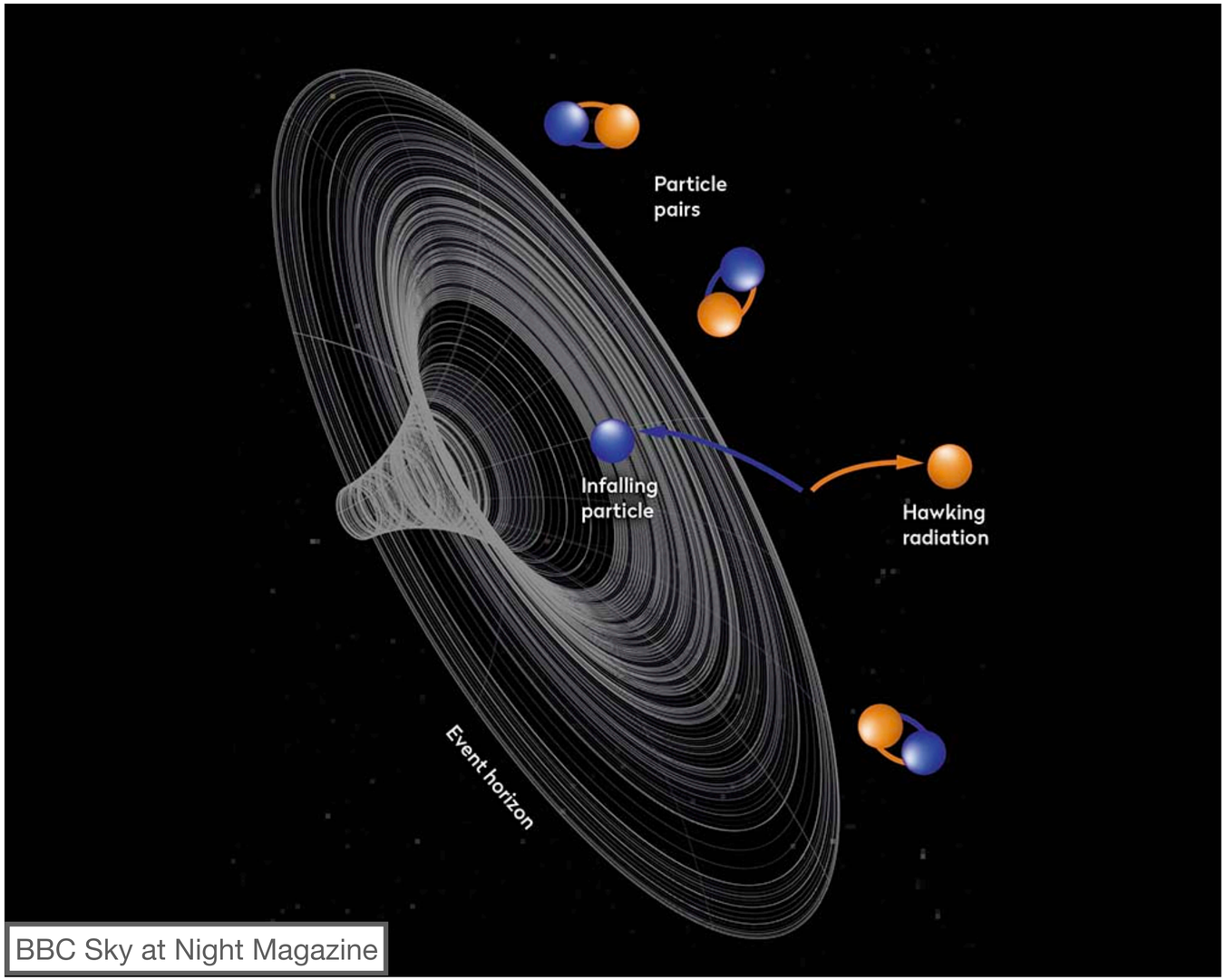
Announcements

- Problem 2 is due Feb 02 at 11:59pm
- Exploration paper 1 due **Feb 09**
- **Spacetime Team Project: due Feb 07**
  - Find your teams on Canvas then pick up your equipment in the Doherty Hall A301 suite of offices Jan 31 or Feb 2, between 12:15 and 4:30 PM, or Feb 5, between 10:30 AM and noon.
  - **NO CLASS ON MONDAY, Feb 5**

Hawking radiation



BBC Sky at Night Magazine

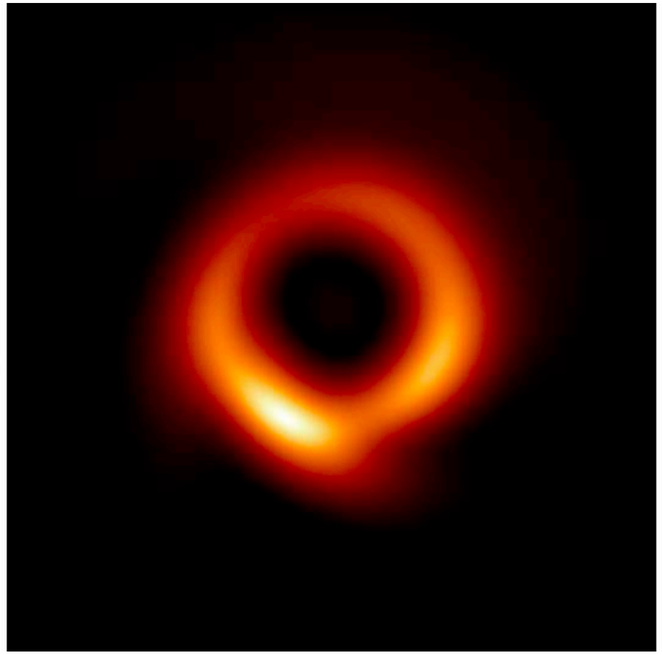
Hawking's own analogy, but scientists have *opinions* on whether this is a **good** analogy

curvature <—> energy

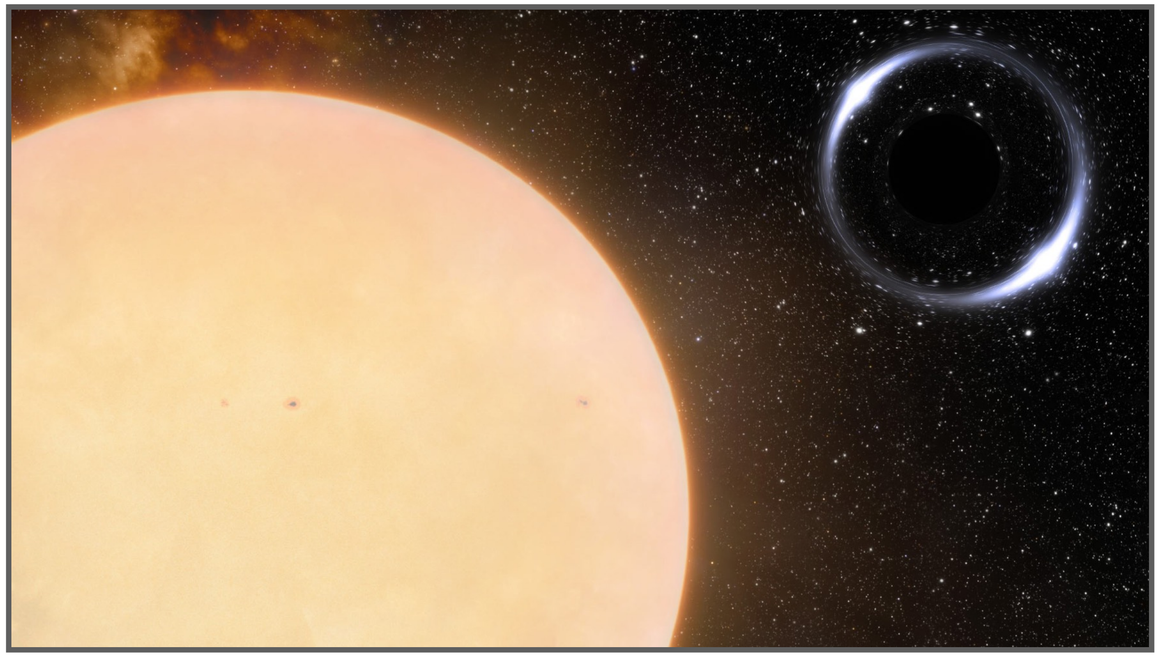
virtual particles pop in/out of existence with real/imaginary energy; by their construction, only *real* particles escape while imaginary particles with negative energy fall in —> always evaporates mass!

See https://bigthink.com/starts-with-a-bang/hawking-radiation-black-holes/ for a deeper discussion!

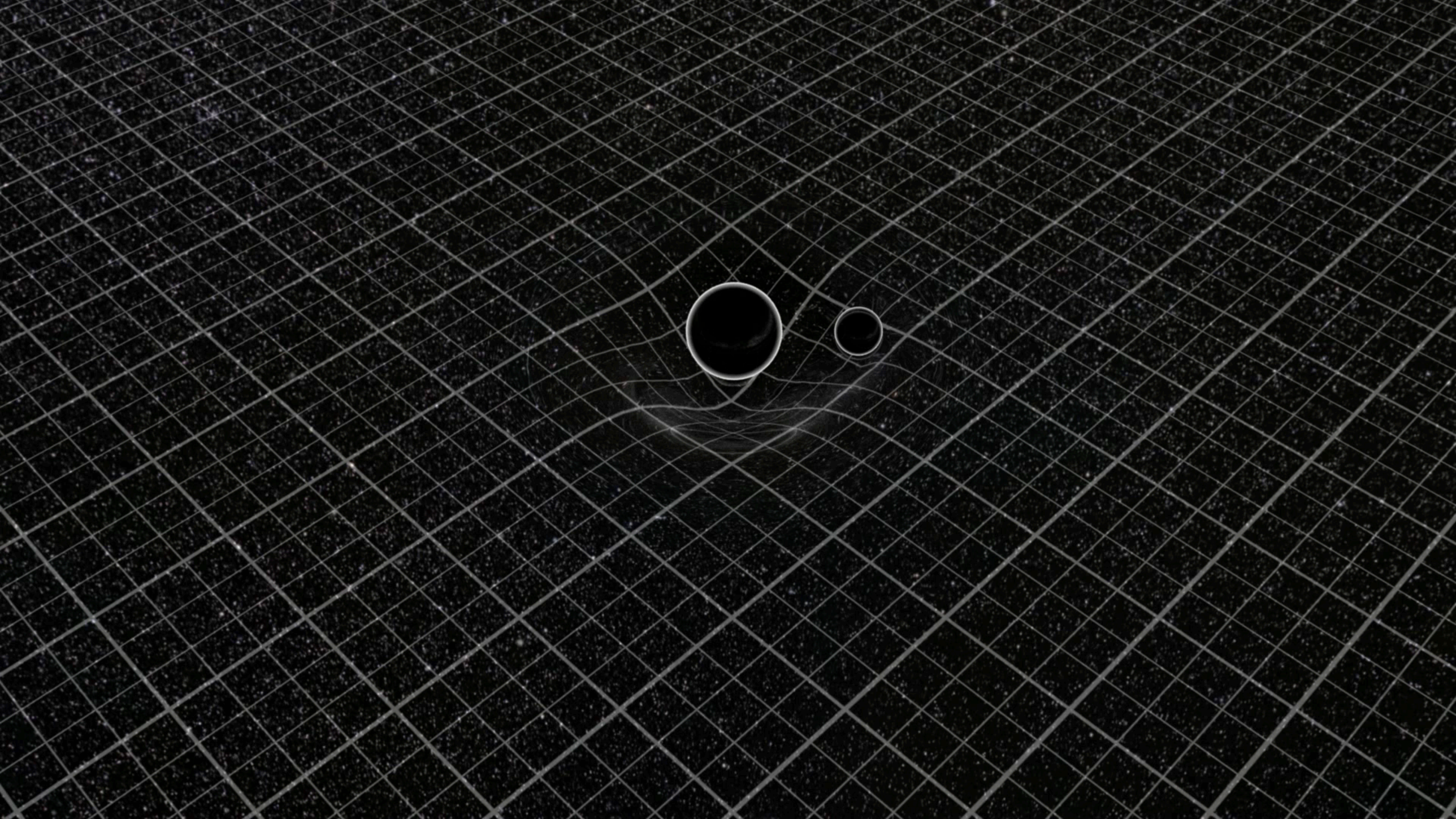
Observing astrophysical black holes



In 2019, the Event Horizon Telescope published the first *image* of M87, a 10^9 $M_\odot$ BH in the center of a galaxy



In 2023, the Gaia satellite discovered two 10 $M_\odot$ BHs by tracking the motion of their stellar companions: Gaia BH1, Gaia BH2

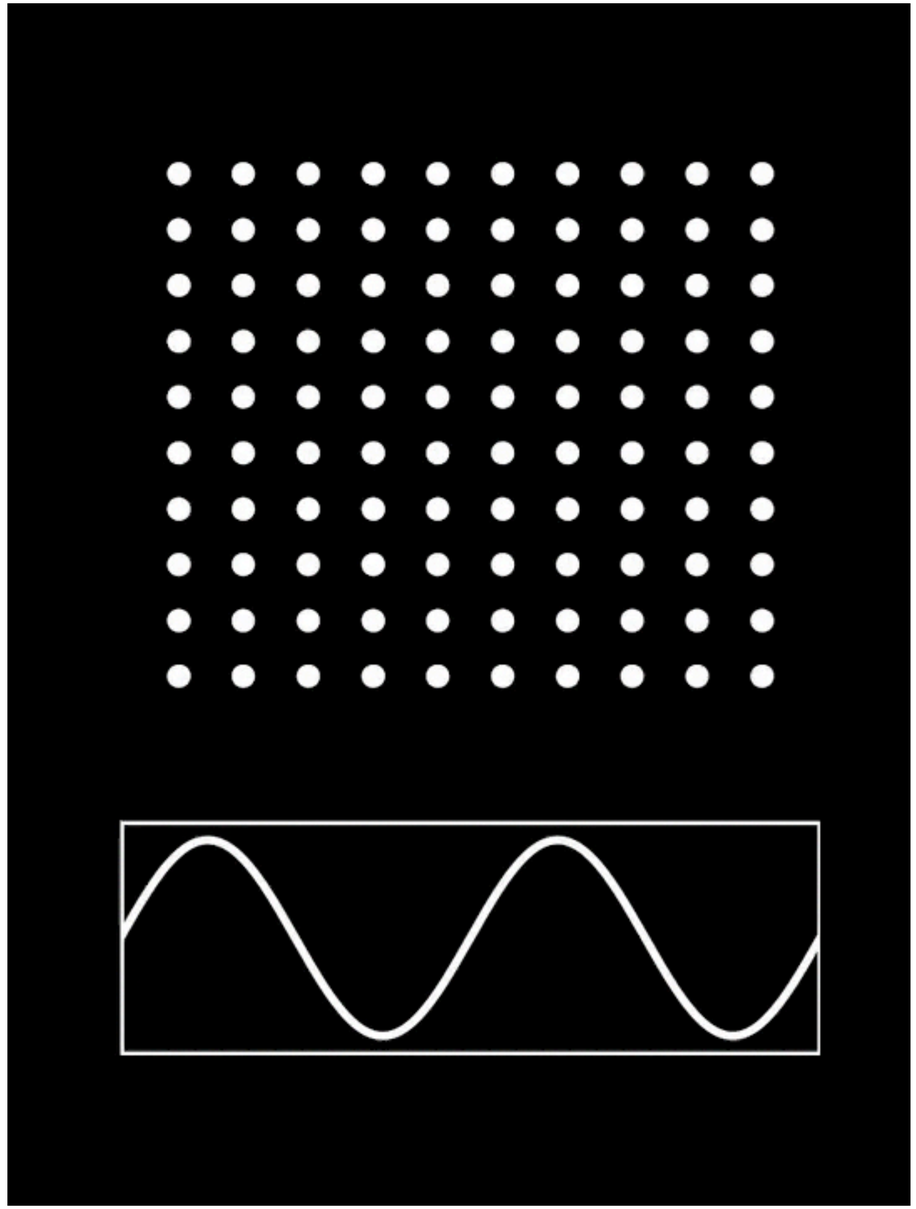


Star Trek VI:

The Undiscovered Country

Directed:
Nicholas Meyer

Paramount (1991)

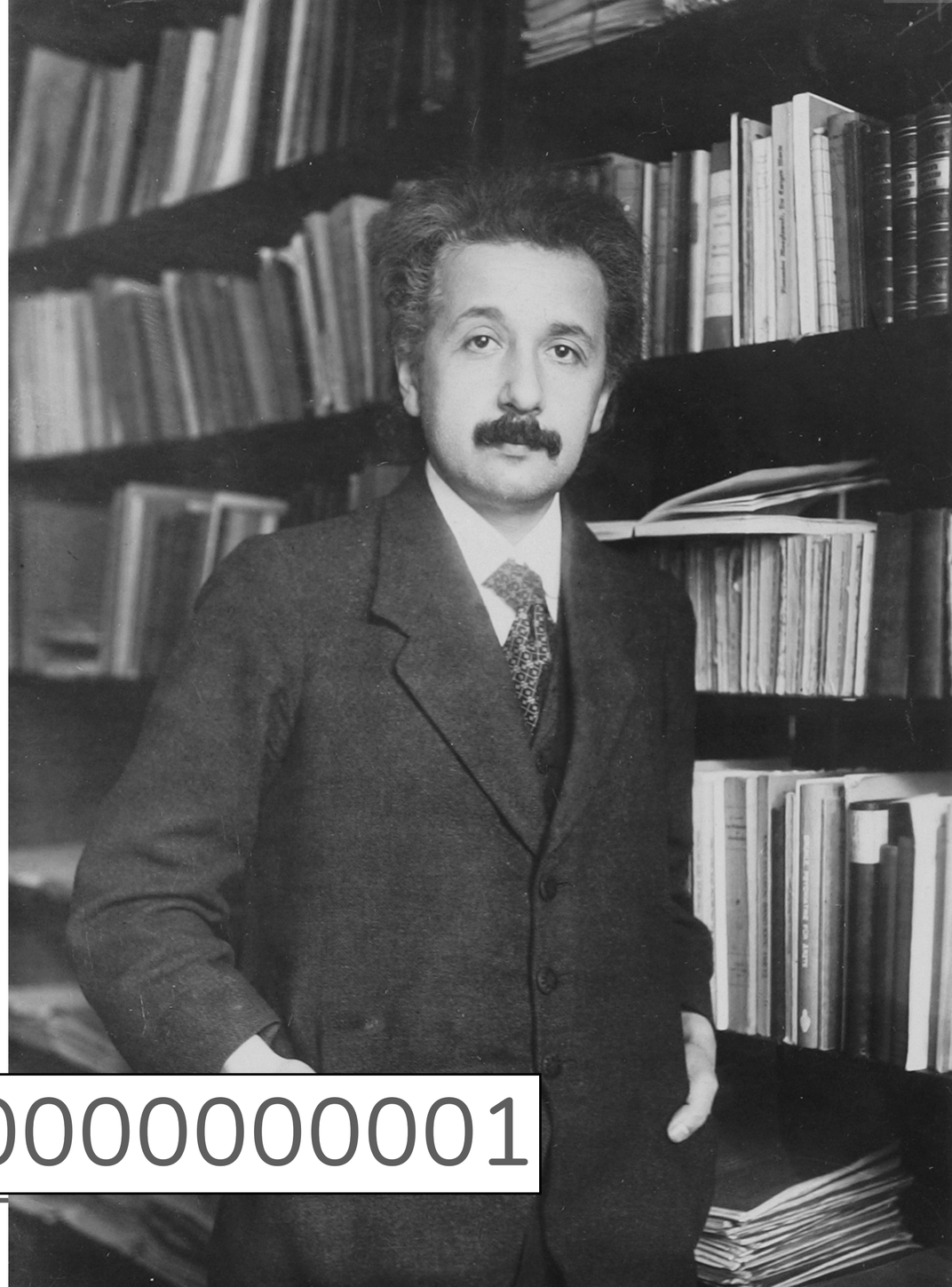


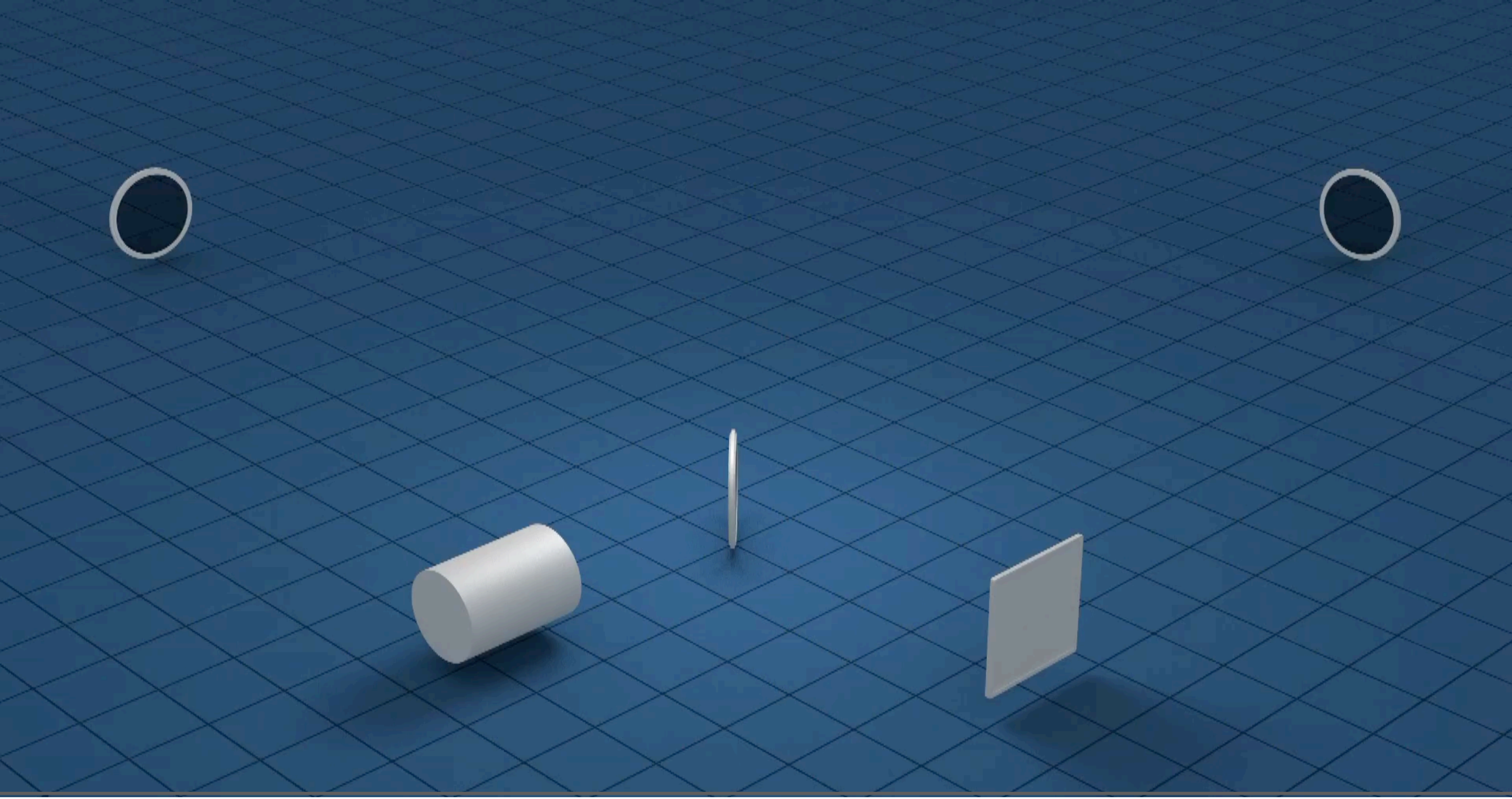
The ripples stretch and squash space and time in *predictable* ways

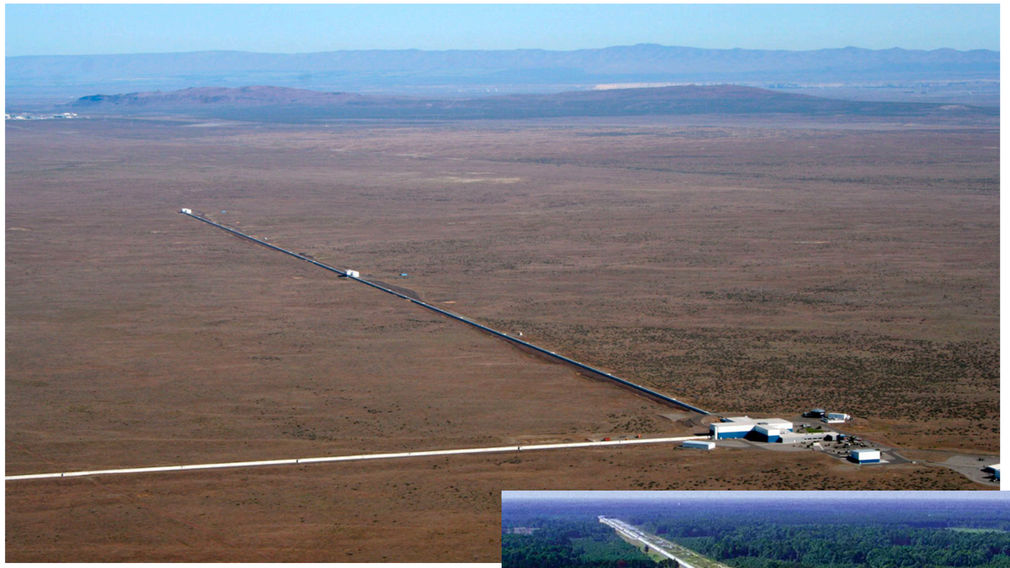
Einstein in 1916:

Gravitational waves exist
but they are way too
small to detect!

Size of stretches
$=10^{-21}$
$=0.000000000000000000001$







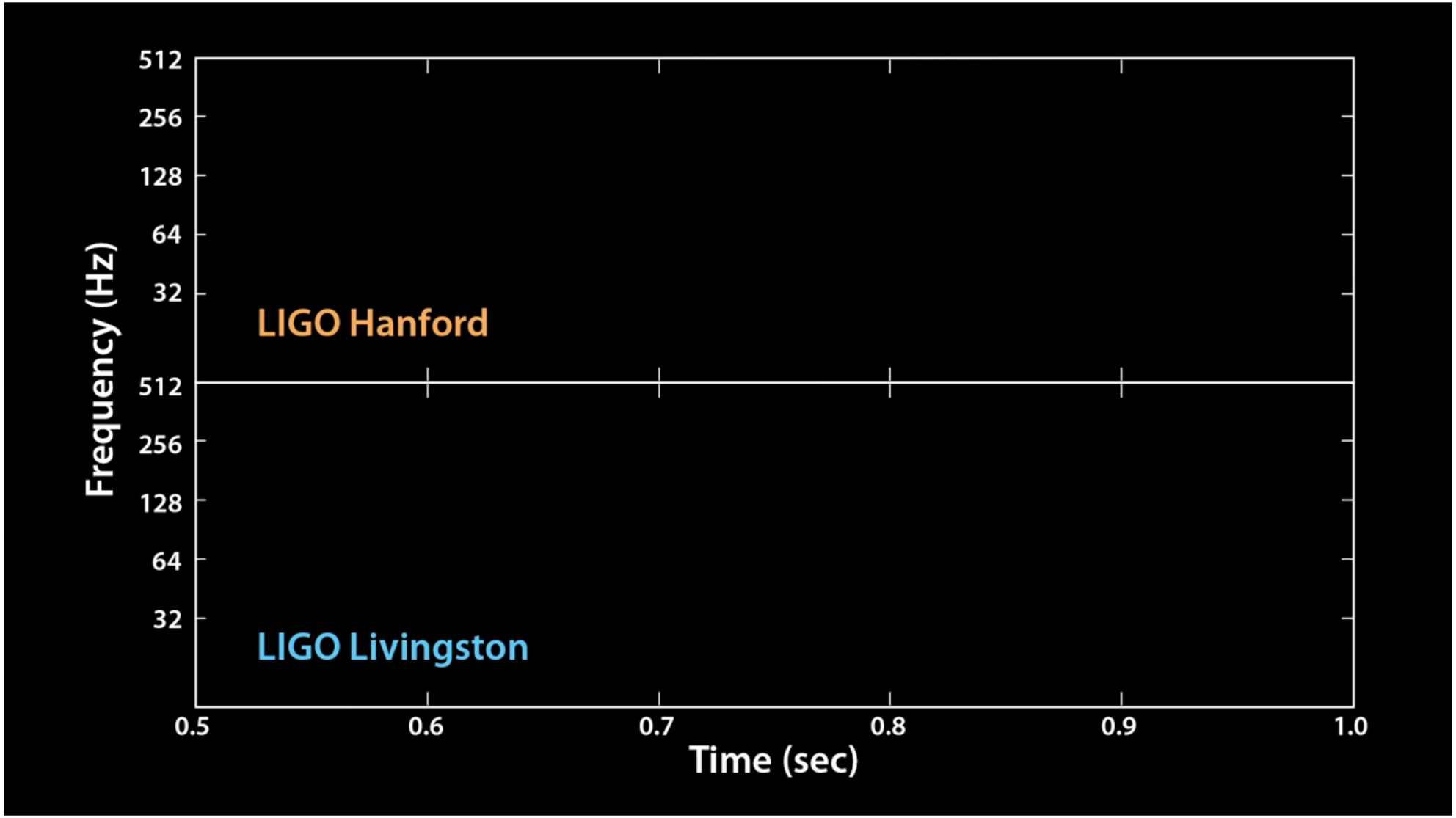
Washington

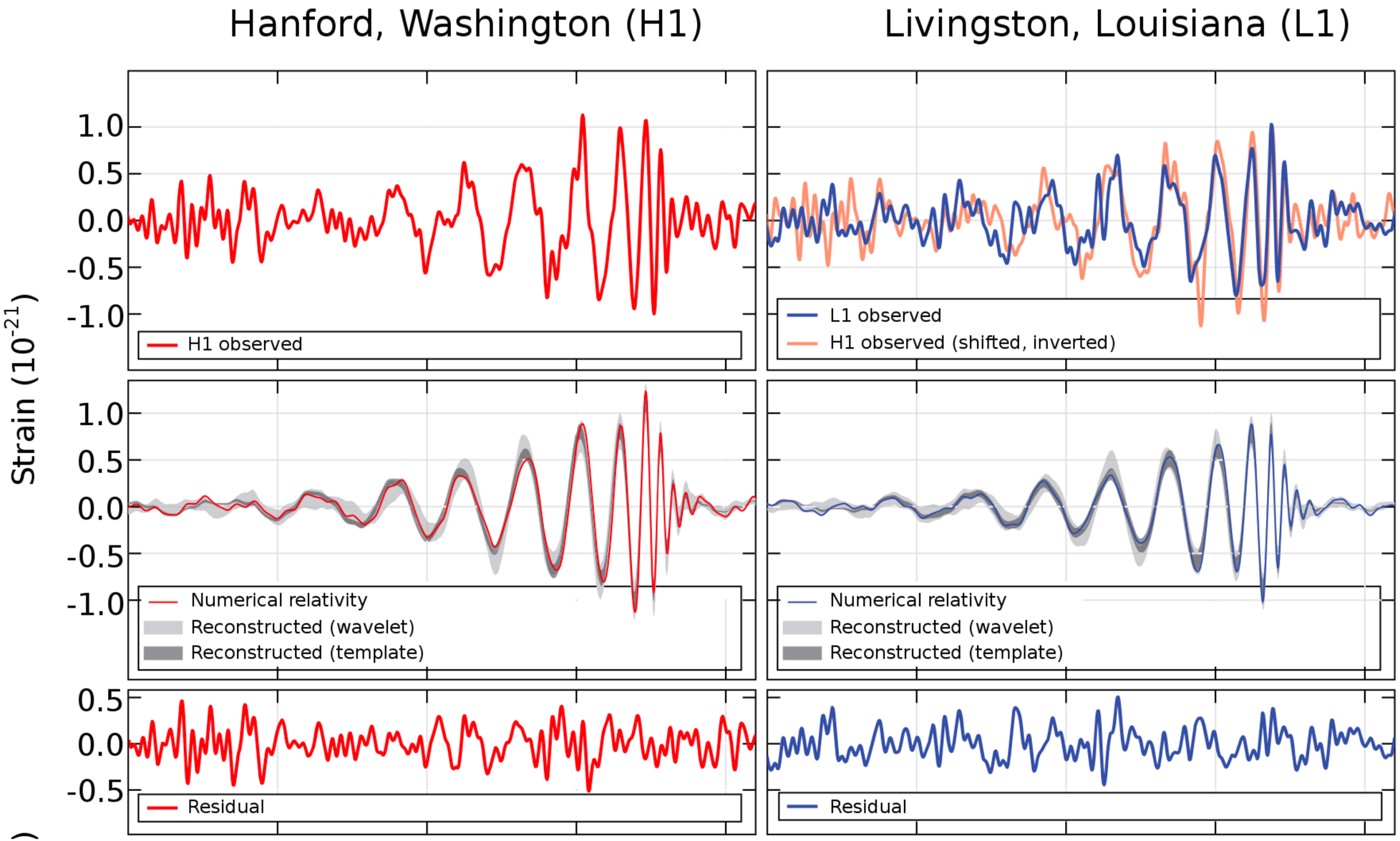
Louisiana

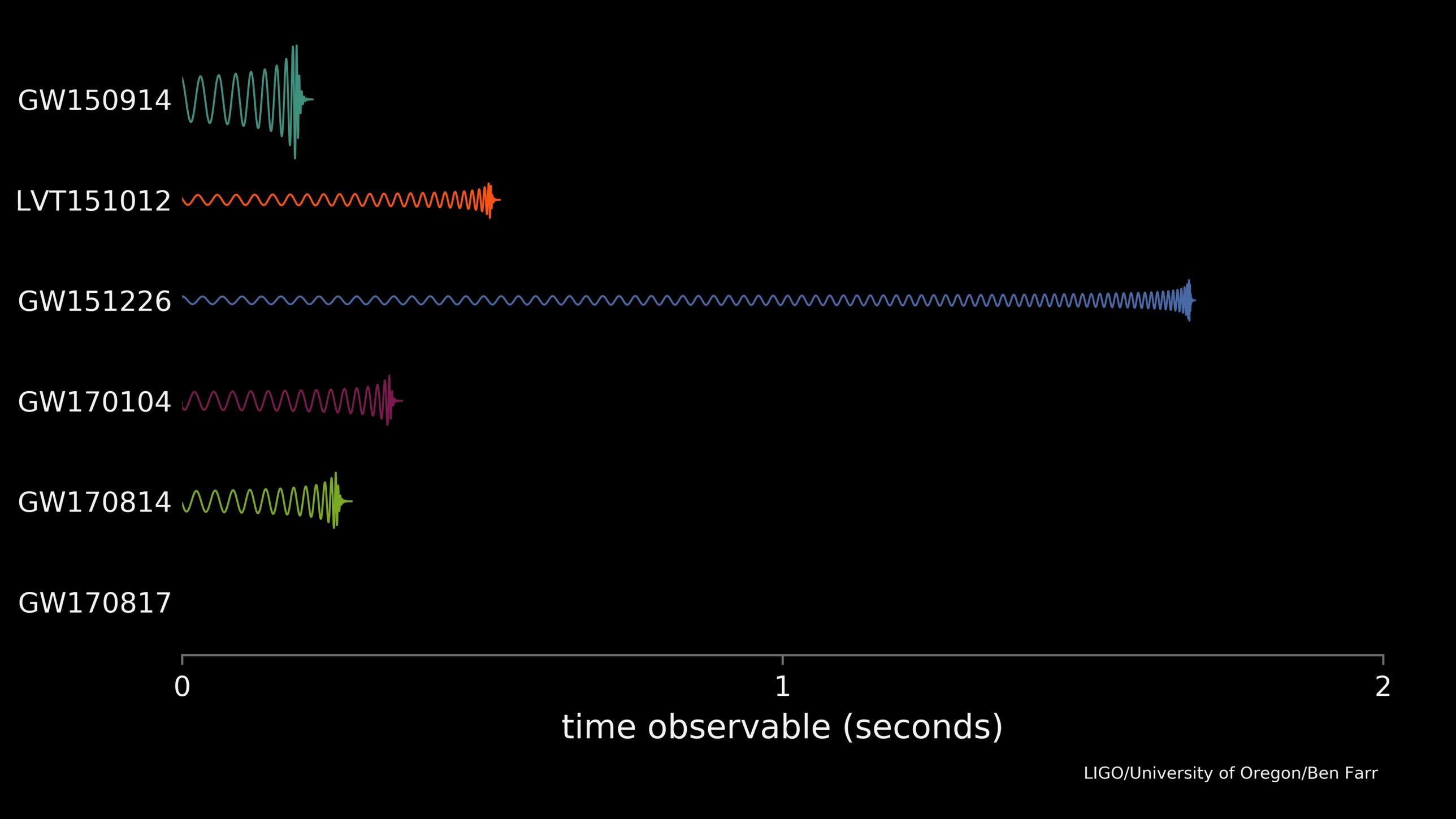
Italy

Spread across the US and Europe to serve as detection confirmation *and* localization of GW sources!

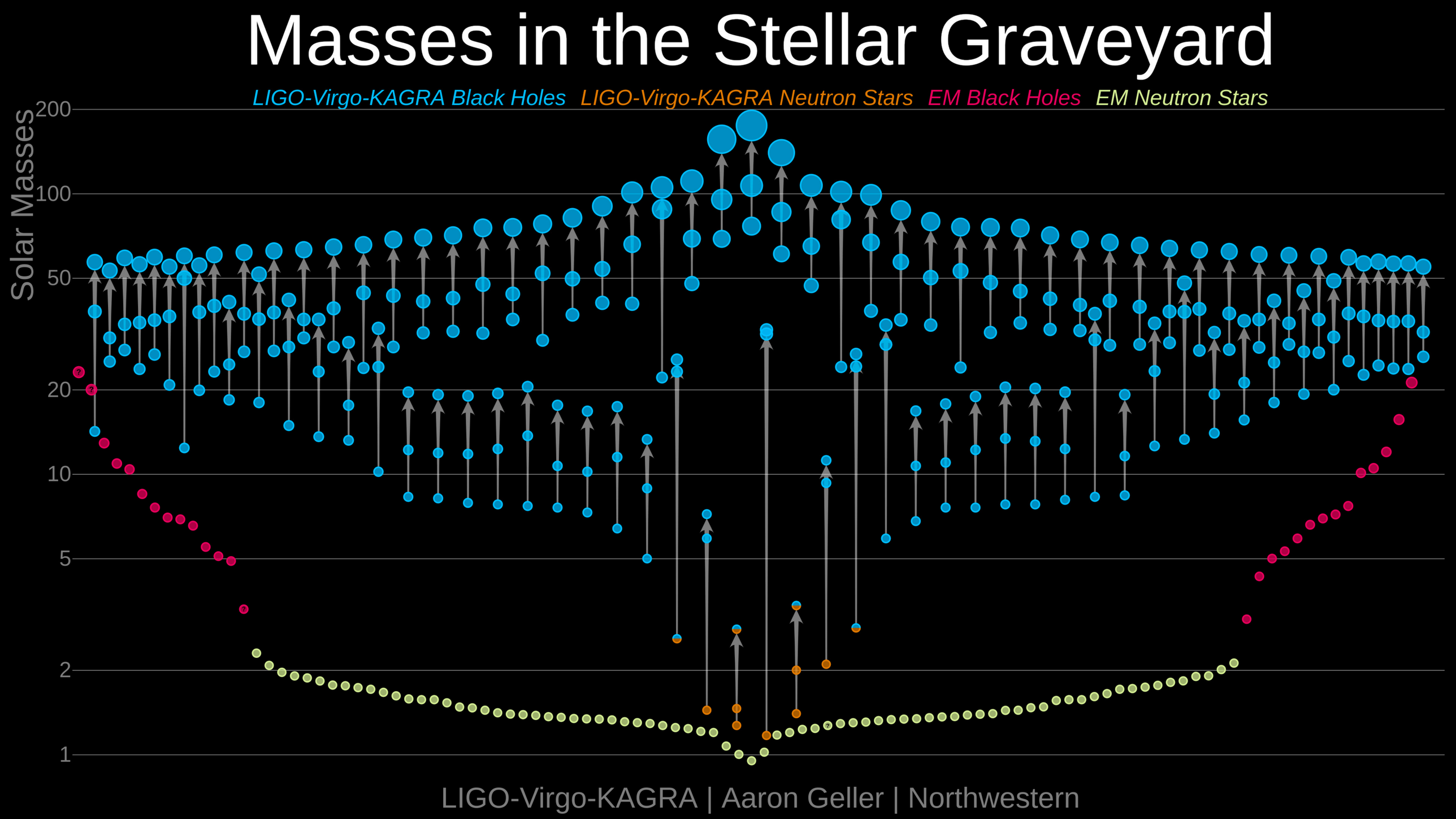
GW150914


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual


GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr

Masses in the Stellar Graveyard



GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

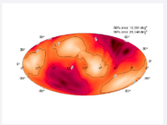
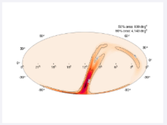
O4 Significant Detection Candidates: **81** (92 Total - 11 Retracted)

O4 Low Significance Detection Candidates: **1610** (Total)

Show All Public Events

Page 1 of 7. next last »

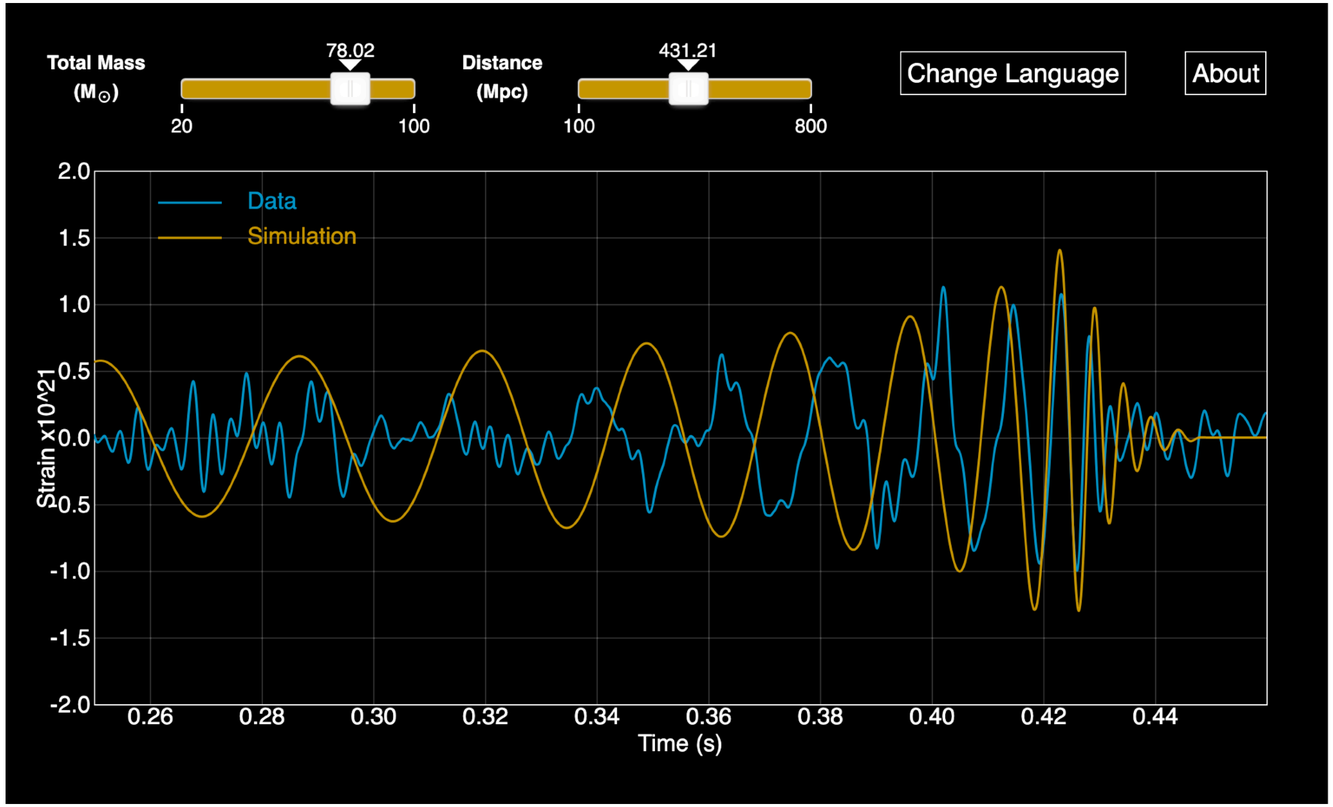
SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240109a	BBH (99%)	Yes	Jan. 9, 2024 05:04:31 UTC	GCN Circular Query Notices | VOE		1 per 4.3136 years	
S240107b	BBH (97%), Terrestrial (3%)	Yes	Jan. 7, 2024 01:32:15 UTC	GCN Circular Query Notices | VOE		1.8411 per year	

You can follow along in realtime when the detectors come back online after an upgrade on March 27

https://gracedb.ligo.org/superevents/public/O4/

Extra Credit Opportunity!



https://data.cardiffgravity.org/waveform-fitter/

Explore how mass and distance affect GW waveforms — fit GW190514's waveform

5 pts: explain how changing the **total mass** affects the waveform shape

5 pts: explain how changing the **distance** affects the waveform shape

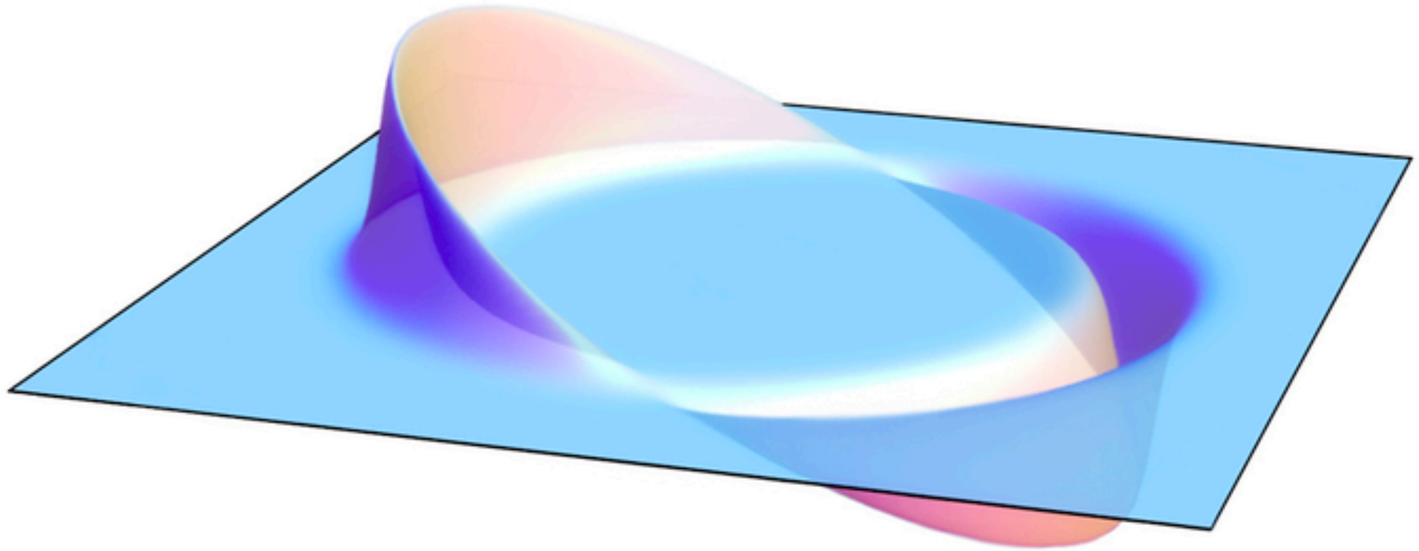
5 pts: modify the **total mass** and the **distance** to get the best fit of the simulation (orange) to data (blue); compare your answers to the measured values for GW150914 (you can look this up on Wikipedia)

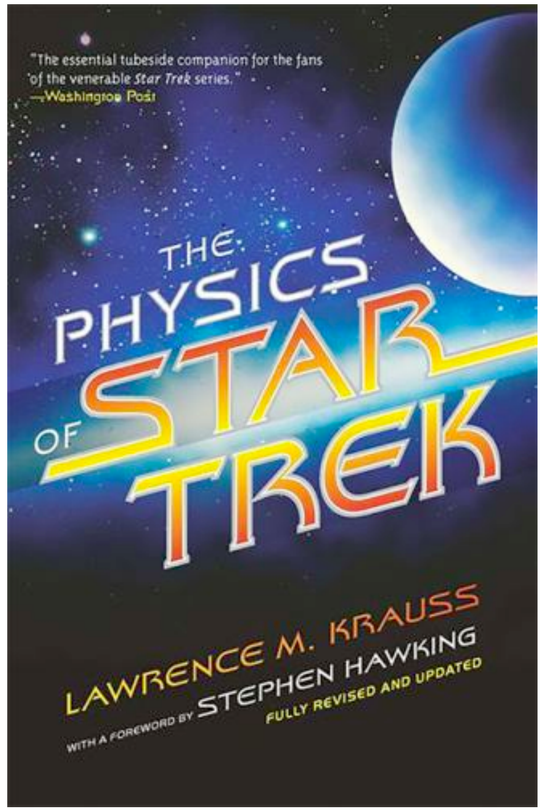
Email your answers to kbreivik@andrew.cmu.edu by ***Monday, Feb 12 at 11am****, to get 15 pts extra!*

Could gravitational waves be used for time travel?

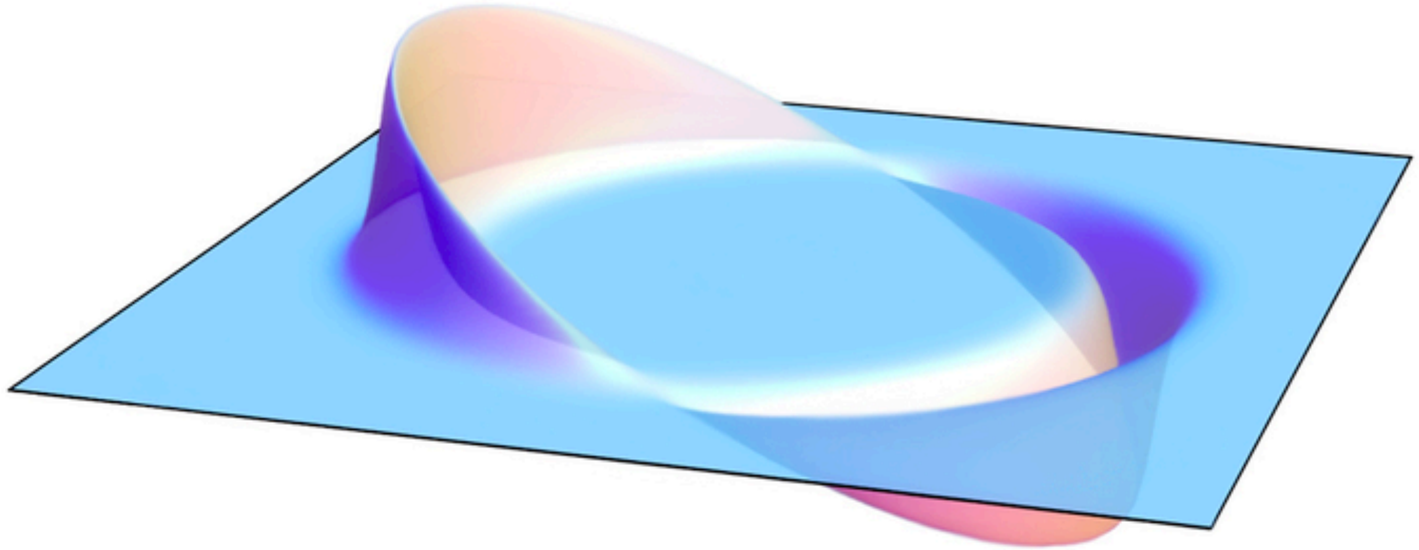
Could gravitational waves be used to travel *faster* than the speed of light?

Alcubierre Drive —> warp drive in Star Trek





Alcubierre Drive



contract spacetime in front of the ship

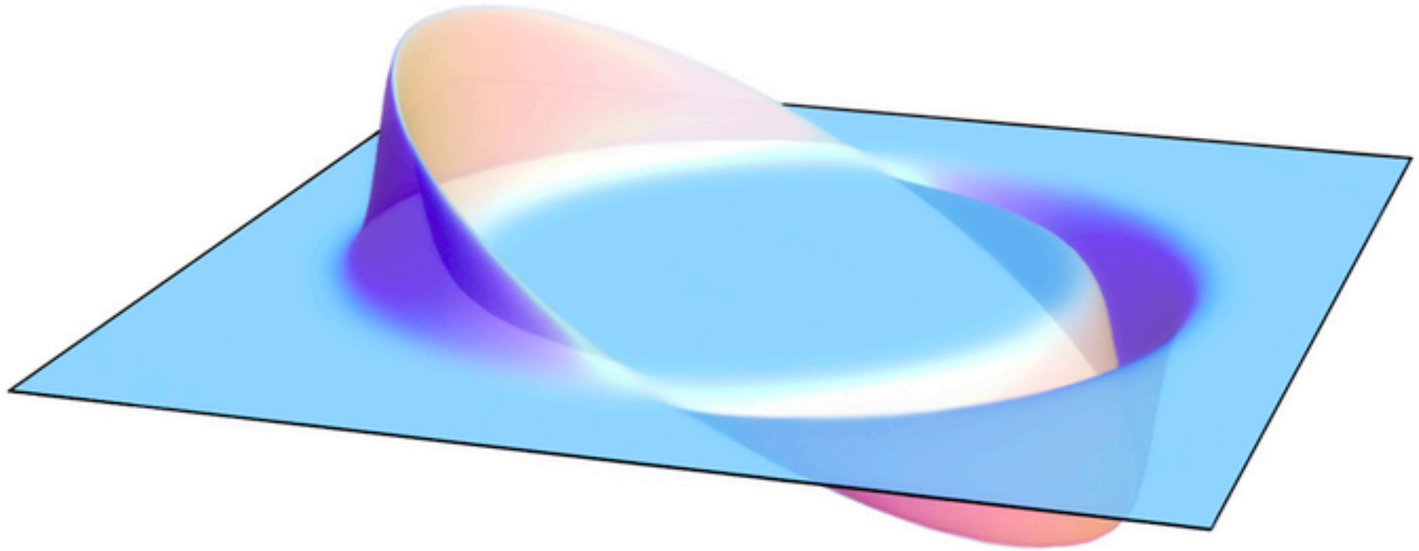
expand spacetime behind the ship

Unites special and general relativity principles:

SR: describes equivalency between mass and energy

GR: describes how spacetime is distorted by mass

Alcubierre Drive



contract spacetime in front of the ship

expand spacetime behind the ship

The warp drive: hyper-fast travel within general relativity

Miguel Alcubierre

Department of Physics and Astronomy, University of Wales,
College of Cardiff, PO Box 913, Cardiff CF1 3YB, UK

Received 19 January 1994, in final form 24 February 1994

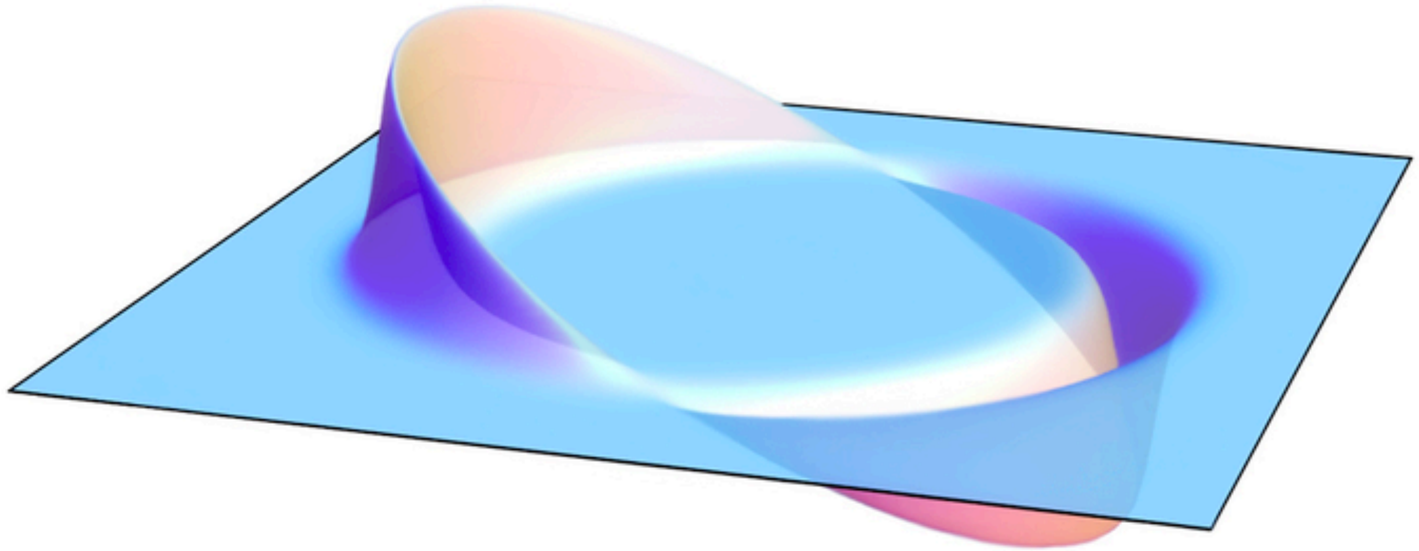
Abstract. It is shown how, within the framework of general relativity and without the introduction of wormholes, it is possible to modify a spacetime in a way that allows a spaceship to travel with an arbitrarily large speed. By a purely local expansion of spacetime behind the spaceship and an opposite contraction in front of it, motion faster than the speed of light as seen by observers outside the disturbed region is possible. The resulting distortion is reminiscent of the 'warp drive' of science fiction. However, just as happens with wormholes, exotic matter will be needed in order to generate a distortion of spacetime like the one discussed here.

PACS numbers: 0420, 0490

Published in
Classical & Quantum Gravity
May 1994

Faster than light travel within general relativity!

Alcubierre Drive —> warp drive in Star Trek



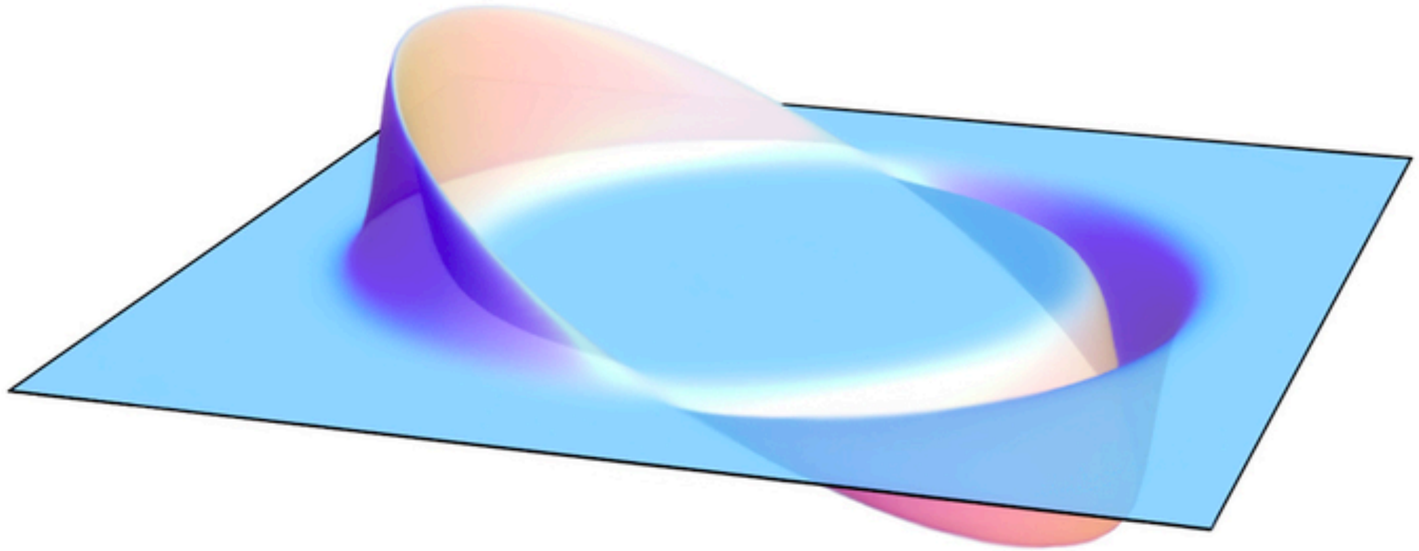
contract spacetime in front of the ship

expand spacetime behind the ship

Enables travel that is *globally* faster than light

By modifying spacetime, the ship can travel faster than light would in the absence of any curvature

Alcubierre Drive



contract spacetime in front of the ship

expand spacetime behind the ship

Requires a *negative energy density*

Implies either exotic matter with negative mass or manipulation of dark energy

Newton & classical physics

Space & time are *independent* from each other

Time passes continuously from past to future

Gravity acts instantaneously over arbitrary distance

Works to describe *almost* all of everyday life here on Earth

Einstein & modern physics

Spacetime is a 4D quantity; perception of space and time depend on relative motion

Clocks run slow at high speed —
Clocks run slow near large masses

The speed of light is constant and the speed limit of the Universe

Gravity is the manifestation of spacetime curvature induced by mass

Newton & classical physics

Space & time are *independent* from each other

Time passes continuously from past to future

Gravity acts instantaneously over arbitrary distance

Works to describe *almost* all of everyday life here on Earth

Einstein & modern physics

Mass and energy are equivalent through the speed of light as: $E=mc^2$

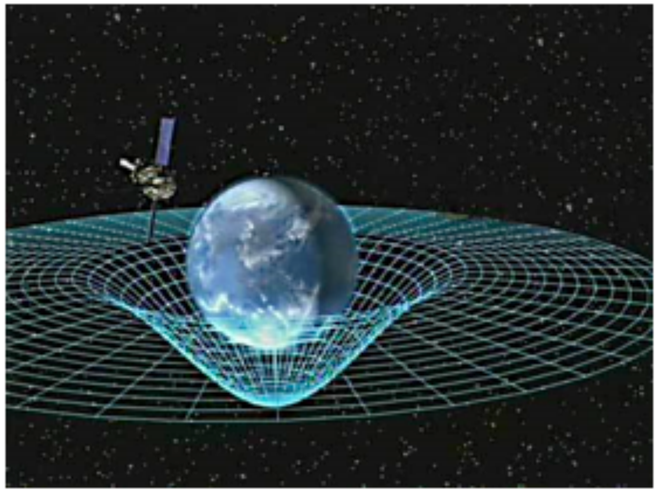
Time travel is possible, but only in the **future direction**

Gravitational waves can probe the Universe in different ways than light — initially believed to be undetectable — discovered in 2015 (100 years after prediction!)

Next week:

No class on Monday!!

- Dive into “future physics”
  - Wormholes
  - Multiverse hypotheses



What is the nature of space and time?