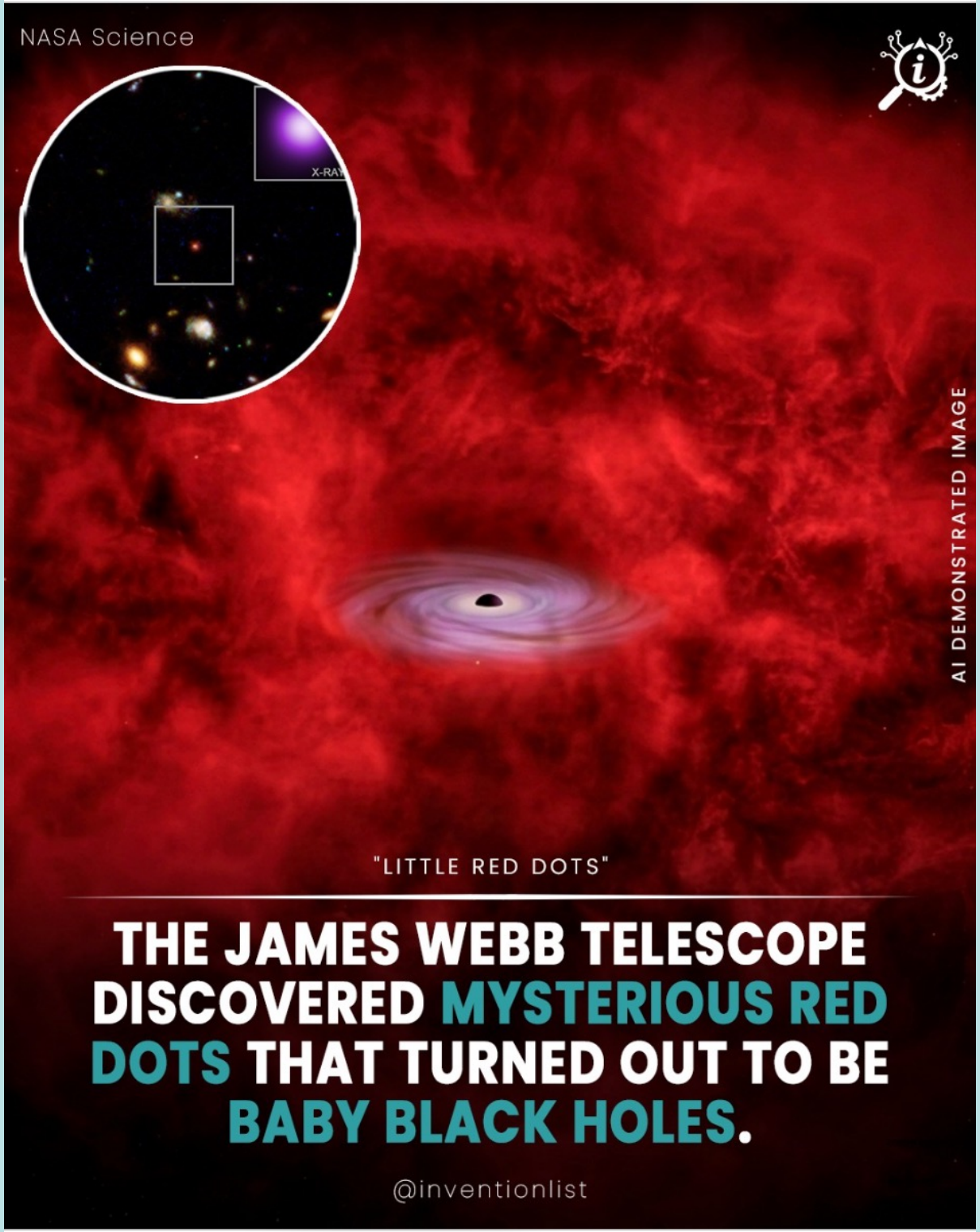
How Supermassive Black Holes Are Born

The heart of most Milky Way–like galaxies holds a black hole weighing billions of solar masses. Astrophysicists have two main ideas for how these monstrosities got so huge.



The resulting supermassive black hole anchors a large galaxy. Dwarf galaxies, by contrast, are thought to resemble earlier steps in the growth process.


Dark matter
Gas
Gas cools very slowly forming a stable disc
First stars: maybe one star per galaxy, up to several hundred times larger than the sun
If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun
Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms
The stellar core collapses into a small black hole, embedded in what is left of the star
The black hole swallows the envelope growing up to ~one million solar masses
Locally unstable gas flows toward the galaxy center
Gas fragments into stars, and a dense star cluster forms
Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun


NASA Science
X-RAY
AI DEMONSTRATED IMAGE
"LITTLE RED DOTS"
THE JAMES WEBB TELESCOPE DISCOVERED MYSTERIOUS RED DOTS THAT TURNED OUT TO BE BABY BLACK HOLES.
@inventionlist

6. Webb exposes the skeletal structure of nearby spiral galaxies in mesmerizing detail.

We already knew that galaxies are collections of stars, planets, dust, gas, dark matter, and black holes: cosmic cities where stars form, live, die, and are recycled into the next generation. But we had never been able to see the structure of a galaxy and the interactions between stars and their environment in such detail. Webb's infrared vision reveals filaments of dust that trace the spiral arms, old star clusters that make up galactic cores, newly forming stars still encased in dense cocoons of glowing dust and gas, and clusters of hot young stars carving enormous cavities in the dust. It also elucidates how stellar winds and explosions actively reshape their galactic homes.



A near- to mid-infrared image from NASA's James Webb Space Telescope highlights details in the complex structure of a nearby galaxy that are invisible to other telescopes. The image of NGC 628, also known as the Phantom Galaxy, shows spiral arms with lanes of warm dust (represented in red), knots of glowing gas (orange-yellow), and giant bubbles (black) carved by hot, young stars. The dust-free core of the galaxy is filled with older, cooler stars (blue).

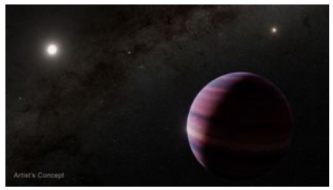
NASA, ESA, CSA, STScI, Janice Lee (STScI), Thomas Williams (Oxford), PHANGS team



Webb Narrows Atmospheric Possibilities for Earth-sized Exoplanet TRAPPIST-1 d

The exoplanet TRAPPIST-1 d intrigues astronomers looking for possibly habitable worlds beyond our solar system because it is similar in size to Earth, rocky, and resides in an area around its star where liquid water on its surface is theoretically...

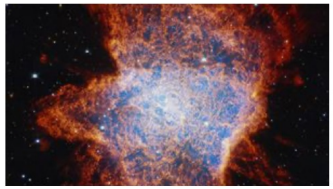
ARTICLE



NASA's Webb Finds New Evidence for Planet Around Closest Solar Twin

Astronomers using NASA's James Webb Space Telescope have found strong evidence of a giant planet orbiting a star in the stellar system closest to our own Sun. At just 4 light-years away from Earth, the Alpha Centauri triple star system...

ARTICLE



NASA's Webb Traces Details of Complex Planetary Nebula

Since their discovery in the late 1700s, astronomers have learned that planetary nebulae, or the expanding shell of glowing gas expelled by a low-intermediate mass star late in its life, can come in all shapes and sizes. Most planetary nebula...

ARTICLE



NASA's Webb Scratches Beyond Surface of Cat's Paw for 3rd Anniversary

It's the cat's meow! To celebrate its third year of revealing stunning scenes of the cosmos in infrared light, NASA's James Webb Space Telescope has "clawed" back the thick, dusty layers of a section within the Cat's Paw Nebula (NGC...

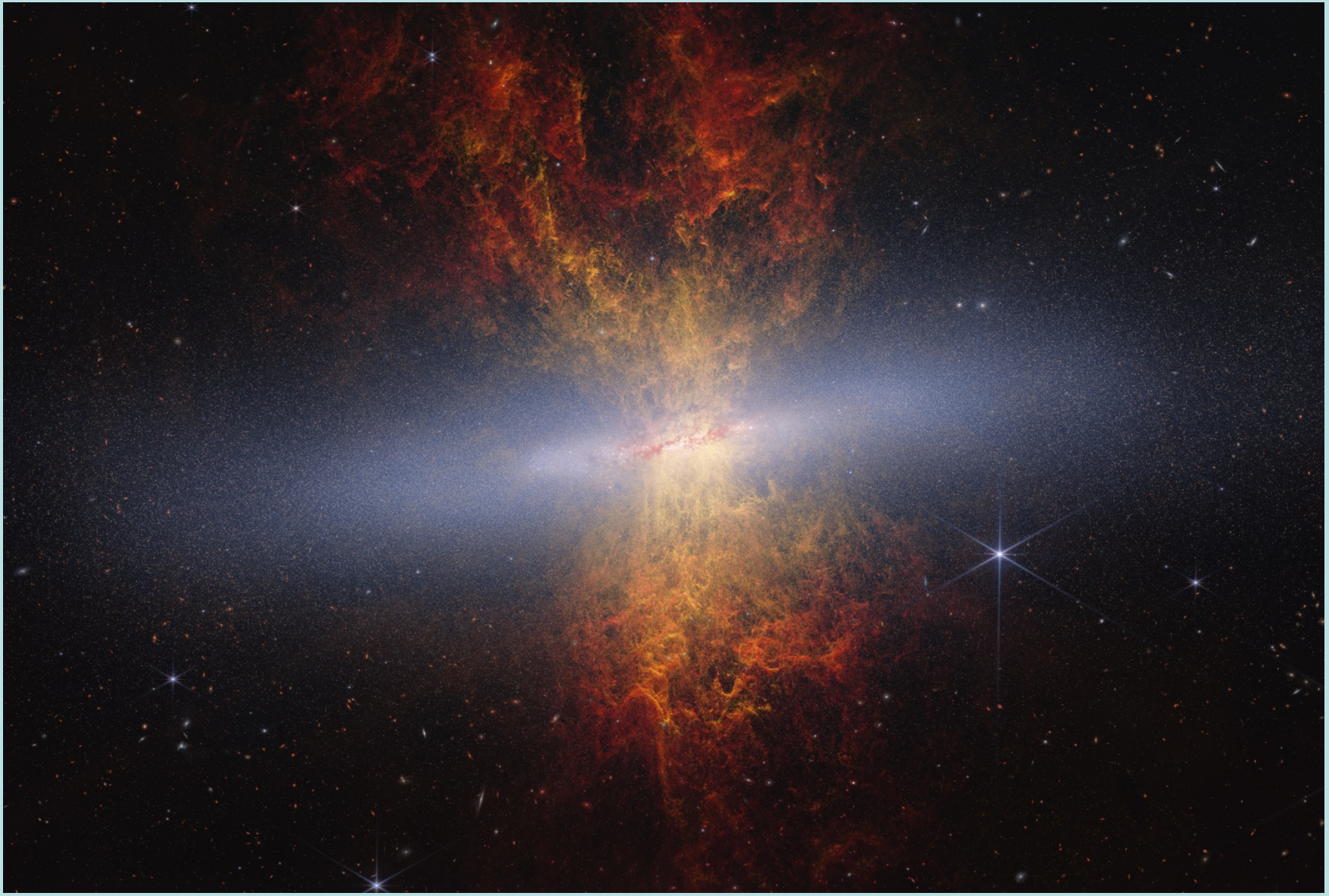
ARTICLE

Downloads



NASA's James Webb Space Telescope's near-infrared view of the Cat's Paw Nebula reveals mini "toe beans." Massive young stars are carving the gas and dust while their bright starlight is producing a bright nebulous glow. Eventually this turbulent region will quench star formation.
NASA, ESA, CSA, STScI.

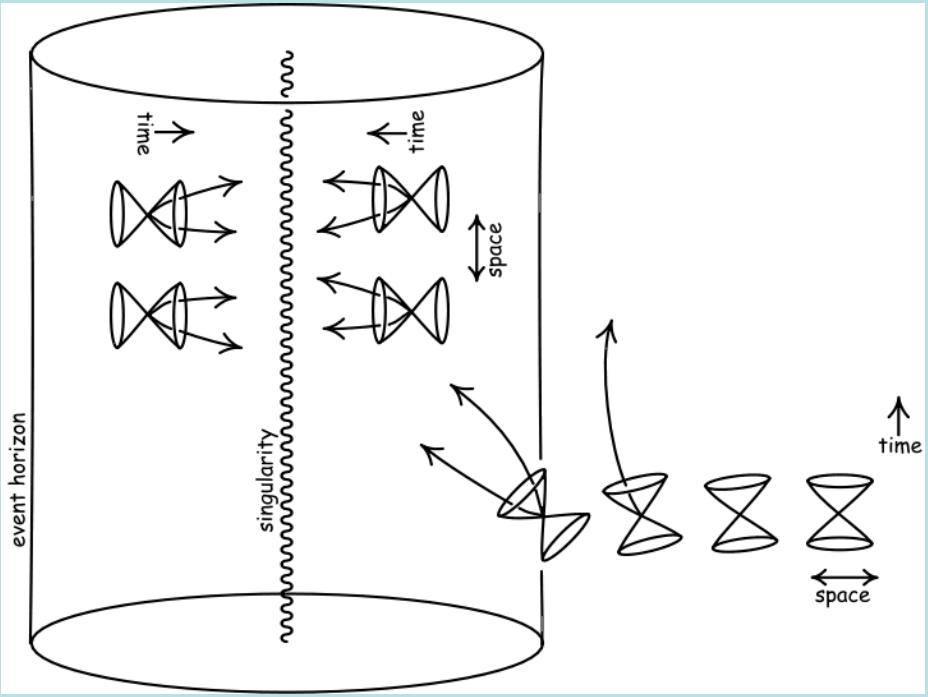

National Aeronautics and
Space Administration
NASA
NIRCam
JAMES WEBB SPACE TELESCOPE
Saturn



時間與空間是分不開的。

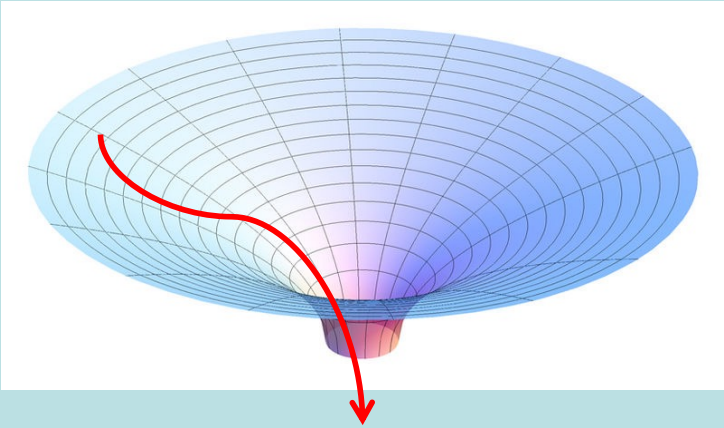
質量會扭曲空間。

質量會扭曲時間與空間



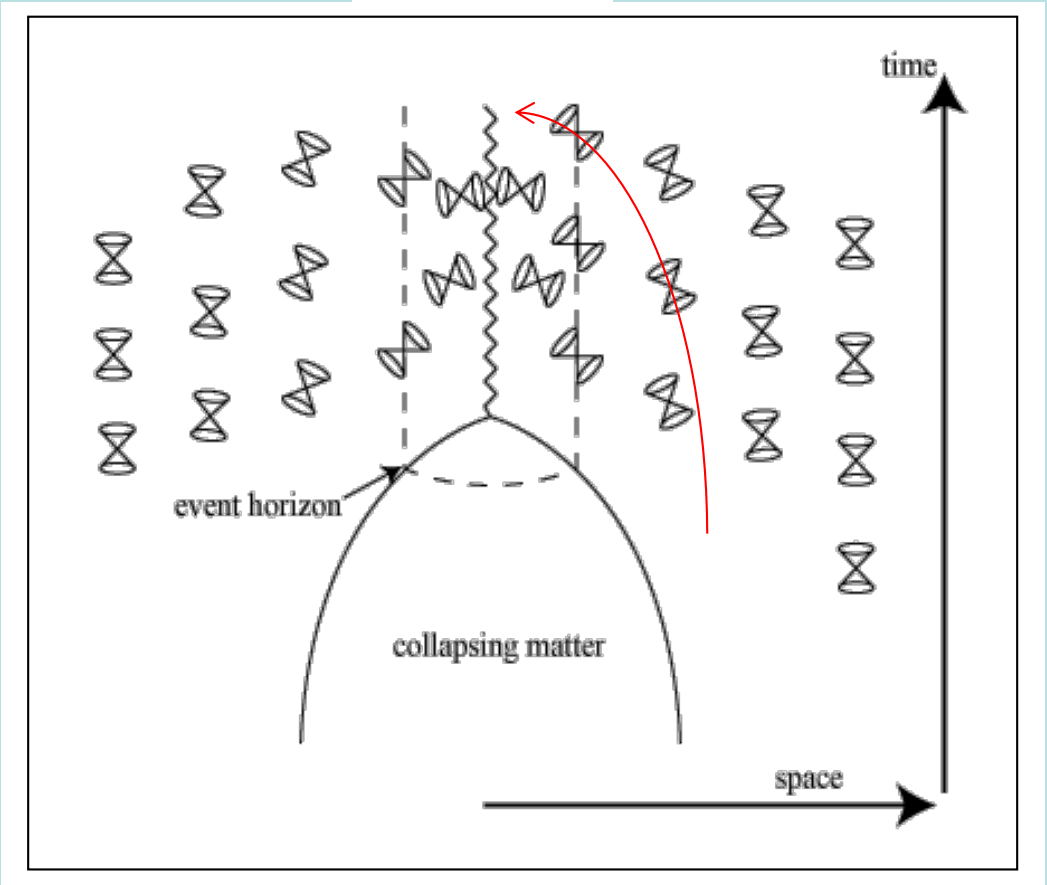
接近黑洞的實驗者的時間，在外界看來彎曲成了空間的方向！





奇異點 singularity

史瓦西度規



掉入黑洞中的物質最後會到哪裡去？

How Eating Meat Contributes to Global Warming (*page 72*)

SCIENTIFIC AMERICAN

Nanomedicine
Revolutionizing the Fight against Disease
page 44

February 2009 www.SciAm

Black holes may have even stranger siblings that violate known laws of physics

NAKED SINGULARITIES

Fold the Brain
How Forces That Shape It Link to Autism and More

Submarine Lava
The Mysterious, Red-Hot Origins of the Ocean Floor

Electric Rockets
Efficient Travel to Deep Space

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Naked Singularities

The black hole has a troublesome sibling, the naked singularity. Physicists have long thought—hoped—it could never exist. But could it?

BY PANKAJ S. JOSHI

KEY CONCEPTS

- Conventional wisdom has it that a large star eventually collapses to a black hole, but some theoretical models suggest it might instead become a so-called naked singularity [*see box on opposite page for definition*]. Sorting out what happens is one of the most important unresolved problems in astrophysics.
- The discovery of naked singularities would transform the search for a unified theory of physics, not least by providing direct observational tests of such a theory.

—*The Editors*

Modern science has introduced the world to plenty of strange ideas, but surely one of the strangest is the fate of a massive star that has reached the end of its life. Having exhausted the fuel that sustained it for millions of years, the star is no longer able to hold itself up under its own weight, and it starts collapsing catastrophically. Modest stars like the sun also collapse, but they stabilize again at a smaller size. Whereas if a star is massive enough, its gravity overwhelms all the forces that might halt the collapse. From a size of millions of kilometers across, the star crumples to a pinprick smaller than the dot on an "i."

Most physicists and astronomers think the result is a black hole, a body with such intense gravity that nothing can escape from its immediate vicinity. A black hole has two parts. At its core is a singularity, the infinitesimal point into which all the matter of the star gets crushed. Surrounding the singularity is the region of space from which escape is impossible, the perimeter of which is called the event horizon. Once something enters the event horizon, it loses all hope of exiting. Whatever light the falling body gives off is trapped, too, so an outside observer never sees it again. It ultimately crashes into the singularity.

But is this picture really true? The known laws of physics are clear that a singularity forms,

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[BASIC PRINCIPLES]

Two Monsters of the Cosmos

A naked singularity is essentially a black hole without the "black" part. It can both suck in and spit out matter and radiation. Accordingly, it would look different and have different effects on its immediate surroundings.

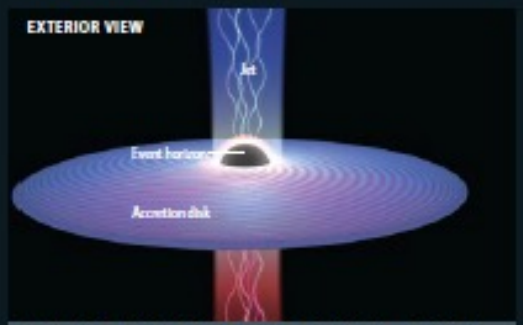
BLACK HOLE

CROSS SECTION



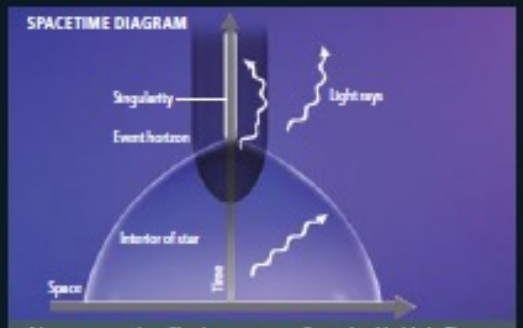
The key feature of a black hole is its event horizon, a surface that material can enter but not exit. Often the horizon is surrounded by a swirling, gaseous disk.

EXTERIOR VIEW



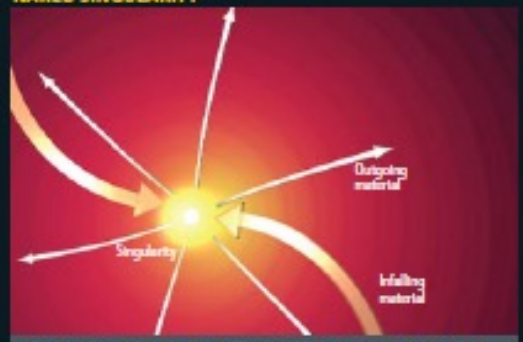
On the outside, the black hole looks like a pitch-black ball. The singularity lies within and cannot be seen. Friction within the surrounding disk generates intense radiation. Some disk material flies out in a jet; other material falls in.

SPACETIME DIAGRAM

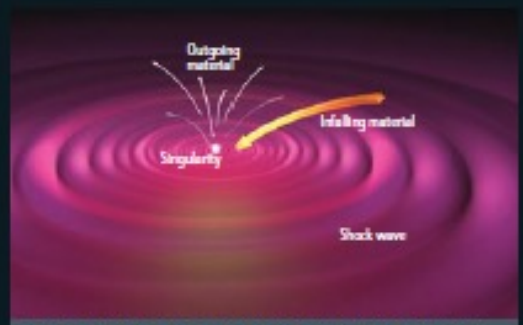


A homogeneous star without gas pressure collapses to a black hole. The star's gravity intensifies, bending the paths of moving objects (including light rays) by an increasing amount and eventually trapping them.

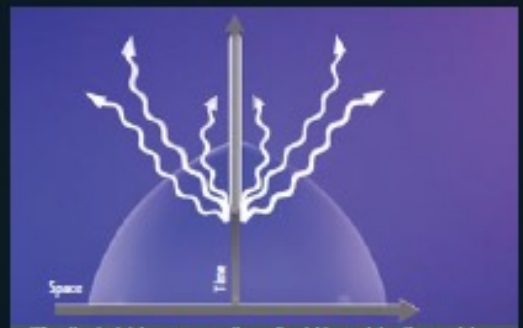
NAKED SINGULARITY



A naked singularity lacks an event horizon. Like a black hole, it can suck in material; unlike a black hole, it can also spit it out.



A naked singularity looks like a tiny dust grain, except that it is almost inconceivably dense. Infalling matter can be seen all the way down to its final impact with the singularity. The intense gravity can generate powerful shock waves.



When the star is inhomogeneous, its gravity might never intensify enough to bend light rays back on themselves. The star collapses to a singularity, but the singularity is visible. *[For step-by-step simulations, see box on next two pages.]*

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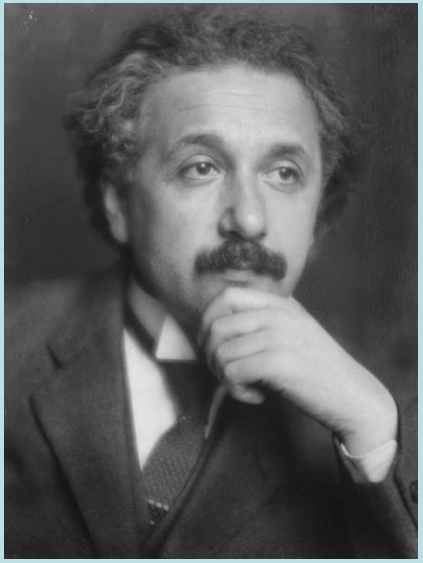
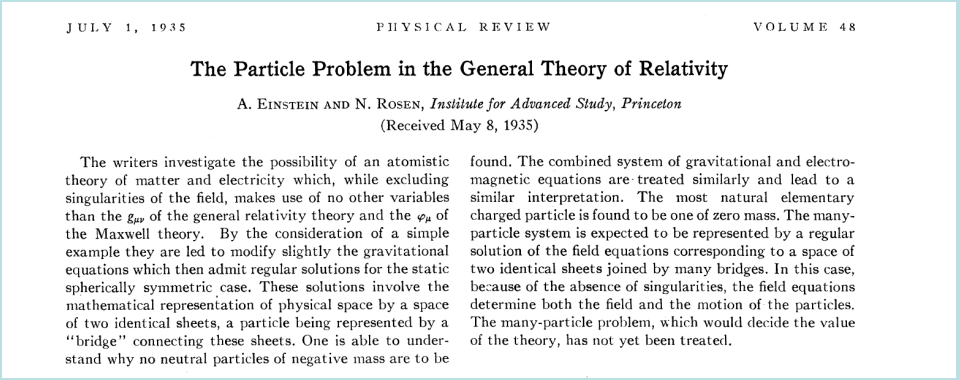
更驚人的結果才正要出現！

Now Einstein again!

他發現如右圖的扭曲時空是廣義相對論所容許的！





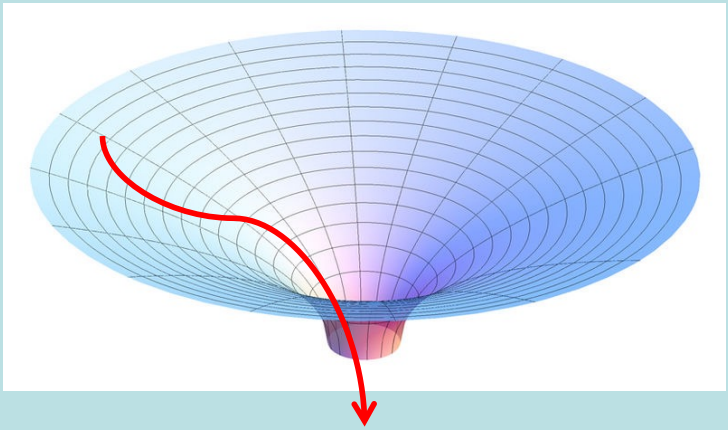
JULY 1, 1935 PHYSICAL REVIEW VOLUME 48

The Particle Problem in the General Theory of Relativity

A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*

(Received May 8, 1935)

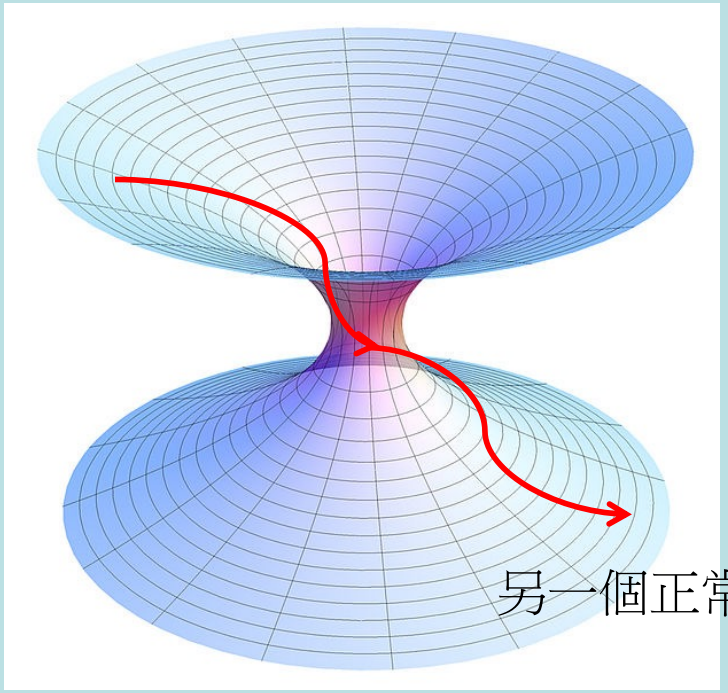
The writers investigate the possibility of an atomistic theory of matter and electricity which, while excluding singularities of the field, makes use of no other variables than the $g_{\mu\nu}$ of the general relativity theory and the φ_μ of the Maxwell theory. By the consideration of a simple example they are led to modify slightly the gravitational equations which then admit regular solutions for the static spherically symmetric case. These solutions involve the mathematical representation of physical space by a space of two identical sheets, a particle being represented by a "bridge" connecting these sheets. One is able to understand why no neutral particles of negative mass are to be found. The combined system of gravitational and electromagnetic equations are treated similarly and lead to a similar interpretation. The most natural elementary charged particle is found to be one of zero mass. The many-particle system is expected to be represented by a regular solution of the field equations corresponding to a space of two identical sheets joined by many bridges. In this case, because of the absence of singularities, the field equations determine both the field and the motion of the particles. The many-particle problem, which would decide the value of the theory, has not yet been treated.



奇異點 singularity

Schwarzschild metric

史瓦西度規

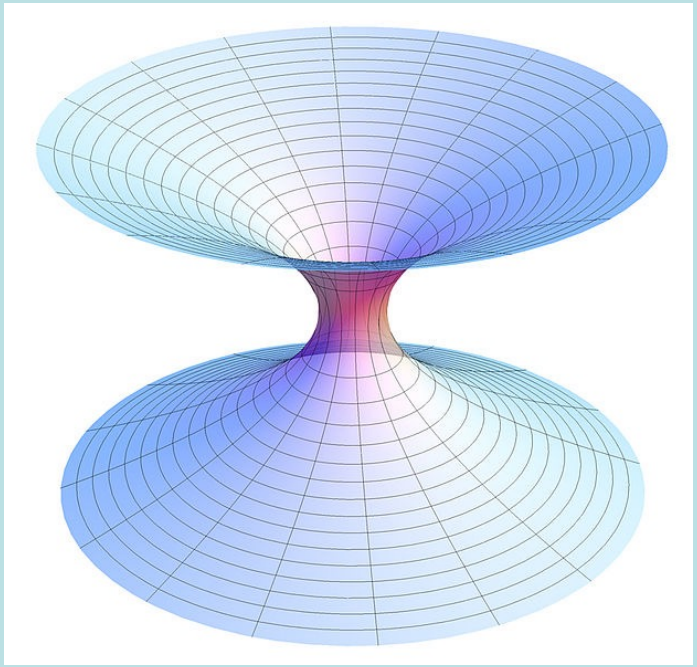


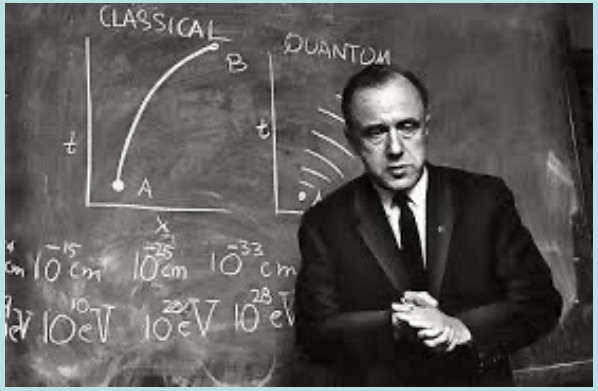
另一個正常世界

Einstein–Rosen bridge

Einstein–Rosen bridge

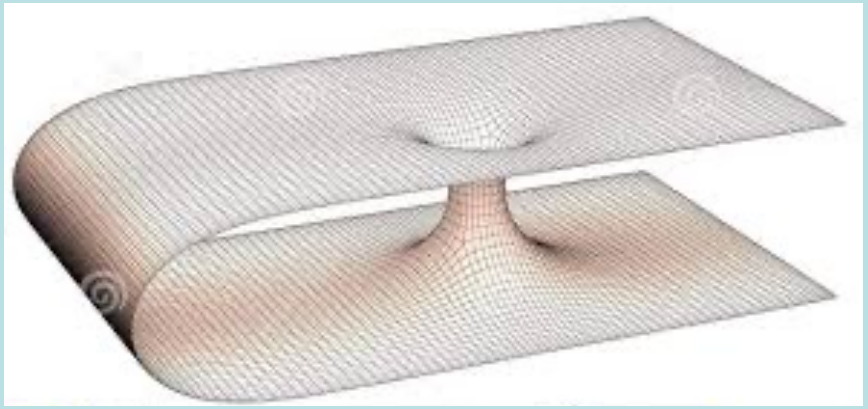
如同連接兩個獨立空間的橋



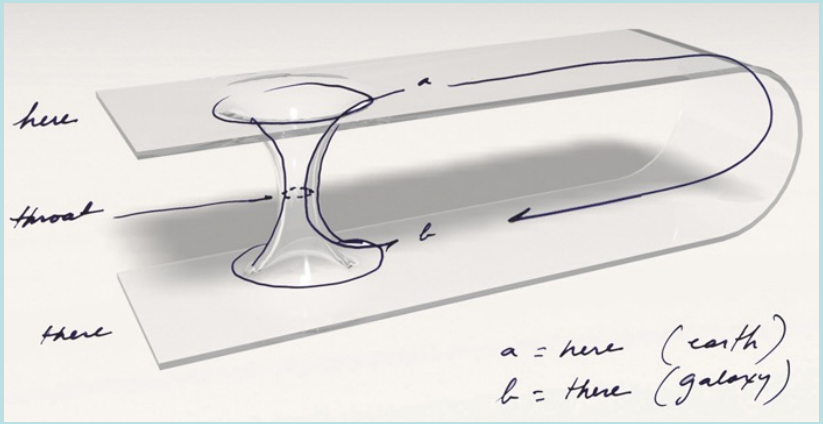


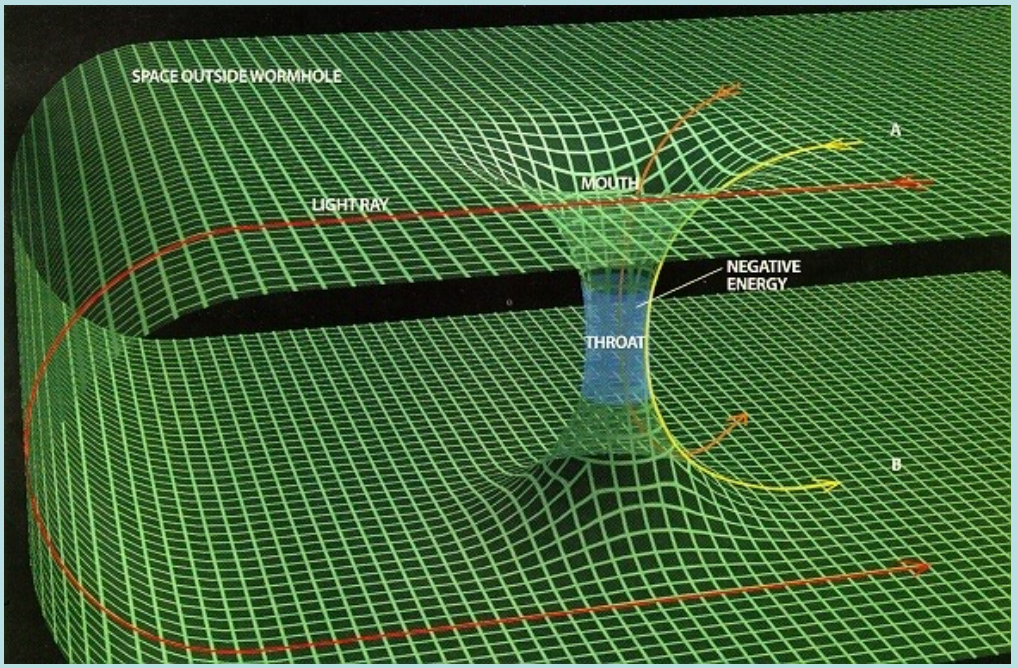
John Archibald Wheeler 1955

這兩個獨立空間可能在遠方是連在一起的！



所以進了黑洞以後，就是空間的遠方！

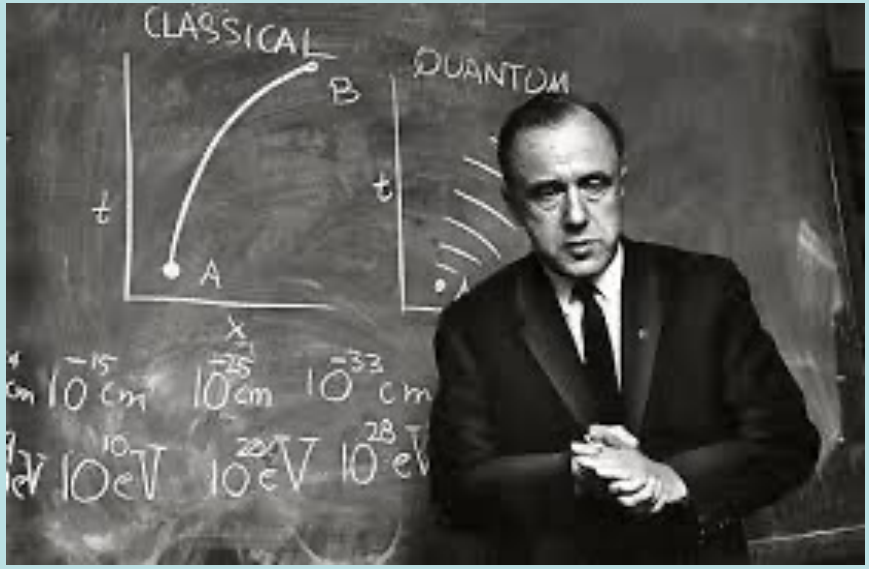




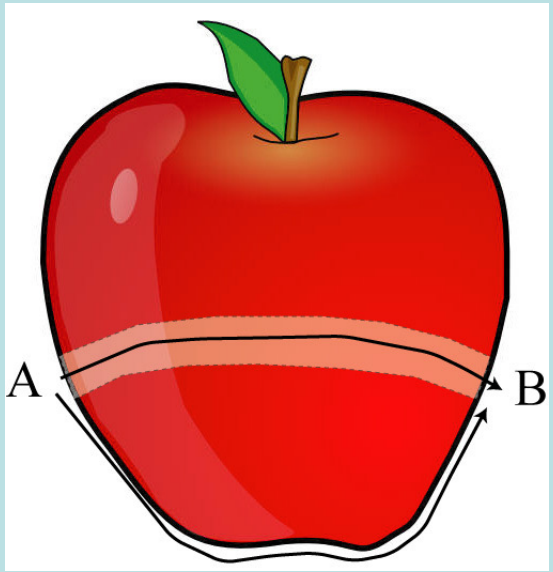
這樣的時空，此處與遠方的時空是相黏的！

此處與遠方的時空中間有一條隧道捷徑！

Wormhole 蟲洞

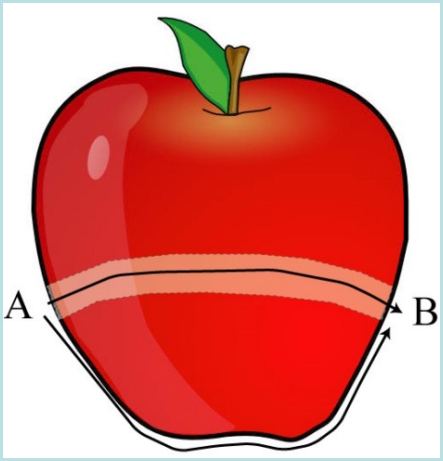


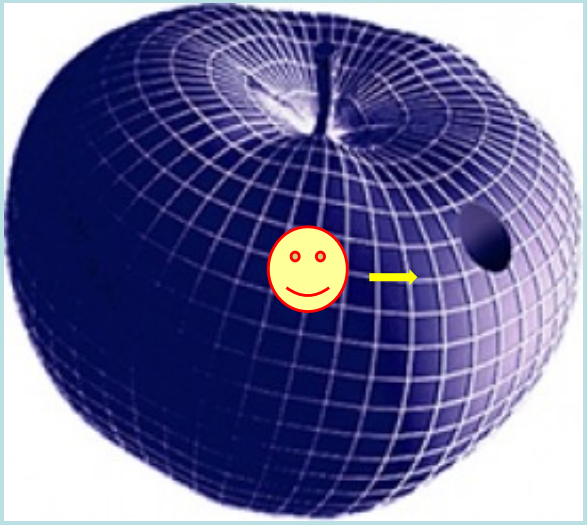
John Archibald Wheeler 1955

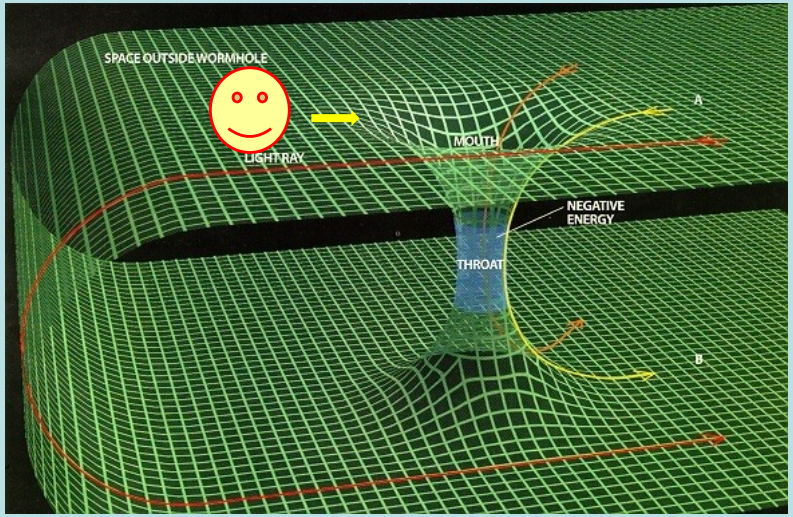


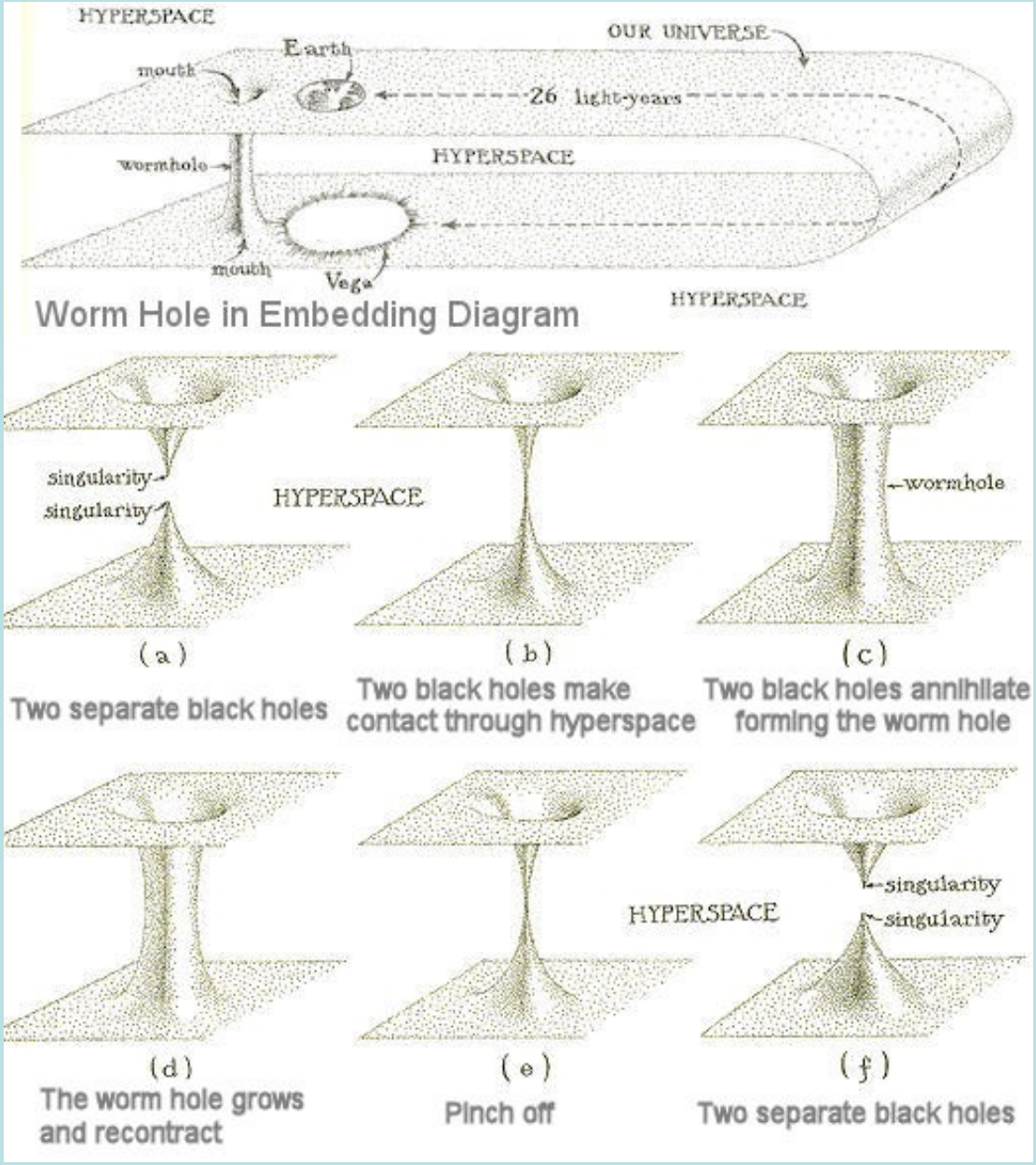


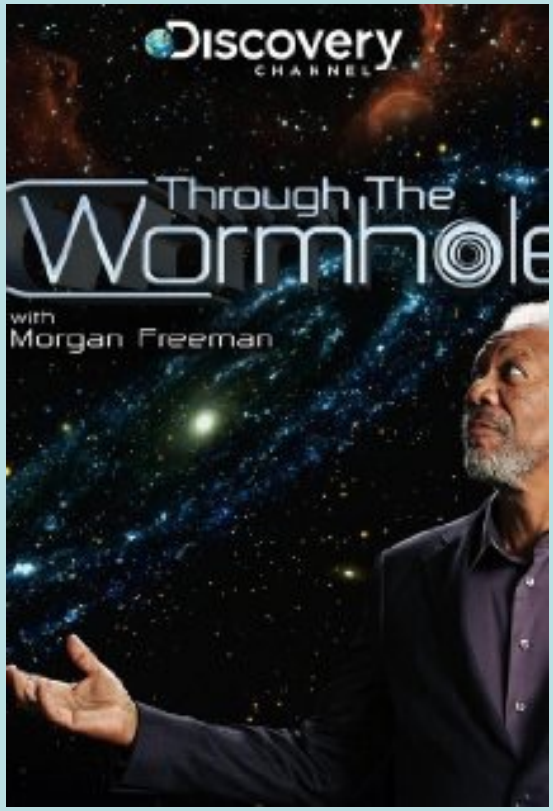
Wormhole 蟲洞


A
B



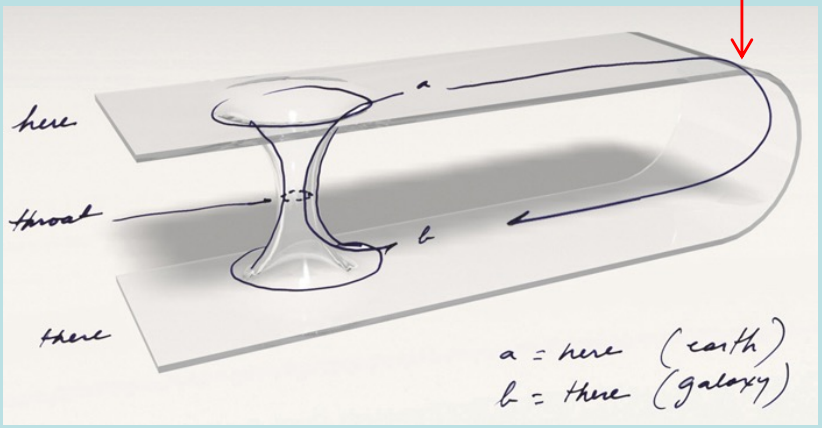

SPACE OUTSIDE WORMHOLE
LIGHT RAY
MOUTH
A
NEGATIVE ENERGY
THROAT
B

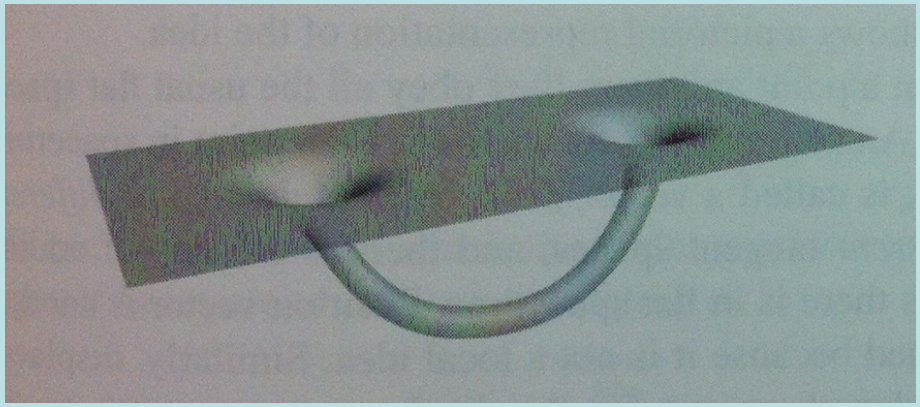

HYPERSPACE
OUR UNIVERSE
Earth
mouth
26 light-years
wormhole
HYPERSPACE
mouth
Vega
HYPERSPACE
Worm Hole in Embedding Diagram
singularity
singularity
HYPERSPACE
wormhole
(a)
Two separate black holes
(b)
Two black holes make contact through hyperspace
(c)
Two black holes annihilate forming the worm hole
(d)
The worm hole grows and recontract
(e)
Pinch off
HYPERSPACE
singularity
singularity
(f)
Two separate black holes


Discovery
CHANNEL
Through The
Wormhole
with
Morgan Freeman

注意此圖垂直於面的空間並不存在！

此處不一定要彎曲





所以左圖的意思就是右圖

PHYSICAL REVIEW VOLUME 97, NUMBER 2 JANUARY 15, 1955

Geons*

JOHN ARCHIBALD WHEELER
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received September 8, 1954)

Associated with an electromagnetic disturbance is a mass, the gravitational attraction of which under appropriate circumstances is capable of holding the disturbance together for a time long in comparison with the characteristic periods of the system. Such gravitational-electromagnetic entities, or "geons"; are analyzed via classical relativity theory. They furnish for the first time a completely classical, divergence-free, self-consistent picture of the

of equations of self-consistent geon; mass and radius values. 4. Transformations and interactions of electromagnetic geons; evaluation of refractive index barrier penetration integral for spherical geon; photon-photon collision processes as additional mechanism for escape of energy from system; restatement in language of coupling of characteristic modes; the thermal geon; comparison of gravitation and virtual electron pair phenomena as

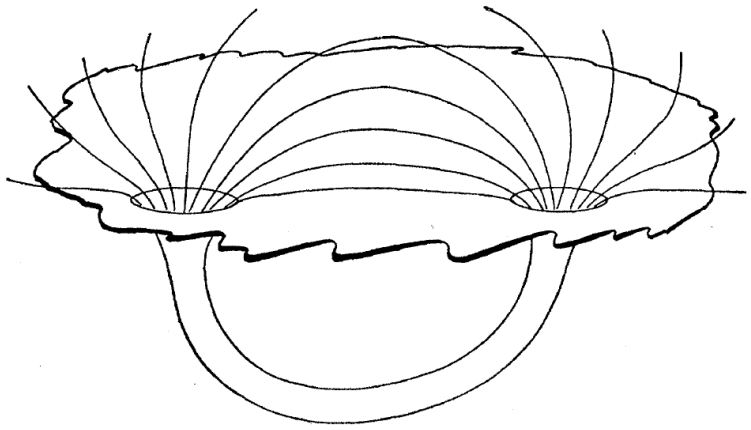
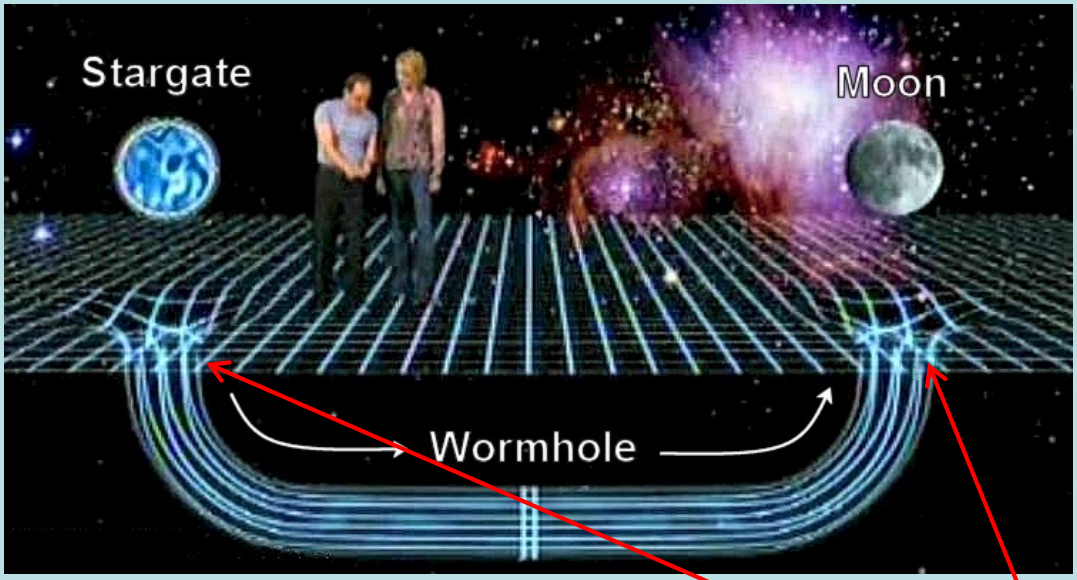


FIG. 7. Schematic representation of lines of force in a doubly-connected space. In the upper continuum the lines of force behave much as if the tunnel mouths were the seats of equal and opposite charges.

sum (102) no
connected me
quantized, lea
ties of which
In this sense
charges in the
tains no charg

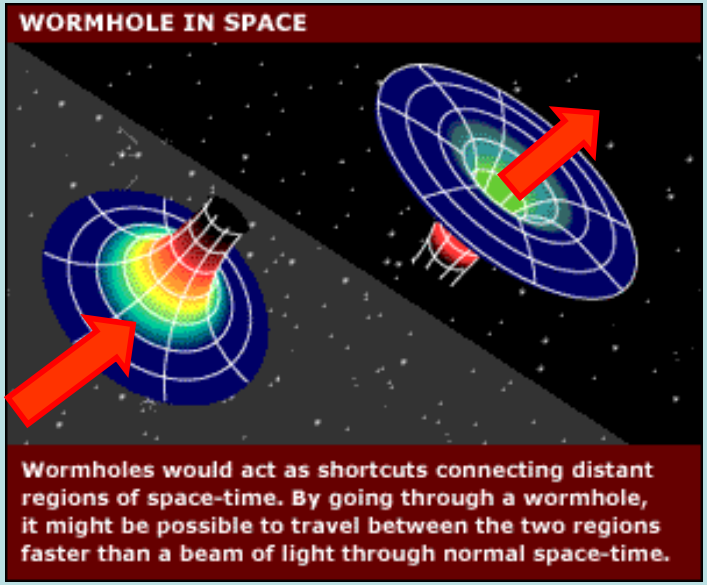
Little progr
quantization
certain wheth
tions gives in
are identical
quantization.
tion of genera
meaning for

這樣的時空，此處與遠方的時空是相黏的！

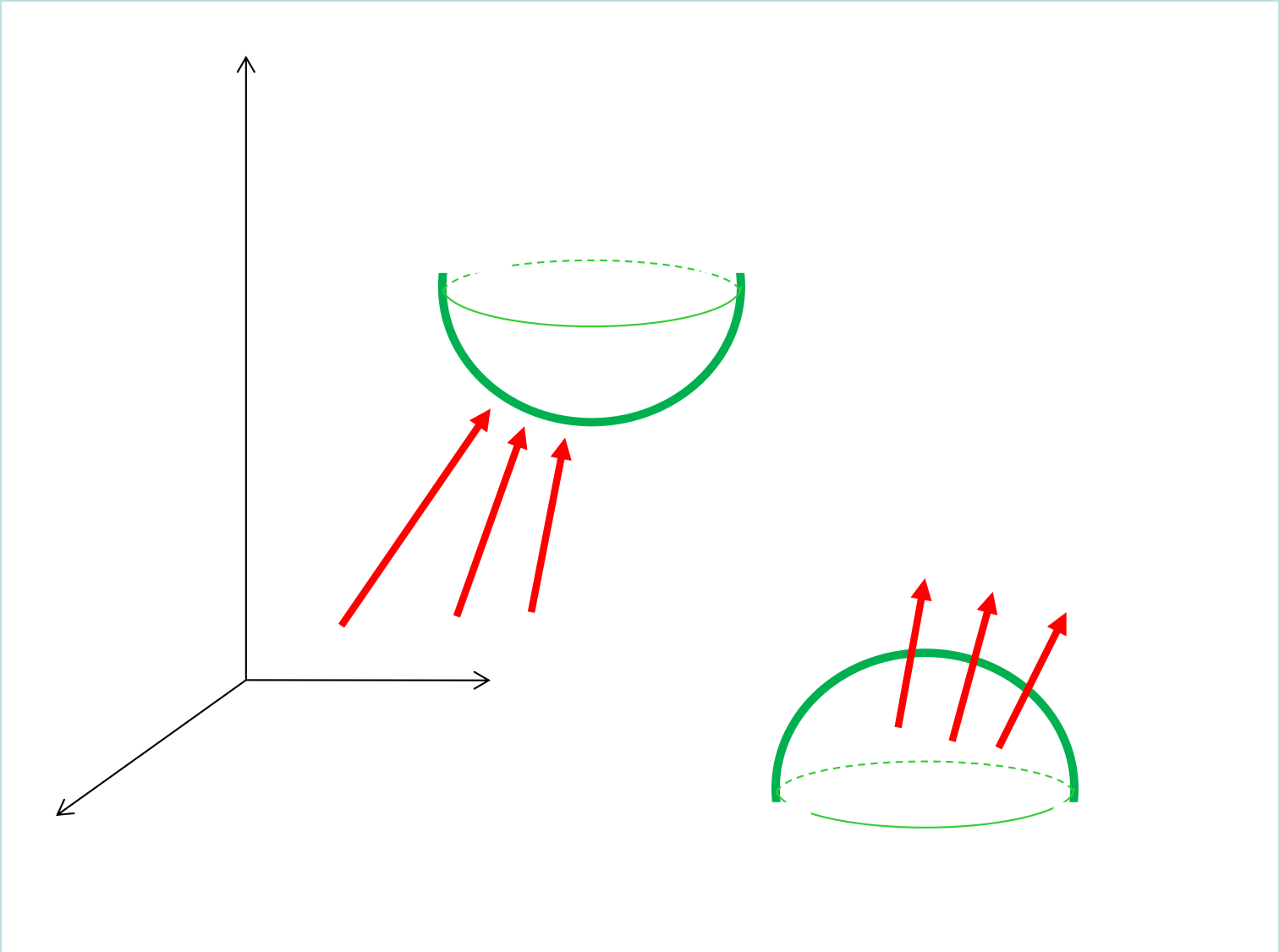


垂直的空間並不存在！

同一點

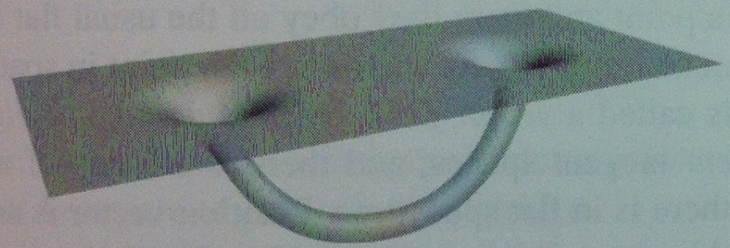


真實觀察到的三度空間圖



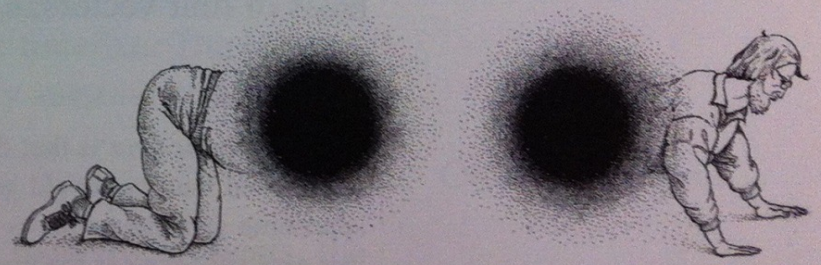
BOX 7.2 Wormholes in Spacetime

The wormhole in the simple geometry of (7.39) illustrated in Figure 7.5 connects two different asymptotically flat regions of spacetime—two "universes" in the language of science fiction. Even more interesting might be a wormhole connecting two places in our own asymptotically flat region of spacetime, as qualitatively illustrated

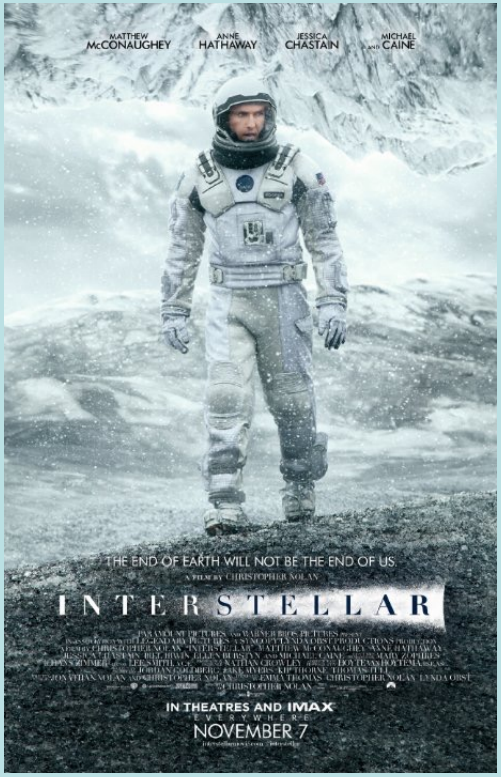


here. The figure shows an embedding diagram of a two-dimensional slice of spacetime at one instant of time in the approximate inertial frame of the asymptotic region. The wormhole "mouths" might appear as roughly spherical regions in space. By crawling through one mouth, one could emerge from the other in a different place, as the distinguished relativist Kip Thorne is shown doing in the figure from his book (Thorne 1994). The distance through the wormhole throat could be much shorter than the distance between the mouths in the region outside, enabling rapid travel between the two places. Indeed, one could imagine arranging the wormhole to connect events in spacetime so that one emerged at an earlier value of time in the approximate inertial frame than the value at which one went in! If the time was early enough, one could walk back in the outside region and meet oneself before one went through the wormhole. That is one way of imagining a machine for going backward in time. (For one that goes forward in time, see Box 9.1 on p. 192.)

There is no need to analyze causal paradoxes that would arise from such a time machine spacetime. The sober truth is that the classical Einstein equation implies that wormholes require matter with negative energy densities, and the energy densities of all known classical fields are positive. Short of invoking quantum fluctuations in spacetime geometry, the future domain of application for wormholes is probably entirely fictional.

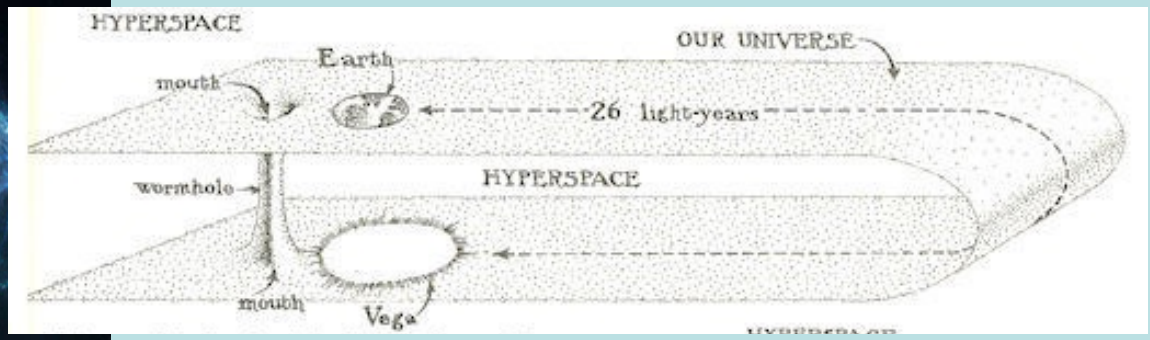






星際效應電影



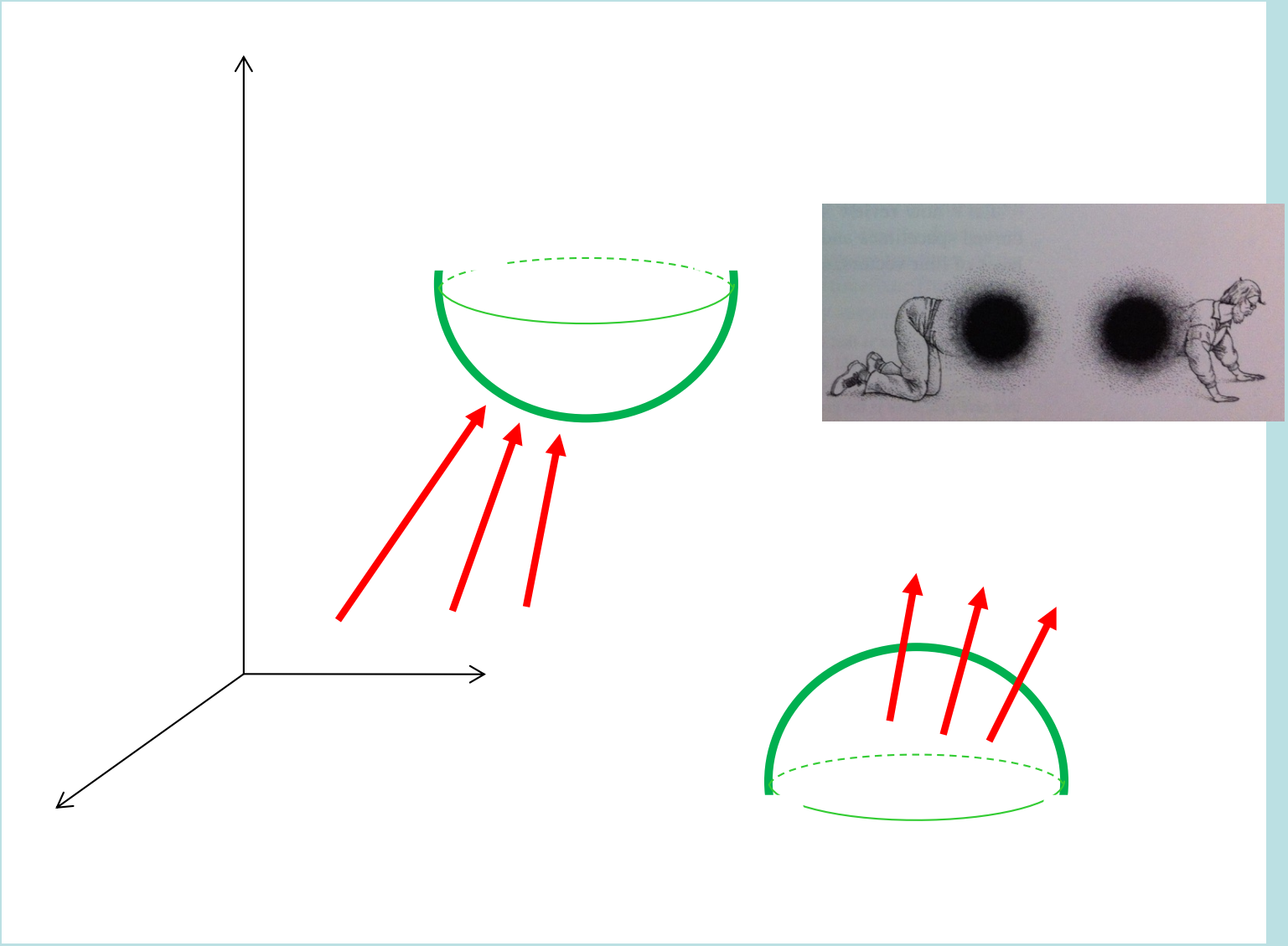


從土星附近，高等文明所創造的蟲洞，到達遠方銀河，尋找遷居地。



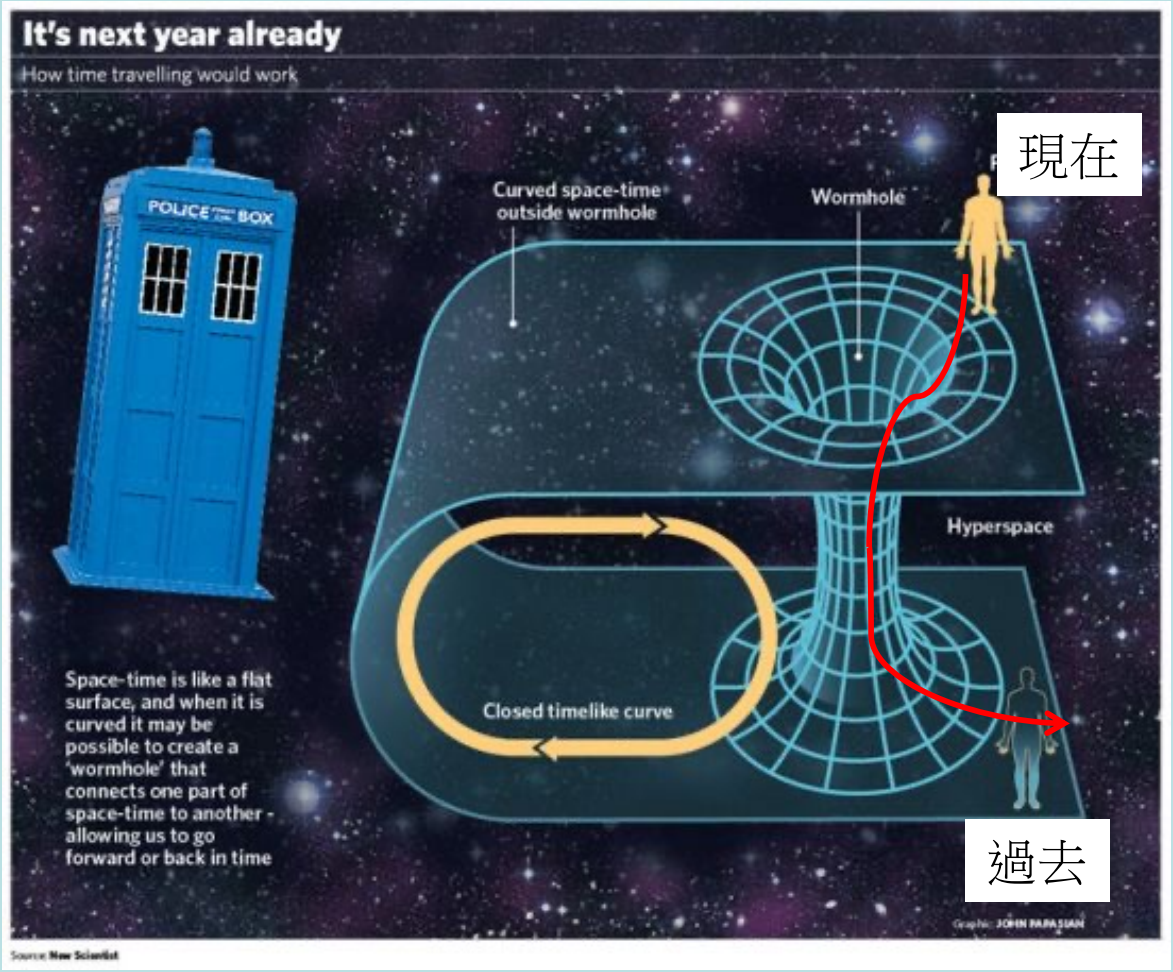
時間與空間是無法分割的！

時間在重力下也會扭曲！



如果蟲洞的出口時間在入口之前呢？

我們就可以透過蟲洞回到過去





因為時空是不可分的，連接空間不同位置的蟲洞，也能連接現在與過去！

廣義相對論暗示時光旅行是有可能的！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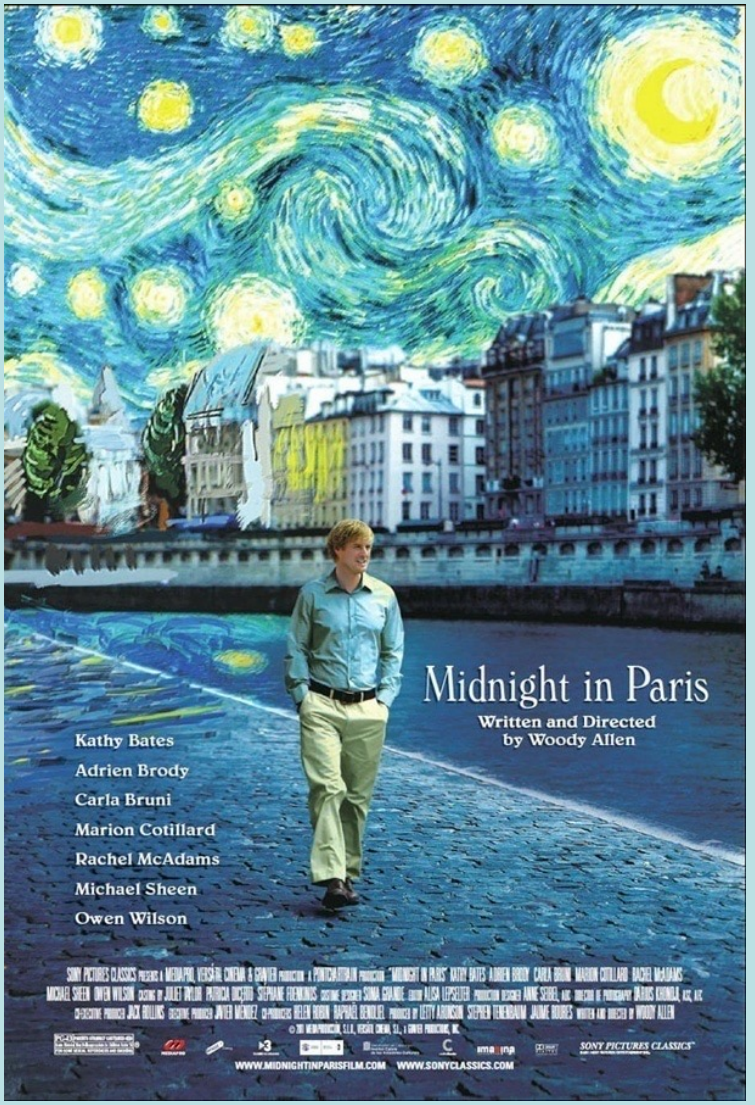
BACK TO THE FUTURE


Midnight in Paris
Written and Directed by Woody Allen
Kathy Bates
Adrien Brody
Carla Bruni
Marion Cotillard
Rachel McAdams
Michael Sheen
Owen Wilson
WWW.MIDNIGHTINPARISFILM.COM
WWW.SONYCLASSICS.COM
SONY PICTURES CLASSICS

午夜巴黎





右邊的那位鬥牛士Garcia是海明威小說午後之死的角色原型



VOLUME 61, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1988

Wormholes, Time Machines, and the Weak Energy Condition

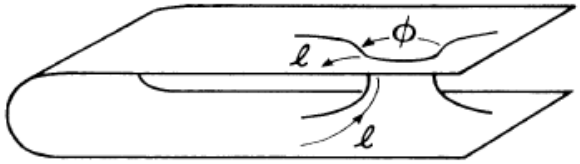
Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 21 June 1988)

It is argued that, if the laws of physics permit an advanced civilization to create and maintain a wormhole in space for interstellar travel, then that wormhole can be converted into a time machine with which causality might be violatable. Whether wormholes can be created and maintained entails deep, ill-understood issues about cosmic censorship, quantum gravity, and quantum field theory, including the question of whether field theory enforces an averaged version of the weak energy condition.

PACS numbers: 04.60.+n, 03.70.+k, 04.20.Cv



Normally theoretical physicists ask, "What are the laws of physics?" and/or, "What do those laws predict about the Universe?" In this Letter we ask, instead, "What constraints do the laws of physics place on the activities of an arbitrarily advanced civilization?" This will lead to some intriguing queries about the laws themselves.



into time machines.

Wormhole creation.— Worm
mild spacetime curvature that
is everywhere valid, must be
timelike curves and/or a nonco
ture light cone,[5] and also by a
ergy condition."[6] Specific spa
Thus, if one could show
forbids violations of AWEC, o
civilizations maintaining traver

Specialize to a static, spheri
time metric[4]

$$ds^2 = -e^{2\Phi}dt^2 + dl^2 + r^2(d\theta^2 + \sin^2\theta\, d\phi^2),$$

The Nobel Prize in Physics 2017

Rainer Weiss, Barry C. Barish, Kip S. Thorne

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The Nobel Prize in Physics 2017



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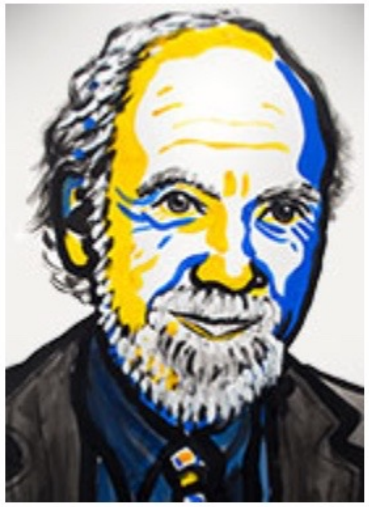
Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4



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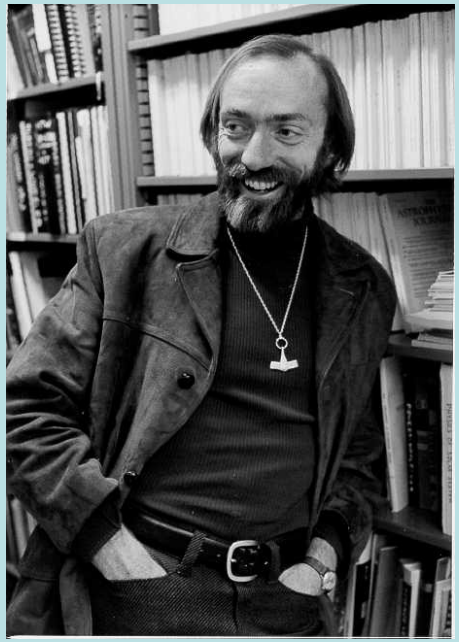
Kip S. Thorne

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"*.

如果某人透過蟲洞回到過去

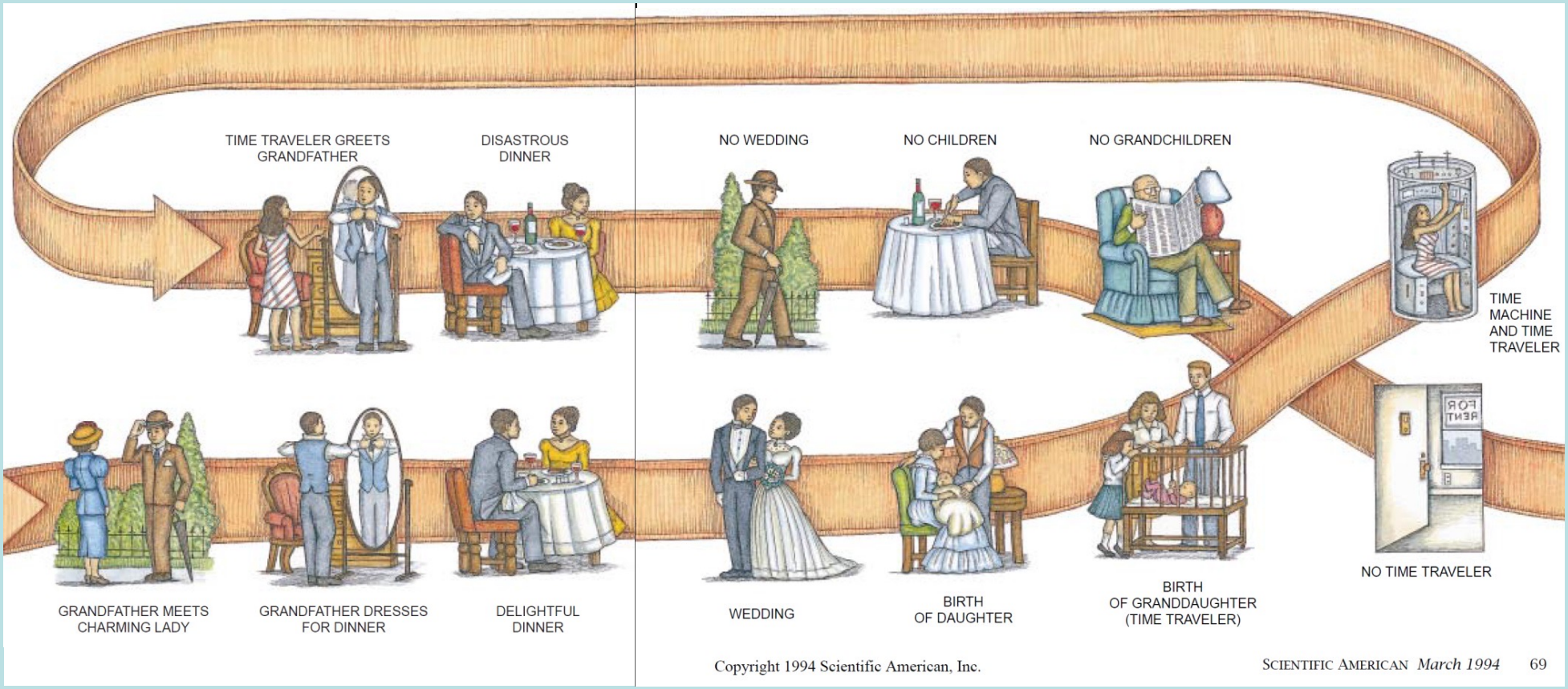


現在

過去

在他父母的婚禮上阻止兩人結婚

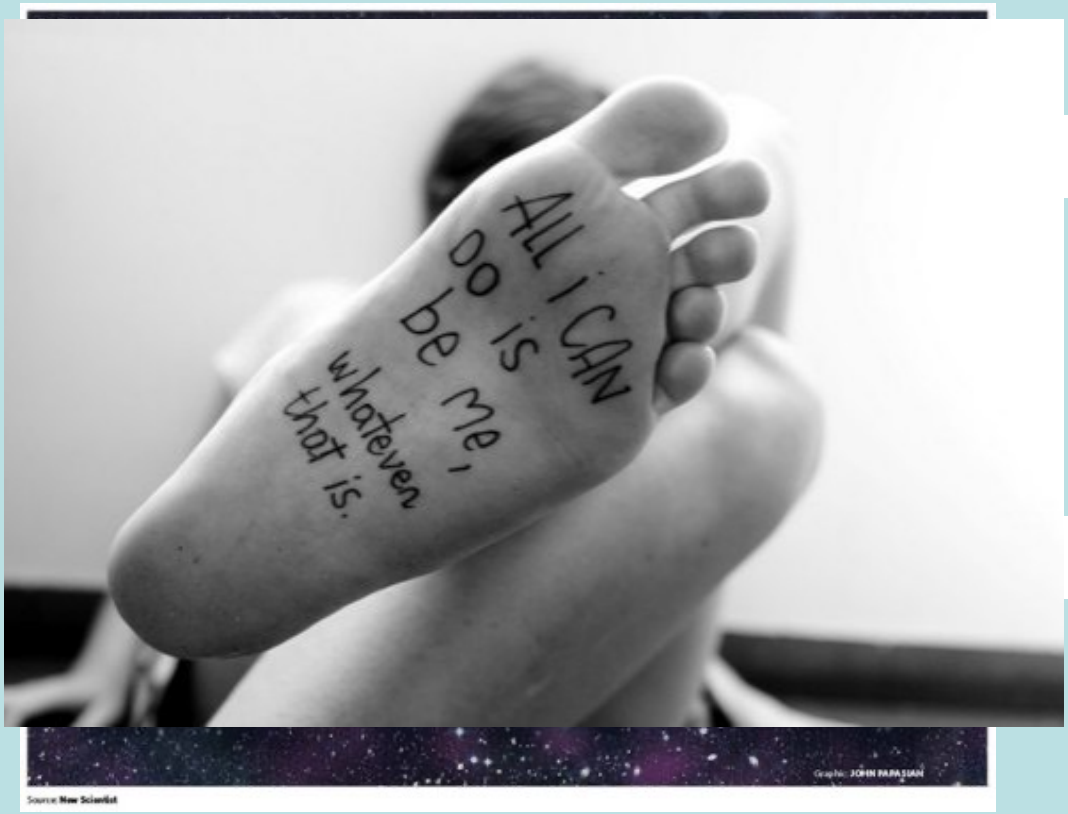
那此人就不能出生，也就不存在！


TIME TRAVELER GREETS GRANDFATHER
DISASTROUS DINNER
NO WEDDING
NO CHILDREN
NO GRANDCHILDREN
TIME MACHINE AND TIME TRAVELER
GRANDFATHER MEETS CHARMING LADY
GRANDFATHER DRESSES FOR DINNER
DELIGHTFUL DINNER
WEDDING
BIRTH OF DAUGHTER
BIRTH OF GRANDDAUGHTER (TIME TRAVELER)
NO TIME TRAVELER
FOR RENT
Copyright 1994 Scientific American, Inc.
SCIENTIFIC AMERICAN March 1994 69

這是不合理的。

如果某人透過蟲洞回到過去，他就不能胡作非為！

時光旅行必定是有隱含的限制！

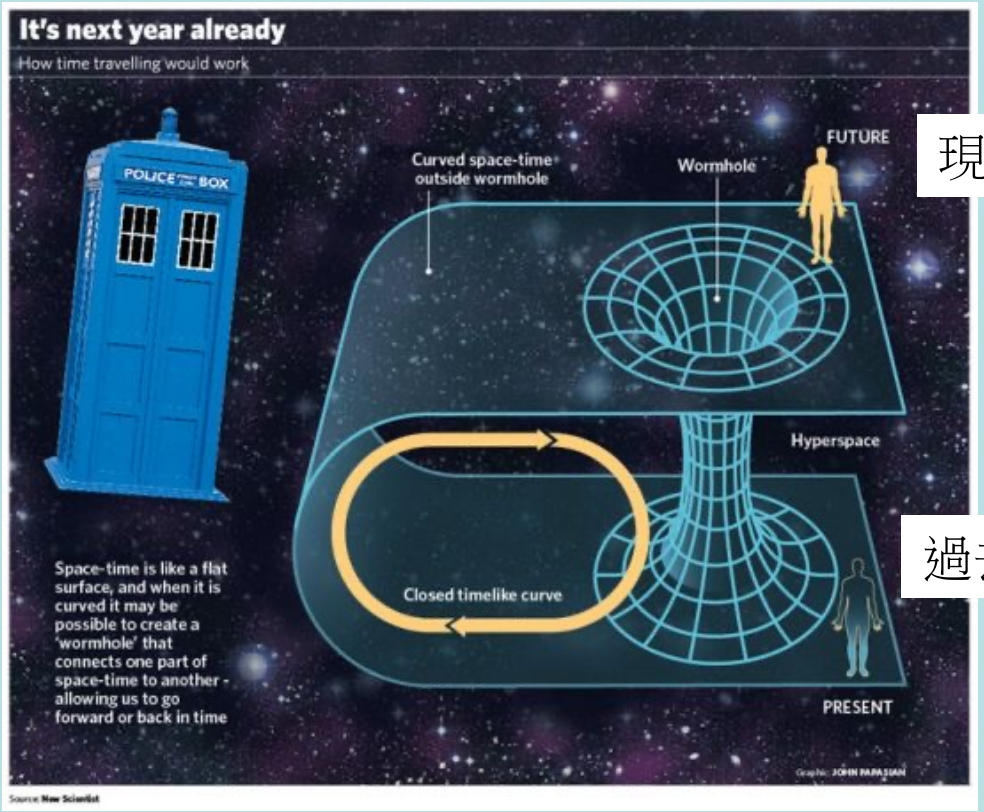


他唯一能做的就是.....

做他自己！

Be yourself.

如果某人透過蟲洞回到過去，他就不能胡作非為！



現在

過去

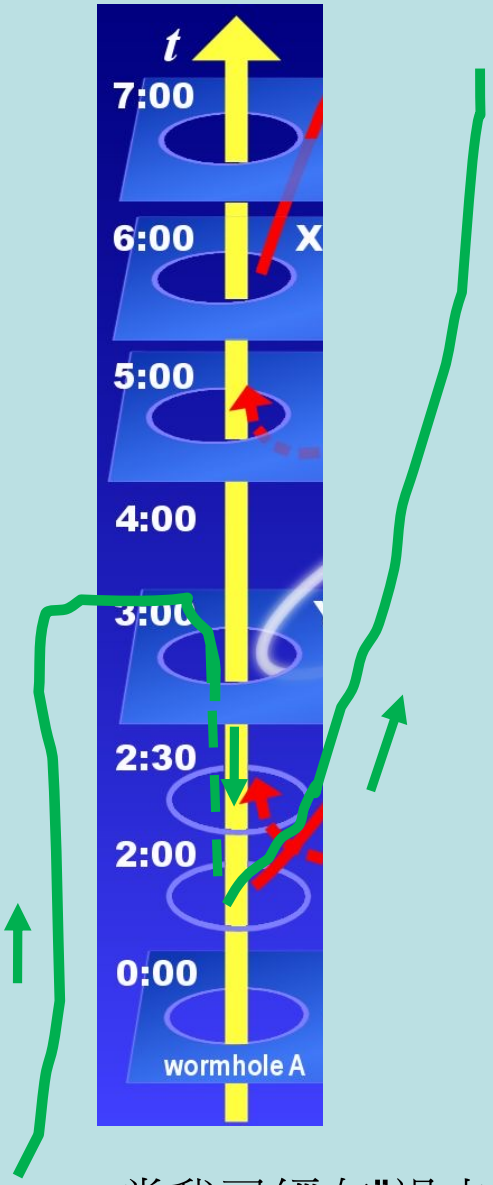
做他自己！做他當初所作的那個自己！

重覆當初過去的那個自己！

他自己的一生會形成一個封閉迴路！

這樣才能維持一致性 consistency　　closed timelike curve

Novikov Self-Consistency Conjecture



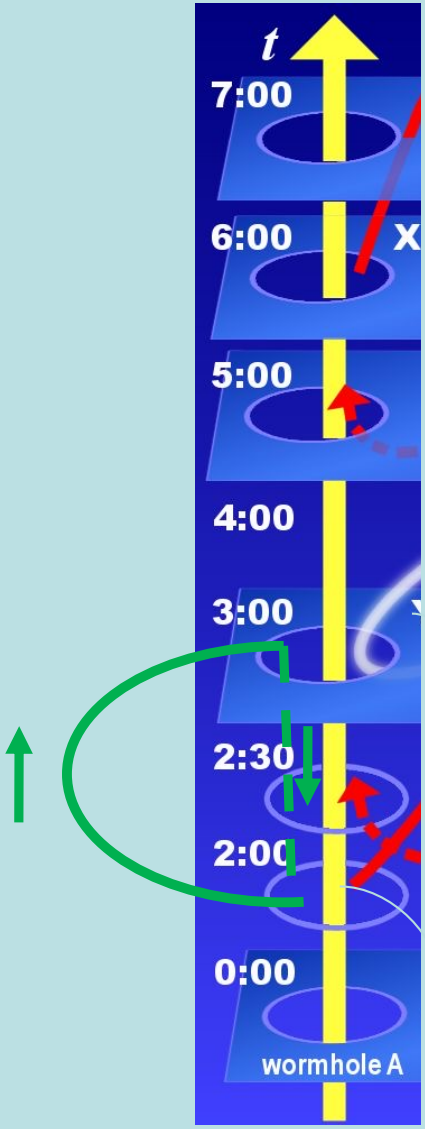
這種一致性隱含很扭曲的一些結果！

我進入時光機器後，出現在過去！

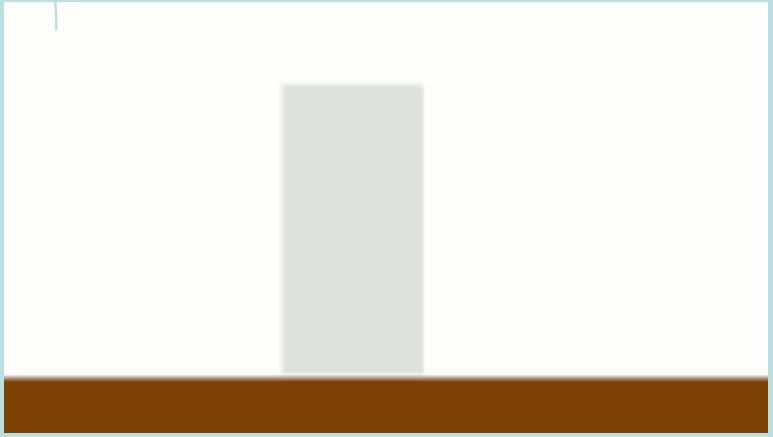


當我已經在”過去”出現”後”，我就不能改變主意不進入時光機器！

選擇進入時光機，就等於放棄自由意志！　　怪！



我進入時光機，回到過去，過了一陣子，再次進入時光機。



我進入時光機，回到過去，過了一陣子，進入時光機，
回到過去，過了一陣子，進入時光機，回到過去……

沒有未來的人！

真怪！

The Quantum Physics of Time Travel

Common sense may rule out such excursions—but the laws of physics do not

by David Deutsch and Michael Lockwood

Imagine, if you will, that our friend Sonia keeps a time machine in her garage. Last night she used it to visit her grandfather in 1934, when he was still courting her grandmother. Sonia convinced him of her identity by re-

Yet, surprisingly, the laws of physics do not forbid such adventures.

Another paradox, which often appears in science fiction, has been discussed by the Oxford philosopher Michael Dummett. An art critic from the

ocre and concludes that the artist has yet to produce those inspired paintings that so impressed future generations. The critic shows the painter a book of reproductions of these later works. The painter contrives to hide this book,

常識可能會rule out時間旅行，但物理定律並沒有辦法。



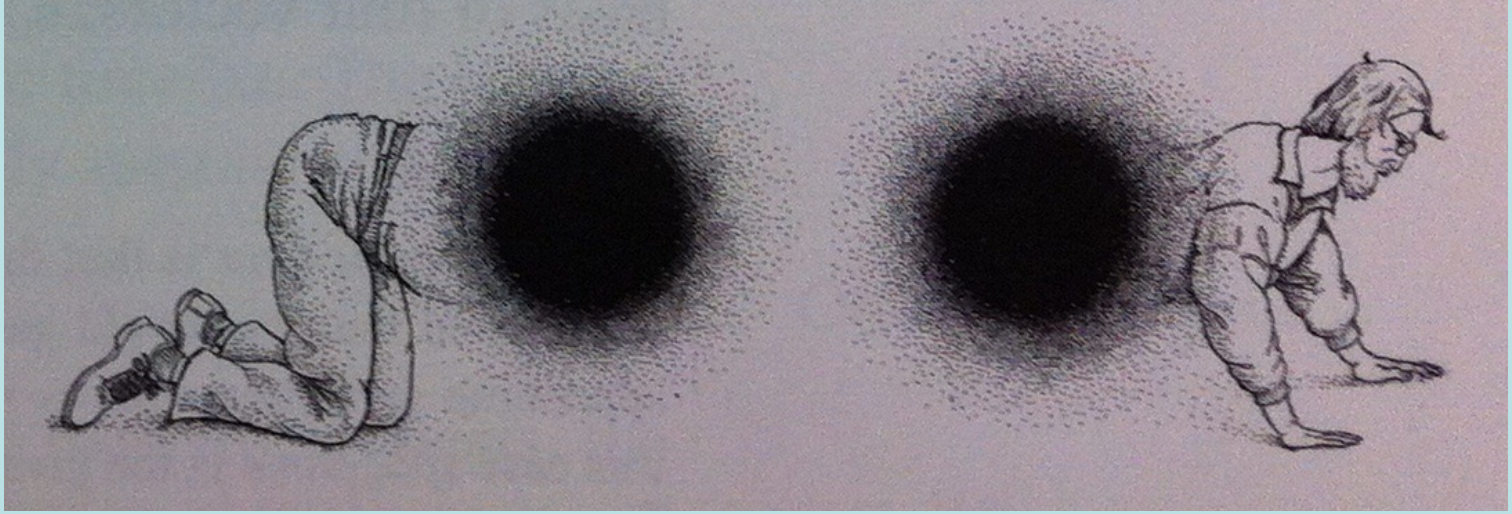




Hawking Chron

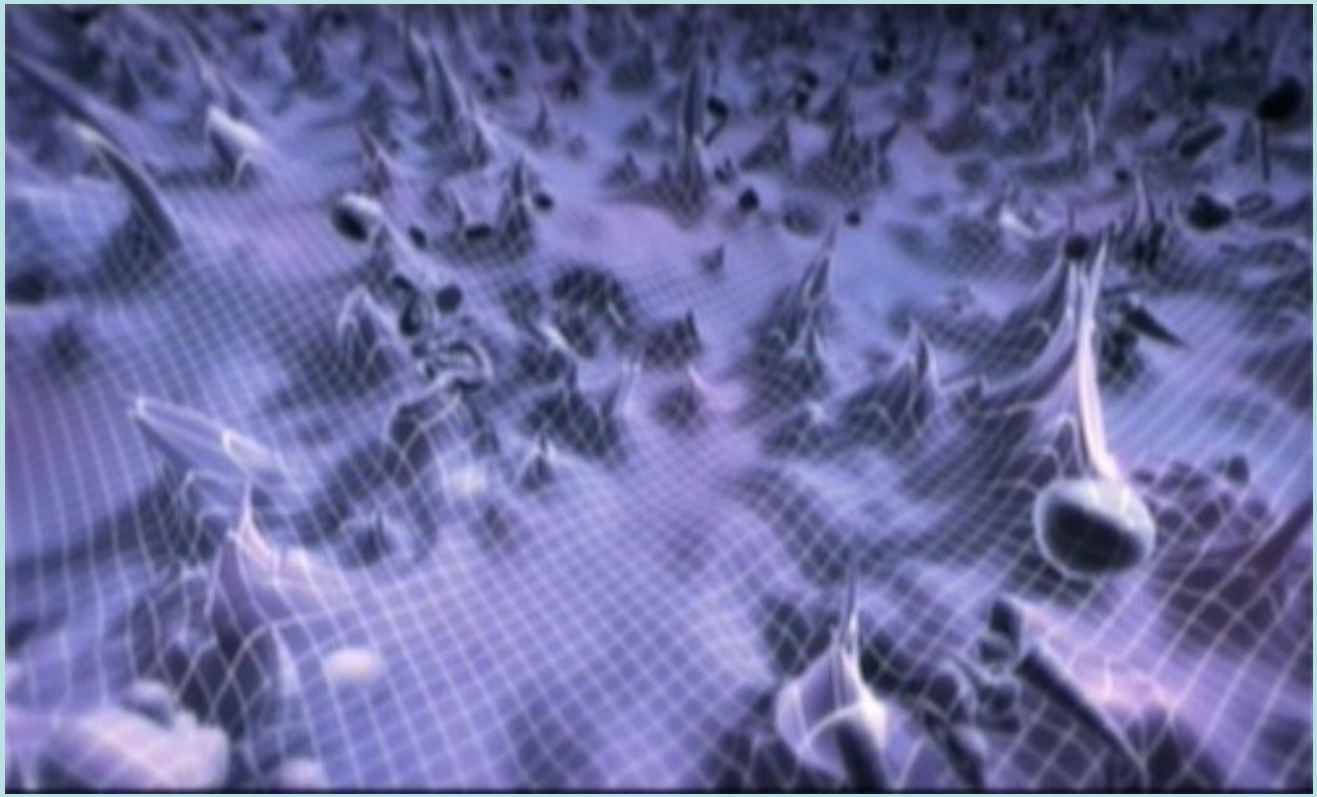
Time travel is s

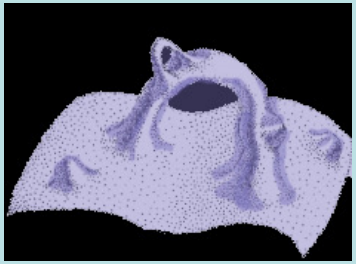
There is no need to analyze causal paradoxes that would arise from such a time machine spacetime. The sober truth is that the classical Einstein equation implies that wormholes require matter with negative energy densities, and the energy densities of all known classical fields are positive. Short of invoking quantum fluctuations in spacetime geometry, the future domain of application for wormholes is probably entirely fictional.



支配重力的廣義相對論容許蟲洞存在！

而且量子效應似乎逼使蟲洞在微觀的尺度一直不斷地產生又消滅。





若是能產生蟲洞並維持夠久，我們就有可以回到過去的時間機器

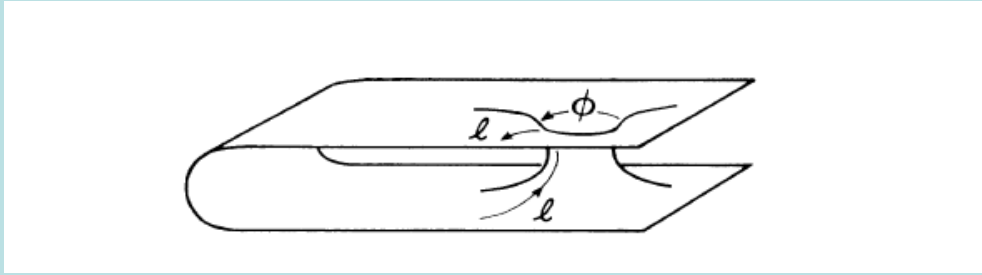
NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEM

Wormholes, Time Machines, and the Weak Energy Condition

Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 21 June 1988)

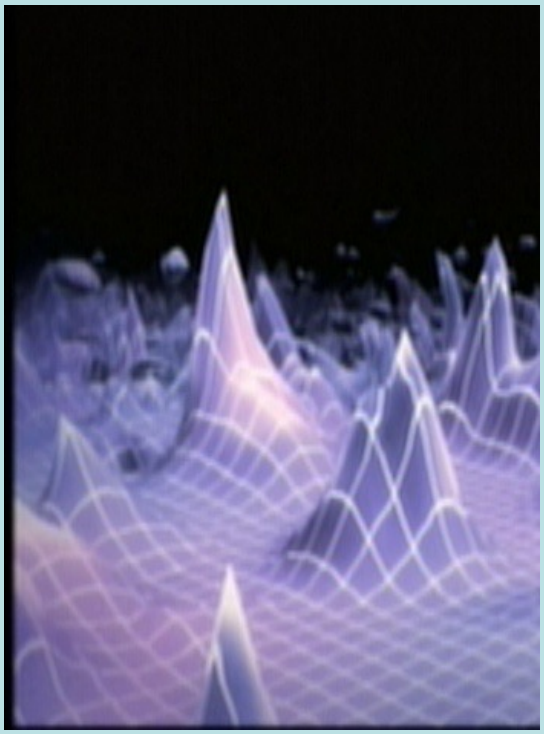
It is argued that, if the laws of physics permit an advanced civilization to create and maintain a wormhole in space for interstellar travel, then that wormhole can be converted into a time machine with which causality might be violatable. Whether wormholes can be created and maintained entails deep, ill-understood issues about cosmic censorship, quantum gravity, and quantum field theory, including the question of whether field theory enforces an averaged version of the weak energy condition.

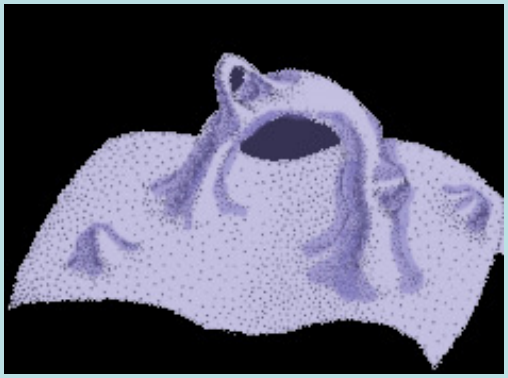




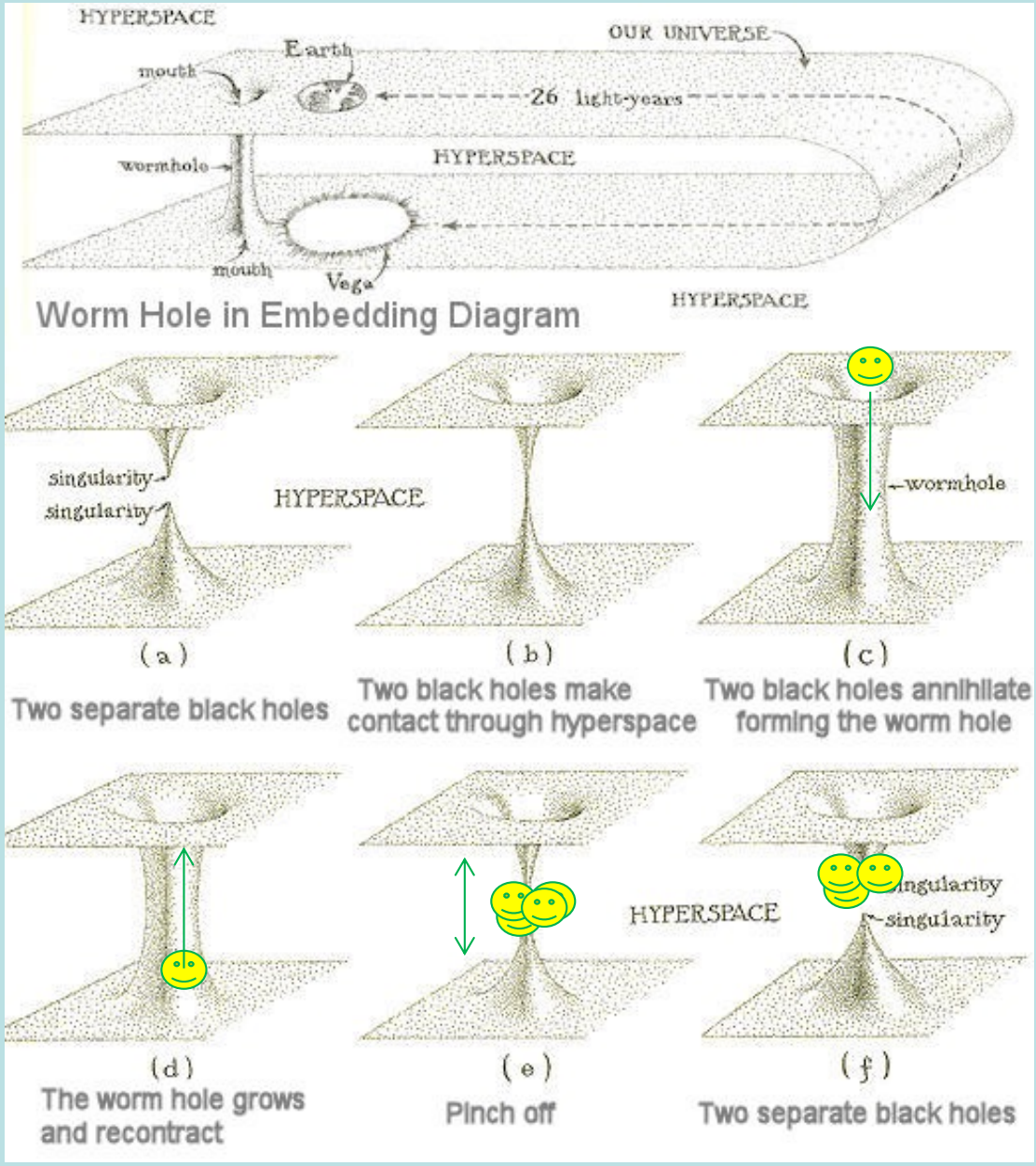
支配重力的廣義相對論容許蟲洞存在！

但是否能產生蟲洞並維持夠久似乎牽扯其他物理定律許多棘手的問題。





最新的結果顯示，蟲洞若存在，也是很小，很不穩定，無法預測！



物理學家推想蟲洞生成後會吸入粒子，從另一端離開的粒子又會被吸回最後在蟲洞內會累積大量能量，以致它變回一個黑洞。

arXiv:gr-qc/0504039v1 8 Apr 2005

Rebuttal to a Paper on Wormholes



L. Susskind

Department of Physics
Stanford University
Stanford, CA 94305-4060

Abstract

In a recent paper on wormholes (gr-qc/0503097), the author of that paper demonstrated that he didn't know what he was talking about. In this paper I correct the author's naive erroneous misconceptions.

arXiv:gr-qc/0503097v3 8 Apr 2005

Wormholes and Time Travel? Not Likely

L. Susskind

Department of Physics
Stanford University
Stanford, CA 94305-4060

Abstract

Wormholes have been advanced as both a method for circumventing the limitations of the speed of light as well as a means for building a time machine (to travel to the past). Thus it is argued that General Relativity may allow both of these possibilities. In this note I argue that traversable wormholes connecting otherwise causally disconnected regions, violate two of the most fundamental principles physics, namely local energy conservation and the energy-time uncertainty principle.

r-qc/0503097v3 8 Apr 2005

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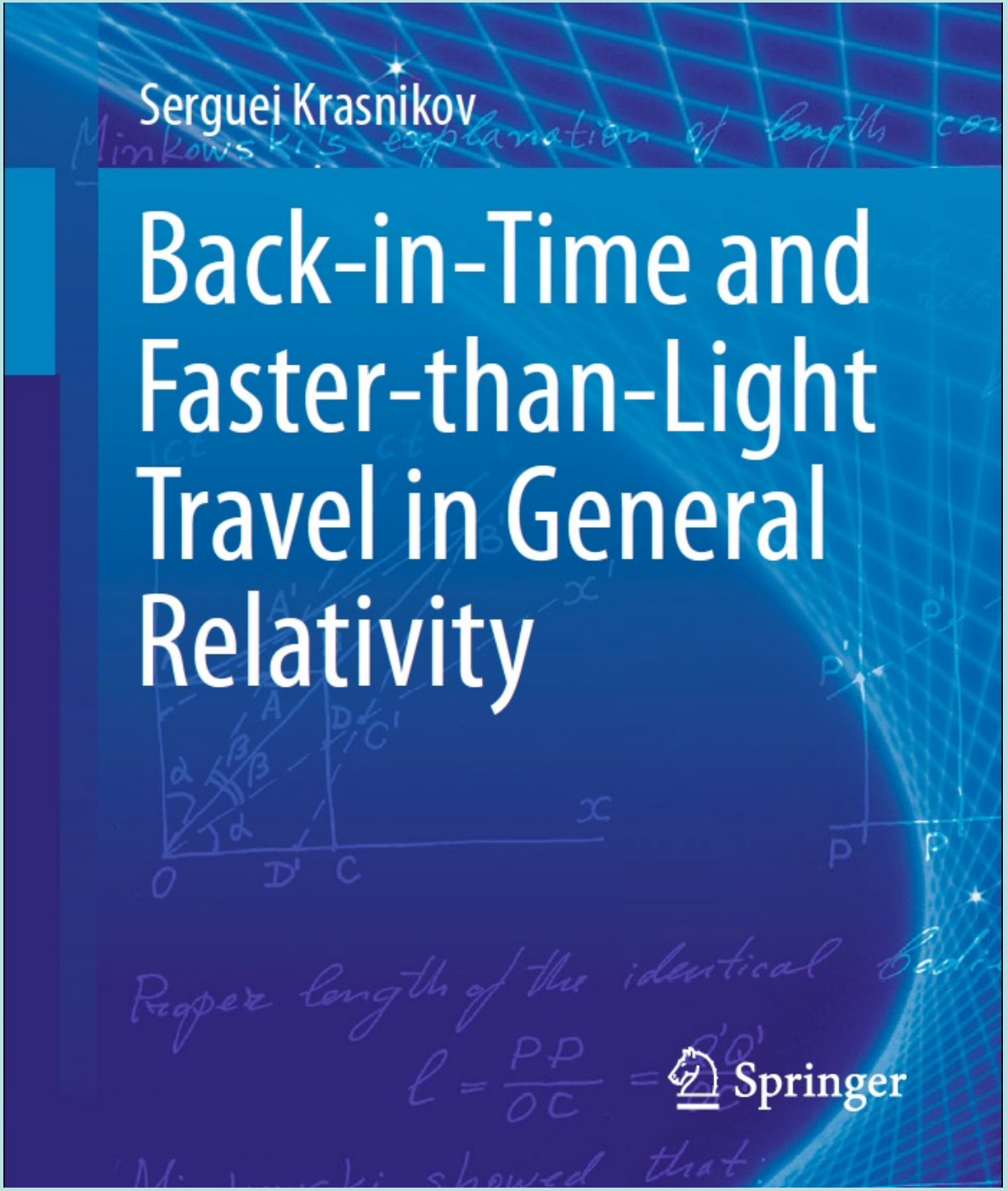
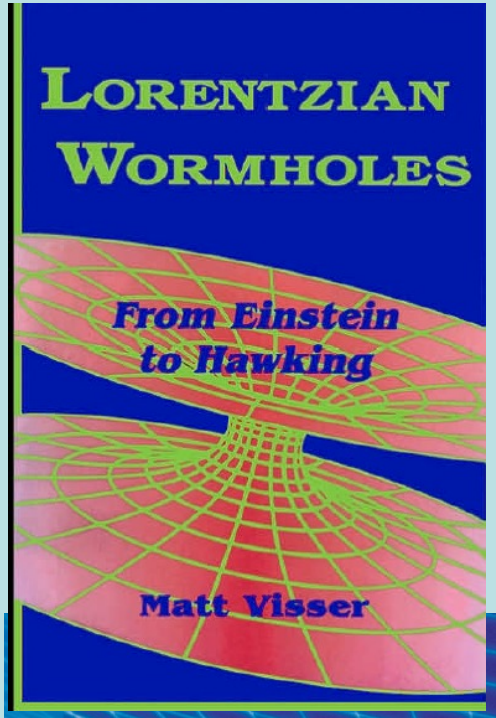
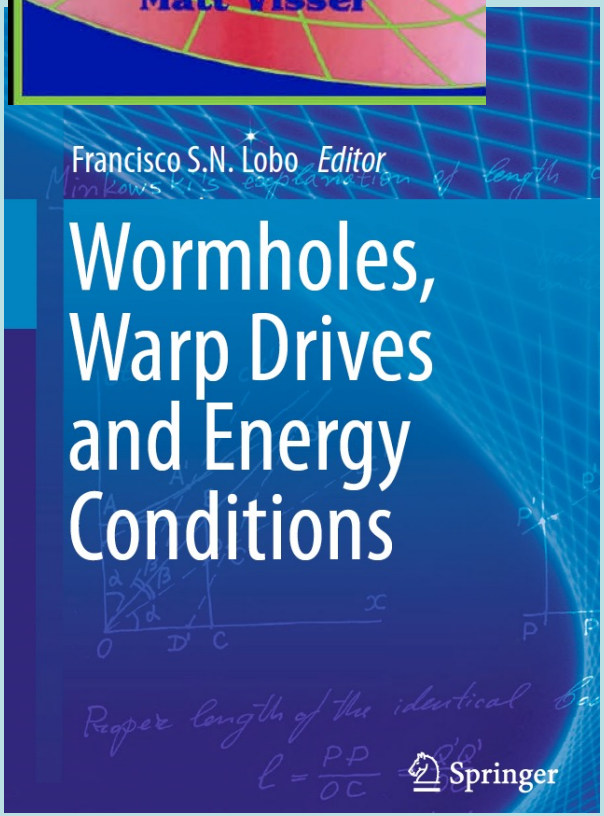

Serguei Krasnikov
Back-in-Time and Faster-than-Light Travel in General Relativity
Springer


LORENTZIAN WORMHOLES
From Einstein to Hawking
Matt Visser


Francisco S.N. Lobo Editor
Wormholes, Warp Drives and Energy Conditions
Springer

arXiv:1608.05687v2 [hep-th] 11 Sep 2017

Traversable Wormholes via a Double Trace Deformation

Ping Gao[1], Daniel Louis Jafferis[1], Aron C. Wall[2]

[1] *Center for the Fundamental Laws of Nature, Harvard University, Cambridge, MA, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ, USA*

Abstract

After turning on an interaction that couples the two boundaries of an eternal BTZ black hole, we find a quantum matter stress tensor with negative average null energy, whose gravitational backreaction renders the Einstein-Rosen bridge traversable. Such a traversable wormhole has an interesting interpretation in the context of ER=EPR, which we suggest might be related to quantum teleportation. However, it cannot be used to violate causality. We also discuss the implications for the energy and holographic entropy in the dual CFT description.

Diving into traversable wormholes

Juan Maldacena[1], Douglas Stanford[1] and Zhenbin Yang[2]

[1]Institute for Advanced Study, Princeton, NJ 08540, USA

[2]Jadwin Hall, Princeton University, Princeton, NJ 08540, USA

or 2017

Traversable wormholes in four dimensions

Juan Maldacena[1], Alexey Milekhin[2] and Fedor Popov[2]

[1]Institute for Advanced Study, Princeton, NJ 08540, U.S.A.

[2]Physics Department, Princeton University, Princeton, NJ 08544, U.S.A.

07.04726v2 [hep-th] 29 Aug 2018

Abstract

We present a wormhole solution in four dimensions. It is a solution of an Einstein Maxwell theory plus charged massless fermions. The fermions give rise to a negative Casimir-like energy, which makes the wormhole possible. It is a long wormhole that does not lead to causality violations in the ambient space. It can be viewed as a pair of entangled near extremal black holes with an interaction term generated by the exchange of fermion fields. The solution can be embedded in the Standard Model by making its overall size small compared to the electroweak scale.

Creating a Traversable Wormhole

Gary T. Horowitz[♯], Don Marolf[♯], Jorge E. Santos[◇], Diandian Wang[♯]

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rXiv:1904.02187v2 [hep-th] 30 Apr 2019

We argue that one can nucleate a traversable wormhole via a nonperturbative process in quantum gravity. To support this, we construct spacetimes in which there are instantons giving a finite probability for a test cosmic string to break and produce two particles on its ends. One should be able to replace the particles with small black holes with only small changes to the spacetime away from the horizons. The black holes are then created with their horizons identified, so this is an example of nucleating a wormhole. Unlike previous examples where the created black holes accelerate apart, in our case they remain essentially at rest. This is important since wormholes become harder and harder to make traversable as their mouths become widely separated, and since traversability can be destroyed by Unruh radiation. In our case, back-reaction from quantum fields can make the wormhole traversable.

Humanly traversable wormholes

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[2]Physics Department, Princeton University, Princeton, NJ 08544, U.S.A.

8v1 [hep-th] 15 Aug 2020

Abstract

We point out that there can be humanly traversable wormhole solutions in some previously considered theories for phys[illegible] the Standard Model, namely the Randall-Sundrum model.

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1. arXiv:2010.07317 [pdf, ps, other] gr-qc hep-th

Traversable wormholes in Einstein-Dirac-Maxwell theory

Authors: Jose Luis Blázquez-Salcedo, Christian Knoll, Eugen Radu

Abstract: We construct traversable wormholes in Einstein-Dirac-Maxwell theory in four spacetime dimensions, without needing any form of exotic matter. Restricting to a model with two massive fermions in a singlet spinor state, we show the existence of spherically symmetric asymptotically flat configurations which are free of singularities, representing localized states. These solutions satisfy a generalized... ▽ More

Submitted 14 October, 2020; **originally announced** October 2020.

Comments: 5 pages, 4 figures

2. arXiv:2010.05298 [pdf, other] gr-qc hep-th

Traversable wormhole solution with a background Kalb-Ramond field

Authors: L. A. Lessa, R. Oliveira, J. E. G. Silva, C. A. S. Almeida

Abstract: We obtain a static spherically symmetric wormhole solution due to the vacuum expectation value (VEV) of a Kalb-Ramond field. The Kalb-Ramond VEV is a background tensor field which produces a local Lorentz symmetry breaking (LSB) of spacetime. Considering a non-minimal coupling between the Kalb-Ramond (VEV) and the Ricci tensor, we found an exact traversable wormhole solution sustain... ▽ More

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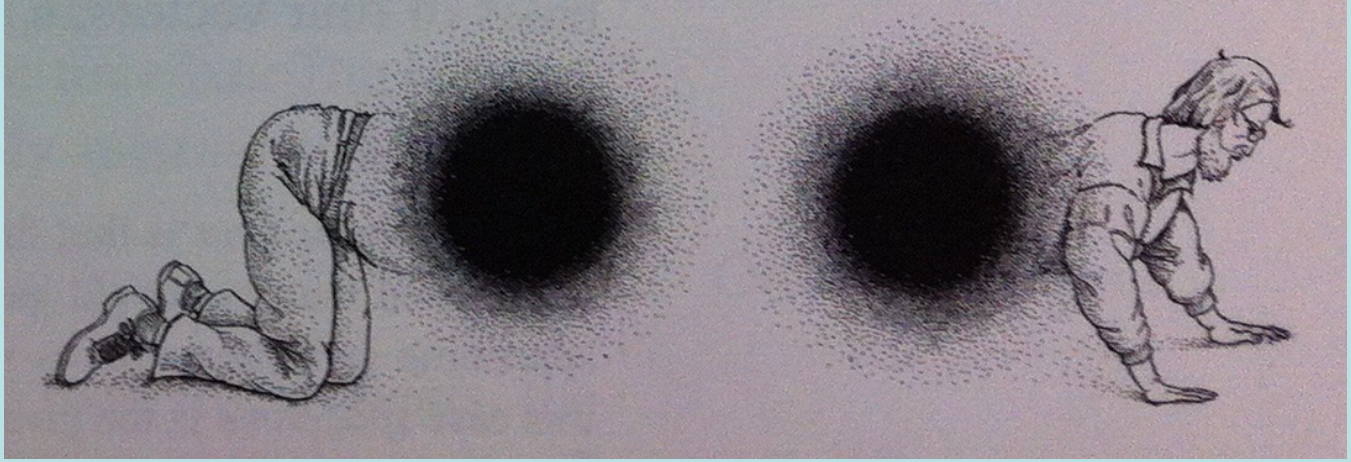
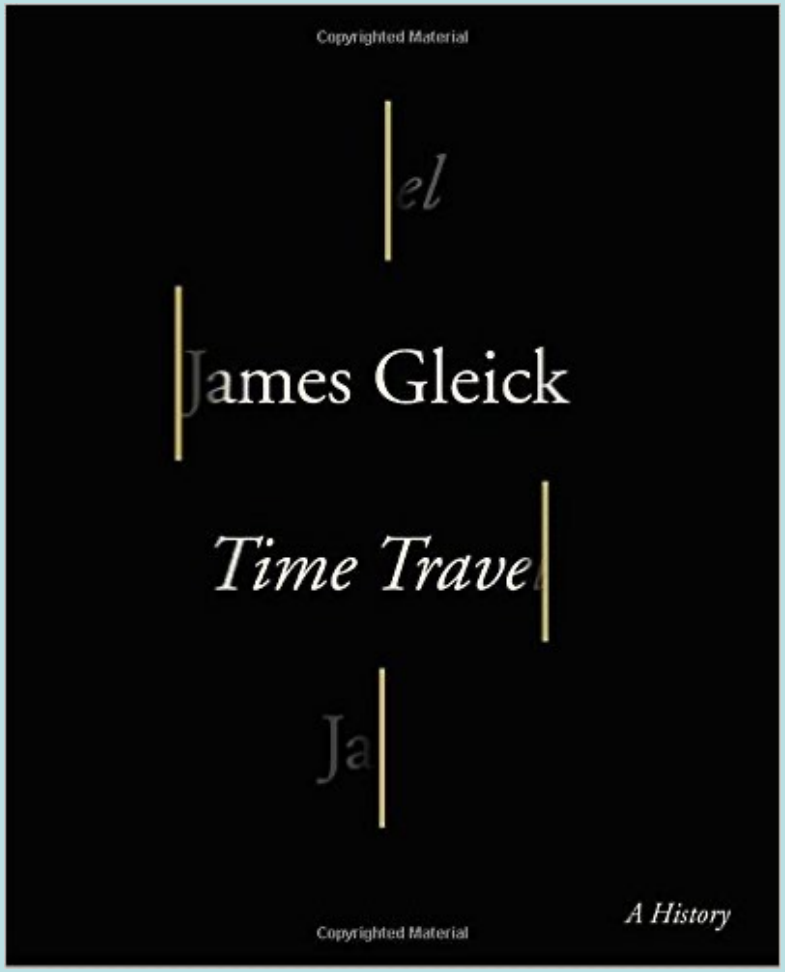
Submitted 11 October, 2020; **originally announced** October 2020.

蟲洞一出現，很快就被摧毀。

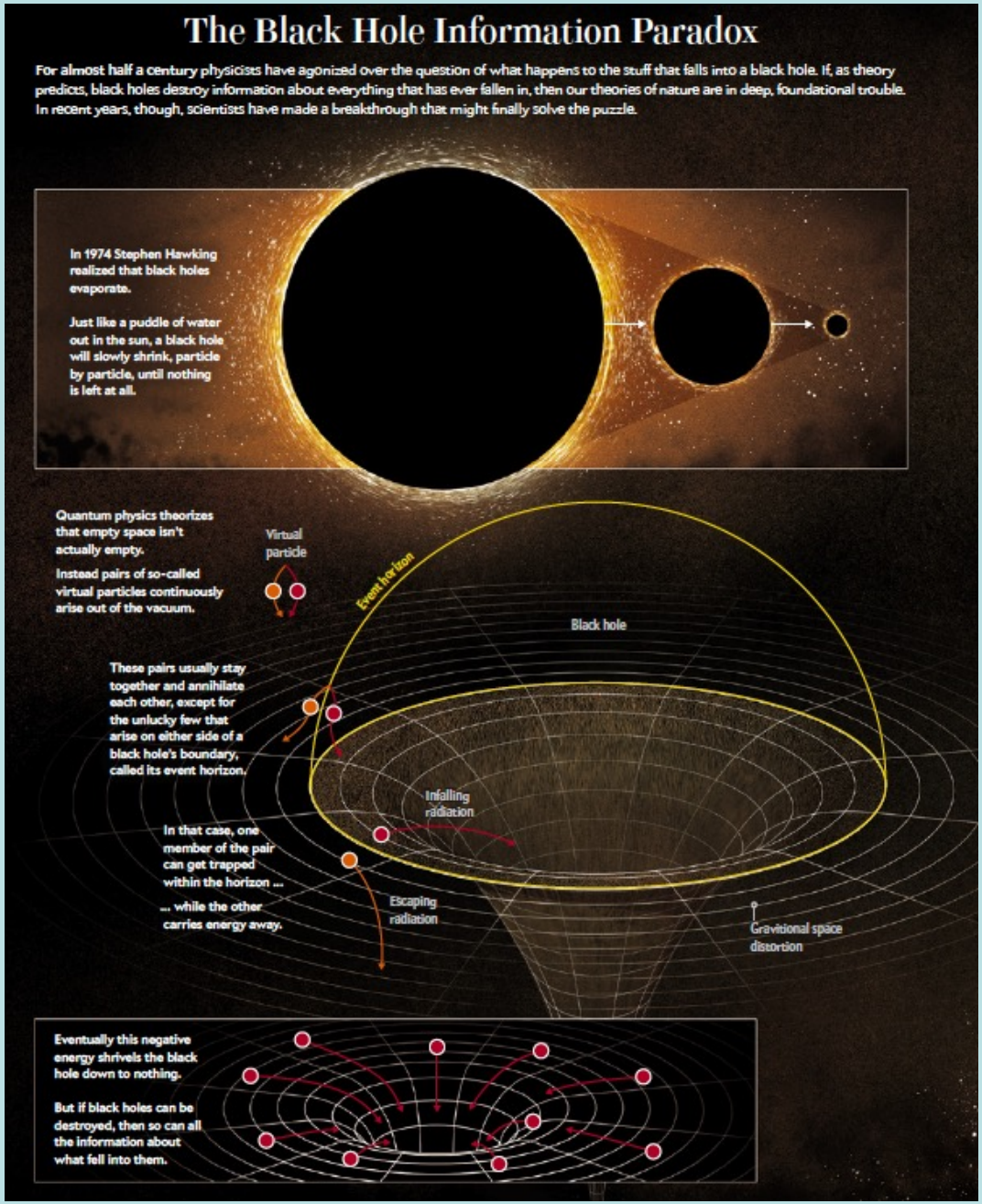
There is no need to analyze causal paradoxes that would arise from such a time machine spacetime. The sober truth is that the classical Einstein equation implies that wormholes require matter with negative energy densities, and the energy densities of all known classical fields are positive. Short of invoking quantum fluctuations in spacetime geometry, the future domain of application for wormholes is probably entirely fictional.



Time travel is still a dream, just a dream.



黑洞可能會蒸發！霍金輻射。

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