

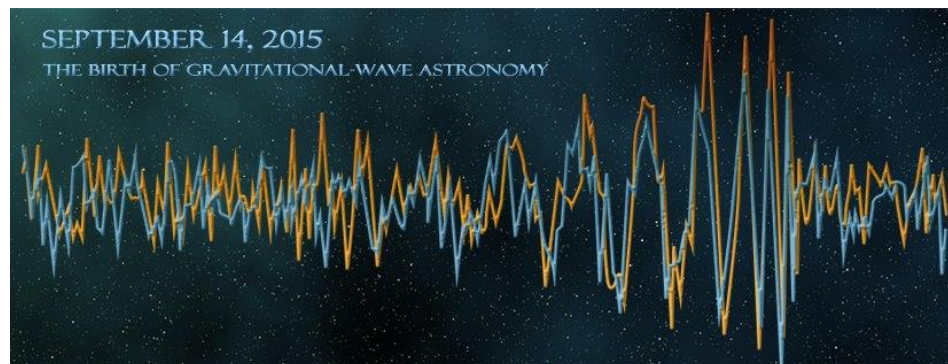
# Searching for – and finding! gravitational waves

Gabriela González

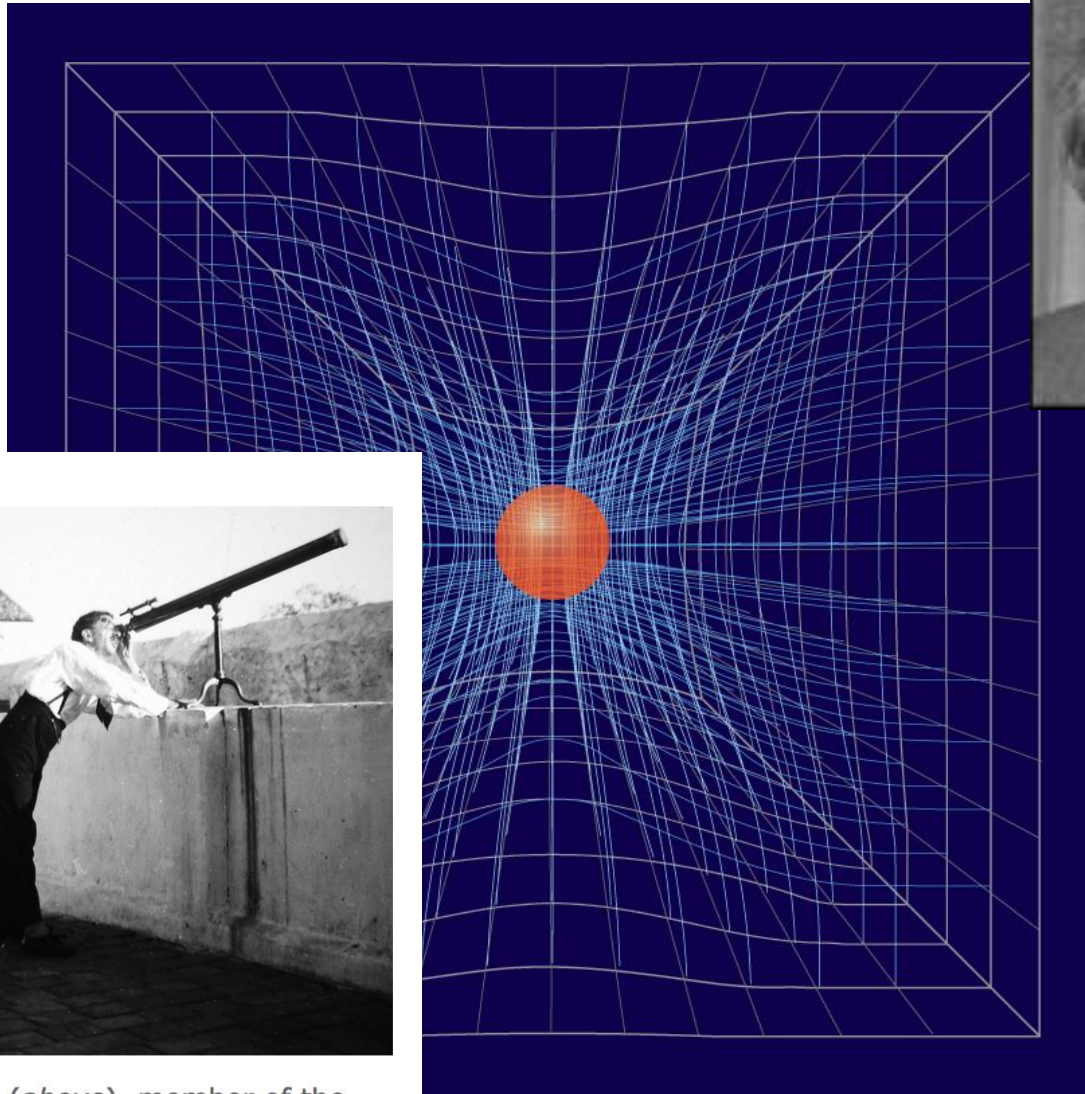
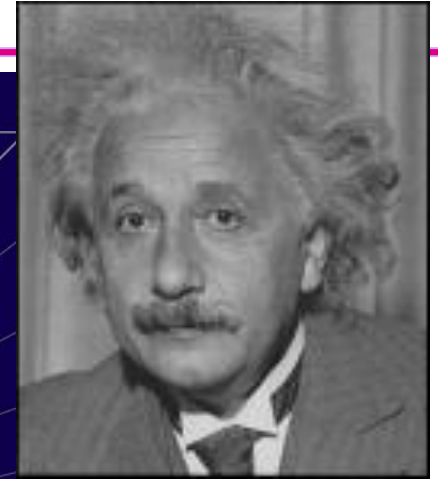
Louisiana State University



Annual meeting, May 8 2018, Rio de Janeiro



# Einstein's gravity



© NATIONAL OBSERVATORY



Astronomer Teófilo H. Lee (*above*), member of the Brazilian team in Sobral, made spectroscopic observations of the Sun's corona

Credit: Aurore Simonnet,  
E/PO Sonoma State University

# Einstein's gravity

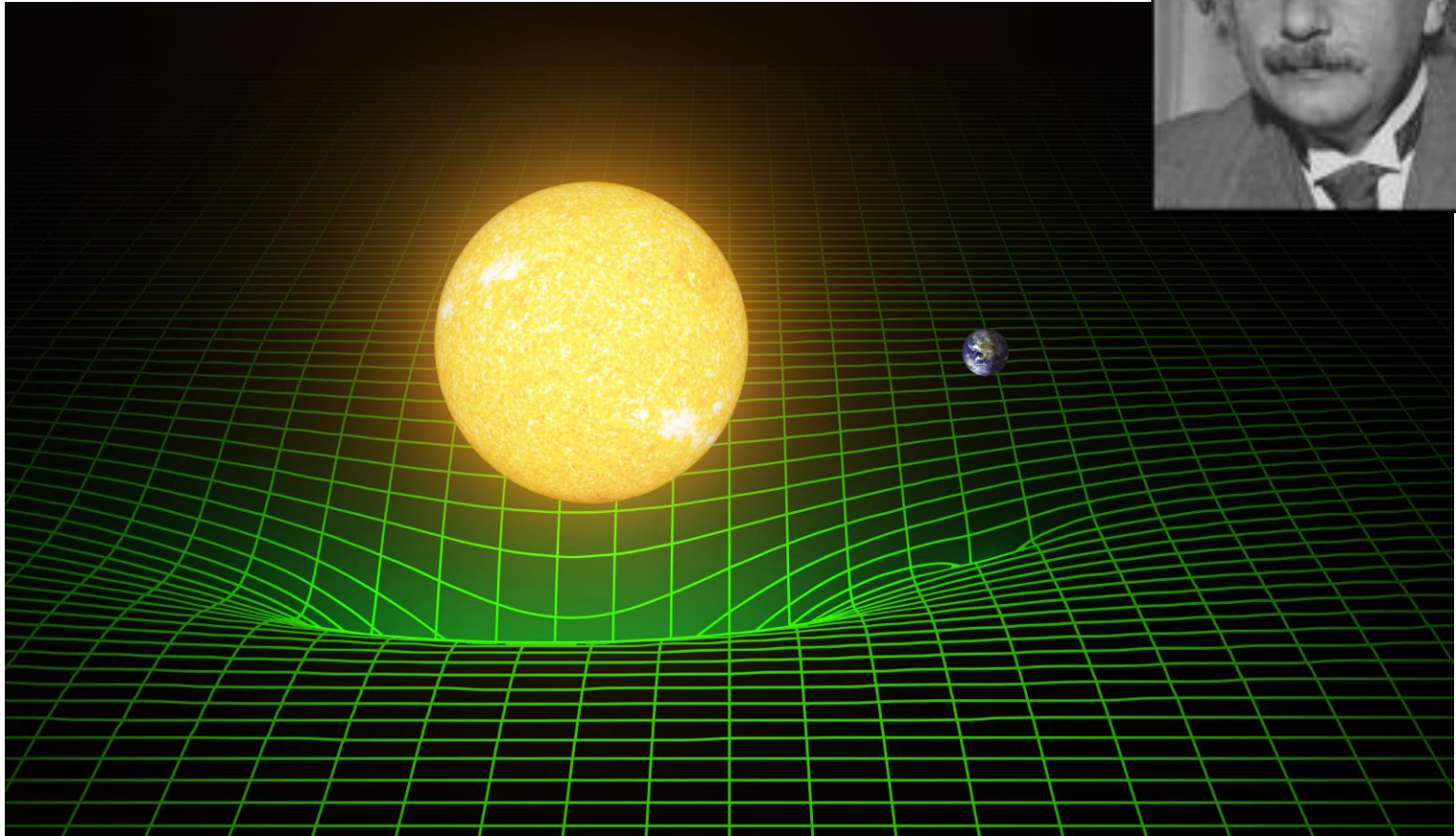
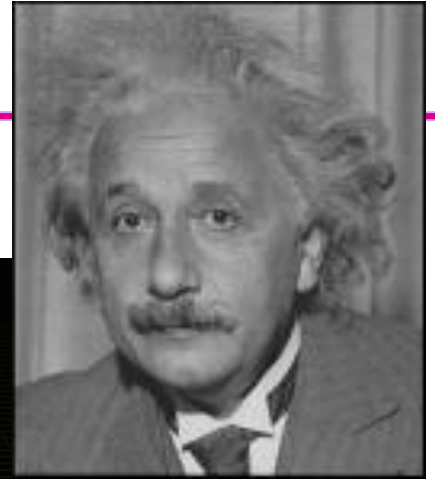


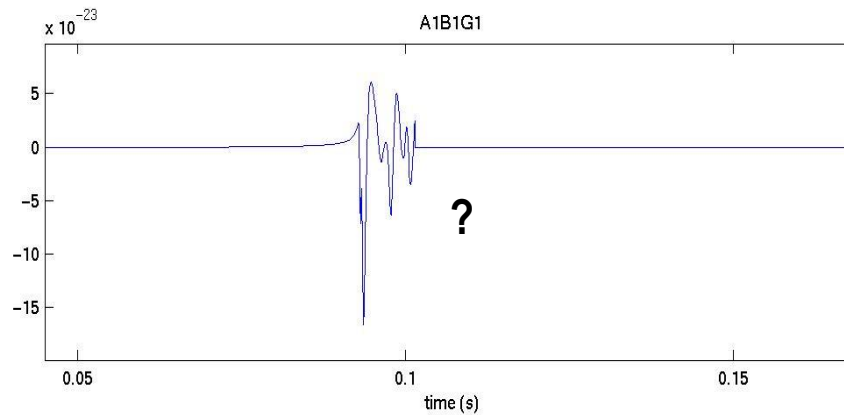
Image Credit: T. Pyle/Caltech/MIT/LIGO Lab

# Searching for gravitational waves



Short transients from  
supernova explosions  
or other sources

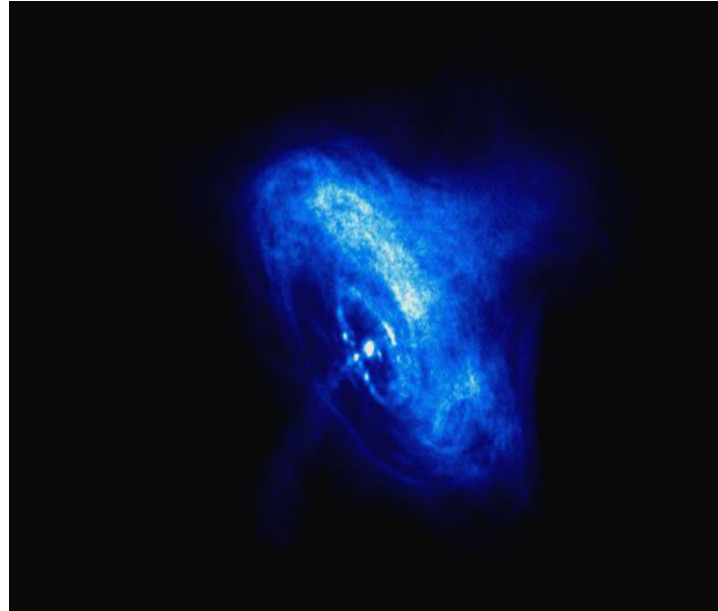
W49B composite;  
X-ray: NASA/CXC/MIT/L.Lopez et al.;  
Infrared: Palomar; Radio:  
NSF/NRAO/VLA



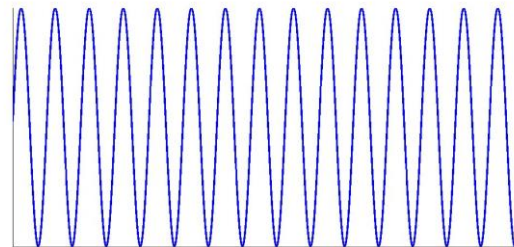


# Searching for gravitational waves

Periodic, continuous waves



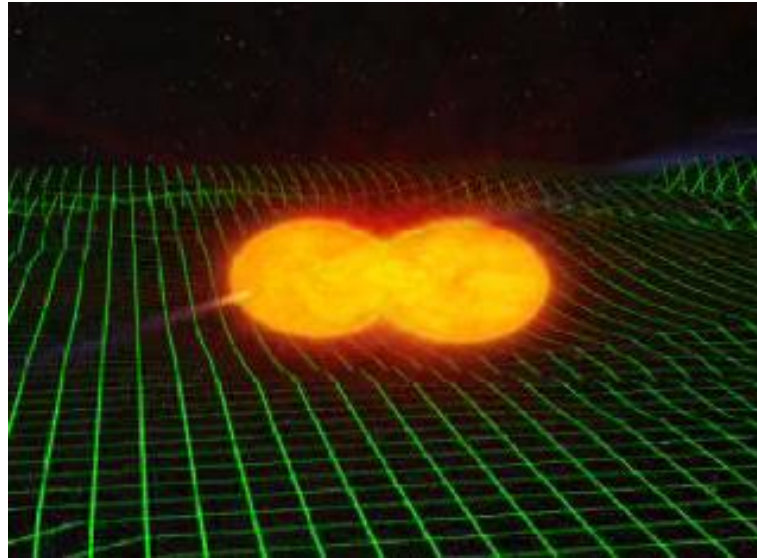
Crab pulsar (NASA, Chandra Observatory)



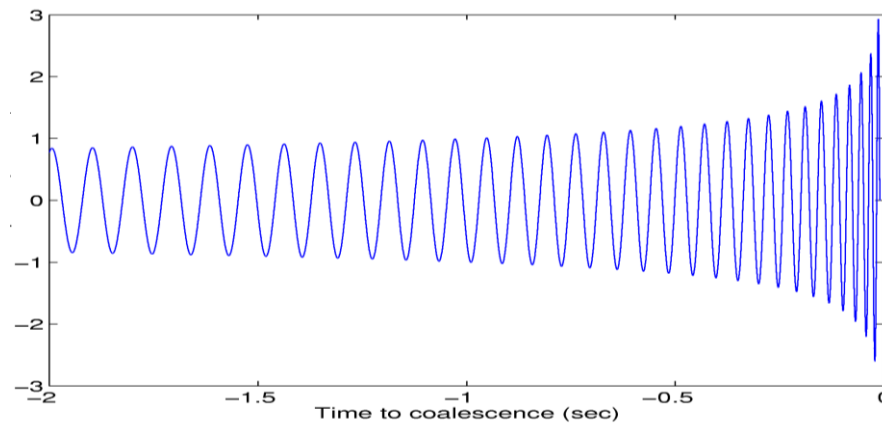
[Einsteinathome.org](http://Einsteinathome.org)

# Searching for gravitational waves

Binary systems

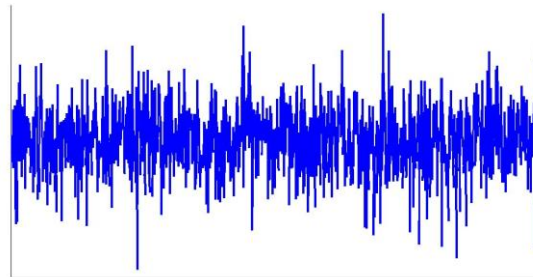
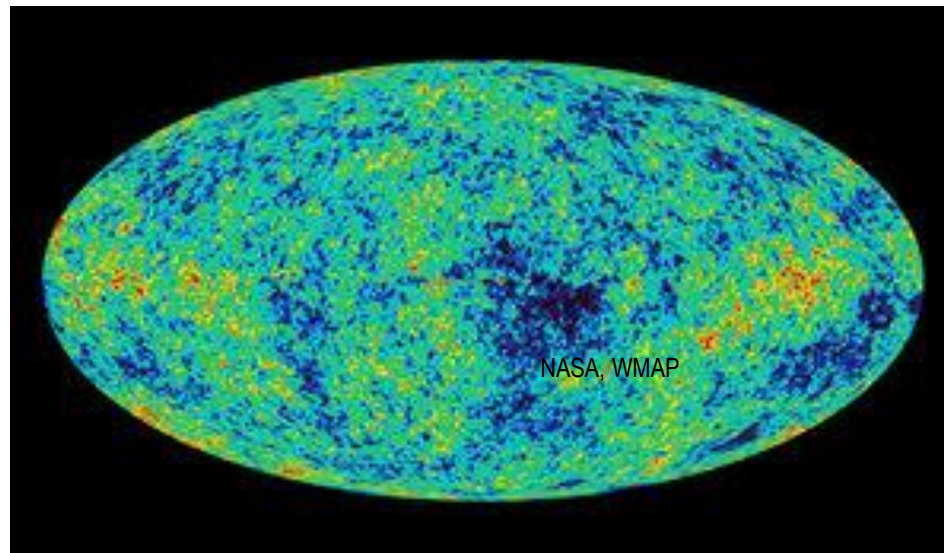


Credit: John Rowe

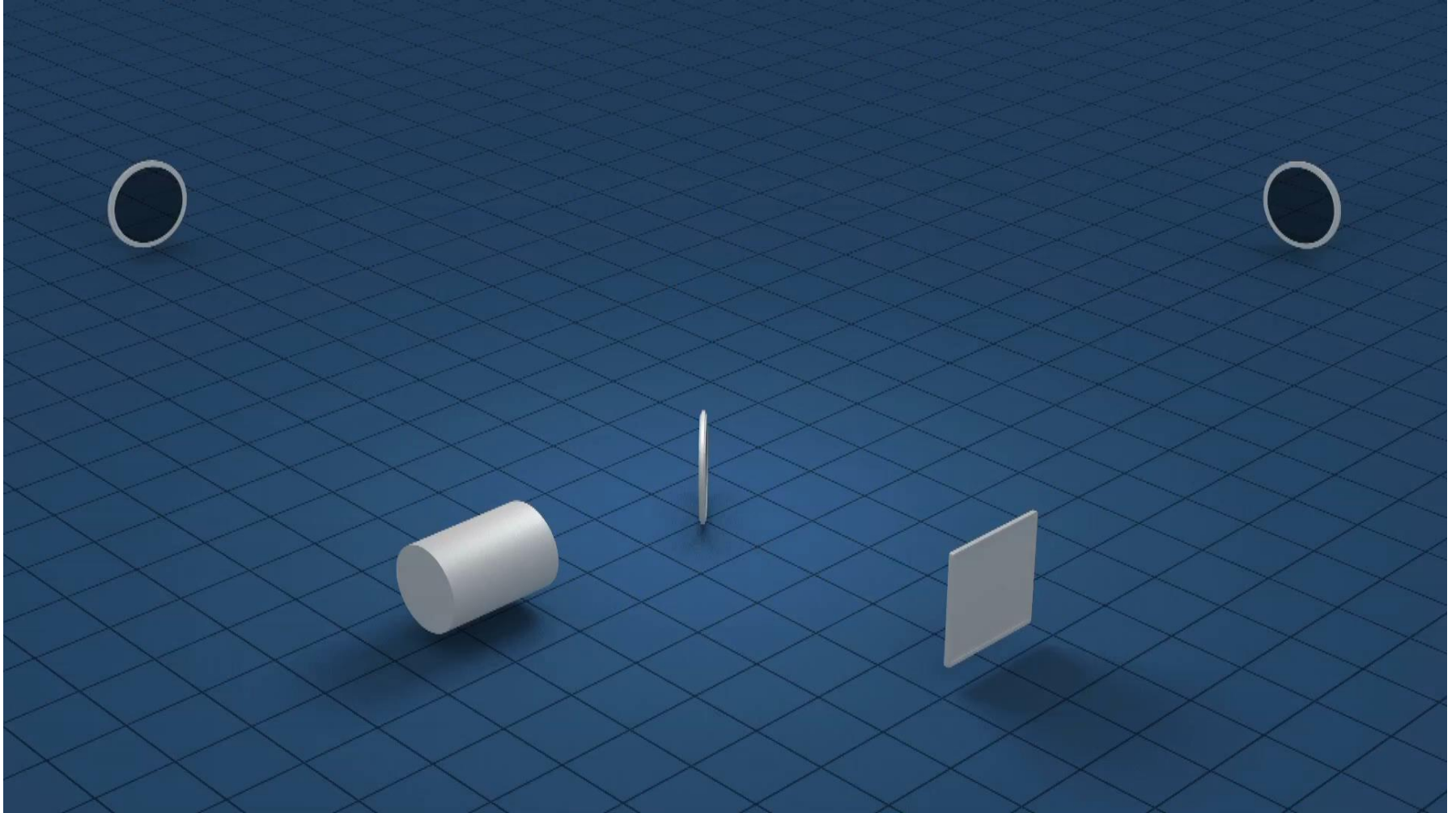


# Searching for gravitational waves

Stochastic background from many unresolved sources, or from the beginning of the Universe



# How to detect gravitational waves: interferometer



Credit: LIGO/T. Pyle



# The LIGO Observatories



LIGO Hanford Observatory (LHO)

H1 : 4 km arms

H2 : 2 km arms



10 ms

LIGO Livingston Observatory (LLO)

L1 : 4 km arms



• Adapted from “The Blue Marble: Land Surface, Ocean Color”

• NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water color, compositing, 3D globes, animation). Data and technical support: MODIS Land (Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

nasa.gov

Common (ocean  
n; MODIS  
ensing Flagstaff



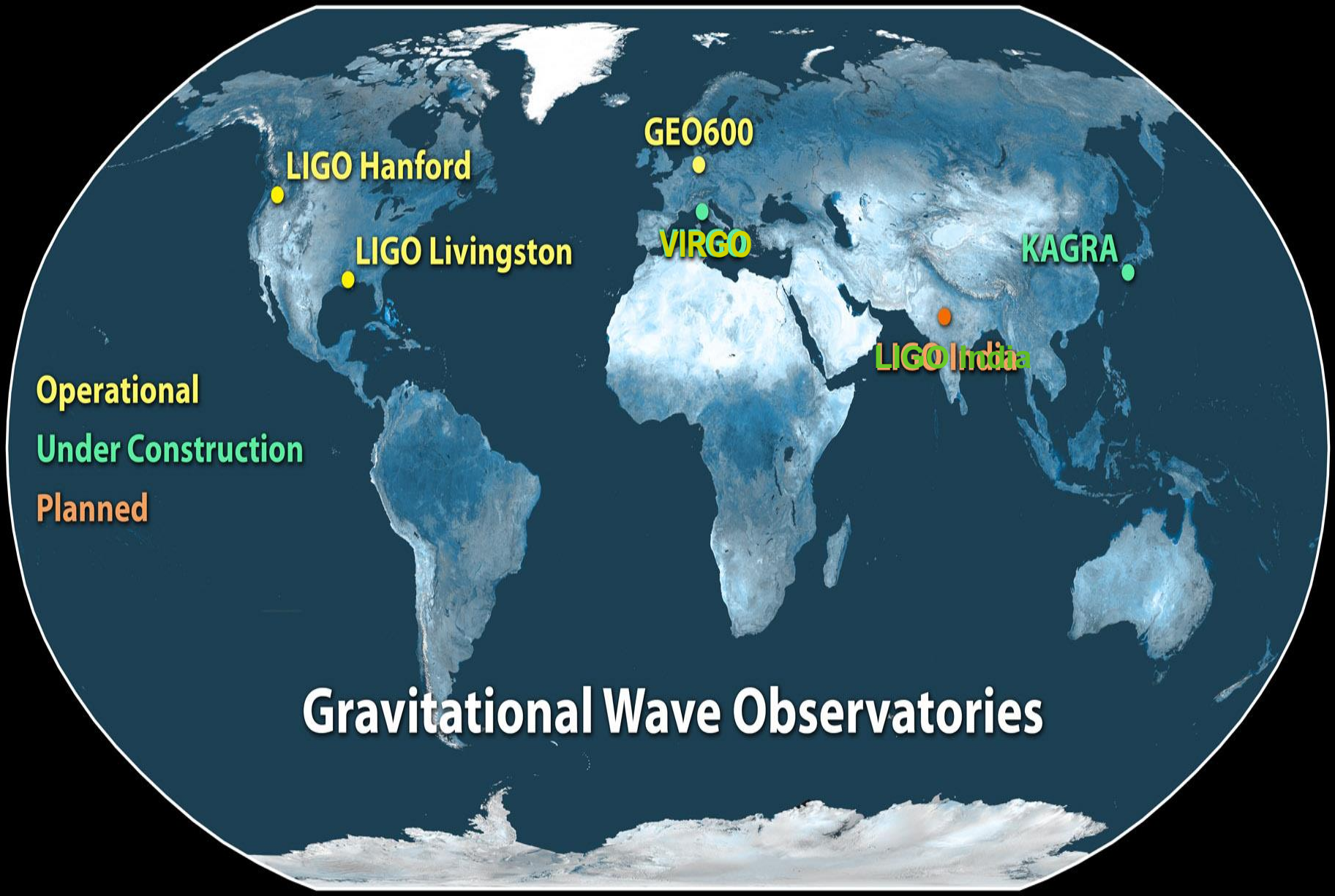
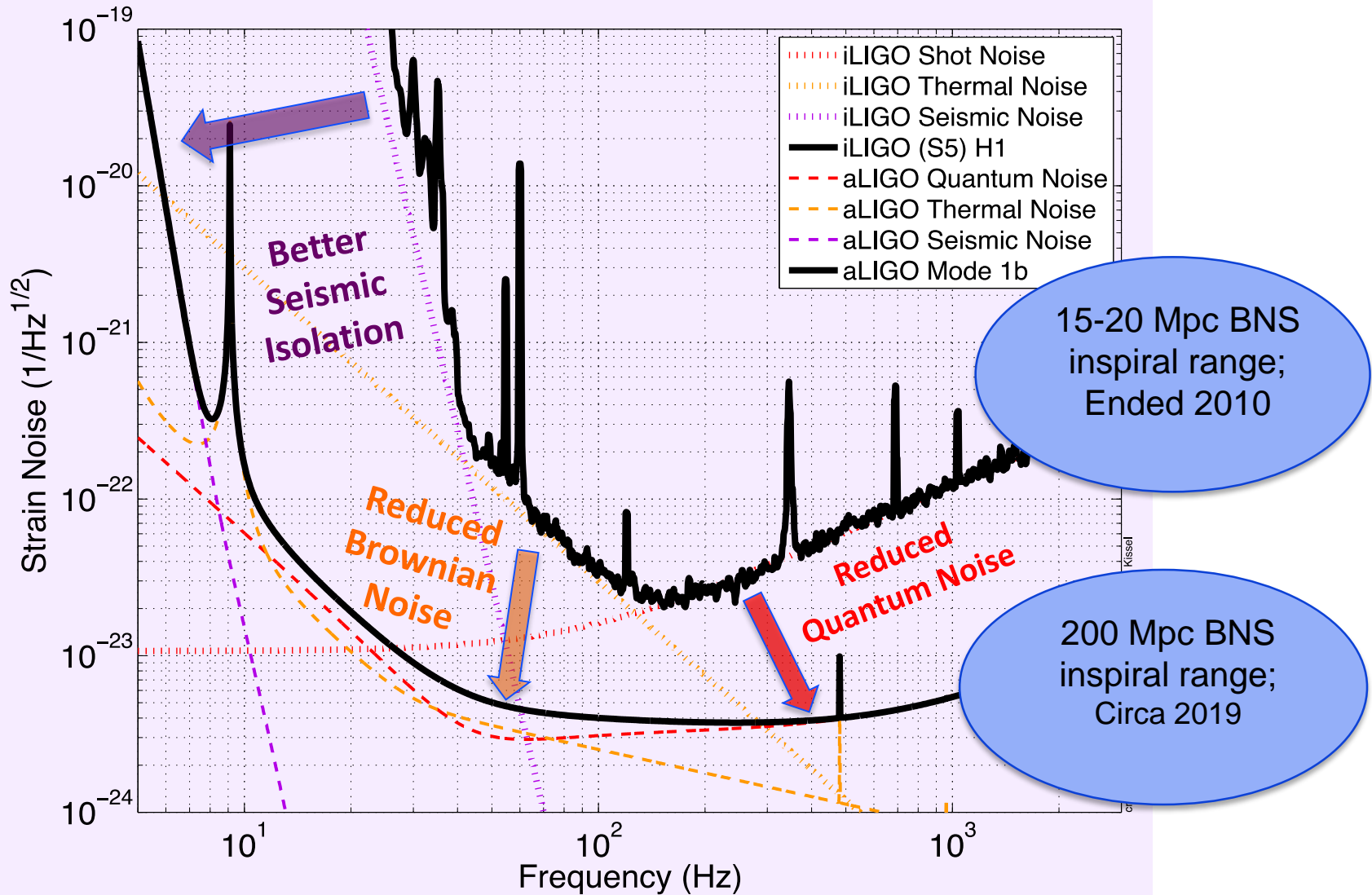
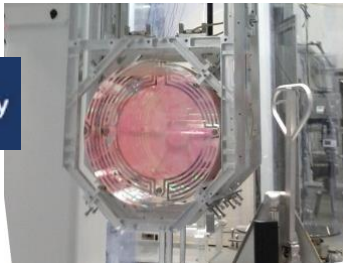
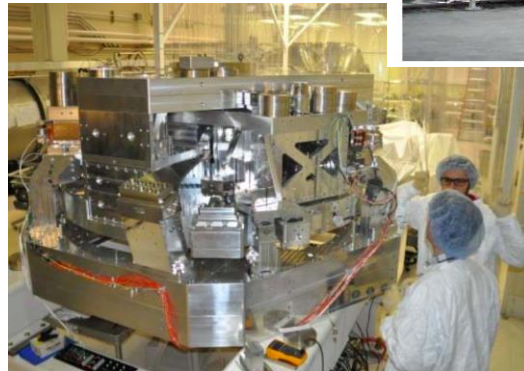
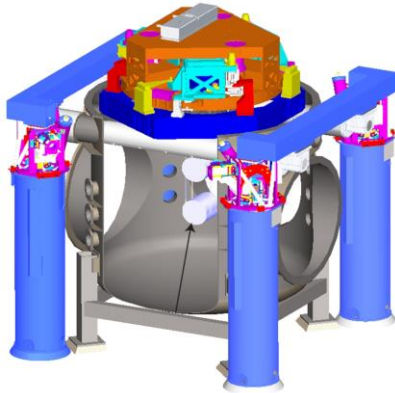
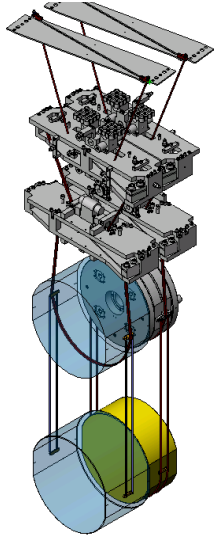
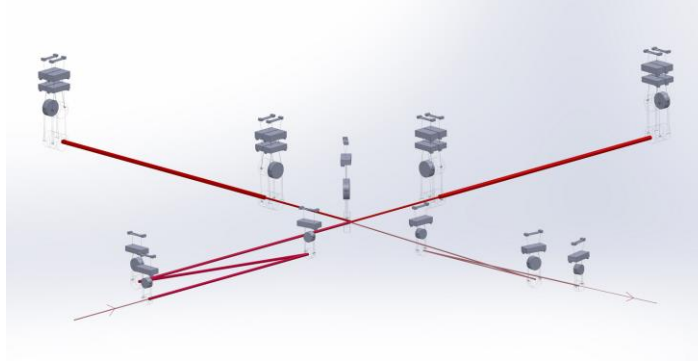


Image Credit: Caltech/MIT/LIGO Lab

# Initial (2001-2010) and advanced (2015+) LIGO



# 2008+: Advanced LIGO detectors





# February 11, 2016: We did it!



## O ESTADO DE S. PAULO

SEXTA-FEIRA

### Governo adia corte e agrava temor sobre política fiscal

Antes do contingenciamento definitivo dos gastos do Orçamento-fca para março, mercado engor...

### Brasil e EUA fecham acordo para vacina contra zika

Dois acordos comerciais foram assinados nesta quinta-feira (10) entre o Brasil e os Estados Unidos para a produção de uma vacina contra o vírus Zika. O acordo prevê a transferência de tecnologia e a produção de milhões de doses para o Brasil.

### Após cem anos, cientistas detectam ondas gravitacionais de Einstein

Dois buracos negros colidiram há 1,3 bilhão de anos, gerando ondas gravitacionais que foram detectadas pela primeira vez. A descoberta confirma uma das últimas grandes previsões da teoria da relatividade geral de Albert Einstein.

## O GLOBO

### Albert Einstein estava certo

Previsões confirmadas após cem anos

### Com previsão de novo rombo, governo não sabe onde cortar

Decisão sobre contingenciamento de gastos é adiada para março

## CORREIO BRAZILIENSE

### Pais aposta em vacina para deter zika virus

### Violência global contra mulheres

### Assassinos de PM pagam 58 anos de prisão

### Brasilândia declara guerra à dengue

### Lula será interrogado por Moro

### Temer se defende atacando o PSDB

### Serviçores Preciso total por reajuste

# O senhor do universo

O descobrimento de uma nova galáxia, Einstein, muito à frente de seu tempo. Não é isso que, apenas agora, um grupo de cientistas locais tentou mostrar com entusiasmo à detecção das ondas gravitacionais previstas por Albert Einstein um século atrás, quando ele apresentou a Teoria da Relatividade Geral. O fato, uma das mais importantes descobertas científicas da história, inaugura uma nova forma de estudar o Cosmos e é o teste definitivo do Princípio da Física. "Esta grande marca e o nascimento de um domínio físico novo como a gravitação, começaram no momento em que Galileu apontou pela primeira vez seu telescópio para o céu", diz Franco Carbone, diretor da Fundação Nacional de Ciências dos Estados Unidos.



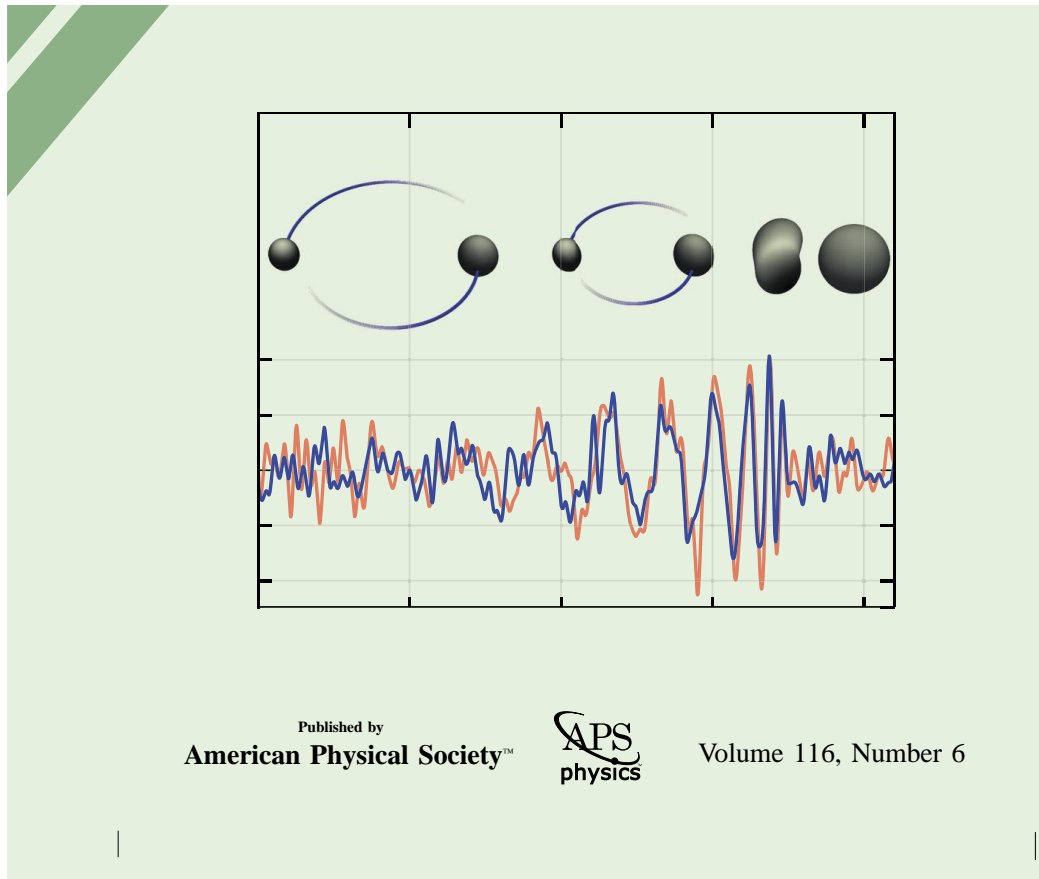


# Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*\*

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



Published by  
American Physical Society™



Volume 116, Number 6



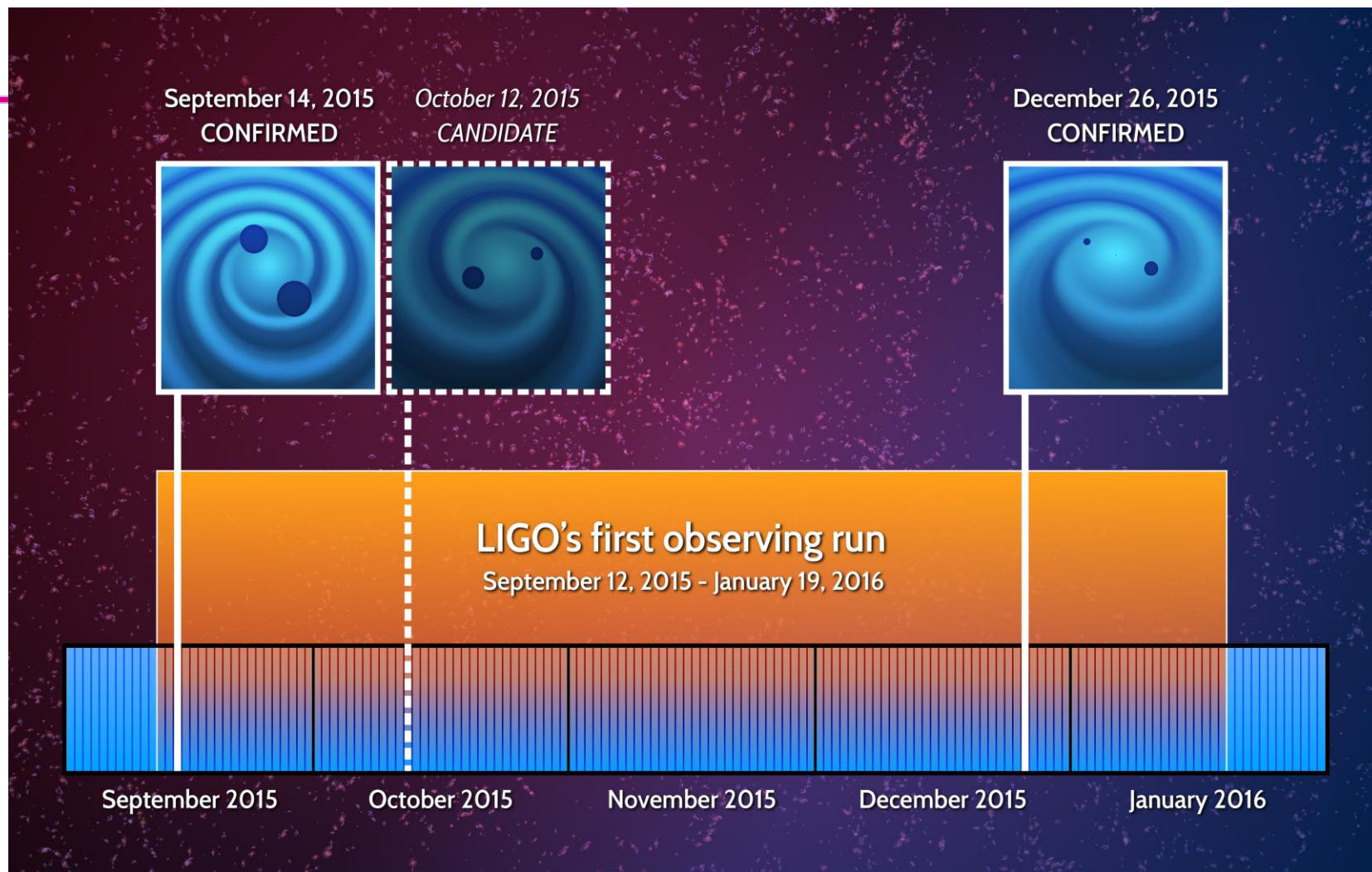
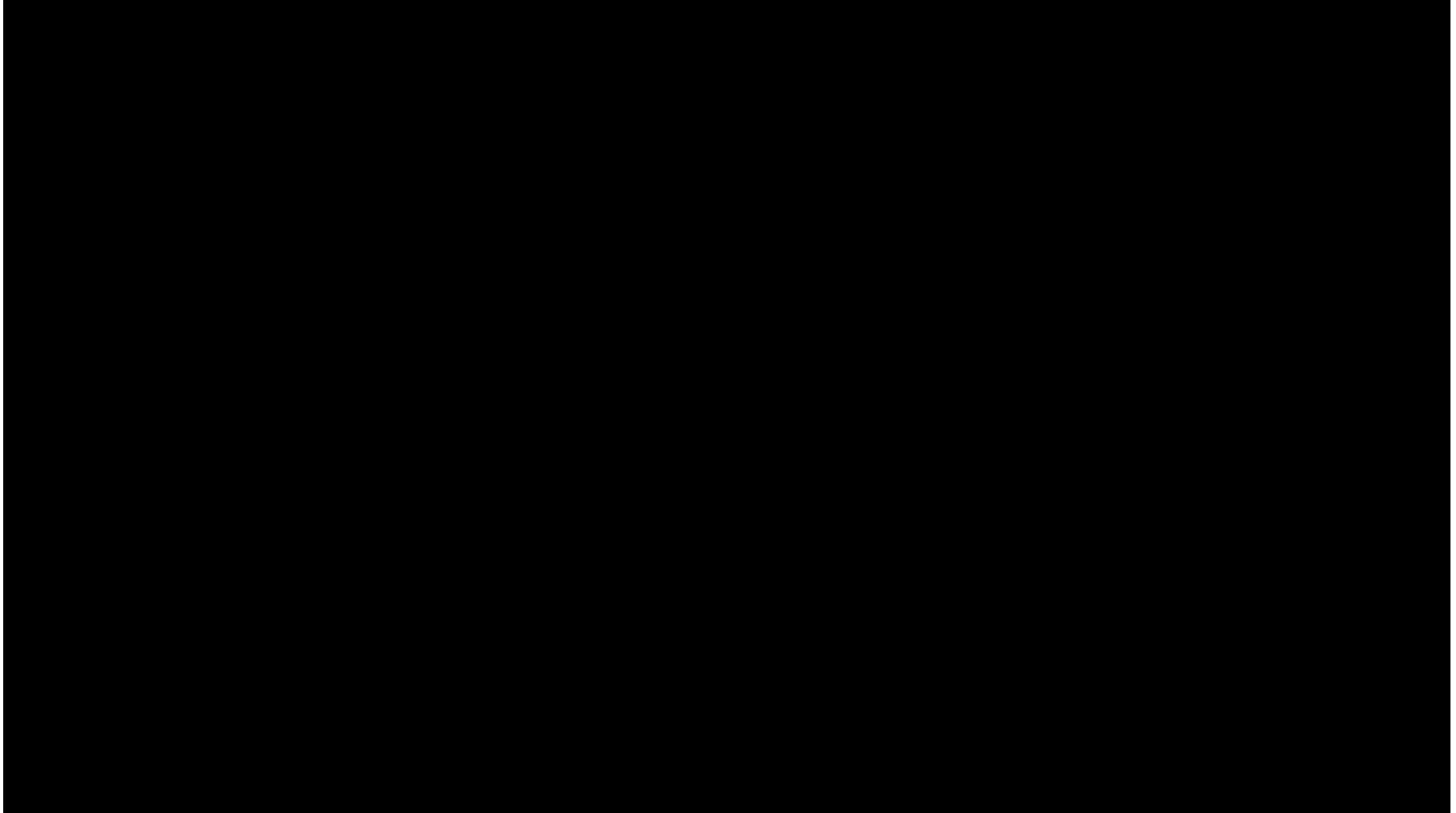


Image credit: LIGO



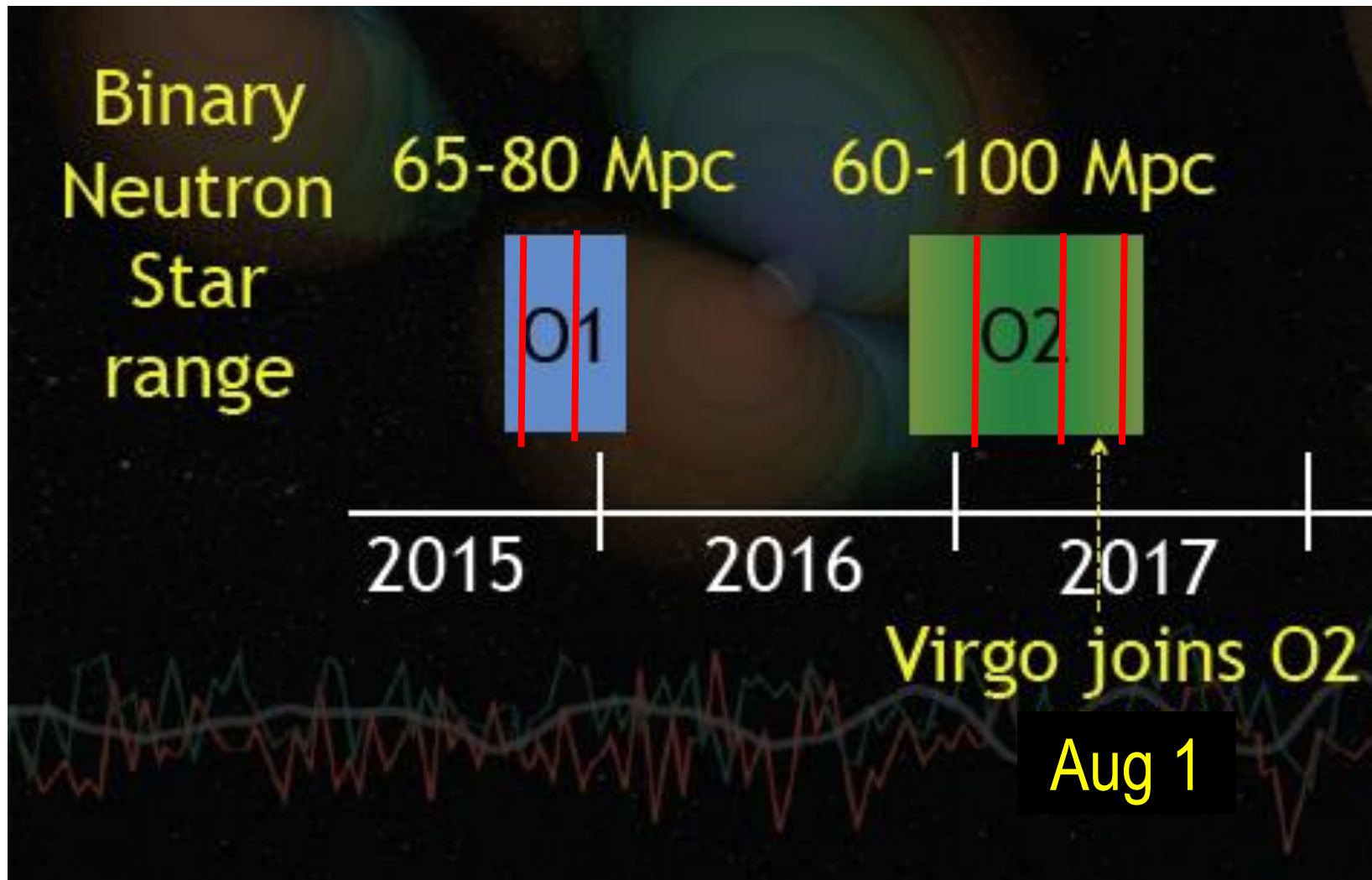
# Gravity's symphony: first two notes

---

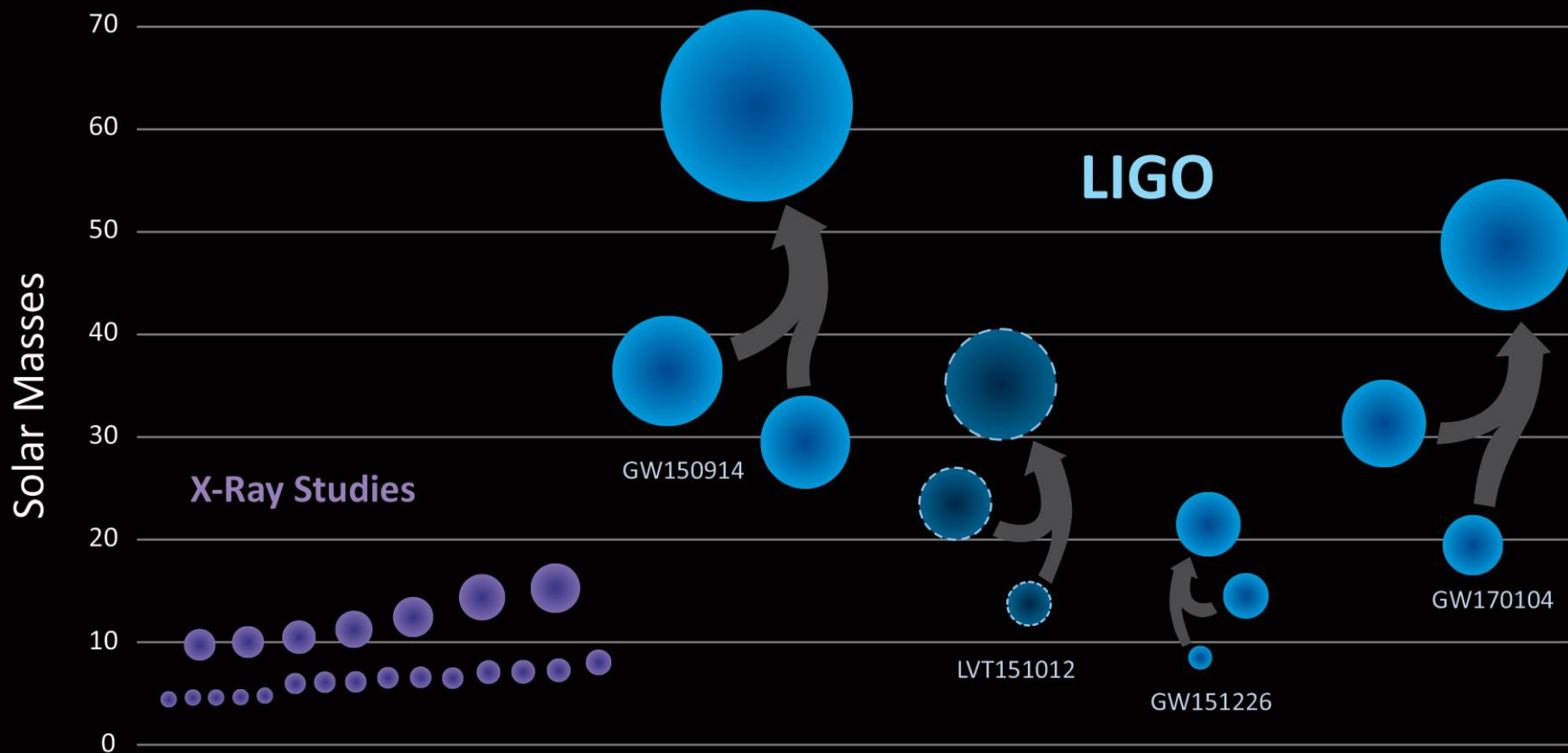


Credit: LIGO

# Nov 30, 2016: O2 started



# Black Holes of Known Mass

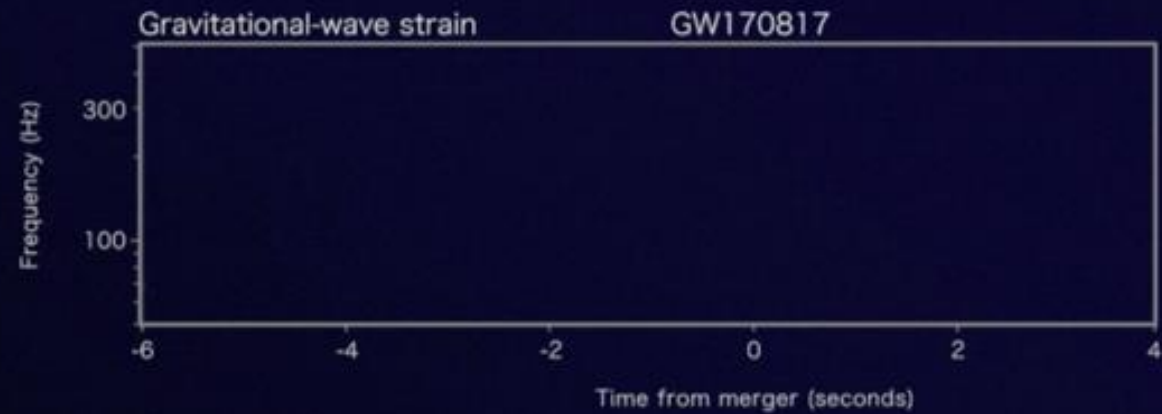


# September 17, 2017

Fermi



LIGO



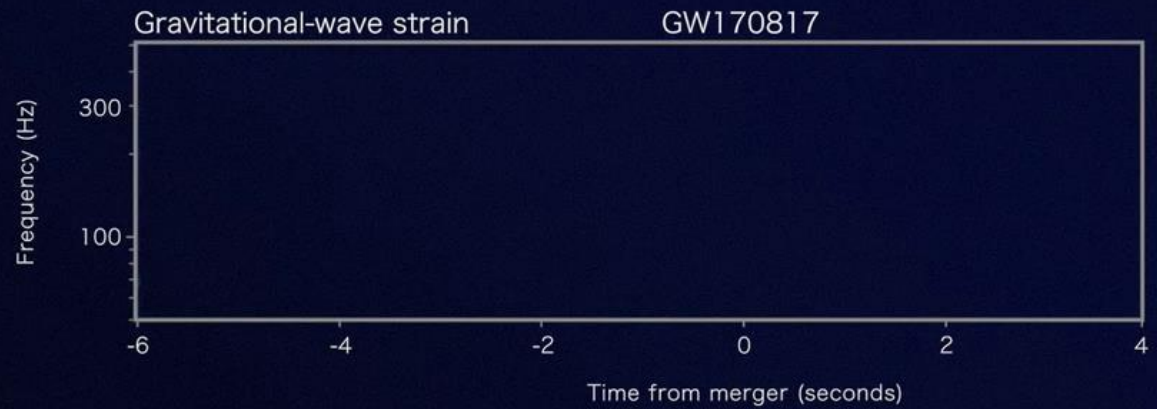


# September 17, 2017

Fermi

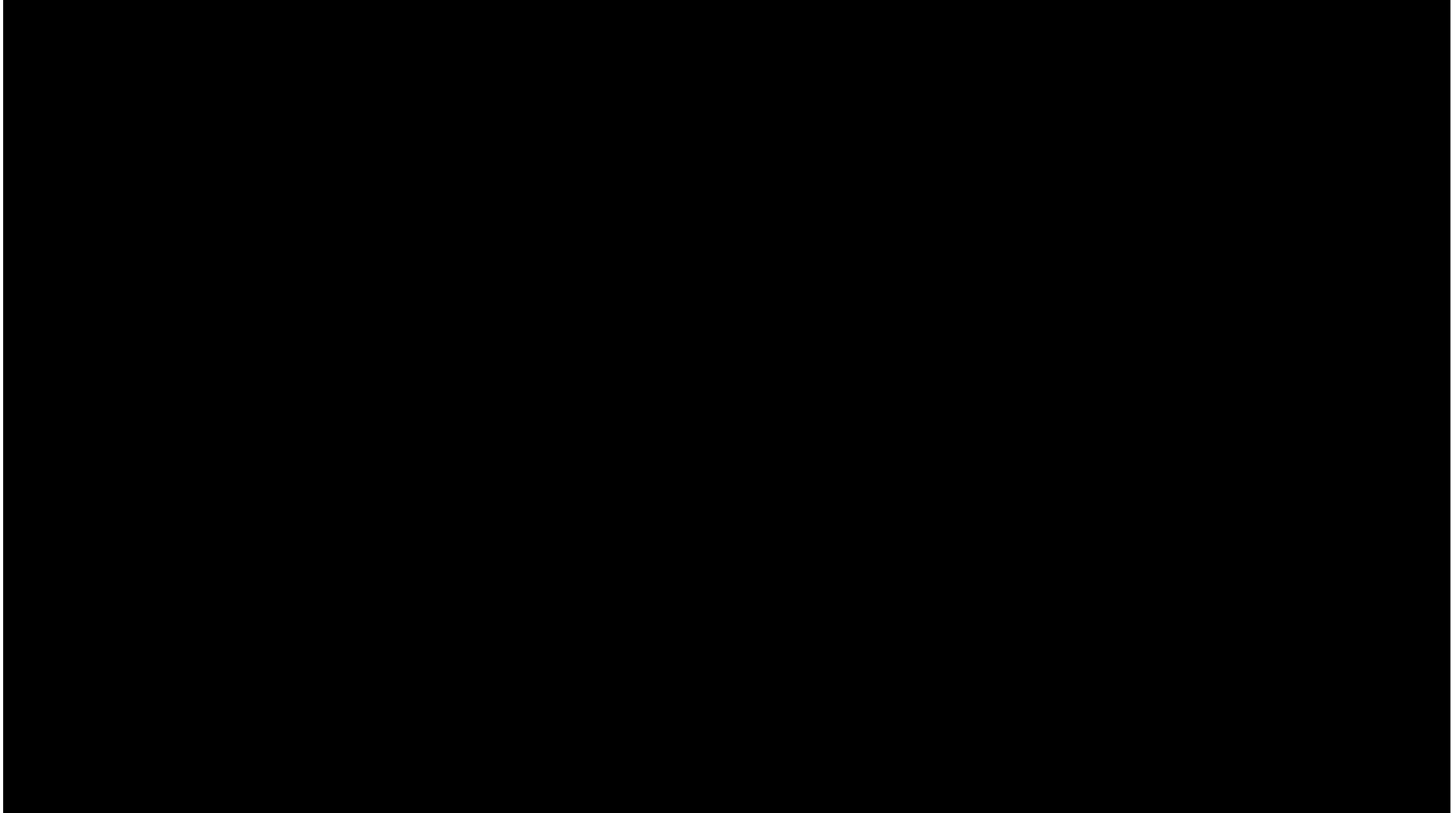


LIGO

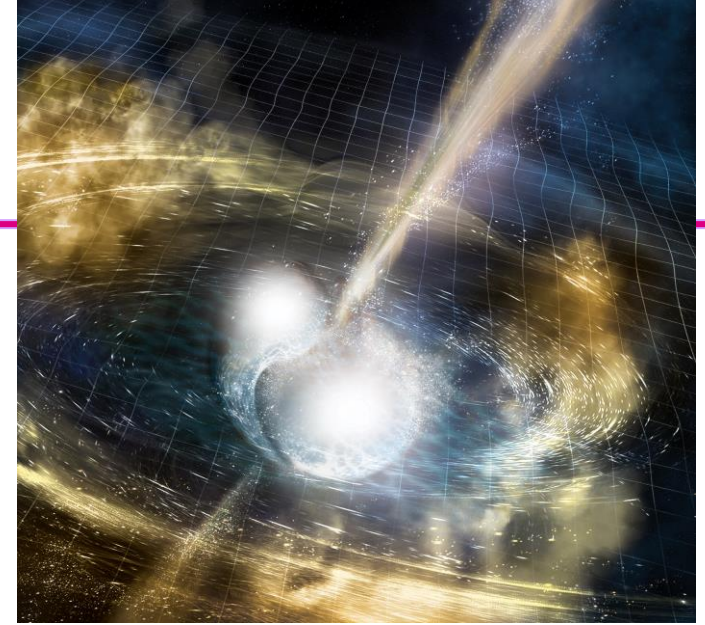


# Binary Neutron Star merger: the movie

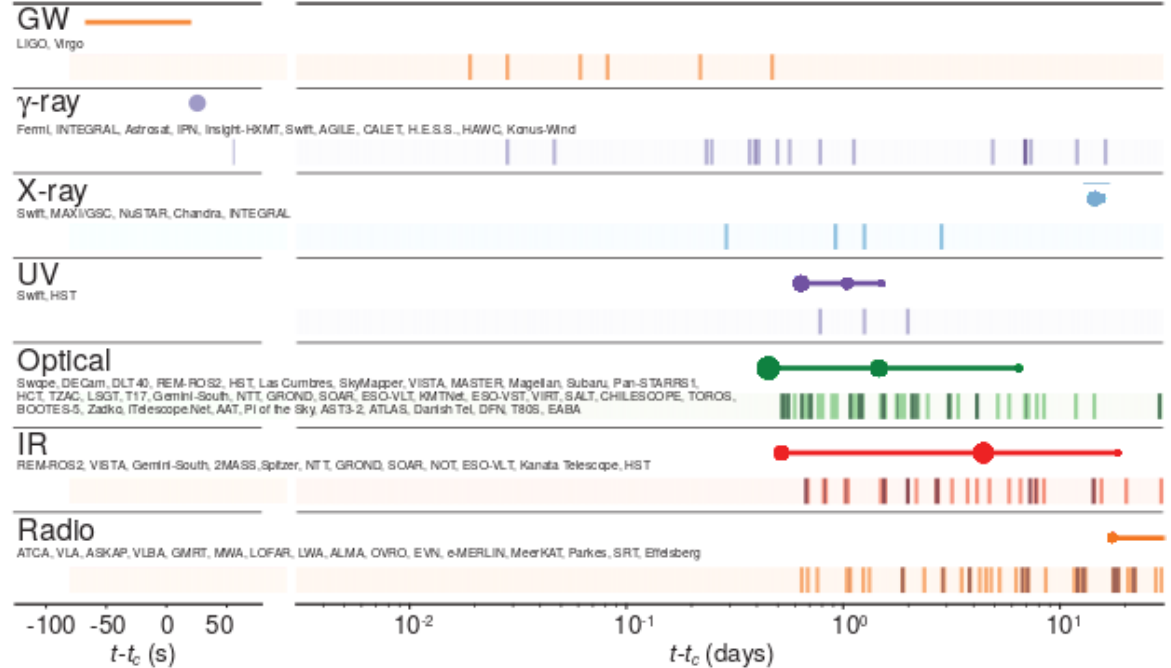
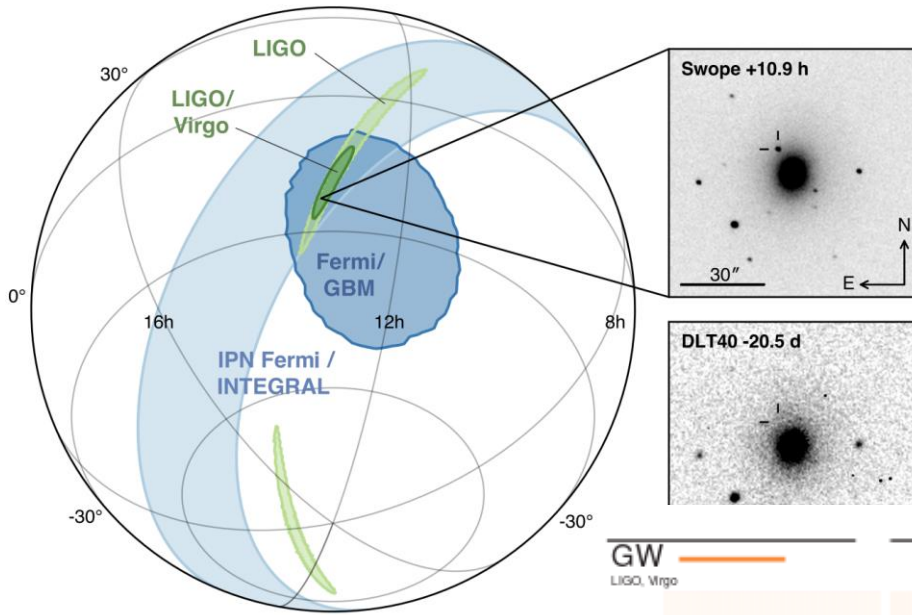
---



# A kilonova rainbow




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





# Gravitational *and* Electromagnetic waves!

PRL 119, 161101 (2017)

 Selected for a Viewpoint in *Physics*  
PHYSICAL REVIEW LETTERS

week ending  
20 OCTOBER 2017



## GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*\*

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20

<https://doi.org/10.3847/2041-8213/aa91c9>

© 2017. The American Astronomical Society. All rights reserved.

**OPEN ACCESS**



## Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAVitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT  
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

# The TOROS Collaboration

M. C. Díaz<sup>690</sup>, L. M. Macri<sup>691</sup>, D. García Lambas<sup>692</sup>, C. Mendes de Oliveira<sup>693</sup>, J. L. Nilo Castellón<sup>694,695</sup>, T. Ribeiro<sup>696</sup>, B. Sánchez<sup>692</sup>, W. Schoenell<sup>693,697</sup>, L. R. Abramo<sup>698</sup>, S. Akras<sup>699</sup>, J. S. Alcaniz<sup>699</sup>, R. Artola<sup>692</sup>, M. Beroiz<sup>690</sup>, S. Bonoli<sup>700</sup>, J. Cabral<sup>692</sup>, R. Camuccio<sup>690</sup>, V. Chavushyan<sup>701</sup>, P. Coelho<sup>693</sup>, C. Colazo<sup>692</sup>, M. V. Costa-Duarte<sup>693</sup>, H. Cuevas Larenas<sup>695</sup>, M. Domínguez Romero<sup>692</sup>, D. Dultzin<sup>702</sup>, D. Fernández<sup>703</sup>, J. García<sup>690</sup>, C. Girardini<sup>692</sup>, D. R. Gonçalves<sup>704</sup>, T. S. Gonçalves<sup>704</sup>, S. Gurovich<sup>692</sup>, Y. Jiménez-Teja<sup>699</sup>, A. Kanaan<sup>697</sup>, M. Lares<sup>692</sup>, R. Lopes de Oliveira<sup>696,705</sup>, O. López-Cruz<sup>701</sup>, R. Melia<sup>692</sup>, A. Molino<sup>693</sup>, N. Padilla<sup>703</sup>, T. Peñuela<sup>690,706</sup>, V. M. Placco<sup>707,708</sup>, C. Quiñones<sup>692</sup>, A. Ramírez Rivera<sup>695</sup>, V. Renzi<sup>692</sup>, L. Riguccini<sup>704</sup>, E. Ríos-López<sup>701</sup>, H. Rodríguez<sup>692</sup>, L. Sampedro<sup>693</sup>, M. Schneider<sup>692</sup>, L. Sodré<sup>693</sup>, M. Starck<sup>692</sup>, S. Torres-Flores<sup>695</sup>, M. Tornatore<sup>692</sup>, A. Zdrożny<sup>690</sup>,  
(TOROS: Transient Robotic Observatory of the South Collaboration),

<sup>690</sup> Center for Gravitational Wave Astronomy and Department of Physics & Astronomy, University of Texas—Río Grande Valley, Brownsville, TX, USA

<sup>691</sup> George P. and Cynthia W. Mitchell Institute for Fundamental Physics & Astronomy, Department of Physics & Astronomy, Texas A&M University, College Station, TX, USA

<sup>692</sup> IATE-OAC, Universidad Nacional de Córdoba-CONICET, Córdoba, Argentina

<sup>693</sup> Instituto de Astronomia, Geofísica e Ciências Atmosféricas da U. de São Paulo, São Paulo, SP, Brazil

<sup>694</sup> Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, Universidad de La Serena, La Serena, Chile

<sup>695</sup> Departamento de Física y Astronomía, Universidad de La Serena, La Serena, Chile

<sup>696</sup> Departamento de Física, Universidade Federal de Sergipe, São Cristóvão, SE, Brazil

<sup>697</sup> Departamento de Física, Universidade Federal de Santa Catarina, Florianópolis, SC, Brazil

<sup>698</sup> Departamento de Física Matemática, Instituto de Física, Universidade de São Paulo, São Paulo, SP, Brazil

<sup>699</sup> Departamento de Astronomia, Observatório Nacional, Rio de Janeiro, RJ, Brazil

<sup>700</sup> Centro de Estudios de Física del Cosmos de Aragón, E-44001 Teruel, Spain

<sup>701</sup> Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, México

<sup>702</sup> Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad de México, México

<sup>703</sup> Instituto de Astrofísica, Pontificia Universidad Católica de Chile, Santiago, Chile

<sup>704</sup> Observatorio do Valongo, Universidade Federal do Rio de Janeiro, Ríó de Janeiro, RJ, Brazil

<sup>705</sup> X-ray Astrophysics Laboratory and CRESST, NASA Goddard Space Flight Center, Greenbelt, MD, USA

<sup>706</sup> Ludwig Maximilian Universität Munich, Faculty of Physics, Munich, Germany

<sup>707</sup> Department of Physics, University of Notre Dame, Notre Dame, IN, USA

<sup>708</sup> Joint Institute for Nuclear Astrophysics—Center for the Evolution of the Elements, USA

# Press Release: The Nobel Prize in Physics 2017

3 October 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017 with one half to

**Rainer Weiss**  
LIGO/VIRGO Collaboration

and the other half jointly to

**Barry C. Barish**  
LIGO/VIRGO Collaboration

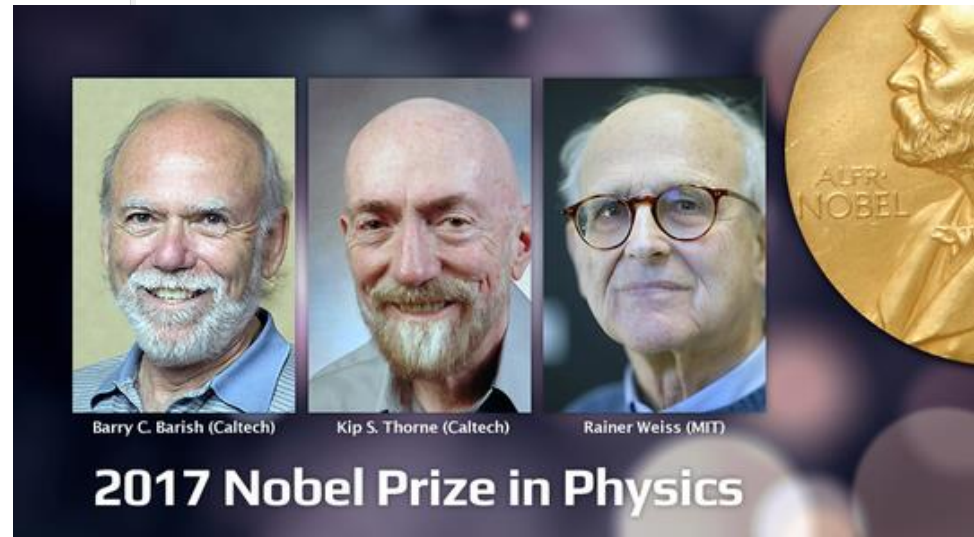
and

**Kip S. Thorne**  
LIGO/VIRGO Collaboration

*"for decisive contributions to the LIGO detector and the observation of gravitational waves"*

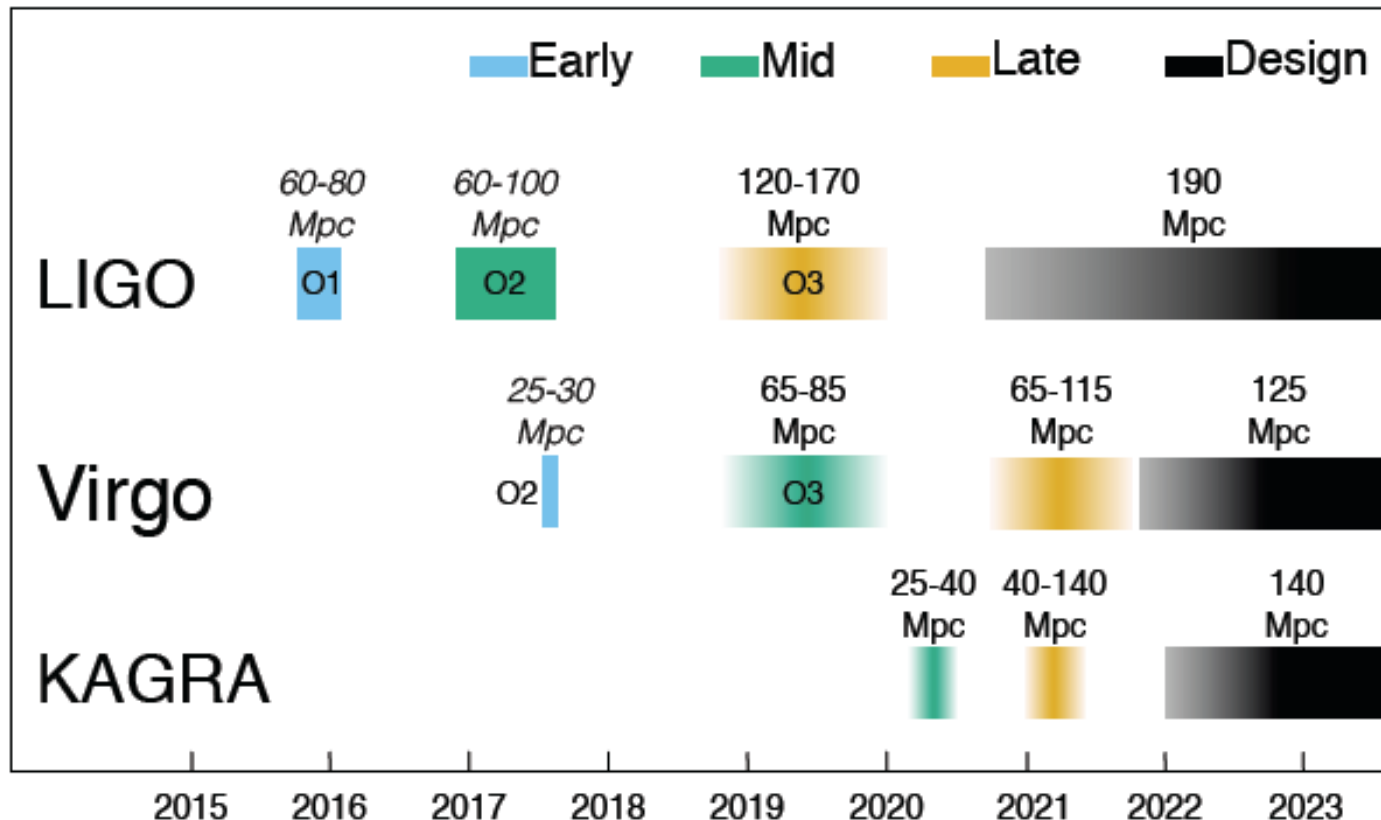
## Gravitational waves finally captured

On 14 September 2015, the universe's gravitational waves were observed for the very first time. The waves, which were predicted by Albert Einstein a hundred years ago, came from a collision between two black holes. It took 1.3 billion years for the waves to arrive at the LIGO detector in the USA.





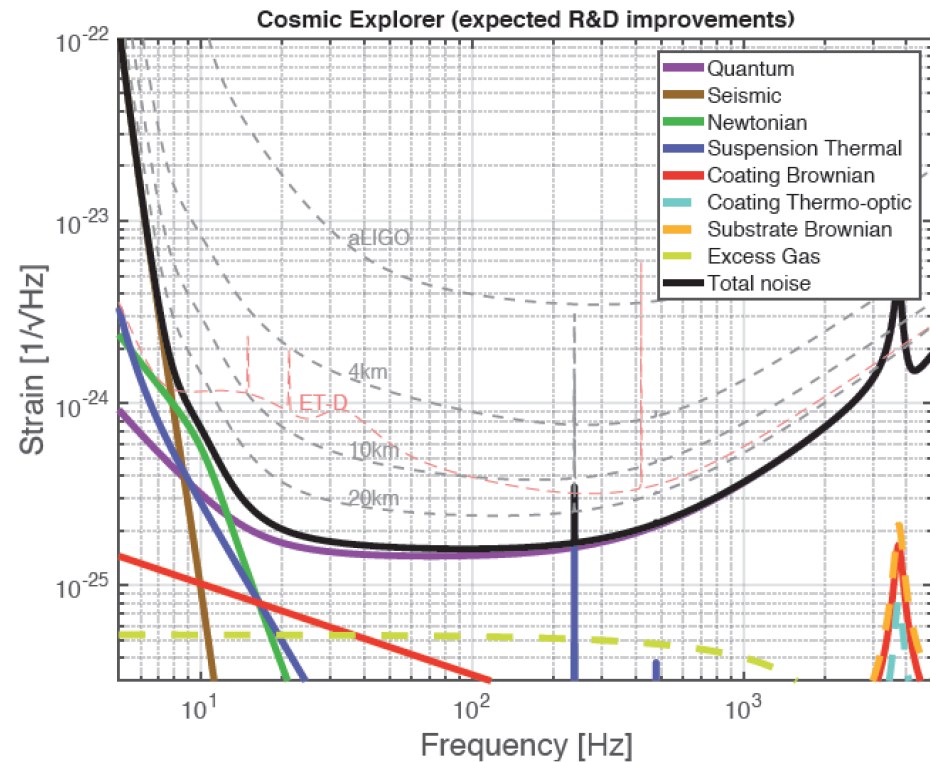
# The next few years



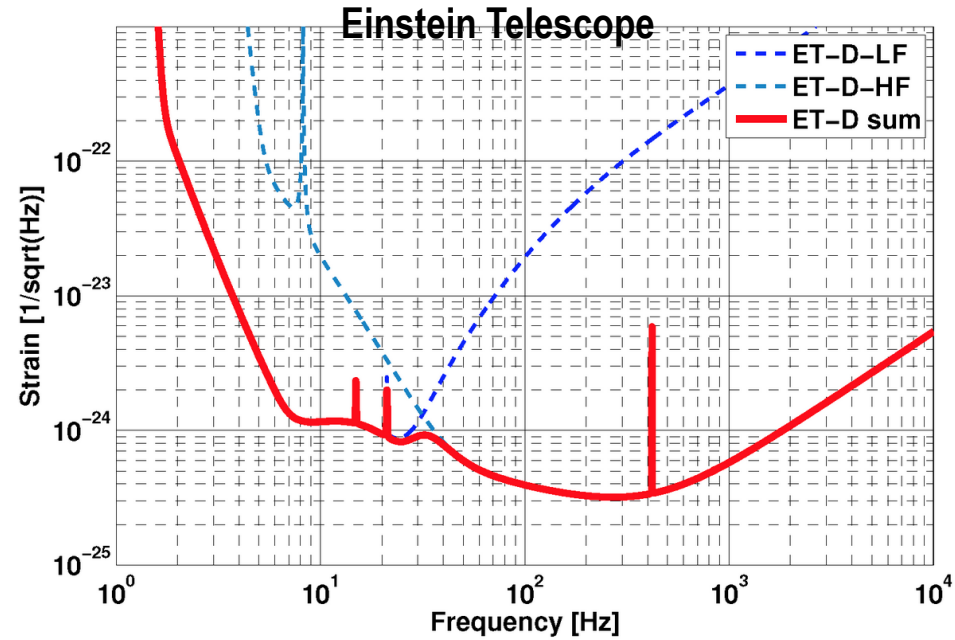
Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA

<https://arxiv.org/abs/1304.0670>

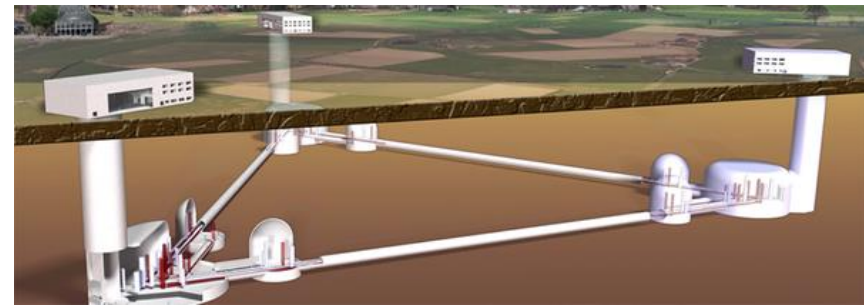
# Imagining the future: 3<sup>rd</sup> generation detectors



Cosmic Explorer  
Class. Quantum Grav. 34 (2017) 044001

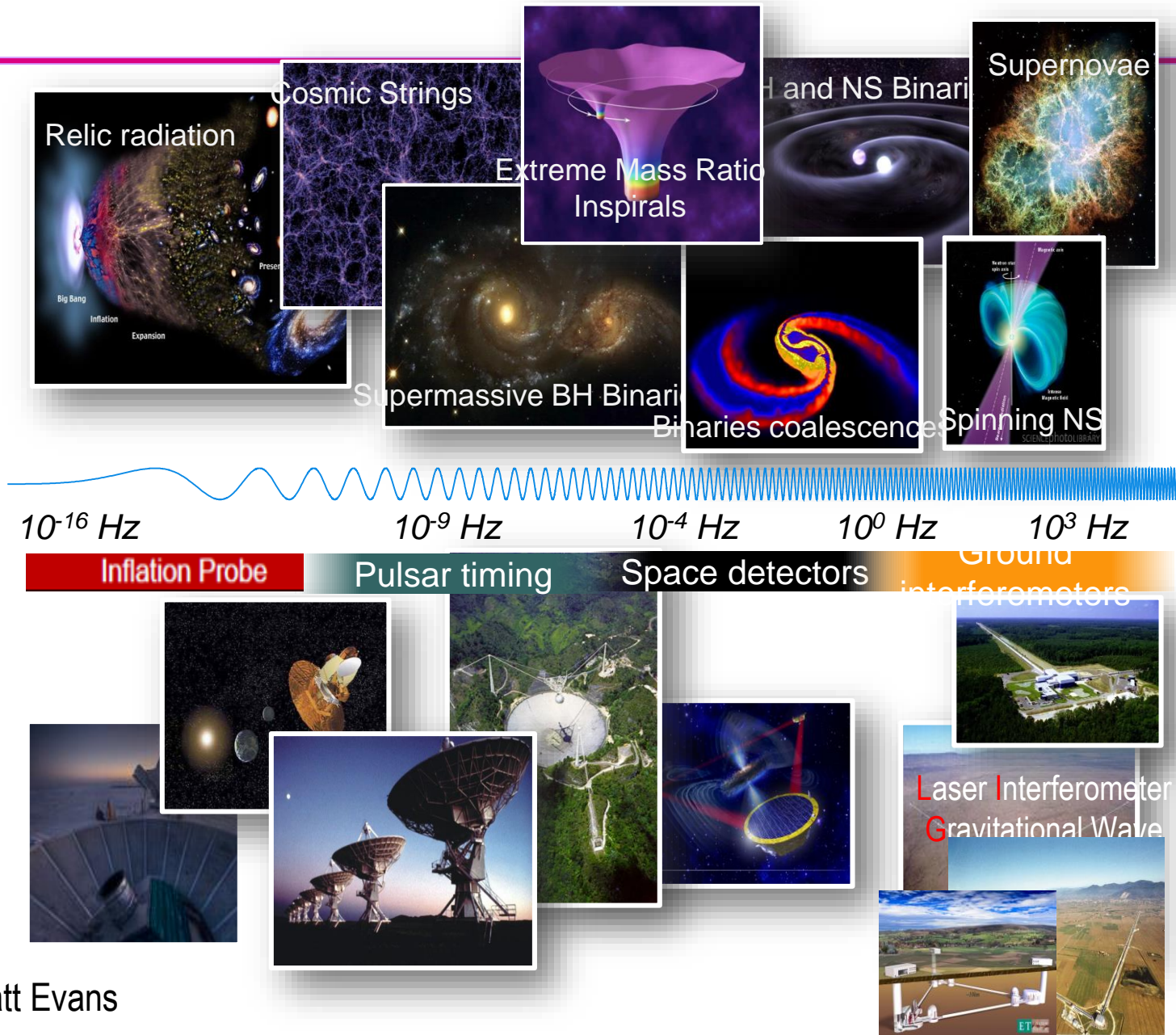


S.Hild et al., Classical and Quantum Gravity, 28 094013, 2011



Einstein Telescope  
<http://www.et-gw.eu/>

# The Gravitational Wave Spectrum



Credit: Matt Evans



# The era of GW astronomy is here!

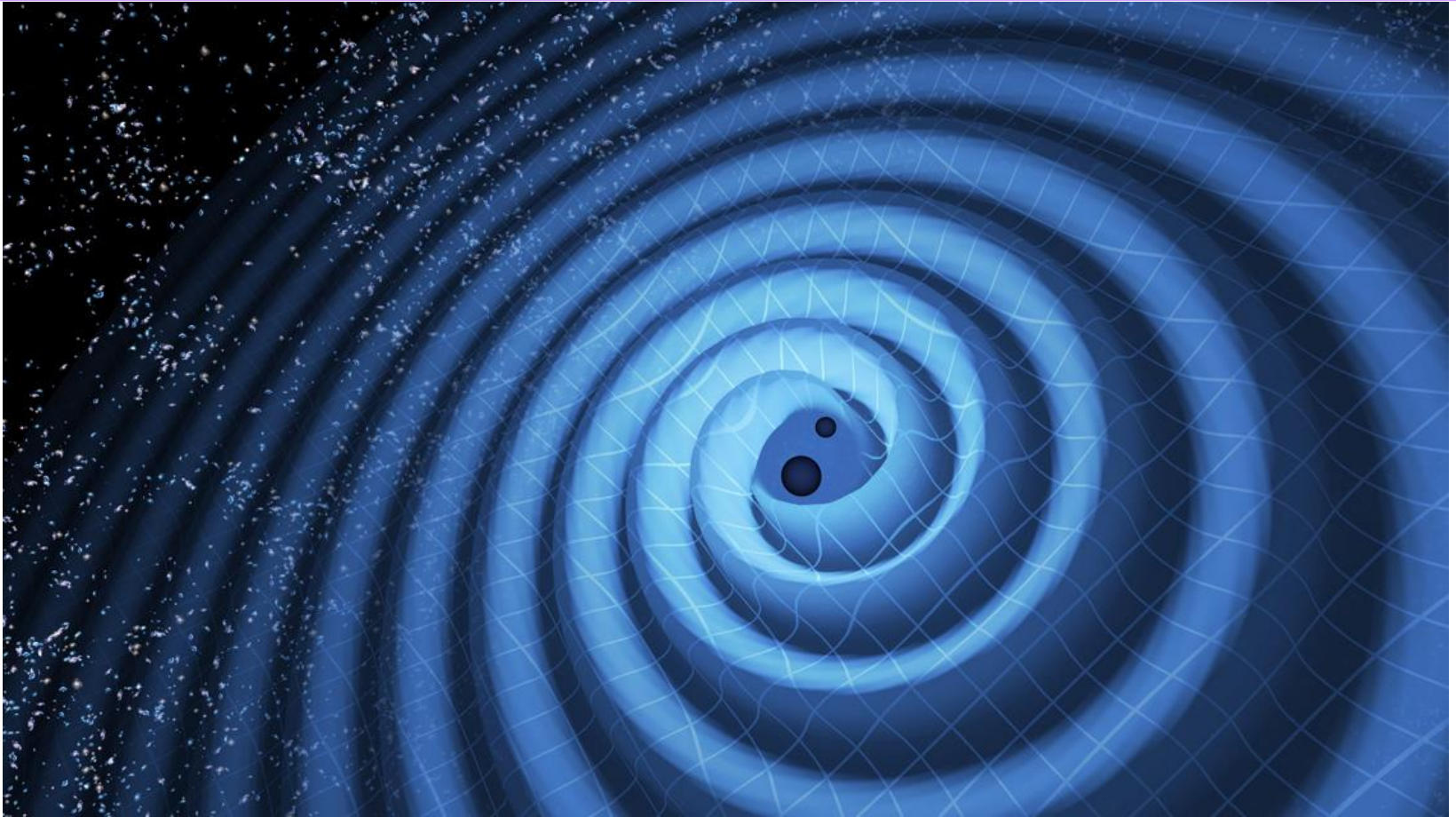


Image credit: LIGO/T. Pyle

[www.ligo.org](http://www.ligo.org)