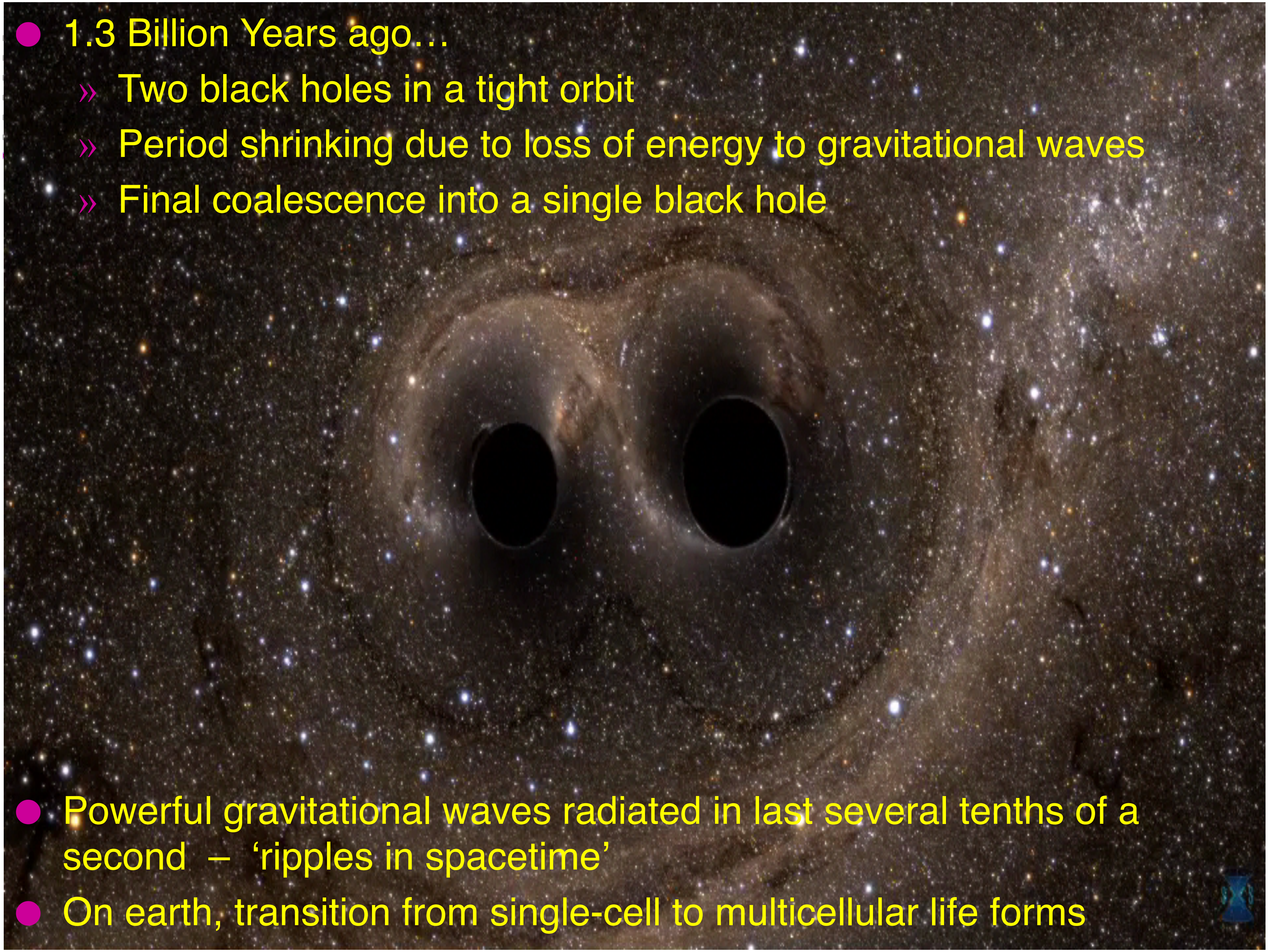
LIGO and Virgo –
Opening Up a New Window on the Universe

Nikhef

12 September 2017

David Shoemaker
For the LIGO and Virgo Scientific Collaborations

Credits
Measurement results: LIGO/Virgo Collaborations,
PRL 116, 061102 (2016); http://arxiv.org/abs/1606.04856
Simulations: SXS Collaboration; LIGO Laboratory
Localization: S. Fairhurst arXiv:1205.6611v1
Photographs: LIGO Laboratory; MIT; Caltech



- 1.3 Billion Years ago…
  - » Two black holes in a tight orbit
  - » Period shrinking due to loss of energy to gravitational waves
  - » Final coalescence into a single black hole
- Powerful gravitational waves radiated in last several tenths of a second – ‘ripples in spacetime’
- On earth, transition from single-cell to multicellular life forms

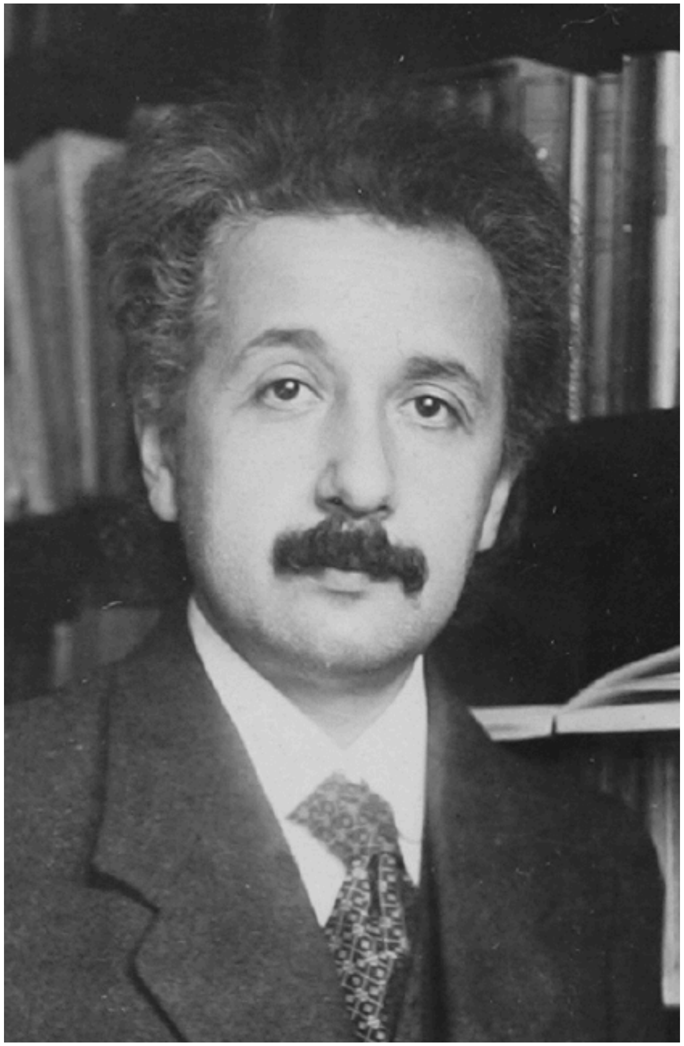
100 years ago

- Albert Einstein is evaluating and processing patent applications…
  - …for transmission of electric signals and electrical-mechanical synchronization of time
  - Musing on relative motion of radio transmitters and receivers
  - → Special Relativity, 1905
- …then dreaming of being in an elevator in space and asking if it is a pull on the cable or gravity...
  - → General Relativity, 1915
- Prediction of gravitational waves (GW) as a consequence of GR in **1916:**

Näherungsweise Integration der Feldgleichungen der Gravitation.

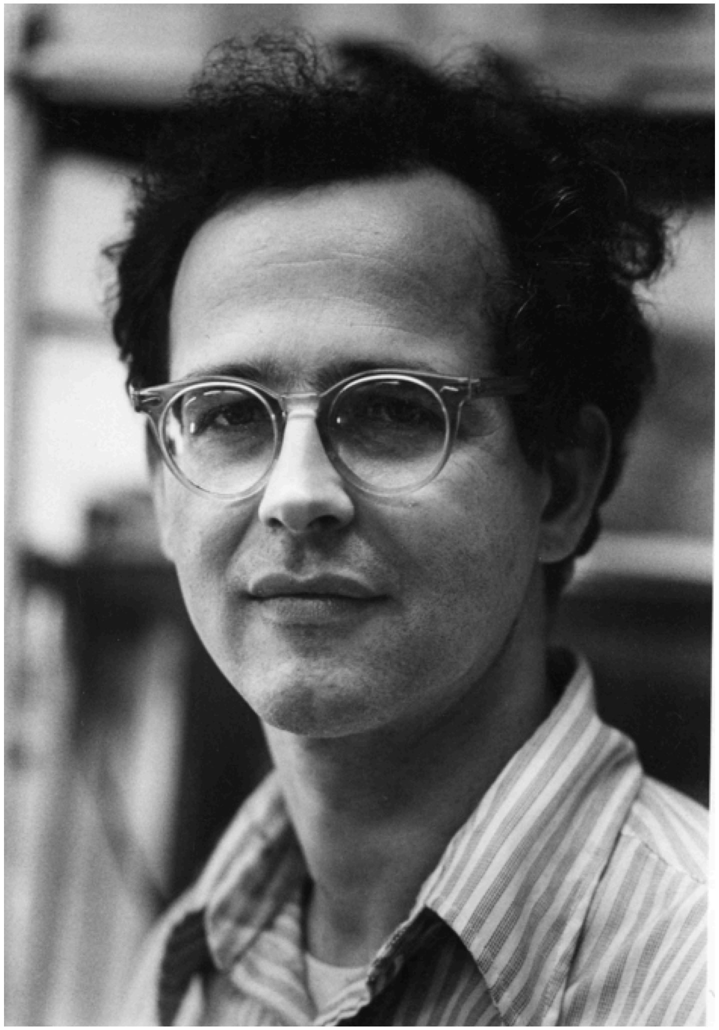
Von A. Einstein.

- Notes that it is of no practical interest as it will not be possible to detect such a small effect



A Half-Century ago

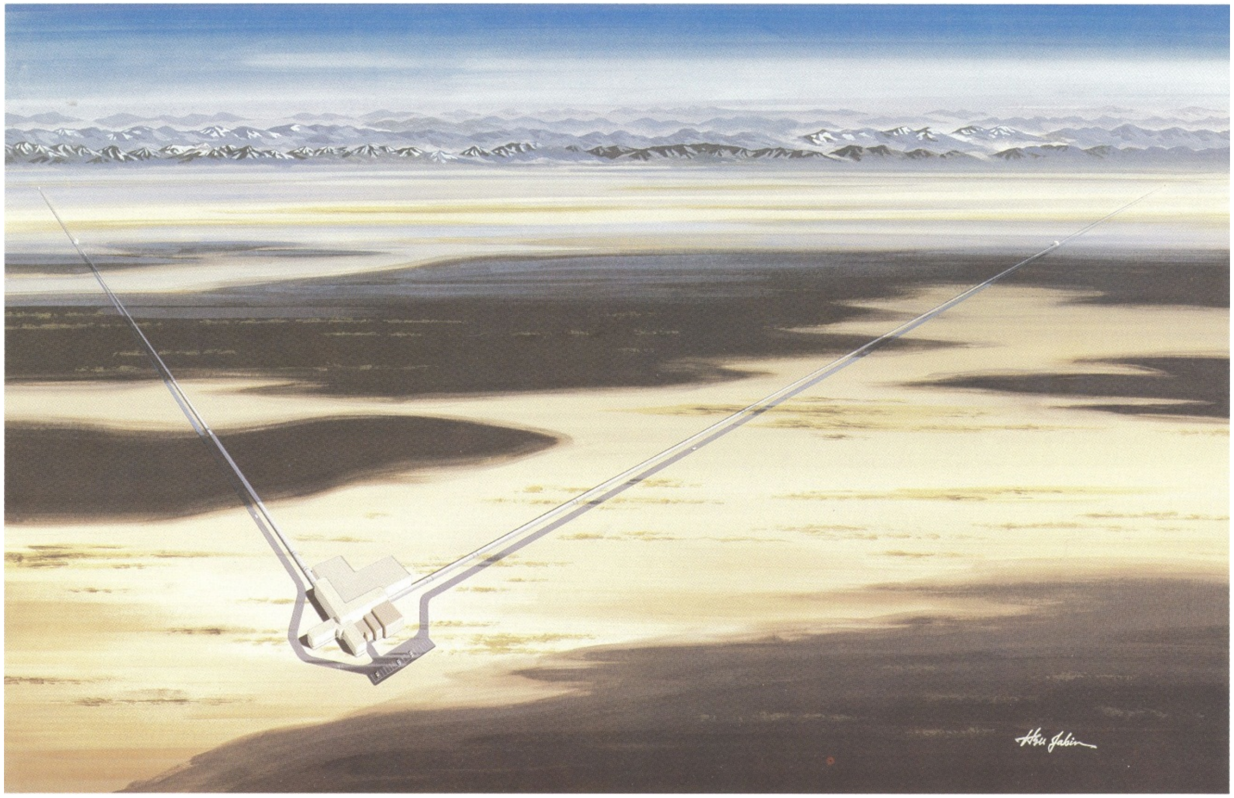
- Several scientists think of using laser interferometry to detect GWs
- Rainer Weiss of MIT invents the idea as a homework problem for students learning General Relativity
- He does the homework, and spends a summer fleshing out the idea
- **In 1972, Weiss publishes an internal MIT report**
  - "Electromagnetically coupled broadband gravitational antenna"
  - Sets the concept and scale of LIGO
  - This roadmap contains also noise sources and how to manage them



Two Decades ago

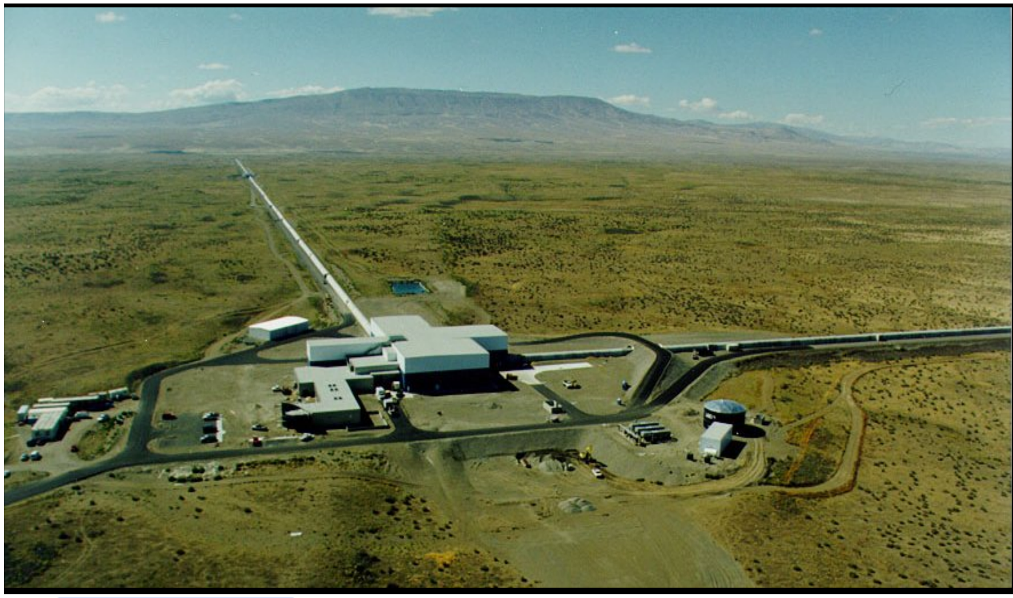
- Caltech and MIT propose to the NSF to establish Observatories
- Proposal states clearly that the initial detectors only have a chance of detections, and that upgraded detectors must be accommodated and foreseen

Proposal cover art →

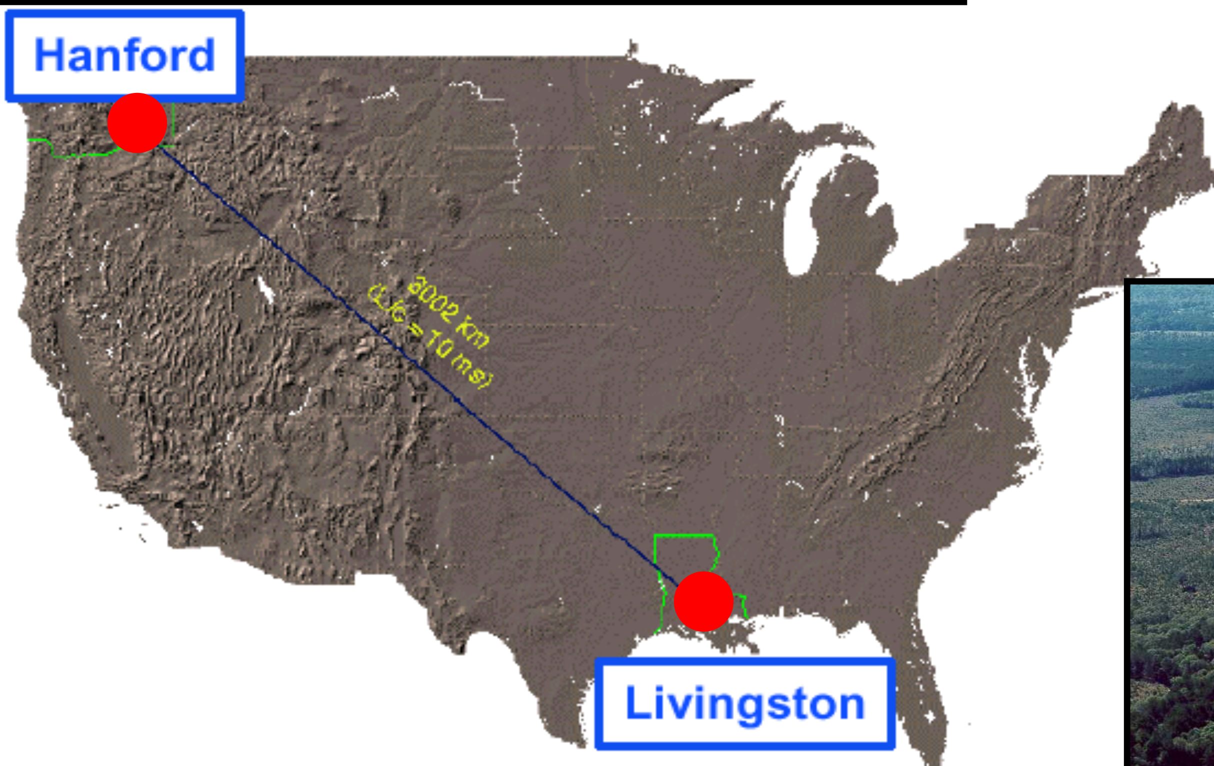


LIGO Laboratory
– Caltech, MIT –

built observatories in ‘90s, and…



…Observed with the initial detectors 2005-2011, and saw…



nothing

Initial Detectors

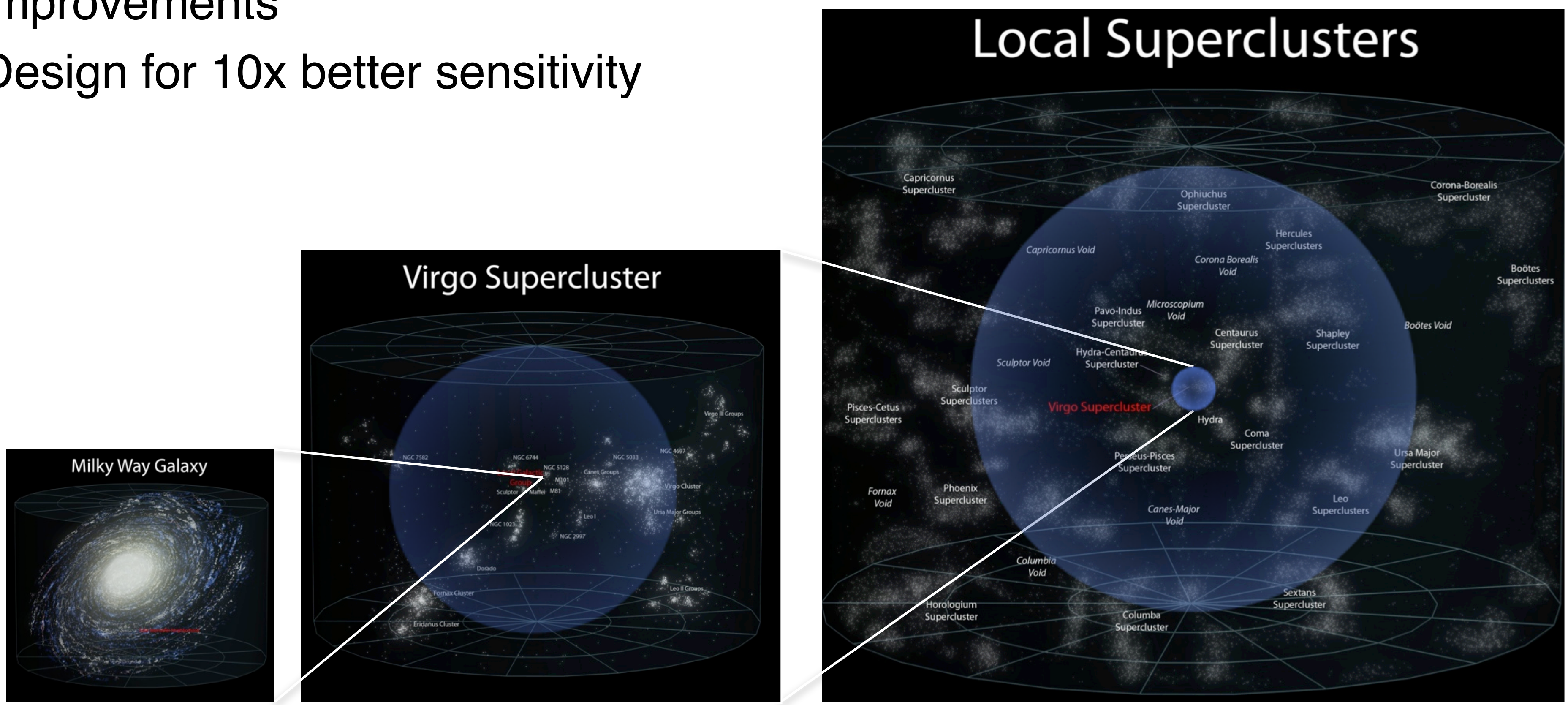
- That is to say, we saw no gravitational-wave signals.
  - » We learned how to build and commission detectors
  - » We learned how to analyze the data
  - » We created new upper limits and significant ‘non-detections’

…but it was clear we needed more sensitive detectors.

Advanced LIGO Sensitivity: a *qualitative* difference

- While observing with initial detectors, parallel R&D led to better concepts
- Initial LIGO proposal included certainty of the need for improvements
- Design for 10x better sensitivity

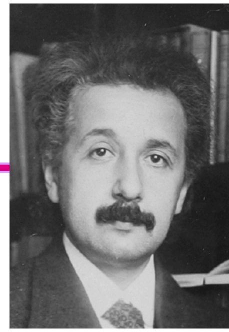
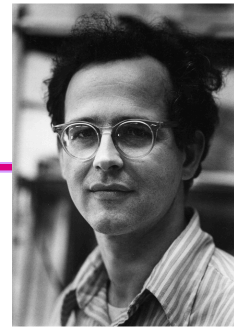
- We measure amplitude, so signal falls as $1/r$
- **1000x more candidates**

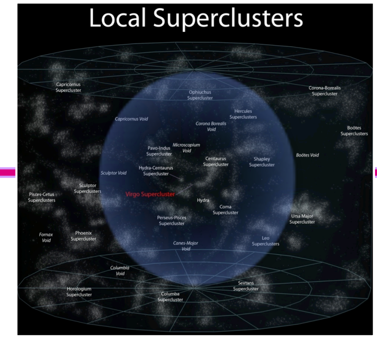


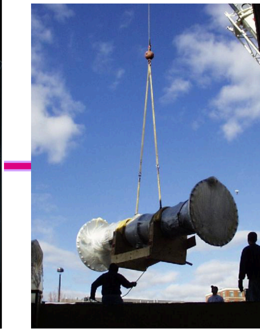
M. Evans

Initial Reach

Advanced Reach





1.3 Billion years after the Black Holes merged..
(and multicellular life started on earth…)

100 years after Einstein predicted gravitational waves…

50 years after Rai Weiss invented the detectors...

20 years after the NSF, MIT, and Caltech Founded LIGO...

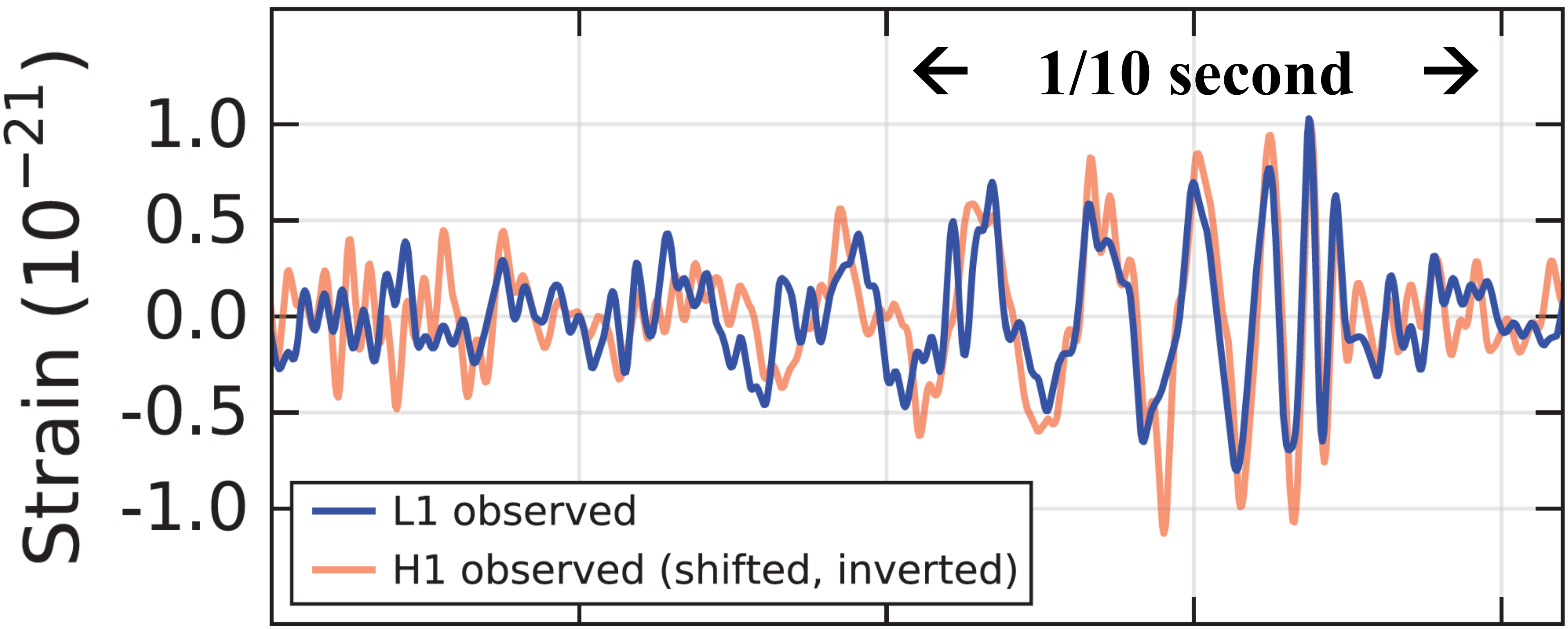
10 years after Advanced LIGO got the ok...

6 months after starting detector tuning...

Two days **after we started observing...**

The first signal

On September 14, 2015 at 09:50:45 UTC

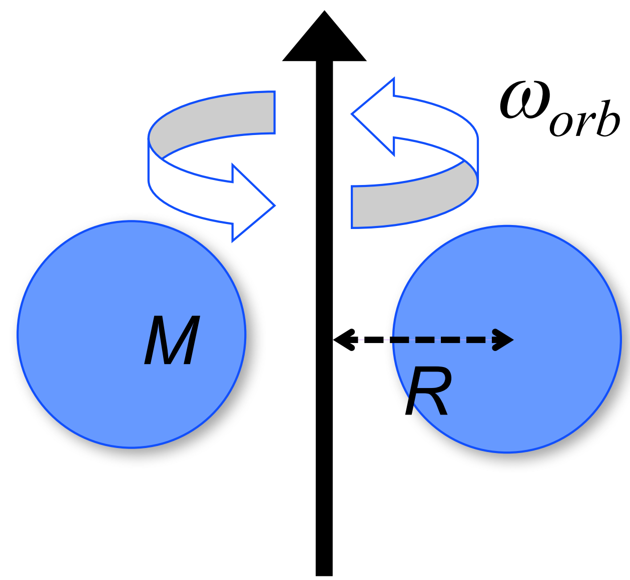


What are Gravitational Waves?

- GWs propagate at the speed of light (according to GR)
- Emitted from rapidly accelerating mass distributions
- Creates a strain h in space

$$h = \frac{\Delta L}{L} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}$$

r = distance from the source to the observer

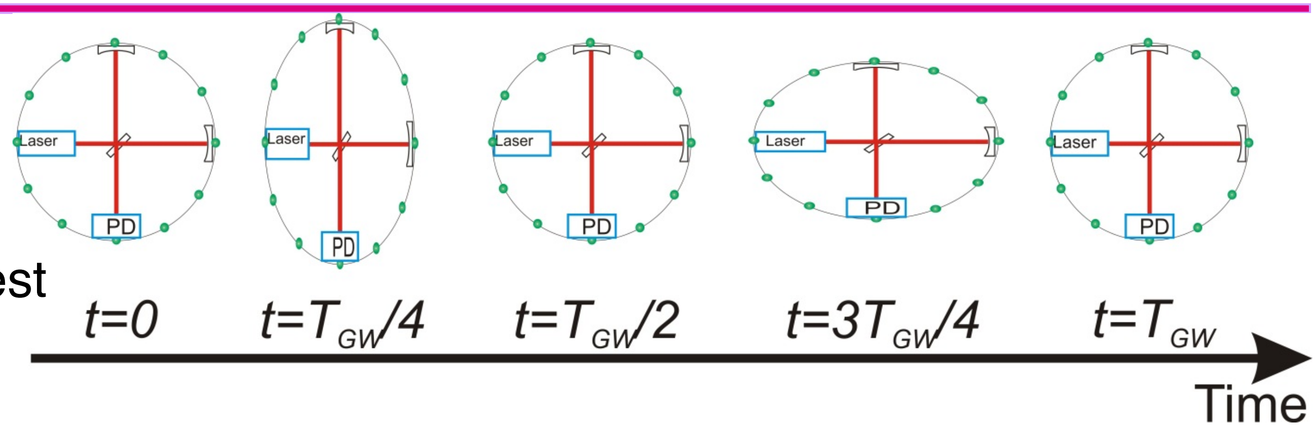


Rotating Dumbbell: $$h \approx \frac{8GMR^2\omega_{orb}^2}{rc^4}$$

- Space is *very* stiff; h is ~10^{-21} for say Neutron Stars in Virgo Cluster
  - …or two ~30-solar-mass Black Holes at 1.2 billion light years...
- Measurable GWs can only be expected from **Stars or Black Holes undergoing incredibly violent accelerations**

What is our measurement technique?

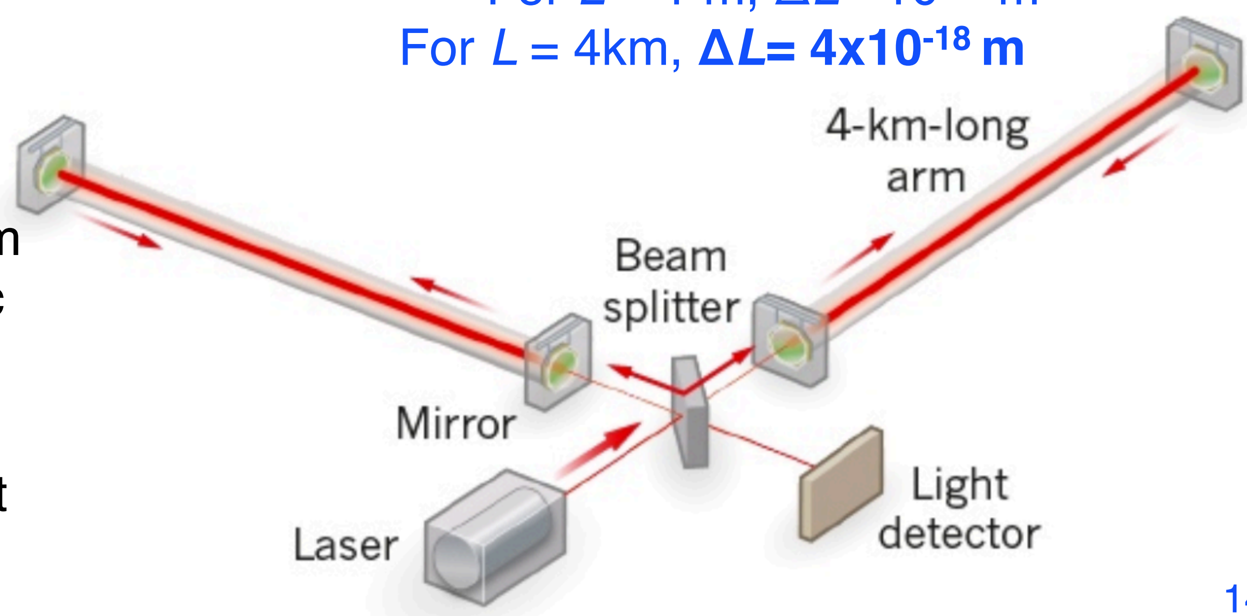
- Enhanced **Michelson interferometers**
- Passing GWs modulate the distance between the end test mass and the beam splitter



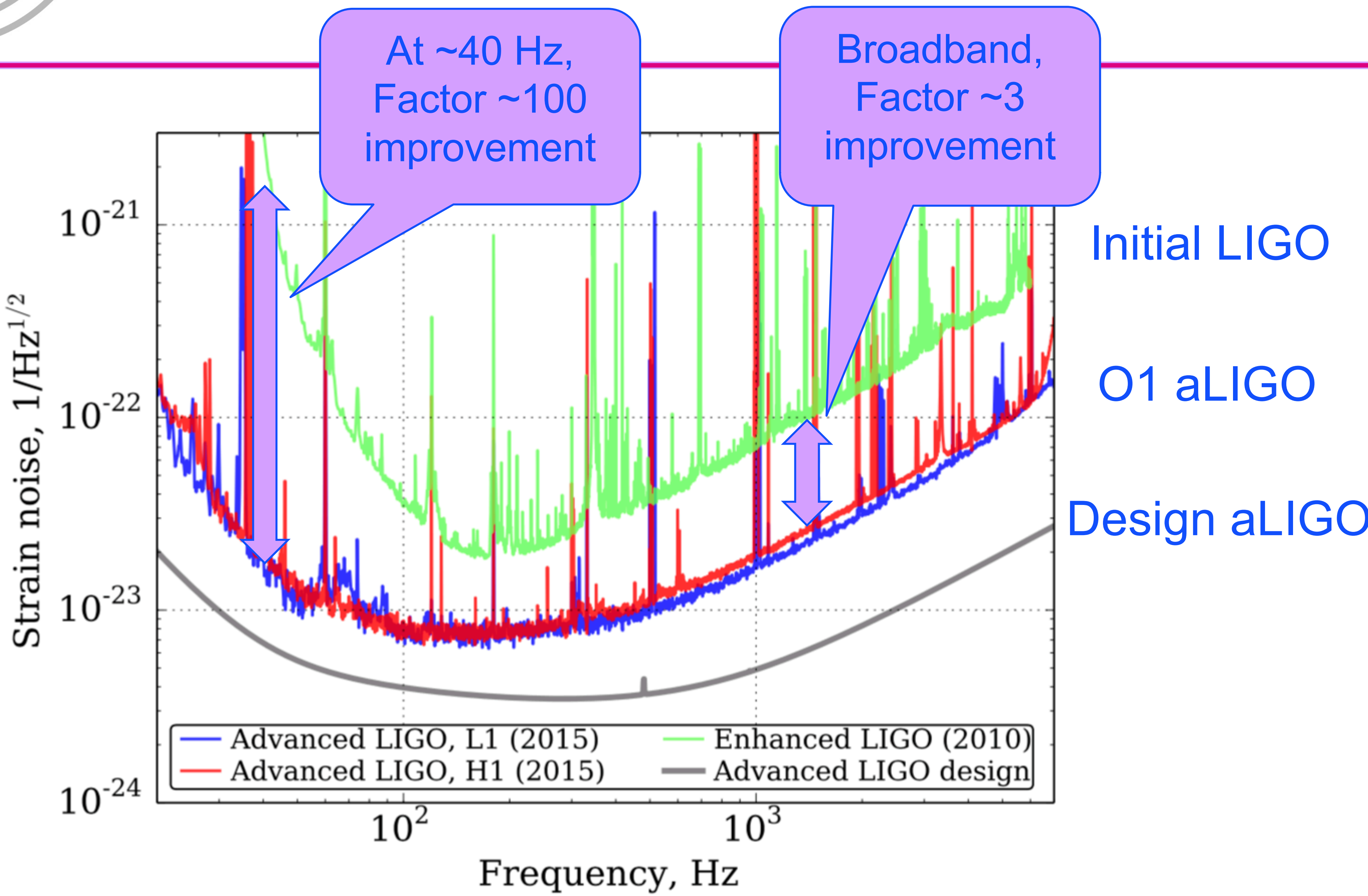
- **Arms are short compared to our GW wavelengths, so longer arms make bigger signals**
  → multi-km installations
- Sensitivity limited by quantum noise, thermal noise, seismic noise
- Einstein's contributions throughout our measurement science!

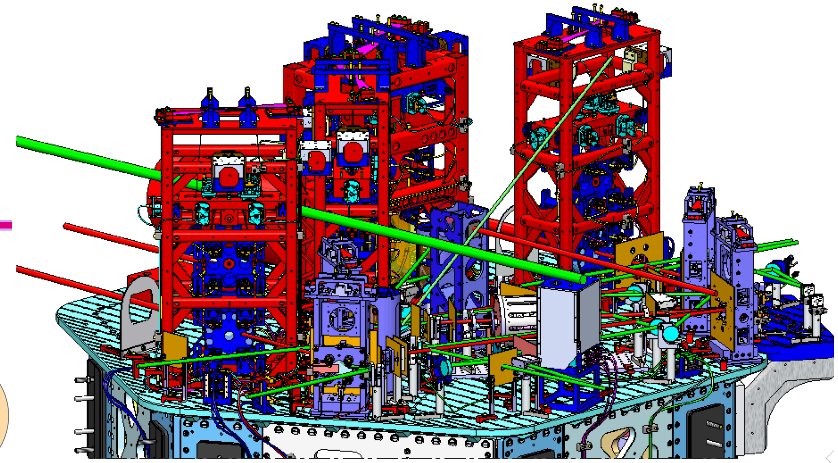
$$h \approx \frac{\Delta L}{L}$$

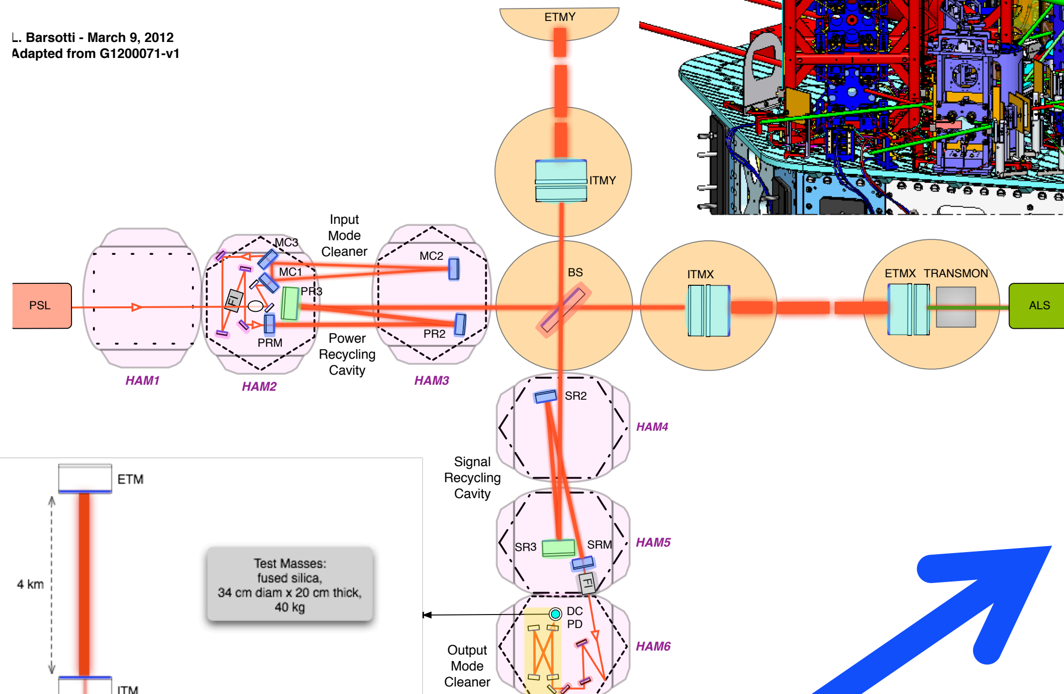
Magnitude of h at Earth:
Largest signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For L = 1 m, $\Delta L = 10^{-21}$ m
For L = 4km, $\mathbf{\Delta L = 4 \times 10^{-18}}$ **m**

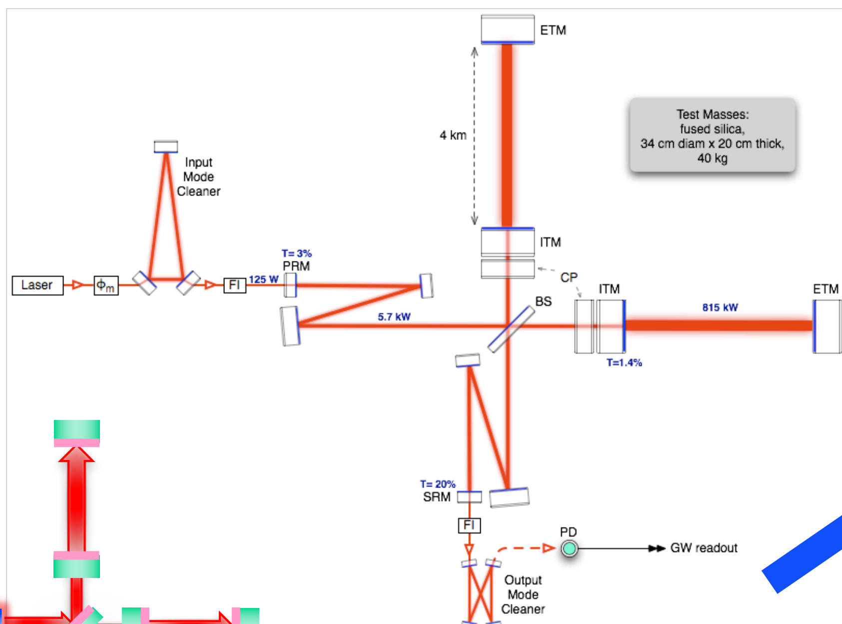


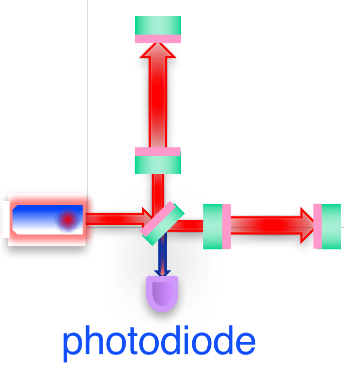
LIGO Sensitivity for first Observing run









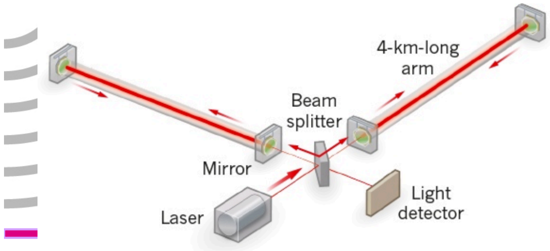


Reality axis

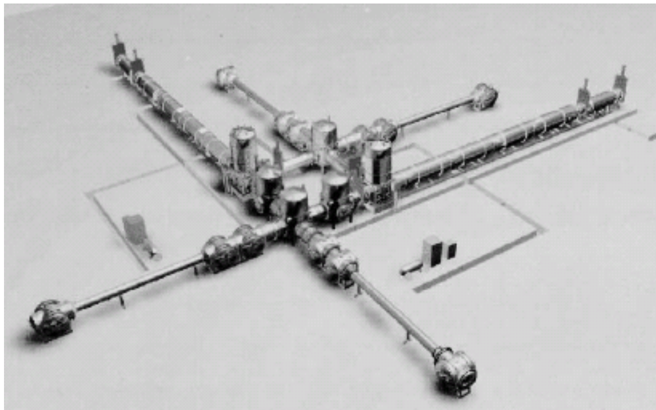
The real instrument is also more complex than a simple Michelson…

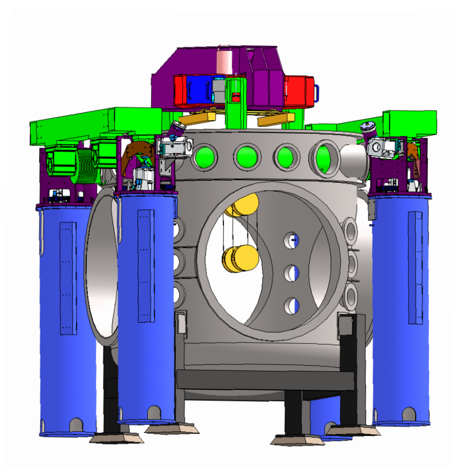
Infrastructure:
4km Beam Tubes

- Light must travel in an excellent vacuum
  - » Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs!
  - » 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters' bullets and the stray car
- Tube is straight to a fraction of a cm…not like the earth's curved surface



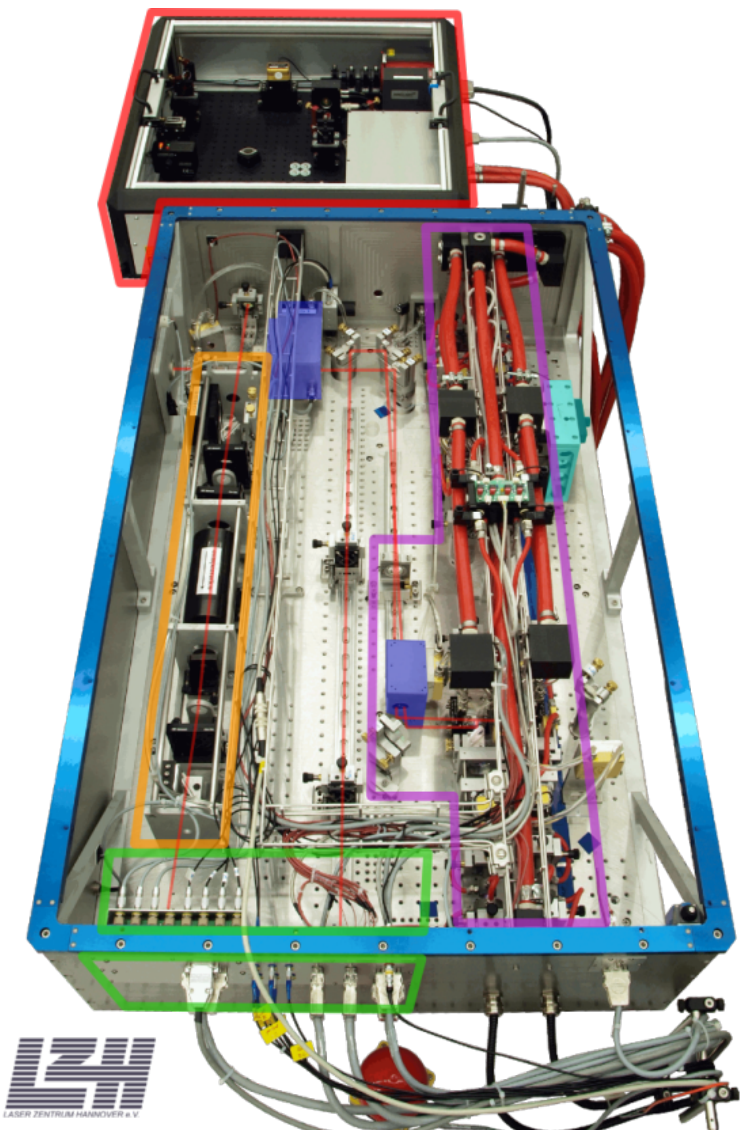
LIGO Vacuum Equipment –
designed for several generations of instruments

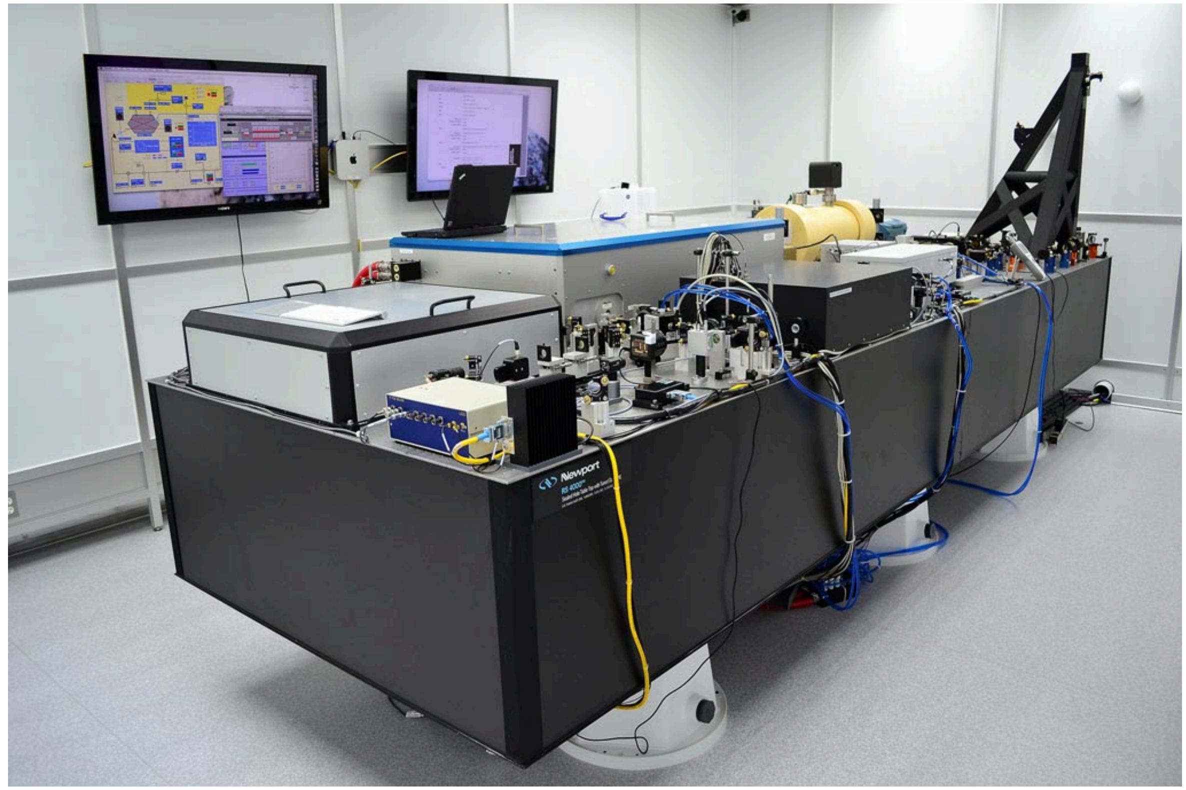




200W CW Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute

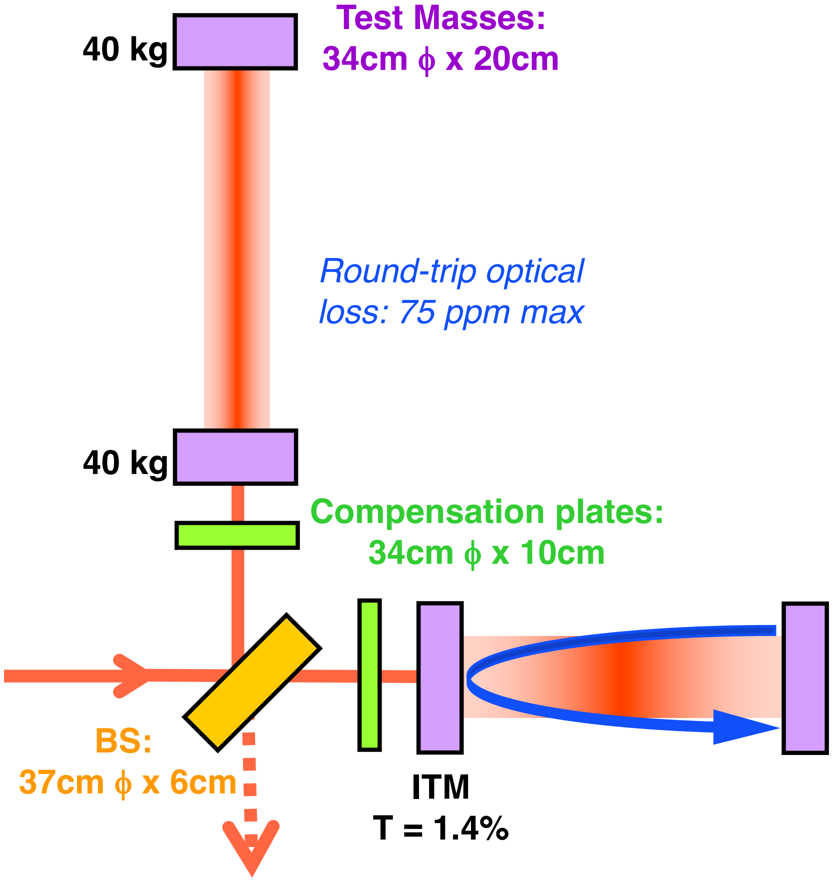


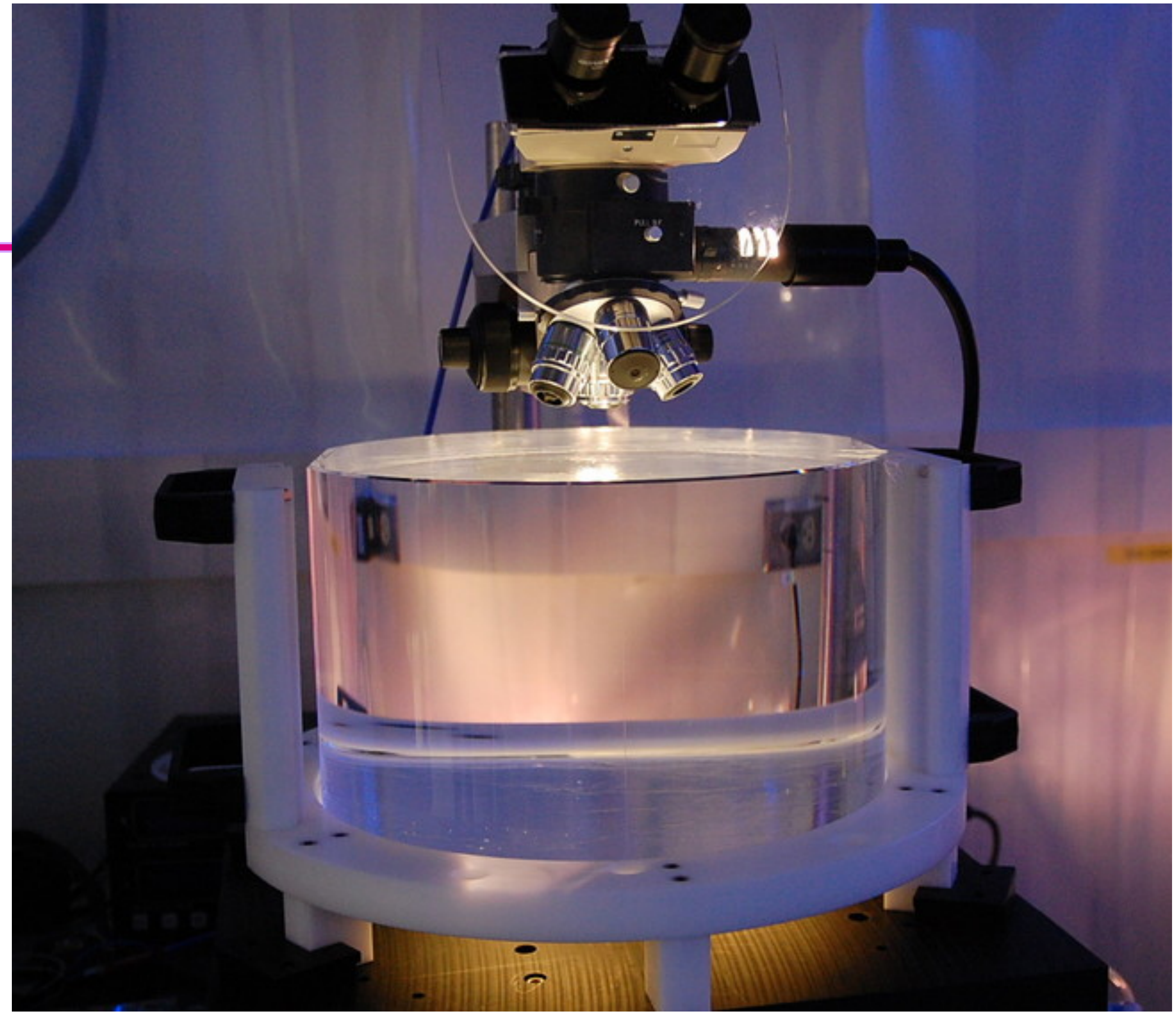


- Stabilized in power and frequency – using techniques developed for time references
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
- Delivers the required shot-noise limited fringe resolution

Test Masses

- Requires the state of the art in substrates and polishing
- Pushes the art for coating!
- Sum-nm flatness over 300mm



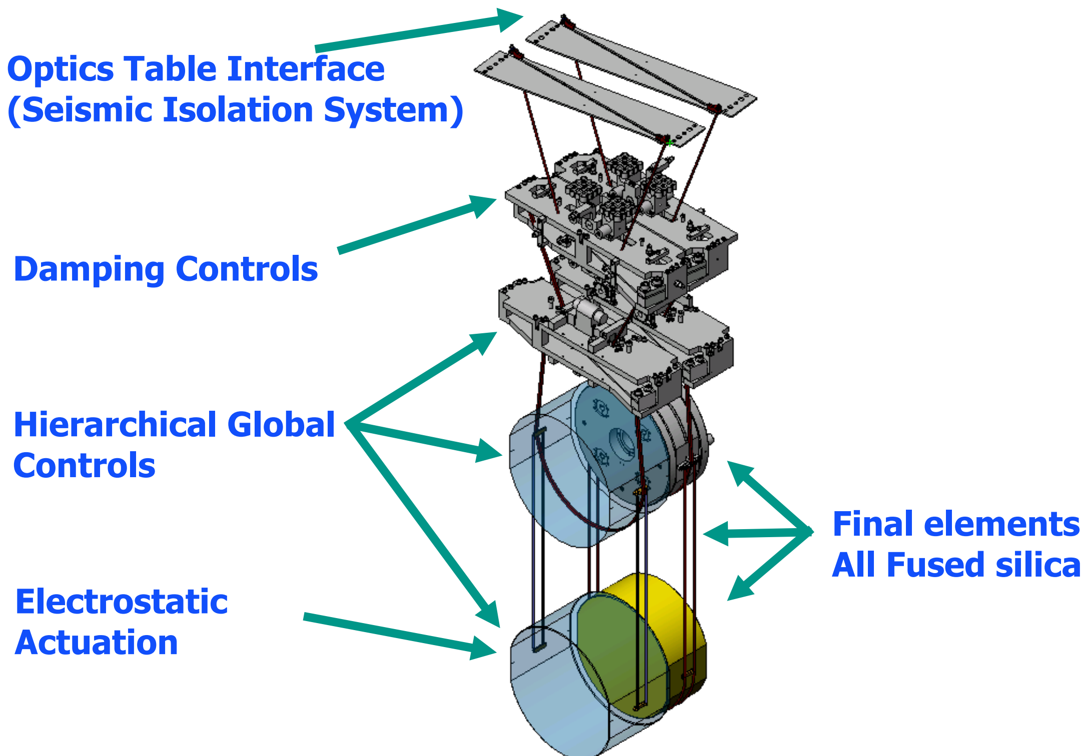


- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and **coating thermal noise,** high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Test Mass Quadruple Pendulum suspension

designed jointly by the UK (led by Glasgow) and LIGO lab,
with capital contribution funded by PPARC/STFC

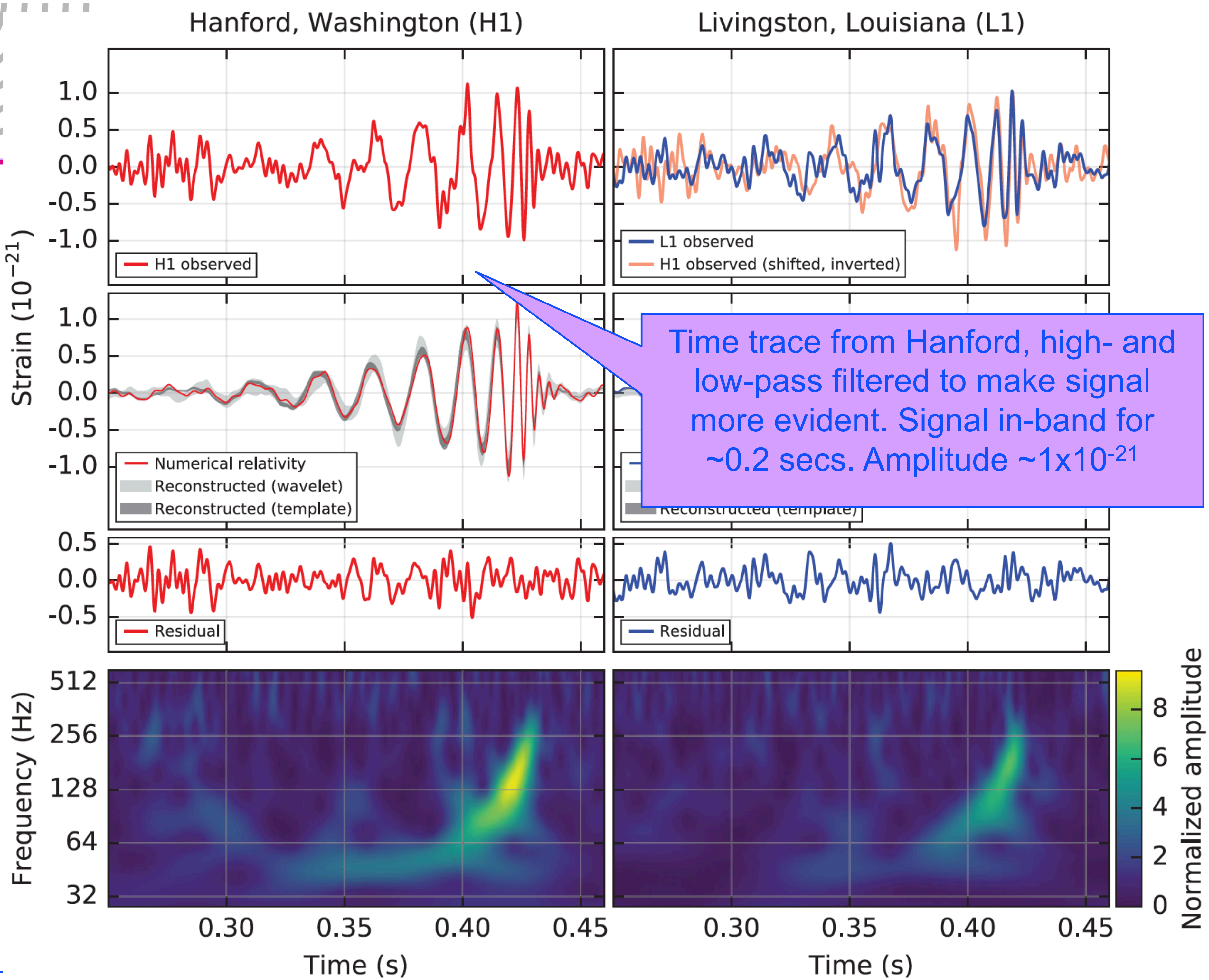
- Quadruple pendulum suspensions for the main optics; second 'reaction' mass to give quiet point from which to push
- Create quasi-monolithic pendulums using GPB star-tracking telescope techniques; Fused silica fibers to suspend 40 kg test mass
  - » VERY Low thermal noise!



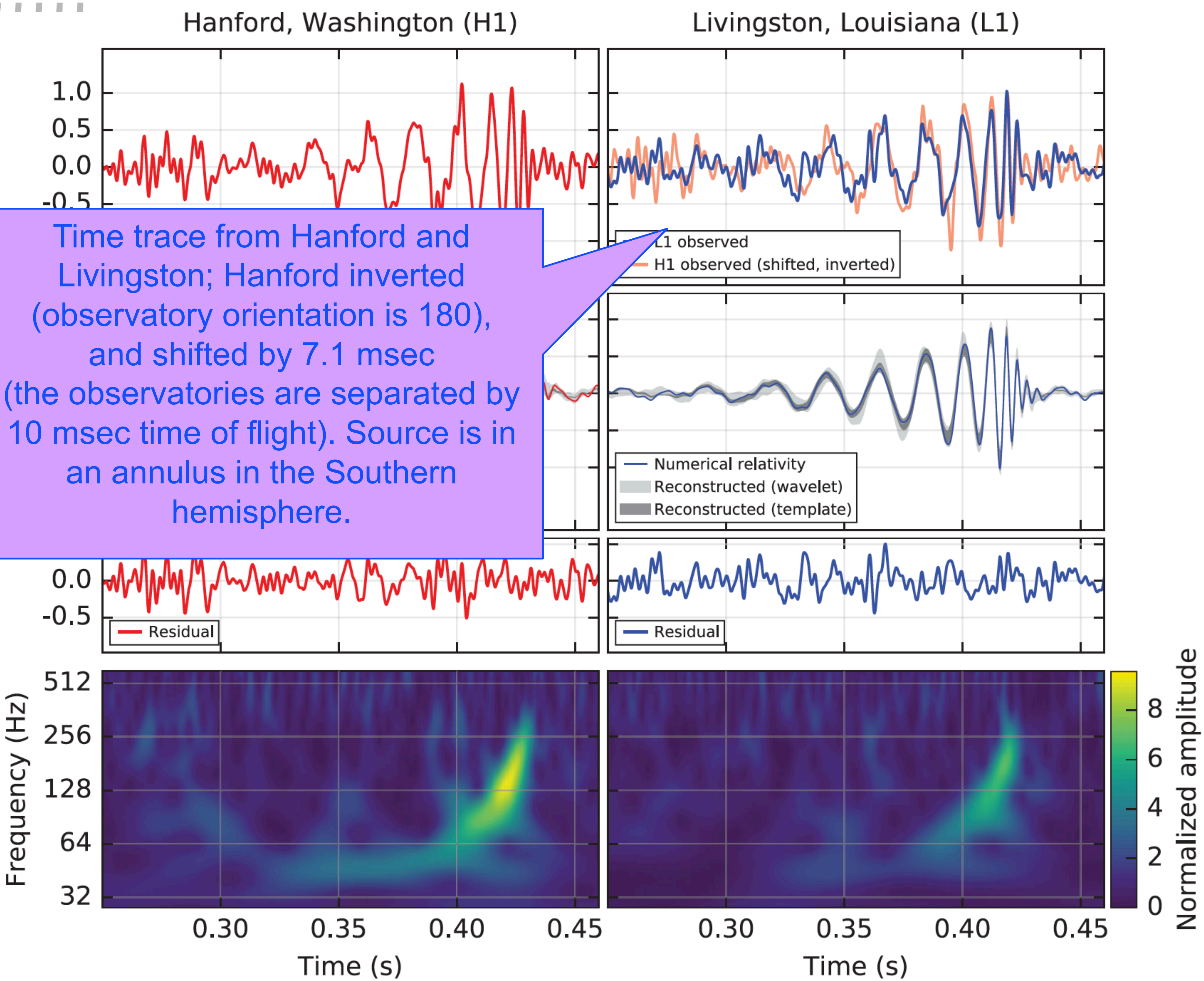
So, that's the LIGO instrument.

How about the detection?

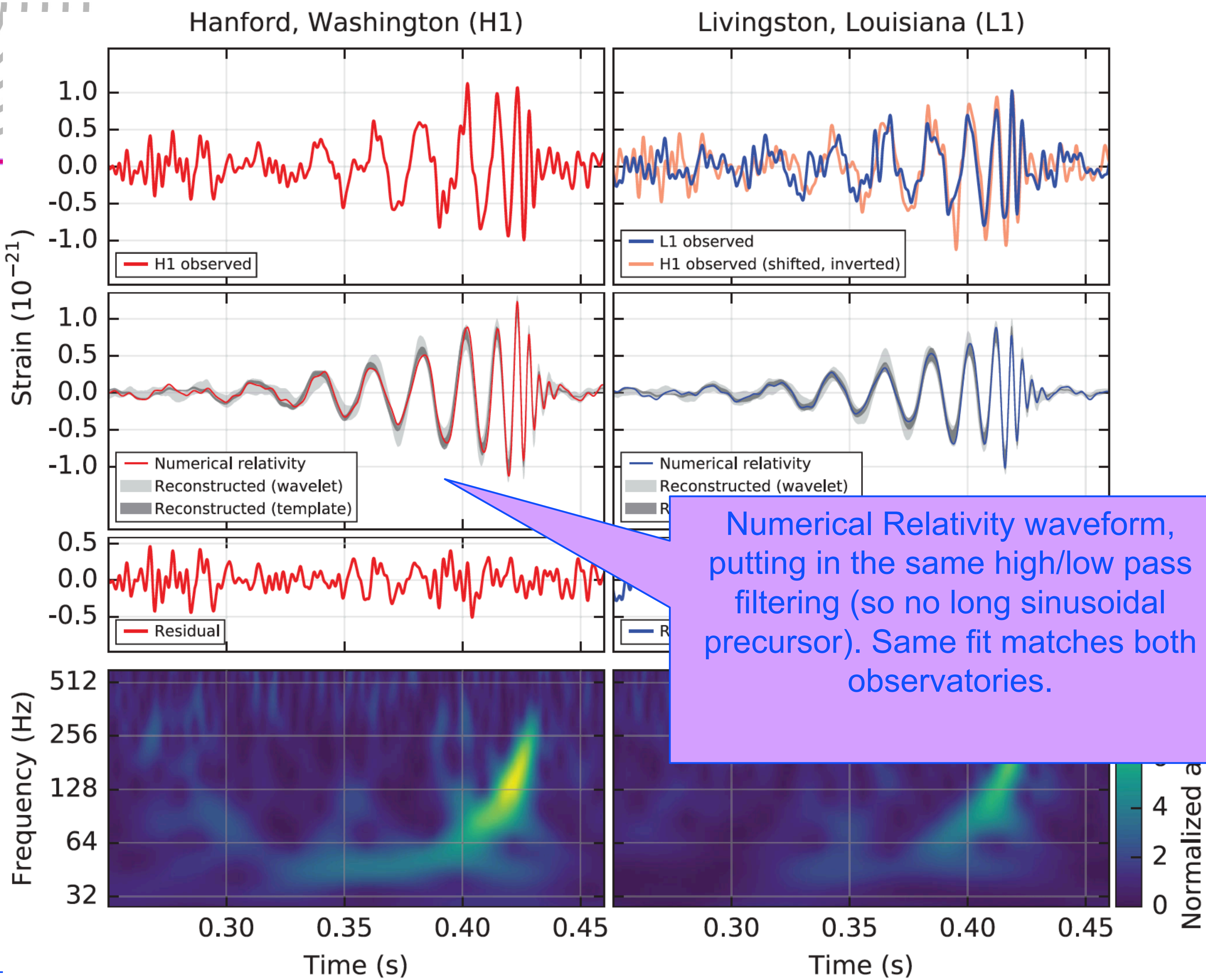
What did we learn from our record of $h(t)$?



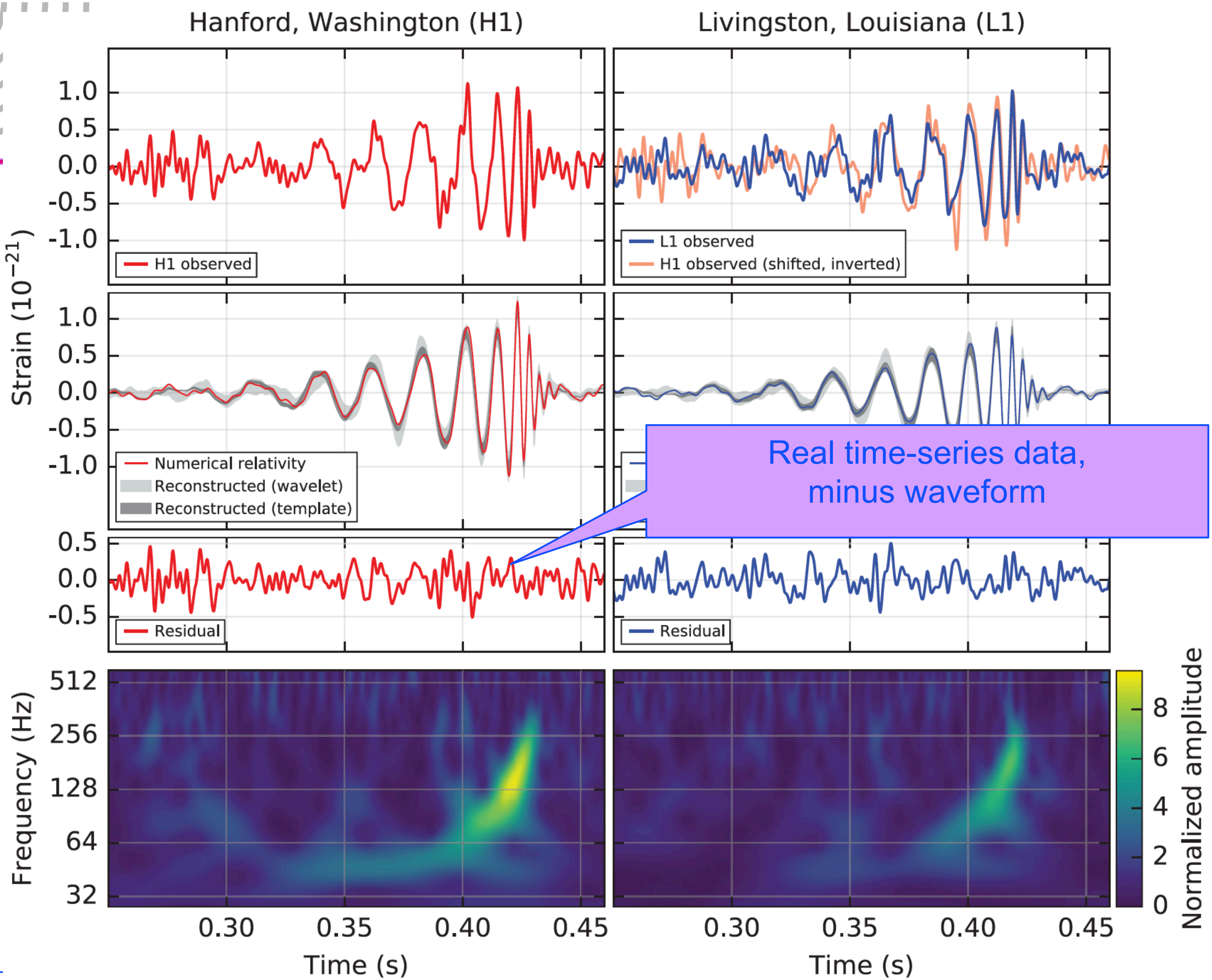
Time trace from Hanford, high- and low-pass filtered to make signal more evident. Signal in-band for ~0.2 secs. Amplitude ~1×10^{-21}

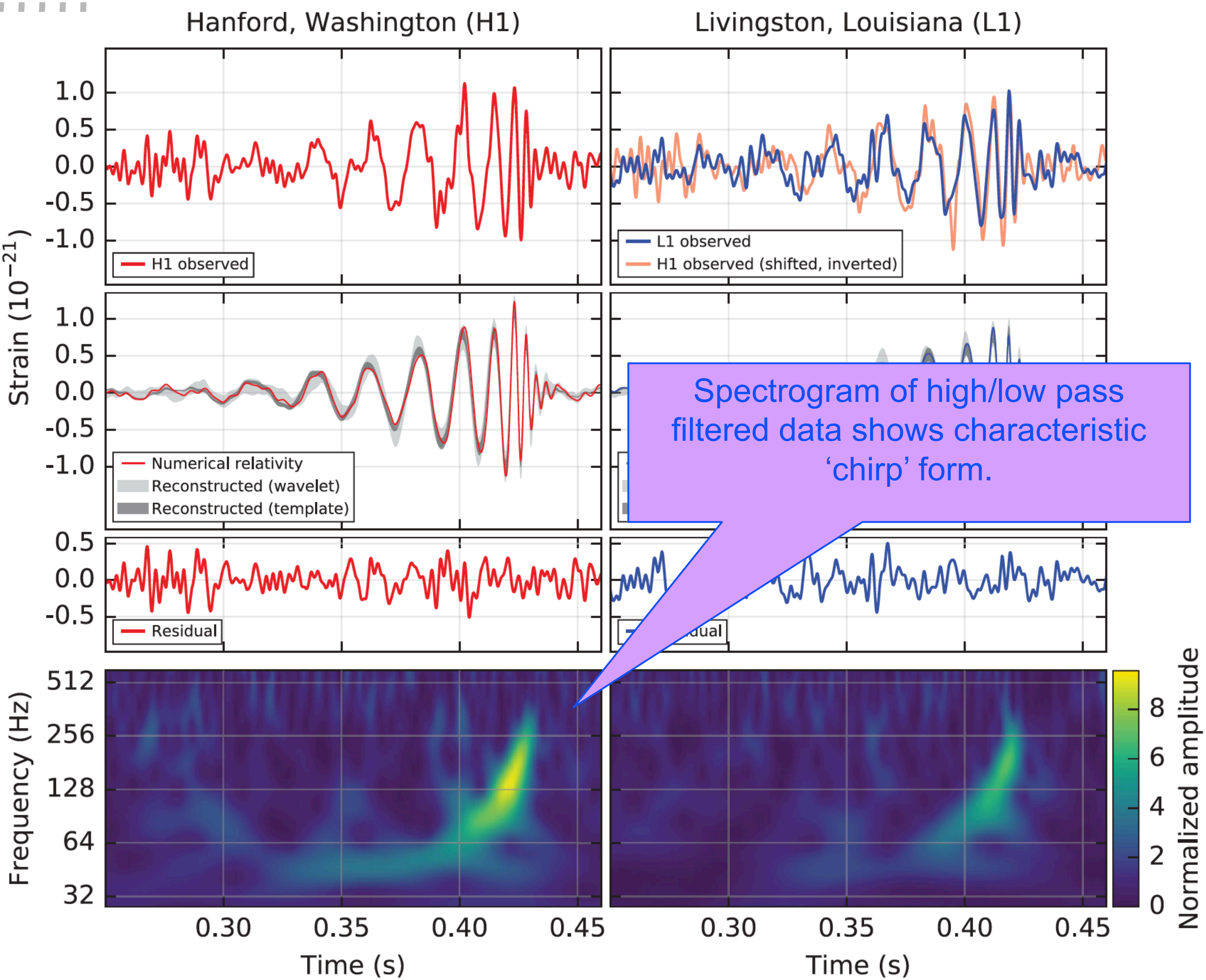


Time trace from Hanford and Livingston; Hanford inverted (observatory orientation is 180), and shifted by 7.1 msec (the observatories are separated by 10 msec time of flight). Source is in an annulus in the Southern hemisphere.

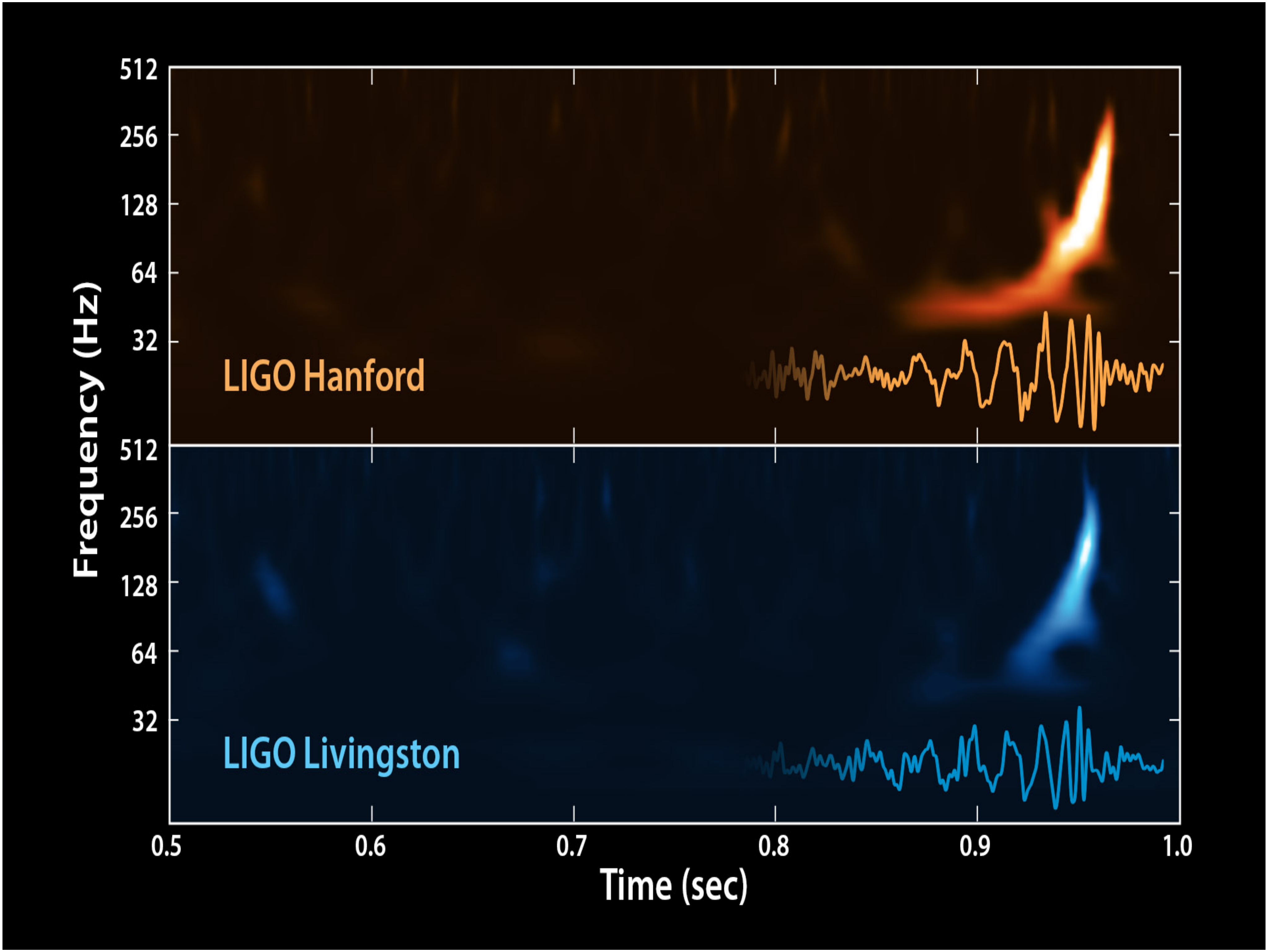


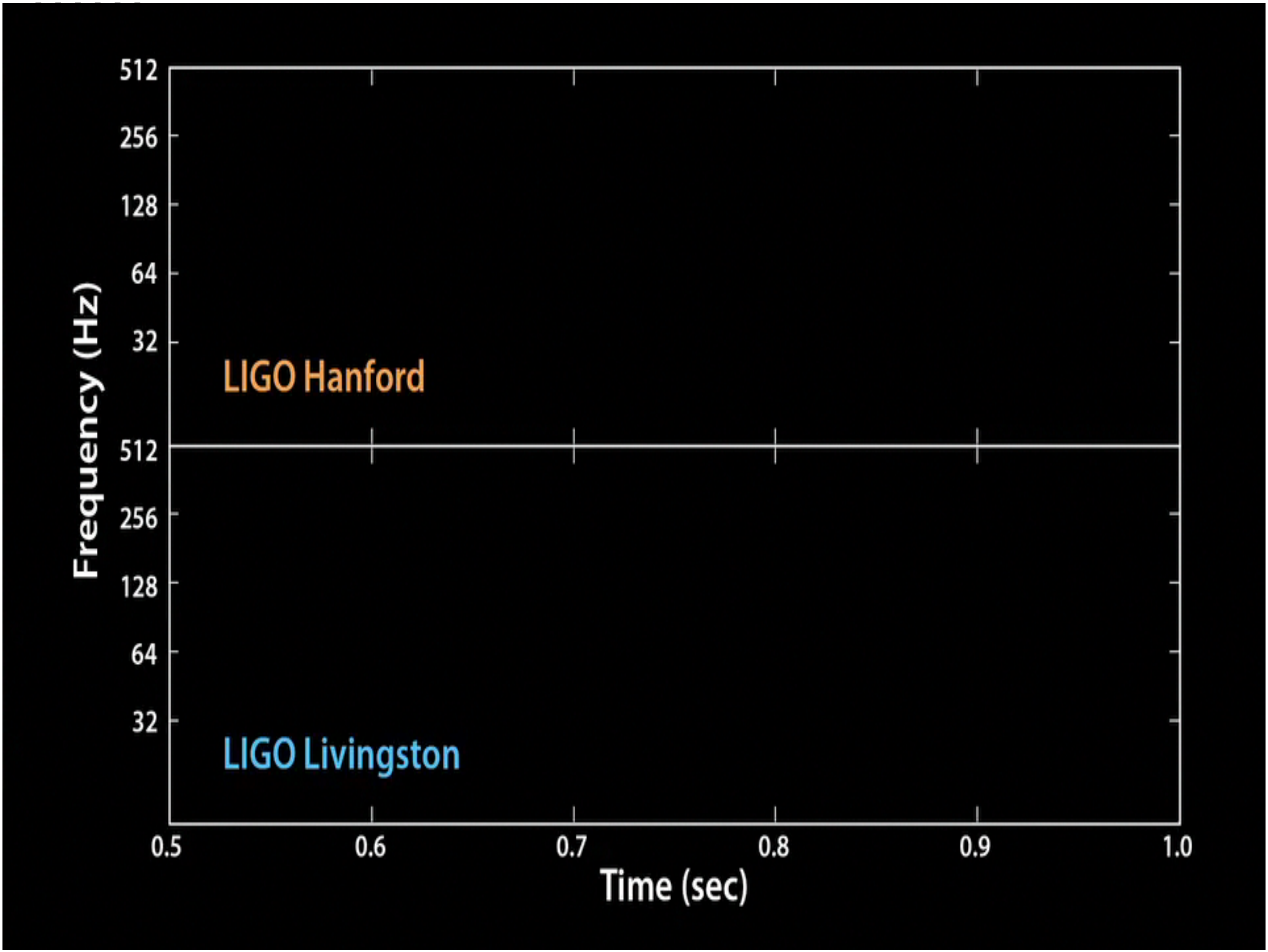
Numerical Relativity waveform, putting in the same high/low pass filtering (so no long sinusoidal precursor). Same fit matches both observatories.


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Residual
Real time-series data, minus waveform
Frequency (Hz)
Time (s)
Time (s)
Normalized amplitude



Spectrogram of high/low pass filtered data shows characteristic 'chirp' form.


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)


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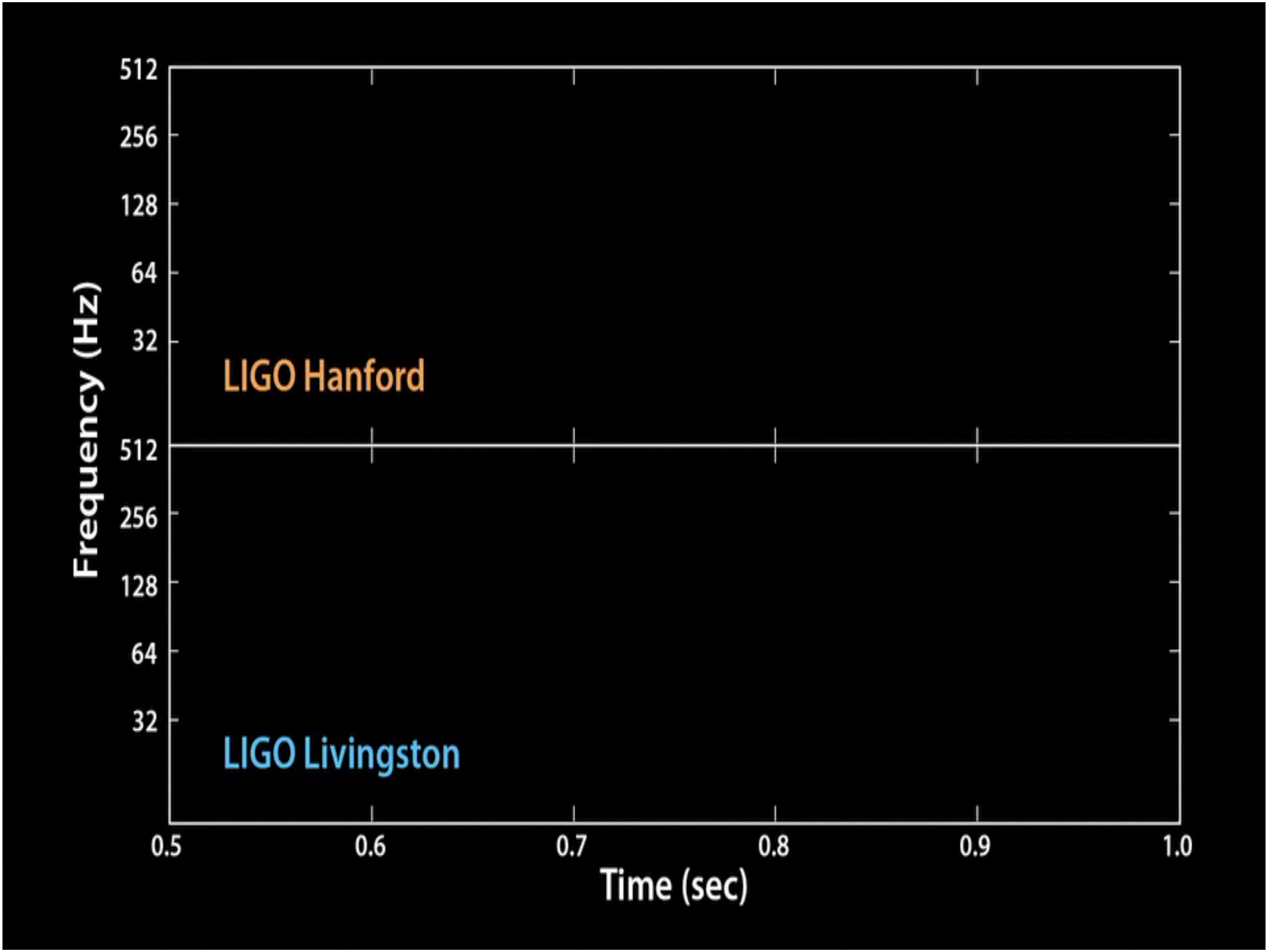
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



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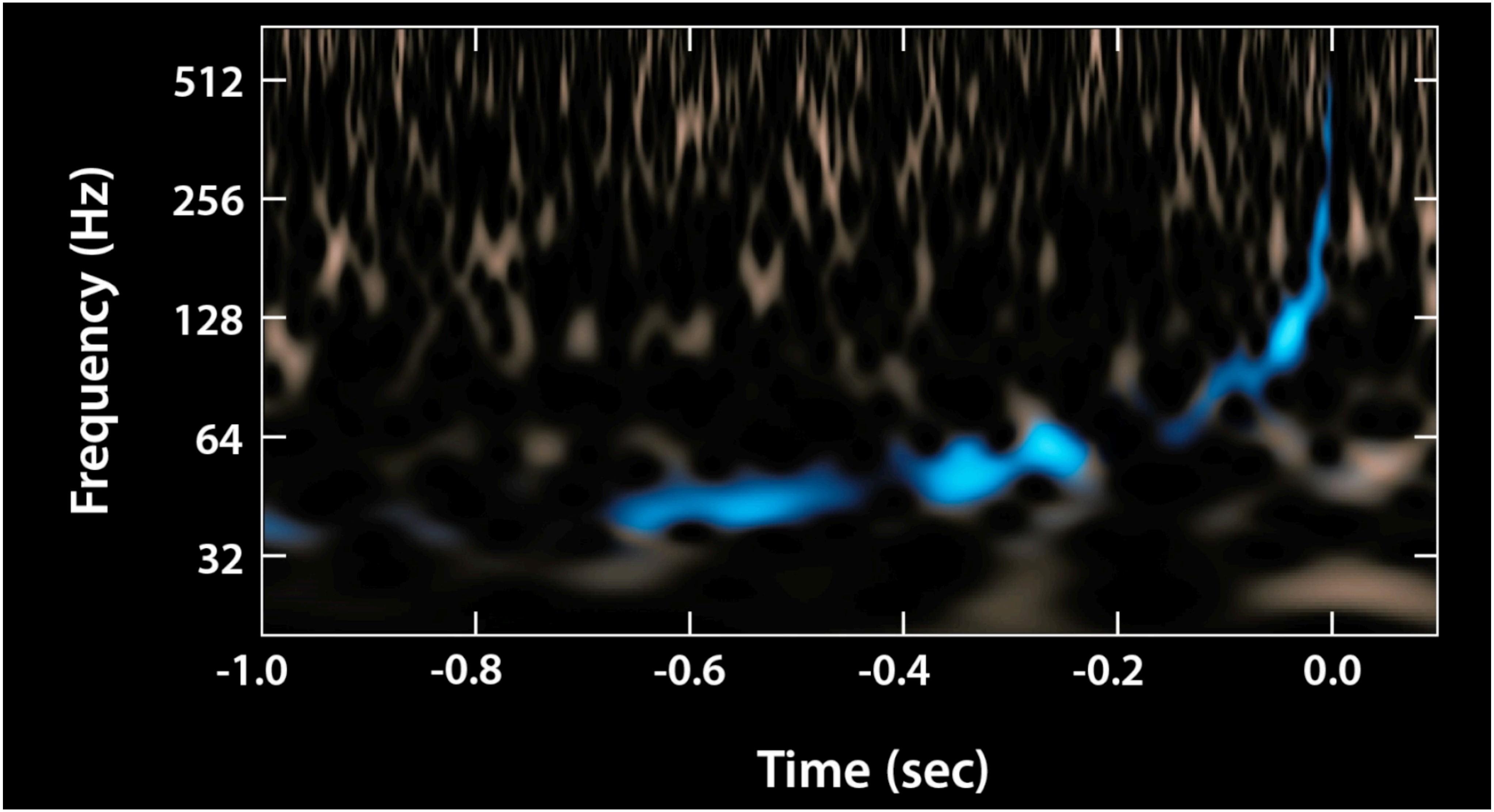
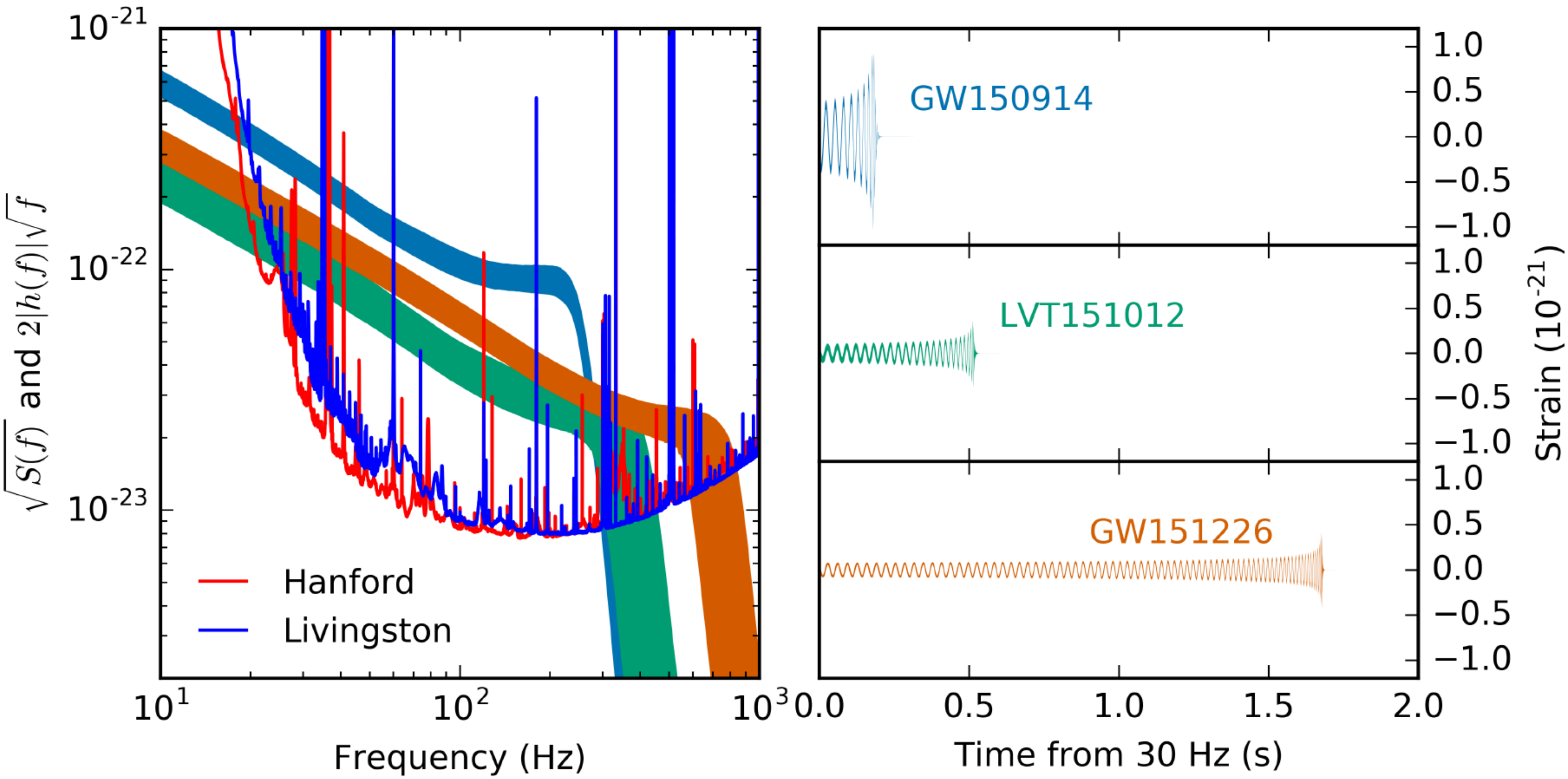
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

One event…was it real?

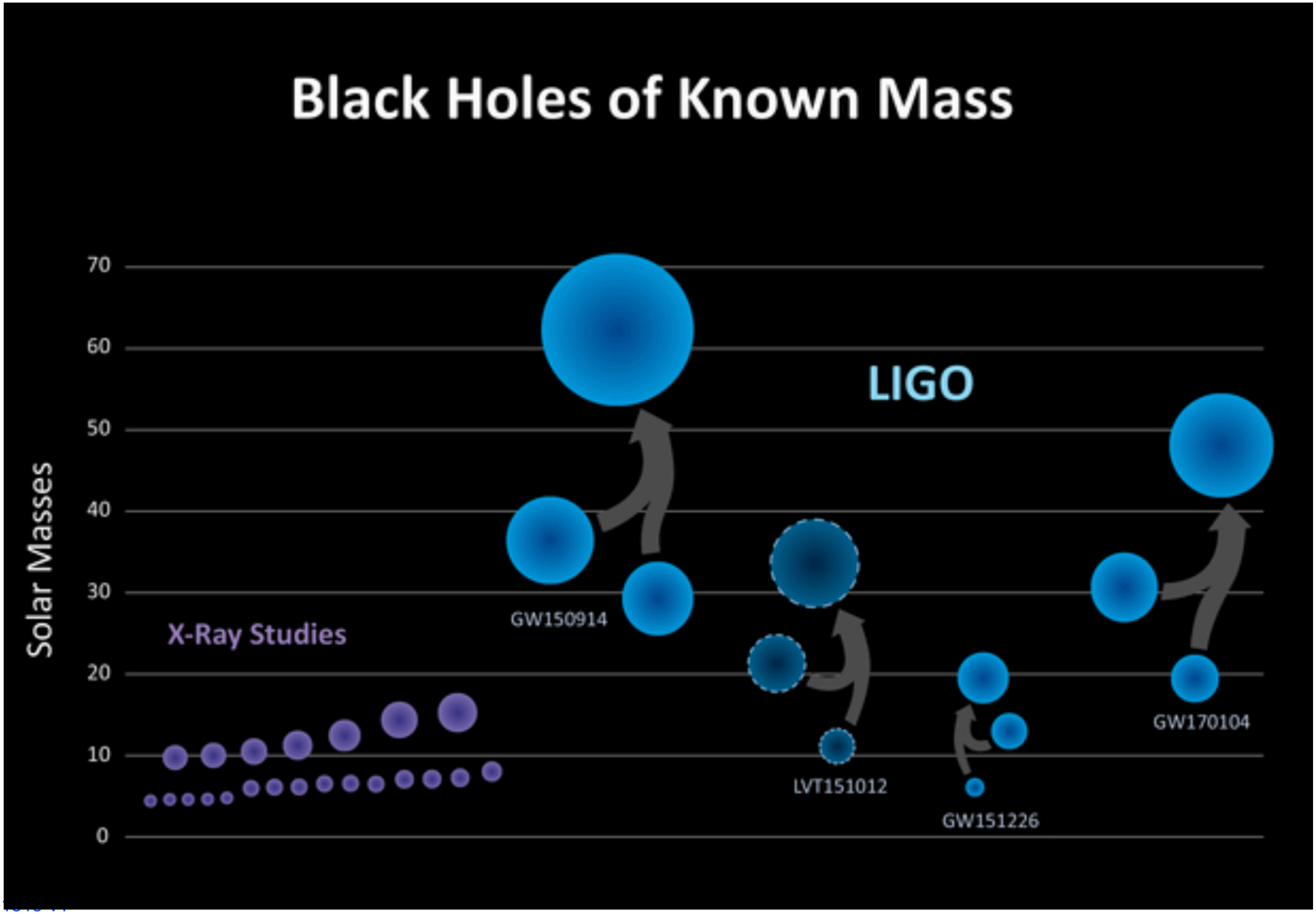
Our second signal, 26 December 2015 – the SNR we *thought* we would be working with



A nice way to look at the signals from O1



And then there were 3! (+1)
4 January 2017

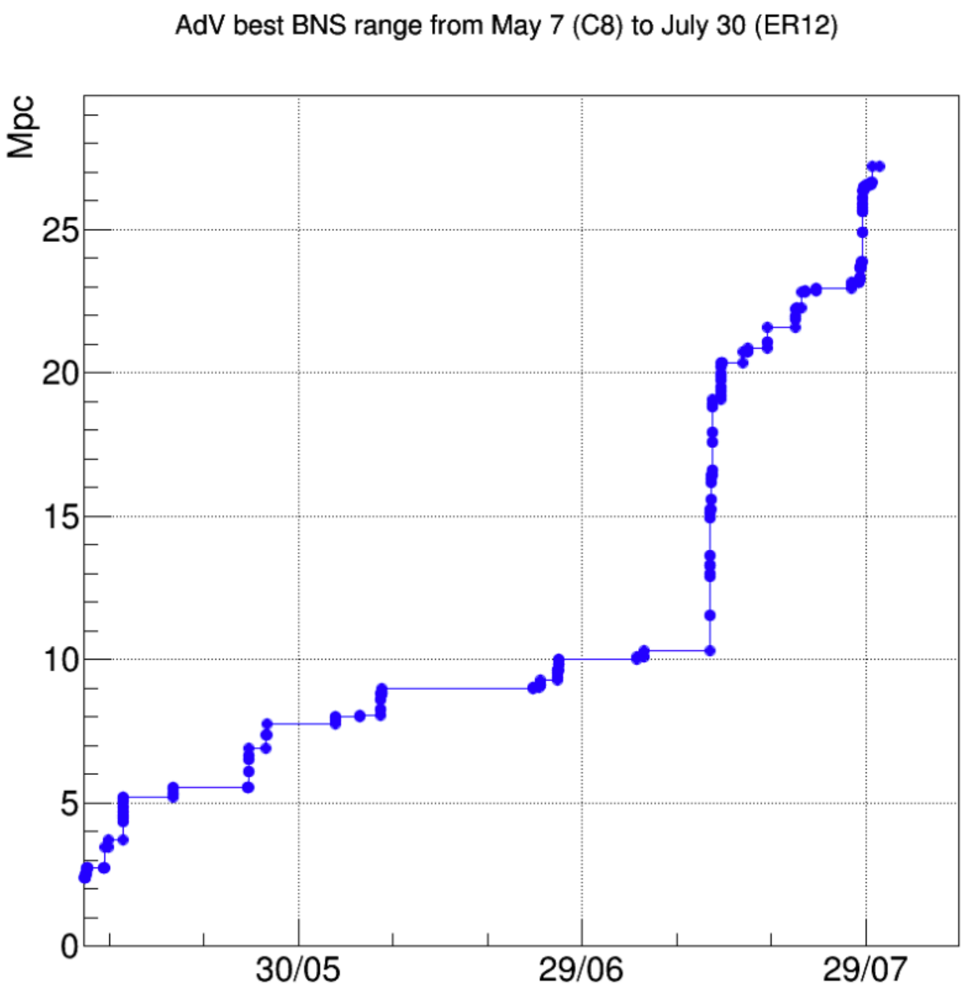


Then…. Virgo joins O2

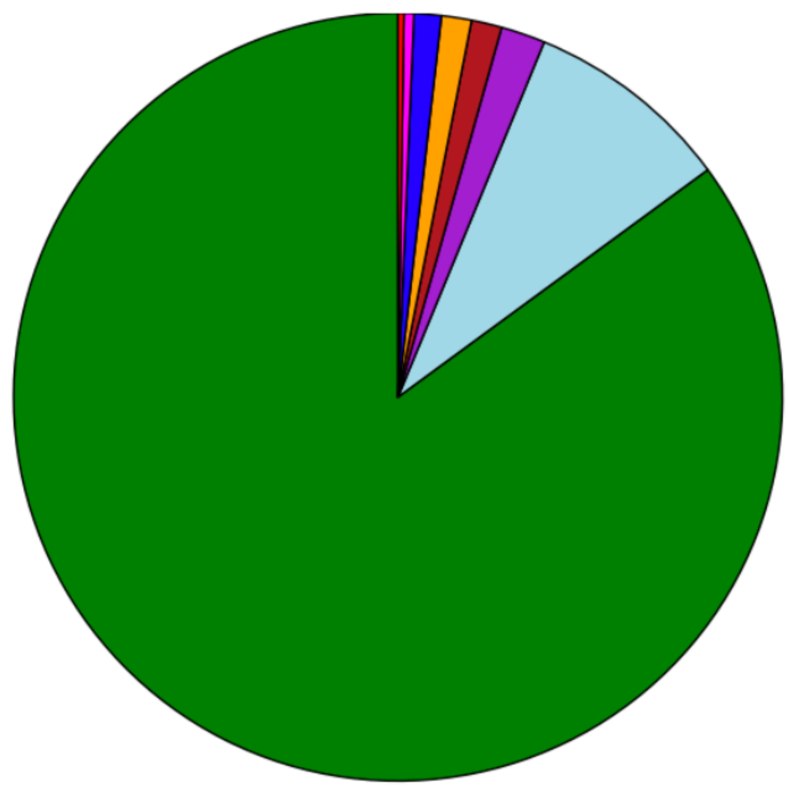
- The EGO Observatory in Cascina, Italy, near Pisa
- Advanced Virgo joined the O2 Observing run on 1 August 2017

Virgo Commissioning and Running

Very rapid progress to a good sensitivity



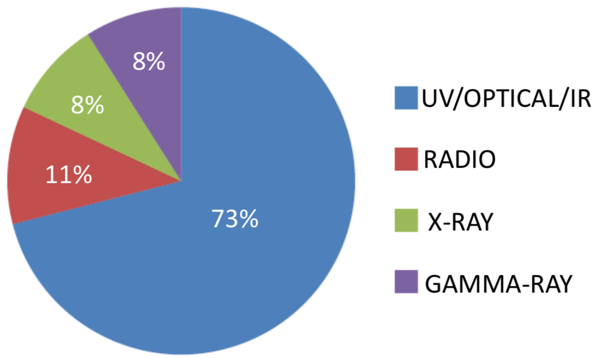
Very high uptime



Virgo-LIGO O2 Run now complete

- **Triple-interferometer observing from 1 August to 25 August**
- Some promising gravitational-wave candidates have been identified in data from both LIGO and Virgo during our preliminary analysis
  - » We have shared what we currently know with astronomical observing partners.
- We are working hard to assure that the candidates are valid gravitational-wave events
  - » It will require time to establish the level of confidence needed to bring any results to the scientific community and the greater public
- **We will let you know as soon we have information ready to share**

Working toward multi-messenger astronomy with gravitational waves



- About 95 Partners from 19 countries
- ~150 instruments covering the full spectrum from radio to very high-energy gamma-rays
- No EM anticipated for black holes
- Really profits from 3rd detector….

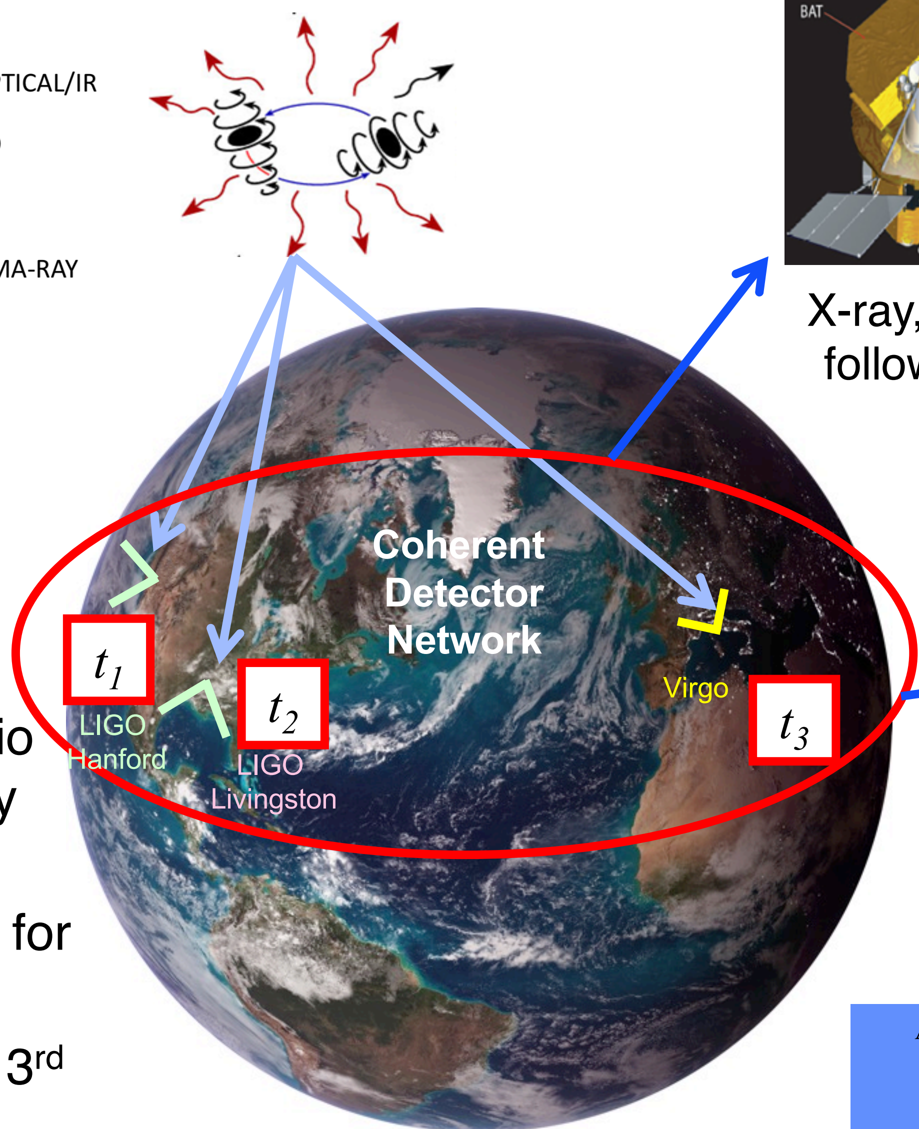
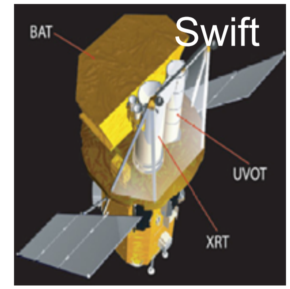


Image: http://earthobservatory.nasa.gov/

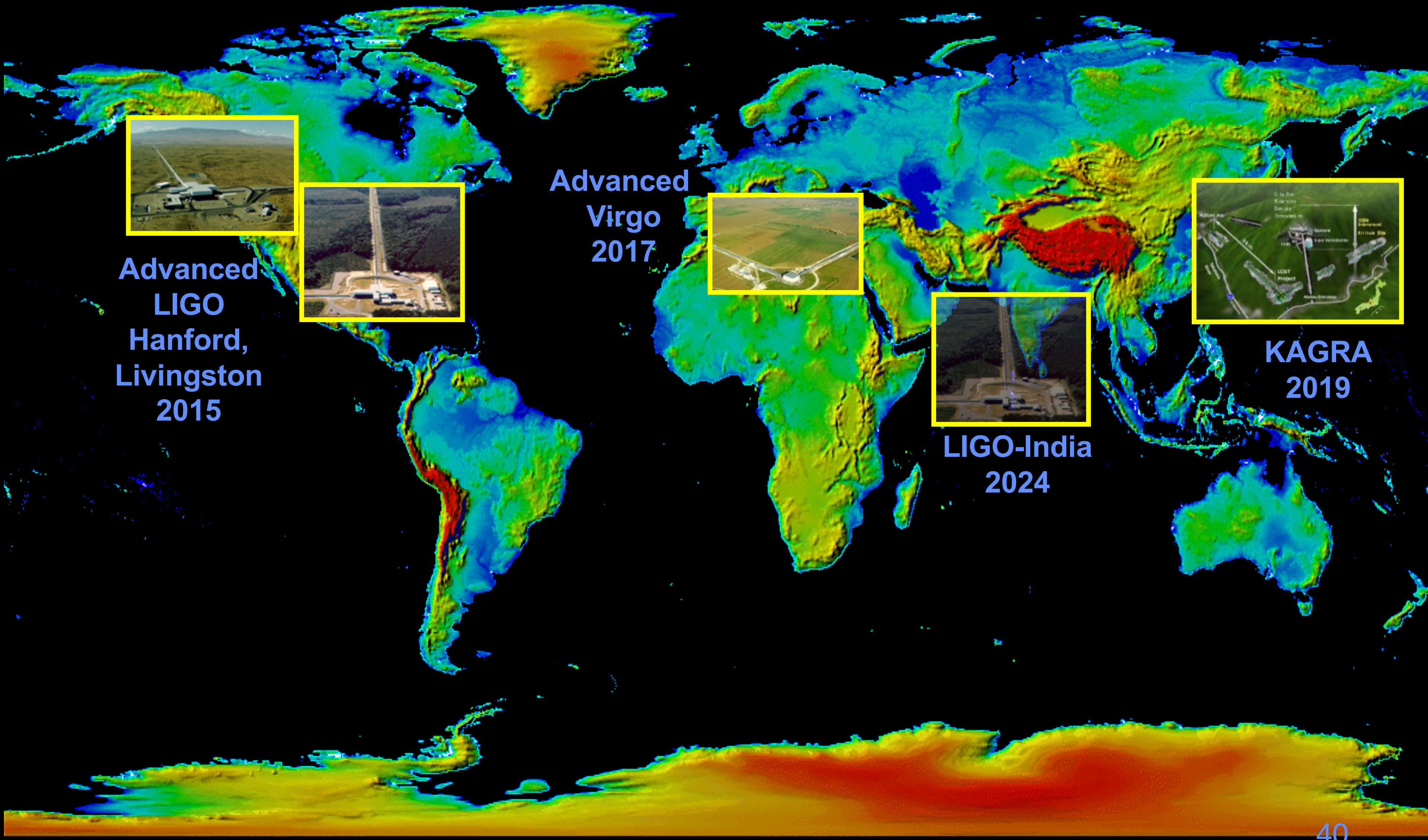


X-ray, γ-ray follow-up

Optical follow-up

Abadie, et al, (LSC & Virgo Collaborations) Astron. Astrophys. 541 (2012) A155.
Nissanke, Kalsiwal, Georgieva, Astrophysical J. 767 (2013) 124.
Singer, Price, et al., Astrophysical J., 795 (2014) 105.

The advanced GW detector network



Contrast of Electromagnetic vs. Gravitational Waves

- **Visible, IR, Xray**
  - High spatial resolution
  - Relatively small masses radiating (atoms!)
  - Exterior surface of astronomical objects
  - Masked and scattered by intervening matter
  - $1/r^2$ fall-off

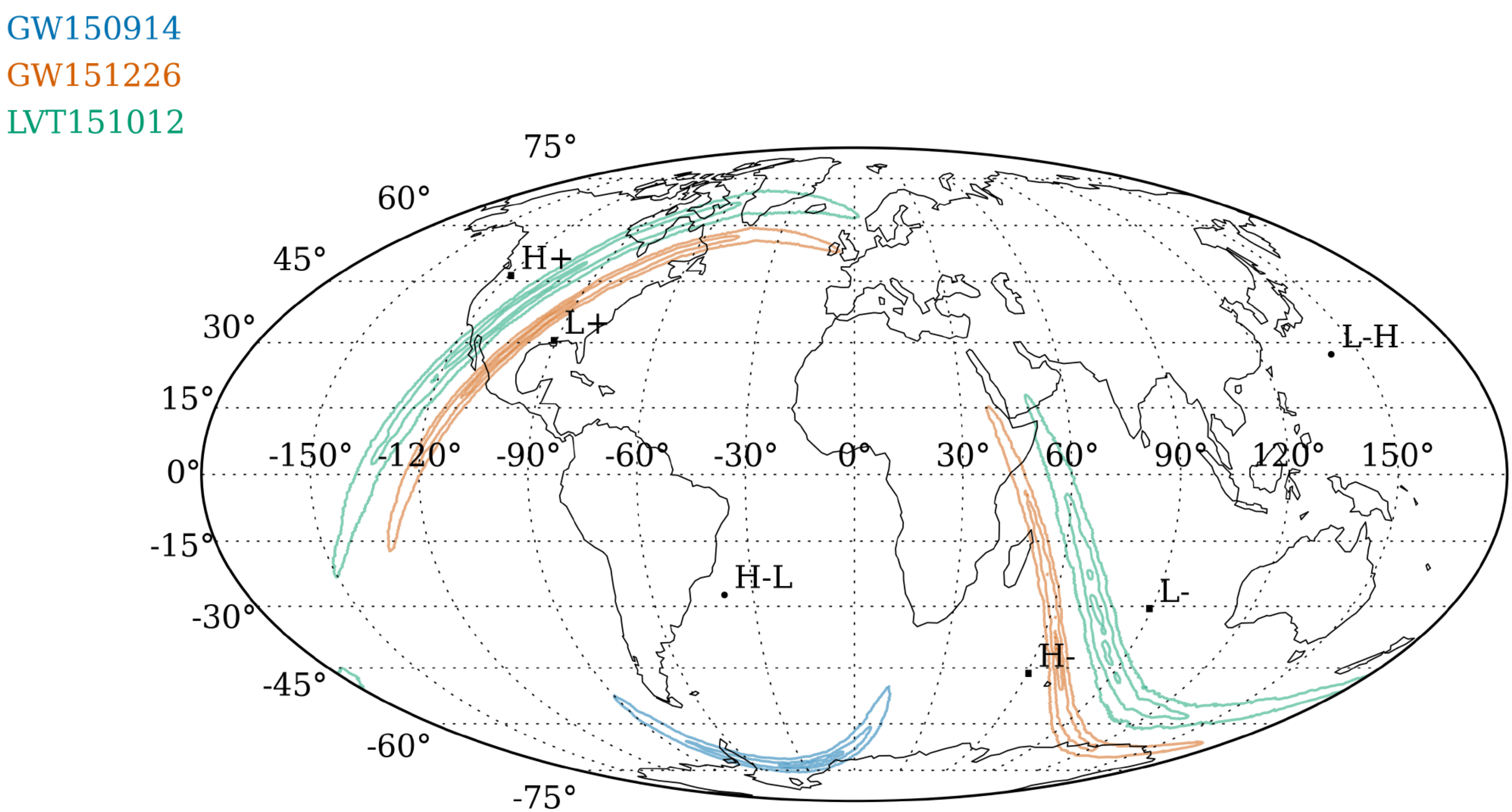
- **Gravitational waves:**
  - Low spatial resolution
  - Coherent motion of Huge masses
  - Deep interior of objects – where the mass is
  - No masking or scattering
  - $1/r$ fall-off

Wonderfully complementary information

What does the near-term future hold?

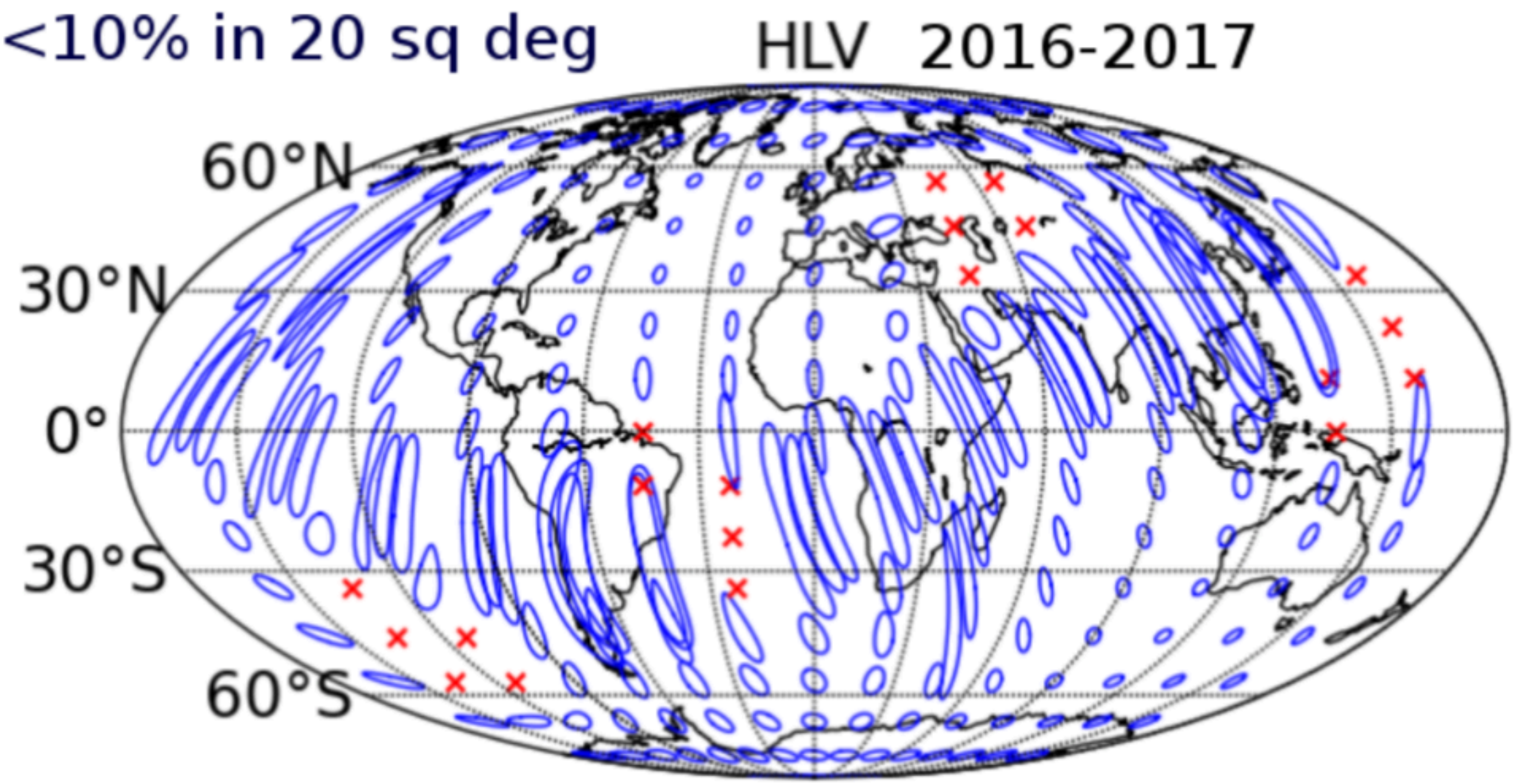
LIGO First Detection Sensitivity/configuration:

2 detectors, 1/3 goal sensitivity
~3 signals in 4 months of observation



2017 Sensitivity/configuration:

3 detectors (Virgo joined 1 August), ***predict***
~1-2 signals per month of observation



And then a year break between O2 and O3 to bring the instruments to better sensitivity

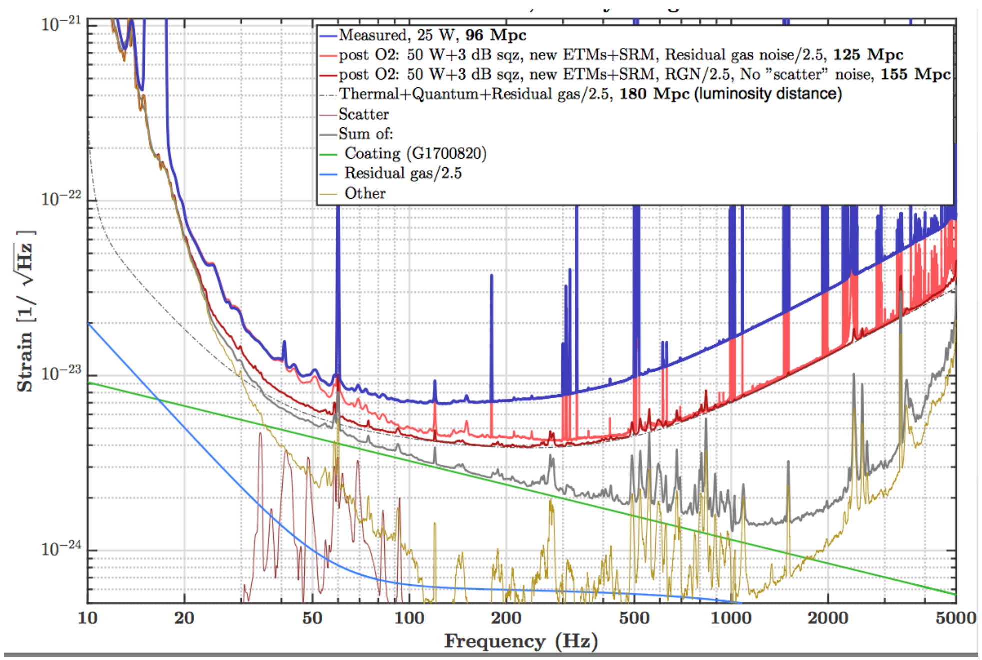
Virgo:

- Monolithic suspensions
- Vacuum upgrade for dust protection
- High power laser
- Squeezing
- Newtonian noise test installation

LIGO:

- Scattered light mitigation
- High power laser
- Optics replacements
- Squeezing

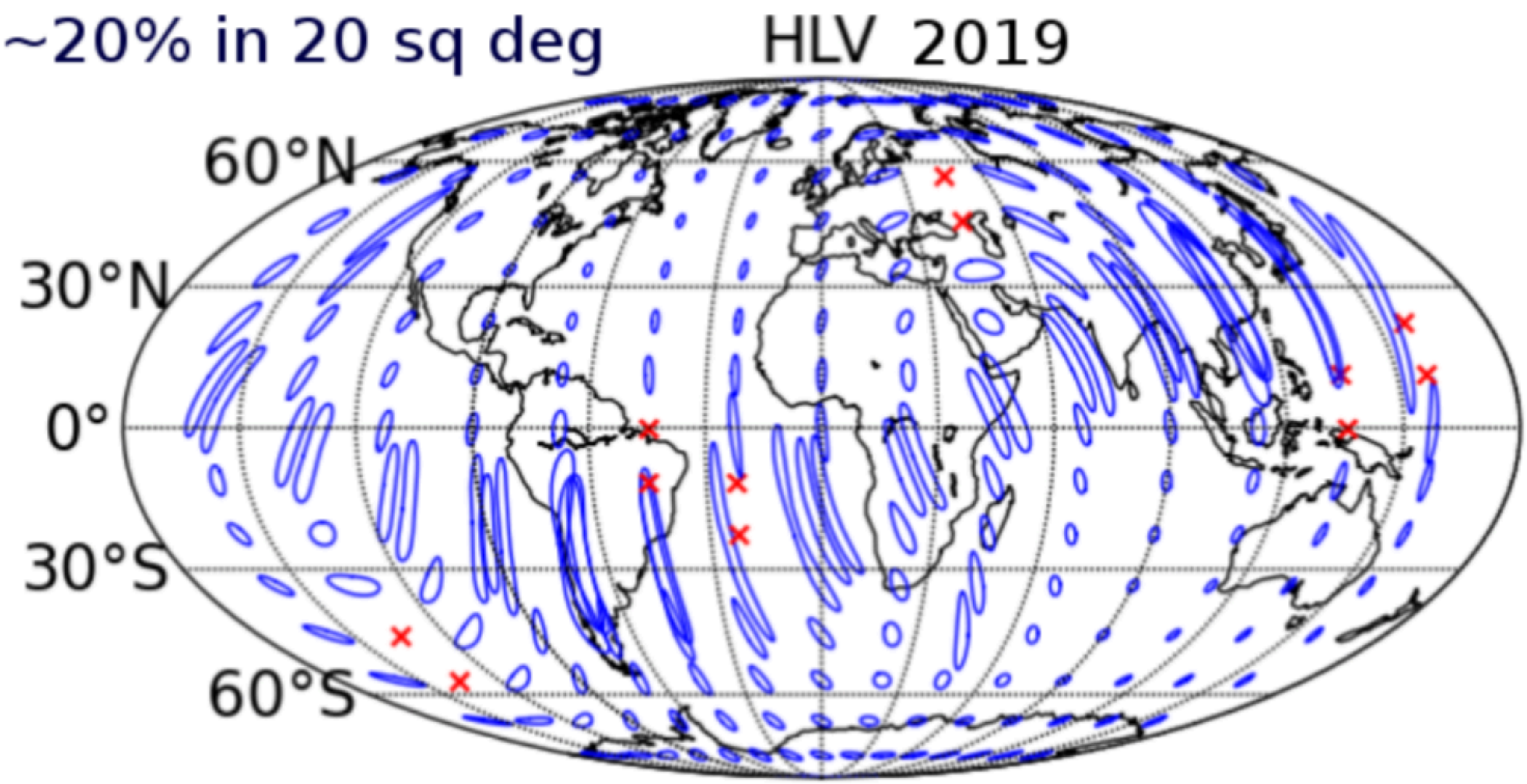
- → ~Factor 2 network sensitivity improvement
- → ~**Factor 8 greater signal rate**



Possible improvements in one of the LIGO detectors

2018-19 Sensitivity/configuration:

3 detectors,
~2-3 signals per week

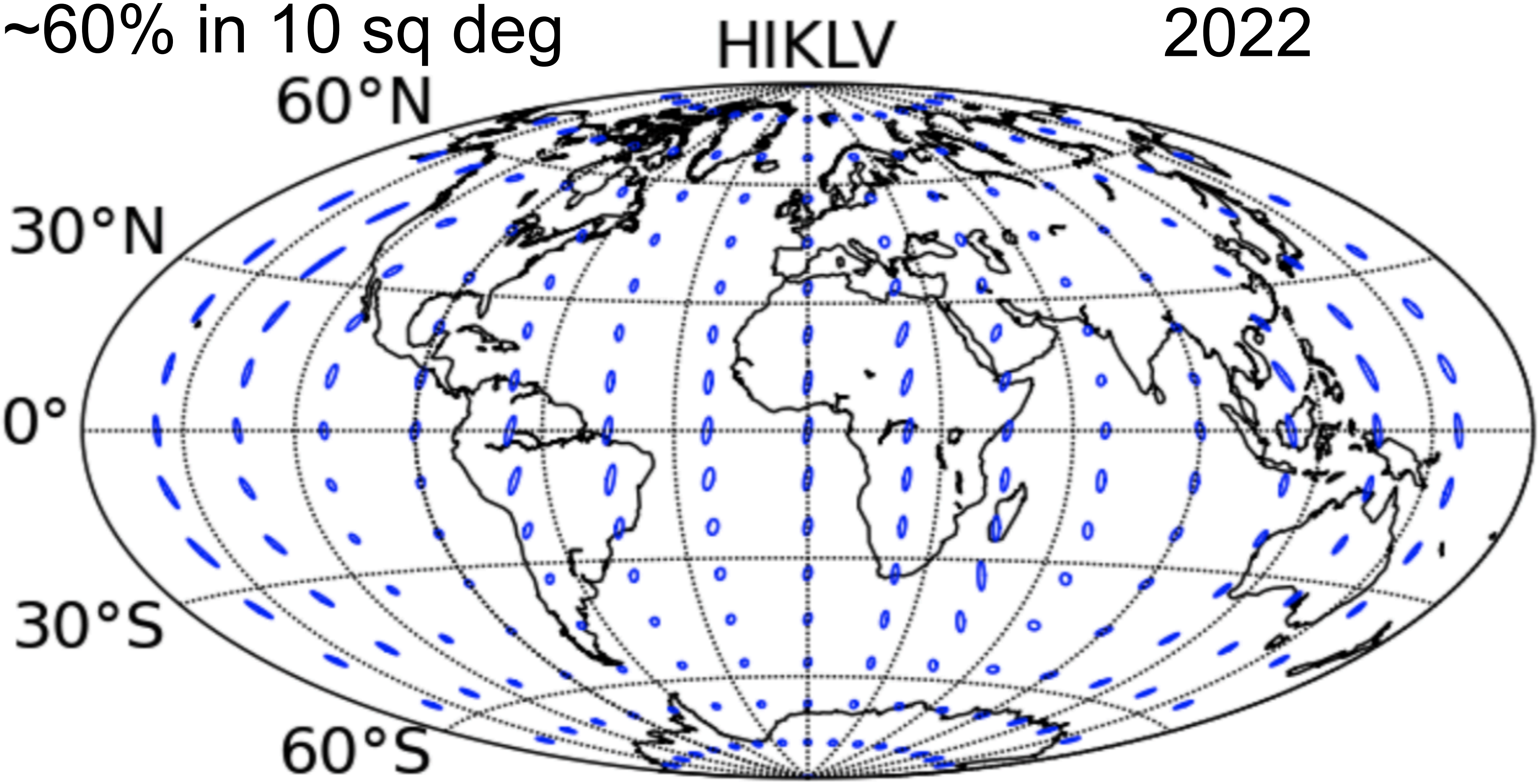


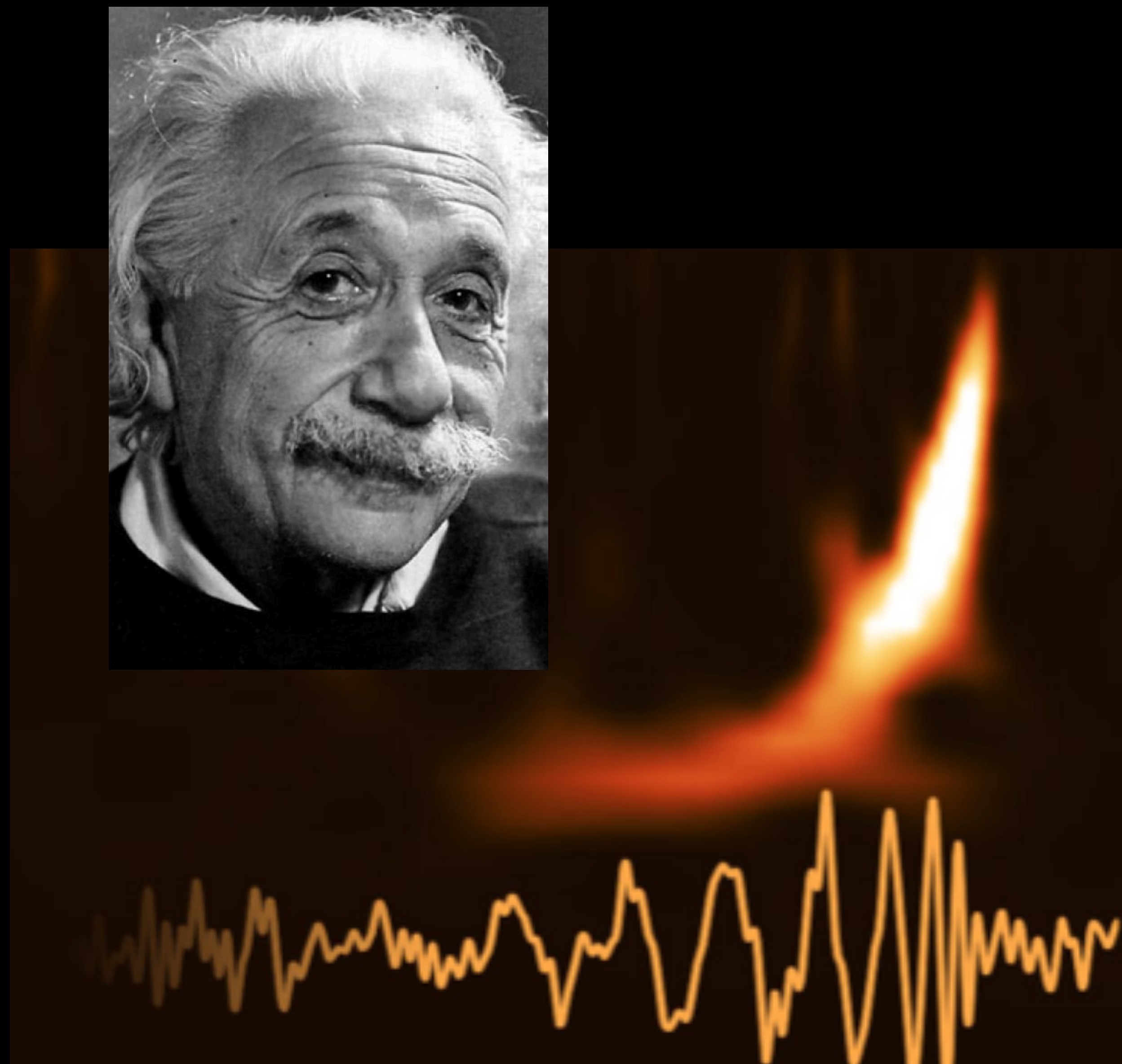
2024 Sensitivity/configuration:

5 detectors (add India and Japan)
far improved source localization

~60% in 10 sq deg

2022





…and this is just the beginning!