Precision measurement from Einstein — and for Einstein

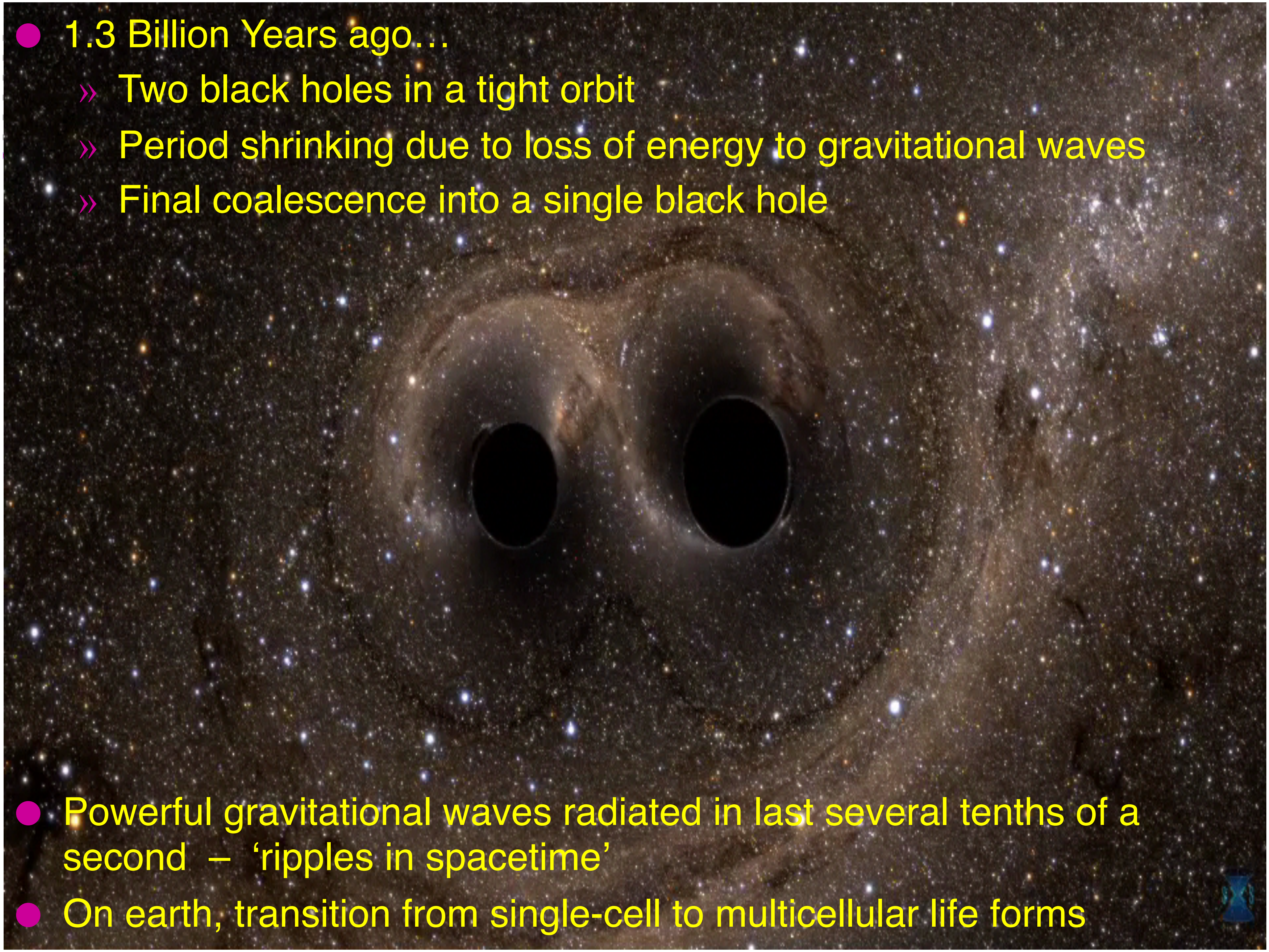
ESS Lund
29 September 2016

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

LIGO-G1601984-v1

- 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

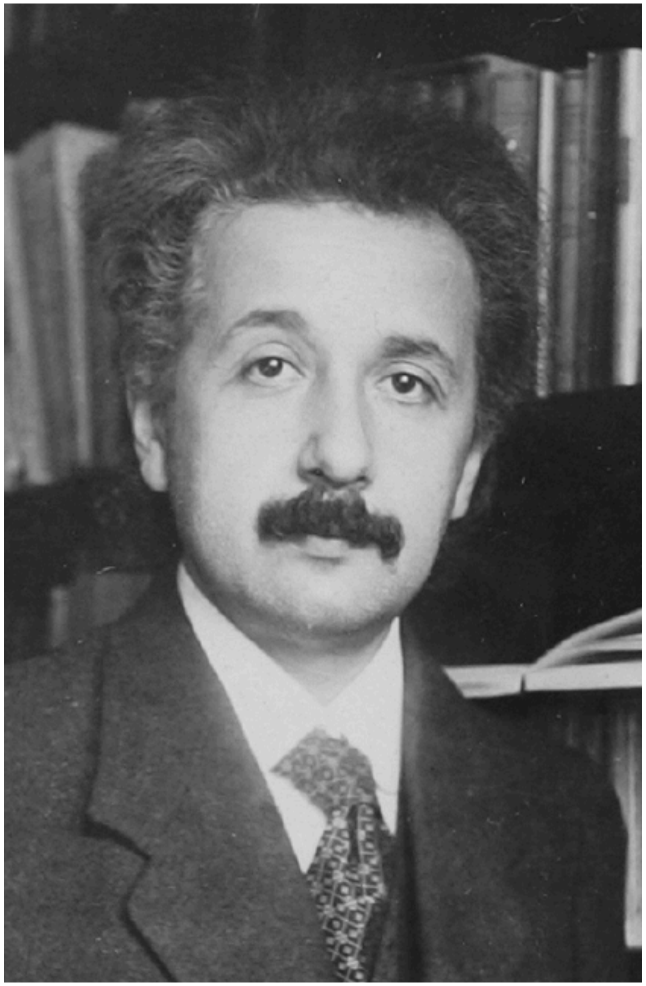
100 years ago

- Albert Einstein is evaluating and processing patent applications…
  - …for transmission of electric signals and electrical-mechanical synchronization of time
  - Musing on relative motion of electromagnetic 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.

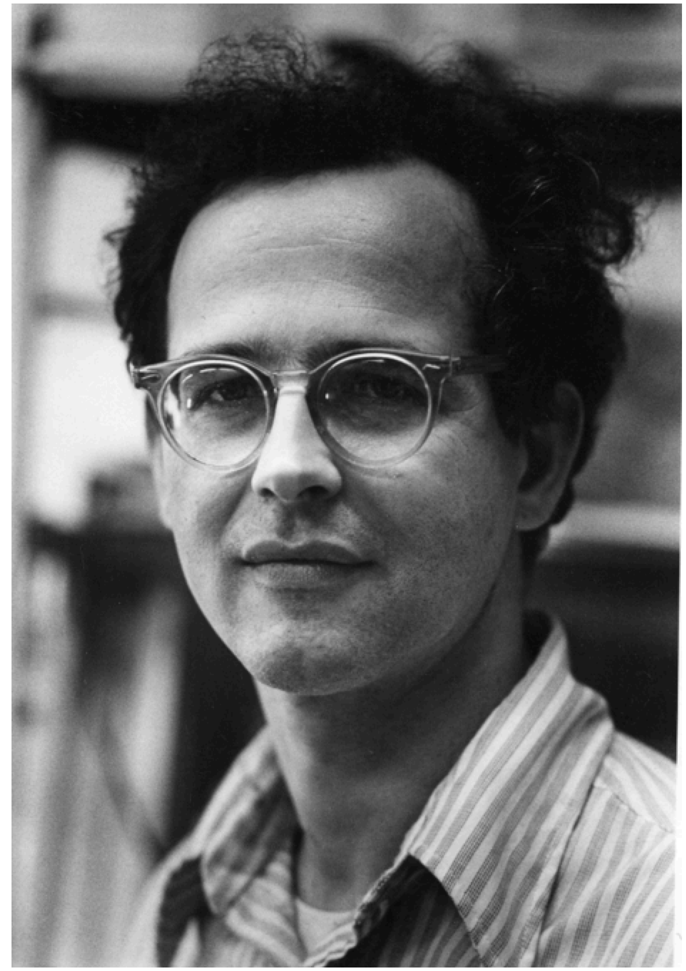
Von A. Einstein.

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



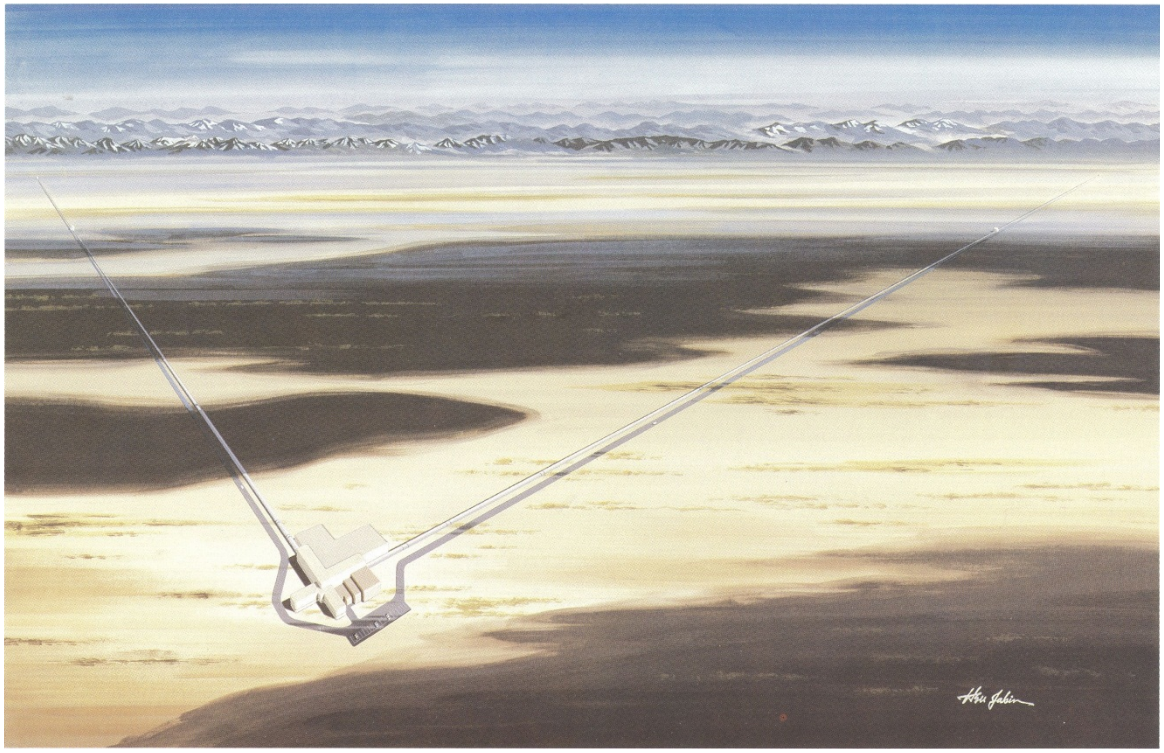
A Half-Century ago

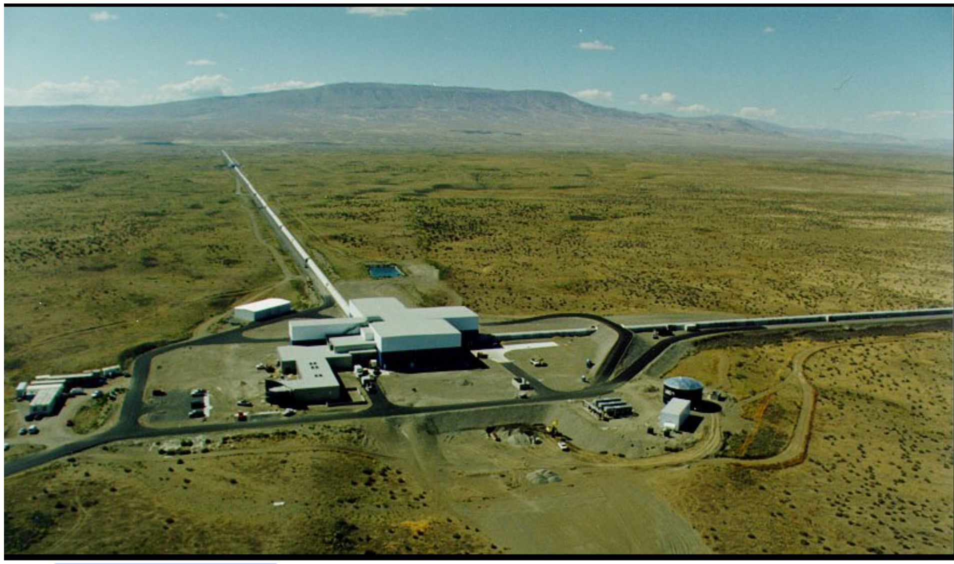
- Several scientists think of using laser interferometry to detect GWs
- Rainer Weiss of MIT invents the idea as a homework problem for students learning General Relativity
- He does the homework, and spends a summer fleshing out the idea
- **In 1972, Weiss publishes an internal MIT report**
  - Sets 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 →

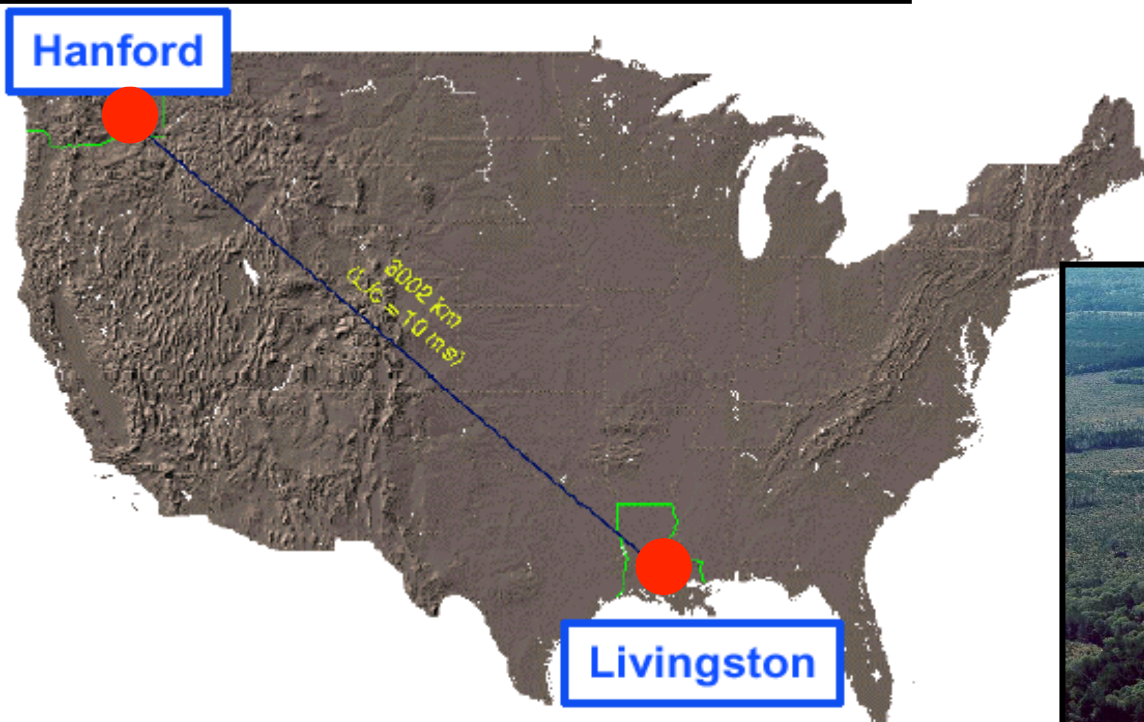




LIGO Laboratory

– Caltech, MIT –

built observatories in ‘90s, and…



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

LIGO-G1601984-v1

nothing

Initial Detectors

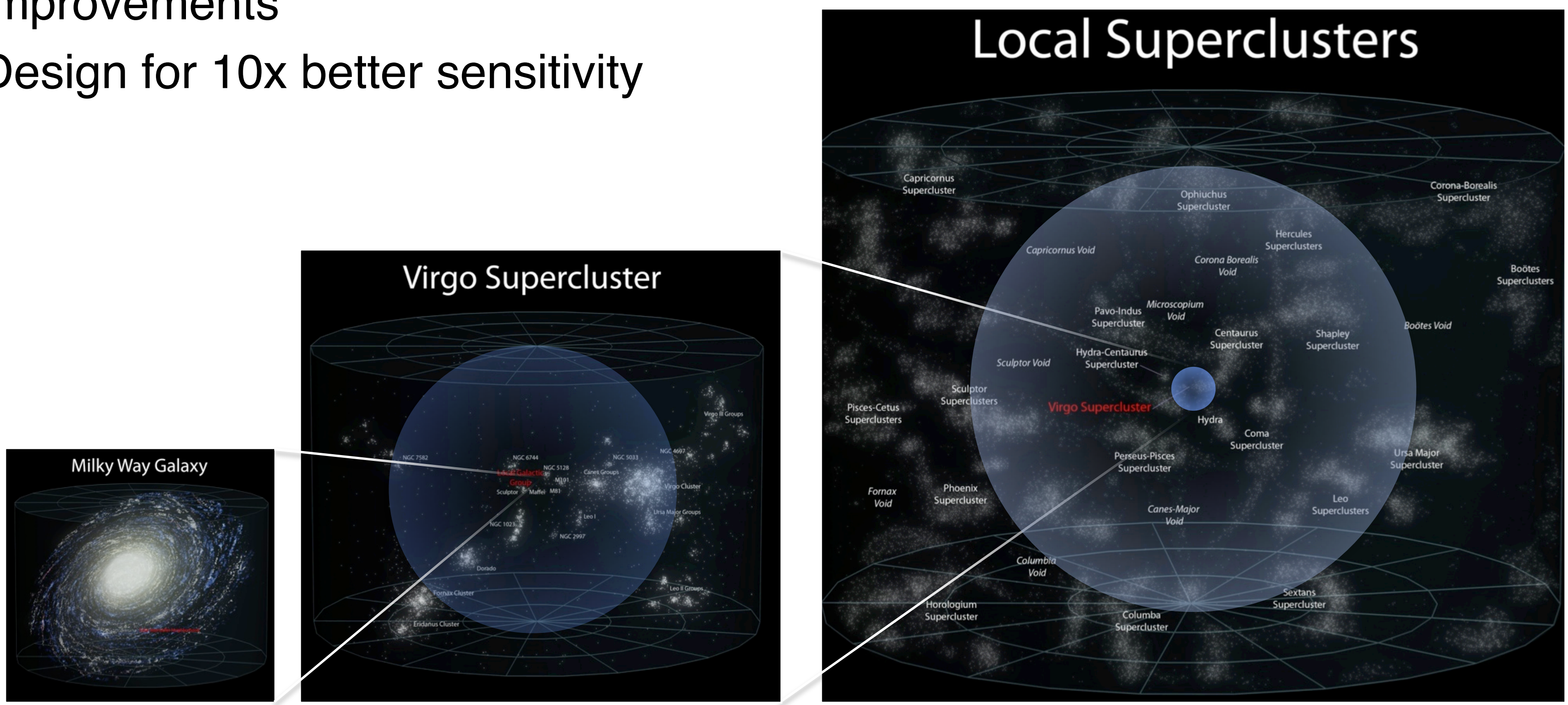
- That is to say, we saw no gravitational-wave signals.
  - We learned how to build and commission detectors
  - We learned how to analyze the data
  - We created new upper limits and significant ‘non-detections’

…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

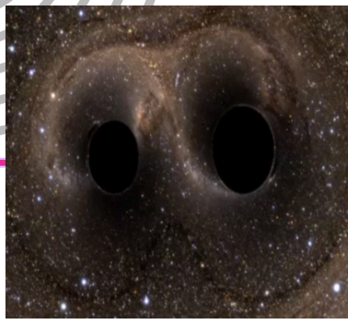
Initial Reach

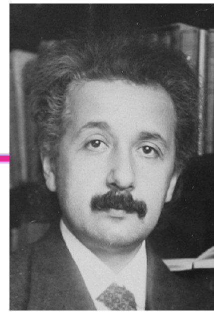
Advanced Reach

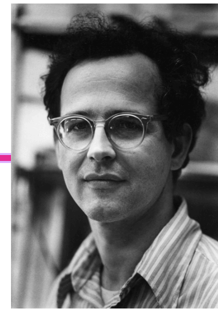
10 years ago

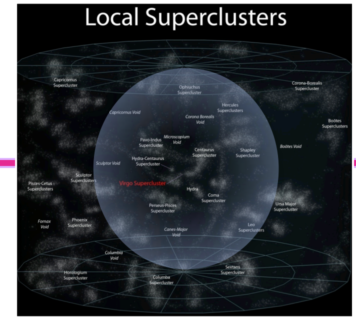
- Advanced LIGO conceived in 1999, funded in 2006: a $205M upgrade of all components, 10x better sensitivity

- Initial LIGO is taken down in 2011, installation starts for Advanced LIGO
- Completed March 2015, initial tuning for sensitivity goes very well









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...

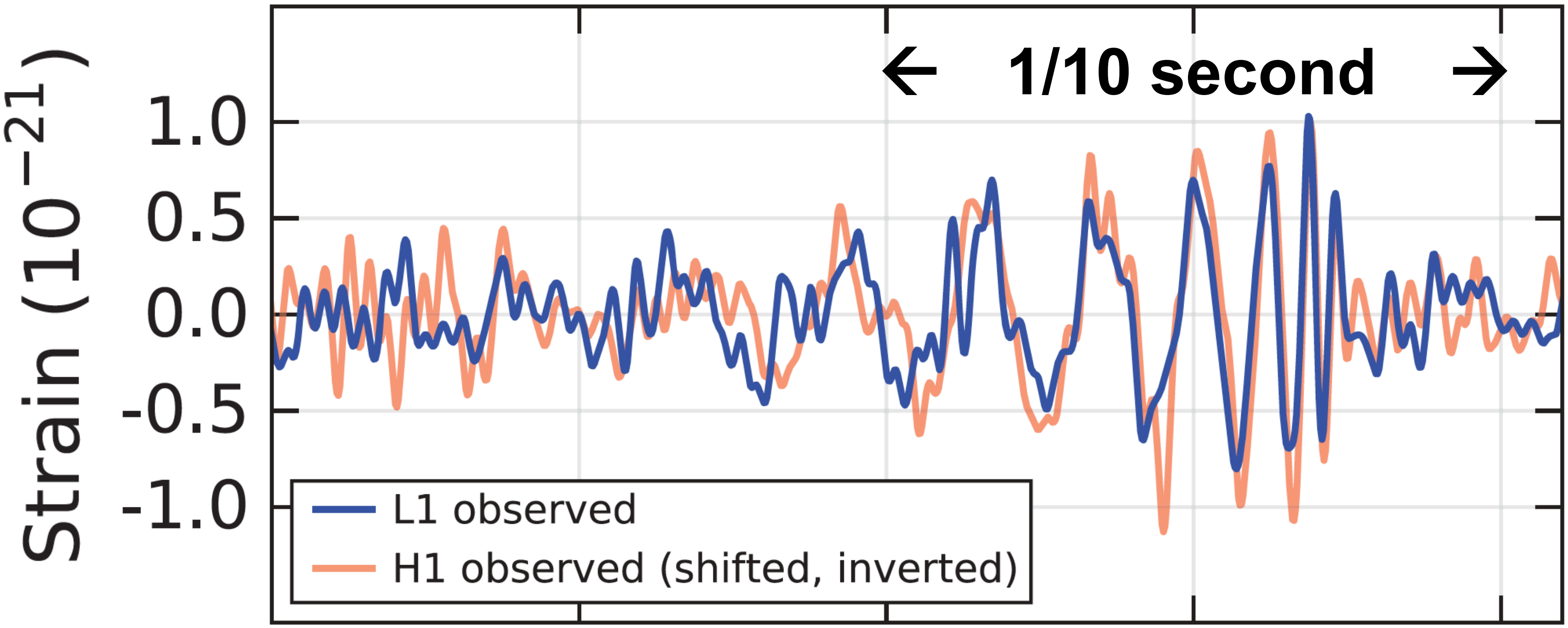
10 years after Advanced LIGO got the ok...

6 months after starting detector tuning...

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

LIGO's first signal

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

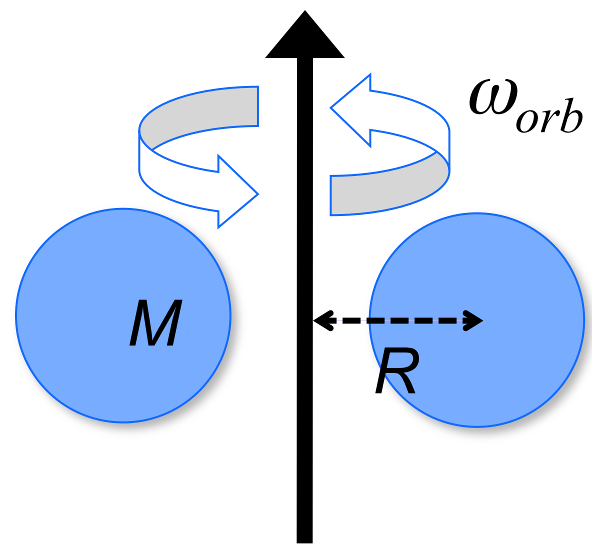


What are Gravitational Waves?

- 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

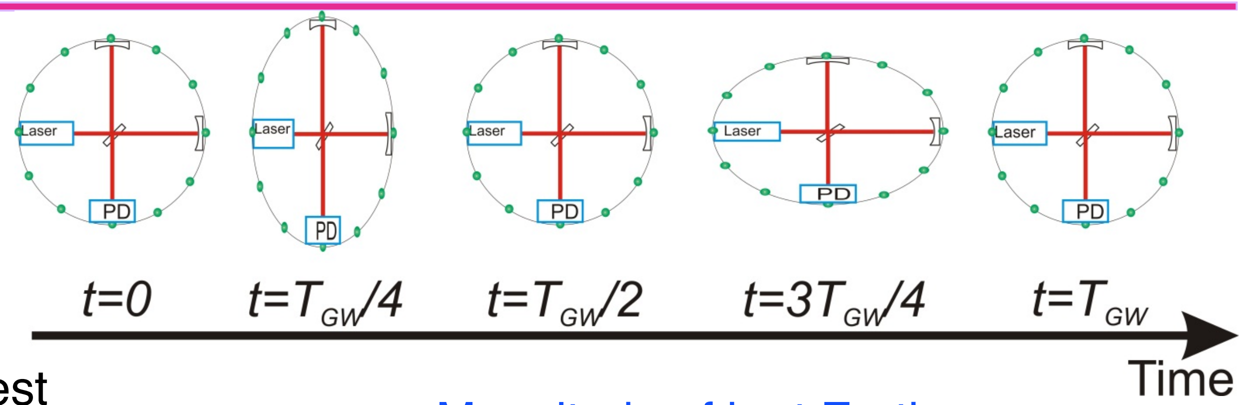


Rotating Dumbbell: $h \approx \frac{8GMR^2\omega_{orb}^2}{rc^4}$

- Space is very stiff; h is ~10^{-21} for say Neutron Stars in Virgo Cluster
  - …or two ~30-solar-mass Black Holes at 420 Mpc...
- Measurable GWs can only be expected from the coherent bulk motion of matter in the highly relativistic regime

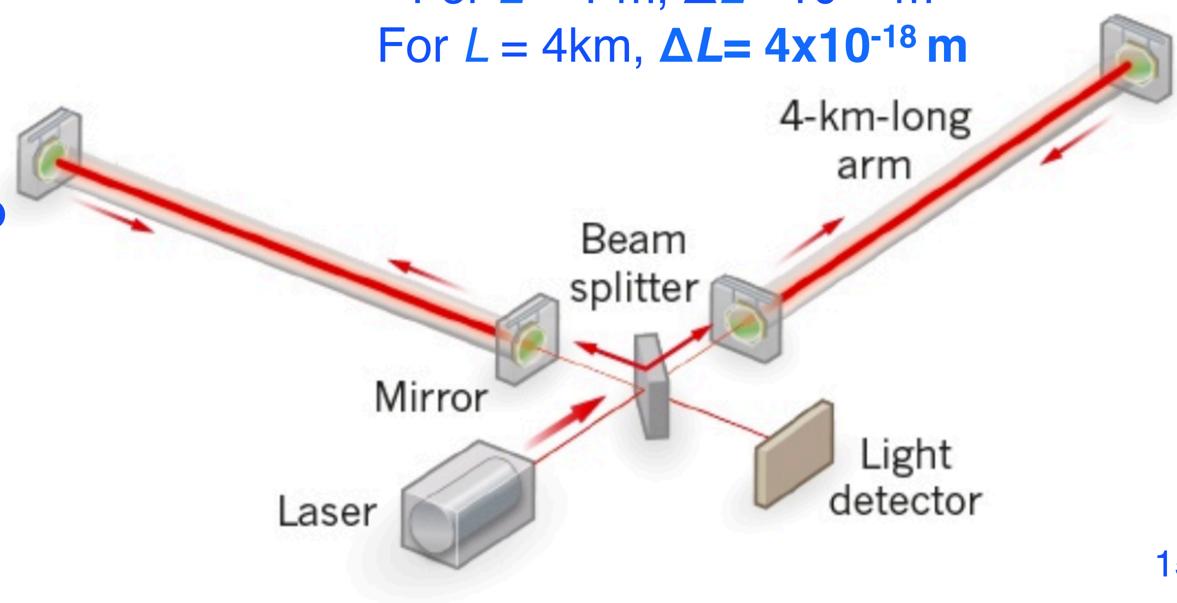
What is LIGO's measurement technique?

- 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….

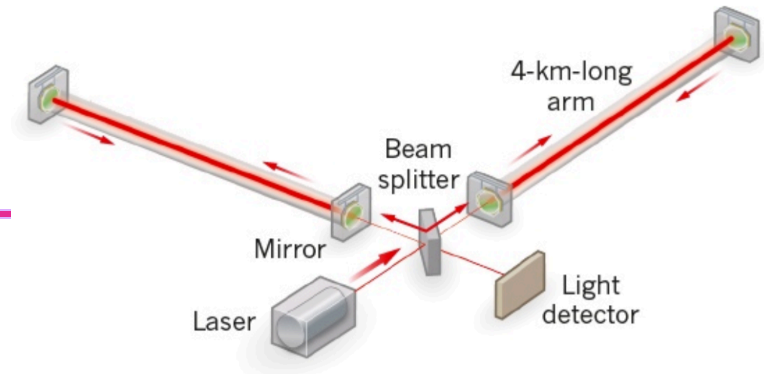


$$h \approx \frac{\Delta L}{L}$$

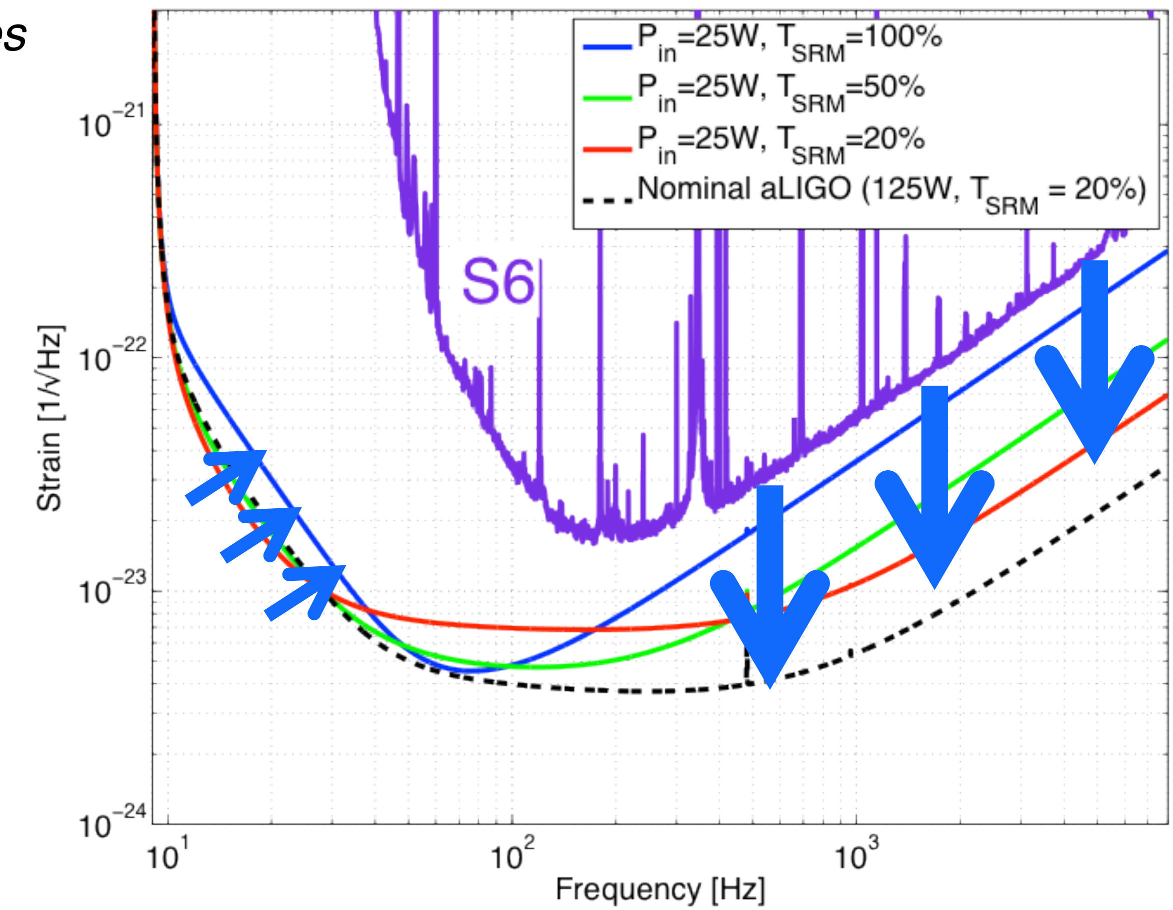
Magnitude of h at Earth:
Largest signals h ~ 10^{-21}
(1 hair / Alpha Centauri)
For L = 1 m, ΔL= 10^{-21} m
For L = 4km, **ΔL= 4x10^{-18} m**



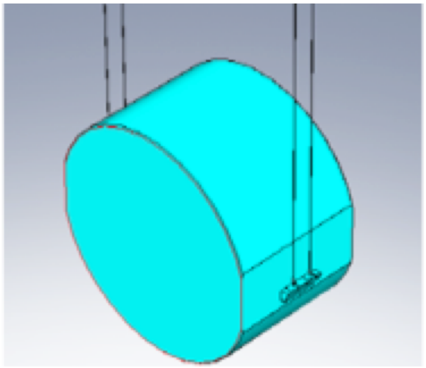
Measuring ΔL= $4x10^{-18}$ m
Readout



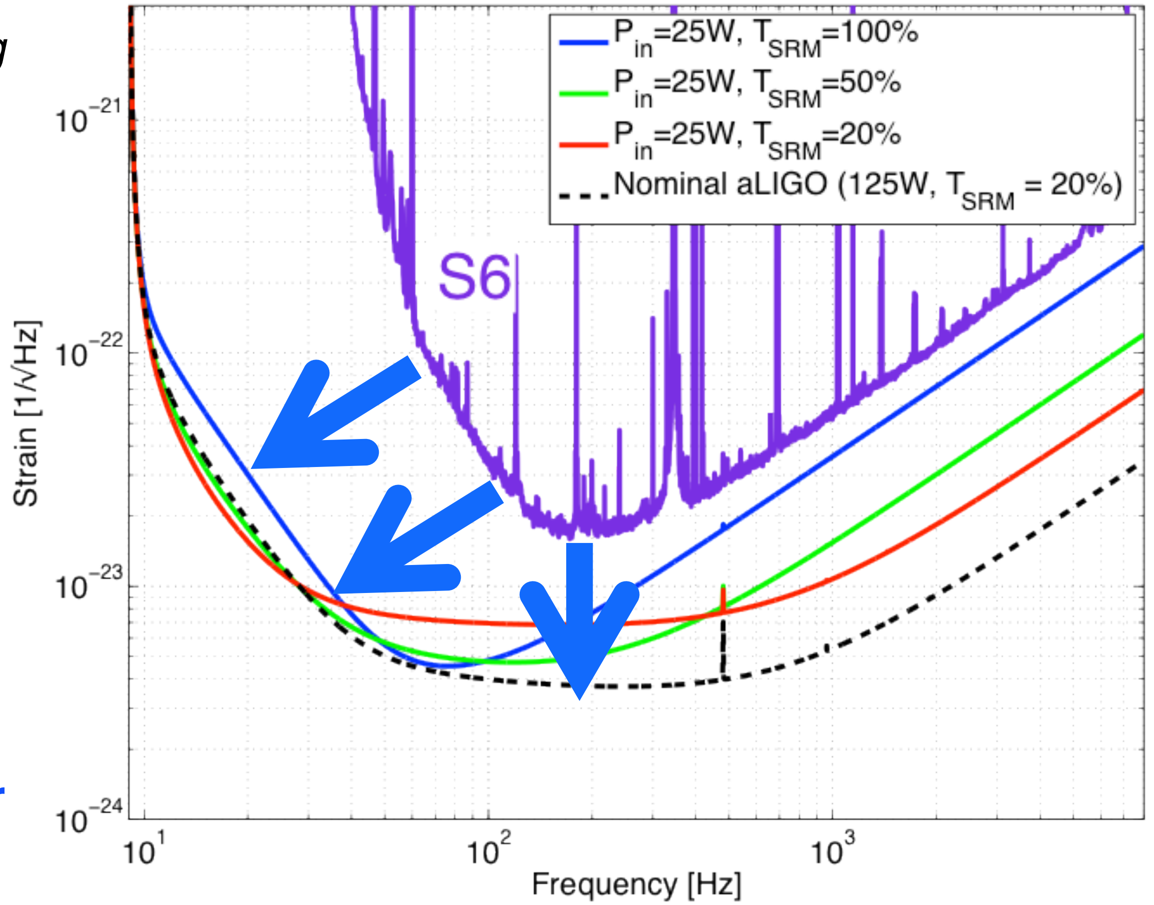
- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- *Zum gegenwärtigen Stand des Strahlungsproblems*, A. Einstein, 1909
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses!
- **'Standard Quantum Limit'**
- Advanced LIGO reaches this limit with its **200W laser, 40 kg test masses**



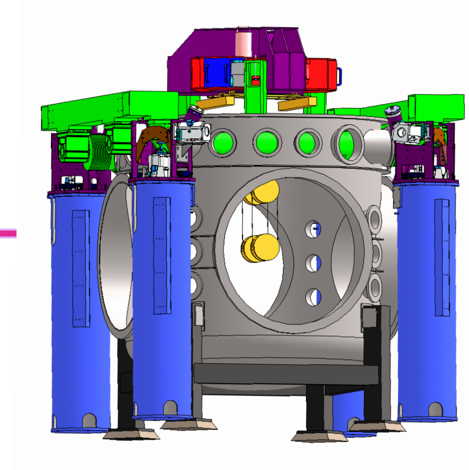
Measuring ΔL= 4x10^{-18} m
Internal motion



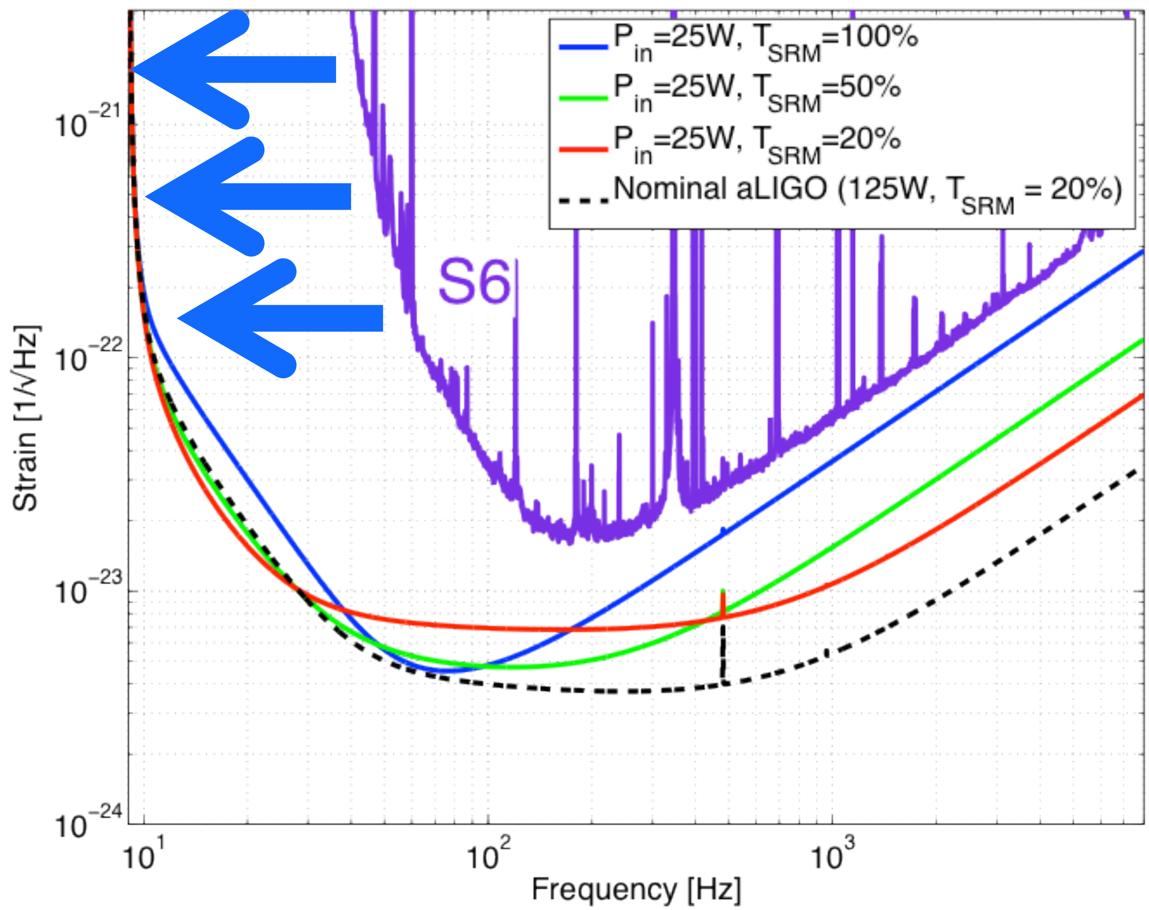
- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen*, A. Einstein, 1905
- Motion of components due to thermal energy masks GW
- Low mechanical loss materials gather this motion into a narrow peak at resonant frequencies
- Realized in aLIGO with an all **fused-silica test mass suspension** – *Q* of order 10^9
- **Test mass internal modes, Mirror coatings engineered for low mechanical loss**



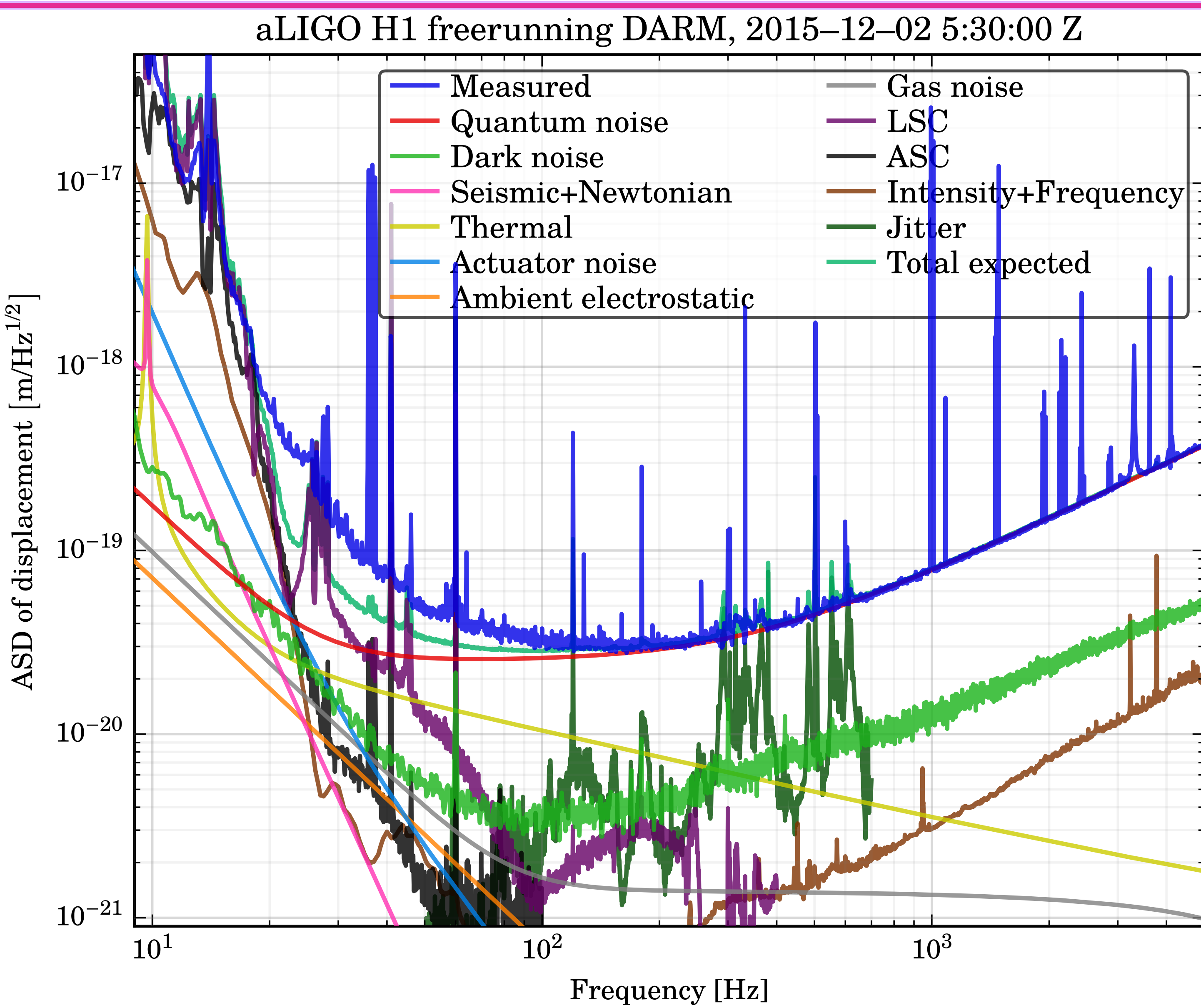
Measuring $\Delta L = 4x10^{-18}$ m
Forces on test mass



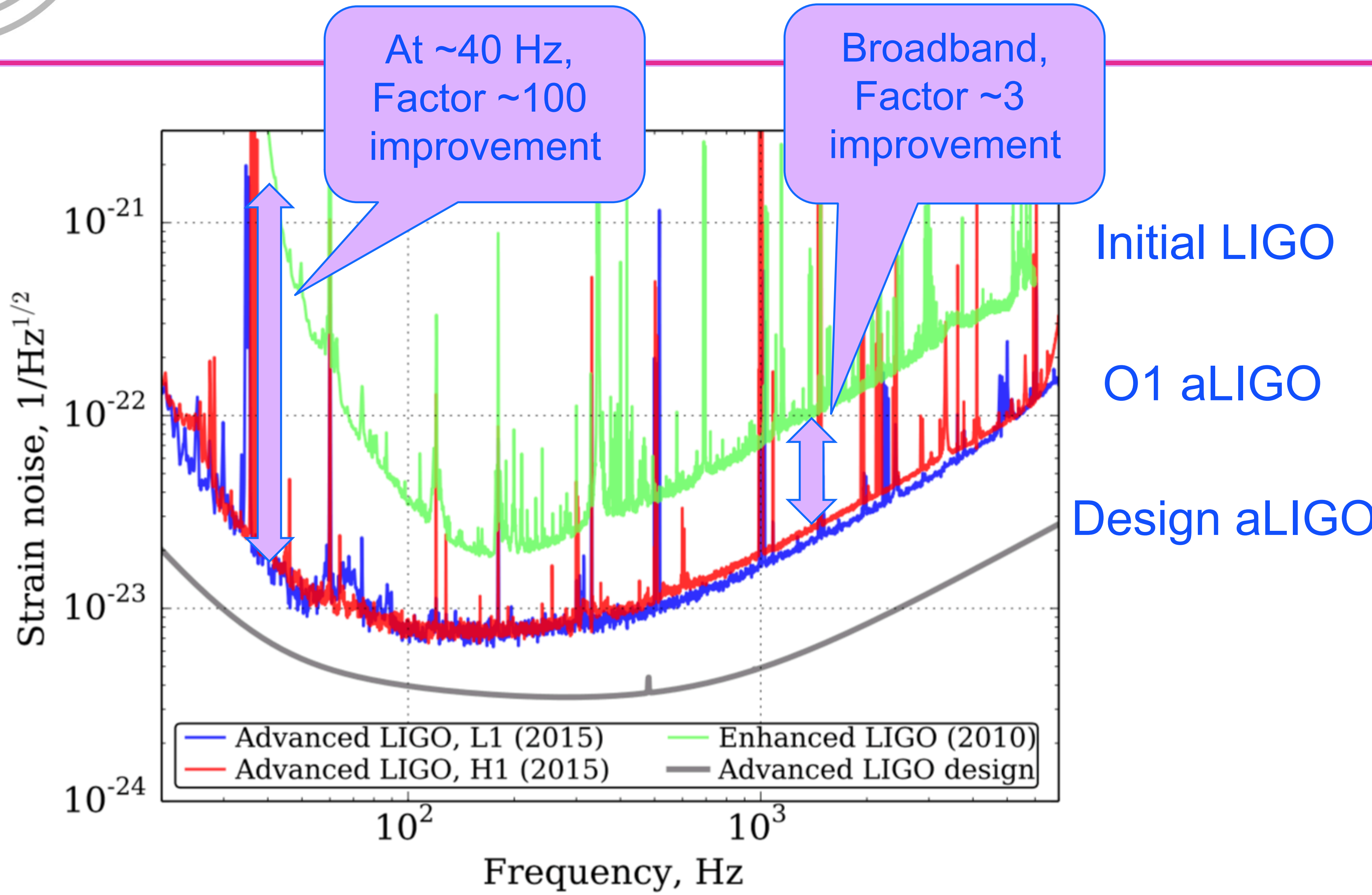
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- *(did Einstein work on seismic motion…?)*
- Motion from waves on coasts… and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance and aligned
- aLIGO uses **active servo-controlled platforms, multiple pendulums**
- Ultimate limit on the ground: Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band

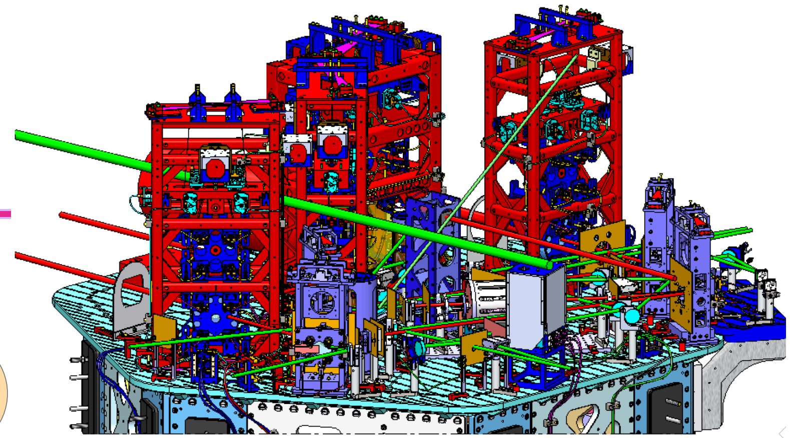


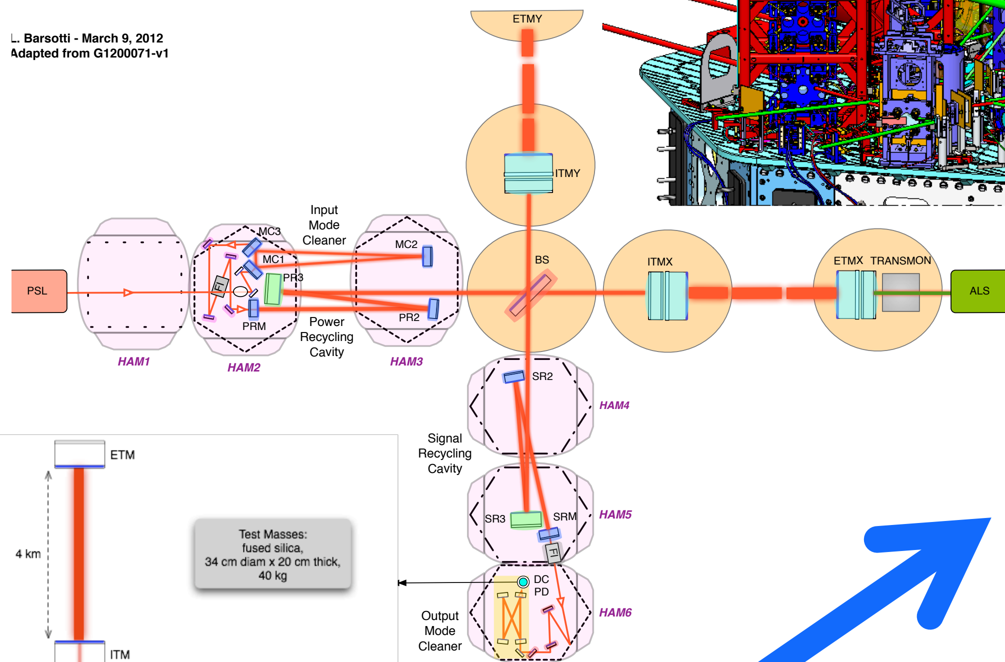
Then there are the technical noise sources….

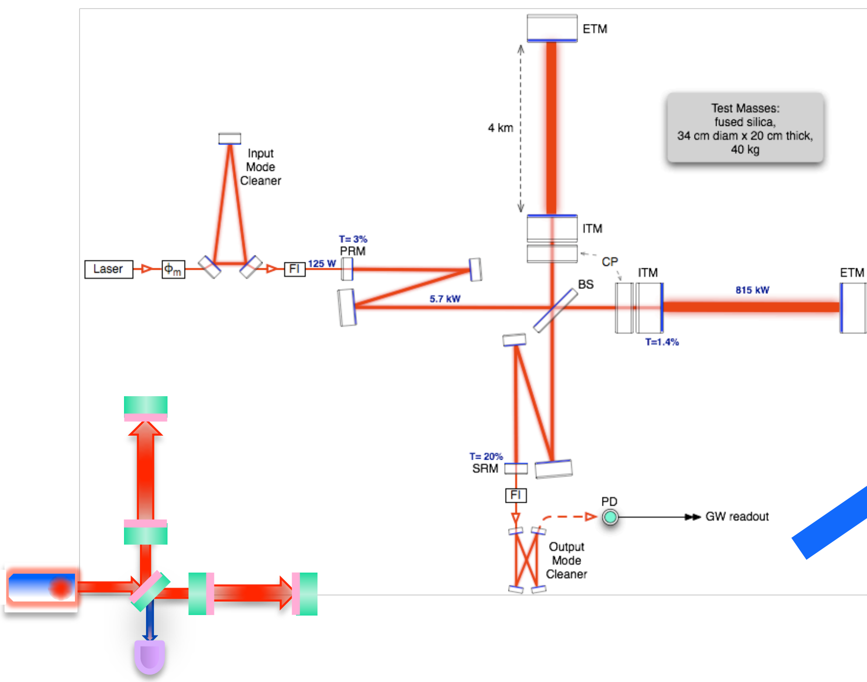


Sensitivity for first Observing run









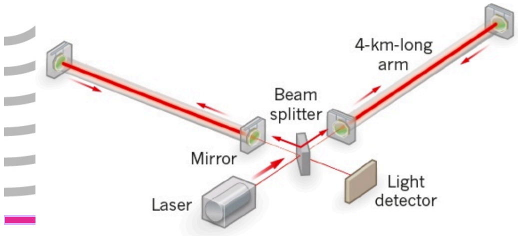
photodiode

Reality axis

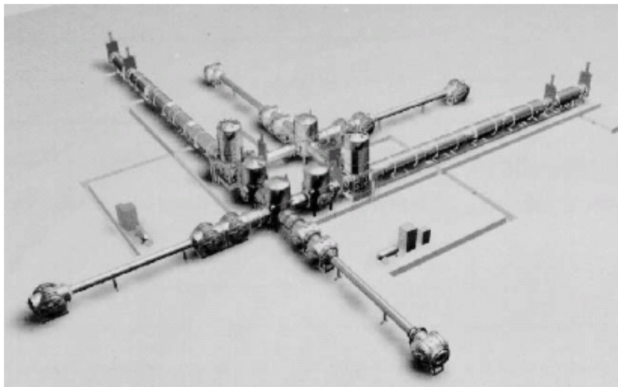
The real instrument is also more complex than a simple Michelson…

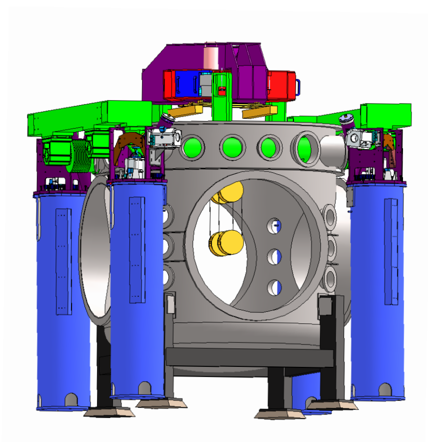
Infrastructure: 4km Beam Tubes

- 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



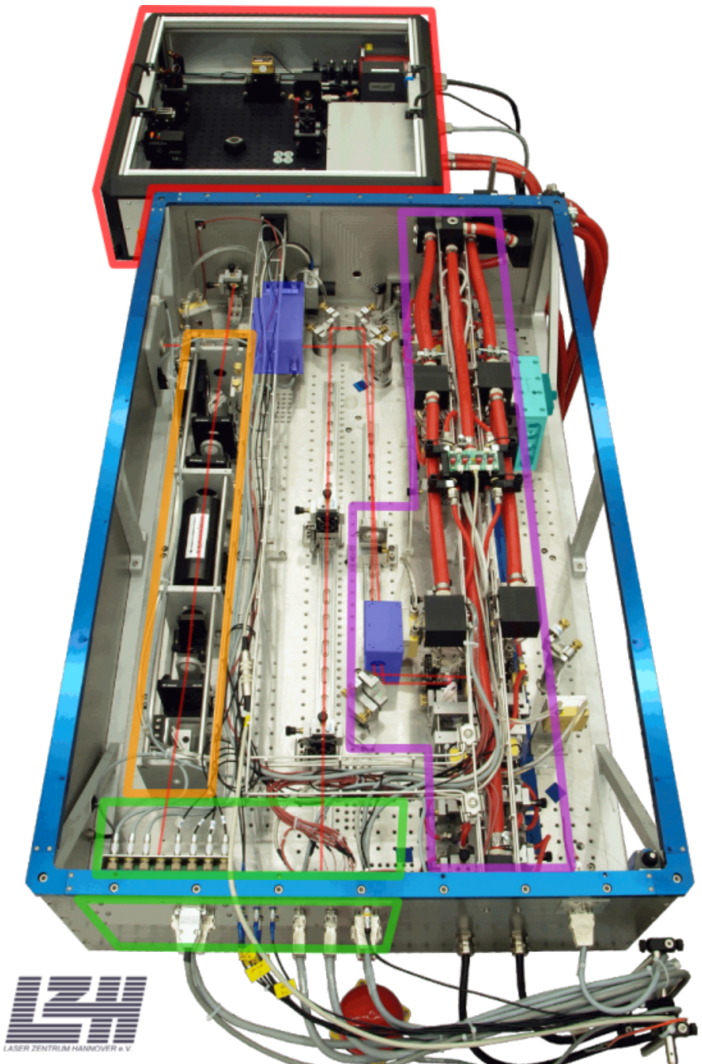
LIGO Vacuum Equipment –
designed for several generations of instruments

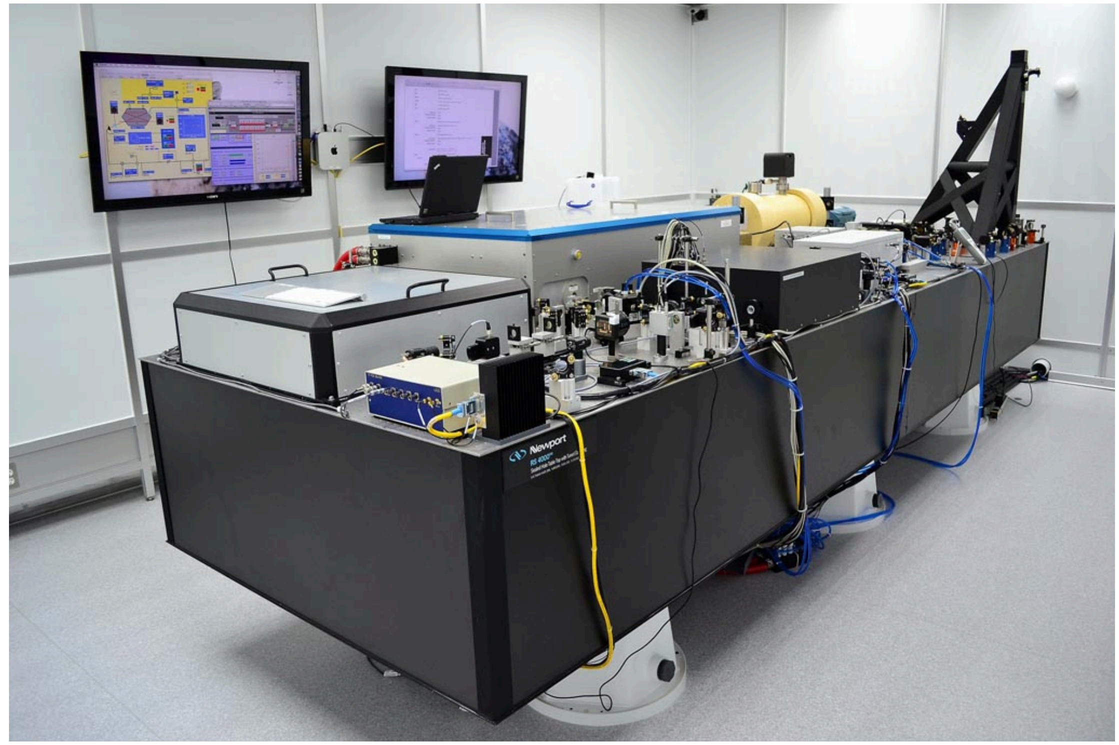




200W CW Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute

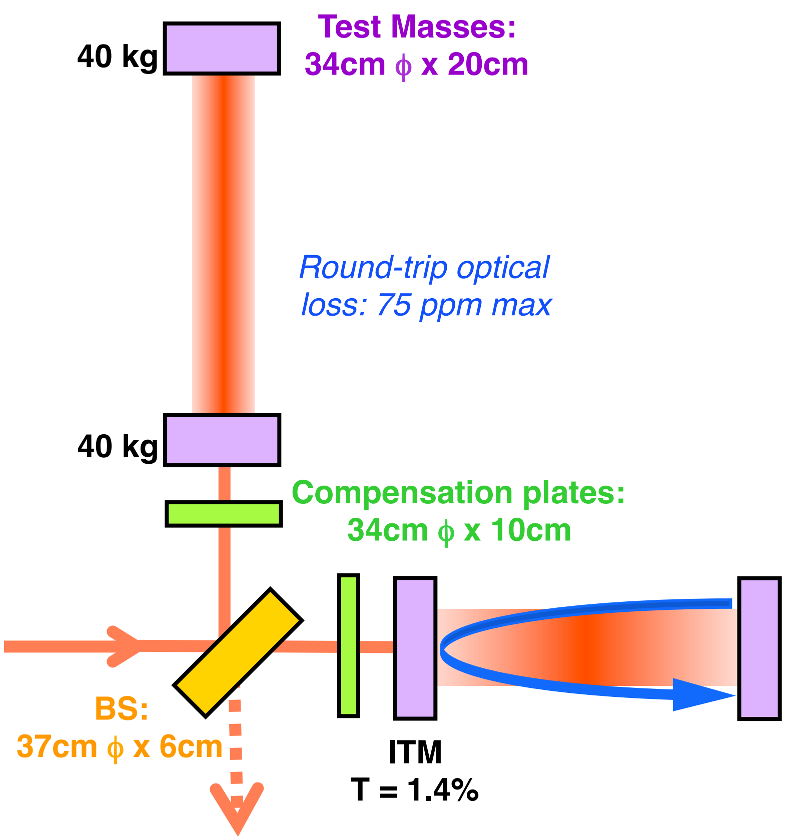


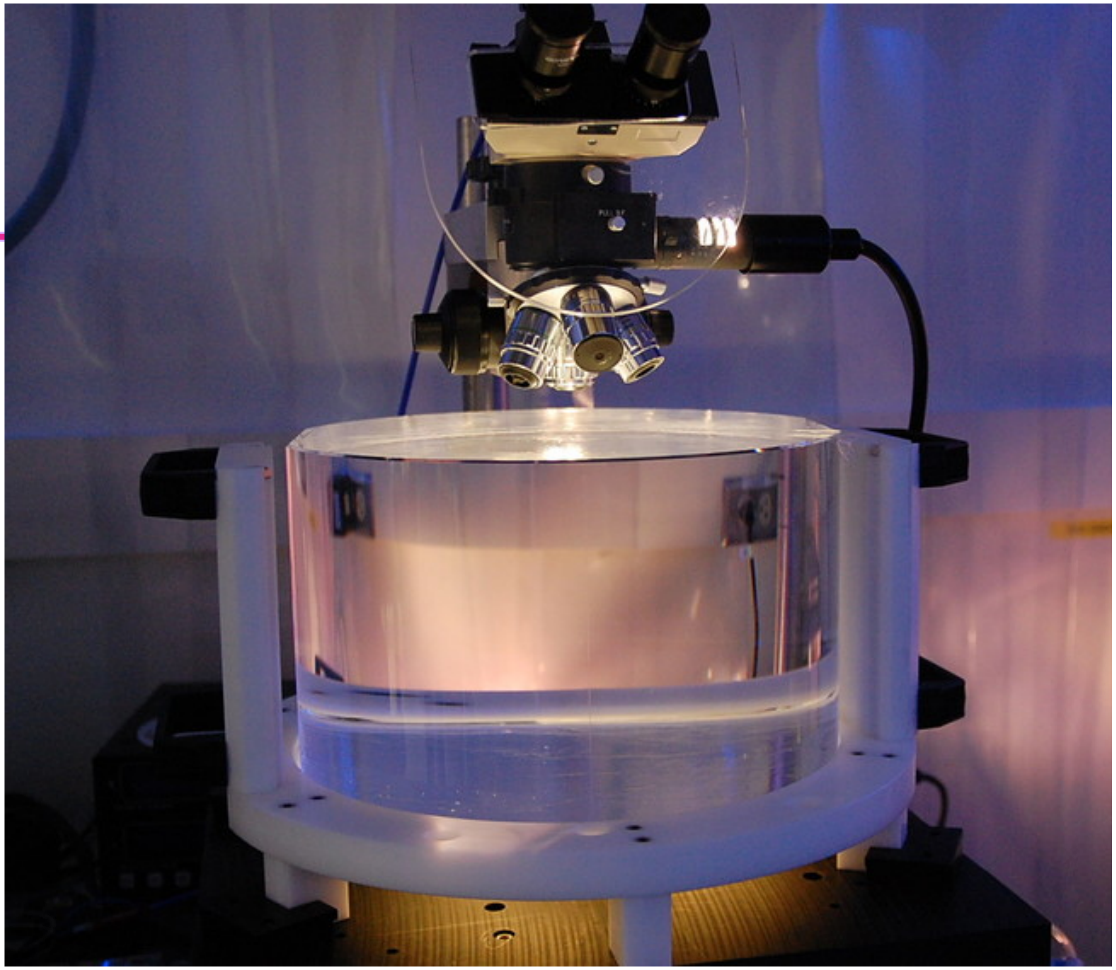


- Stabilized in power and frequency – using techniques developed for time references
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
- Delivers the required shot-noise limited fringe resolution

Test Masses

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



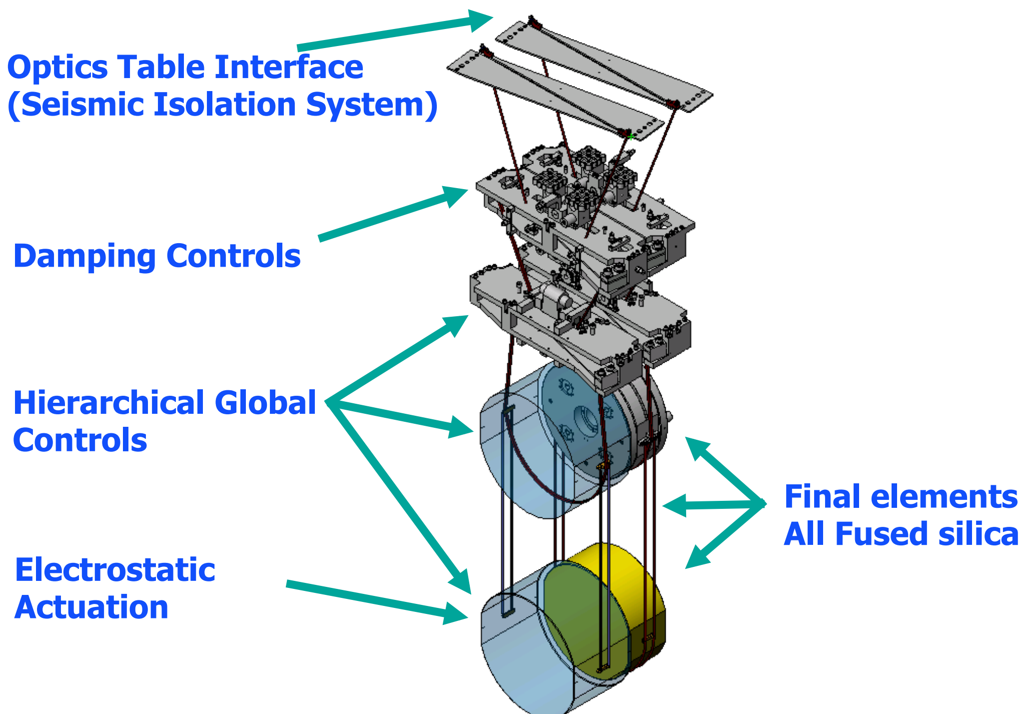


- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and **coating thermal noise,** high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

Test Mass Quadruple Pendulum suspension

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

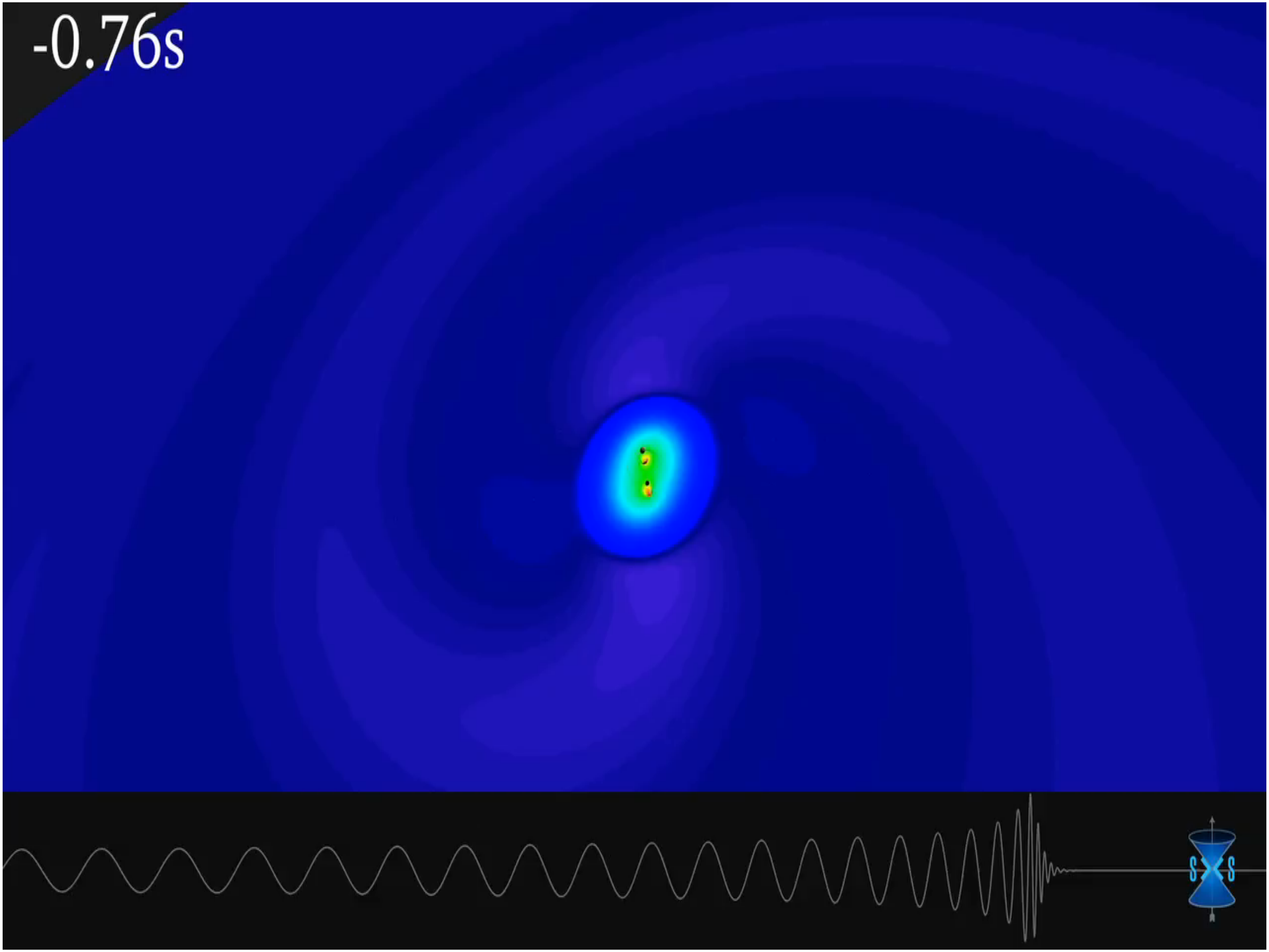
- Quadruple pendulum suspensions for the main optics; second ‘reaction’ mass to give quiet point from which to push
- Create quasi-monolithic pendulums using GPB star-tracking telescope techniques; Fused silica fibers to suspend 40 kg test mass
  - » VERY Low thermal noise!



So, that's the instrument.

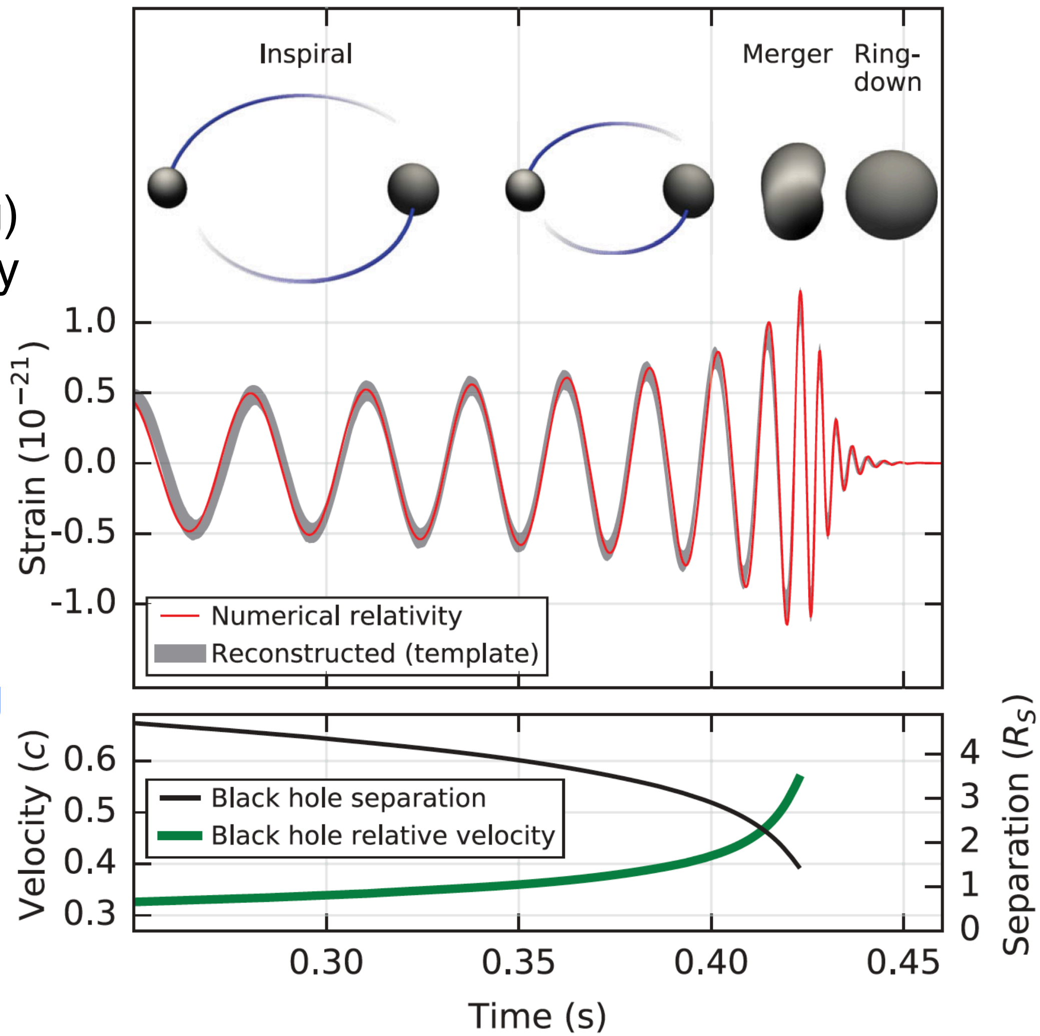
How about the detection?

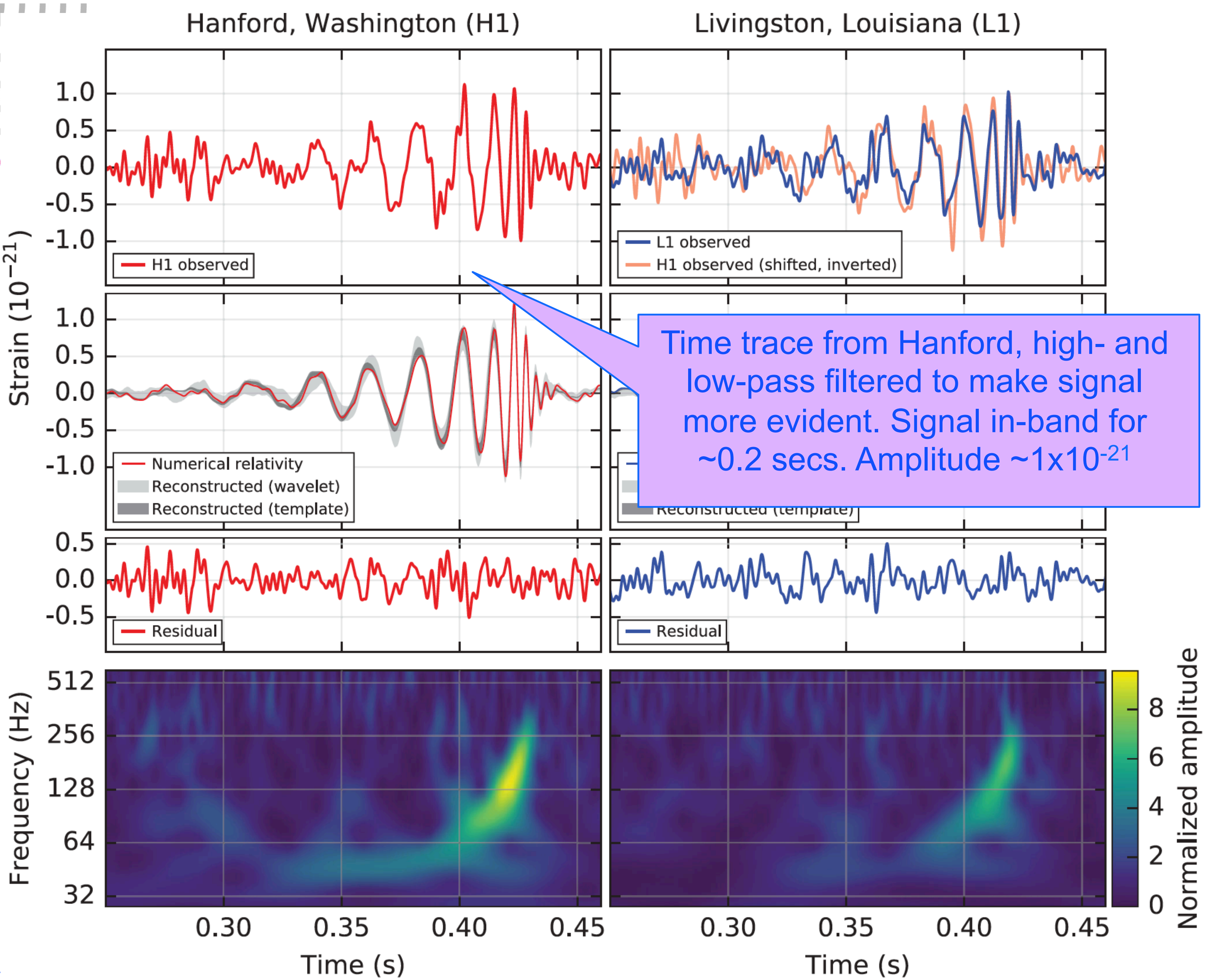
What did we learn from our record of $h(t)$?


-0.76s
SXS

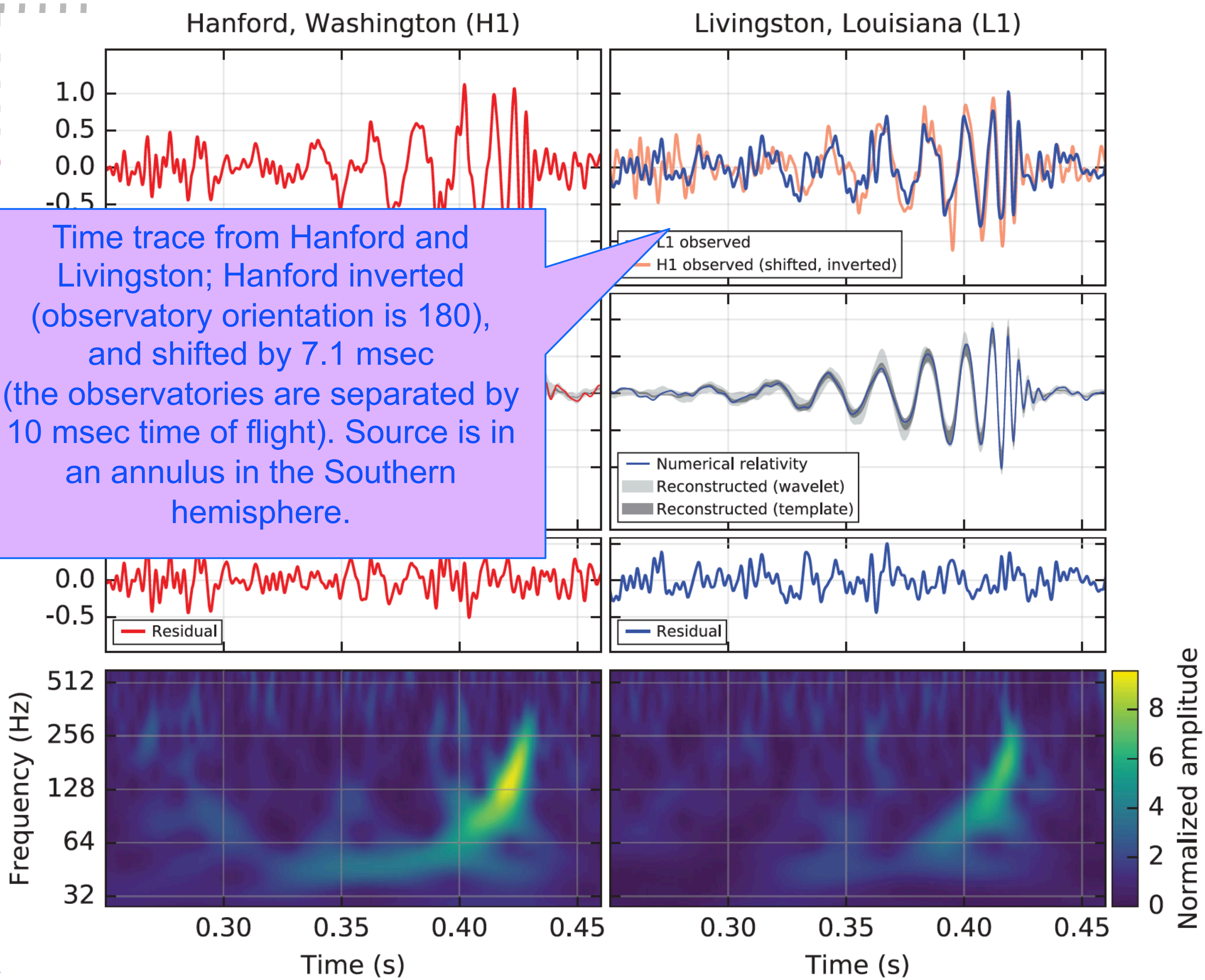
LIGO measures *h(t)* – think 'strip chart recorder'

- 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!

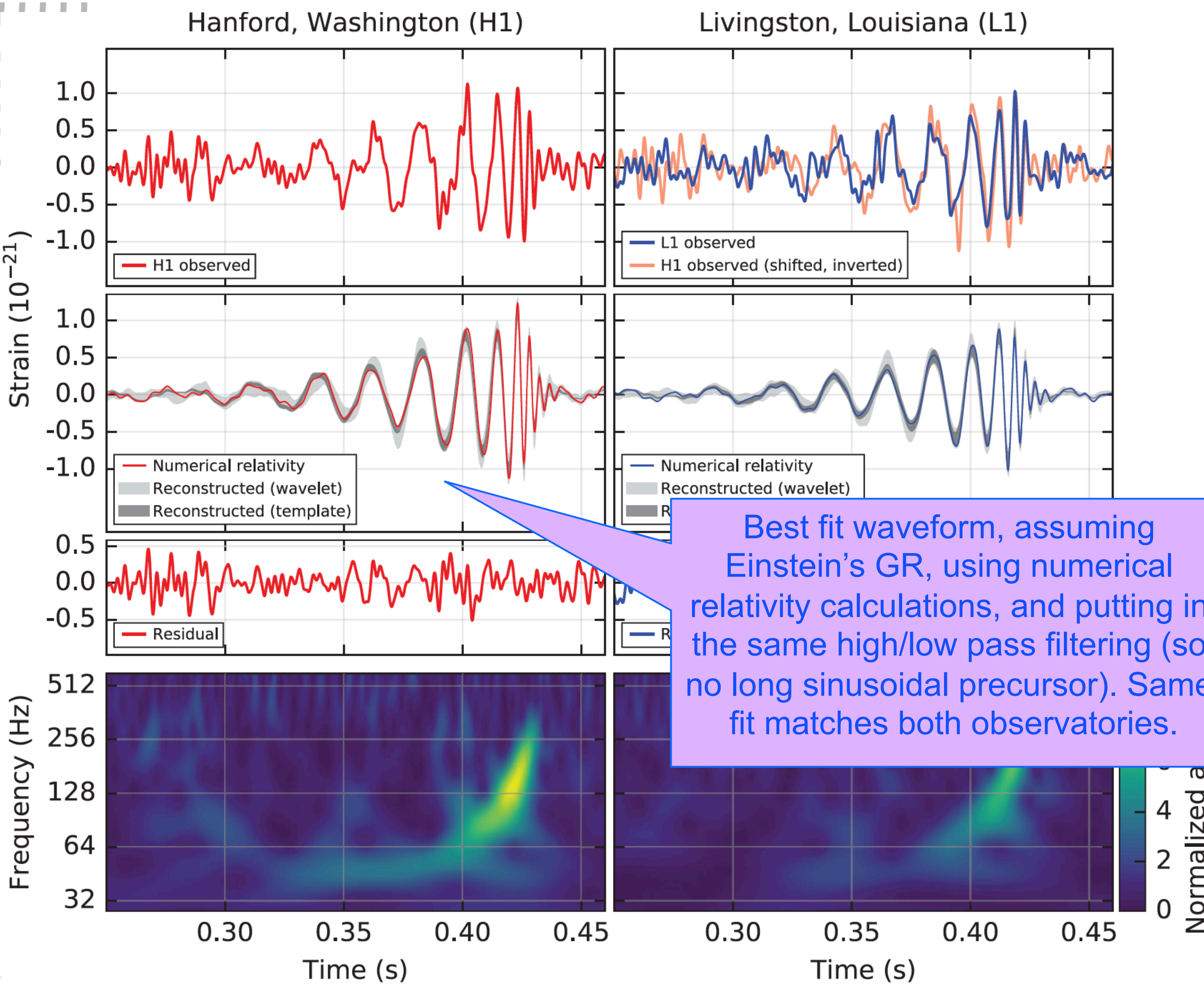




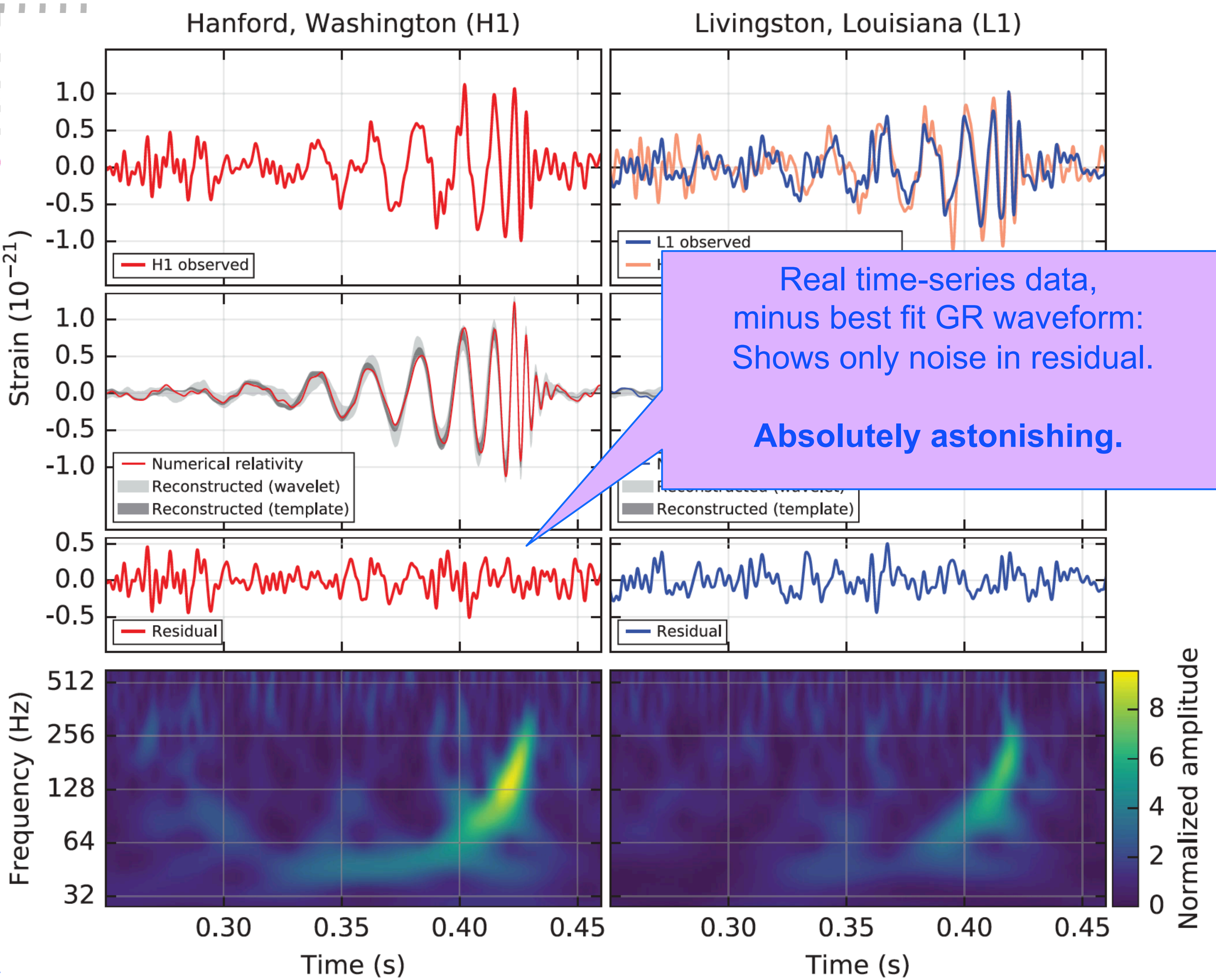
Time trace from Hanford, high- and low-pass filtered to make signal more evident. Signal in-band for ~0.2 secs. Amplitude ~1x10^{-21}



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.

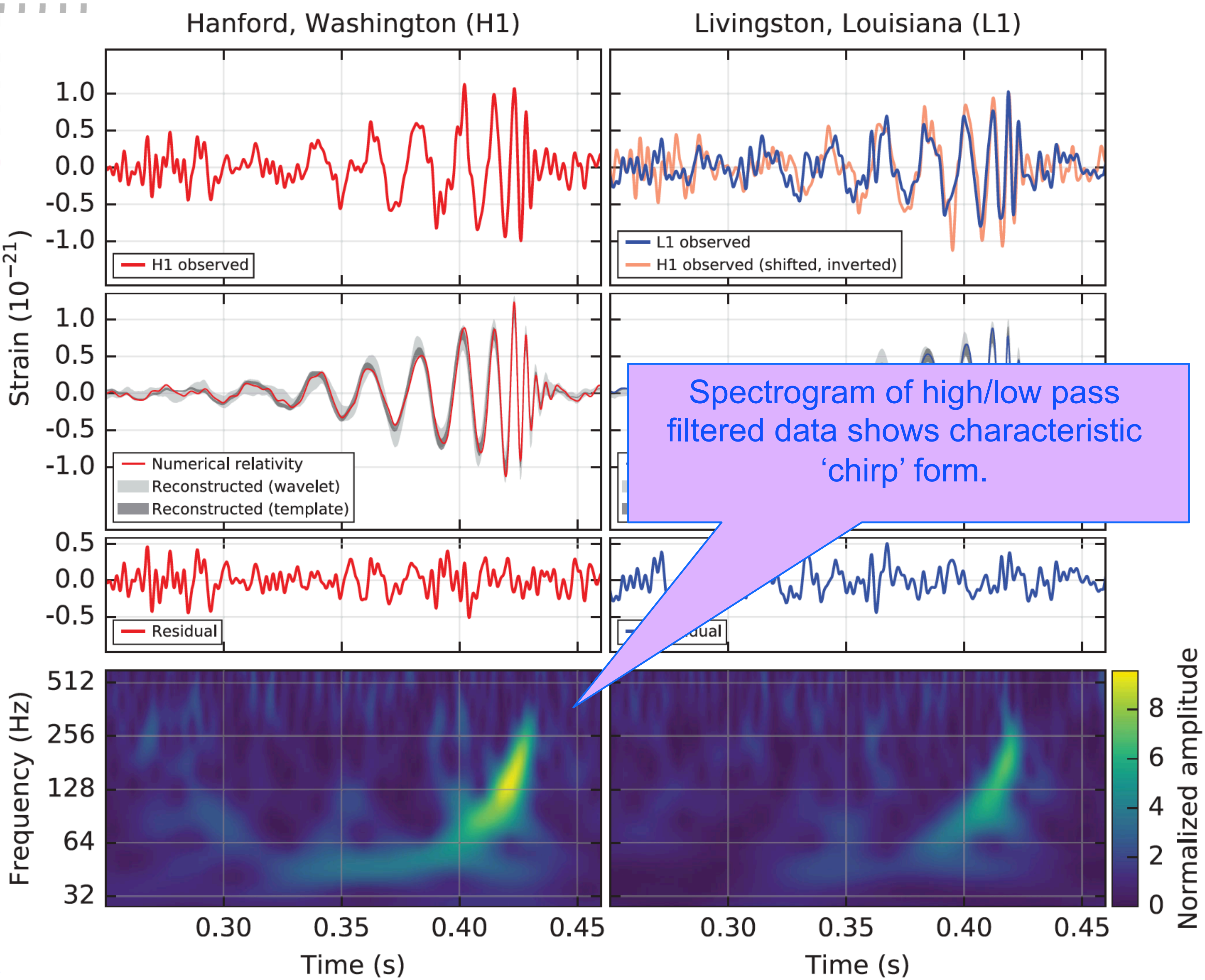


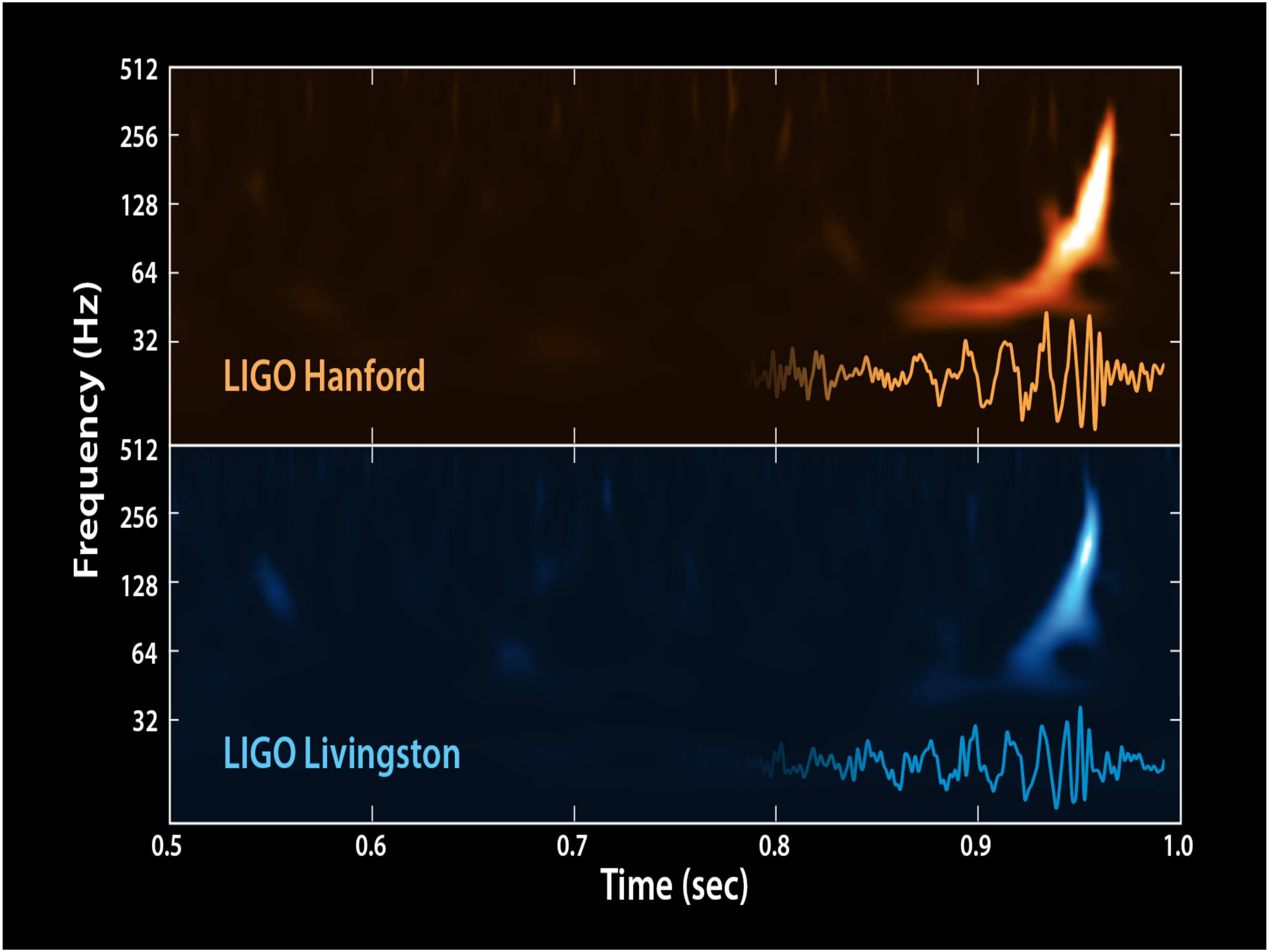
Best fit waveform, assuming Einstein's GR, using numerical relativity calculations, and putting in the same high/low pass filtering (so no long sinusoidal precursor). Same fit matches both observatories.



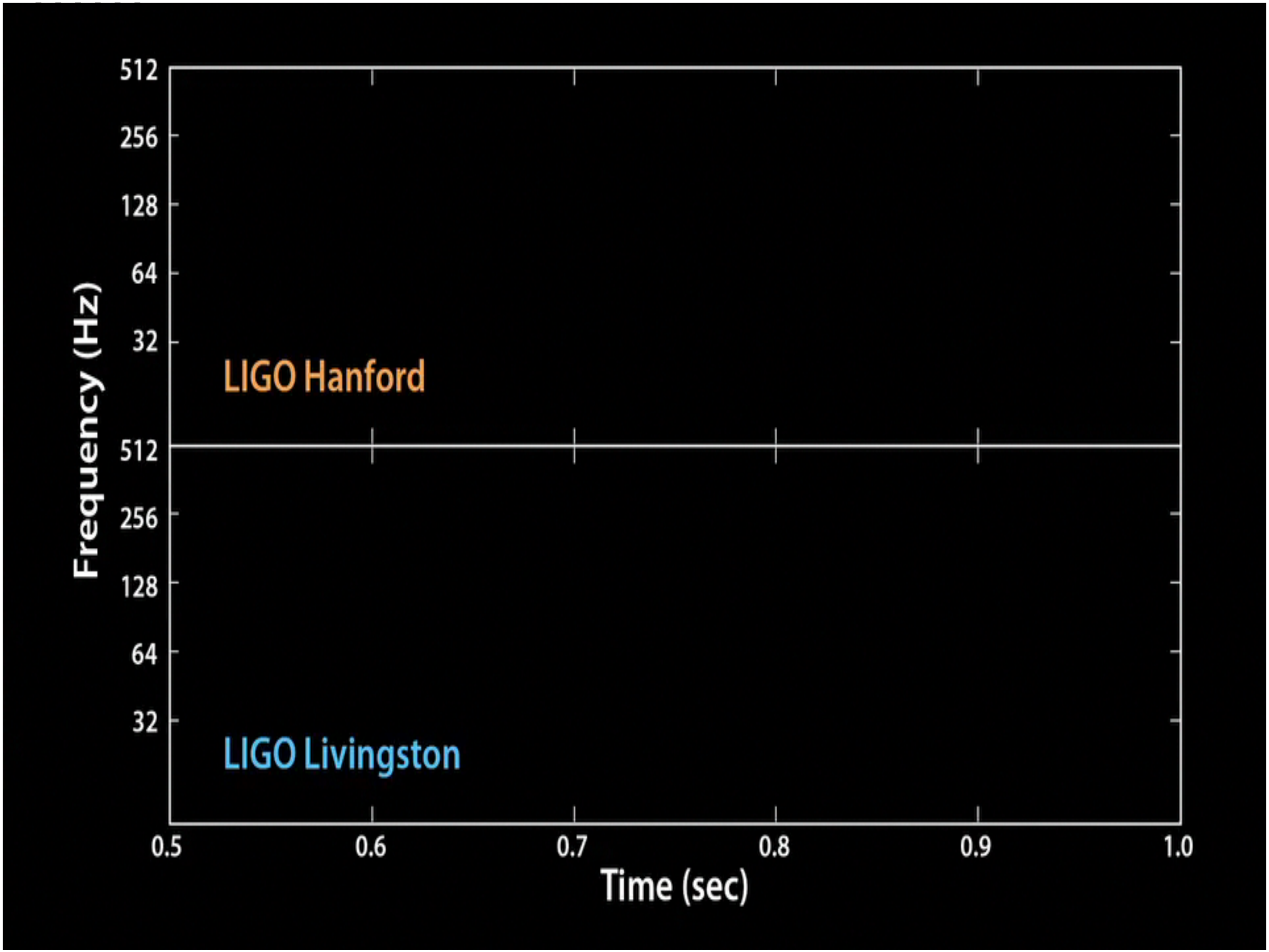
Real time-series data,
minus best fit GR waveform:
Shows only noise in residual.

Absolutely astonishing.


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
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
8
6
4
2
0
Spectrogram of high/low pass filtered data shows characteristic 'chirp' form.



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


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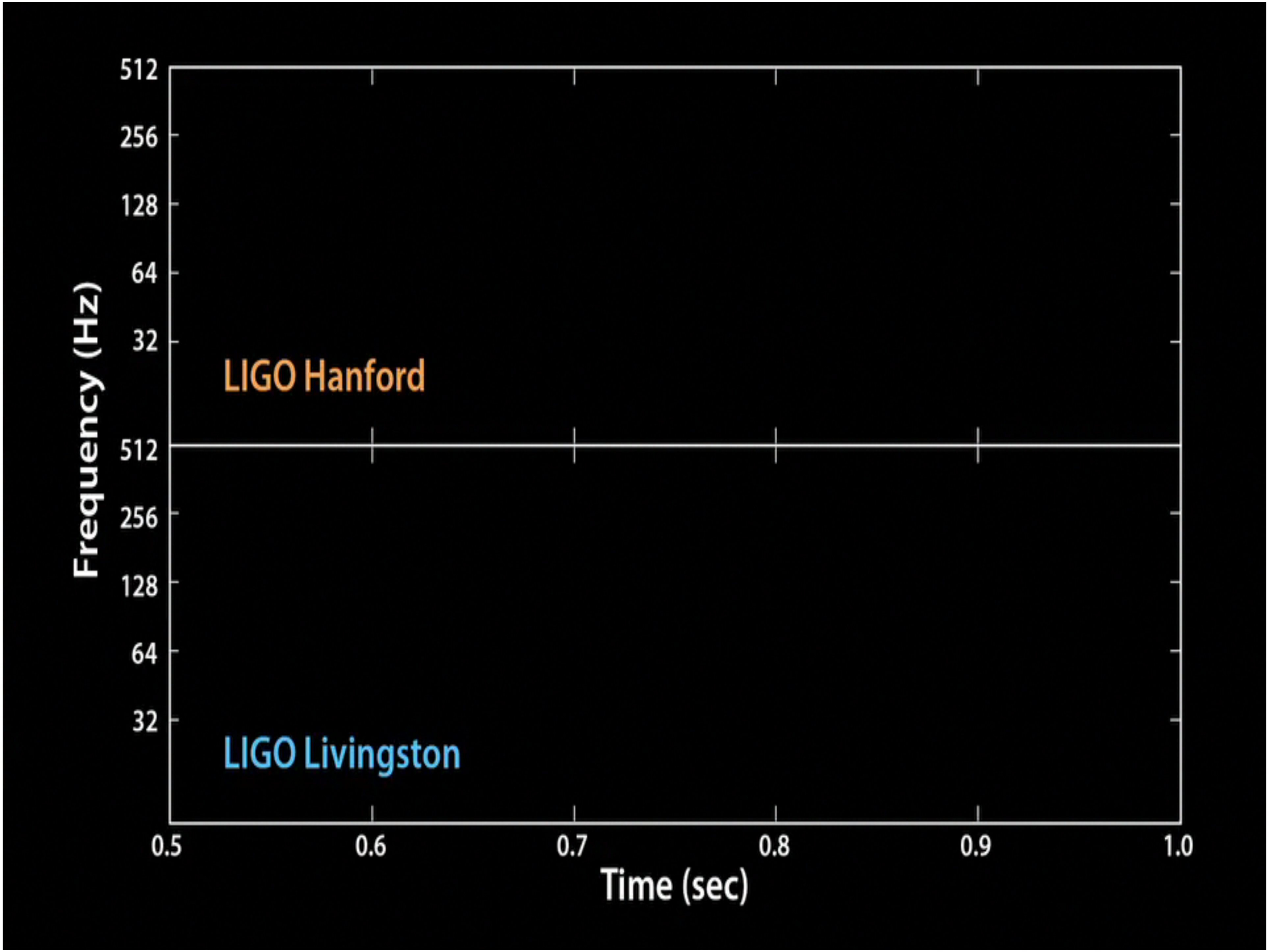
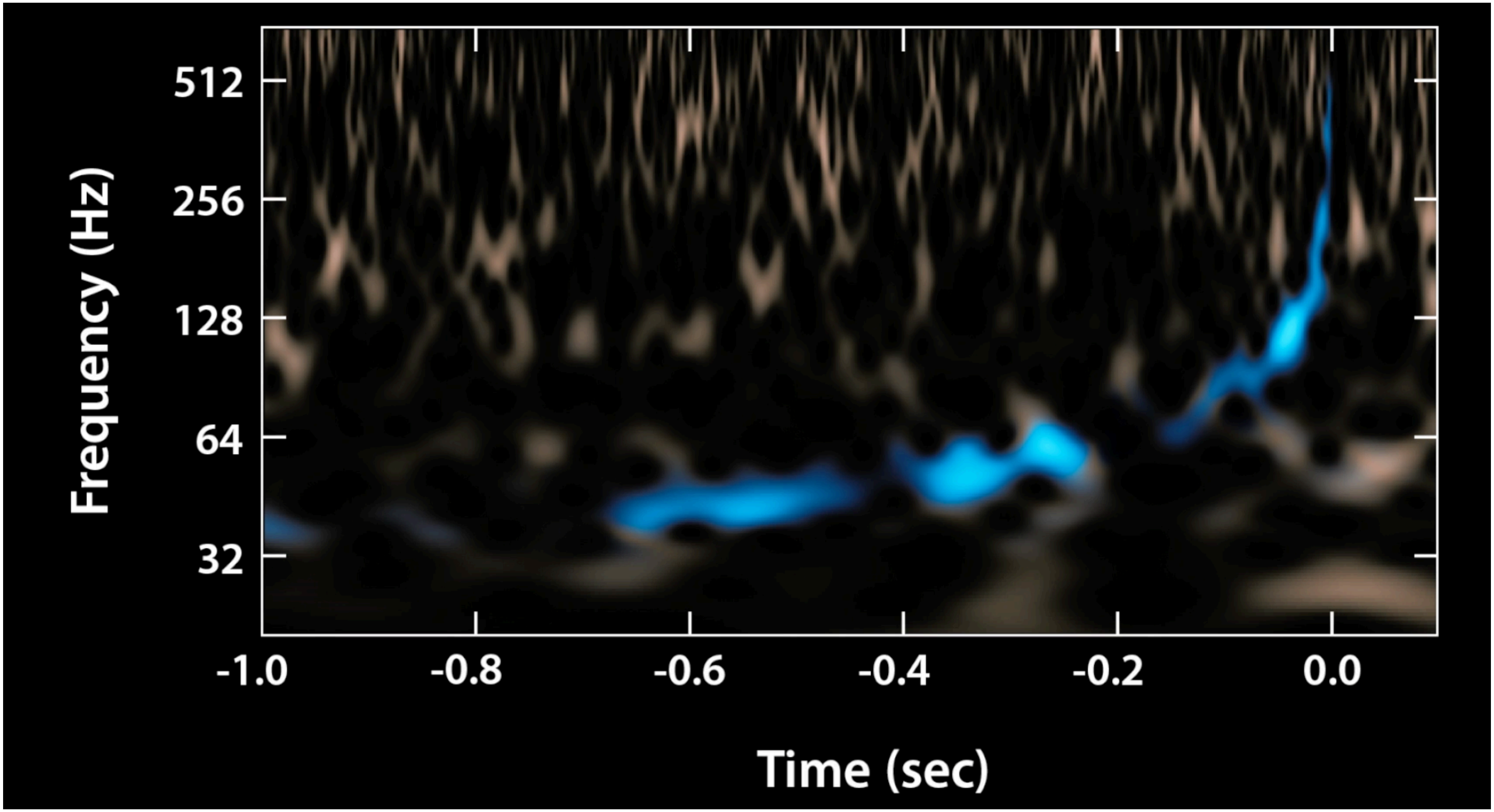
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



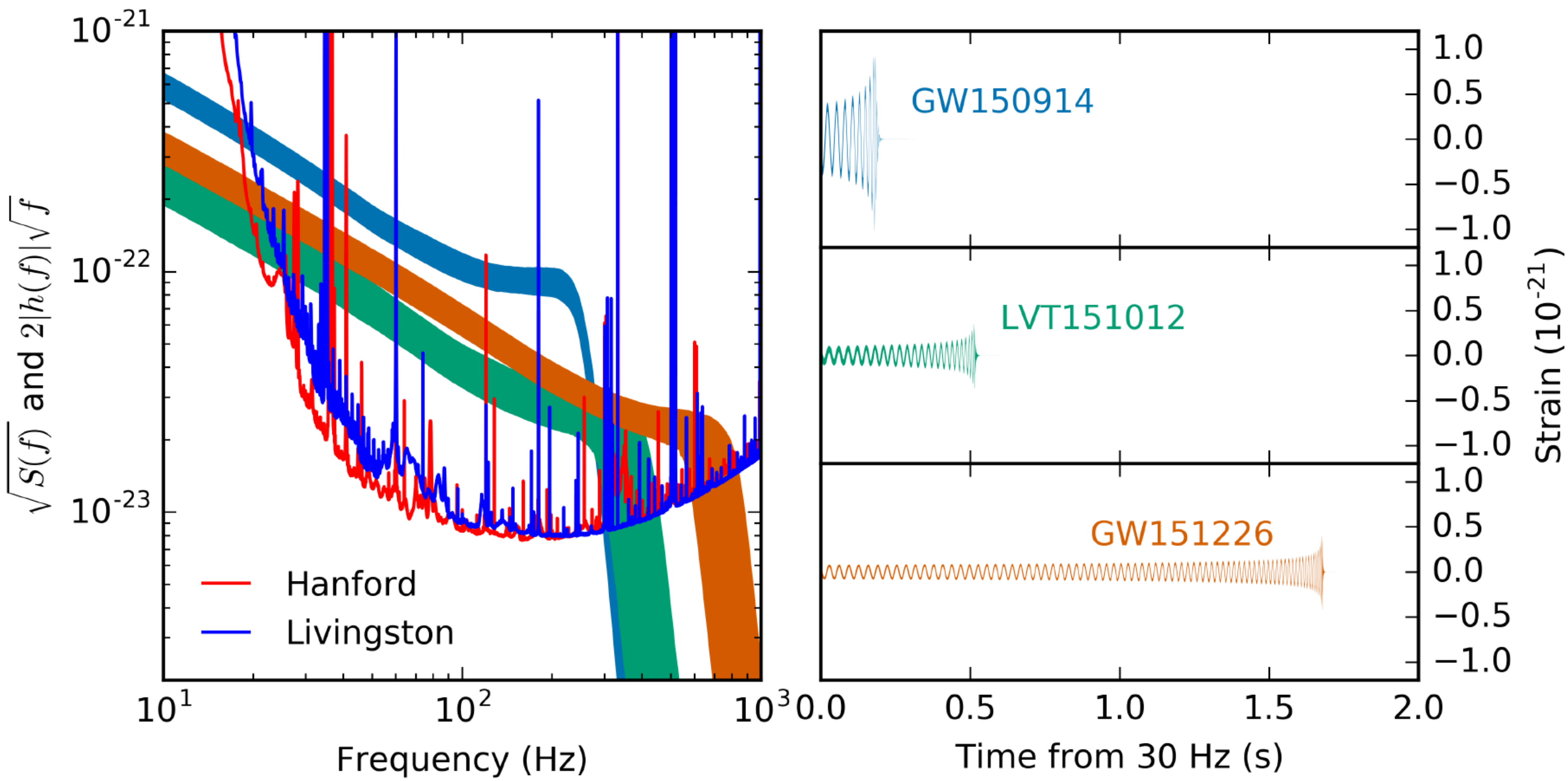
Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)

One event…was it real?

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



Our 2+1 signals to date



LIGO Scientific Collaboration

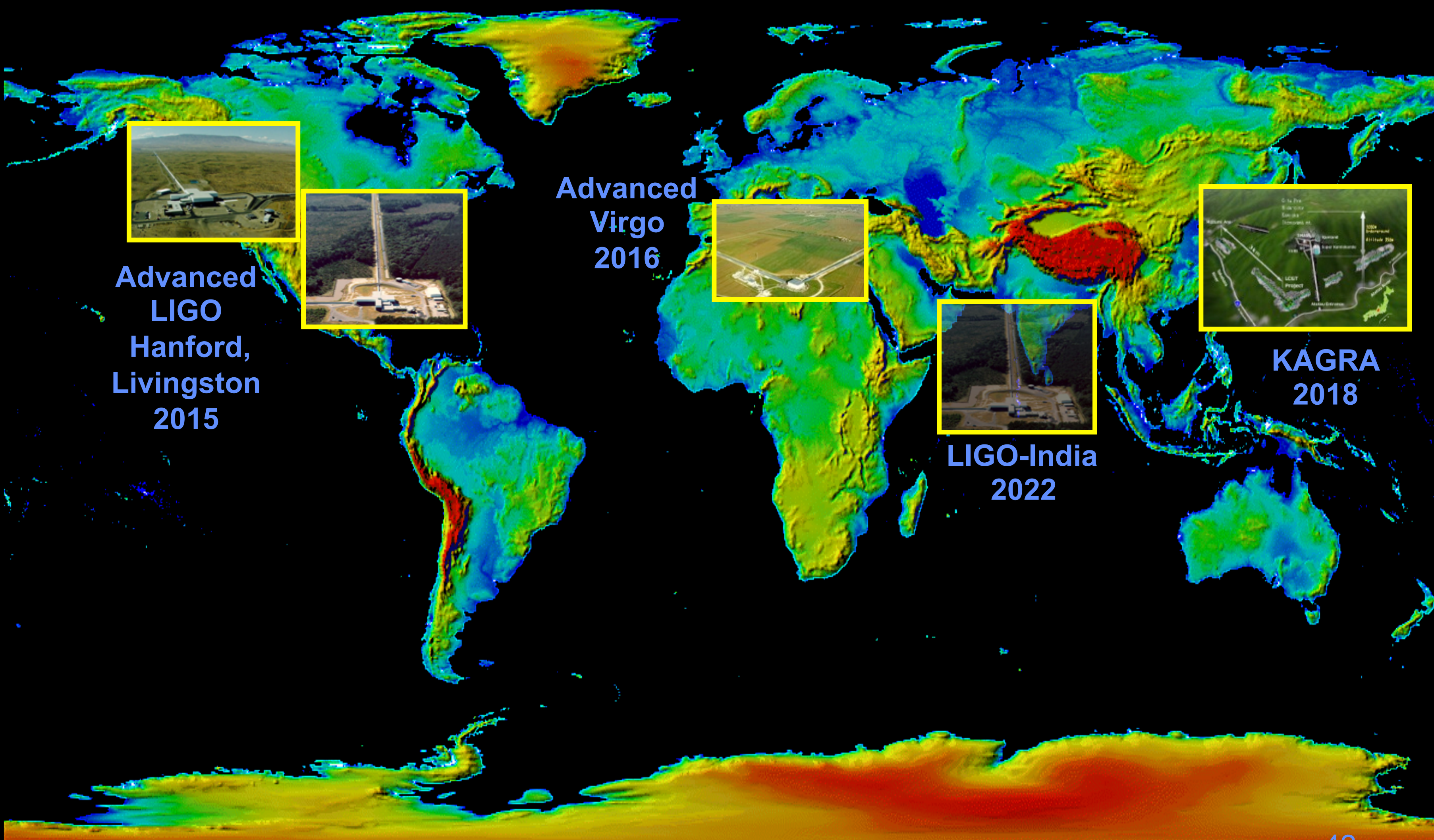
The LSC is the organization the conducts the science of LIGO

www.ligo.org

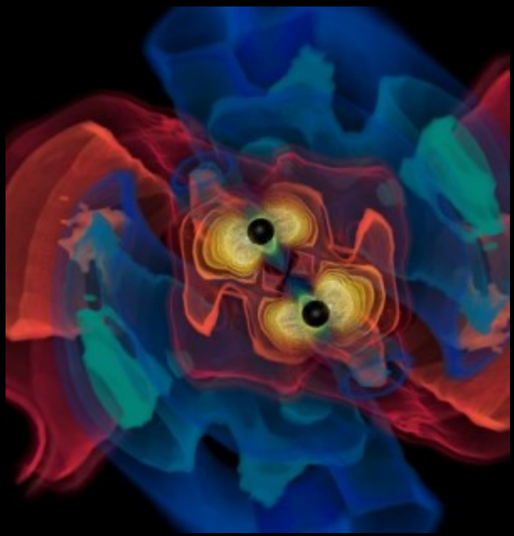
1000+ members, 90 institutions, 16 countries

Slide: Gabriela González

The advanced GW detector network



Astrophysical Targets for Ground-based Detectors

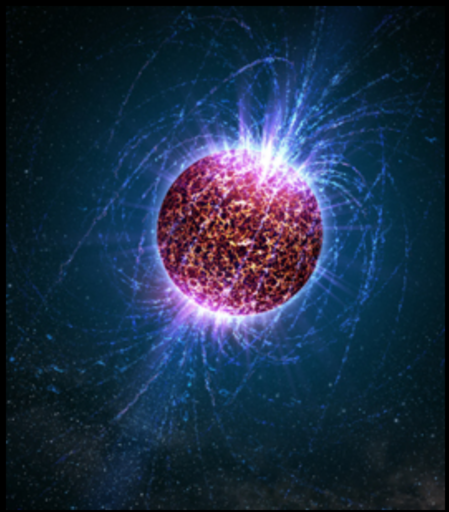


Credit: AEI, CCT, LSU

Coalescing Binary Systems

• Well-modelled

•Neutron stars, low mass black holes, and NS/BS systems



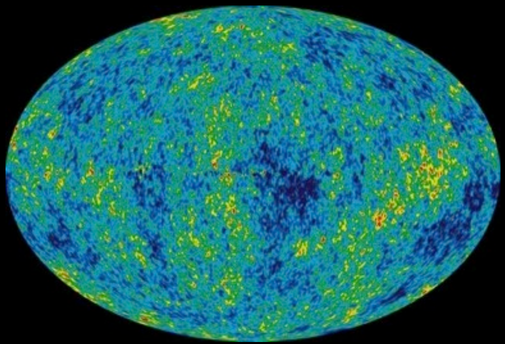
Casey Reed, Penn State

Continuous Sources

• Essentially Monotone

•Spinning neutron stars

• probe crustal deformations, equation of state, 'quarki-ness'



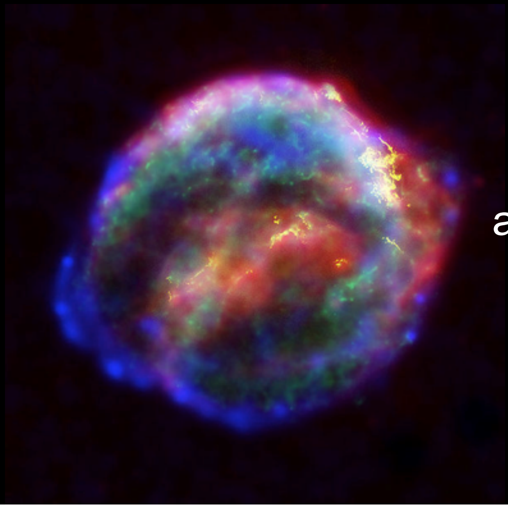
NASA/WMAP Science Team

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'

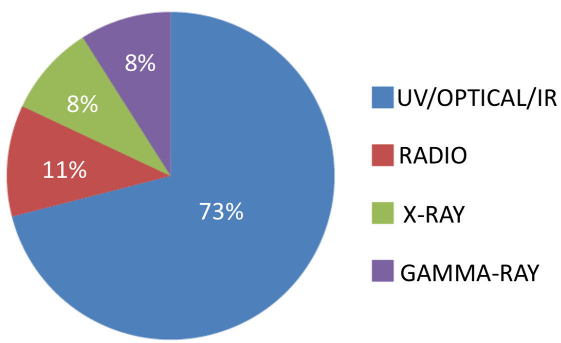
• Unmodelled

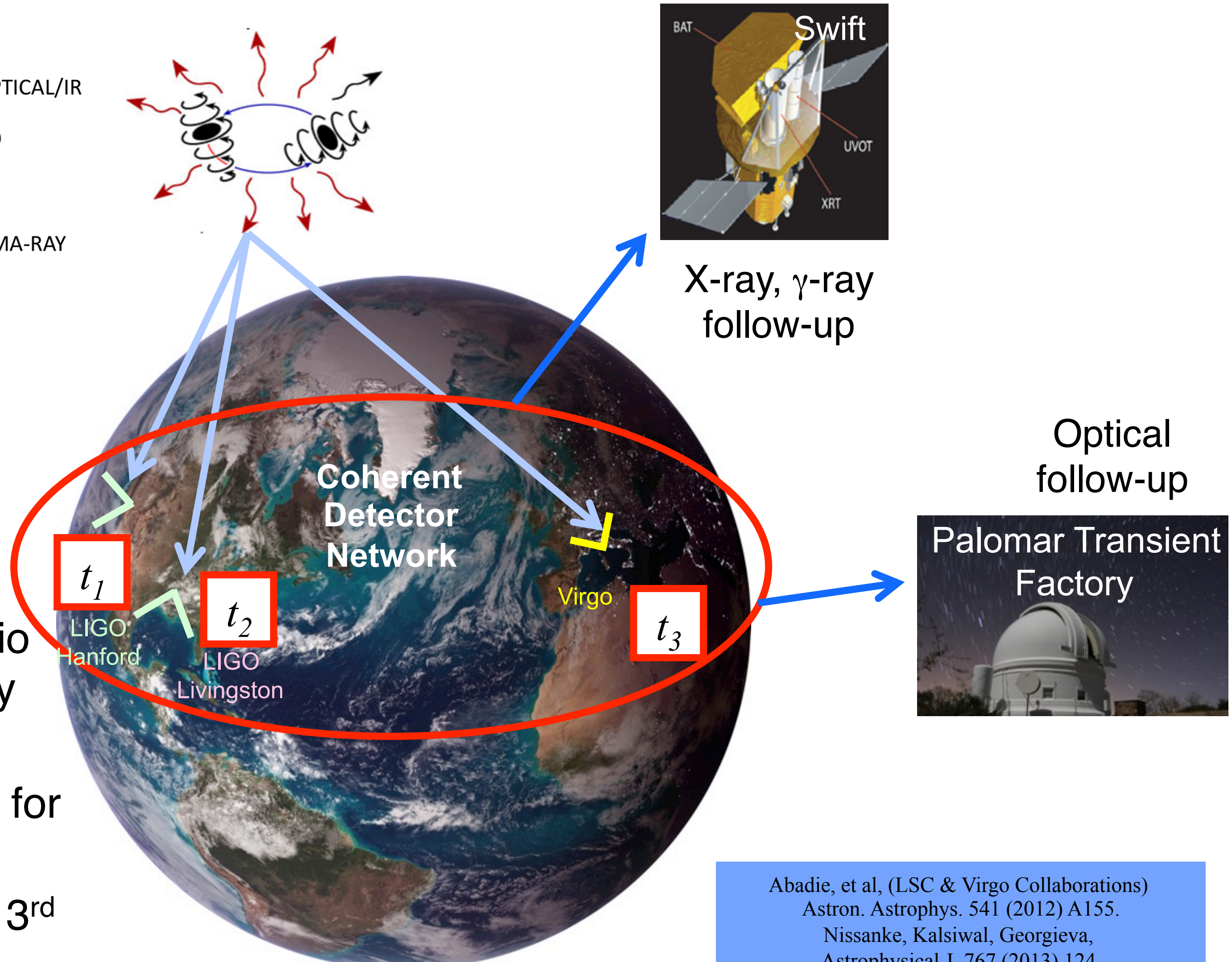
•galactic asymmetric core collapse supernovae

• 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/

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 Electromagnetic vs. Gravitational Waves

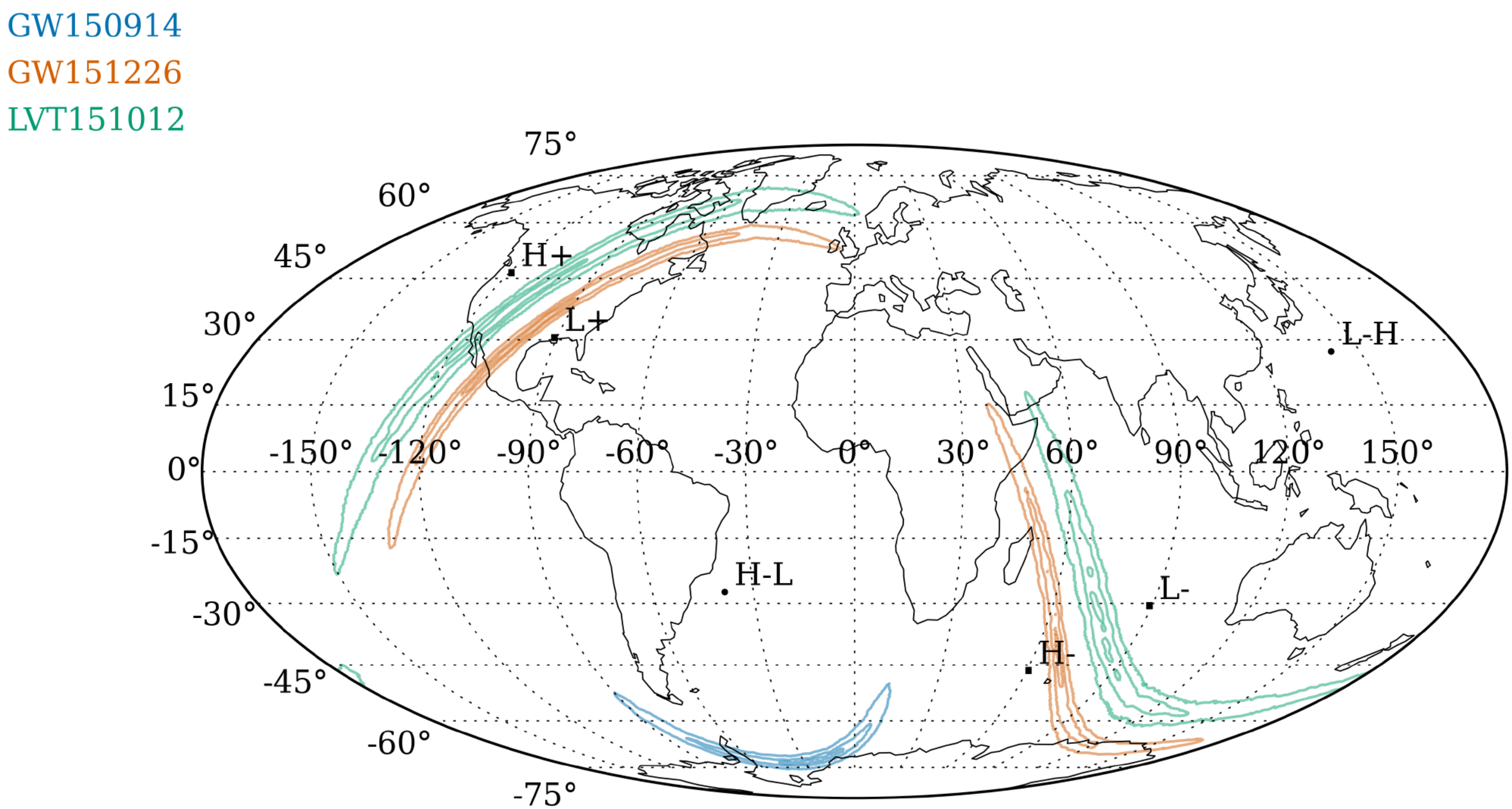
- **Visible, IR, Xray**
  - » High spatial resolution
  - » Relatively small masses radiating (atoms!)
  - » Exterior surface of astronomical objects
  - » Masked and scattered by intervening matter
  - » $1/r^2$ fall-off
- **Gravitational waves:**
  - » Low spatial resolution
  - » Coherent motion of Huge masses
  - » Deep interior of objects – where the mass is
  - » No masking or scattering
  - » $1/r$ fall-off

Wonderfully complementary information

What does the future hold?

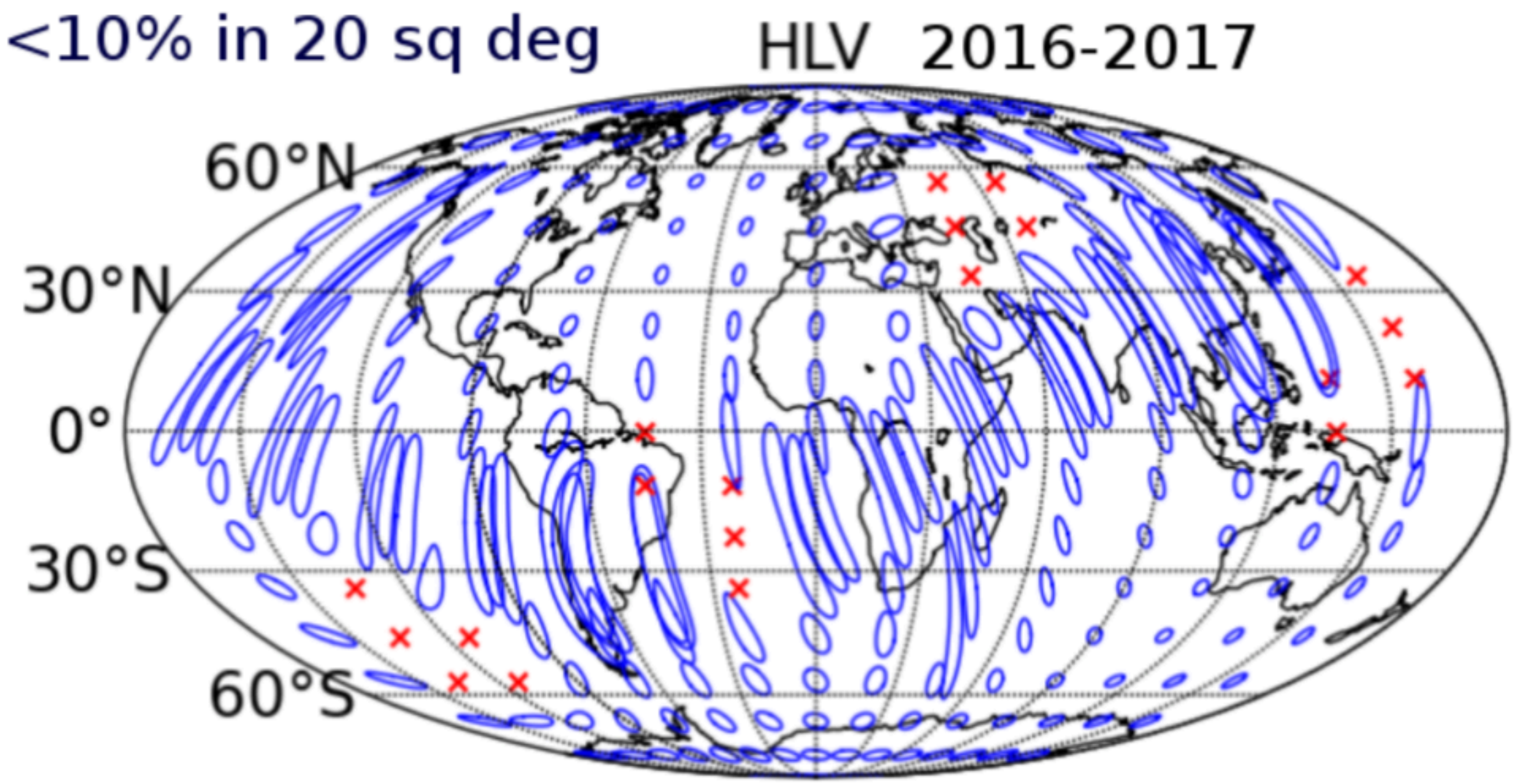
First Detection Sensitivity/configuration:

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



2017 Sensitivity/configuration:

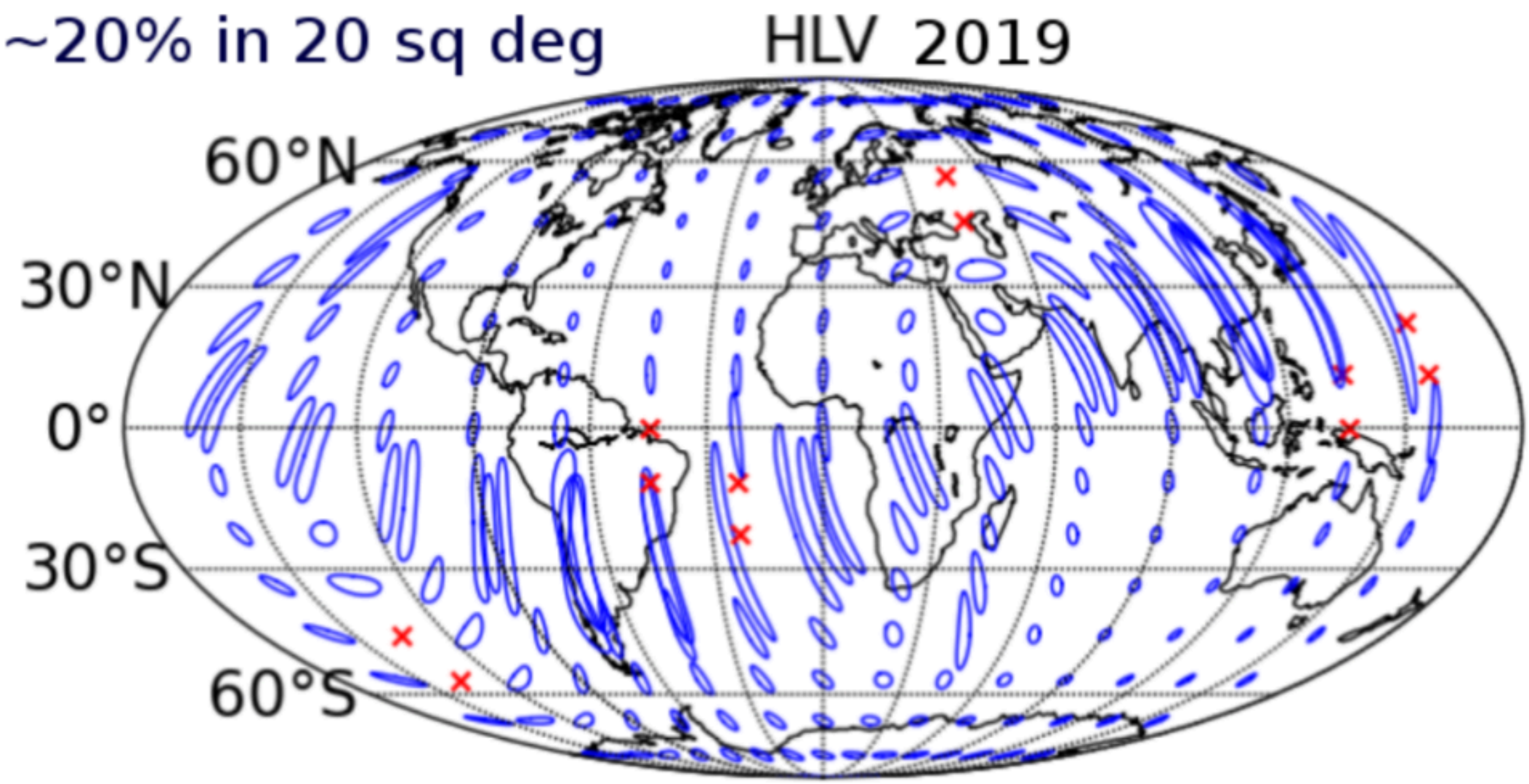
3 detectors (add Virgo), ~1/2 goal sensitivity
~2-3 signals per month of observation



2018-19 Sensitivity/configuration:

3 detectors, **full goal sensitivity**

~1 signal *per day*



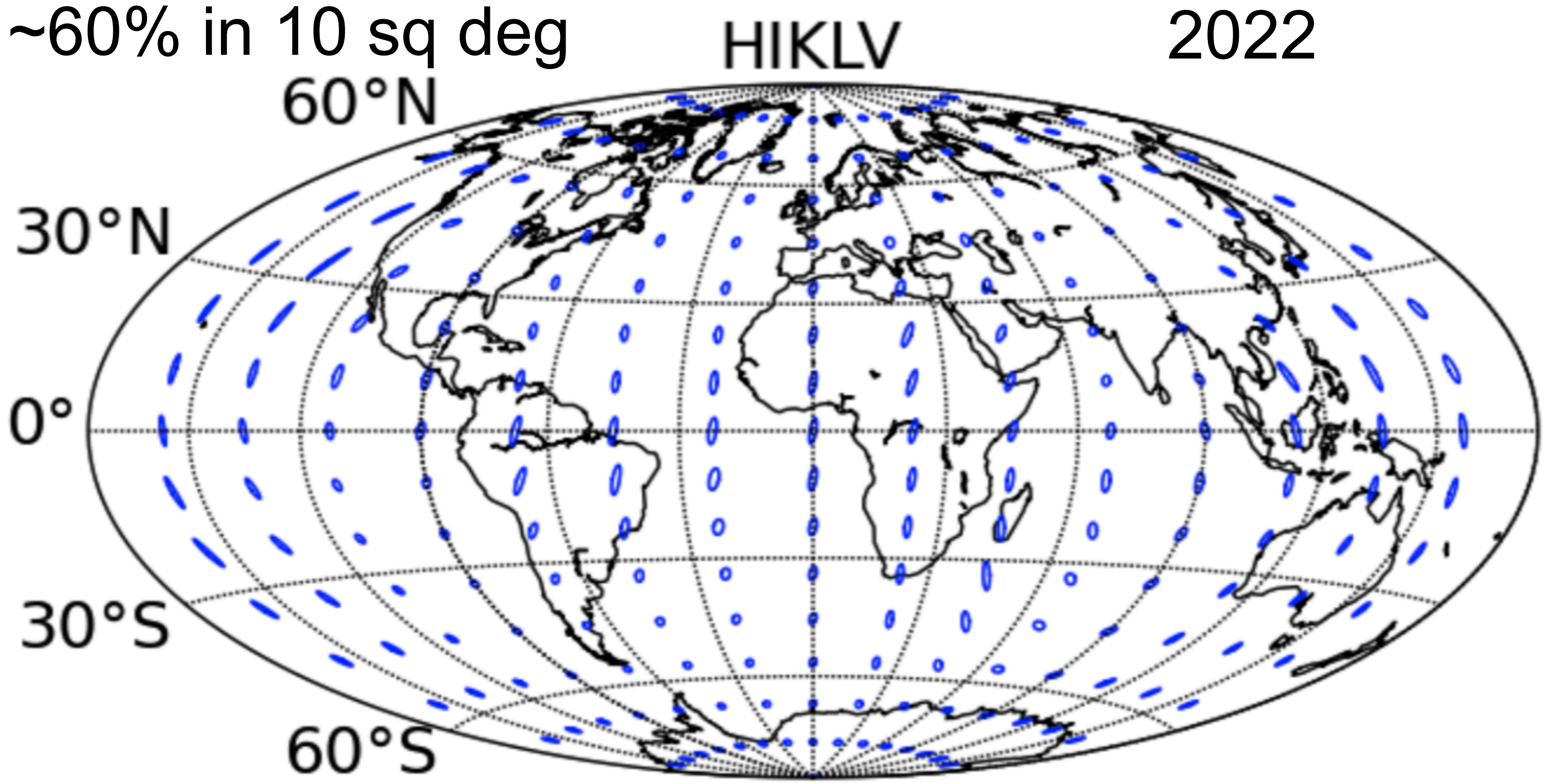
LIGO

2022 Sensitivity/configuration:

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

~60% in 10 sq deg

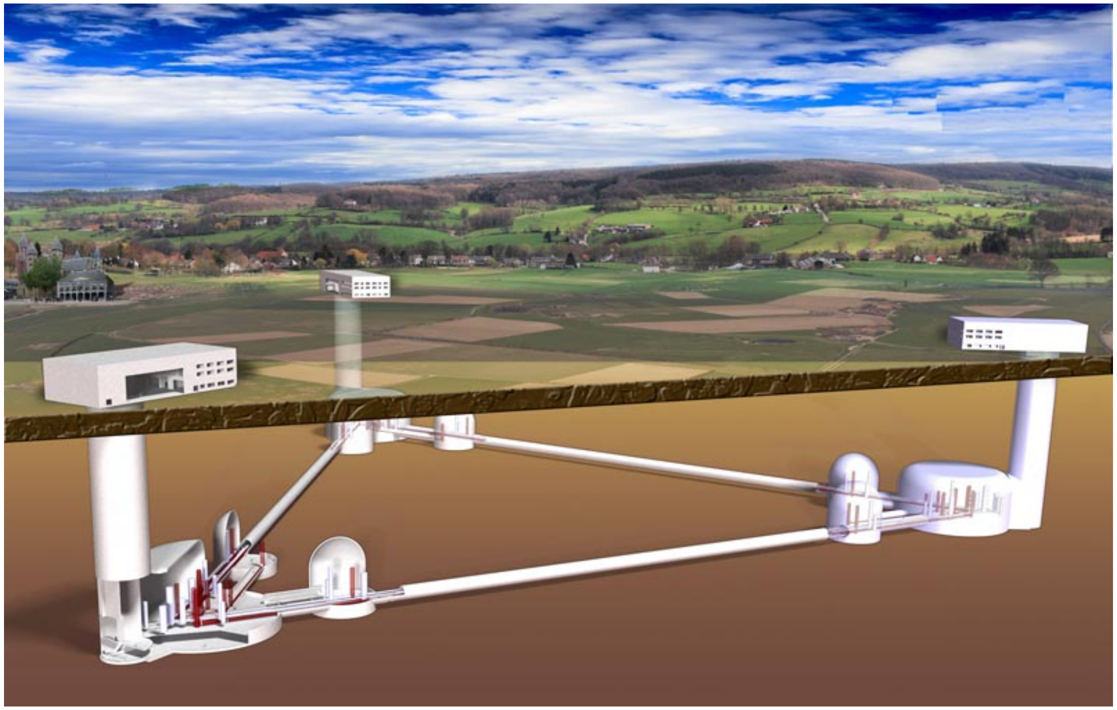
2022



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)

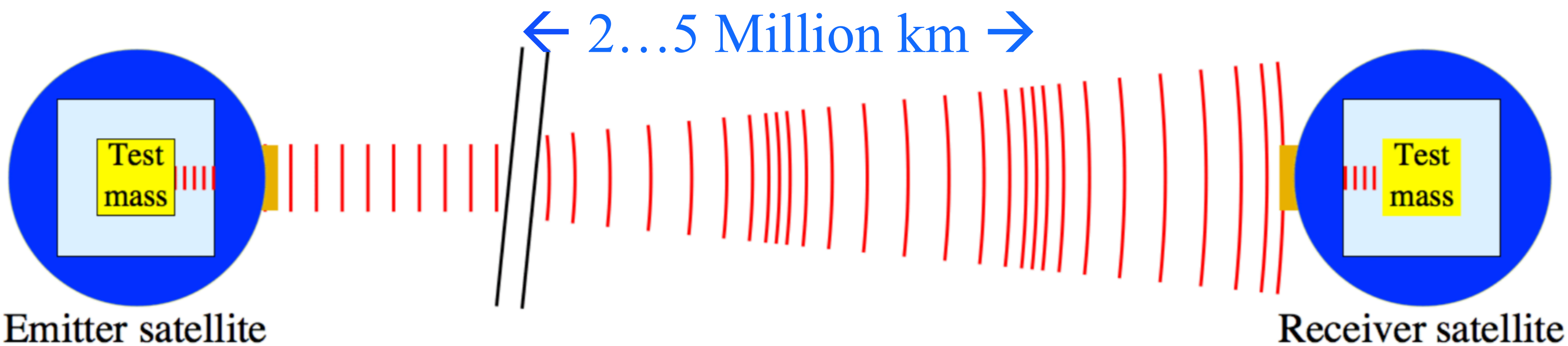
- Factor 10: perhaps by 2035
- Underground construction?
- A longer baseline, e.g. 4 → 40km
- Almost all noise sources stay constant –
  but signal grows a factor of 10
- Models indicate feasibility
- Need to establish field first!



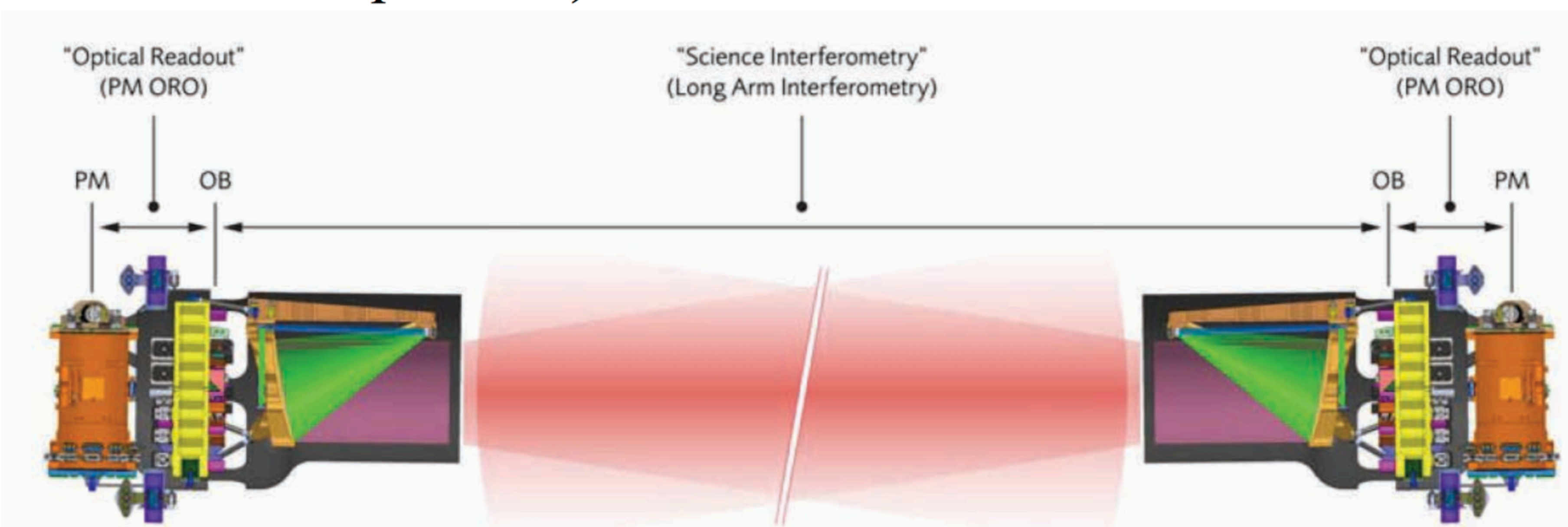
...and a detector in Space: **LISA**

- Once you are there, vacuum is inexpensive – make *very* long arms
  - Very high signal-to-noise – precision tests of gravitation
- Can observe much larger masses
  - Galaxies with black holes of a million solar masses coalescing
- Analogous to adding Radio Astronomy to Optical Astronomy

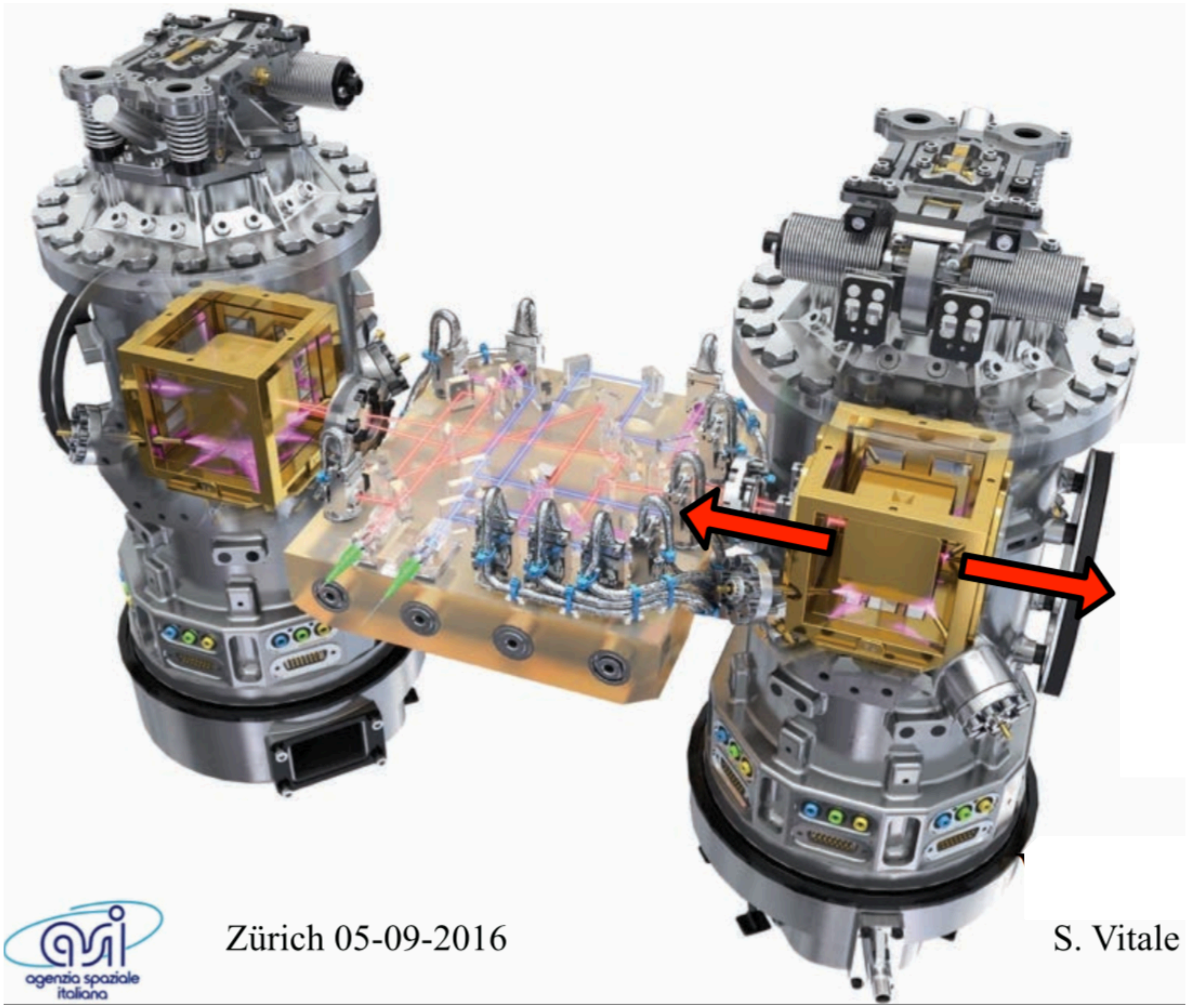
The LISA link



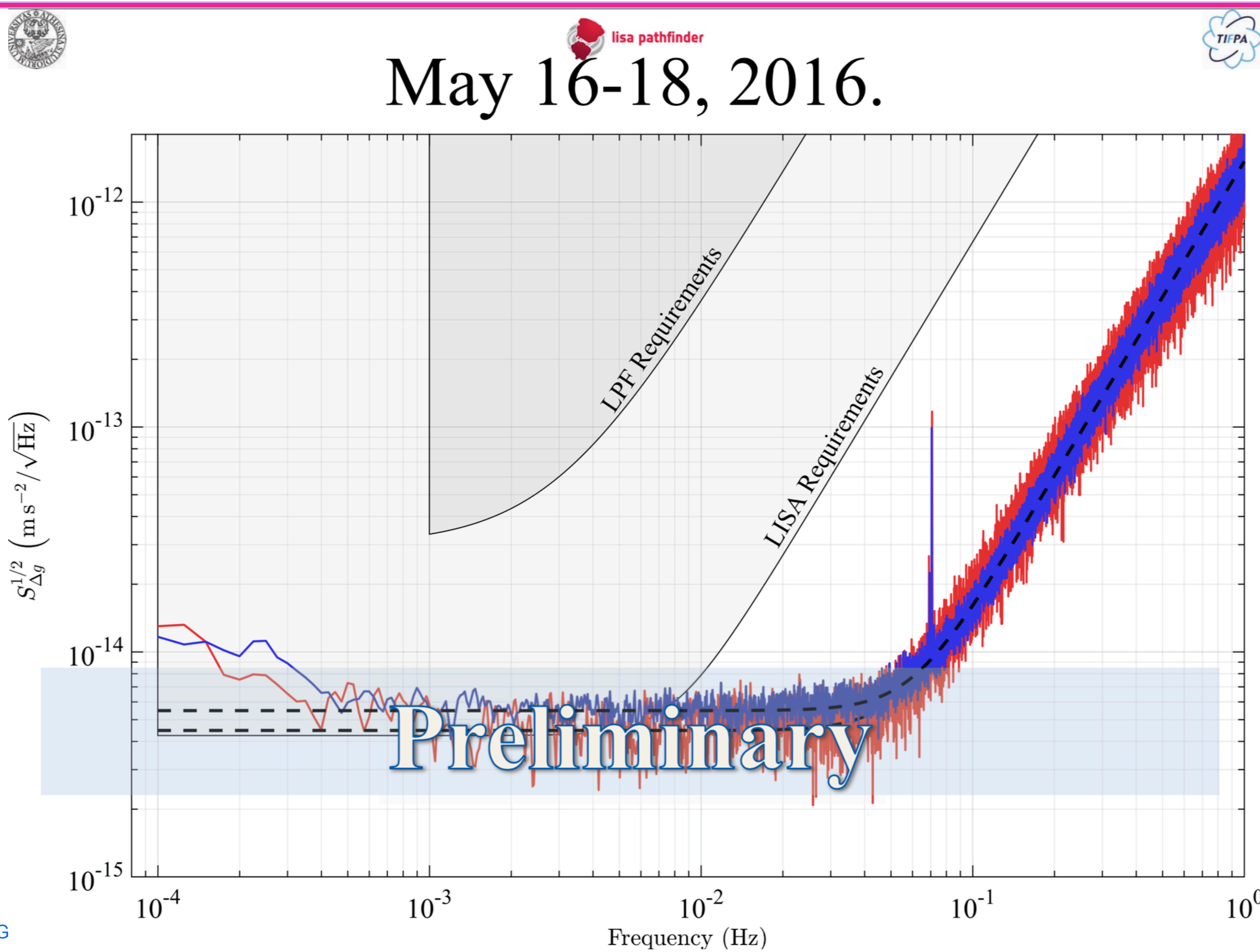
- Inertial observer are replaced by test-masses
- (Satellites accelerate too much because of solar radiation pressure)



LISA Pathfinder test mission, now underway: interferometry between two LISA test masses

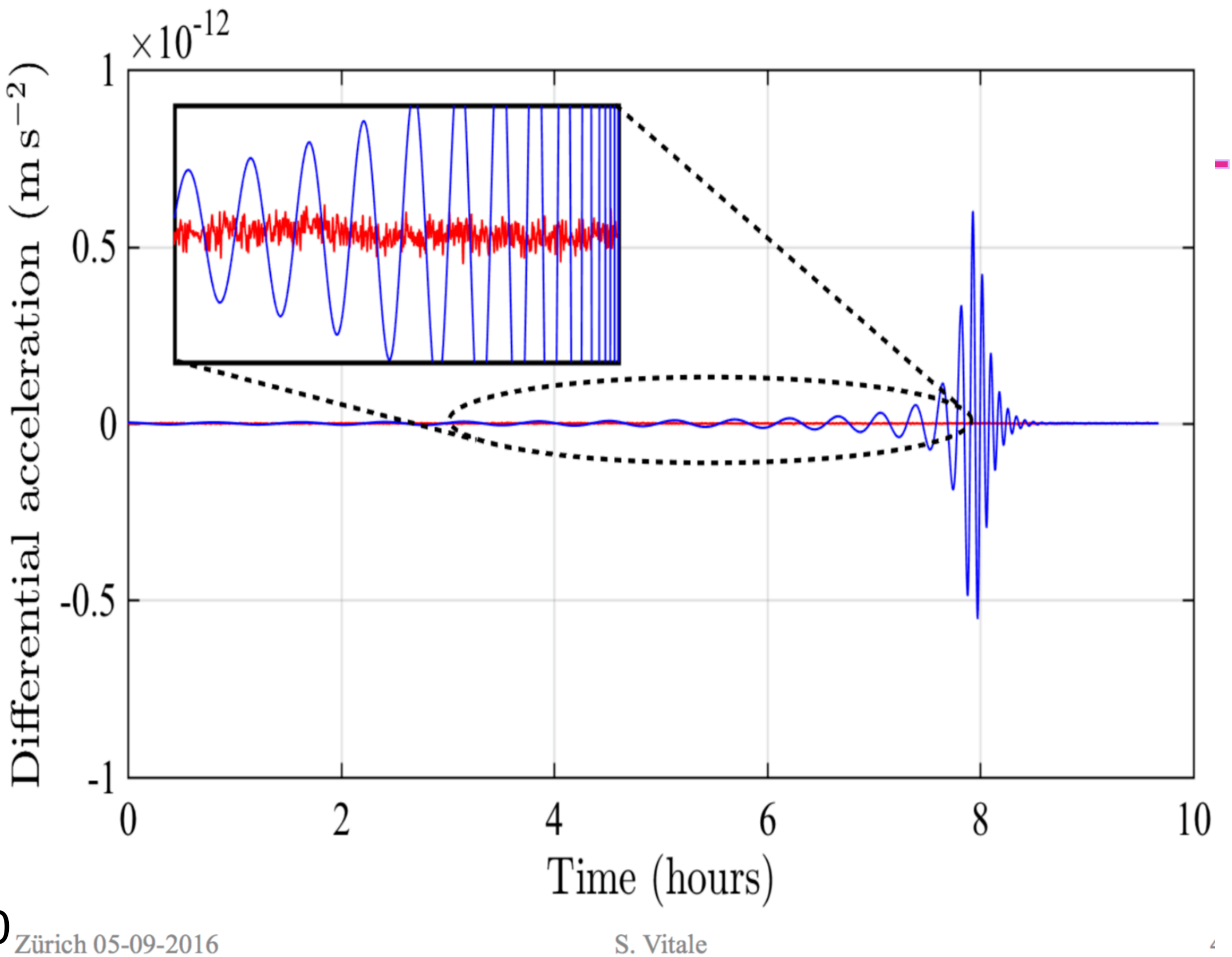


LISA Pathfinder Performance



LIGO LISA

- ESA-led mission; NASA minority partner
- ESA-NASA discussions on program elements
- EU-US community (re-)forming joint collaboration
- Phase A imminent; mission adoption possible in 2020
- Launch date nominally 2034; may bring in to ~2030



- …and then *great* science:
- Blue: Simulated signal for inspiral of two $5x10^5$ Black Holes inspiraling at z=5
- Red: LISA Pathfinder interferometer performance