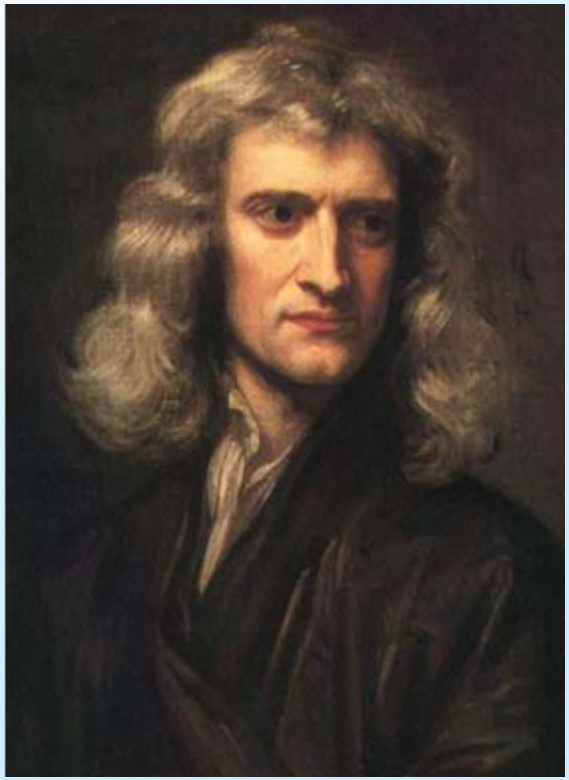
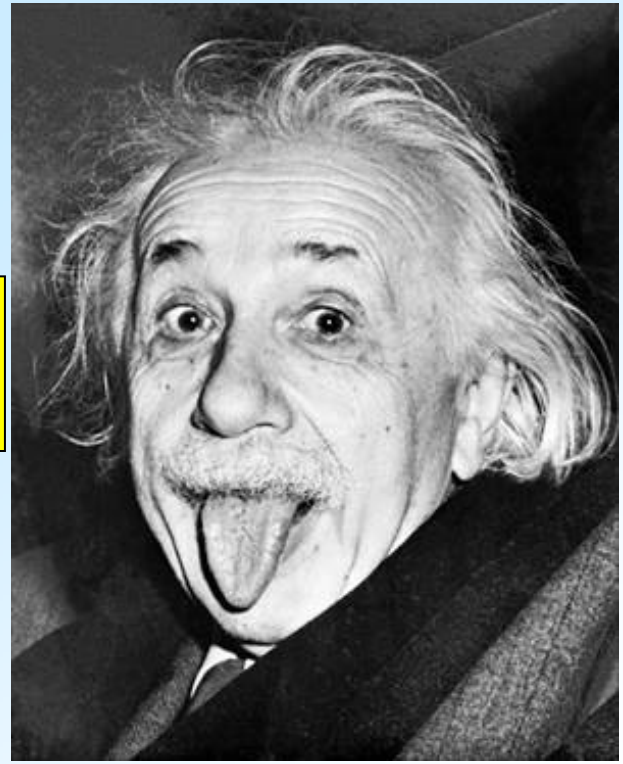
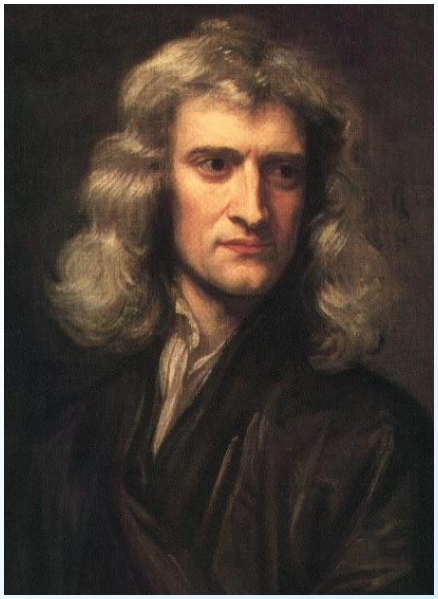
愛因斯坦的革命
從牛頓的蘋果到時空彎曲



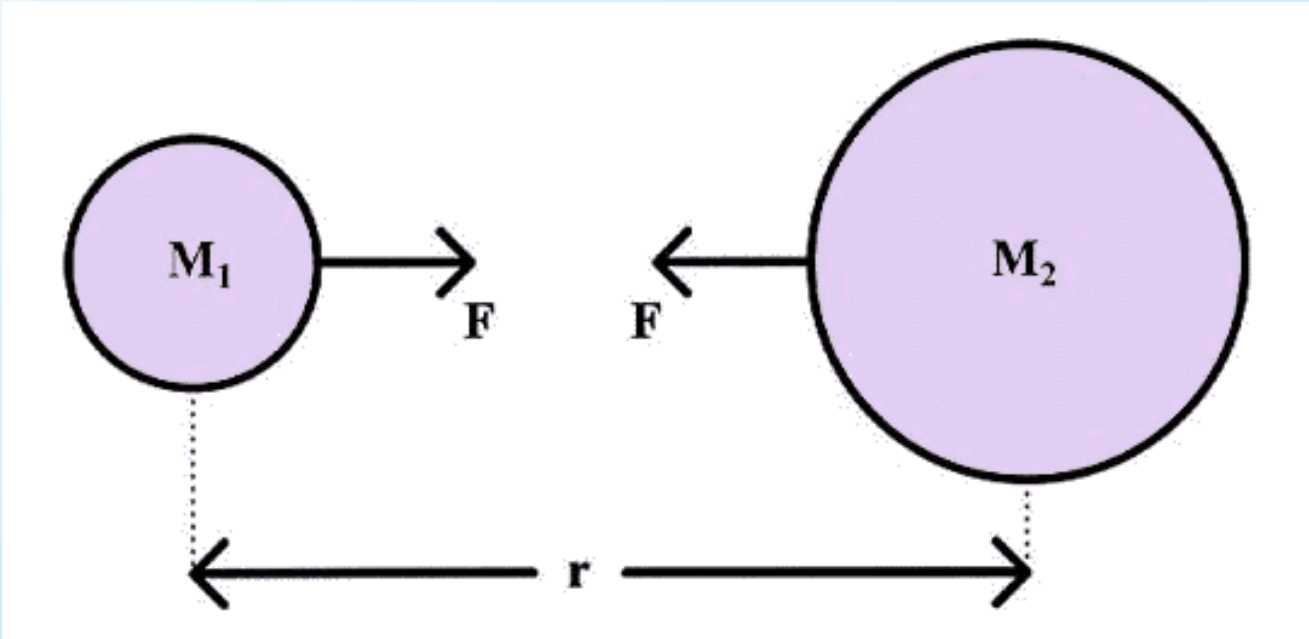
練立明
香港中文大學物理系



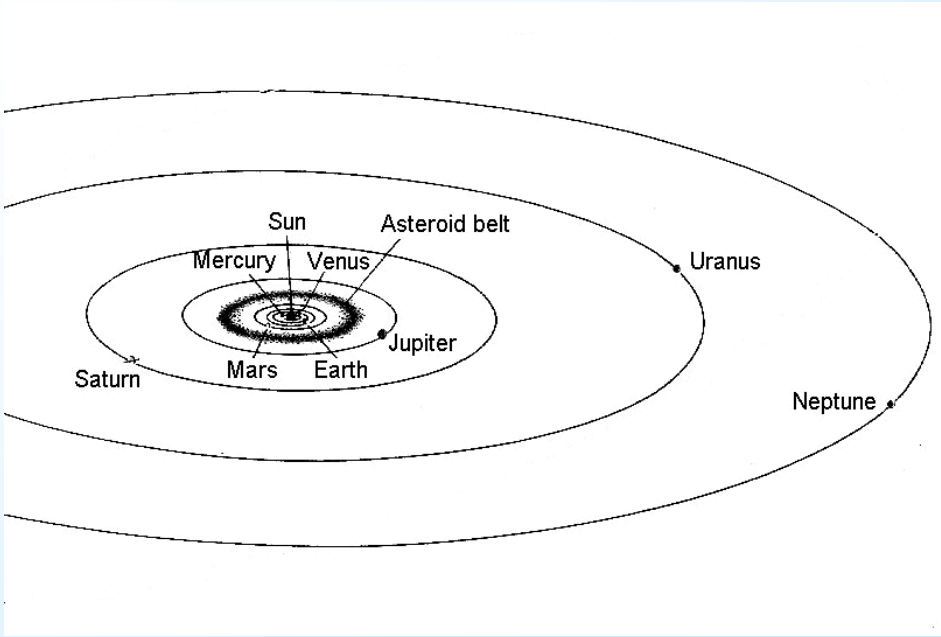
萬有引力?
(重力)

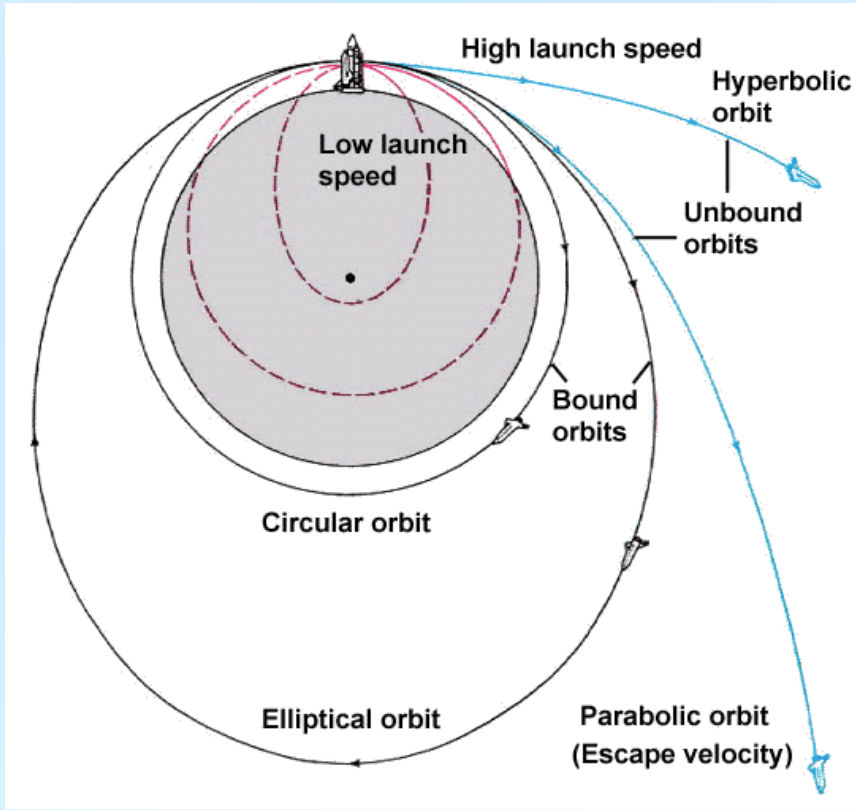


牛頓 (1642-1727)



$$F = \frac{GM_1M_2}{r^2}$$

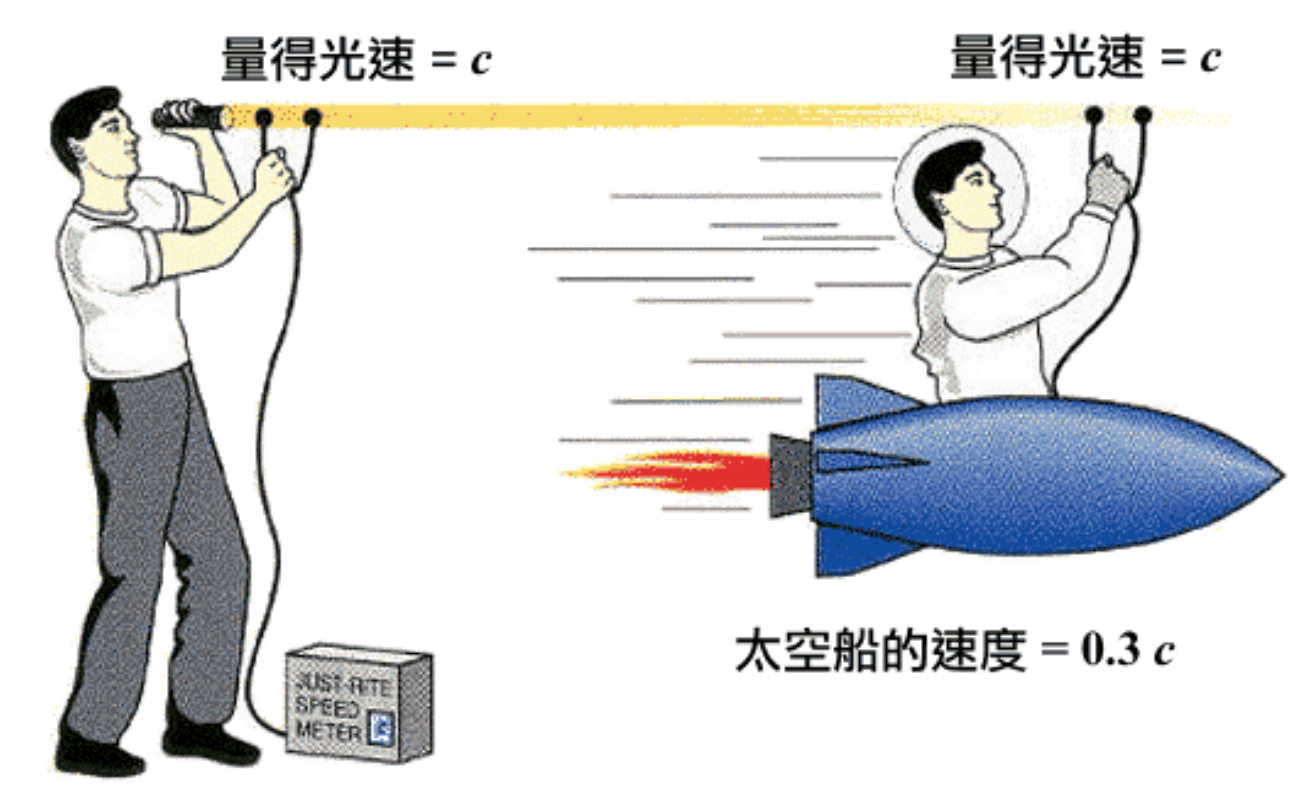

Sun
Asteroid belt
Mercury
Venus
Uranus
Jupiter
Saturn
Mars
Earth
Neptune


High launch speed
Hyperbolic orbit
Low launch speed
Unbound orbits
Bound orbits
Circular orbit
Elliptical orbit
Parabolic orbit
(Escape velocity)

但是……
科學理論不一定是永遠正確的！

光速的絕對性
(19世紀末的重大發現)

●對所有(慣性)觀測者來說，光在真空中的速度皆不變。



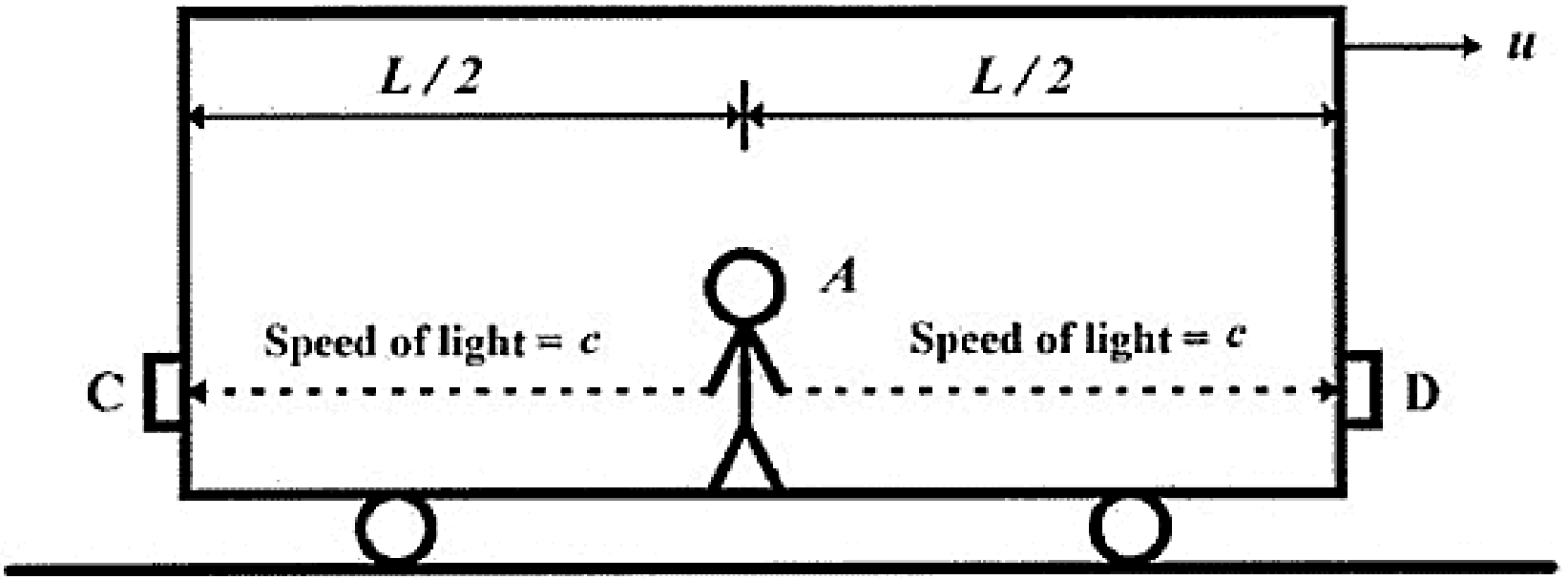
$c = 3\times10^8$ m/s

狹義相對論 (1905)
Special Relativity

愛因斯坦
(1879-1955)

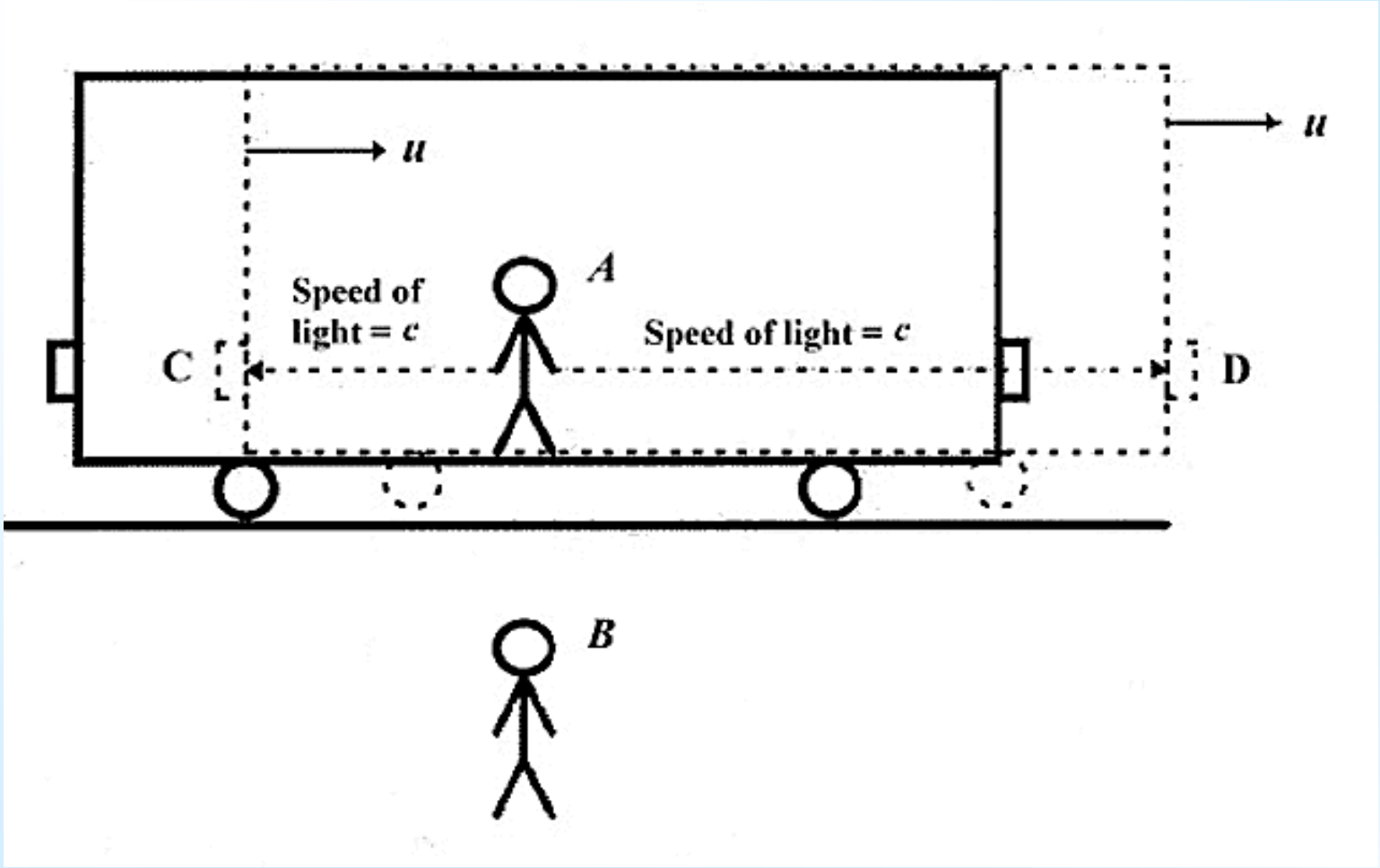
- 基於光速的絕對性，愛因斯坦在 1905年提出狹義相對論。
- 時間和空間 (時空)的新認識 。

同時之相對性



A 從火車正中心同時向C 及D 放射兩束光。

A 所見：二光束以相同速度走相同距離→同時到達C及D 。

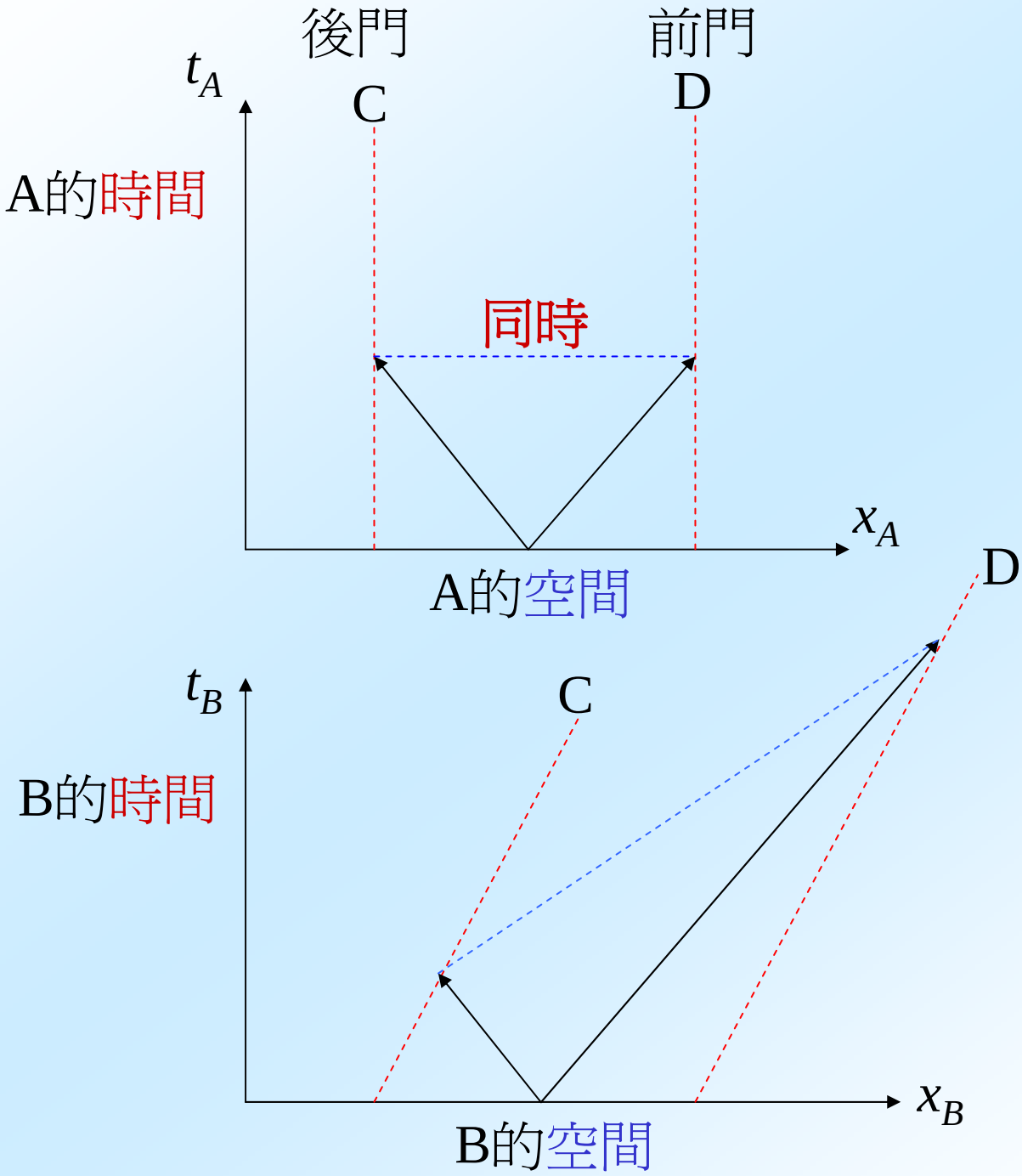


B看到 C 追向光束，而D在移離。

B所見：光束應**先到C**，後到D。

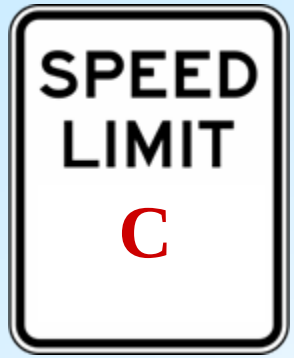
“同時” 是相對的

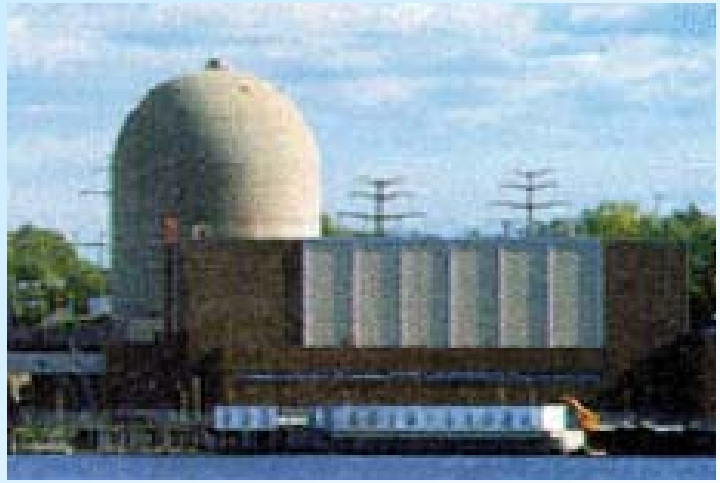
愛因斯坦:時間是相對的,
空間是相對的.


後門
前門
t_A
C
D
A的時間
同時
x_A
A的空間
D
t_B
C
B的時間
x_B
B的空間

更多 “奇怪”結果:

- 時間延滯 (Time dilation)
- 長度縮短 (Length contraction)
- 光速 = 速度極限
- 能量 = 質量 ($E = mc^2$)

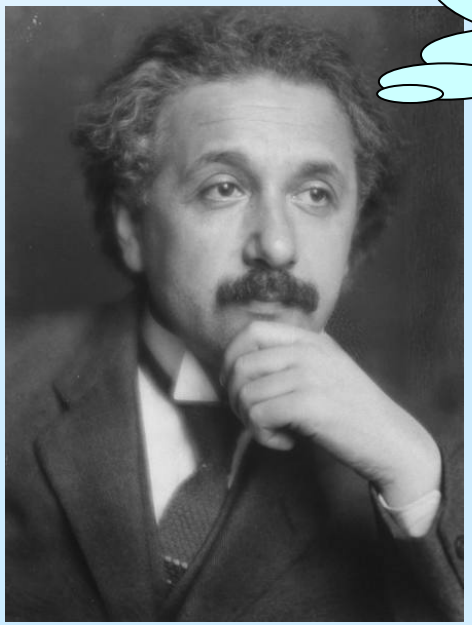




相對論 + 重力？

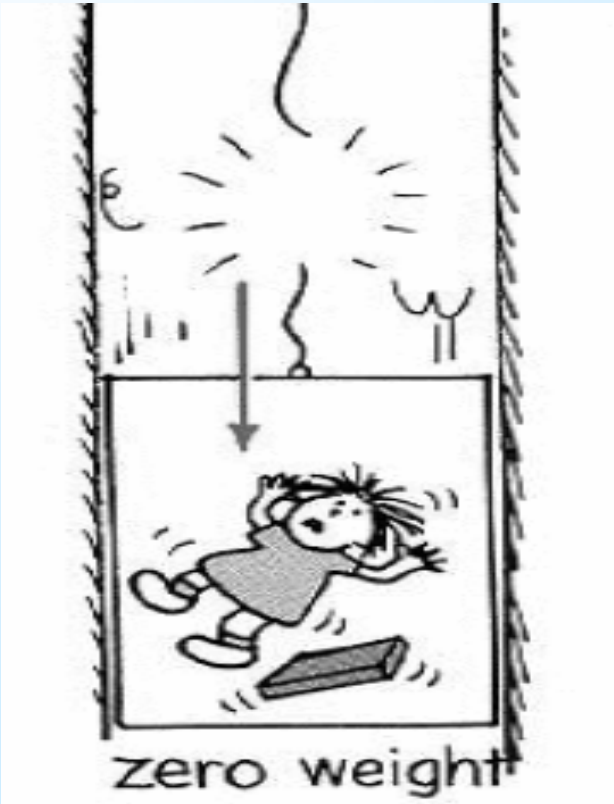
●牛頓的重力理論不滿足狹義相對論!

如何把重力與相對論結合？



$$F = \frac{GM_1M_2}{r^2}$$

小念頭….大發現 (1907)

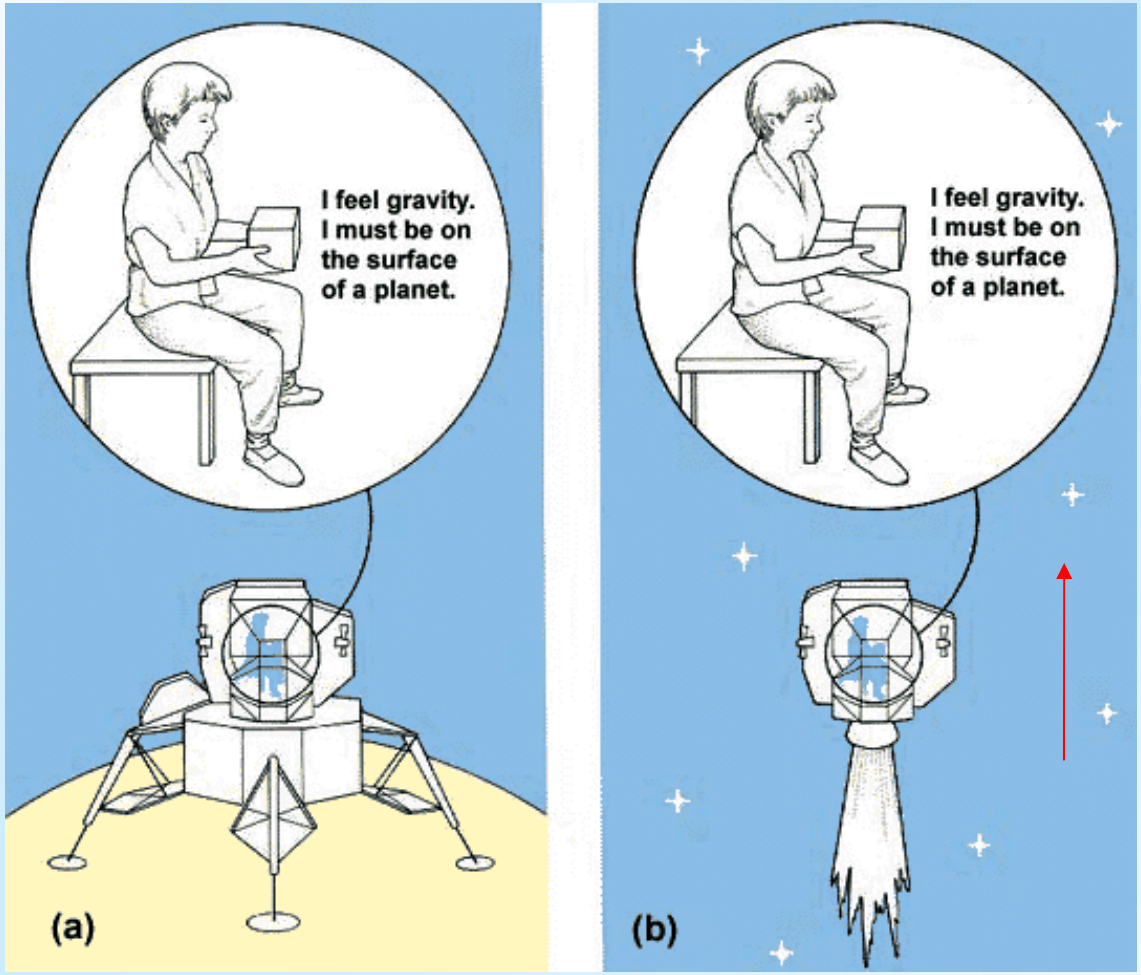


這個觀測者所看見的是
沒有重力的物理現象!
(狹義相對論適用)

"…If a person falls freely, he will not feel his own weight… "
"…the happiest thought of my life…."

———愛因斯坦

重力可以假扮的!

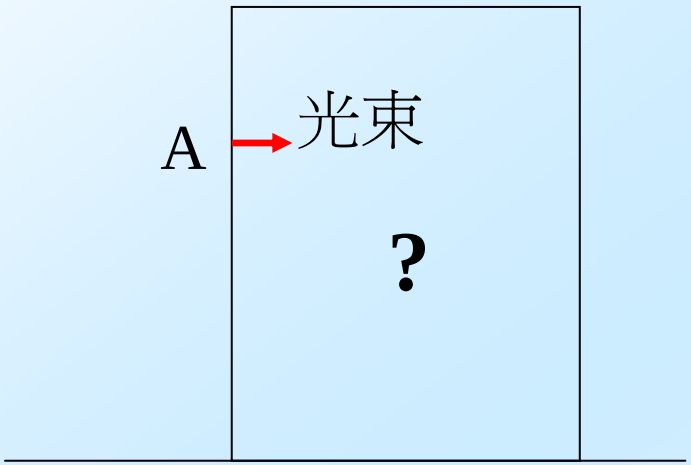


$a = g$

$= 9.8\ ms^{-2}$

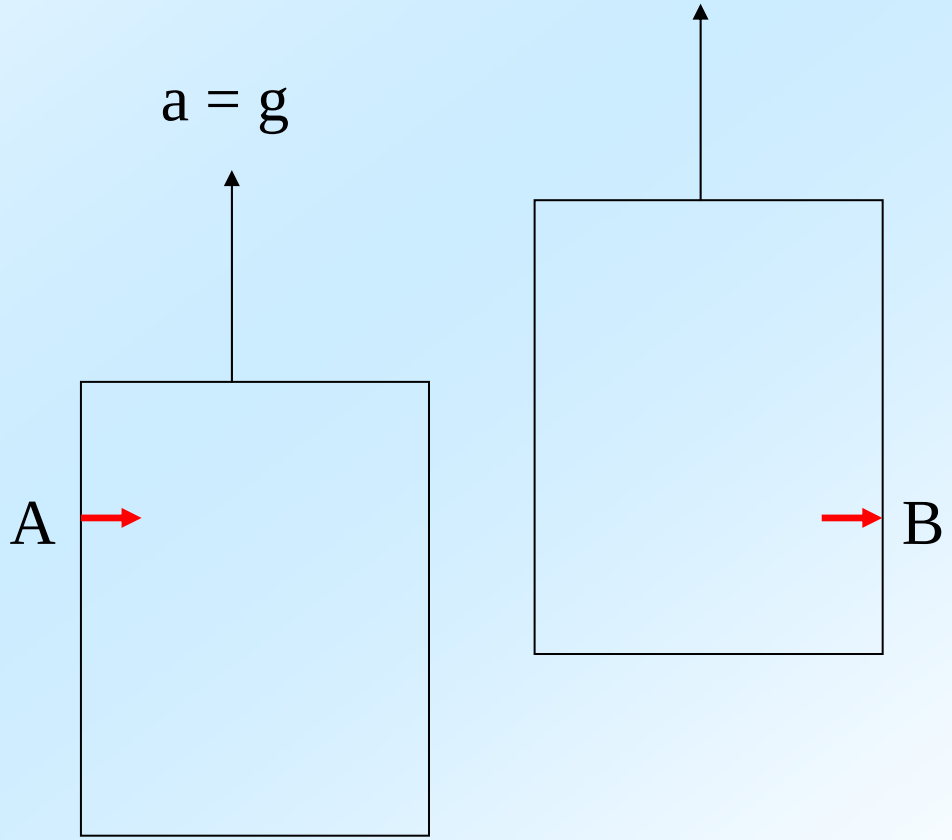
有重力　　有加速

重力對光的影響



有重力

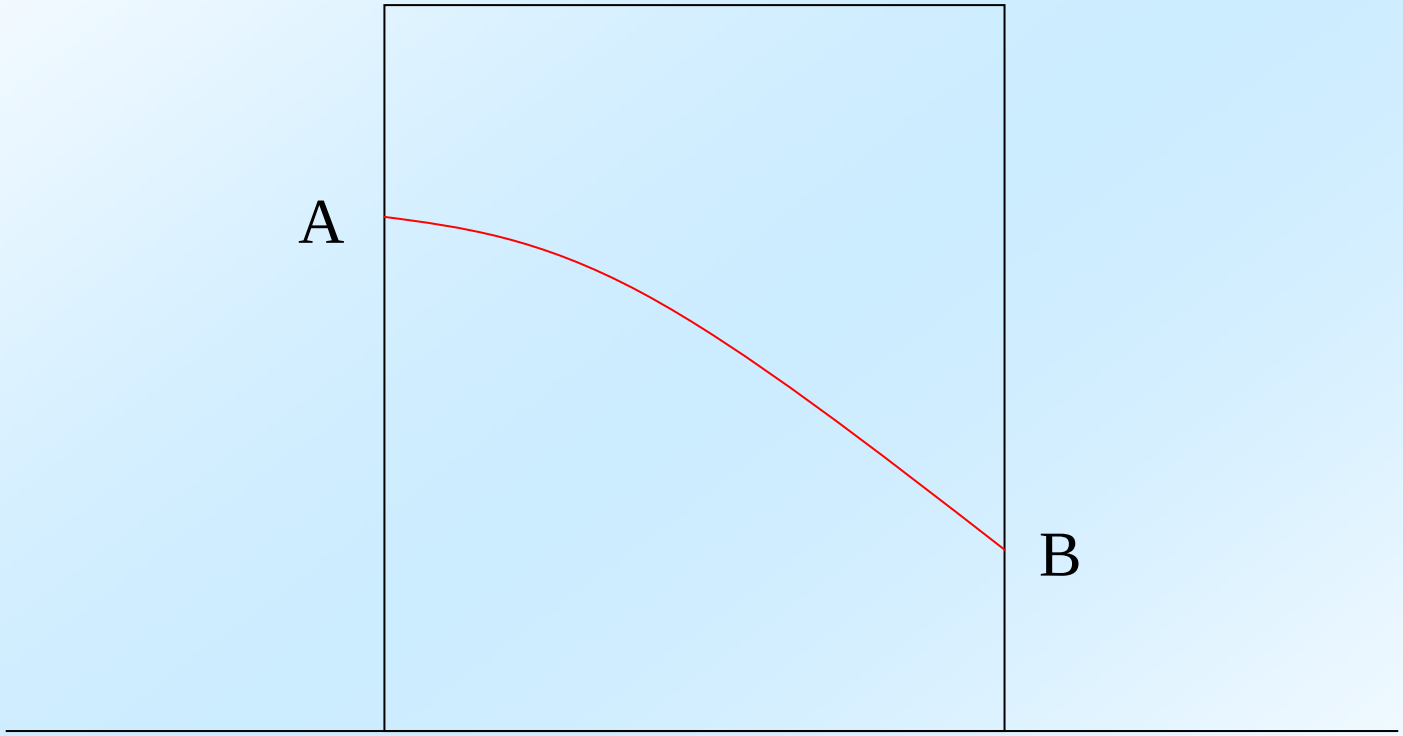
(在地面)



有加速

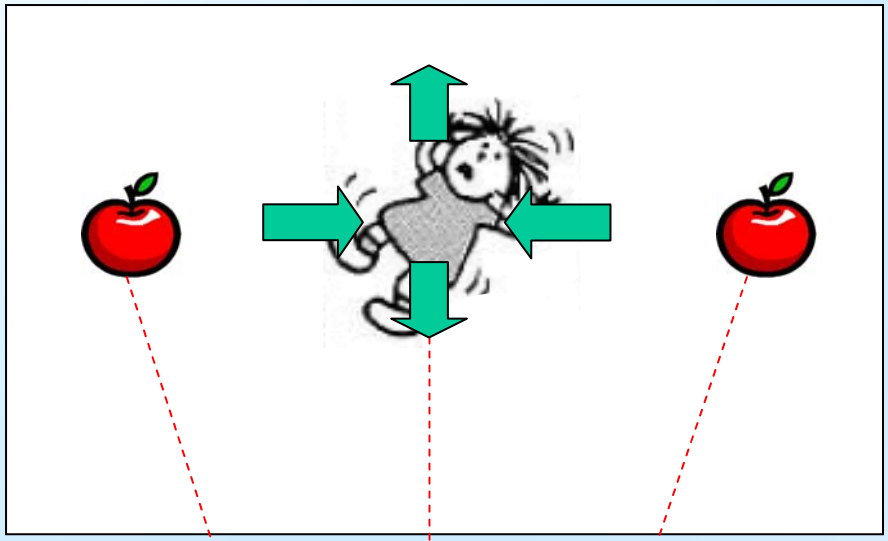
(在太空)

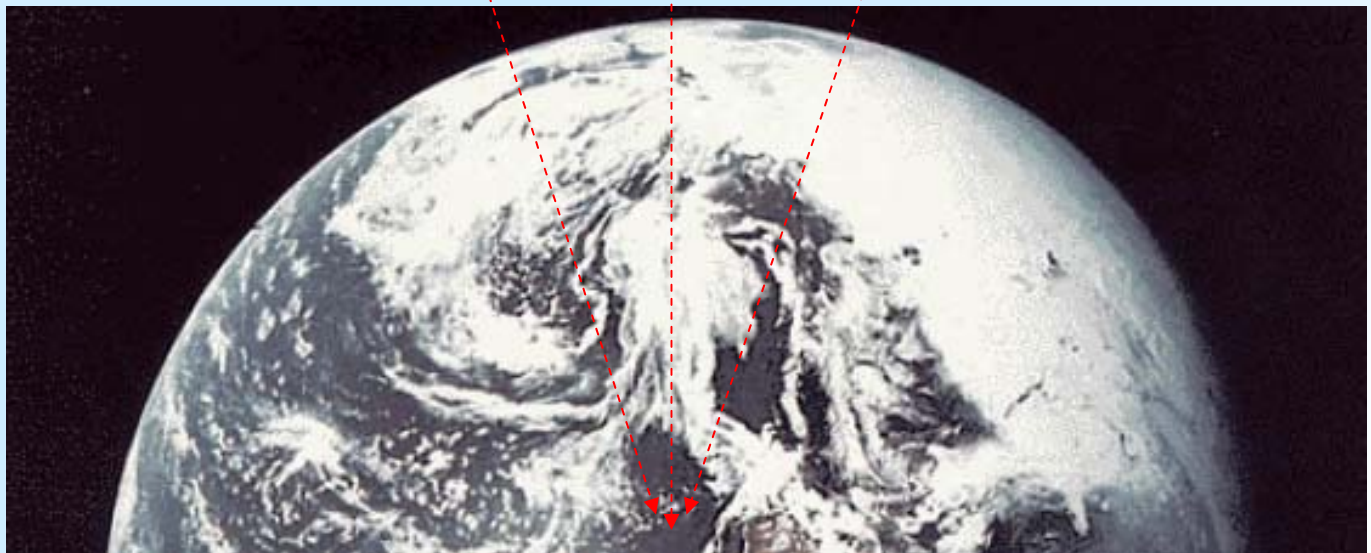
重力扭曲光線

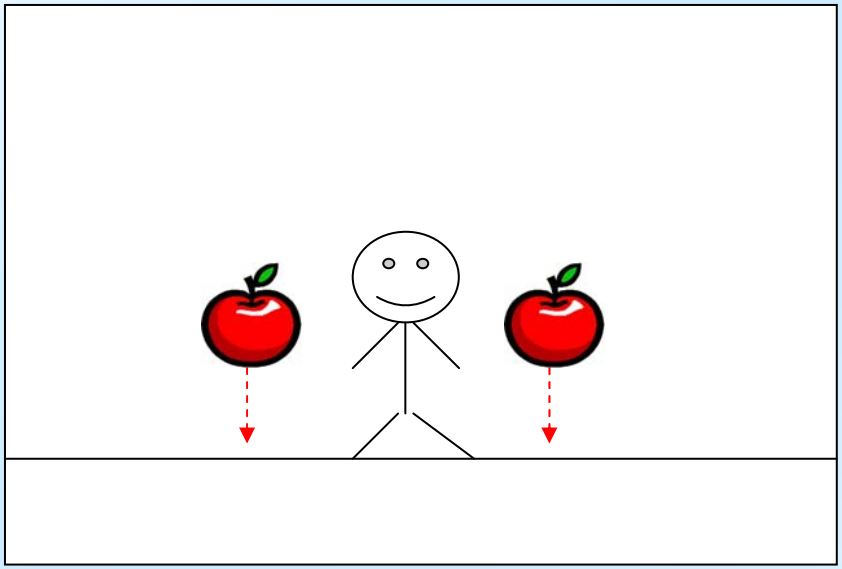


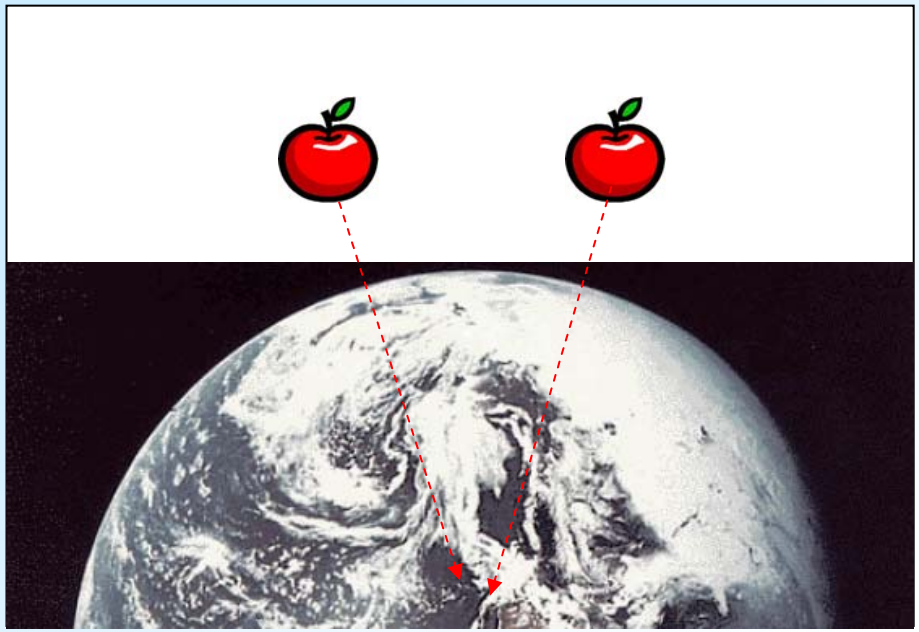
有重力
(在地面)

潮汐重力(Tidal gravity) (1911)

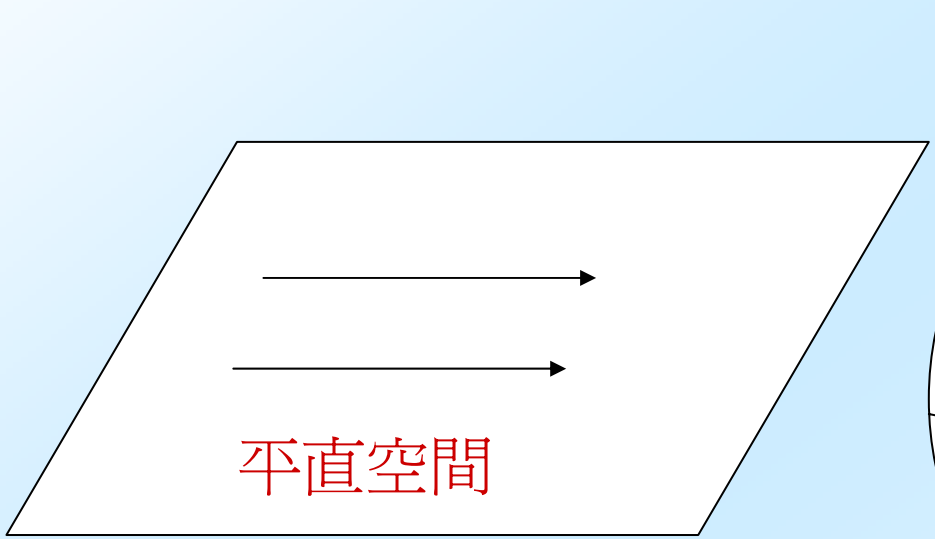


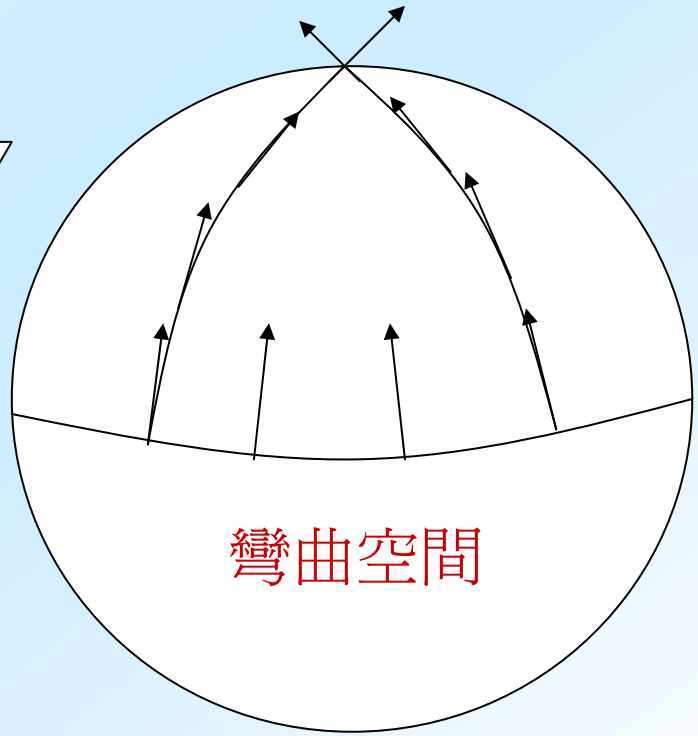




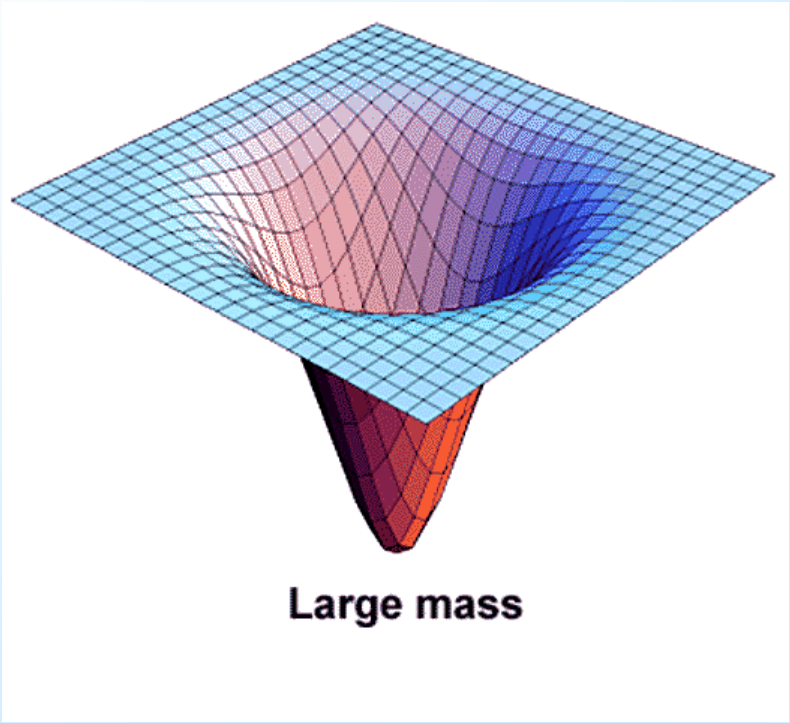


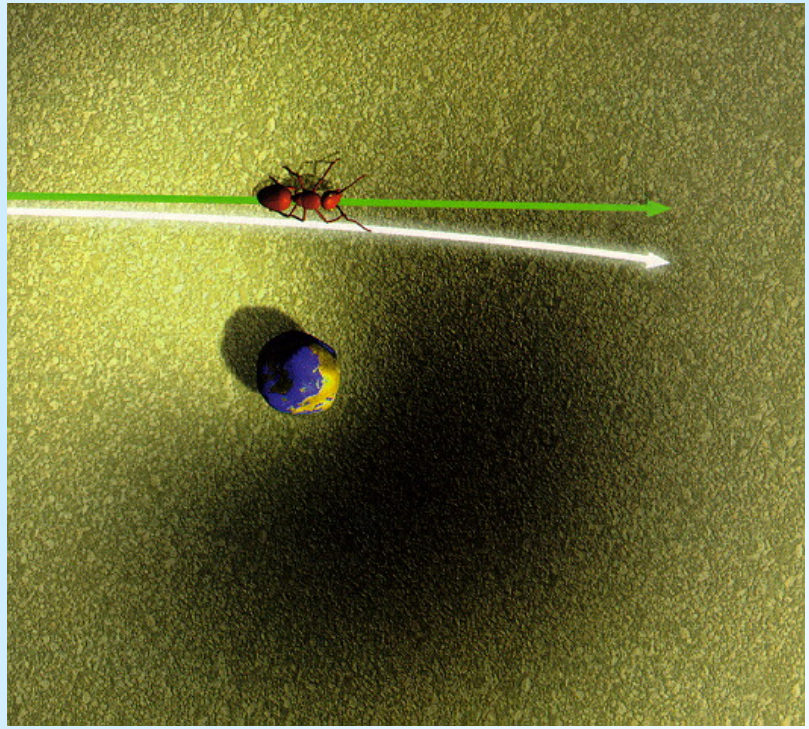
潮汐重力 $\overset{?}{=}$ 彎曲時空





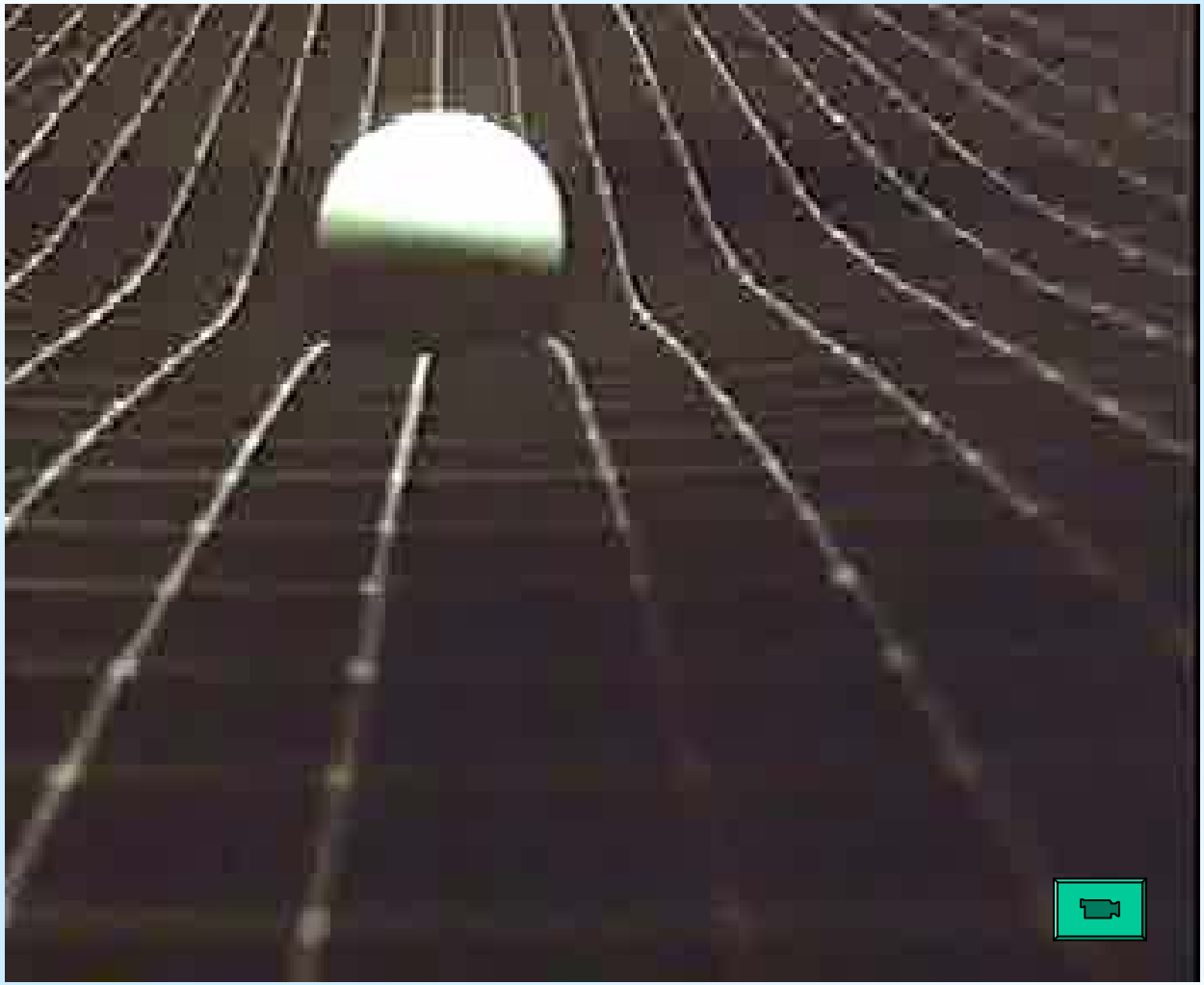
廣義相對論 (1915)
General Relativity





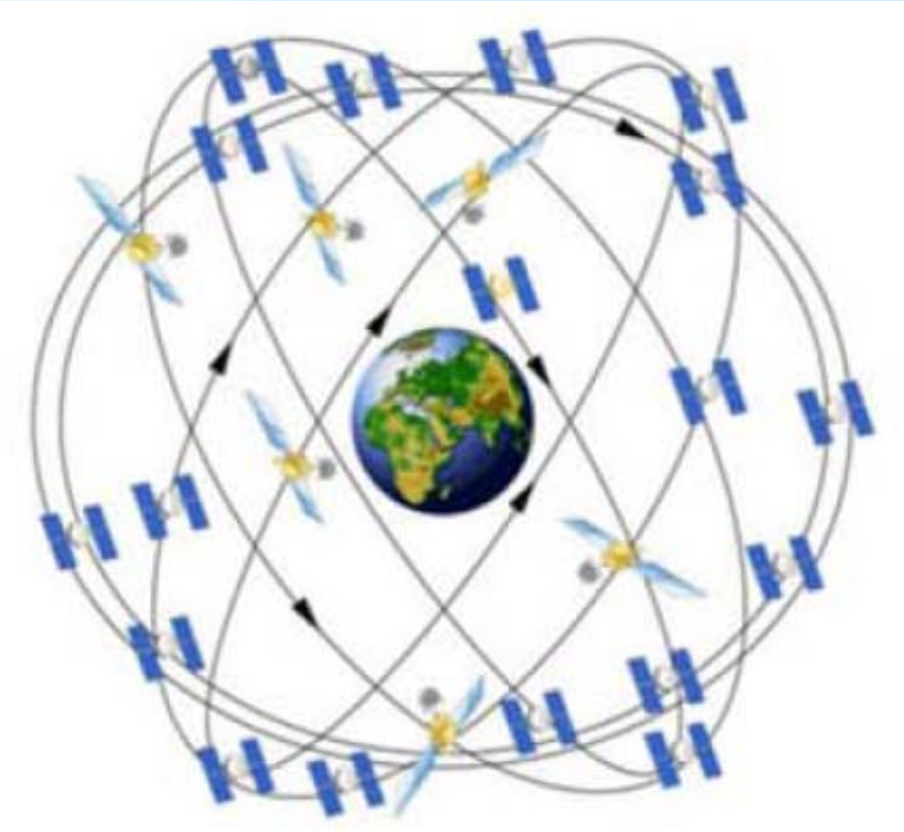
- 物質扭曲時空，彎曲時空影響物質軌跡。
- 質量愈大，時空彎曲愈大。

彎曲時空



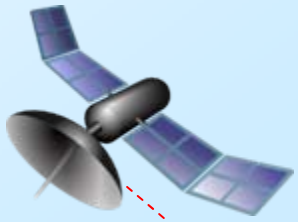
相對論的應用

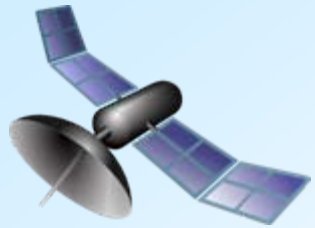
全球定位系統
(Global Positioning System)



(www.gps.gov)

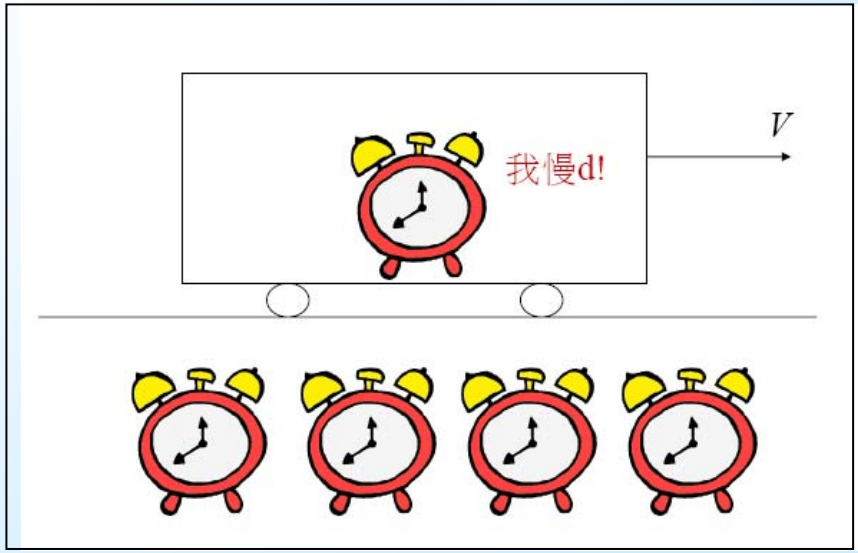
半徑 $= c\,[\,T(\text{接收}) - T(\text{發射})\,]$





光速 $c = 3\times10^8$ m/s

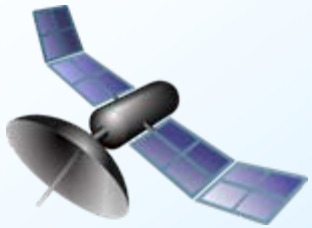
時間延滯
(狹義相對論效應)



移動的鐘行慢些!
(相對靜止的鐘)

重力時間延滯
(廣義相對論效應)

地面的鐘行慢些!



GPS衛星

- 速度 ≈ 3.9 km/s (1.3×10^{-5} c)
- 高度 ≈ 2.7×10^{4} km

相對於在地面靜止的鐘 (每秒):

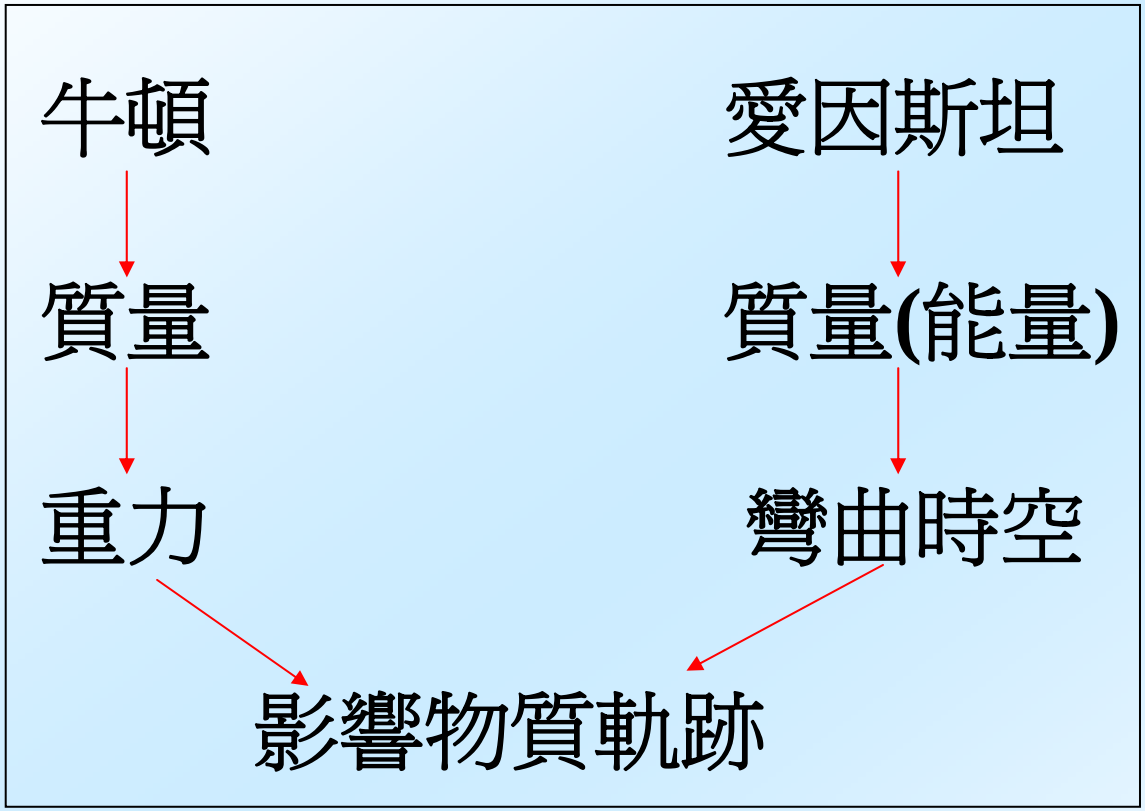
狹義相對論效應: 慢 ≈ 0.84×10^{-10} s

廣義相對論效應: 快 ≈ 1.6×10^{-10} s

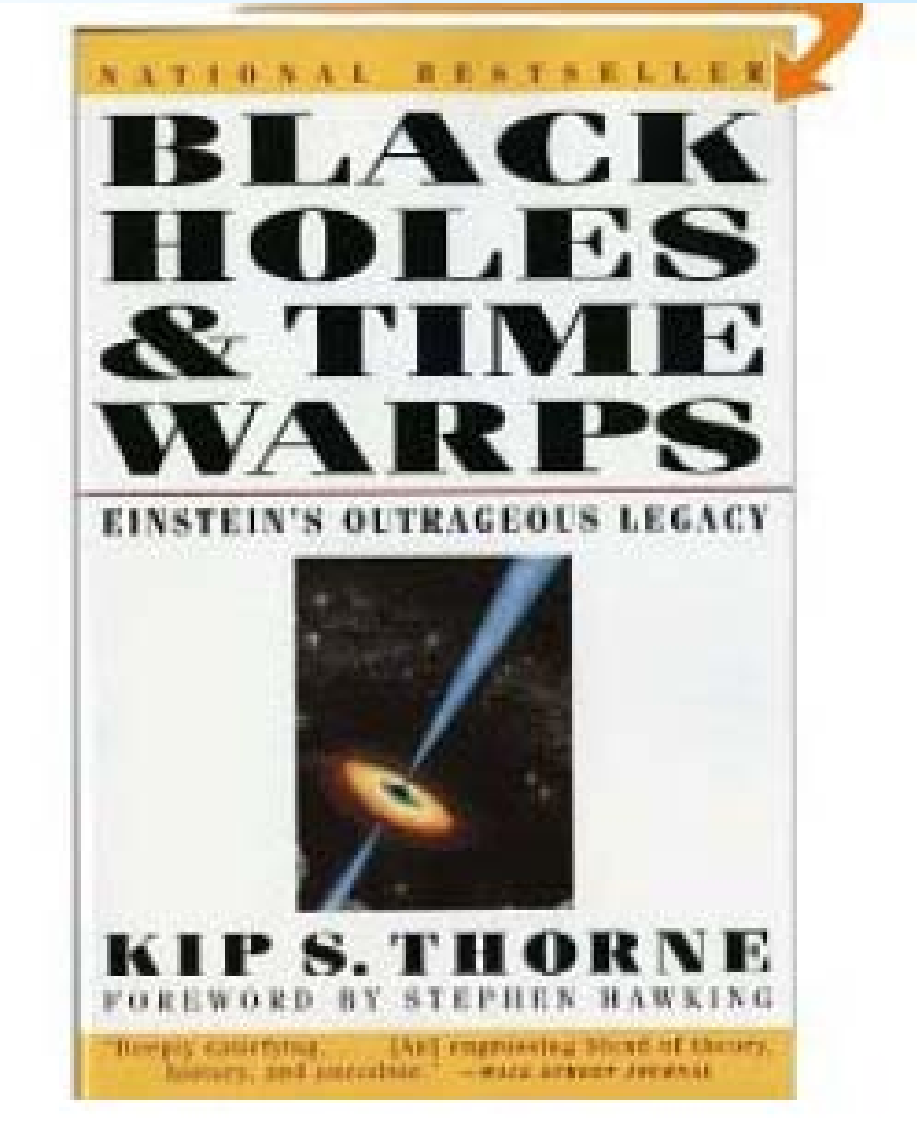
如要GPS準確度 = 2 m :

衛星的鐘與地面的鐘要準確到 60×10^{-10} s

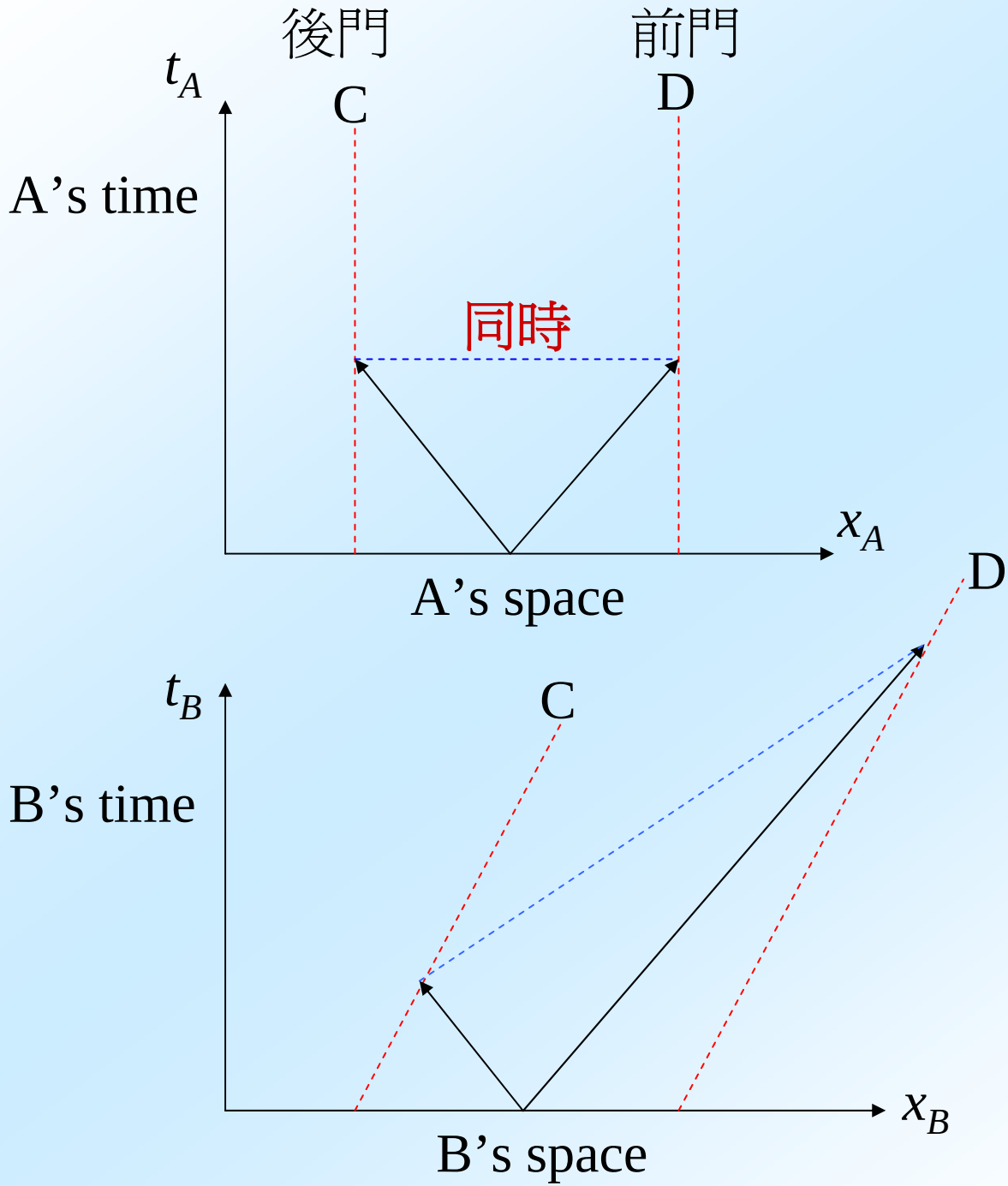
總結:



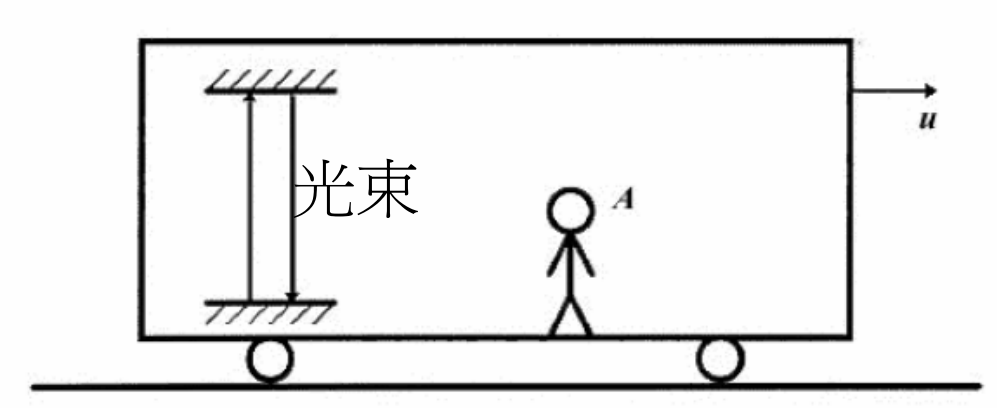
多謝！

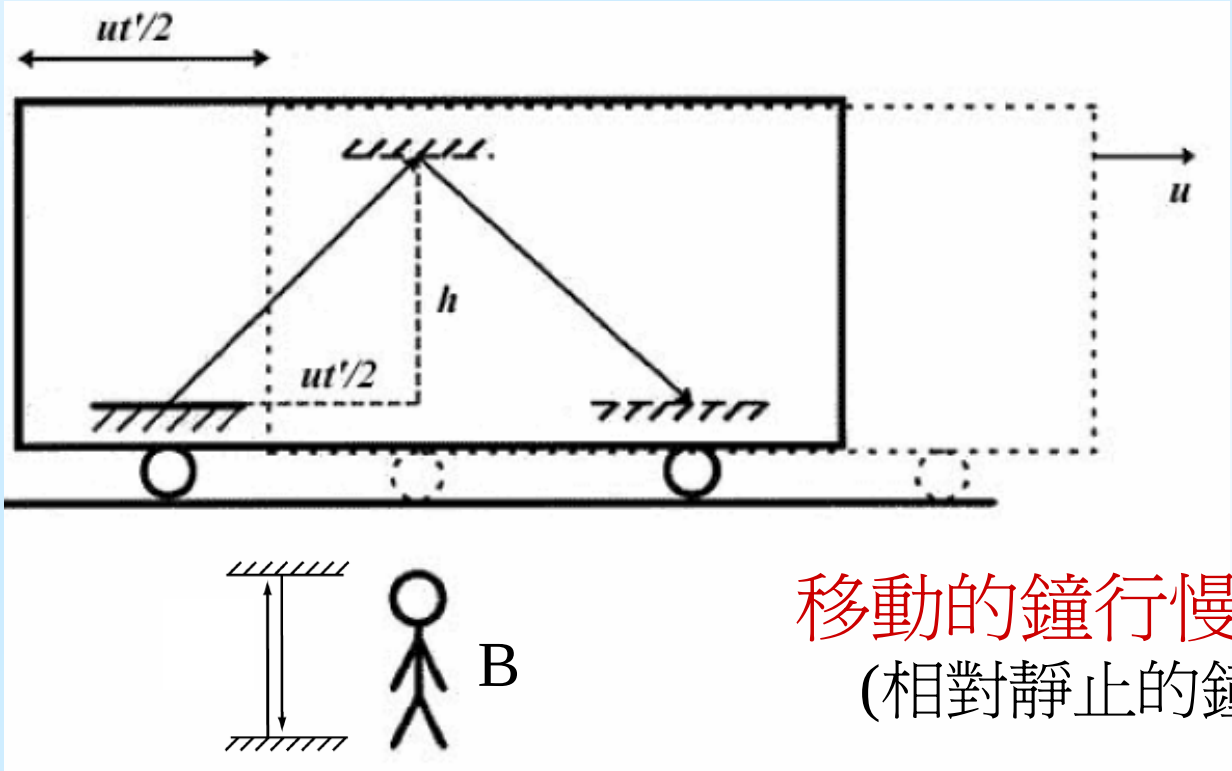

NATIONAL BESTSELLER
BLACK HOLES & TIME WARPS
EINSTEIN'S OUTRAGEOUS LEGACY
KIP S. THORNE
FOREWORD BY STEPHEN HAWKING

Appendix


後門
前門
t_A
C
D
A’s time
同時
x_A
A’s space
D
t_B
C
B’s time
x_B
B’s space

時間延滯 (Time dilation)

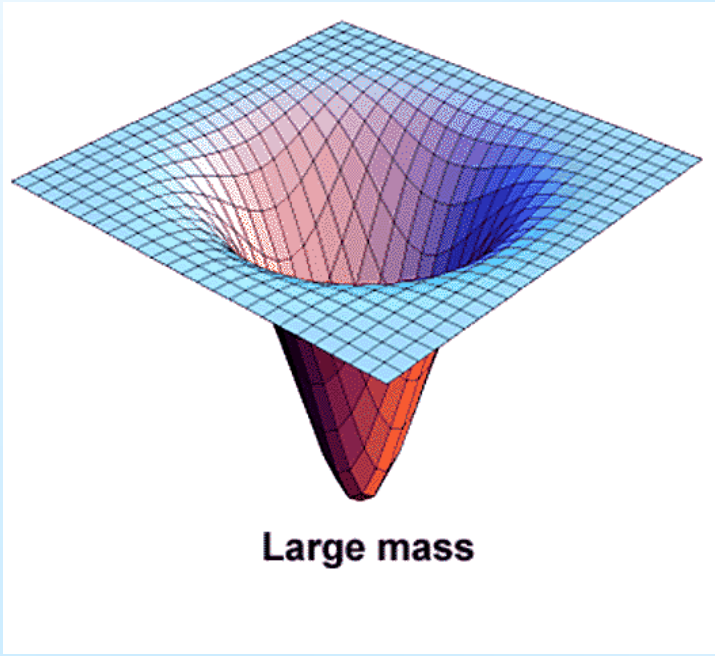




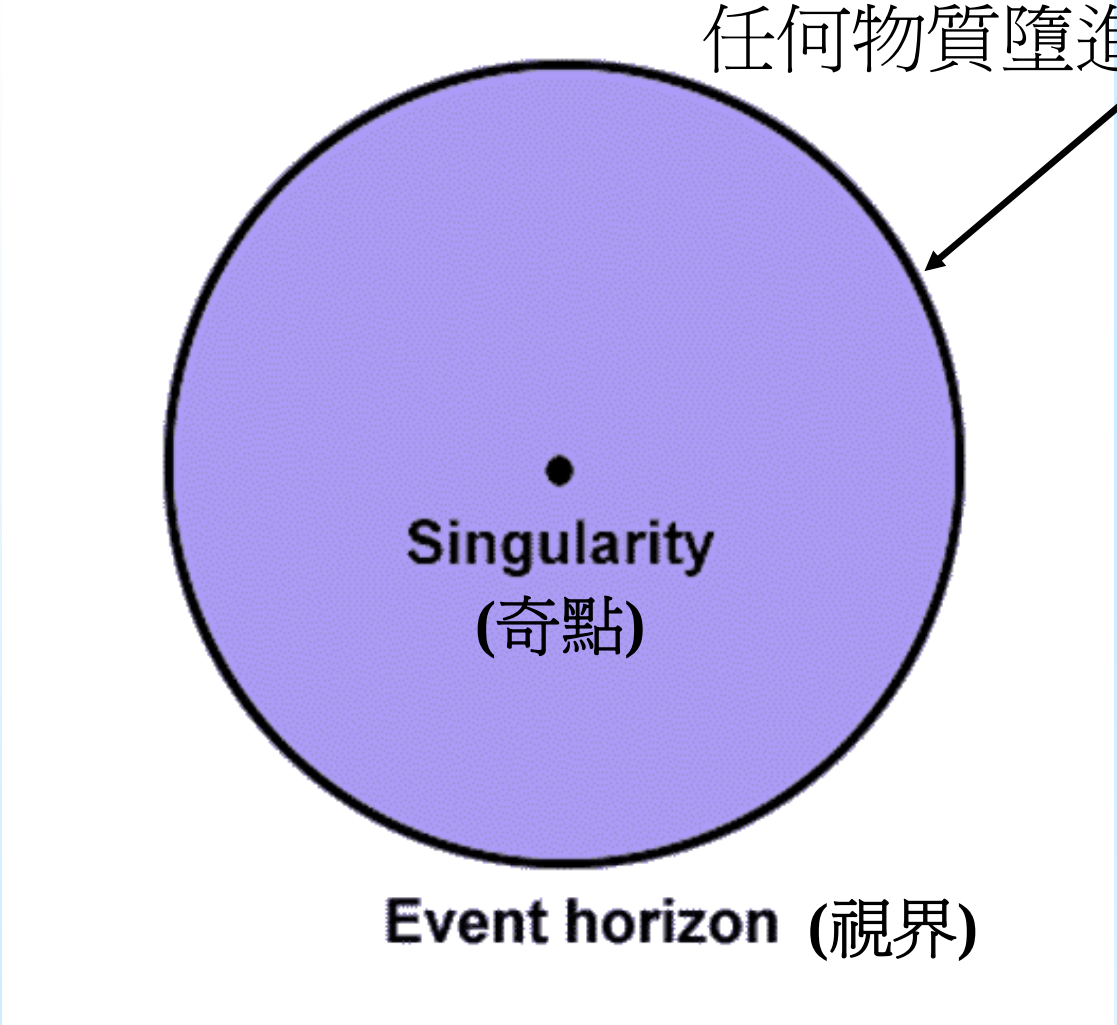
移動的鐘行慢些!

(相對靜止的鐘)

黑洞



- 質量太大，時空彎曲太大。
- 形成時空深洞。
- 光亦受困於洞內，不能逃出來。

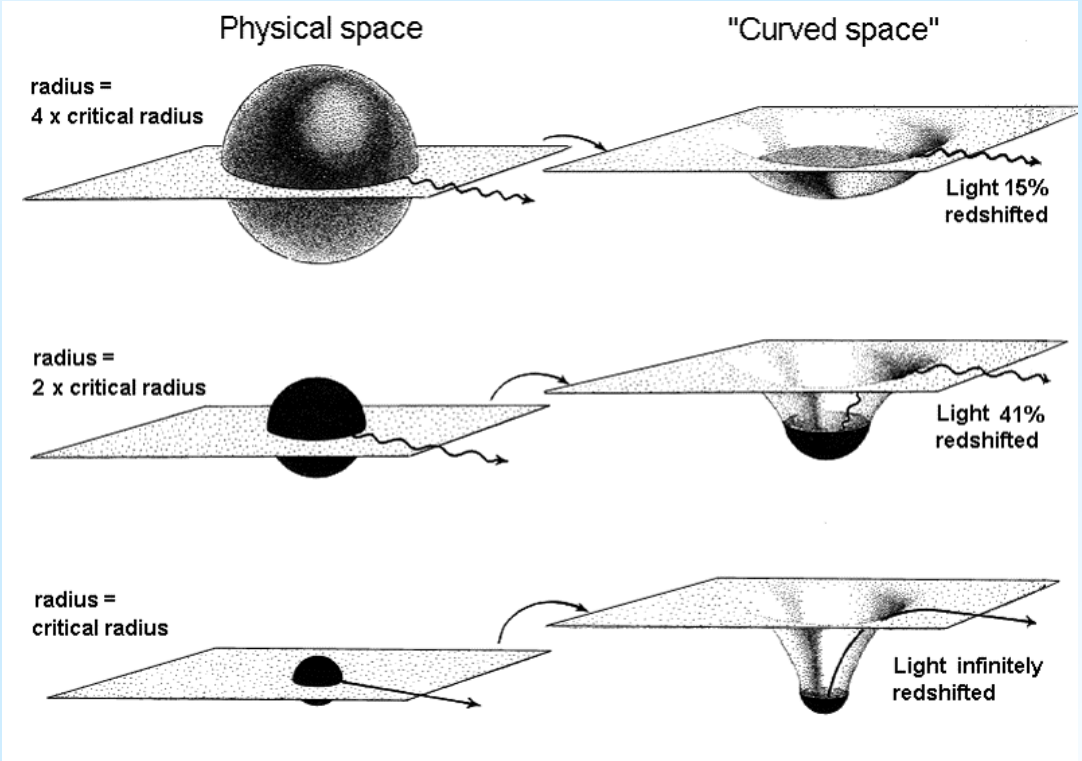


奇點: 密度趨無限大，但已知物理定律不再適用!

臨界半徑 (Critical radius)

- 對應每一質量，若物體半徑小於臨界半徑，便成爲黑洞。

例： 太陽 ~ 3 km
地球 ~ 1 cm

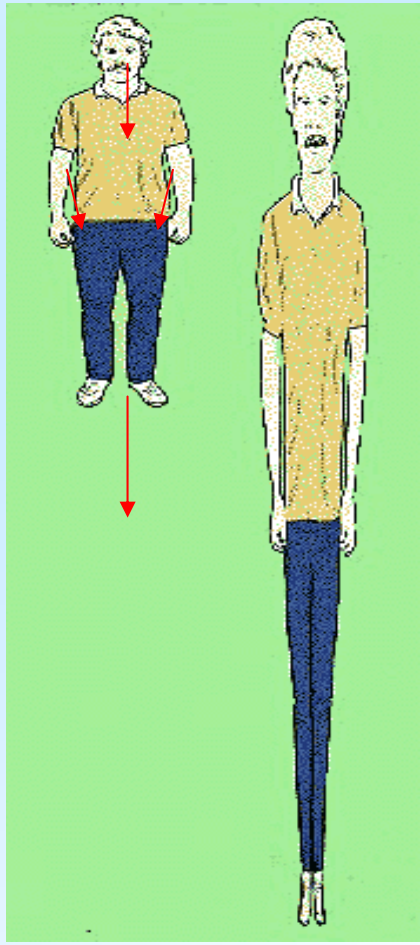


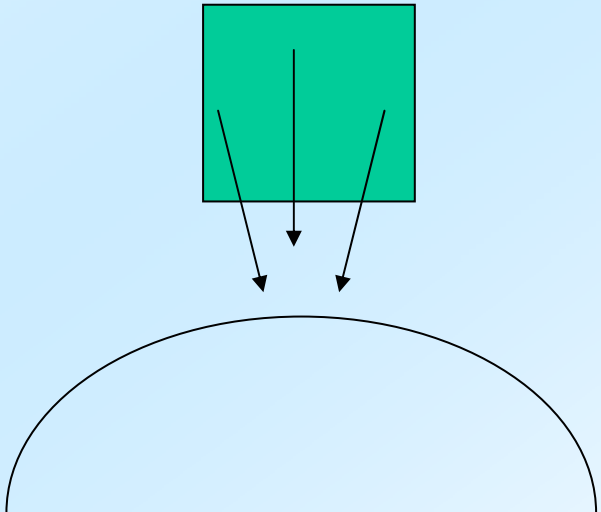
黑洞遊

- 潮汐作用**(Tidal effect)**

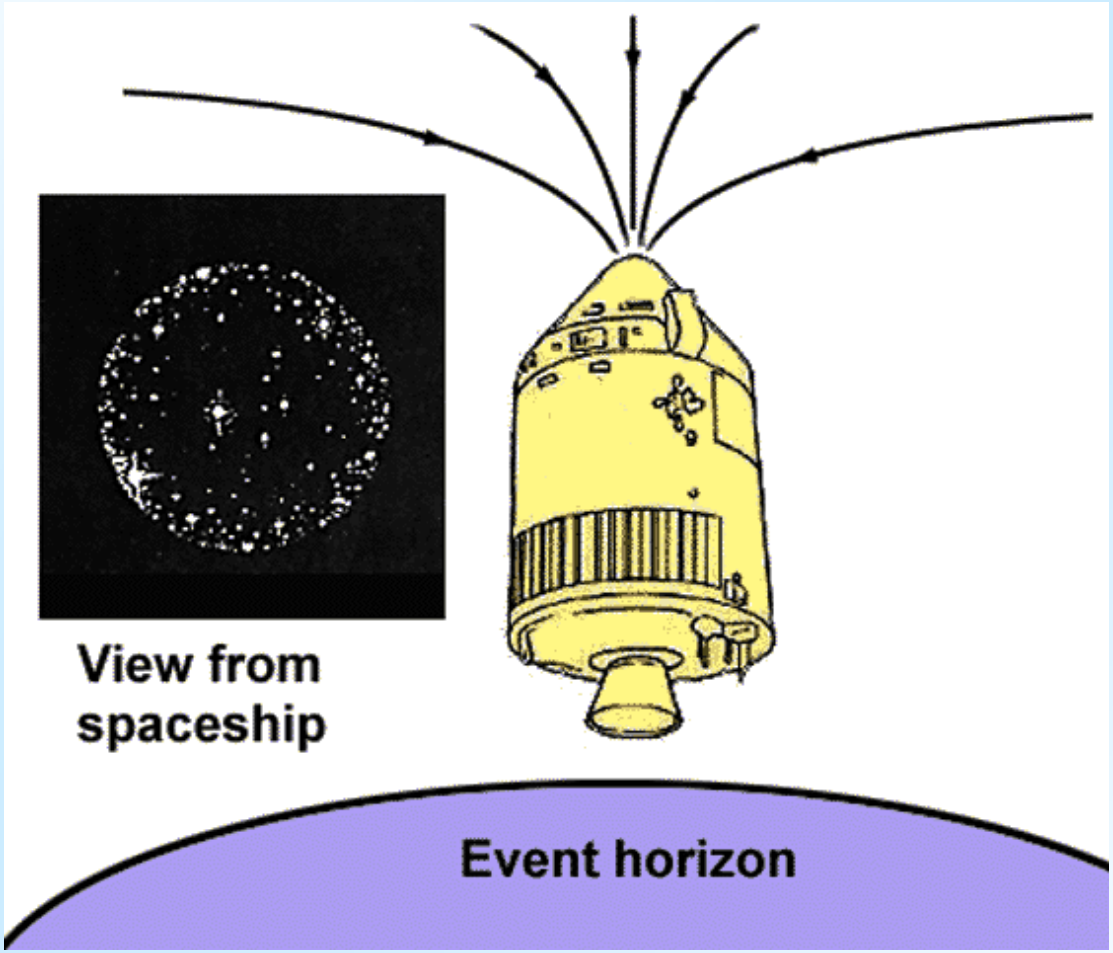
  重力隨距離而減低→物體不同部份受到引力不同

  例：人站在地面，腳所受重力大於頭

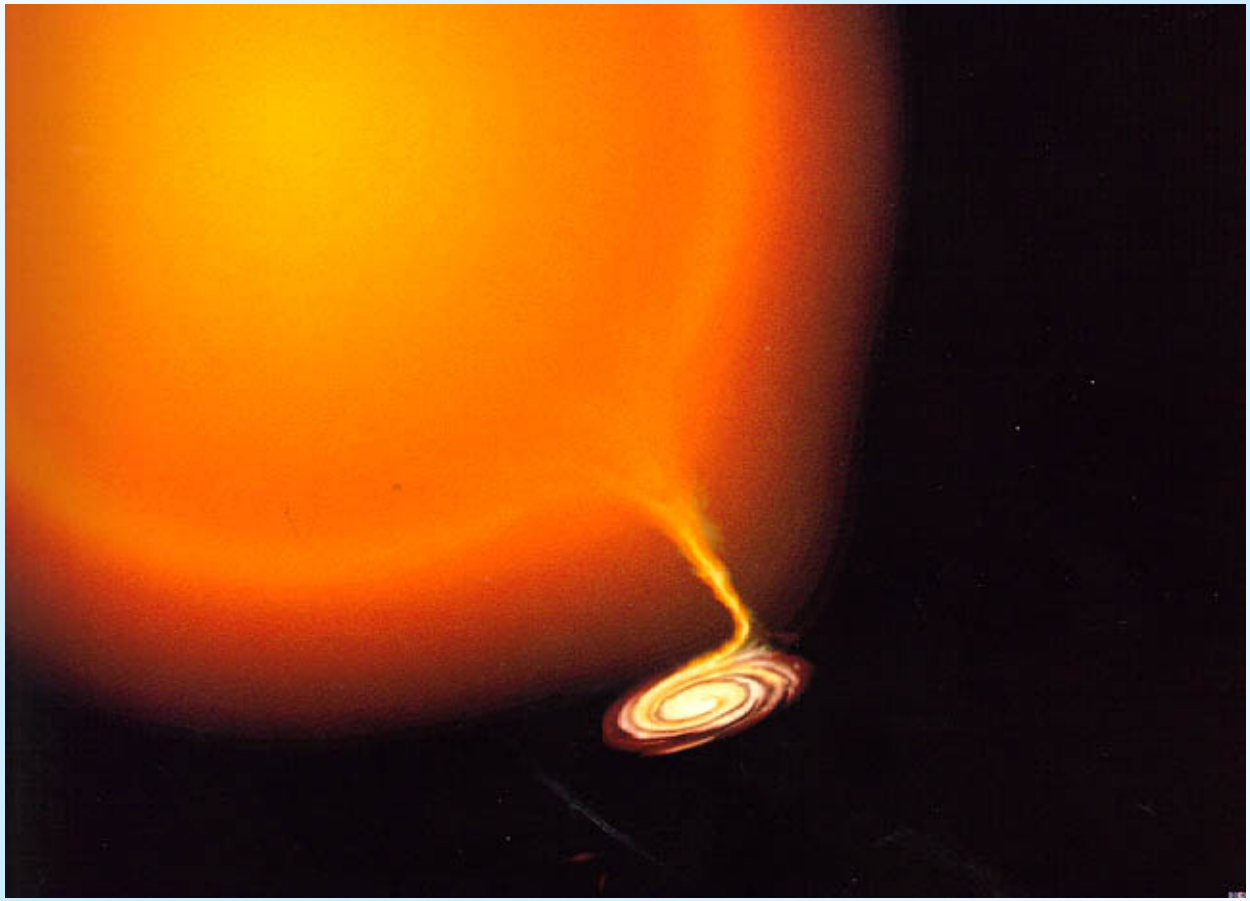




- 光線扭曲

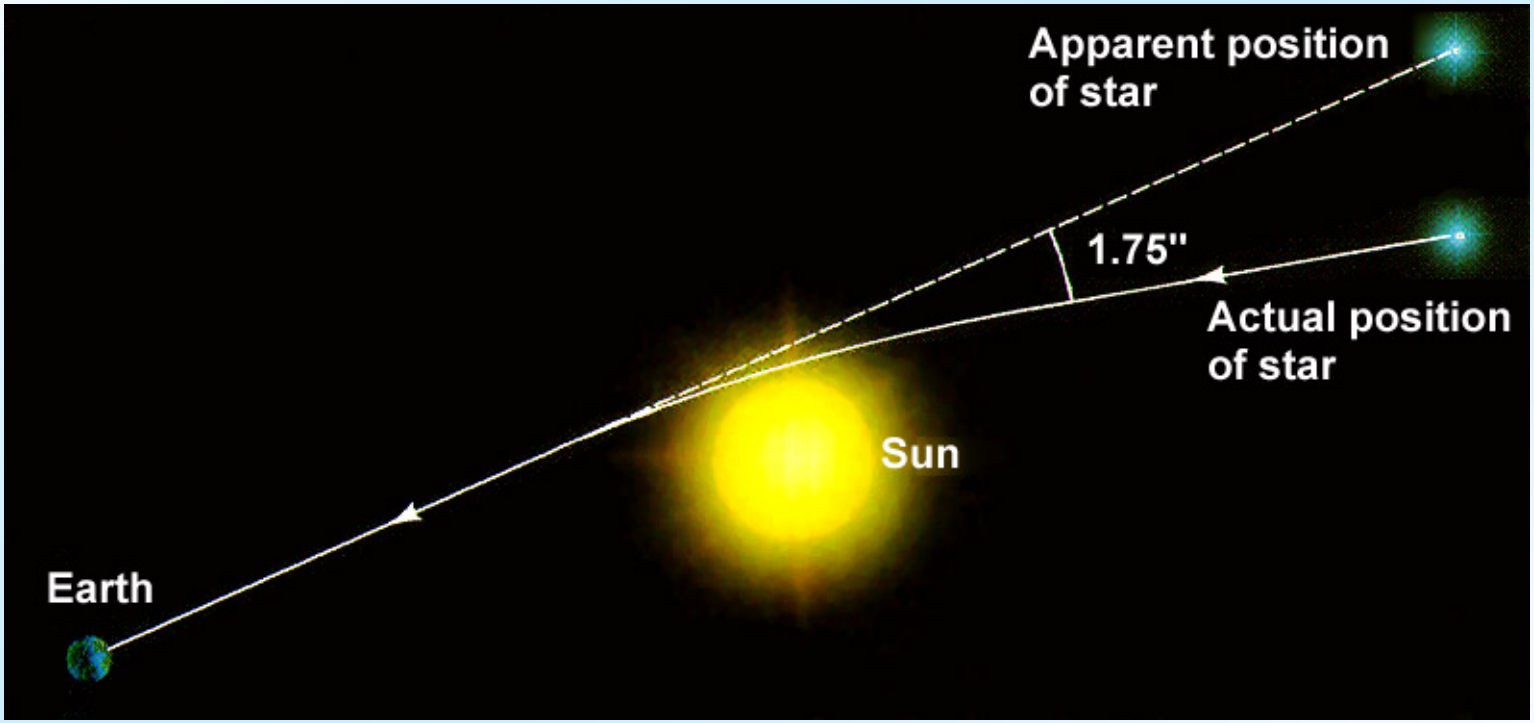


寻找黑洞？



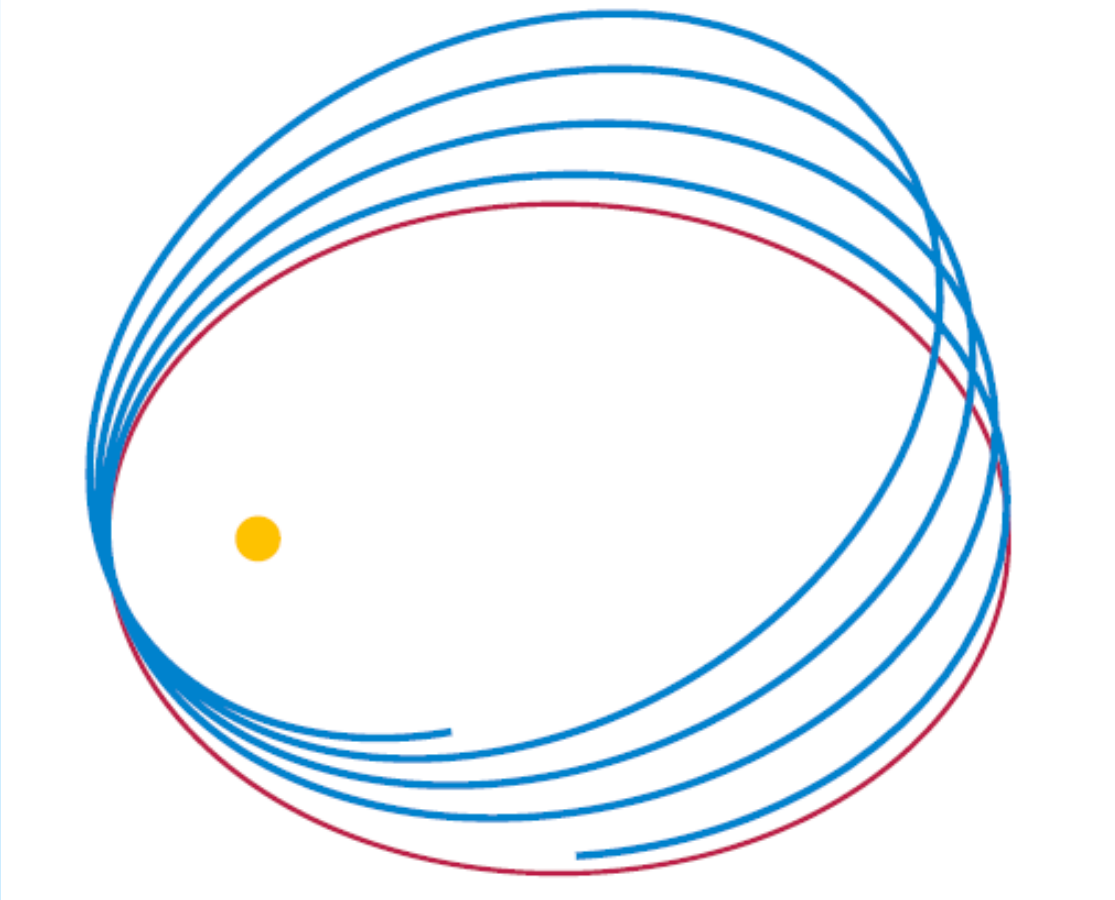
廣義相對論的一些預測

光線偏折 **(Light deflection)**



1”=1/3600^{o}

水星近日點的進動



42.98” per century
(after subtracting various known Newtonian effects ~ 5557”)