Observation of Gravitational Waves from a Binary Black Hole Merger

Committee of Scientific Society Presidents
10 May 2016

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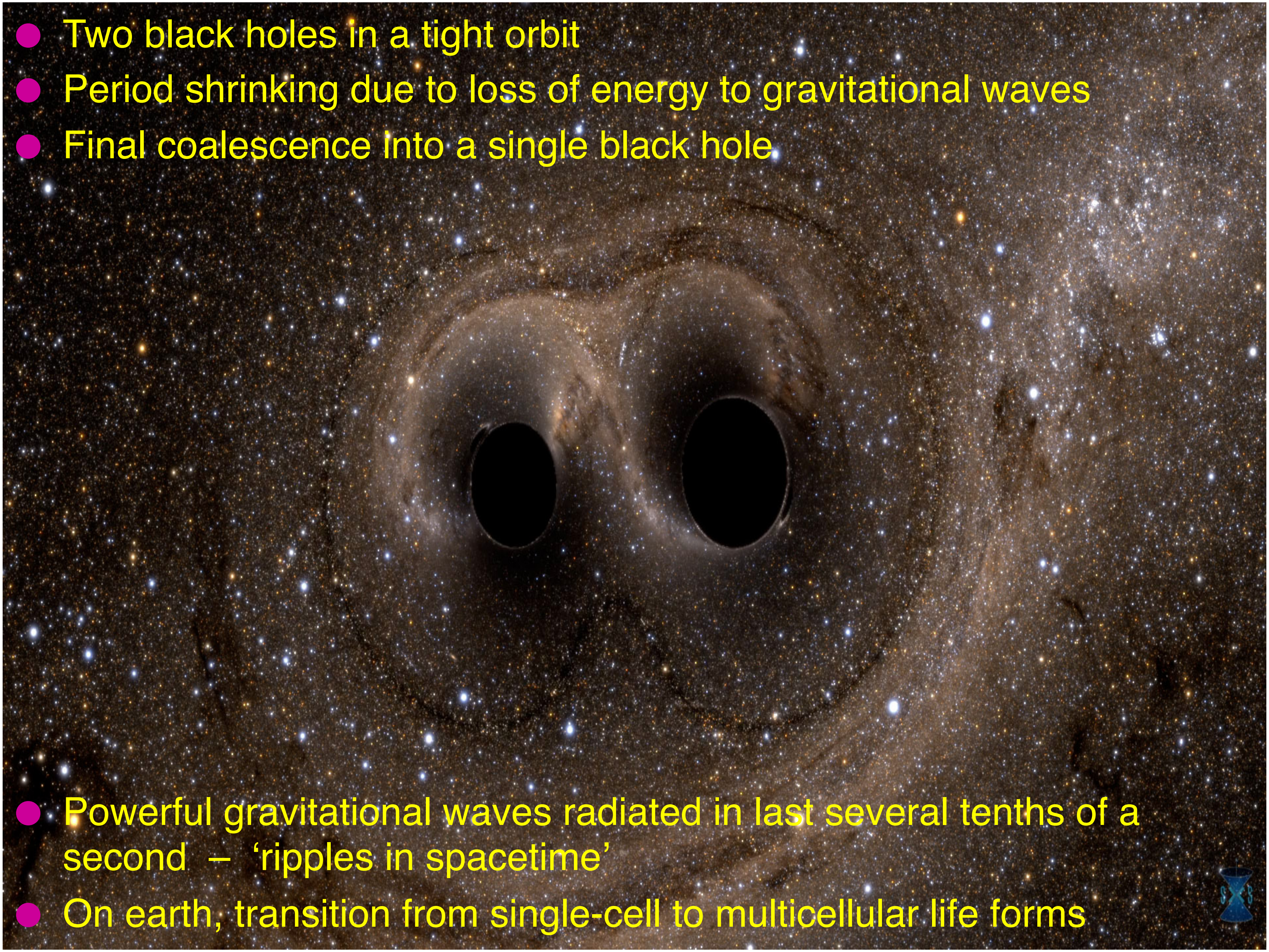
For the LIGO and Virgo Scientific Collaborations

LIGO-G1600999-v2

The story starts in the usual way:

Once upon a time, 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

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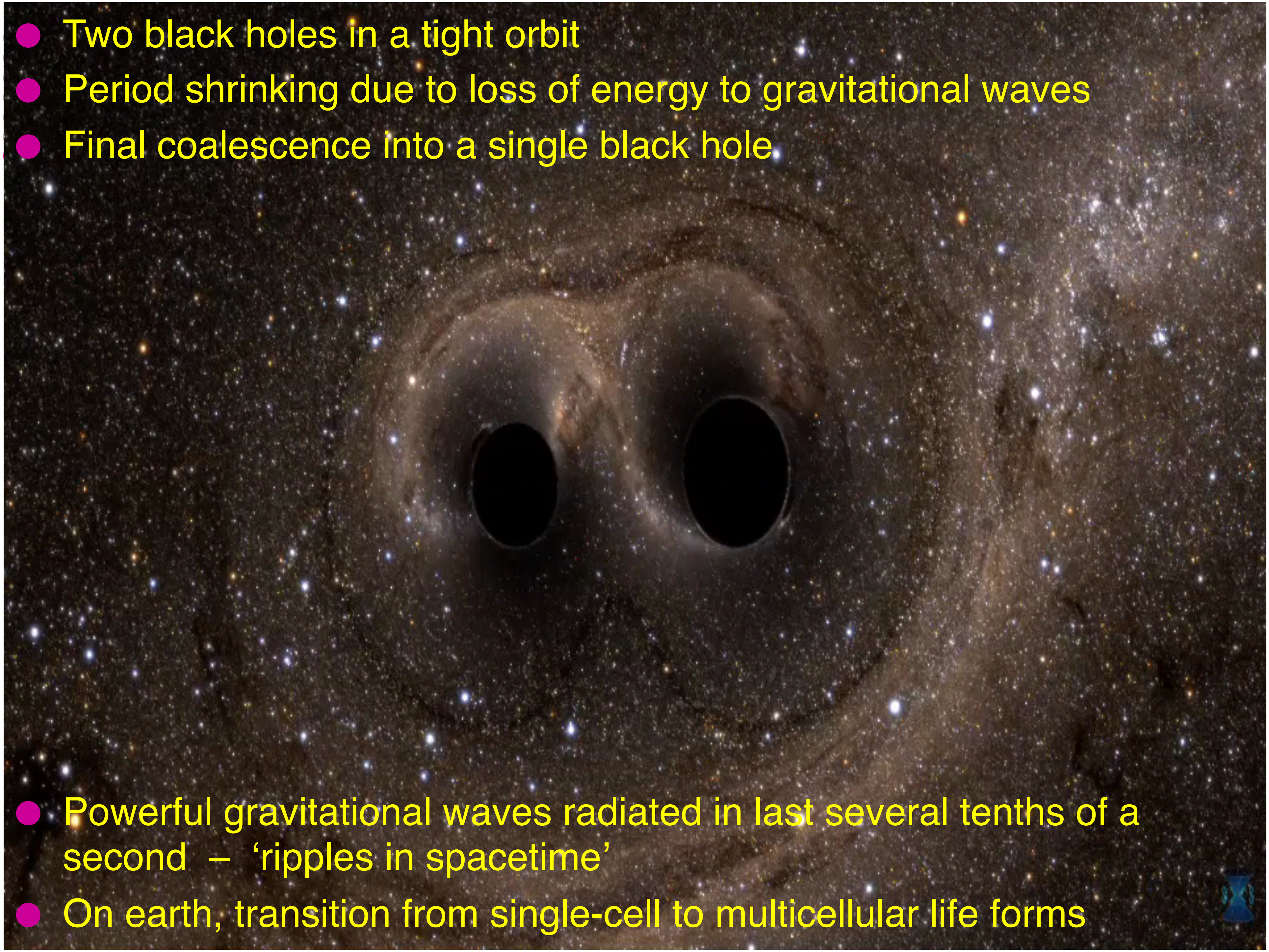

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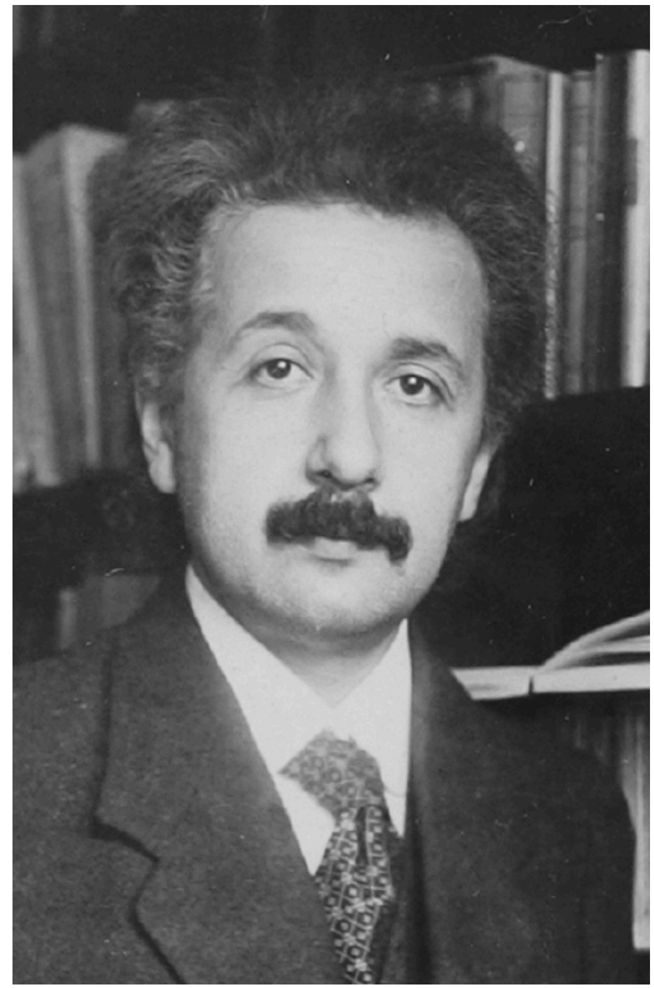
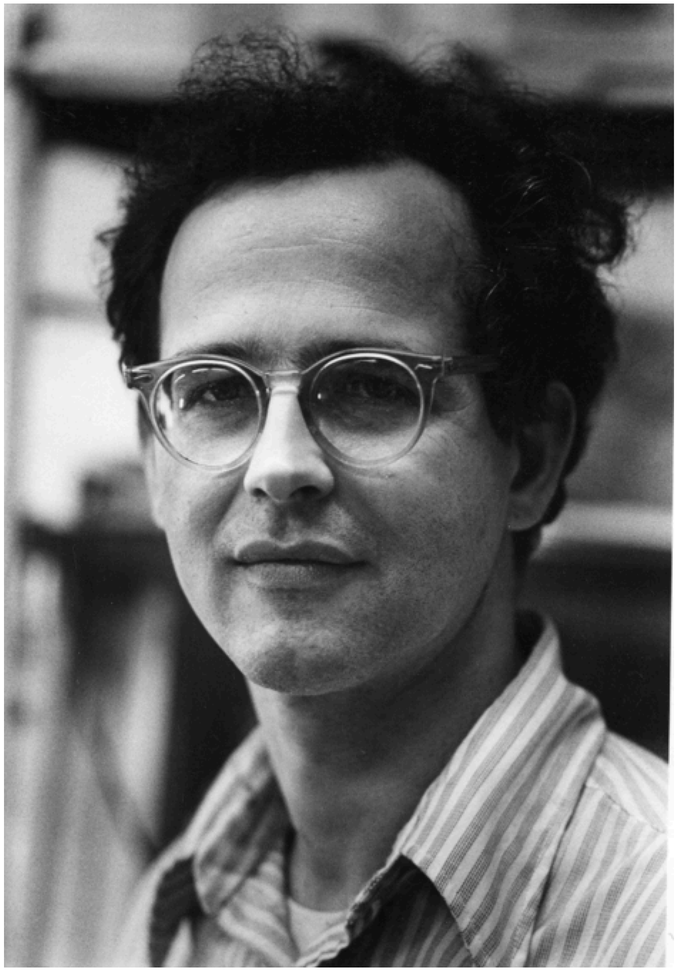
Much later, only 100 years ago

- Albert Einstein is evaluating and processing applications…
  - …for transmission of electric signals and electrical-mechanical synchronization of time
- The result: General Relativity is published in 1915
- First paper indicating that gravitational waves (GW) in 1916
- In a second paper in 1918 Einstein indicates that the effect is of no practical interest since the effect is too small to be detected
- Indeed: at that time there were no means that could have succeeded
  - Einstein did in separate work establish the basis for lasers, quantum measurement, understanding of thermal noise – all ultimately needed for the detection!



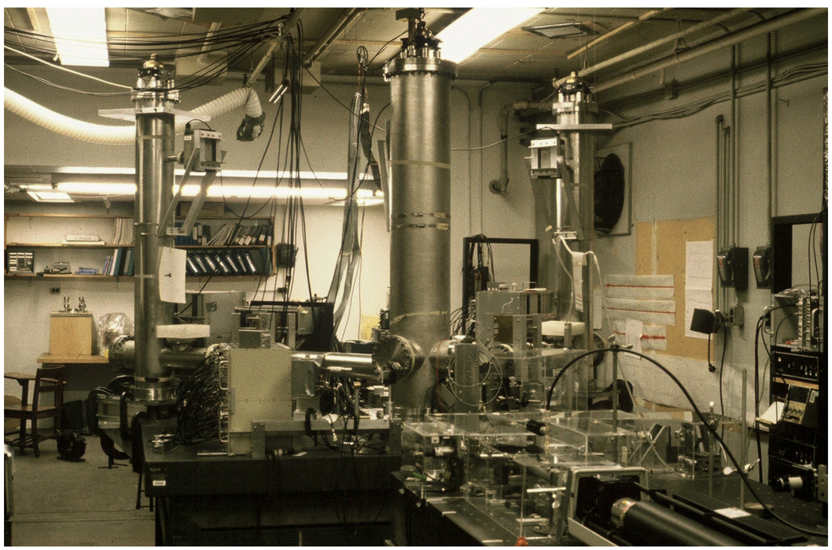
A brief history of the experimental field

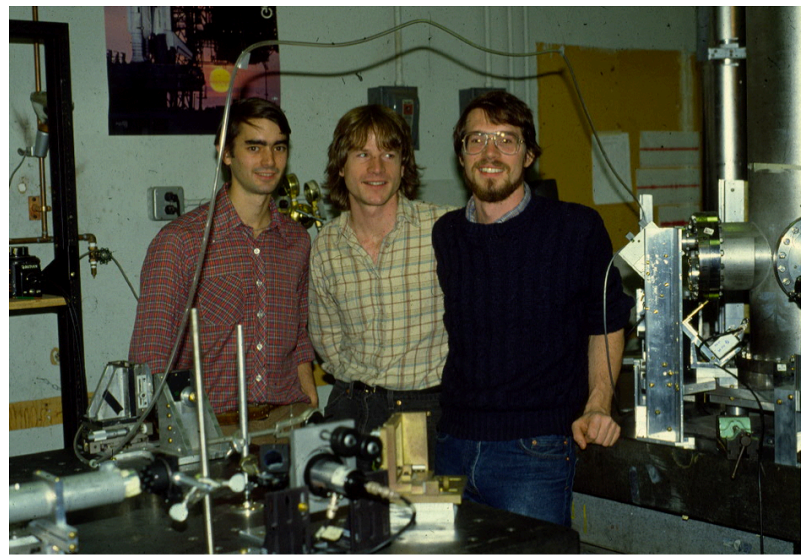
- Gertsenstein and Pustovoit, 1963: theoretical study of using laser interferometry to detect GWs (Russian)
- Others re-invent the notion – among them Joe Weber, who pioneered in developing ‘acoustic bar’ GW sensors
- Rainer Weiss of MIT also re-invents the idea as a homework problem for students learning General Relativity
- He does the homework, and spends a summer fleshing out the idea
- **In 1972, Weiss publishes an internal MIT report**
  - » Sets the concept and scale of LIGO
  - » This roadmap contains also noise sources and how to manage them
- Weiss has continued to be the constant of motion for the field in terms of science, technology, collaboration, and mentoring



Evolution from concept to discovery

- Weiss' 1972 paper gave a litany of limitations to the technique and a roadmap to start to pursue them
- Table-top prototypes in the late 70's, at MIT, Glasgow, Caltech, Max Planck Munich, talking at conferences but not really collaborating
  - » MIT: Team of 3 students: Jeff Livas, DHS, Dan Dewey





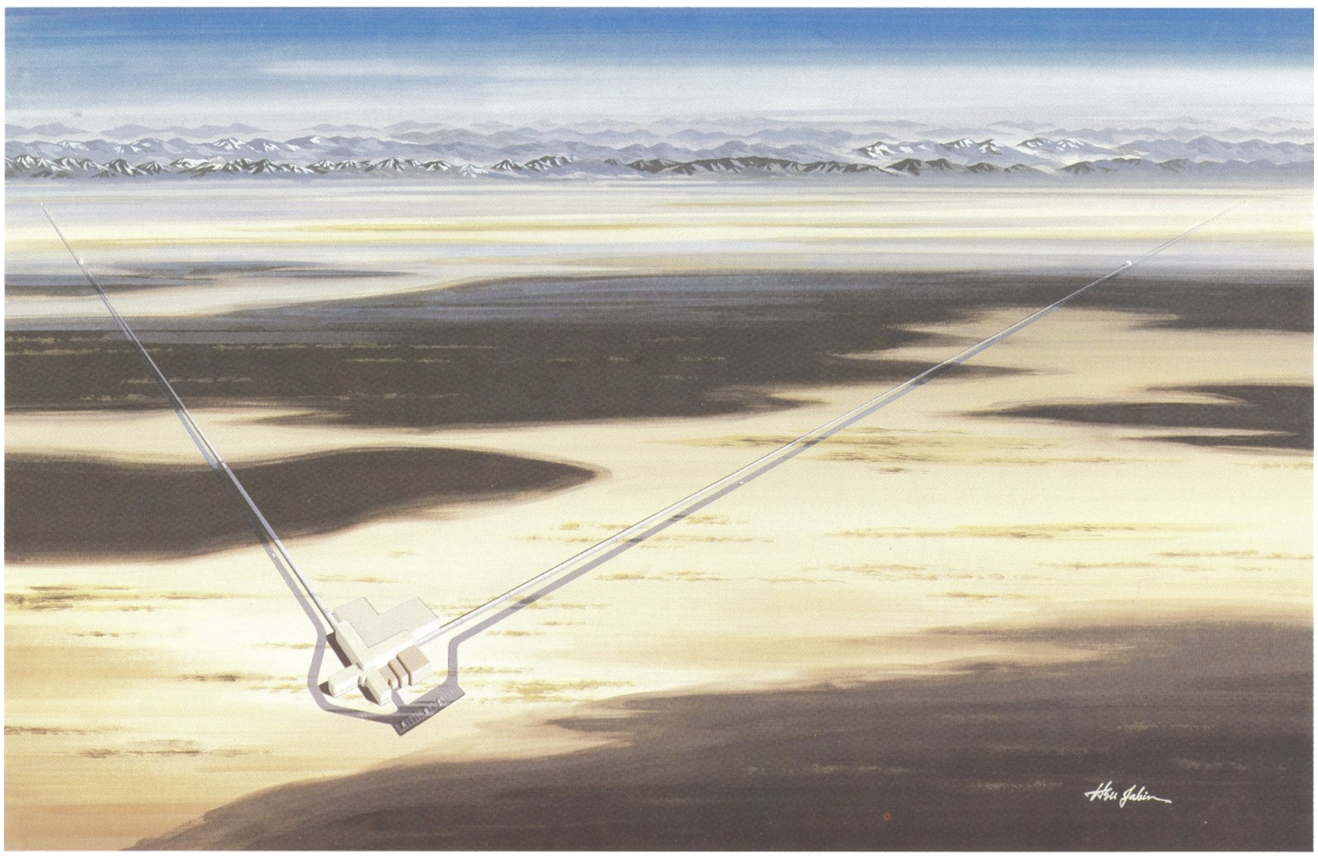
- Mid 80's: 30m prototype at Max Planck was the first to be well understood with methodical alignment of models with performance
  - » First appearance of engineering discipline
  - » DHS plays role of grain of sand in the oyster

LIGO takes form

- 80's: Realization by Weiss of the necessity for a unified effort in the US
  - » Strong resonance, and in fact leadership, at the NSF – Rich Isaacson, Marcel Bardon, others; key to LIGO's success
- MIT and Caltech start to orbit around each other to coordinate research
  - » MIT contracts for engineering study of a multi-km interferometer
  - » LIGO Proposal starts to take form
  - » Caltech takes lead
- Proposals in Germany (reunification stops this) and Italy/France
  - » DHS was in Paris getting PhD, helps write the Virgo proposal
- Scientists Weiss, Thorne, Drever leading LIGO for a while – but not well suited to role
- Robbie Vogt of Caltech given leadership, focuses effort, communicates with Congress…start of transition to Big Science

1989

- 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



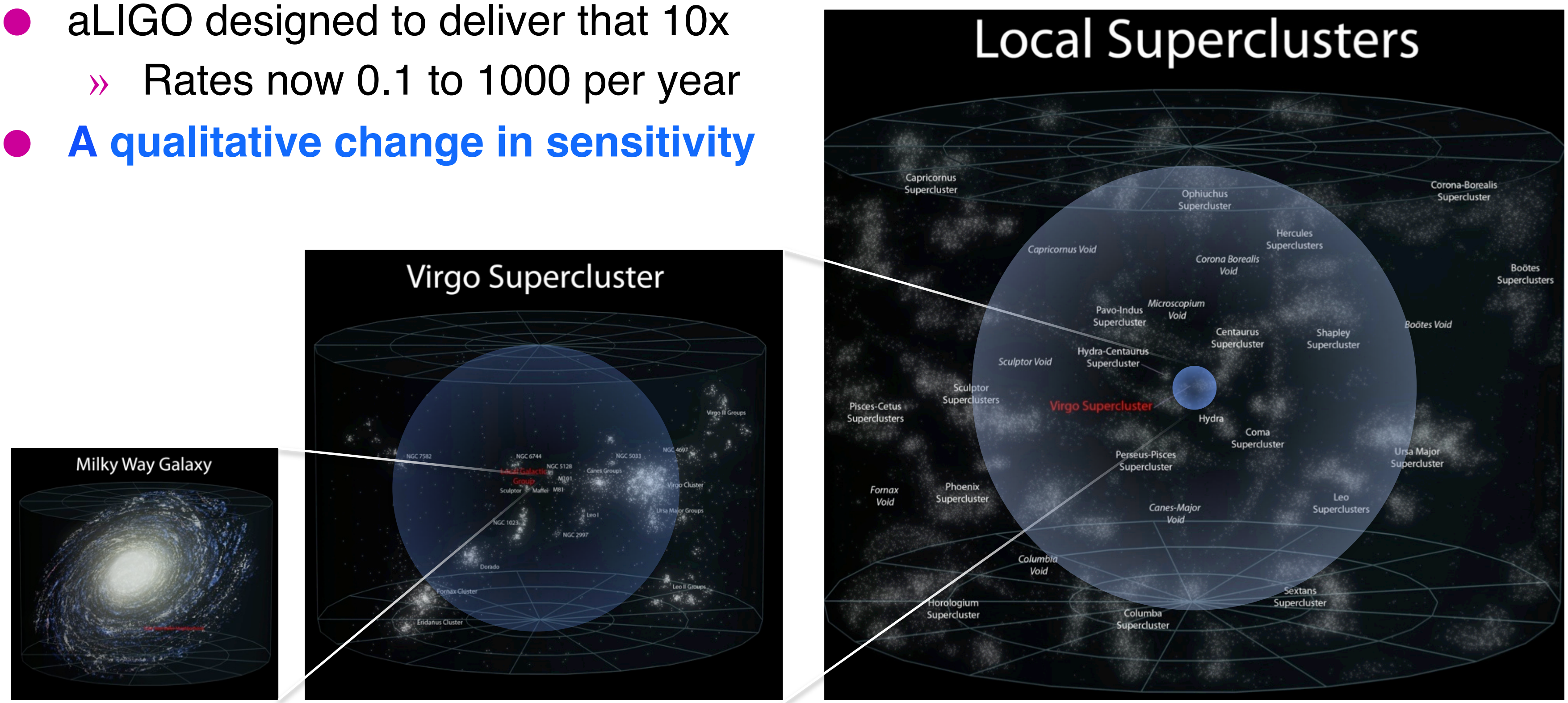
LIGO Era

- 1990: start of LIGO activities
  - Still proving out basic instrument technologies; Caltech and MIT start working very closely together
  - Transition from table-top thinking to Big Science; staff turnover
- 1994: Groundbreaking at LIGO Observatories; Caltech's Barry Barish leads Project, the Lab from '94 – 2006
  - Experience in high energy physics, managing interface with funding
- 1999: LIGO Inauguration
- 2001: Instrument starts to function; interleave observing/commissioning
  - Difficult path to sensitivity – many things not working, wrongly designed, tools lacking for diagnostics, few experts
  - DHS Deputy Detector Leader, responsible for some of the chaos
  - Lessons learned for Advanced LIGO instrument design and process
- 2005: Design sensitivity reached, good duty cycle –

  6 years after installation complete
- 2005-2011: Observation with initial LIGO, many papers written on upper limits and interesting non-detections – but **no detections made**

Advanced LIGO

- Uncertainty in rates of anticipated signals is (…was) huge – a range of 10,000
  - » Initial LIGO projected to maybe see 1 signal per year – or 1 signal per 10,000 years
- We detect amplitude; if our reach is 10x greater, 1000x more candidates
- aLIGO designed to deliver that 10x
  - » Rates now 0.1 to 1000 per year
- **A qualitative change in sensitivity**



M. Evans

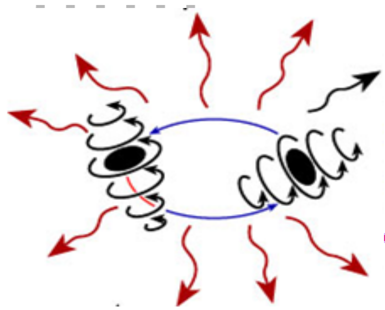
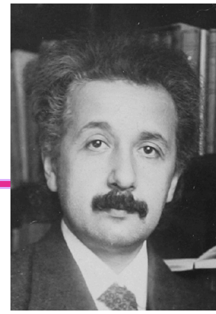
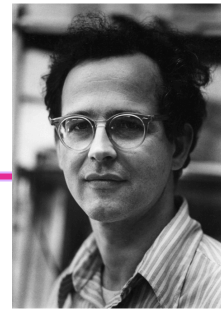
Initial Reach

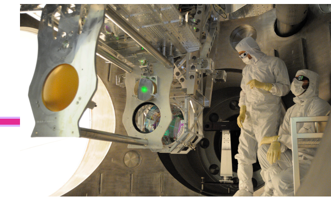
Advanced Reach

Advanced LIGO Era

- 1995-2000: R&D throughout the community on 2nd generation ideas
  - LIGO Lab consumed with building initial LIGO
  - Most research done elsewhere – U. Glasgow very productive
- 1999: White Paper describes Advanced LIGO, maps needed research
  - Eric Gustafson (Stanford), Ken Strain (Glasgow), DHS (MIT)
- LIGO Scientific Collaboration (LSC) starts to form
  - LSC agreement to sacrifice individual research interests to focus on specific goals relevant to Advanced LIGO; very important!
  - NSF uses LSC White Papers to guide proposal reviews
- Lab forms management team, brings in project skills and machinery
  - DHS (leader), Carol Wilkinson (Project Mgr), Dennis Coyne (Chief Engineer)
- 2003: Proposal for Advanced LIGO (aLIGO) to NSF; they are receptive
- 2008: Initial LIGO reaches NSB criterion of 1 year data; aLIGO starts
- 2015 March: **aLIGO Project completes on time, on budget**
- 2015 September: aLIGO ready for first observation –

6 months after installation complete

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...

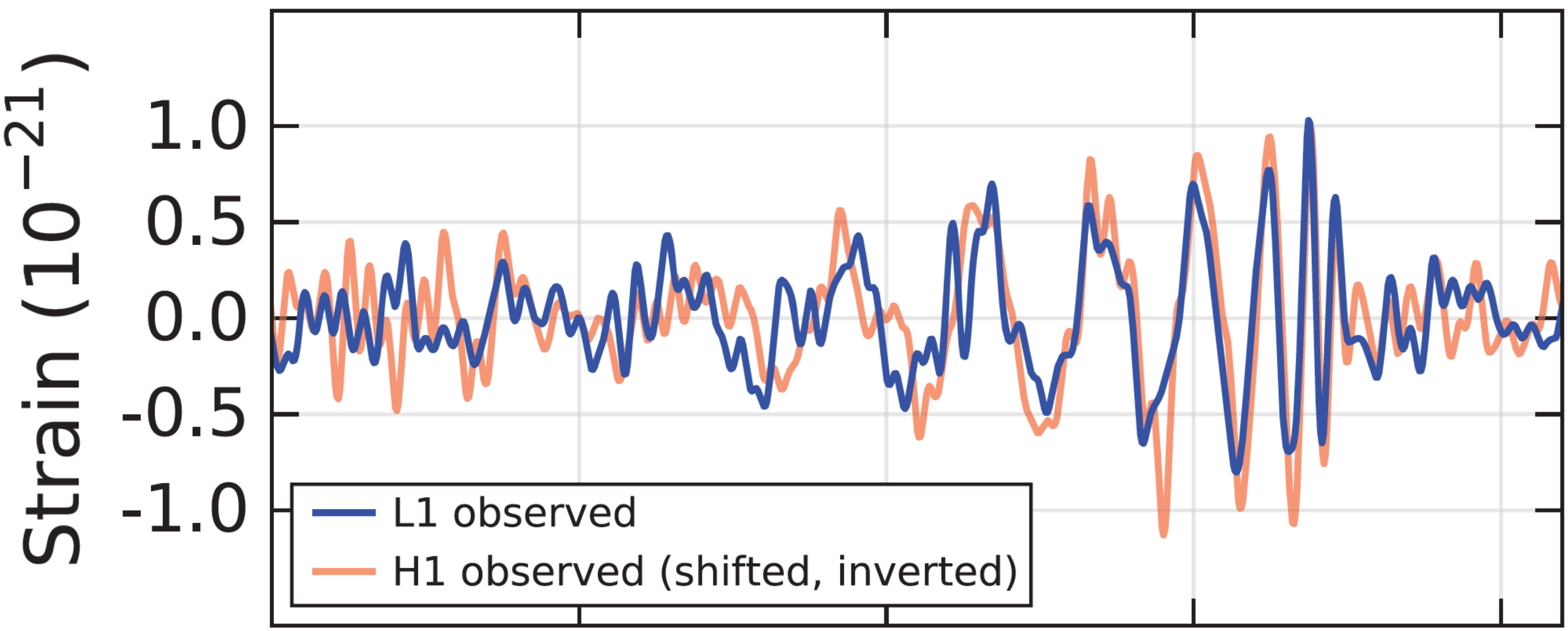
10 years after Advanced LIGO got the ok...

6 months after starting detector tuning...

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

The waves from those Black Holes arrive at Earth

- On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory observed a transient gravitational-wave signal.
  - 3 minutes later, flagged in data



Significance of the Discovery: Confirmation of General Relativity


The New York Times.

LIGHTS ALL ASKEW IN THE HEAVENS

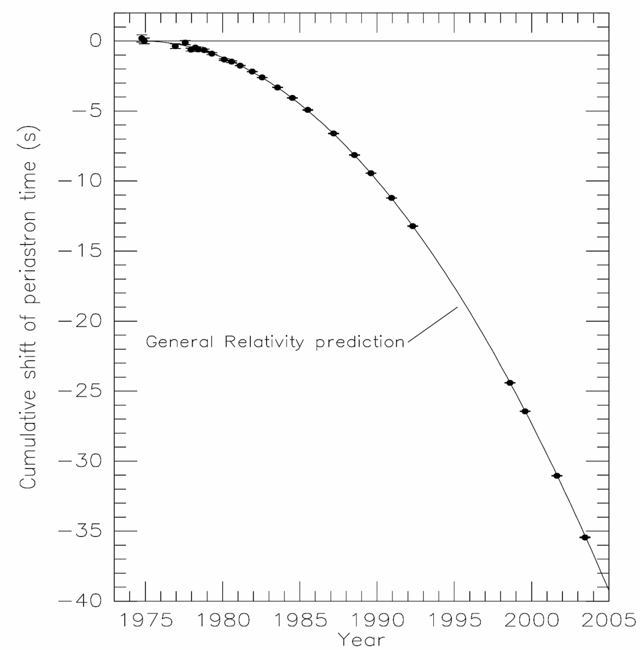
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

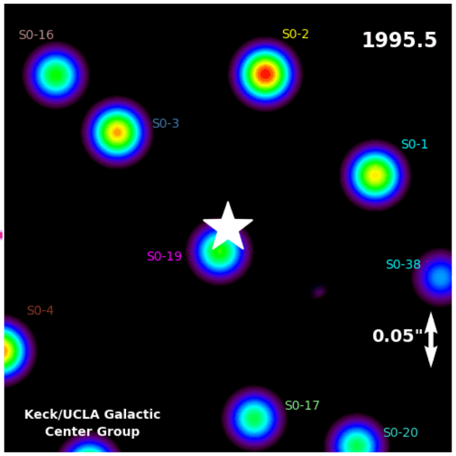
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

- Previous tests of GR have spanned a large range of phenomena
- Bending of starlight around the sun – and now gravitational lensing as an astrophysics observational tool
- Precession of Mercury
- Gravitational redshift, on earth, and as astrophysics tool

- Gravitational waves – seen in the decay of the period of binary systems including pulsars
  - » Weisberg; Hulse/Taylor Nobel Prize
  - » Confirms 1st order GR prediction exquisitely
  - » $v/c \sim 2 \times 10^{-3}$
- LIGO's observation is at v/c ~ 0.5 – **the first test in the highly relativistic regime**
  - » Speed of propagation
  - » Higher order terms
  - » Excellent agreement with GR, within measurement uncertainty



Significance of the Discovery: Observation of Black Holes



- Many galactic-center Black holes have been inferred
- Beautiful measurements of motion of stars around the Milky Way central black hole
  - » *These images/animations were created by Prof. Andrea Ghez and her research team at UCLA and are from data sets obtained with the W. M. Keck Telescopes.*
- Getting close to imaging something close to the horizon using photons

- LIGO's observation confirmed that few-to-hundreds solar mass Black Holes exist, and gives a first number for their frequency in the cosmos
- An important datum to explain the growth of large-scale structure
- May be the explanation of dark matter (that's very speculative!)

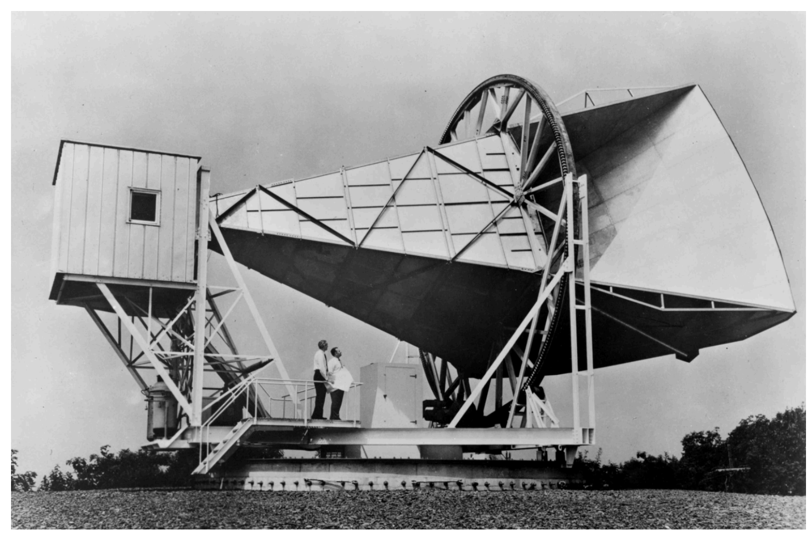
- Coalescence observed, obeys GR, confirms Numerical Relativity

- Quasi-normal-mode oscillation of final black hole probably observed
  - » **Most direct confirmation of black holes of any size**, and their character

Significance of the Discovery: Opening a new window on the Universe

- Every time a new tool has been invented, it has led to remarkable new insights and many surprises
- Most observations to date with photons – IR, visible, X-ray, gamma; some neutrino observations
- Expect GWs to similarly prove also very useful as a complementary tool to EM astronomy
- To make discoveries impossible otherwise – e.g., Black Holes – no light signal!

‘Expect’ surprises



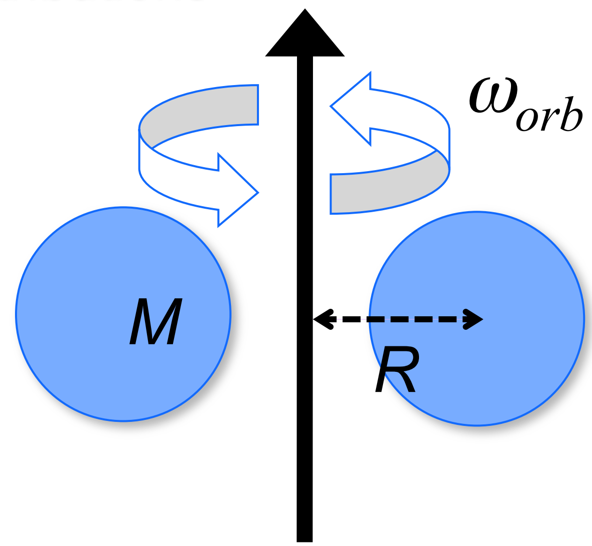
What are Gravitational Waves?

- GWs propagate at the speed of light (according to GR)
- Emitted from rapidly accelerating mass distributions

$$h_{\mu\nu} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}_{\mu\nu}$$

r = distance from the source to the observer

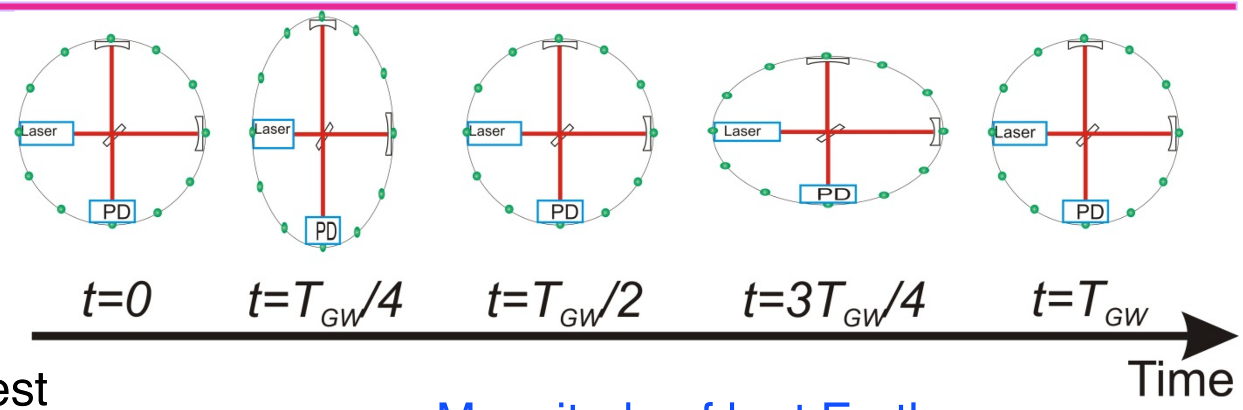
Rotating dumbbell $\longrightarrow$ $$h \approx \frac{8GMR^2\omega_{orb}^2}{rc^4}$$



- Space is very stiff; h is ~10^{-21} for say Neutron Stars in Virgo Cluster
- Measurable GWs can only be expected from the coherent bulk motion of matter in the highly relativistic regime

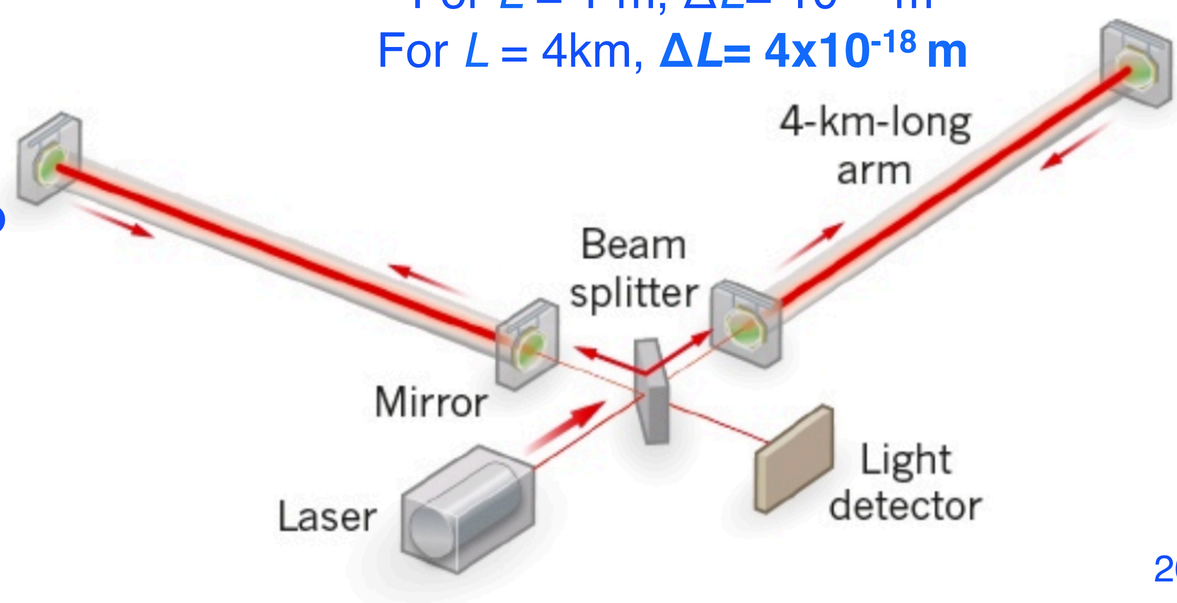
What is LIGO's measurement technique?

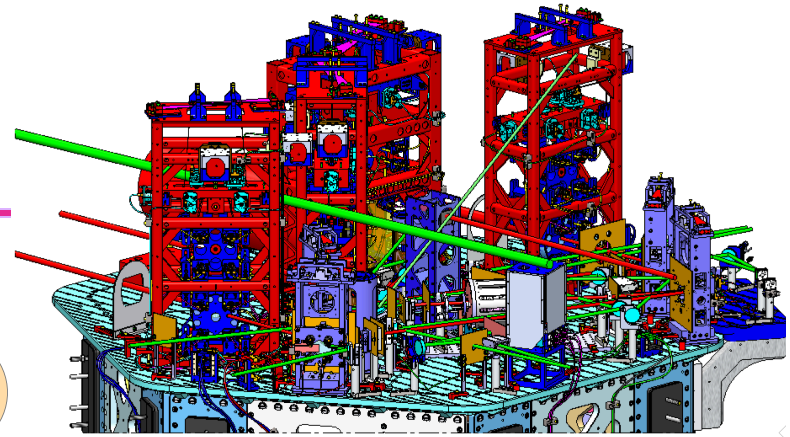
- Enhanced **Michelson interferometers**
  - » LIGO, Virgo, and GEO600 use variations
- Passing GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent proportional to the strain amplitude
- **Arms are short compared to our GW wavelengths, so longer arms make bigger signals → multi-km installations**
- Arm length limited by taxpayer noise….

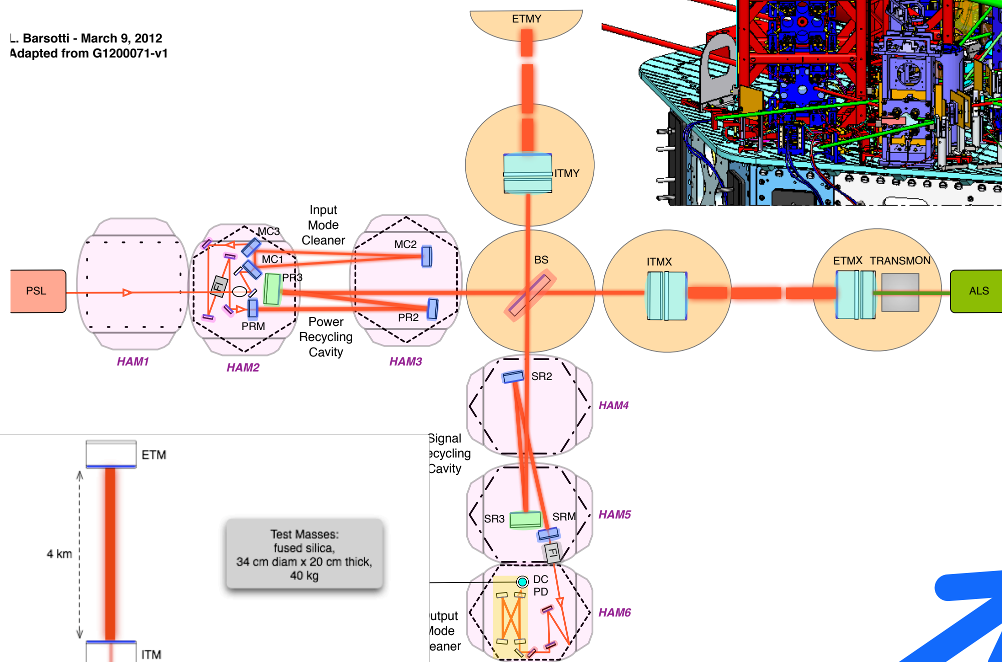


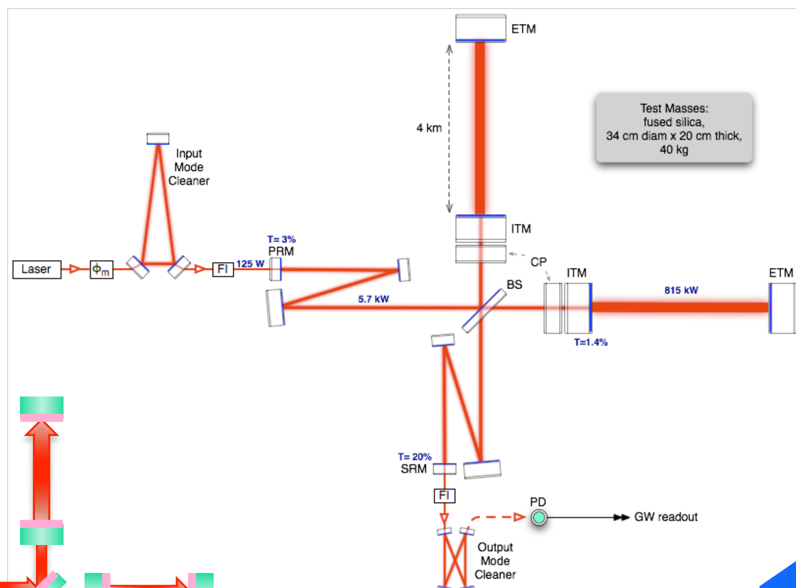
$$h \approx \frac{\Delta L}{L}$$

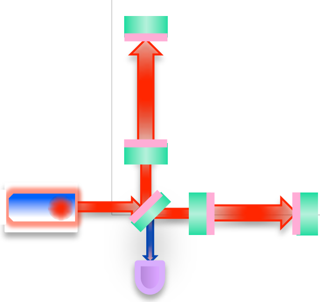
Magnitude of h at Earth:
Largest signals $h \sim 10^{-21}$
(1 hair / Alpha Centrauri)
For L = 1 m, $\Delta L = 10^{-21}$ m
For L = 4km, **$\Delta L = 4\times10^{-18}$ m**

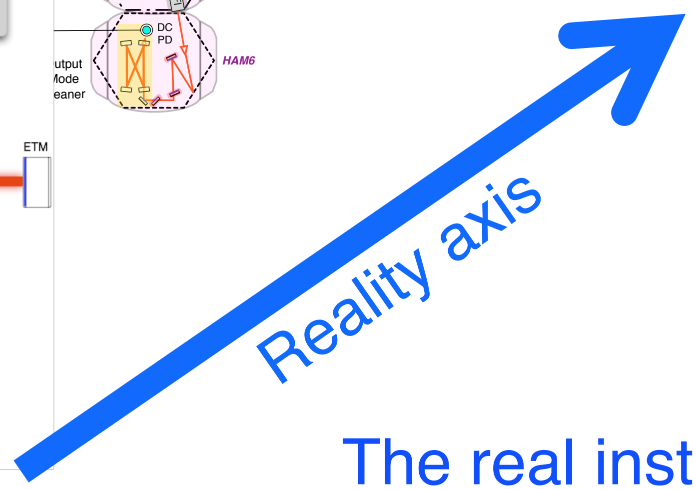










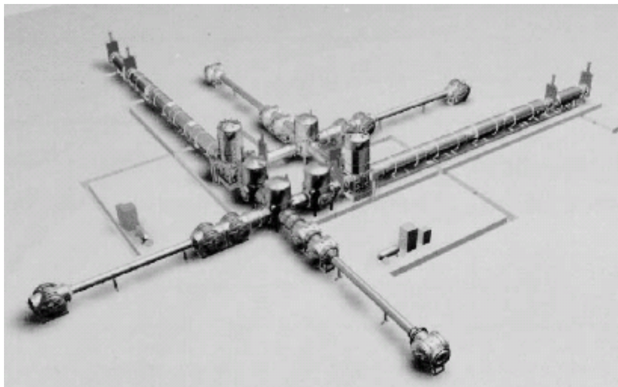


The real instrument is far more complex…

Infrastructure:
4km Beam Tubes

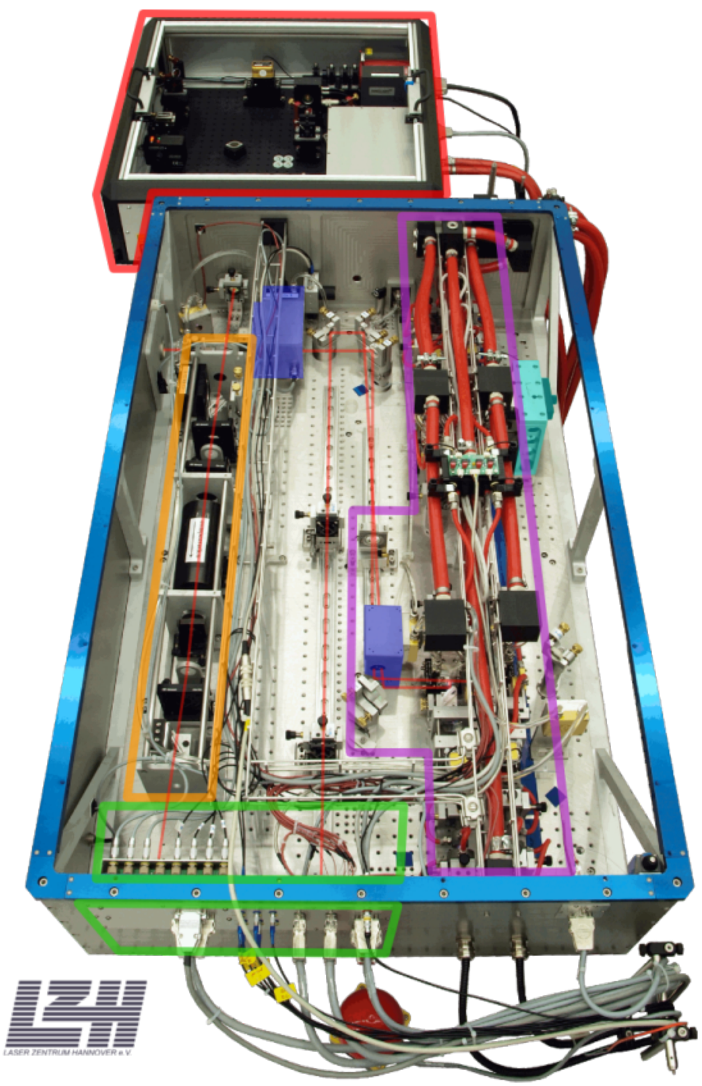
- Light must travel in an excellent vacuum
  - » Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs!
  - » 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters' bullets and the stray car
- Tube is straight to a fraction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

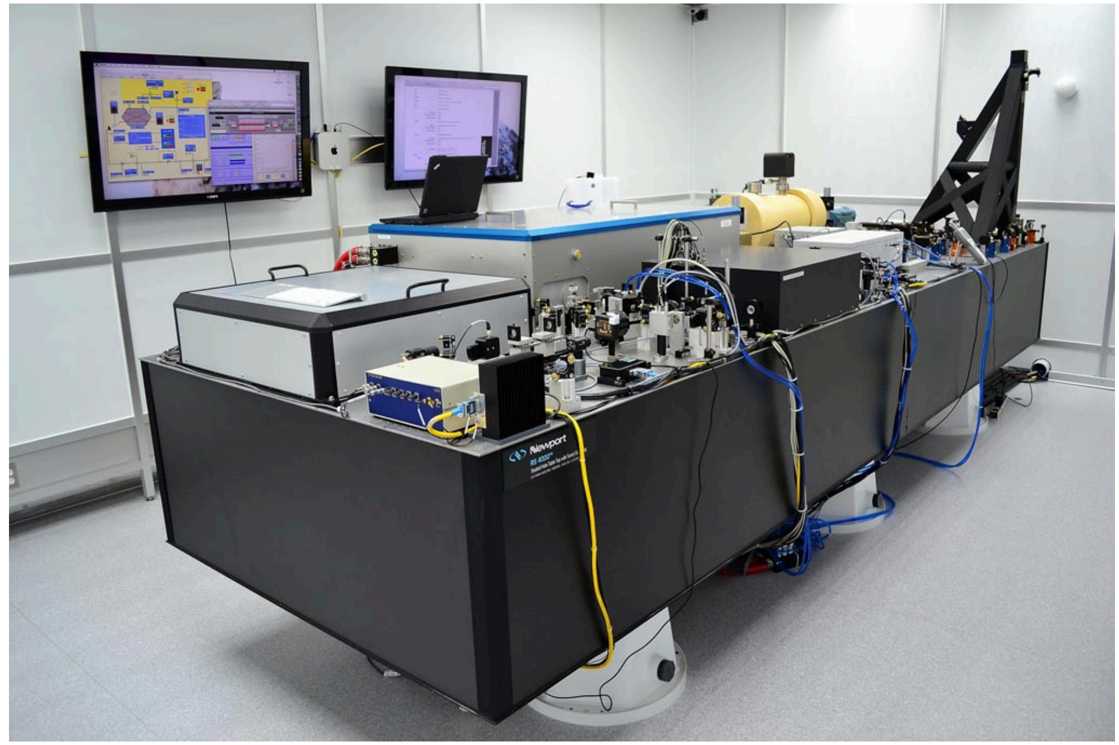
LIGO Vacuum Equipment – designed for several generations of instruments



200W Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute

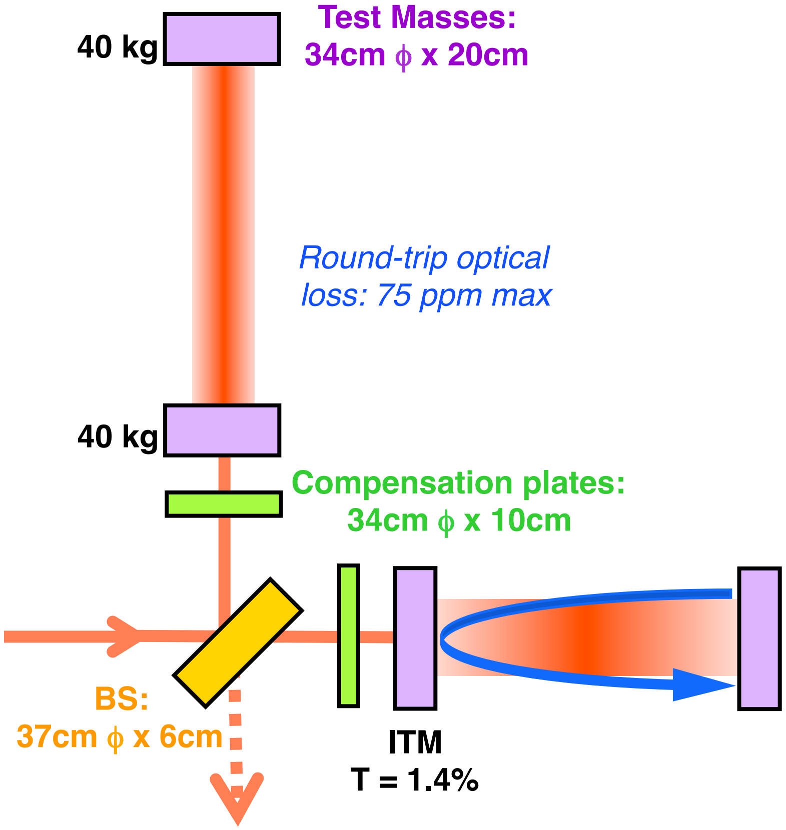


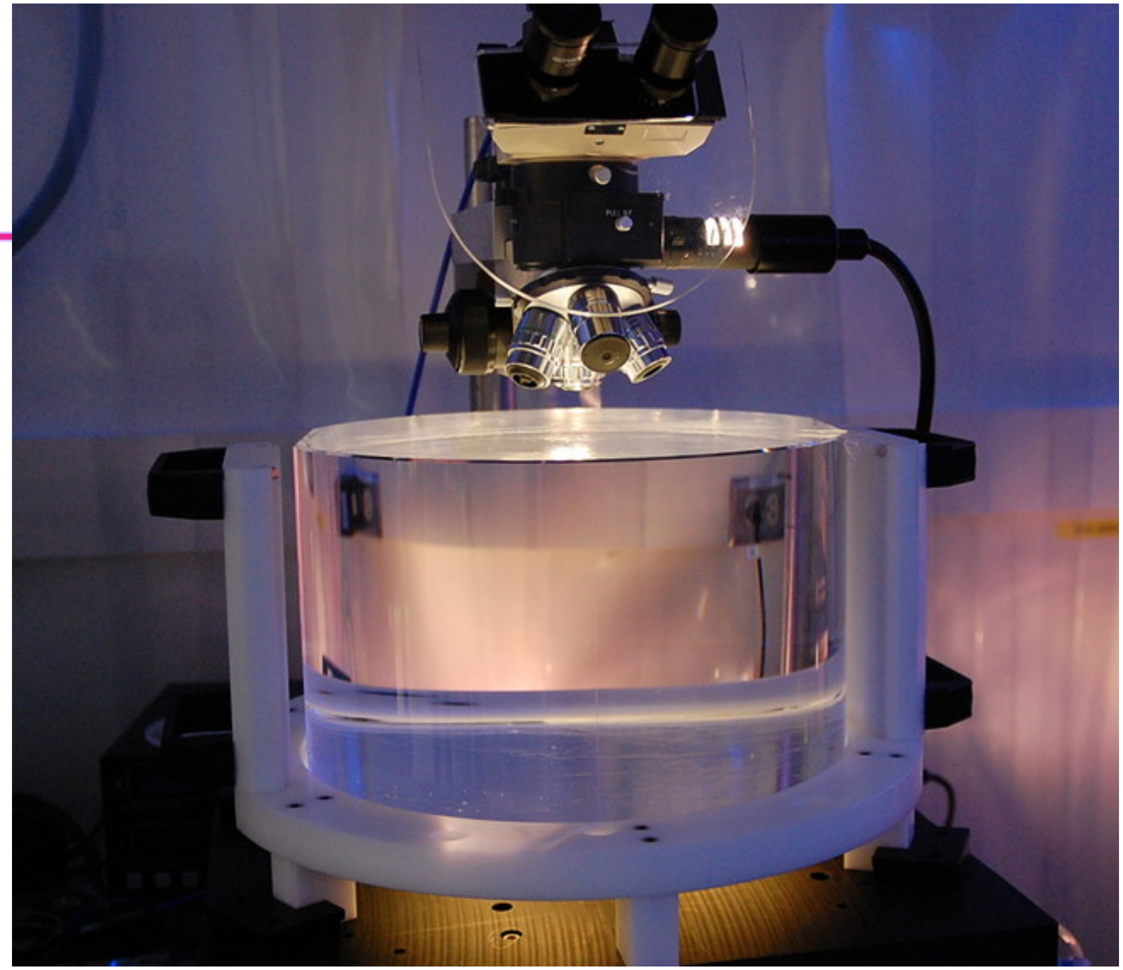


- Stabilized in power and frequency – using techniques developed for time references
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
- Delivers the required shot-noise limited fringe resolution

Test Masses

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



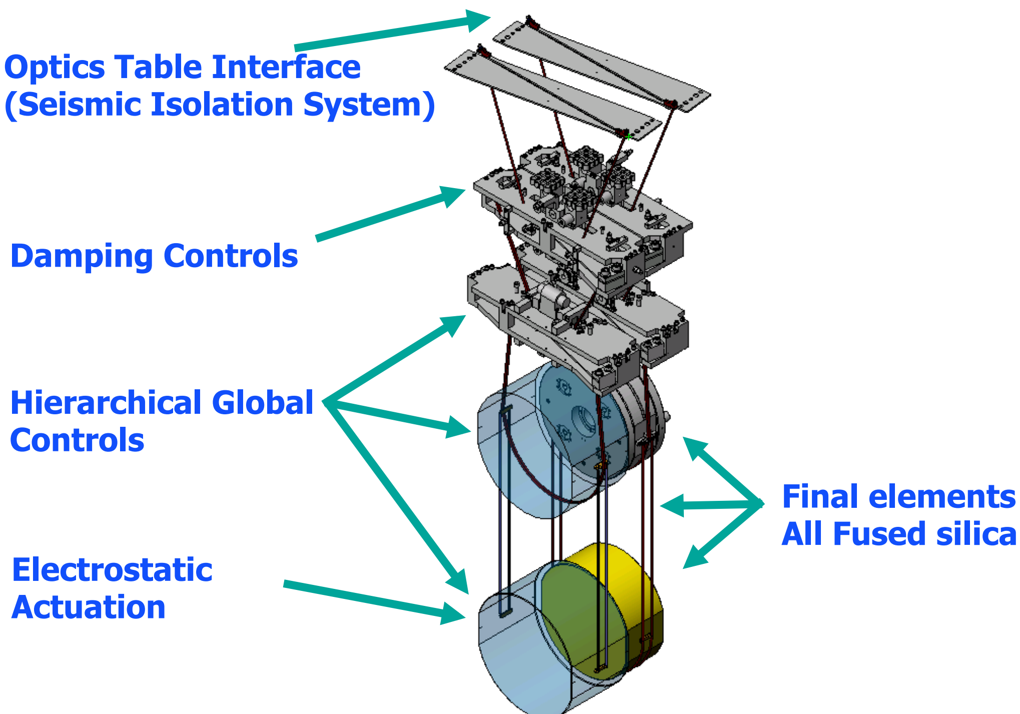


- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Test Mass Quadruple Pendulum suspension

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

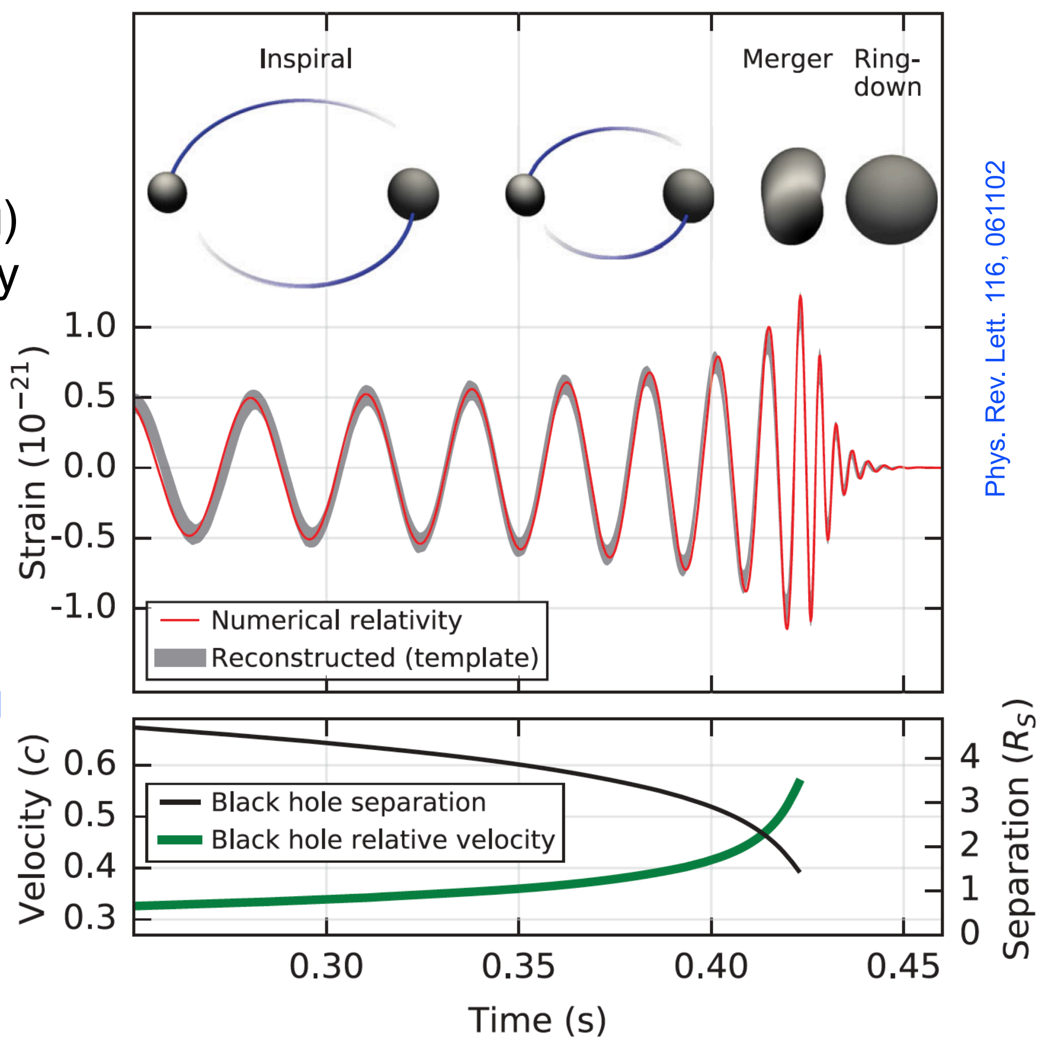
- Quadruple pendulum suspensions for the main optics; second 'reaction' mass to give quiet point from which to push
- Create quasi-monolithic pendulums; Fused silica fibers to suspend 40 kg test mass
  - » VERY Low thermal noise!



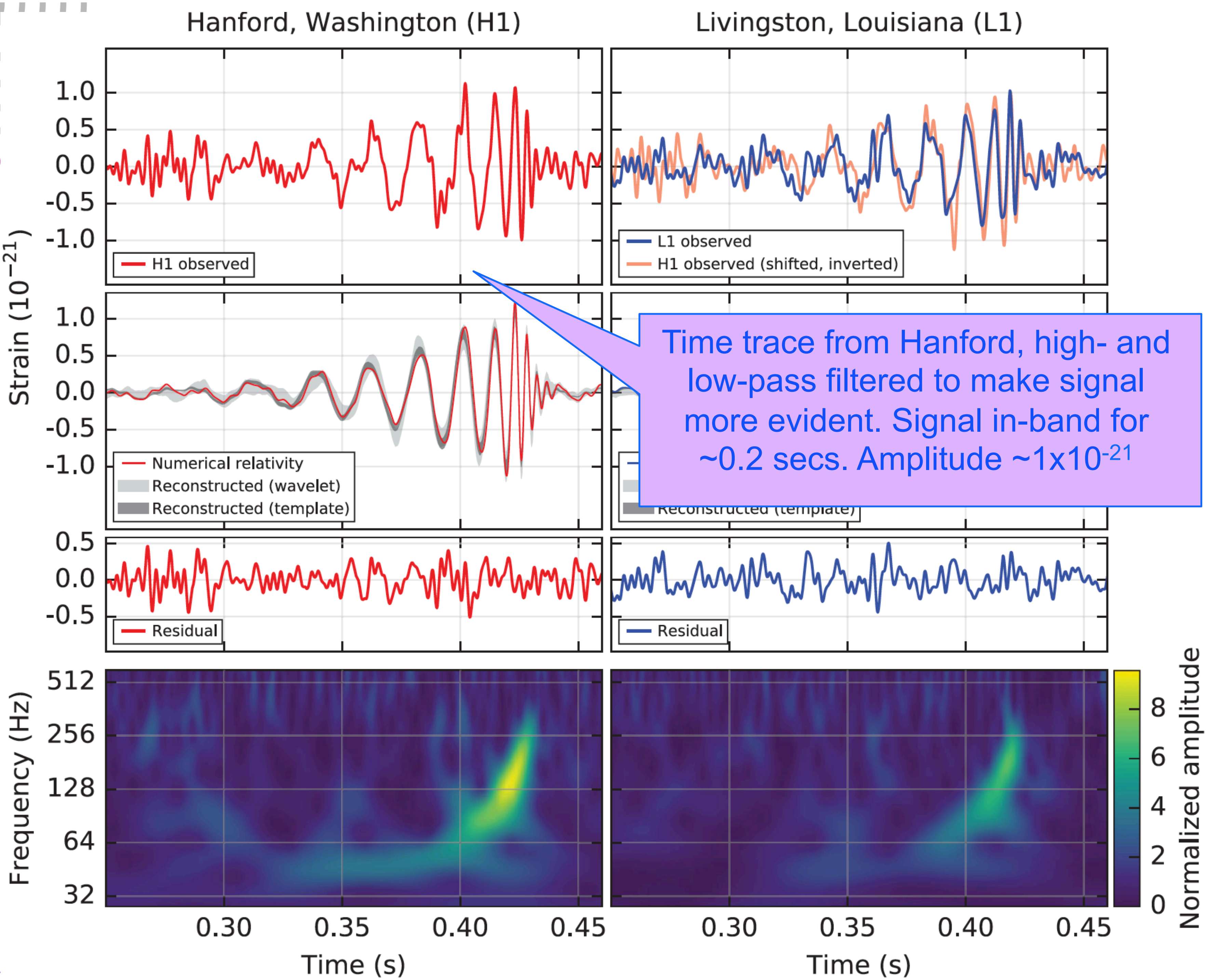
What did we learn from our record of $h(t)$?

LIGO measures *h(t)* – think 'strip chart recorder'

- The output of the detector is the (signed) strain as a function of time
- Earlier measurements of the pulsar period decay (Taylor/Hulse/Weisberg) measured energy loss from the binary system – a beautiful experiment
  - » *Inference* of gravitational waves as loss mechanism, confirmed to *remarkable* precision
- **LIGO can actually measure the change in distance between our own test masses, due to a passing space-time ripple**
  - » More 'direct' (in some sense)
  - » Much richer information!

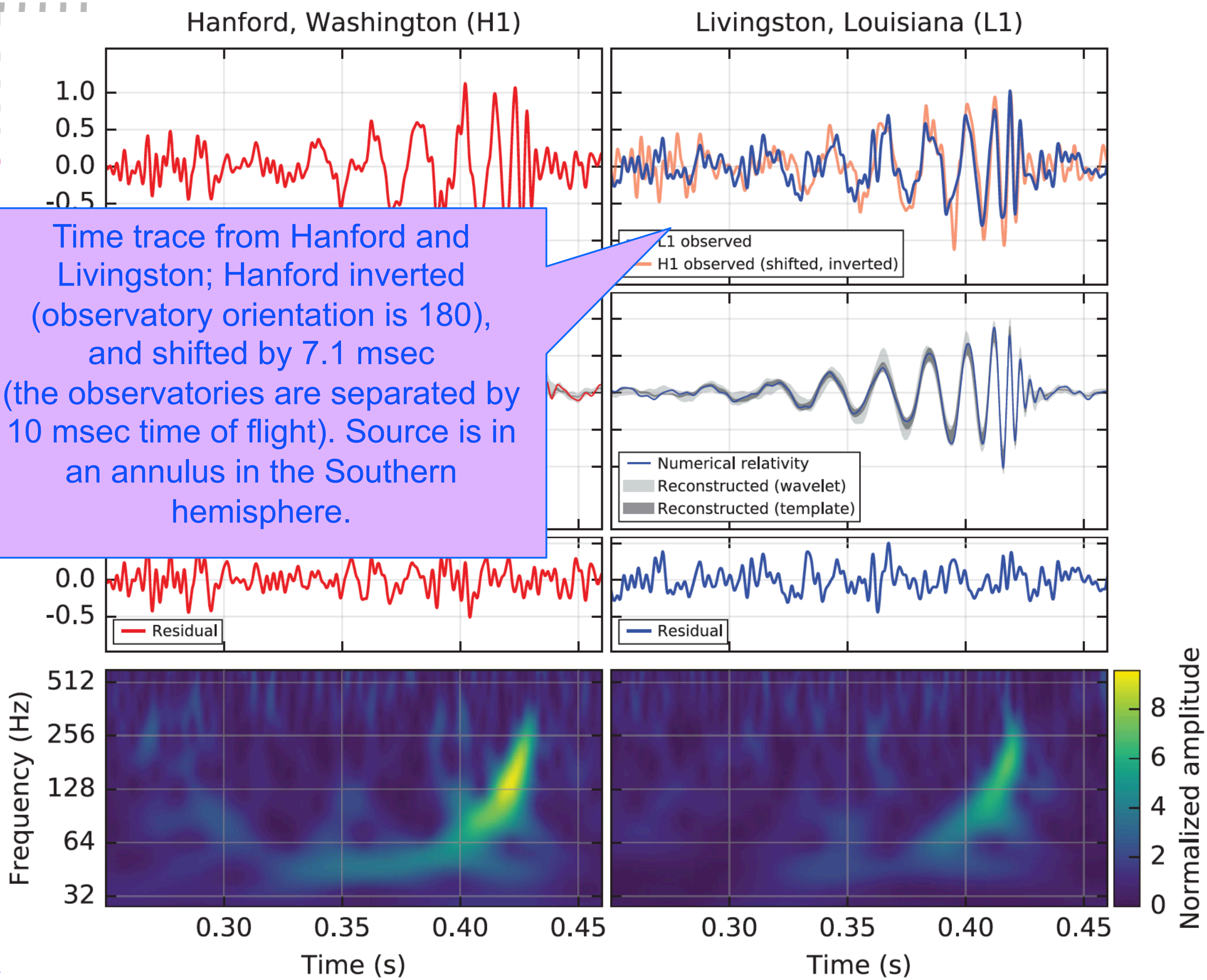


Phys. Rev. Lett. 116, 061102

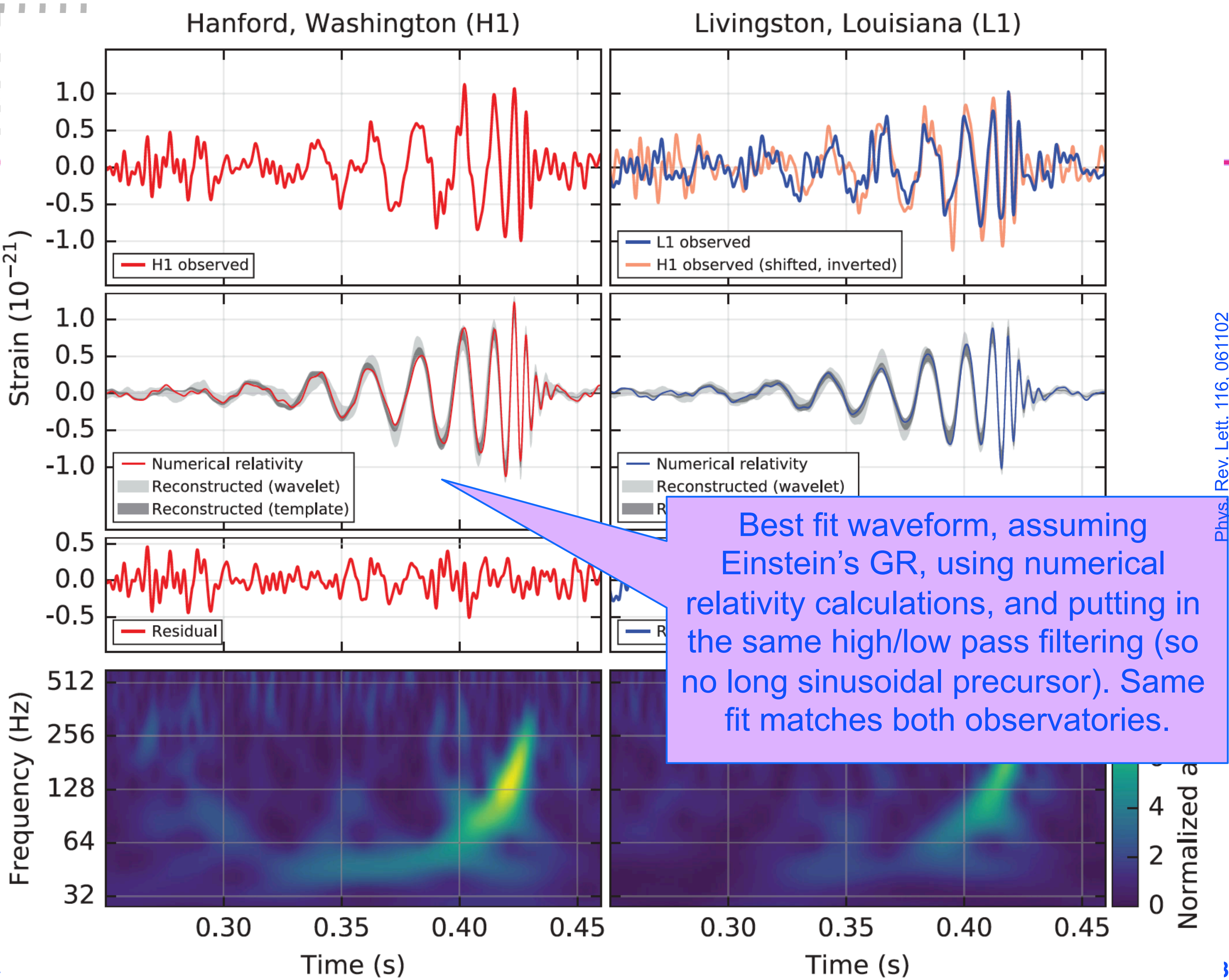


Time trace from Hanford, high- and low-pass filtered to make signal more evident. Signal in-band for ~0.2 secs. Amplitude ~1x10^{-21}

Phys. Rev. Lett. 116, 061102



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.



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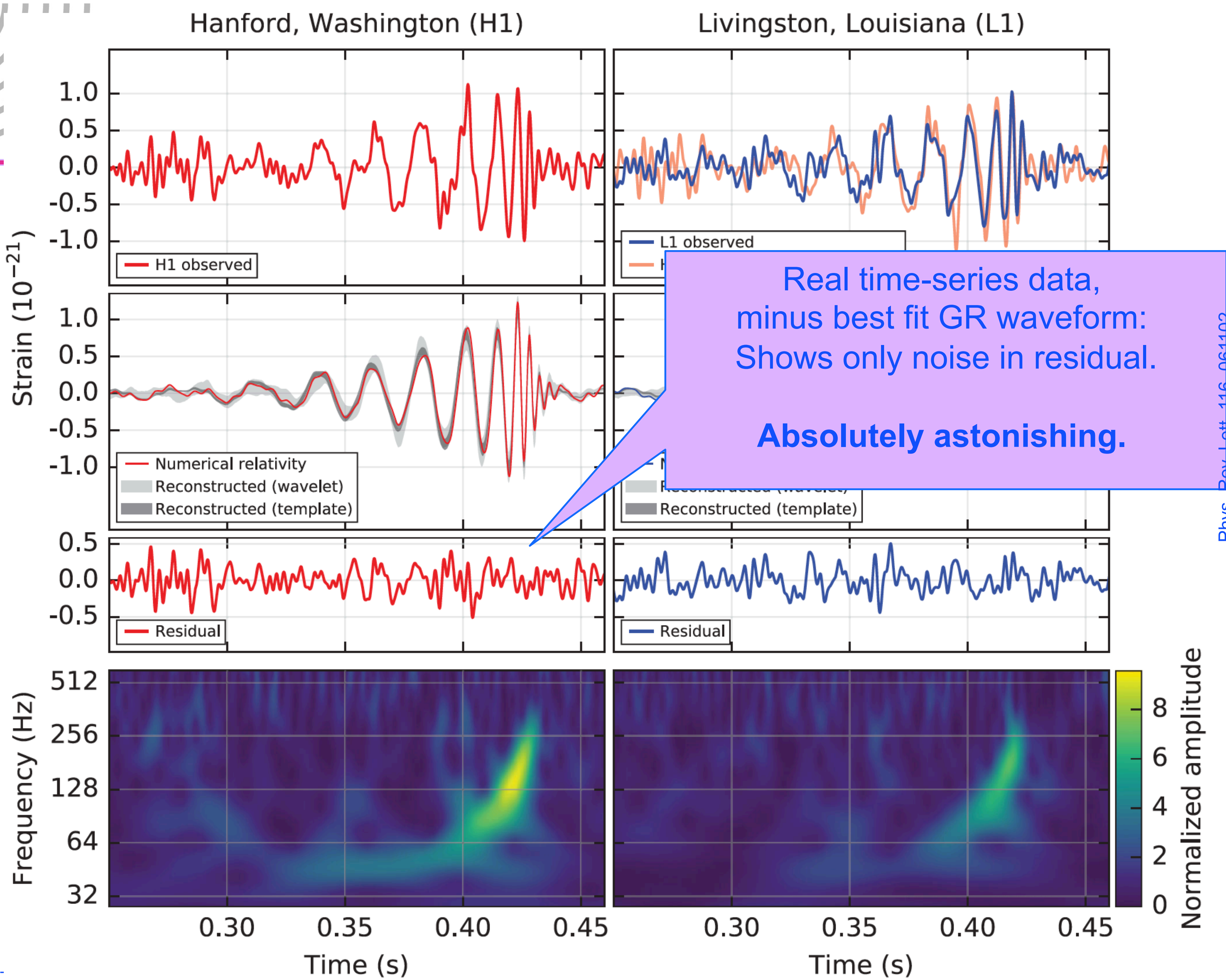
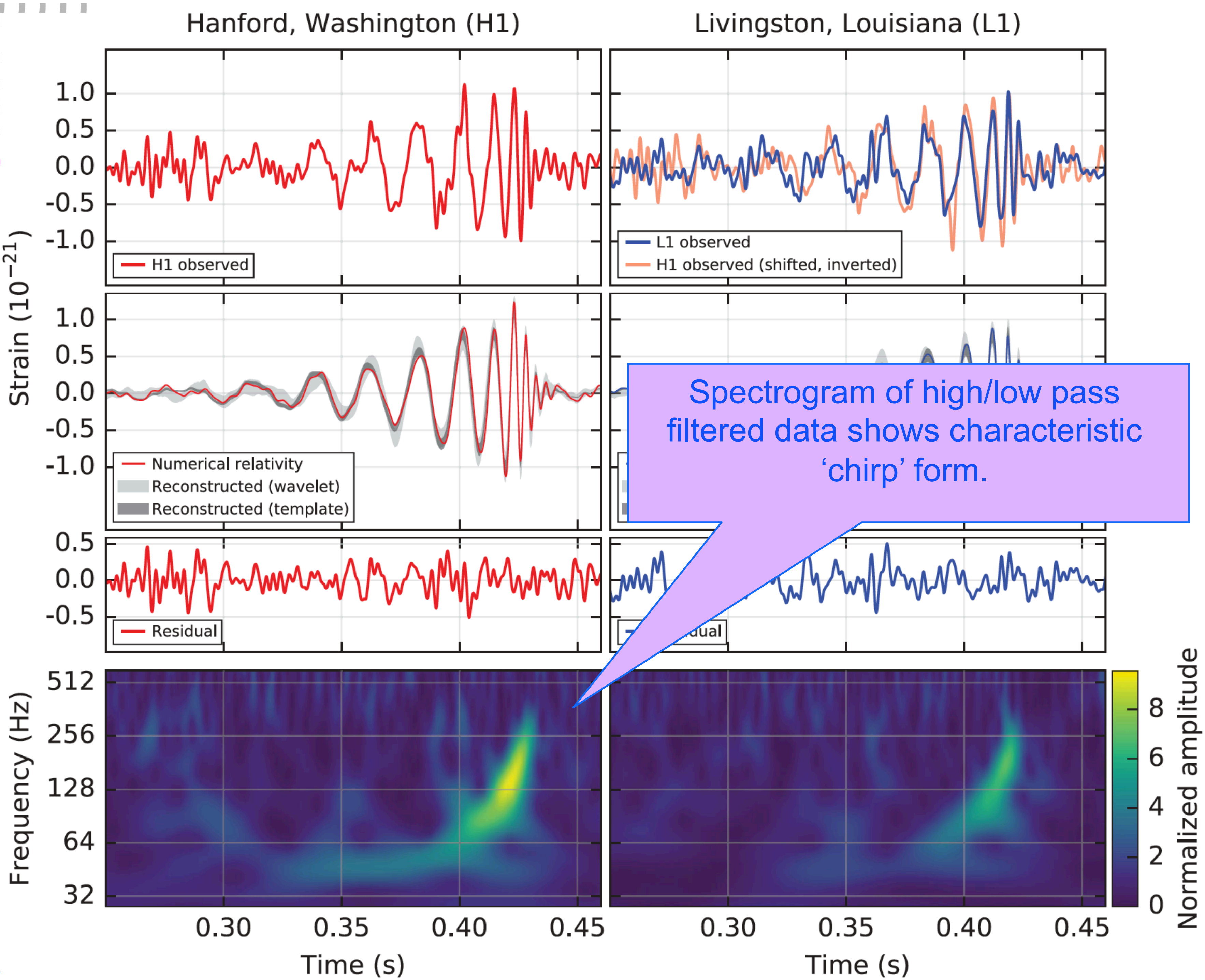


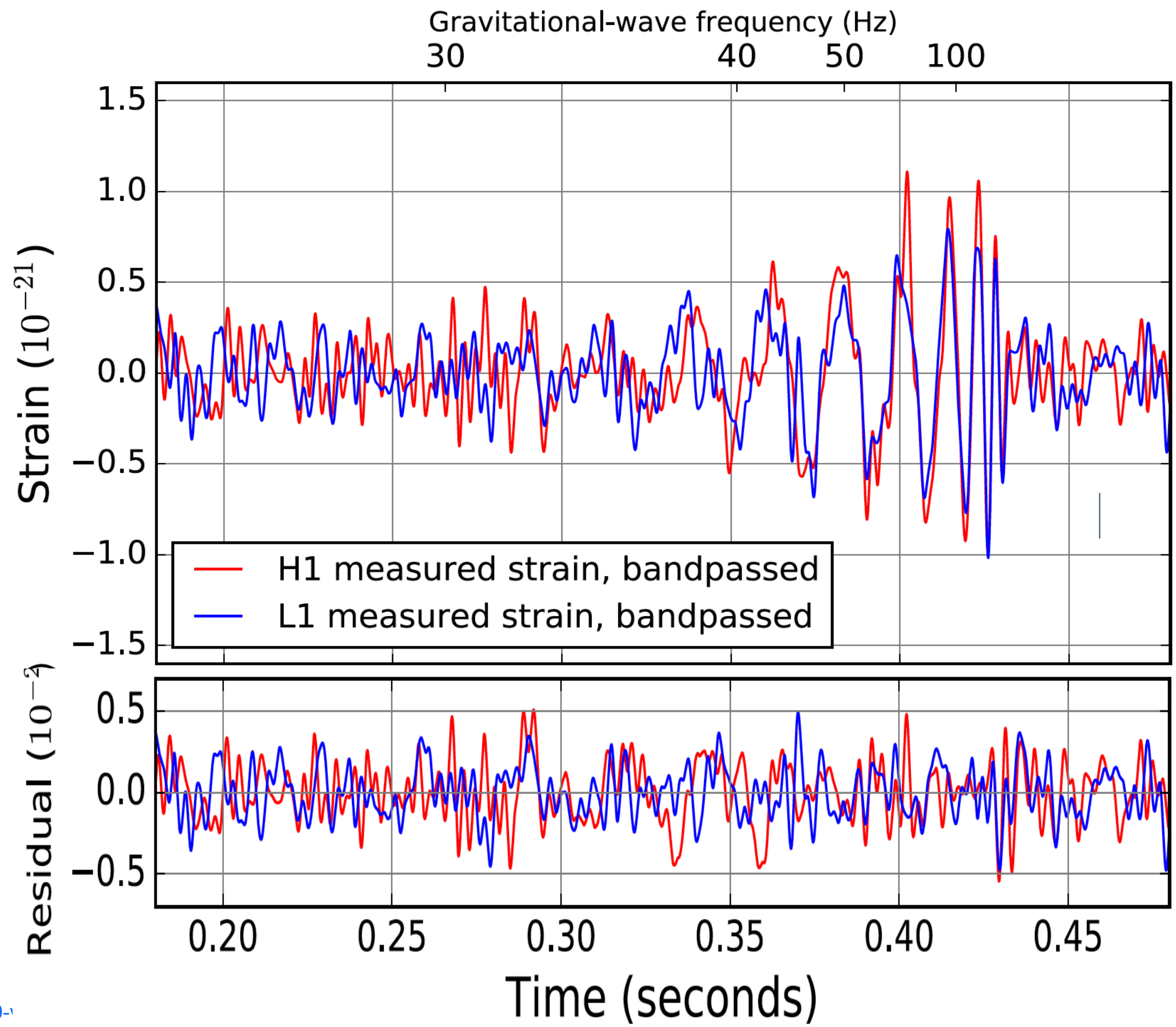
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Time (s)
Normalized amplitude
Real time-series data,
minus best fit GR waveform:
Shows only noise in residual.
Absolutely astonishing.
Phys. Rev. Lett. 116, 061102



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

Phys. Rev. Lett. 116, 061102

The two signals (LHO time shifted), and the two time series with GR/NR waveforms subtracted



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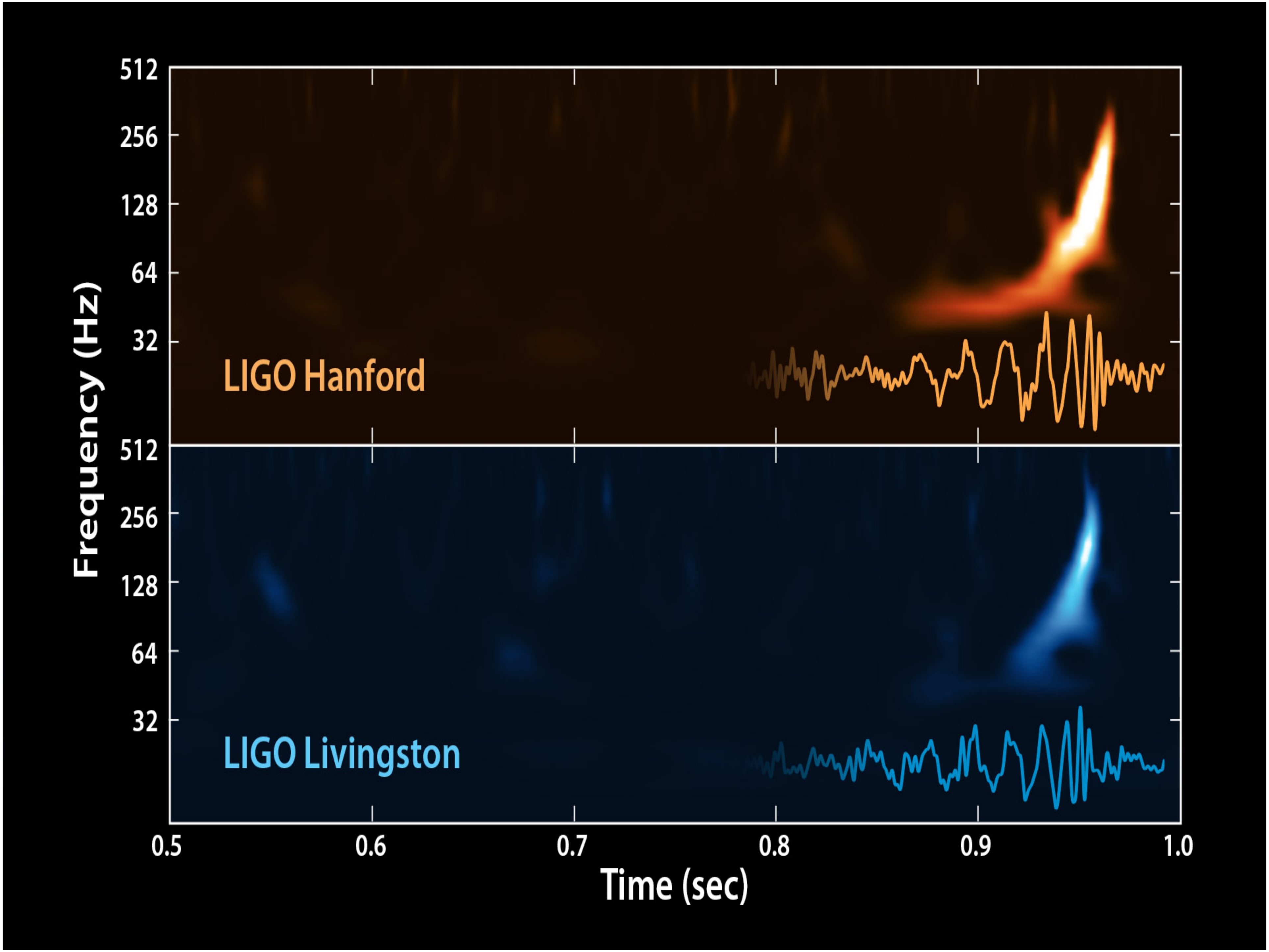
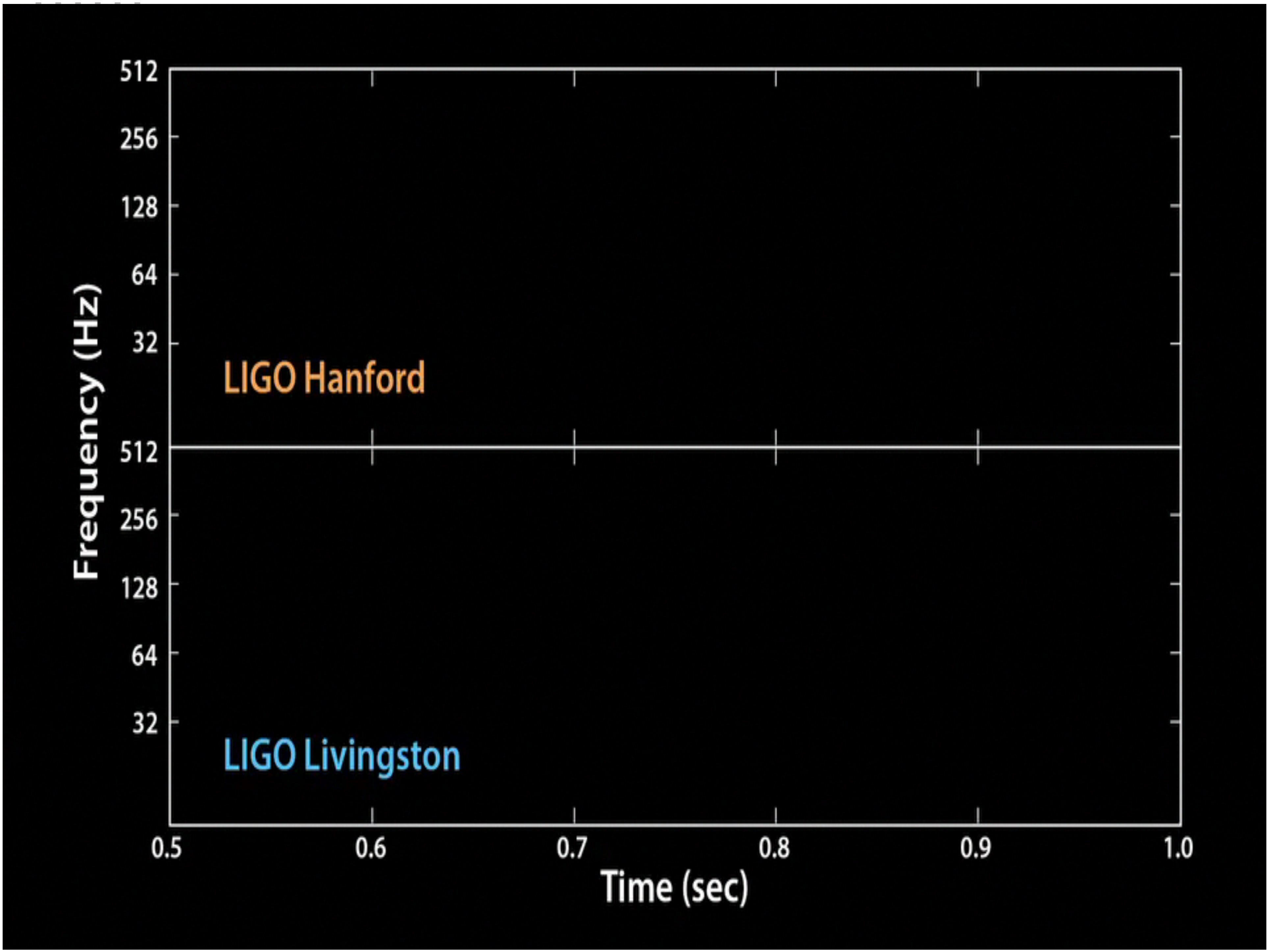

512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



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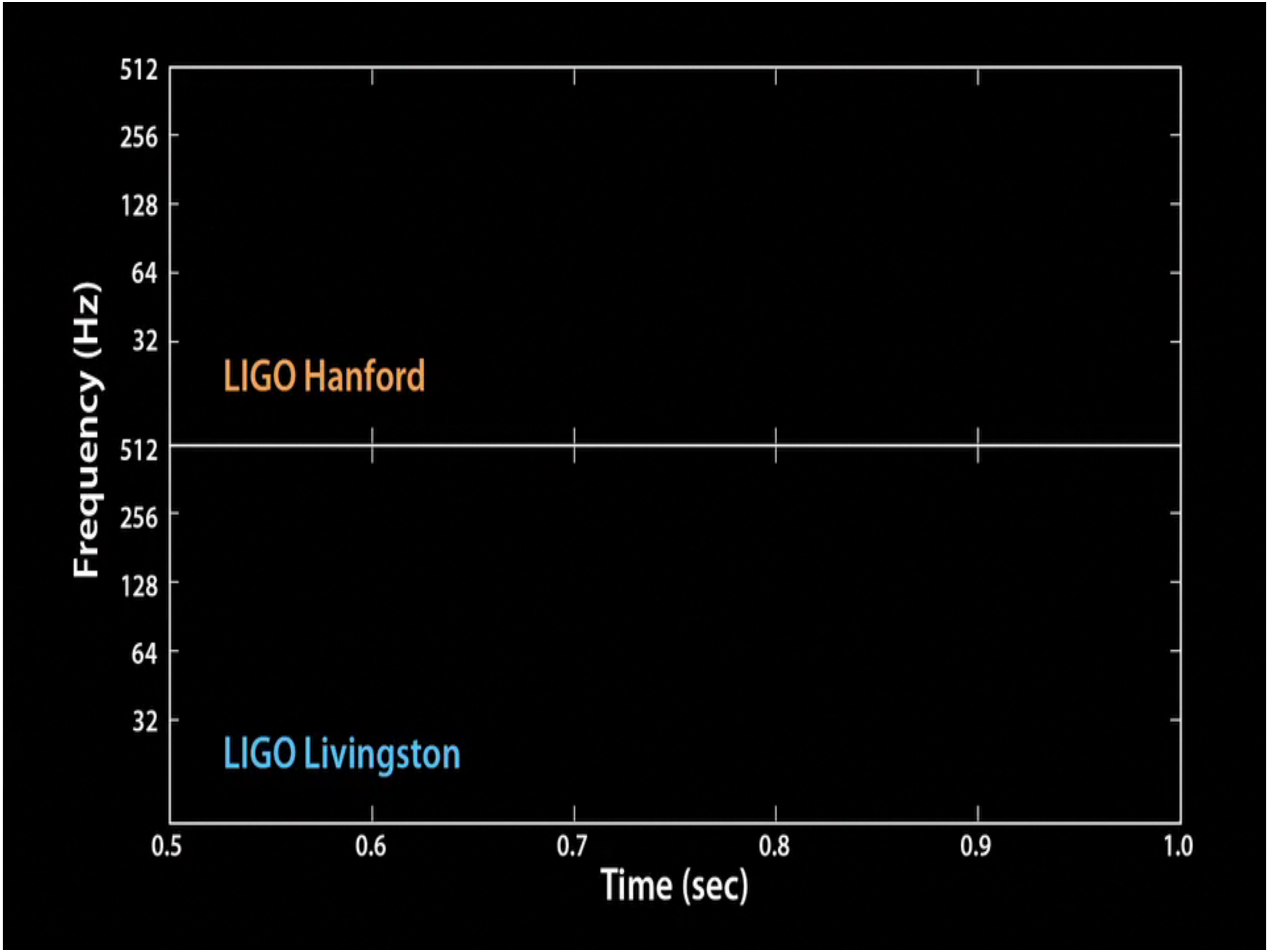
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64
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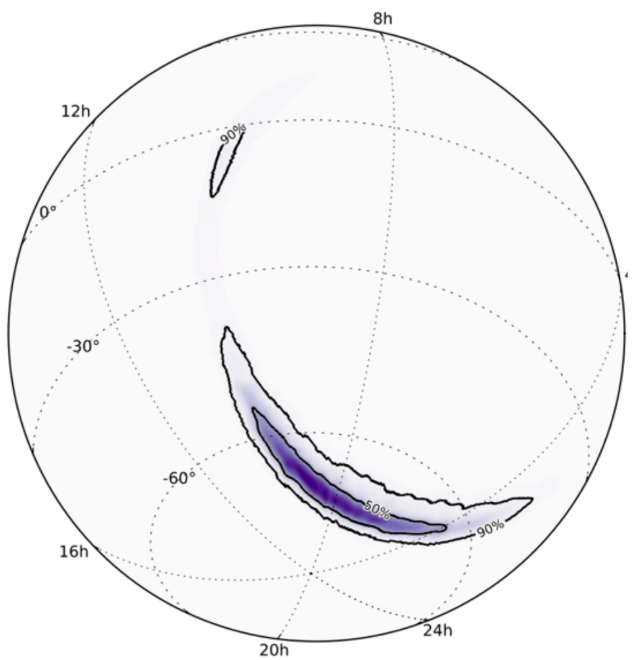
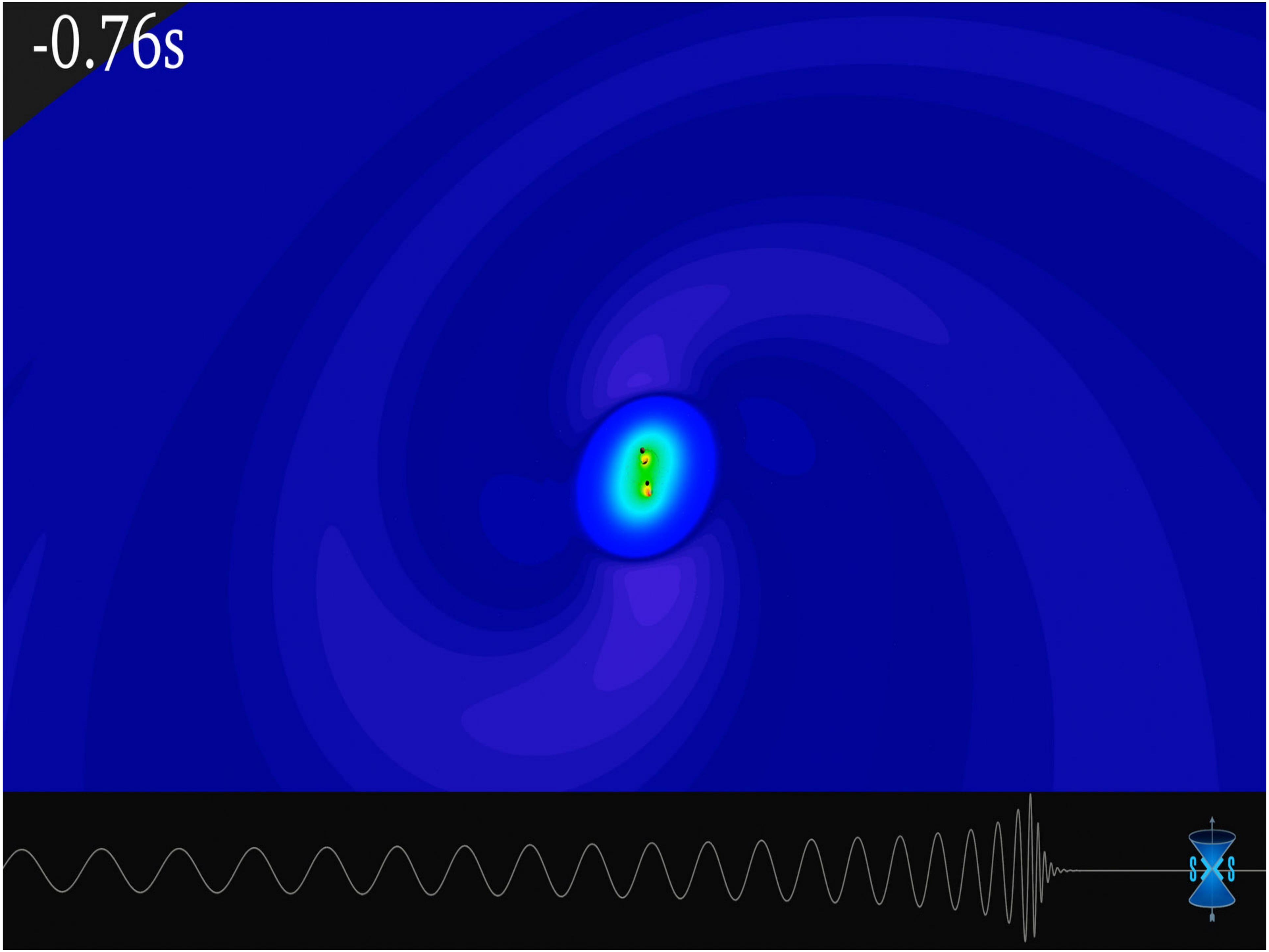
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

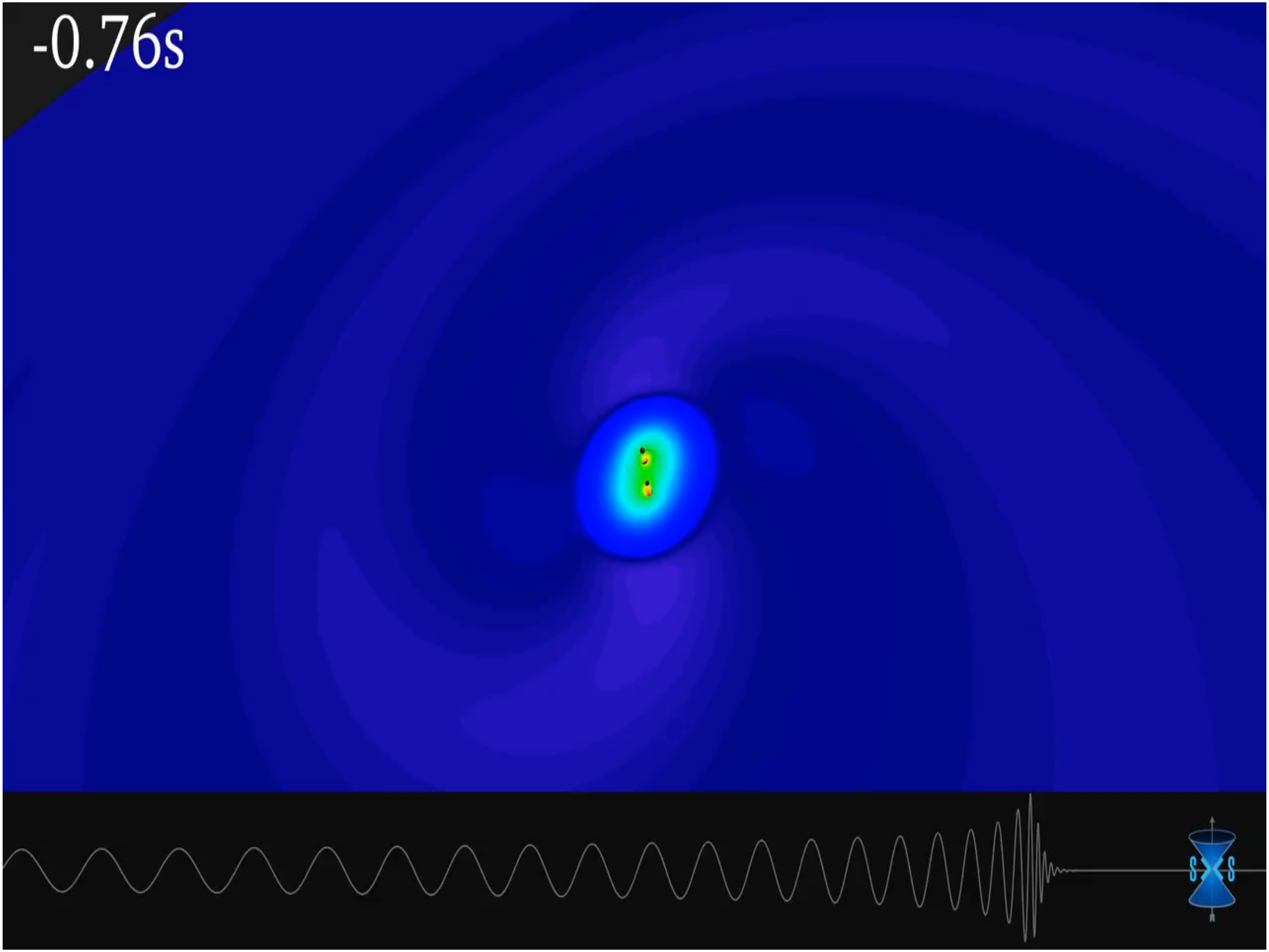
Source characteristics

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



- 3 $M_\odot$ radiated in GWs;
  36 + 29 = 62....+3
- Initial spins not well constrained ('face off' position)
- Degeneracy in position and distance (only 2 detectors… need additional detectors - Virgo!)
  - » In the Southern Hemisphere, an annulus with some preference in angle
- Can determine a rich set of conclusions due to
  - » 'time trace' of amplitude of strain,
  - » Absolute calibration of the instrument in strain, and
  - » Excellent match to GR


-0.76s


-0.76s

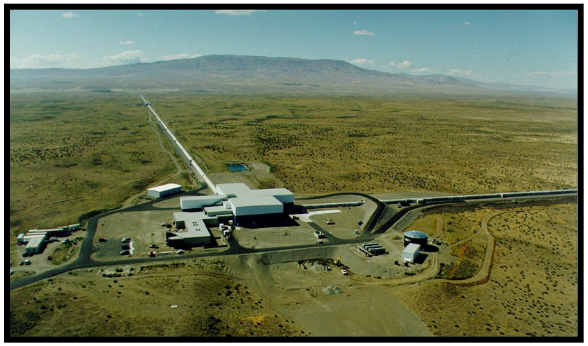
How do we know it is a real signal?

- Each LIGO observatory independently saw a signal, and the two were perfectly consistent
  - Same waveform (modulo instrument noise)
  - Timing (7.1 msec difference – within the 10msec time-of-flight)
  - Relative amplitudes consistent with instrument ‘antenna pattern’ and the inferred location on the sky
- The match of the signal with General Relativity – it was a very simple system with no deviations from GR
- The noise statistics of the instruments around the time of the signal show the signal could be chance no more often than every 200,000 years
- Careful characterization of the instrument environmental susceptibility (magnetic, EMI, cosmic rays, acoustics, etc.) with exhaustive monitoring
- Careful hardware inspections, occupancy tracking indicate no tampering with the instruments
- Careful inspection of the many inter-related channels of data show effective impossibility (and no evidence of) of insertion of a fake signal
- …skeptics should insist on additional signals!

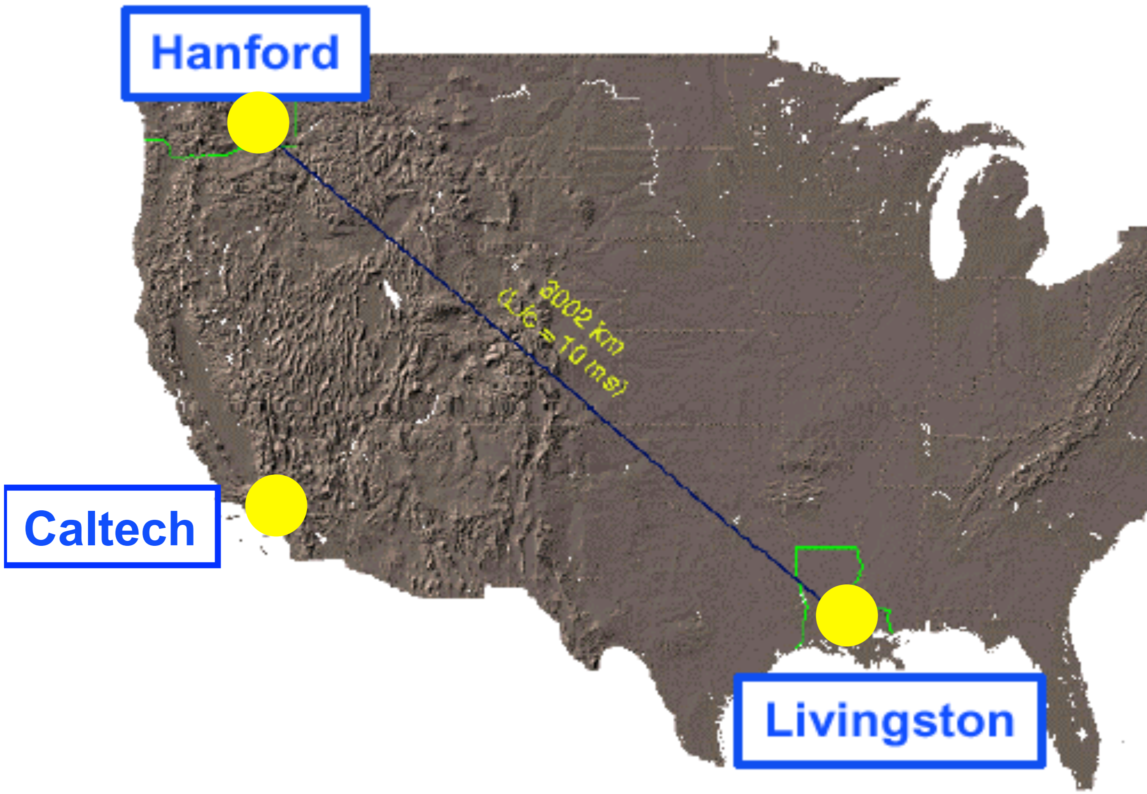
Gravitational waves and the bigger picture

- GWs are exceedingly weak, and (to our knowledge) have had little influence on the evolution of the universe
- GW most likely connection to ‘the bigger picture’ is as a ‘sensor’
  - Showing how large scale structure grows
  - Illuminating composition of e.g., neutron stars
  - New population of black holes may be the missing dark matter
  - Deviations from GR could shed light on dark energy
  - Any deviation from GR potentially incredibly impactful on e.g., unification of forces, string theories, and the like
- Primordial (i.e., from Big Bang) waves
  - Unlikely to make a direct detection in coming decades (small signal)
  - Ground-based ‘BICEP2’-like observations may well see an indirect signal in infrared cosmic background soon
  - Could shed light on the origin of the universe, string theories, etc.
  - Would be our earliest look at the universe

LIGO Laboratory:
two Observatories and Caltech, MIT campuses



- Mission: to develop gravitational-wave detectors, and to operate them as astrophysical observatories
- Jointly managed by Caltech and MIT
- Requires instrument science at the frontiers of physics fundamental limits



LIGO Scientific Collaboration

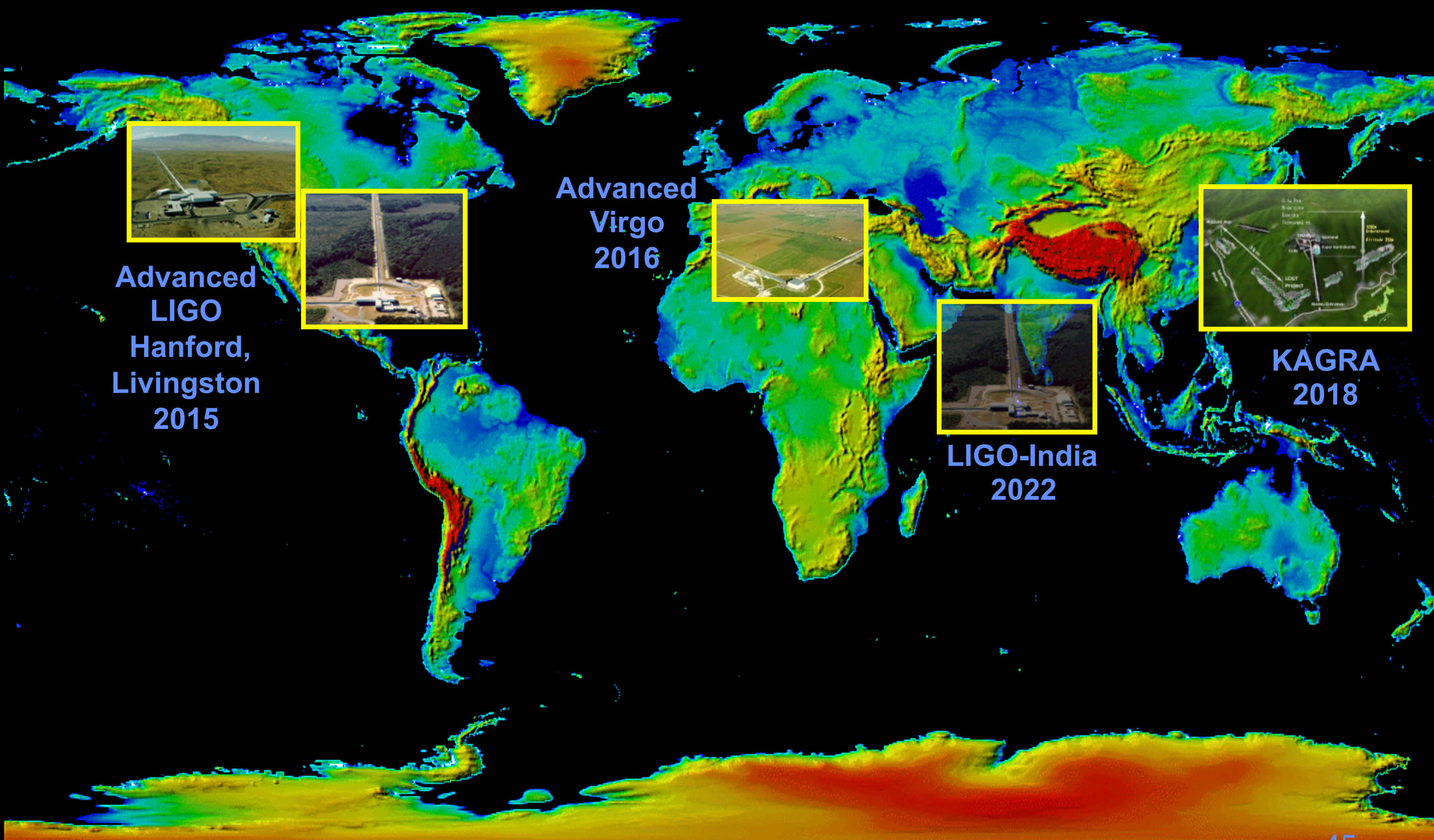
The LSC is the organization the conducts the science of LIGO

www.ligo.org

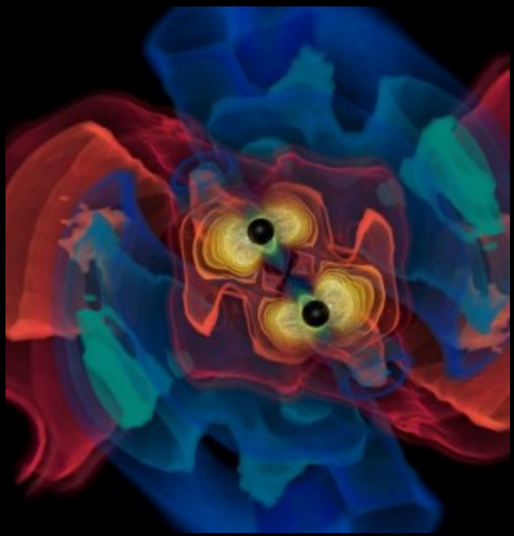
1000+ members, 90 institutions, 16 countries

Slide: Gabriela González

The advanced GW detector network



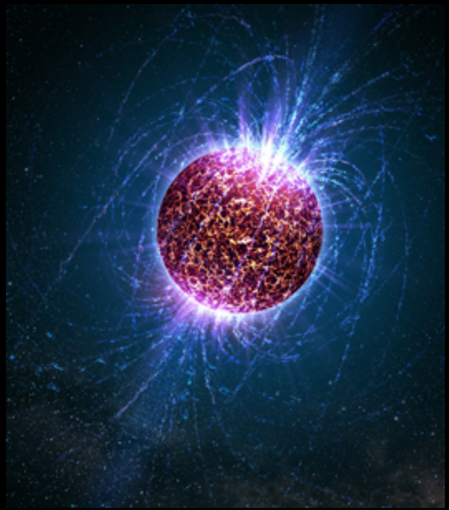
Astrophysical Targets for Ground-based Detectors



Credit: AEI, CCT, LSU

Coalescing Binary Systems

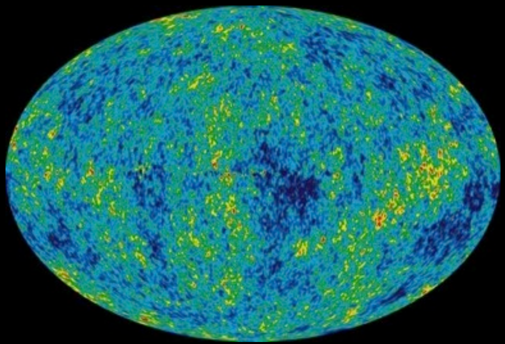
- Well-modelled
- Neutron stars, low mass black holes, and NS/BS systems



Casey Reed, Penn State

Continuous Sources

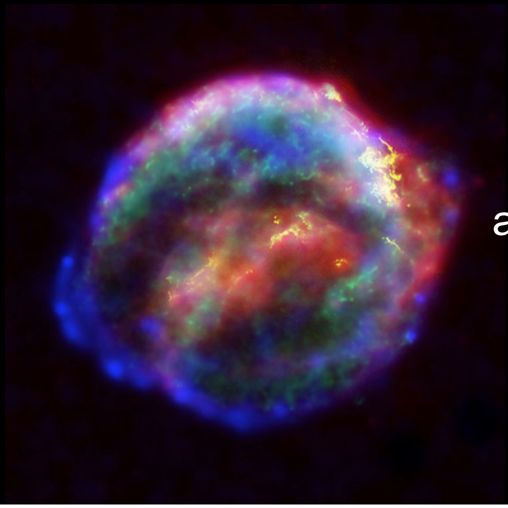
- Essentially Monotone
- Spinning neutron stars
- probe crustal deformations, equation of state, 'quarki-ness'



NASA/WMAP Science Team

Stochastic GWs

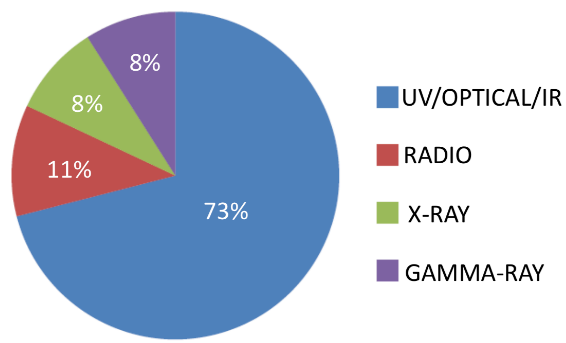
- Noise
- Incoherent background from primordial GWs or an ensemble of unphased sources
- primordial GWs unlikely to detect, but can bound in the 10-10000 Hz range



'Bursts'

- Unmodelled
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???

Working toward multi-messenger astronomy with gravitational waves



- About 60 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….

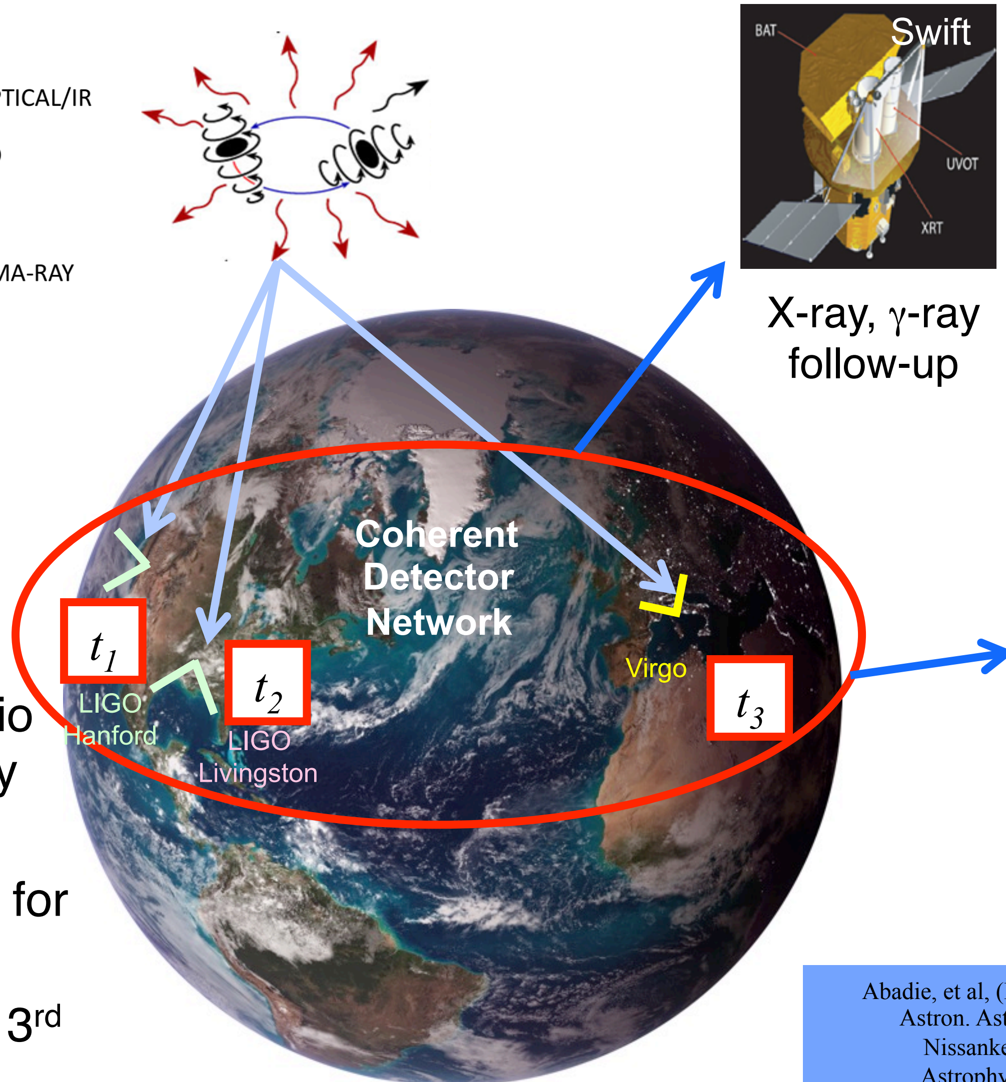


Image: http://earthobservatory.nasa.gov/

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.

Contrast of Information from 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

Contrast of Nature
Electromagnetic vs. Gravitational Waves

- **Electromagnetic (light etc.)**
  - Speed of light
  - Action is transverse to direction of propagation
  - Polarizations at 90^{O}
  - Two charges, +, –
  - Source: Accelerating charge
  - Measurable signal from one electron shaking at modest speeds
  - Signal (photons) travels in space-time

- **Gravitational waves:**
  - Speed of light
  - Action is transverse to direction of propagation
  - Polarizations at 45^{O}
  - One charge: mass
  - Source: Accelerating masses
  - Measurable signal requires a star shaking at nearly the speed of light
  - Signal (gravitons) *is* space-time warping

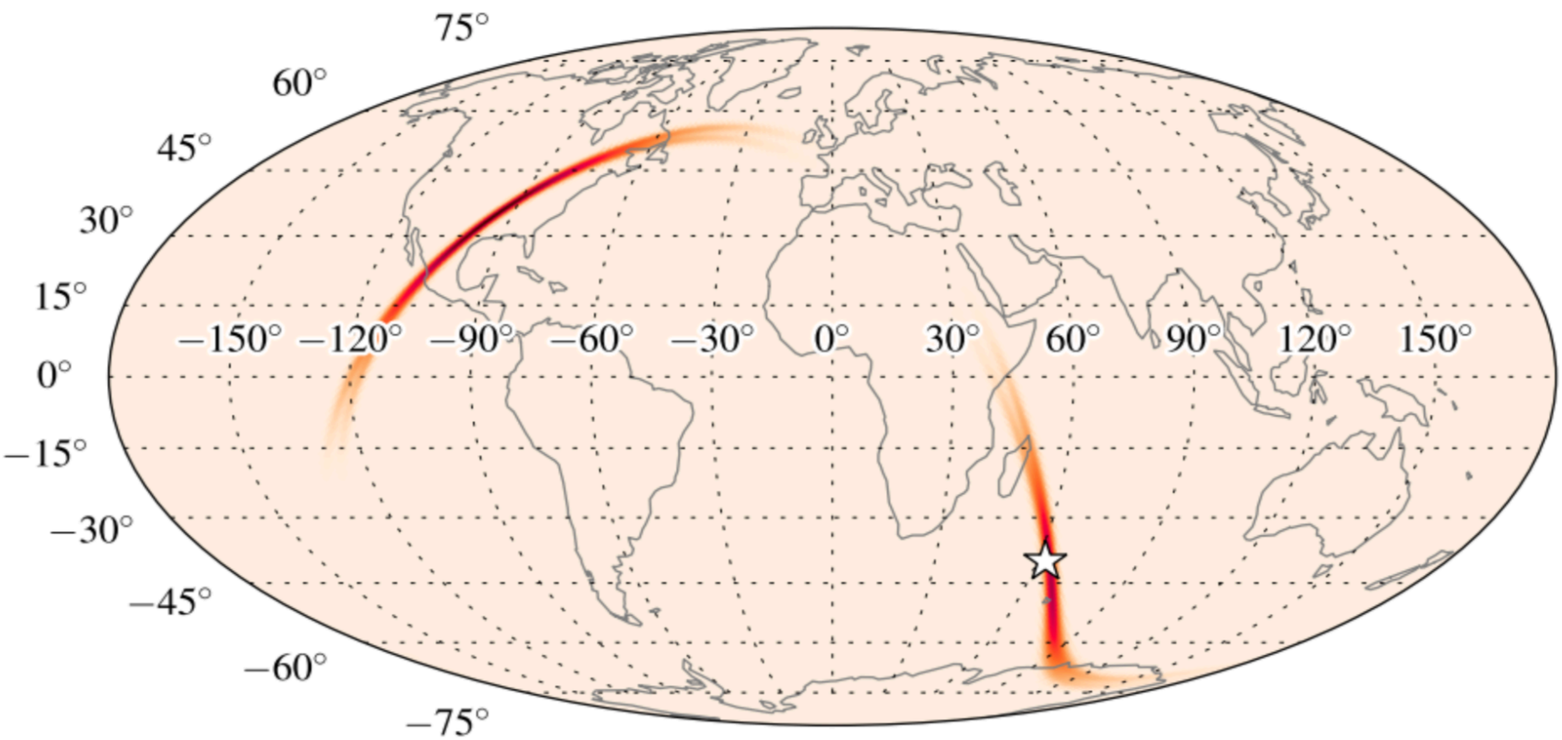
Intriguing parallels and differences

LIGO

What does the future hold?

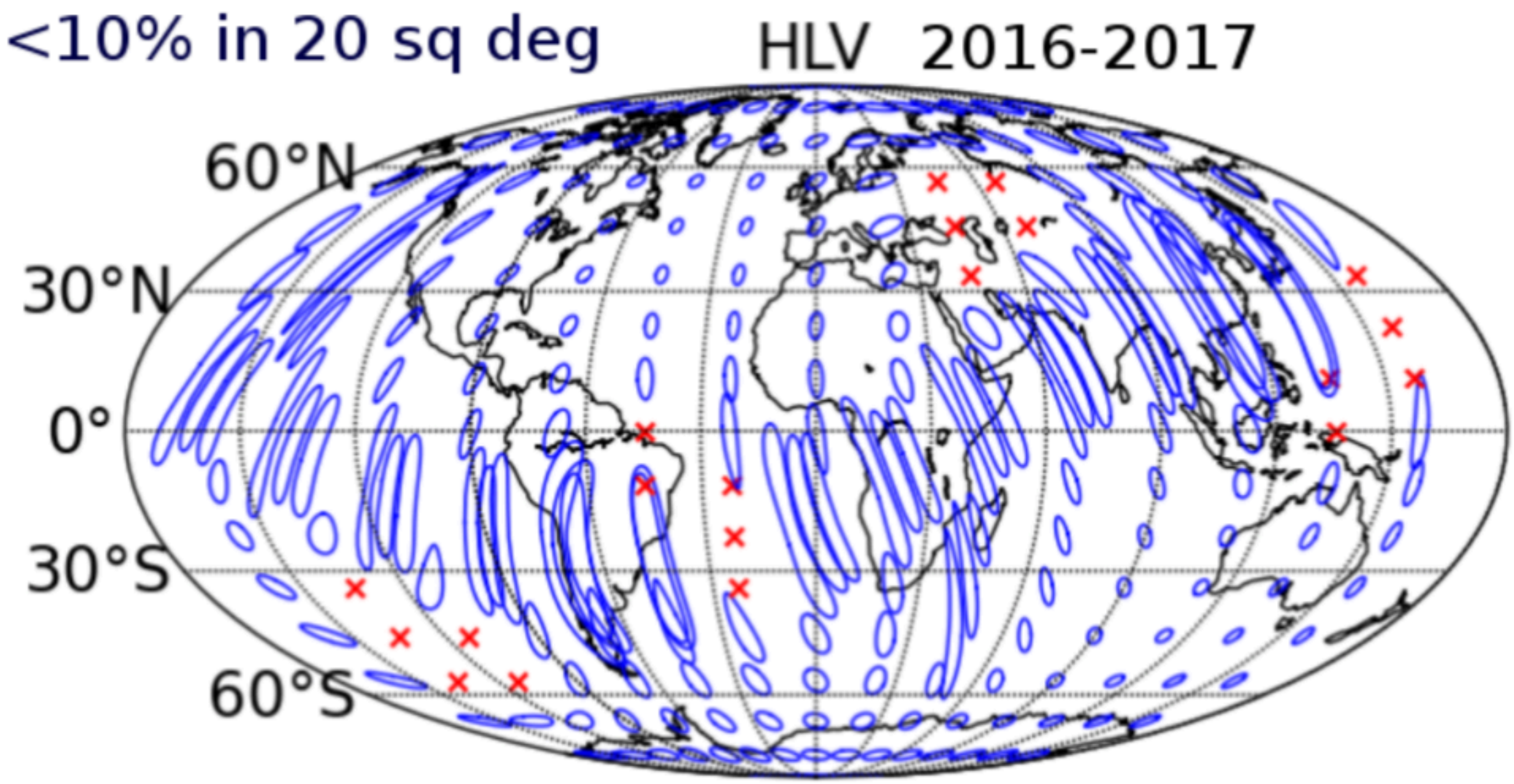
Present Sensitivity/configuration:

2 detectors, 1/3 goal sensitivity
1 signal in 1 month of observation



2016-17 Sensitivity/configuration:

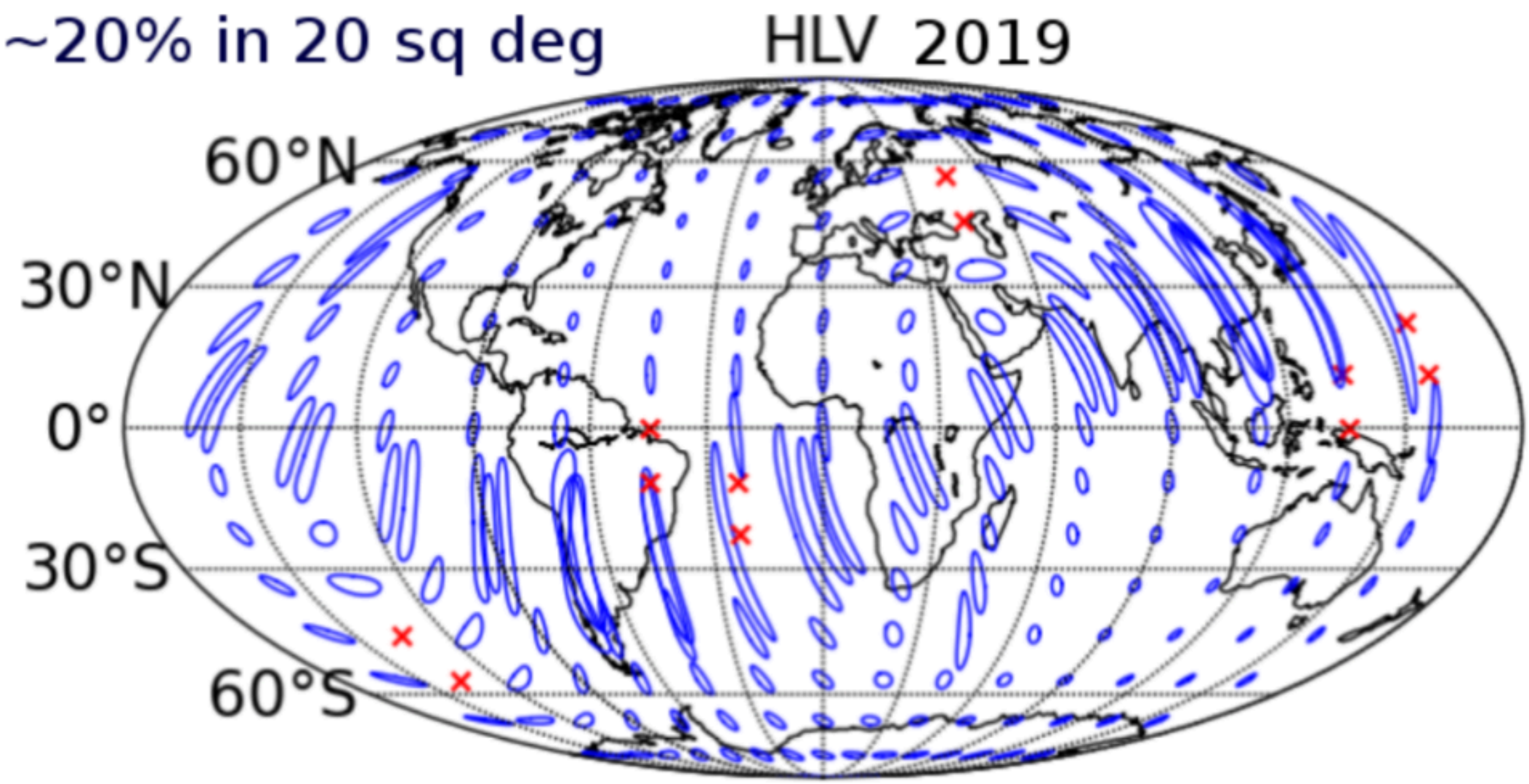
3 detectors (add Virgo), ~1/2 goal sensitivity
~2-3 signals per month of observation



http://relativity.livingreviews.org/Articles/lrr-2016-1/

2018-19 Sensitivity/configuration:

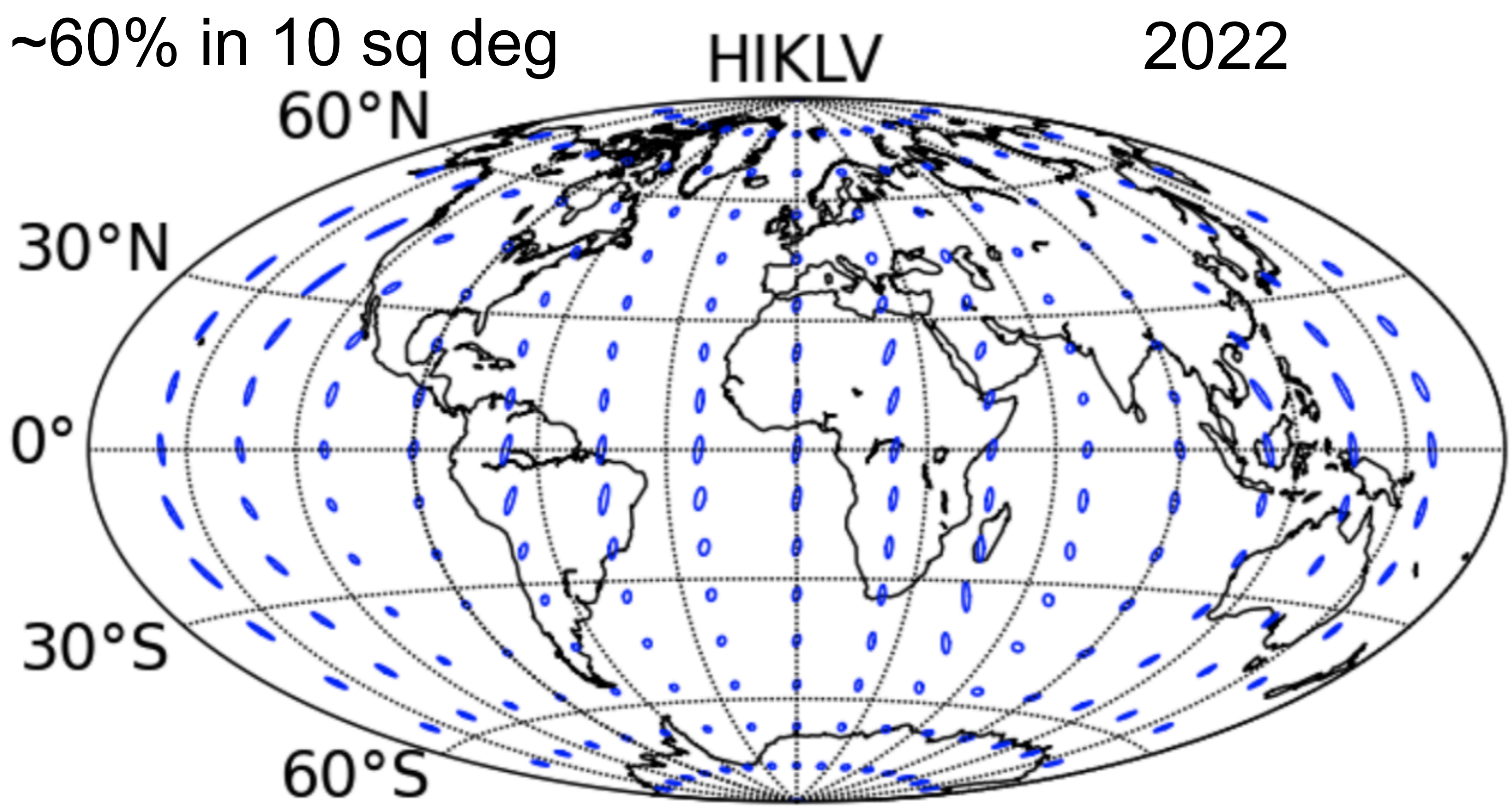
3 detectors, **full goal sensitivity**
~1 signal *per day*



http://relativity.livingreviews.org/Articles/lrr-2016-1/

2022 Sensitivity/configuration:

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

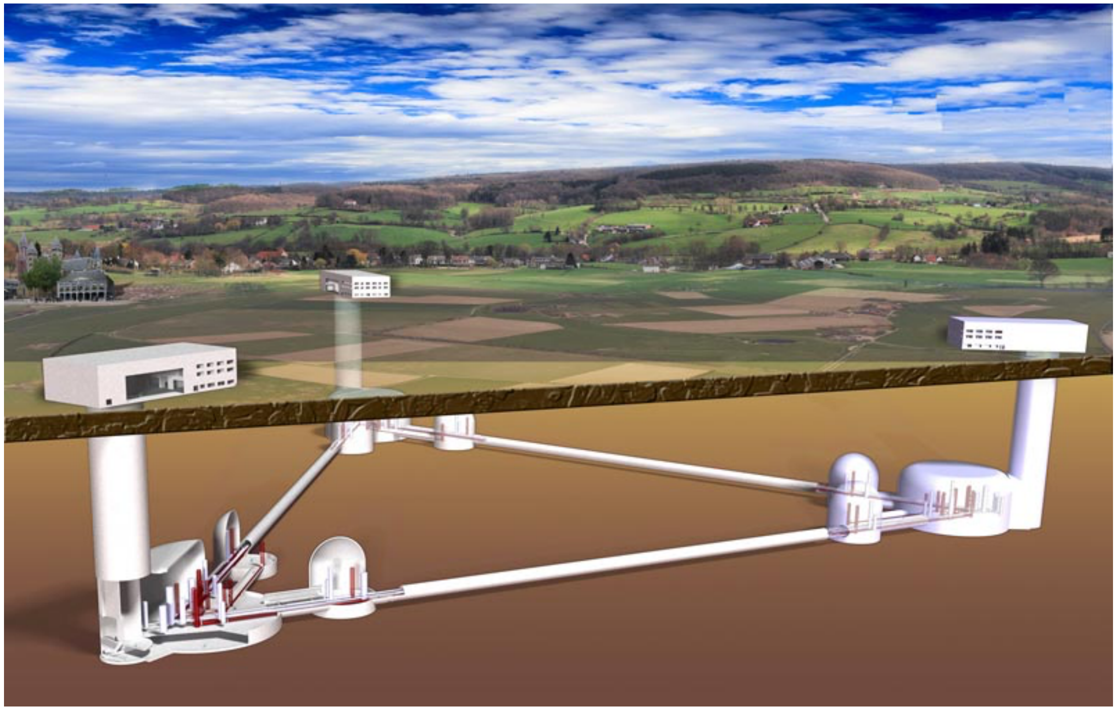


http://relativity.livingreviews.org/Articles/lrr-2016-1/

Future Improvements: Reaching even further

- Want to fully exploit the instrument we designed
- **But then we will all want more sensitive detectors!**
- R&D continuing; see paths to yet better sensitivity near-term and longer-term
- Factor ~1.7 in sensitivity: possible as early as 2018 ("A+")
  - Would give increase in event rate of ~5
- Use of squeezed light expected (and demonstrated)

- Factor 10: perhaps by 2035
- Underground construction?
- A longer baseline, e.g. 4 → 40km
- Almost all noise sources stay constant –
  but signal grows a factor of 10
- Models indicate feasibility
- Need to establish field first!



...and a detector in Space: **LISA**

- Once you are there, vacuum is inexpensive – make *very* long arms
  - This makes for very large signals
  - Also focuses on long GW-wavelengths – this means low frequencies and very large masses will be the signal sources
- A Triangle of spacecraft makes a good 'single point' observatory possible

LIGO

More on Space

- A 50-50 joint NASA ESA GW Space mission – LISA – was cancelled in 2011 due to cost overruns elsewhere in the NASA science budget
  - » Not the only cancellation at that time
- ESA now planning a mission (“L3”) with a nominal 2034 launch date
  - » NASA currently a 10% partner
- Limitations to ground-based GW antennas will:
  - » Limit best signal-to-noise we can achieve, so can only e.g., test GR so far, probe to a finite level of detail neutron-star inspirals, etc.
  - » Limit the lowest GW frequency we can detect, so e.g., cannot explore mergers of entire galaxies and other very massive objects
- Analogous to adding Radio Astronomy to Optical Astronomy

- This is currently being studied by the Astronomy mid-decadal review to see if we have
  - » An appropriate timeline (might be able to pull in launch date)
  - » An appropriate level of US participation

Take Home (i.e., to DC!) Message

- Ensure some programs in funding agencies are designed for high-risk high-reward research, and capable of decades of continuity
- Enable scientists with vision – backed up by sound proposals – to undertake risky projects
- Ensure that program managers in funding agencies may, and are *encouraged*, to act as advocates for programs in funding agencies
- Recognize scientific leadership as a discipline to be taught
  - …and require schooling for leaders for big projects
- Facilitate the transition from small to Big science where needed
  - Again, teach this to PIs and 'middle managers' in Big Science
- Fund projects robustly, with contingency – but then require build to cost
- Provide stable career paths for professional (non-faculty) scientists
- Ensure the sponsor review process is productive: transparency on the part of the scientists, and a vision of collaboration and support from sponsor
- Require System Engineering, internal QA, quality documentation as core elements of Big Science proposals, plans, and reviews