

Gravitational Waves

重力波理論與觀測

Kin-Wang Ng (吳建宏)

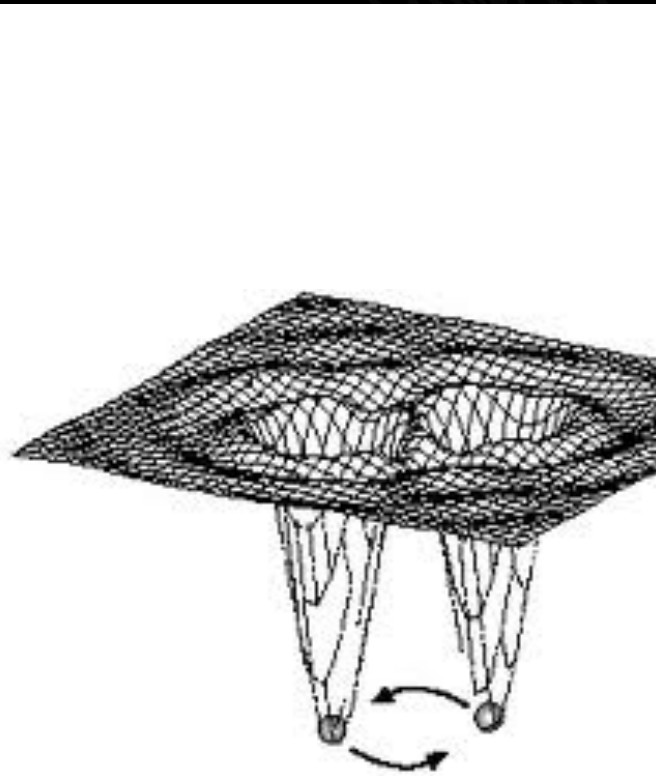


ASIoP (中央研究院物理所) &
ASIAA (中央研究院天文所)

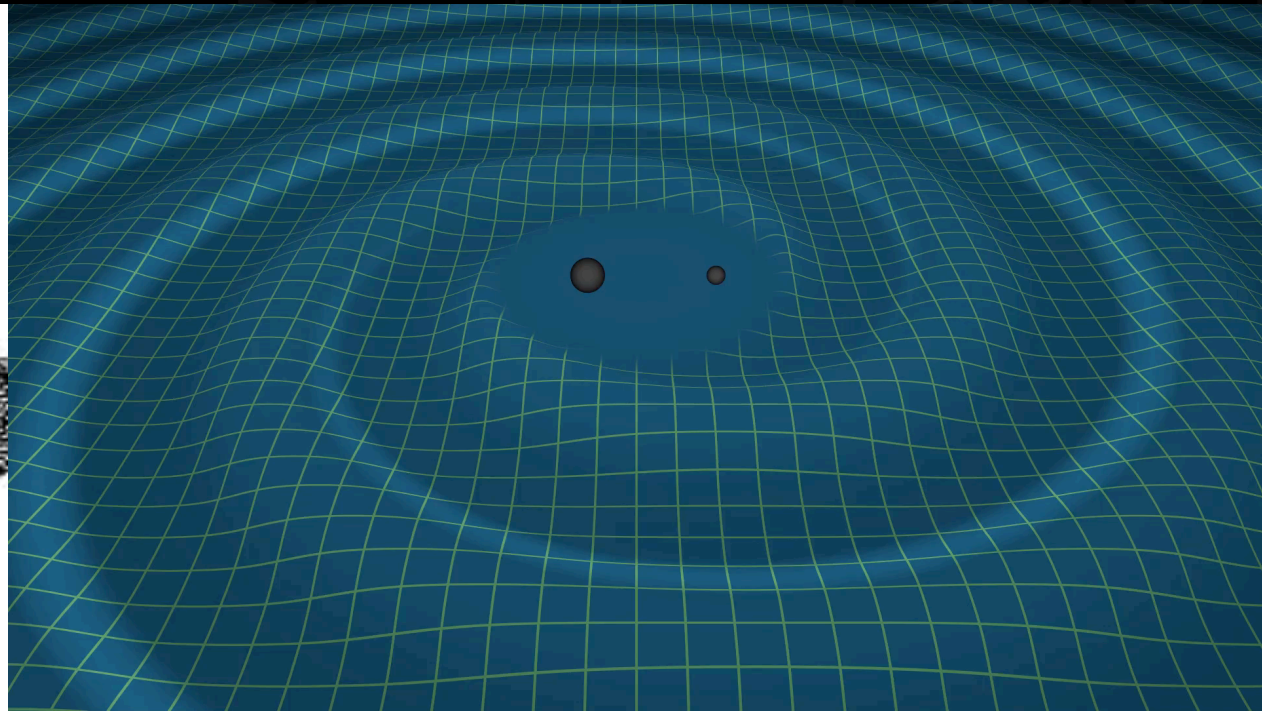
NCTS-HEP workshop 2026
NCTS-NTU
July 1-3, 2026

重力波 —— 時空的漣漪

Gravitational Wave Is the Ripple of Spacetime



A binary system of compact massive objects rapidly orbiting each other produces ripples in spacetime.



雙黑洞併合產生重力波

Gravitational Waves in Expanding Universe

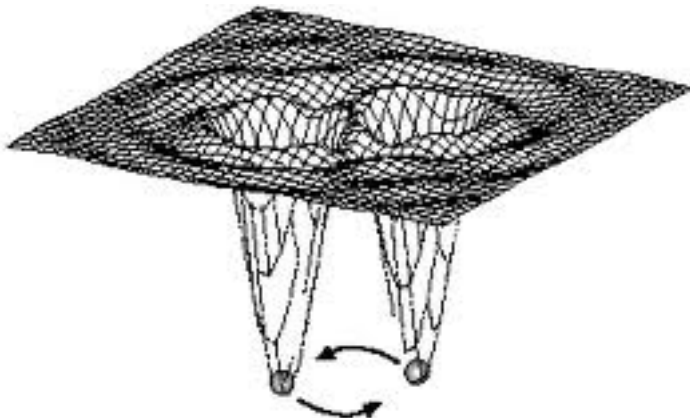
$$ds^2 = dt^2 - a^2(t) d\mathbf{x}^2$$
$$= a^2(\eta) (d\eta^2 - d\mathbf{x}^2)$$

conformal time

$$d\eta = dt/a(t)$$

$$g_{\mu\nu} = a^2(\eta)(\eta_{\mu\nu} + h_{\mu\nu}), \quad h_{\mu\nu} \ll 1$$

gravitational waves are
ripples of space-time

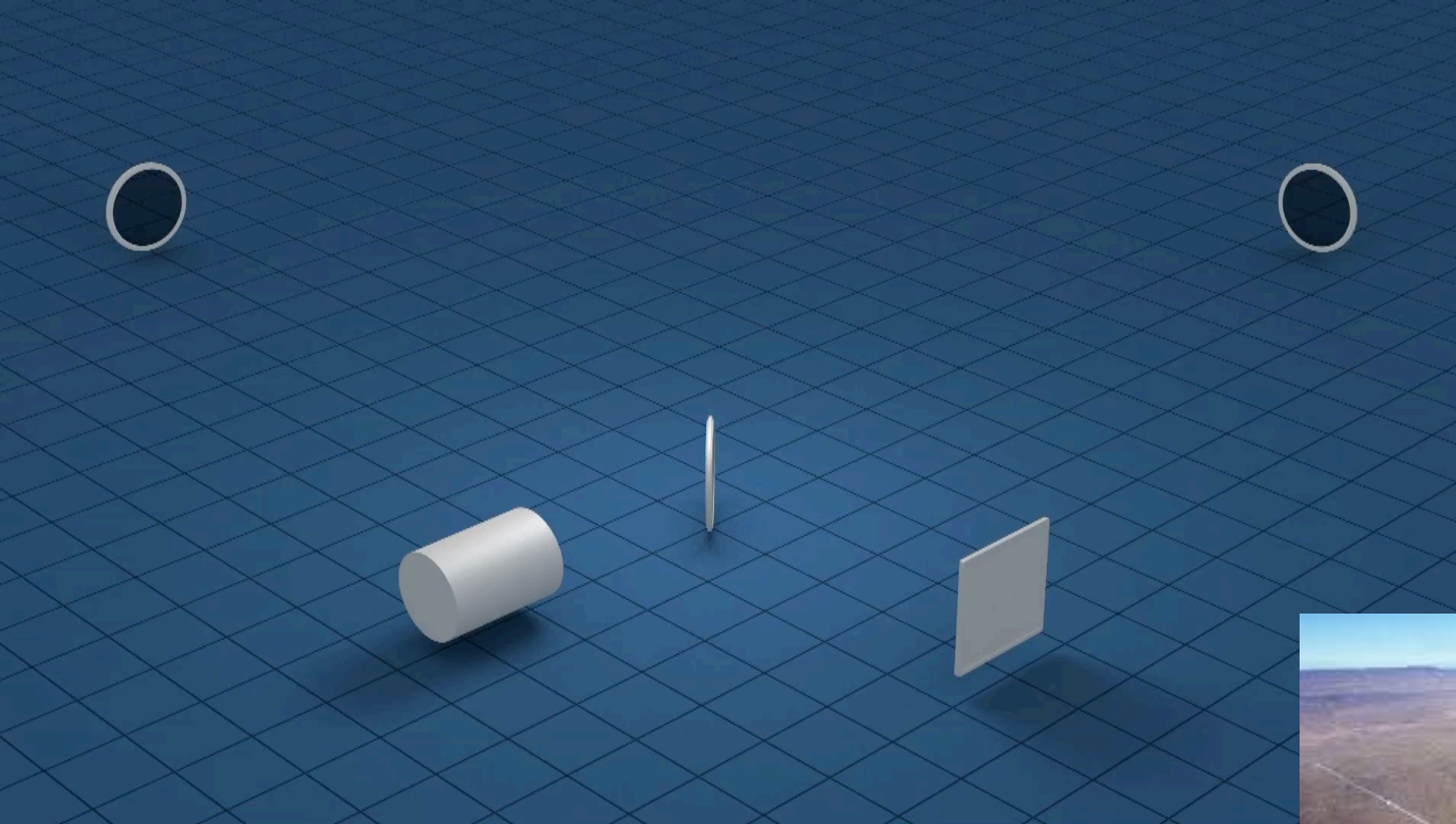


binary black holes



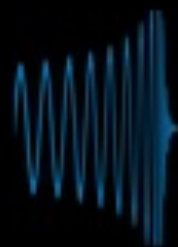
雷射干涉重力波天文台

Laser Interferometer Gravitational-Wave Observatory



LIGO Hanford, USA





GW150914



2015年9月14日

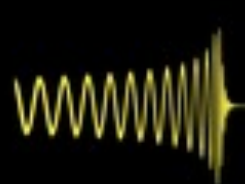
LIGO 首次觀測到重力波！



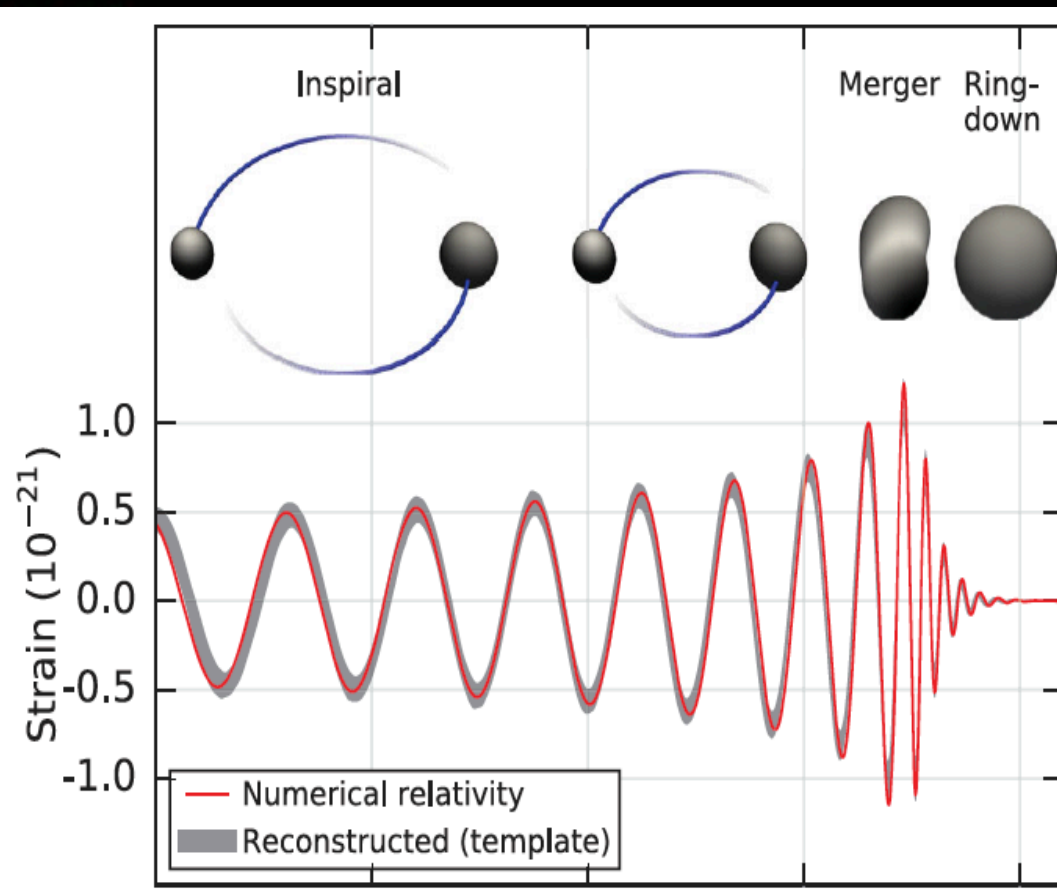
LVT151012



GW170104



GW170814



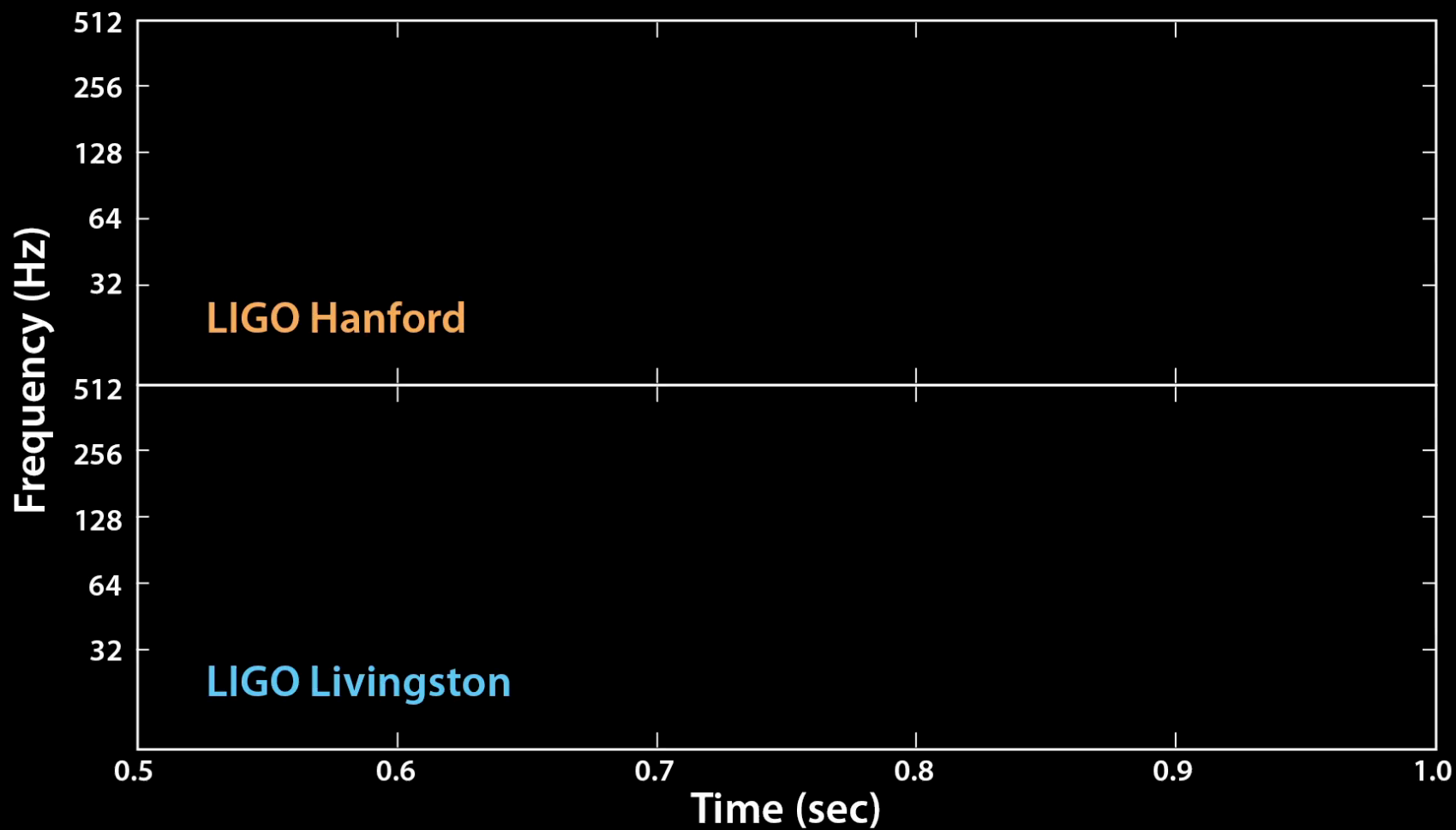
0 sec.

1 sec.

2 sec.

time observable by LIGO-Virgo

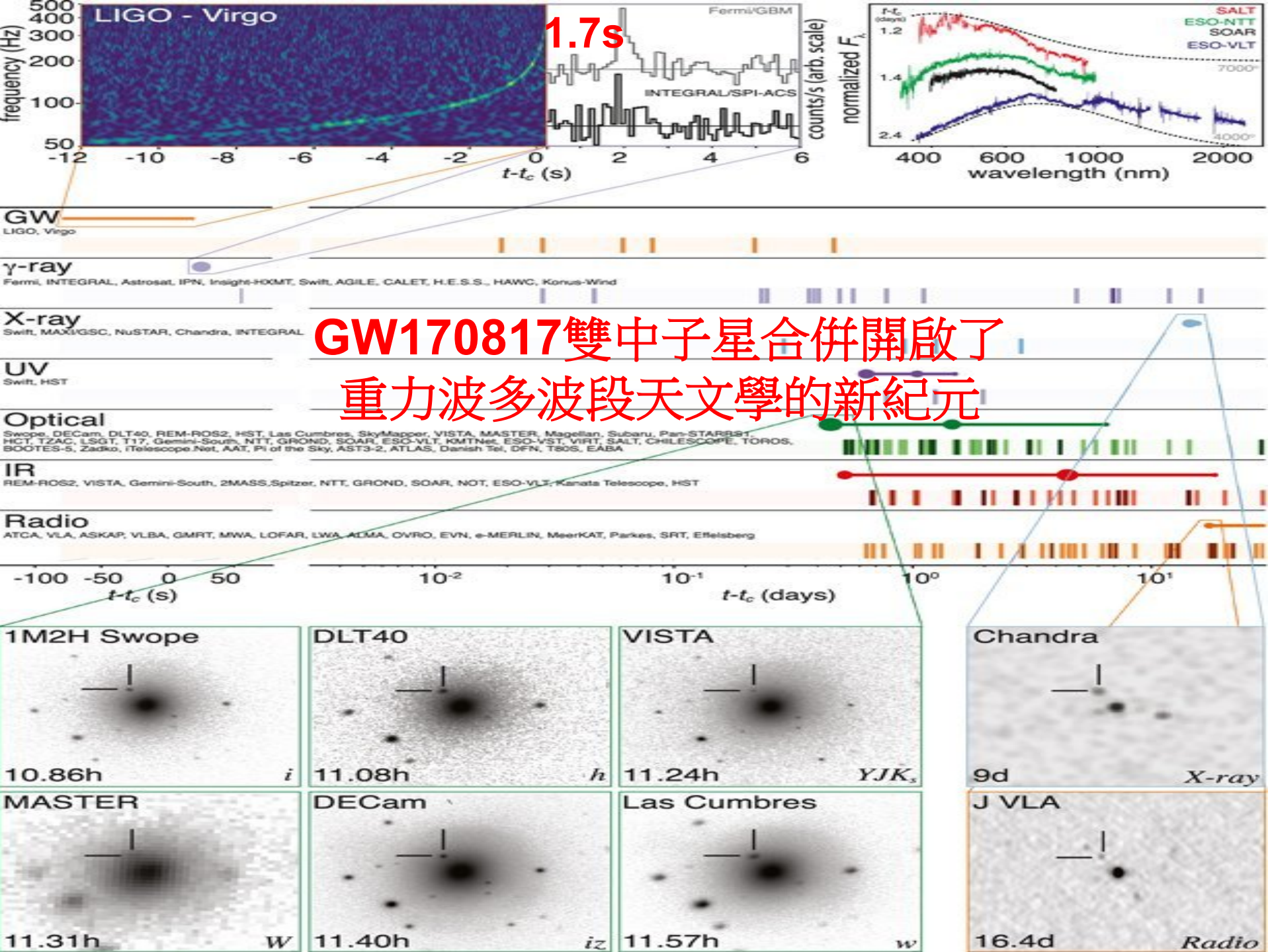




GW150914產生多少重力波？

第一個黑洞質量	36個太陽質量
第二個黑洞質量	29個太陽質量
合併黑洞質量	62個太陽質量
合併黑洞自旋	0.67
與地球距離	13億5千萬光年
紅移	0.09

- 驚! 雙黑洞併合產生的重力波能量，等同**3**個太陽質量。即是在**1**秒內燒掉**3**個太陽! (太陽已經燒了**46**億年)
- 重力波來到地球的振幅是 10^{-22} 比**1**，比一個原子還小。



2017 諾貝爾物理獎



中央研究院物理研究所 **2015 李水清物理講座**
SHUI-CHIN LEE PHYSICS LECTURESHIP, INSTITUTE OF PHYSICS, ACADEMIA SINICA

【相對論 100 YEARS】

FROM THE
**BIG BANG TO
BLACK HOLES
AND INTERSTELLAR**

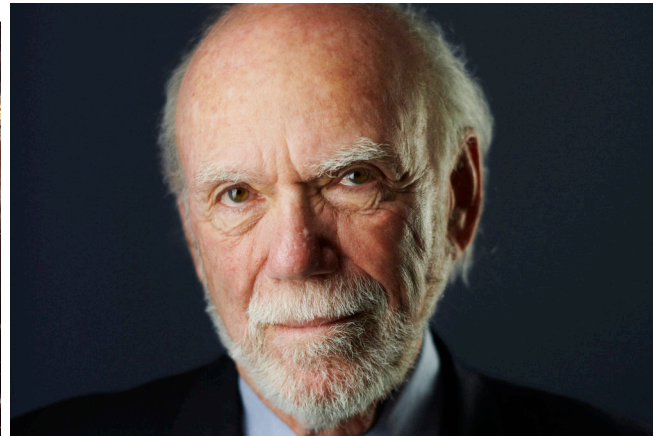
2015 10 / 28 14:00~15:30
中央研究院人文社會科學館 3F 國際會議廳

基普·索恩
KIP THORNE
加州理工學院 理論物理費曼講座教授
【星際效應】電影執行監製

A Century of Relativity:
From the Big Bang to
Black Holes and Interstellar

The lecture will be delivered in English.
<http://www.phys.sinica.edu.tw/~asiopsclpl/>

主辦單位：中央研究院物理研究所
贊助單位：財團法人水清基礎科學發展文教基金會
協辦單位：中華民國重力學會



Barry Barish
Caltech
中央研究院物理所
外評審委員2009-



Rainer Weiss
MIT

Kip Thorne, Caltech

台灣參與LIGO及日本神岡重力波探測器



主持人: **Takaaki Kajita ICRR**
2015 諾貝爾物理獎



Institute of Physics Academia Sinica, Taiwan

THE UNIVERSITY OF TOKYO

Special Colloquium

Gravitational Wave Detection and the KAGRA Observatory

梶田隆章 所長 (Prof. Takaaki Kajita)

2015年諾貝爾物理學獎・日本東京大學宇宙線研究所
(Nobel Laureate in Physics, 2015 &
Director, Institute for Cosmic Ray Research, University of Tokyo, Japan)



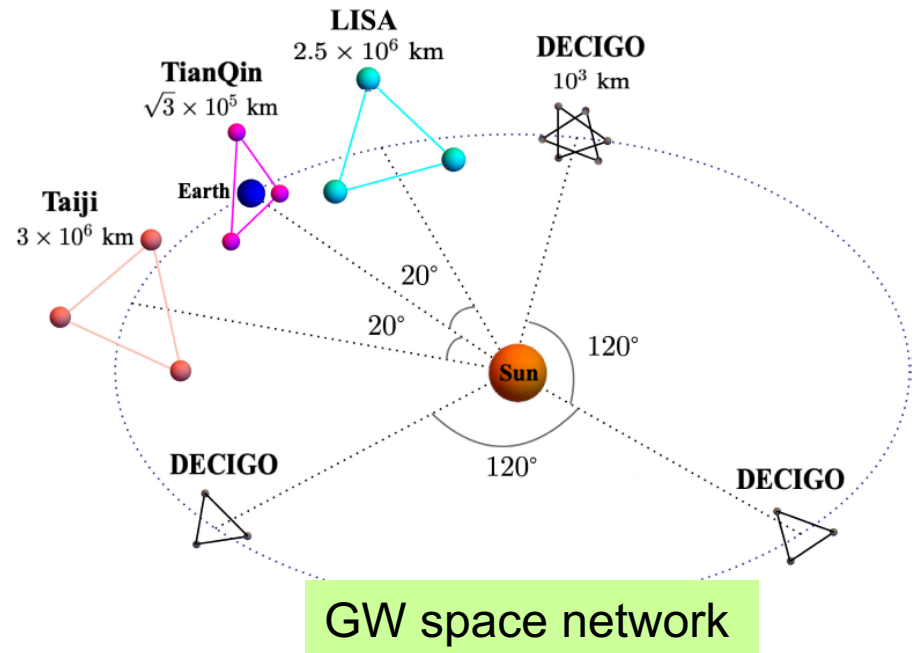
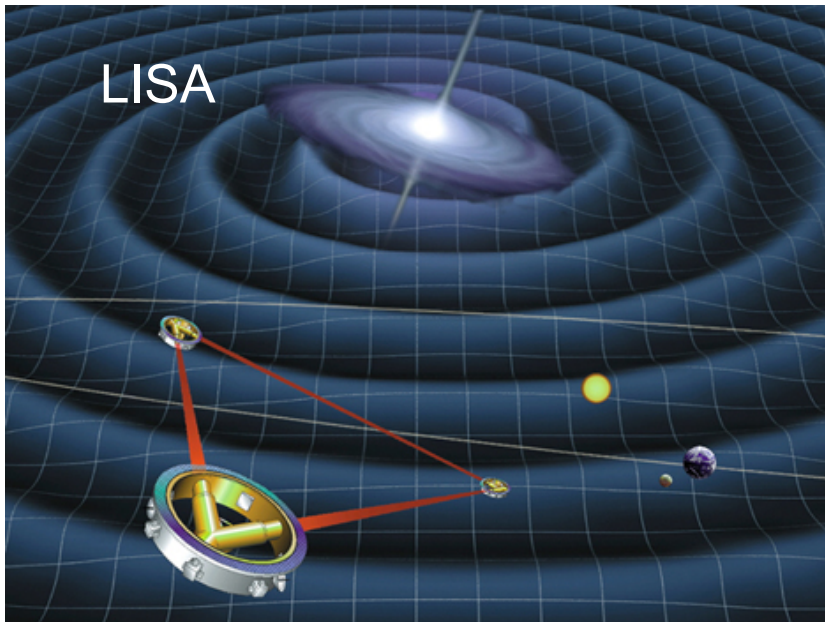
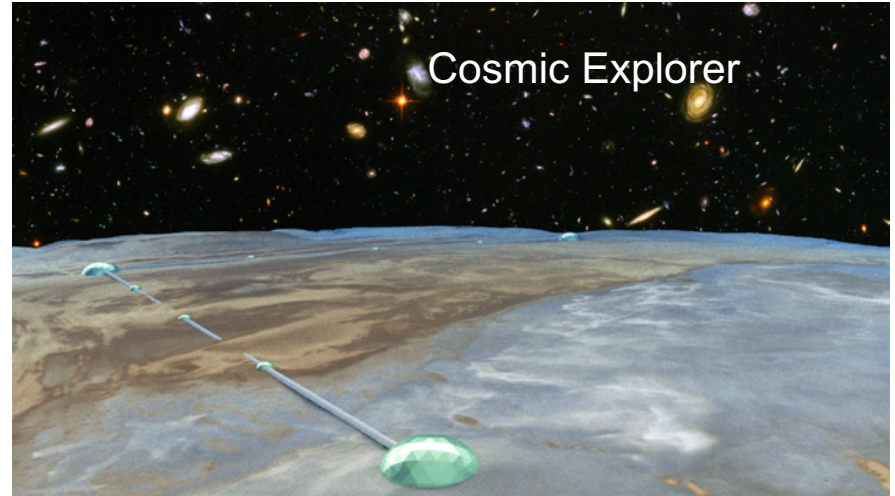
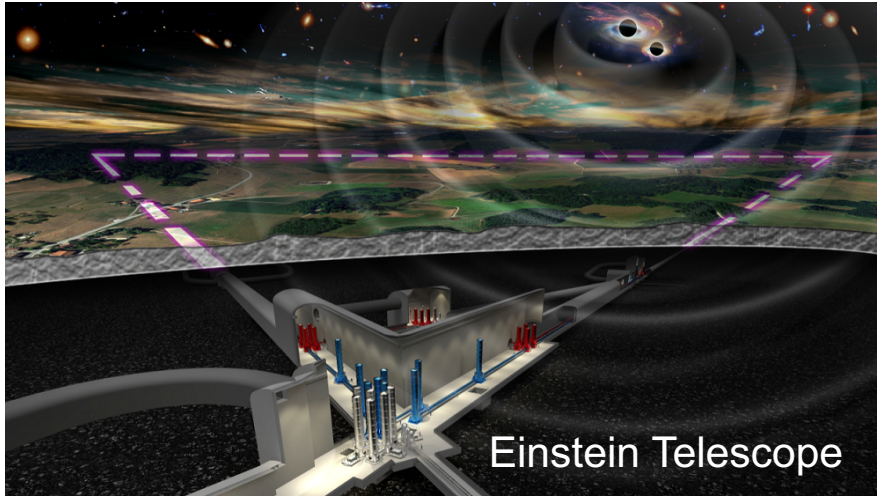
Dec 21, 2015 (Mon.) 15:30

一樓演講廳(The Auditorium on 1F)

Hosted | 王子星 研究員兼副所長
(Research Fellow and Deputy Director Wang/Hong Tu King)

Contact 李慶芳 #02-2759-8983

計劃中的地表和太空衛星重力波實驗



宇宙演化的標準模型

宇宙演化的標準模型

現在

130億年

50億年

第一個超新星

星及星系形成

10億年

宇宙變透明

物質與輻射分離

原子形成

10¹³秒

光子時期

氦核合成

10²秒

正子消失

夸克禁錮

中子、質子形成

反夸克消失

10⁻¹⁰秒

電弱時期

夸克時期

10⁻¹²秒

磁單極？

宇宙暴脹？

10⁻³⁶秒

大統一時期

量子重力時期

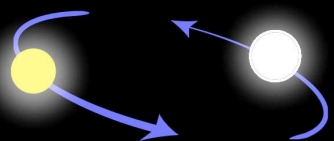
10⁻⁴³秒

Big Bang

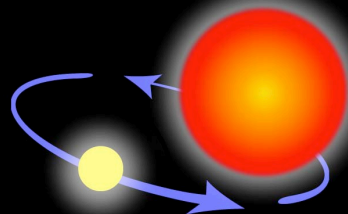
- 
- Springer

恆星重力塌縮產生超新星，形成中子星、黑洞

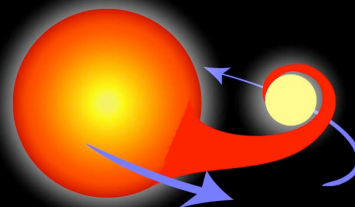
恆星團黑洞



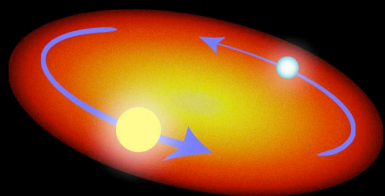
Two normal stars are in a binary pair.



The more massive star becomes a giant...



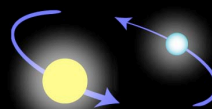
...which spills gas onto the secondary star, causing it to expand and become engulfed.



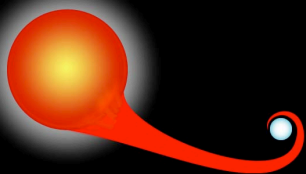
The secondary, lighter star and the core of the giant star spiral inward within a common envelope.



The common envelope is ejected, while the separation between the core and the secondary star decreases.



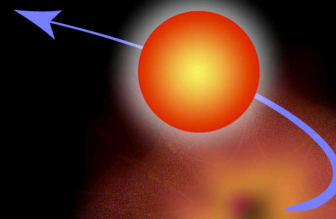
The remaining core of the giant collapses and becomes a white dwarf.



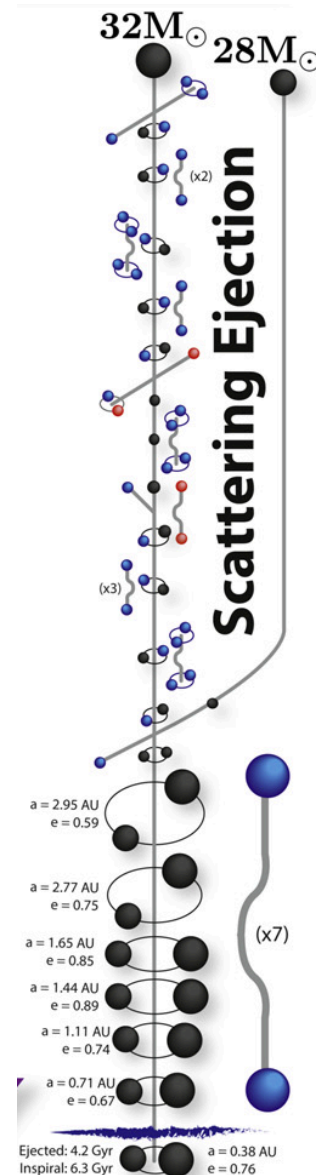
The aging companion star starts swelling, spilling gas onto the white dwarf.



The white dwarf's mass increases until it reaches a critical mass and explodes...



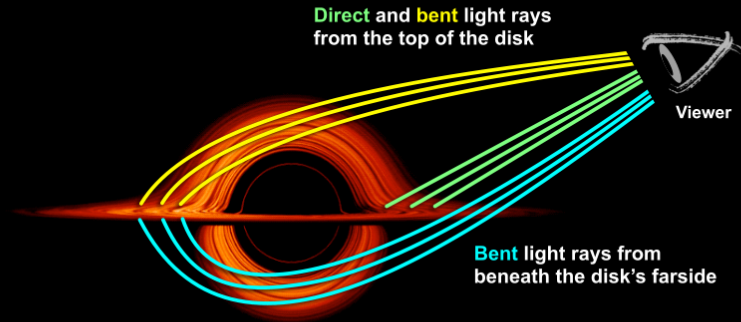
...causing the companion star to be ejected away.



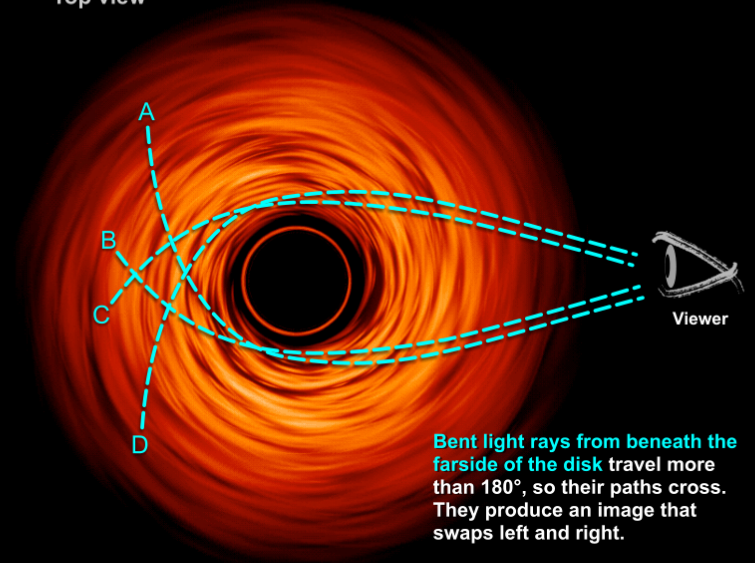
黑洞吸積盤

A Warped Look at Black Hole Optics

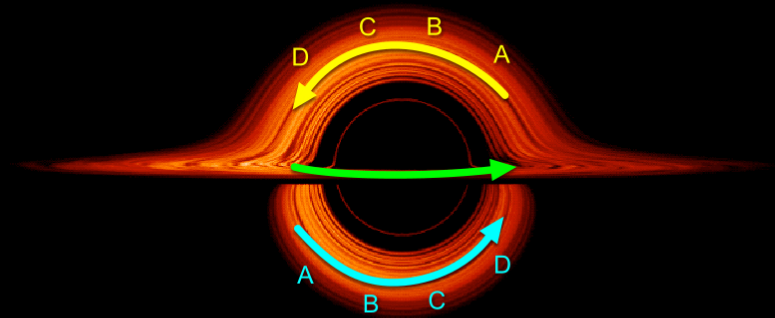
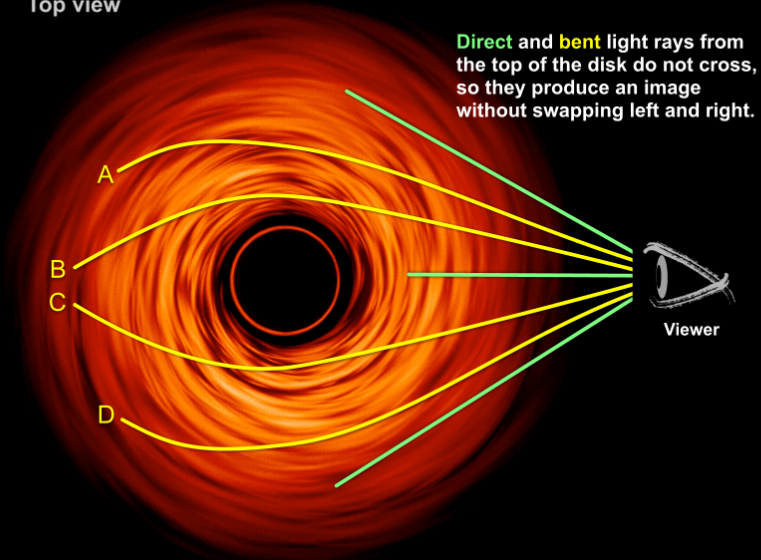
Side view



Top view

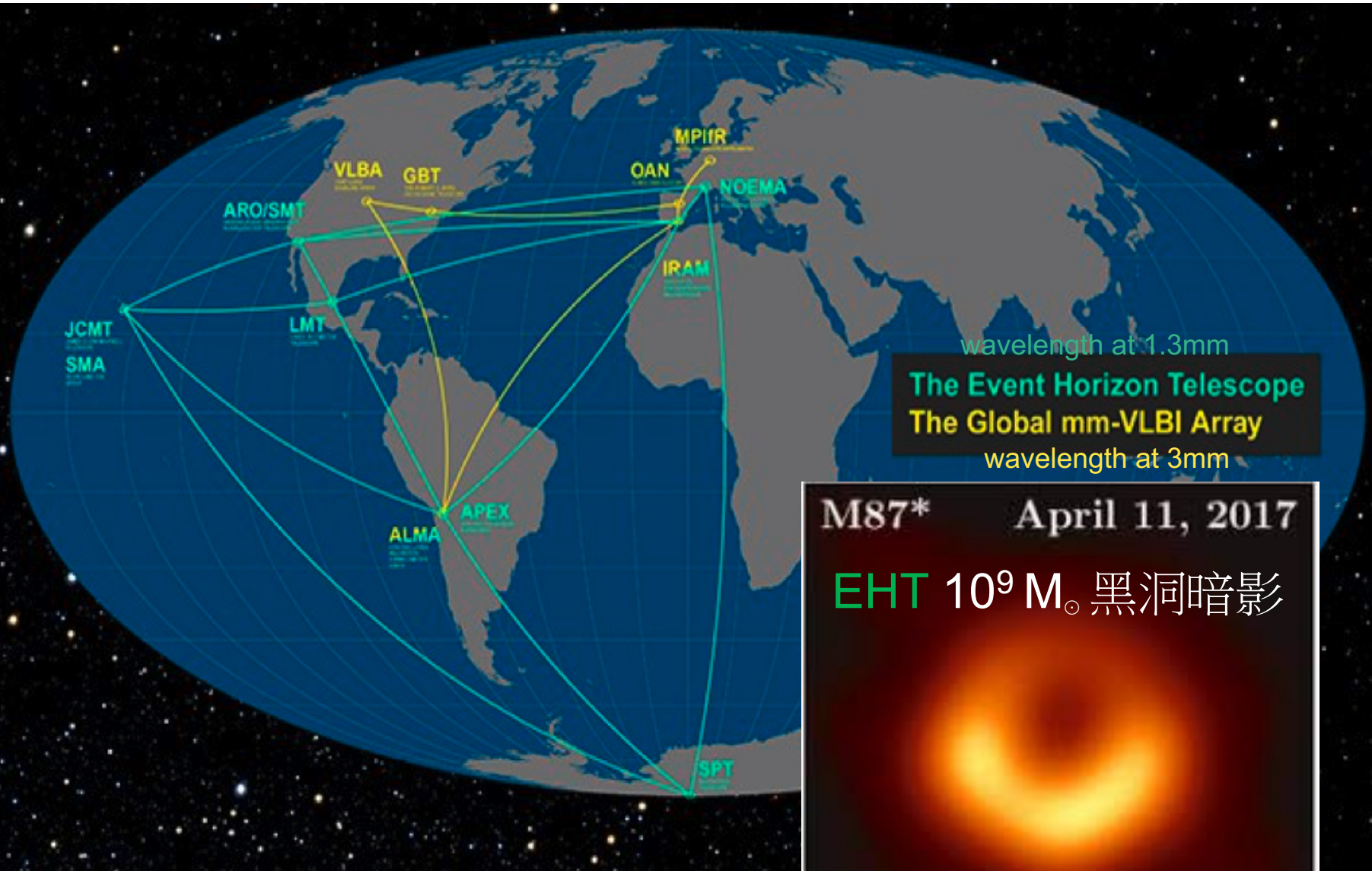


Top view



Apparent image and disk motion

超長基線干涉列陣 (VLBI)



M87*

April 11, 2017

EHT $10^9 M_{\odot}$ 黑洞暗影

50 μas

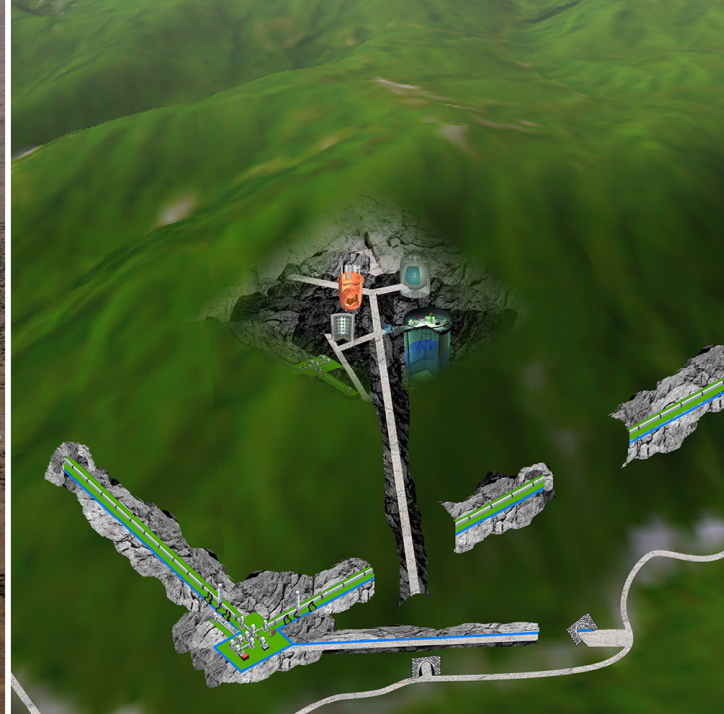
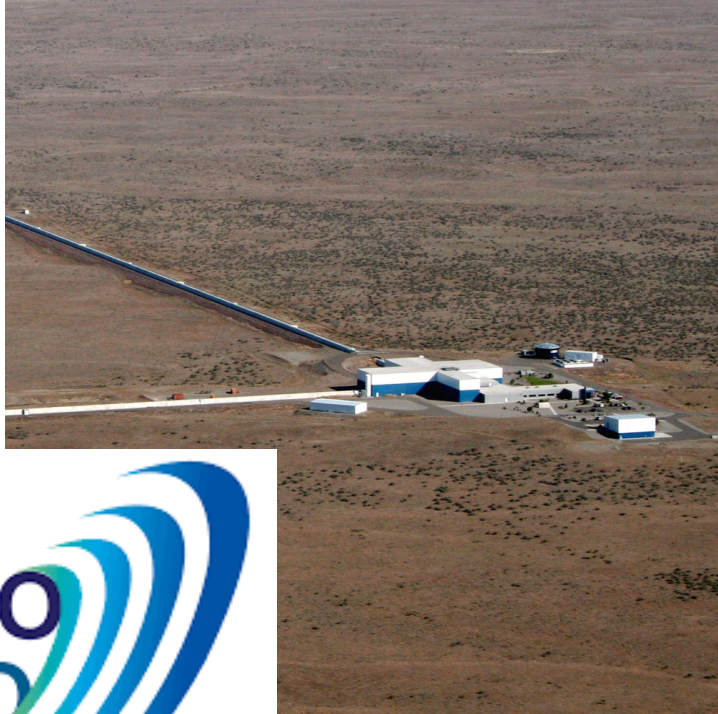
Event Horizon Telescope collaboration to announce groundbreaking Milky Way results on May 12th, 2022, at 13:00 UT

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).

- Garching bei München, European Southern Observatory, see [**ESO Media Advisory**](#) (15:00 CEST) - Live streaming at [**ESO Website**](#) and [**ESO YouTube Channel**](#)
- Mexico City, CONACyT, see [**CONACyT Media Advisory**](#) (08:00 CDT) - Live streaming at [**CONACyT YouTube Channel**](#)
- Santiago de Chile, Joint ALMA Observatory, see [**ALMA Media Advisory**](#) (09:00 CLT)
- Shanghai, Shanghai Astronomical Observatory, see [**Shanghai Astronomical Observatory Media Advisory**](#) (21:00 CST)
- Taipei, Academia Sinica Institute for Astronomy and Astrophysics (21:00 CST)
- Tokyo, National Astronomical Observatory of Japan
- Washington D.C., National Press Club, see [**National Science Foundation Media Advisory**](#) (09:00 EDT) - Live streaming at [**NSF Webpage**](#) and [**NSF Facebook**](#)

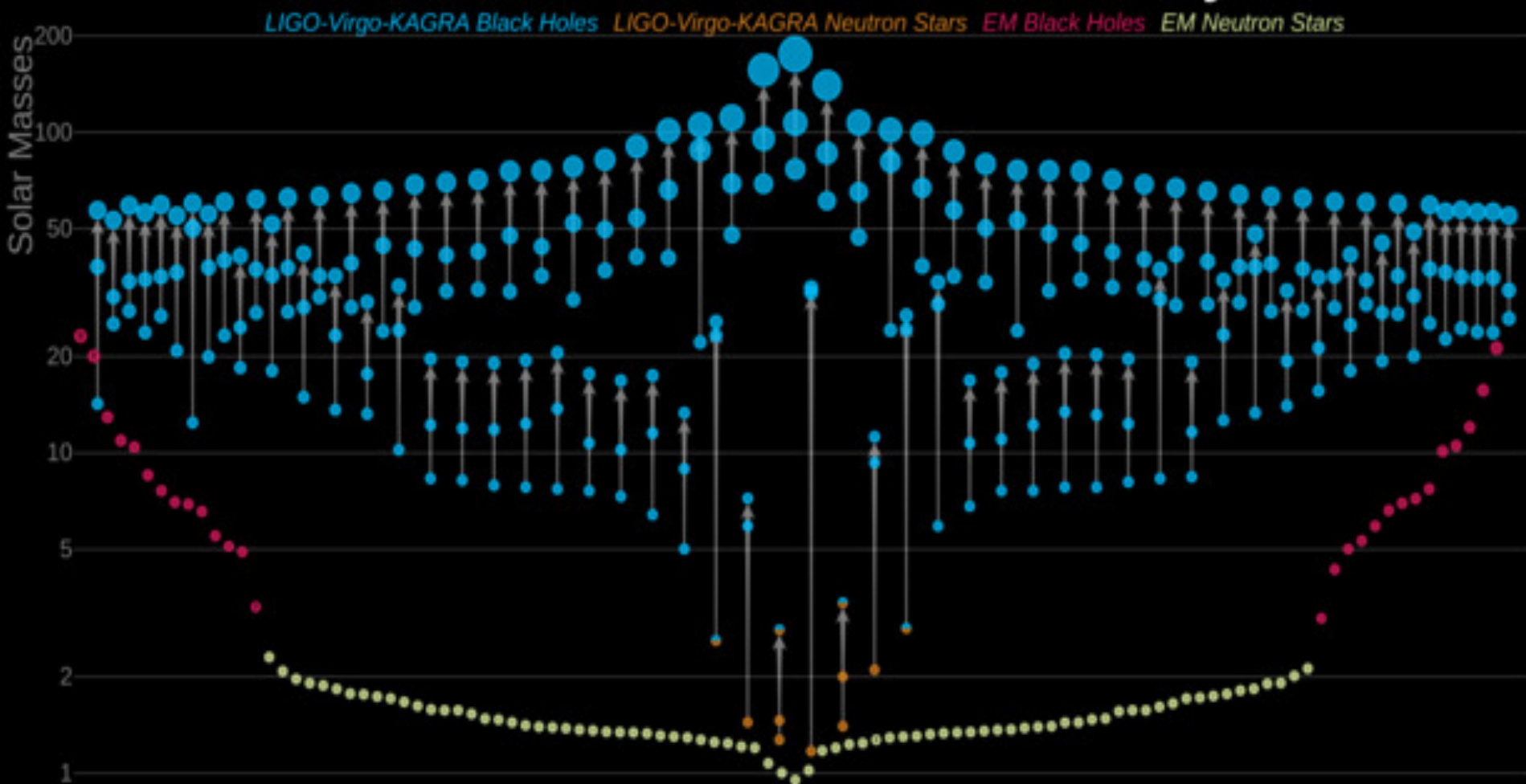
Additional events are planned in Madrid (15:00 CEST), South Korea (22:00 KST), and other locations. Further updates will be provided in this blog entry. For further information, please follow the links above.



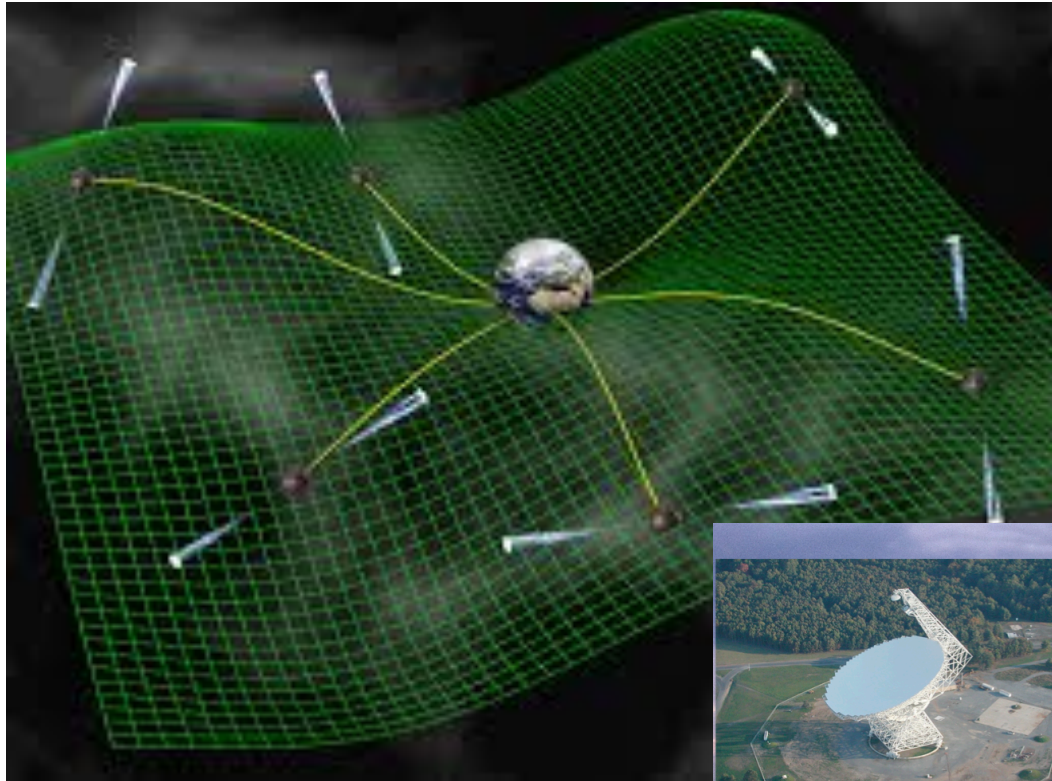
恆星墳場

Masses in the Stellar Graveyard

太陽質量



正在進行的脈冲星週期監測 (PTA)



天際間的奈米-Hz
重力波會引起毫秒
無線電波脈冲星週
期的變化

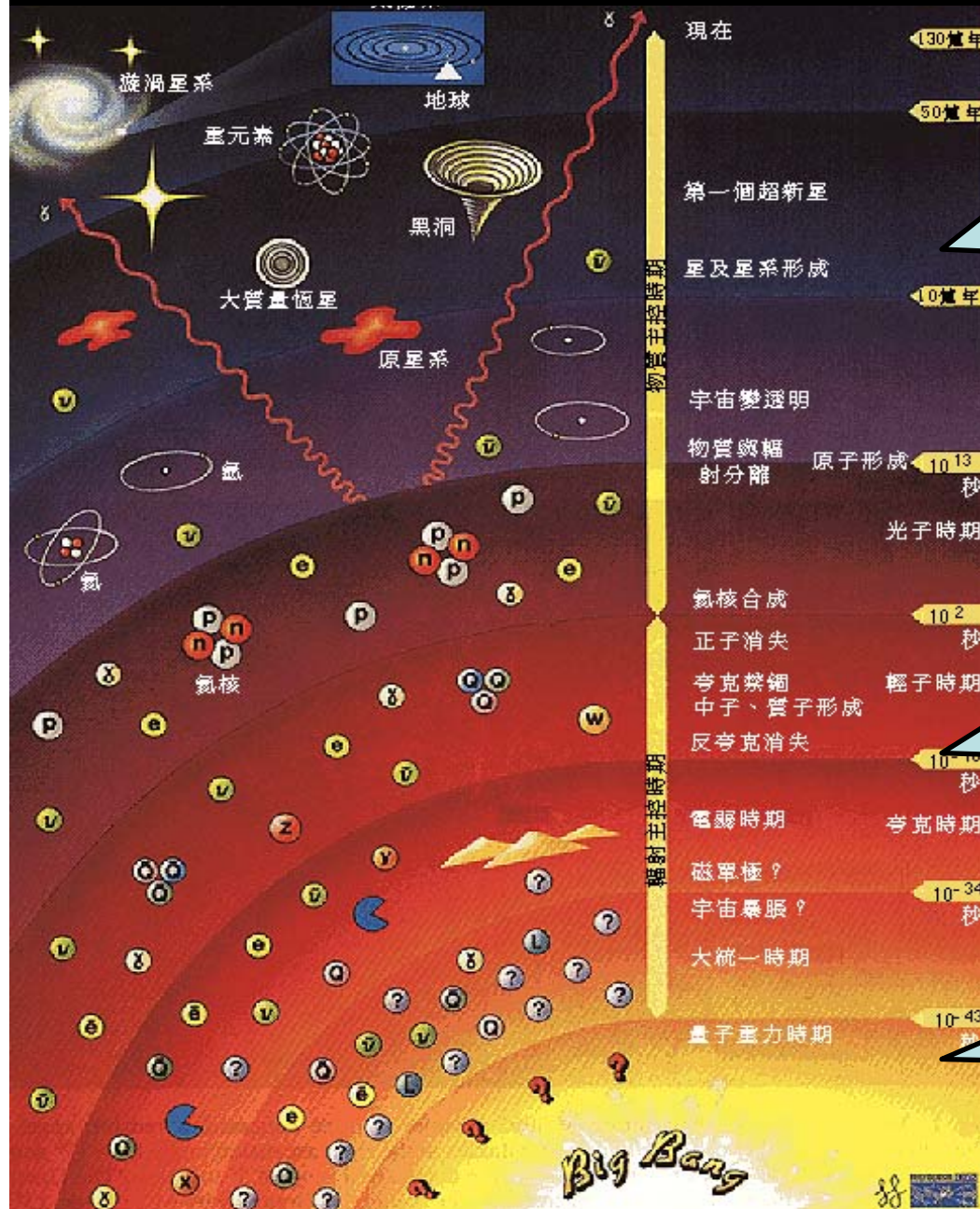
國際合作
Pulsar Timing Arrays



Future SKA will observe thousands of millisecond pulsars



早期宇宙形成的黑洞和產生的重力波



原星系、原大質量恆星、超重黑洞的形成？

M87星系中心
超重黑洞

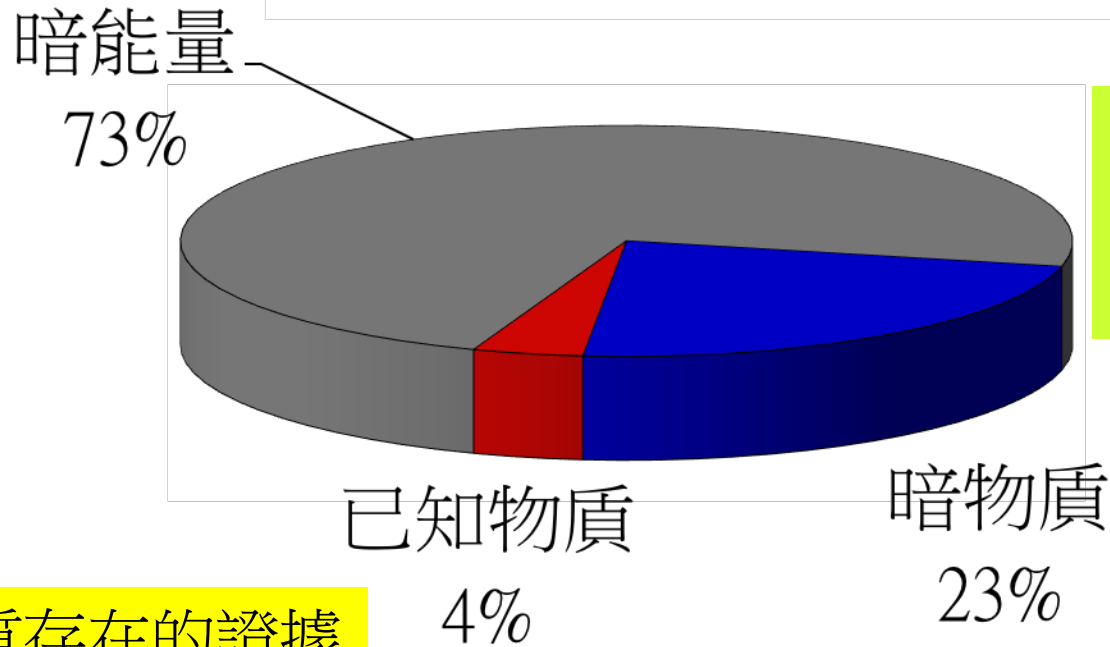
10個億太陽質量



霍金：太初黑洞的形成？

大霹靂產生重力波？

宇宙的物质与能量



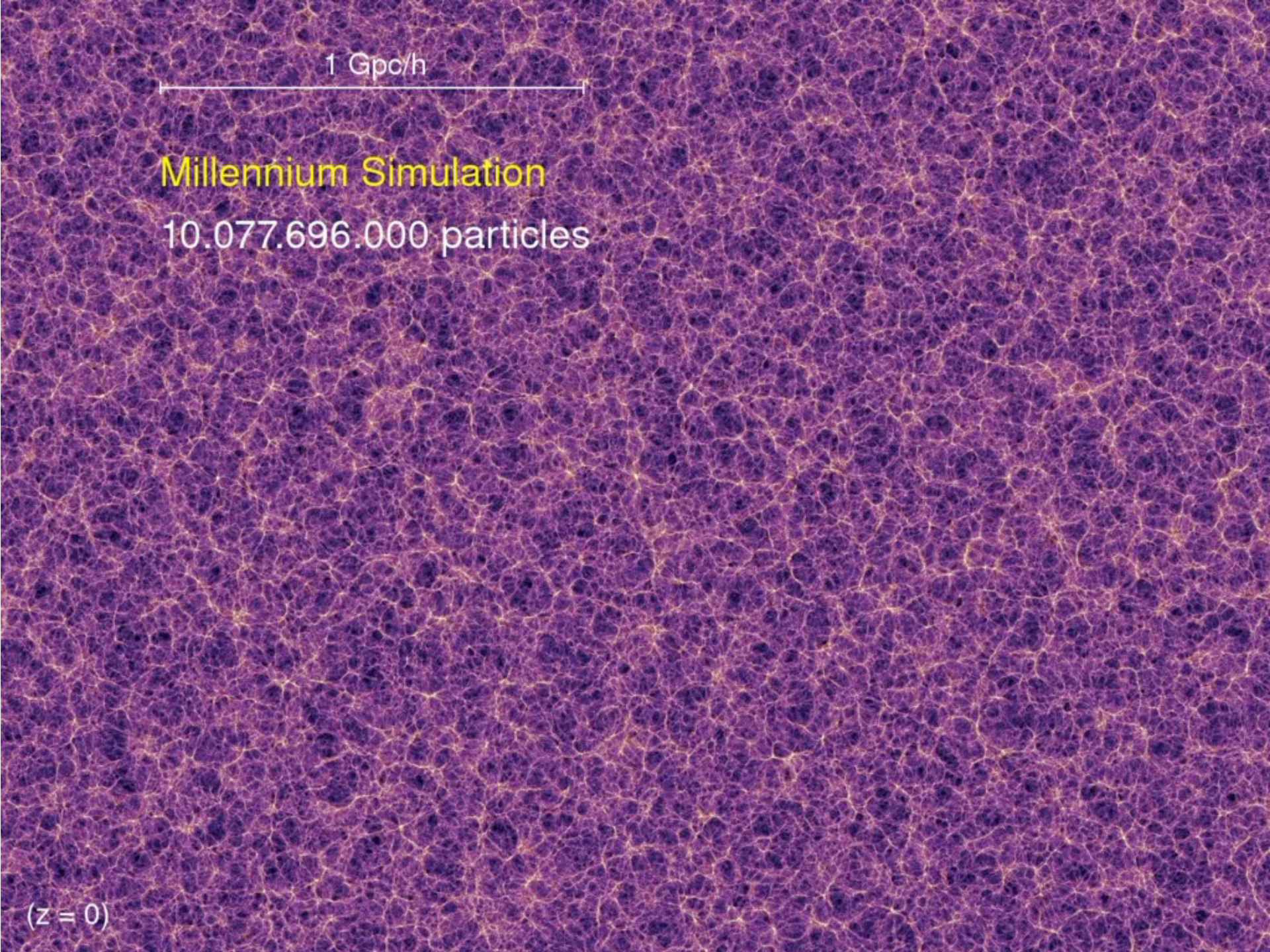
90% 以上不發光
但可以利用重力
得知它們的存在

暗物质存在的證據

大尺度結構

重力透鏡

星系團對撞

A visualization of the Millennium Simulation, showing a vast, dense network of yellow and orange filaments and nodes against a dark purple background. The filaments represent the cosmic web, with nodes indicating regions of high density. A horizontal scale bar at the top left indicates a distance of 1 Gpc/h.

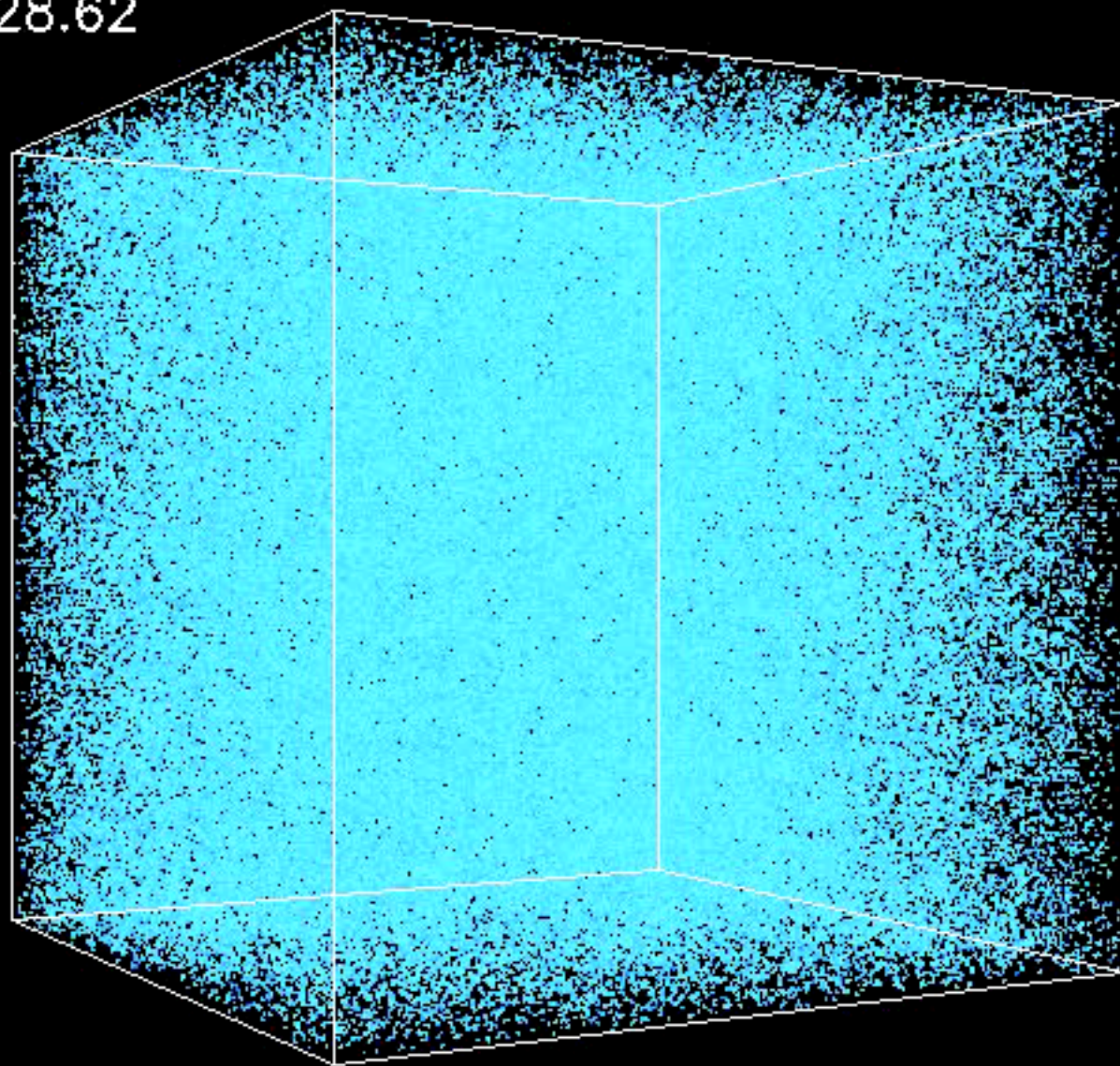
1 Gpc/h

Millennium Simulation

10.077.696.000 particles

($z = 0$)

$z=28.62$

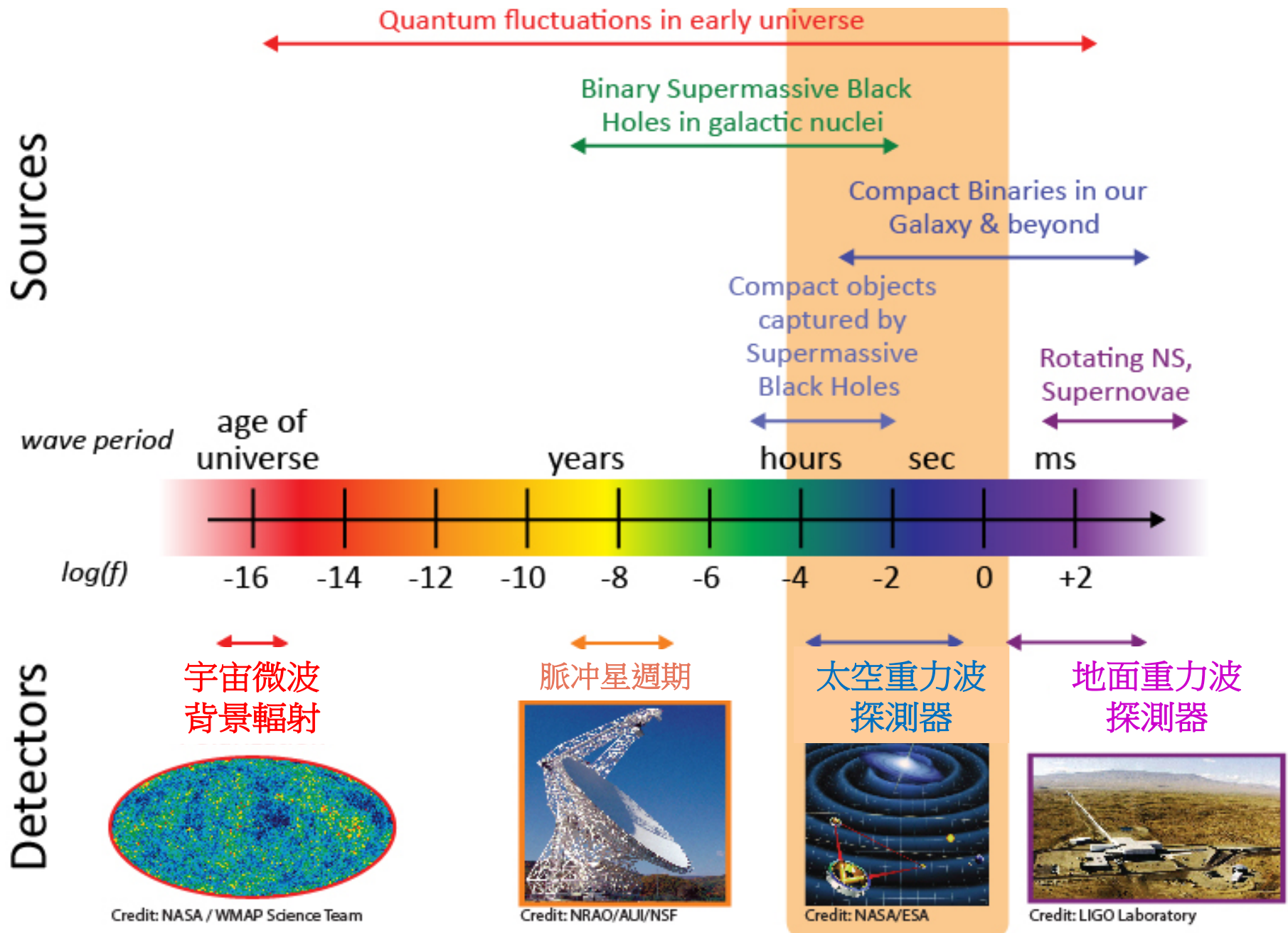


波力舞



重力波的穿透力超強，
能夠穿越宇宙空間，傳遞
原始生成的訊息。

宇宙重力波的能譜



結語

- LIGO-Virgo-KAGRA
實驗探測到雙黑洞併
合產生的重力波
- 開啟了重力波天文、
宇宙學的新紀元
- 俾能利用重力波窺探
早期宇宙