

# Einstein surfing Gravitational Waves from Black Holes



Gabriela González

Louisiana State University

Results on behalf of the LIGO-Virgo-KAGRA collaborations

# Einstein's gravity: Space time is curved

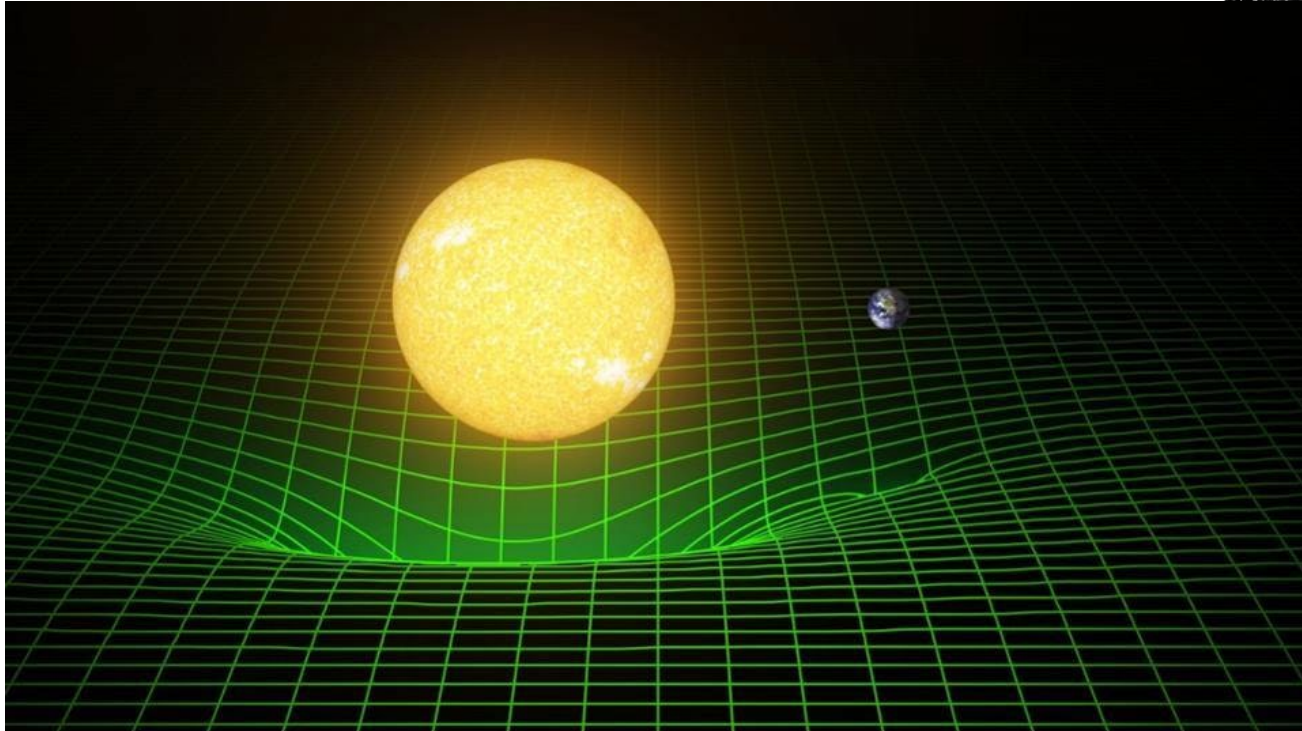
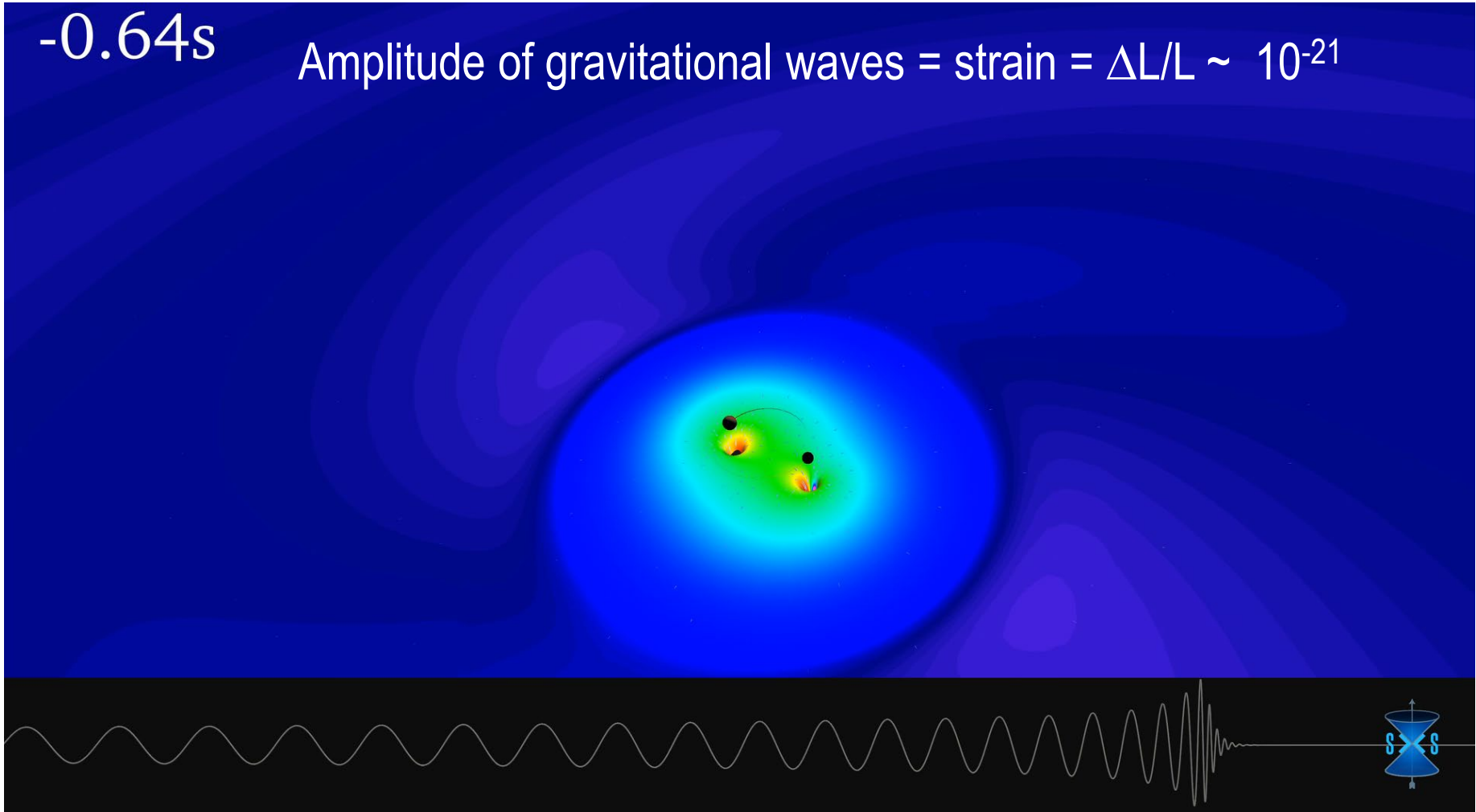


Image Credit: T. Pyle/Caltech/MIT/LIGO Lab

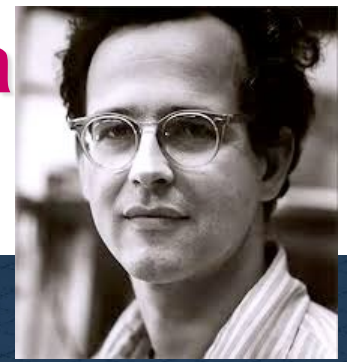
# Black holes can dance the tango

-0.64s

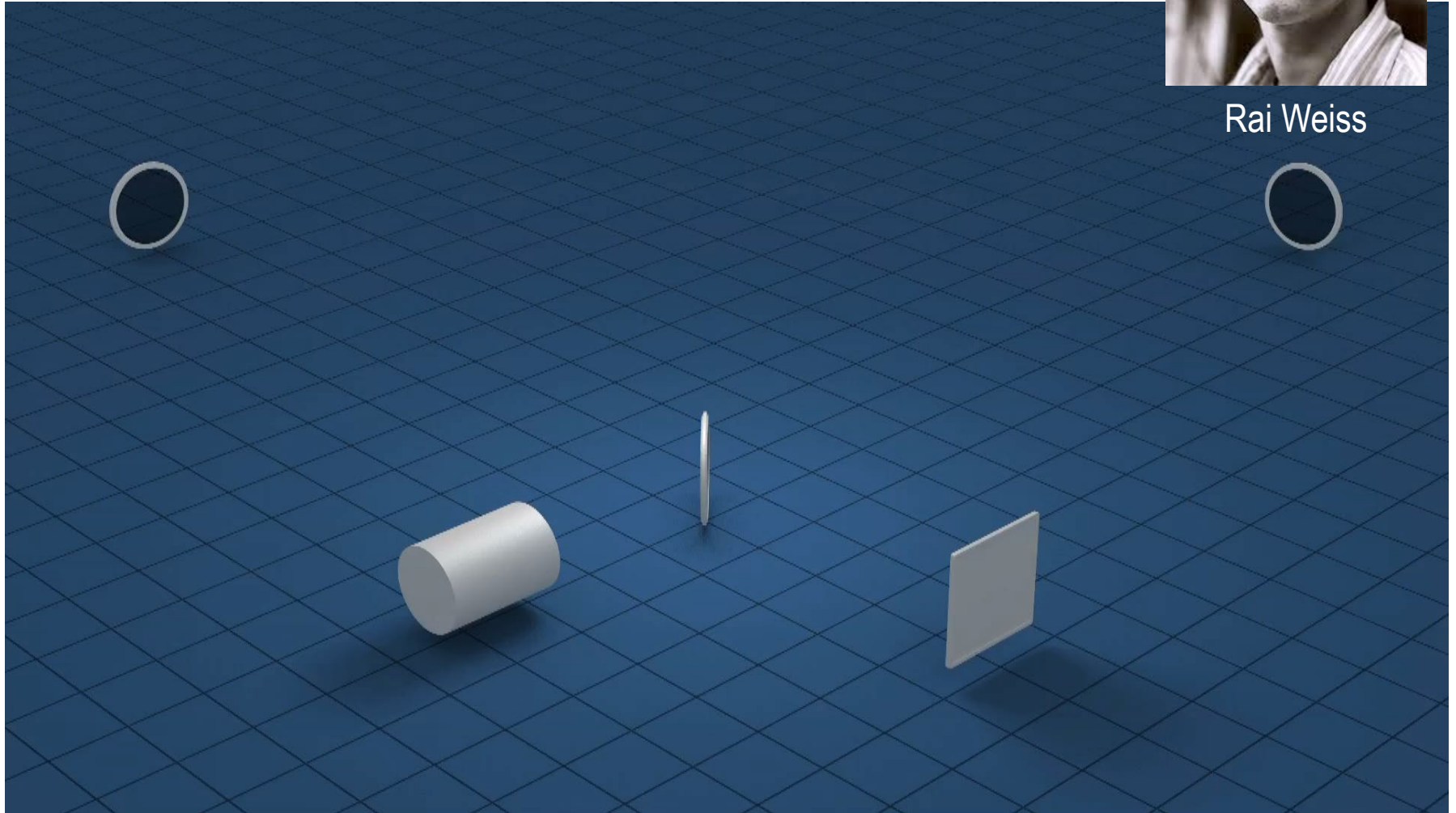
Amplitude of gravitational waves = strain =  $\Delta L/L \sim 10^{-21}$



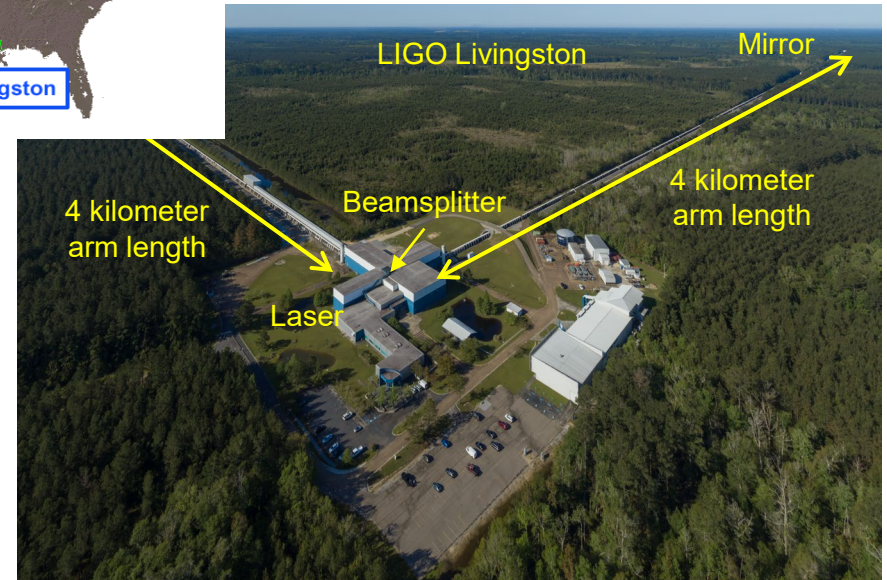
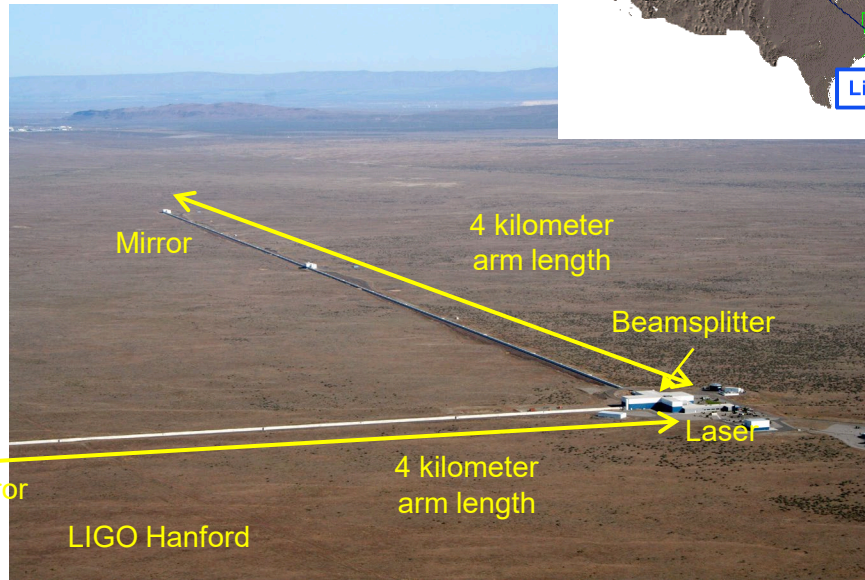
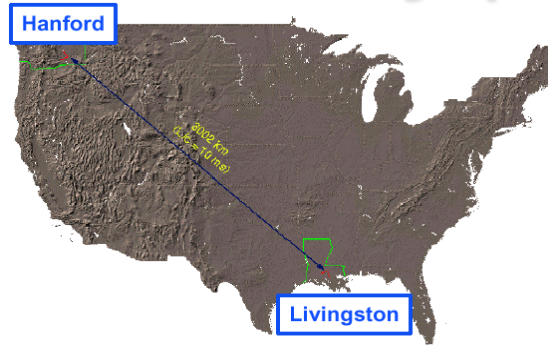
# How to detect gravitational waves: interferometer



Rai Weiss

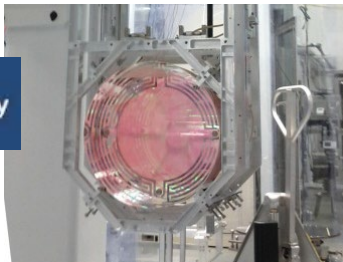
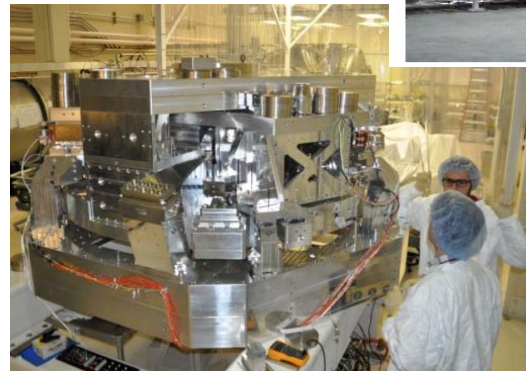
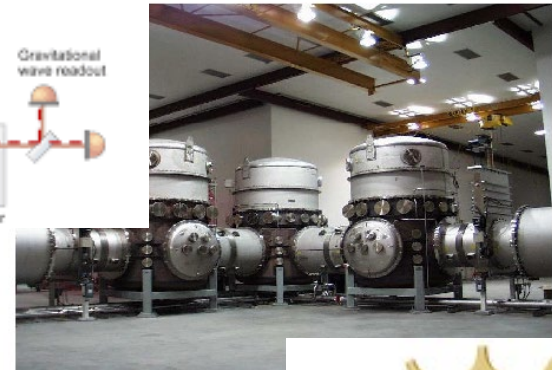
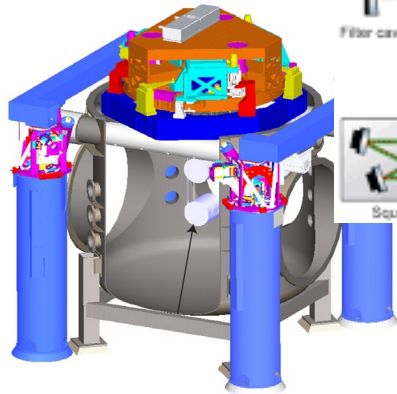
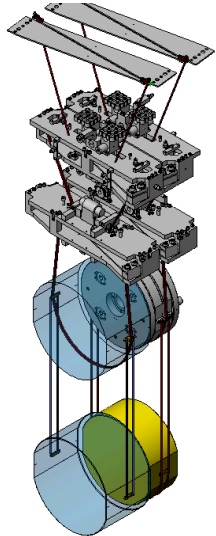
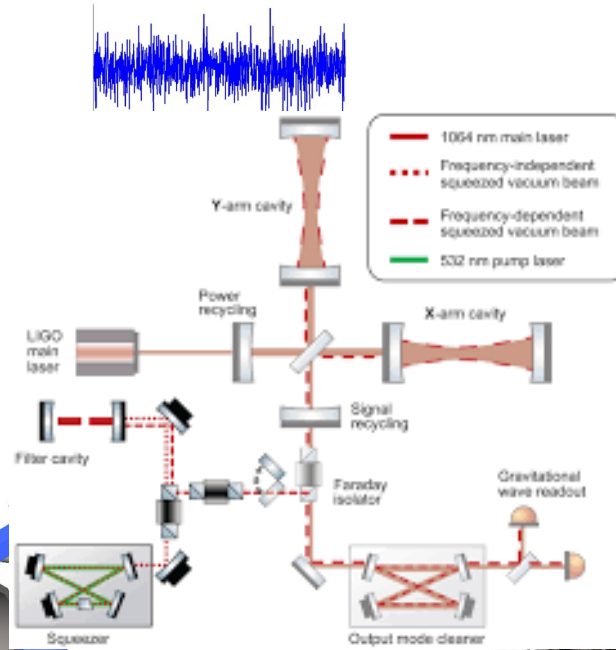


# The Laser Interferometer Gravitational-wave Observatory (LIGO)

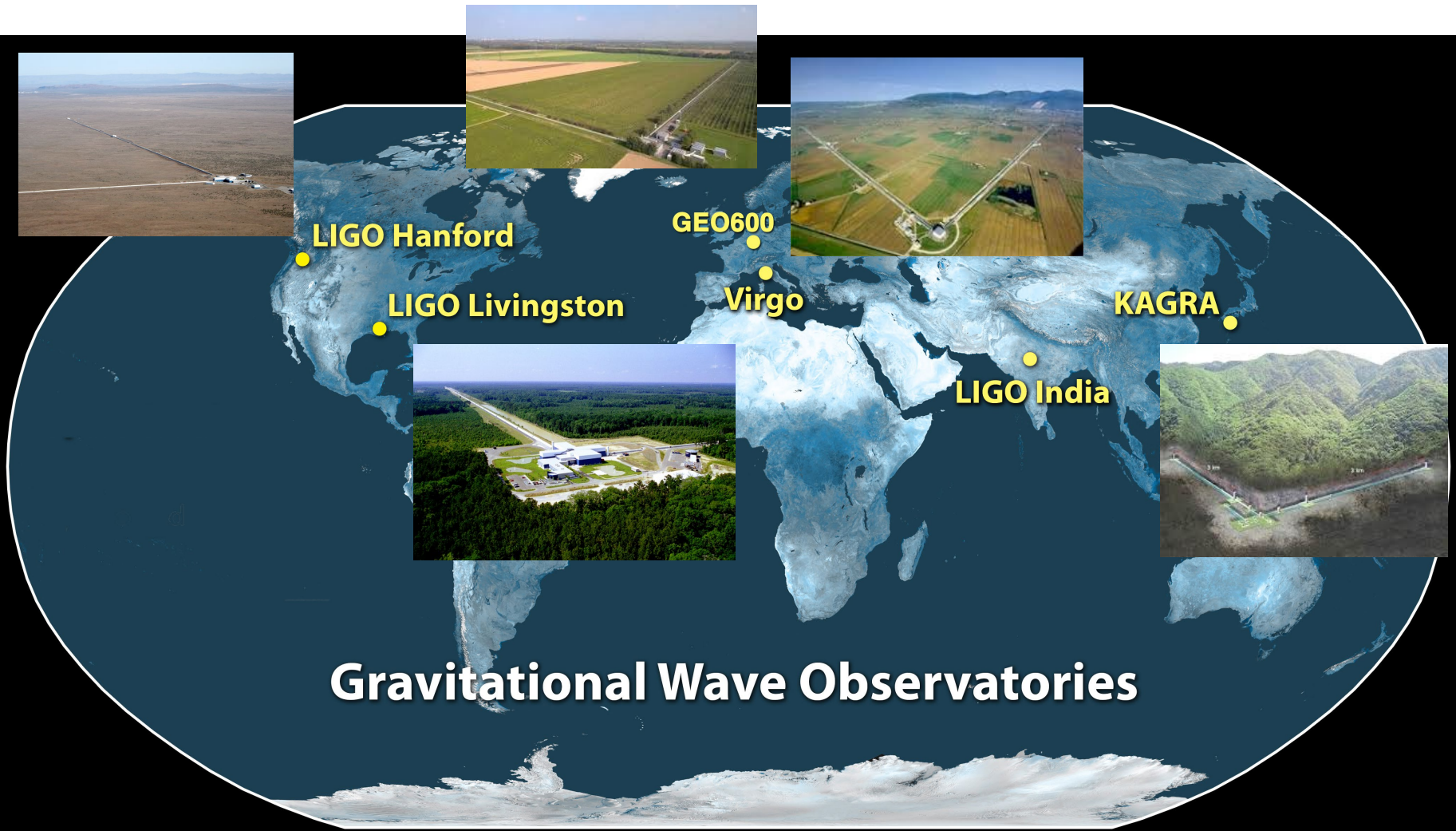


4 km long arm lengths  $\rightarrow$  requires measuring displacements  $\Delta L$  to less than  $10^{-18}$  meter

# Advanced LIGO detectors

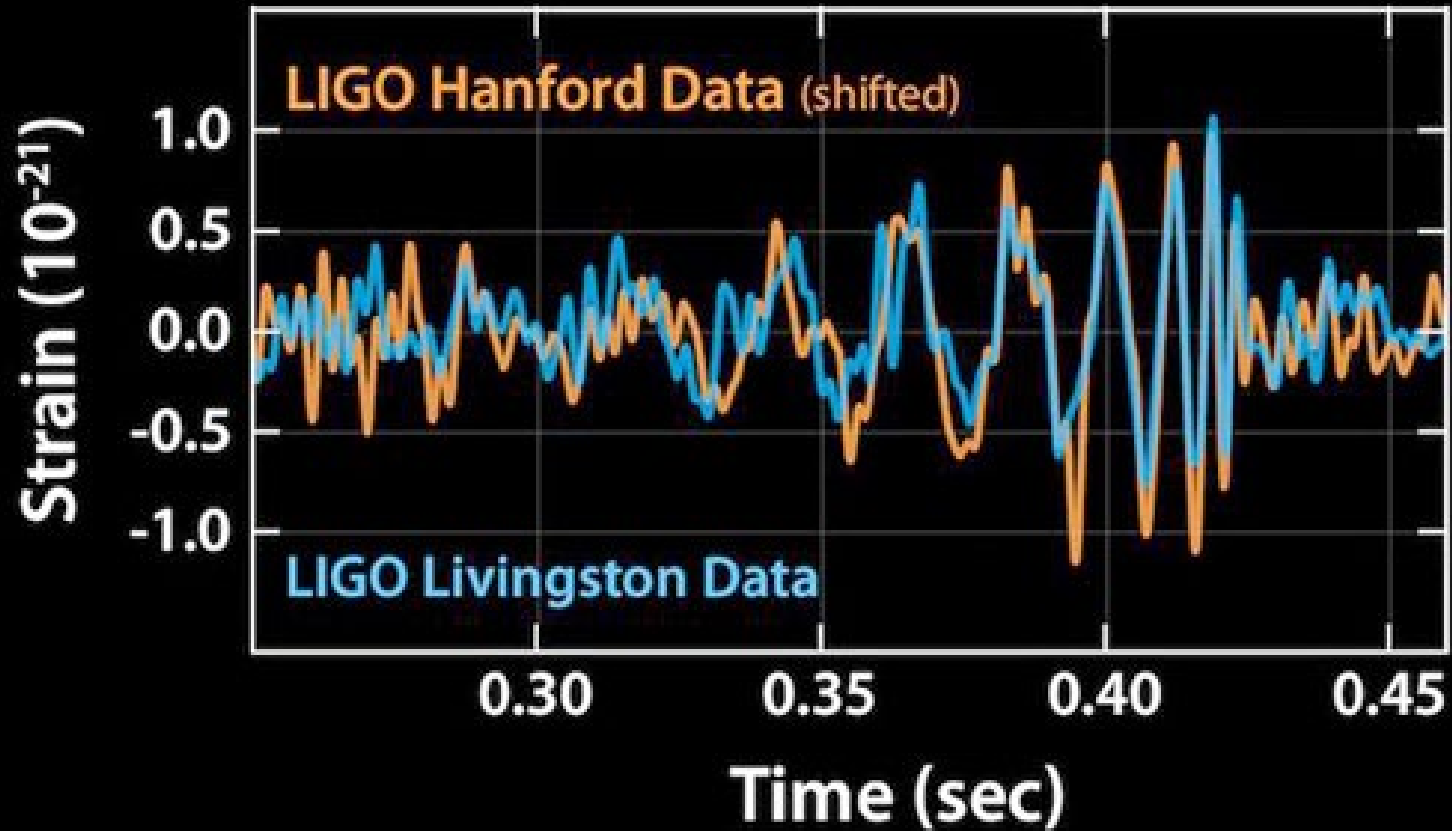


# GW detectors network



**Gravitational Wave Observatories**

September 14, 2015



# February 11, 2016: We did it!



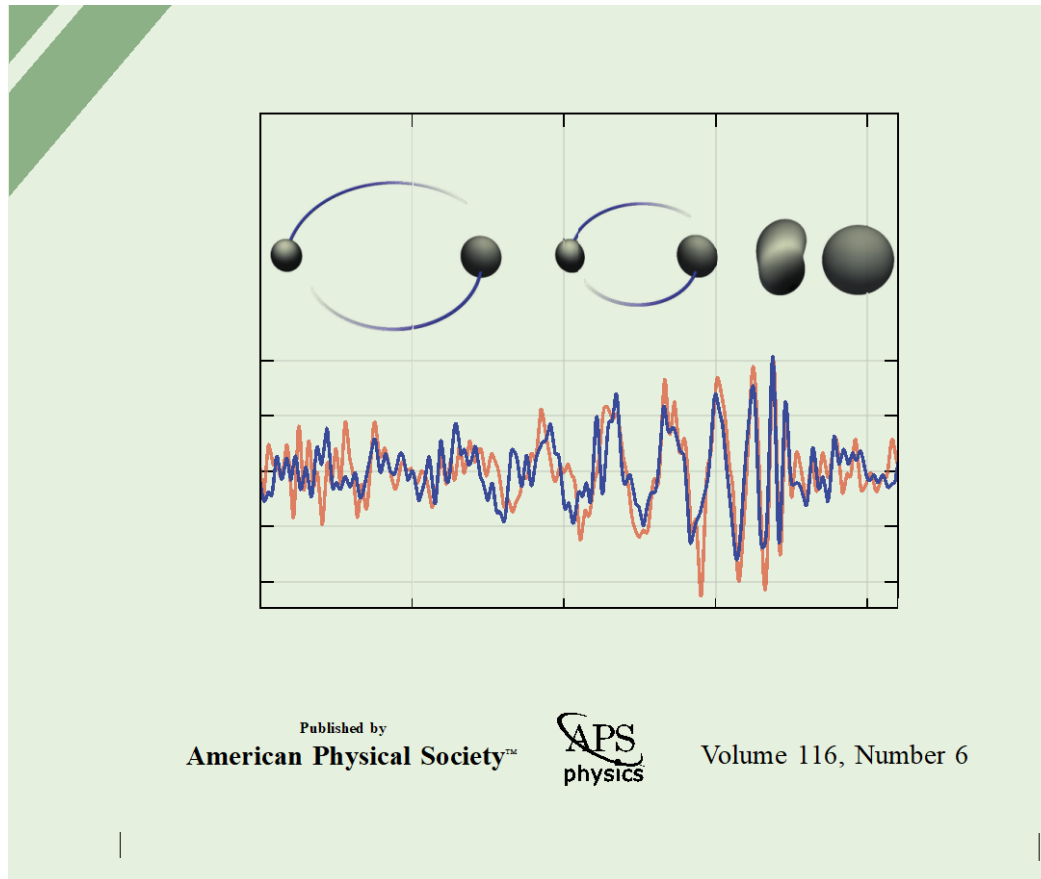


# Observation of Gravitational Waves from a Binary Black Hole Merger

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

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

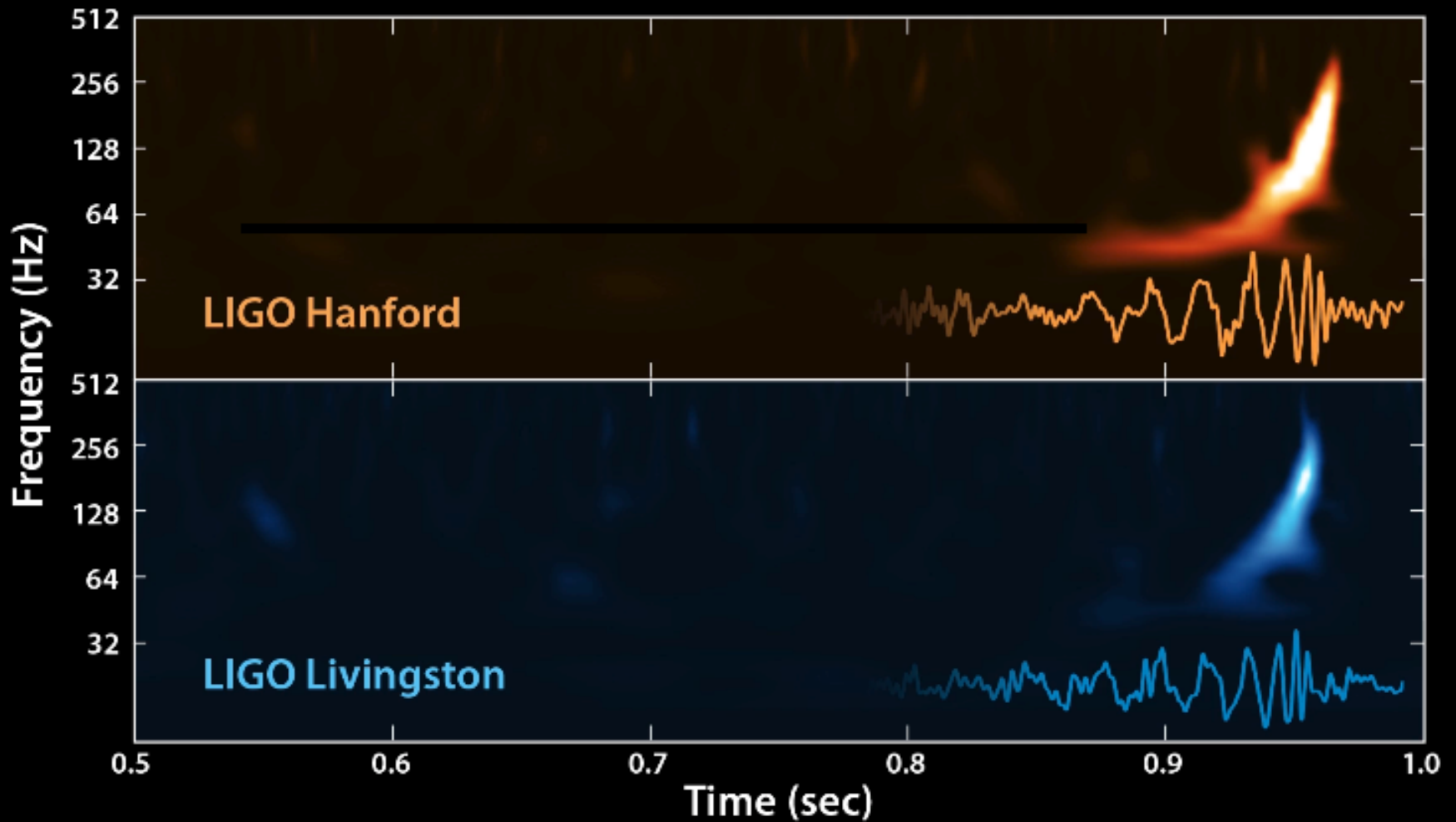


Published by  
American Physical Society™

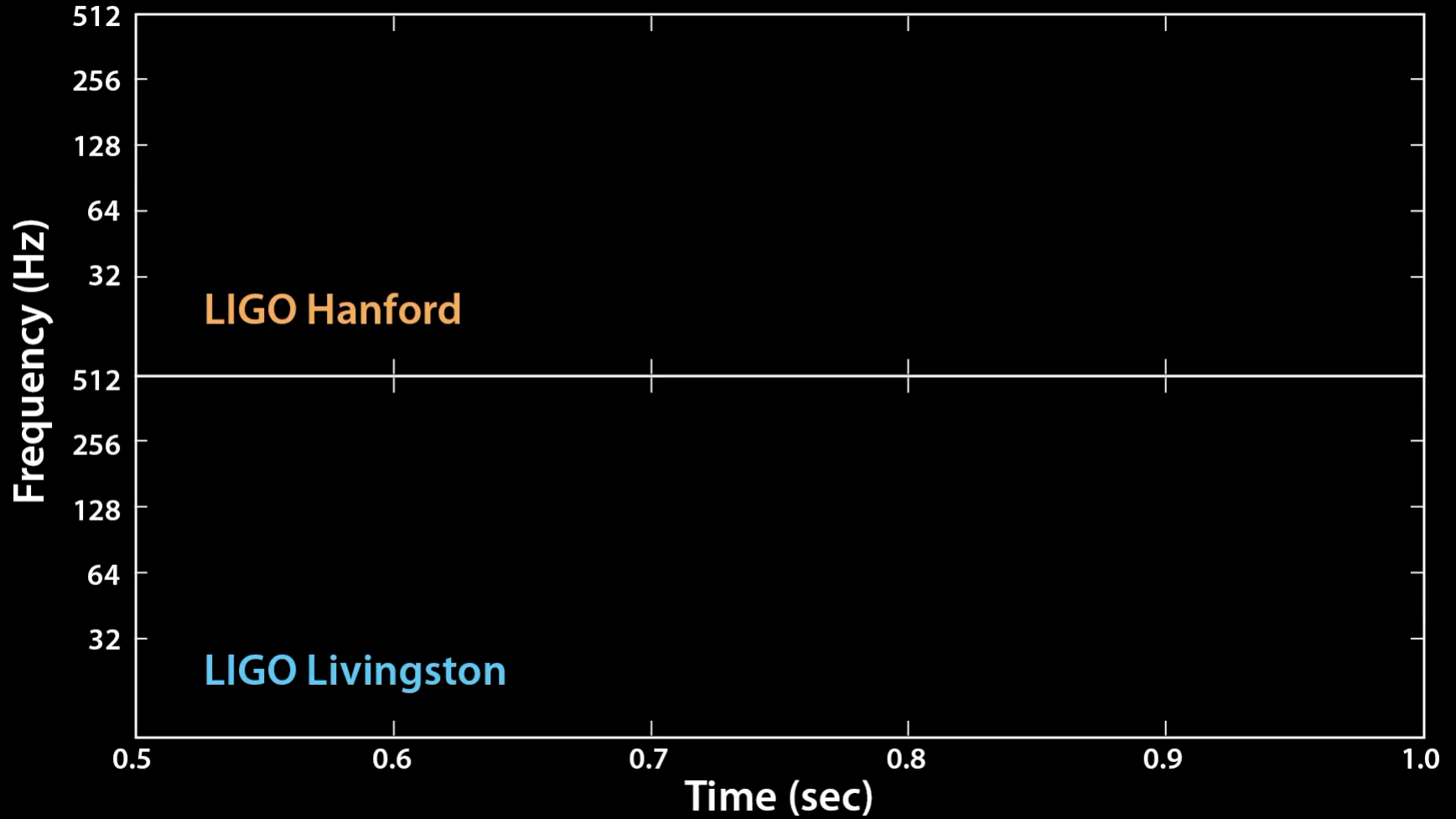


Volume 116, Number 6

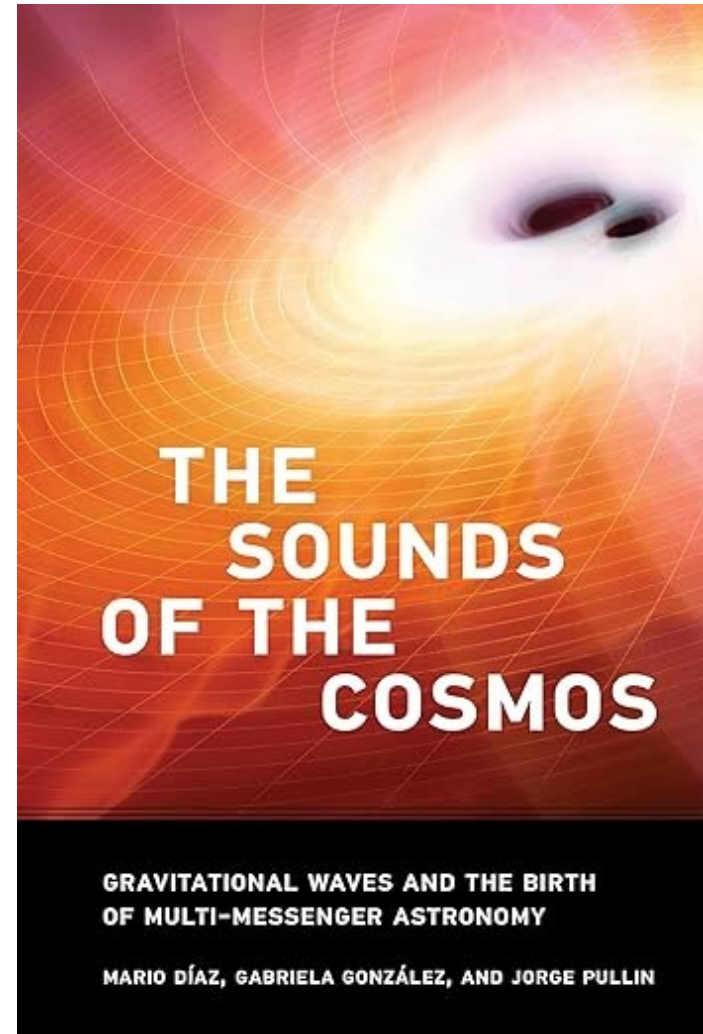
# The music of the Universe



# The music of the Universe



# The music of the Universe



# 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

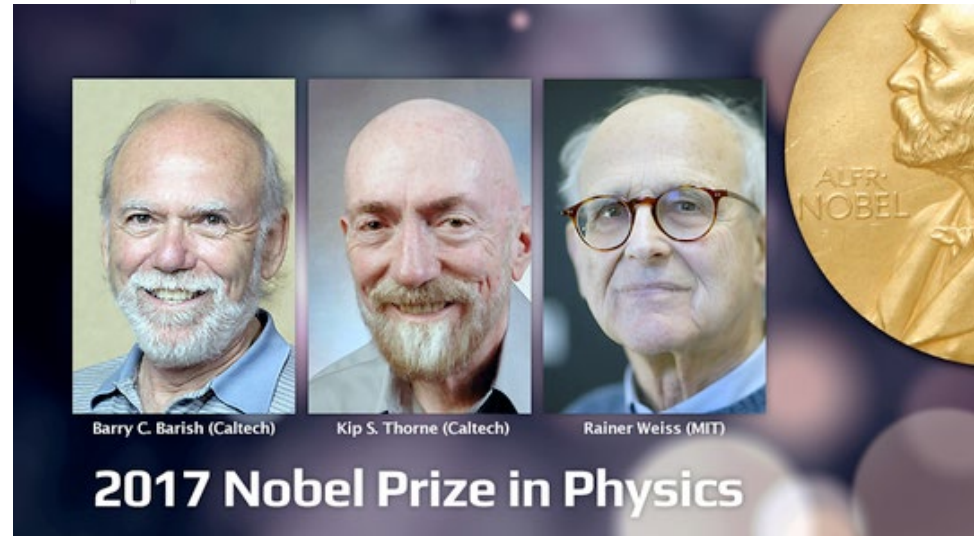
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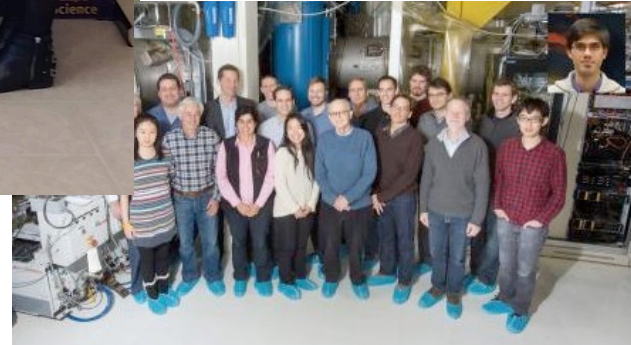
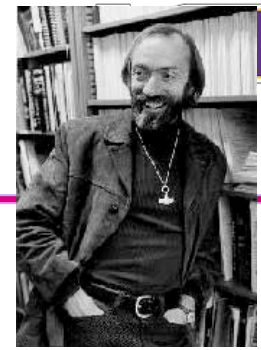
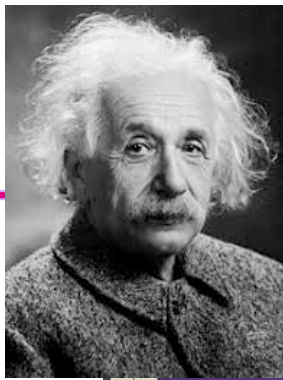
**Kip S. Thorne**  
LIGO/VIRGO Collaboration

*"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.

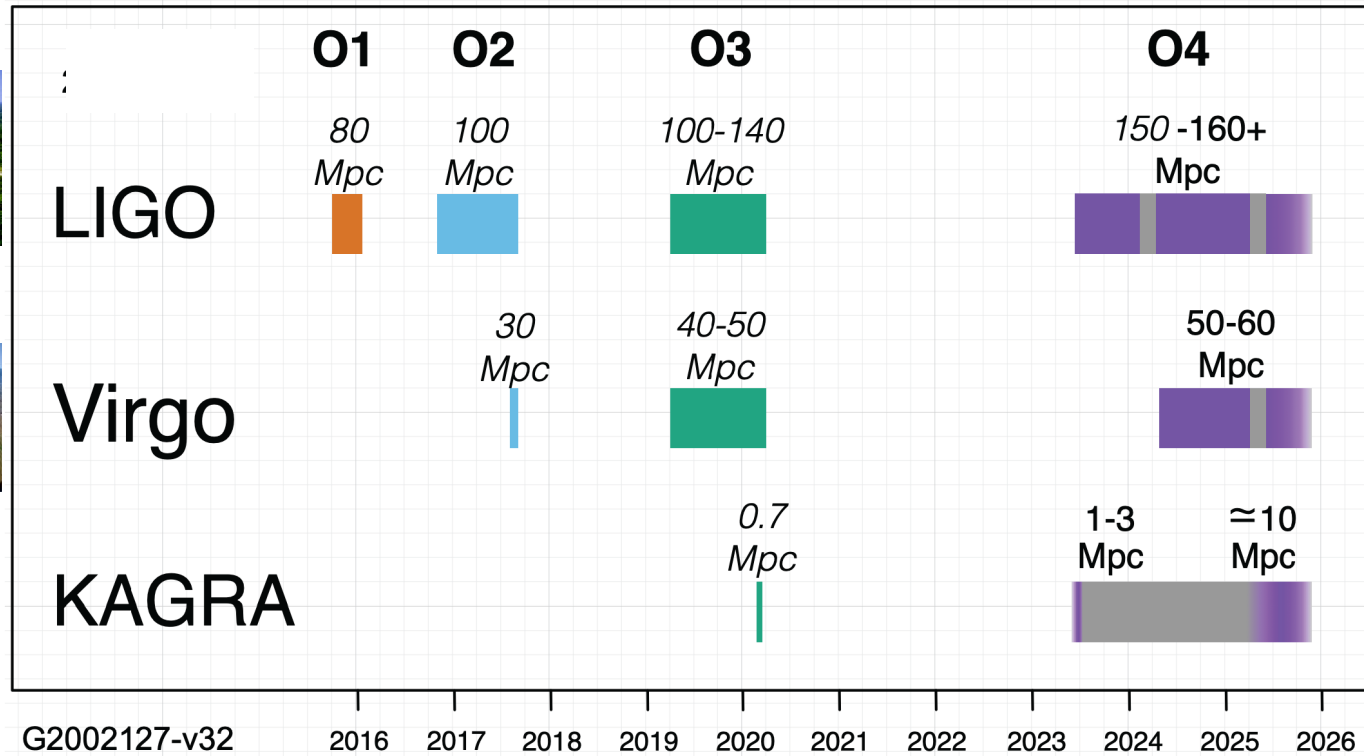
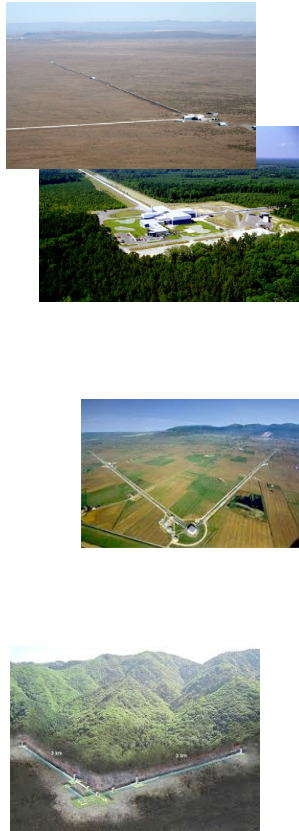




# LVK Collaborations

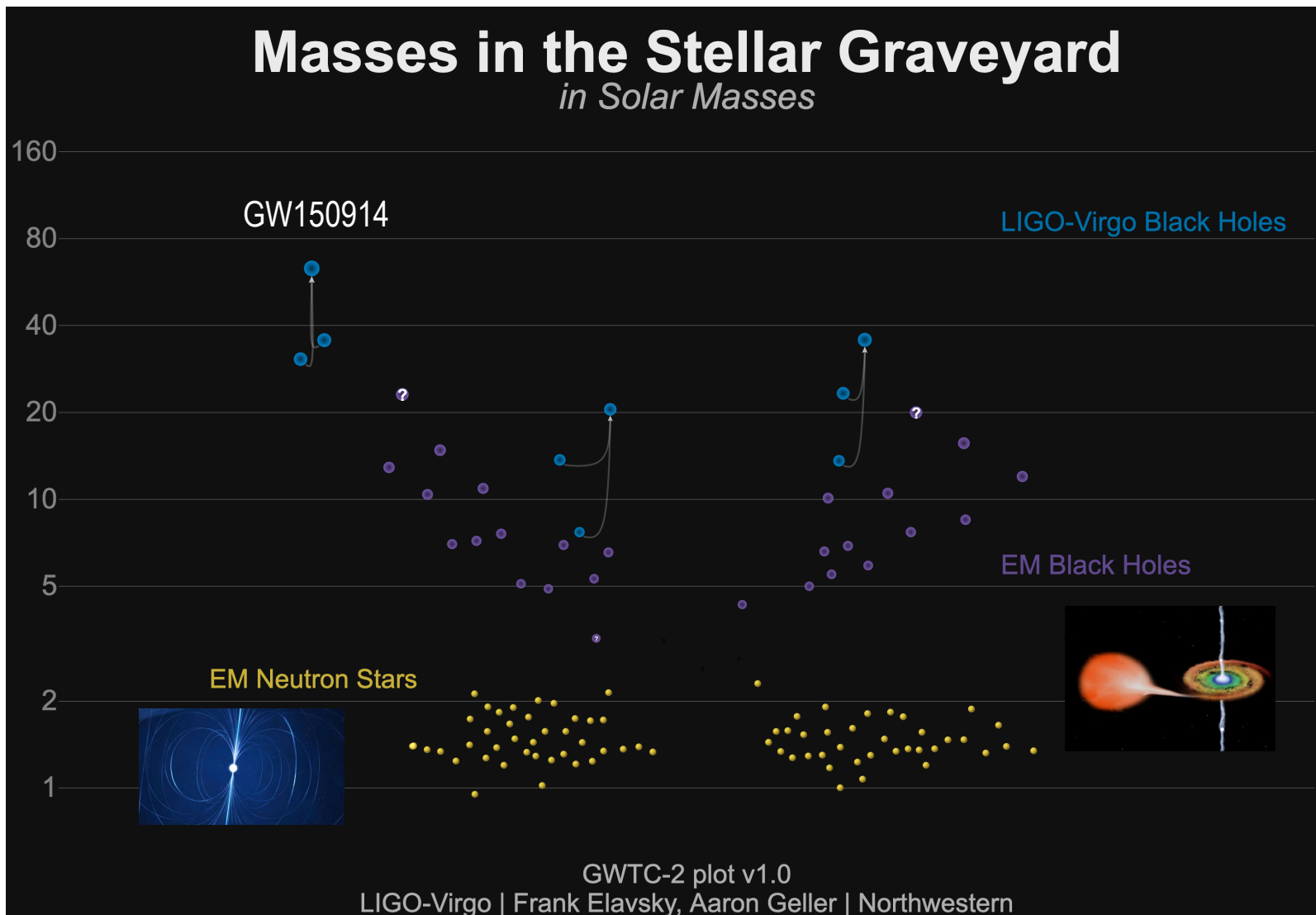


# LVK Observing Plan 2015-2026

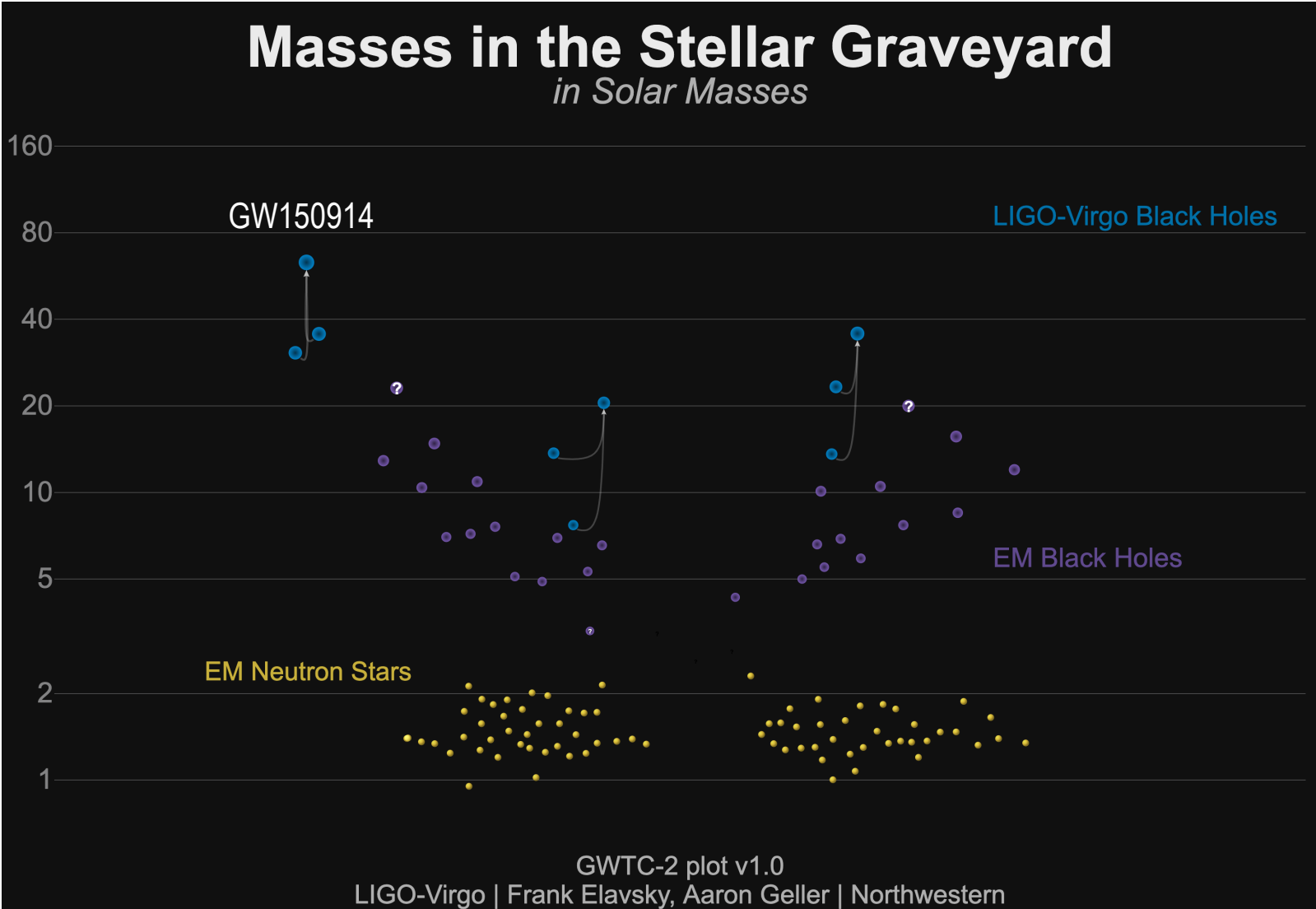


<https://observing.docs.ligo.org/plan/>

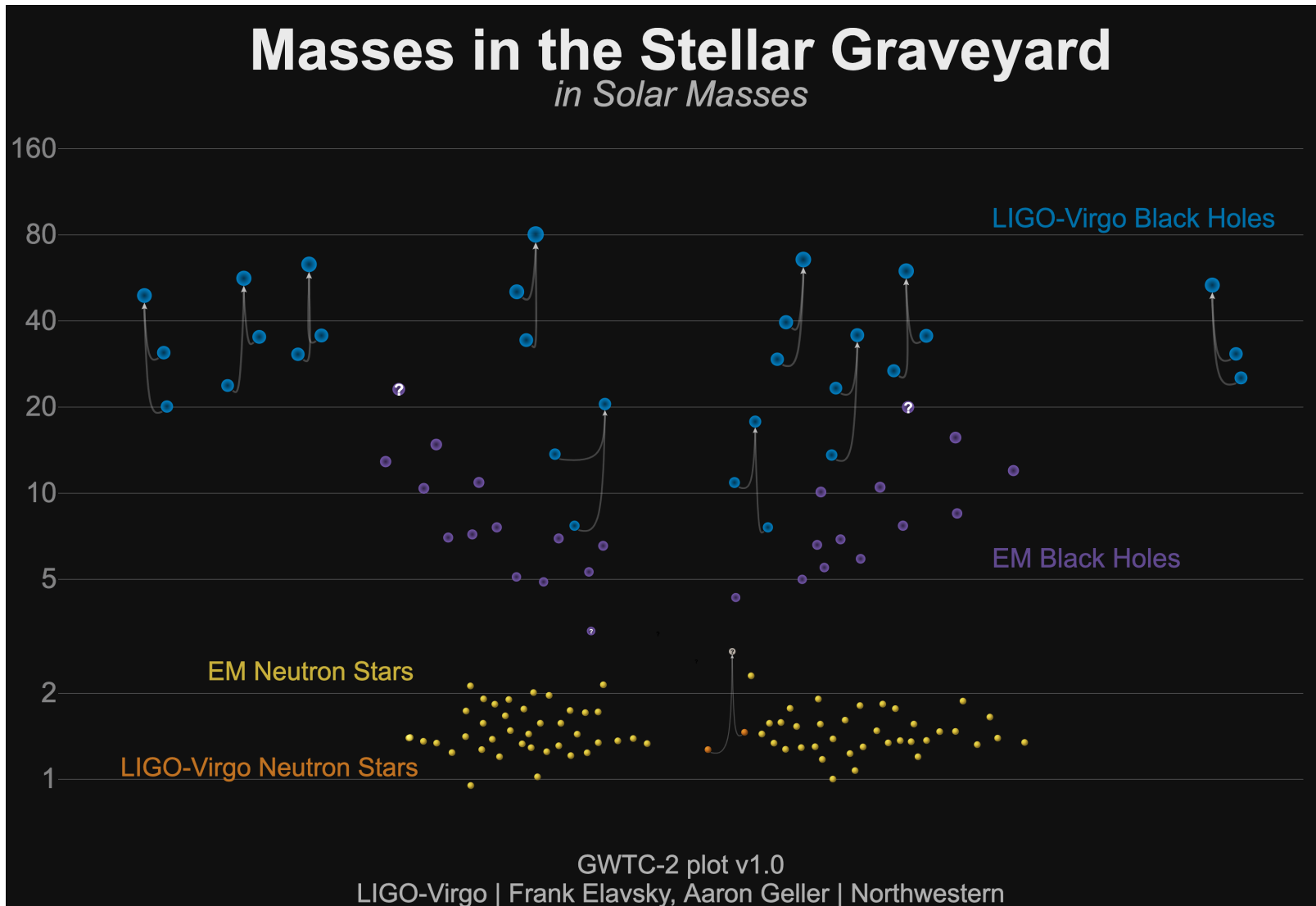
# GW detections – 2015-2016



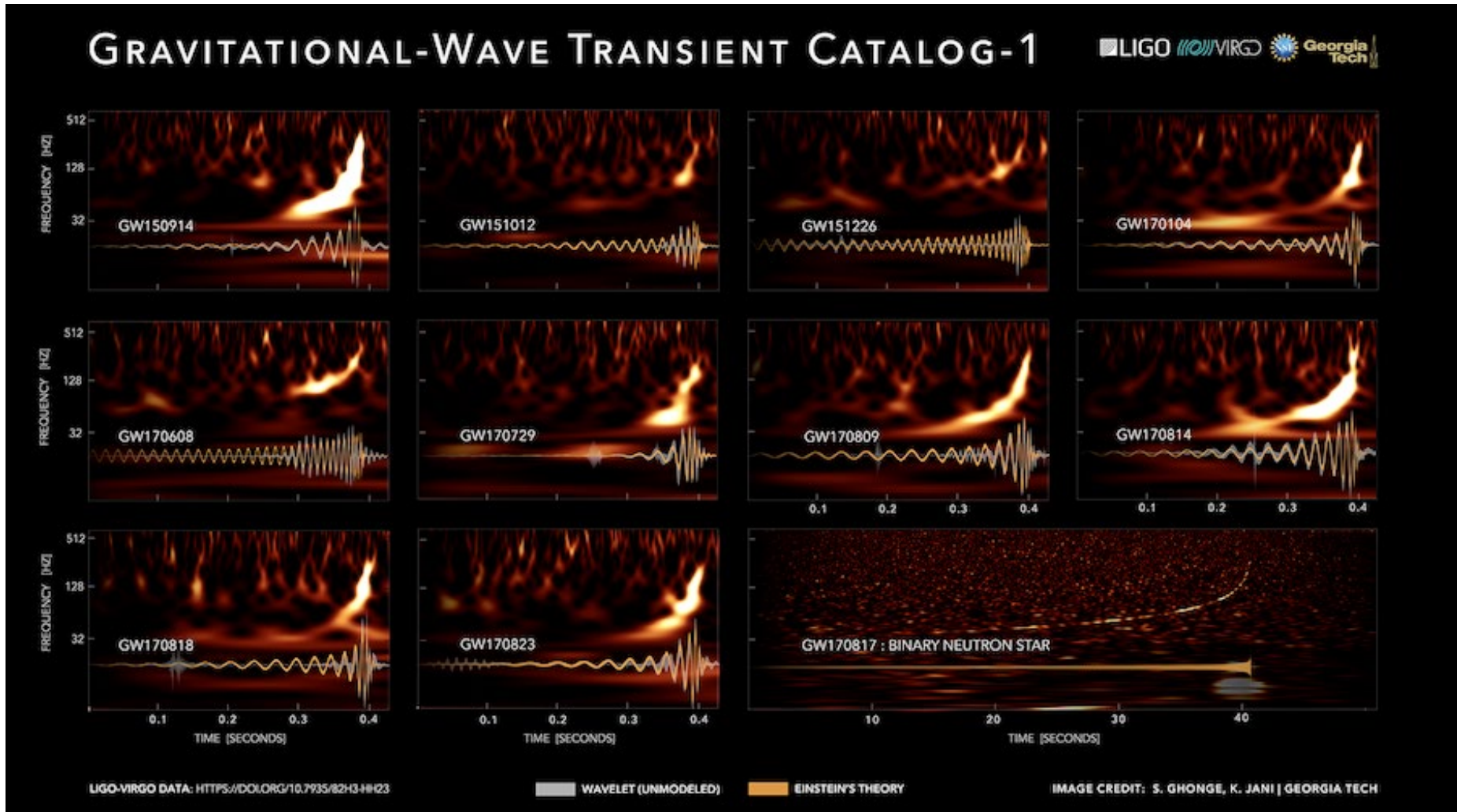
# GW detections – 2015-2016



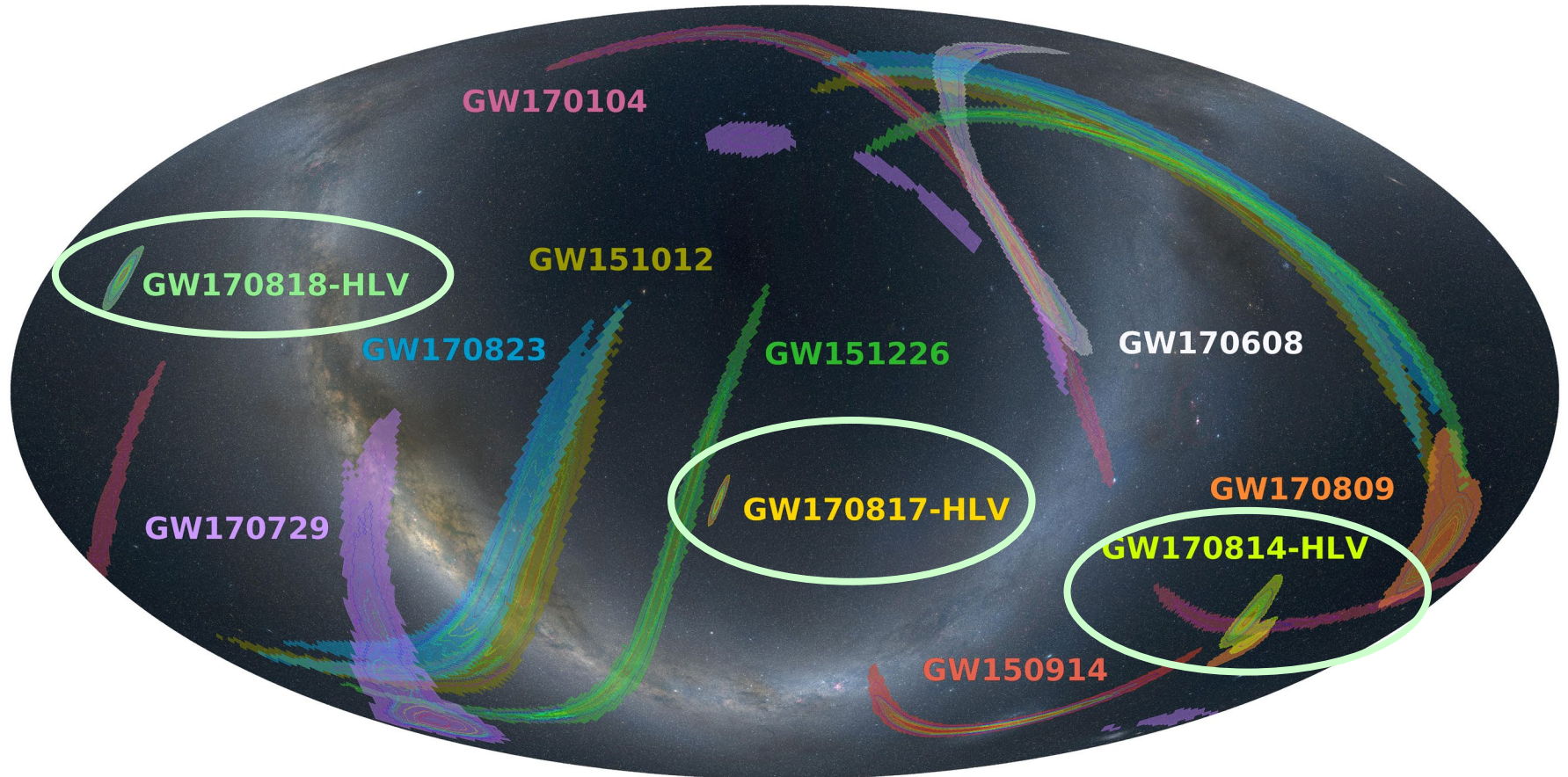
# GW detections O1-O2 (2015-2017)



# 2015-2017: 11 detections



# Where do GWs come from?

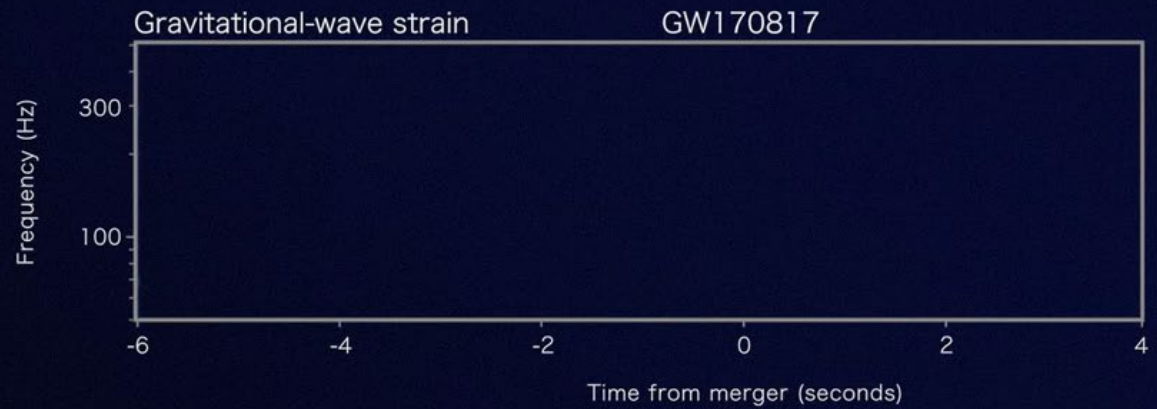


# GW170817: fireworks too!

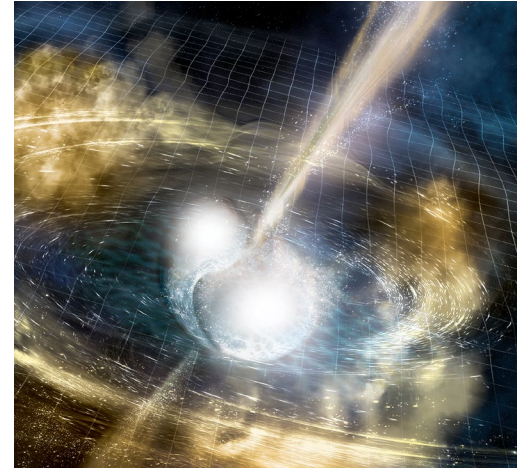
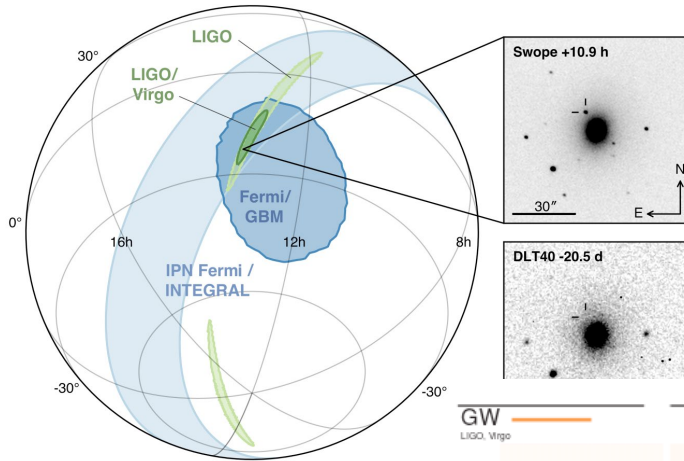
Fermi



LIGO

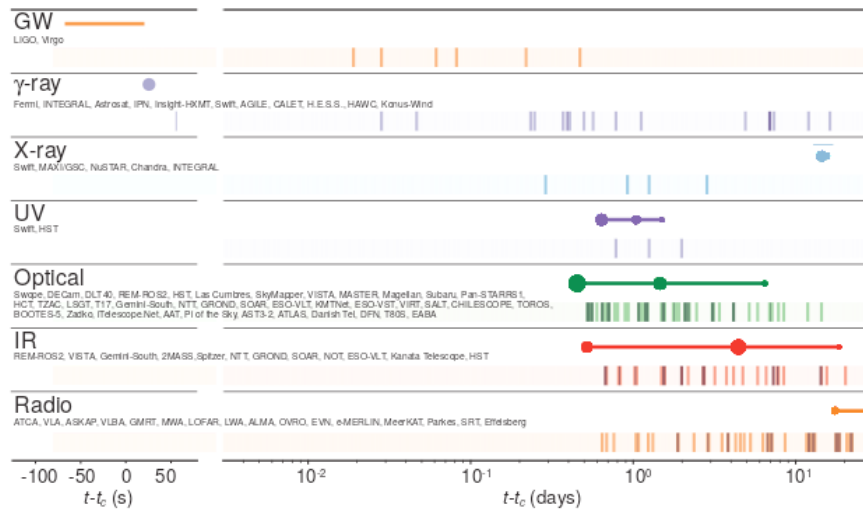


# 2017: A kilonova rainbow



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

Astrophys. J. Lett. 848, L12 (2017)

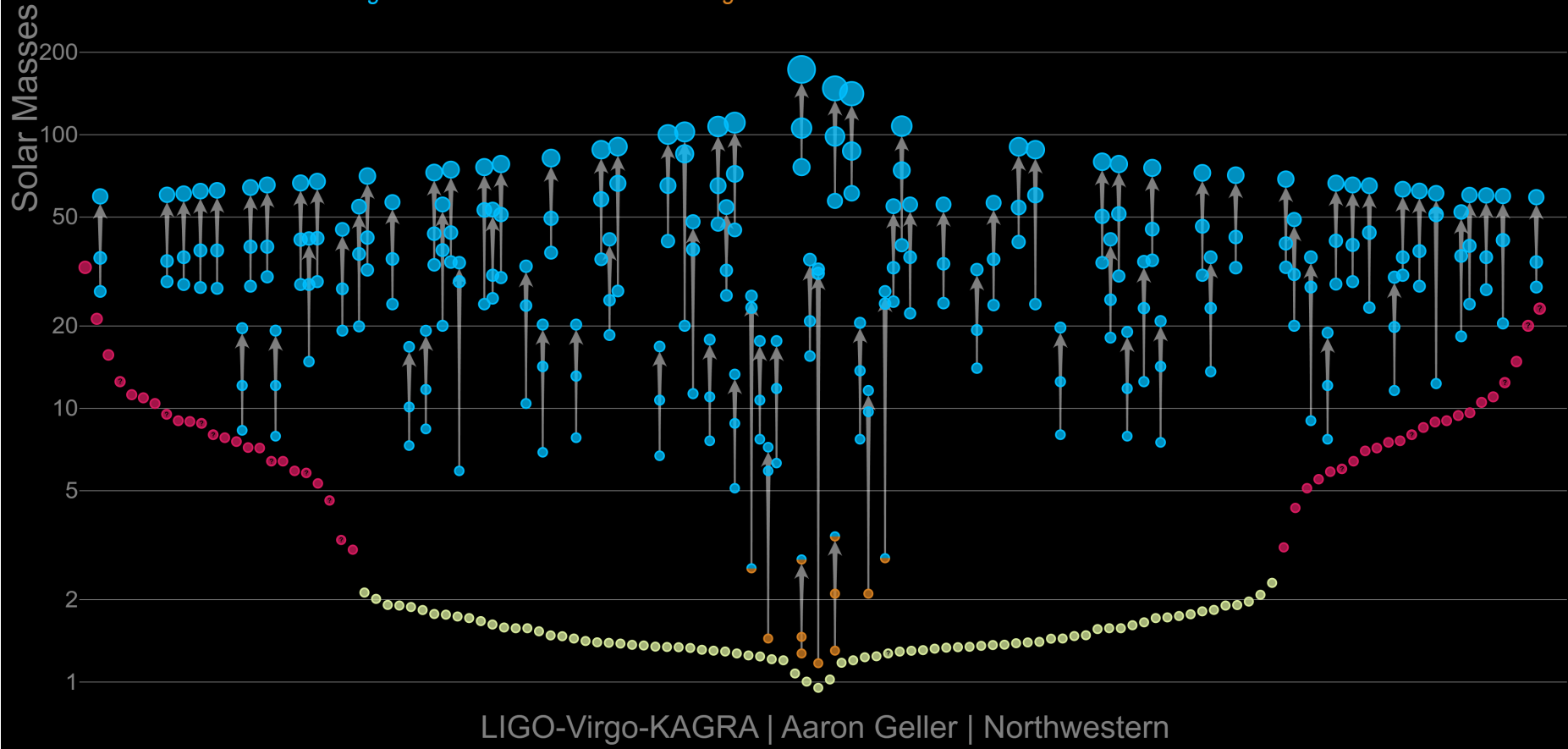


# GW detections O1 – O3 (2015-2020)

## A catalog with 90 signals

### Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars

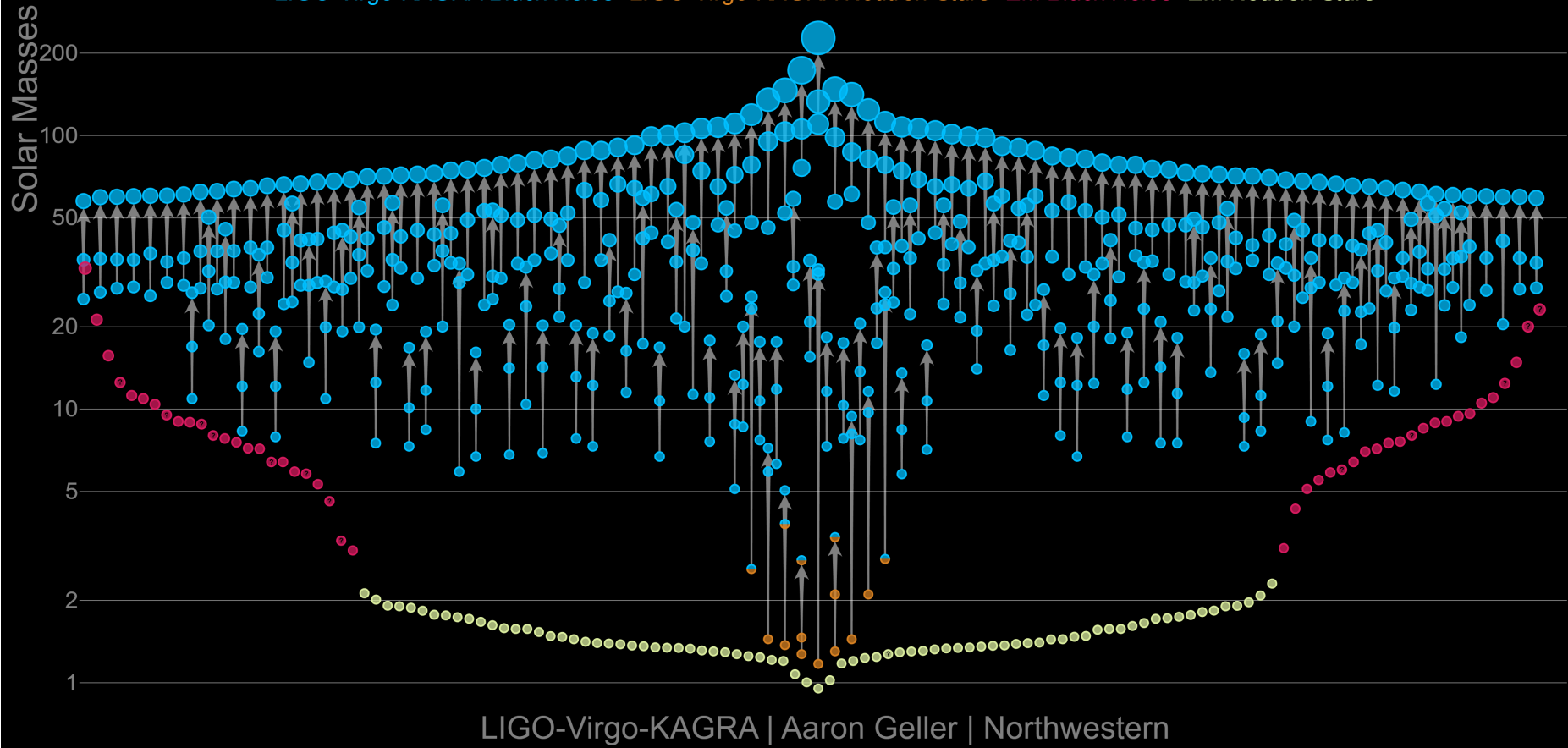


# GW detections (2015- Jan 2024)

## Latest catalog: 218 signals

### Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



# O4 detection

137 TIMES THE MASS OF OUR SUN

103 TIMES THE MASS OF OUR SUN

## Meet GW231123

a gravitational-wave signal from the most massive binary black hole observed to date

travelling from

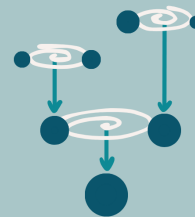
2 – 13 billion light years away ...

### SPINS

Not only are these black holes massive, they are highly spinning.

Each is rotating at ~80-90% of the maximum possible rate, corresponding to ~400,000 times Earth's rotation speed!

### HIERARCHICAL ORIGIN STORY?



The high masses and spins of GW231123's components indicate that they could come from previous black hole mergers.

GW231123 was detected on November 23, 2023 at 13:54 UTC by

H1 LIGO Hanford

and

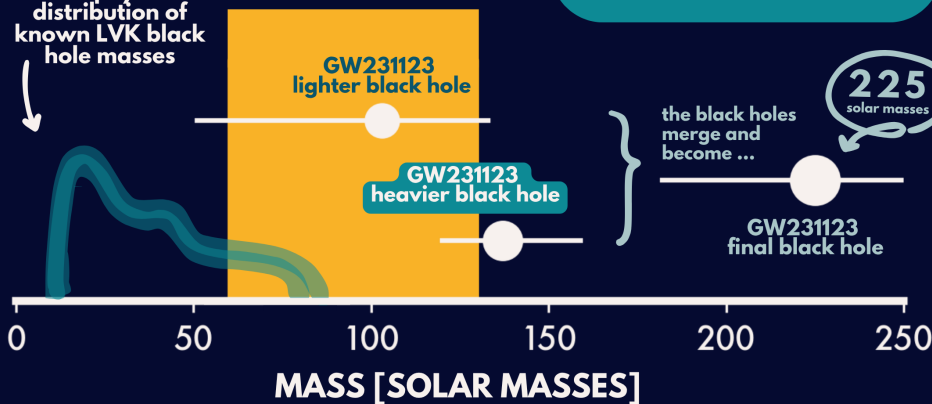
L1 LIGO Livingston



for a duration of 0.1 seconds.

astrophysical distribution of known LVK black hole masses

### "UPPER MASS GAP"

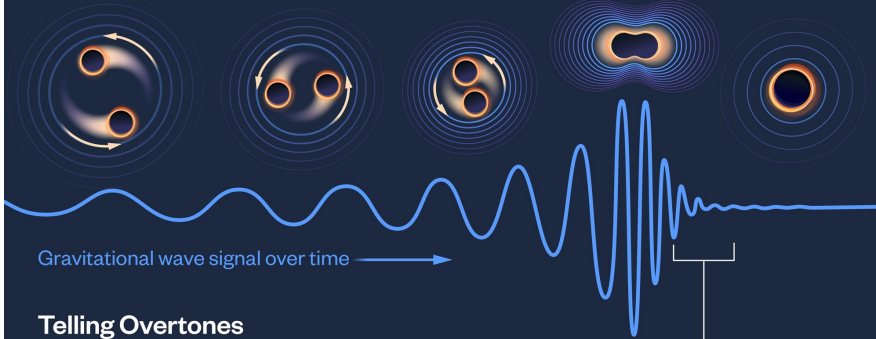


credit: Simona J. Miller / Caltech

# Clear Signal Sheds Light on Black Holes

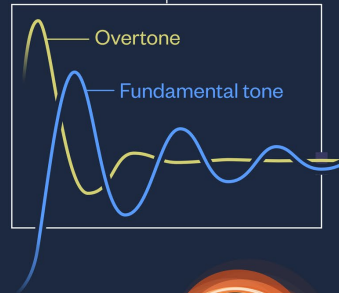
When two black holes (BHs) collide and merge, they release gravitational waves. These waves can be detected by sensitive instruments on Earth, allowing scientists to determine the mass and spin of the BHs. The clearest BH merger signal yet, named GW250114, recorded by LIGO in January 2025, offers new insights into these mysterious cosmic giants.

Two BHs release gravitational waves as they spiral inward      Merger      BH stabilizes



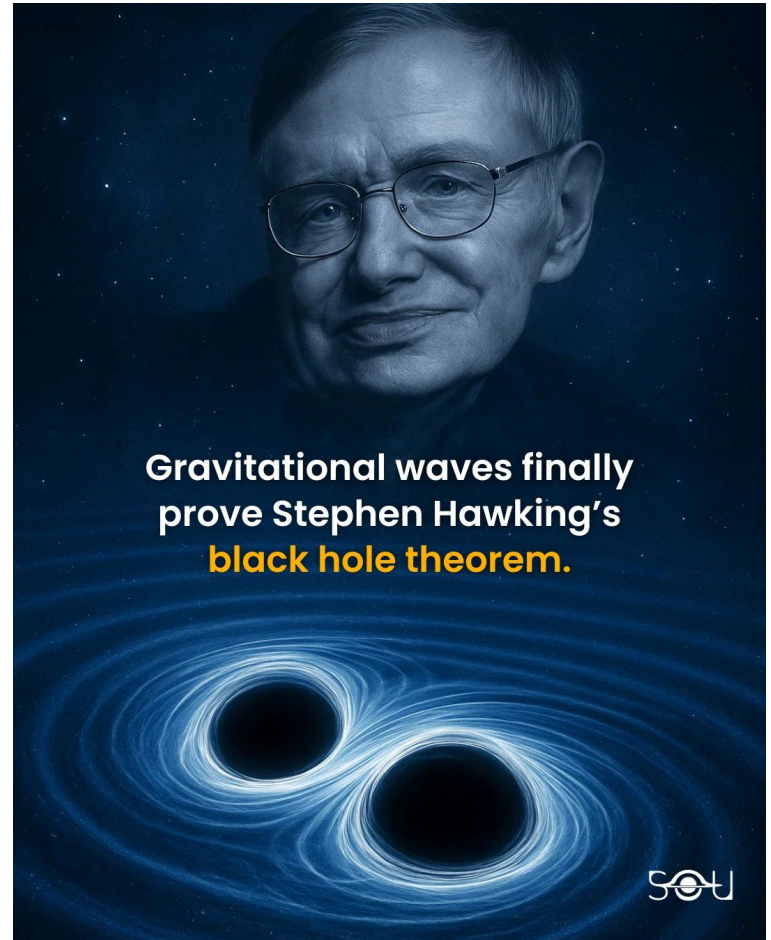
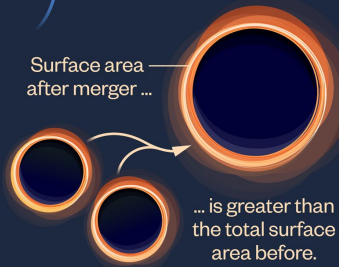
## Telling Overtones

A fleeting secondary tone was detected in the signal, offering a rare chance to test the “**Kerr solution**,” which describes a rotating BH using only mass and spin. Excitingly, the mass and spin values from this **overtone** matched those from the **fundamental tone**. If they had differed, it would imply that additional properties are necessary to describe a BH, but a match confirms that — at least for this BH — no other details are needed.



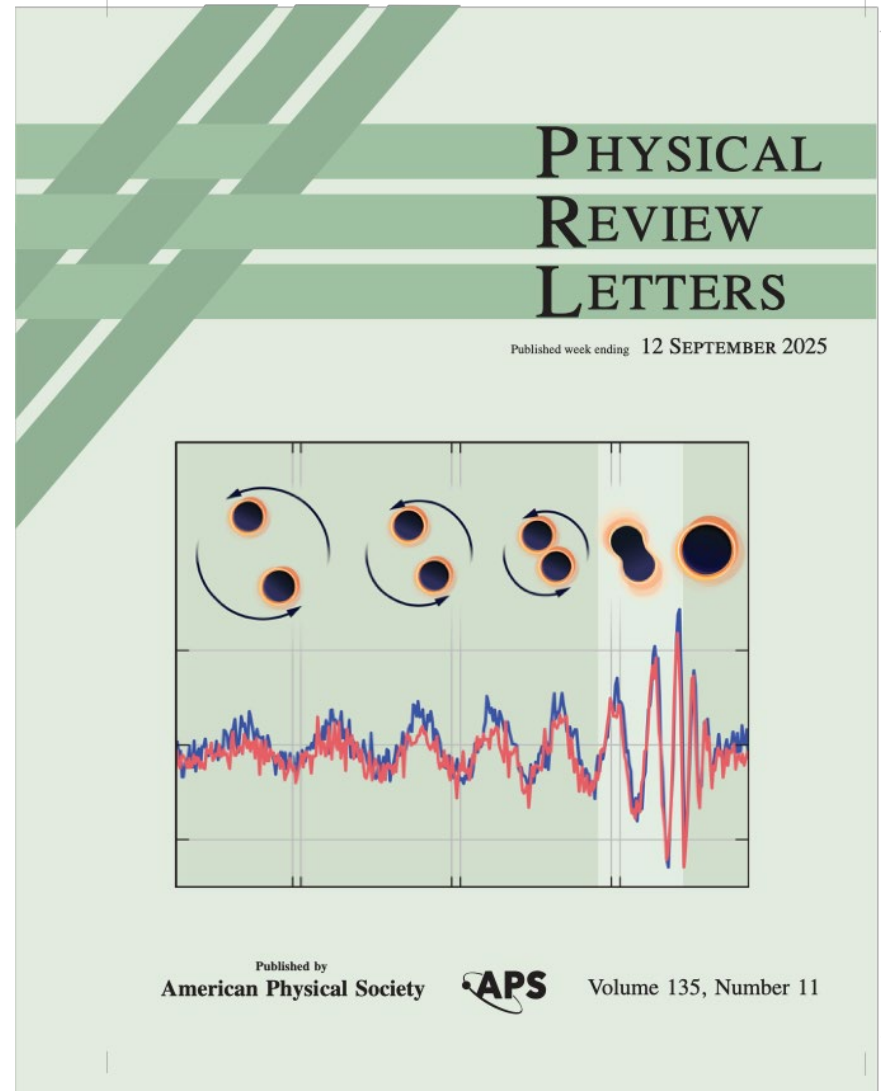
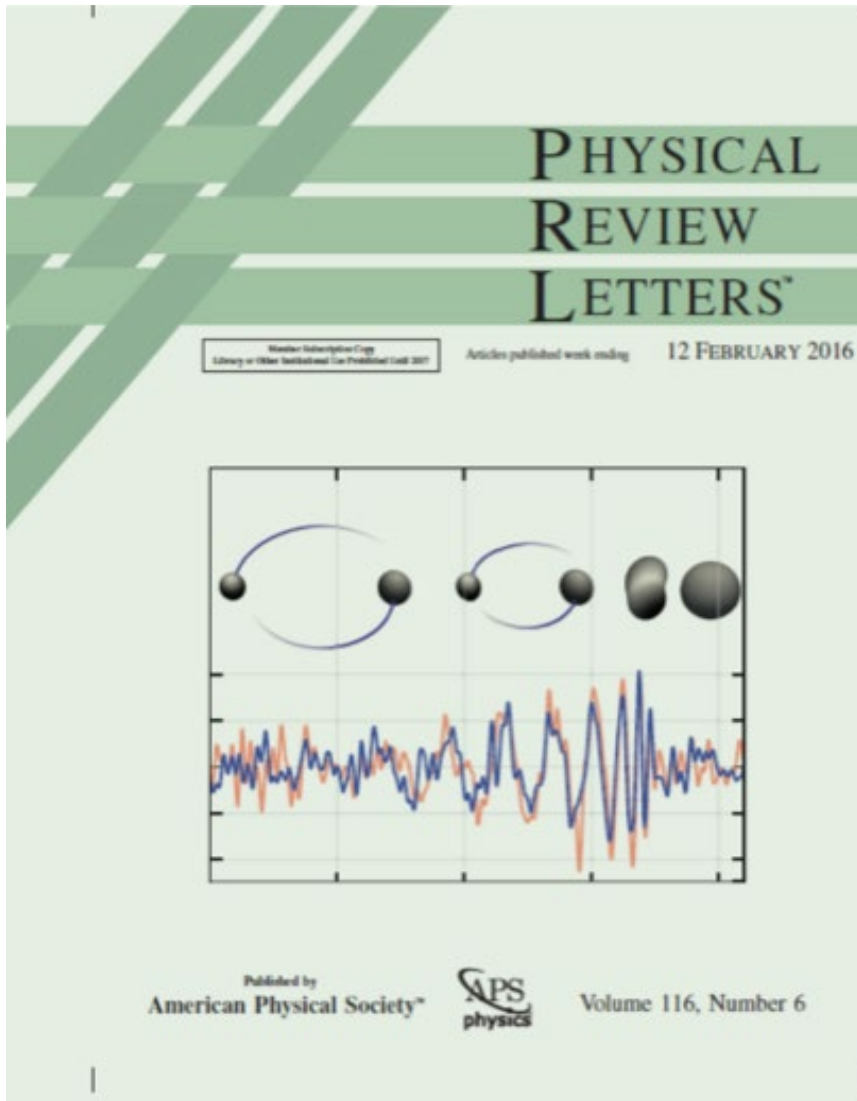
## Forever Growing

The signal also tested **Hawking’s area theorem**, which states that a BH’s surface area can never decrease — it can only grow. Surface area of a BH is determined by the area of its **event horizon** and is proportional to the square of the BH’s mass. Comparing the BHs before and after the merger confirmed that the surface area had increased, supporting the theorem.

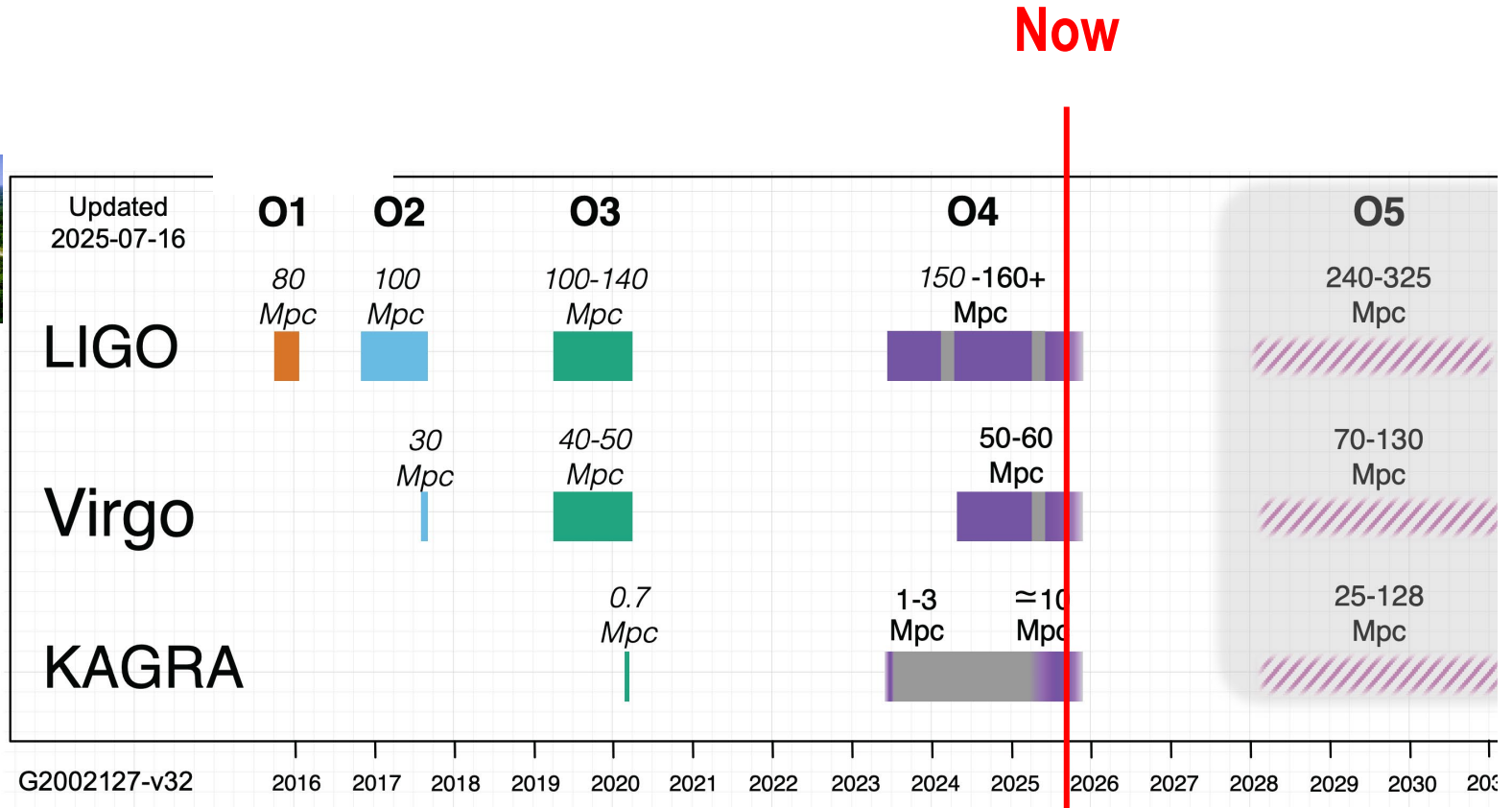


Credit: Secrets of the Universe

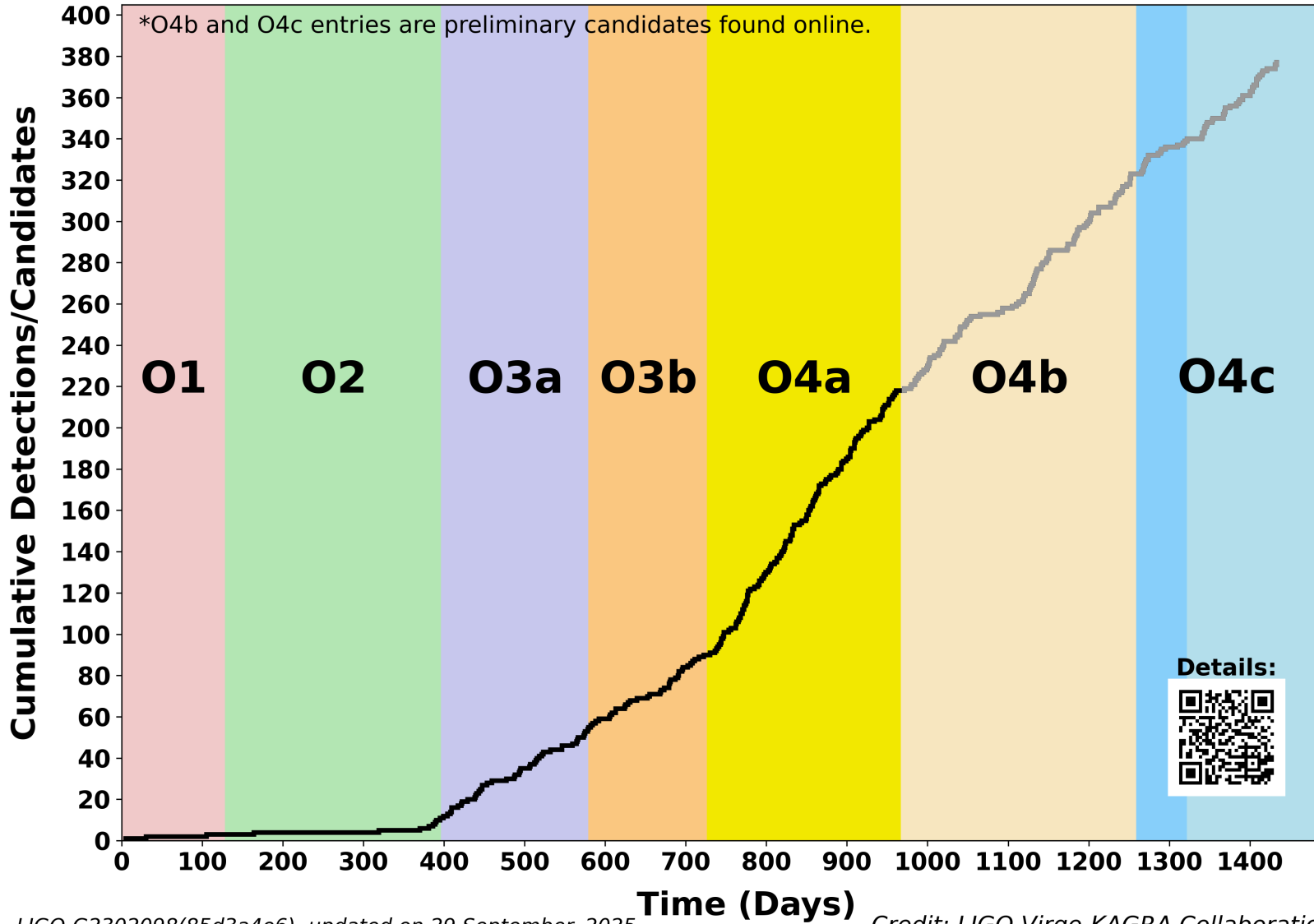
# 10 years' progress



# LVK Observing Plan 2015-2022



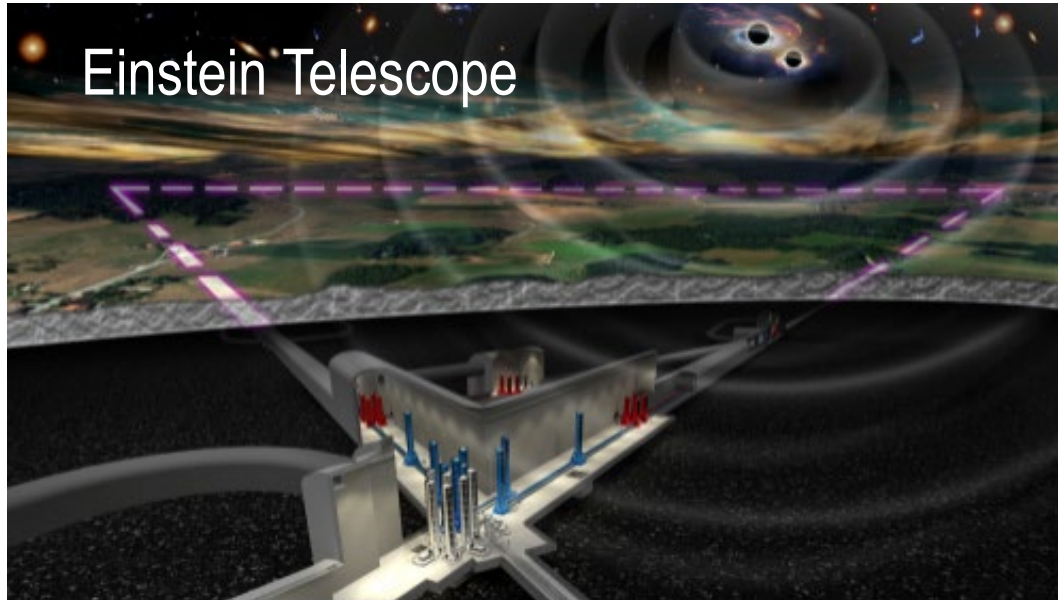
**O1+O2+O3+O4a = 218, O4b\* = 105, O4c\* = 54, Total = 377**



LIGO-G2302098(85d3a4e6), updated on 29 September, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

# Next generation detectors (ground-based)

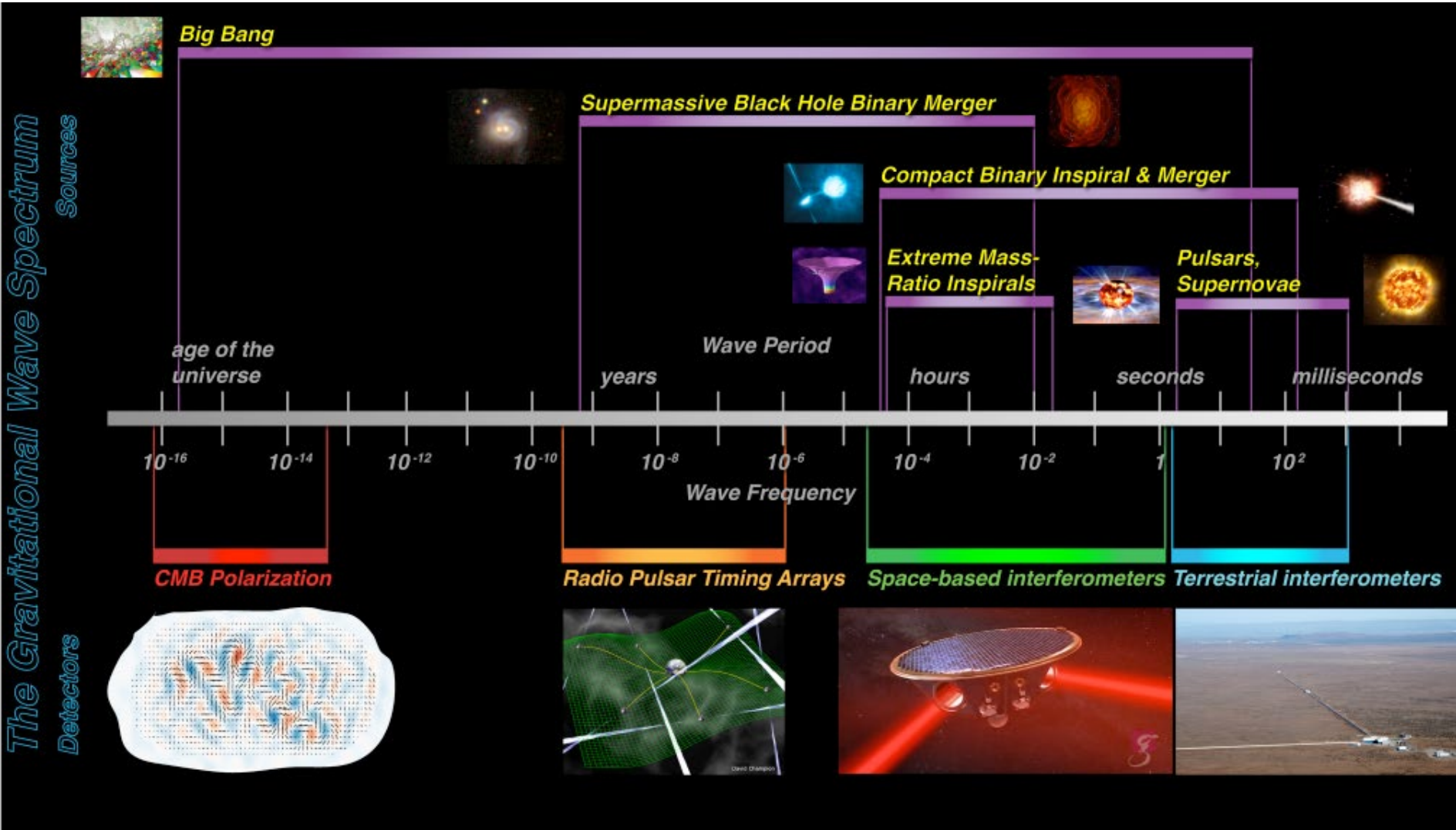


<http://www.et-gw.eu/>



<https://cosmicexplorer.org/>

# Different sources have different wavelengths and need different instruments



The Gravitational Wave Spectrum

# A cosmic hum was heard ...

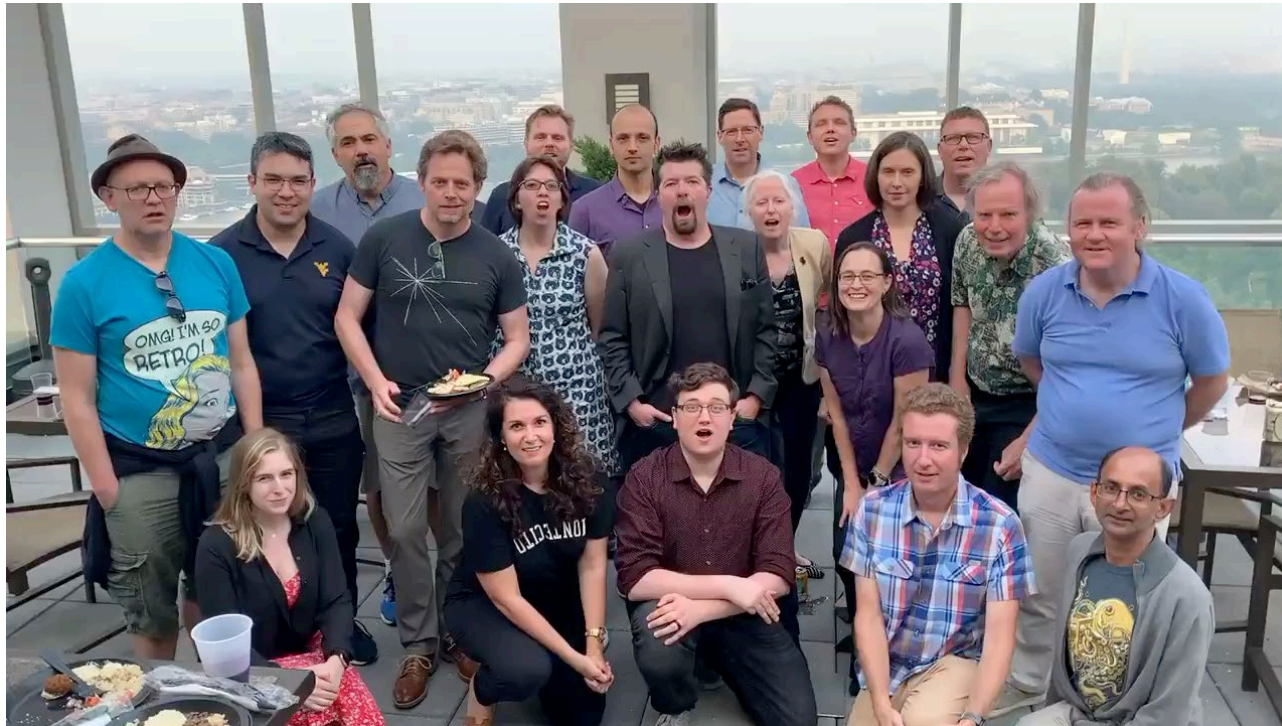
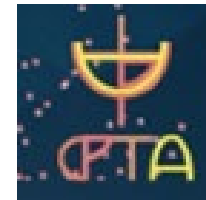
THE ASTROPHYSICAL JOURNAL LETTERS, 951:L8 (24pp), 2023 July 1  
© 2023. The Author(s). Published by the American Astronomical Society.

**OPEN ACCESS**

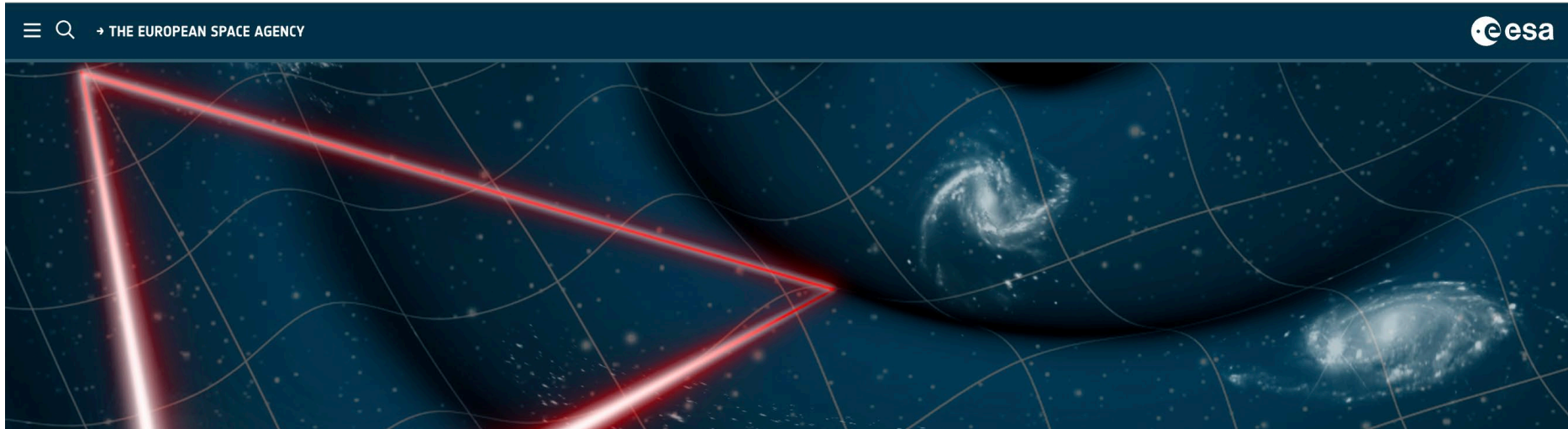
<https://doi.org/10.3847/2041-8213/acdac6>



## The NANOGrav 15 yr Data Set: Evidence for a Gravitational-wave Background



# LISA: space-based observatory



## Construction of ESA's ambitious LISA mission begins

17/06/2025 7591 VIEWS 44 LIKES

ESA / Science & Exploration / Space Science / LISA

Today, the European Space Agency (ESA) and [OHB System AG](#) sealed their agreement to build ESA's [Laser Interferometer Space Antenna, LISA](#). A bold scientific enterprise, the triple-spacecraft mission will be the first space-based observatory to study gravitational waves: ripples in spacetime caused by the most powerful events in the Universe, such as pairs of supermassive black holes colliding and merging.

From left, ESA Director of Science, Carole Mundell, and OHB System AG CEO, Chiara Pedersoli shake hands at the signature event



# Gravitational waves astronomy: this is just the beginning!

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



Credit: Kevin Sylvester