Observation of Gravitational Waves from a Binary Black Hole Merger


Alexander Beach, Bora Basa, Carina Baker, Shraddha Agrawal

December 7, 2018
• Gravitational waves – Einstein’s Equation
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- The (strong) principle of equivalence implies a correspondence between spacetime geometry and gravity: 
  \[ \text{Gravity} \sim \text{Spacetime curvature due to matter} \]
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Einstein’s Equation

Geometrically, spacetime is the data \((M, g_{\mu\nu})\) with causal constraints (Lorentzian manifold). It is dynamical in the sense that \(g_{\mu\nu}\) obeys the field equation

\[ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \text{Tr}_g R_{\mu\nu} + g_{\mu\nu} \Lambda = 8\pi T_{\mu\nu}, \]

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- The solutions of Einstein’s equations correspond to the possible configurations of the Universe at large length scales.
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  - At first order in $\epsilon$ the field equations are linear:
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    \partial^2 \bar{h}_{\mu\nu} - 2\partial(\mu \partial^\rho \bar{h}_{\rho\nu}) + \eta_{\mu\nu} \partial^\sigma \partial^\rho \bar{h}_{\rho\sigma} = -16\pi T_{\mu\nu}
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    where we use trace-reversed metric perturbation,
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A small metric perturbation is a gravitational wave that propagates at the speed of light! It is generated by accelerating mass just as an electromagnetic vector potential is generated by accelerating charge. [Tiec and Novak, 2017]
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[Tiec and Novak, 2017]
• So a gravitational wave is just a wave in spacetime!
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• Predicted by Einstein in 1916, but the amplitude is so small that "detecting them is like measuring the distance to a star ten light-years away with a precision equivalent to the diameter of a strand of hair"

  -Royal Swedish Academy of Sciences
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    • ’Weber bars’ were designed to detect gravitational waves
  • In the 1970’s proposals for laser based interferometers were drafted
    • In the late 90’s the first sets of interferometers were built, including TAMA 300, GEO 600, LIGO, and Virgo
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- **BICEP2 – Gravitational Waves?**
  - March 2014, BICEP 2 reported detection of B-mode primordial gravitational waves
• BICEP2 – Gravitational Waves?
  • It was just cosmic dust
• LIGO – Laser Interferometer Gravitational-Wave Observatory
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LIGO – Laser Interferometer Gravitational-Wave Observatory

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- Each arm is 4 km long
- Detect changes in length less of a ten-thousandth the charge diameter of a proton
Sensitivity of Detector

Most sensitive at \(~150\, \text{Hz}\)
Background

Experiment

Analysis

Future

Conclusions

L1
Livingston, LA

H1
Hanford, WA
• September 14, 2015 Advanced LIGO detected a gravitational wave event

- First detection of a black hole merger event, and first direct observation of gravitational waves
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First detection of a black hole merger event, and first direct observation of gravitational waves
• Collision Parameters
  • Redshift of 0.09
  • Primary black hole mass 36 $M_\odot$
    • Spin 0.32
  • Secondary black hole mass of 29 $M_\odot$
    • Spin 0.44
  • Final black hole mass of 62 $M_\odot$
    • Spin 0.67
• Collision Waveform
  • Model merger event using combination of analytic and numerical techniques

- Inspiral
- Merger
- Ring down

Post-Newtonian theory
Numerical Relativity
BH perturbation theory

\[ h(t) \]
• Raw LIGO Data
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  • How do they know *this* was 2 black holes?
• Binary Coalescence Search
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    • Masses and spins of the black holes are parameter space
    • $\sim 250000$ templates generated
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- For remaining signals, the background is re-estimated without the contribution of the signal
• Generic Transient Search
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    \[ \eta_c = \sqrt{\frac{2E_c}{(1 + \frac{E_n}{E_c})}} \]
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- Determine background noise
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- Test masses are suspended in a quadruple pendulum system
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- Each site has seismometers, accelerometers, magnetometers, microphones, radio receivers, weather sensors, ac power line monitors, and cosmic ray detectors
• Further Developments
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Future Plans

- Upgrades to LIGO to reduce sensitivity to noise
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  • Improved simulations
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    • Faster and more accurate numerical methods
  • Improving the match filtering process
    • Better detection statistics
    • Expecting to see much higher frequency of events in the future
• Future Plans
  • In 2034 the European Space Agency plans to begin launching a Laser Interferometer Space Antenna (LISA)
    • Vacuum of space is better than vacuum achievable in LIGO
    • Almost no noise from Earth
    • The interferometer arms can be much larger than on Earth
• Future Plans
  • Fermilab E-990 – ‘Holometer’
    • Most sensitive interferometer in the world
    • Meant to detect change in space-time due to quantum fluctuations
    • [https://holometer.fnal.gov/faq.html#logo](https://holometer.fnal.gov/faq.html#logo)
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    • This correlation is maximised for both the signal and the noise, using the 6.9 ms time lag of the LIGO paper
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This correlation is maximised for both the signal and the noise, using the 6.9 ms time lag of the LIGO paper.

This paper is excellent in all other respects.

Well written and unambiguous.

Careful and thorough.

Great example of international collaboration.
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- 1970s: Existence of gravitational waves indirectly demonstrated (binary pulsar merger)
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• Carefully isolated from environmental noise
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• Numerical models: mass and spin determined independently from the early stage and late stage agree.
• Why care?
  • Last piece of GR
  • New kind of astronomy
Background Experiment Analysis Future Conclusions


Group 1

PHYS 596 36/37
What it sound like though???