Christopher Berry Institute of Gravitational Wave Astronomy LIGO Scientific & Virgo Collaboration





Discoveries of gravitational wave astronomy

Image: NSF/LIGO/Sonoma State University/A. Simonnet





Pulsars







Image: Daniel Berehulak/ Getty Images

Gravitation is universal

Objects move in straight lines



Relativity

Space and time are linked

Nothing can travel faster than the speed of light

Image: BBC

Space-time

Space tells matter how to move, matter tells space how to curve

Image: WGBH Boston

Accelerating masses create gravitational waves, ripples in space-time

Image: Swinburne Astronomy Productions



theoretical predictions to superb accuracy

Stretch and squash



LIGO Livingston 4 km arms

Image: LIGO

Detector network



15 September 2015 We observed gravitational waves







GW170817

17 August 2017

Credit: LVC





Credit: LVC



GW170817

17 August 2017

Credit: LVC

Video: LVC/NASA/L. Singer



Image: LIGO



Credit: LVC+

Spectrum of observations



Credit: LVC+

Heavy elements



Hubble constant



Gravitational waves are a new way to do astronomy

We have observed the first neutron star coalescence

Neutron stars are the source of short gamma-ray bursts and kilonovae

birmingham.ac.uk/gravitational-waves/ ligo.org/science/



Combined observations tell a more complete story

Image: NSF/LIGO/Sonoma State University/A. Simonnet

The neutrino sky



Image: Super-Kamiokande



The puzzle of Mercury's orbit

General relativity









Cosmological constant





Mass

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

More in All the World Could No Comprehend It, Said Einstein When His Daring Publishers Accepted It.

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Credit: New York Times

The black hole from Interstellar

Image: James et al. (2015)

☑LIGO LIGO Scientific Collaboration

CALIFORNIA STATE UNIVERSITY Abilene Christian University WASHINGTON STATE Andrews 🔕 University **UNIVERSITY FULLERTON** Albert-Einstein Institut TRINITY THE UNIVERSITY OF MONTCLAIR STATE University UNIVERSITY Of Glasgow ALABAMA IN HUNTSVILLE Andrews University UNIVERSITY indig SonomA Australian American University National California Institute of Technology University WHITMAN 大学 California State Univ., Fullerton COLLEGE AMERICAN Tsinghua University UNIVERSITY TEXAS TECH Canadian Inst. Th. Astrophysics Carleton College for Gravitational Physics College of William and Mary ALBERT EINSTEIN INSTITUTE Columbia U. in the City of New York MND THE UNIVERSITY OF Jniversità legli Studi del Sannio ICTP Embry-Riddle Aeronautical Univ. CITA ICAT PAH WESTERN UNIVERSITY OF SAIFR CAMBRIDGE AUSTRALIA Eötvös Loránd University М MONASH University SOUTHERN Georgia Institute of Technology CHICAGO 🖆 COLUMBIA UNIVERSITY MONTANA STATE UNIVERSITY HE UNIVERSITY Goddard Space Flight Center OF ADELAIDE MISSISSIPPI Hobart & William Smith Colleges UNIVERSITY Caltect BIRMINGHAM **ICTP-SAIFR** Universitat MELBOURN IndIGO UNIVERSITY OF WASHINGTON IAP-Russian Acad. of Sciences 6 0 0 UNIVERSITY# WISCONSIN (JTRG) Inst. Nacional Pesquisas Espaciais ARDIF INIVERSITY Kenyon College PRIFYSGO Northwestern Korean Gravitational-Wave Group **CAERDY** 🗷 MONASH Louisiana State University **JF FLORIDA** GeorgiaInstitute Montana State University University Travitational-Wave Group ofTechnology Montclair State University University of Southampton CHARLES STURT Moscow State University NIVERSITY National Tsinghua University PennState Leibniz A. Science & Technology Facilities Council Universität EMBRY-RIDDLE Northwestern University Rutherford Appleton Laboratory Hannover

LIGO Laboratory: California Institute of Technology, Massachusetts Institute of Technology, LIGO Hanford Observatory, LIGO Livingston Observatory

Australian Consortium for Interferometric Gravitational Astronomy (ACIGA):

Australian National University, Charles Sturt University, Monash University, University of Adelaide, University of Melbourne, University of Western Australia

German/British Collaboration for the Detection of Gravitational Waves (GEO600):

Cardiff University, Leibniz Universität Hannover, Albert-Einstein Institut, Hannover, King's College London, Rutherford Appleton Laboratory, University of Birmingham, University of Cambridge, University of Glasgow, University of Hamburg, University of Sheffield, University of Southampton, University of Strathclyde, University of the West of Scotland



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Stanford University

Syracuse University

Texas Tech University

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University of Mississippi

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West Virginia University

Whitman College

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University of Oregon

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University of Florida

Szeged University

Trinity University

Tsinghua University

Sonoma State University

Rochester Institute of Technology

Southern Univ. and A&M College

Universitat de les Illes Balears

University of Alabama in Huntsville

Univ. of Texas-Rio Grande Vallev

University of Wisconsin-Milwaukee

Waves



Image: LVC



Image: ButterflyLove1

Image: NASA/JPL-Caltech

Tidal distortion



Credit: LVC



Gammarays

Credit: LVC/Fermi/INTEGRAL

Spectrum of observations

GW LIGO, Virgo								
γ-ray								
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, S	Swift, AGILE, CALET, H.E.S.S., HAWC, Kon	us-Wind						
X-ray								
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL								, in the second s
UV Swift, HST				•				
Optical								
Swope, DECam, DLT40, REM-ROS2, HST, Las C	Cumbres, SkyMapper, VISTA, MASTER, Mag	ellan, Subaru, Pan-STA	ARRS1,					
BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the	Sky, AST3-2, ATLAS, Danish Tel, DFN, T80	S, EABA	DI E, TONOS,					
IR				-				
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitz	er, NTT, GROND, SOAR, NOT, ESO-VLT, Ka	anata Telescope, HST						
Radio								•
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAF	R, LWA, ALMA, OVRO, EVN, e-MERLIN, Mee	erKAT, Parkes, SRT, Eff	elsberg					
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Expansion of the Universe



Black holes and neutron stars are the remains of stars

Gravitational waves give us a new way to observe these remarkable objects

@cplberry

Image: Double Negative