LIGO’s First Detection of Gravitational Waves

Pedro Marronetti and Mark Coles
Physics Division / MPS

April 7, 2016
(Image and movie credits: LIGO.org)
What are gravitational waves?

Spiraling Black Holes
Animation created by the Simulating eXtreme Spacetimes (SXS) project
• A ring of test particles that is ‘hit’ by a gravitational wave perpendicular to the screen will be deformed like this:

• They are very weak! the relative variation in size is one part in $10^{22}$. This is the equivalent of measuring the distance from here to Alpha Centauri (4.37 light years) with a precision of microns.
What do they look like?

A ring of test particles that is ‘hit’ by a gravitational wave perpendicular to the screen will be deformed like this:

Gravitational waves do not interact with matter(fields between source and observer ⇒ they shine a light in phenomena otherwise obscured by gas and dust (e.g., supernovae and GRB engines).
How do you detect GWs?

Most Precise Ruler Ever Constructed
Animation created by T. Pyle, Caltech/MIT/LIGO Lab
How do you detect GWs?

Livingston, LA

Hanford, WA
What did LIGO detect on Sept 14, 2015?

The merger of two black holes and the birth of a new one.

**Event GW150914**
- Original black holes: 29 and 36 solar masses ($M_\odot$).
- Final black hole: 62 $M_\odot$ with dimensionless spin 0.67
- Energy emitted: 3 $M_\odot$
- Power emitted: 200 $M_\odot$/s
  - (140 billion trillion times that of the Sun)

Most powerful explosion recorded not including the Big Bang!
Where did this happen?

Distance: 410 Mpc or 1.3 Billion light-years (redshift \( z = 0.1 \))

90% confidence area: 600 deg\(^2\)
  (full moon area: 0.2 deg\(^2\))

With LIGO India: 2-7 deg\(^2\)
Has a new era of GW Astrophysics started?

arXiv.org Search Results

Showing results 1 through 25 (of 39 total) for title:GW150914

1. arXiv:1604.00865 [pdf, other]
   AGILE Observations of the Gravitational Wave Event GW150914

2. arXiv:1603.08895 [pdf, other]
   Theoretical Physics Implications of the Binary Black-Hole Merger GW150914
   Nicolas Yunes, Kent Yagi, Frans Pretorius

   Primordial black hole scenario for the gravitational wave event GW150914
   Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, Shuichiro Yokoyama
   Comments: 7 pages, 1 figure
   Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc)

   XMM-Newton Slew Survey observations of the gravitational wave event GW150914
   E. Troja, A. M. Read, A. Tiengo, R. Salvaterra
   Comments: 6 pages, 3 figures, 2 tables. Accepted for publication in ApJ Letters

5. arXiv:1603.02635 [pdf, other]
   Constraints on cosmological viscosity from GW150914 observation
   Gaurav Goswami, Subhendra Mohanty, A. R. Prasanna
   Comments: 5 pages, 3 figures
   Subjects: High Energy Physics - Phenomenology (hep-ph); Cosmology and Nongalactic Astrophysics (astro-ph.CO); General Relativity and Quantum Cosmology (gr-qc)

   IPTF Search for an Optical Counterpart to Gravitational Wave Trigger GW150914
   Comments: Revised
What do these papers report?

• 12 papers from the LIGO and Virgo Scientific Collaborations
  • First direct evidence of Binary Black Holes that inspire and merger within the age of the Universe
  • BHs are relatively heavy ($M \geq 25 M_\odot$) $\Rightarrow$ weak massive stellar winds $\Rightarrow$ low metallicity environments.

• 12 papers from EM & Neutrino counterpart searches (all but one with negative results)

• 7 papers about the possible association between a Fermi GBM event and GW150914

• 8 about GW150914 detection implications for gravitational theory
Observing Strong & Dynamical Gravitational Fields

First observations of strong gravitational fields:

• Solar system gravitational tests: $M/R \sim 10^{-5}$; GW150914: $M/R \sim 1$

GW150914 merger places constraints on:

• The type of final object (gravastars & boson stars are ruled out)

GW150914 radiation mechanism places constraints on:

• The presence of dipole radiation (e.g. due the scalar fields)
• BH mass leakage due to large extra dimensions
• Time variation of Newtonian constant G (Local Position Invariance)
• Lorentz Invariance effects in emission

GW150914 propagation mechanism places constraints on:

• Dispersion relation of GWs
  • Graviton mass ($10^{-22}$ eV or $2 \times 10^{-58}$ Kg)
  • Lorentz Invariance effects in propagation
• Shapiro delay freq.-dependent violations
• Cosmological fluids viscosity

Abbott et al., Blas et al., Chirenti & Rezzolla, Ellis et al., Goswami et al., Kahya & Desai, Yunes et al.
Advanced LIGO
Commissioning & Future Upgrades

Projections toward aLIGO+ (Comoving Ranges: NSNS 1.4/1.4 $M_\odot$ and BHBH 20/20 $M_\odot$)

  - Goal > 1.2 $\times$ sens. of O1
- O2: Fall 2016 – Spring 2017
  - 2.0-2.2 $\times$ sens. of O1
- O3: Fall 2017 – Summer 2018
  - Design Sens.: 2019
    - 2.5 $\times$ sens. of O1
- A+: Early 2020s
  - 3.7 $\times$ sens. of O1
What is Next for LIGO?
LIGO India

• In 2012 NSF approved the delay in installation of the 2\textsuperscript{nd} Hanford interferometer, studying the possibility of a LIGO India site.

• In Feb. 2016, the Indian Gov. approved (in principle) the construction of LIGO India.

• Last week NSF and Indian Dep. of Atomic Energy (DAE) and Dep. of Science and Techn. (DST) signed the MoU in the presence of the Indian Prime Minister N. Modi.

• Construction to start in 2017 and operations around 2023
Currently two sites are under consideration. Decision to be announced next week.
Voyager represents a design of the best that can be done with the current LIGO sites.

- It could start in middle to late 2020s.
- New laser (1550nm, 300W).
- Larger and cryogenic mirrors and suspensions (sapphire).

Voyager Noise Curve: $P_{\text{in}} = 300.0 \text{ W}$
What is Next for LIGO?
Cosmic Explorer / Einstein Telescope

- Design studies are very preliminary (ET) or non-existent (CE).

- Construction would start in 10-15 years.

- ET: Underground, triangular geometry, 10km arm-length,

- CE: L-shaped, 40km arm-length
Thank you!

After half a century unwavering support from NSF and the stoic efforts of the gravitational physics community, LIGO has detected GWs marking the dawn of a new field.

This is just the beginning: stay tuned for the next LIGO paper!
Advanced VIRGO (Cascina, Italy)

- Franco-Italian collaboration (19 institutes across Europe).
- Dimensions: 3km x 3km.
- Initial Virgo observed from 2008 to 2010.
- Advanced Virgo Avanzado is under construction with operations expected in 2016/17.
KAGRA (Kamioka, Japan)

• Underground project. Cryogenic mirrors and suspensions (~123K). 200 scientists from more than 60 Japanese institutions.

• Arm-length 3km x 3km.

• Kagra is under construction, operations are planned for 2018.
Most asked questions about GWs

Has an EM counterpart of GW150914 been detected?

LIGO Sky map

Fermi (GBM) Sky map

LIGO + Fermi Sky maps