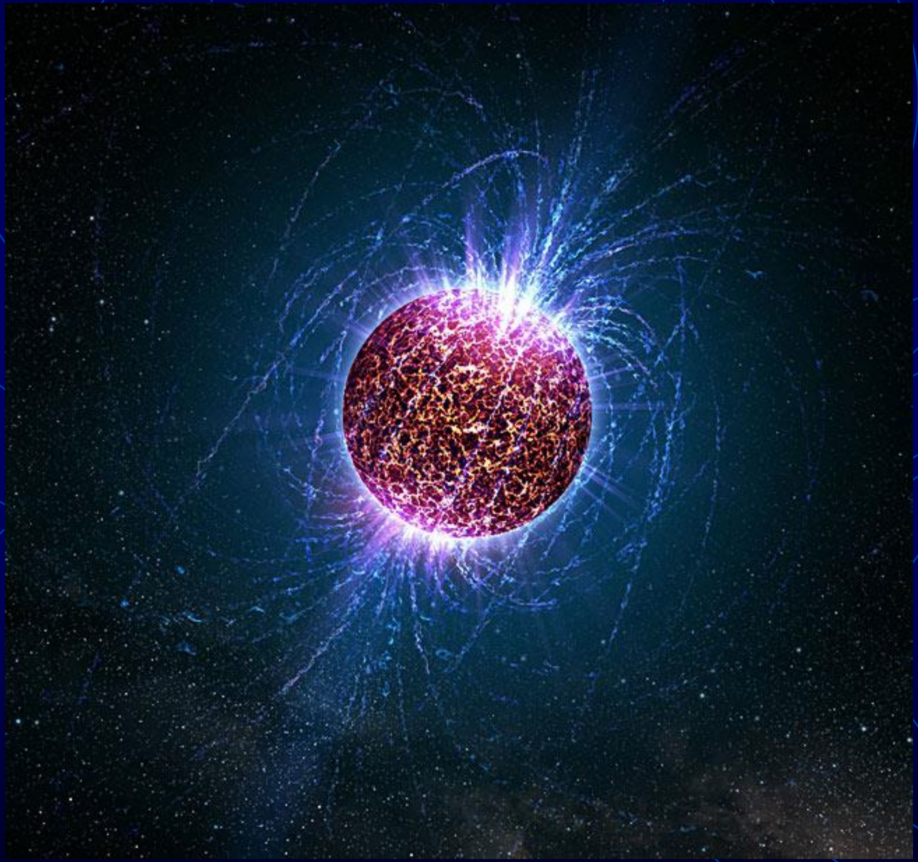
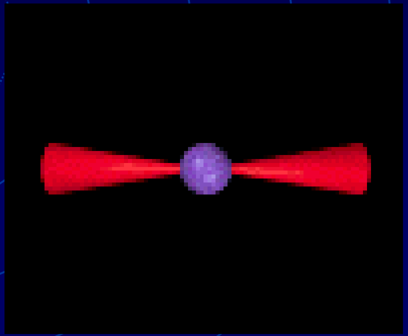
Compact Objects
--- Neutron Stars and Black Holes

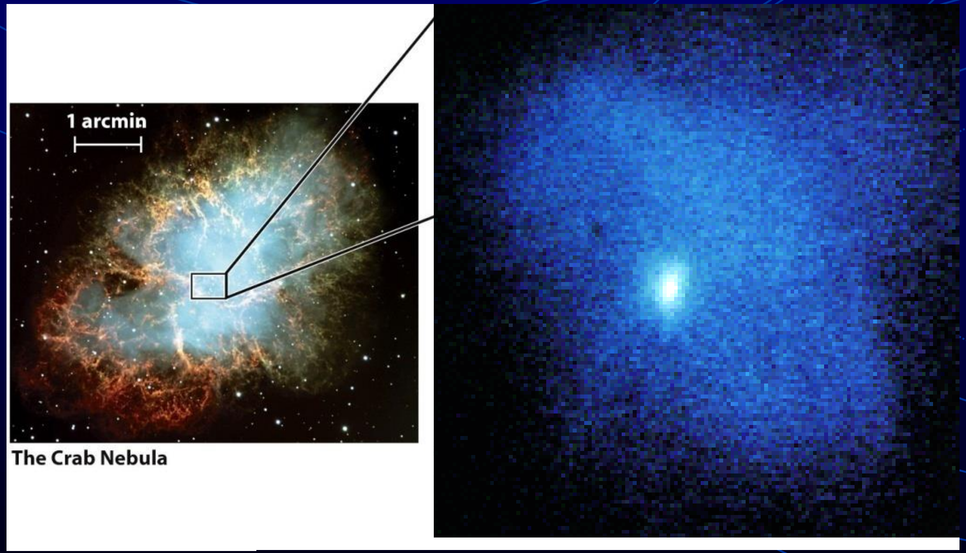


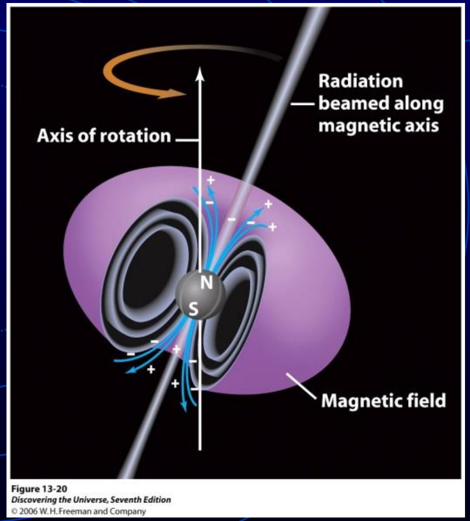
Credit: Casey Reed/Penn State University

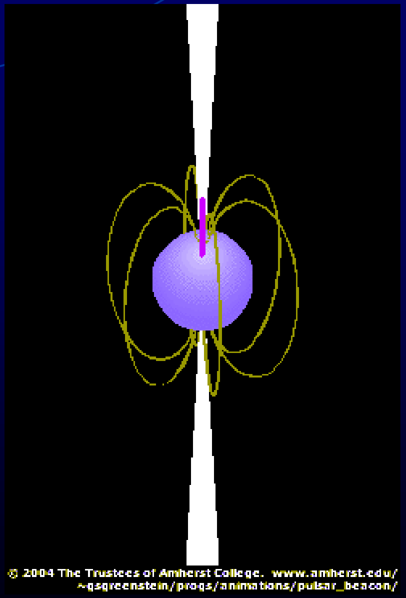
http://www.wwu.edu/depts/skywise/img/blackhole_42.jpg

- 若天體質量大，以致收縮後連電子簡併壓力都撐不住
  → 中子星 (neutron star)
- 中子星比白矮星還小得多。太陽 (D~140 萬 km) 核心成為白矮星，大小約與地球（1萬多 km）相當
- 中子星更小，直徑只有10～15 km（cf 中壢市）
- 磁場強大、旋轉快速 → 脈衝星 (pulsar)
  每秒發出數百到數千次脈衝（燈塔效應）

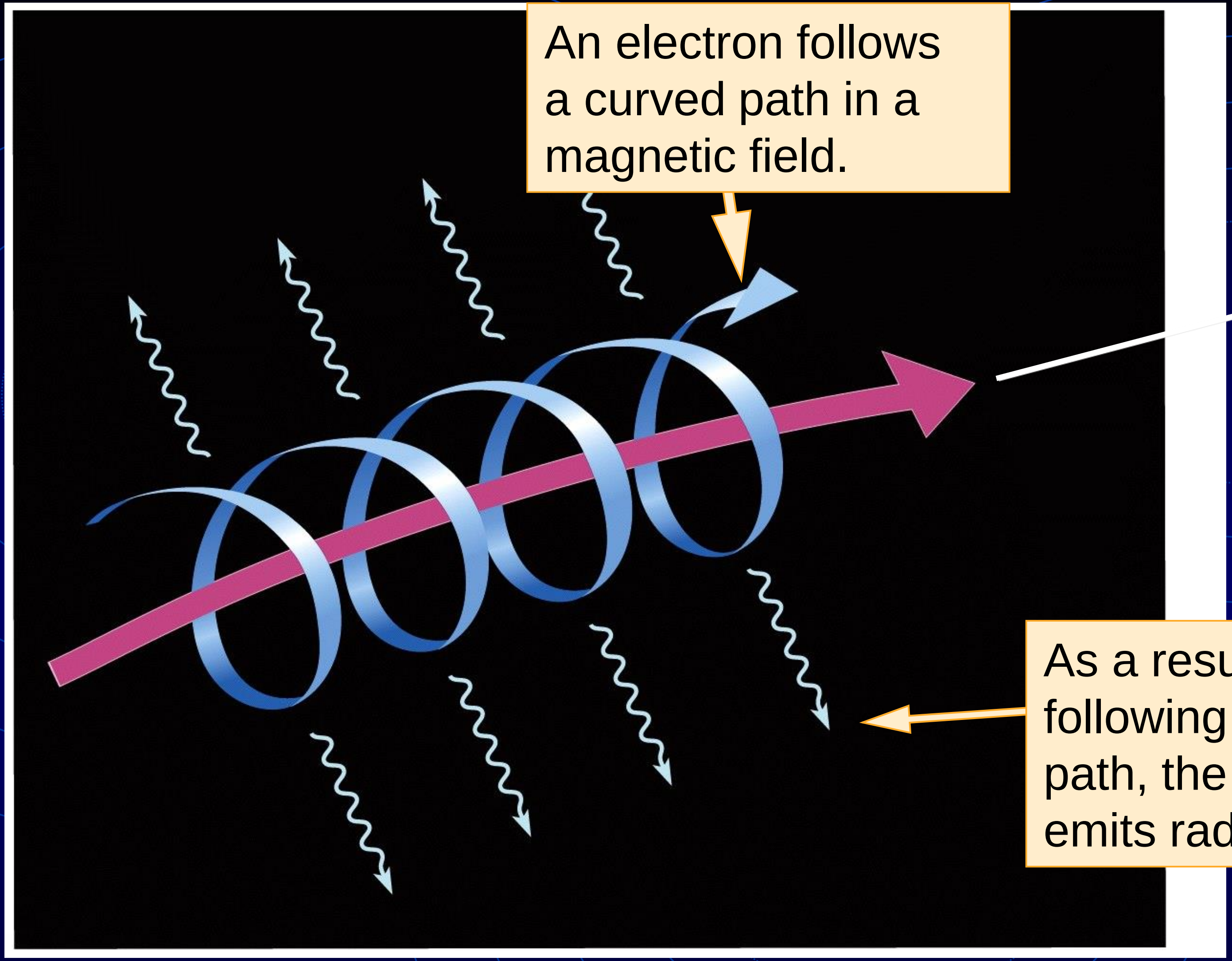








http://www.amherst.edu/~gsgreenstein/progs/animations/pulsar_beacon/

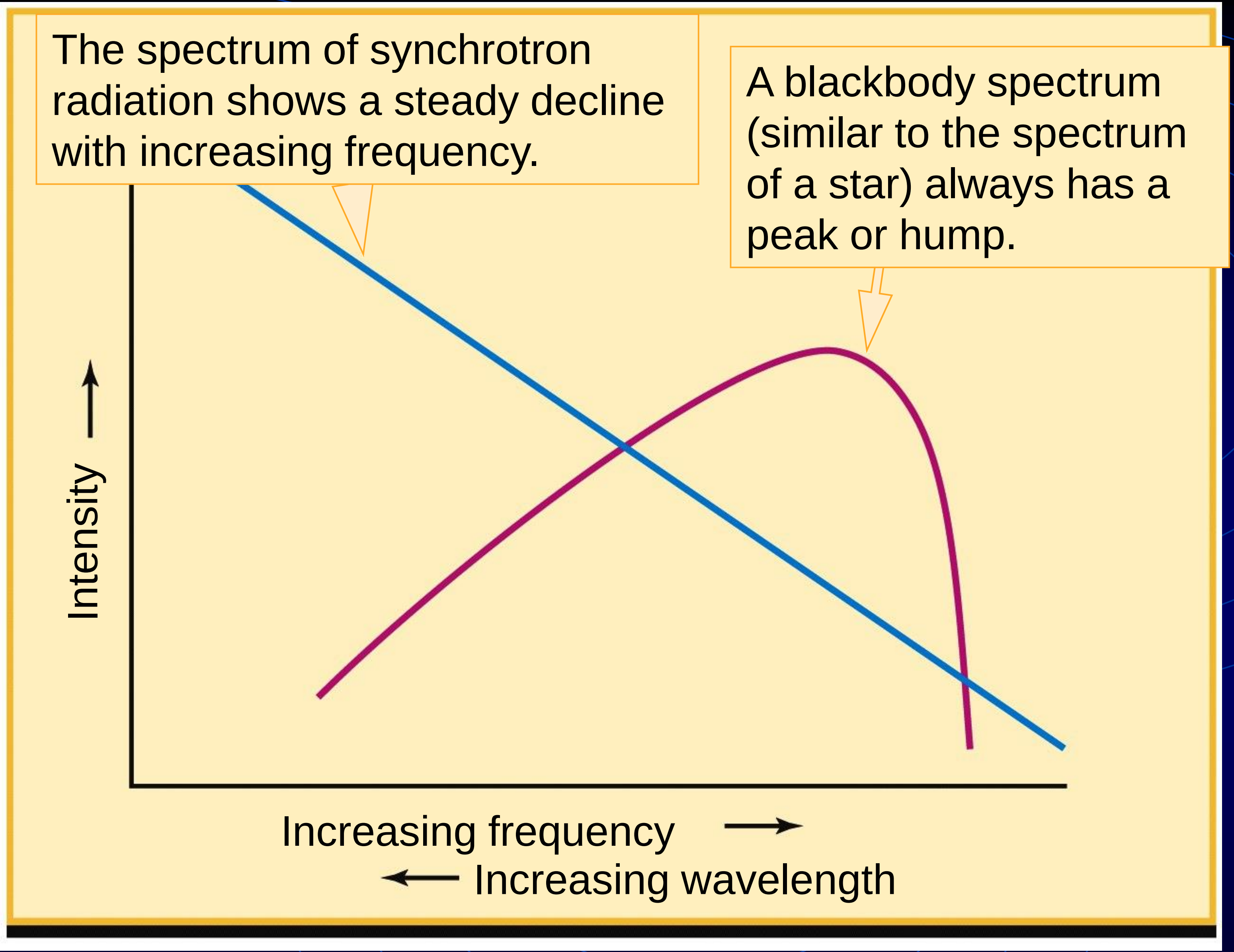


電子被磁場加速 ➔ 放出

同步輻射 (synchrotron radiation)

$a \perp v$

polarized



Synchrotron radiation differs from blackbody radiation in spectral shapes.

Angular Momentum Conservation

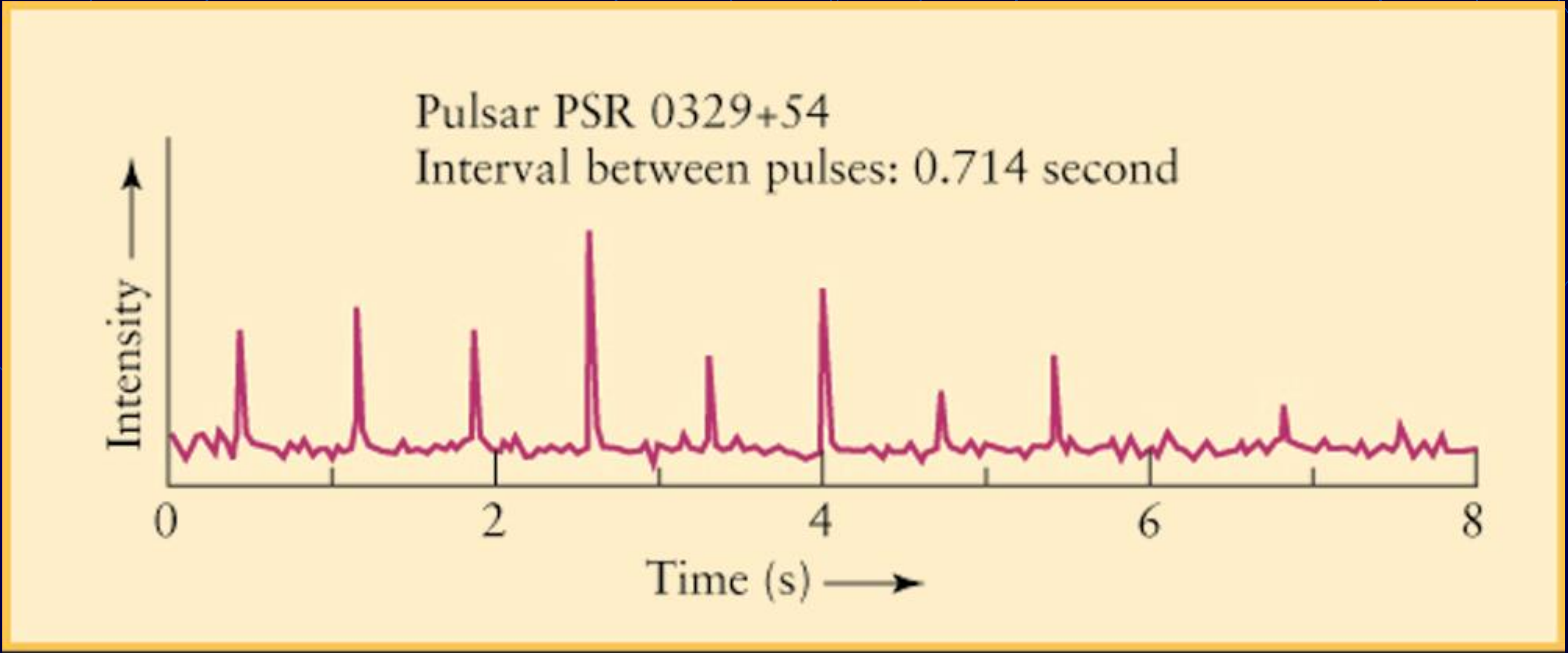
$J = m\,\omega\,r^2$

- Consider how fast the Sun (rotation period of ~30 days, radius about 700,000 km) would rotate if it were to shrink to r ~ 15 km, if angular momentum is conserved.

- Period = $2\pi/\omega$
- $P_{after}/P_{before} = \omega_{before}/\omega_{after} = (r_{after}/r_{before})^2$
- P_{after} = 30 days x 86400 s/day $(15/7\text{x}10^5)^2$
  ~ 0.001 s, i.e., milliseconds

cf The break-up speed → $P > 3.8 \times 10^{-4}$ s, so OK

PSR 0329＋54 P ~ 0.714 s

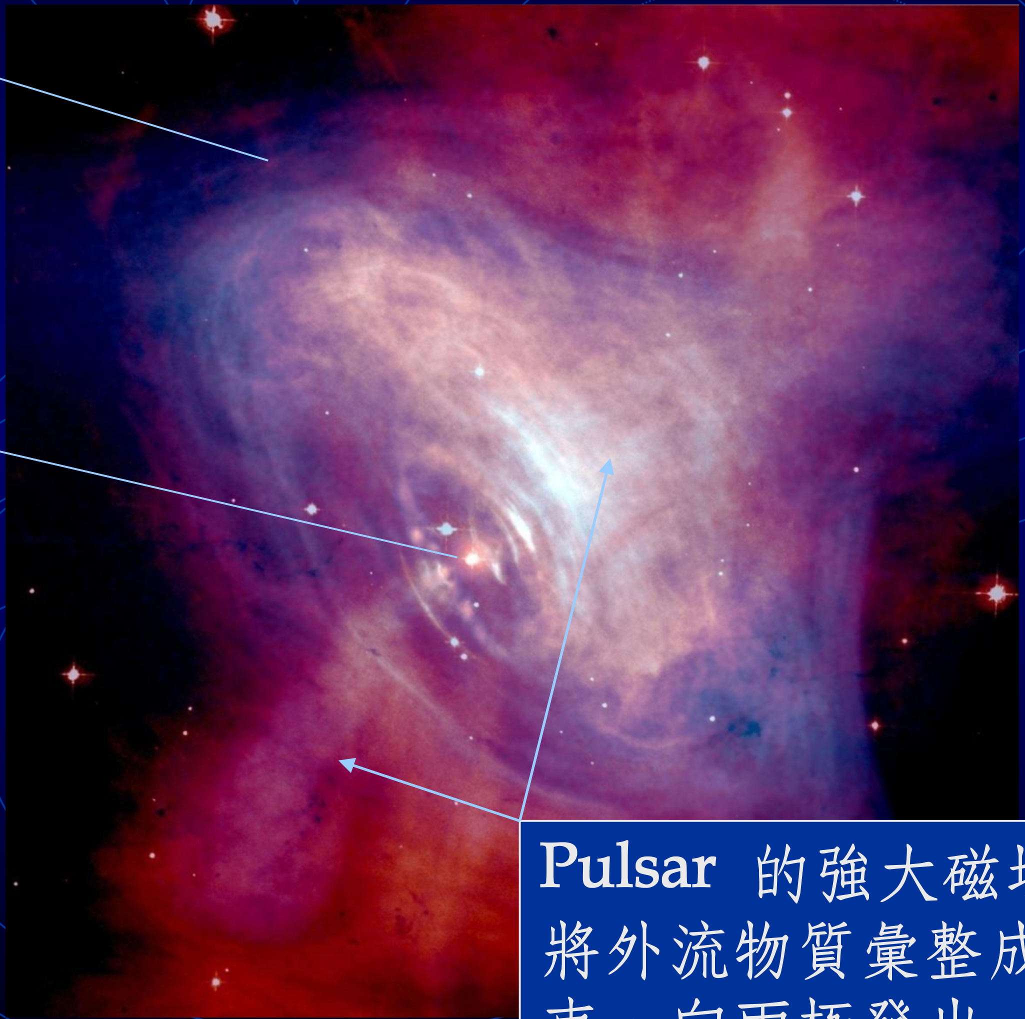


Pulsars 輻射 後果 ➔ 自轉越來越慢

A slow-motion movie of the Crab Pulsar taken at 800 nm using a Lucky Imaging camera from Cambridge U, showing the bright pulse and fainter interpulse …

脈衝星放出高速物質，產生衝擊波，發射高能 X 射線

The Crab pulsar



Pulsar 的強大磁場將外流物質彙整成束，向兩極發出

The Crab pulsar by HST (in red) and Chandra (in blue)

- A neutron star consists mostly of neutrons
  Assuming 1.5 $M_{\odot}$, r = 10 km, the density is $\rho \sim 4.8 \times 10^{14}$ g cm^{-3}
  → nuclear density~10^{15} g cm^{-3}
- A neutron star is very hot, supported by the Pauli exclusion force between neutrons.
- Structure of a neutron star is understood currently only by mathematical models.
- 一湯匙的中子星物質，重達50億公噸
- 表面存在非常薄（~1 m) 的大氣層，為普通的原子、電子
- 越往內部，密度越高 → 自由中子

Gravitational Red Shift

Total mass-energy $\mathcal{E} \equiv mc^2 = m_0 c^2 + \frac{m_0 \, GM}{r} = m_0 c^2 \, (1 + \frac{GM}{rc^2})$

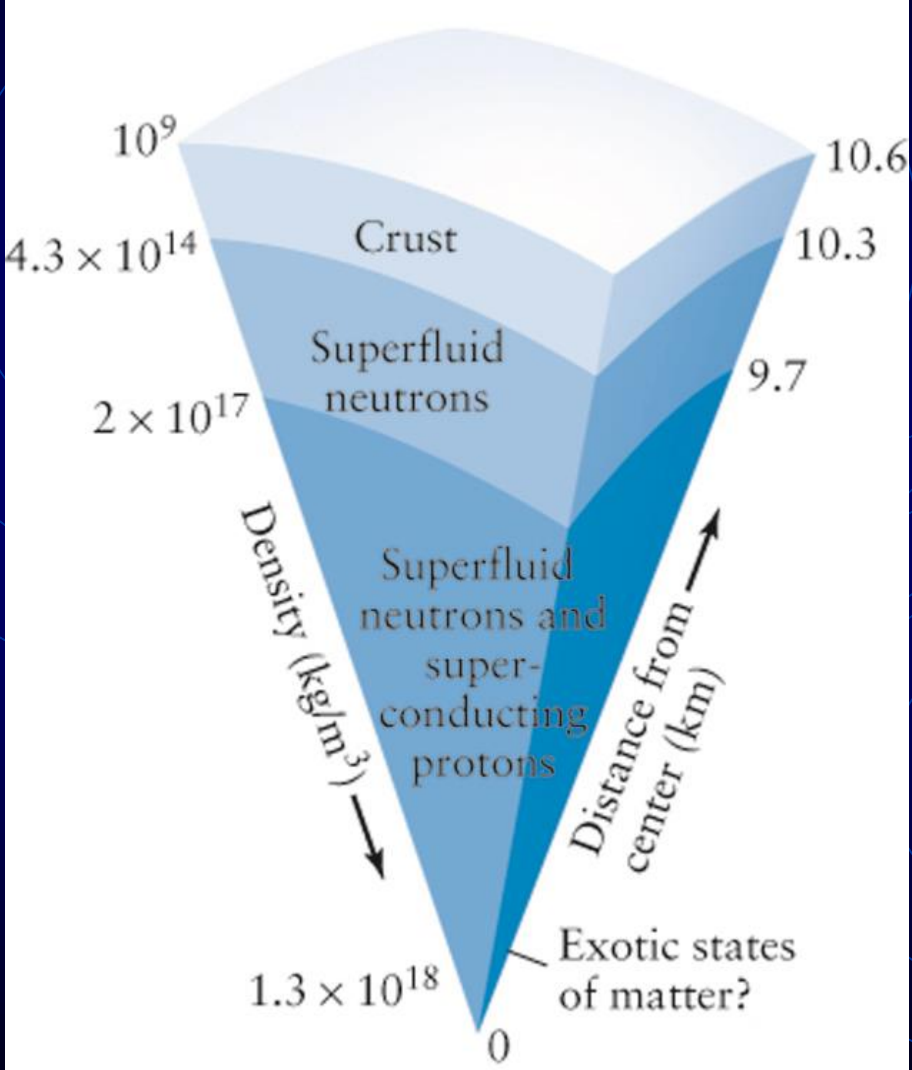
… conversion of potential to kinetic energy

A photon loses energy, so its frequency is red shifted)

$$\nu = \nu_0 \, [1 - GM/(rc^2 \,)]$$

$$\frac{\Delta\nu}{\nu_0} = \frac{\nu' - \nu_0}{\nu_0} = -\frac{GM}{rc^2}$$

中子星內部結構



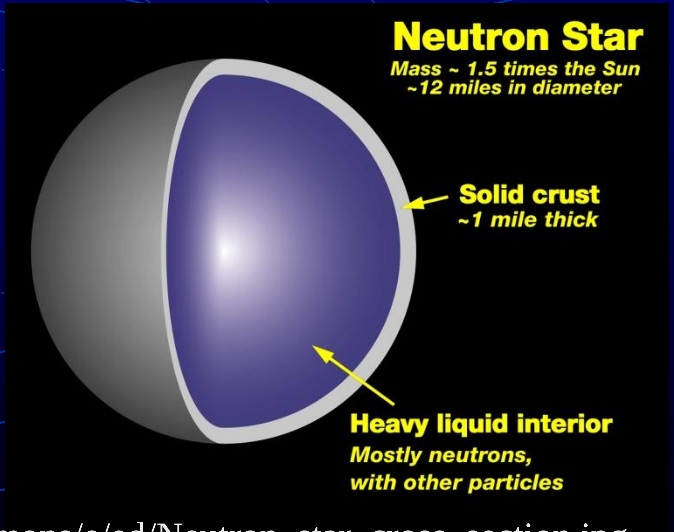
理論計算 → 內部處於

超流體 (superfluidity)

與

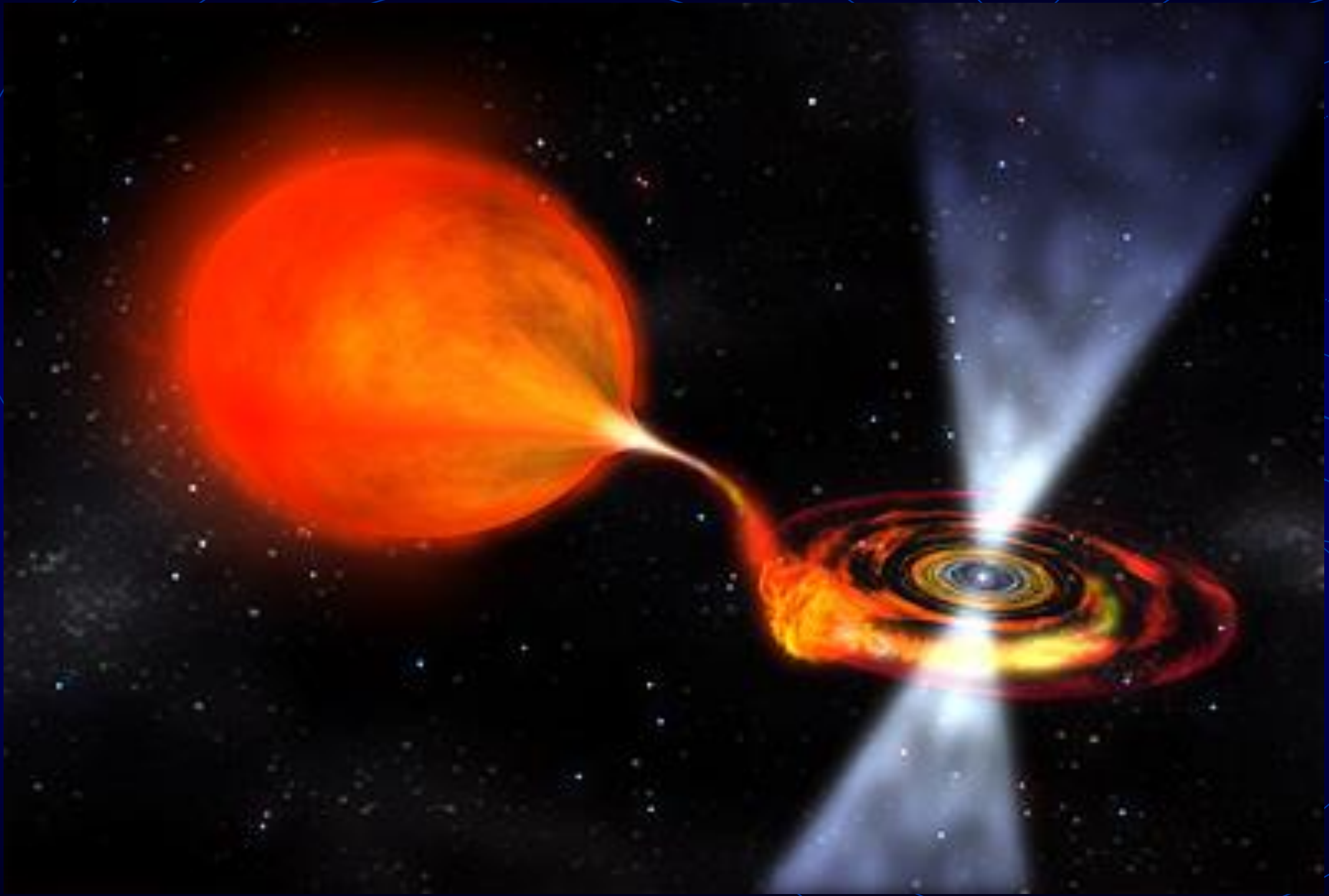
超導體 (superconductivity)

狀態



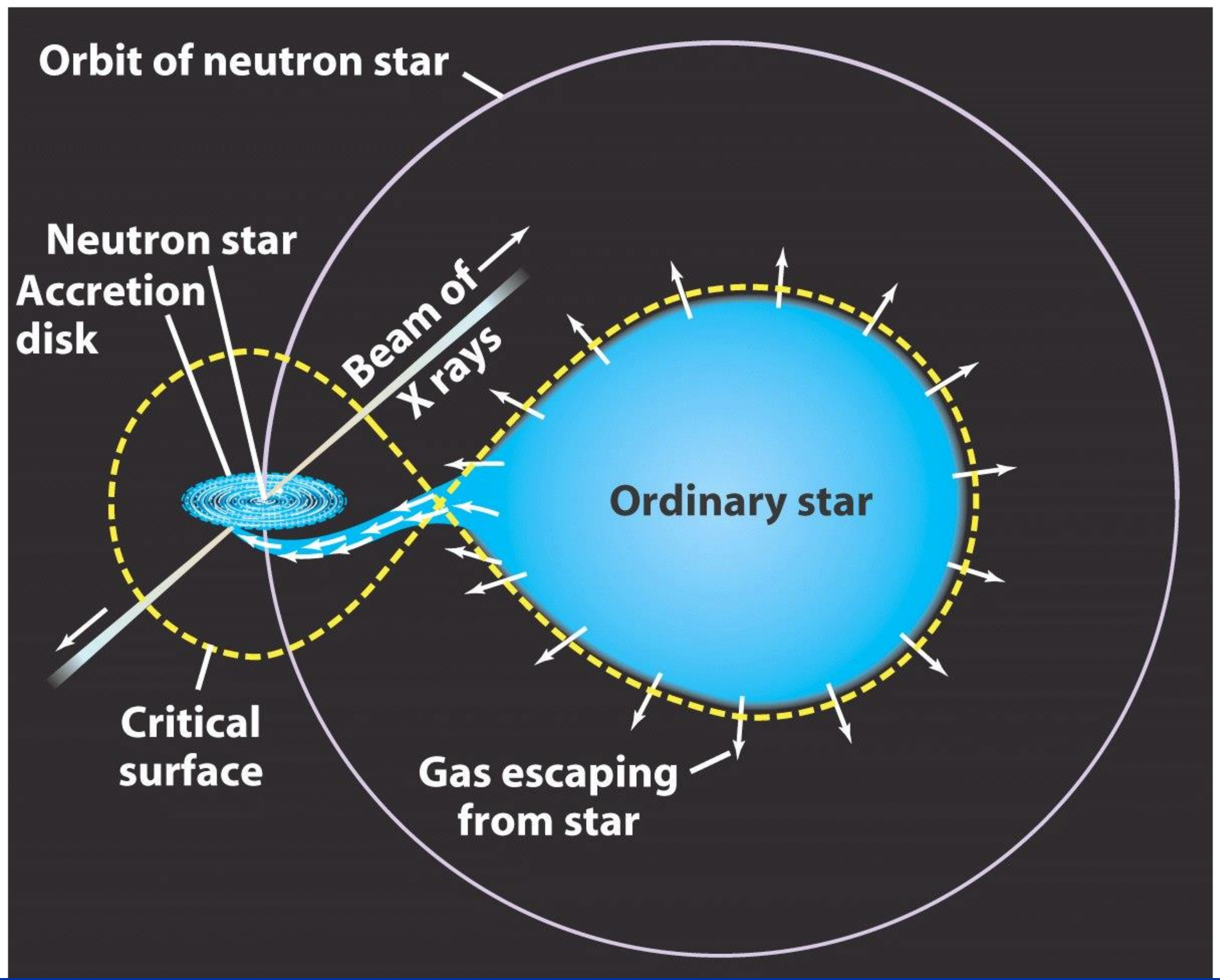
http://upload.wikimedia.org/wikipedia/commons/e/ed/Neutron_star_cross_section.jpg

中子星與吸積作用



銀河系中據估計可能存在上億顆中子星，但如果並非pulsars 或是雙星系統中有吸積活動，中子星不易被偵測到

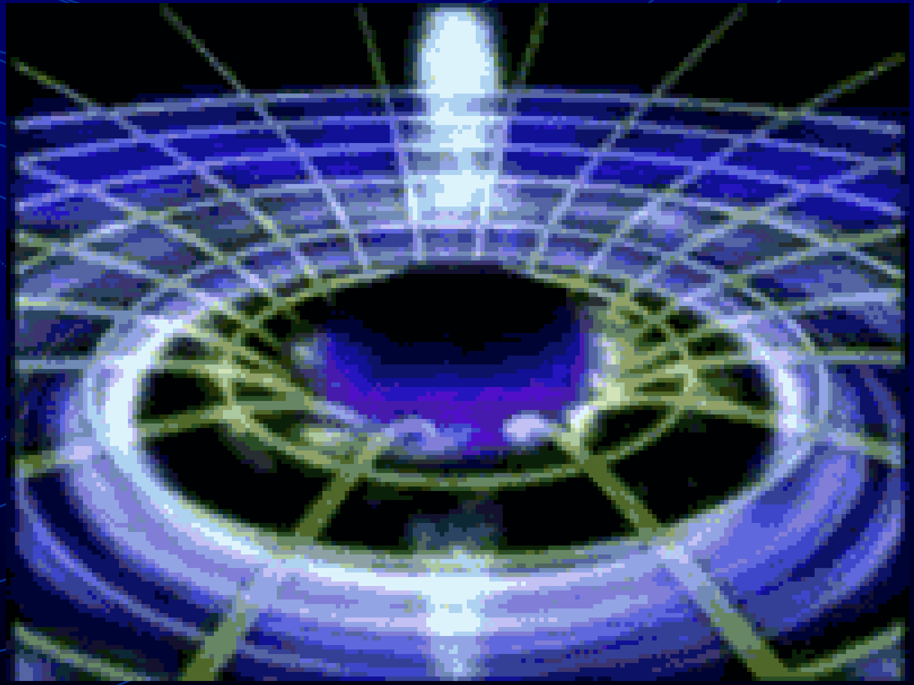
http://www.esa.int/esaCP/SEMWSAA5QCE_index_3.html



A pulsating X-ray Source

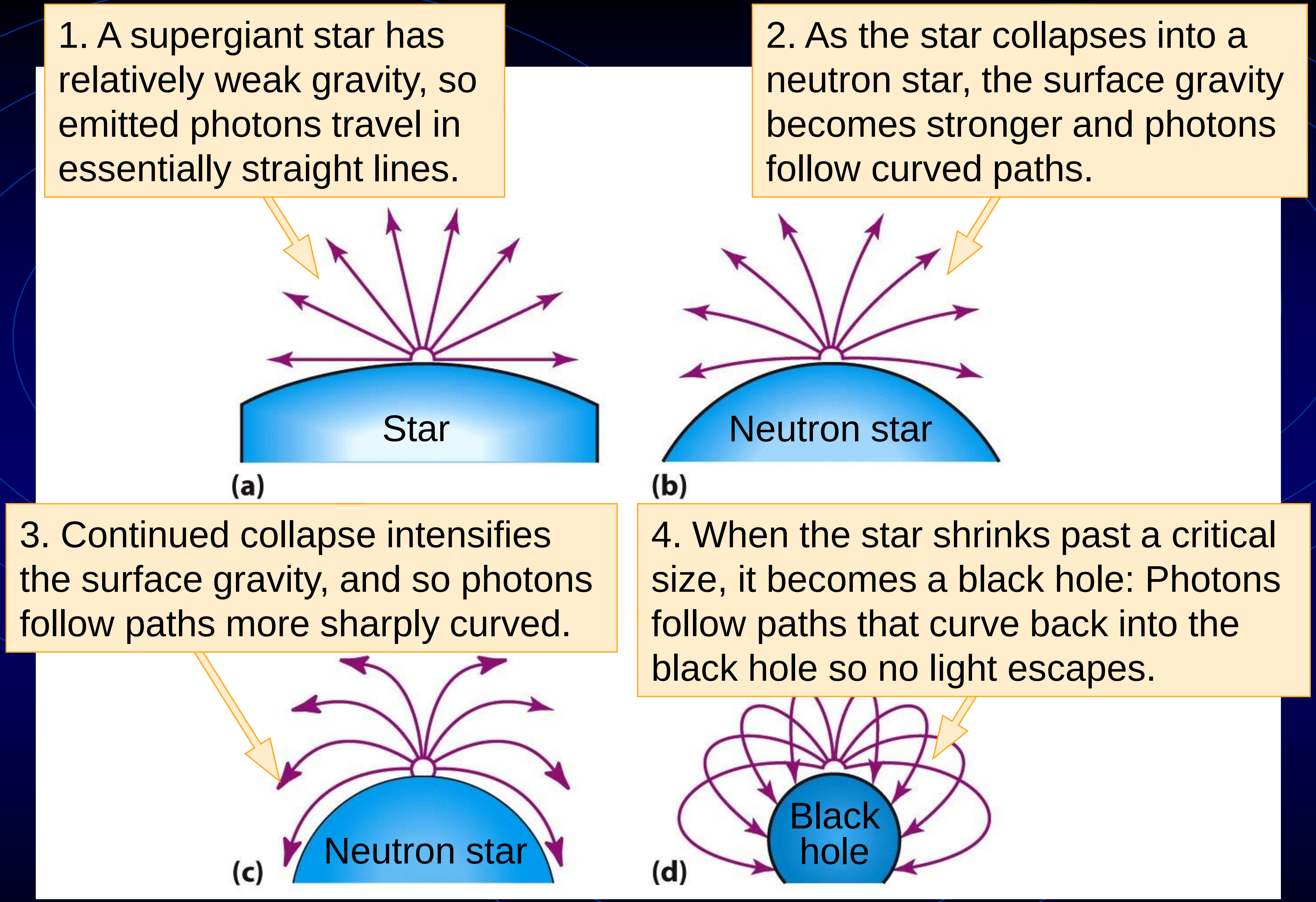
大質量恆星晚年

- 例如核心質量大於太陽3倍
- 連中子或夸克的支撐力量都抵擋不住巨大的萬有引力
  → 星體塌縮
- 強大的萬有引力連光線都跑不出來
  → **黑洞 (black hole)**
- 黑洞是種簡單的質能狀態，
  其「表面」的逃脫速度等於光速



脫離速度 (escape velocity)

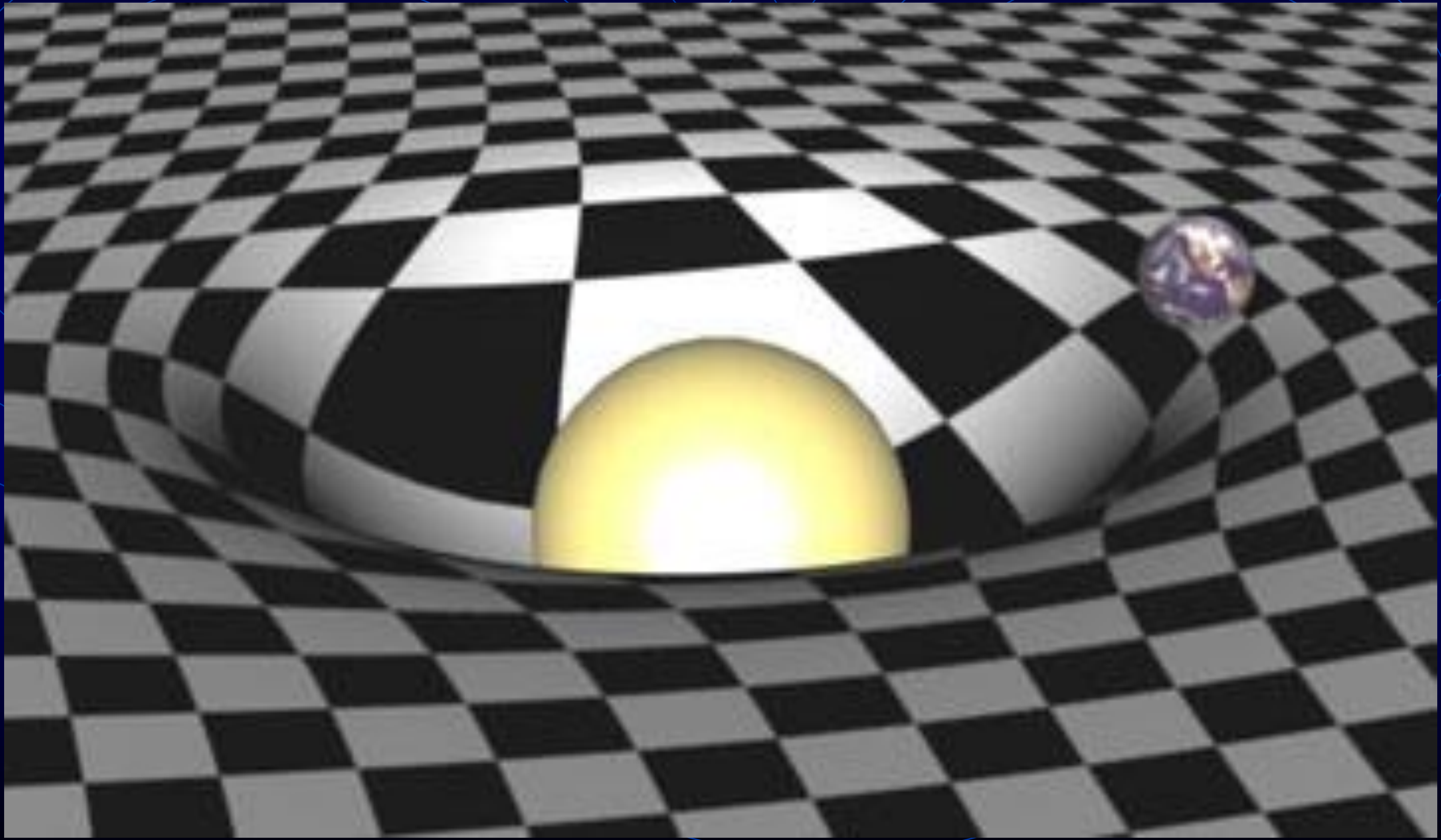
- 拋個銅板向上…銅板向上飛，達到最高點後停止，接著向下飛
- 如果用力拋個銅板向上…
- 但是如果真的很用力（夠快），越高處離地心越遠，引力越弱，便無法讓銅板停止
- 這個開始拋速度稱做「逃脫速度」
- 地球的 escape velocity 為 40,200 km/h 或 11 km/s；大於這個速度毋須額外力量就可脫離地球


1. A supergiant star has relatively weak gravity, so emitted photons travel in essentially straight lines.
2. As the star collapses into a neutron star, the surface gravity becomes stronger and photons follow curved paths.
Star
(a)
Neutron star
(b)
3. Continued collapse intensifies the surface gravity, and so photons follow paths more sharply curved.
4. When the star shrinks past a critical size, it becomes a black hole: Photons follow paths that curve back into the black hole so no light escapes.
Neutron star
(c)
Black hole
(d)

Q：如果太陽塌縮成了黑洞，對地球有何影響？

- 會被吸進去嗎？
- 不再有春、夏、秋、冬？
- 從此適合天文觀測？

如果物質夠緻密（在一定的體積內有太多物質）
→ 造成周圍空間彎曲



Space and Time

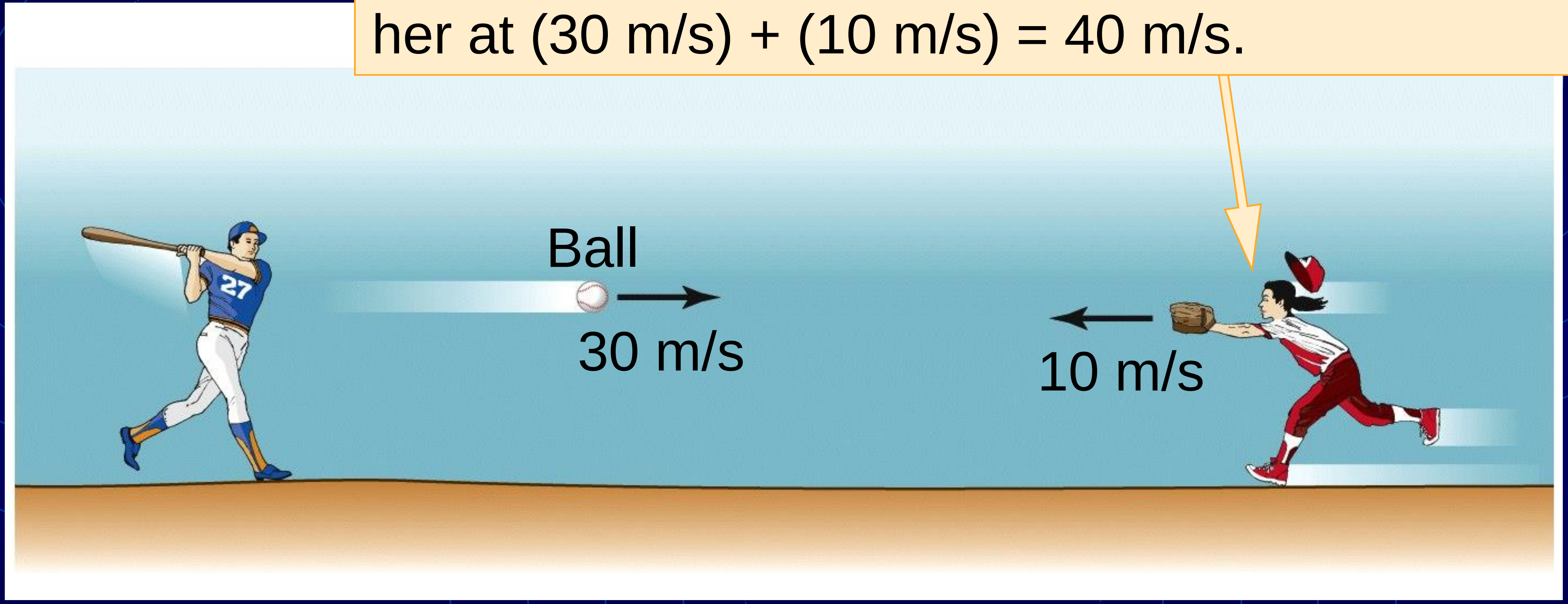
Special Theory of Relativity --- how motion affects our measurements of distance and time (special, because gravity is not included)

與古典牛頓力學不同，特殊相對論中，時間與空間<u>沒有</u>絕對參考座標系統

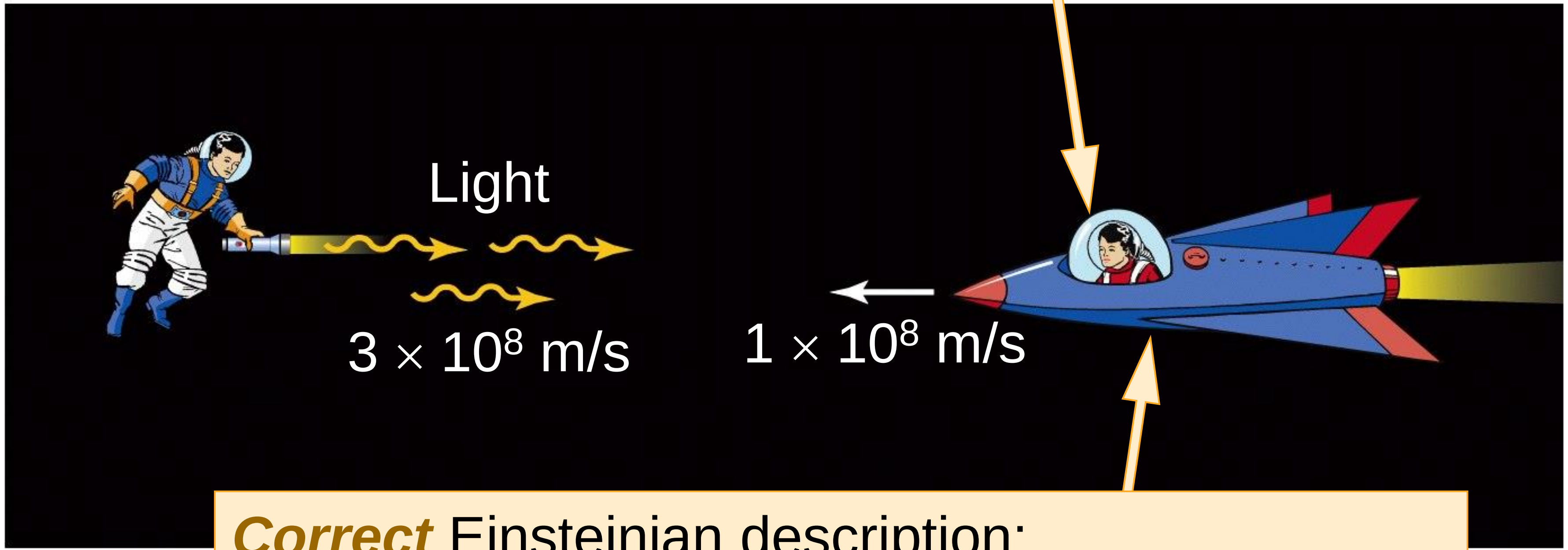
1. 只要等速直線運動，看到的事情都一樣
2. 任何等速直線運動觀察者量到相同光速

Spacetime as a 4-dimensional entity

As seen by the outfielder, the ball is approaching her at (30 m/s) + (10 m/s) = 40 m/s.



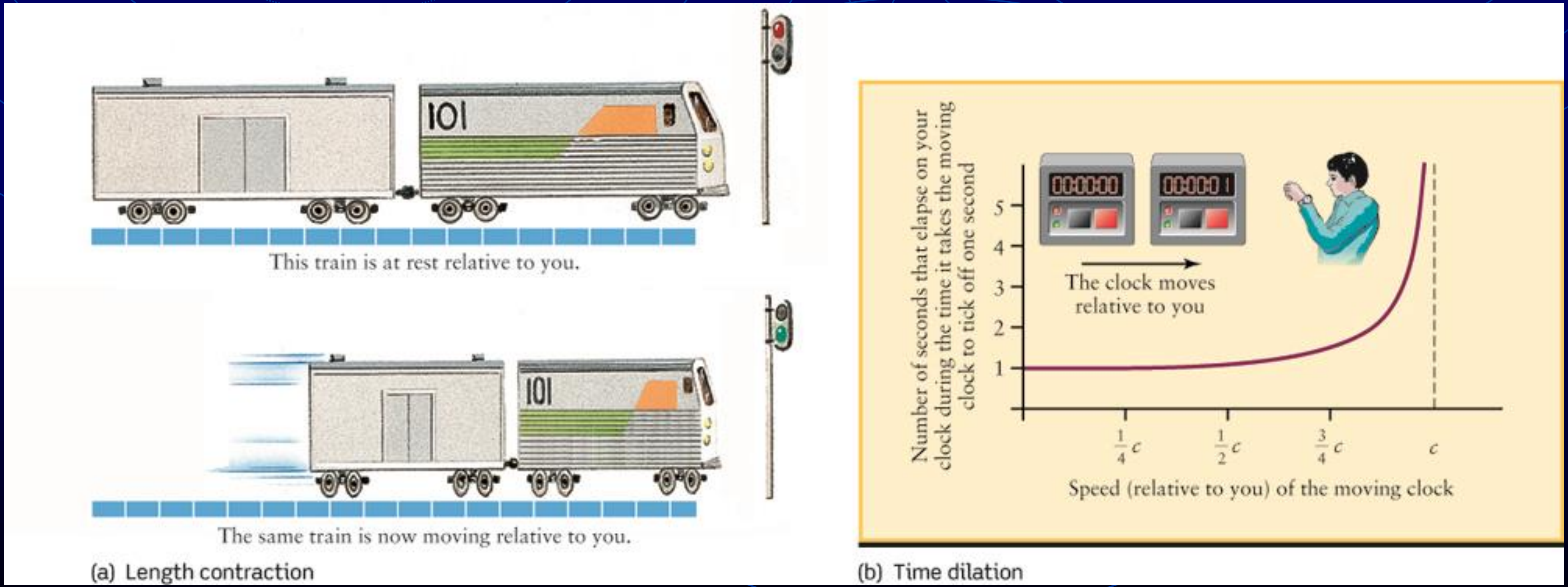
Incorrect Newtonian description:
As seen by the astronaut in the spaceship, the light is approaching her at $(3 \times 10^8$ m/s$) + (1 \times 10^8$ m/s$) = 4 \times 10^8$ m/s.



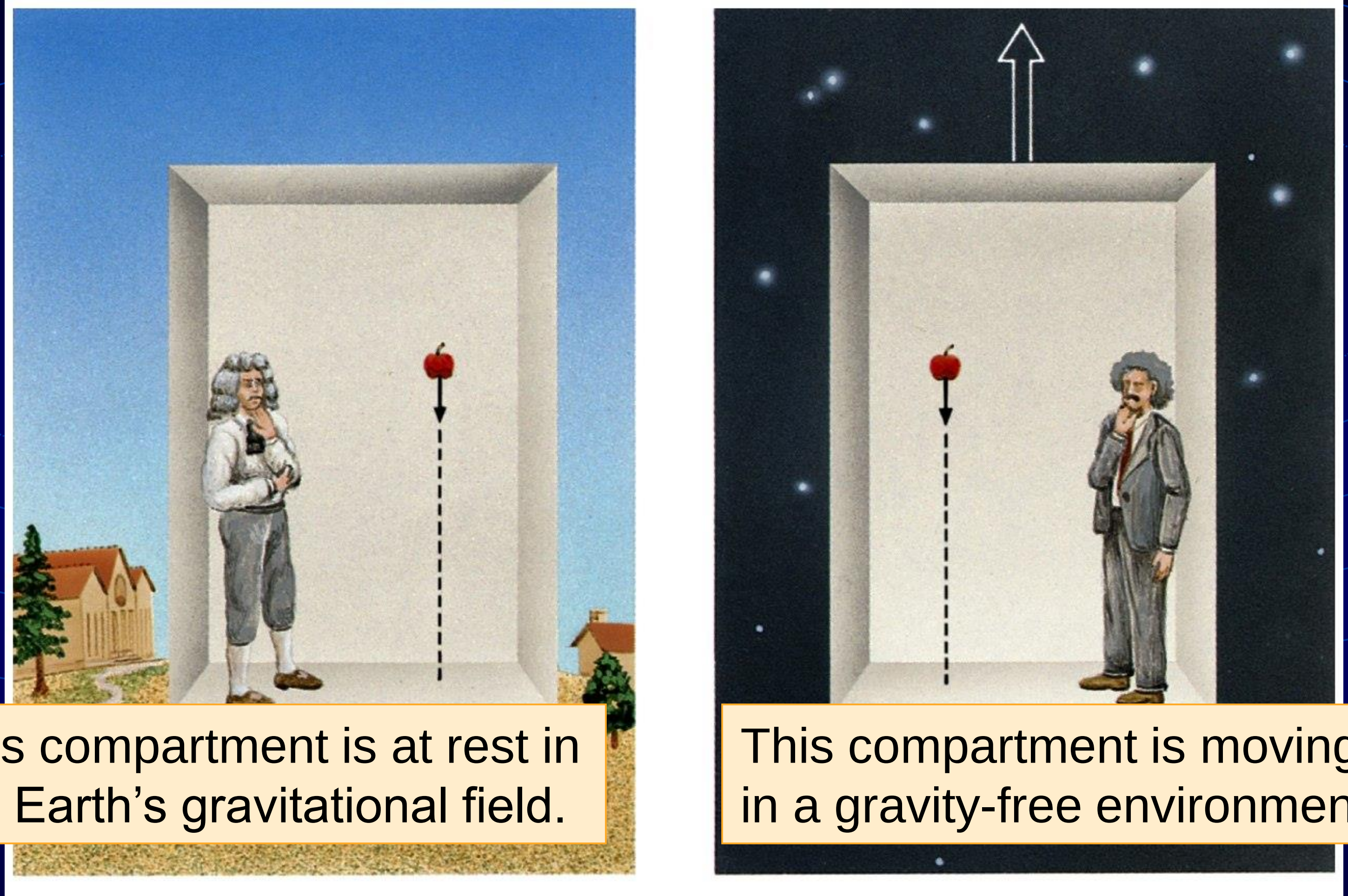
Correct Einsteinian description:
As seen by the astronaut in the spaceship, the light is approaching her at 3×10^8 m/s.

特殊相對論

- **Length Contraction**
  速度越快者長度越短
- **Time Dilation**
  速度越快者時間越慢
- **Mass Increase**
  速度越快者質量越大



廣義相對論



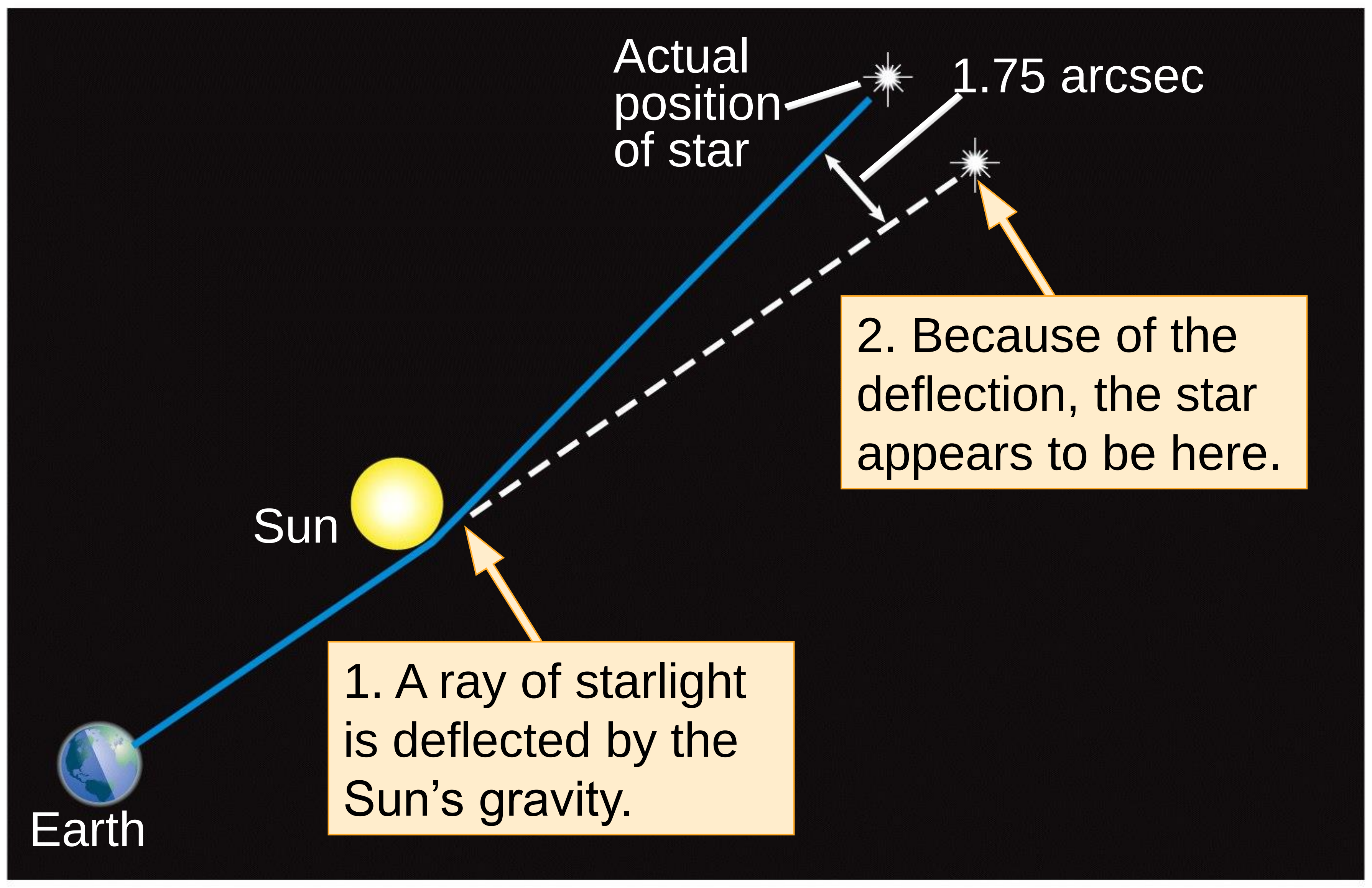
This compartment is at rest in the Earth's gravitational field.

This compartment is moving in a gravity-free environment.

(a) The apple hits the floor of the compartment because Earth's gravity accelerates the apple downward.

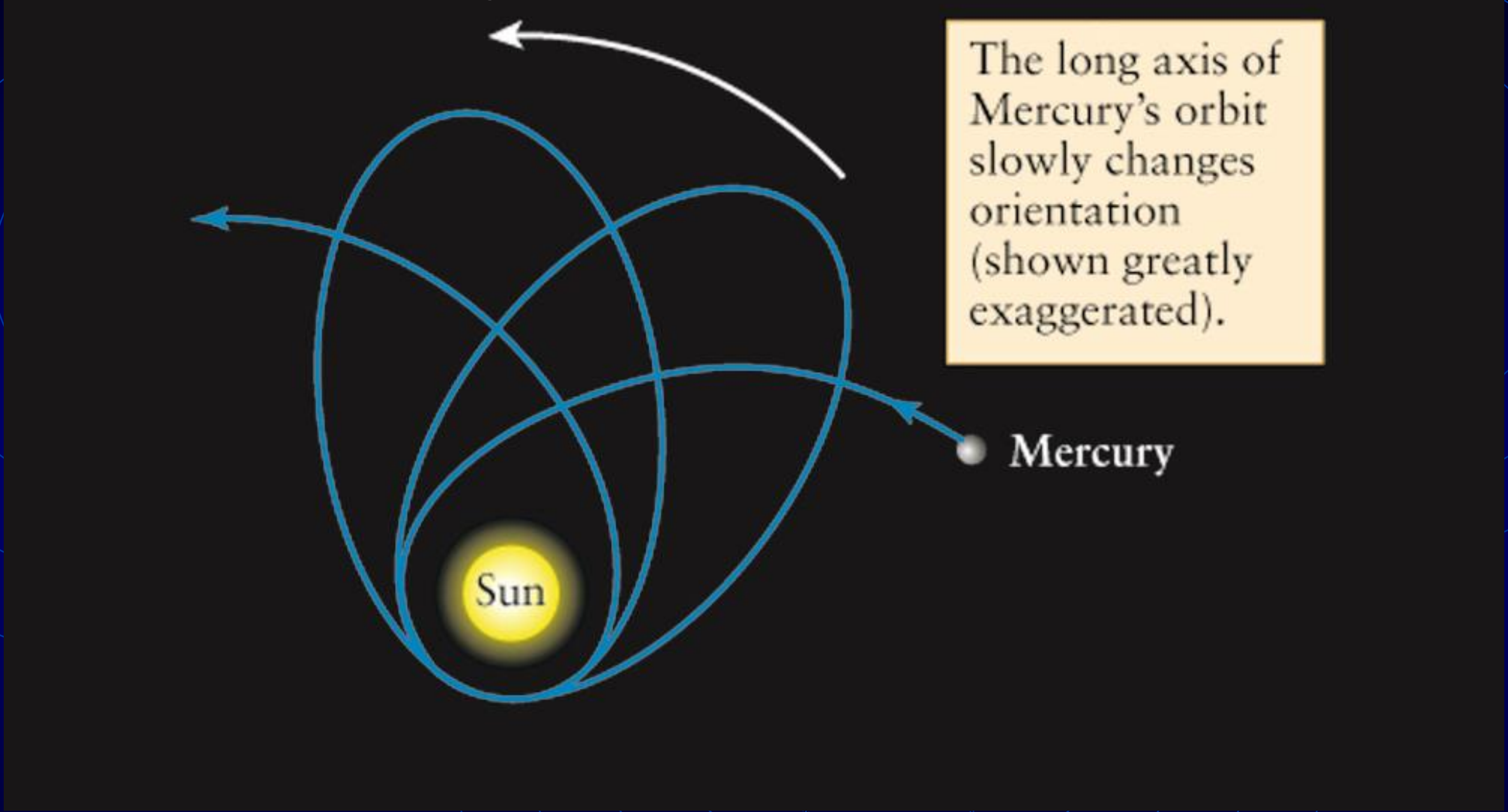
(b) The apple hits the floor of the compartment because the compartment accelerates upward.

Testing General Relativity I



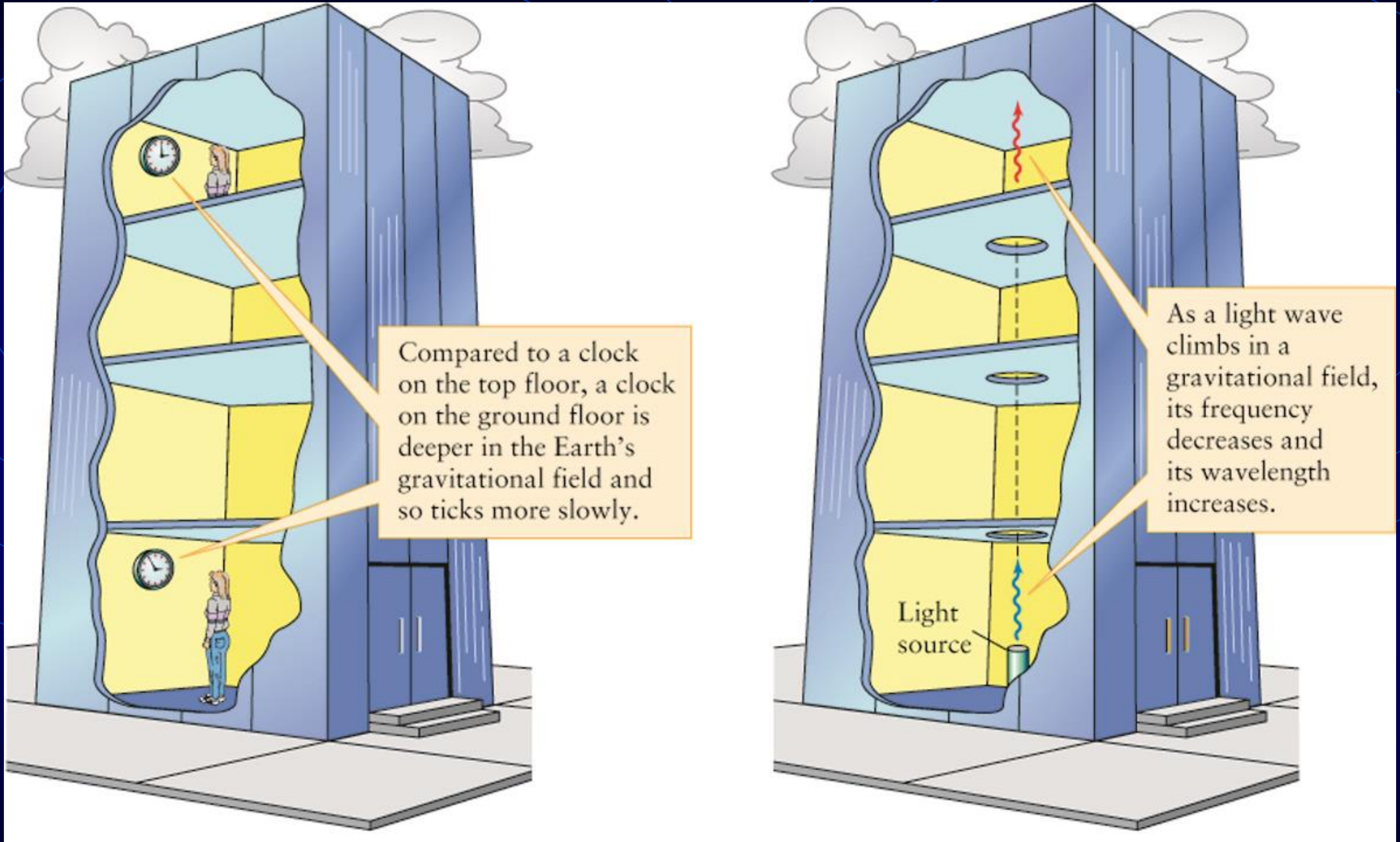
Confirmed during a solar eclipse in 1919.

Testing General Relativity II



Precession caused by pull of planets → 531”/century, but 574”/century observed

Testing General Relativity III



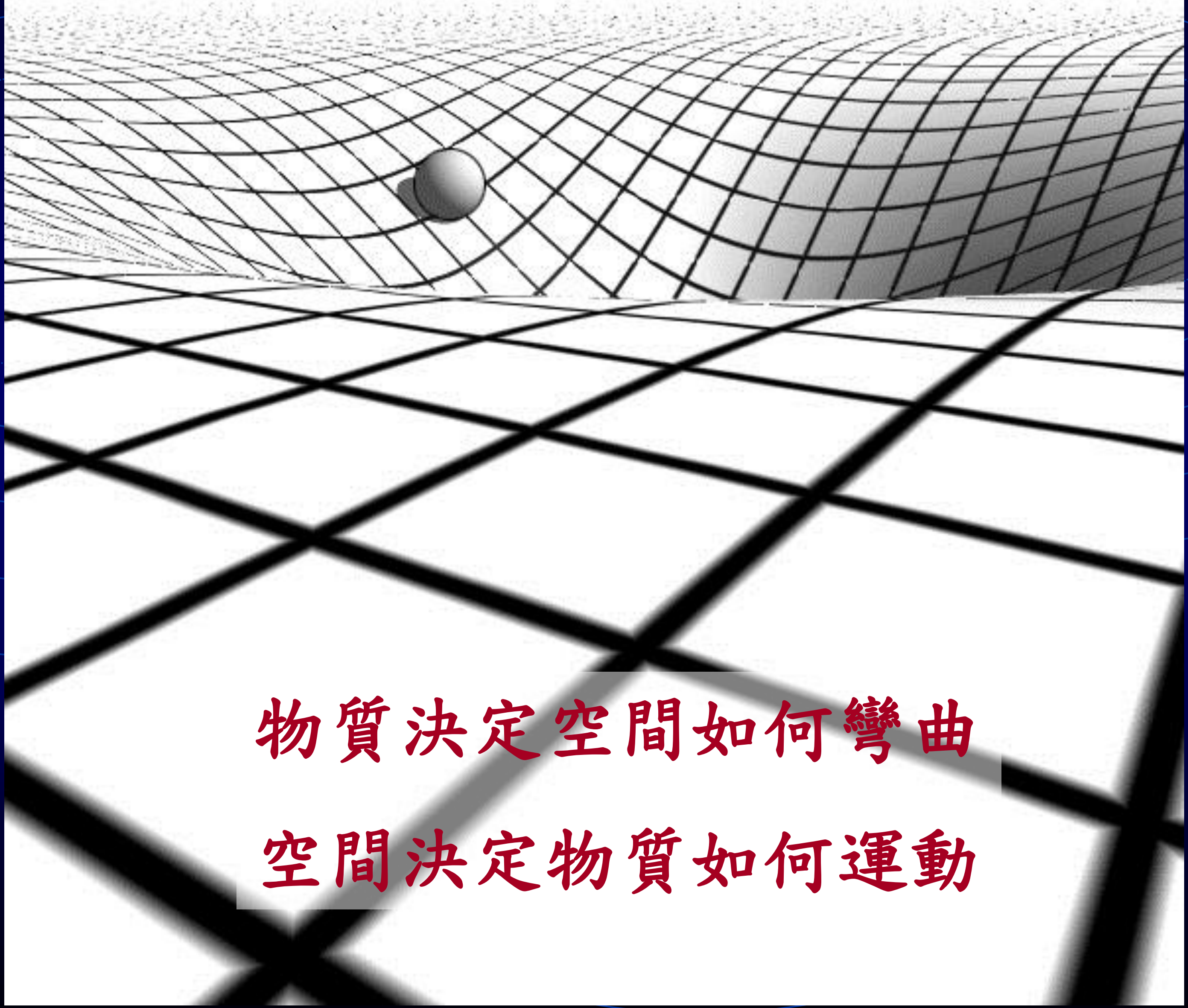
(a) The gravitational slowing of time

(b) The gravitational redshift

樓下的鐘比較慢

脫離重力場的光子損失能量

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



物質決定空間如何彎曲

空間決定物質如何運動

- 決定某個天體逃脫速度的因素包括它的質量以及大小（直徑）

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

- 若某天體相對於體積，質量很大，逃脫速度等於光速
  ➔黑洞
- 該半徑稱為 **Schwarzchild radius 史瓦茲半徑**），
  該球面稱為 **事件地平面 (event horizon)**
  其內的訊息跑不出來

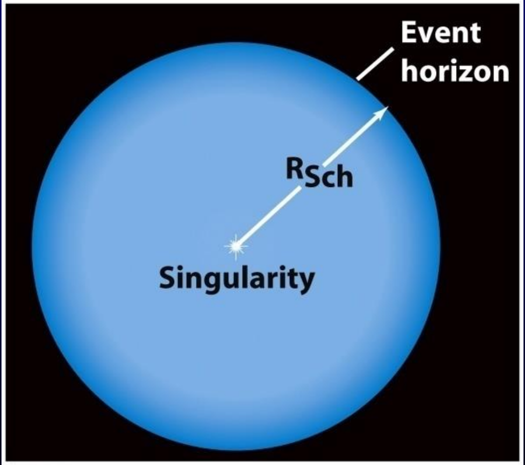


Figure 14-10
Discovering the Universe, Seventh Edition

史瓦茲半徑

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

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

- 如果太陽成為黑洞，半徑約為 3 公里

→ 如果地球成為黑洞，半徑約為 1 公分

→ 如果喜馬拉雅山變成黑洞，大小有多大？

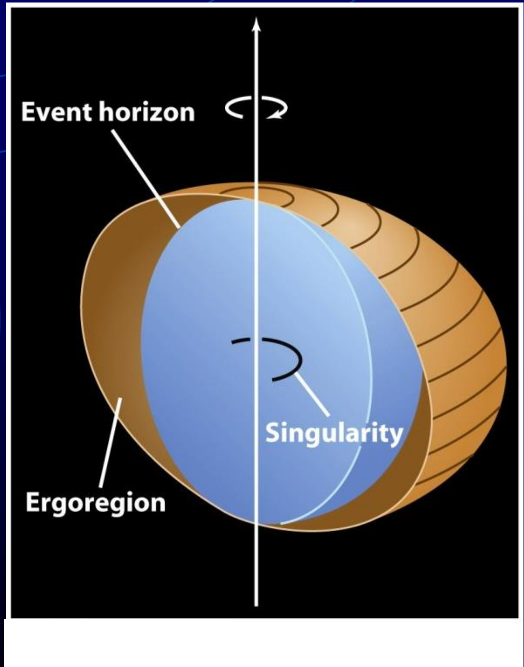
→質量為太陽質量 1 億倍的黑洞，其大小為...

這相當於多大？（和地日距離比）　　密度呢？

黑洞的種類

- **Schwarzchild black holes**
  沒有自轉的黑洞 （原來的物質就沒有自轉），
  物質全集中在奇異點，該處密度無窮大

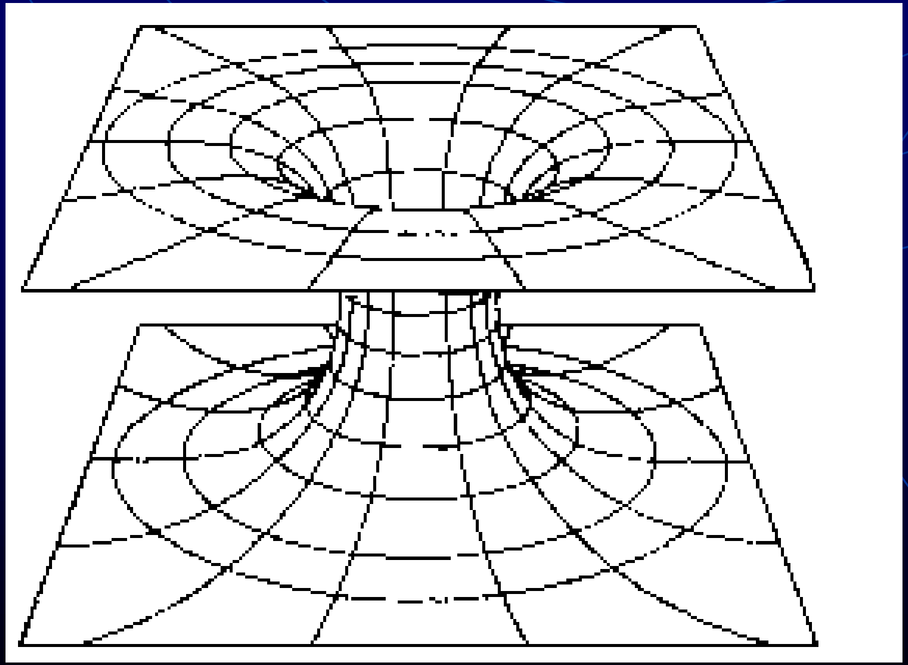
- **Kerr black holes**
  自轉黑洞，每秒達數千轉。
  Beyond the event horizon
  ergoregion（動區），
  被黑洞帶著一起旋轉



	Non-rotating	Rotating
Uncharged	Schwarzschild	Kerr
Charged	Reissner–Nordström	Kerr–Newman

時空扭曲可以成為「捷徑」，通往宇宙其他角落？

時空旅行？

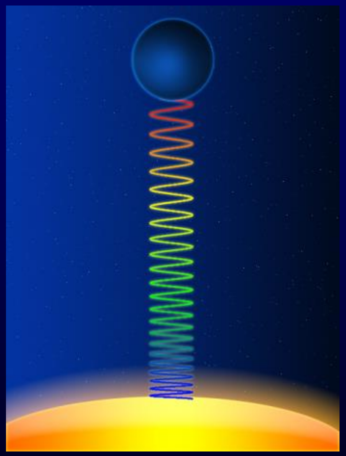


Traveling to a black hole

Which kind of a black hole? A supermassive black hole is drastically different from a stellar black hole.

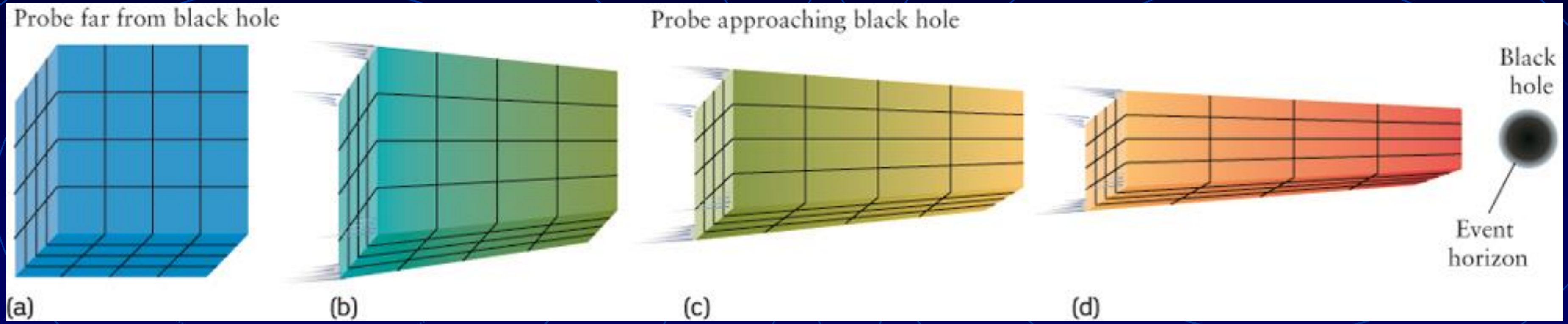
The experience/view is very different for the traveler from that for a distant observer.

- Strong gravitation force/tidal disruption
- Special Relativity: Length contraction, Time dilation, Relativistic mass
- Gravitational redshift



http://en.wikipedia.org/wiki/Gravitational_redshift#/media/File:Gravitational_red-shifting2.png

黑洞附近奇特的時空現象



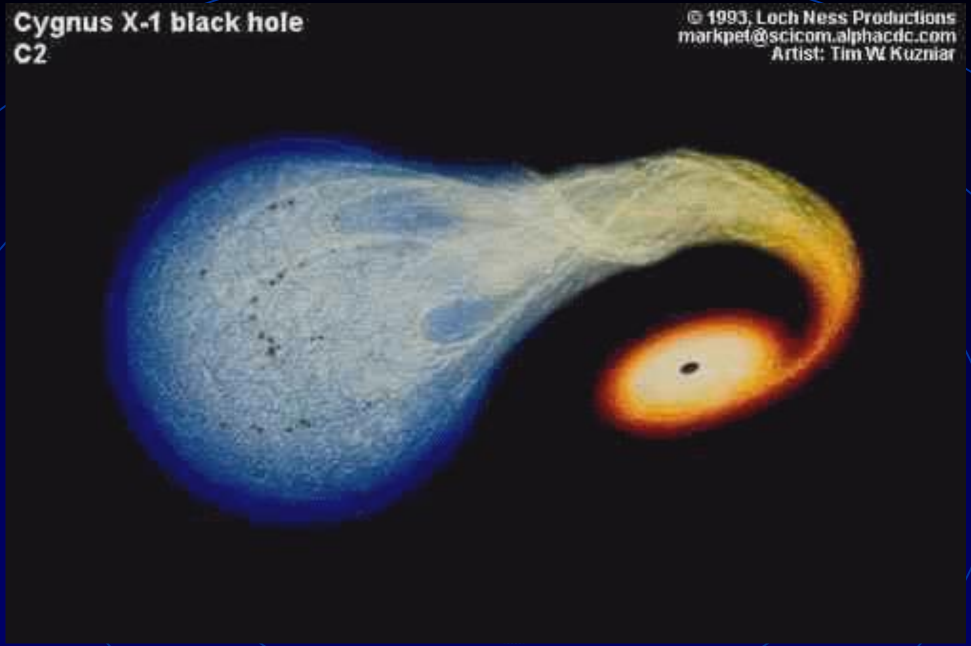
For a distant observer:

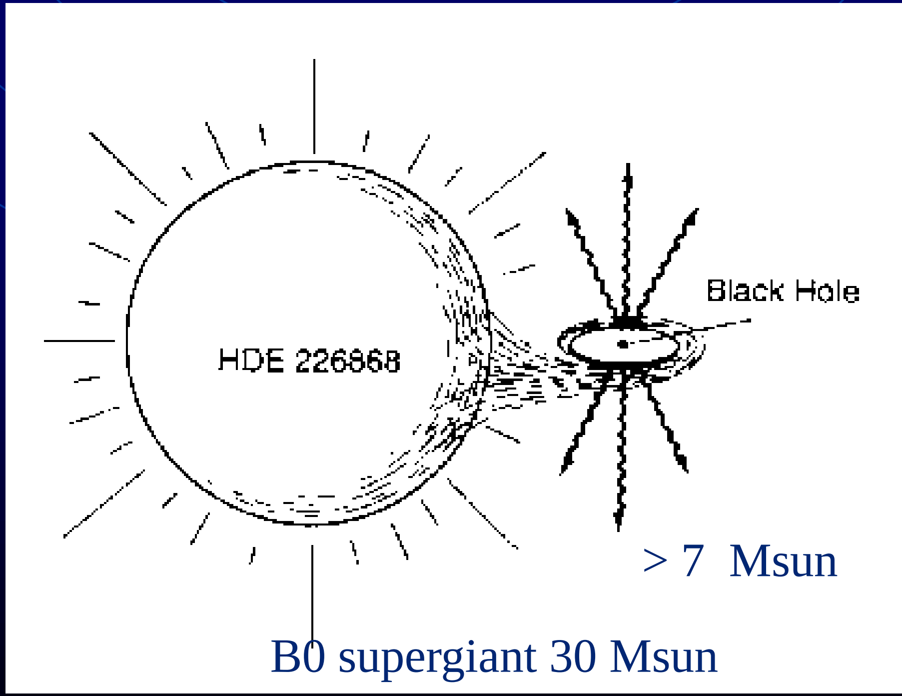
- Gravitational redshift
- Tidal force → stretching, stripping apart
- Time dilation → Probe slowing down

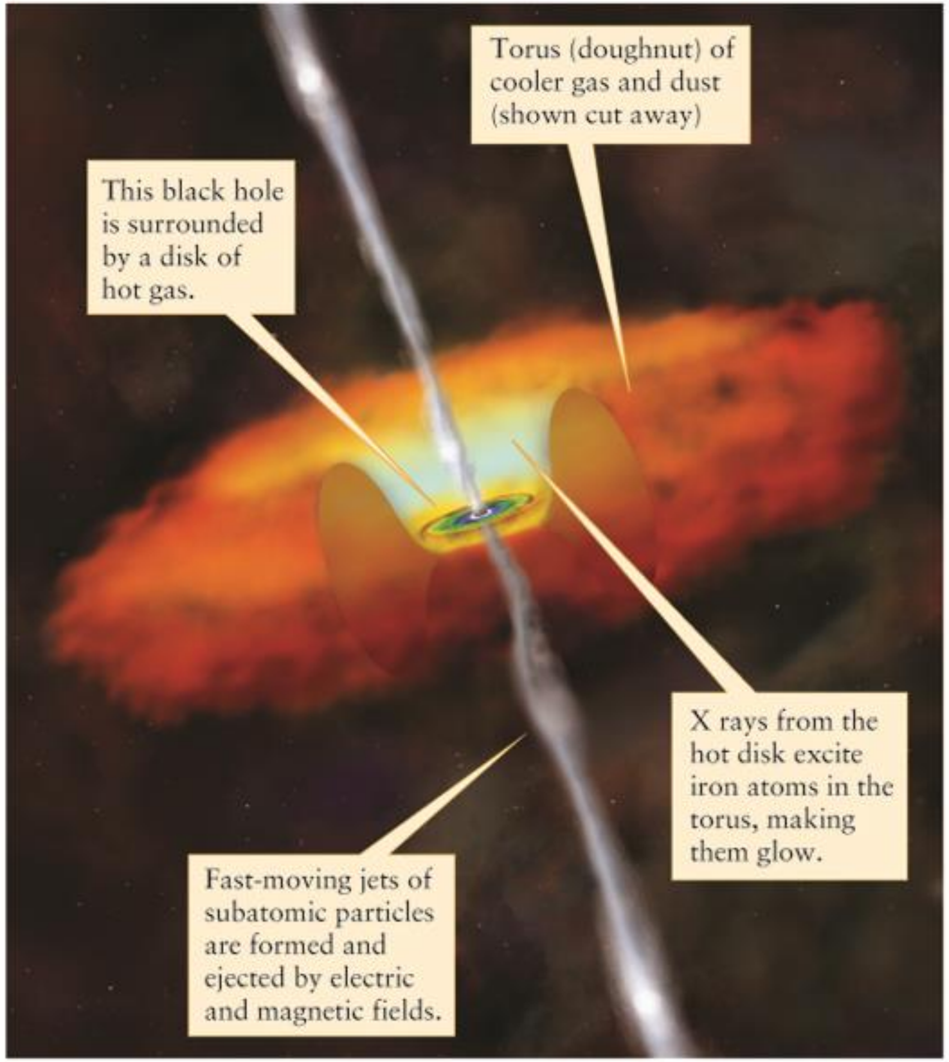
For a passenger on the probe toward the BH:

- No slowing down

利用黑洞對伴星的引力作用，藉以發現黑洞







Environment of an accretion black hole

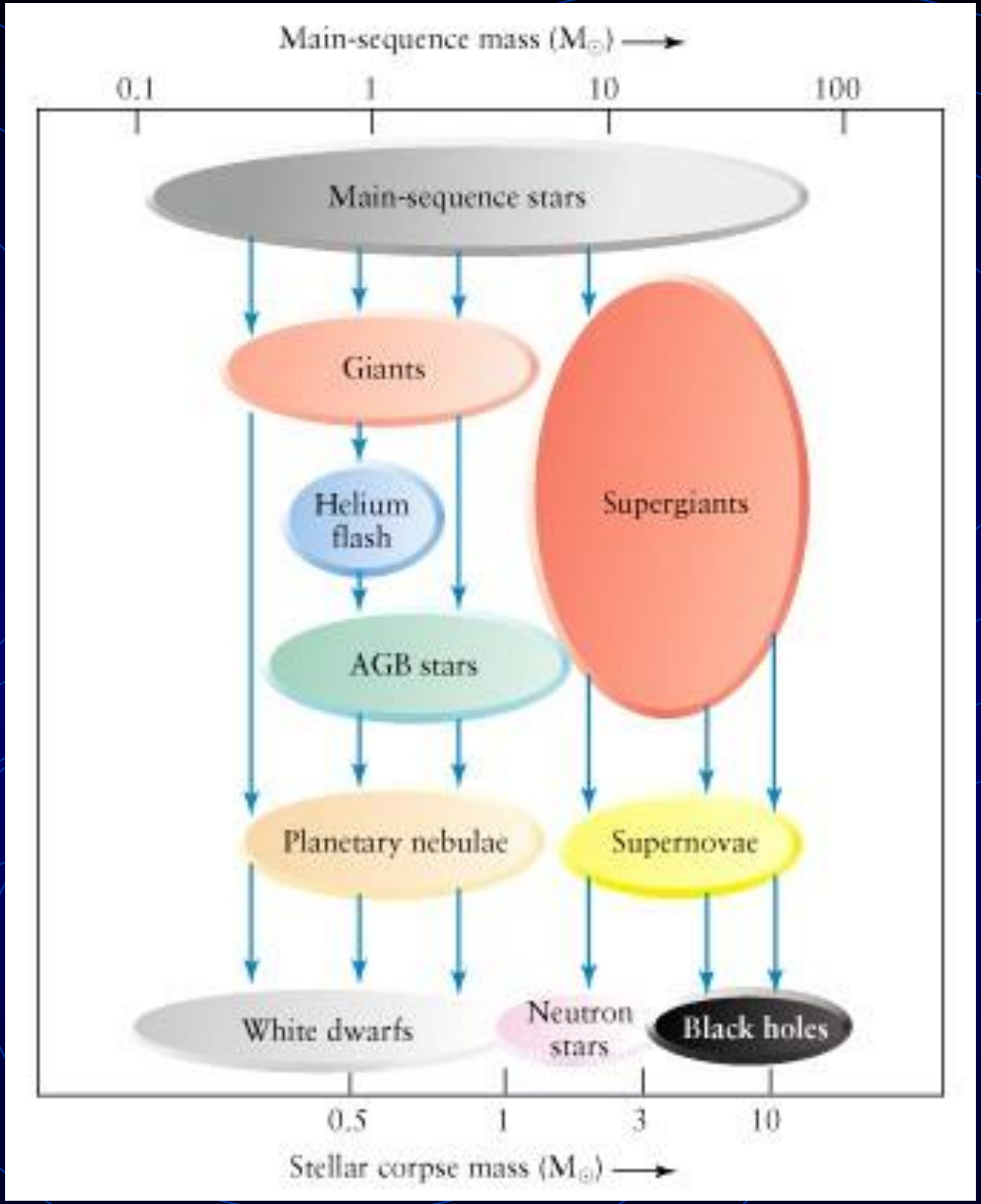
BH rotates → electric and magnetic fields

Channeling accreted material and accelerating as jets along rotation axis

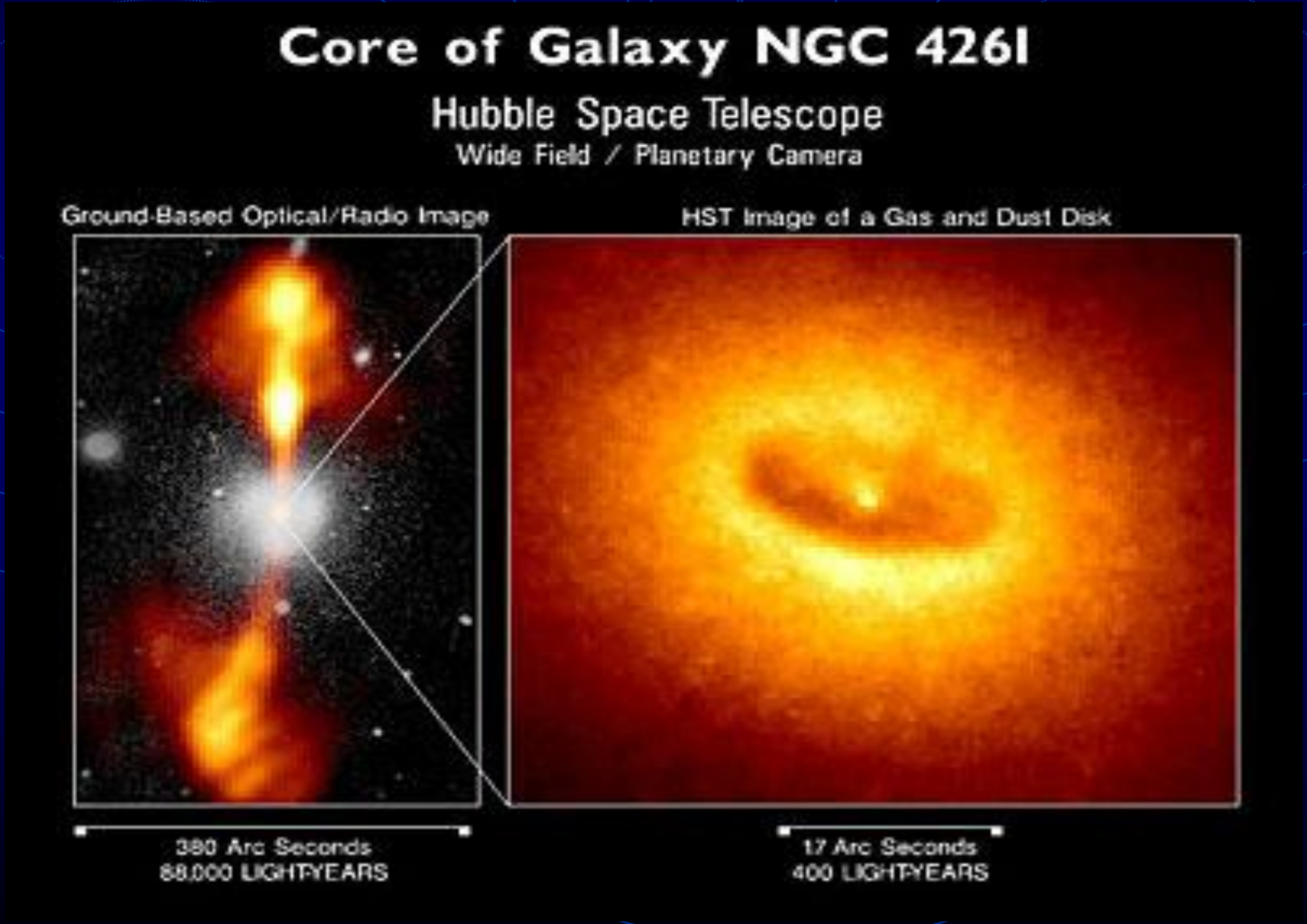
恆星在主序時的質量

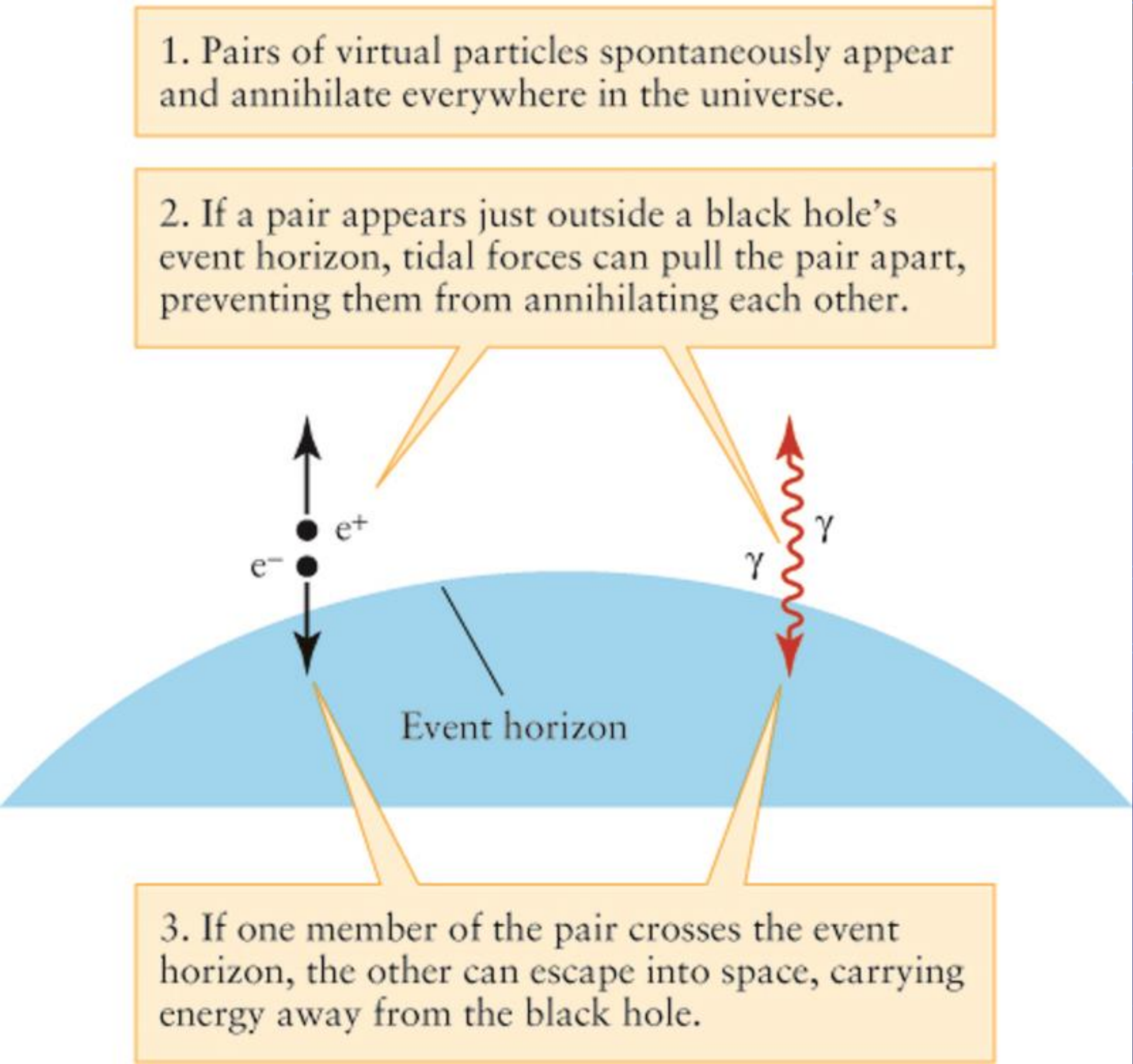
質量流失

恆星死亡時的質量



一些星系的核心可能也有
超大質量黑洞 (supermassive black holes)





A 10^{10} kg BH will take 15 billion years to evaporate.

A 5 $M_{\odot}$ BH will take 10^{62} years.

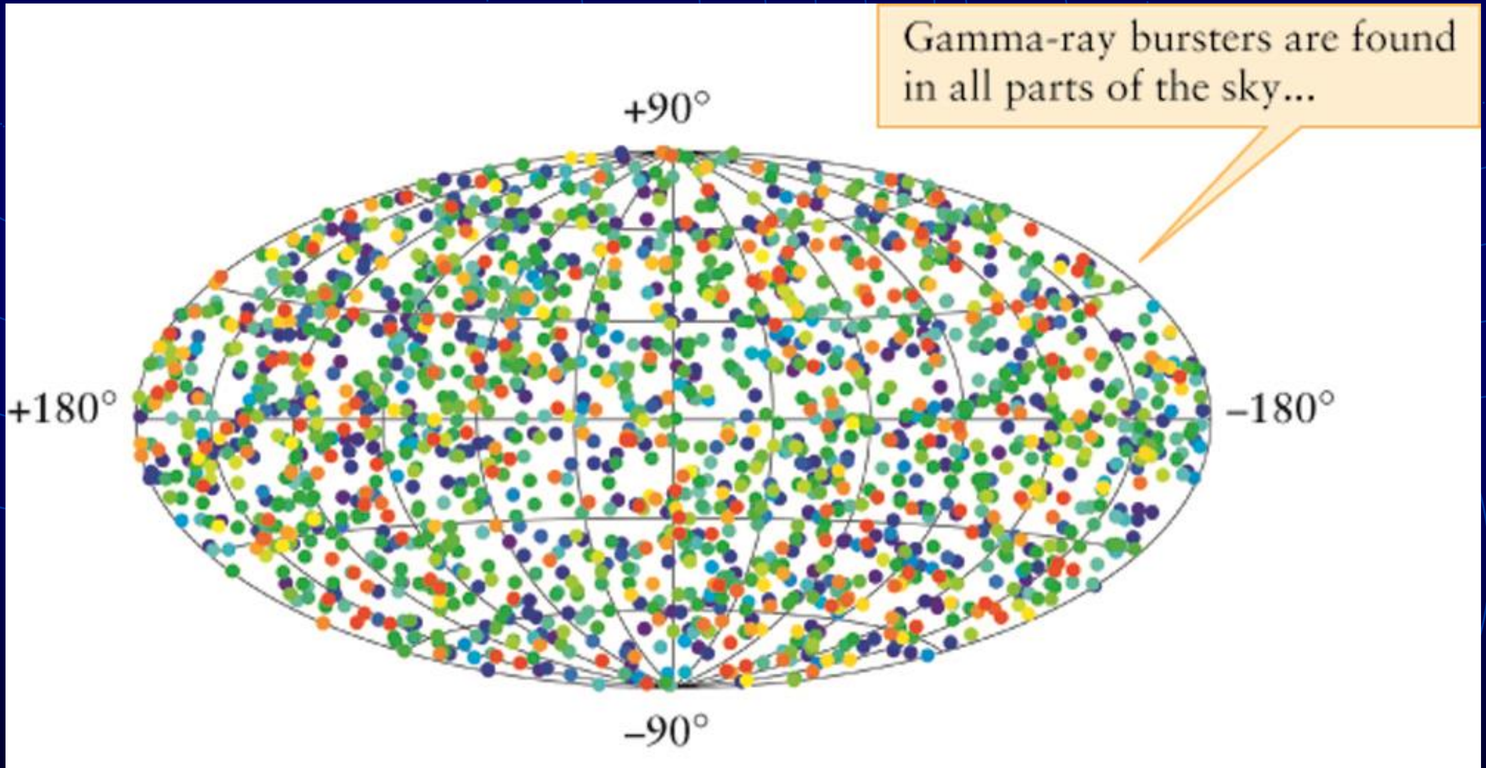
A supermassive (5 million $M_{\odot}$) BH will take 10^{80} years.

黑洞會「蒸發」，逐漸消失 **(Hawking process)**

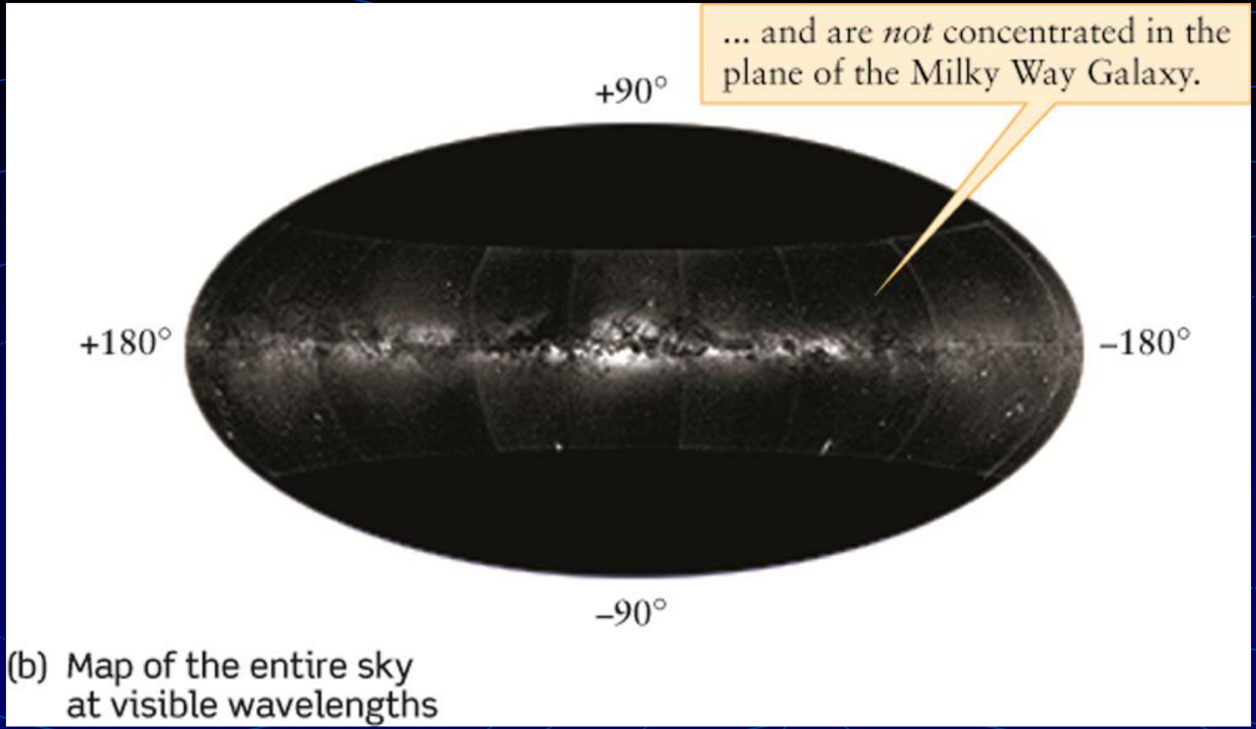
Gamma-ray Burst

Incredibly intensive gamma-ray flashes

→ gamma-ray bursters 伽碼線爆源 (GBRs)

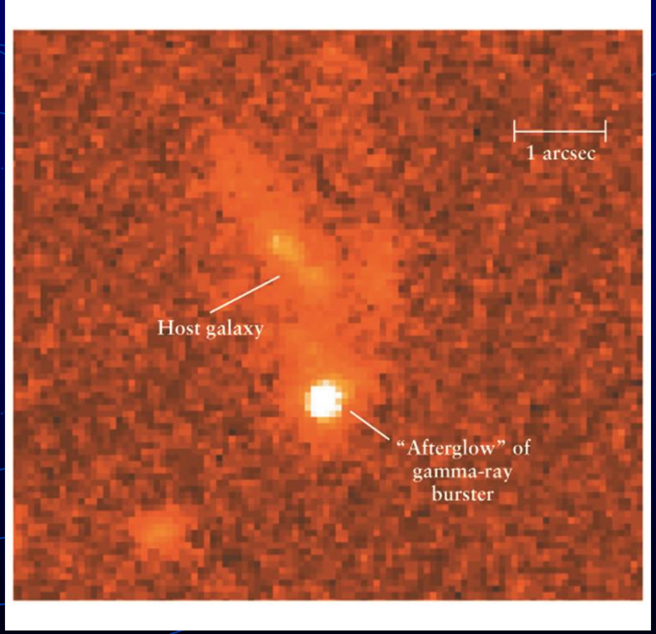


(a) Map of the entire sky showing the positions of gamma-ray bursters



This means GRBs are of extragalactic origin
→ formation of BHs?

Hosting galaxies have been identified in some cases.



奇怪的天體

- 太空中還可能有更奇怪的天體
- 白矮星的質量上限 → Chandrasekhar limit
- 中子星也有質量上限 → **Oppenheimer-Volkov limit**
  大約是 3 $M_{\odot}$
- 很多基本粒子（包括質子、中子，但不包括電子）由夸克組成
- 如果星體壓力太大，中子分解成 quarks → **quark stars**
  性質仍不清楚，但質量可能與 Oppenheimer-Volkov 相當
- **strange matter → a strange star**

Dawn spacecraft zooms in to Ceres …