

掉進 黑洞 怎麼辦？

What if You Fell into a Black Hole?



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物理	Physics	「東西的道理」	運動、能量、力量	Reasons of things
化學	Chemistry	「東西的本質」	物質組成、結構、變化	Makeup of things
生物	Biology	「某種特殊東西」	的結構、功能、演化	Special kinds of things
歷史	History	「事情的來龍去脈」	過往的紀錄	Time record; who's who
地理	Geography	「周遭的環境」	地形、地貌、居住者	Where's where

對象是宇宙、天體 → 天文學 Astronomy: all the above in space

問天大的問題

窮其一生問問題，找答案

Research---Search and Search again, for questions & and answers

- ♠ 黑洞是什麼？ What is a black hole?
- ♥ 有哪些種黑洞 What are the kinds of BHs?
- ♦ 靠近黑洞會怎麼樣 What happens if nearing one?
- ♣ 掉進黑洞呢？ And what happens if you fell into it?

- 可不可以講黑洞，但是不講物理？

Is it possible to talk about BHs without physics?

可以，但乏味多了！

Of course, but it'll be dull.

- 物質狀態：固態、液態、氣態、電漿
(離子)態 ...

“State” of matter: solid, liquid, gas, plasma (ionized), ...

- 由哪些條件決定？溫度與壓力

depends on pressure and temperature



蒸發 (evaporation)

液體分子彼此碰撞 → 脫離表面成為氣態 (任何溫度)

沸騰 (boiling)

液體分子碰撞 → 整體在特定溫度成為氣態

若少了大氣壓著，蒸發快，更易沸騰

a lower atmospheric pressure (e.g., at a high altitude)

→ easier to evaporate and to boil



黑洞是種質能狀態，當某處塞進
太多東西（太擠），就成了黑洞

When a place is squeezed into too much matter (too crowded), it becomes
an energy-matter state --- a black hole

質量 = 東西有「多少」

密度 = 東西有「多擠」

Mass: how much “stuff”

Volume: how large it is

Density: how compact = M/V

$$\text{密度} = \frac{\text{質量}}{\text{體積}} = \frac{\text{質量}}{\text{長} \times \text{寬} \times \text{高}} = \frac{\text{質量}}{\text{尺寸}^3}$$

水的密度 = $1 \text{ g/cm}^3 = 1 \text{ kg/m}^3 = 1 \text{ kg/L}$

冰的密度 = 0.9 g/cm^3

鐵的密度 = 7.8 g/cm^3 ; 鉛的密度 = 11.3 g/cm^3

Compression \rightarrow denser

同樣東西 壓縮越小 \rightarrow 密度越大

萬有引力：「萬有」=萬物皆有
「引力」=互相吸引

$$\text{引力場} \propto \frac{\text{質量}}{\text{距離}^2}$$

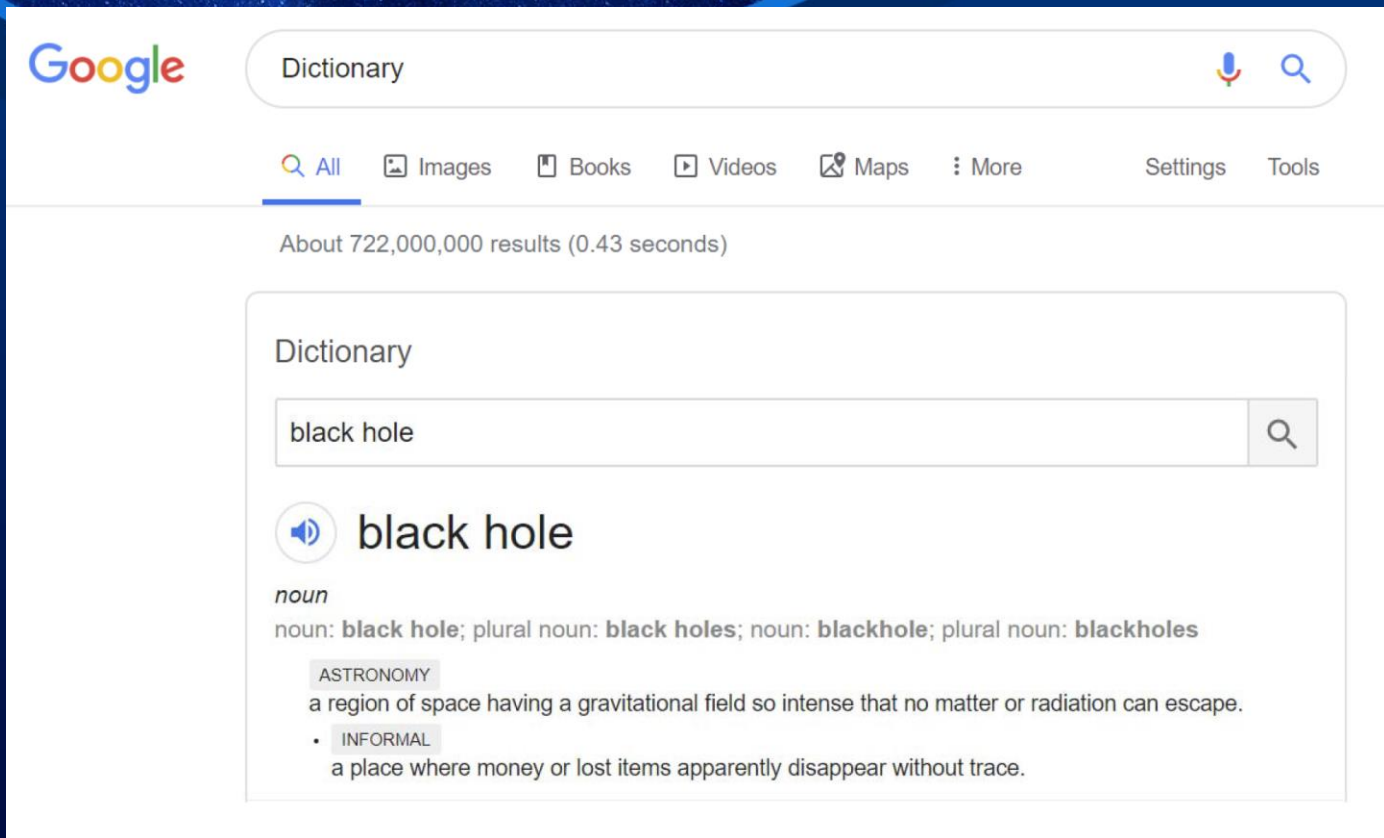
Gravitation: ubiquitous

$$\text{物體表面引力場} \propto \frac{\text{質量}}{\text{尺寸}^3}$$

同樣東西 越小 → 引力場越大

Surface gravity: the smaller, the stronger

何謂黑洞？



The image shows a screenshot of a Google search interface. At the top left is the Google logo. The search bar contains the word "Dictionary" and has a microphone icon and a search icon on the right. Below the search bar are navigation links: "All", "Images", "Books", "Videos", "Maps", "More", "Settings", and "Tools". The search results show "About 722,000,000 results (0.43 seconds)". The main content area displays the word "black hole" in a search box. Below the search box, there is a speaker icon and the text "black hole". Underneath, it says "noun" and "noun: black hole; plural noun: black holes; noun: blackhole; plural noun: blackholes". There are two definitions: one under "ASTRONOMY" describing a region of space with a strong gravitational field, and one under "INFORMAL" describing a place where things disappear without trace.

Google


Dictionary

All Images Books Videos Maps More Settings Tools

About 722,000,000 results (0.43 seconds)

Dictionary

black hole

 black hole

noun

noun: **black hole**; plural noun: **black holes**; noun: **blackhole**; plural noun: **blackholes**

ASTRONOMY

a region of space having a gravitational field so intense that no matter or radiation can escape.

- INFORMAL**
- a place where money or lost items apparently disappear without trace.

太空中某處引
力場極強，以
致沒有物質或
能量能夠逃脫



首度揭開財政黑洞 - 特別企劃

businessweekly.com.tw/Event/feature.aspx?ID=301

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評比報告全文下載 台灣20縣市財政昏迷指數 各縣市政府回應 意見交流區

若對這一切，我以國家求情，可惜香港政府的司法權，強正務...
 而解釋，所以我國要求，可惜香港政府的司法權，強正務...
 如此解決偏局，可惜香港政府的司法權，強正務...
 點：而港府拒絕的理由是，從屬關係也不受優待...
 我們因而得知，港府重視司法主權，自屬當然也不受優待...
 如果港府知道要維護司法主權，背後當然...
 在香港人民以反送中而發起全面示威運動，背後當然...
 在港人心中，特首林鄭月娥欲將幾乎一手一手...
 崩解危機之際，特首林鄭月娥欲將幾乎一手一手...
 有政治聲望，這是基本常識。朝野對進退爭議，各有盤算。於台...
 陳阿佳事件引發港台當局鬥爭，一方假司法正義欲甩甩手...
 陳阿佳事件引發港台當局鬥爭，一方假司法正義欲甩甩手...
 山手，一方既開政治防線又逃避在野追擊，兩者兼得，才...
 既而，既要護司法主權，也要護司法正義，兩者兼得，才...
 是定勝。大事當前，朝野須齊心，槍口對外。若不識大體，

生，如同深圳證交所的中小企業板與...
 則及，科创板成立之初也引發轟動

典範。港府以...
 掌握民意，快速調整策略...
 實踐一接招不如出招，被動...
 繼續打下去，港府討不了便...
 但國共鬥爭的歷史教訓告...
 身邊，每當面對外部挑戰時...
 扯自家後腿，這才是最令...
 上

A BH is a state of matter --- where a volume of space confines too much matter that even light cannot escape.

It makes no sense to ask how big a typical BH is; this would be like asking how large “water” is (a glass of water versus a lake, an ocean?)

當某區域引力極大，以致光線
都跑不出來，就是黑洞

光線跑不出來？

What does it mean that light cannot escape?

靜者恆靜、動者恆動、轉者恆轉

保持原狀不需要力量，要改變狀態才要力量

Inertia --- to keep the status quo. Without external force, an object remain the same motion status, i.e., to stand still or to move in the same way.

光線沒有質量，但能動，有能量

Light has no mass, but it “moves”, and carries energy.

光線有「力量」，可以推東西

光線也會被引力彎曲

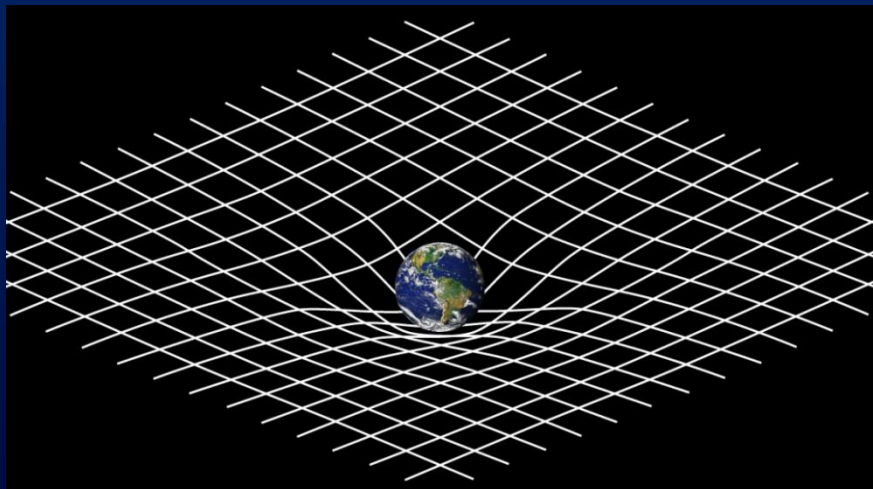
Light can push things, and can be bended.

引力彎曲？

Light can be bended by gravity.

「引力」和「加速度」分不出來
地面不動的電梯 與太空加速向上的電梯

An elevator on the ground = one accelerated (upwards) in space



彎曲的時空

物質決定了時空如何彎曲
時空決定了物質如何運動

Matter tells the space-time how to curve; the curved space-time tells matter how to move.

脫離速度 (escape velocity)

- 拋銅板向上...銅板向上飛，到最高點後停止，接著向下飛 Flip up a coin → reaching a max height then coming back down
- 如果用力向上拋銅板... Throw harder; reach higher.
- 但是如果真的很用力（夠快），越高處離地心越遠，引力越弱，便無法讓銅板停止 Throw hard, and it never comes back.
- 臨界速度稱做「逃脫速度」 This critical velocity/speed is called the escape velocity.
- 地球的脫離速度為 11 km/s 或 40,200 km/h ; 大於這個速度毋須額外力量就可脫離地球

On earth surface, the escape velocity is 11 km/s.



- 天體逃脫速度的快慢取決於它的質量及直徑

In general, the escape velocity depends on the mass and size of an object.

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

When the escape velocity becomes the speed of light (fastest motion in the Universe), this volume of space is called a black hole.

- 若某天體逃脫速度等於光速 → 黑洞

- 該半徑稱為 **史瓦茲半徑** (Schwarzschild radius) ,

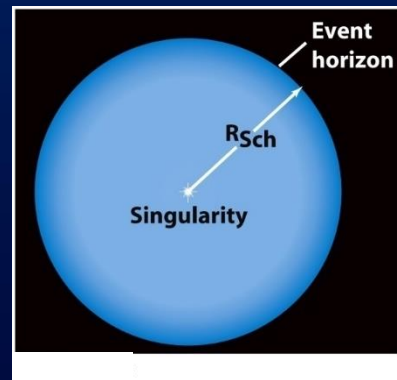
該球面稱為 **事件視界** (event horizon)

其內的訊息跑不出來

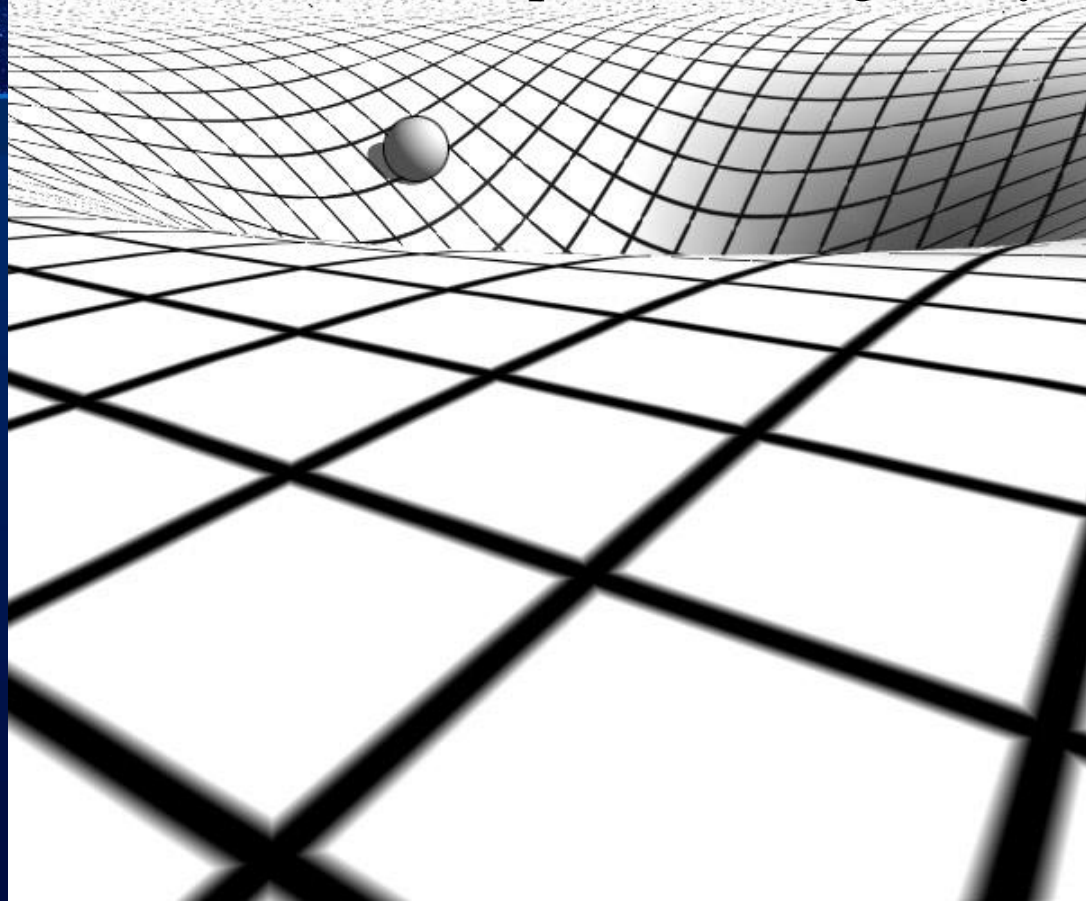
The boundary is named the “event horizon”, within which no information leaks out. .

- 最中央為時空奇異點

The radius (size) of the volume = Schwarzschild radius.



黑洞：物質壓縮，密度無限大
→ 時空奇異點 (spacetime singularity)



史瓦茲半徑

The size of a GH goes (linearly) with its mass.

$$R_{Sch} \approx 2 GM/c^2 \approx 3(\mathcal{M}/\mathcal{M}_{\odot}) [\text{km}]$$

其中 \mathcal{M} 代表黑洞的質量， \mathcal{M}_{\odot} 為太陽質量

Twice the mass, twice the size,
but density = (twice mass)/ (1/8 the volume)

- 把太陽壓縮成黑洞，半徑約為 **3 公里** A BH Sun, size = 3 km
- 把地球壓縮成黑洞，半徑約為 **1 公分** A BH Earth = 1 cm
- 質量為太陽1億倍的黑洞，其大小為**3億公里 = 2 au**
平均密度 $\sim 1 \text{ g/cc}$ (水!) A BH of 100 million suns,
size = 2 au, mean density = water

太陽核心1500萬度，進行核融合反應，產生更複雜的元
素，同時釋放出能量

Center of a star, 15 million deg, nuclear fusion:
4 H into 1 He

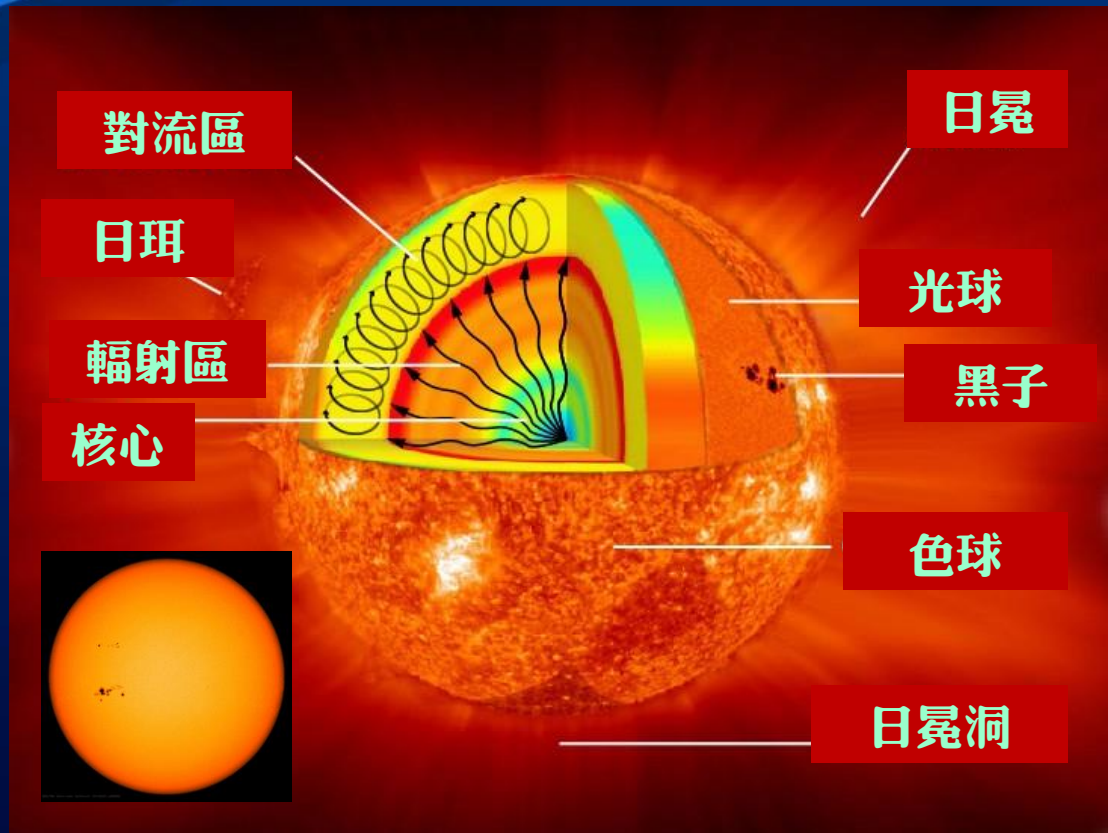
Byproducts: ever more complex
elements + Energy

這些能量讓氣體
高速運動，產生熱
壓力，向外膨脹，
平衡了向內收縮的
引力

Energy → expanding
pressure to balance gravity

太陽就這麼發光發
熱活了50億年

Sun has lived for 5 billion years.



據估計太陽還可以繼續存活50~70億年。一旦核心的核子燃料（氫、氦 …）用完，核心就收縮成「白矮星」（靠電子彼此推擠抵擋引力）

Sun will live for another 5 billion years. Once the nuclear fuel runs out at the core, the core collapses to become a white dwarf, supported by electrons excluding each other.

比太陽質量更大的恆星，一旦核心燃料用完，就收縮成「中子星」（靠中子彼此推擠抵擋引力）

A more massive star, once its nuclear fuel runs out, the core collapses to become a a neutron star, supported by neutrons pushing each other.

質量差不多是太陽八倍的恆星，一旦核心燃料用完，就收縮成「黑洞」（連中子彼此推擠也抵擋不住引力）

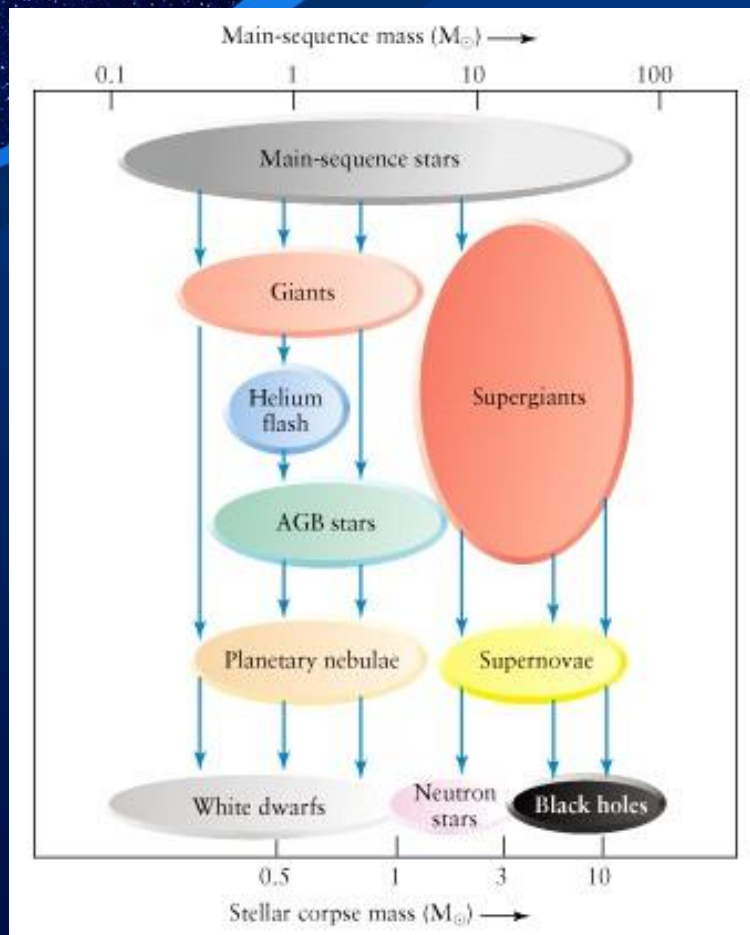
A star more massive than 8 times solar, the core collapses to become a black hole; even the neutron pressure fail to support it.

恆星在主序時的質量 Mass of a “healthy” star

質量流失

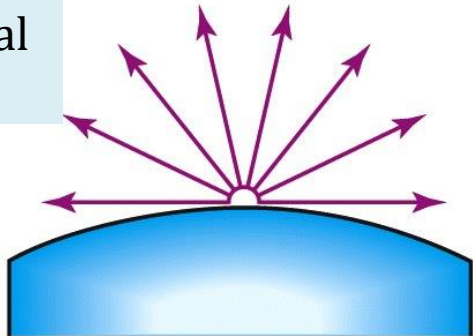
Mass loss ...

恆星死亡時的質量
Mass when it dies.



一般恆星引力小，發出的光線幾乎不受影響

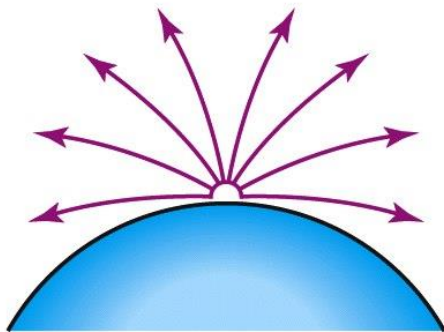
Light from a normal star leaves readily.



(a)

白矮星引力大，發出的光線稍許彎曲

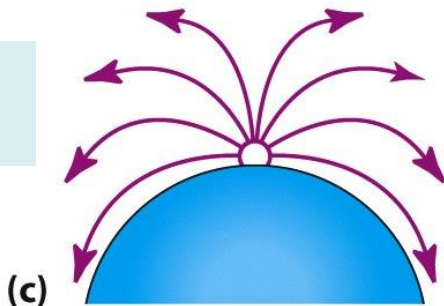
Light leaving a WD bends a bit when



(b)

中子星引力非常大，發出的光線明顯彎曲

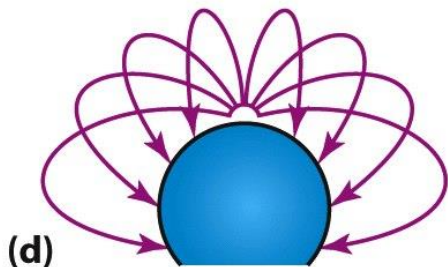
Light leaving a NS bends noticeably.



(c)

黑洞引力極大，發出的光線彎曲回去

Light leaving a BH bends noticeably.



(d)

利用黑洞對伴星的引力作用，藉以發現黑洞

If BH emits nothing, “see” one by its influence.

黑洞不發光，那怎麼觀察？

1. 引力對周遭物體的影響

by pulling a neighbor

2. 擋住光線

by blocking background

3. 吸積盤（阻力）、噴流

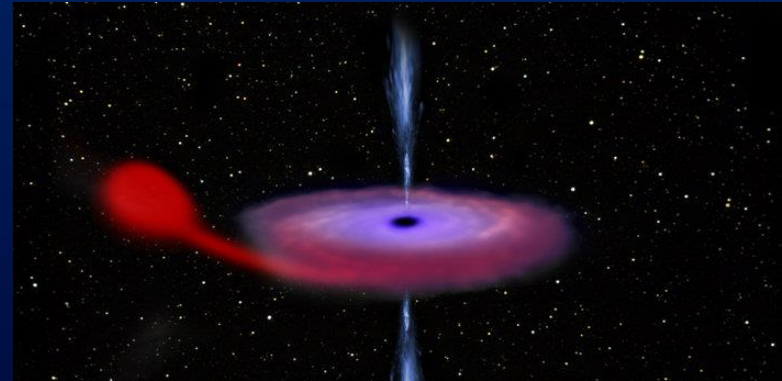
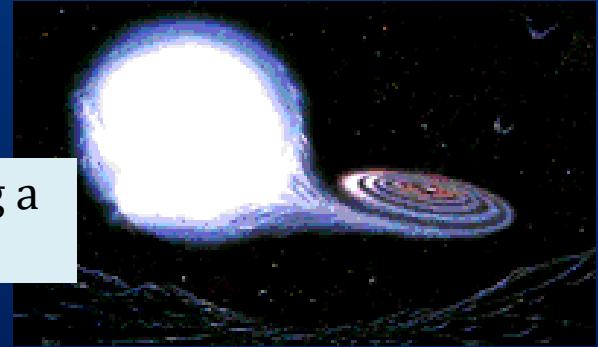
4. 引力波

by accreting matter or a jet

Gravitational wave

黑洞周圍可以非常明亮

A BH surroundings can be luminous.



電影 星際效應
當中的黑洞特效



The BH special effect seen in the film “*Interstellar*”

恆星級黑洞

Stellar black holes

例如與其他星球互繞、合併

... end life of massive stars



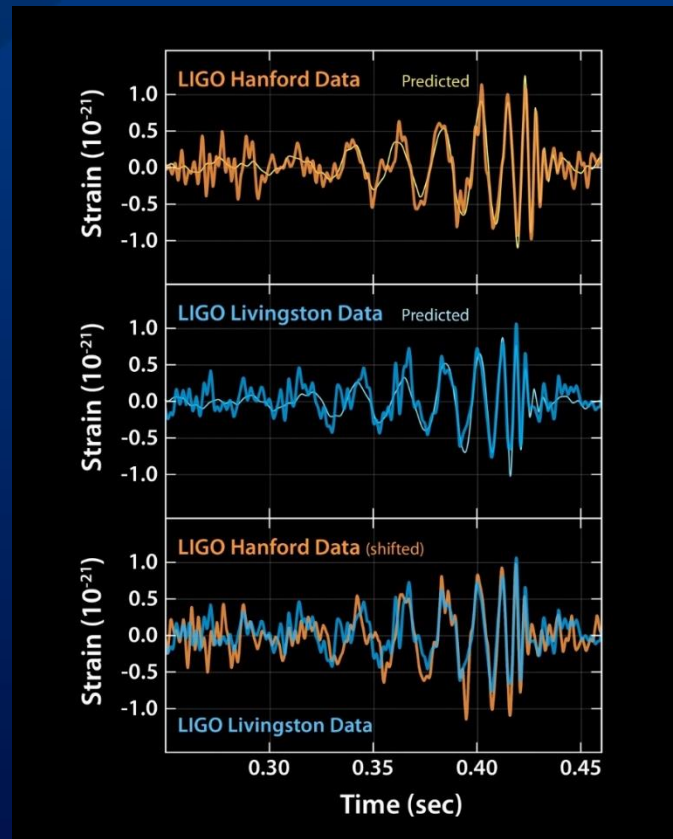
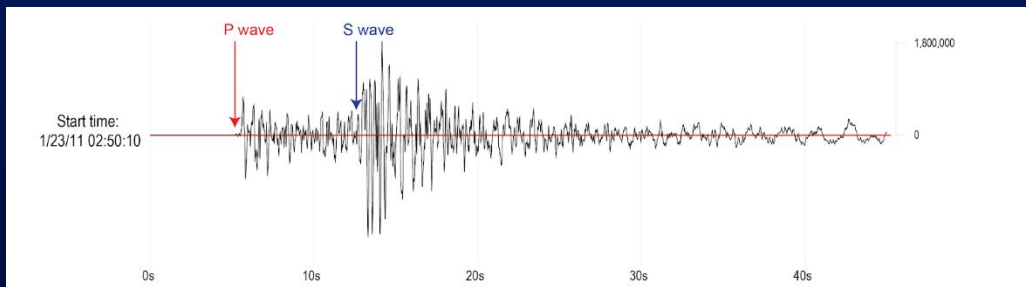
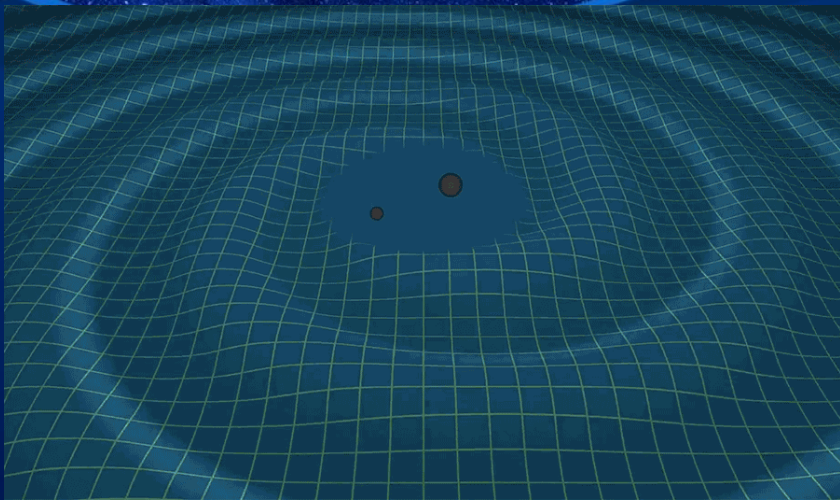
中等質量黑洞

Intermediate-mass black holes

某地區存在「很多」恆星、很明亮
例如球狀星團中心的黑洞

... centers of rich star clusters

2016 年偵測到兩個黑洞合併引發的重力波



Detection in 2016 the gravitational wave (spacetime ripples) from merging of two BHs

超大質量黑洞

Supermassive black holes

某地區沒看到東西，但是周遭
天體（恆星、氣體）動得很快

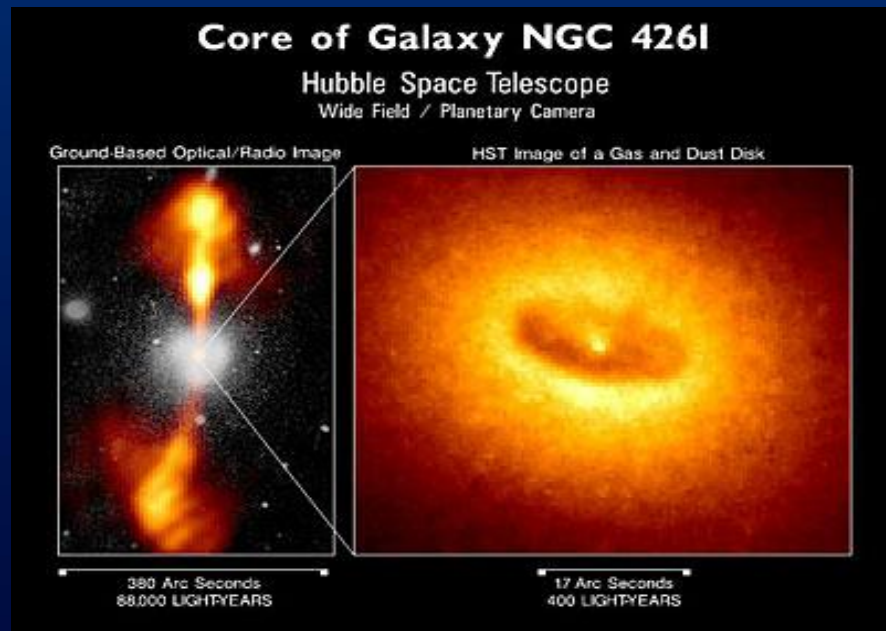
Nothing visible, but
neighboring stars/gas
moves exceedingly fast.

例如銀河系中心4百萬
倍太陽質量的黑洞

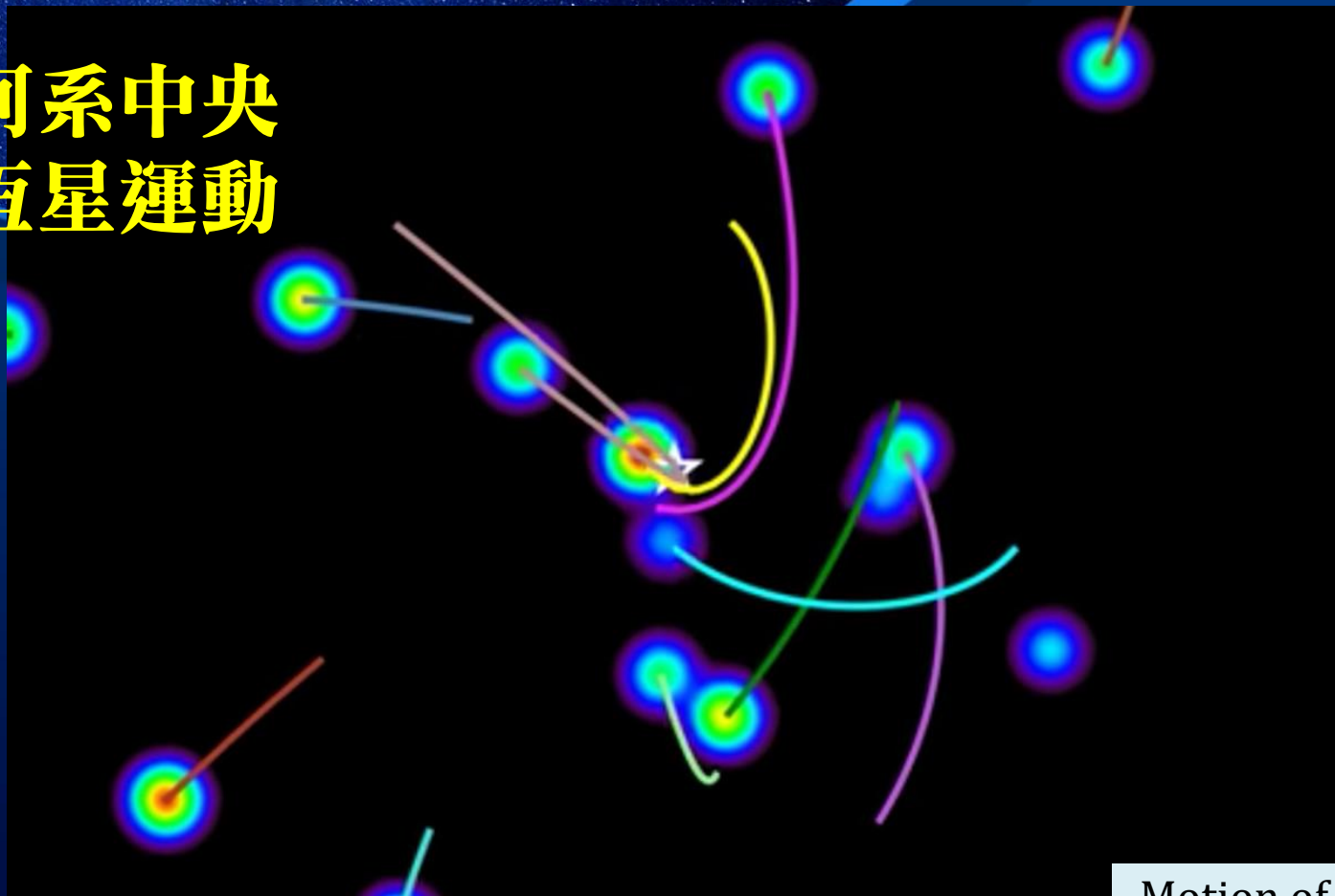
The SMBH at the center of our Milky
Way galaxy, with mass of 4 million suns

某些星系核心有數億倍
太陽質量的黑洞

Some galaxies host SMBHs at the
centers with mass of billions of suns



銀河系中央 的恆星運動

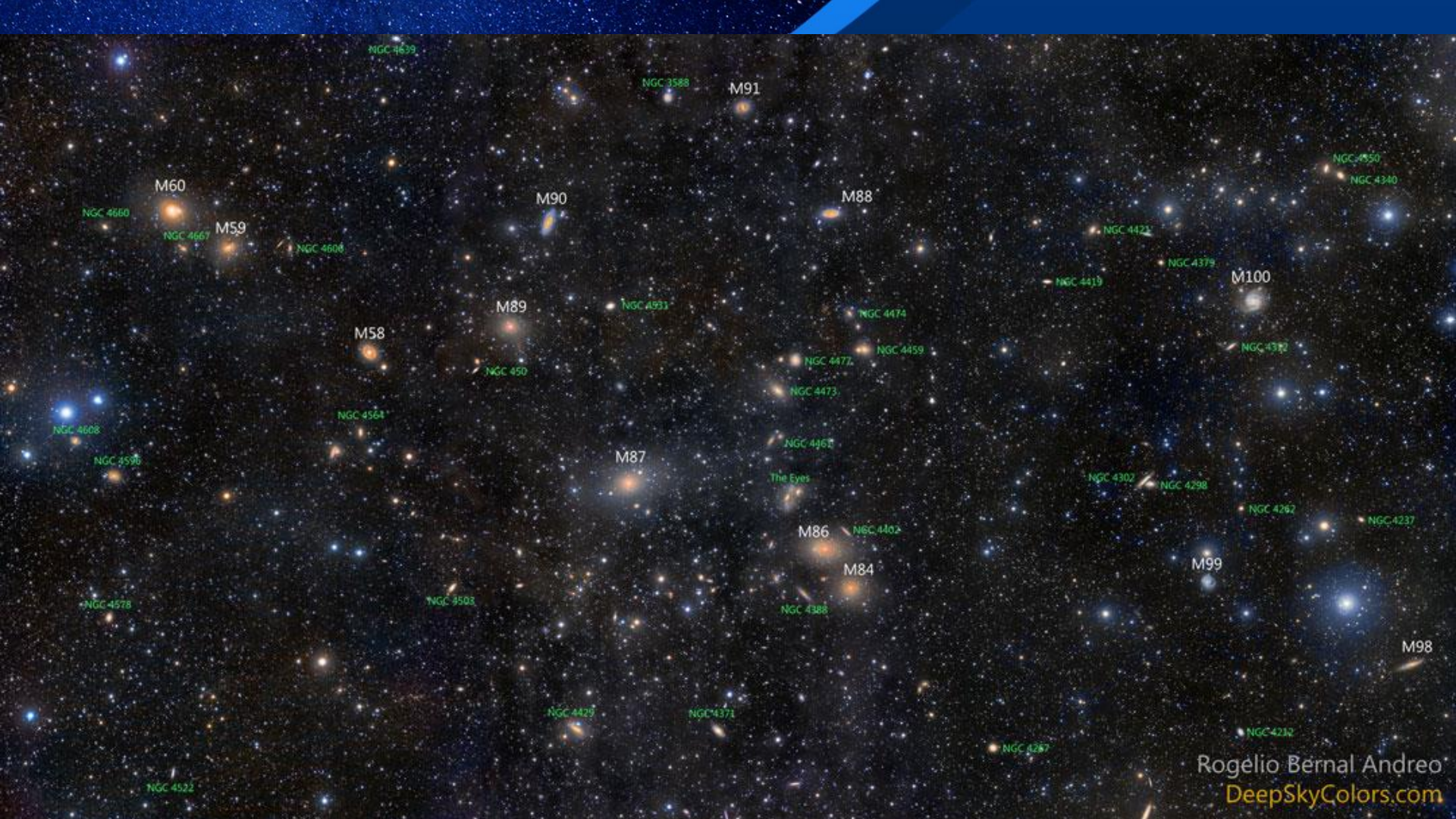


<https://youtu.be/AZhUQI-wmq0>

Motion of stars near the
Galactic center.

M87 is a prominent galaxy among the 1200+ galaxies in the Virgo Cluster (of galaxies).

室女座星系團 (Virgo Cluster) 是離我們最近 (5500萬光年) 的星系團，在天空中跨了10度範圍，形狀不規則，至少包含1200個星系。梅西耶目錄中109個天體，室女座星系團的成員占了15個，最有名的就是M87，也稱為 Virgo A 或 NGC 4486。



NGC 4639

NGC 3588

M91

NGC 4550

NGC 4340

M60

NGC 4660

NGC 4667

M59

NGC 4606

M90

M88

NGC 4422

NGC 4379

M100

NGC 4419

M89

NGC 4531

NGC 4474

M58

NGC 450

NGC 4477

NGC 4459

NGC 4372

NGC 4808

NGC 4564

NGC 4461

NGC 4473

NGC 3596

M87

The Eyes

NGC 4302

NGC 4298

NGC 4262

NGC 4237

NGC 4578

NGC 3503

M86

NGC 4402

M99

M84

NGC 4388

M98

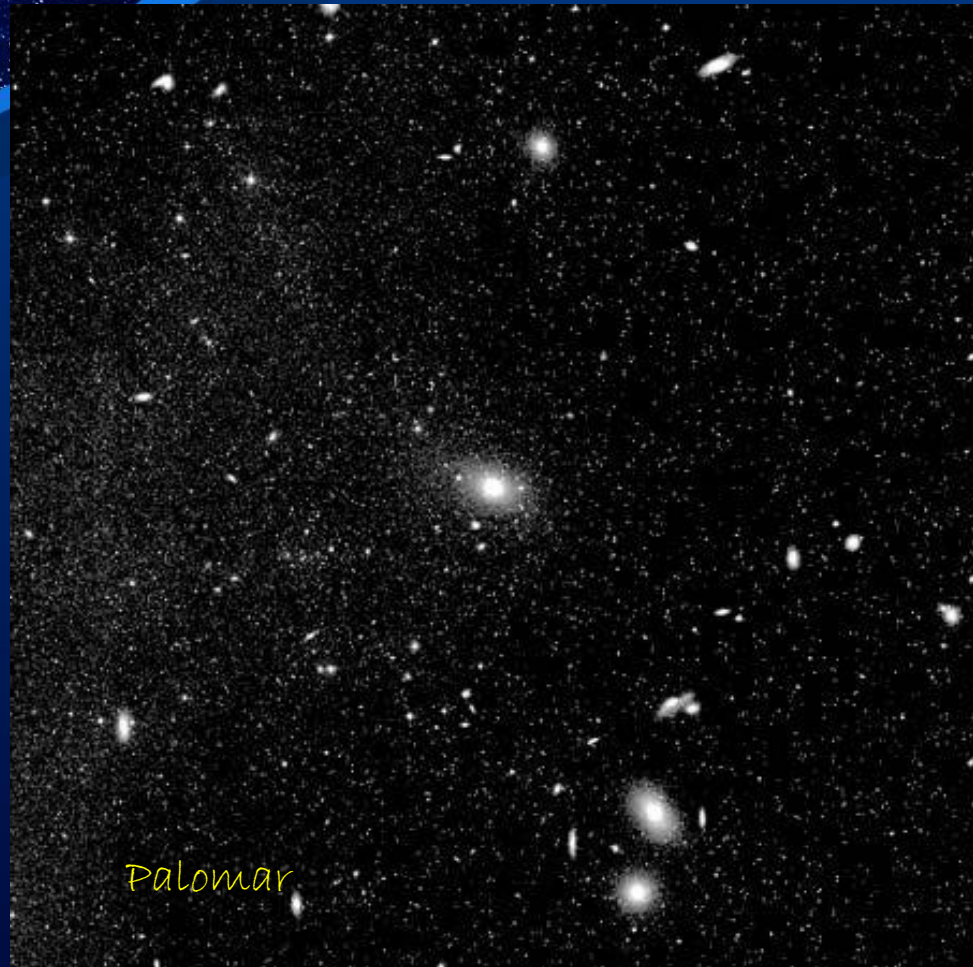
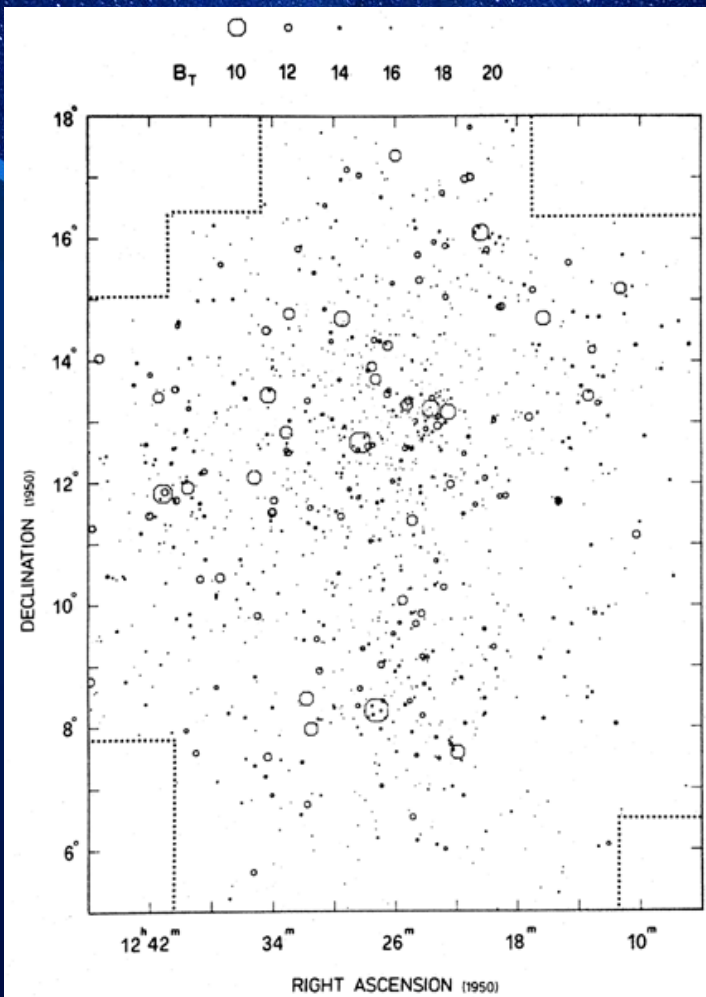
NGC 4429

NGC 4371

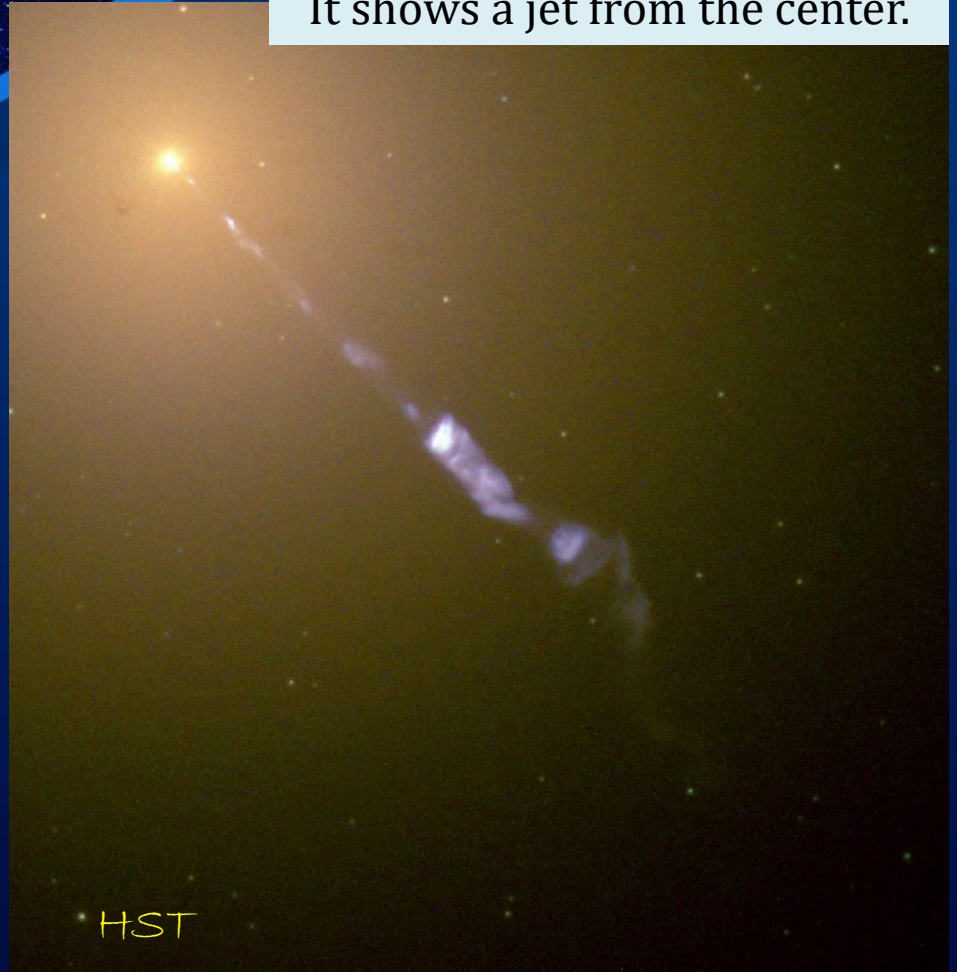
NGC 4212

NGC 4287

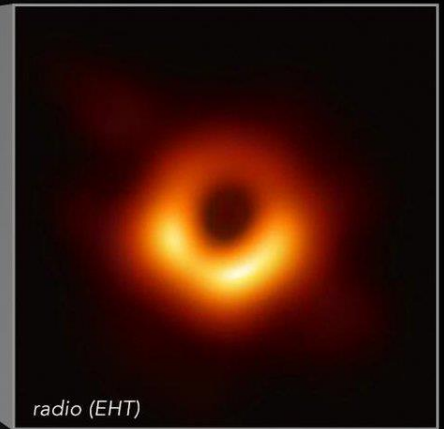
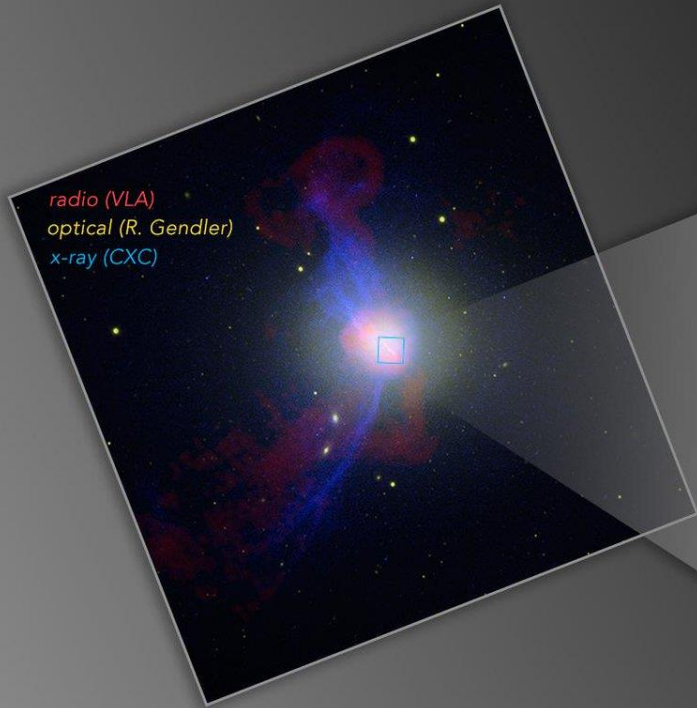
NGC 4522



It shows a jet from the center.



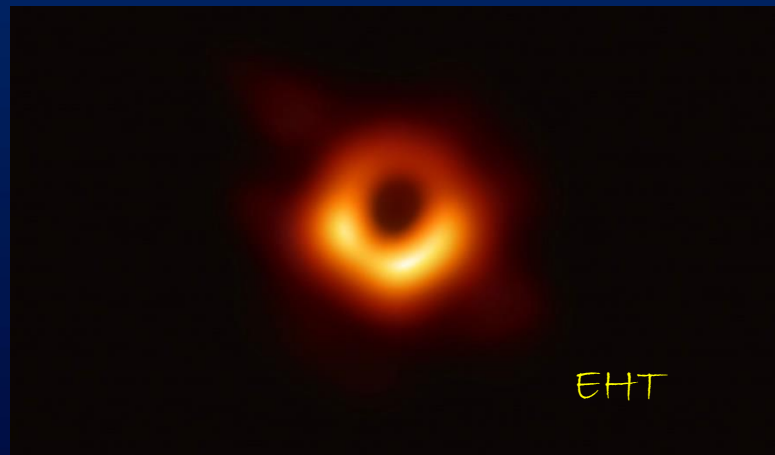
M87's Black Hole in Context



2017年「事件視界望遠鏡」(Event Horizon Telescope) 取得M87星系核心「超大質量黑洞」(相當於8億個太陽質量，大小38億公里)的剪影

The SMBH detected by the EHT. Mass of 800 million suns, 3.8 billion km across.

光線來自電子的同步輻射，一邊比較亮是因為黑洞自轉造成的都卜勒效應



A donut-shape silhouette; rotation/spin makes one side brighter.

An artist's rendition
of a BH and its jet.



<https://youtu.be/zXRgCs94cV8>

A black hole is not seen, until it eats.

The Universe itself
is a black hole.

宇宙本身就是個黑洞？

10^{53} kg, $R_s = 1.3 \times 10^{26}$ m (137 ly)

所以光線跑不出去；外面另有洞天？

宇宙原始黑洞？

黑洞的種類

「黑洞無毛」

BHs have no hair.

■ 史瓦茲（靜態）黑洞 Schwarzschild

沒有自轉的黑洞（原來的物質就沒有自轉），
質能全集中在奇異點，該處密度無窮大

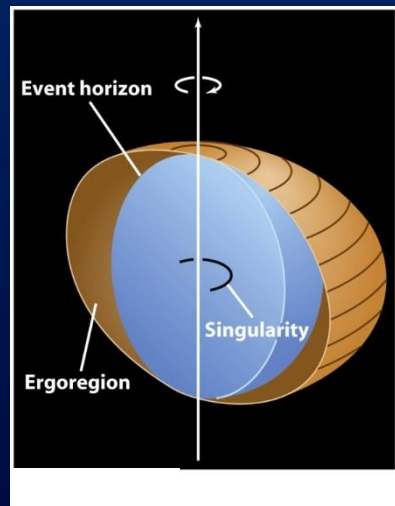
■ 克爾（旋轉）黑洞 Kerr A spinning BH

自轉黑洞，每秒達數千轉；事件視界
之外還有「動區」跟著黑洞一起旋轉

■ 紐曼（帶電）黑洞 Newman

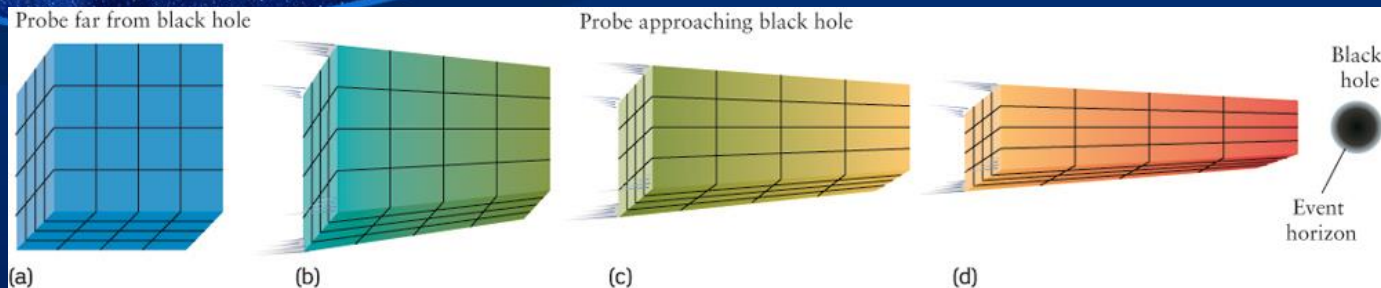
帶電自轉黑洞

A charged BH



接近黑洞會如何？

What happens when nearing a BH?



■ 時間變慢

Time slows down.

Gravity pull strengthens.

■ 引力變大，而且引力「差」變大，會「麵條化」spaghettification

Gravity difference amplifies.

■ 重力紅移（東西會變紅；人人是網紅）

Appears redder.

掉進黑洞呢？

If falling in?

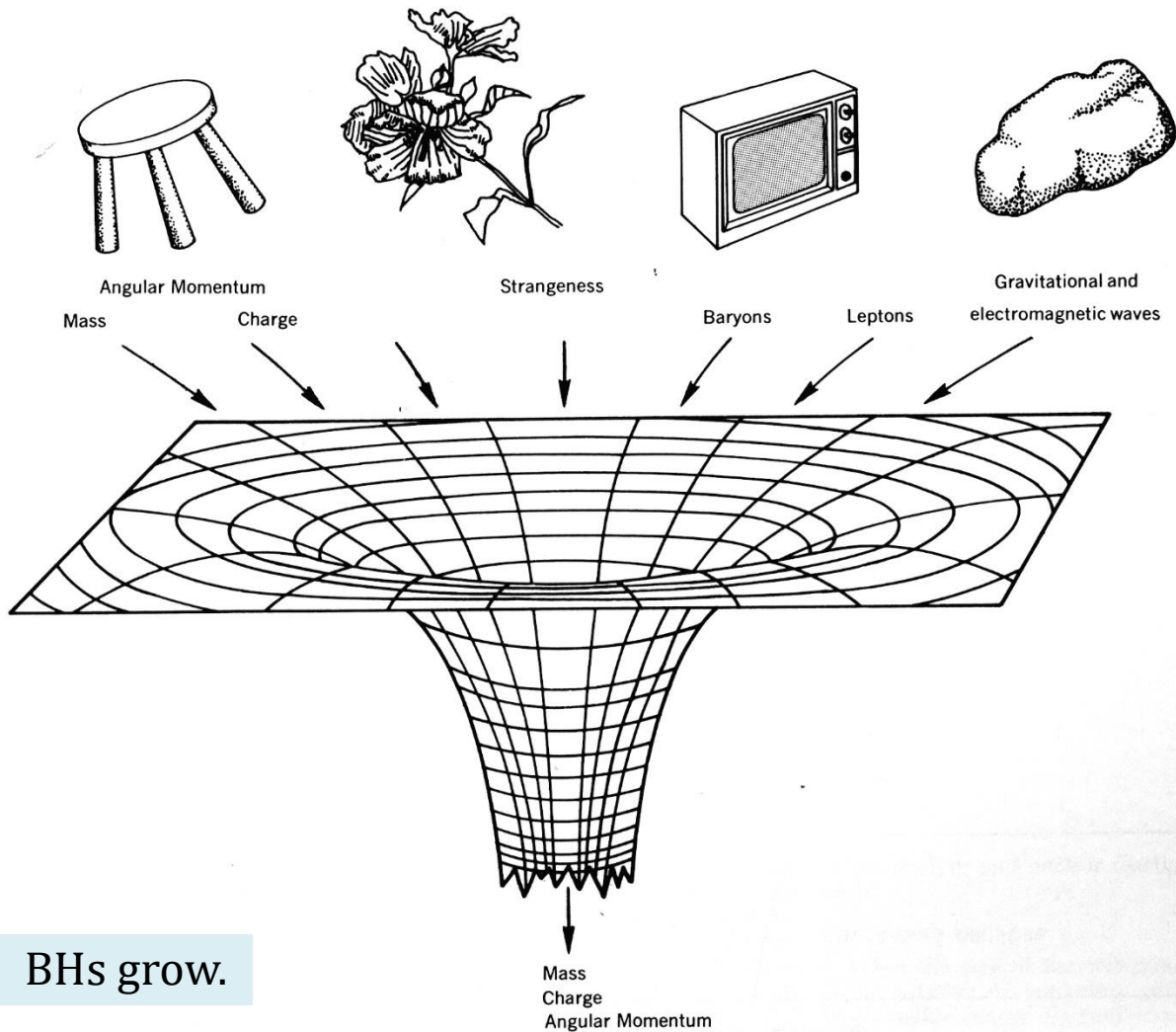
粉身碎骨

Totally smashed

什麼東西掉進
黑洞...
就變成黑洞

... becomes part of the BH.

黑洞長大！



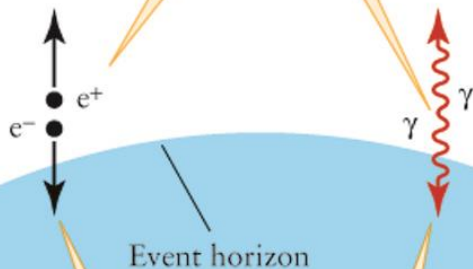
In a unfortunate encounter with a BH during space travel, it'd better be a Kerr BH.

太空旅行要是遇到黑洞，
祈禱最好是克爾黑洞！

黑洞會逐漸消失：霍金蒸發 (Hawking process)

1. Pairs of virtual particles spontaneously appear and annihilate everywhere in the universe.

2. If a pair appears just outside a black hole's event horizon, tidal forces can pull the pair apart, preventing them from annihilating each other.



3. If one member of the pair crosses the event horizon, the other can escape into space, carrying energy away from the black hole.

BHs can lose weight.

10^{10} kg 的黑洞蒸發完畢
需時 150 億年

$5 M_{\odot}$ 的黑洞需時 10^{62} 年

500 萬 M_{\odot} 的超大質量黑洞
需時 10^{80} 年

But the process is extraordinarily slow.

那有白洞嗎？

A white hole?

假想時空區域，
東西能出不能進

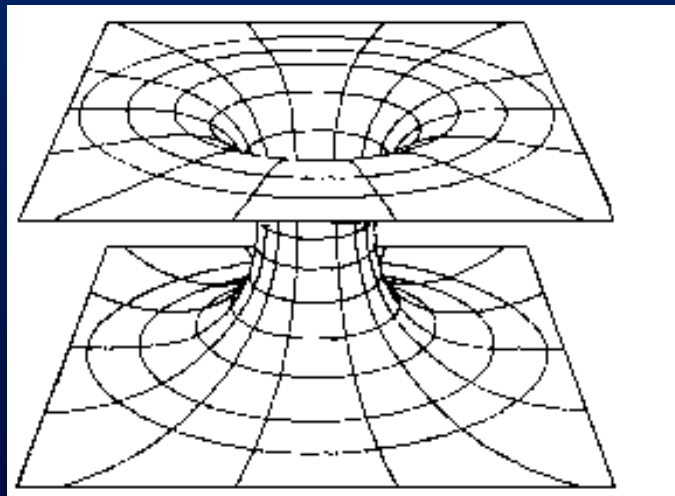
蟲洞呢？

A worm hole?

(愛因斯坦—羅森 橋)
時空扭曲可以成為「捷徑」，
通往宇宙其他角落？

時空旅行？

An Einstein-Rosen bridge:
a shortcut in space-time





Wen-Ping Chen

12小時 · 地球 · 分享

掉進黑洞怎麼辦

1. 看是誰？是自己跳進去，還是被推的
2. 爬出來？
 - 2.1 希望不大，決定叫外賣，結果發現下面滿坑滿谷都是外賣員
 - 2.2 好不容易爬出來，結果發現還在選舉期間，決定又跳回去
3. 判斷是哪種黑洞
 - 3.1 恆星級黑洞、中質量、大質量、超大質量黑洞
 - 3.2 史瓦茲（靜止）黑洞、克爾（旋轉）黑洞、紐曼（帶電旋轉）黑洞
 - 3.3 如果是財政黑洞，都推給前朝
 - 3.4 如果是政治黑洞，一定是老共打壓
4. 掉進去的過程
 - 4.1 強大潮汐力把身體拉長，決定要變高，還是變胖
 - 4.2 重力會讓人變紅，想當網紅者把握機會
 - 4.3 時間會變慢，不會老這麼快
5. 一旦掉進去
 - 5.1 要不就出現在宇宙另一個角落，但是回不來
 - 5.2 要不粉身碎骨，成為黑洞的一部份，胖到黑洞

掉進黑洞怎麼辦？

What if You Fell into a Black Hole?



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