GW170104: OBSERVATION OF A 50-SOLAR-MASS BINARY BLACK HOLE COALESCENCE AT REDSHIFT 0.2

GW170104: 红移量为 0.2，质量为 50 个太阳质量的双黑洞合并事件观测

INTRODUCTION

介绍:

In September 2015 the twin advanced detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) made the first ever direct detection of gravitational waves from the merger of two massive black holes more than a billion light years away. This discovery event, known as GW150914, came one hundred years after the prediction of gravitational waves by Albert Einstein's General Theory of Relativity, and was followed by another candidate event (known as LVT151012) in October 2015 and then a second confirmed detection (known as GW151226) in December 2015 – again involving the merger of a pair of black holes.

2015 年 9 月，两台高新引力波激光干涉仪天文台（LIGO）的探测器首次直接探测到从超过十亿光年的双致密黑洞合并释放出的引力波。这一事件，被称为 GW150914，发生在爱因斯坦广义相对论预言引力波存在的一百年之后，紧接着 2015 年 10 月再次发现一个引力波候选事件（称为 LVT151012）。然后在 2015 年 12 月，LIGO 第二次确认检测到另一个双黑洞引力波事件（命名为 GW151226）。

Advanced LIGO began its second Observing Run in late November 2016, after upgrades designed to further enhance the detectors' remarkable sensitivity. It was just over a month before a third confirmed detection of gravitational waves was made from an event known as GW170104. In this article. we summarise how GW170104 was detected, what we have learned about the black holes that produced it, and how this new LIGO discovery improves our understanding of the nature of gravity and spacetime.

高新 LIGO 经过一系列改进，其探测灵敏度得到了显著的提高，并于 2016 年 11 月下旬开始了第二轮数据观测。仅一个多月之后，第三次确认的双黑洞合并引力波事件（称为 GW170104）又被探测到。在这篇文章中。我们总结性地介绍了 GW170104 如何被检测到，其双黑洞源的特征，以及这个新的 LIGO 发现如何提高我们对引力波和时空性质的理解。

DETECTION OF THE GW170104 SIGNAL

GW170104 信号 的检测

GW170104 was observed by the advanced LIGO detectors in Hanford Washington and Livingston Louisiana, following an automatic alert triggered by the Livingston data. Thorough investigations of the detectors' status at the time, similar to those carried out for the previous detections (see here and here), revealed that both detectors were operating normally.

位于华盛顿州 Hanford 和路易斯安那州 Livingston 的 LIGO 探测器一起探测到了 GW170104，当时 Livingston 的数据系统发出了自动警报。随后对探测器的状态进行了彻底的检测，类似于以前的检测（参见这里和这里），显示这两个检测器均处于正常运行状态。

The top two panels of Figure 1 show the data measured by the two LIGO instruments at the time of the merger. The GW170104 signal closely resembles that of GW150914: in both cases the LIGO data clearly display the characteristic "chirp" pattern expected for the gravitational waves emitted from the merger of two black holes – i.e. a sharp upward sweep in amplitude and frequency as they orbit each other ever faster before they merge.

图 1 的第一排两个子图显示合并时由两台 LIGO 探测器测量到的数据。GW170104 信号非常类似于 GW150914 的信号：在这两种情况下，LIGO 数据清楚地显示了从两个黑洞的合并发射的引力波具有所期望的"Chirp"模式——即在合并之前由于每个黑洞绕对方旋转的速度愈来愈快导致释放的引力波幅度和频率都是呈急剧上升的状态。

Using a technique known as matched filtering (see also here and here), the GW170104 data were compared to a bank of theoretical waveforms, to find the best match and extract some physical properties of the candidate source – such as its constituent masses and its sky position. Rough estimates of these properties were sent very quickly to our astronomer partners around the world so they might look for 'electromagnetic counterparts' – emission in the form of light that might be associated with the gravitational-wave event. (You can read more here about the searches for an associated electromagnetic counterpart of GW150914).

通过匹配滤波技术（另见这里和这里），将 GW170104 数据与一组理论波形进行比较，找到最佳匹配状态时对应的源的一些物理特性 - 例如源的质量构成和位置。对这些特征的粗略估计很快发送给了我们在世界各地的天文学合作伙伴，所以他们可能会寻找"电磁对应体"—— 发光可能与引力波事件有关。（您可以在这里阅读更多关于 GW150914 相关电磁对应体的搜索）。

DETERMINING THE PROPERTIES OF GW170104

确定 GW170104 的性质

A more thorough matched filtering analysis of the data was then carried out "offline", over several weeks, using powerful supercomputers. The goal of this analysis was first to determine the significance of the detection by calculating a false alarm rate for the event – i.e. how often could we expect to see a signal similar to GW170104 simultaneously in both detectors, purely as a result of coincident features in the detectors' background 'noise'? The lower the false alarm rate, the higher the significance of the detection (More details about how the false alarm rate is calculated for LIGO data can be found in the GW150914 science summary here).

然后，在数周内使用强大的超级计算机，在"线下"对数据进行更全面的匹配滤波分析。该分析的目的是首先通过计算事件的误报率来确定检测的准确度——即我们多久能在两个检测器中同时检测到类似于 GW170104 的信号，且该信号完全是在探测器的背景"噪音"中得到的偶合事件？误报率越低，检测的准确度越高（关于如何计算 LIGO 数据的误报率的详细信息，请参见 GW150914 科学概要这里）。

Our analysis computed a false alarm rate of less than once every 70,000 years – rare enough to confirm that GW170104 was indeed a highly significant detection of a real, astrophysical event!

我们此次分析的误差率小于每 70,000 年一次误报，这是很罕见的，足以证实 GW170104 确实是一个真实的天体物理引力波事件！

The third panel of Figure 1 shows a comparison between the best-fitting waveform model and the time series data (expressed as gravitational-wave strain, equal to the fractional change in the distance between two measurement points as a gravitational wave passes by) observed by the LIGO detectors at the time of the GW170104 merger event. The lowest panel shows the residual difference between these data and the best-fitting model; we can see that the best-fit model gives a good match to the data.

图 1 的第三个子图比较了此次被 LIGO 探测到的 GW70104 合并事件最佳拟合波形模型和时间序列数据之间的差异（表示为引力波应变，等于引力波经过两个测量点之间的距离变化差）。底部这幅子图显示这些数据与最

佳拟合模型之间的差别;我们可以看出，最佳拟合模型给出了一个很好的数据匹配。

Further supercomputer analysis then allowed us to extract more precise estimates of the parameters of GW170104 – i.e. the physical characteristics of the event, including the masses of the merging compact objects, their distance from the Earth and position on the sky, the orientation of their orbital plane and constraints on the rate at which they are spinning and their orbit is precessing. The process of parameter estimation involves carefully checking millions of combinations of these model characteristics and testing how well the gravitational waveform predicted for each set of parameters matches the signal measured by the LIGO detectors. (See also here and here, for more information about how gravitational-wave parameter estimation is carried out).

进一步的超级计算机分析使我们能够更准确地对 GW170104 进行参数估计 - 即事件的物理特征，包括合并的致密星体的质量，与地球的距离和位置，其轨道平面的方向和对他们的自旋及其轨道进行限制。参数估计的过程包括仔细检查数百万个具有这些模型特征的组合形式，并测试每组参数预测的引力波形是否与由 LIGO 探测器测量的信号相匹配。（有关如何进行引力波参数估计的更多信息，另见这里和这里，）。

We can estimate the uncertainty on the GW170104 model parameters – both individually and in combinations. As an example, Figure 2 shows what we can infer about the masses of the two compact objects, which we found to be about 30 times and 20 times the mass of the Sun respectively – indicating that GW170104 was the merger of a pair of black holes. From the estimated mass of the *final* black hole we found that the equivalent of about two times the mass of the Sun was radiated in the form of gravitational-wave energy during the merger event. This corresponds to a peak gravitational-wave luminosity that was many times larger than the combined light power of every star in the entire observable Universe!

我们可以单独地和组合地估计 GW170104 模型参数的不确定性。例如，图 2 显示了我们可以从两个致密物体的质量推断出来的问题，我们发现它们分别是太阳质量的 30 倍和 20 倍，表明 GW170104 是一对黑洞的合并。从最终黑洞的估计质量来看，我们发现，在合并事件中，相当于约 2 倍太阳质量的能量以引力波的形式被释放。这说明峰值引力波发光度相当于整个可观测宇宙中每颗恒星加起来的总发光功率的很多倍！

We also estimated the *distance* of GW170104 and found that this event probably occurred about twice as far away as GW150914, at a distance of about 3 billion light years. In fact GW170104 is so remote that by the time its gravitational waves reached the Earth they had been stretched by about 20% due to the expansion of the Universe – a familiar phenomenon, known as the cosmological redshift, seen when observing the light from distant galaxies.

我们还估计了 GW170104 源的距离，发现这个事件可能发生在 2 倍 GW150914 对应源位置的地方，距离约 30 亿光年。事实上，GW170104 是如此遥远，当它的引力波到达地球时，由于宇宙的扩张，它们被拉伸了约 20％ - 这是一个大家熟悉的现象，被称为宇宙红移，发生在观察远距离星系发光时。

A table showing all the best-fit parameters of GW170104 can be found in the published article, and can also be found in this fact sheet.

一个显示 GW170104 的所有最佳拟合参数的表格可以在已发表的文章中找到，也可以在本说明书中找到。

WHAT DOES GW170104 TELL US?

GW170104 告诉我们什么?

The population of stellar mass black holes

恒星质量级黑洞的数量

GW170104 is the third confirmed direct detection of gravitational waves, and the fourth member (including the candidate event LVT151012) of our growing family 'portrait' of heavy black hole binary systems with directly measured masses. Figure 2 also shows how the estimated masses for the GW170104 black holes compare with those of the other three events; we see that GW170104 sits neatly in the gap between GW150914 and LVT151012. Moreover, its detection has improved our estimate of the global rate at which black hole mergers occur. Although this rate is still quite uncertain, it already appears mildly inconsistent with some astrophysical models for how black holes might form and merge.

GW170104 是人类第三次直接检测到引力波，第四个成员（包括候选事件 LVT151012）是我们不断增加的被直接观测到的致密双黑洞系统的“标本”。图 2 还显示了 GW170104 对应双黑洞系统的估计质量与其它三个事件对应源的质量相比;我们看到 GW170104 刚好介于 GW150914 和 LVT151012 之间。此外，对它的探测改善了我们对黑洞并合事件发生率的全球估计。虽然这个发生率还是很不确定的，但如何形成黑洞并进行合并这一过程似乎与一些天体物理学模型略有不同。

A further handle on these formation models can be obtained from measurements of black hole spin – since, for example, they make different predictions about how well aligned with each other the black holes' axes of rotation should be. Although these spin parameters are not yet very well constrained, our observations do already hint towards a possible tendency for the spin axes in a merging binary system to be misaligned.

对这些双黑洞形成模型的进一步修正可以通过测量黑洞自旋来获得，因为例如，它们对黑洞的自旋方向是否与轨道角动量方向一致作出了不同的预测。尽管这些自旋参数还没有被很好地约束，但我们的观察结果已经暗示了并合的双黑洞系统中的双黑洞自旋方向不一致。

Testing General Relativity

检验广义相对论

The addition of a third, confirmed gravitational-wave detection has also improved our ability to test some fundamental aspects of general relativity (GR). Combining our new observations with those of GW150914 and GW151226, we compared them with some specific GR predictions for how the waveforms should evolve, and searched for any systematic departures from those GR predictions in the data. The results were consistent with our previous findings (see here and here), meaning that Einstein's theory once again passed the test with flying colours!

第三次成功检测到引力波也为检验广义相对论（GR）提供了更多实验依据。将我们的新观测结果与 GW150914 和 GW151226 的观测结合起来，我们将其与 GR 预测的波形演化进行了比较，并搜索数据中是否存在对 GR 预测的偏离。所得结果与我们之前的研究结果一致（见这里和这里），这意味着爱因斯坦的引力理论再次通过实验验证。

The large distance of GW170104 also allowed us to test another prediction of GR: that gravitational waves travel at the speed of light and are *non-dispersive*. In some situations a wave can be dispersed as it travels through a material, meaning that the wave becomes ‘spread out’ because components with different frequencies travel at different speeds. (Everyday examples of this phenomenon include the spreading out of white light into a rainbow, or the distortion of e.g. sounds heard underwater in a swimming pool. On the other hand, to a good approximation sound waves are *not* dispersed very much as they travel through the air in a concert hall; if they were, then the audience at an orchestral concert would hear the notes from the piccolo and the double bass arrive out of step with each other).

GW170104 的大距离传播还给我们提供了测试另一个 GR 预测的机会：引力波以光速传播，无色散。在某些情况下，当波穿过材料时，波会发生色散，这意味着由于具有不同频率的单色波以不同的速度传播，波会“分散展开”。（这种现象的日常生活中很常见，例如：将白光发散成彩虹，在游泳池水中听到失真的声音，另一方面，为了更好地接近原声，声波在传播时不会分散的很厉害比如音乐在音乐厅空气中的传播; 否则管弦乐演奏会上的观众会听到短笛声和双重低音的相互干扰）。

According to GR, however, the gravitational waves from GW170104 should *not* have been dispersed as they travelled across billion of light years to reach us. To test this we considered a simple model for the dispersion, motivated by some alternative theories to GR in which the phenomenon is predicted to occur, and compared these predictions with our GW170104 observations, again combining with those of GW150914 and GW151226.

根据广义相对论，GW170104 的引力波经过十几亿光年的传播到达地球时不应该有色散。为了测试这一点，我们考虑了一个简单的色散模型，选择一个非 GR 的引力理论，这种理论预测引力波会有色散发生，并将这些预测与 GW170104 以及之前的 GW150914 和 GW151226 观测进行比较。

Figure 3 shows our constraints on the magnitude of the possible dispersion, for different values of another parameter, α, of the model. We see that only a tiny amount of dispersion is allowed in order to maintain consistency with our observations, meaning that the GR prediction (in which there would be exactly *zero* dispersion) again passed the test. Although even tighter limits have been placed on the dispersion of electromagnetic waves as they travel through the vacuum of space, our analysis represents the first time this test has been extended to gravitational waves.

图 3 显示了对于不同引力理论对应不同的参数α时，我们对色散幅度的限制。可以看到，为了保持与观察结果的一致性，只可能有极其微弱的分散存在，这意味着零色散的结果再次被证实。尽管之前对真空中电磁波的色散给出过更严格的限制，但现在我们第一次将这方面的测试延伸到了引力波。

The second Advanced LIGO observing run will continue until mid 2017, with Advanced Virgo also expected to begin data taking shortly. As more detections are added in the future, we can expect to gain further insight into models for the formation and evolution of stellar mass black holes, and to put General Relativity even more rigorously to the test.

升级后的 LIGO 第二轮数据观测将持续到 2017 年 6 月左右，同时升级后的 Virgo 探测器即将开始数据观测。随着未来更多的引力波事件被探测到，我们可以进一步明确恒星质量黑洞形成和演化的模型，并将更加严格的验证广义相对论的正确性。

图像标题

Figure 1: *The upper two panels show a plot of the frequency evolution of the signal measured by each of the Advanced LIGO*

detectors, over a roughly 0.1 second interval, at the time of the detection of GW170104. The strength, or amplitude, of the signal is represented by the color bar. The third panel compares the best-fitting gravitational waveform model (shown in black) for the black hole merger with the gravitational-wave strain data measured by both LIGO detectors. The data have been adjusted for the 3-millisecond difference in arrival time of the signal at the Hanford and Livingston detectors, and for the different orientation of the detectors' interferometer arms. The lowest panel shows the residual difference between these data and the best-fit model; we can see that the residuals appear to show no obvious pattern.

图 1：上面的第一排两个子图显示了每个升级后的 LIGO 探测器在检测到 GW170104 发生前后大约 0.1 秒时间内信号的频率变化曲线。信号的强度或幅度由彩条表示。第三个子图将黑洞并合的最佳拟合引力波波形模型（黑色显示）与两个 LIGO 探测器测量的引力波数据应变进行比较。针对 Hanford 和 Livingston 探测器的信号到达时间存在 3 毫秒差异以及探测器干涉仪臂的方向不同，我们对数据已经进行了相应的调整。底部子图显示这些数据与最佳拟合模型之间的差异;我们可以看出，差异似乎并不明显。

Figure 2: *This image shows which black hole masses, in units of the mass of the Sun, are consistent with the GW170104 signal. The contour map in the upper right part of the figure shows which combinations of black hole masses are consistent, for the two black holes considered together. Regions where the contour map is darker show mass combinations that have higher probability of being correct. The grey 'hills' (known as histograms) show the relative probability of different masses for each black hole considered separately, and peak at about 30 and 20 solar masses respectively. Probability contours for the black hole masses measured for the other three confirmed and candidate events are also shown in light grey.*

图 2：该图显示与 GW170104 对应的黑洞质量（以太阳质量为单位）。图中右侧部分的等高线显示了与双黑洞等效的黑洞复合质量。轮廓图较暗的区域表示相应的黑洞复合质量具有更高的概率。灰色“丘陵”（称为直方图）显示了分别考虑每个黑洞不同质量的相对概率，并在约 30 和 20 个太阳质量出分别出现了峰值。另外三个确认和候选引力波事件对应黑洞质量的概率也以浅灰色轮廓显示。

Figure 3: *Upper limits on the magnitude of the dispersion parameter, A, permitted by the GW170104 data, for different assumed values of the other model parameter, α. The model allows for both positive and negative values of A, and we see that similar constraints are obtained in both cases. General Relativity predicts a value of A that is exactly zero.*

图 3： GW170104 引力波数据允许的色散幅度 A 的上限，随不同模型对应不同色散参数α的变化。该模型允许 A 可正可负，我们看到在这两种情况下都得到了相似的约束。广义相对性预测 A 值恰好为零。