Gravitational waves: a new window onto the universe

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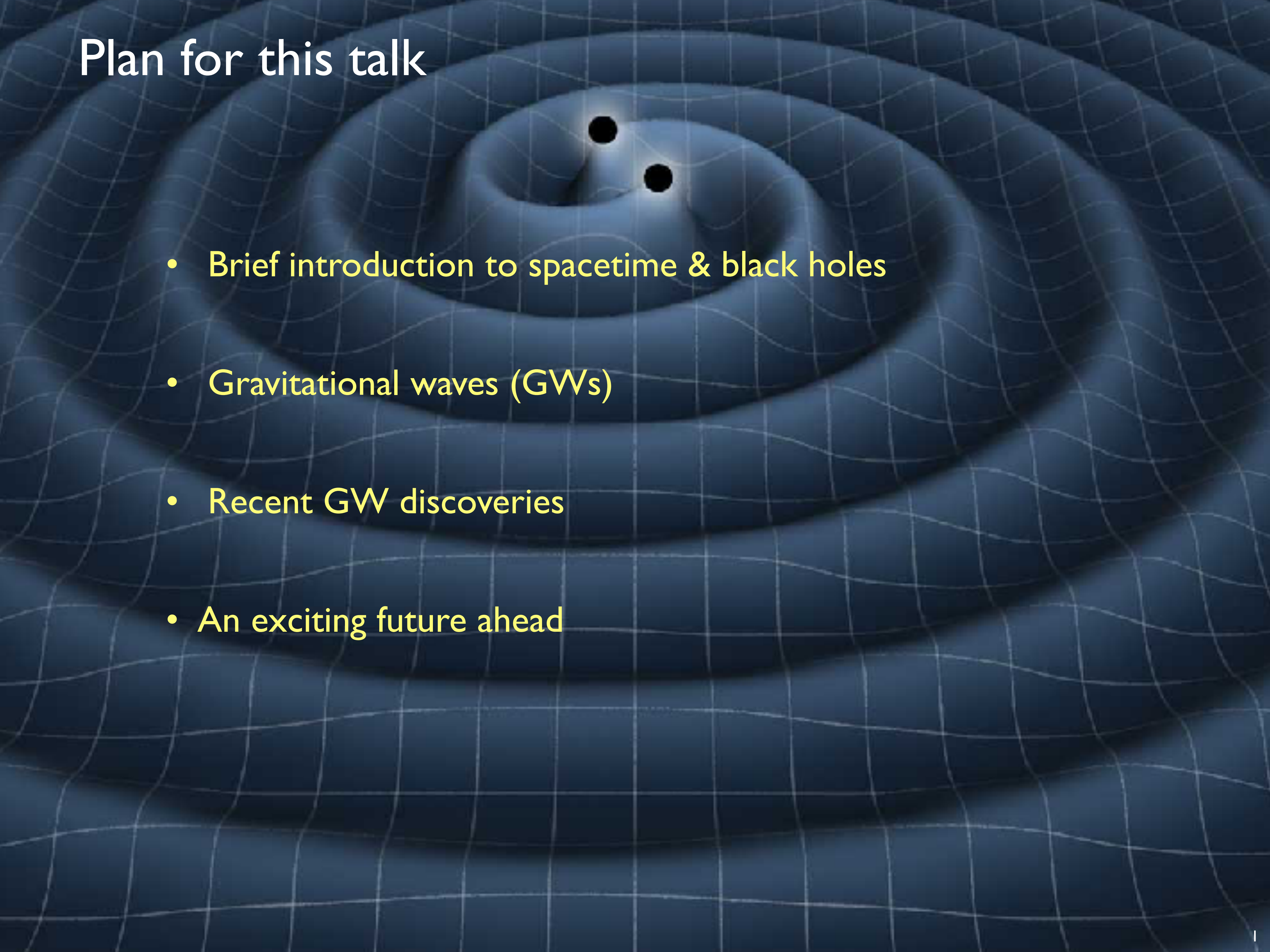
10th KSETA Plenary Workshop

March 29,2023


Plan for this talk
• Brief introduction to spacetime & black holes
• Gravitational waves (GWs)
• Recent GW discoveries
• An exciting future ahead
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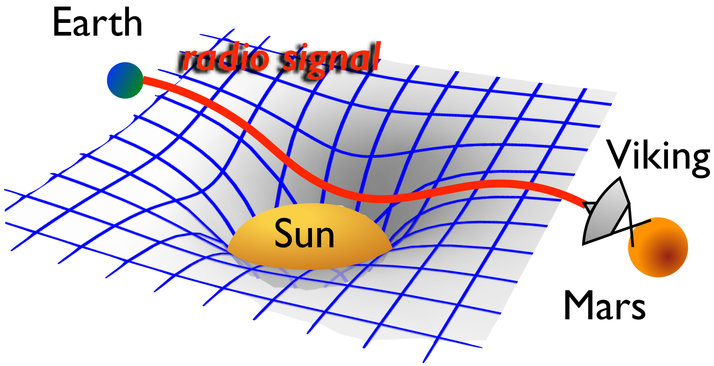
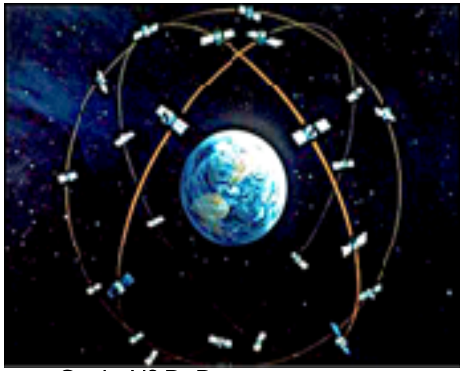
The nature of gravity

A. Einstein

Matter & energy curve space …

250 μs delay of radio signals for roundtrip to Mars measured in 1976





Credit: US DoD

… and warp time

time flows slower on Earth than at the GPS satellites at 20000km

after one day: 17 μs difference,

affects positioning by 5km/day

gravity is a manifestation of spacetime curvature

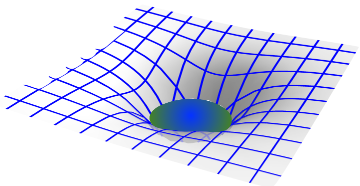
objects move along straightest path in curved spacetime geometry

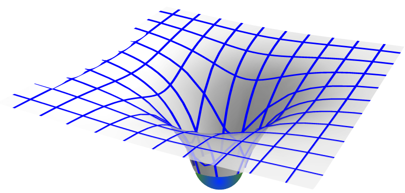
Extremes of curvature: black holes

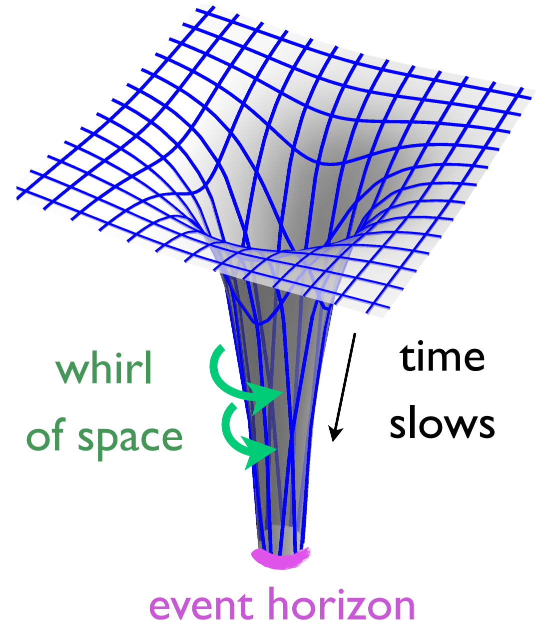
crushed

crushed

curvature







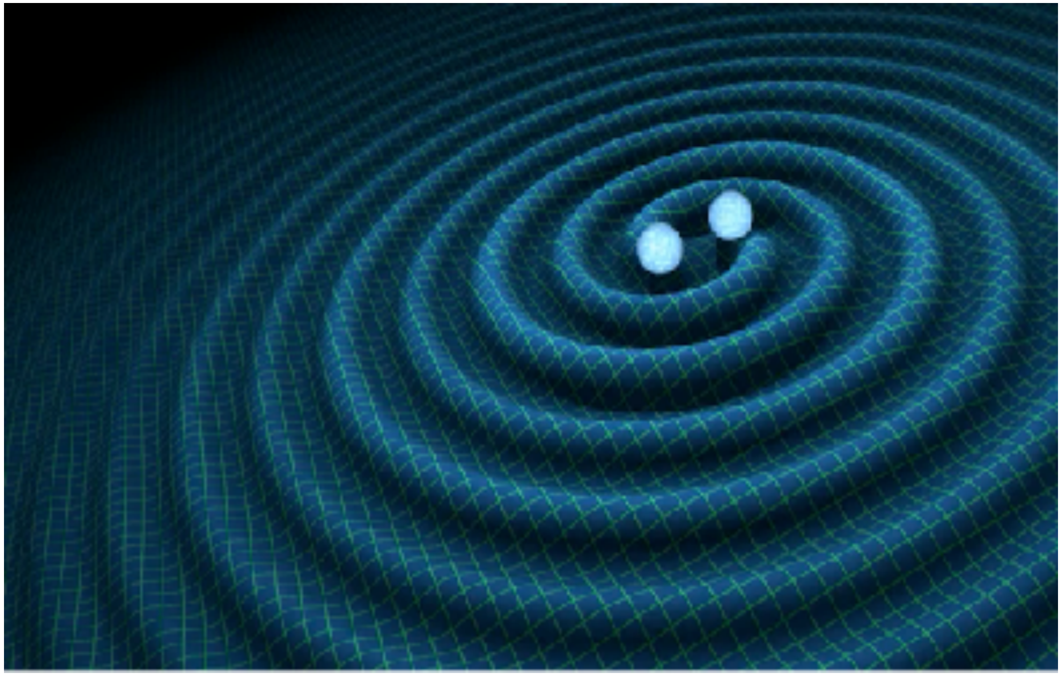
barrier for information

black hole

- region of immense spacetime curvature
- no surface
- From far away: described entirely by its mass and spin

Gravitational waves (GWs)

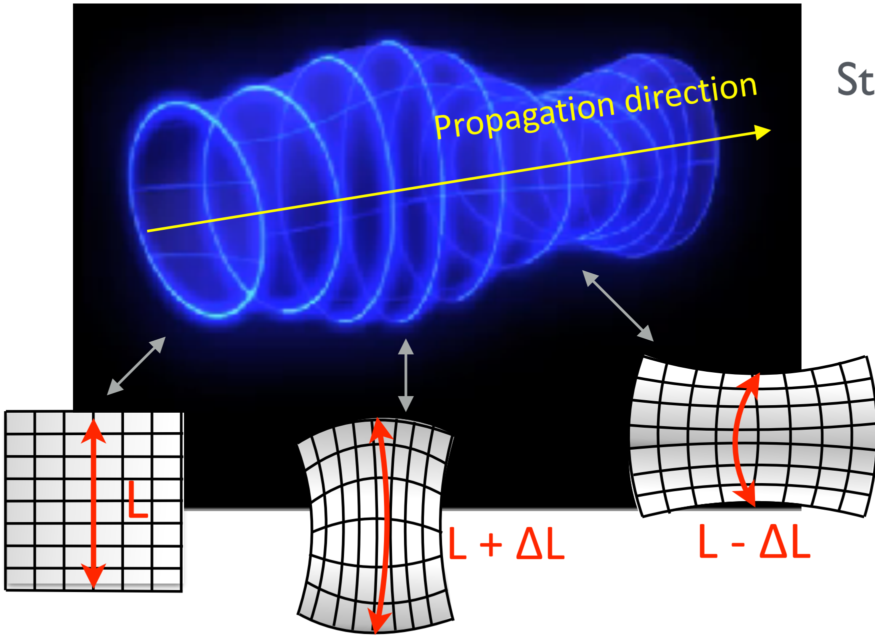
- Accelerating masses generate ripples in spacetime curvature: gravitational waves



- Enormous energy creates just tiny waves
- Interact very weakly with matter:

  travel through the universe essentially uncontaminated by absorption, attenuation, dispersion

The effect of GWs



Stretching and squeezing of space

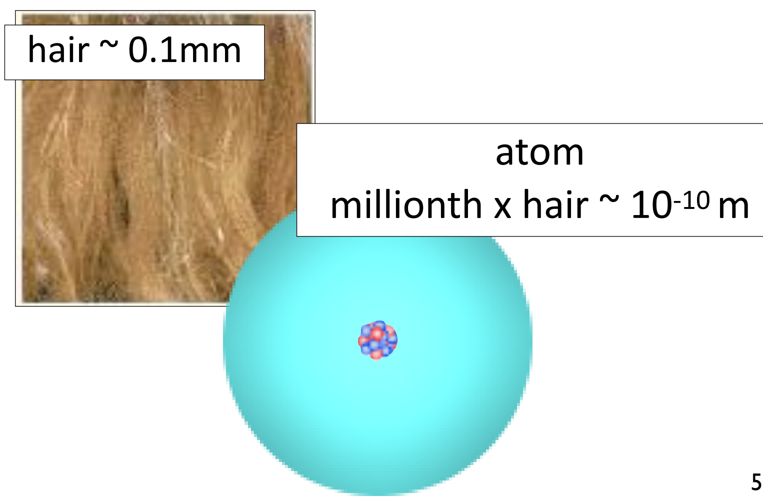
$$\frac{\Delta L}{L} \sim h(t)$$

Wave amplitude

(Fractional deviation from flat space)

Strong sources: earth deforms by

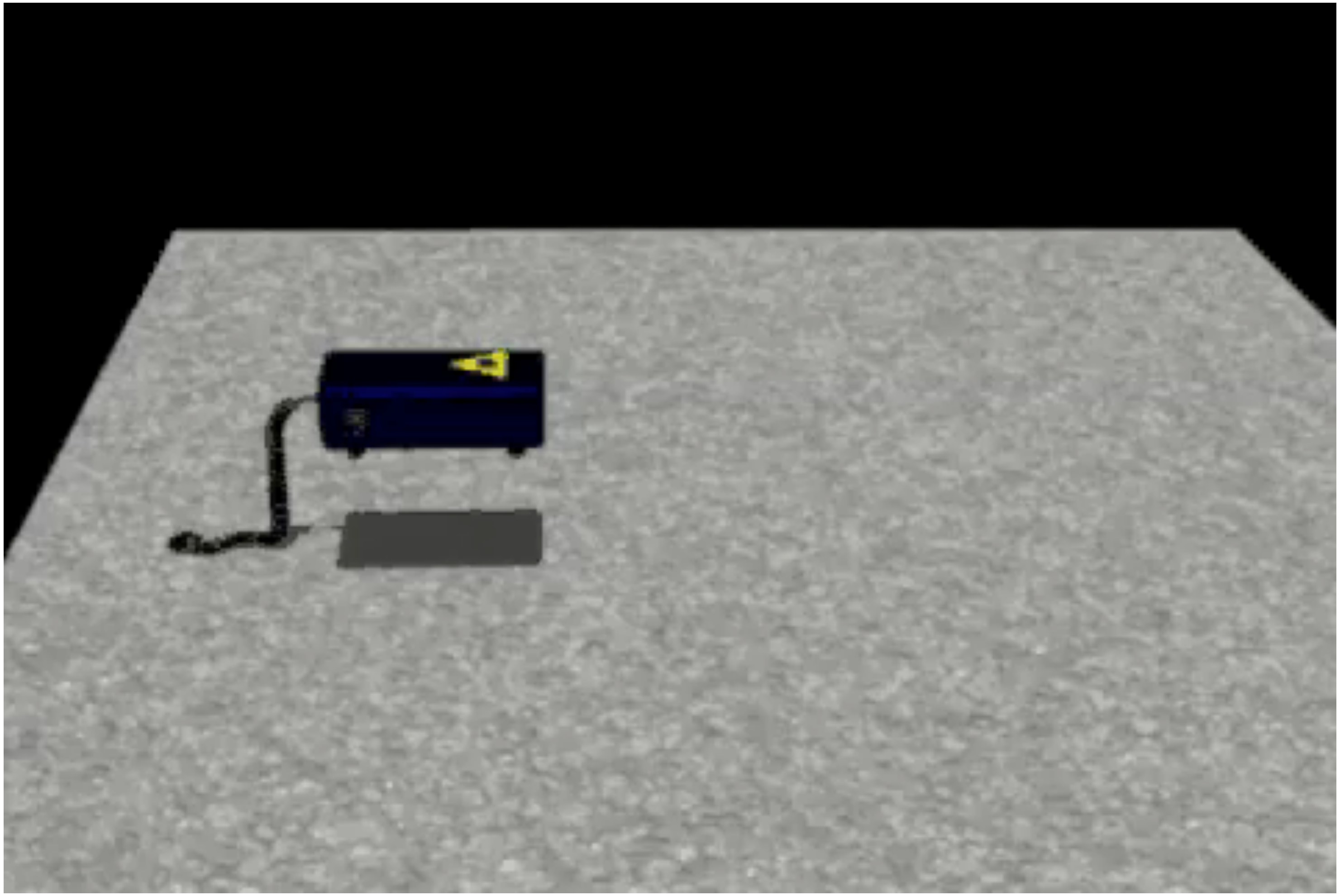
ΔL ~ 10^{-15} m = 1/100 000 x atom



Detecting GWs

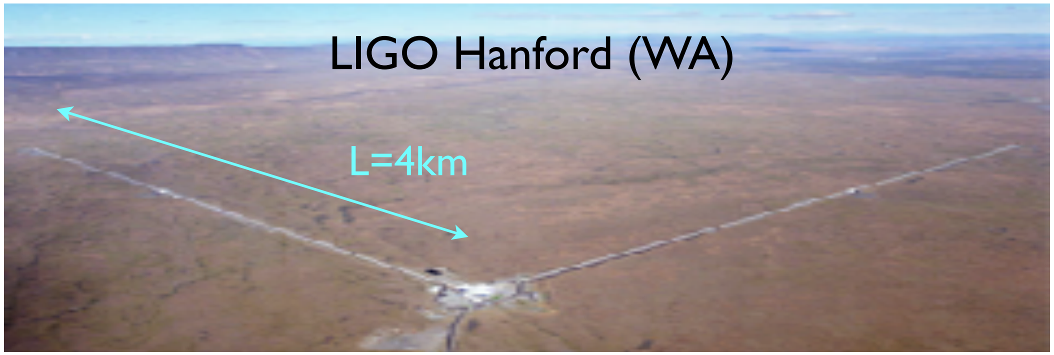
the small effect is very difficult to measure

it is possible with laser interferometers



Worldwide network of interferometer detectors

Laser **I**nterferometer **G**ravitational wave **O**bservatories (USA)

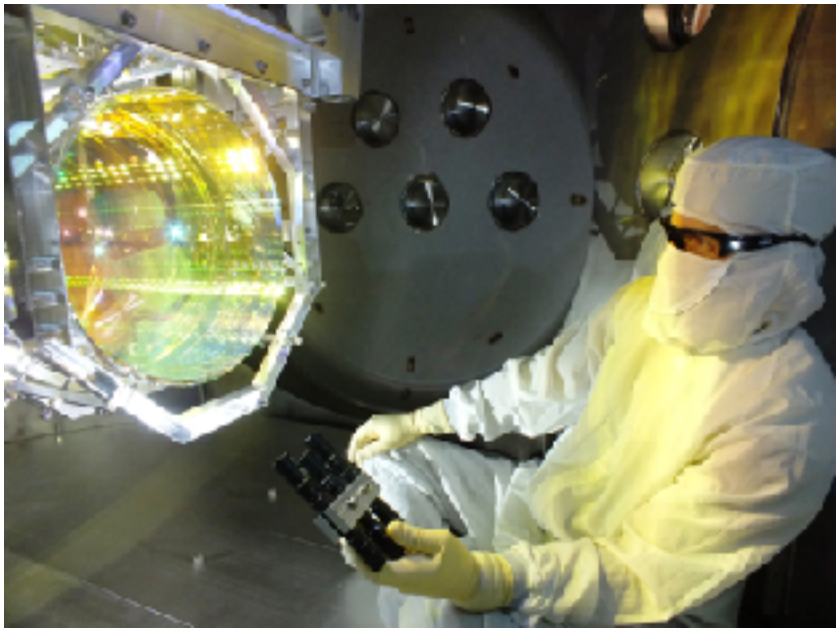


Virgo / EGO (Pisa, Italy)

GEO600

(Hannover, Germany)

A glimpse inside the detectors



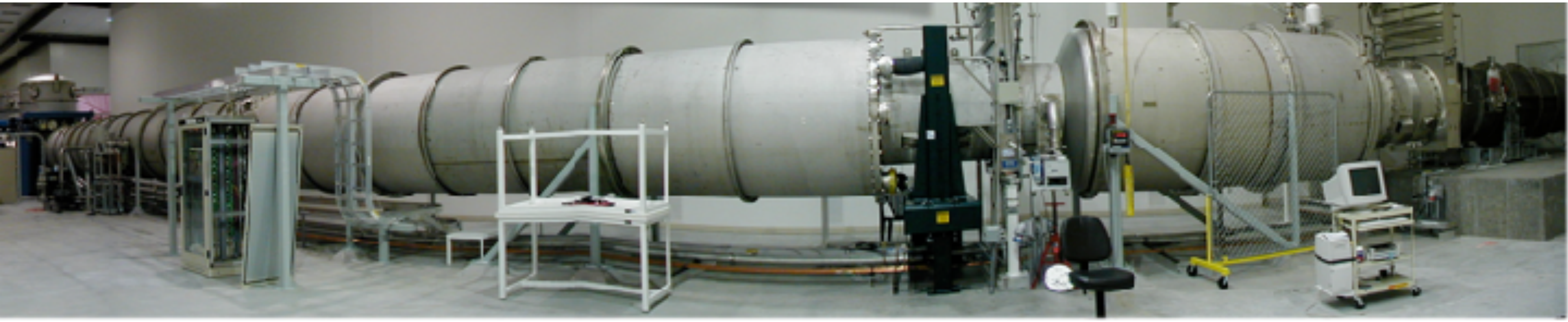
Livingston mirror
(40 kg)

Seismic isolation

age credit: LIGO/ F. Raab

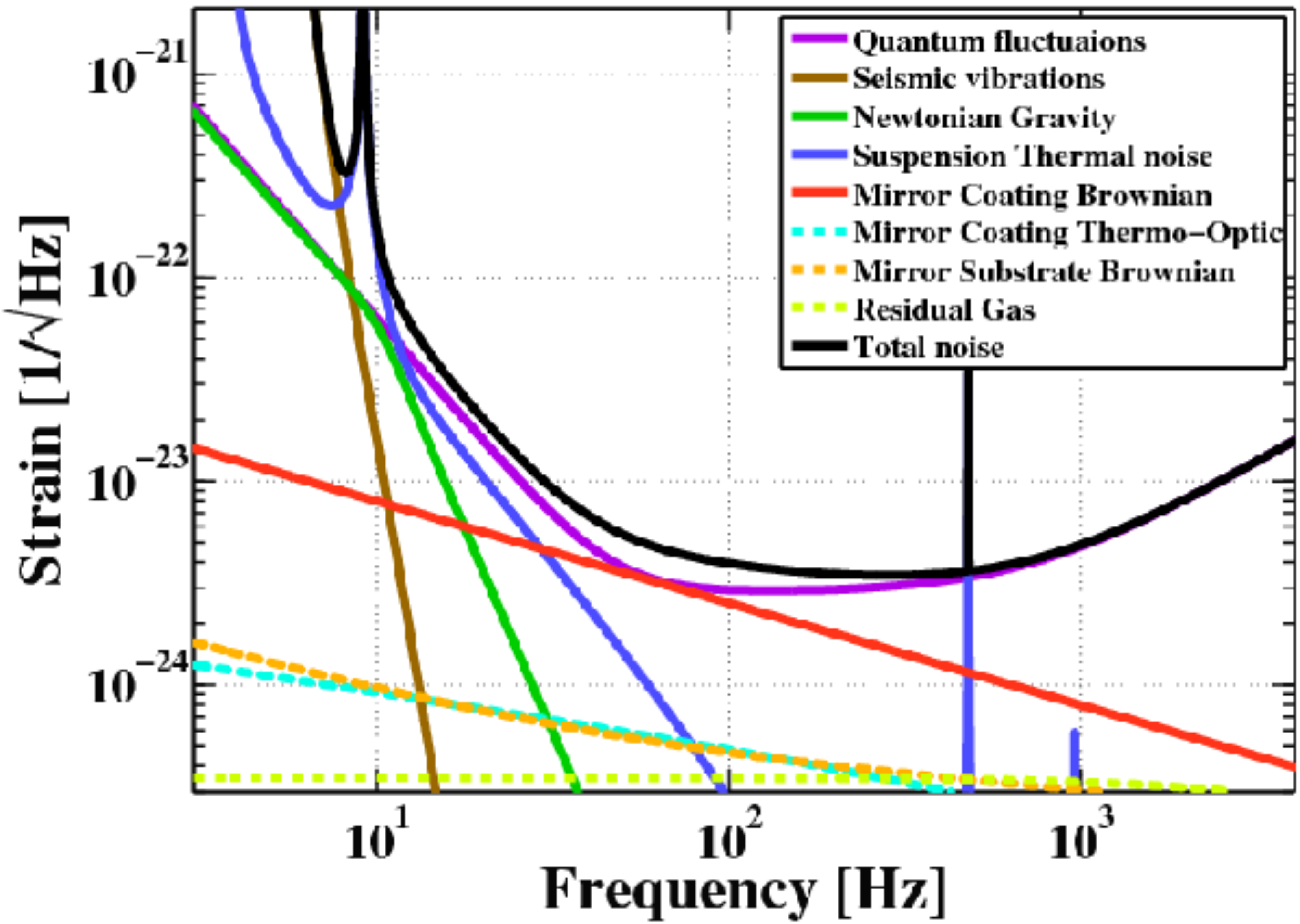
A glimpse inside the detectors

beam tubes: ultrahigh vacuum



Portable power supply for bakeout

Expected limitations due to various noise sources



Noise power spectral density on a given day

https://www.gw-openscience.org/detector_status/day/20190903/

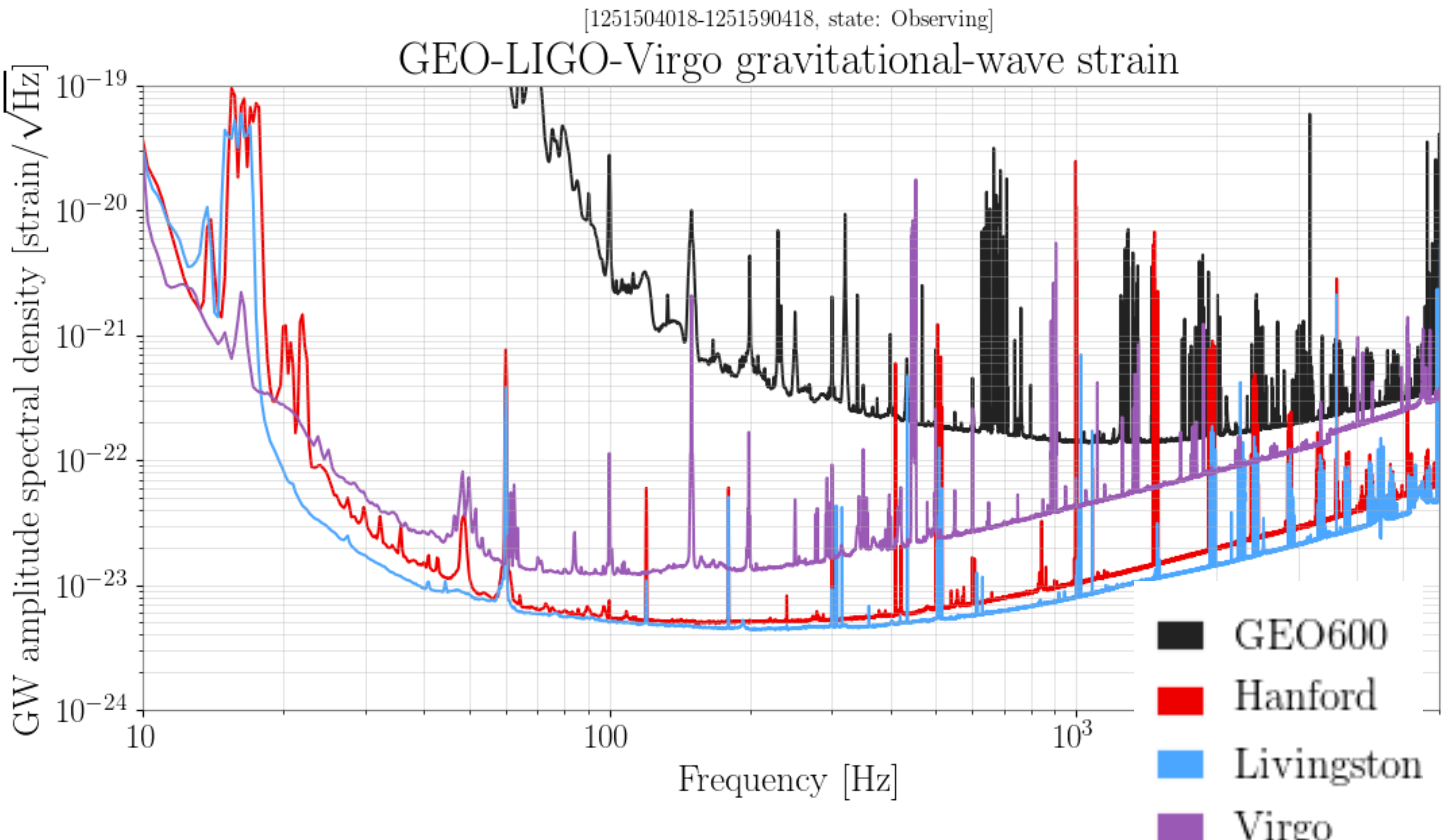
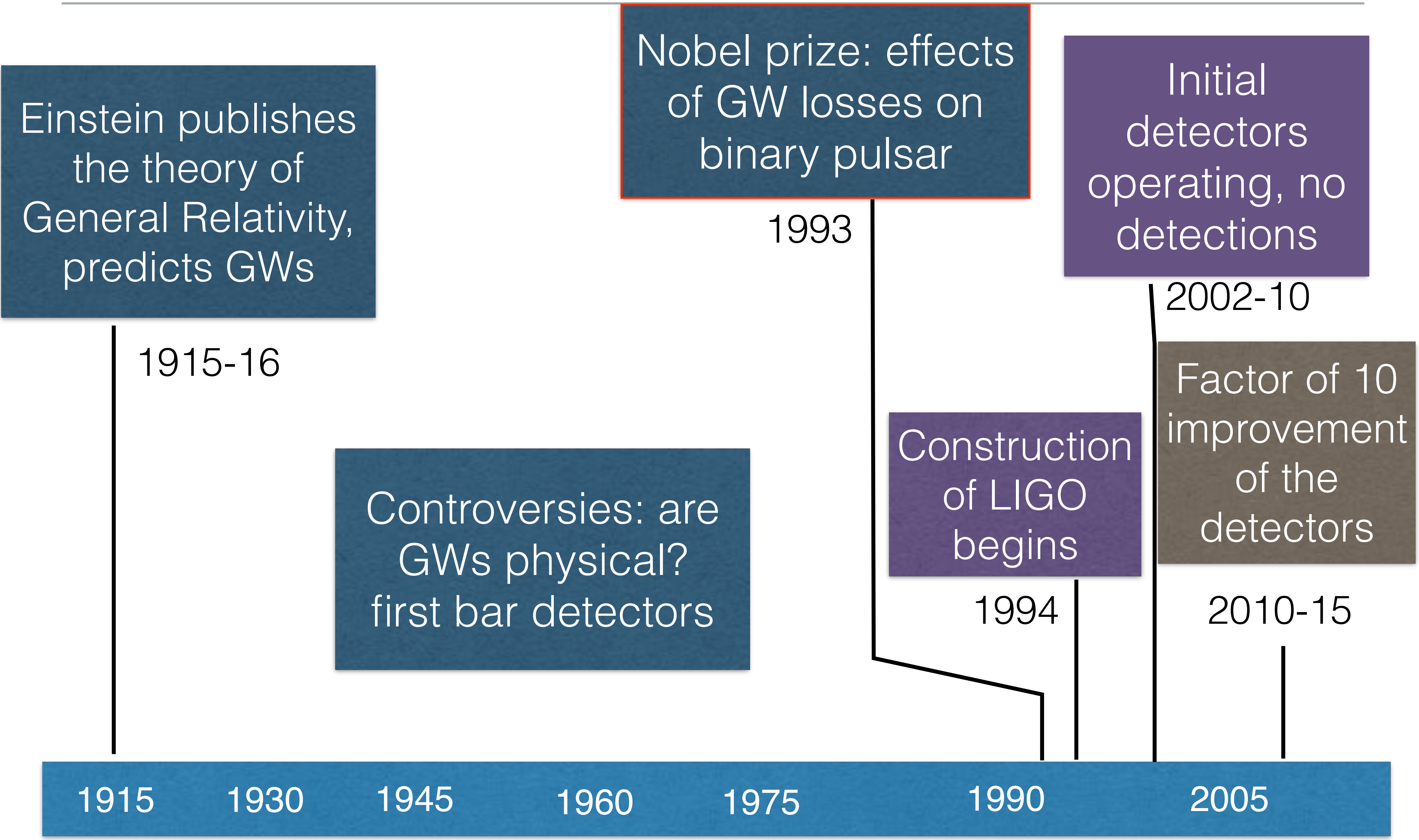


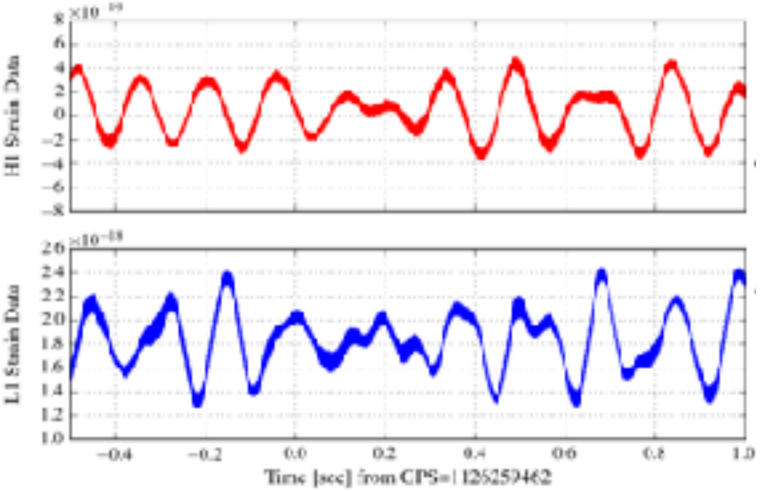
Image credit: LIGO

A long effort …



… until the first detection 14 September 2015, 10:45 CET

Data output **LIGO Hanford** and **Livingston**



[credit: Harry & LSC]

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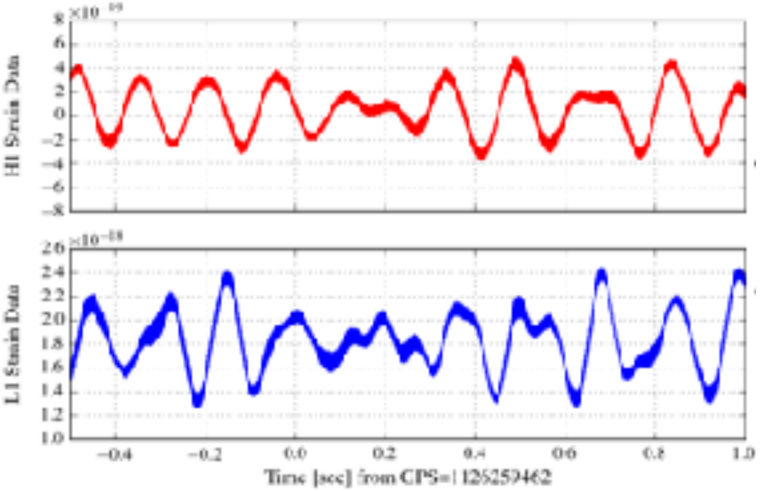
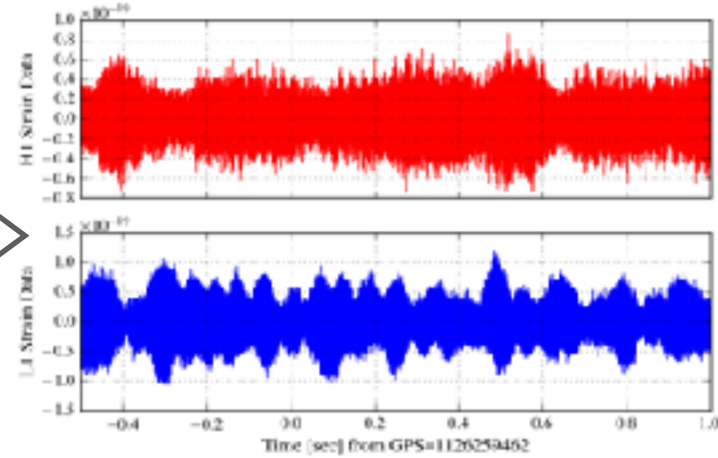


Highpass filter



[credit: Harry & LSC]

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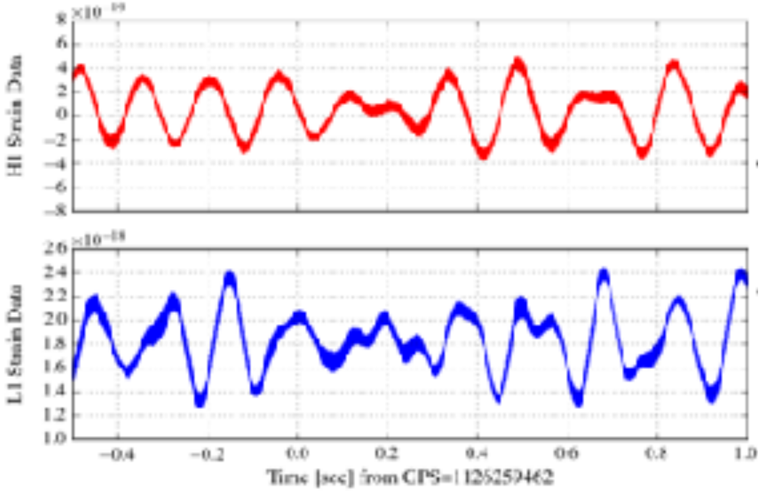

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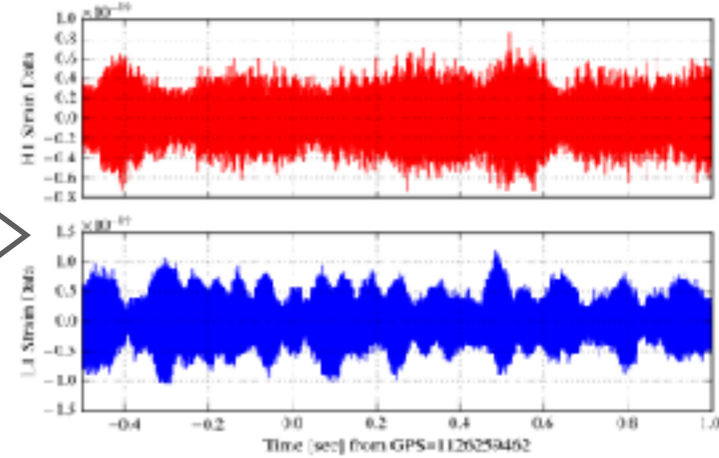
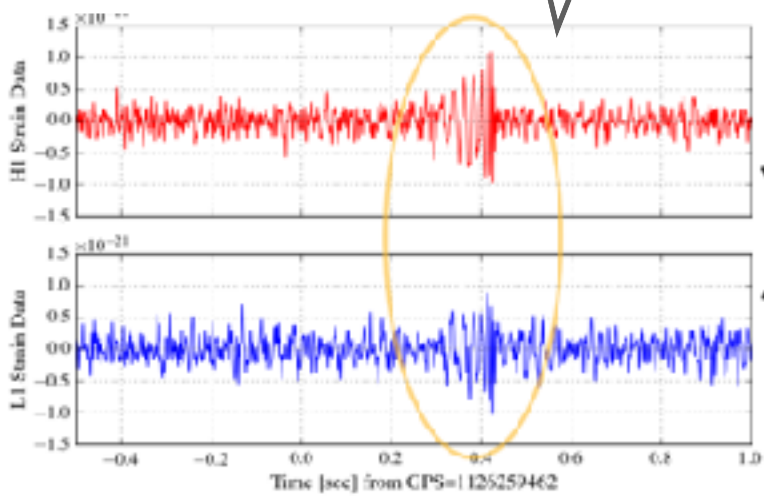
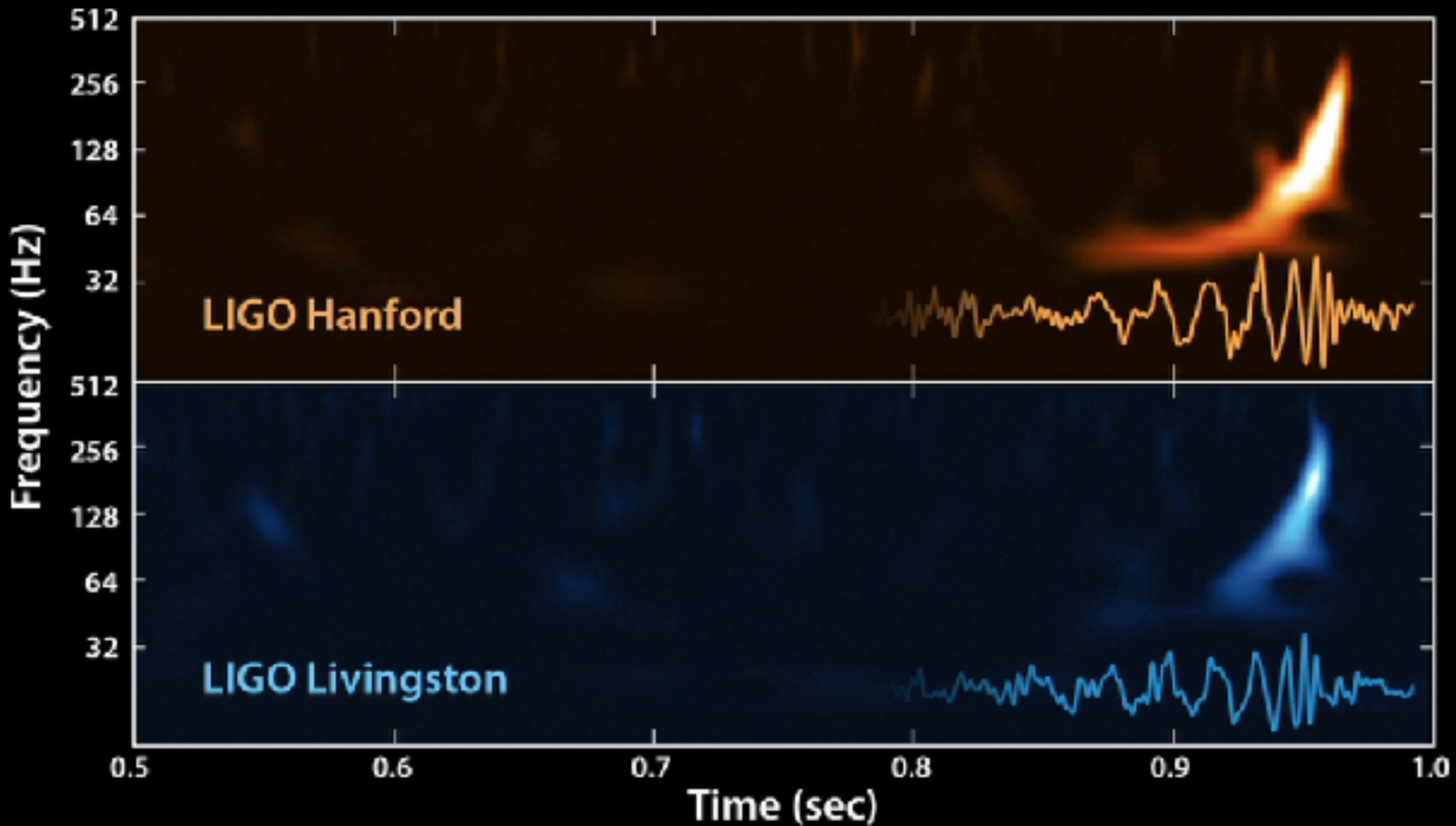


[credit: Harry & LSC]

whitening

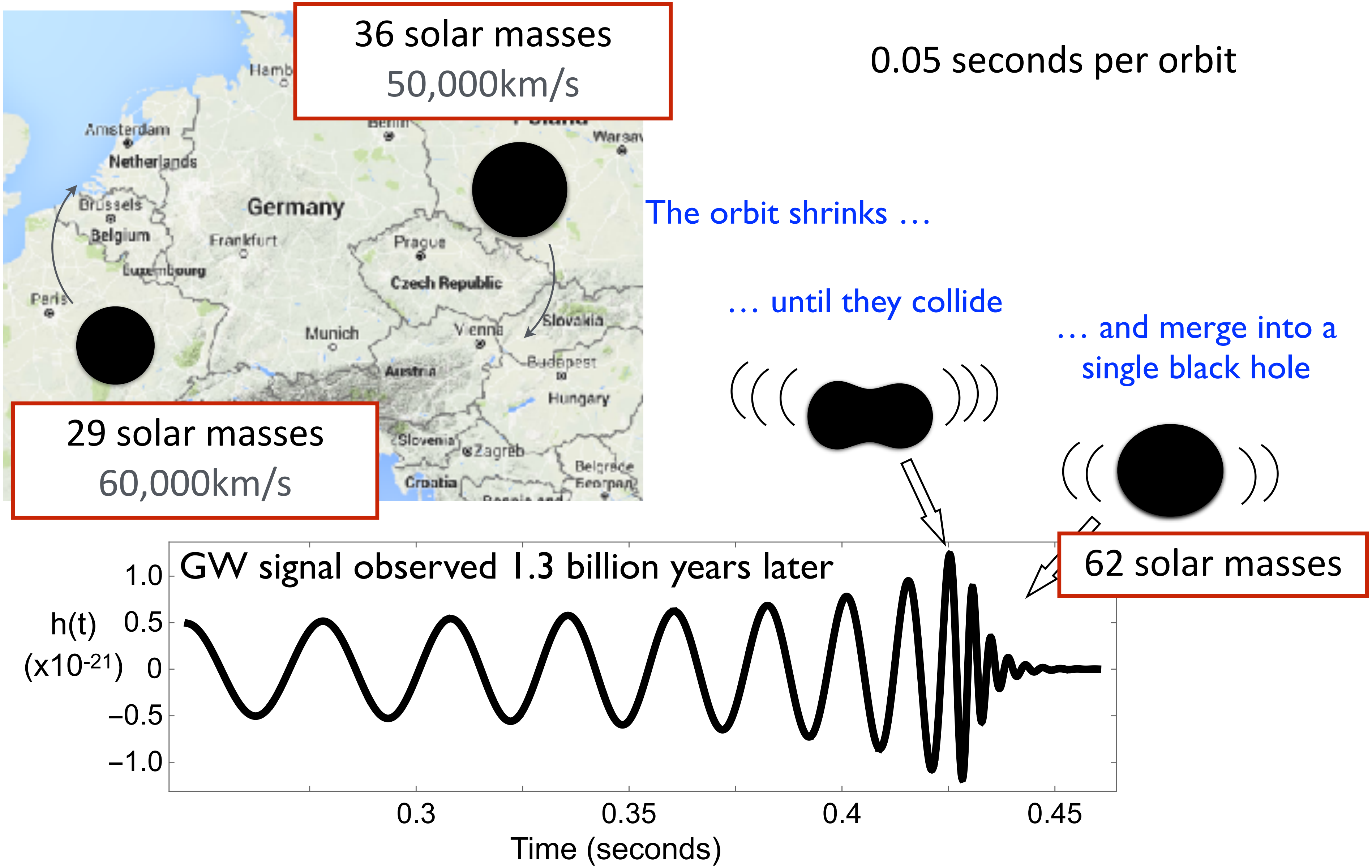


14. September 2015, 10:45:45 CET

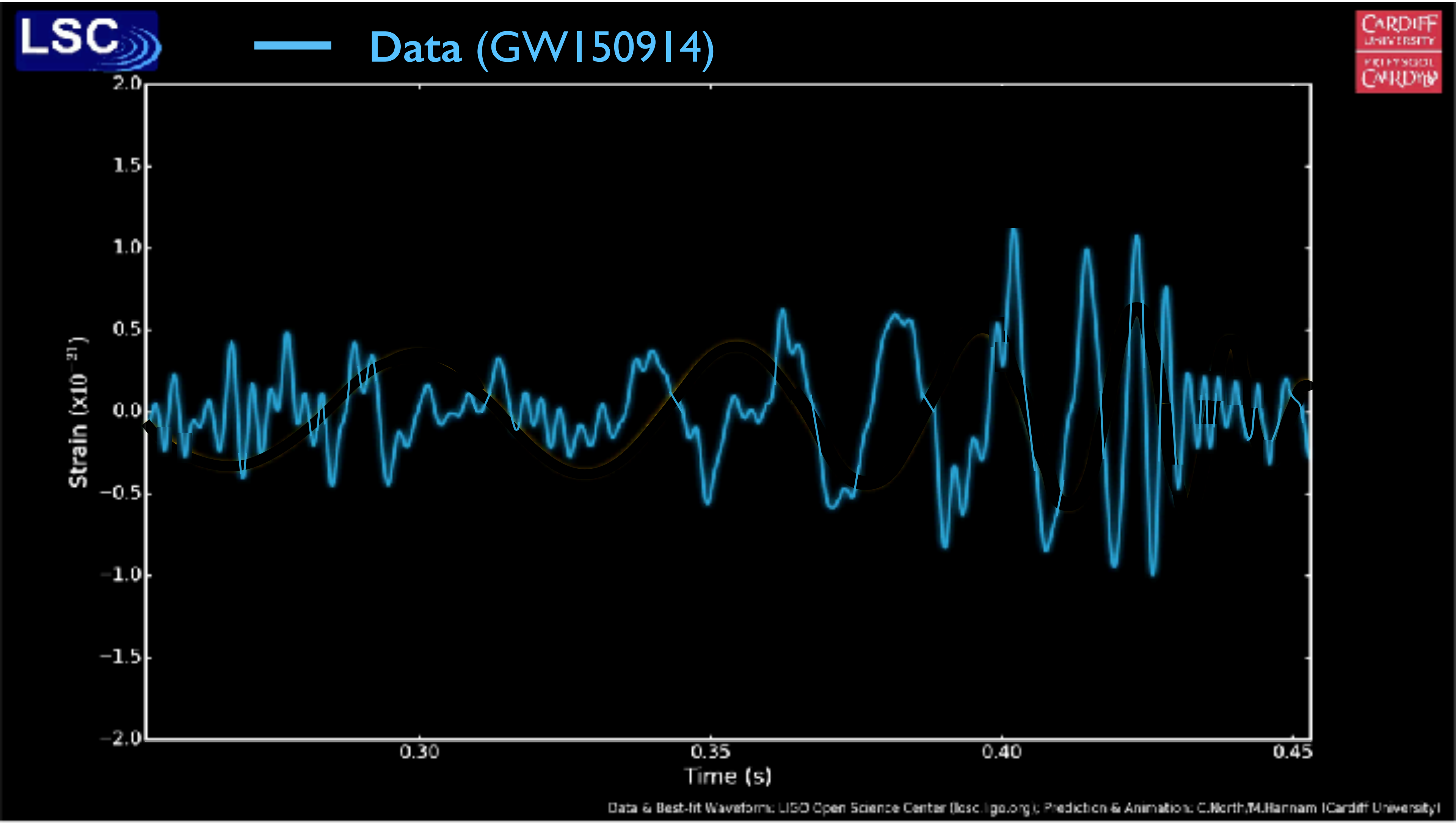


Same feature in detectors thousands of kilometers apart

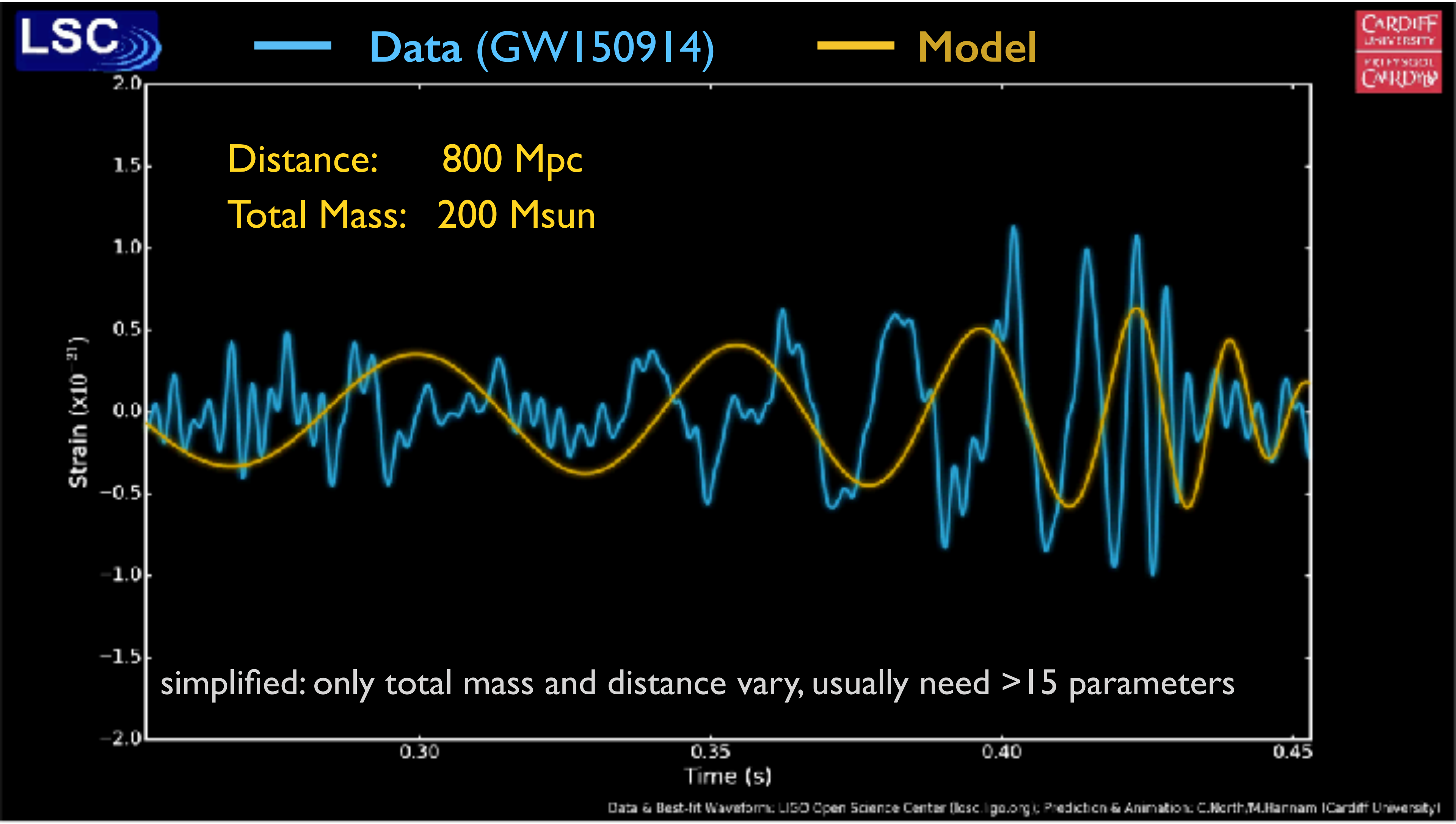
Gravitational-wave signal from a black hole merger



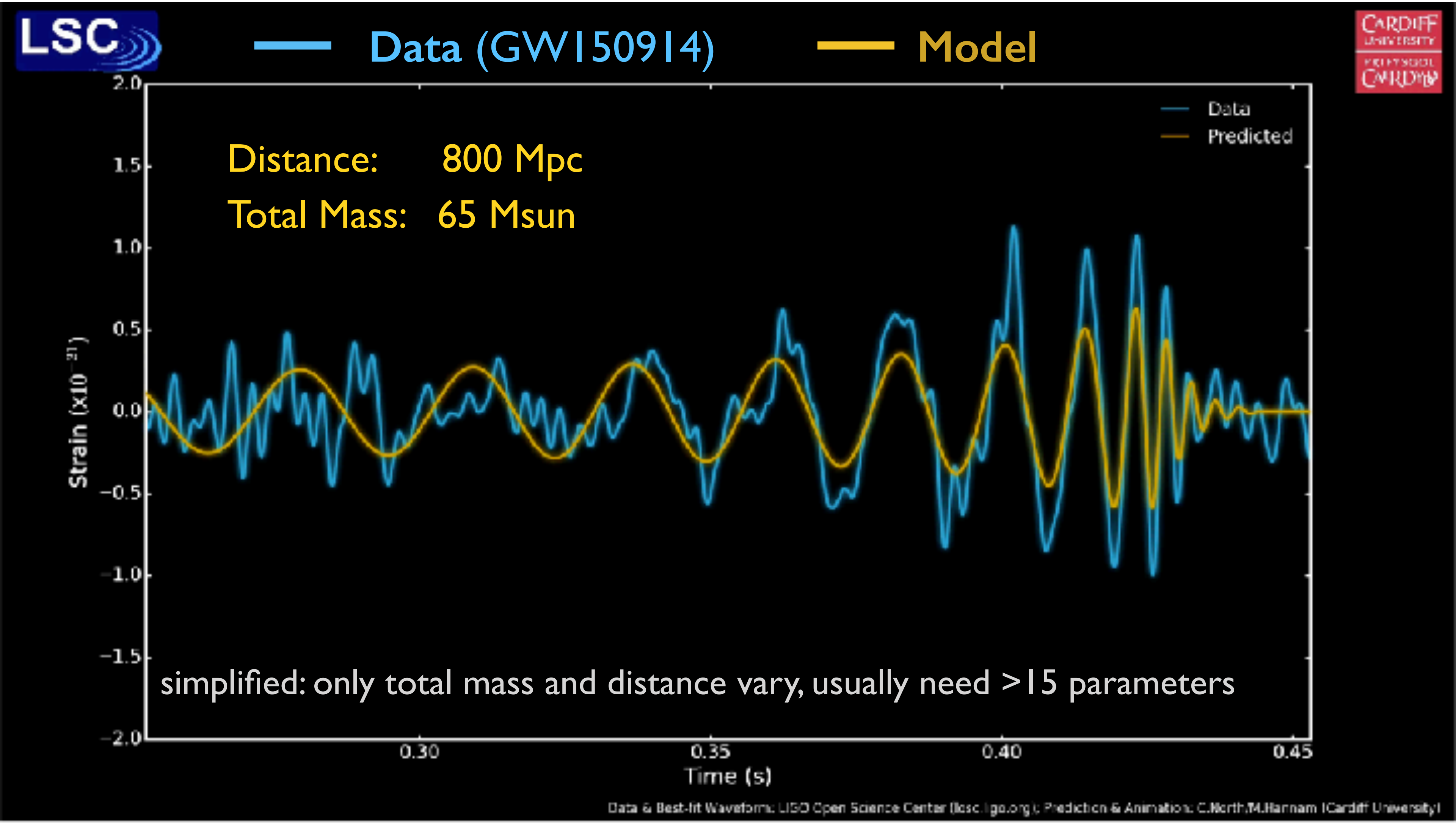
Interpreting GW signals from binaries



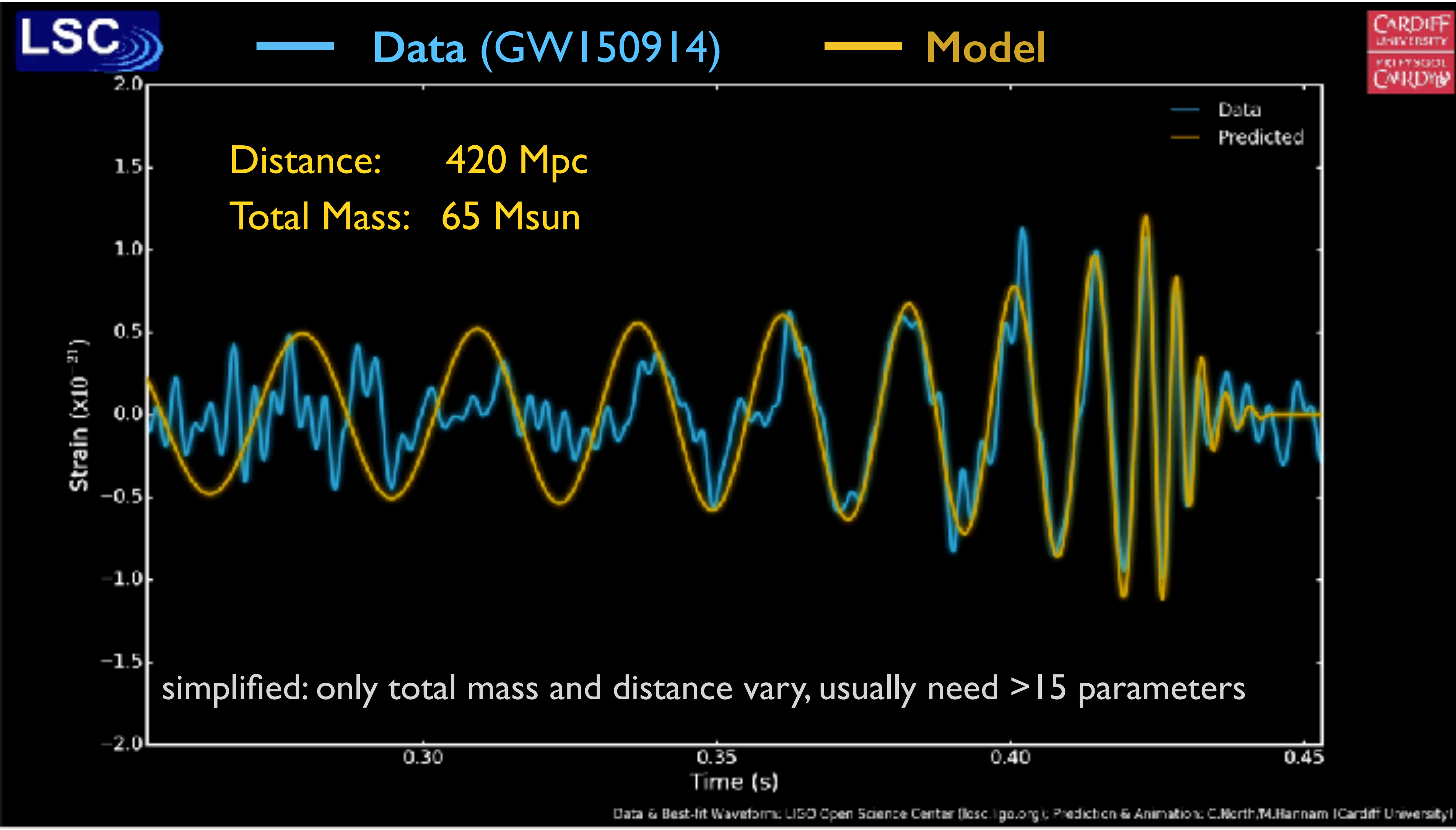
Interpreting GW signals from binaries



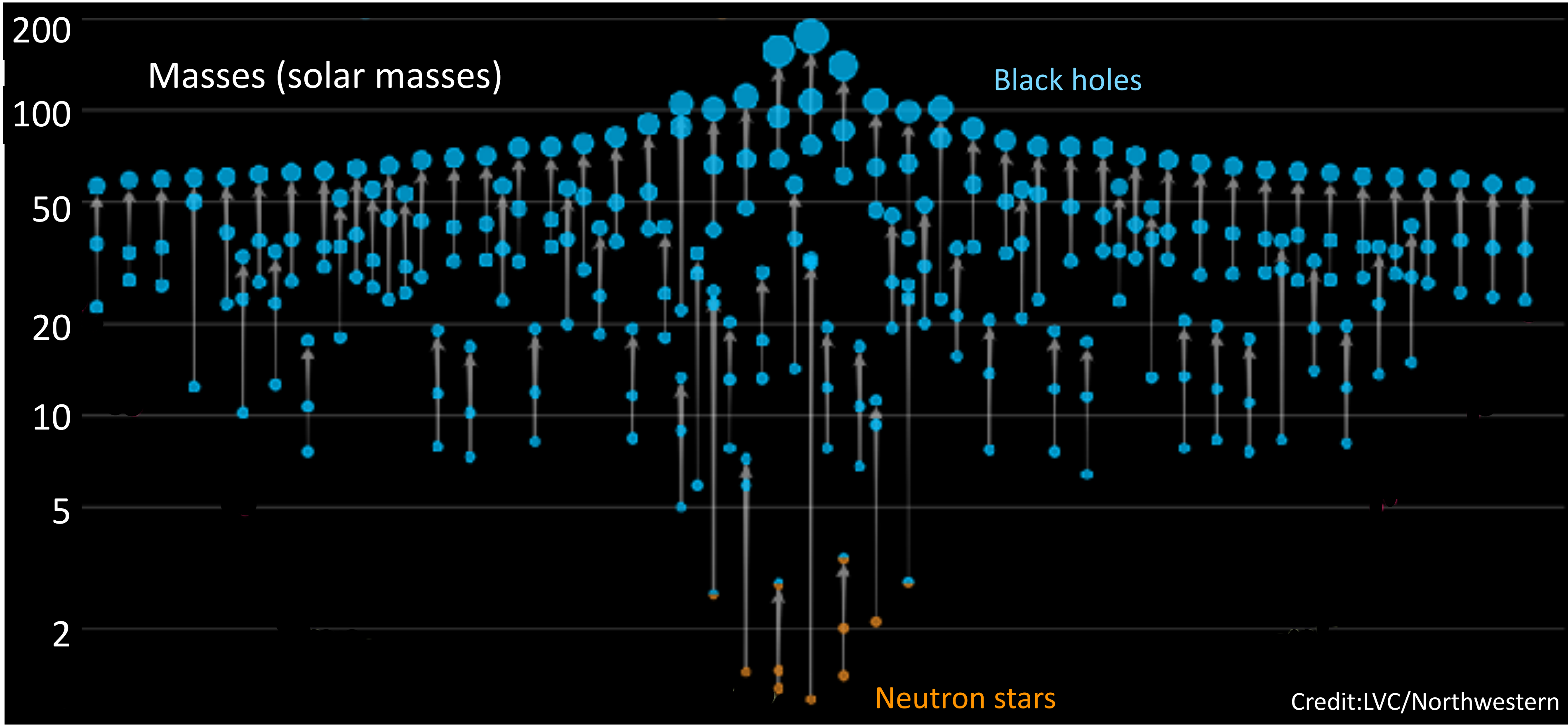
Interpreting GW signals from binaries



Interpreting GW signals from binaries

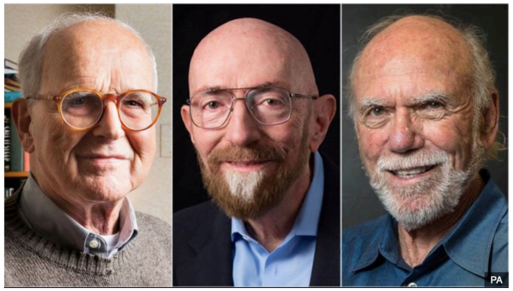


Many more black hole mergers have been measured



2017 Nobel prize

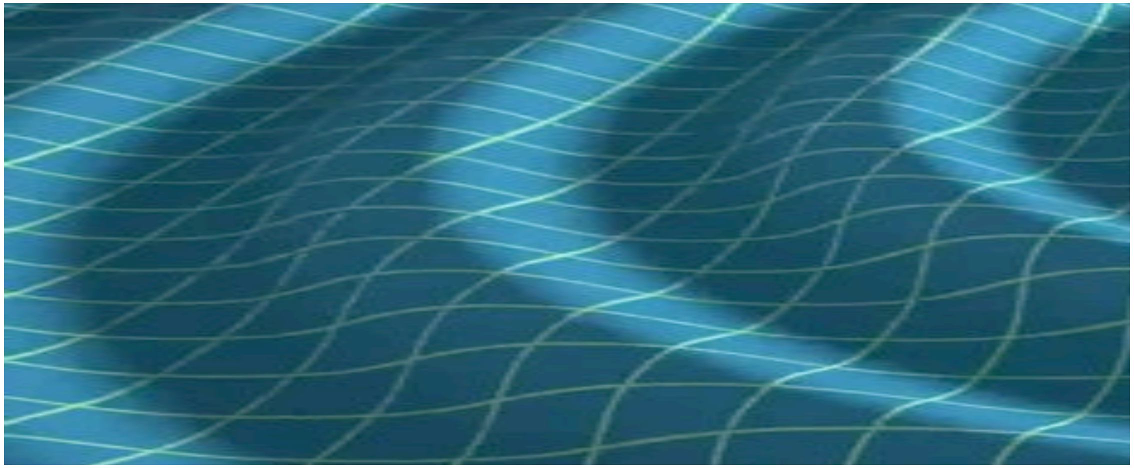
R. Weiss, K. Thorne, B. Barish



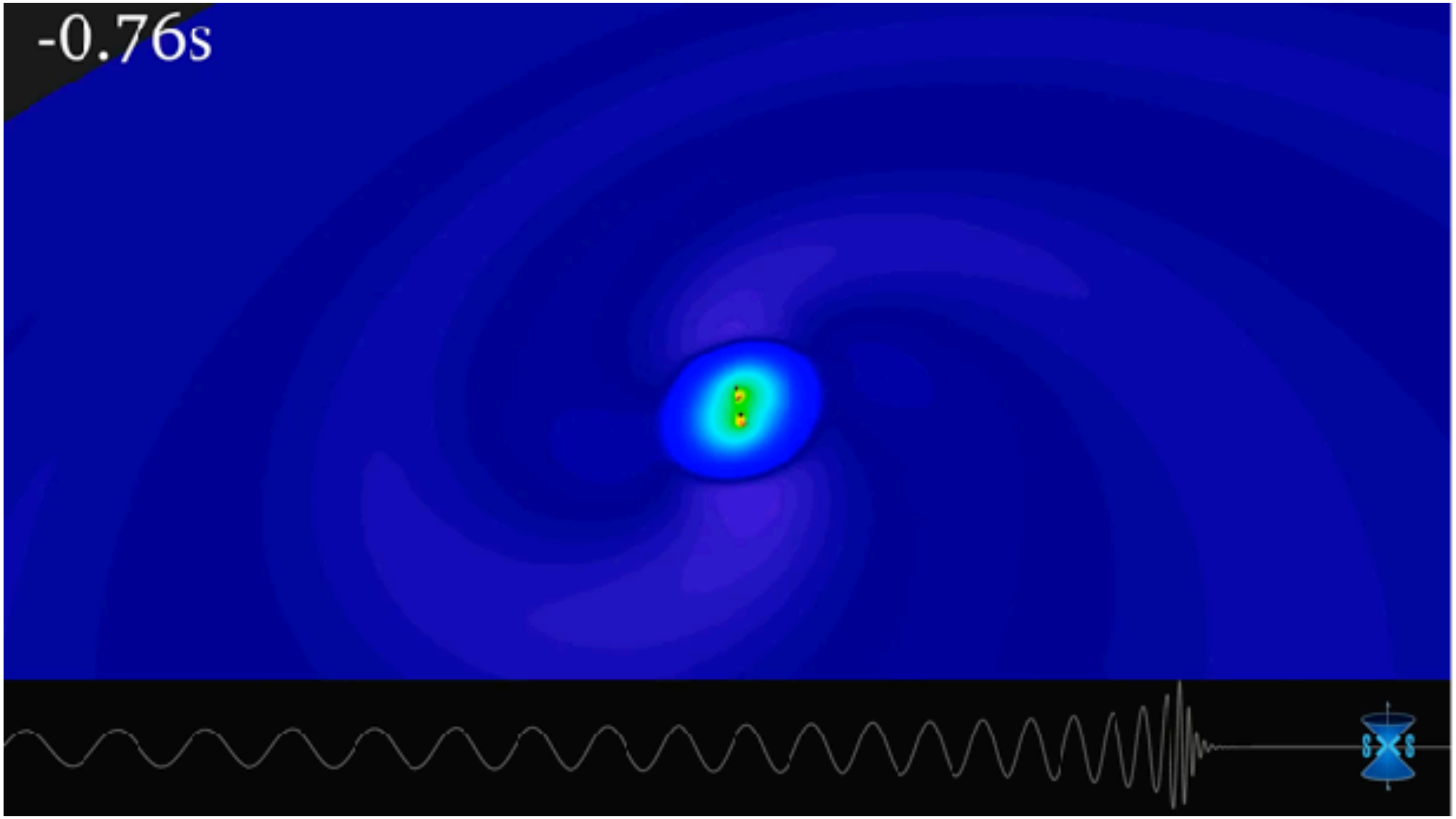
Probing fundamental properties of spacetime

Details of the waveforms encode a wealth of additional information, e.g.:

- How does spacetime behave in nonlinear, dynamical regimes?
- Does Einstein's theory still hold? Hints of a theory of quantum-gravity?



Numerical relativity simulation of GW150914

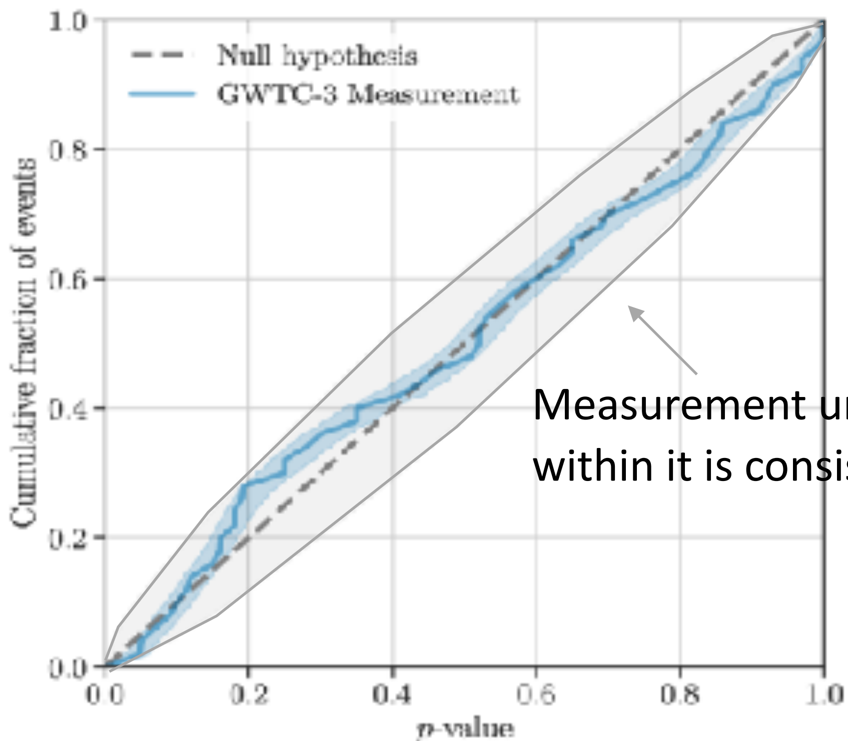


Solve the nonlinear field equations of General Relativity for the dynamical spacetime of the binary black hole system (~ 1 month on supercomputers)

Example: Tests of gravity

Consistency test: look for residuals in the data after subtracting the waveforms predicted by General Relativity

Null hypothesis: residuals are just detector noise

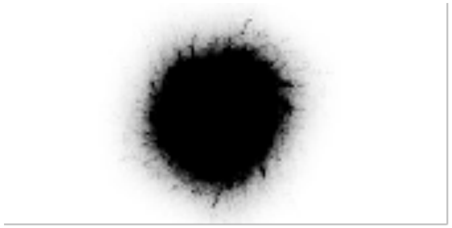


Measurement uncertainty region: anything within it is consistent with the null hypothesis

LIGO-Virgo-KAGRA collaboration: Tests of General Relativity with GWTC-3
arXiv: 2112.06861

The fundamental nature of black holes

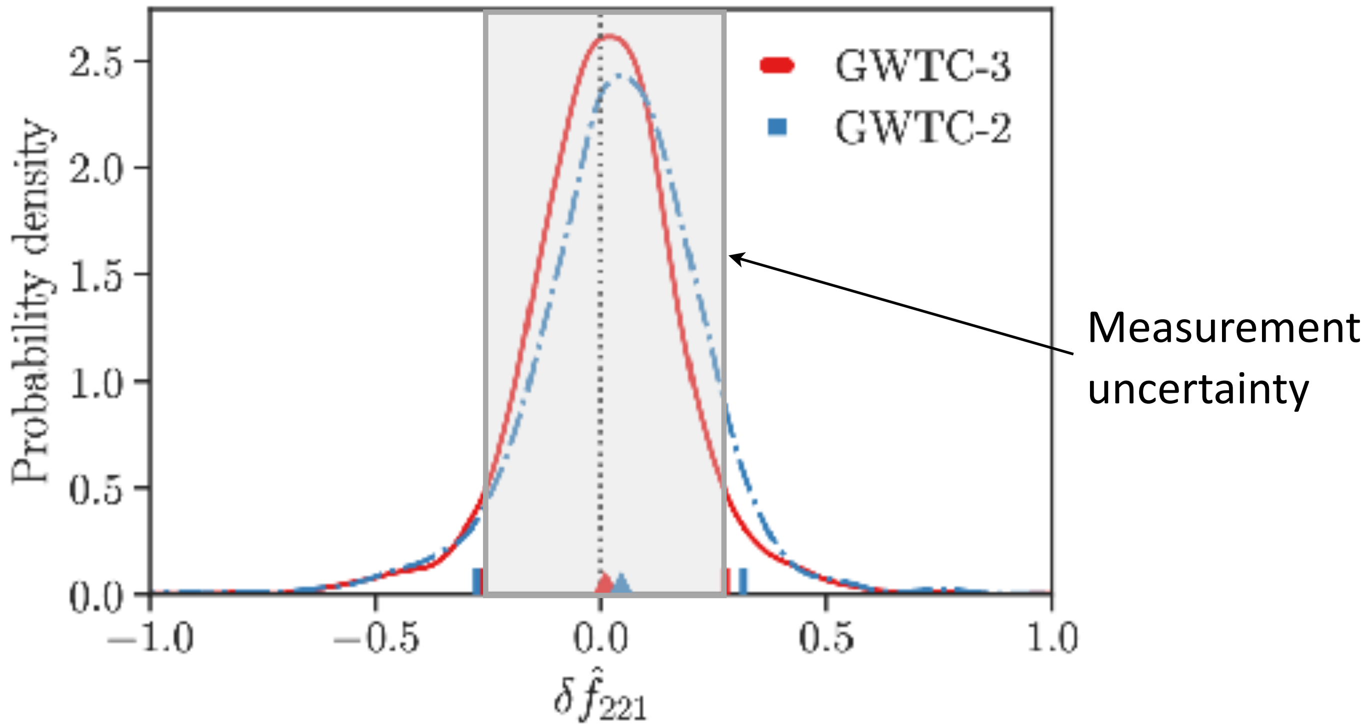
- Black holes:
  - General Relativity: only warped spacetime, horizon, singularity
  - String Theory: 'fuzzballs'
  - Many other possibilities



'Fuzzball'

Example: tests of the remnant black hole

Deviations of the final objects from black holes



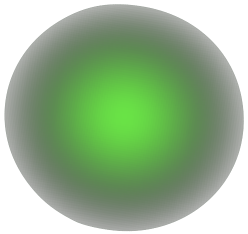
Parameter characterizing deviations from a black hole

LIGO-Virgo-KAGRA collaboration: Tests of General Relativity with GWTC-3
arXiv: 2112.06861

More fundamental physics with GWs from binary systems

- Dark matter, new particles around black holes?

- Gravitational condensates of new fields?



  - Extra (scalar, vector) fields are ubiquitous in beyond-standard-model physics, incl. dark matter, inflation
  - over cosmic time, condensates generically form

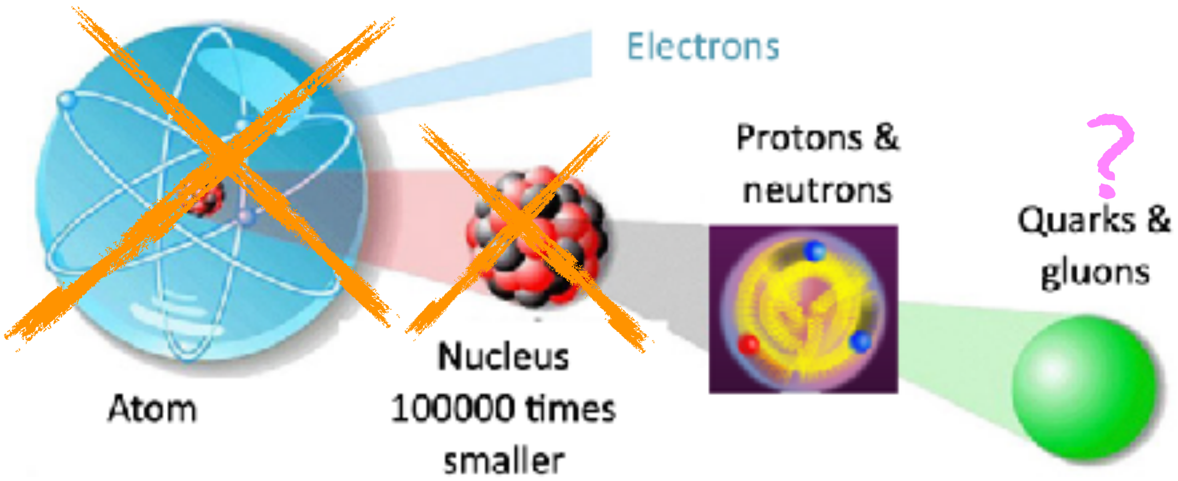
- GWs travel enormous distances through the universe: dark energy, cosmology

More fundamental physics with GWs from binary systems

- Probing new regimes of subatomic physics with neutron stars

- Gravity compresses matter to ~ several times nuclear density
- Large extrapolation from known physics

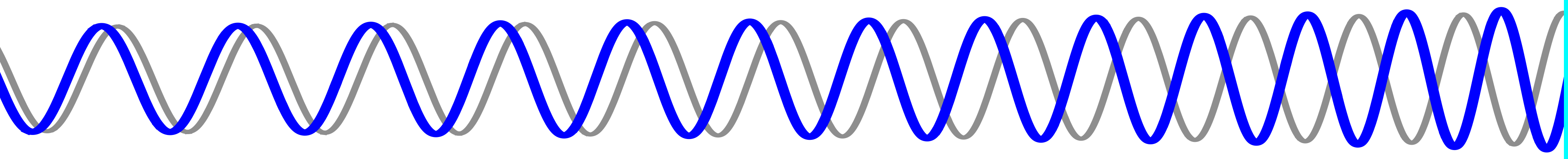
Building blocks of matter



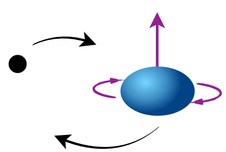
No longer exist in the extreme conditions in neutron star interiors

GW signatures of interior structure during inspiral

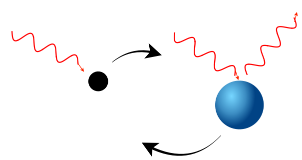
Two black holes (low mass) — Black hole - other object



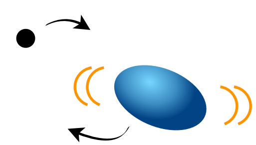
Spin-induced deformations



Absorption

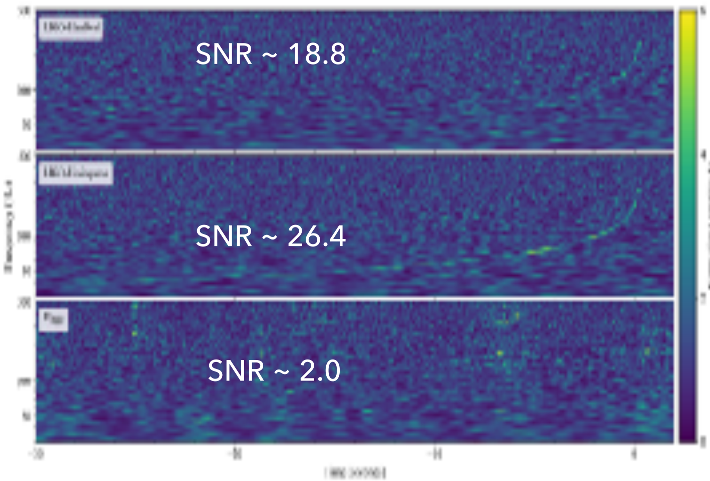


Various tidal effects



Small but cumulative imprints characteristic of the object's interior structure

Aug. 17, 2017: binary neutron star merger GW170817



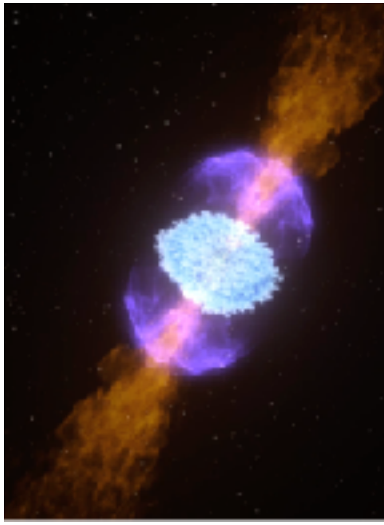
Distance: ~40 Mpc

Total mass: ~ 2.74 Msun

[LVC Abbott et al 2017]

GWs measured from the inspiral: signatures of tidal effects yielded constraints on dense matter physics

Artistic visualizations, credit NASA



Collision was outside the detector’s sensitive band in GWs, but the aftermath was visible as spectacular EM counterparts

Wealth of science with combined multi-messenger information

Finally in 2020: neutron-star — black hole discoveries

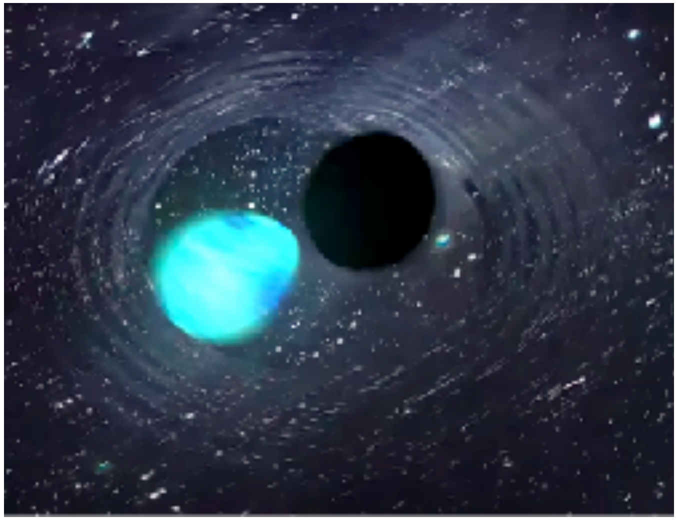
LVK arXiv: 2106.15163

GW200105:

$8.9^{+1.2}_{-1.5}\,M_\odot$ and $1.9^{+0.3}_{-0.2}\,M_\odot$

GW200115:

$5.7^{+1.8}_{-2.1}\,M_\odot$ and $1.5^{+0.7}_{-0.3}\,M_\odot$



Artist's impression by C. Knox

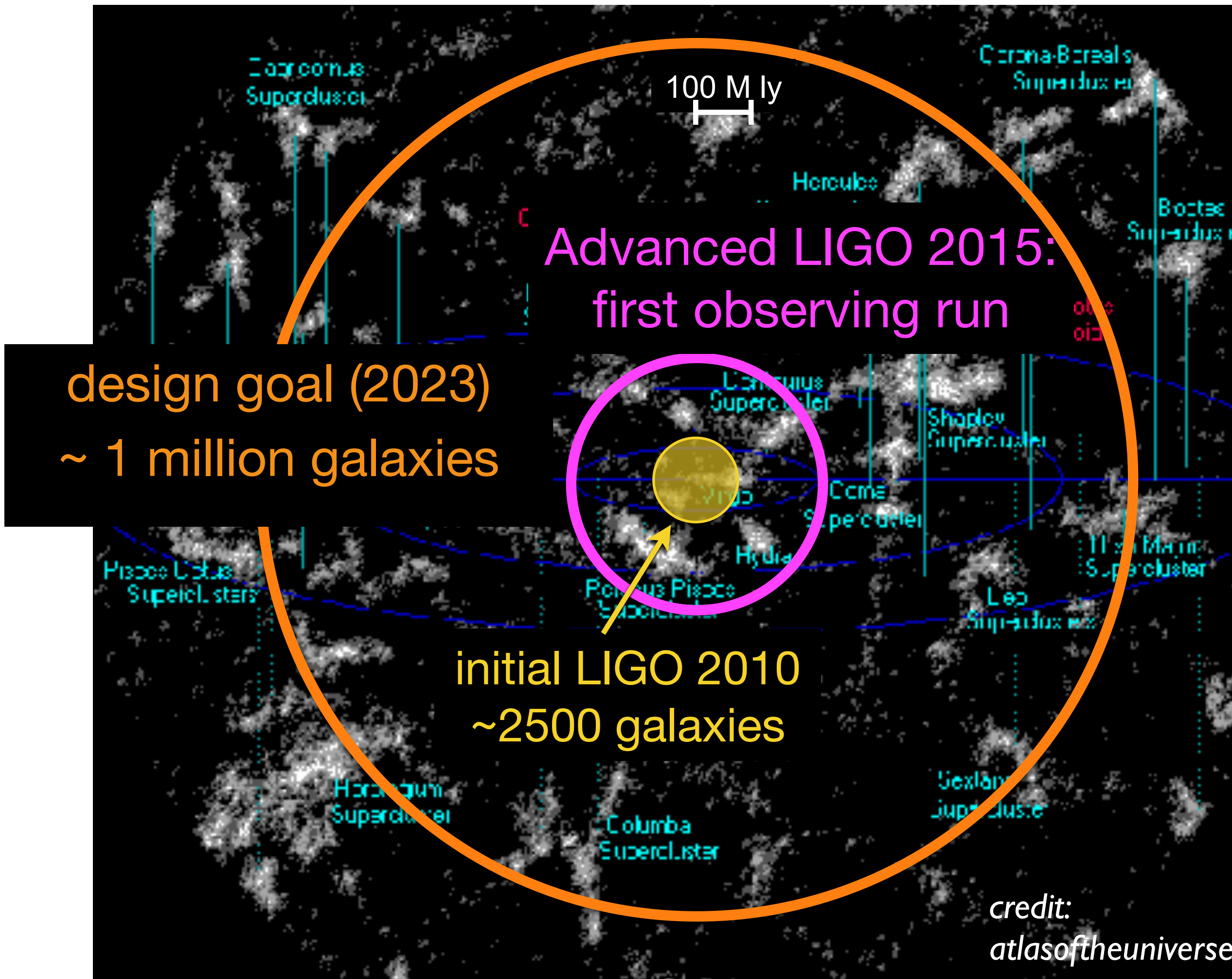
The lighter object (most likely a neutron star) was probably 'swallowed whole'

The next years

Detectors currently being improved in sensitivity: next science run to start end of May 2023

Visible volume of the universe (benchmark binary)

- Greater number, diversity of events
- Higher precision studies



Chirp Home Latest All Alerts About Contact Network Status: G1 H1 L1 V1 K1

https://chirp.sr.bham.ac.uk/

Chirp - Keep track of the latest gravitational wave alerts

Gravitational waves are ripples in space-time. The two LIGO detectors, Hanford and Livingston along with Virgo have a proven track record of successful observations and are now issuing public alerts of possible gravitational waves events via the Gamma Ray Coordinates (GCN) system.

Chirp is a web-app that listens to the GCN system and displays the information in a friendly format, with links to LIGO-Virgo Gravitational Wave Candidate Event Database (GraceDB) pages for more detailed information. For more information about this app check out our about page.

LIGO's O3 Observing run has been suspended due to the COVID-19 pandemic. For more infornation, see the Press Release.

Latest Alert All Alerts

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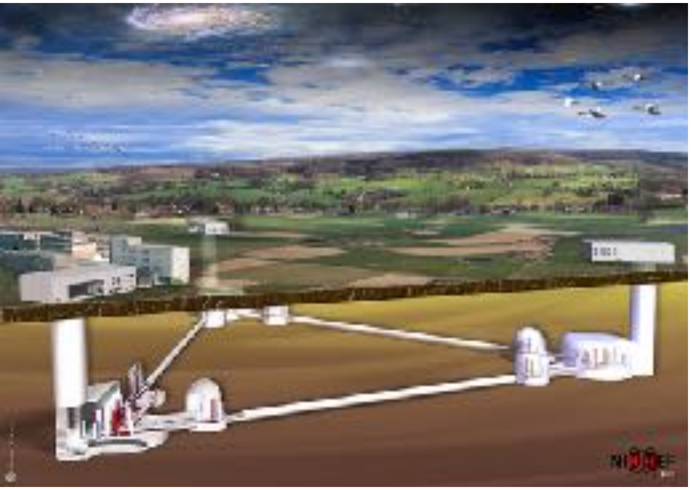
Ongoing efforts for next decade's detectors

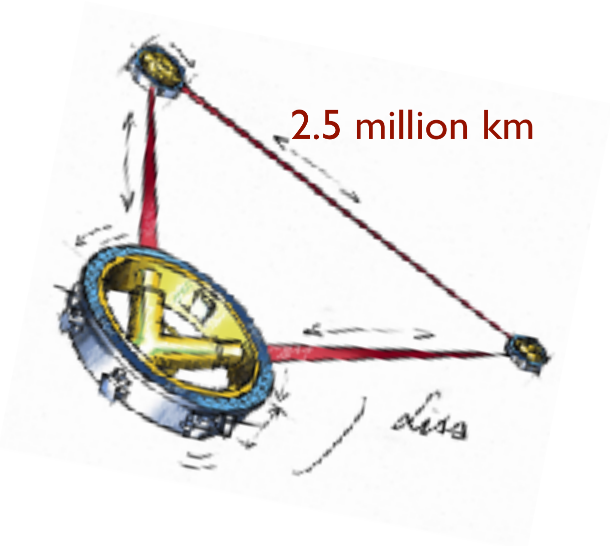


- Plans for next-generation detectors (2030s), Europe:

  Einstein Telescope
- 10 times better sensitivity
- stellar-mass black hole mergers in nearly the entire universe
- Many other sources
- Hundreds of thousands detections per year

Einstein Telescope pathfinder at Maastricht

The space-based detector LISA



LISA: Laser Interferometer Space Antennae

- ESA-led mission, NASA involvement
- Scheduled for launch mid-2030s
- Pathfinder was exceedingly successful (2017)

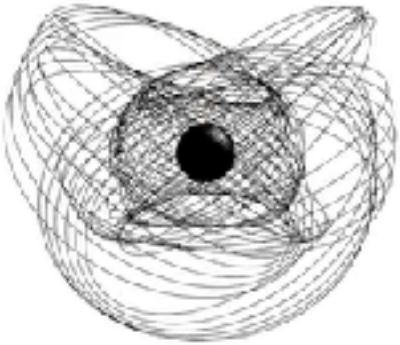
Access to different classes of sources,

new discovery space. For example:

Merging supermassive black holes (> millions Msun) through cosmic time

Signal-to-noise ratio as high as ~5000

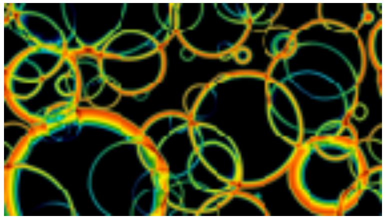
Extreme mass ratio inspirals



Orbit of inspiraling object

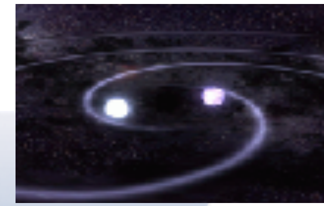
The GW spectrum: over 20 decades in frequency

Relics from big bang, inflation, early universe, phase transitions, cosmic strings



black holes in merging galaxies

compact binaries



Sources

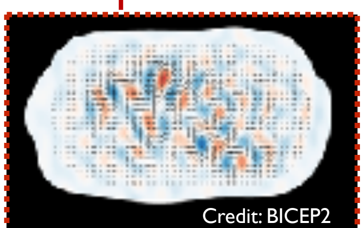
compact objects captured by massive black holes

rotating neutron stars, supernovae

wave period: age of the universe | years | hours | sec | ms

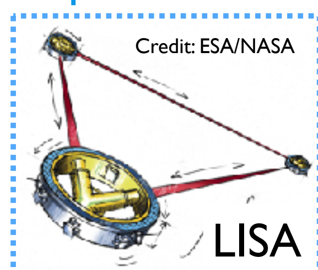
Frequency [Hz]: 10^{-16} | 10^{-8} | 10^{-4} | 1 | 10^{2}

CMB polarization



pulsar timing

space-based



terrestrial

Conclusion and outlook

- Gravitational waves: a new tool for science
  - Probe dark sectors of the universe
  - Unprecedented insights (gravity, black holes, dense matter, and much more)
- Detectors will continue to improve in sensitivity, new instruments underway
- Exciting prospects for the future — however, much work remains to be done to fully realize the enormous scientific potential