

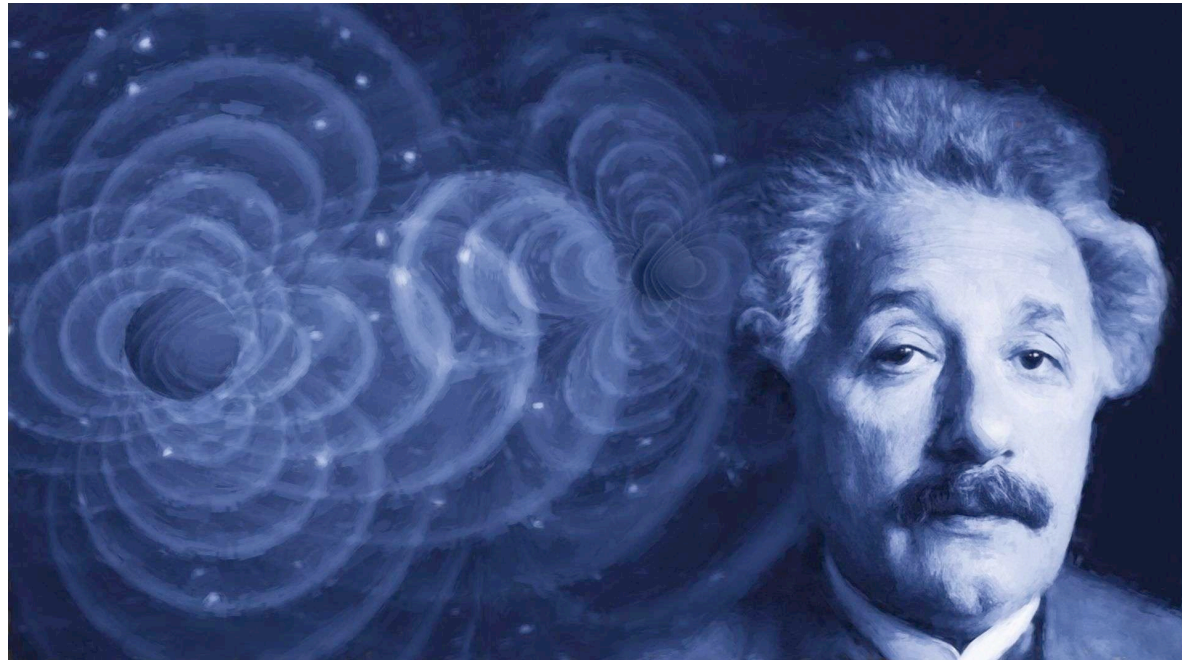
Einstein, black holes and gravitational waves



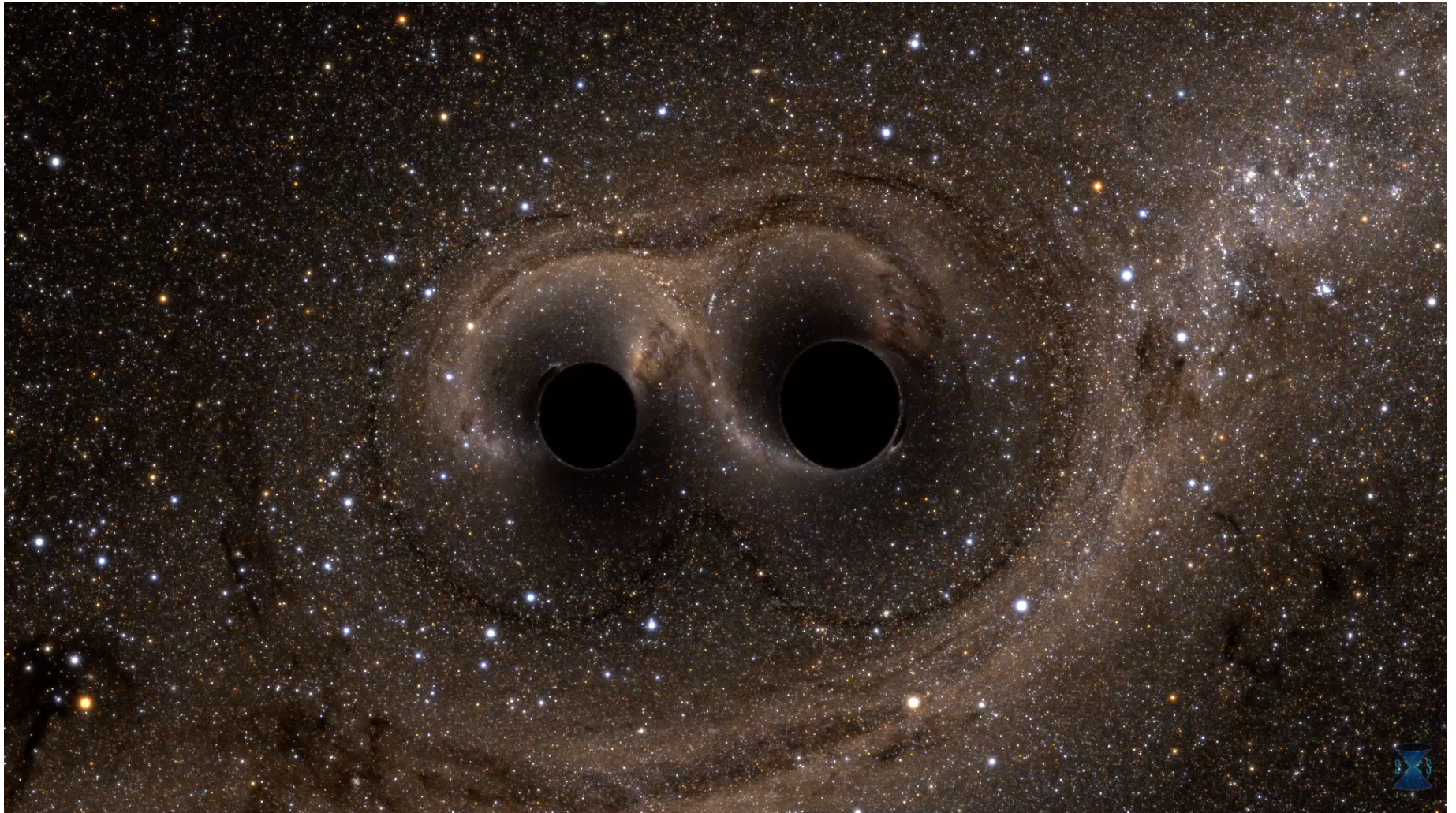
Gabriela González

Louisiana State University

For the LIGO Scientific Collaboration and Virgo Collaboration

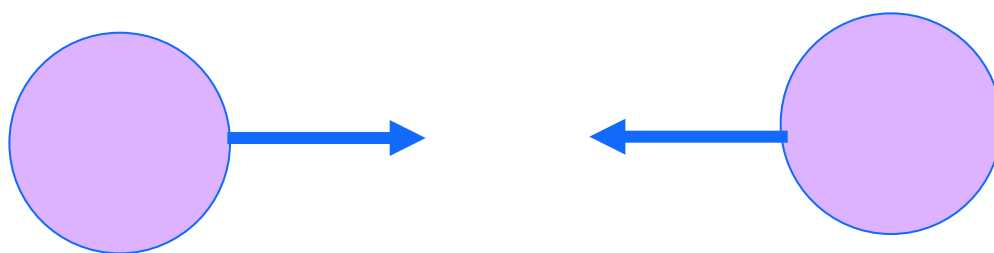


About a billion years ago...

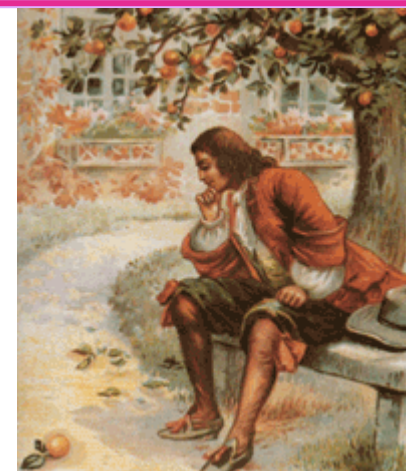


Credit: The SXS (Simulating eXtreme Spacetimes) Project

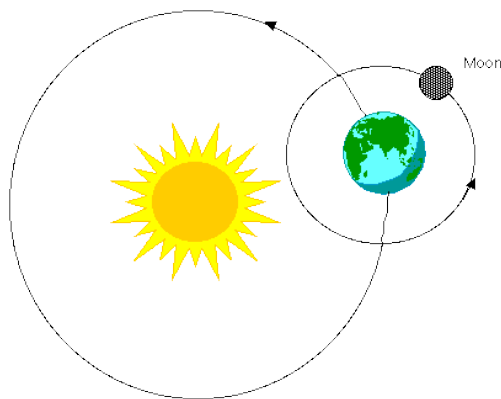
Newton's gravity



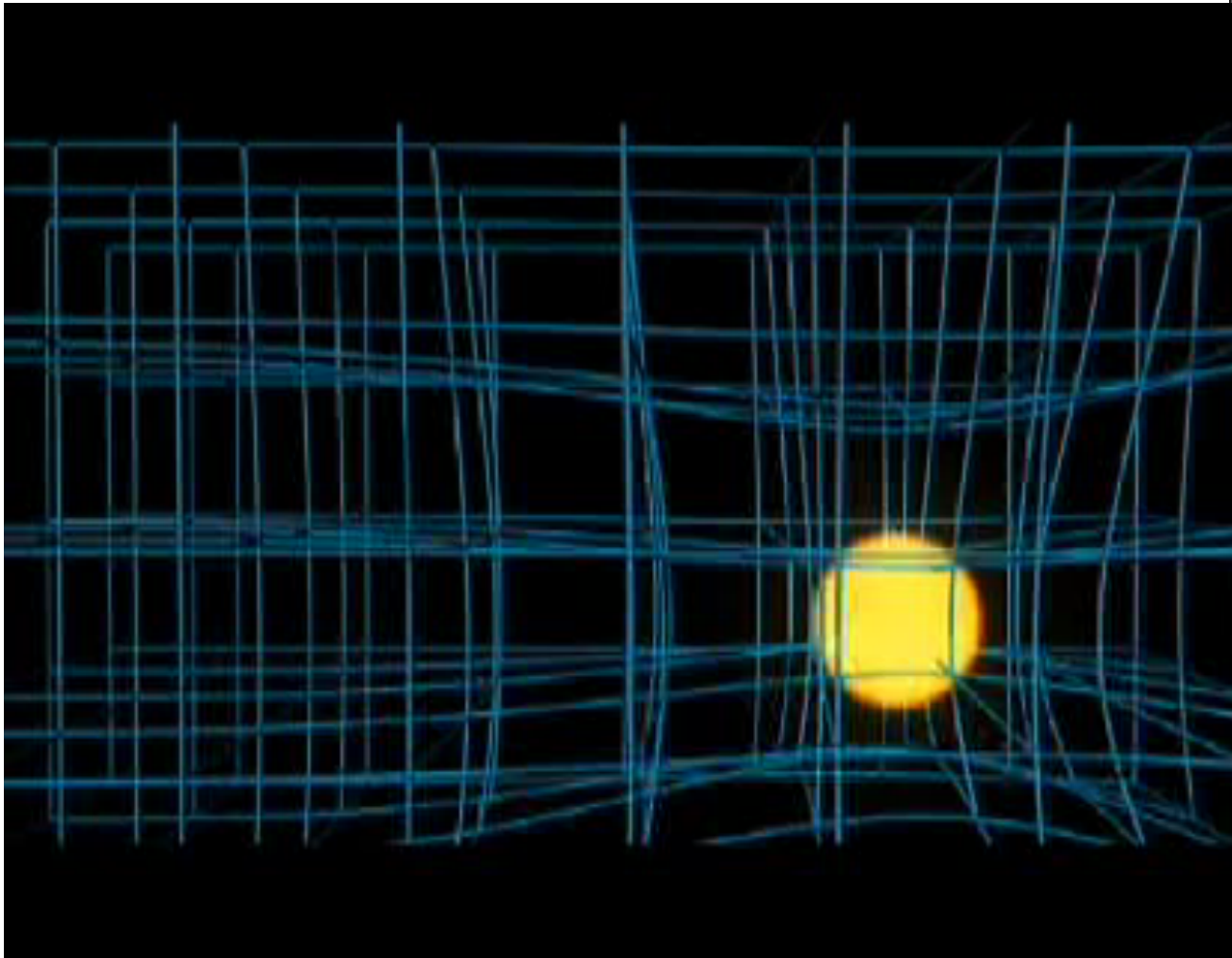
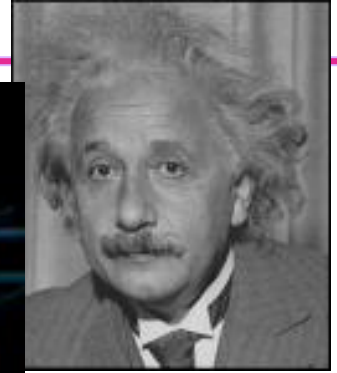
"Newton's law": $F = Gm_1m_2/r^2$



Explains why apples fall, why the planets move around the Sun,...



Einstein's gravity

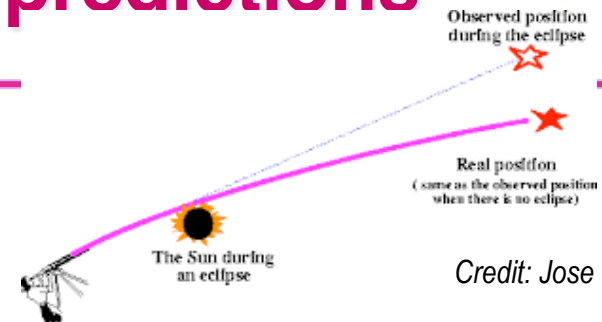


American Museum of Natural History,
"Gravity: Making waves" Science Bulletin

(Some of) Einstein's predictions

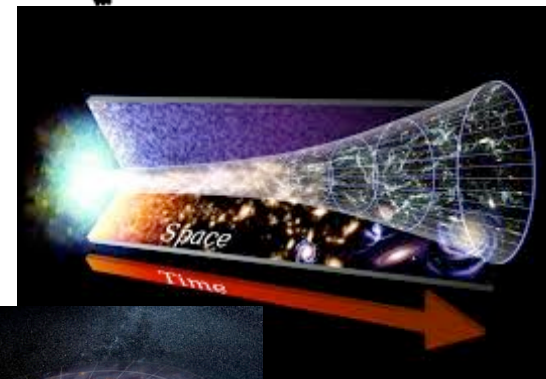


- Light bends its path around matter (following curved space-time).

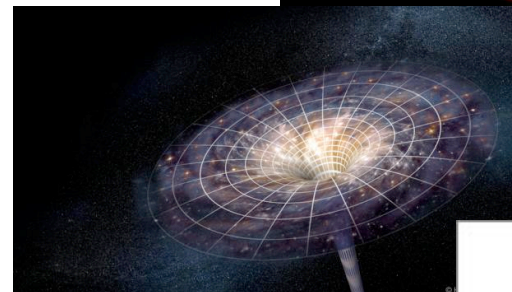


Credit: Jose Wudka

- The Universe expands.
- There are "black holes".

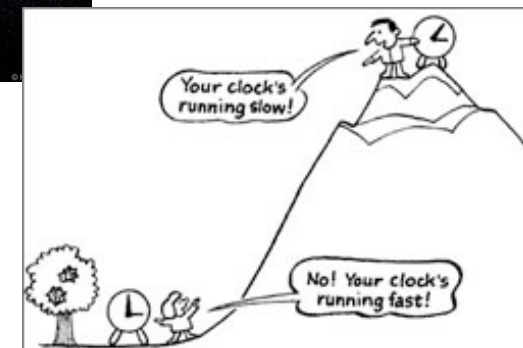


ard Space Flight Center



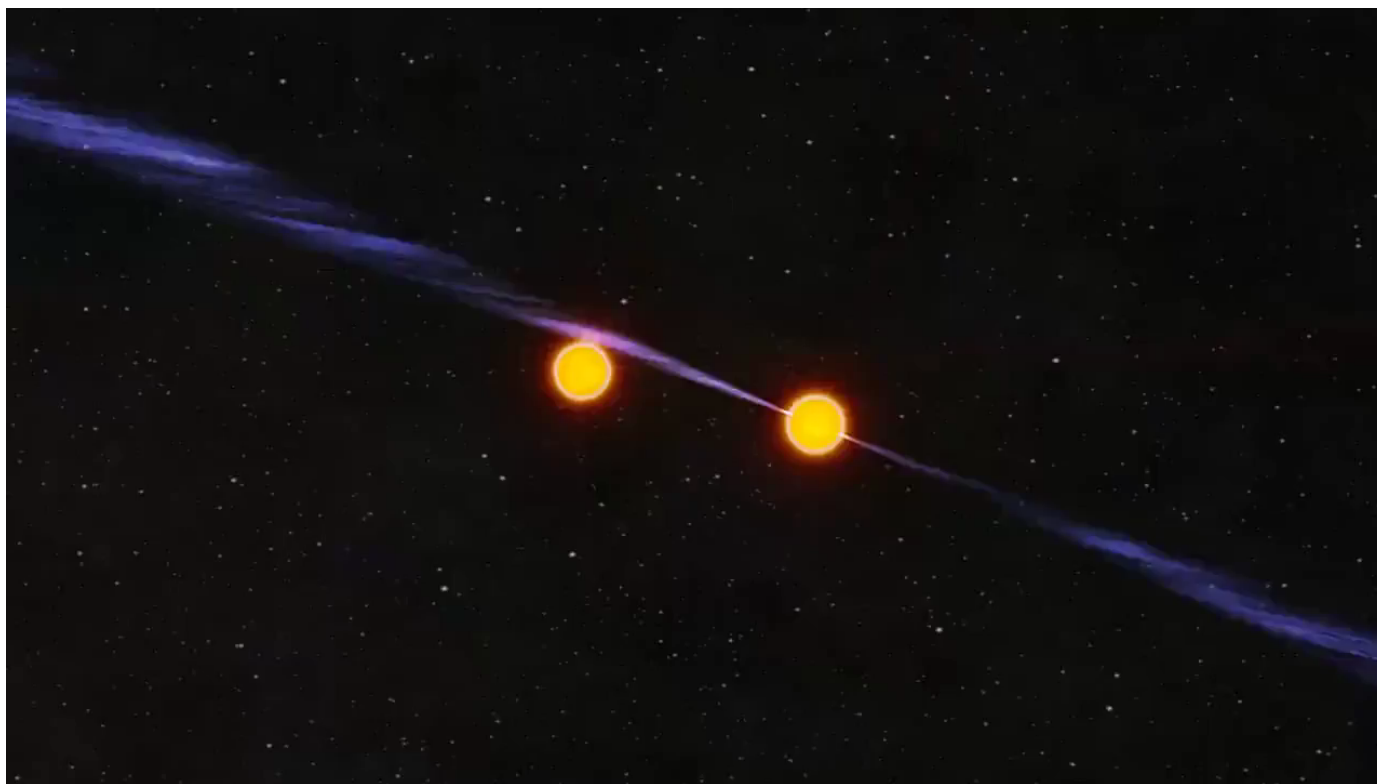
Credit: Henning Dalhoff/SPL

- Clocks run at different rates at different heights.



From npl.co.uk

Gravitational waves

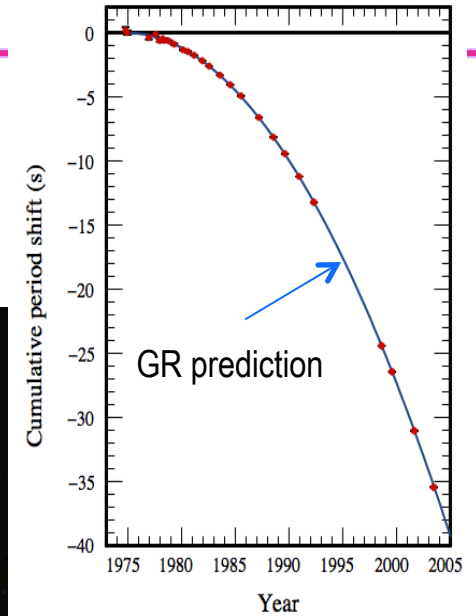
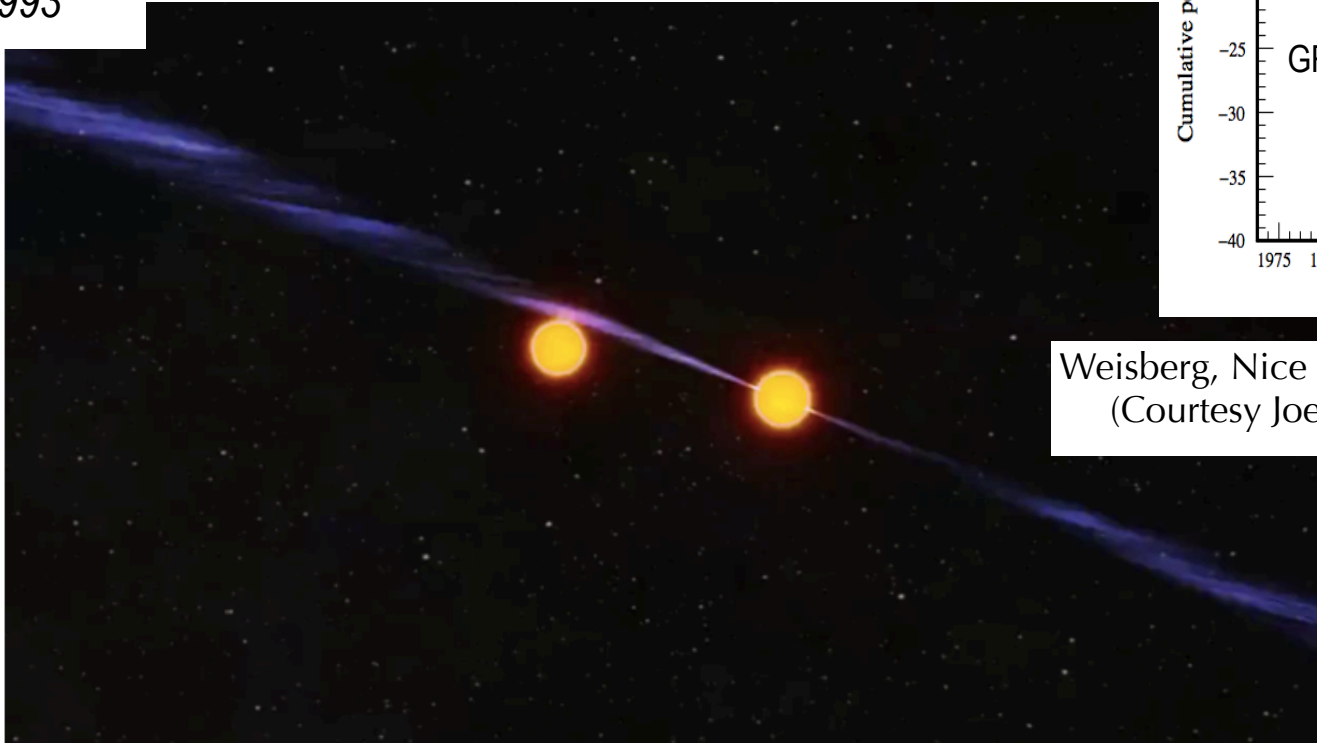


Credit: [John Rowe animations](#)

Gravitational waves

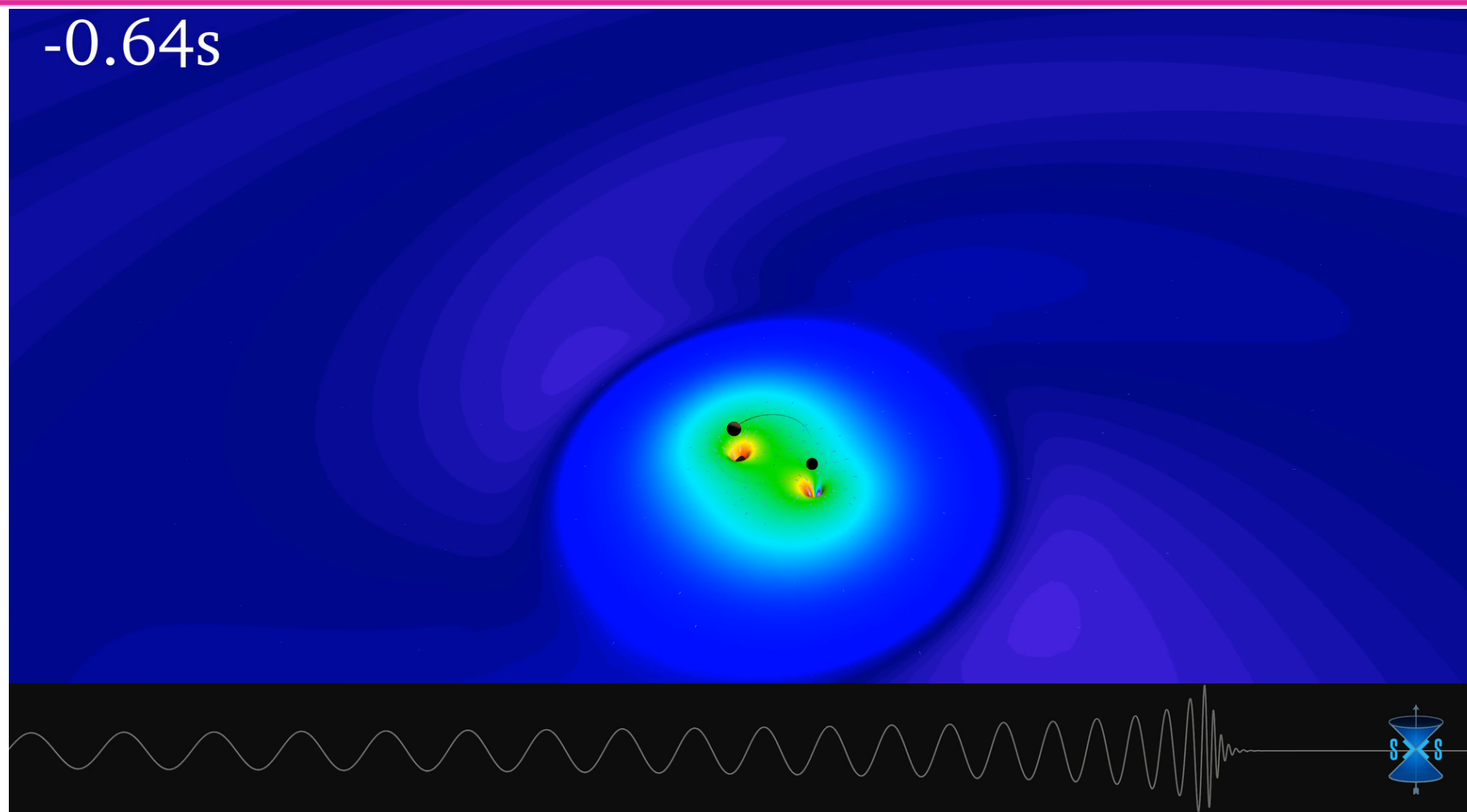


*Hulse,
Taylor
Nobel Prize
1993*

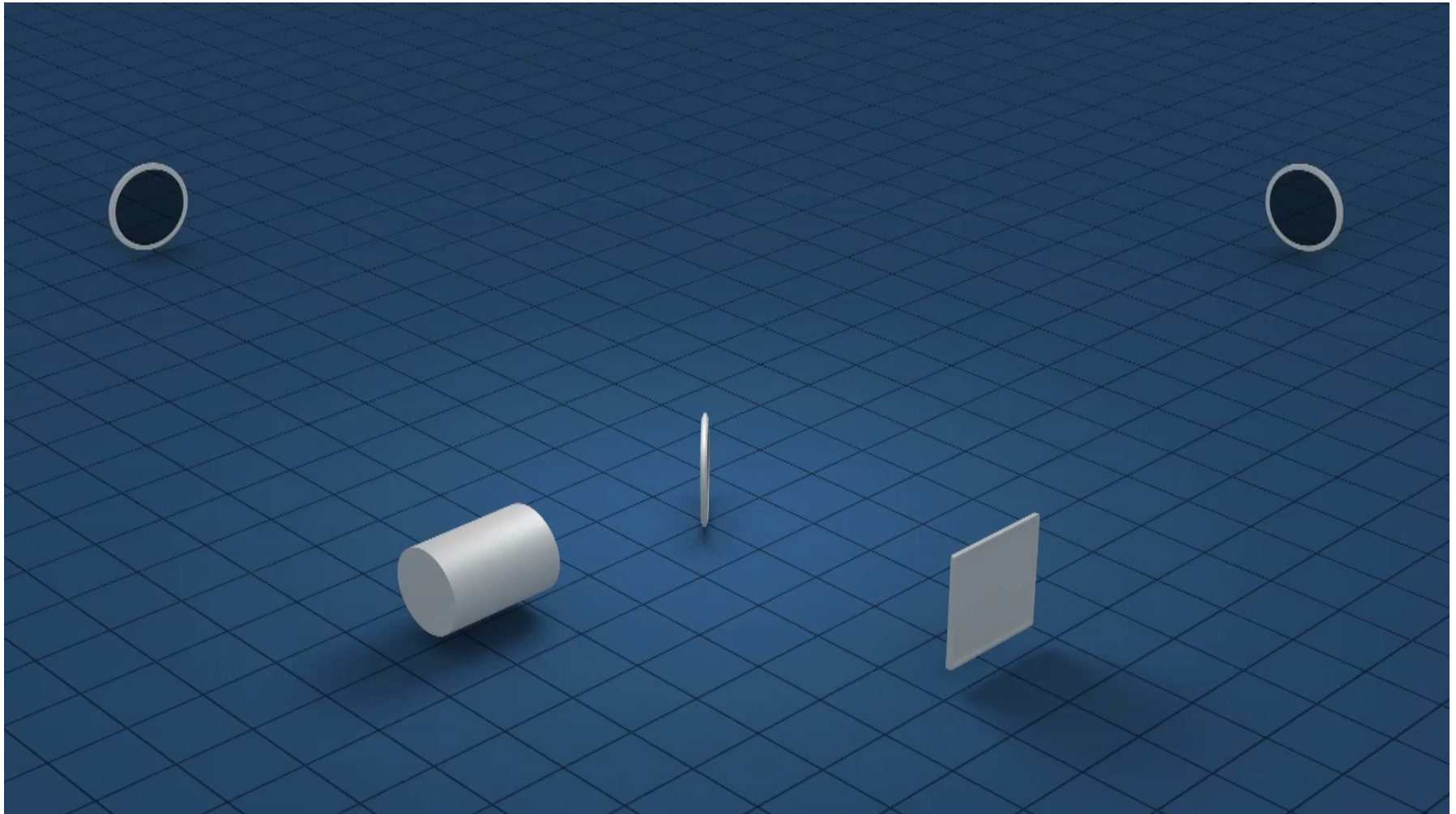


Weisberg, Nice & Taylor, 2010
(Courtesy Joel Weisberg)

Solving Einstein's equations on computers

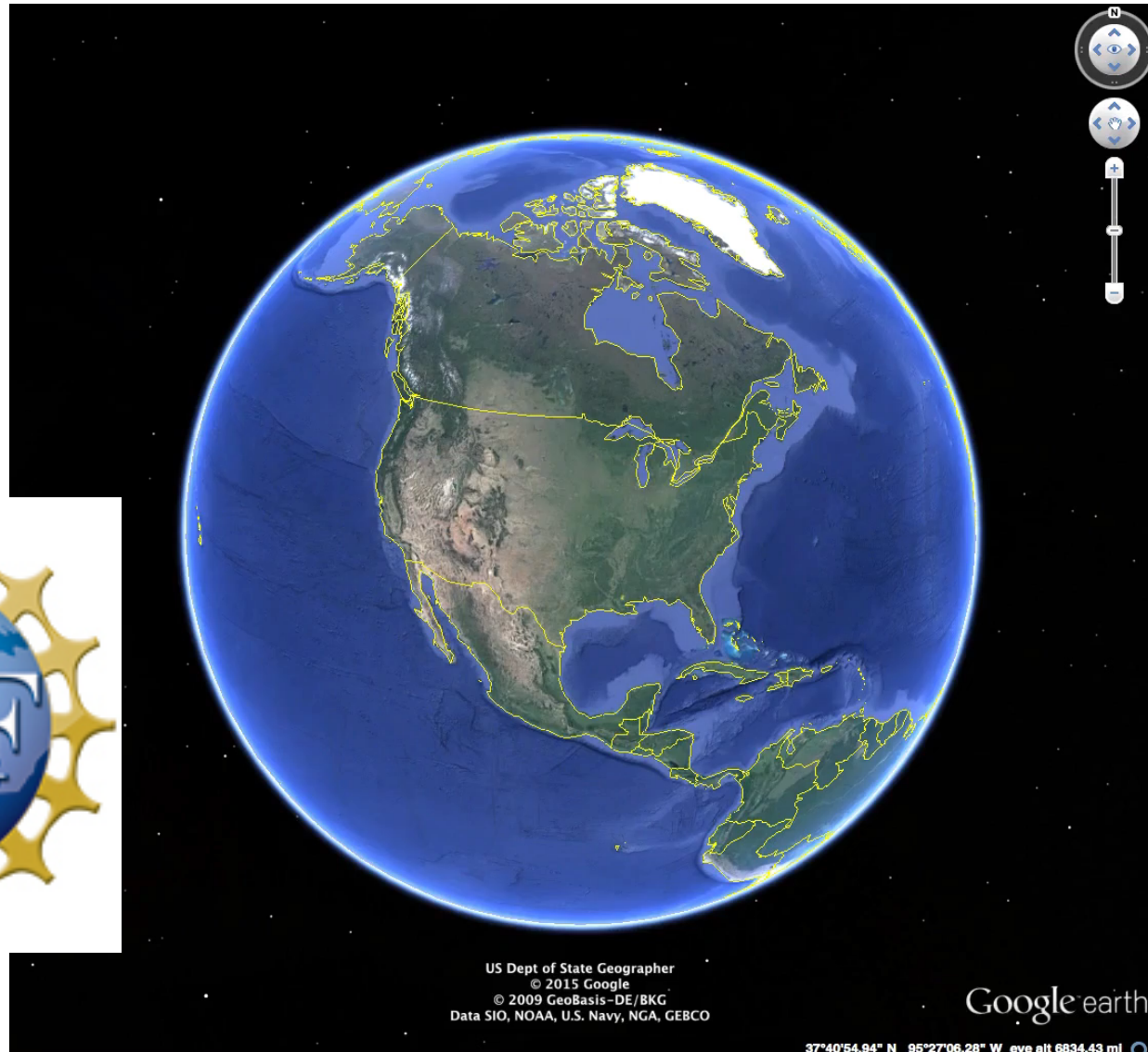


How to detect gravitational waves: interferometer

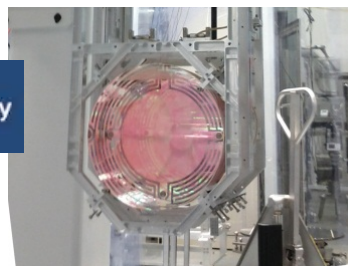
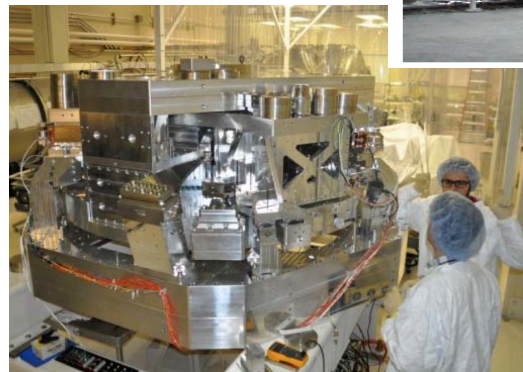
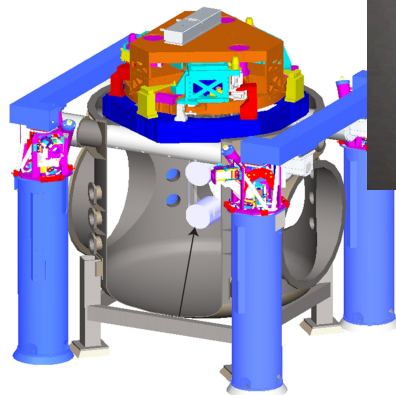
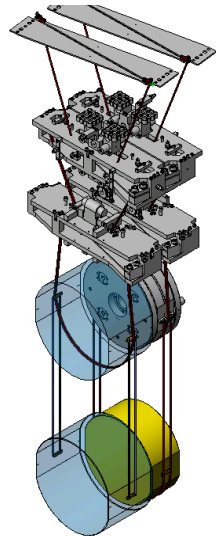
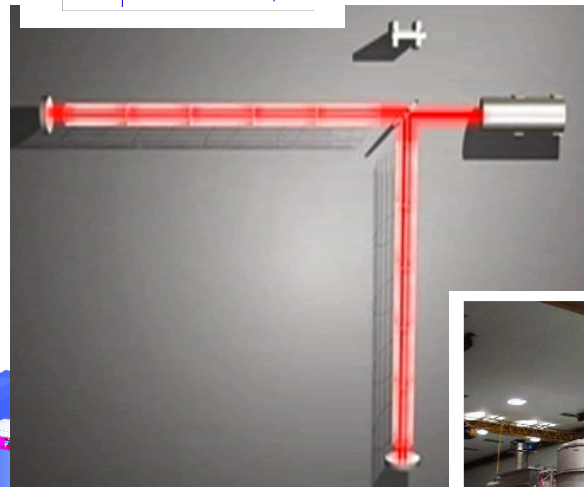
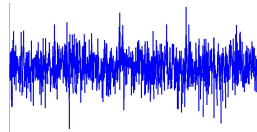


Credit: LIGO/T. Pyle

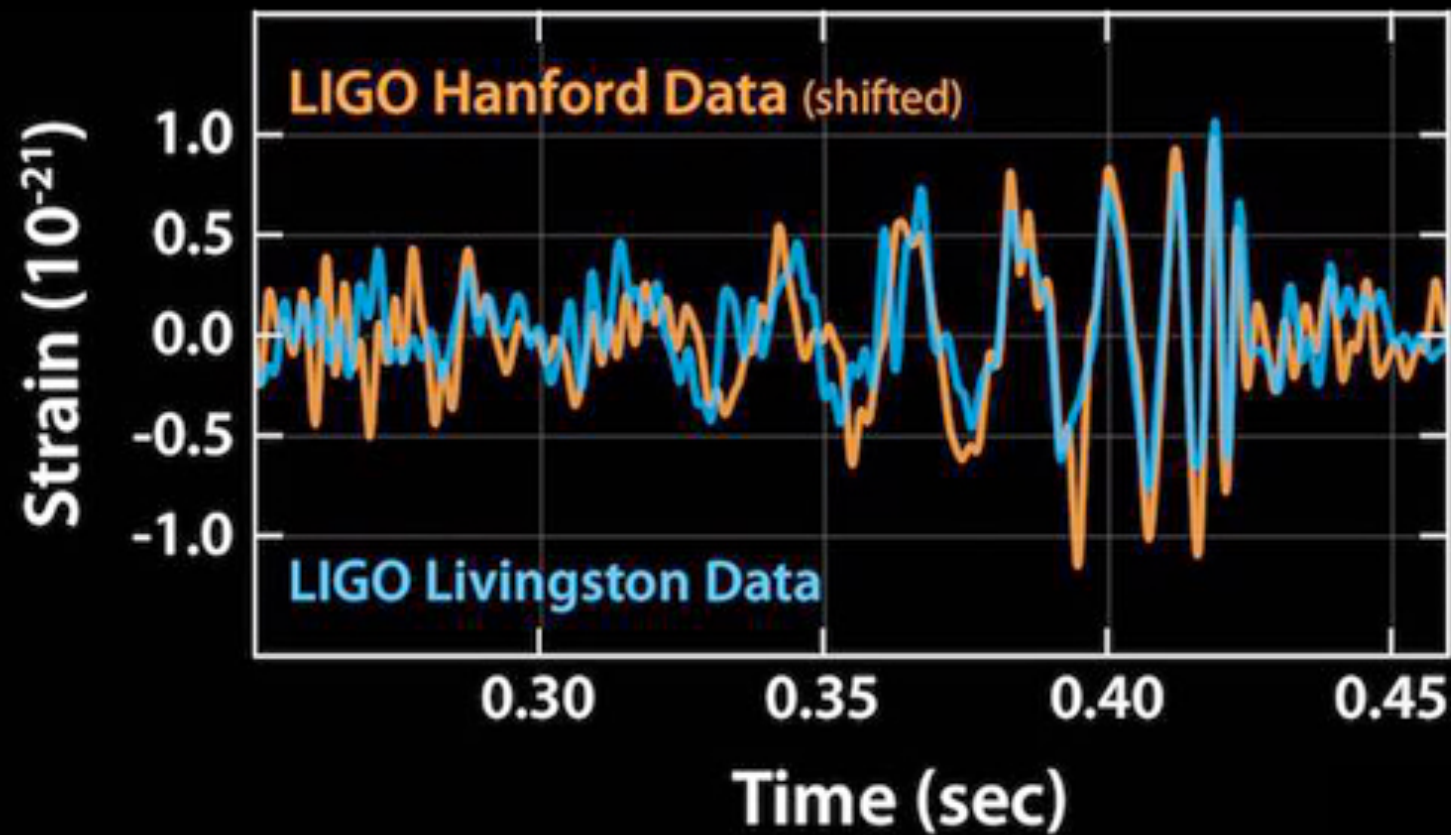
In the 90s, LIGO detectors were built



2008+: Advanced LIGO detectors

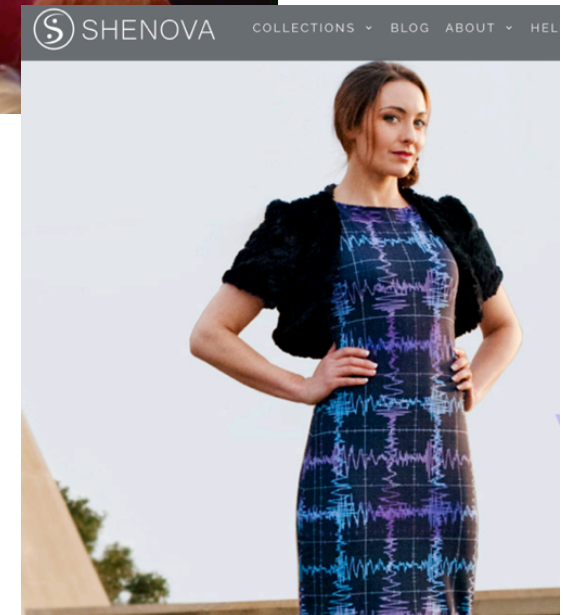
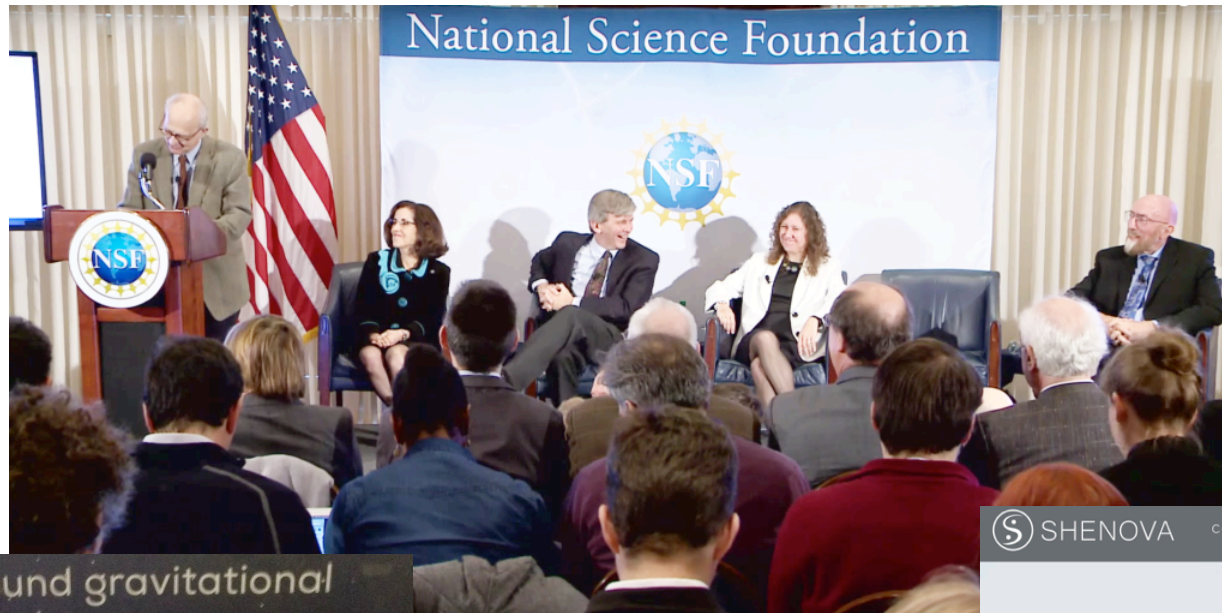


On Sept 14 2015...



Credit: LIGO

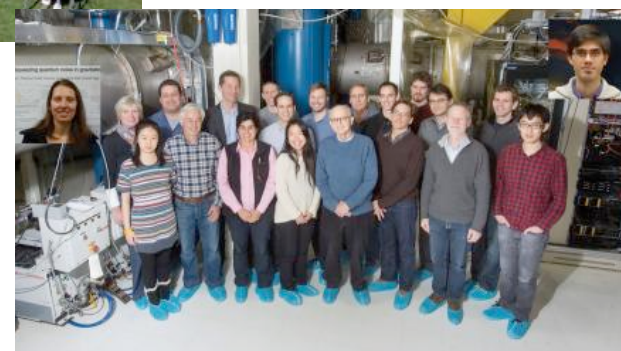
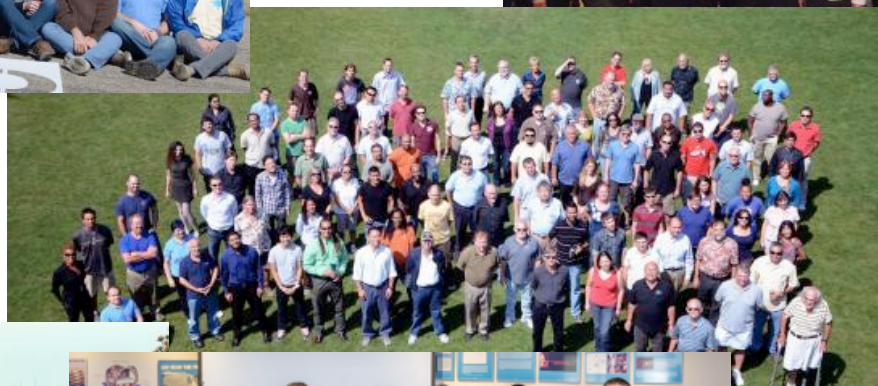
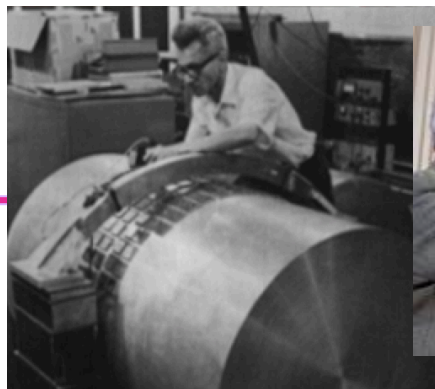
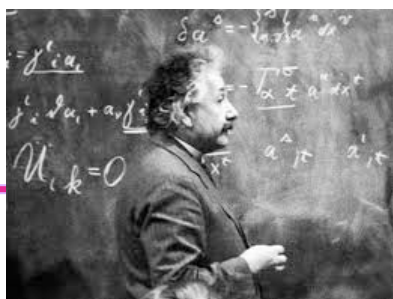
February 11, 2016: We did it!





“We” = LIGO Scientific Collaboration
(and Virgo Collaboration)





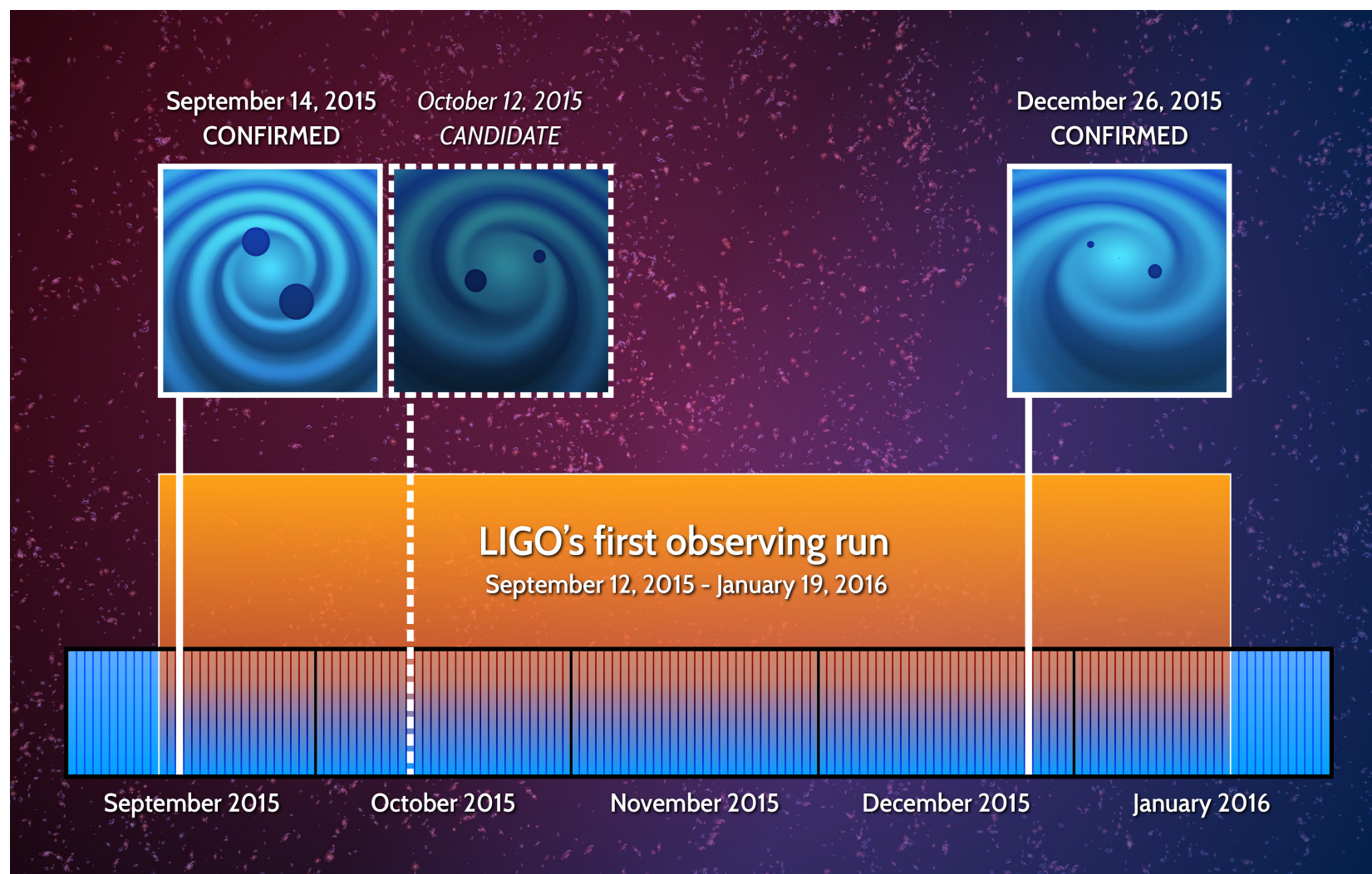
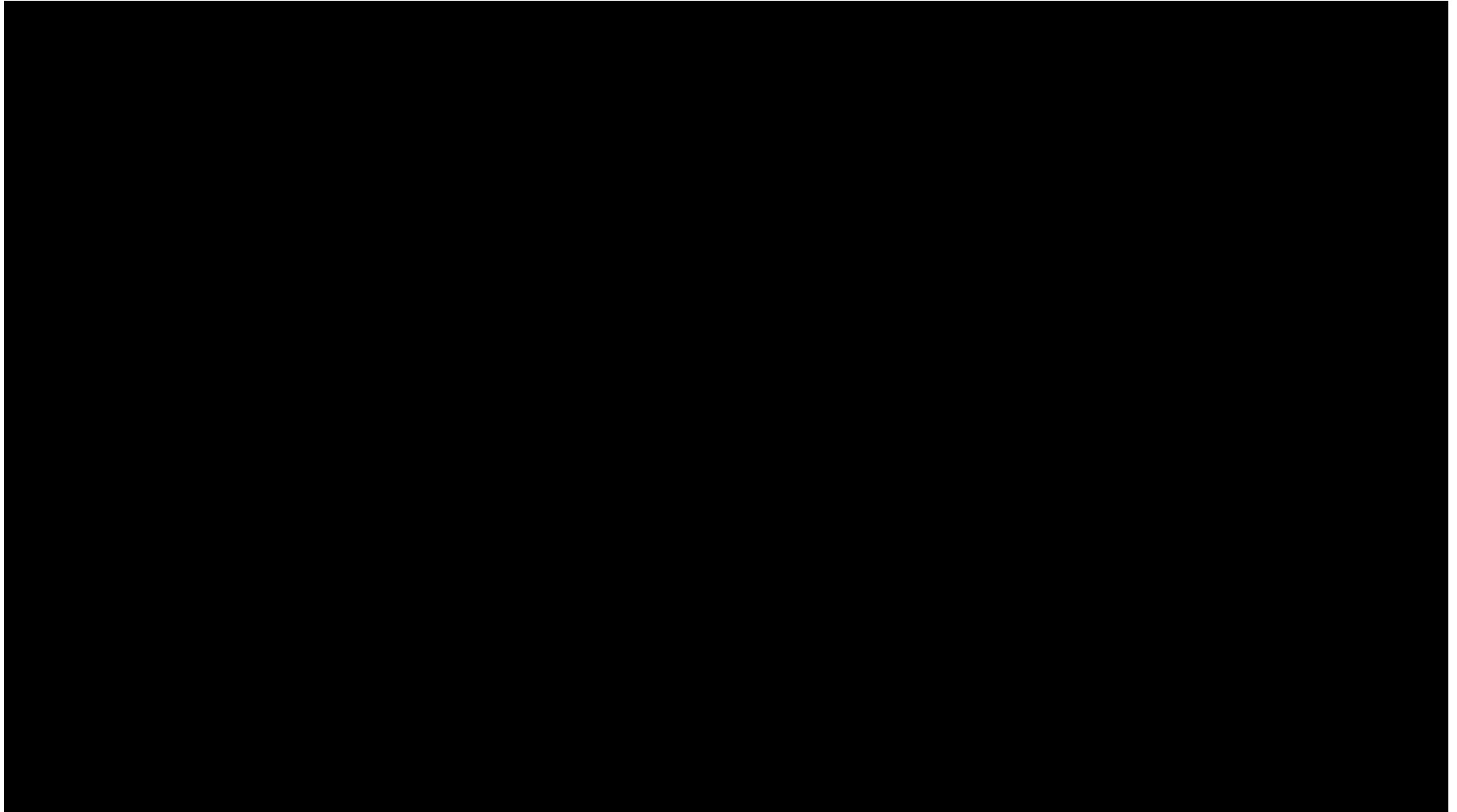


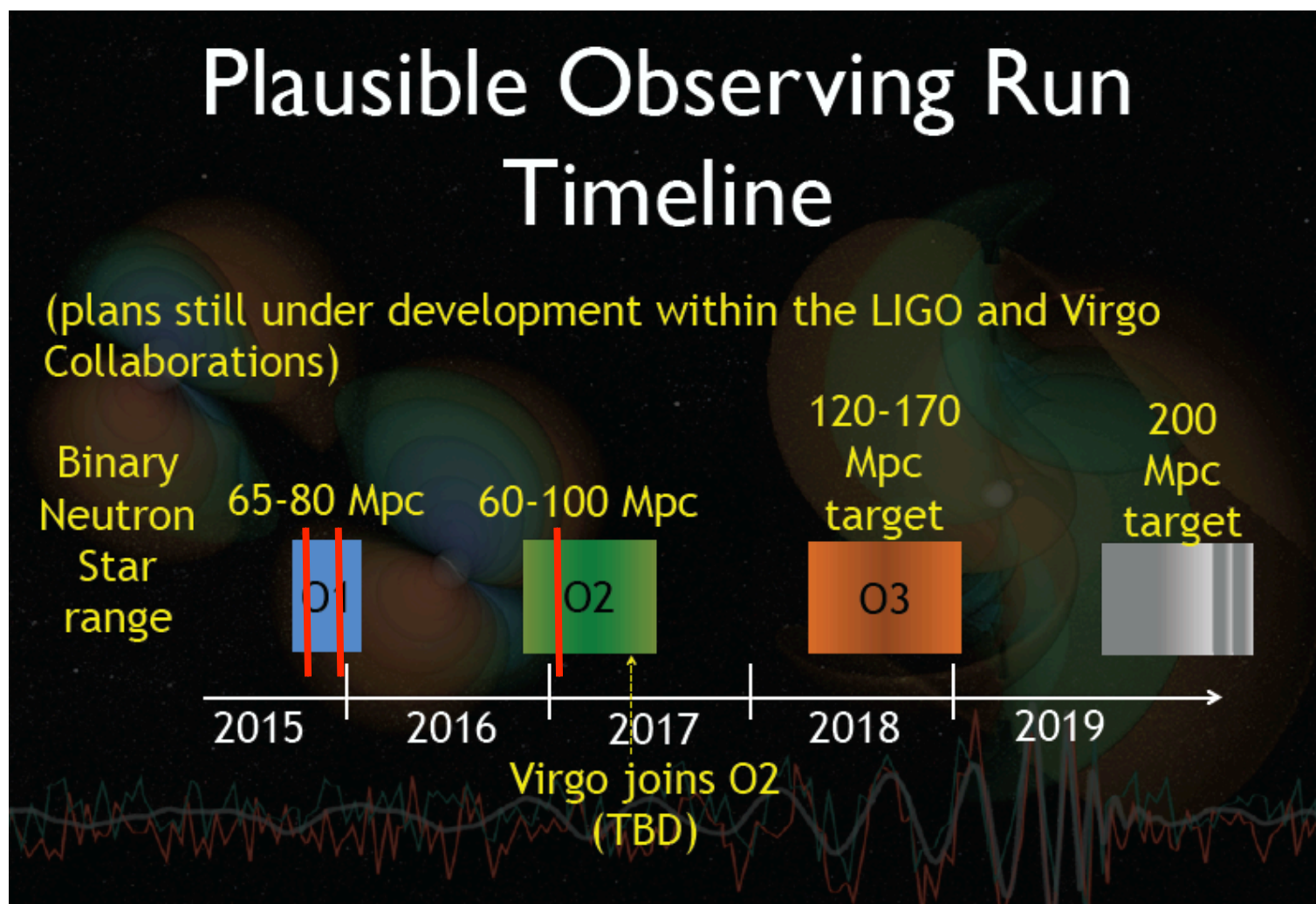
Image credit: LIGO

Gravity's symphony: first two notes



Credit: LIGO

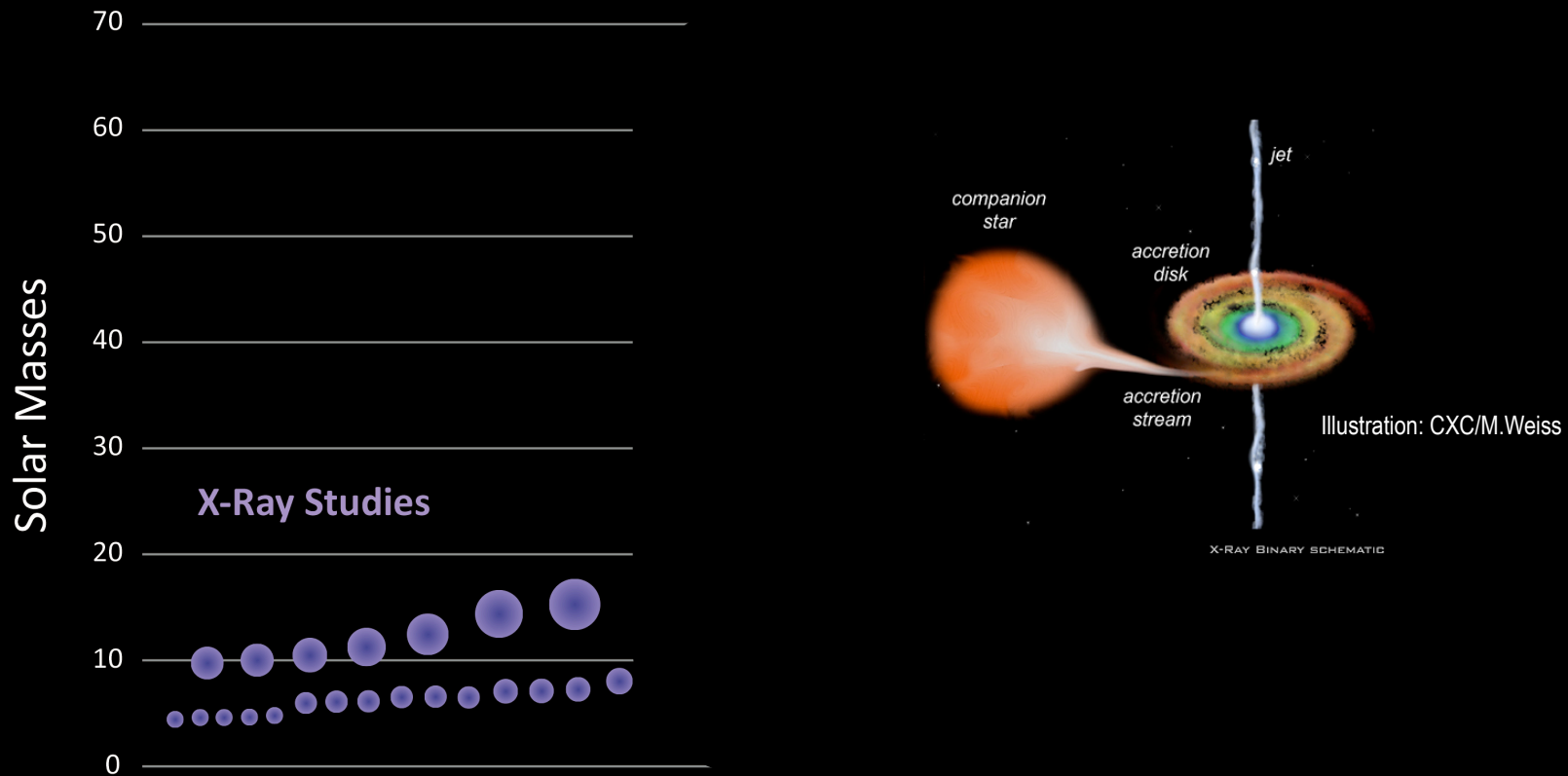
What happened since 2016? What will happen in the next few years?



Filling in the black hole catalog



Black Holes of Known Mass

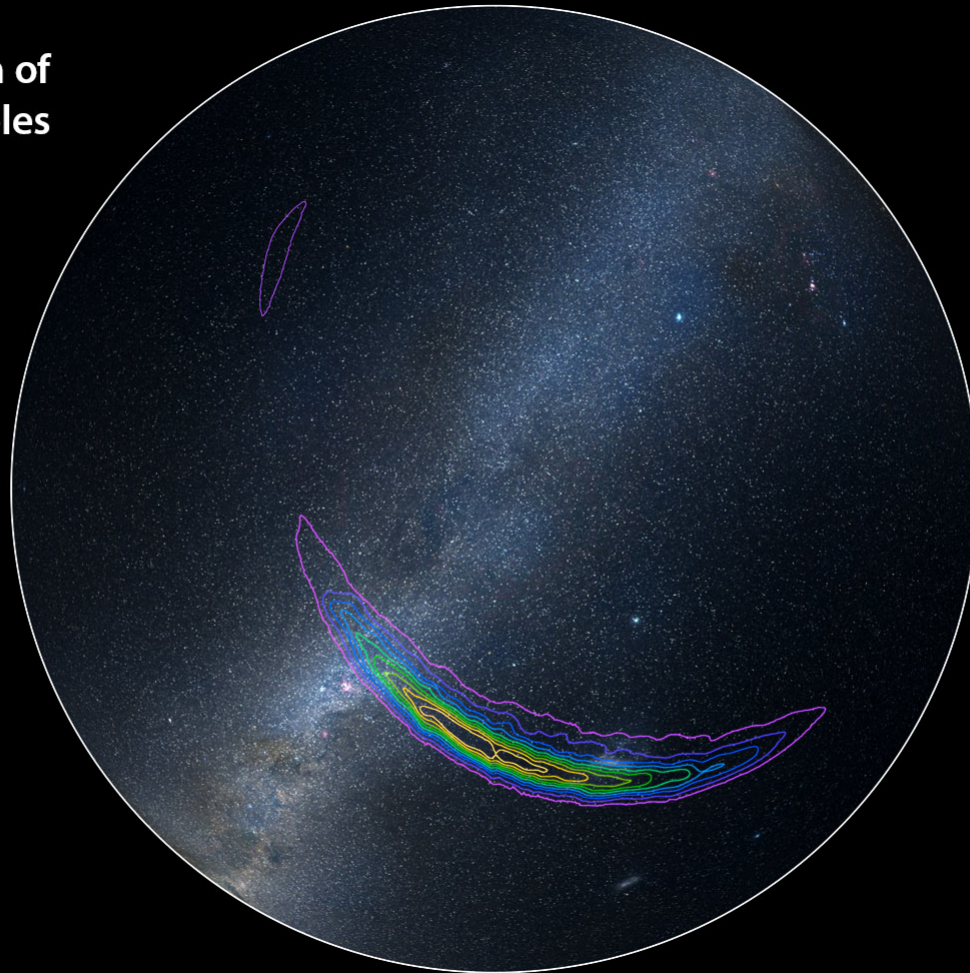


Credit: LSC/Sonoma State University/Aurore Simonnet

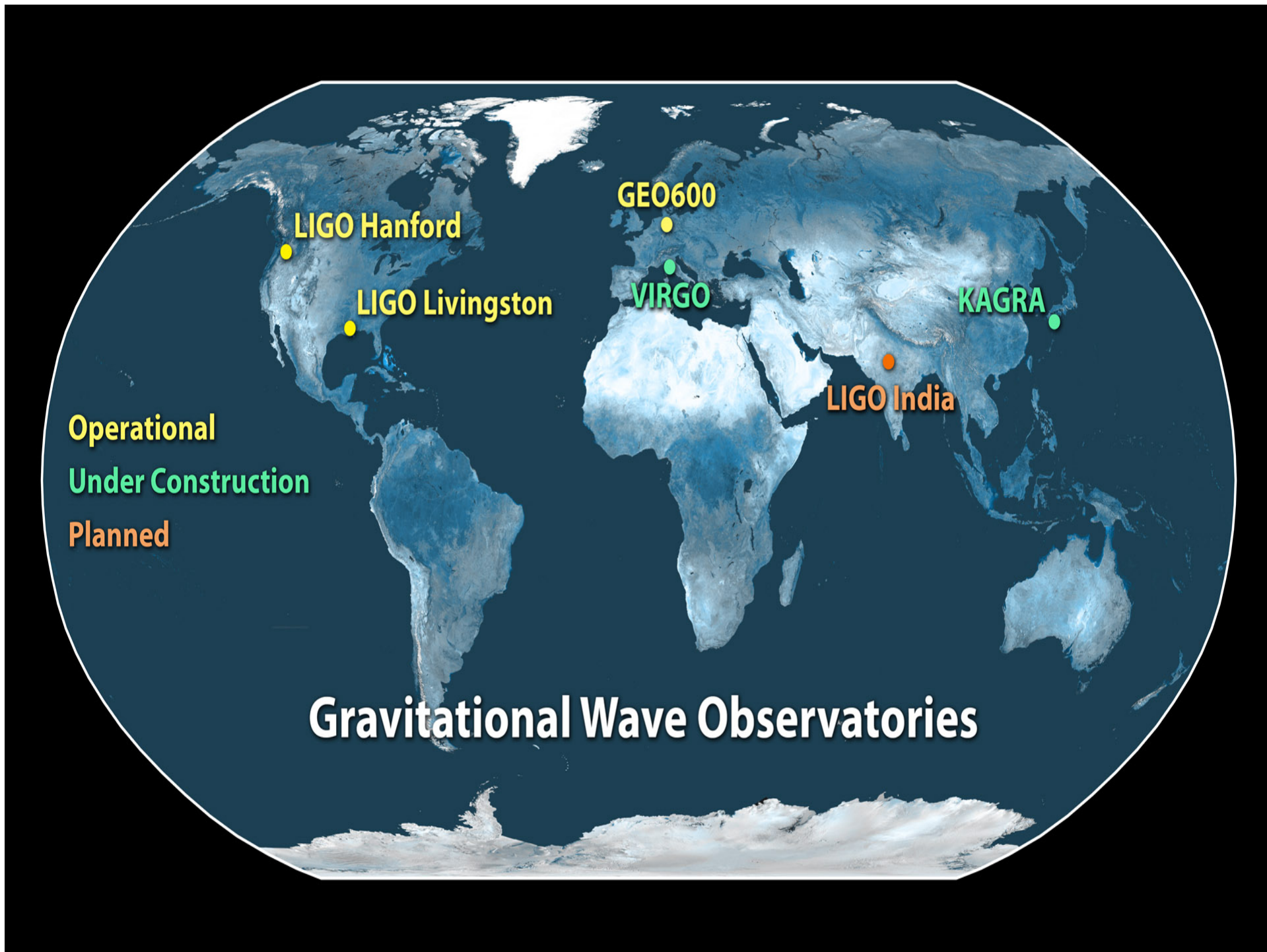
Where did the event come from?



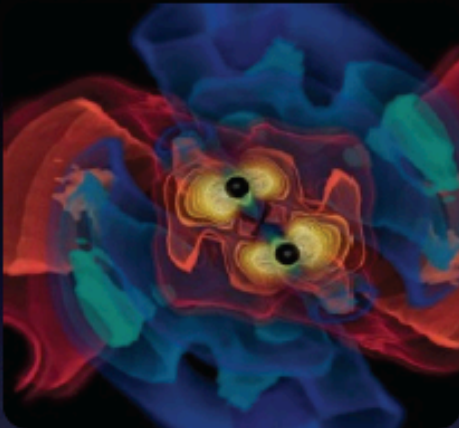
Probable location of
merging black holes



Credit: LIGO/Axel Mellinger



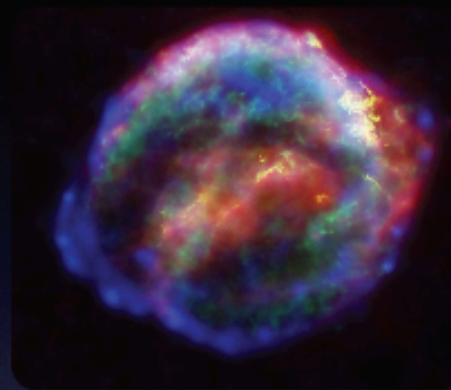
Sources of gravitational waves: not just black holes!



Coalescing Binary Systems

Neutron Stars,
Black Holes

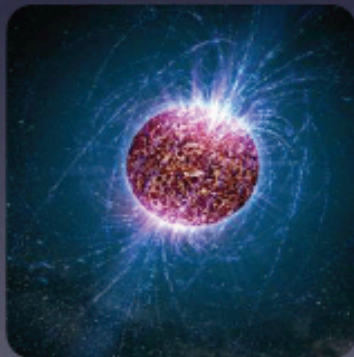
Credit: AEI, CCT, LSU



'Bursts'

asymmetric core
collapse supernovae
cosmic strings
???

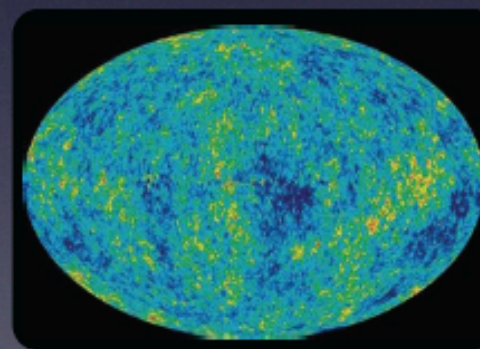
Credit: Chandra X-ray Observatory



Continuous Sources

Spinning neutron stars
crustal deformations,
accretion

Casey Reed, Penn State



Astrophysical or Cosmic GW background

stochastic,
incoherent
background

NASA/WMAP Science Team

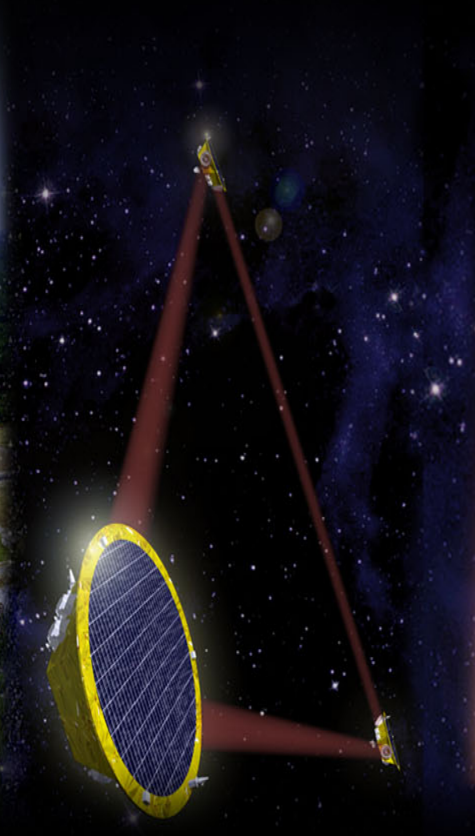
Gravitational Wave Periods

Milliseconds



LIGO

Minutes
to Hours



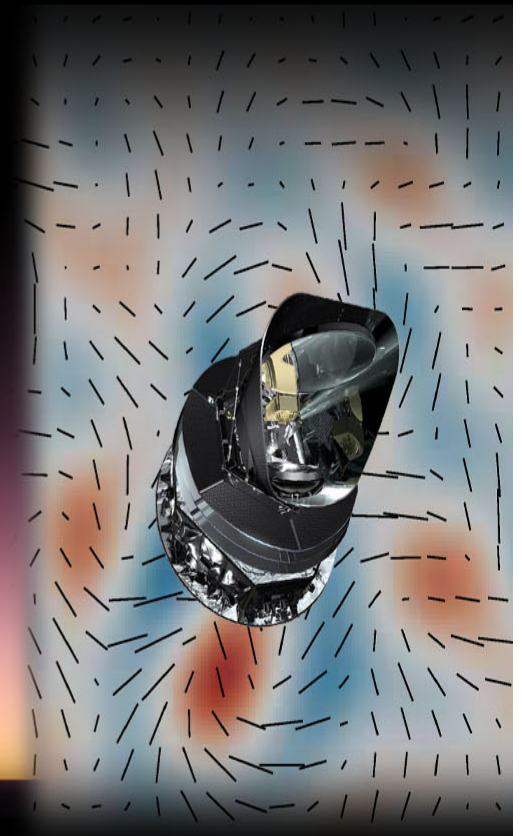
LISA

Years
to Decades



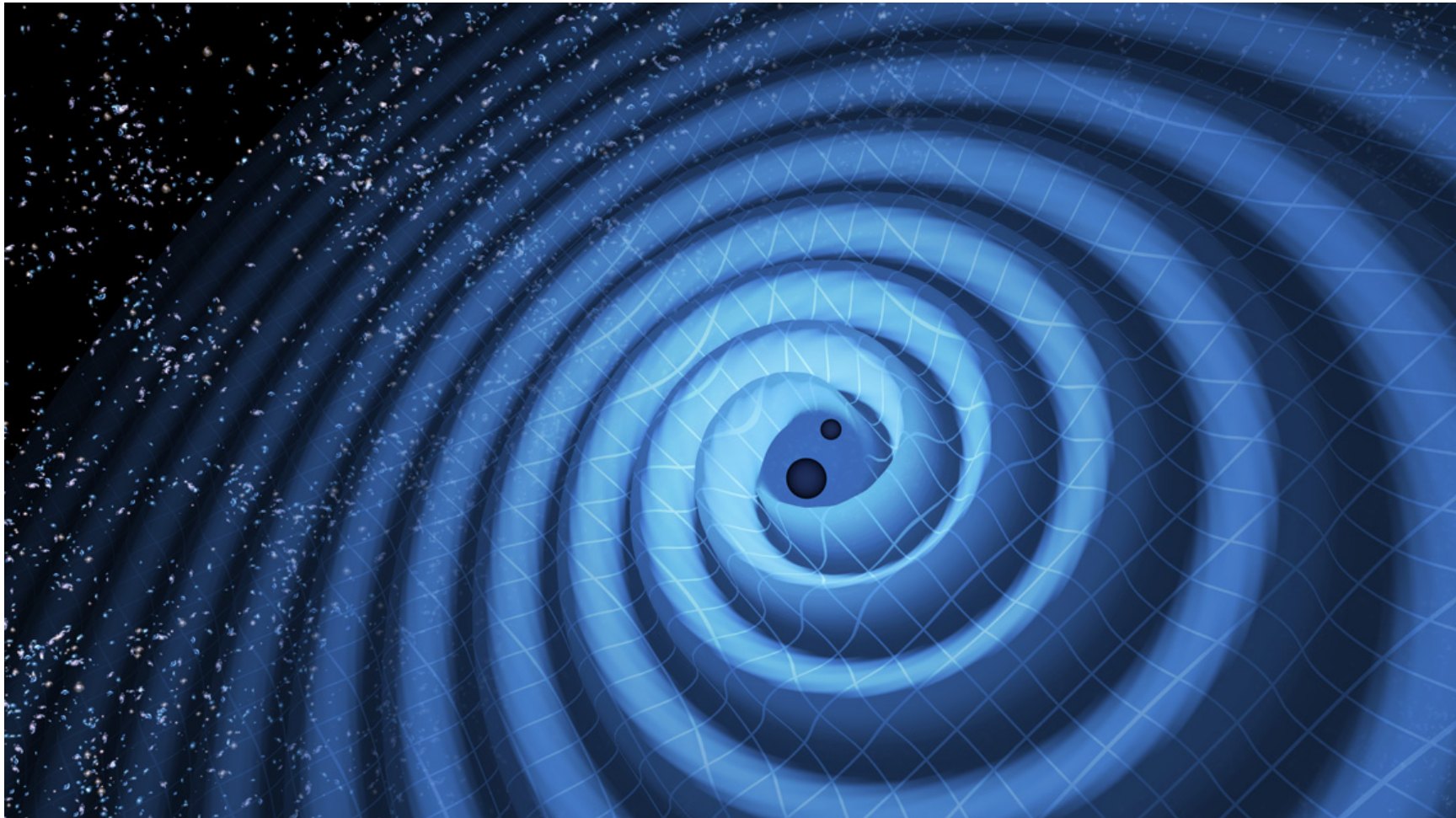
Pulsar timing

Billions
of Years



CMB polarization

Gravitational waves astronomy: this is just the beginning!



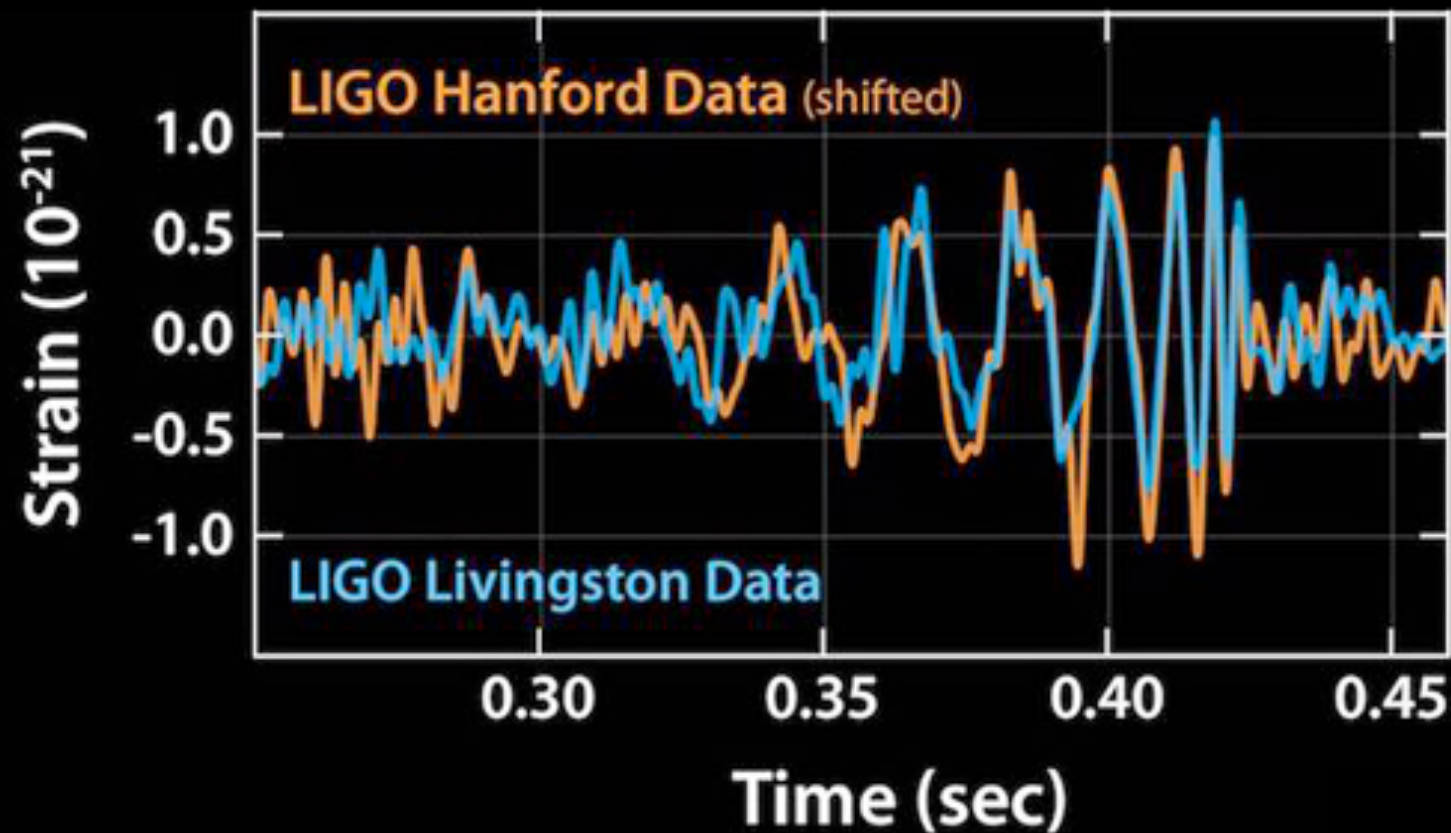
www.ligo.org

How did we know these are black holes?



Credit: LSC/Cardiff/C. North/M. Hannam

How did we know these are black holes?



Credit: LIGO

Where did the event come from?



GW170104

GW151226

LVT151012

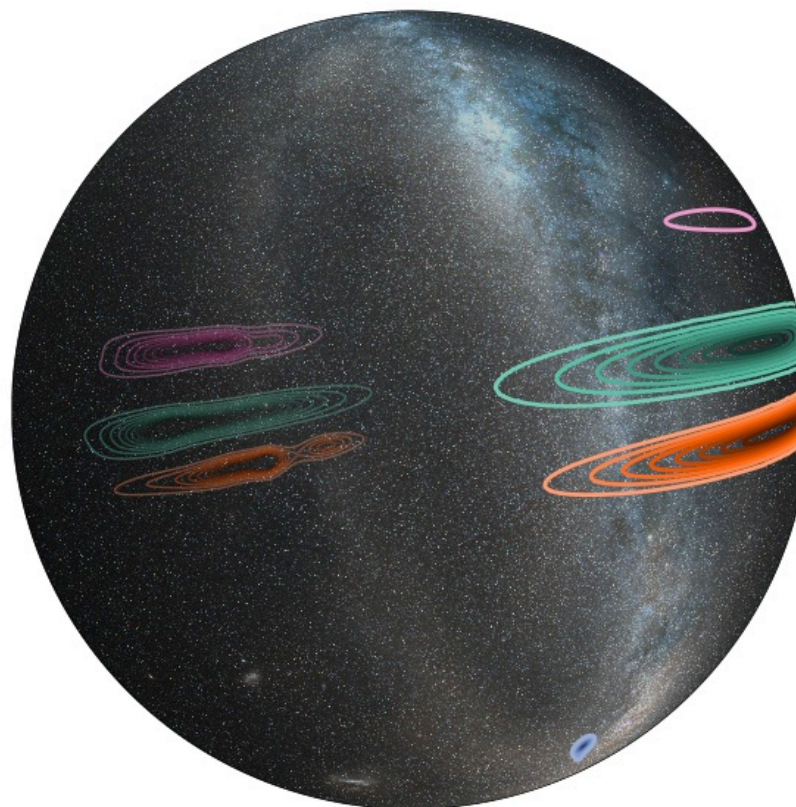
GW150914

Credit: LSC/Leo Singer (Milky Way image: Axel Mellinger)

Where did the event come from?



Simulated data with LIGO and Virgo



GW170104

GW151226

LVT151012

GW150914

Credit: LSC/Leo Singer (Milky Way image: Axel Mellinger)

If Virgo detector had been on at these times,
localization would have been much better – this is the future!