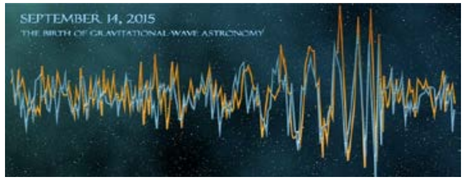


"Observation of Gravitational Waves from a Binary Black Hole Merger"
by Abbott et al. 2016, Phys. Rev. Lett. **116**, 061102

*LIGO: The Beginning of Gravitational-wave Astronomy**
(GW150914)

Stephen C. McGuire, PhD

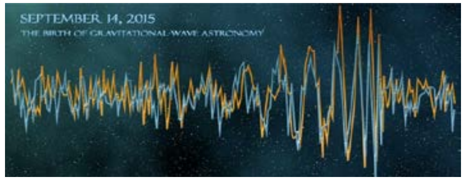
James & Ruth Smith Endowed Professor of Physics
Principal Investigator – LIGO Scientific Collaboration
Southern University and A&M College
Baton Rouge, Louisiana 70813

***Work supported by NSF Grants No(s). PHY-0101177, PHY-0701652, PHY- 0355471, PHY-0917543 and Board of Regents Grant No. 05-231SUBR-CMSS.**

Update:

"GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence" Abbott et al. 2016, Phys. Rev. Lett. **116**, 241103

LIGO



SOUTHERN UNIVERSITY And Agricultural & Mechanical College

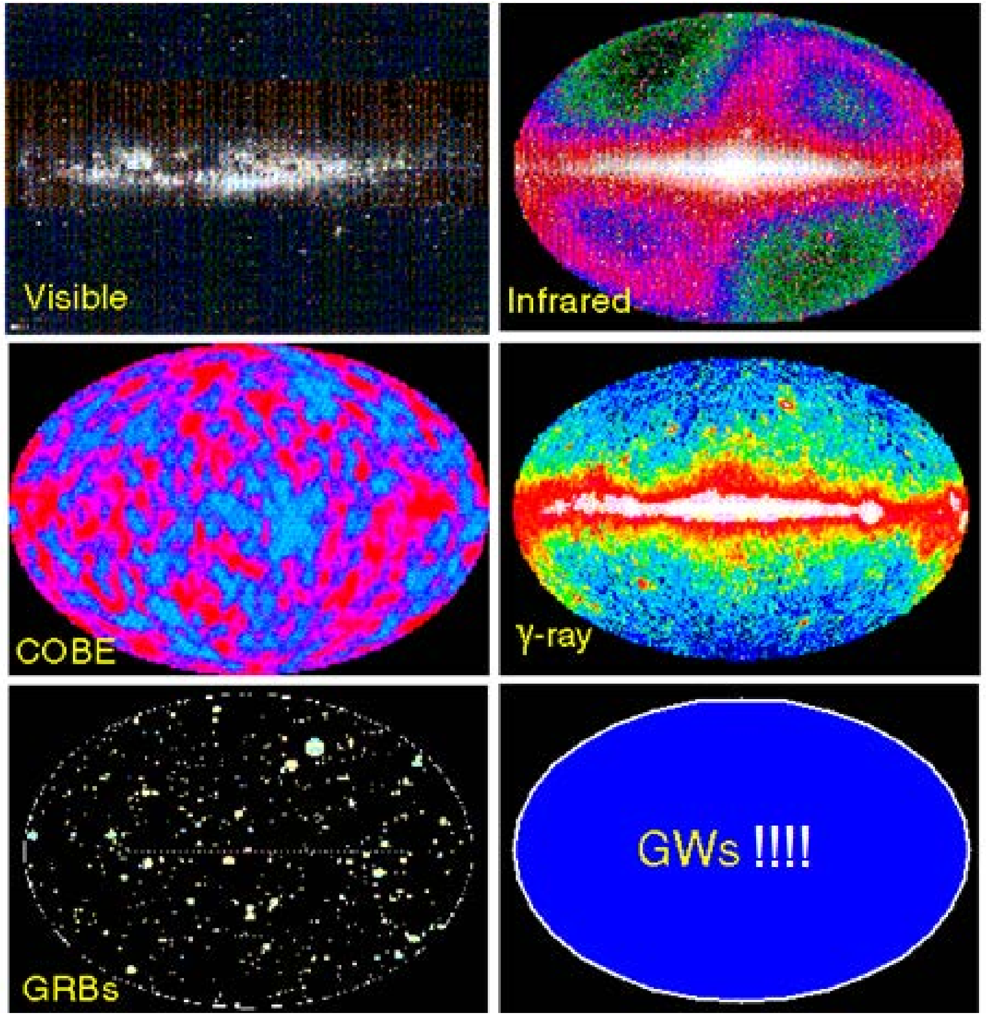
INCORPORATED 1880 RELOCATED 1914

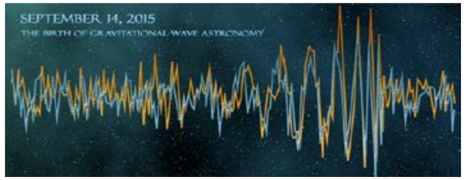
Talk Outline

- Gravitational Waves and their detection by LIGO
- Southern University’s Role in LIGO
  ---- Optical Materials Science
  -----Teacher Education and Science Literacy
- Current Work
- Summary and Future Activities

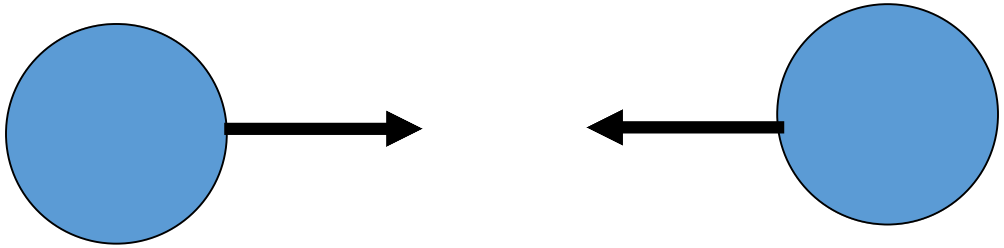
Scientific Mission of LIGO

- LIGO's quest, ~400 yrs after invention of optical astronomical telescopes, is to create a radically new way to perceive the universe, by directly listening to the vibrations of space itself
- LIGO consists of large, high-tech, earth-based, detectors that act like huge microphones, listening for "space quakes" created by the most violent events in the universe.





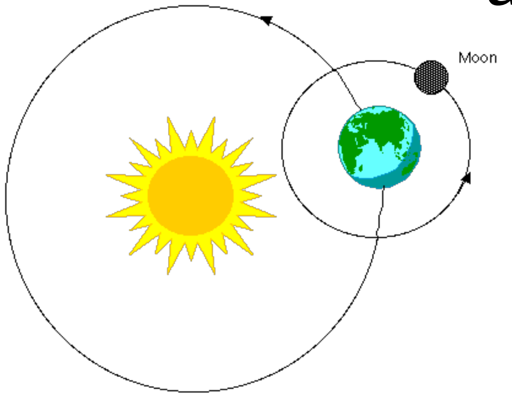
Newton’s Gravitation

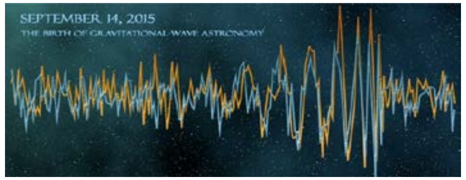


Newton’s law: $F=Gm_1m_2/r^2$

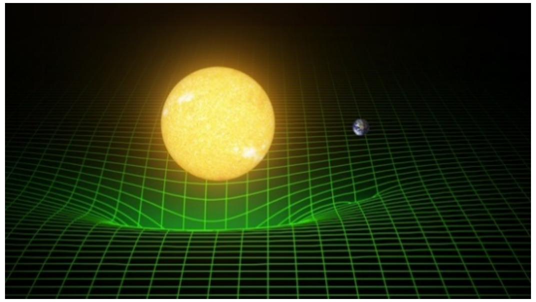
Explains why things fall down,

and planetary motion.

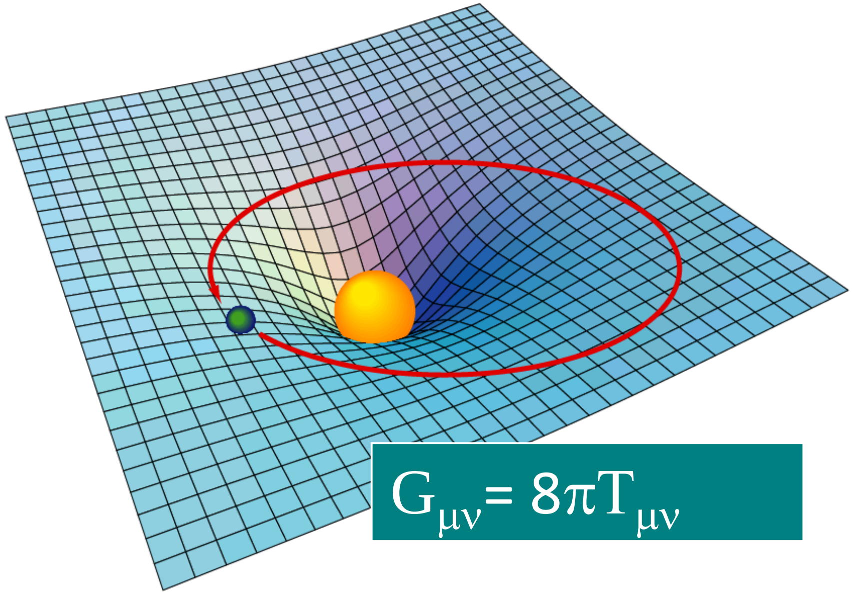




General Relativity

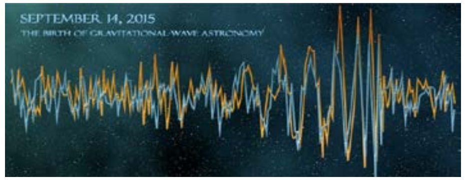


Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object

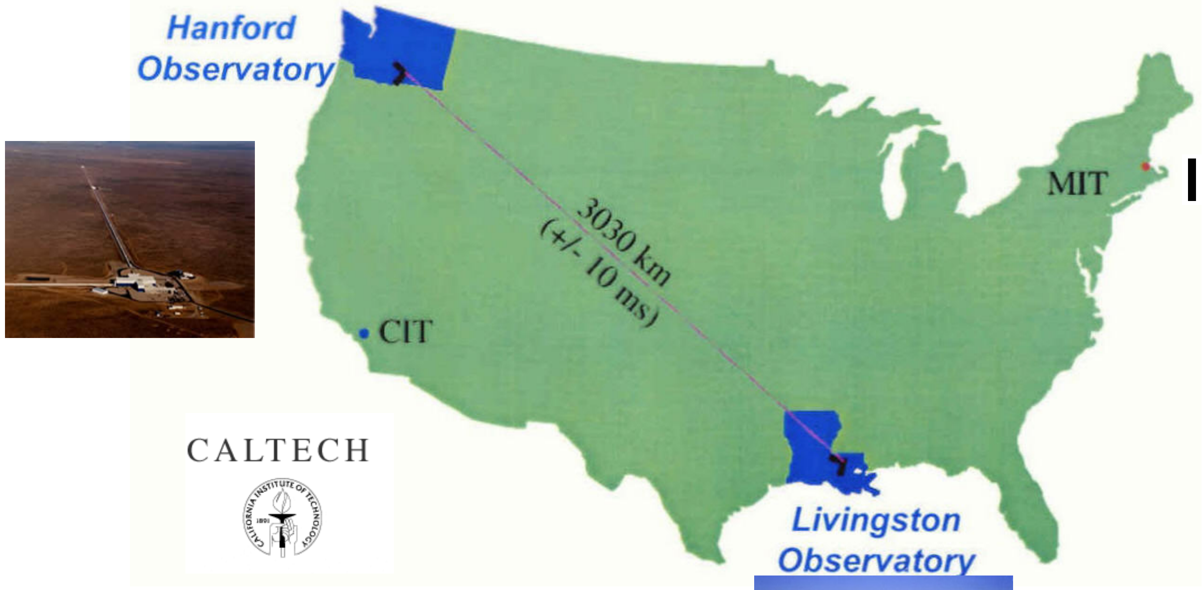


$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

- **Imagine space as a stretched rubber sheet.**
- **A mass on the surface will cause a deformation.**
- **Another mass dropped onto the sheet will roll toward that mass.**

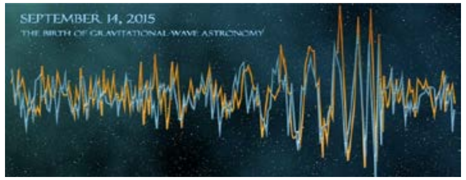


Laser Interferometer Gravitational-wave Observatory Sites



Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for about 1000 LIGO Scientific Collaboration (LSC) members worldwide.

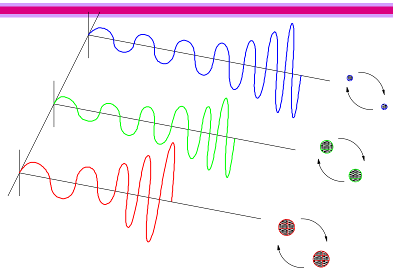
Astrophysical Sources of Gravitational Waves



Compact binary inspiral: ***"chirps"***

NS-NS

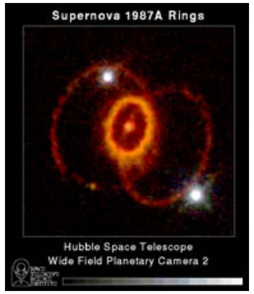
BH-BH



Supernovae / GRBs: ***"bursts"***

burst signals in coincidence with signals in electromagnetic radiation

prompt alarm (~ one hour) with neutrino detectors

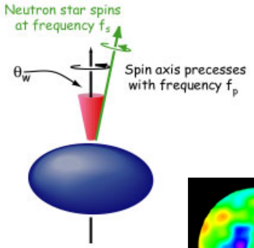


Pulsars in our galaxy: ***"periodic signals"***

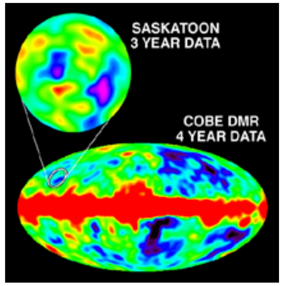
search for observed neutron stars (frequency, doppler shift); Einstein@home

all sky search (computing challenge)

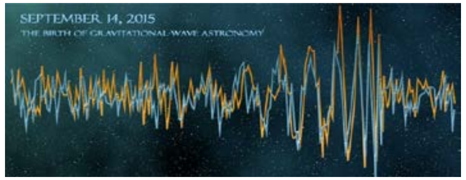
r-modes



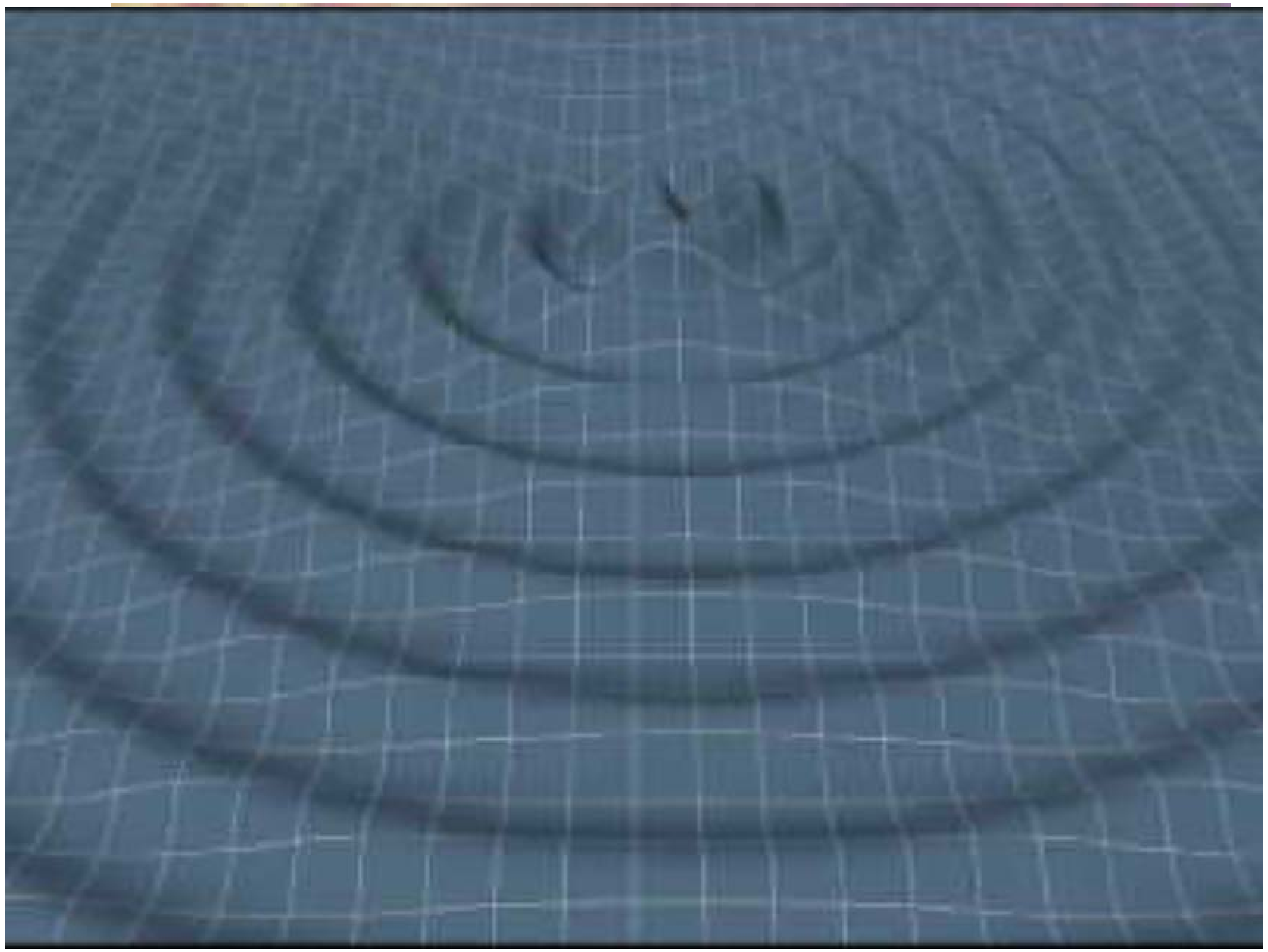
Cosmological Signals ***"stochastic background"***

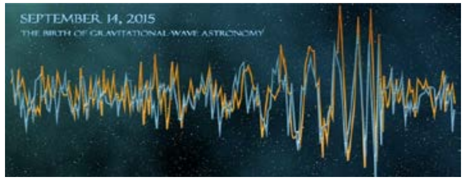


WHAT EXACTLY ARE GRAVITATIONAL WAVES?



RIPPLES IN SPACE-TIME!

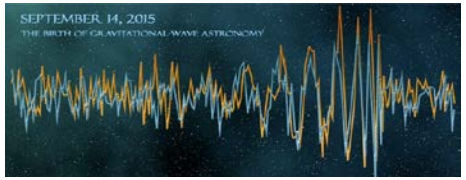




The first binary black-hole merger observed by LIGO: A Simulation

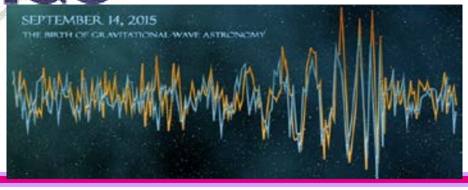
http://www.aei.mpg.de/1824987/?page=4

“Observation of Gravitational Waves from a Binary Black Hole Merger”
by Abbott et al. 2016, Phys. Rev. Lett. **116**, 061102

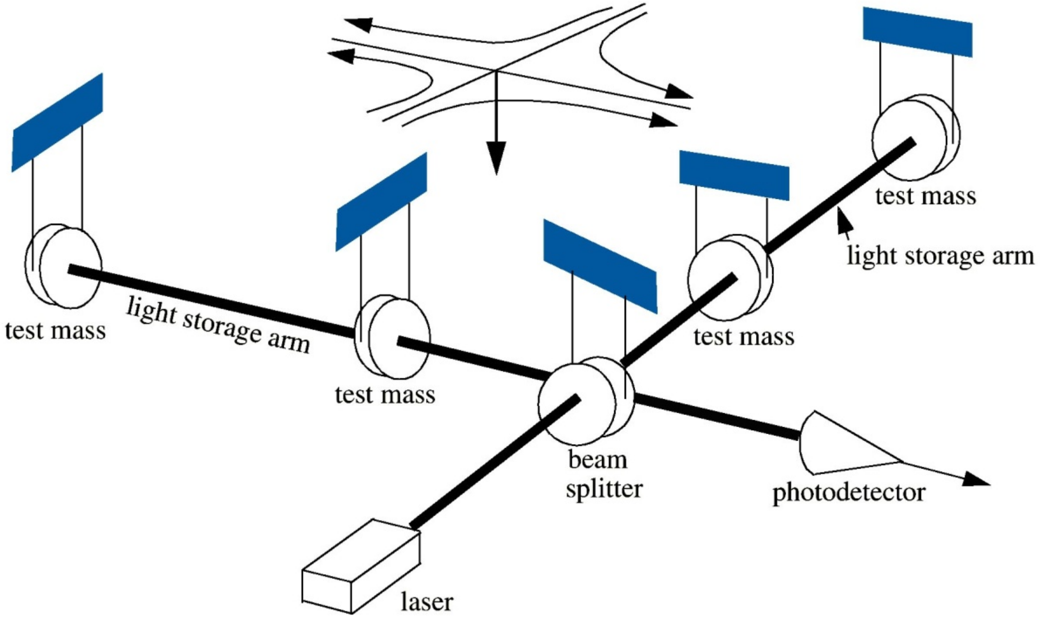


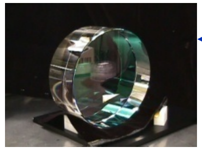
From Theory to Detection Timeline

~100 years ago: Albert Einstein published his theory of General Relativity, including the prediction of gravitational waves.
~50 years ago: Joseph Weber builds bar antennas to attempt detection of the waves.
~45 years ago: Key ideas for interferometric antennas developed by Rainer Weiss and others.
~40 years ago: NSF funding of pre-LIGO R&D.
~25 years ago: LIGO proposed to the NSF and approved. (1992)
~20 years ago: LIGO site construction began.
~18 years ago: McGuire began work with LIGO.
~5 years ago: Advanced LIGO installation began.



Gravitational Wave Detection
(Why did it take so long?)





suspended mirrors

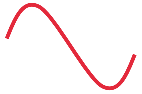
Strain = h = δL/L

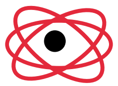
LIGO (4 km), stretch (squeeze) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^4 Hz.

How Small is 10^{-18} Meter?

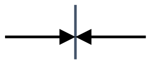
One meter, about 40 inches

÷10,000  *Human hair, about 100 microns*

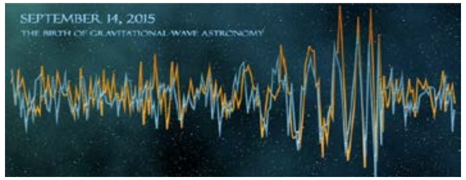
÷100  *Wavelength of light, about 1 micron*

÷10,000  *Atomic diameter, 10^{-10} meter*

÷100,000  *Nuclear diameter, 10^{-15} meter*

÷1,000  *LIGO sensitivity, 10^{-18} meter*

LIGO



https://youtu.be/tQ_telUb3tE

Interferometer Detector Concept

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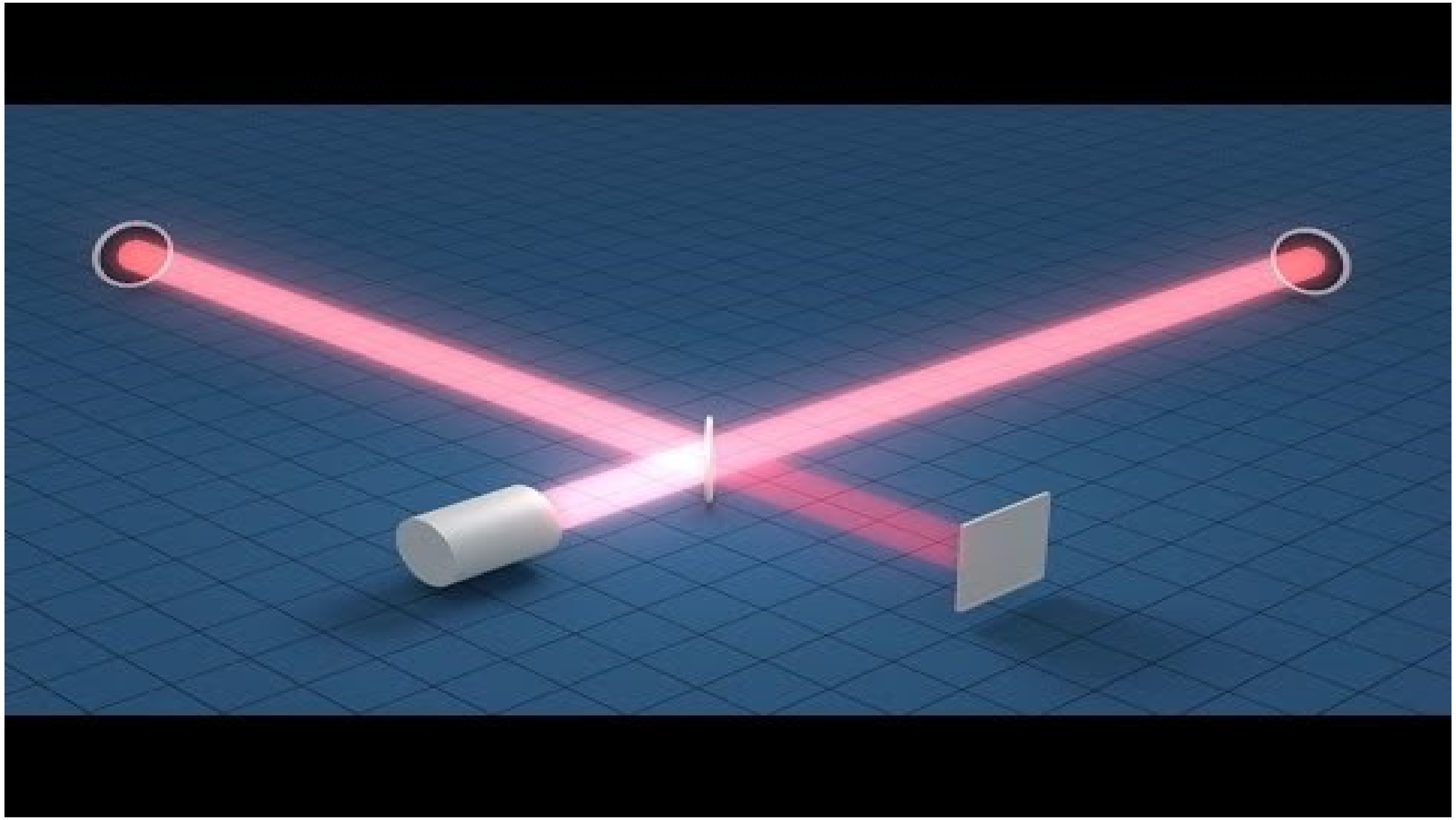

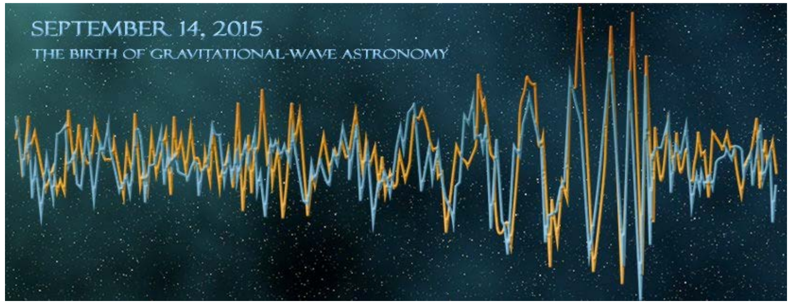

LIGO

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GW150914

*

Livingston, Louisiana
- September 14, 2015 - 09:50:45 UTC: GW150914 is detected by the Livingston instrument, L1.

Hanford, Washington
- September 14, 2015 - 09:50:45 UTC: GW150914 is detected by the LIGO Hanford instrument, H1. This coincident detection occurs ~7 ms later than at L1, within the light travel-time between the two sites.

Having interacted briefly with the LIGO test masses, GW150914 propagates onwards essentially undisturbed.

LLO Electronic Logbook – September 14, 2015, 09:05 UTC – William Parker:

LLO General

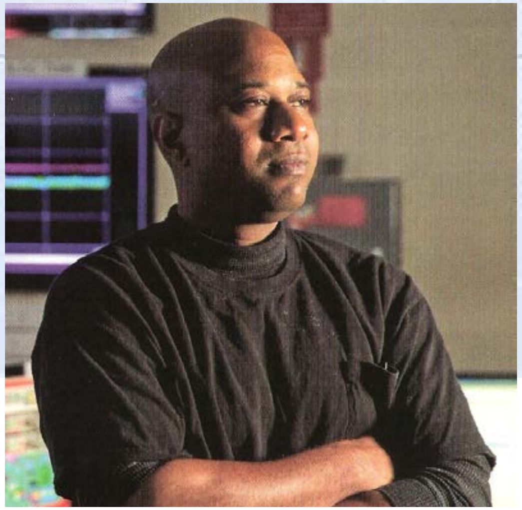
william.parker@LIGO.ORG - posted 04:05, Monday 14 September 2015 (20526)

IFO Status

Operating Mode: Observing

Range: 68 Mpc

seismic is quiet; weather is clear

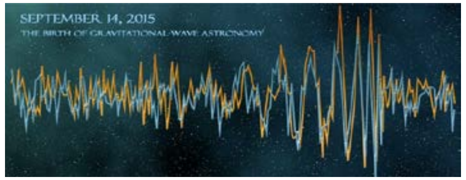


SU graduate in the Control Room at LLO during historic discovery[1]

*Excerpted from LIGO Magazine Issue #8 3/2016, p.10.

[1]*225* Magazine, April 2016, photo by Colin Ritchie.

LIGO



February 11, 2016
Detection Announcement Day!

INCORPORATED 1880 RELOCATED 1914
SOUTHERN UNIVERSITY And Agricultural & Mechanical College

SUBR LIGO Team Members

$2.00 THE NATION'S NEWS FEBRUARY 12 - 14, 2016

USA TODAY WEEKEND

GRAVITATIONAL WAVES CONFIRMED

Gravitational waves, ripples that can be unleashed by movements of massive objects in space, travel at the speed of light through the fabric of space-time. Albert Einstein had predicted their existence in 1916.

- Two black holes swinging around each other create gravitational waves as they spiral closer together.
- Ultimately, the black holes (center of spiral) collide, releasing more gravitational waves.

ILLUSTRATION BY R. HURT, CALTECH/JPL, VIA EPA

'A WHOLE NEW WINDOW ON THE UNIVERSE'

NEWSLINE

IN NEWS

Clinton, Sanders agree systems in U.S. are broken

Discovery affirms Einstein theory

Traci Watson
Special to USA TODAY

In a discovery that promises to revolutionize astronomy, scientists have made the first direct observations of gravitational waves – bizarre ripples in space time foreseen by Albert Einstein a century ago.

The find is a triumph for Einstein's celebrated general theory of relativity, the basis of his 1916 prediction that the fabric of the universe is perturbed by gravitational energy. The find is also a triumph for the mammoth scientific apparatus – the Laser Interferometer Gravitational-wave Observatory (LIGO) – that was the first to pick up the stealthy advance of these waves, in this case created by the violent union of two black holes 1.3 billion years ago.

Other scientists hailed the find as the kind of advance that comes along only once or twice in a lifetime.

Because gravitational waves carry information about their source, the ability to detect these weird undulations will allow researchers to study distant and elusive features of the universe. Black holes too far way to study using today's techniques, for example, should become easy scientific prey with the help of gravitational waves.

Study of the universe via gravitational waves "will be the astronomy of the 21st century," predicted Arizona State University's Lawrence Krauss, who is not part of the LIGO team. "This is a whole new window on the universe."

As far back as the 1970s, scientists garnered indirect evidence for such waves, spawned by the movements of massive objects in space, such as spinning supernovae or whirling pairs of neutron stars. The $1 billion LIGO directly captured the wave itself, which, if confirmed, would be "a monumental extra step," said Cole Miller of the University of Maryland, who is not affiliated with LIGO.

LIGO's twin detectors, one in Hanford, Wash., the other in Livingston, La., picked up the wave on Sept. 14, 2015 – several days before official data collection was scheduled to resume after a five-year renovation of the equipment.

The gravitational waves detected by LIGO came from the final moments before the collision of two black holes somewhere in the Southern Hemisphere.

RUSSIA, U.S. REACH DEAL IN SYRIA WAR

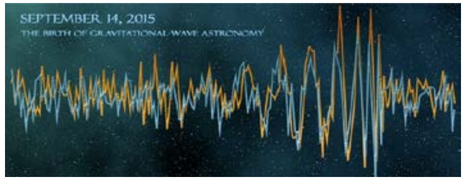
Cease-fire could begin in a week, but it's far from certain

Jim Michaels
USA TODAY

Diplomats meeting in Munich agreed early Friday to implement a "cessation of hostilities" in Syr-

LIGO Livingston Observatory

LIGO



It truly took a worldwide village!

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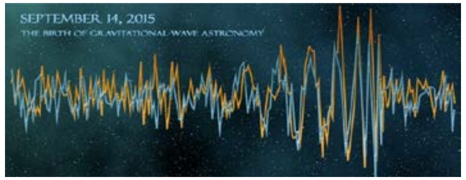
LIGO



White House Response

Image credit: Wikimedia Commons.

White House Congratulates the LIGO Team

Feature Story • February 12, 2016

On Feb 11, 2016, President Obama tweeted his congratulations to the LIGO team:

> Einstein was right! Congrats to **@NSF** and **@LIGO** on detecting gravitational waves - a huge breakthrough in how we understand the universe.
> — President Obama (@POTUS) **February 11, 2016**

On Feb 12, 2016, John P. Holdren, Assistant to the President for Science and Technology and Director of the White House Office of Science and Technology Policy, posted a statement on the White House blog with congratulations to the LIGO team.

> OSTP Dir Holdren on the groundbreaking detection of gravitational waves. Congrats to **@NSF** & all behind the effort! → **https://t.co/KO7WBz5Qxs**
> — The White House OSTP (@whitehouseostp) **February 12, 2016**

Read **the full statement** on https://www.whitehouse.gov/blog.

Statement on the Detection of Gravitational Waves

FEBRUARY 12, 2016 AT 10:32 AM ET BY JOHN P. HOLDREN

TWITTER FACEBOOK EMAIL

Summary:

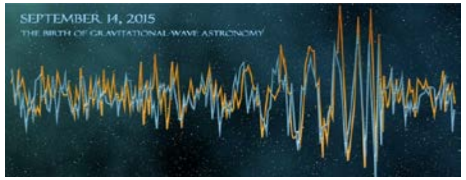
OSTP Director John Holdren congratulates the team behind the groundbreaking detection of gravitational waves.

.

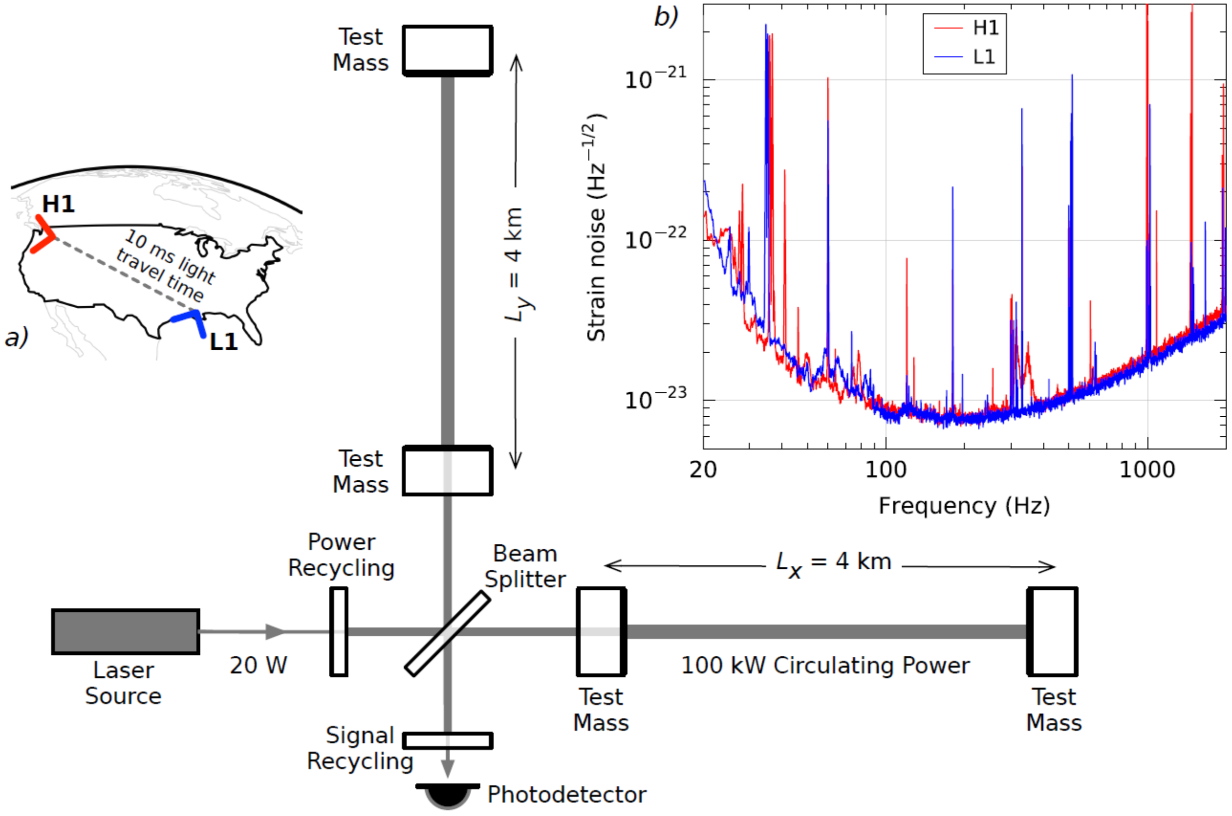
.

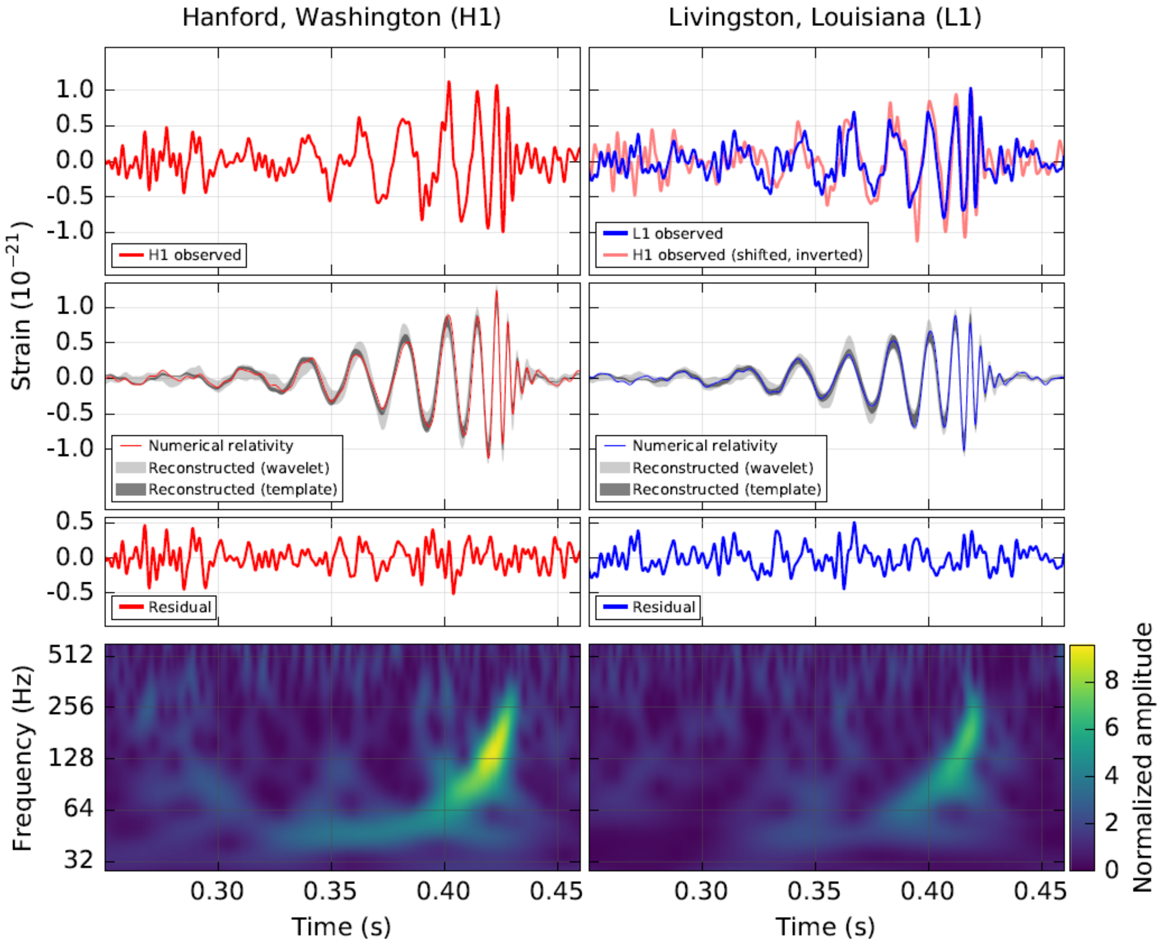
“The LIGO effort involved more than 1,000 researchers—some 250 students among them—from 15 countries and a larger number of universities. I join, I’m sure, the entire global scientific community in congratulating them and their funders, foremost among them the National Science Foundation, for their vision, ingenuity, persistence, and collaboration in the successful pursuit of one of history’s greatest scientific discoveries.”

.

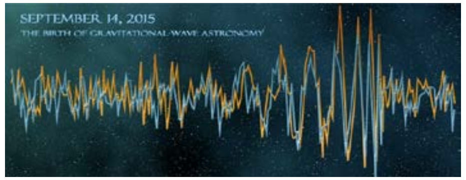


GW150914 Signals





GW150914



“Observation of Gravitational Waves from a Binary Black Hole Merger”
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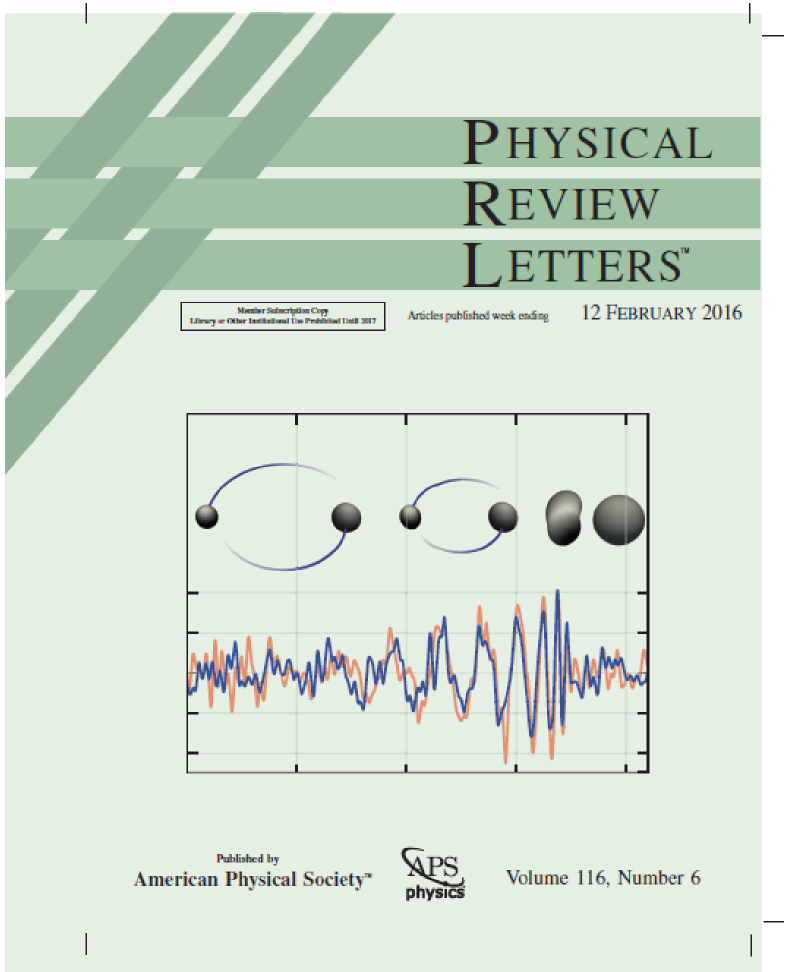
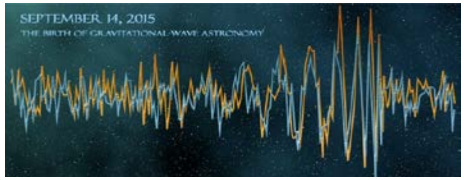


VIII. CONCLUSION

The LIGO detectors have observed gravitational waves from the merger of two stellar-mass black holes. The detected waveform matches the predictions of general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. 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.

LIGO



Southern University Optical Coatings Research

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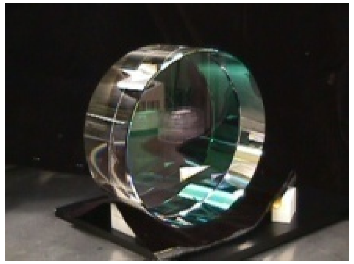
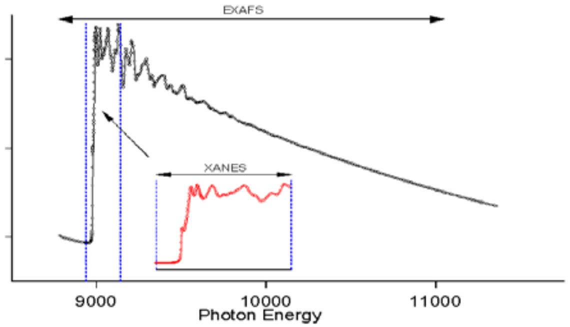
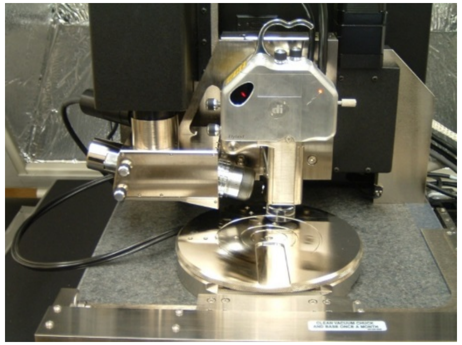


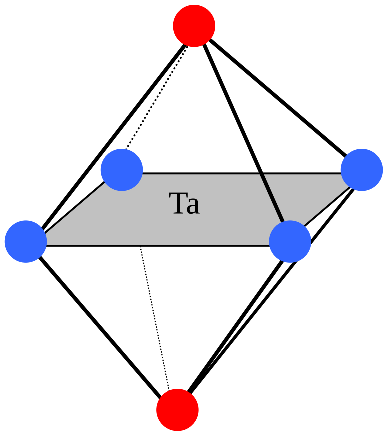
Ta_2O_5 coatings



2 axial Oxygen atoms

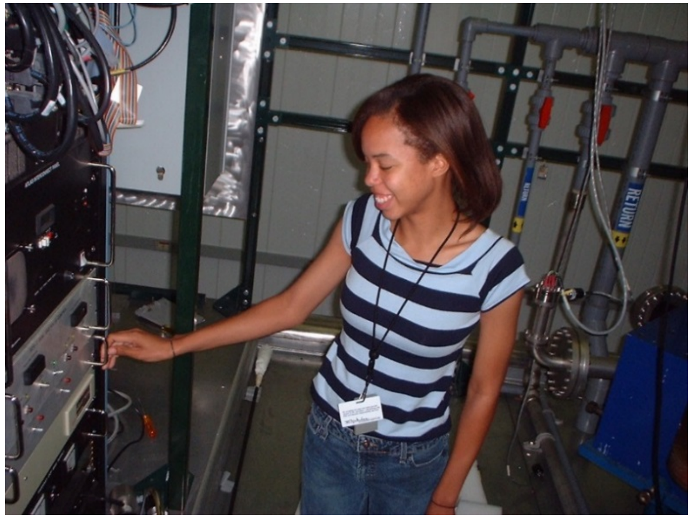


Reducing Noise in Mirrors via Coating Structure Studies



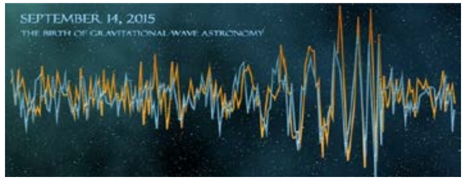
4 in-plane Oxygen atoms

National Institute of Standards and Technology



Cacey S. Stevens "Thermal Noise Interferometer Test Mass Coating Studies" --- Caltech MURF 2006.

Louisiana State University
Center for Advanced Microstructures & Devices

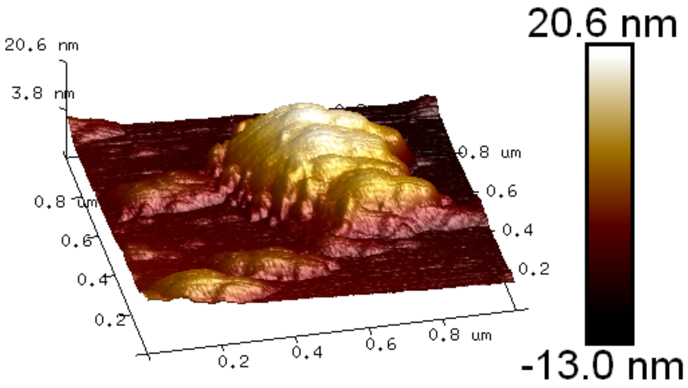


Surface Morphology and Crystallinity Studies using AFM and XRD Methods

SUBR–LIGO Advanced Optical Materials Laboratory

LIGO-G1401108-v1 (2014)

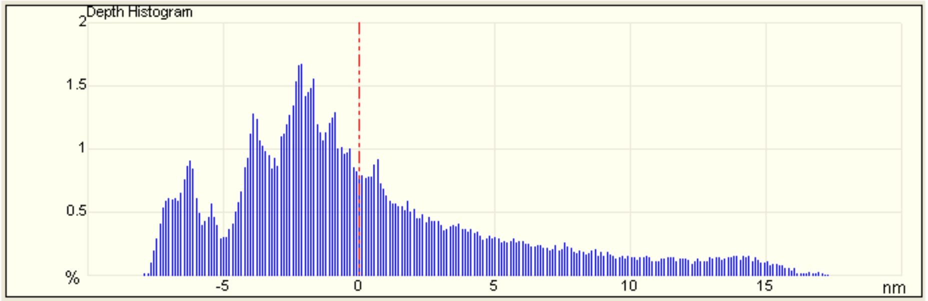
SiO_2/Ta_2O_5 Sample no. 39



Mean Roughness[1,2] : R_a = 0.586 nm
where

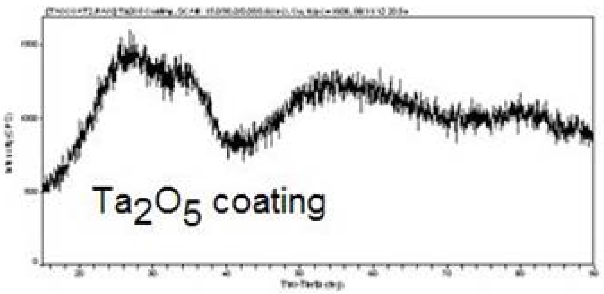
$$R_a = \frac{1}{N}\sum_{j=1}^{N}|Z_j|$$

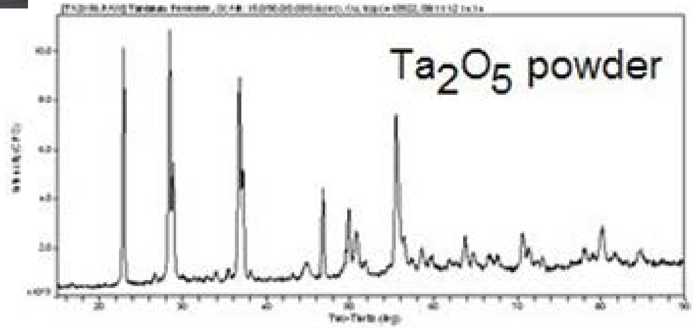
[1]ASME B46.12,"Surface Roughness, Waviness and Lay"
[2]ISO 25178.



Distribution of surface height deviations, $|Z_j|$.

Rachel D. McKinsey, *AAPM* Undergraduate *Fellow*, Southern University, 2004.



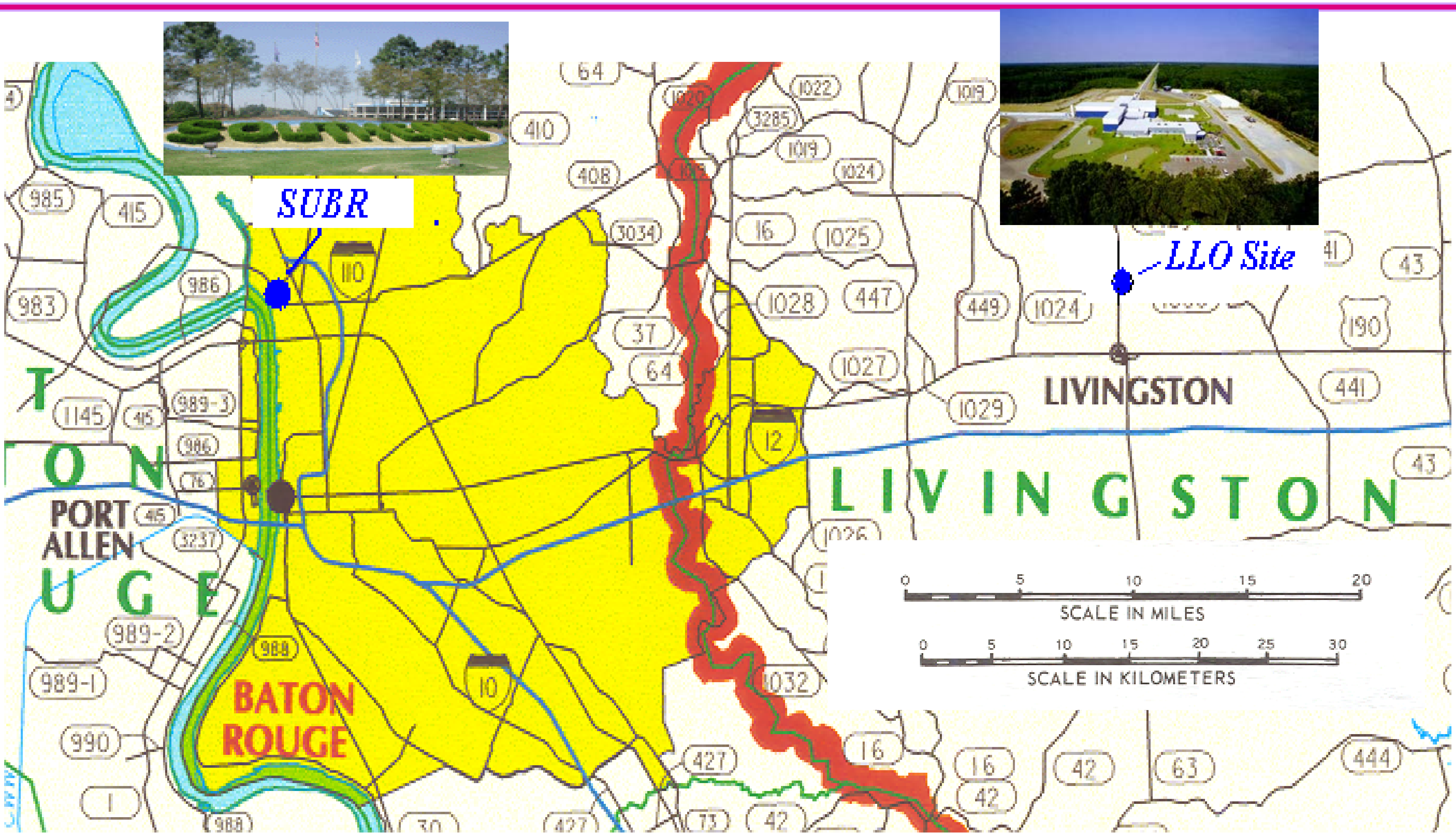


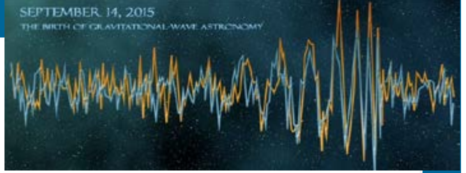
Ronald D. Alexander, “X-ray crystallographic studies of materials having optical applications”, *Southern University Honors College* thesis, 2012.

Science Education Outreach

Opportunities abound for formal and informal science education collaborations and partnerships between the BIG science of LIGO and the local and regional communities!!

Proximity of LIGO site to Southern University





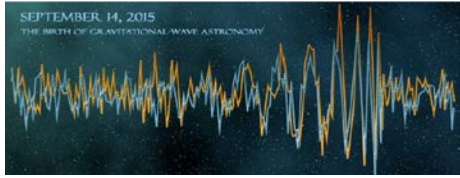
The LIGO Laboratory Charter (2002 - 2006)
October, 2001,
LIGO-M010213-01-M

Science Education Program

As a national facility based upon an exciting scientific research mission, LIGO can provide a focus for educational programs in science. A Science Education Program will reach beyond the traditional university role of educating undergraduate and graduate students to reaching K-12 grade level students. The managers of the Caltech, MIT, Hanford and Livingston groups will develop and lead programs in educational outreach to the general public, in on-site educational programs at the Observatory sites, as well as the university campuses, and in supporting program development consistent with other NSF educational initiatives.

LIGO Outreach

Local Educational Outreach Partnership

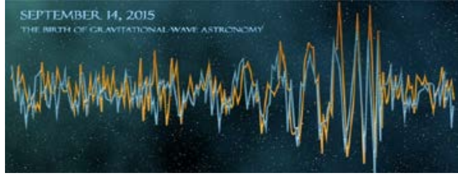


LIGO Science Education Center (SEC)

“Using Exhibit-Based Teaching and Learning to Enhance Science Literacy”

Local Educational Outreach Partnership

LIGO Science Education Center Partnership



“Using Exhibit-Based Teaching and Learning to Enhance Science Literacy”

MISSION

- **To develop a Center at the LIGO Livingston Observatory (LLO) equipped with interactive exhibits in LIGO–related science.**
- **To integrate the LLO Center, its exhibits and activities, into pre–service and in–service education at Southern University Baton Rouge (SUBR).**

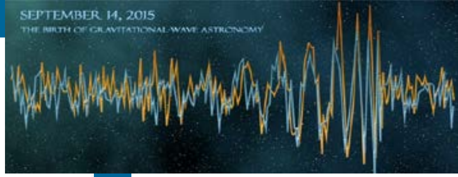
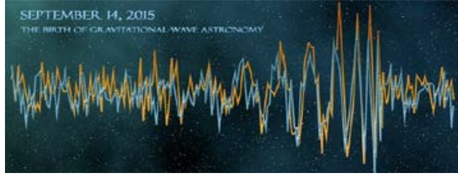


Exhibit training workshops

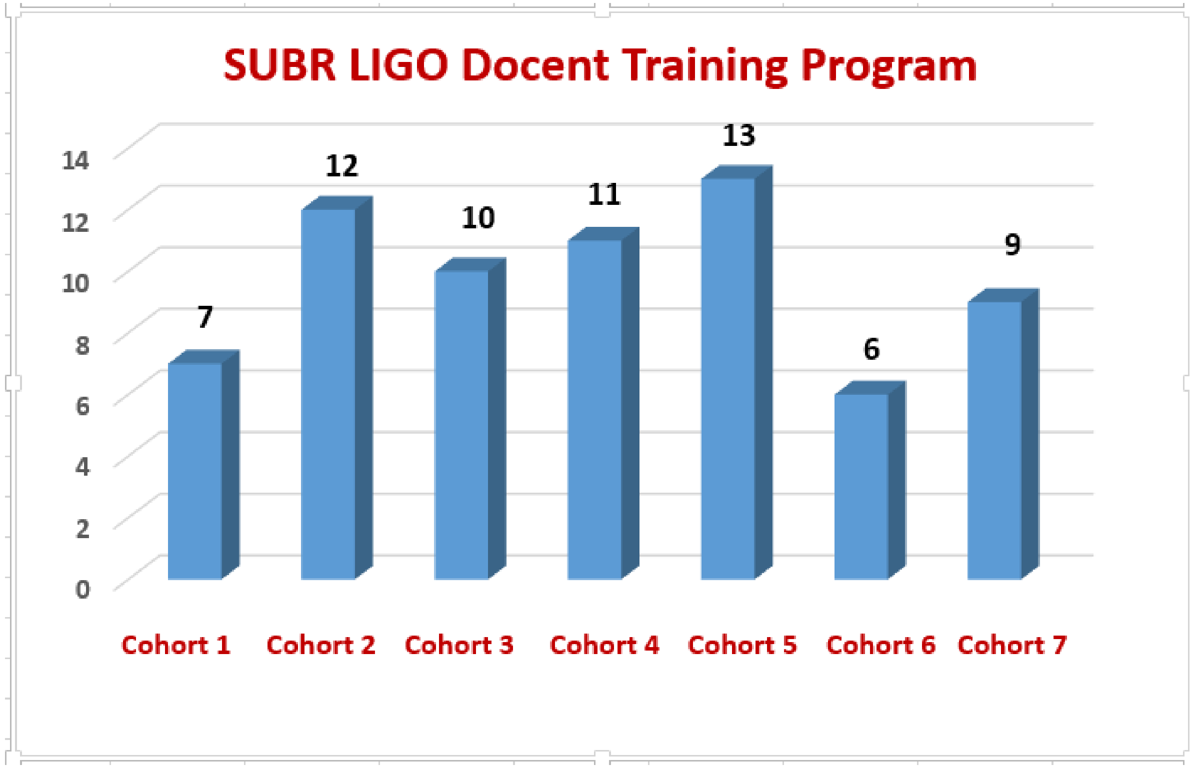
LIGO Outreach

Local Educational Outreach Partnership



Pre- and In-service teacher preparation and docent training

SUBR LIGO Docent Training Program*

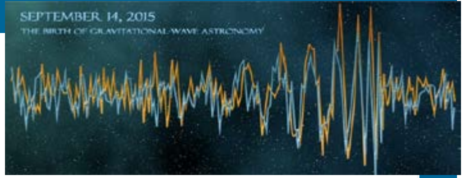


Disciplines Represented

Physics
Mathematics
Chemistry
Biology
Computer Science
Education
Mechanical Engineering
Electrical Engineering
Business
Agriculture
English

*Southern University at Baton Rouge (SUBR), Annual Collaborative Report (Phase II, Year 5) September 30, 2014, L. Young and J. Meyinsse.

http://www.aapt.org/abstractsearch/FullAbstract.cfm?KeyID=24069



Broadening Participation Going Forward

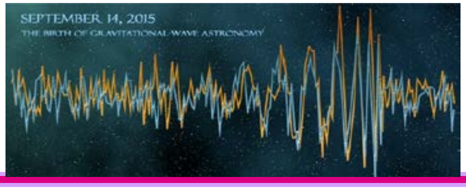
Phase III Funding: $2.5 M for 5 years ; NSF PHY-1506269

Goal:

- Strengthen teacher candidate training and clinical faculty professional development focused on inquiry based teaching and learning, using exhibits and "snacks."

Partners:

- LIGO Livingston Observatory (Livingston, LA)
- SUBR's Departments of Education, Physics, Mathematics, and Science/Mathematics Education Doctoral (SMED) Program
- San Francisco Exploratorium
- Southern University at New Orleans (SUNO)
- CORE Element (Coordinator of PD in the NOLA area)
- University of Glasgow, Scotland



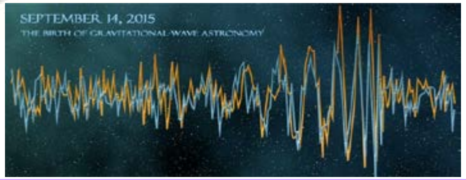
Summary

- The detection of gravitational waves from binary black hole mergers has given birth to the new field of gravitational-wave astronomy.
- Southern University occupies a unique role in the optical materials research and science education areas within Advanced LIGO.
- Significant improvements in our research infrastructure are being realized as a result of our collaboration with LIGO.
- Ongoing major enhancements to our science teacher preparation programs are being created and supported by the SUBR-LIGO Local Science Education Partnership.

Work supported by NSF Grants No(s). PHY-0101177, PHY-0701652 and PHY-0355471, Board of Regents Grant No. 05-231SUBR-CMSS

Partners, Collaborators and Supporters

LIGO Science Education Center (SEC)



From the Research Lab to Everyday Life

A Quick Look Back:

Nobel Prizes in Physics

1956 "……… discovery of the transistor" W. B. Shockley, J. Bardeen and W. H. Brattain

2000 "for basic work on communication technology" Z. I. Alferon and H. Kramer; Jack Kilby "for his part in the invention of the integrated circuit"

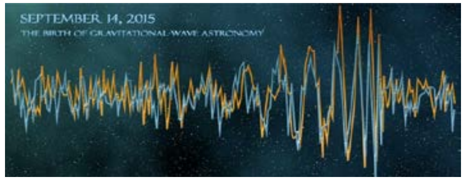
2007 "for the discovery of Giant Magnetoresistance" A Fert and P. Grünberg

2009 "for the invention of an imaging semiconductor circuit - the CCD sensor" W. Boyle and G. E. Smith

1981 "contributions to laser spectroscopy" M. Bloembergen and A. L. Schawlow

Lastly, let us not forget that the proper function of the GPS system relies upon Einstein's relativity!

LIGO



Meanwhile, stay tuned … this is just the beginning!

SOUTHERN UNIVERSITY And Agricultural & Mechanical College

INCORPORATED 1880 RELOCATED 1914

Thank You!!

Work supported by NSF Grants No(s).

PHY-0101177, PHY-0701652 and PHY-0355471

Board of Regents Grant No. 05-231SUBR-CMSS