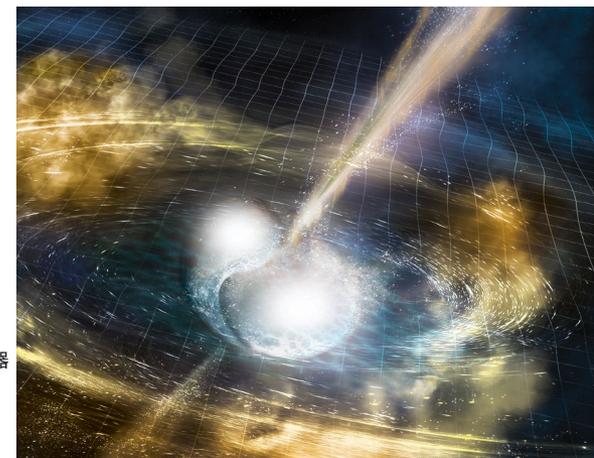
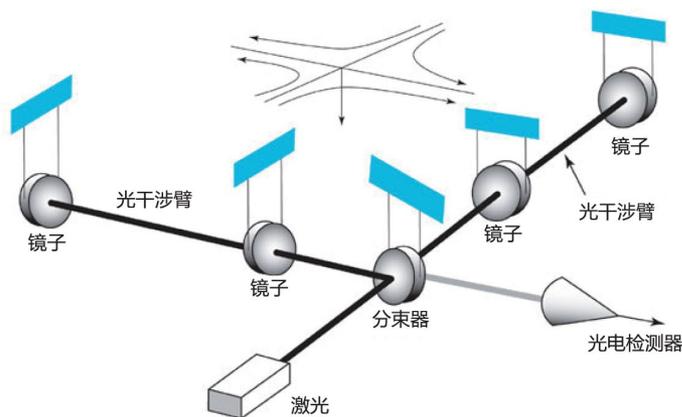
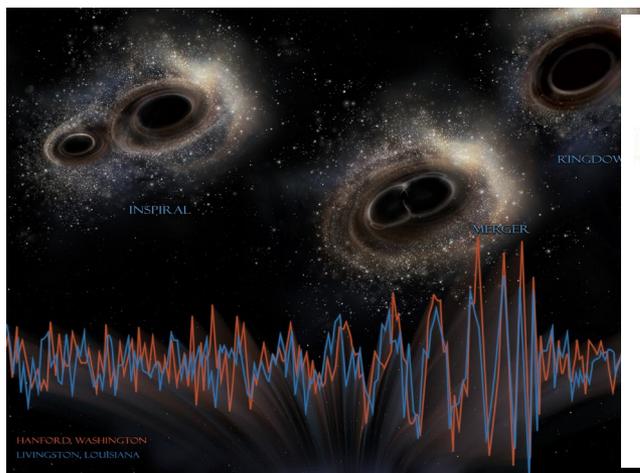


高频引力波天文学简介



范锡龙
武汉大学

大纲

■ 引力波简介

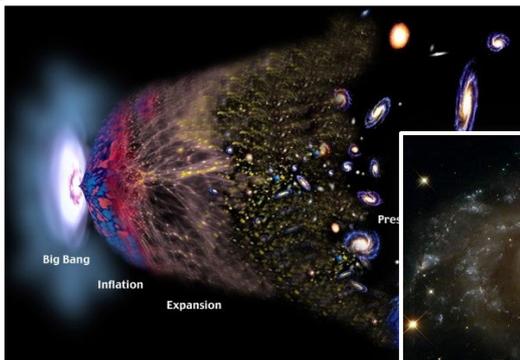
■ 引力波作为天体物理探针

- 引力波多信使联合探测
 - 波源群组性质
 - 致密星状态方程
 - 宇宙学与基础物理学（透镜系统）
-

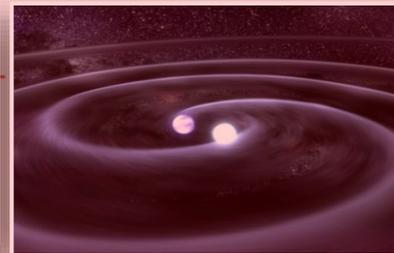
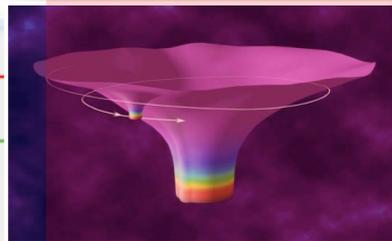
已知 引力波谱

引力波源

极早期宇宙中的量子涨落



星系核中的超大质量双黑洞

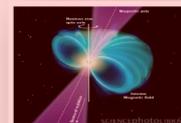


黑洞、被星系核中心超大质量黑洞俘获的致密星

并合的双中子星，遥远星系中的恒星级黑洞

星系中的双星

具有隆起的快转脉冲星



波周期

宇宙年龄

年

小时

秒

毫秒

频率

10^{-16}

10^{-14}

10^{-12}

10^{-10}

10^{-8}

10^{-6}

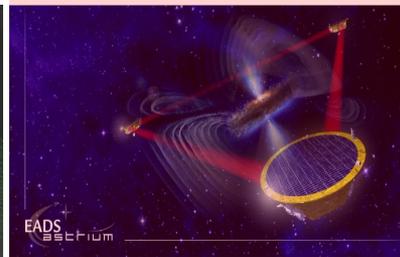
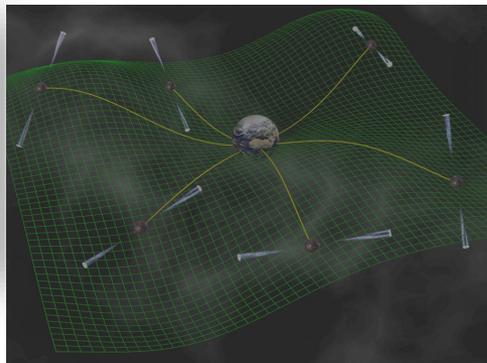
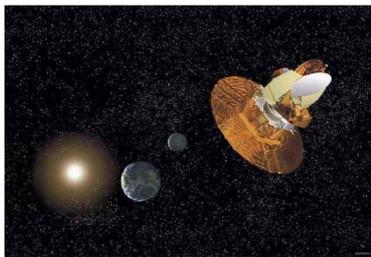
10^{-4}

10^{-2}

1

10^2

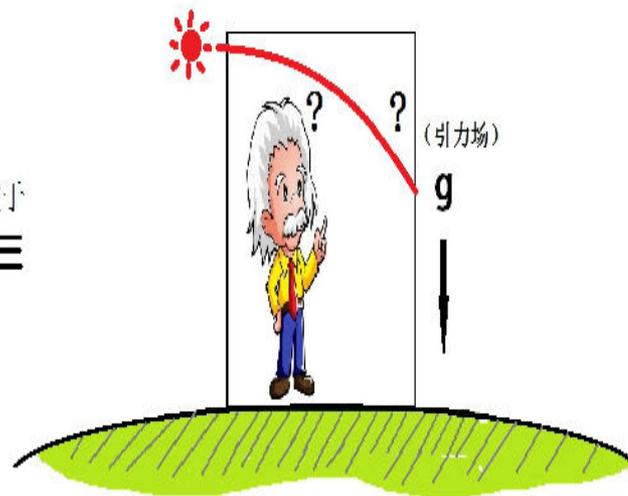
探测器



引力真实存在!

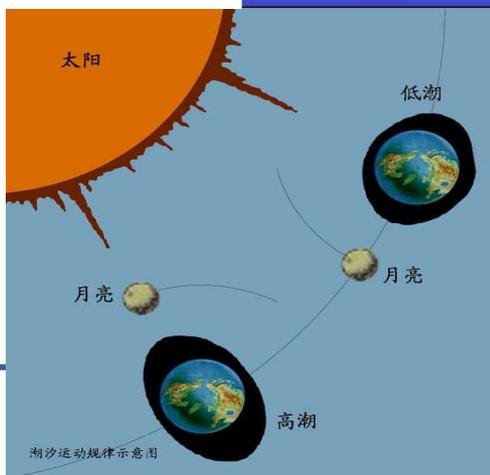


等效于
≡

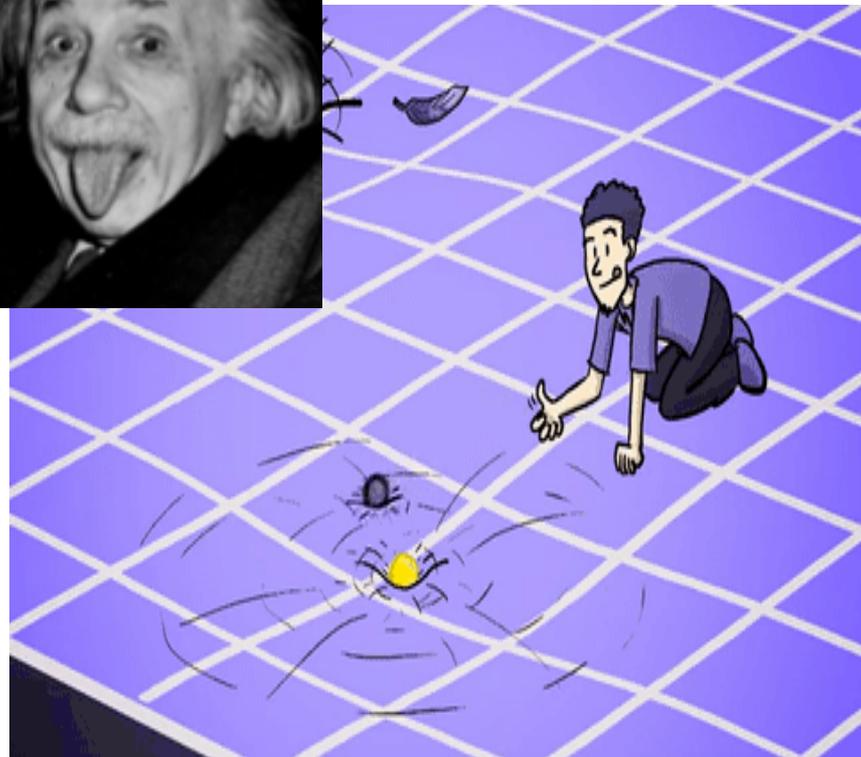
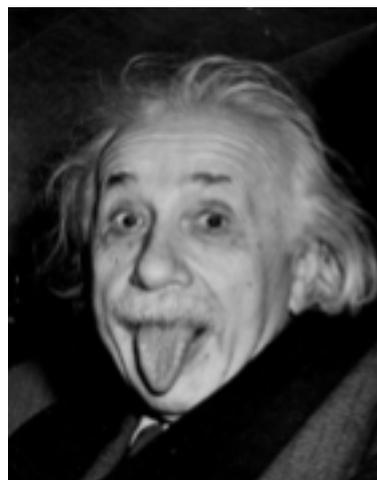
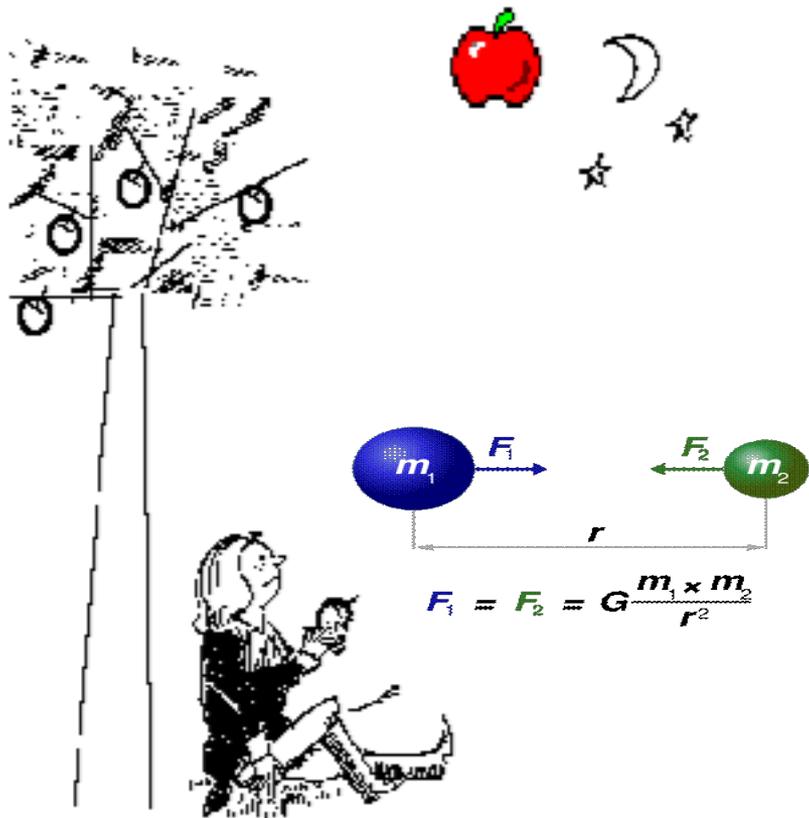


(a) 加速上升的宇宙飞船

(b) 地面上向下的引力场



引力是什么？引无数英雄尽折腰



牛顿：苹果落地和月亮围绕地球转
被同一种作用（引力）统治！（1684年）
时间空间是绝对的、独立的。

爱因斯坦：引力=时空几何（1915年）??
惠勒：时空告诉物质如何运动，物质告诉时空如何弯曲（1990）

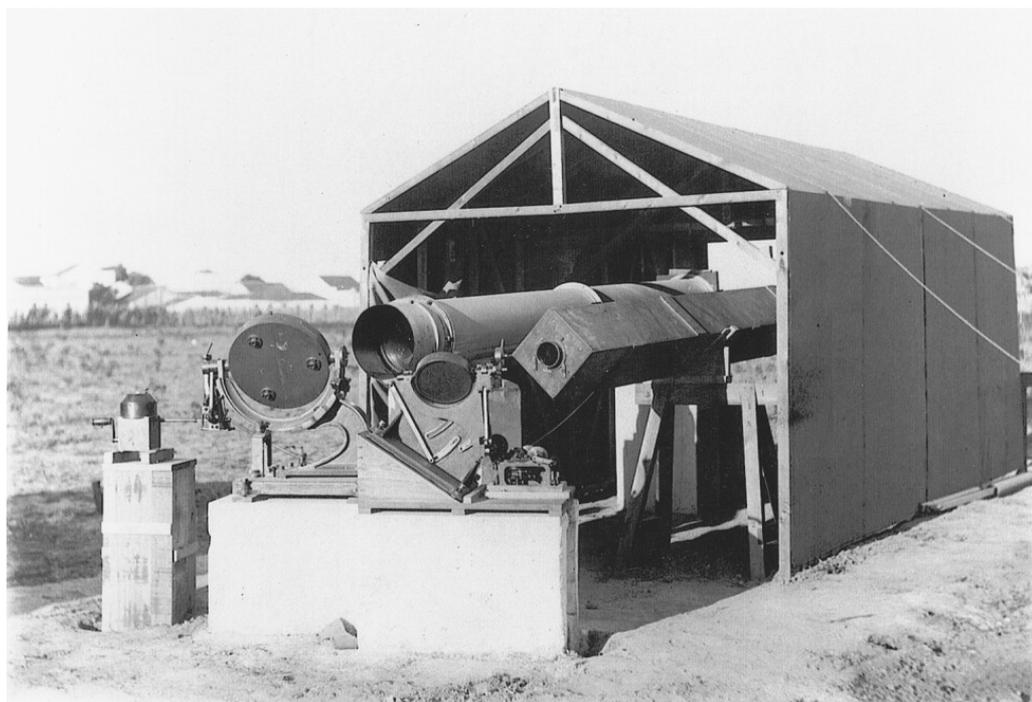
现代时空观：引力场中的时间变慢

- 地球上的时钟比卫星时每天钟慢：38,000 纳秒
- GPS 精度需要20-30 纳秒



全球定位系统(GPS)必须考虑广义相对论的影响

时空是很硬的！



1919年5月29日的日全食
毕宿星团偏离了**1.75''**

© Science Museum/Science and Society Picture Library

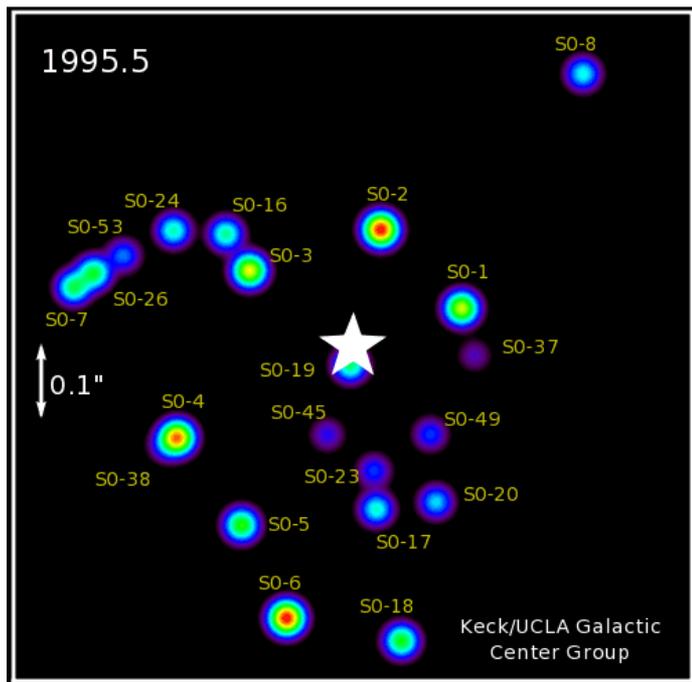
数学、天文学和物理学的黑洞

- 1916年，史瓦西，广义相对论静态球对称解
- 1963年，克尔，旋转轴对称解
- . . .

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

银河系中心~4百万太阳质量“黑洞”（2020年诺奖）

太阳史瓦西半径~3千米
地球史瓦西半径~9毫米



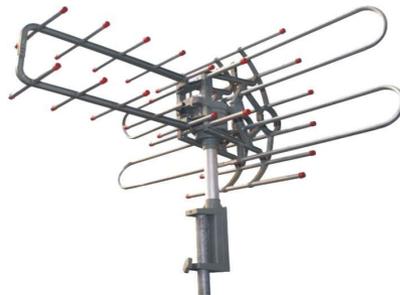
天鹅座X-1~10太阳质量“黑洞”，落入气体发射x射线



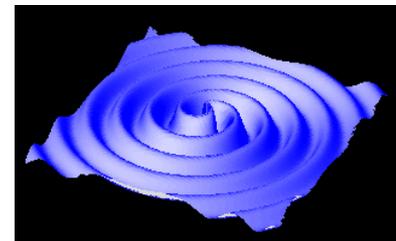
- 2015年，测到双黑洞并合发射的引力波

引力波是什么？

■ 什么是波？



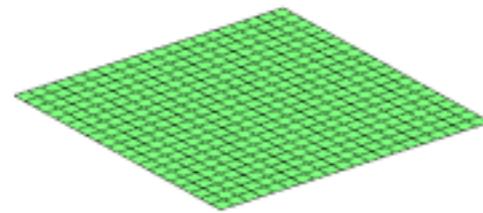
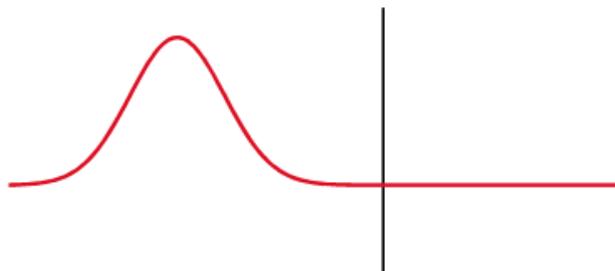
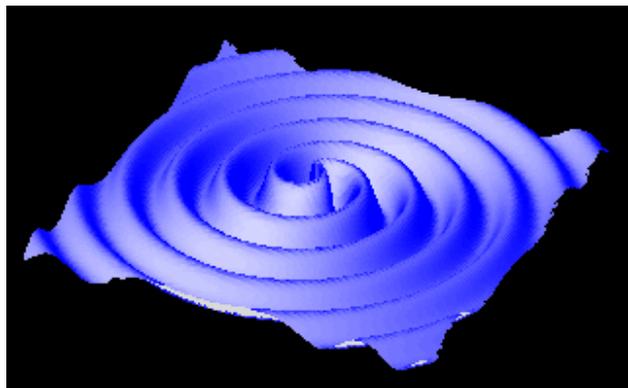
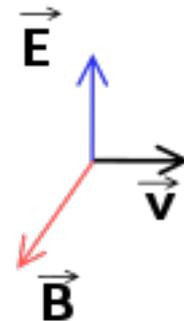
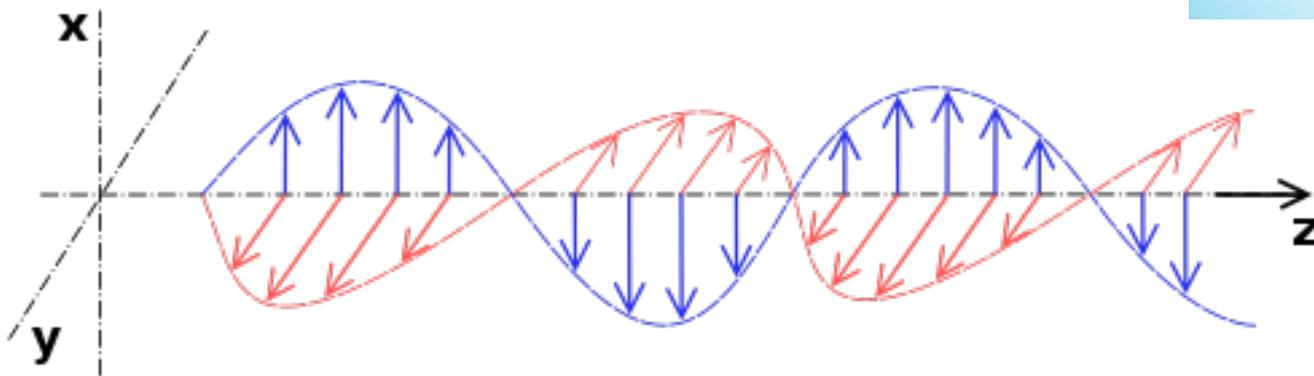
- 引力波：广义相对论预言的时空涟漪（扰动的传播）
 - 当时空本身发生变化时，时空的扰动以光速传播
- 电磁波、机械波的传播 - - 在舞台上表演的人
- 引力波 - - 舞台本身在震动



什么是波

■ 波动方程

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$$



引力波是什么？

- Will gravitational waves confirm Einstein' s General Relativity? arXiv:0907.2162

- 引力场方程:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} .$$

- 线形近似: $g_{\mu\nu}(\vec{x}, t) = \eta_{\mu\nu} + h_{\mu\nu}(\vec{x}, t),$

更严格的证明请咨询
章颖理

- 波动方程: $\square \bar{h}_{\alpha\beta} = -16\pi T_{\alpha\beta} .$

- Transverse-traceless 规范下平面波解

$$h_{ab}^A(t, \vec{x}) = \text{Re}\{h_A e^{i2\pi f(\hat{\Omega} \cdot \vec{x}/c - t)} e_{ab}^A(\hat{\Omega})\}.$$

光速传播

引力波很弱

■ Einstein 1916

$$A = \frac{\kappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \quad (21)$$

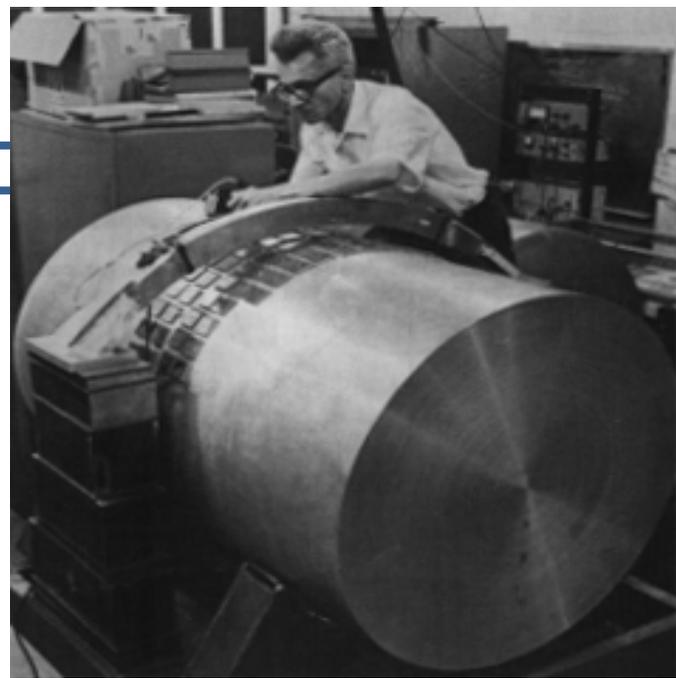
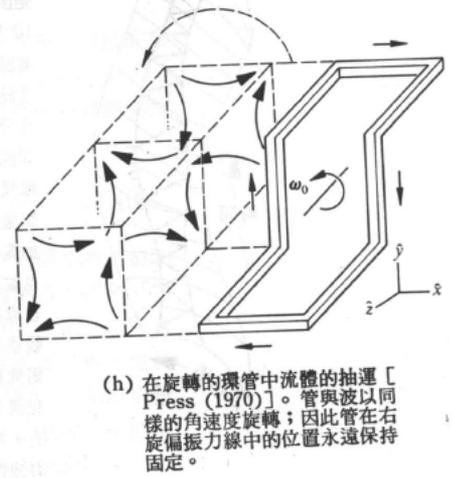
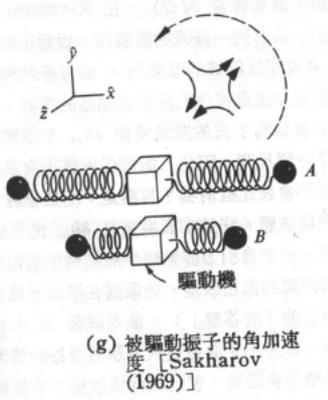
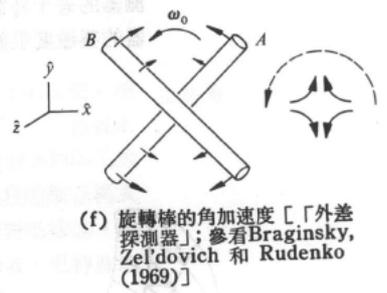
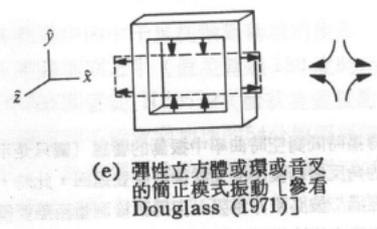
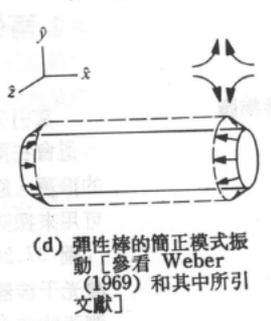
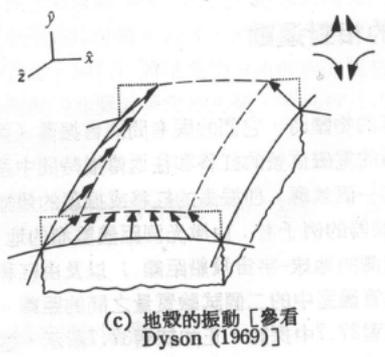
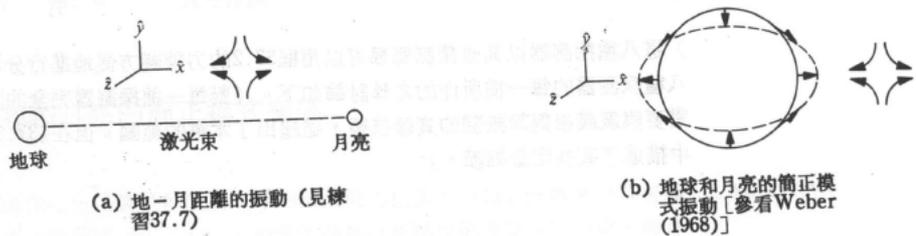
Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\kappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

“.....in any case one can think of A will have a practically vanishing value.”

爱因斯坦：在所有能想到的情况下，引力波的辐射都可以被忽略。

引力波的科学探测





May 17, 1919 – September 30, 2000

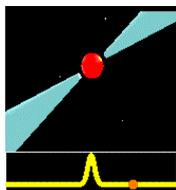


- 60年代韦伯开创了引力波探测这个领域
- 他的实验结果没有被重复, 也很难找到对应的天体起源

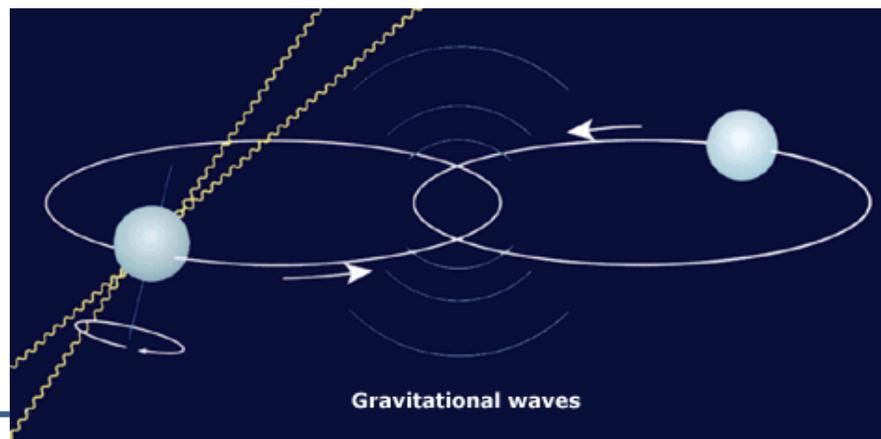
圖 37.2 各種類型的引力波探測器。

70年代：引力波间接存在证据

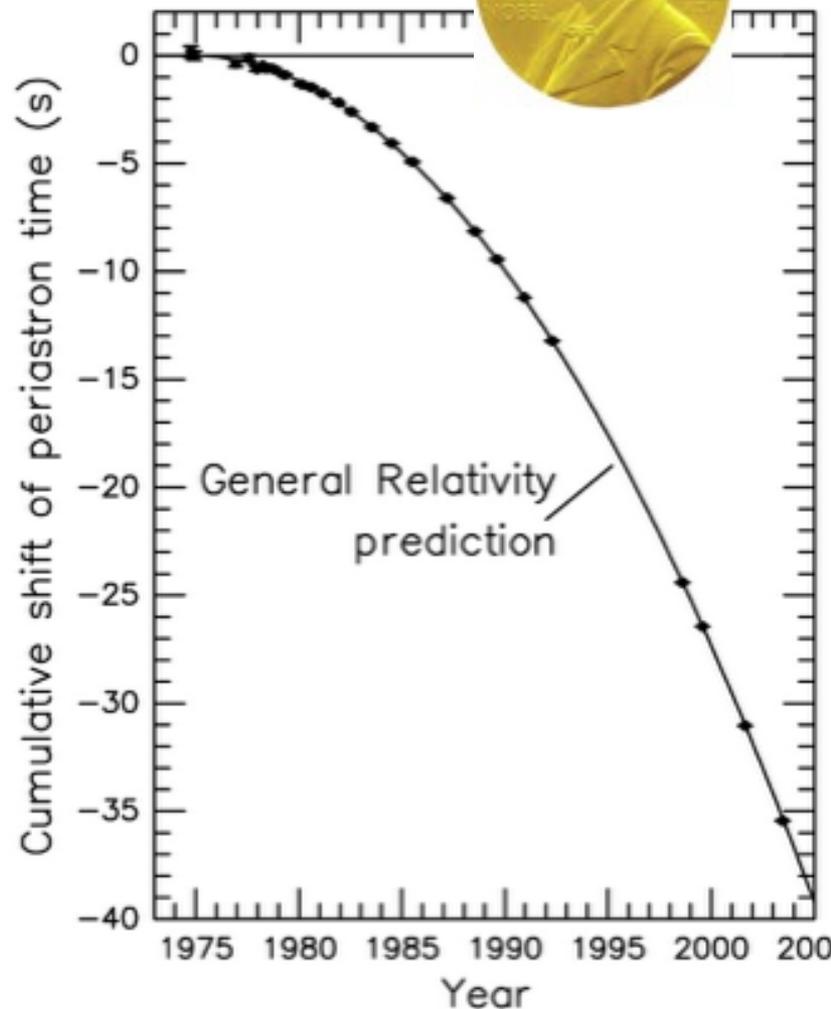
- 引力波携带能量
- 双星绕转轨道变小，频率变快，周期变小
- 1974年，Hulse 和 Taylor 发现脉冲星双星PSR1913+16



- 从1975年到2003年，轨道周期减小了 35秒

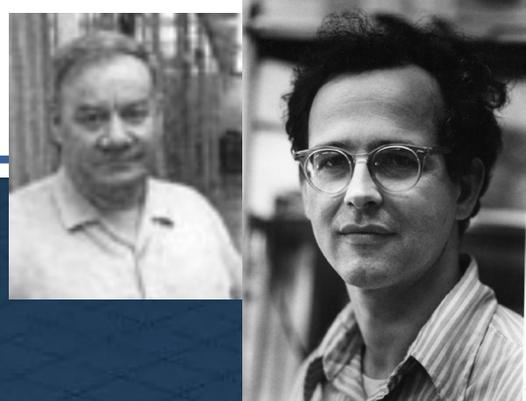


1993 诺贝尔物理学奖



70年代：用激光干涉仪！

纳德·德雷弗
雷纳·韦斯



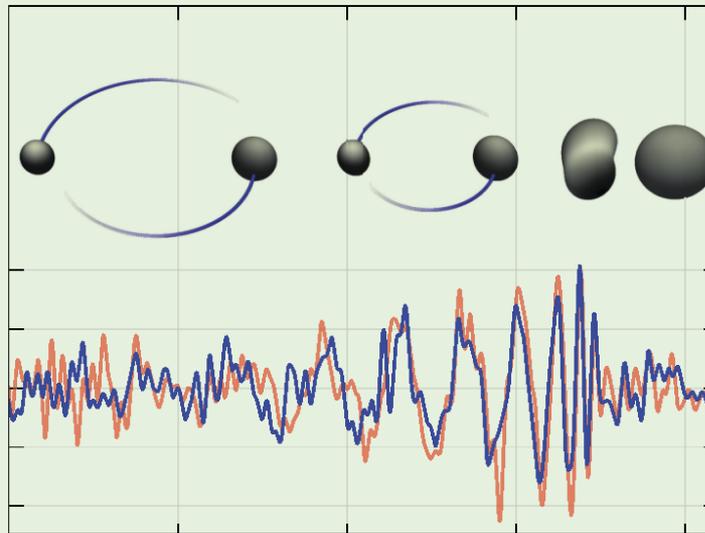
迈克尔逊干涉仪(1883),1887年进行了著名的迈克尔逊-莫雷实验，并证实了以太的不存在。

PHYSICAL REVIEW LETTERS™

Member Subscription Copy
Library or Other Institutional Use Prohibited Until 2017

Articles published week ending

12 FEBRUARY 2016



Published by
American Physical Society™

APS
physics

Volume 116, Number 6



Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21} . It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ . The source lies at a luminosity distance of 410_{-180}^{+160} Mpc corresponding to a redshift $z = 0.09_{-0.04}^{+0.03}$. In the source frame, the initial black hole masses are $36_{-4}^{+5} M_{\odot}$ and $29_{-4}^{+4} M_{\odot}$, and the final black hole mass is $62_{-4}^{+4} M_{\odot}$, with $3.0_{-0.5}^{+0.5} M_{\odot} c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

PRL 116, 061102 (2016)



¹²⁷Janusz Gil Institute
¹²⁸Ani

1
¹³¹Ur

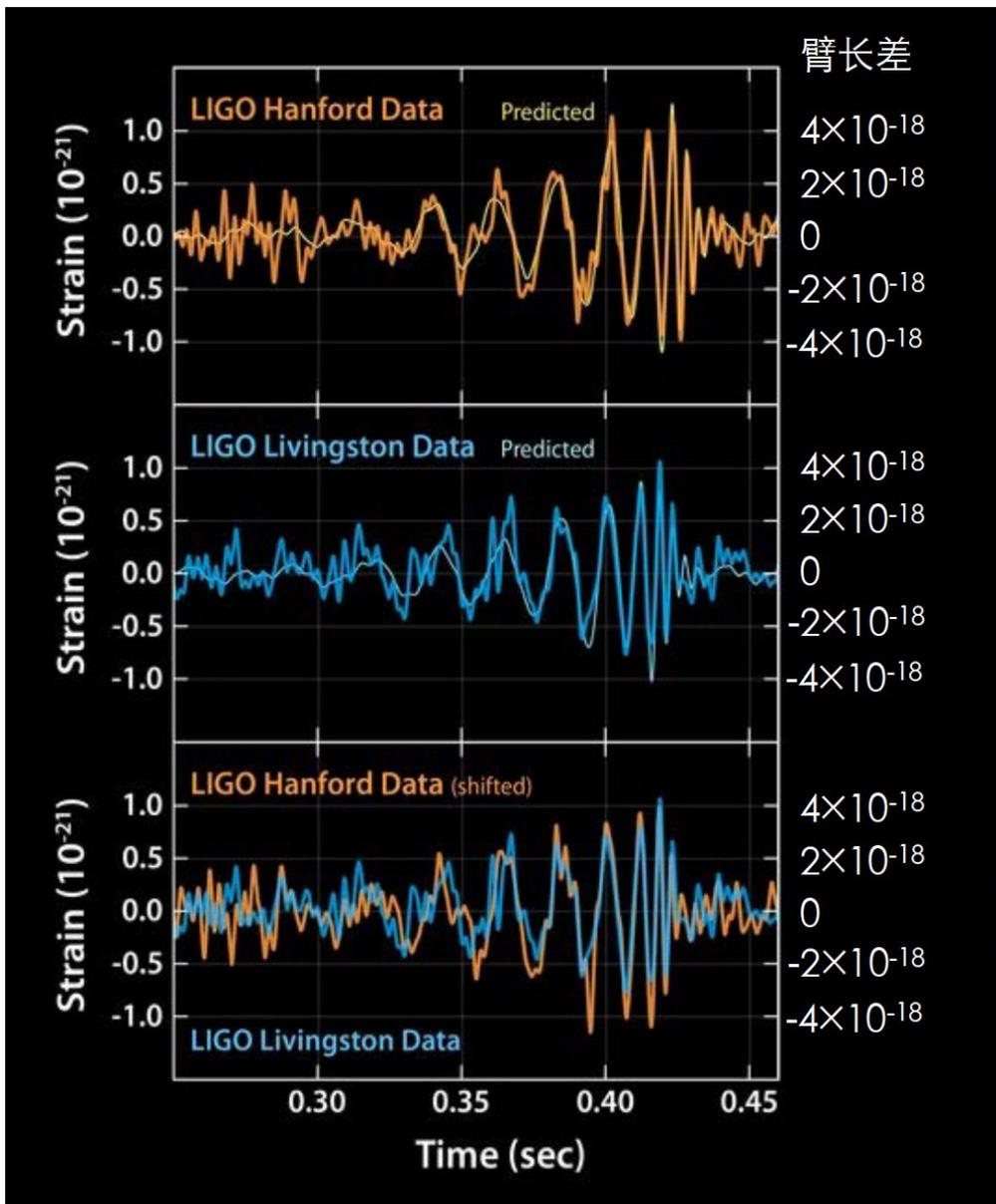
¹³³A

^aDeceased, April 2012.

^bDeceased, May 2015.

^cDeceased, March 2015.

GW150914 (PRL,116,061102 (2016))



13亿光年外

36 太阳质量黑洞

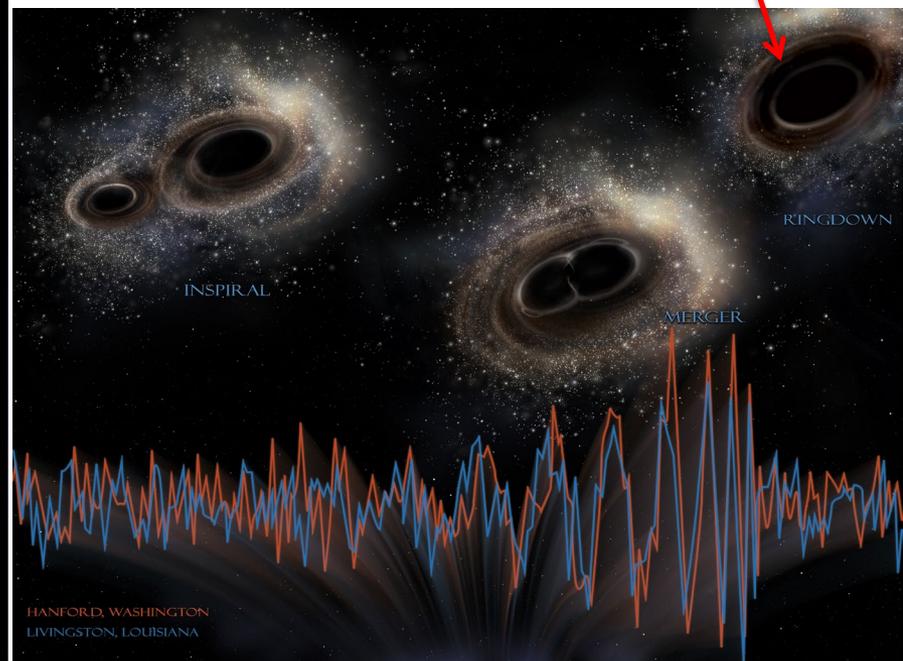


29 太阳质量黑洞

并合



62 太阳质量
旋转黑洞



3 太阳质量的能量以引力波形式释放
功率峰值是可见宇宙辐射的50倍

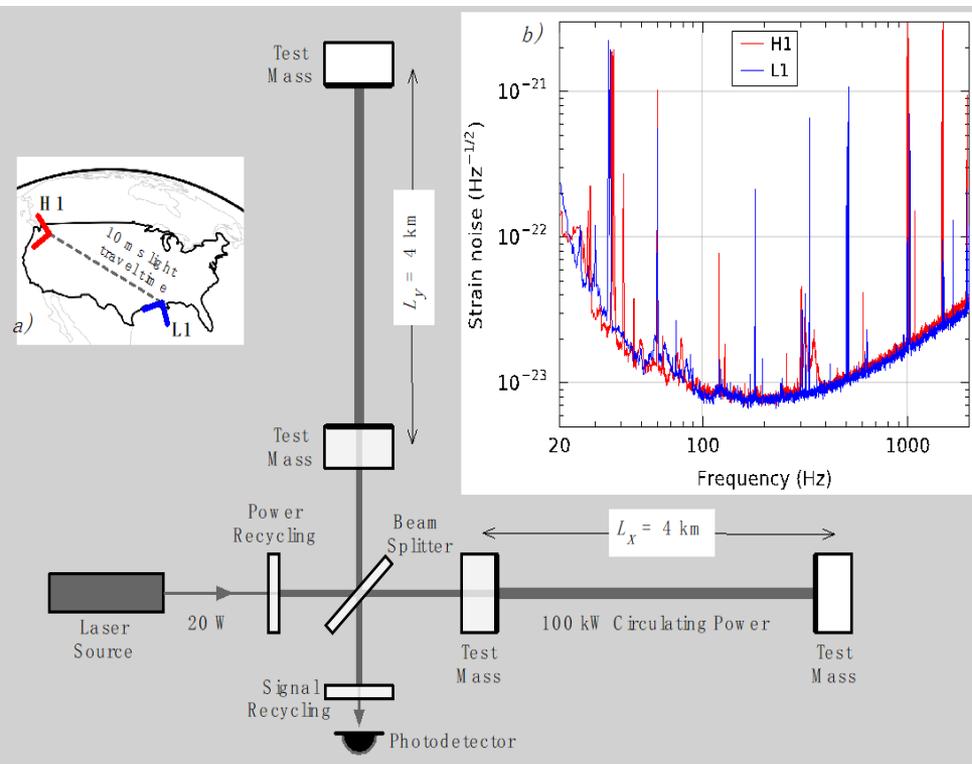
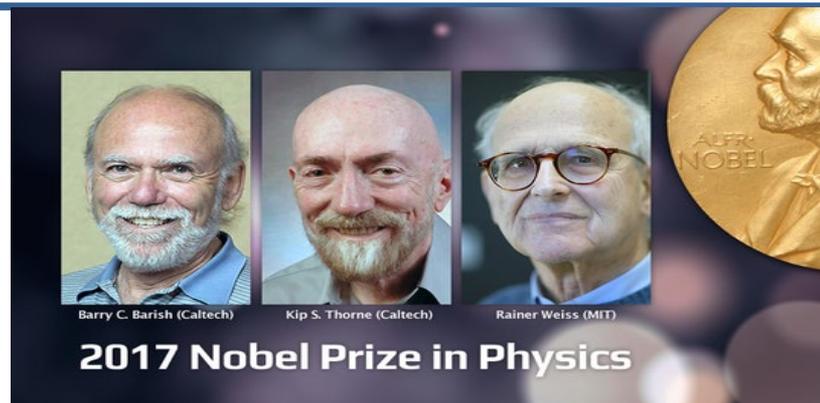
匹配滤波法:

振幅 (距离) + 波形 (质量, 旋转)

The detection (GW150914)

PRL 116, 061102 (2016)

- 引力波存在!
- $\sim 30M_{\odot}$ 黑洞存在
- 双黑洞能在宇宙时间内并合



高频引力波源

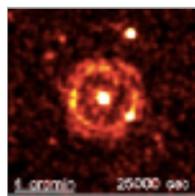
■ 致密双星绕转:

- BBH, BNS, NS-BH

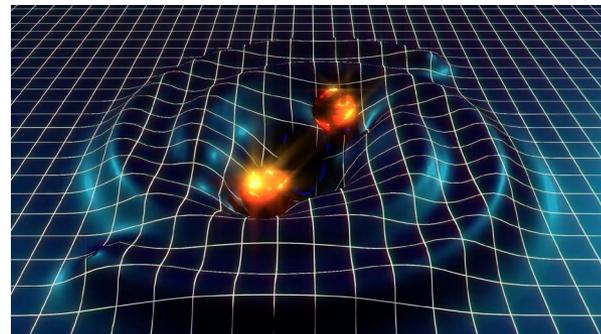
■ 引力波爆: 银河系内可测

- 超新星爆发

$$R_{\text{burst}} \simeq \left[\frac{G}{2\pi^2 c^3} \frac{E_{\text{GW}}}{S(f_0) f_0^2 \rho_{\text{det}}^2} \right]^{1/2}$$



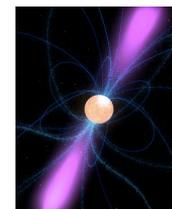
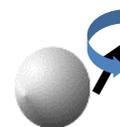
XMM Newton



■ 周期引力波源: 银河系内可测

- 脉冲星

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz} \varepsilon f_{\text{rot}}^2}{d}$$

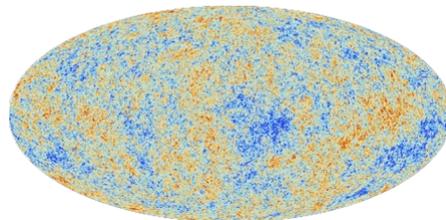


NASA

“Mountain” on neutron star

■ 随机引力波背景:

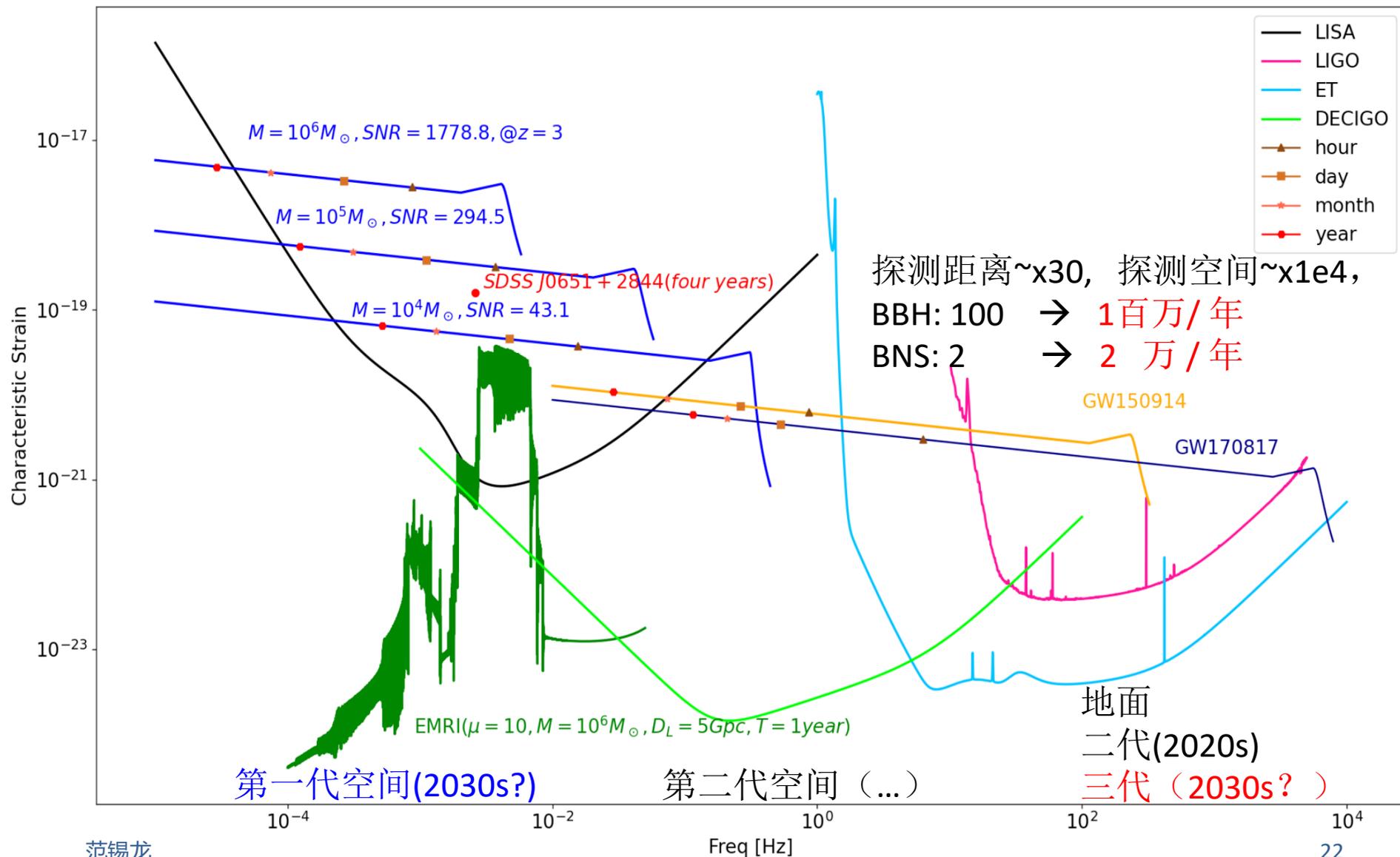
- 宇宙学起源
- 天体源起源



Planck Team

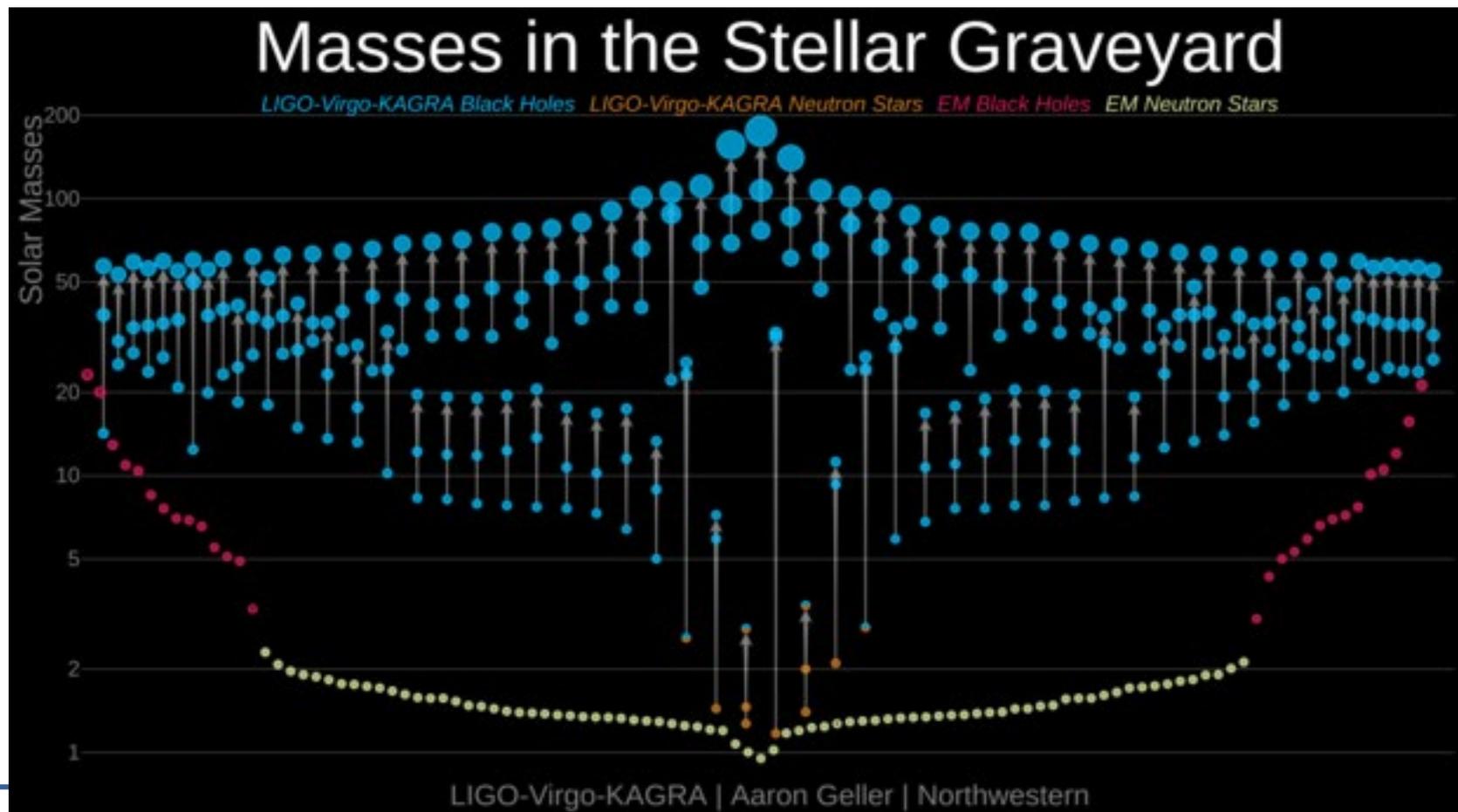
$$\Omega_{\text{GW}}(k) \equiv \frac{1}{12} \left(\frac{k}{Ha} \right)^2 \frac{k^3}{\pi^2} \overline{\langle h_{\mathbf{k}}(\eta) h_{\mathbf{k}}(\eta) \rangle},$$

未来激光干涉仪探测器双星引力波源



The third Gravitational-wave Transient Catalog

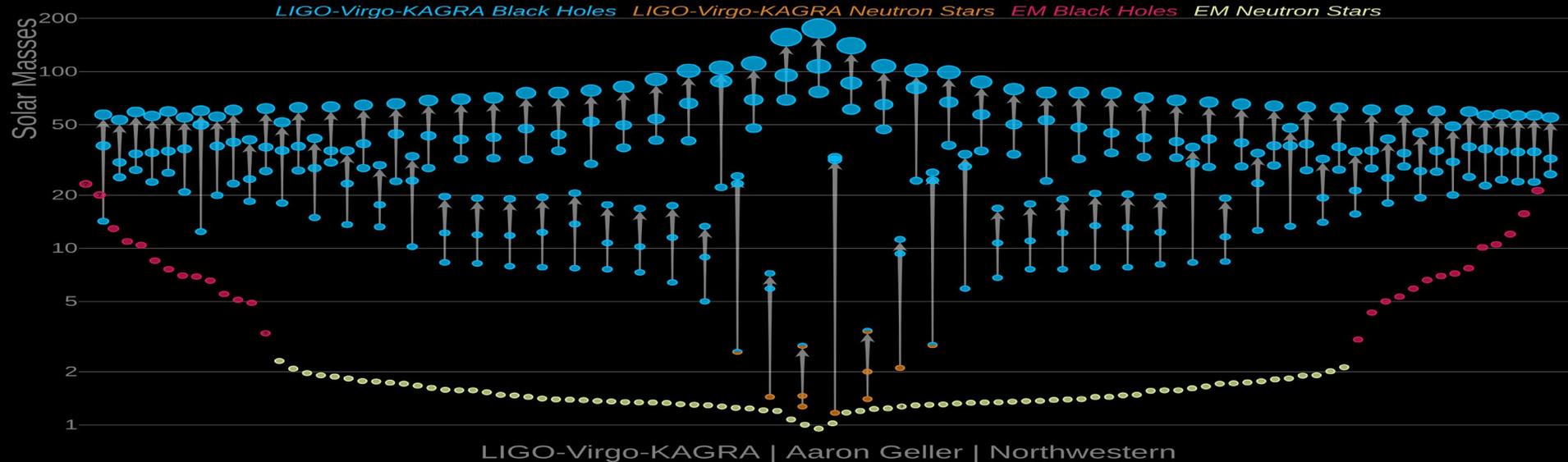
- 累计有效观测时间合计为23个月，共发现了90次引力波
(双星并合引力波: 83 BBH, 2 BNS, 3+2 BH-NS)



LVC 2016-2020 观测结果

O3 events

Masses in the Stellar Graveyard



- Where are they ?
 - A. Wide field surveys
- Why are they so massive ?
 - B. Stellar astrophysics and Galactic structure and evolution
- How can we use them ?
 - C. Cosmic transients and cosmology

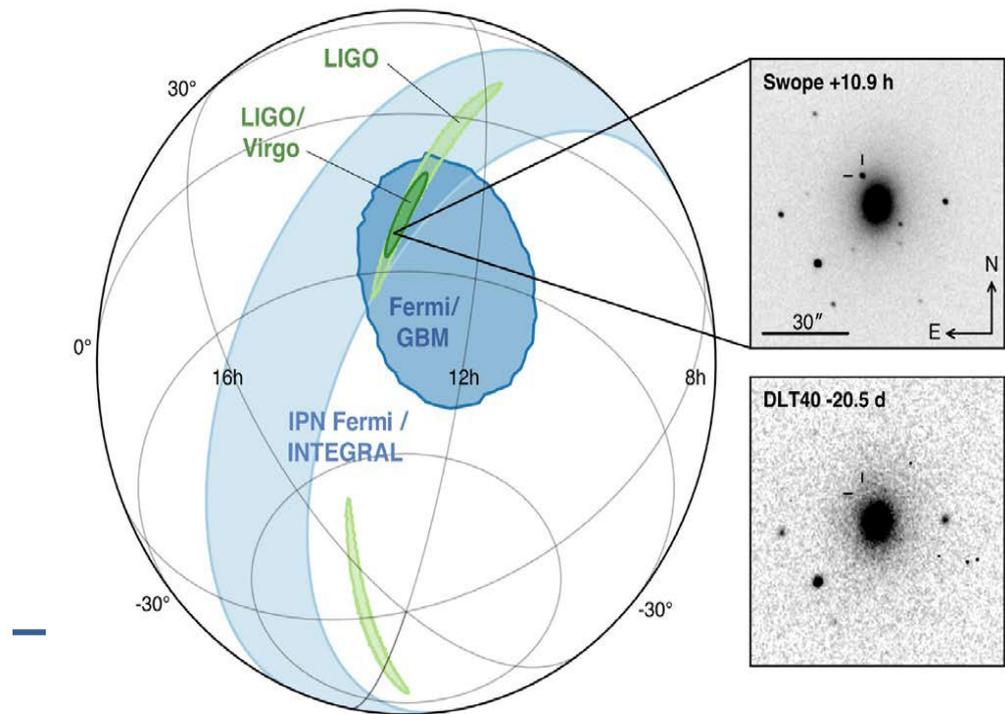
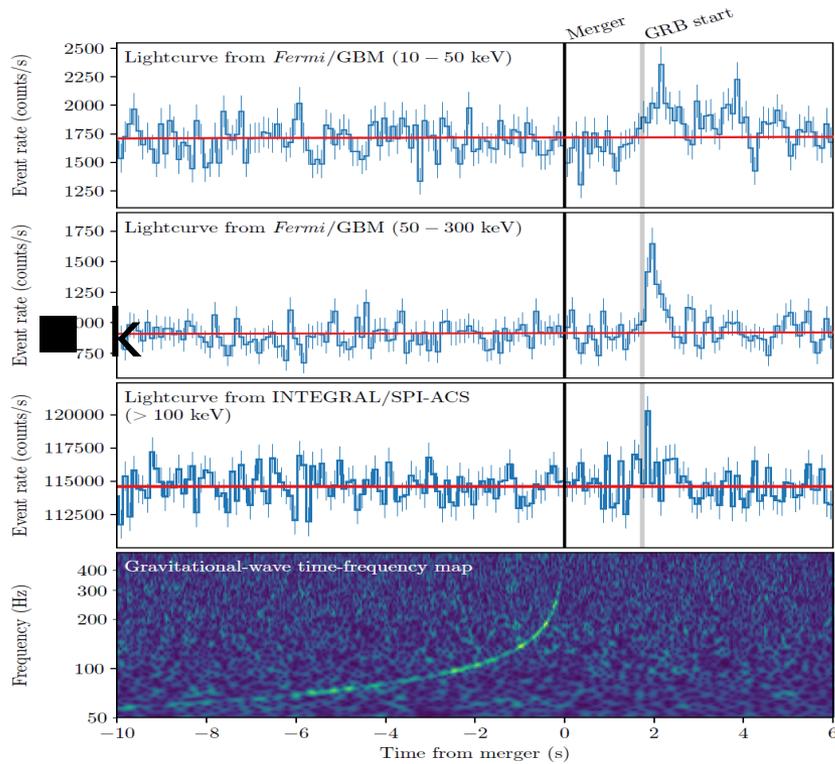
大纲

- 引力波简介

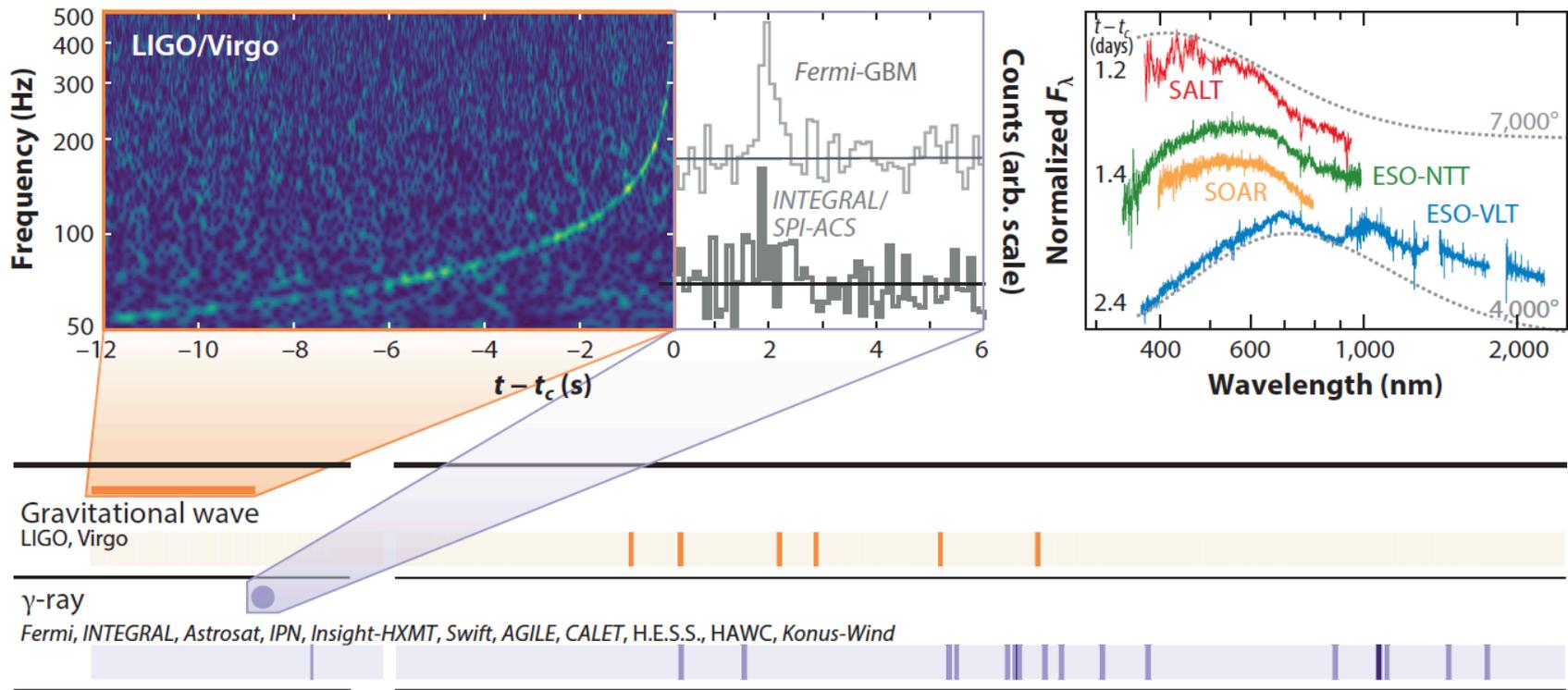
 - 引力波作为天体物理探针
 - 引力波多信使联合探测
 - 波源群组性质
 - 致密星状态方程
 - 宇宙学与基础物理学（透镜系统）
-

The Multi-Messenger Astrophysics event

- LIGO-Virgo: GW170817 (双中子星并合引力波)
- Fermi GBM: 90% of the burst fluence observed over $T_{90} = 2.0 \pm 0.5$ s. (伽马暴)
- Swope telescope : i-band: 17.057 ± 0.018 Mag (千新星)
10.6'' from the center of NGC4993, ~40 Mpc (宿主星系)

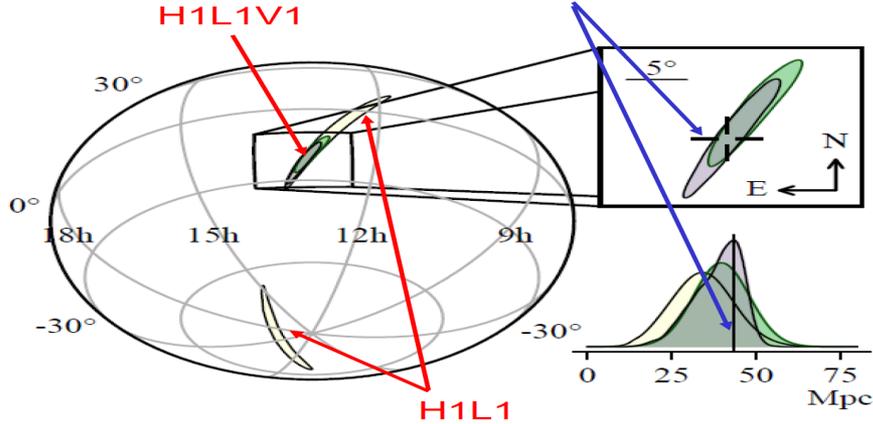


双中子星并合多信使信号

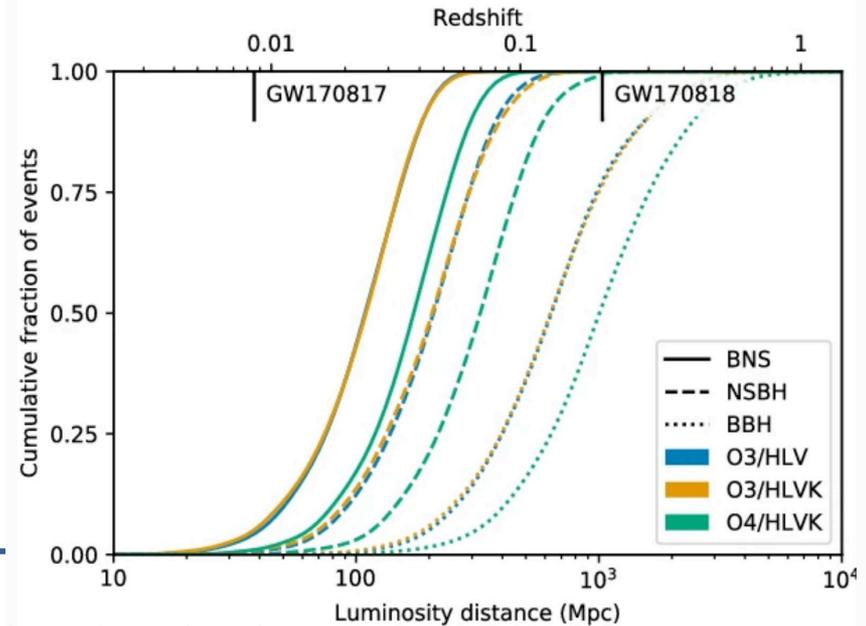
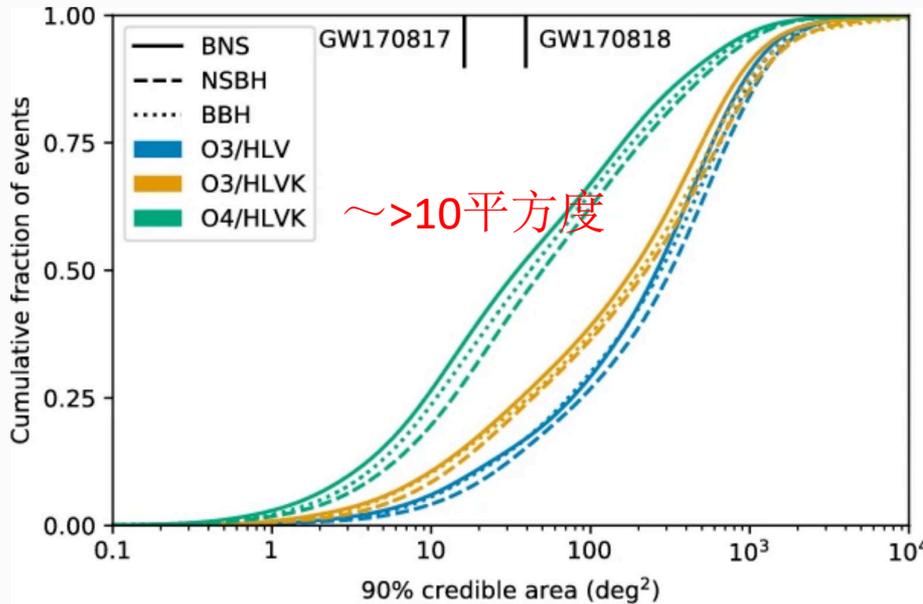
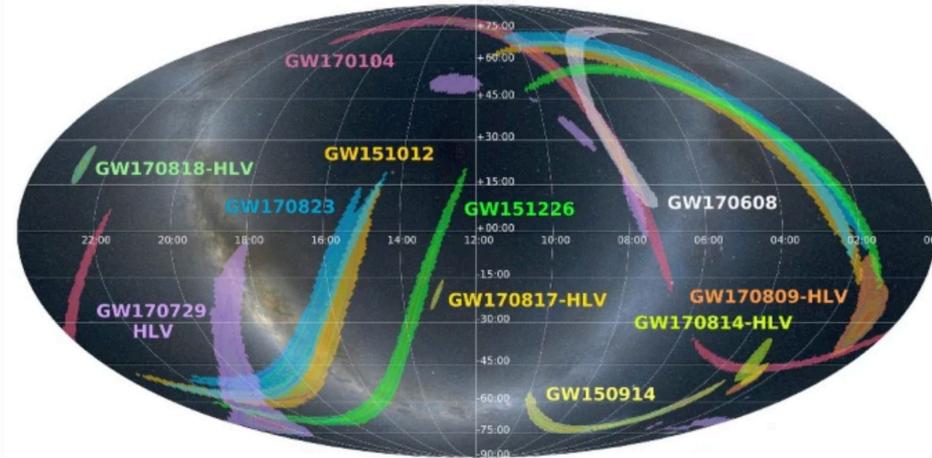


引力波天文学：引力波定位？

GW170817 ~ 30 平方度 NGC4993



PRL **119**, 161101 (2017)



我理解的多信使天文学

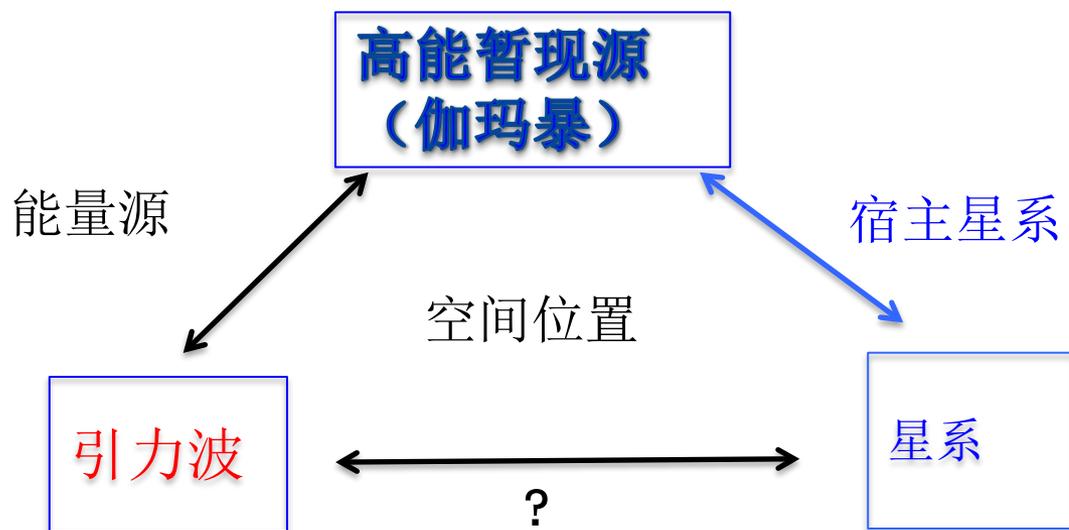
- 如何确定引力波和电磁波来自同一个天体？
 - 联合数据能对应到一个**物理联系**吗？

 - 我们能从联合探测中学到什么？
 - 除去确定探测到引力波，引力波和电磁波研究能相互得到什么**新信息**？
-

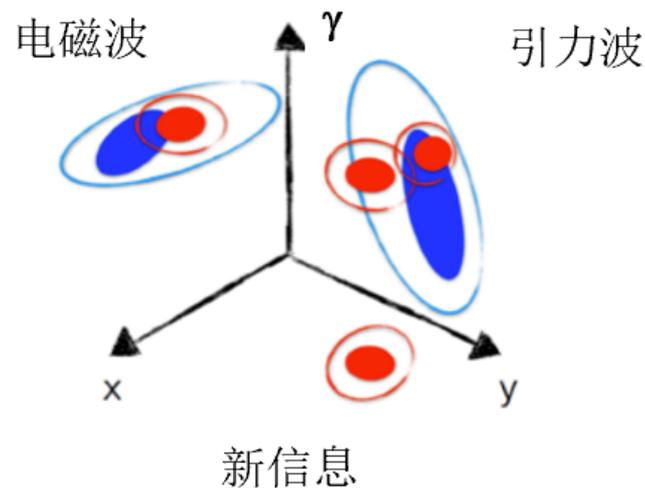
天图和物理性质

■ Observational triangle

Fan, Messenger & Heng, ASSP, 2015



Fan, Messenger & Heng, ApJ 2014



From GW data analysis

From EM data analysis

$$p(\gamma, \phi, \omega | \mathbf{S}, \mathbf{D}, M, I) = \frac{p(\mathbf{D} | M, I) p(\gamma, \phi | \mathbf{S}, M, I) p(\gamma, \omega | \mathbf{D}, M, I)}{p(\mathbf{D} | \mathbf{S}, M, I) p(\gamma | M, I)}$$

The prior of γ used in GW or EM data analysis

A Bayesian approach : GRB luminosity

- GW170817 and GRB 170817A
(LVC+ Fermi+ INTEGRAL, APJL, 2017)

estimated using a Bayesian approach proposed by Fan (2017).

PRL 119, 181102 (2017)

PHYSICAL REVIEW LETTERS

week ending
3 NOVEMBER 2017

Probing Intrinsic Properties of Short Gamma-Ray Bursts with Gravitational Waves

Xilong Fan,^{1,2,*} Christopher Messenger,² and Ik Siong Heng²

¹*School of Physics and Electronics Information, Hubei University of Education, 430205 Wuhan, China*

²*SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

(Received 13 July 2017; revised manuscript received 18 September 2017; published 3 November 2017)

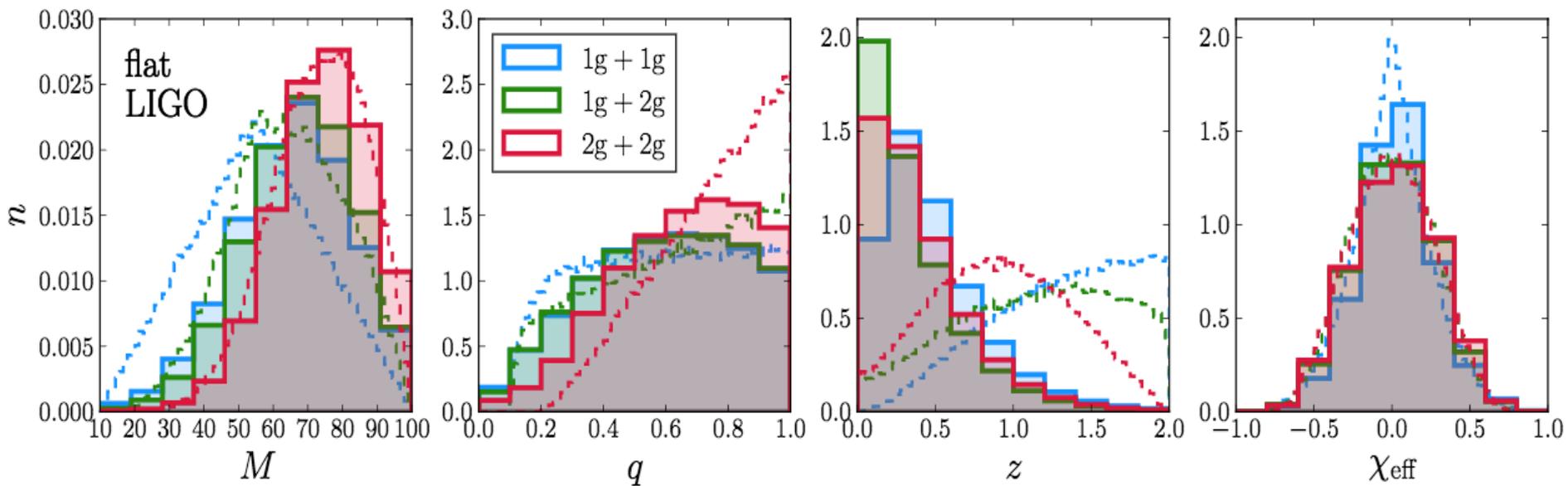
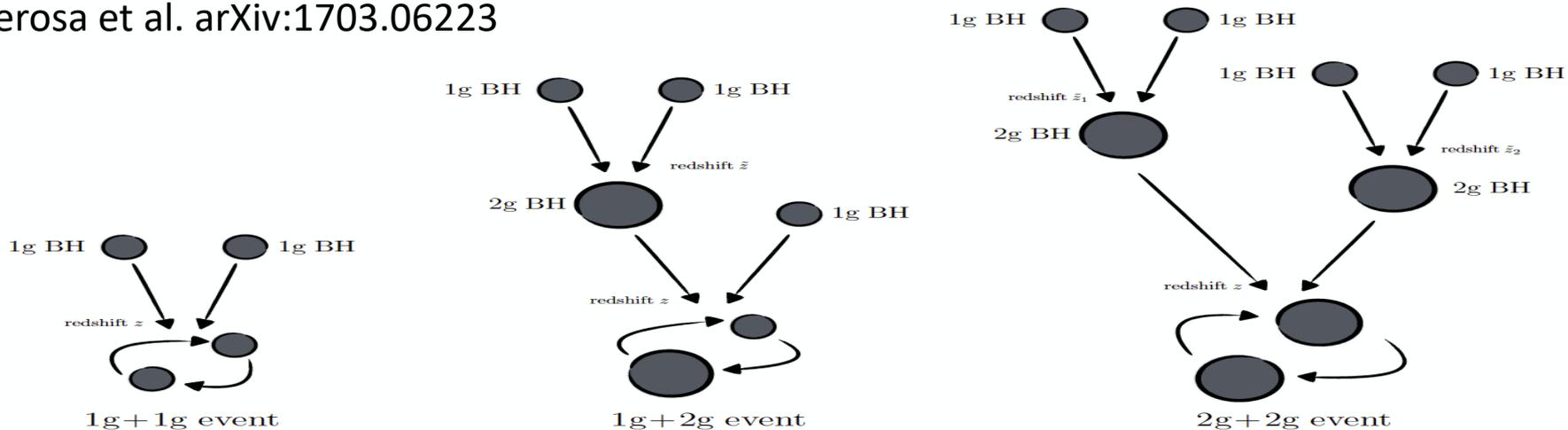
大纲

- 引力波简介

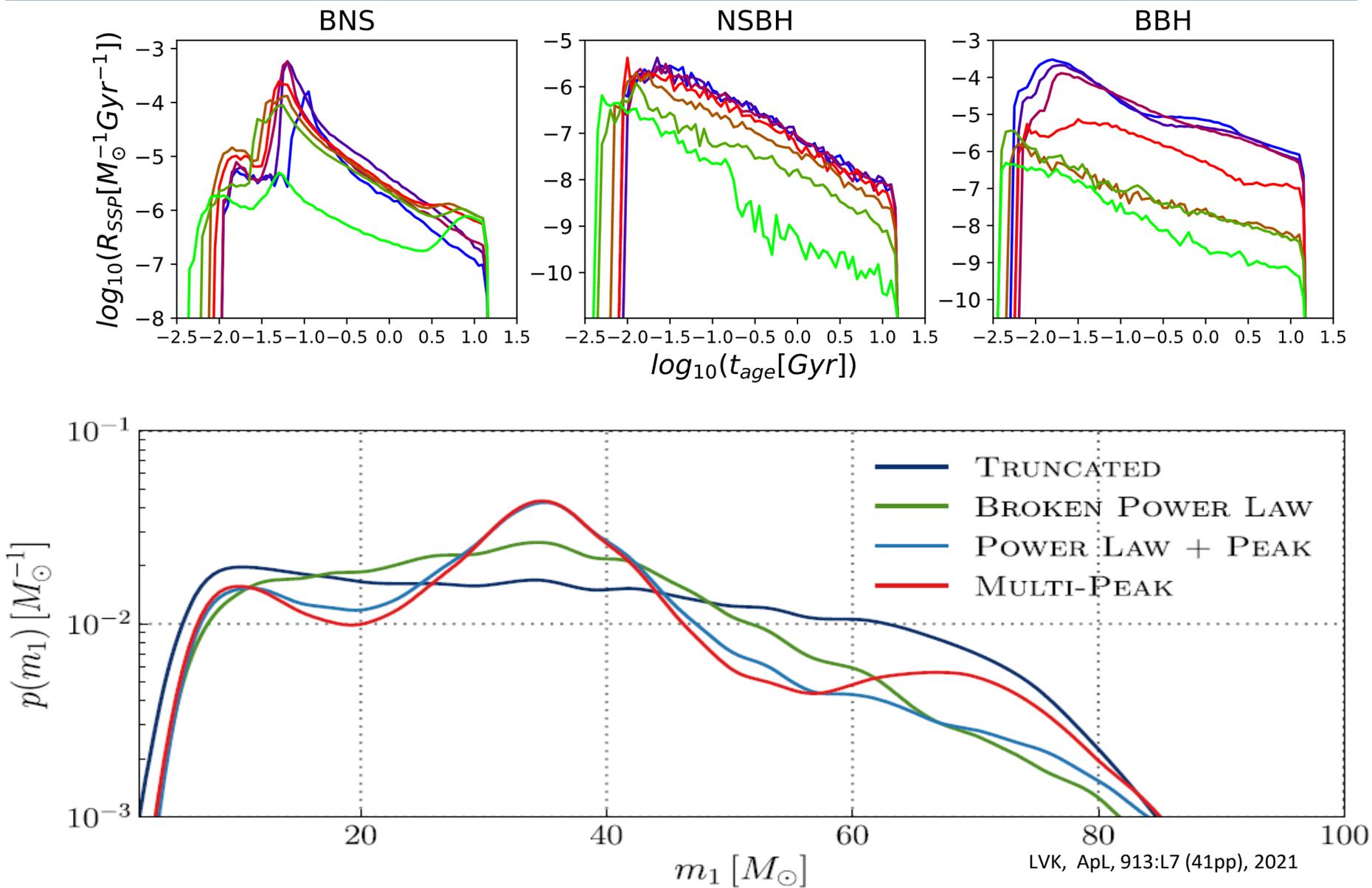
 - 引力波作为天体物理探针
 - 引力波多信使联合探测
 - 波源群组性质
 - 致密星状态方程
 - 宇宙学与基础物理学（透镜系统）
-

群组信息:

Gerosa et al. arXiv:1703.06223



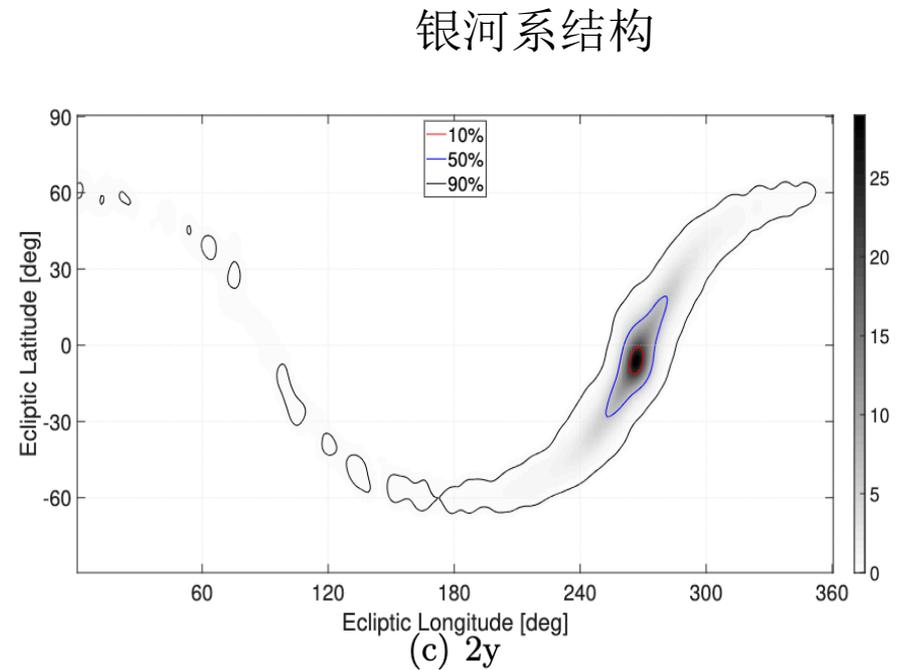
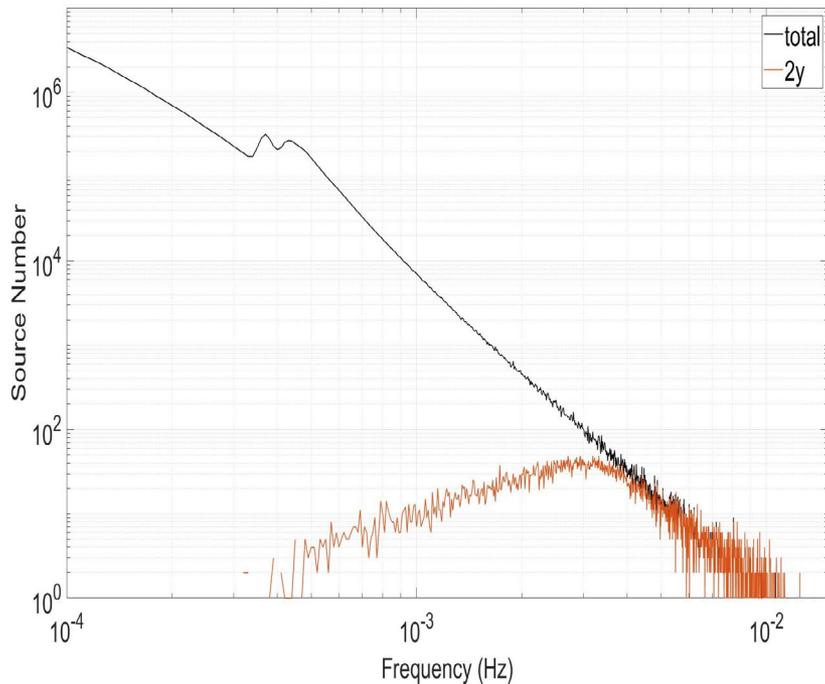
星族演化+星系演化预测 vs 观测质量分布



银河系内双白矮星

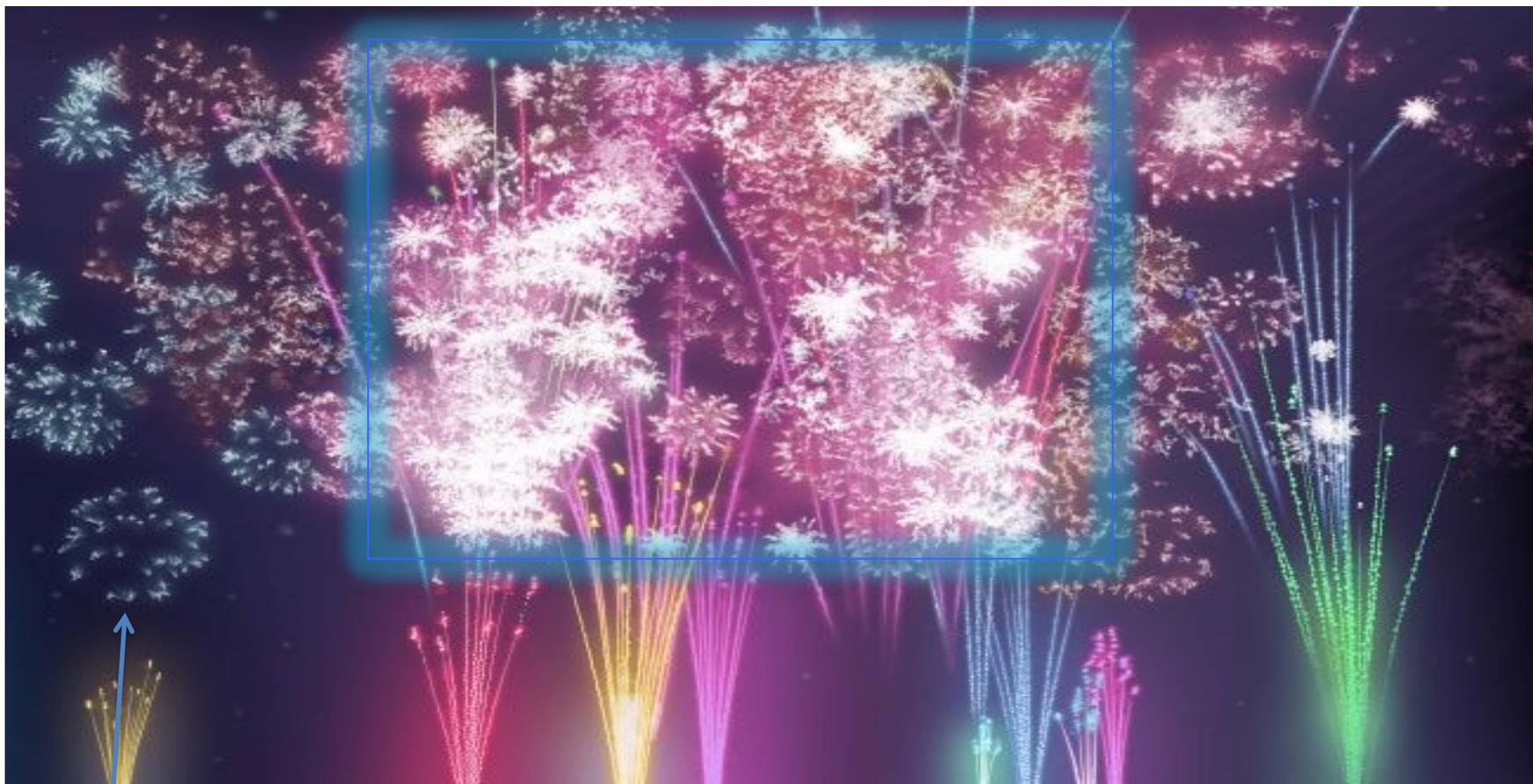
■ Detection by space detectors

- $\sim 10^4$ of 10^7 galactic binaries by two years observations
- ~ 10 mins orbits (useful for binary evolution model?)



天体起源引力波背景

- 大量不可分辨的天体源产生的引力波叠加在一起

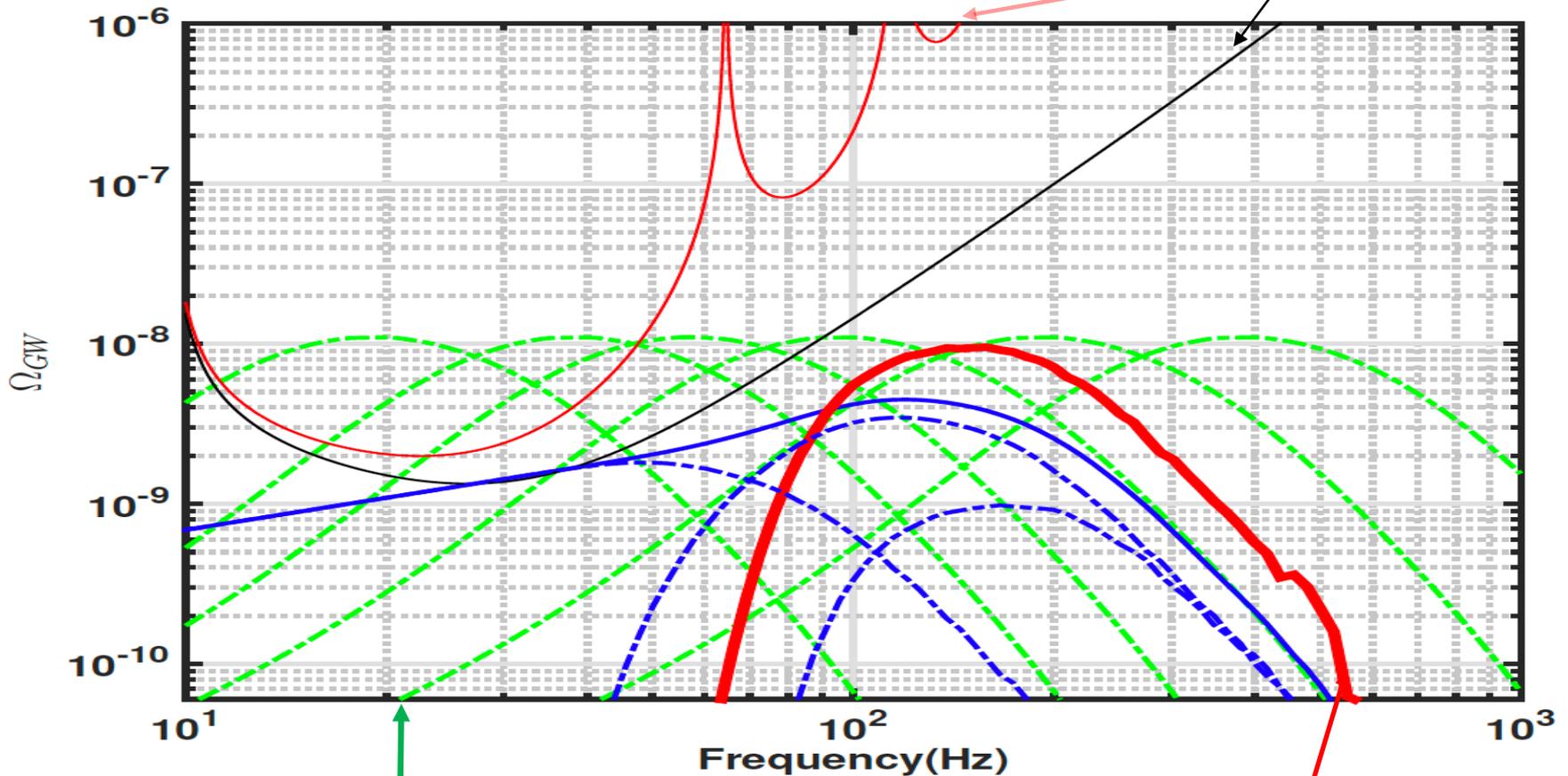


单个引力波源

Total energy density spectrum

■ Extracting the SD background?

$$\Omega_* \equiv \frac{S_h^{\text{AdvLIGO}} f^3}{\gamma_{\text{HL}}} \sqrt{\frac{1}{2\Delta f T} \frac{10\pi^2}{3H_0^2}},$$



Fan et al. 2018.PRD, arXiv: 1712.00784

SD-Gaussian models

SD-QNM model

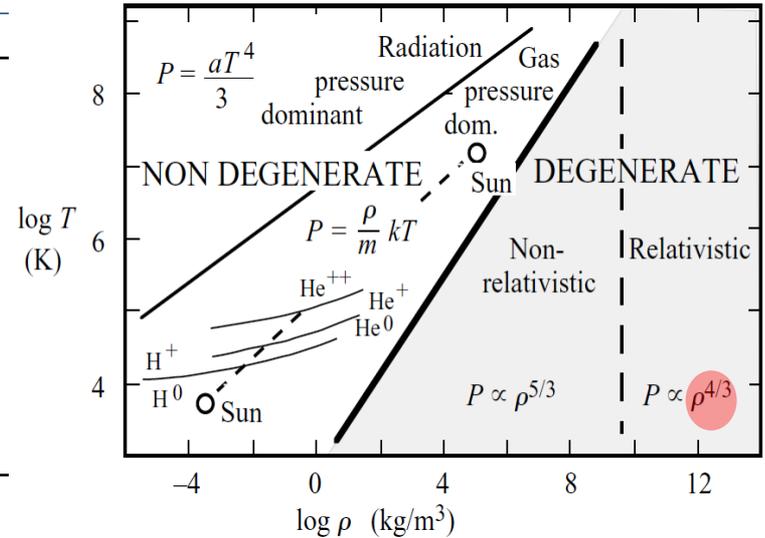
大纲

- 引力波简介

 - 引力波作为天体物理探针
 - 引力波多信使联合探测
 - 波源群组性质
 - 致密星状态方程
 - 宇宙学与基础物理学（透镜系统）
-

EOS 和 $T_{\mu\nu}$

$$T^{\alpha\beta} = \begin{pmatrix} \text{energy density} & \text{energy flux} \\ \text{mom. density} & \text{stress tensor} \end{pmatrix}.$$



<ASTROPHYSICS PROCESSES> By HALE BRADT

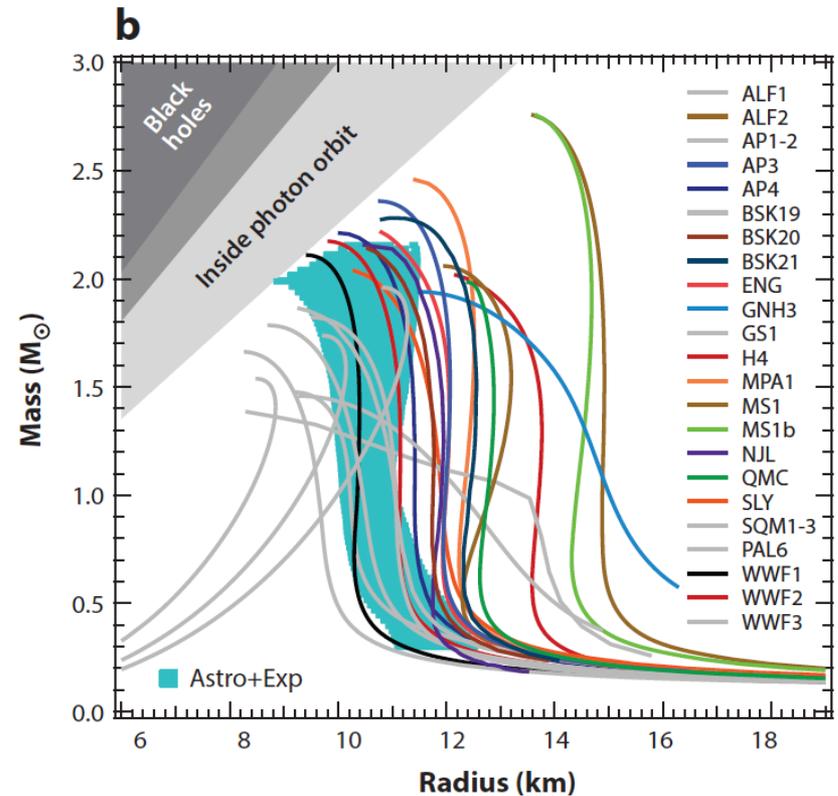
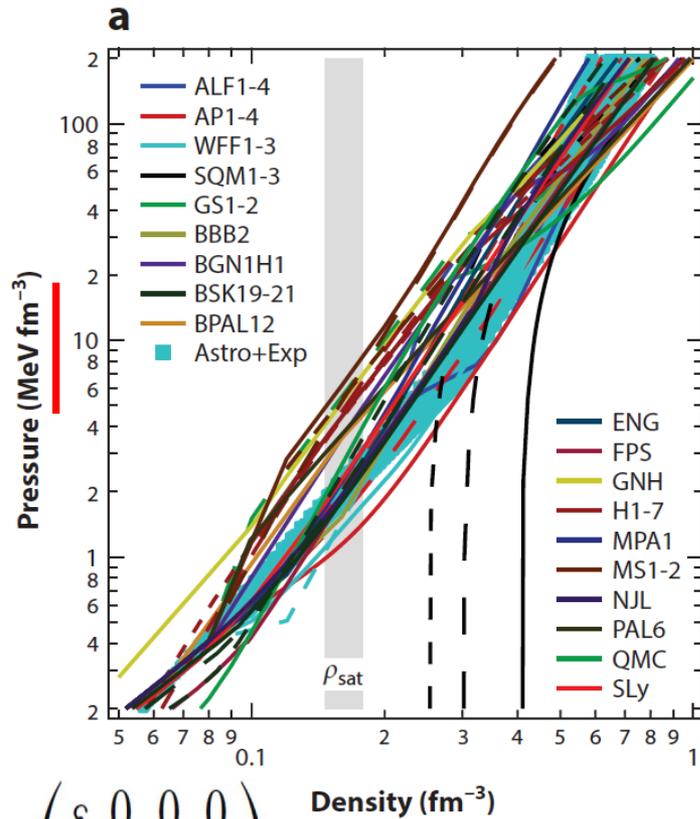
2.1 The energy-momentum tensor of a perfect fluid in Cartesian coordinates and in the rest-frame of the fluid has the following form

$$\|T^{\mu\nu}\| = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}, \quad (2.60)$$

where ε and P are, respectively, the energy density and the pressure of the fluid.

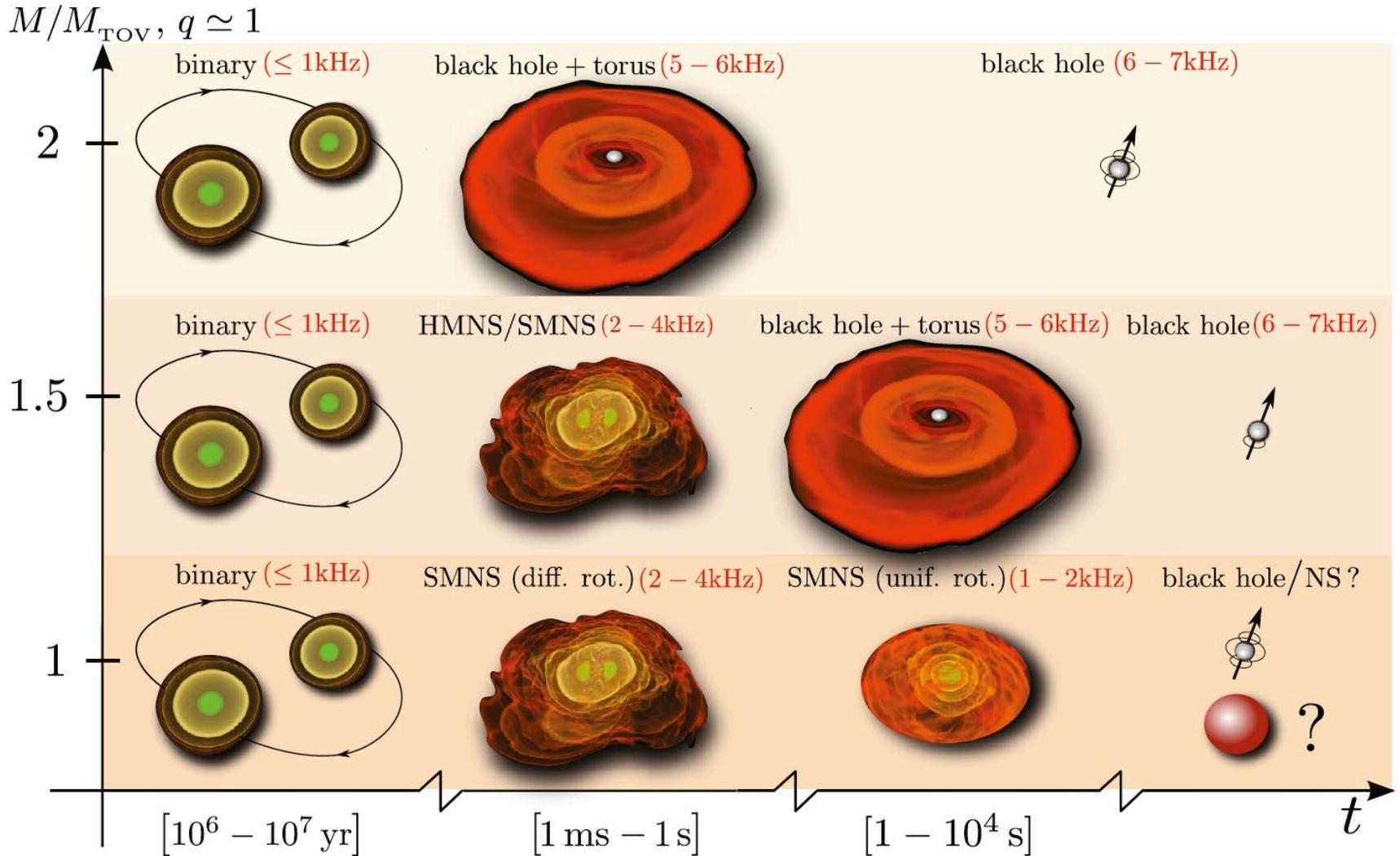
中子星的EOS...

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} = -\kappa T_{\mu\nu}.$$



$$\|T^{\mu\nu}\| = \begin{pmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

前景很美好



GW asteroseismology: 微扰路径

$$\delta [G_{\mu\nu} - 8\pi T_{\mu\nu}] = 0 \quad \text{Einstein equations,} \quad (134)$$

$$\delta [u^\mu \nabla_\alpha T^\alpha_\mu] = 0 \quad \text{energy conservation,} \quad (135)$$

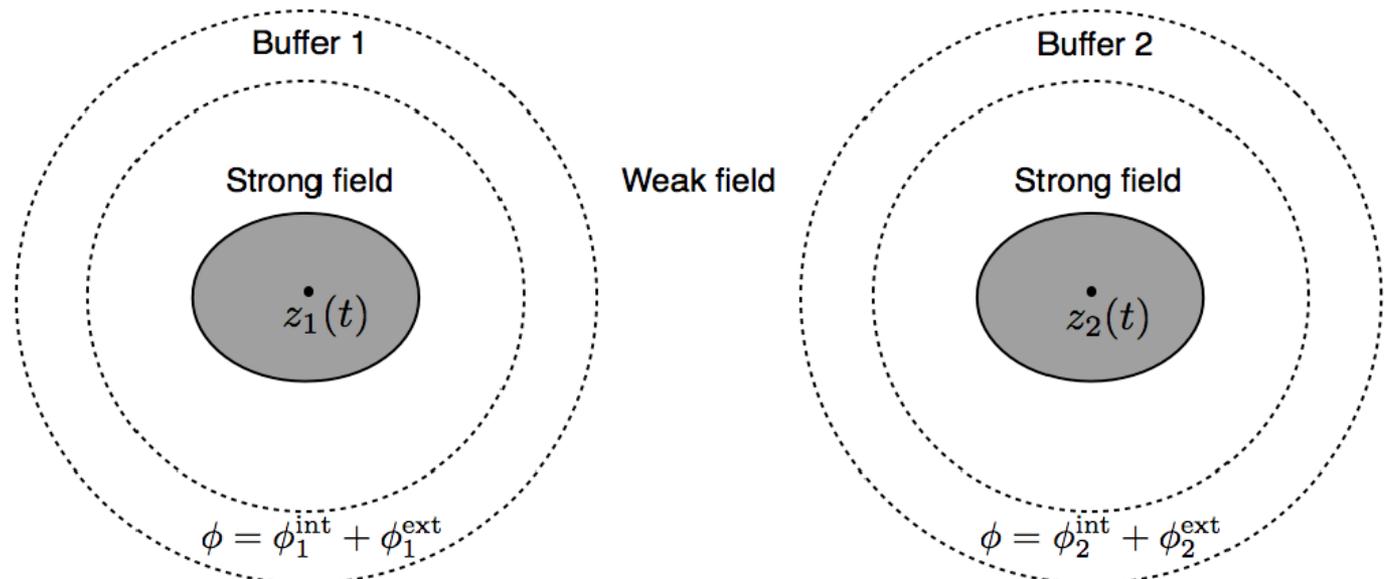
$$\delta [P^\mu_r \nabla_\alpha T^\alpha_\mu] = 0 \quad \text{momentum conservation,} \quad (136)$$

$$\delta [\nabla_\mu (n u^\mu)] = 0 \quad \text{baryon number conservation,} \quad (137)$$

$$\frac{\Delta p}{p} = \Gamma_1 \frac{\Delta n}{n} \quad \text{adiabatic condition,} \quad (138)$$

Luciano

2003, gr-qc/0302025v1



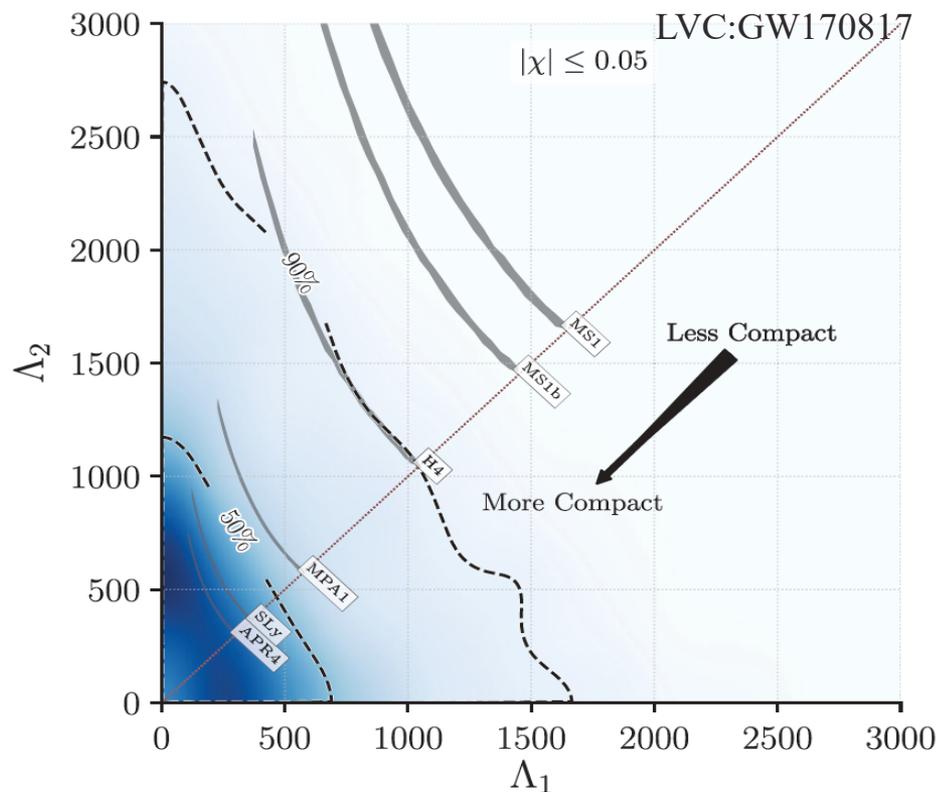
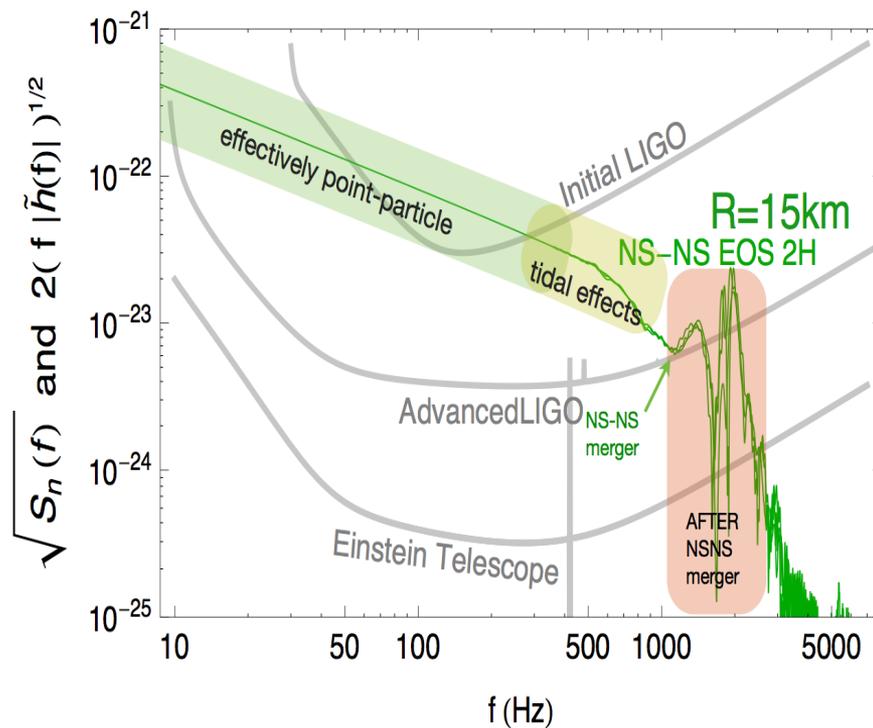
PN 方式, Lackey 2012

致密双星绕转：状态方程

■ Tidal effect phase:

Hybrid spectrum, 1.35-1.35, 100 Mpc

optimally oriented binary



Read et al. 2013

中子星简化处理

$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + \epsilon h_{\mu\nu}$$

$$p = p^{(0)} + \epsilon \delta p$$

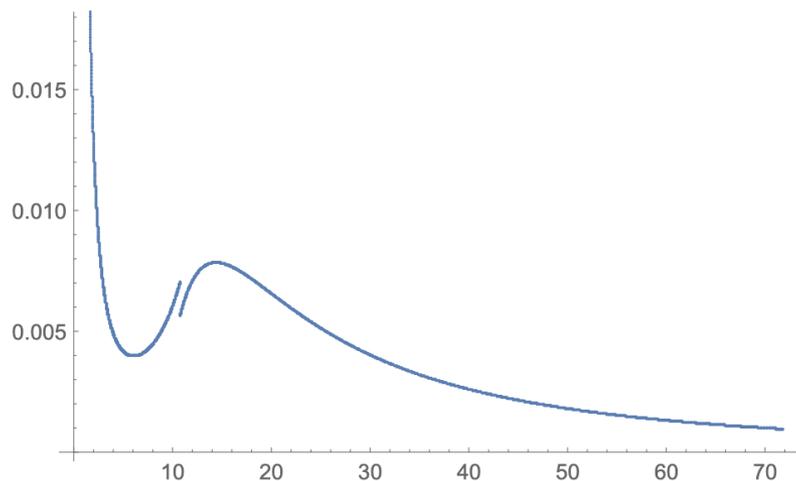
$$\rho = \rho^{(0)} + \epsilon \delta \rho$$

$$u_{\mu} = u_{\mu}^{(0)} + \epsilon \delta u_{\mu}$$

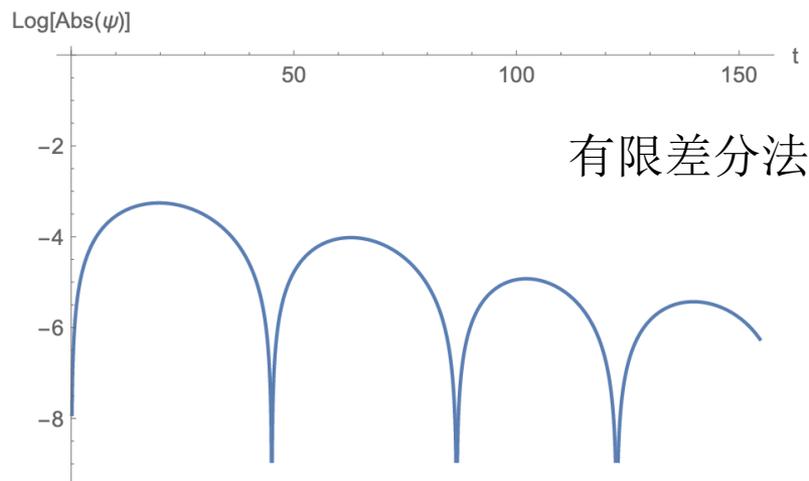
$$\Phi = \Phi^{(0)} + \epsilon \delta \Phi,$$

- 理想流体
 - the polar (even-parity) equations
 - **couple** the thermodynamical variables to the metric variables. (太难了)
 - polar w-modes
 - coupled to fluid motion (“太难了”)
 - very weakly (但是可以改变轨道)
 - **similar to the axial w-modes**
 - the axial (odd-parity) perturbations
 - do not induce fluid motion except for a stationary rotation; (中子星转动很慢)
 - The fluid shapes the potential barrier associated to the spacetime curvature. (TOV)
 - 问题转化为在中子星背景下的Regge–Wheeler 方程
 - Schrodinger-like equation
 - 有效势
 - 边界条件
-

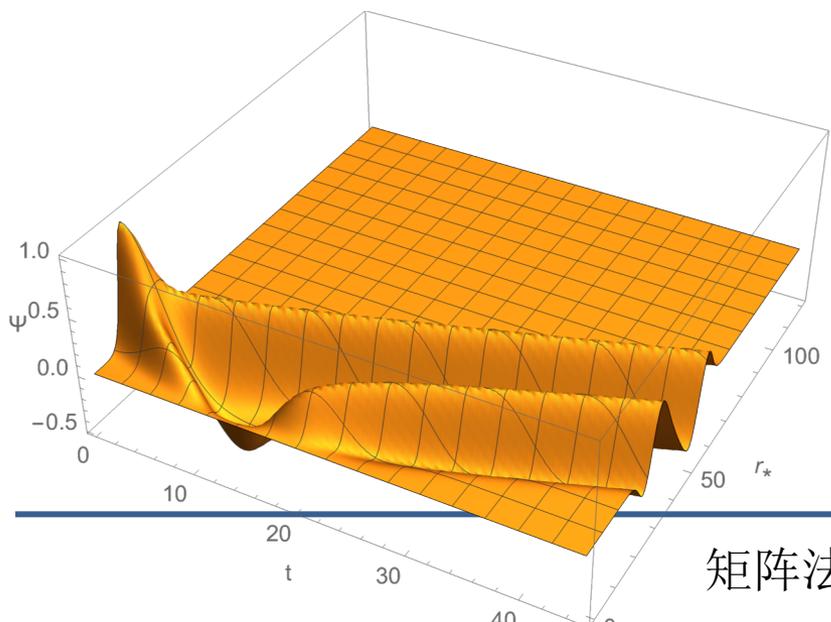
初值问题：QNM从初值问题中提取



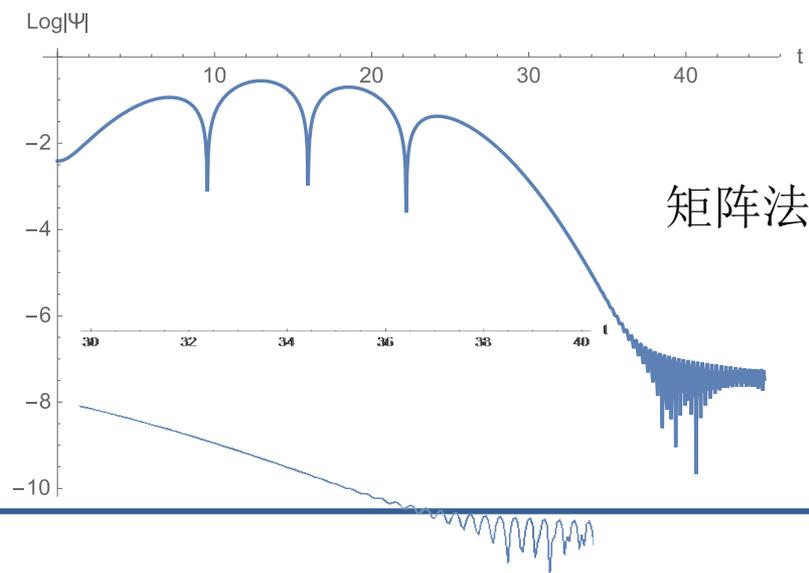
(e) Strangeon 星有效势 $V(r)$.



(f) Strangeon 星 QNM, $l = 2$.

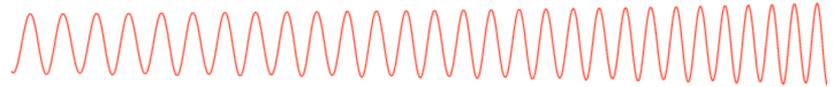


矩阵法



The EOS of WD TDE by GW

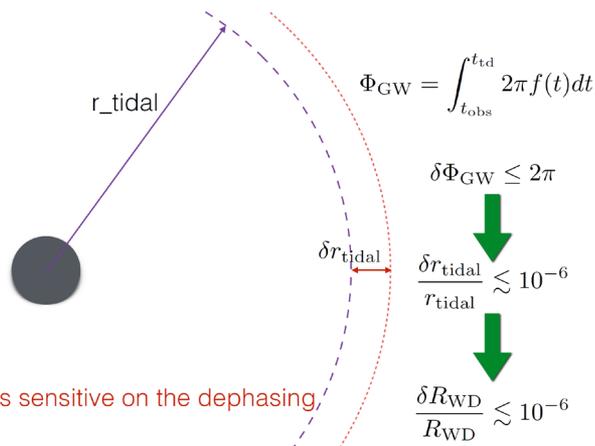
From the inspiralling GWs



LISA/Taiji/Tianqin can constrain binary parameters

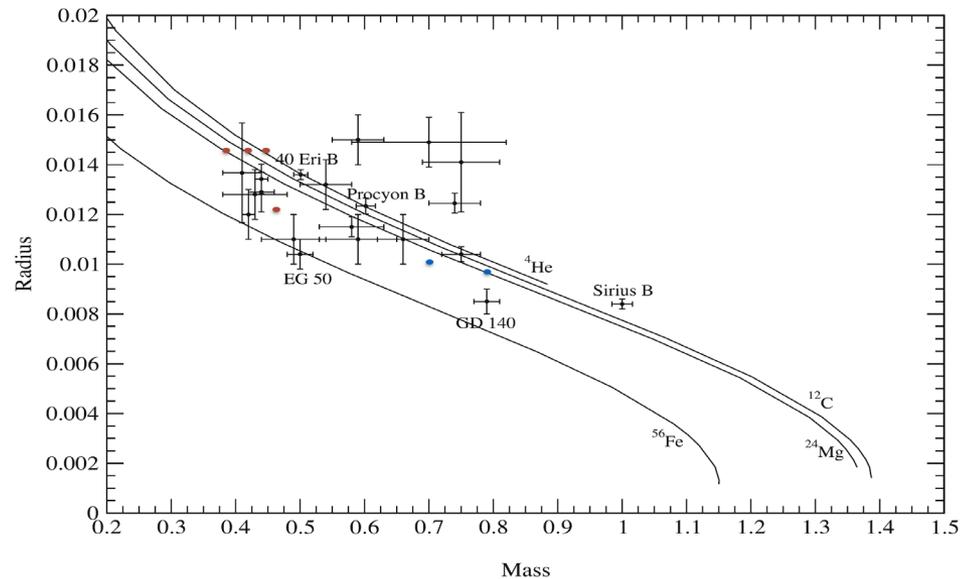
$$\delta m/m \sim 10^{-4}, \delta M/M \sim 10^{-5}$$

0.1% WD radii difference
 0.57h and 2.59h TDE's EM signals
 arrival difference!



LISA is sensitive on the dephasing

WD's mass-radii with GW and EM observations



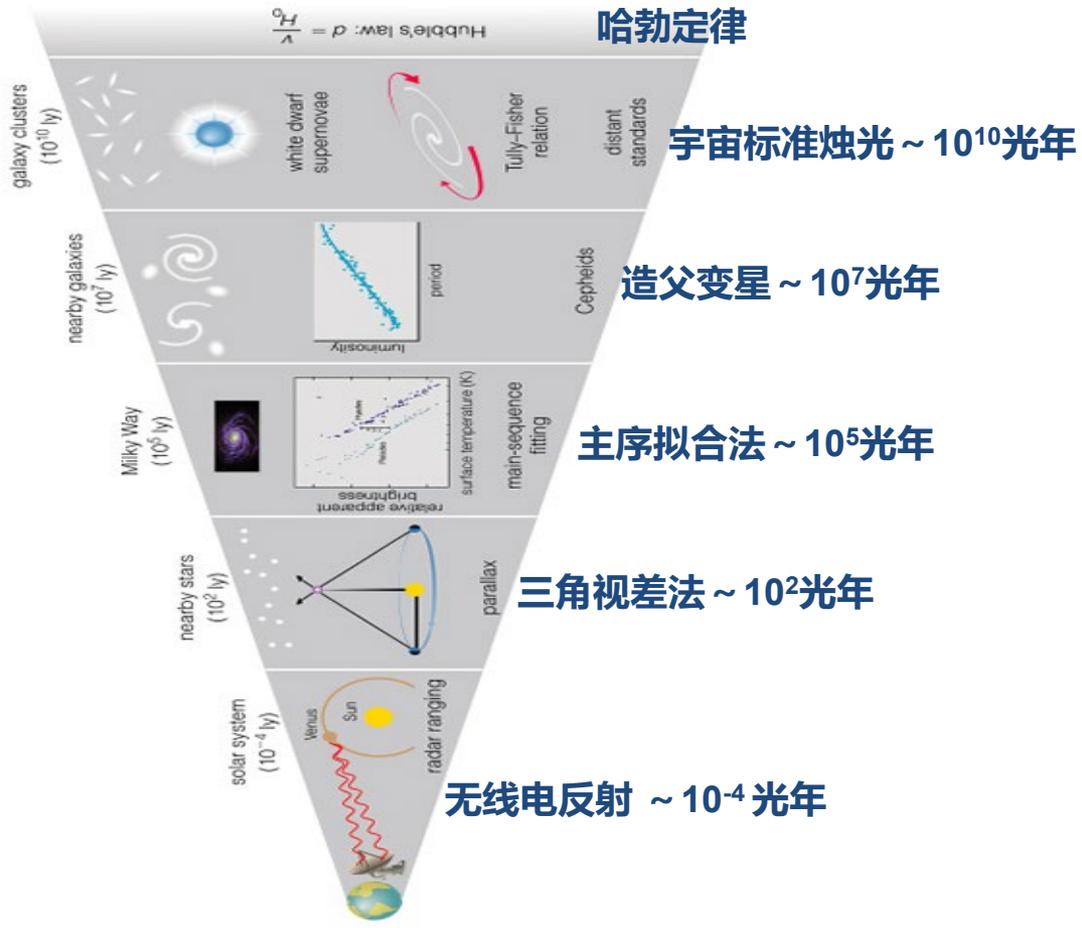
大纲

- 引力波简介

 - 引力波作为天体物理探针
 - 引力波多信使联合探测
 - 波源群组性质
 - 致密星状态方程
 - 宇宙学与基础物理学（透镜系统）
-

双星绕转引力波源：测距

“宇宙学的阶梯” 和 “标准铃声”



振幅正比于 $\frac{M_z^{5/6}}{d_L}$
 [Schutz, Nature (1986)]



距离大爆炸的时间

38万年

1亿年

10亿年 40亿年

137亿年



[2011诺贝尔物理学奖] 宇宙加速膨胀



爱因斯坦“最大的错误”：
阻止宇宙膨胀

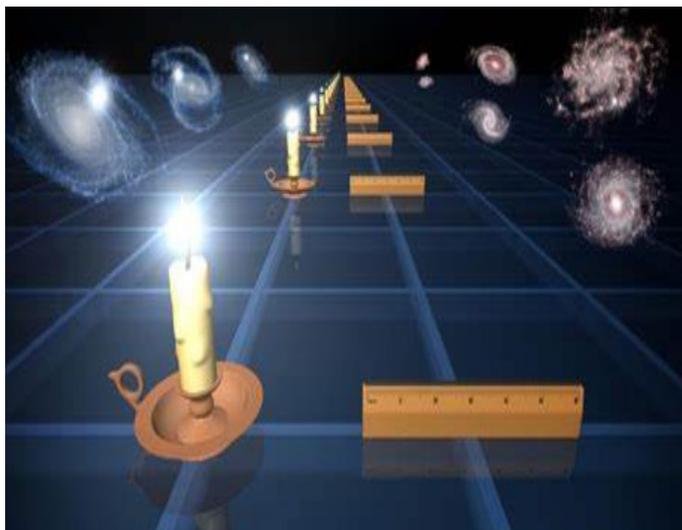


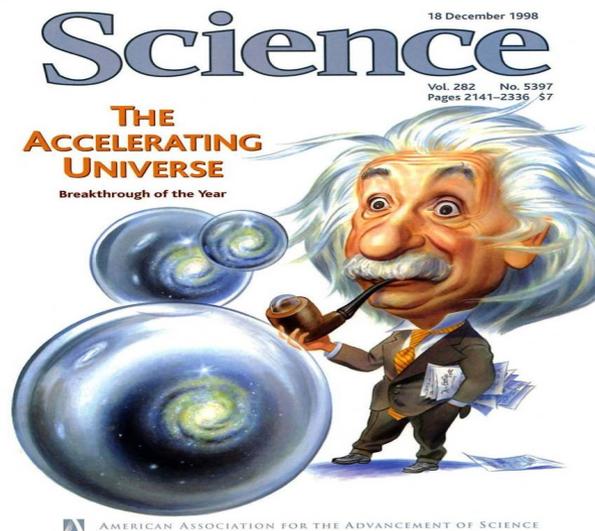
Photo: Ariel Zambelich, Copyright © Nobel Media AB
Saul Perlmutter



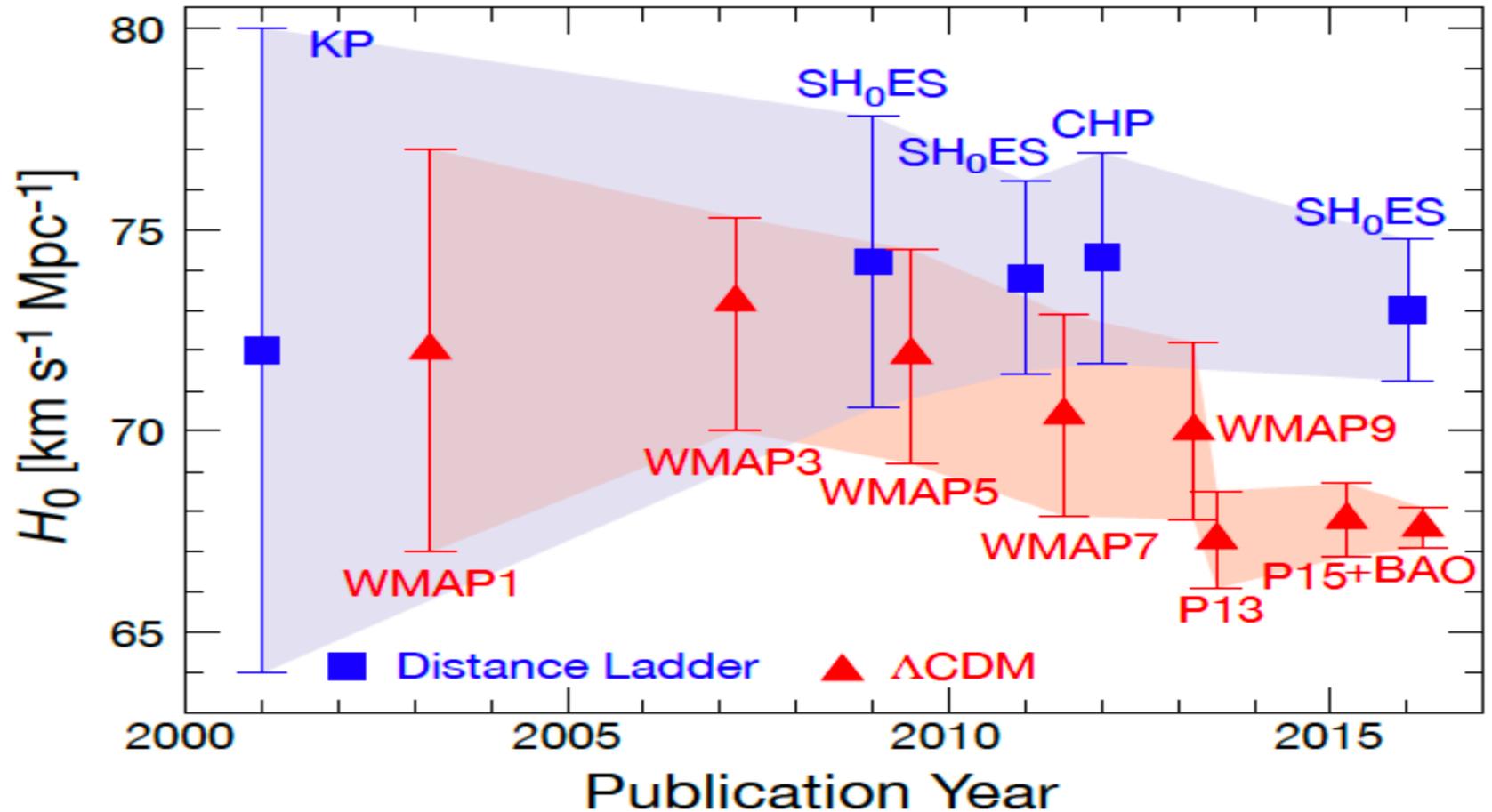
Photo: Belinda Pratten, Australian National University
Brian P. Schmidt



Photo: Homewood Photography
Adam G. Riess



Tension With the Hubble Constant



Freedam, Nature Astronomy, 1, 0169 (2017)

Figure 1: Recent values of H_0 as a function of publication date since the Hubble Key

Project (adapted from Beaton et al. 2016). Symbols in blue represent values of H_0

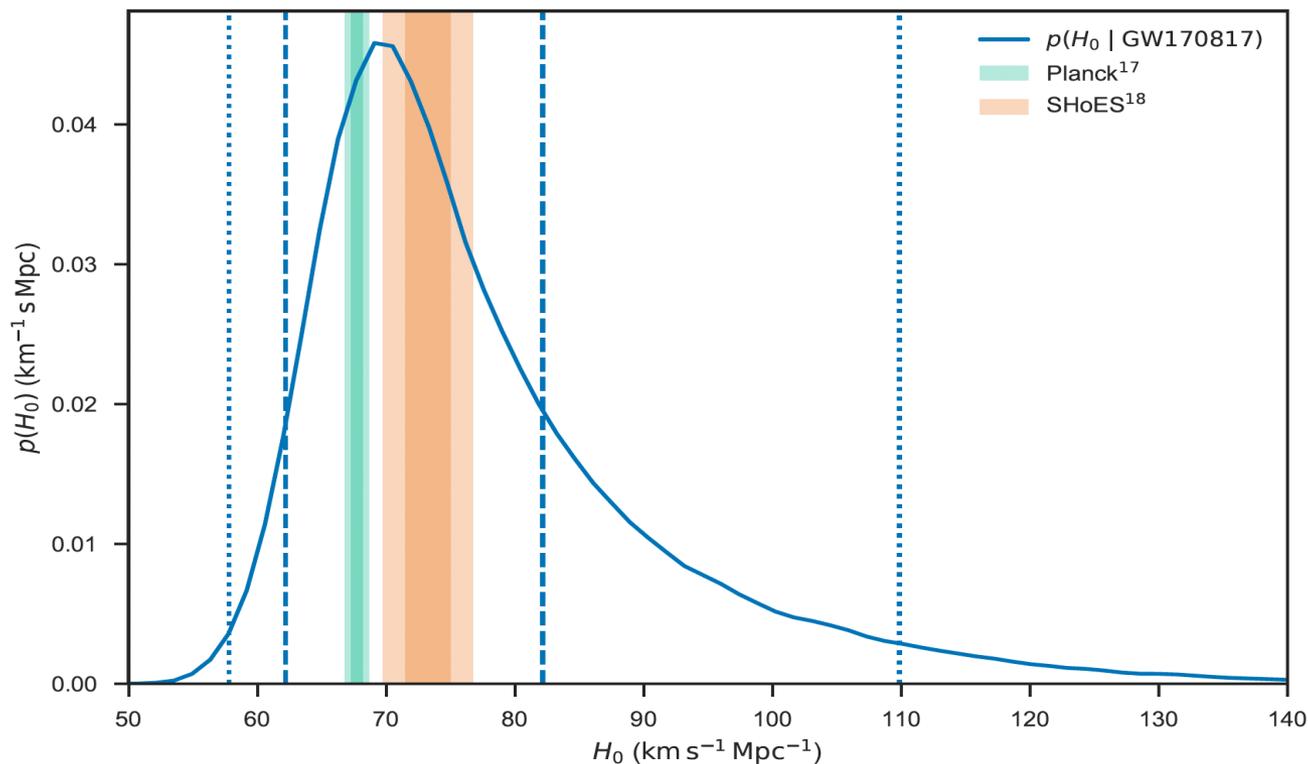
GW170817 应用

■ 引力波测量哈勃常数

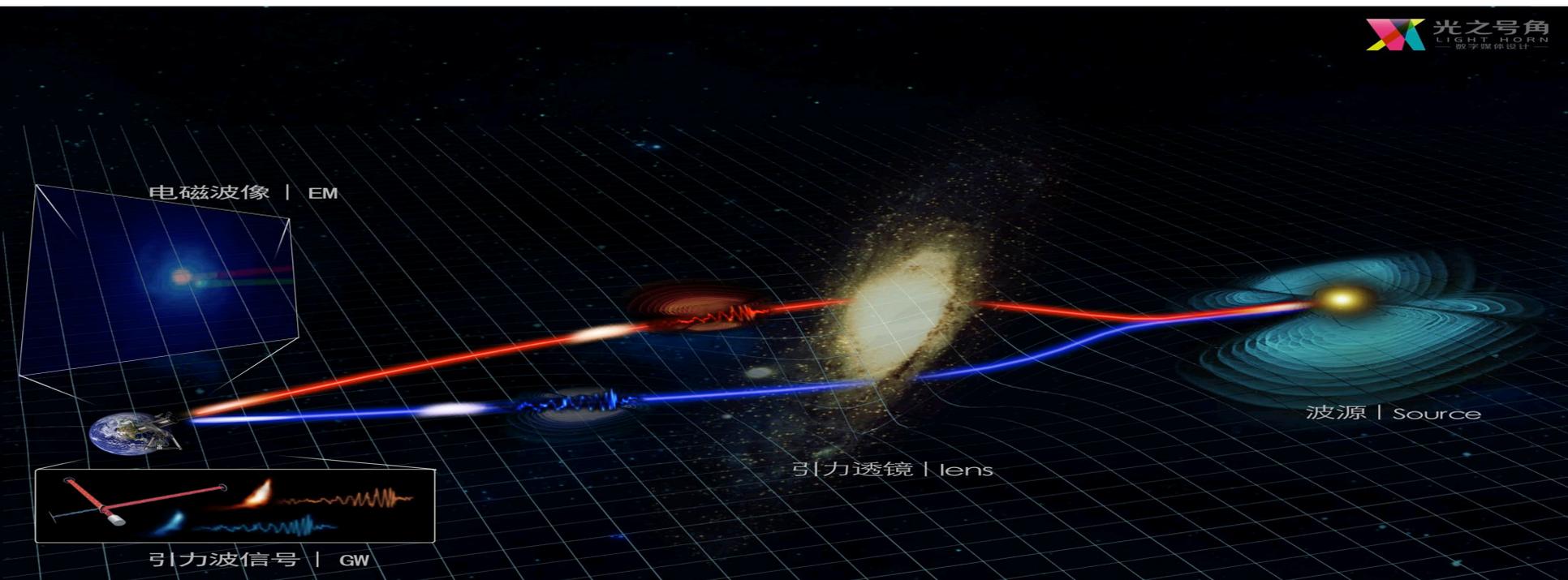
$$v_H = H_0 d$$

$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}.$$

宿主星系NGC4993 (“哈勃流”速度) + GW170817(距离)



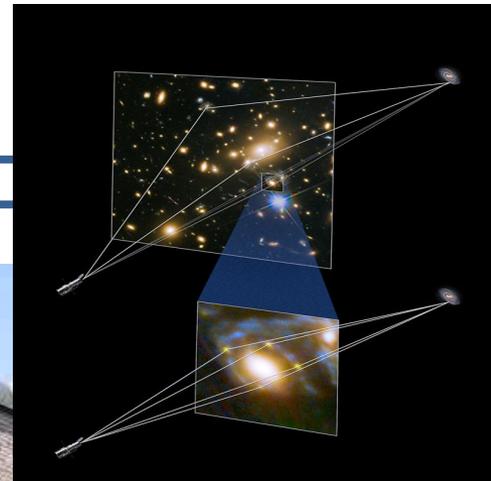
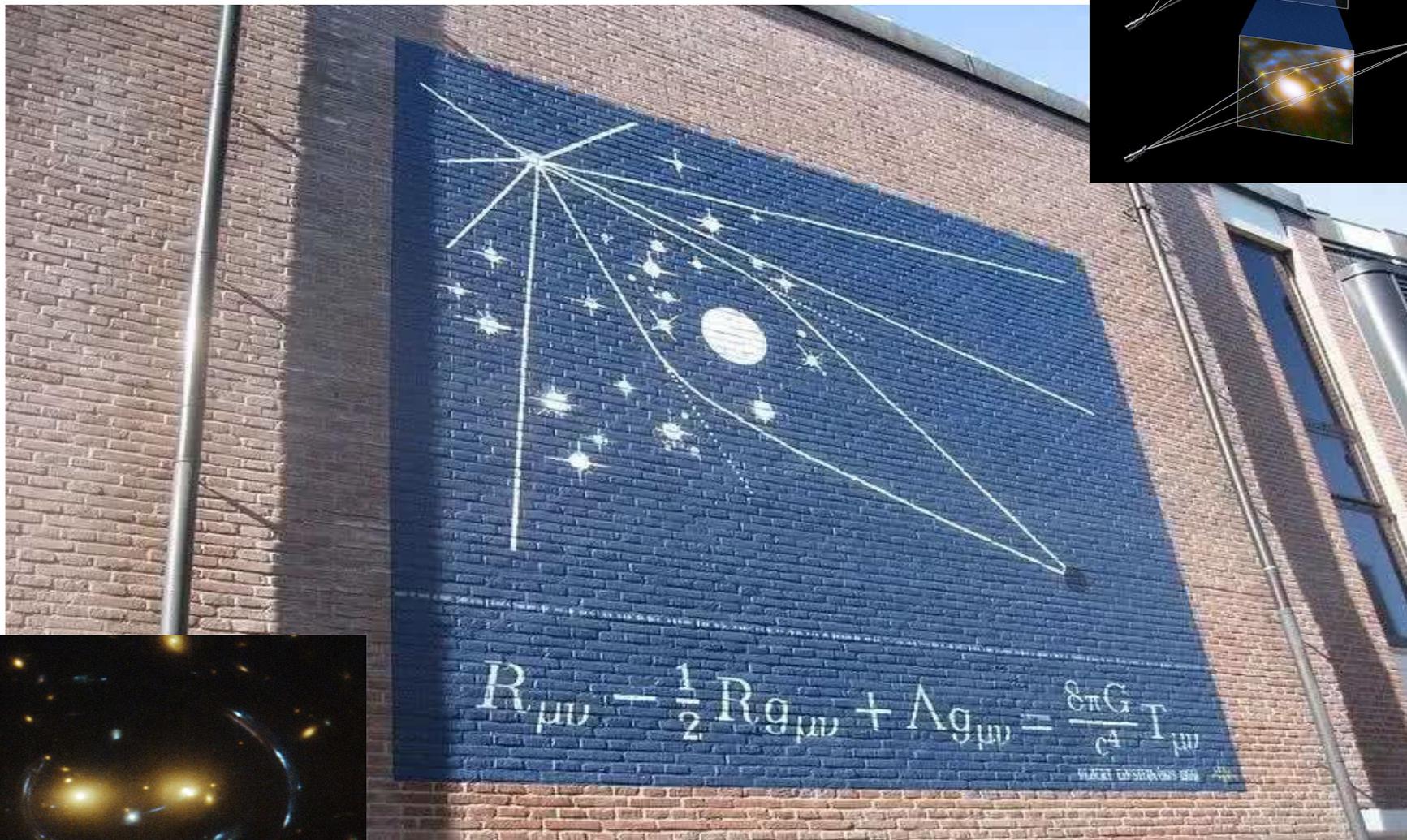
引力透镜化引力波-电磁波系统



■ GW --> 测时, EM --> 定位, 红移

- 测量引力波速度 [Fan et al. PRL, 2017]
- 限制哈勃常数 [Liao et al. NC, 2017]
- 限制宇宙几何 [Li et al. ApJ, 2019]

引力透镜



荷兰布尔哈夫科学博物馆

■ 振幅波动光学及其应用

- 波动性探测可行性: Liao, Biesiada & **Fan***, 2019, ApJ
- 引力波泊松斑: Zhang & **Fan***, 2018, arxiv:1809.06511

■ 振幅几何光学及其应用

- 引力波速度: **Fan***, Liao, Biesiada, Piórkowska-Kurpas, & Zhu*, PRL, 2017
- 哈勃常数: Liao, **Fan***, Ding, Biesiada & Zhu*, 2017, Nature Communications
- 暗物质晕分布: Liao*, Ding, Biesiada, **Fan**, & Zhu, 2018, ApJ
- 宇宙曲率: Li, **Fan***, & Gou 2019, ApJ
- 干涉效应: Hou, **Fan***, Ding, Zhu*, & Liao. 2020, PRD
- 超越短波近似: Hou*, **Fan***, & Zhu*. 2020, PRD

■ 振幅波动-几何过度系统

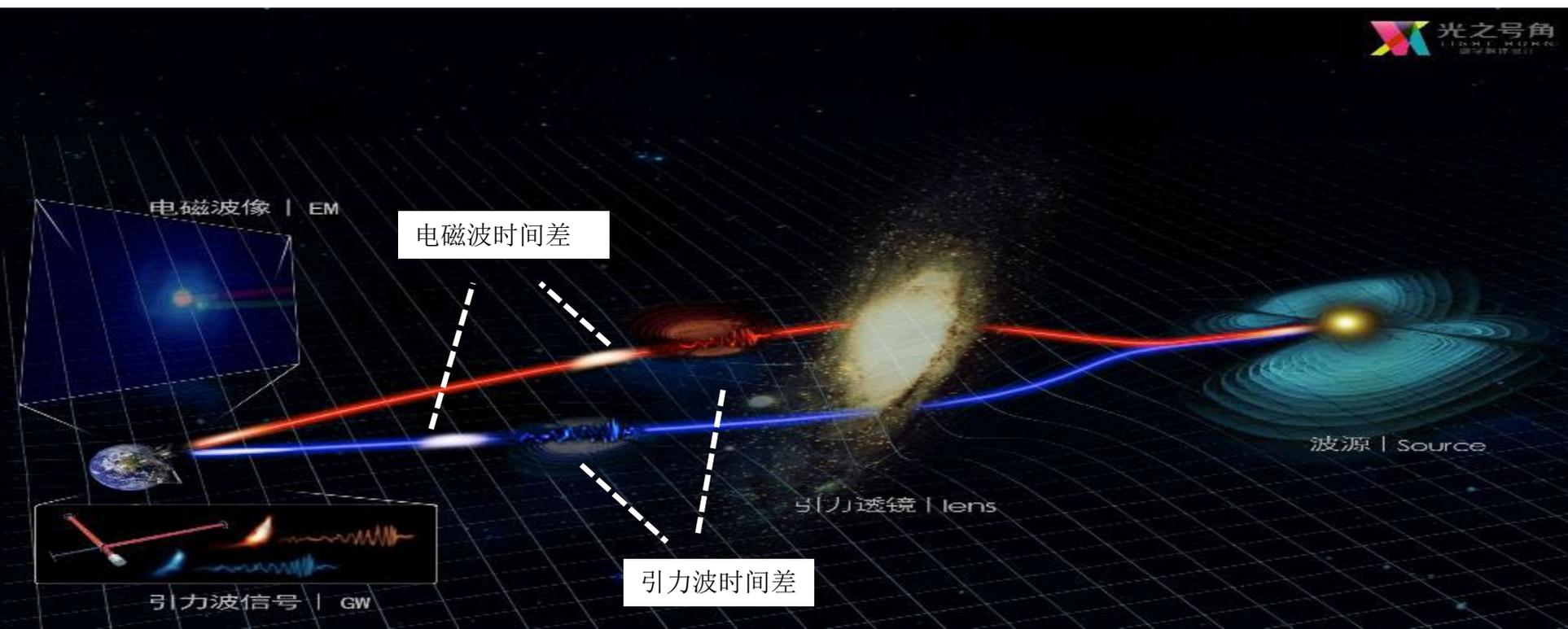
- 拍现象: Sun, **Fan***, 2019 arXiv:1911.08268

■ 张量波波动性

- Hou, **Fan***, & Zhu* 2019, RRD
-

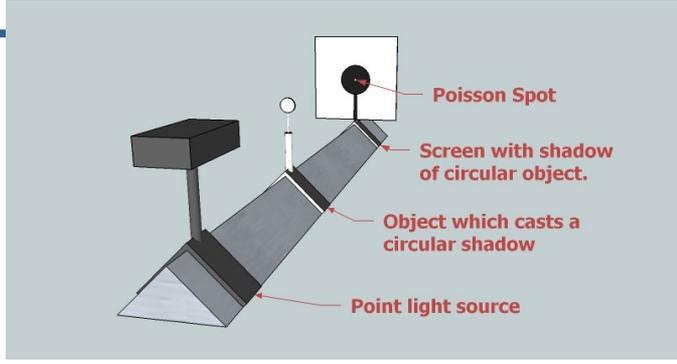
测量引力波速度

- 测量不同路径的时间差: $V = (D1 - D2) / (T1 - T2)$, Fan et al. 2017 PRL
- 如果时间差($T1 - T2$) 不一样, 那么 \rightarrow
 $V_{gw} \neq V_c$

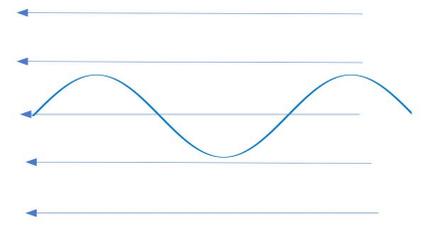
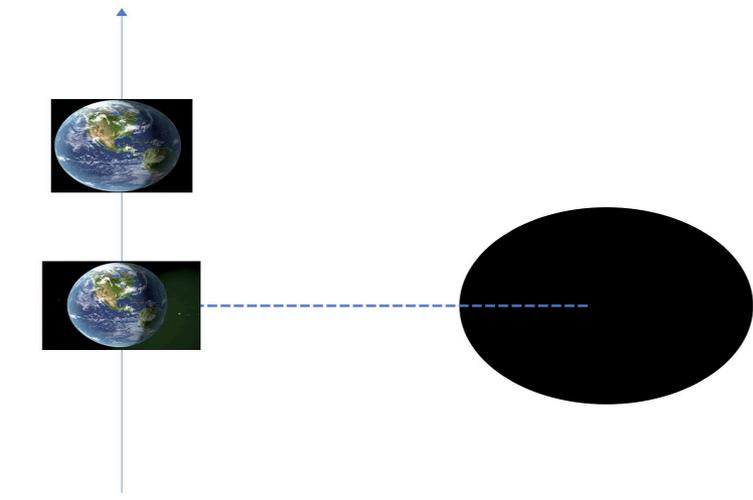
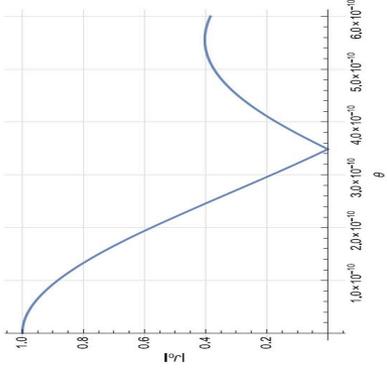


引力波泊松-阿拉贡亮斑

- 光的波动性：
 - 泊松-阿拉贡亮斑 (阿拉贡, 1818 年)



- 我们的预言：
 - 黑洞作为“不透明”障碍物，引力波正入射
 - 引力波泊松-阿拉贡亮斑 [Zhang, Fan*, SCPMA, 2021]
 - 可以被未来空间引力波探测器探测到



引力波振幅在空间中的分布

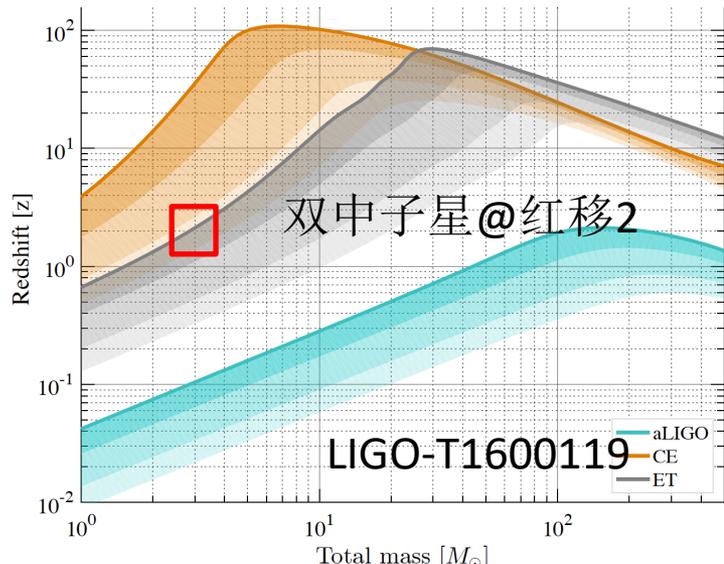
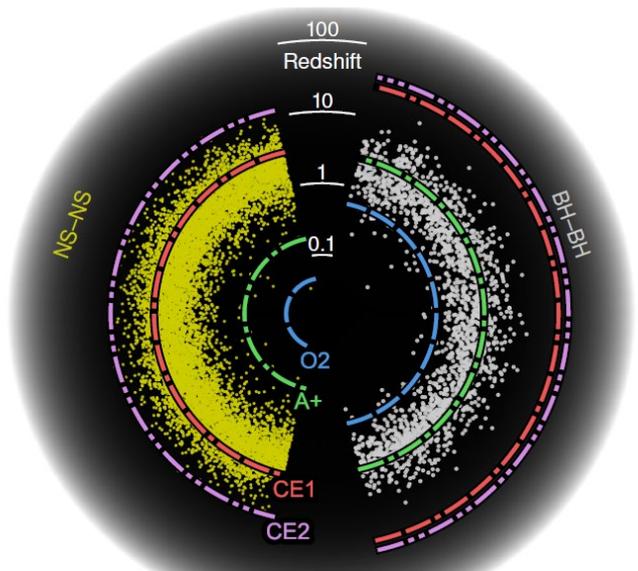
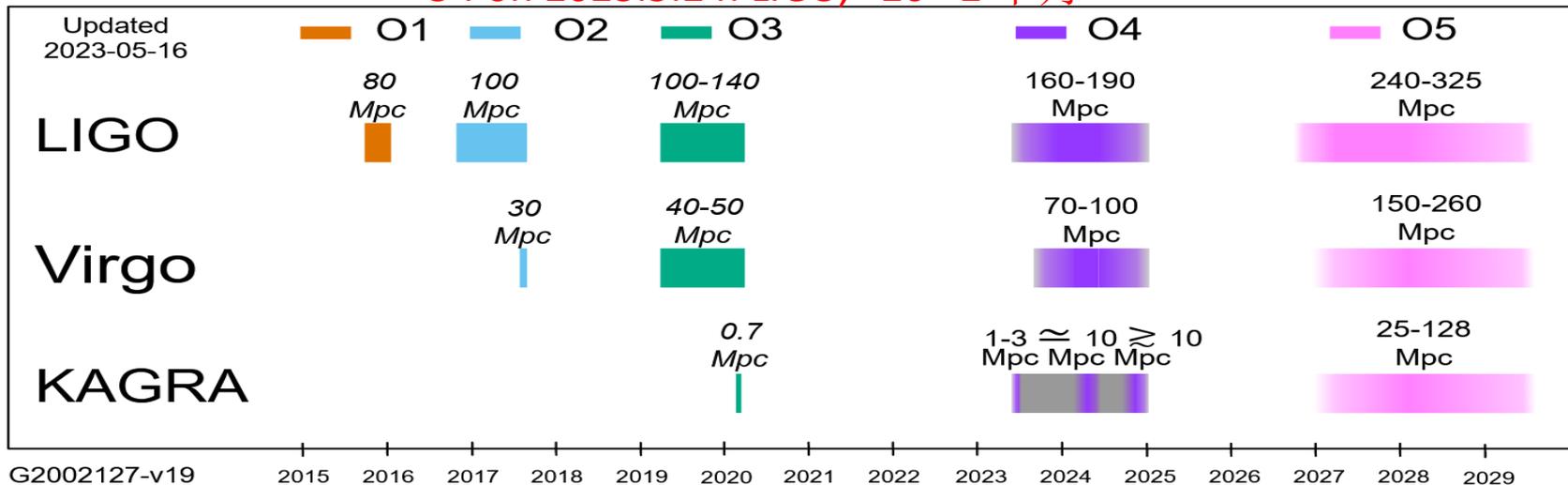
地球穿越时空

黑洞

引力波

未来2020s观测计划 (探测距离~x3)

O4 on 2023.5.24: LIGO, 20+2 个月



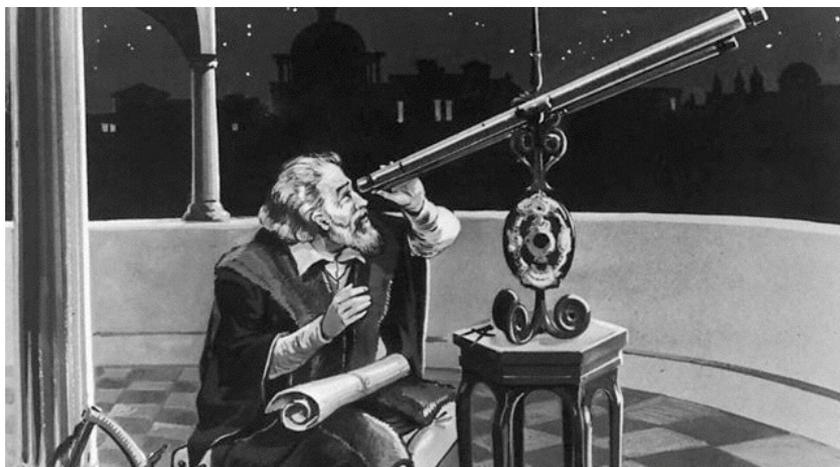
Astro2020 Science White Paper

第三代地面引力波探测器 (2030s?)

Figure 8: Astrophysical reach of Cosmic Explorer for equal-mass (non-spinning) compact

这是一个新时代的开始

1609:伽利略用望远镜仰望星空



2017:人类用多信使了解宇宙



中子星状态方程
超新星爆发机制
伽玛爆光度、张角
引力波速度
群组性质
检验相对论

。 。 。



星系化学演化，宇宙学。。。

那么，问题来了！



引力波 学校哪家强

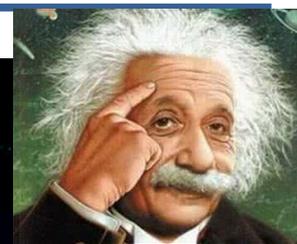
欢迎报考中国最美大学引力波研究团队研究生!!!

Here presents its selection of the top 10 most beautiful college campuses in China.

- Wuhan University. ...
- Peking University. ...
- Shenzhen University. ...



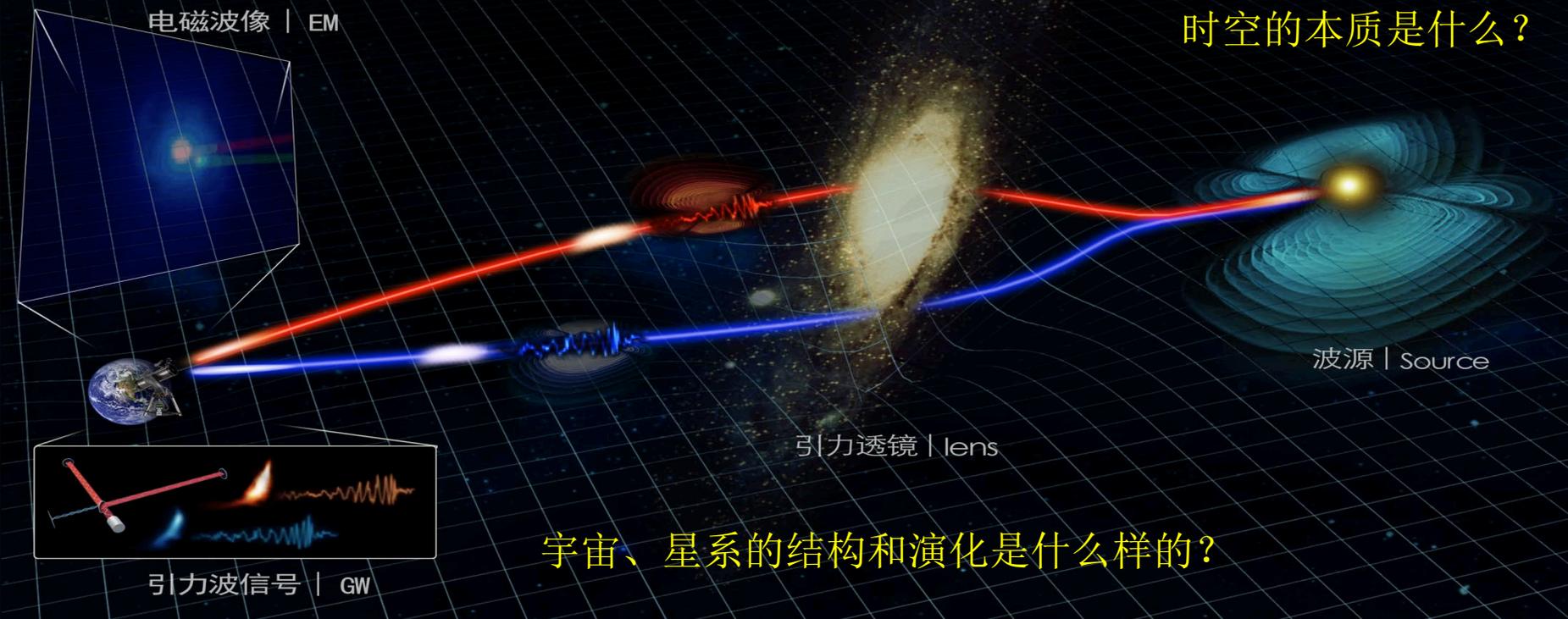
总有一款适合你



武汉大学引力波天文学团队邀您探索

如何挖掘数据信息？
机器学习可以代替物理学家？

时空的本质是什么？



宇宙、星系的结构和演化是什么样的？