LIGO

Observation of Gravitational Waves from a Binary Black Hole Merger

University of Washington
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For the LIGO and Virgo Scientific Collaborations

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

- Two black holes in a tight orbit
- Period shrinking due to loss of energy to gravitational waves
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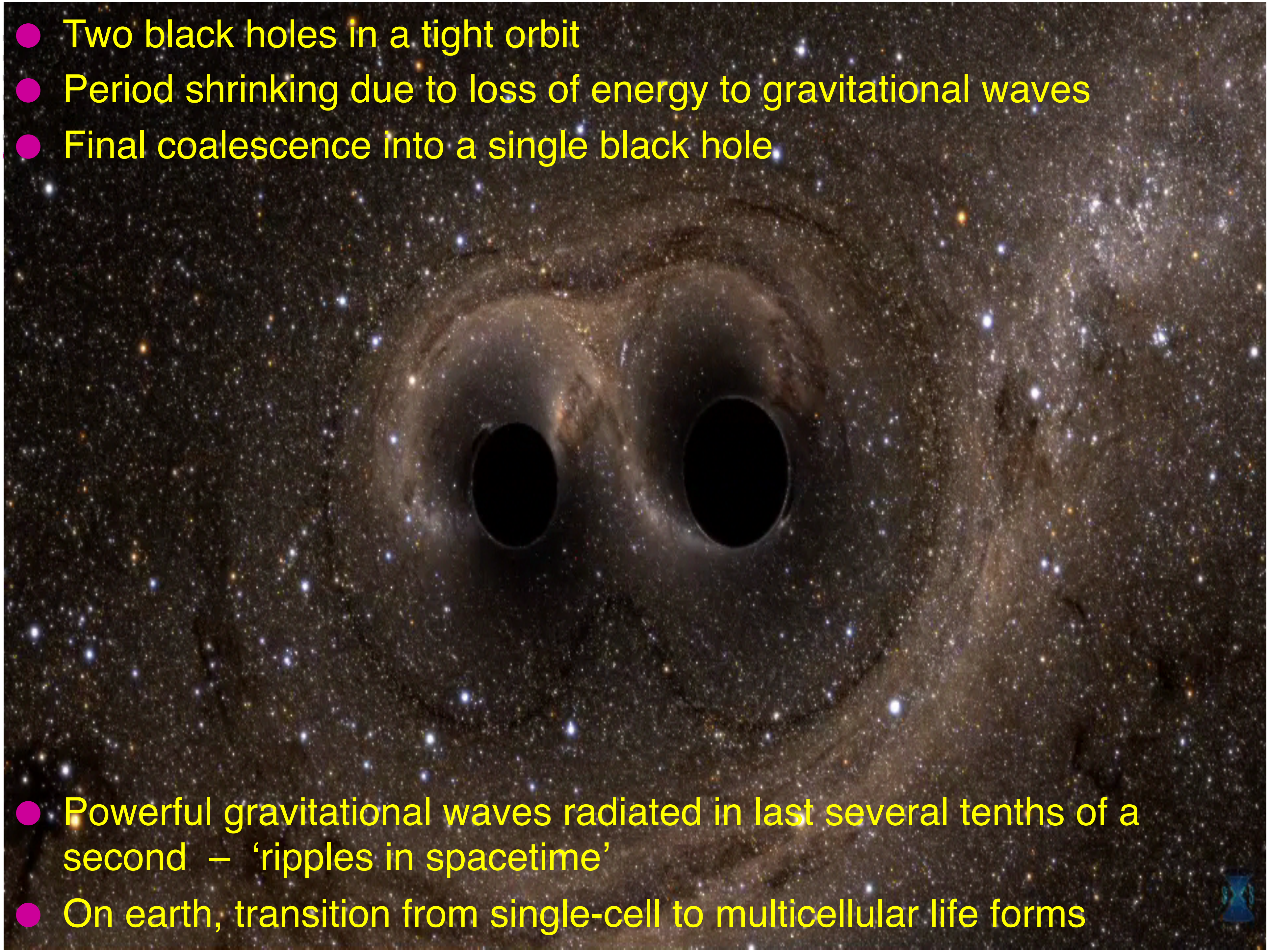
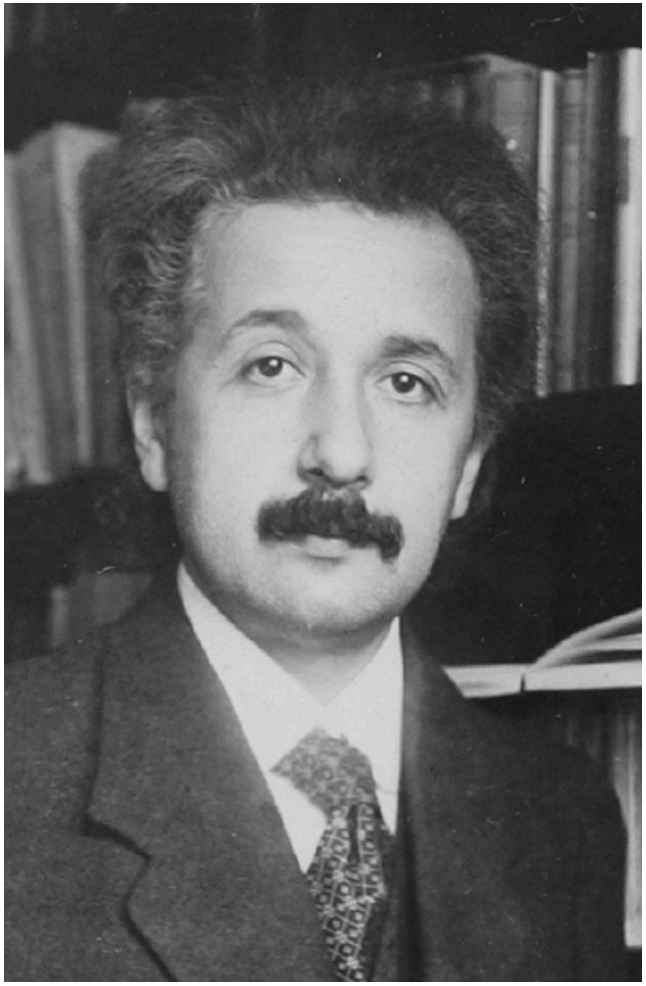


- Powerful gravitational waves radiated in last several tenths of a second – ‘ripples in spacetime’
- On earth, transition from single-cell to multicellular life forms

Much later, only 100 years ago

- Our favorite patent clerk in Zurich is evaluating and processing applications…
  - » …for transmission of electric signals and electrical-mechanical synchronization of time
- The result: General Relativity is published in 1915 by the former clerk (now Professor) A. Einstein
- First paper indicating that gravitational waves (GW) in 1916
  - » Contains an algebraic error, leading Einstein to think that no energy is carried by GWs
- Second paper in 1918 corrects this error, but Einstein indicates that the effect is of no practical interest since the effect is too small to be detected



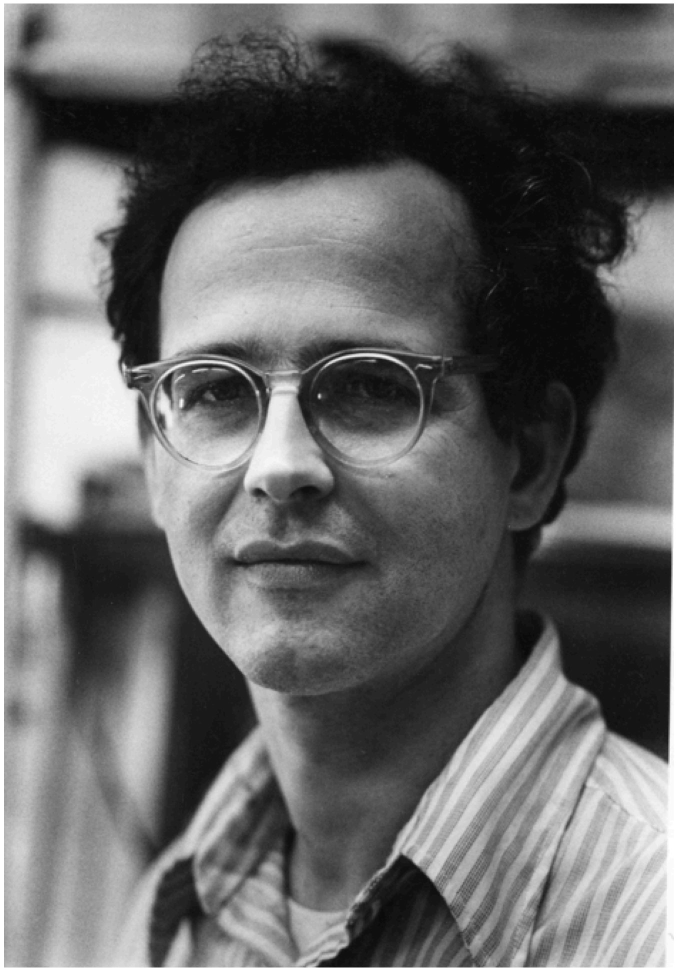
Meanwhile….

- *The gravitational waves from the binary black-hole merger cross Gacrux, a star in the Southern Cross*

A half-century ago

(as the wave passes HR 2225 in Canis Major)

- 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
- Interest grows in Max Planck Garching (Germany), U. Glasgow, Caltech in this interferometric technique

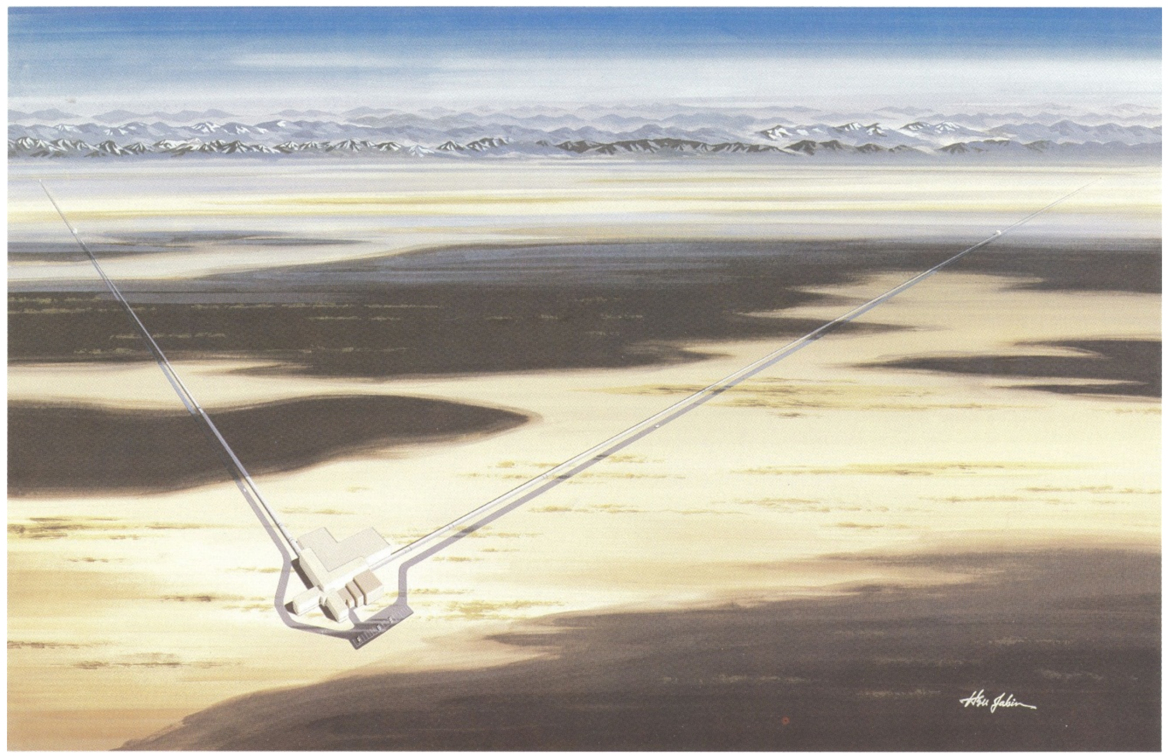


Two decades ago

- 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

- Artist's conception of what an observatory might look like

- *Waves passing 82 Eridani…*



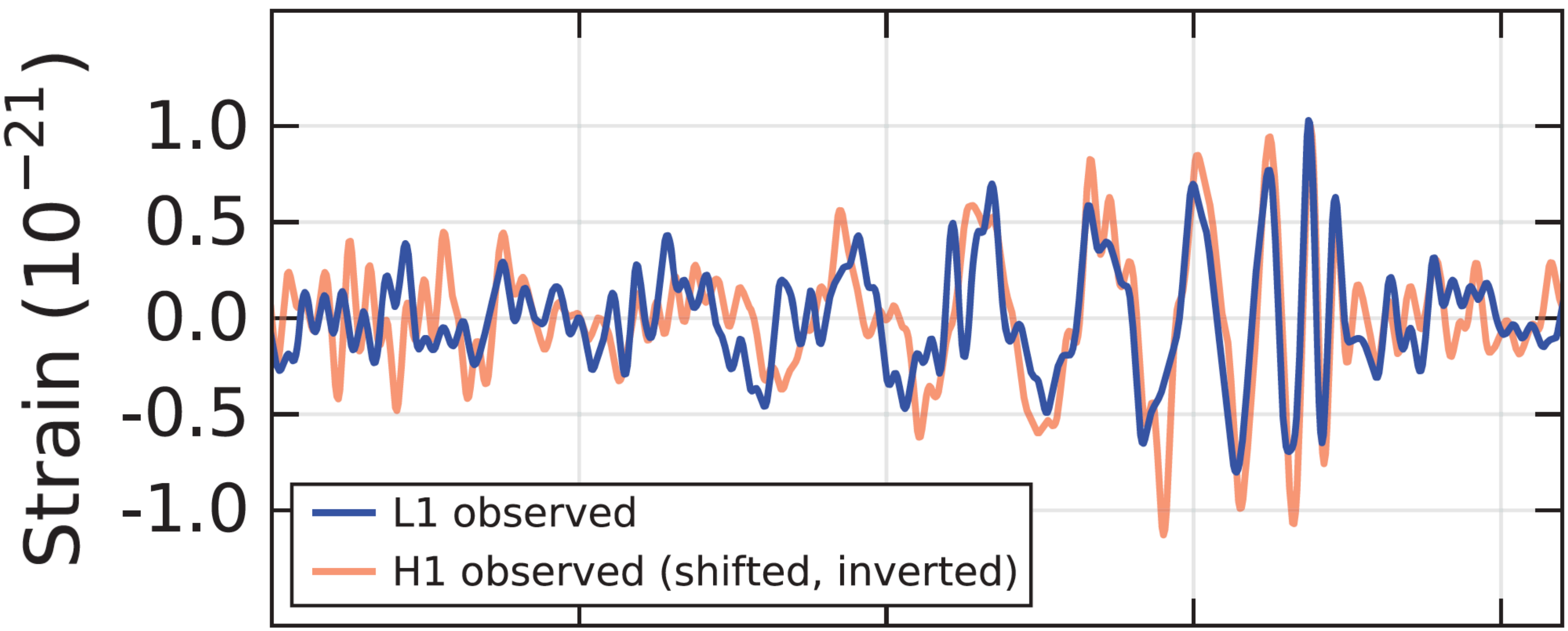
Recent History

- Advanced LIGO is funded in 2006: an upgrade of all components, 10x better sensitivity
  - *Our BHBH signal crosses Sirius*

- Initial LIGO is taken down in 2011, installation starts for Advanced LIGO
  - *GWs from the BH-BH cross Alpha Centauri, the closest star, just 4.4 light years away*

One more date:
The waves arrive at Earth

- On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal.
  - » 3 minutes later, flagged in data – *the waves are already half-way to sun*



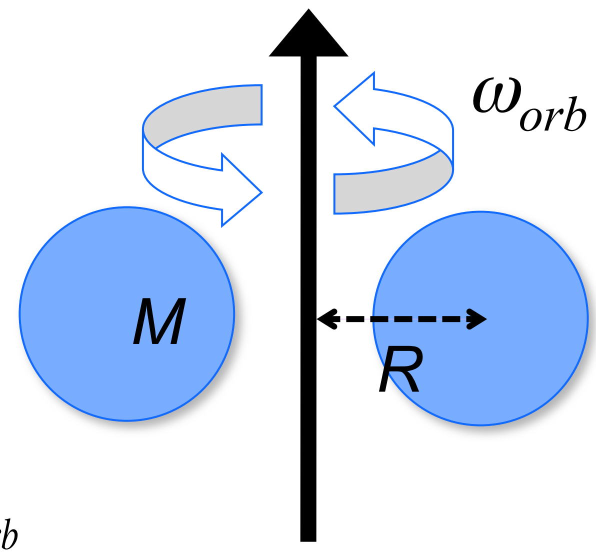
What is the Laser Interferometer Gravitational Observatory, or LIGO?

Gravitational Waves

- 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

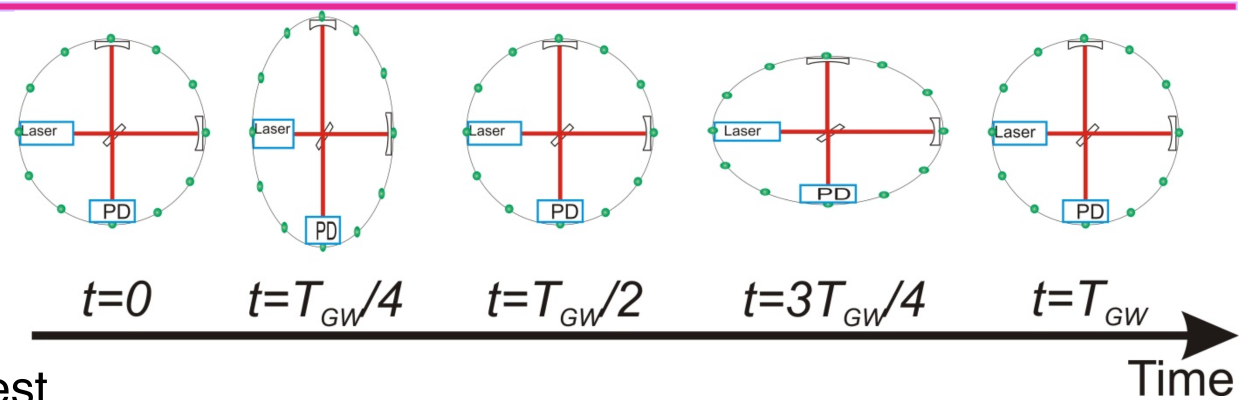


Rotating dumbbell → $h \approx \dfrac{8GMR^2\omega_{orb}^2}{rc^4}$

- GWs propagate at the speed of light (according to GR)
- GWs carry direct information about the coherent bulk motion of matter in the highly relativistic regime

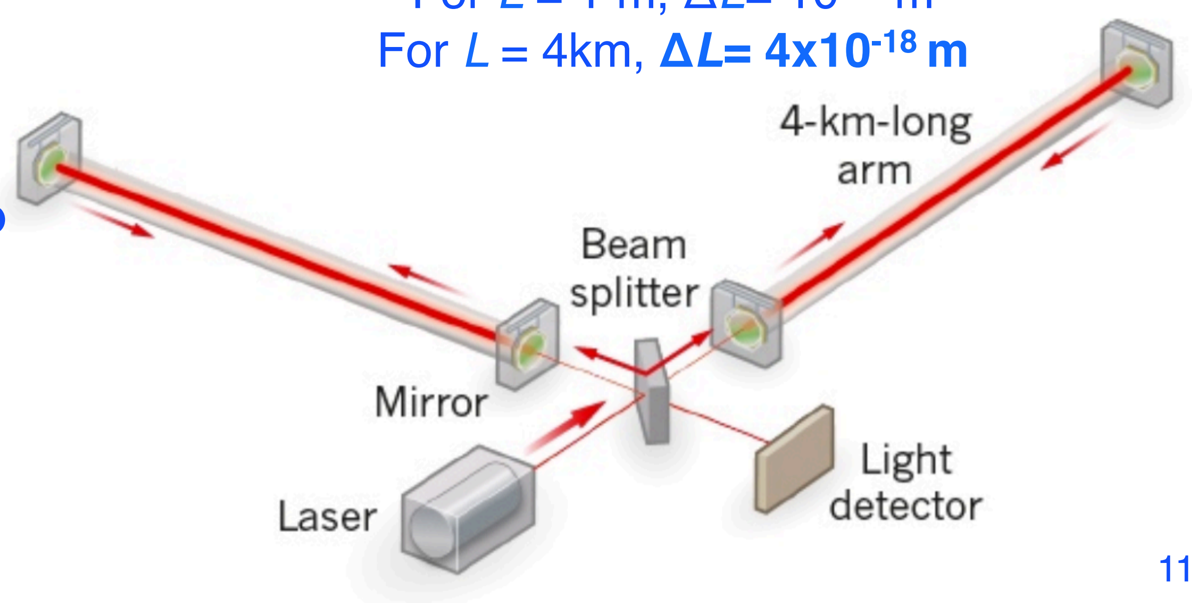
What is LIGO's measurement technique?

- 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….



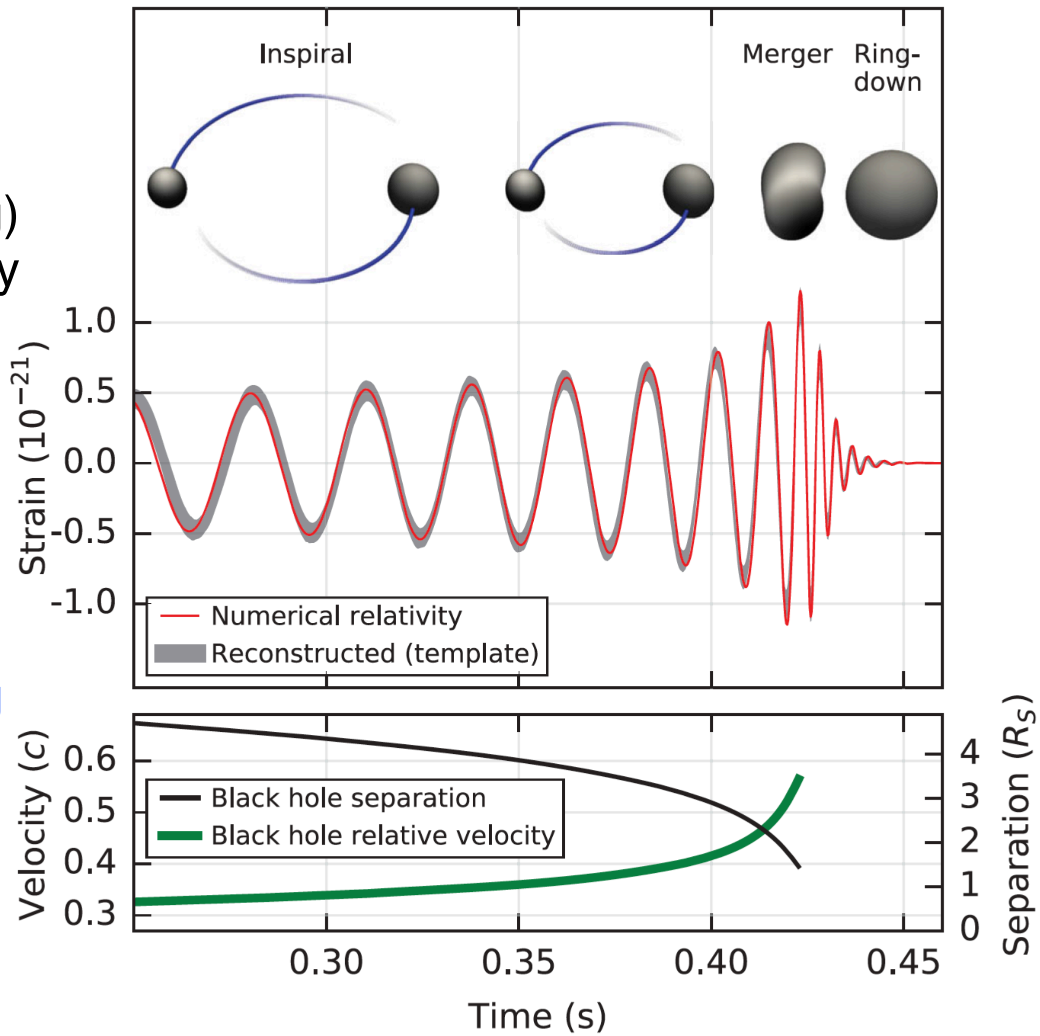
$$h \approx \frac{\Delta L}{L}$$

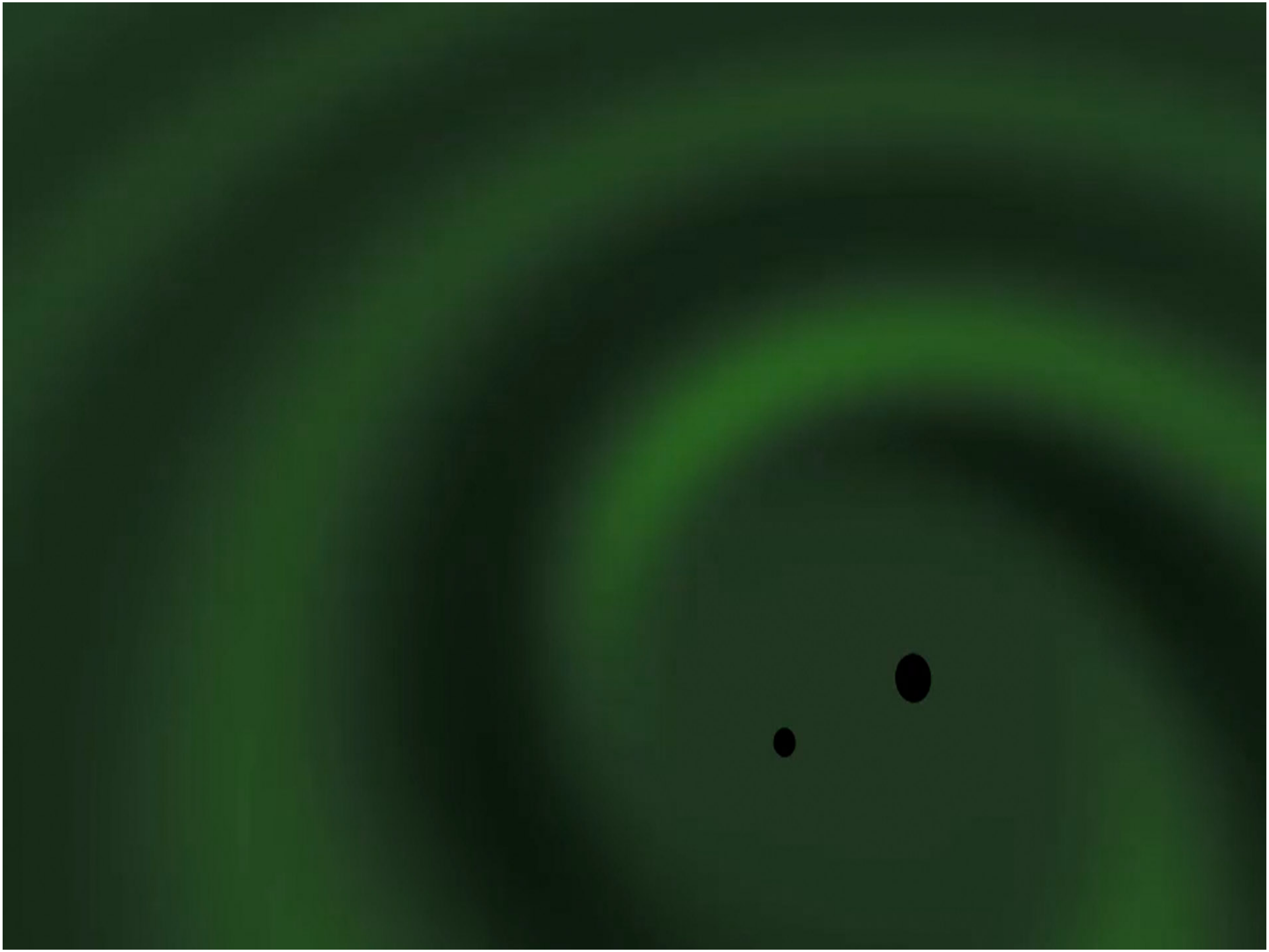
Magnitude of h at Earth:
Largest signals h ~ 10^{-21}
(1 hair / Alpha Centrauri)
For L = 1 m, ΔL= 10^{-21} m
For L = 4km, **ΔL= 4×10^{-18} m**

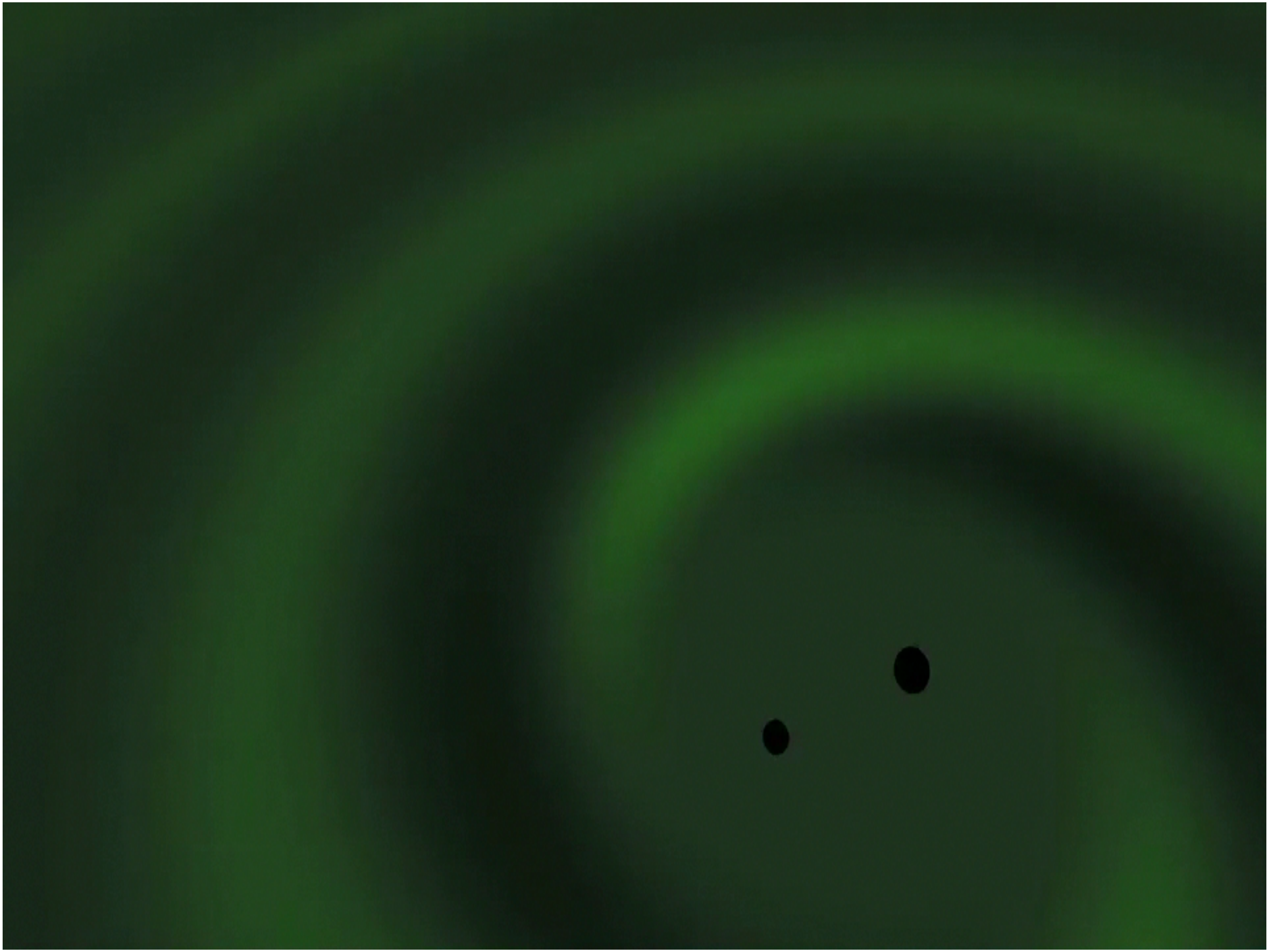


LIGO measures *h(t)* – think 'strip chart recorder'

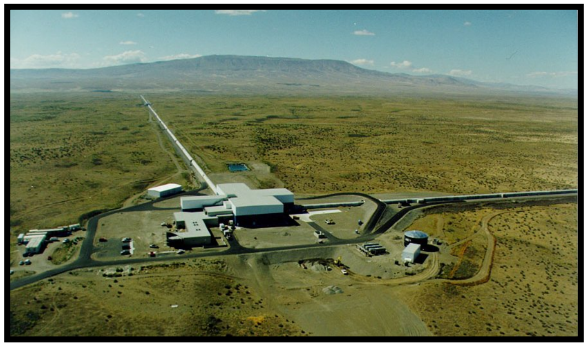
- The output of the detector is the (signed) strain as a function of time
- Earlier measurements of the pulsar period decay (Taylor/Hulse/Weisberg) measured energy loss from the binary system – a beautiful experiment
  - *Inference* of gravitational waves as loss mechanism, confirmed to *remarkable* 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!



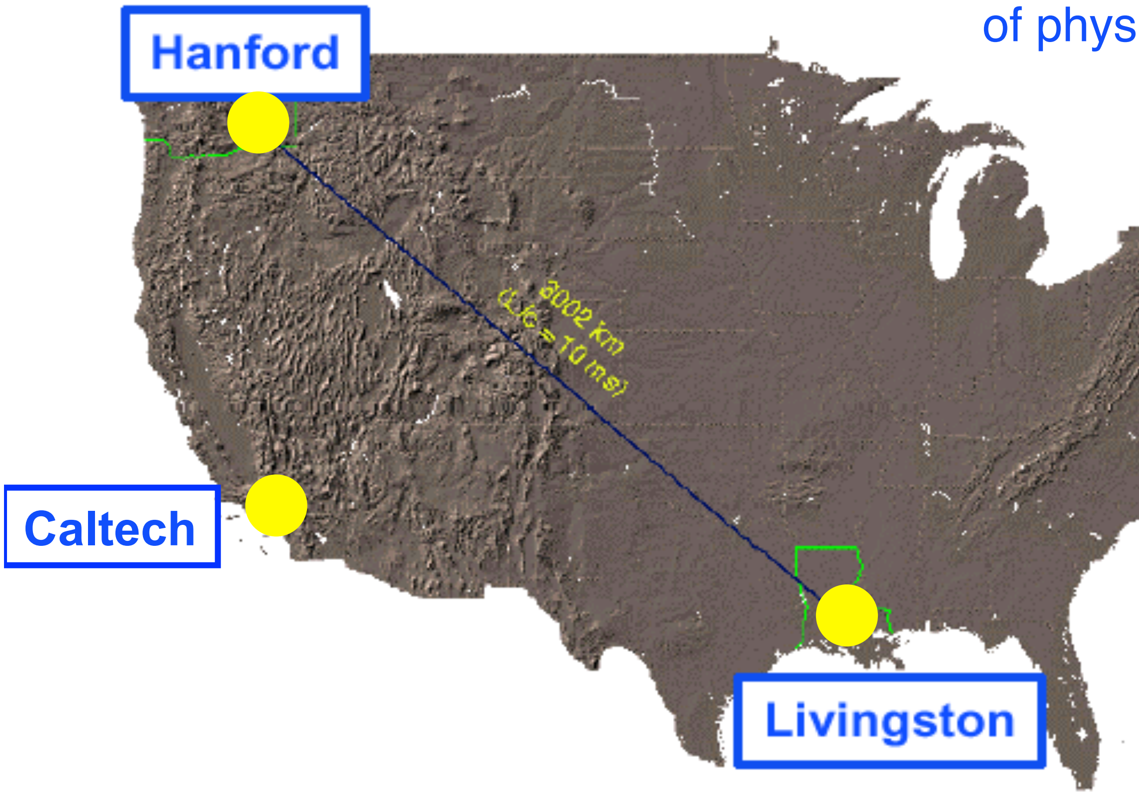




LIGO Laboratory:
two Observatories and Caltech, MIT campuses



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



LIGO Scientific Collaboration

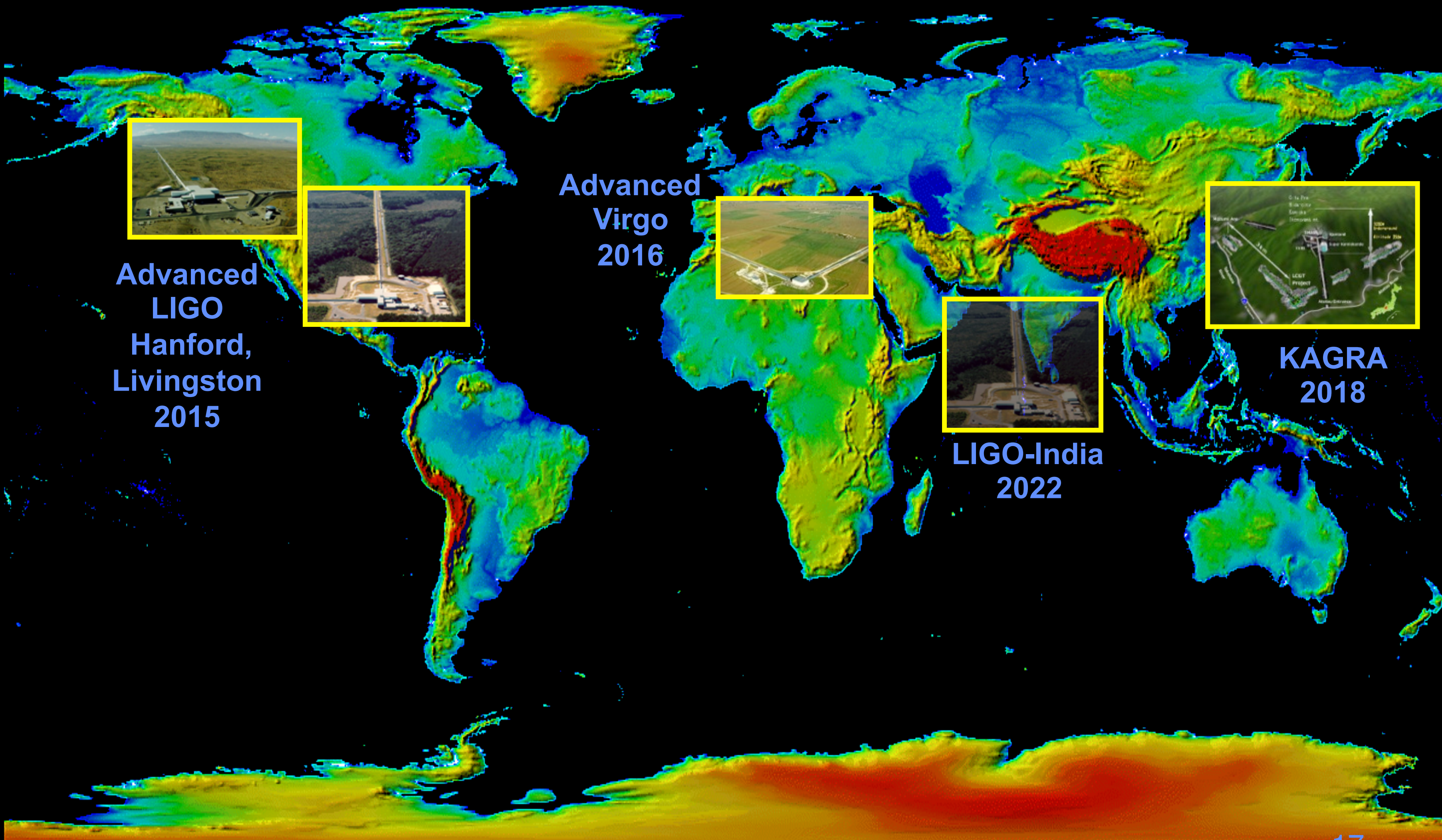
The LSC is the organization the conducts the science of LIGO

www.ligo.org

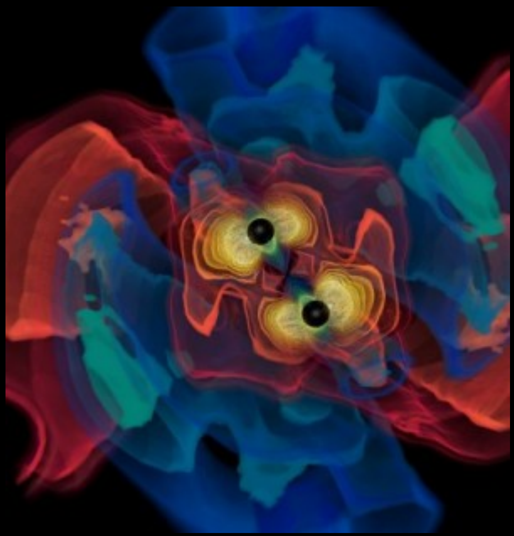
1000+ members, 90 institutions, 16 countries

Slide: Gabriela González

The advanced GW detector network



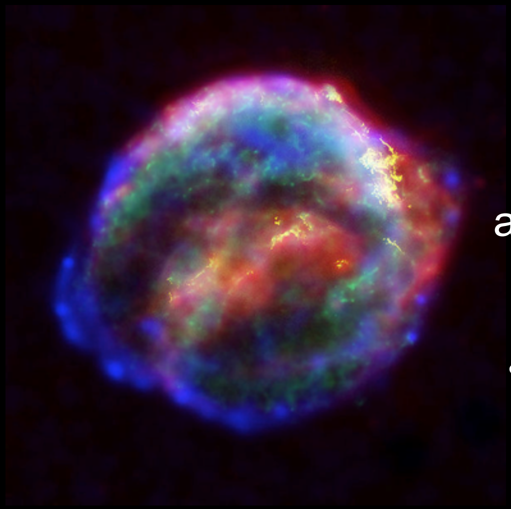
Astrophysical Targets for Ground-based Detectors



Credit: AEI, CCT, LSU

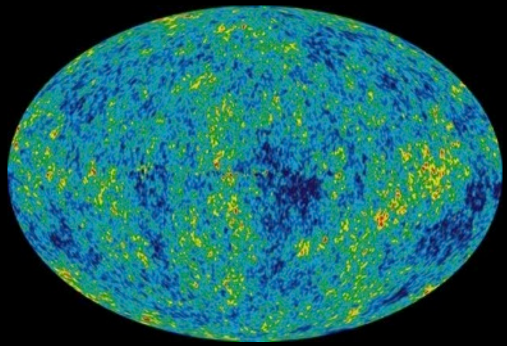
Coalescing Binary Systems

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



'Bursts'

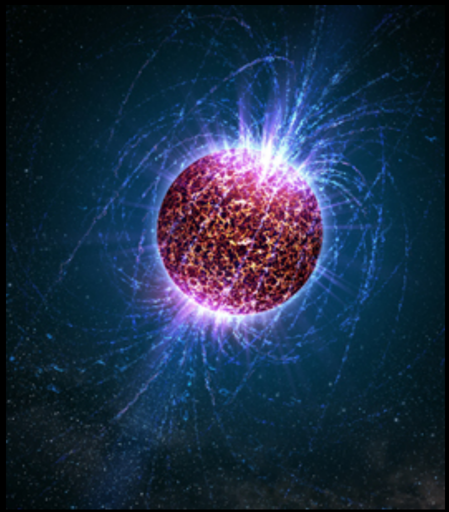
- Unmodelled
- galactic asymmetric core collapse supernovae
- cosmic strings
- ???



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

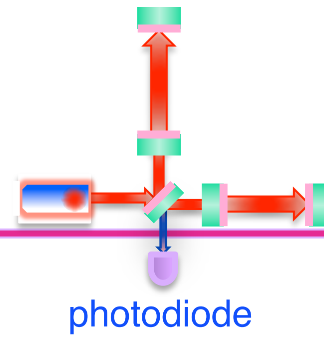


Casey Reed, Penn State

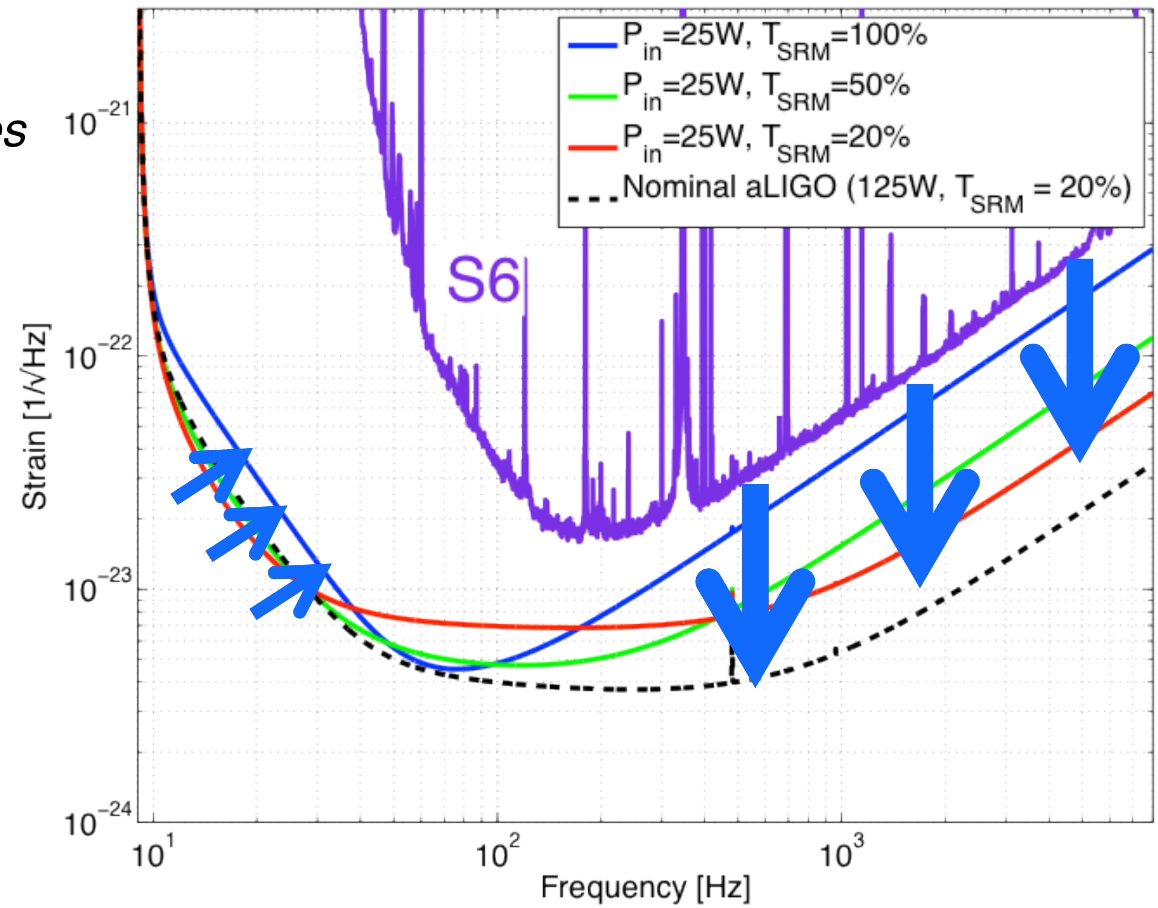
Continuous Sources

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

Measuring Δ*L*= 4x10^{-18} m
Addressing limits to performance

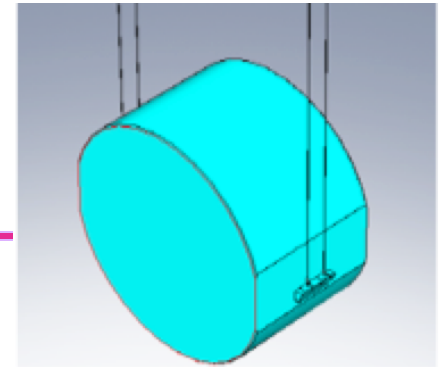


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- *Zum gegenwärtigen Stand des Strahlungsproblems*, A. Einstein, 1909
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$
- Point of diminishing returns when buffeting of test mass by photons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

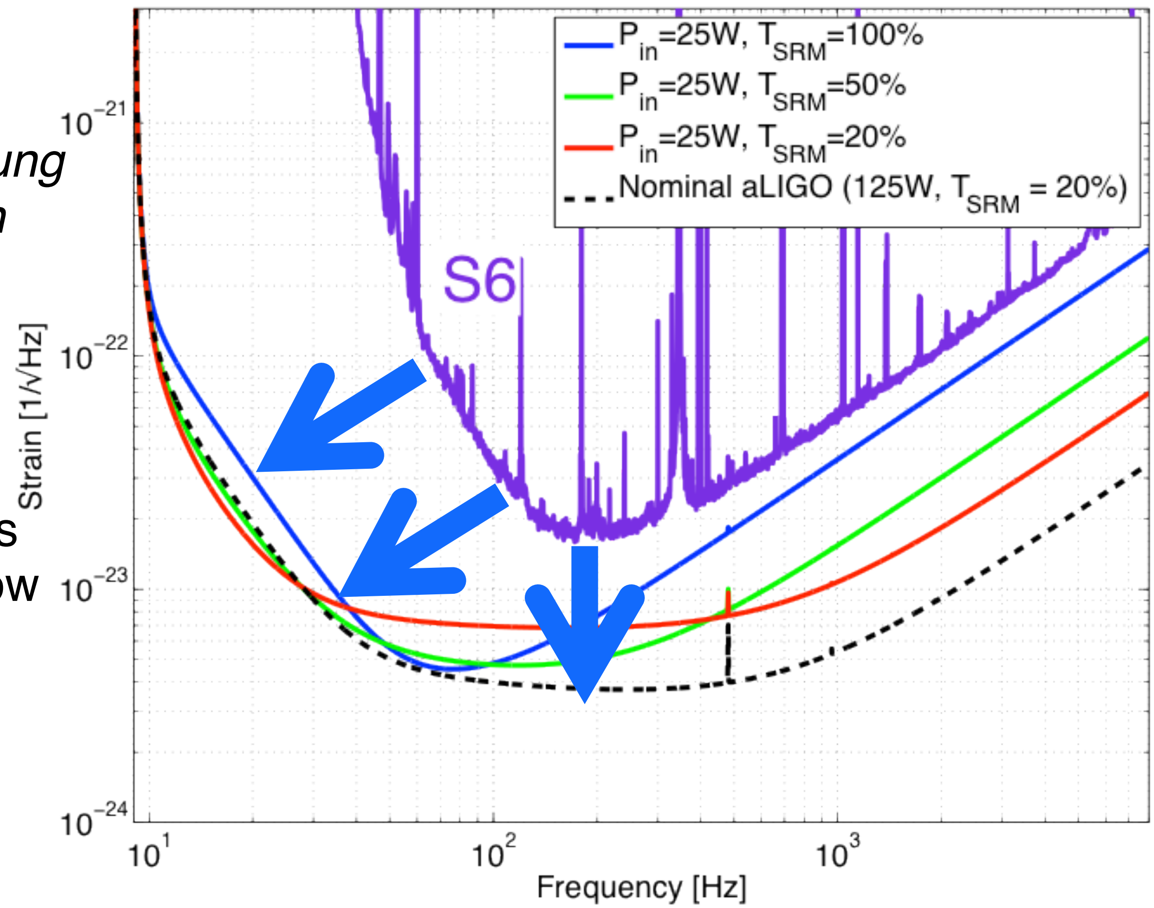


Measuring $\Delta L = 4 \times 10^{-18}$ m

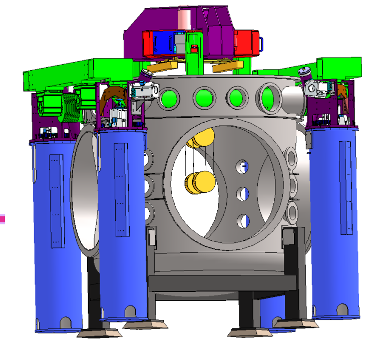
Addressing limits to performance



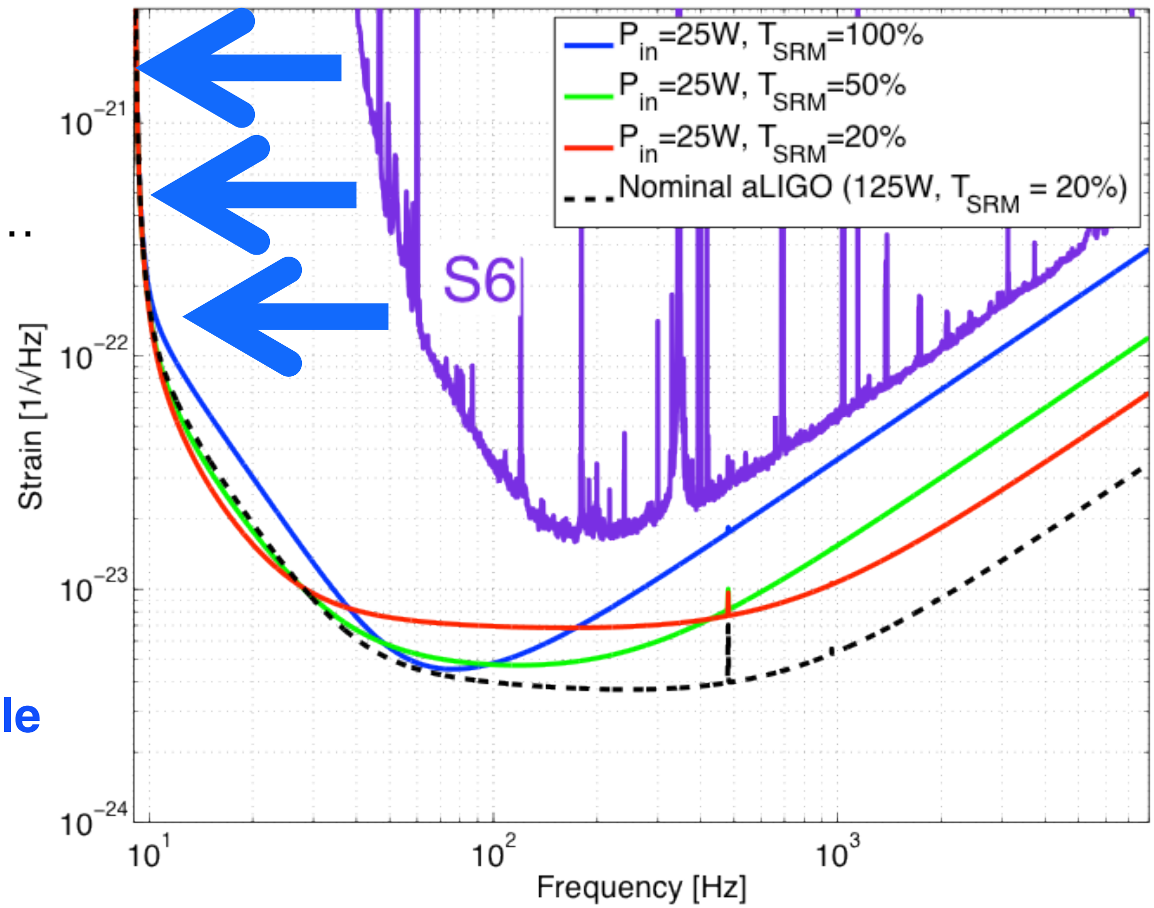
- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen*, A. Einstein, 1905
- Motion of components due to thermal energy masks GW
- Low mechanical loss materials gather this 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**

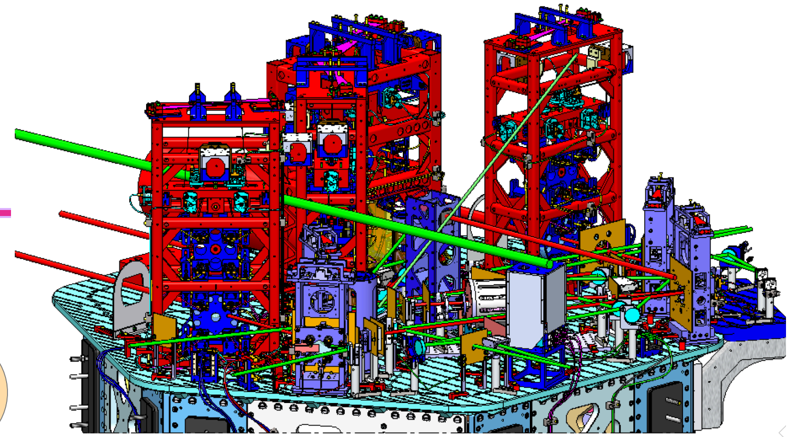


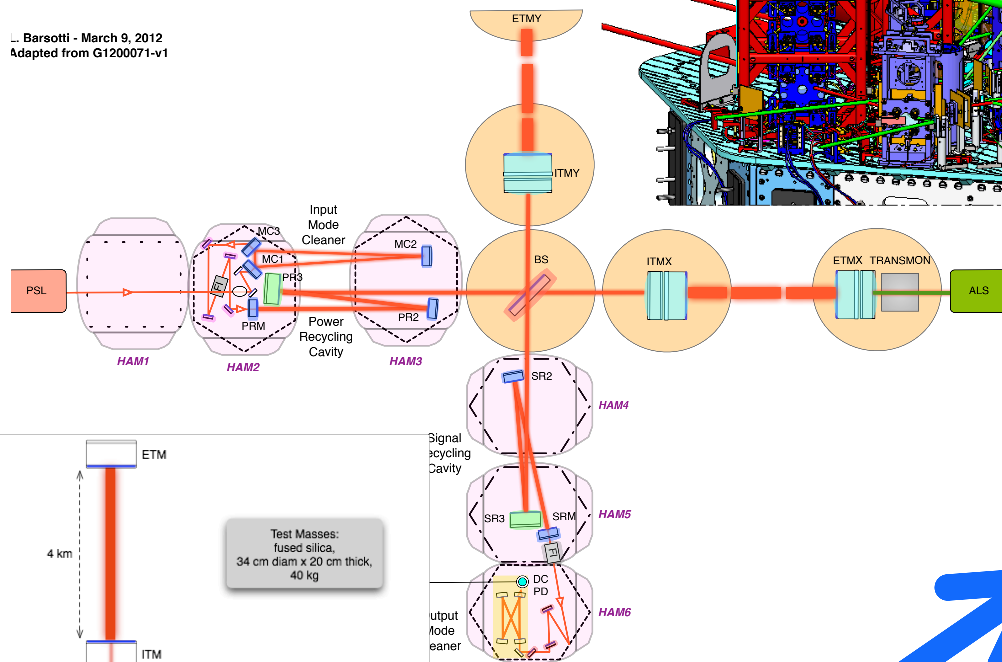
Measuring $\Delta L = 4 \times 10^{-18}$ m
Addressing limits to performance

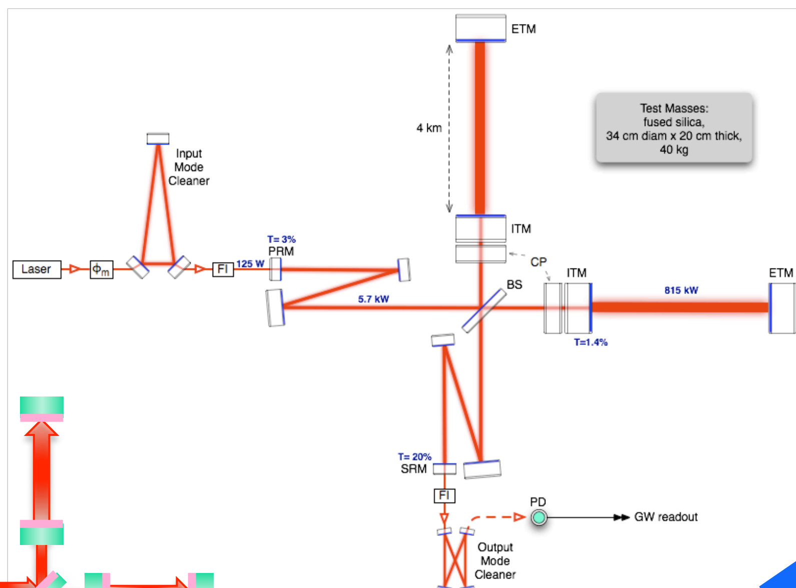


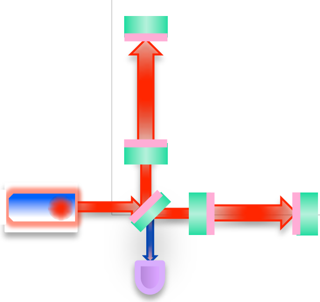
- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- *(did Einstein work on seismic motion…?)*
- Motion from waves on coasts… and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance 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



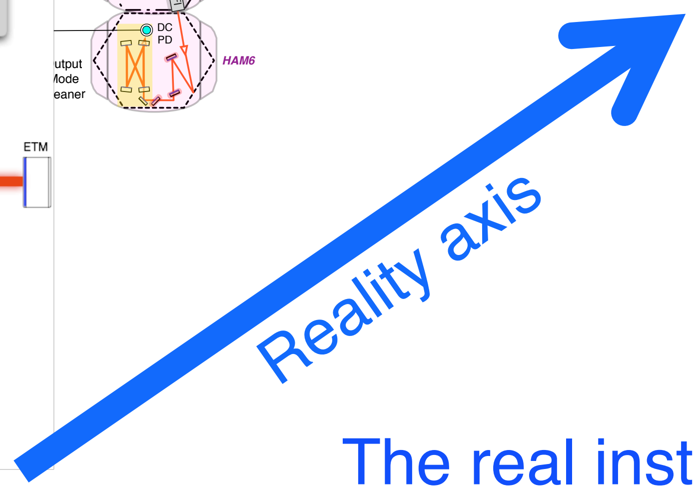








photodiode

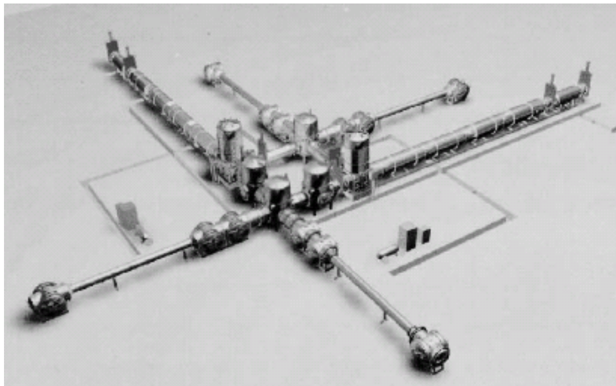


The real instrument is far more complex…

Infrastructure: 4km Beam Tubes

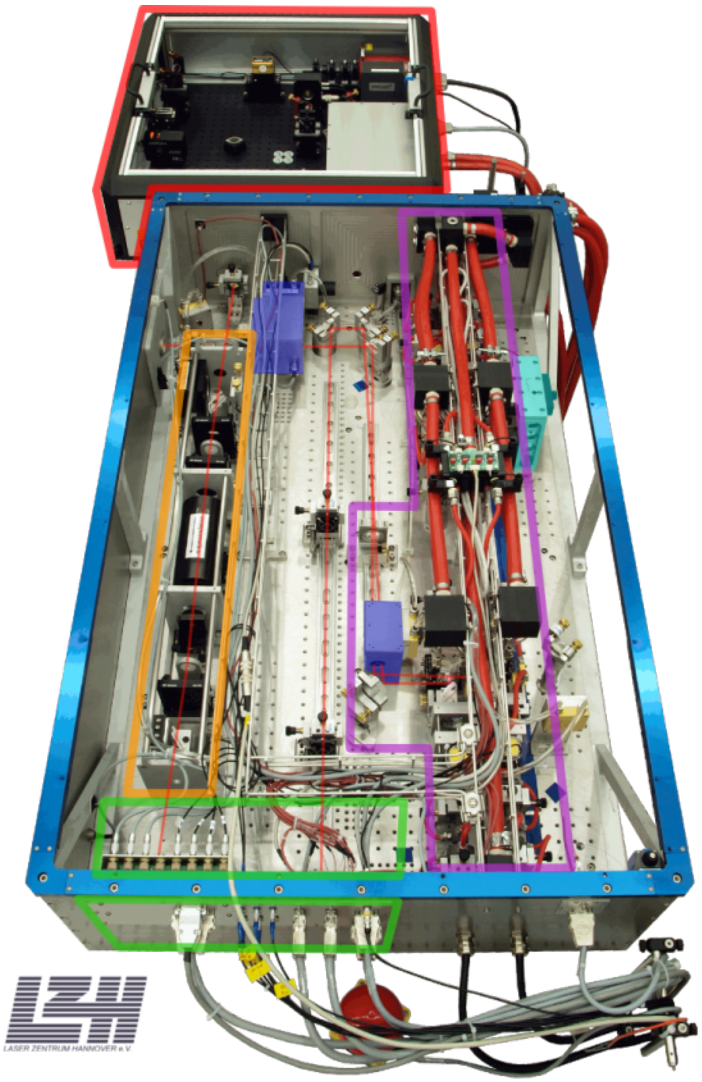
- Light must travel in an excellent vacuum
  - » Just a few molecules traversing the optical path makes a detectable change in path length, masking GWs!
  - » 1.2 m diameter – avoid scattering against walls
- Cover over the tube – stops hunters' bullets and the stray car
- Tube is straight to a fraction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

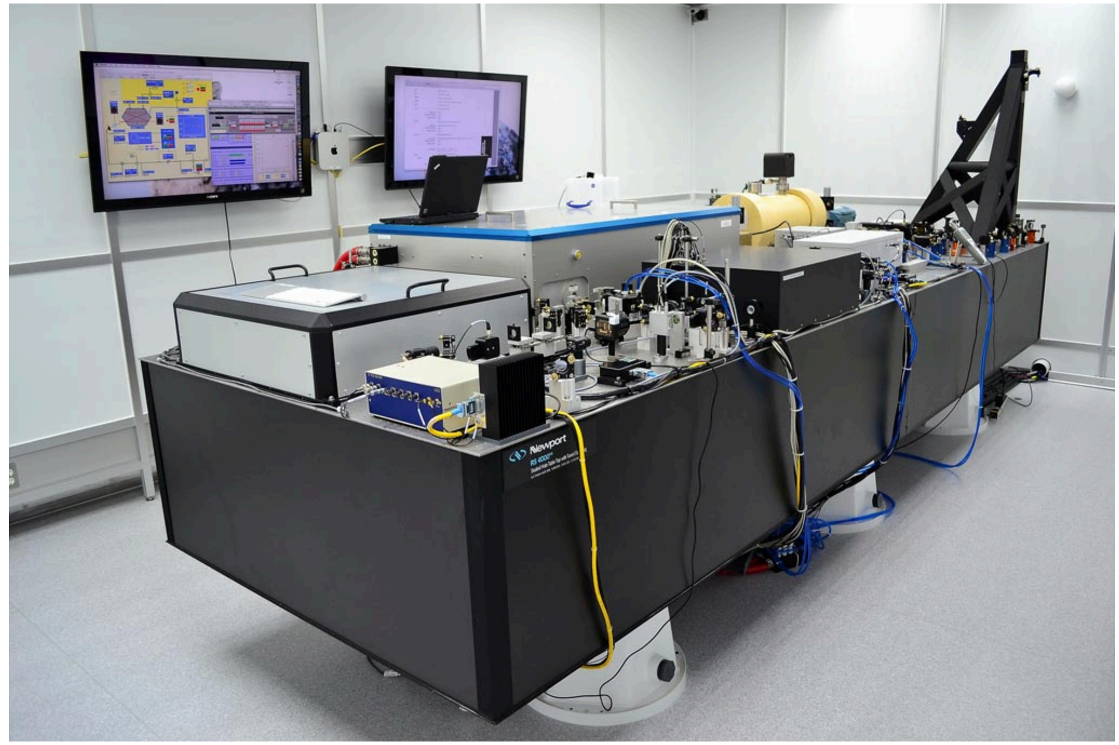
LIGO Vacuum Equipment – designed for several generations of instruments



200W Nd:YAG laser

Designed and contributed by Max Planck Albert Einstein Institute

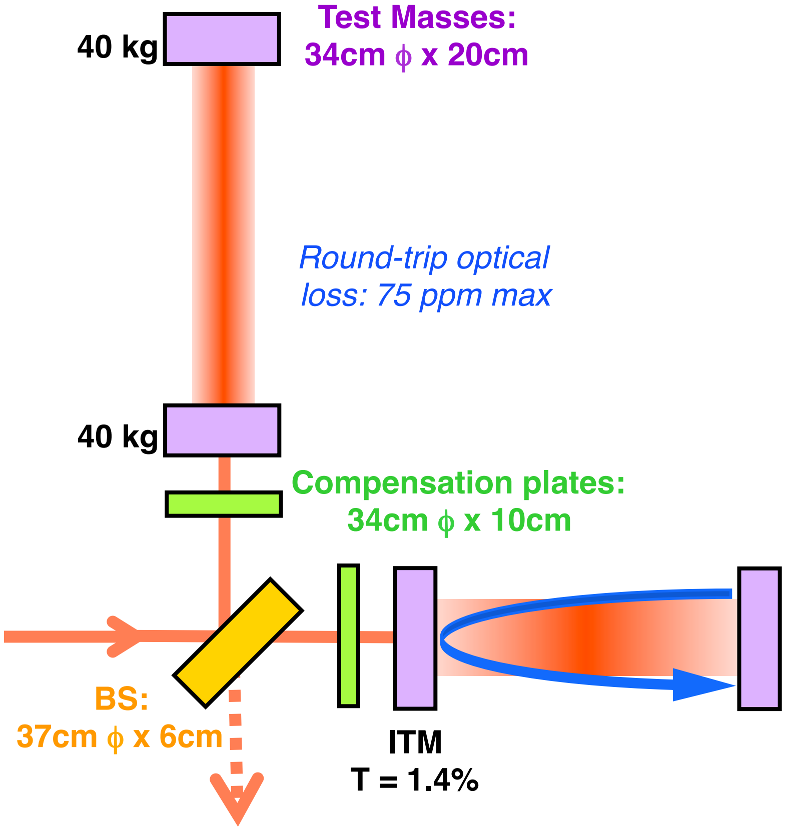


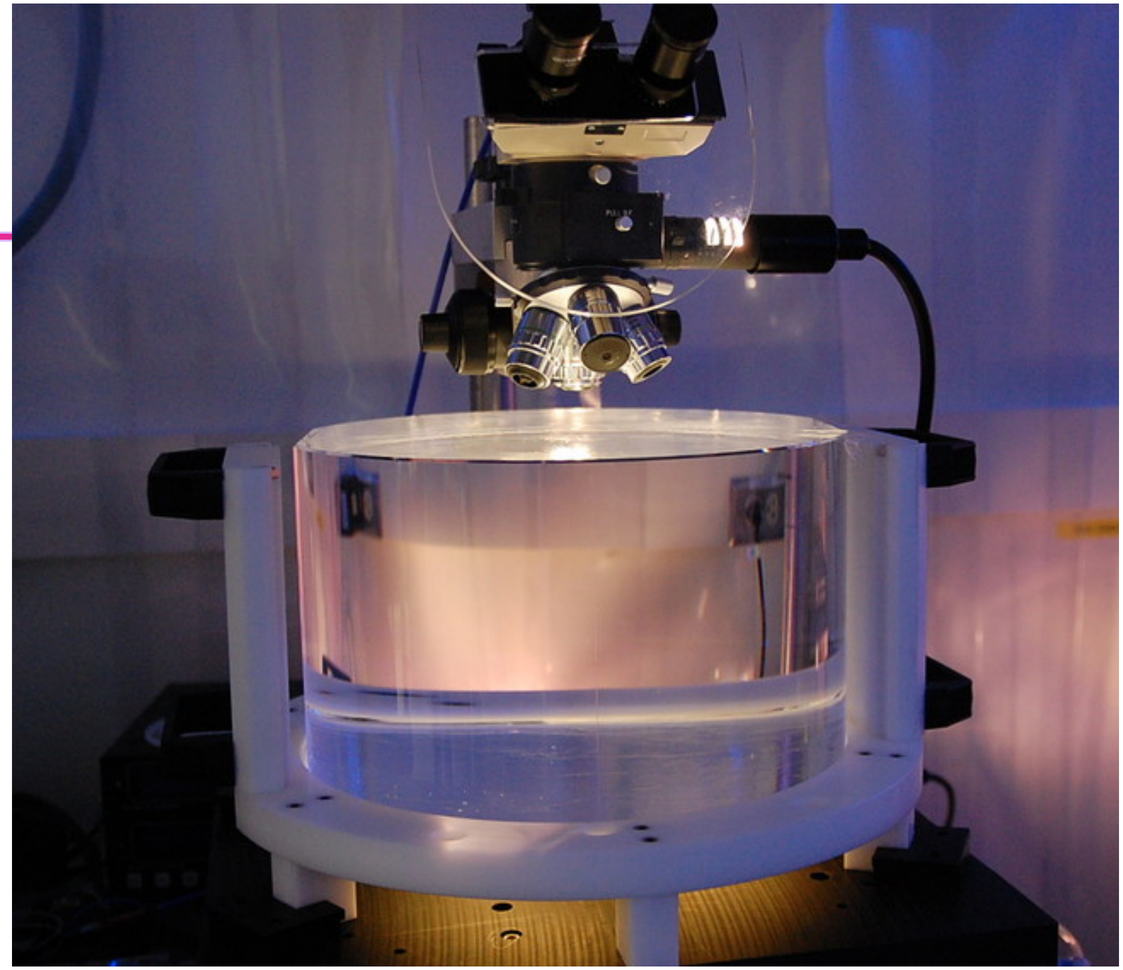


- Stabilized in power and frequency – using techniques developed for time references
- Uses a monolithic master oscillator followed by injection-locked rod amplifier
- Delivers the required shot-noise limited fringe resolution

Test Masses

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



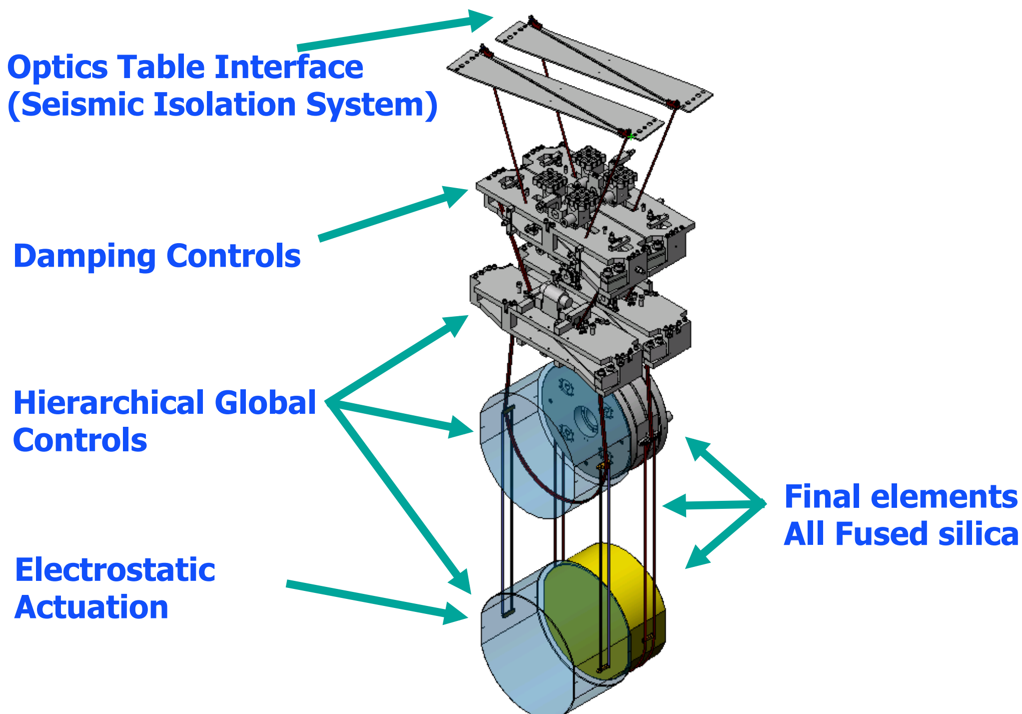


- Both the physical test mass – a free point in space-time – and a crucial optical element
- Mechanical requirements: bulk and coating thermal noise, high resonant frequency
- Optical requirements: figure, scatter, homogeneity, bulk and coating absorption

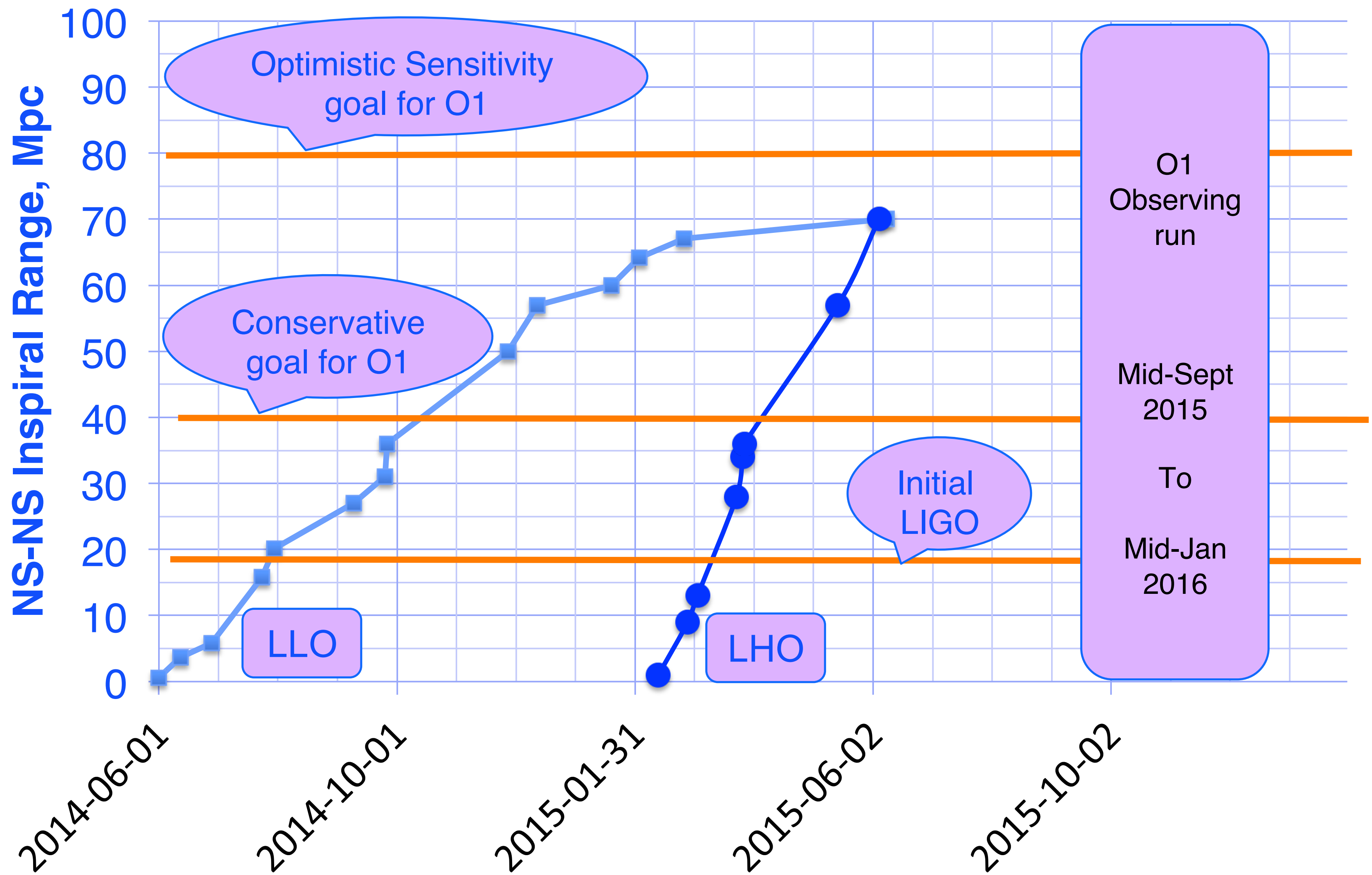
Test Mass Quadruple Pendulum suspension

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

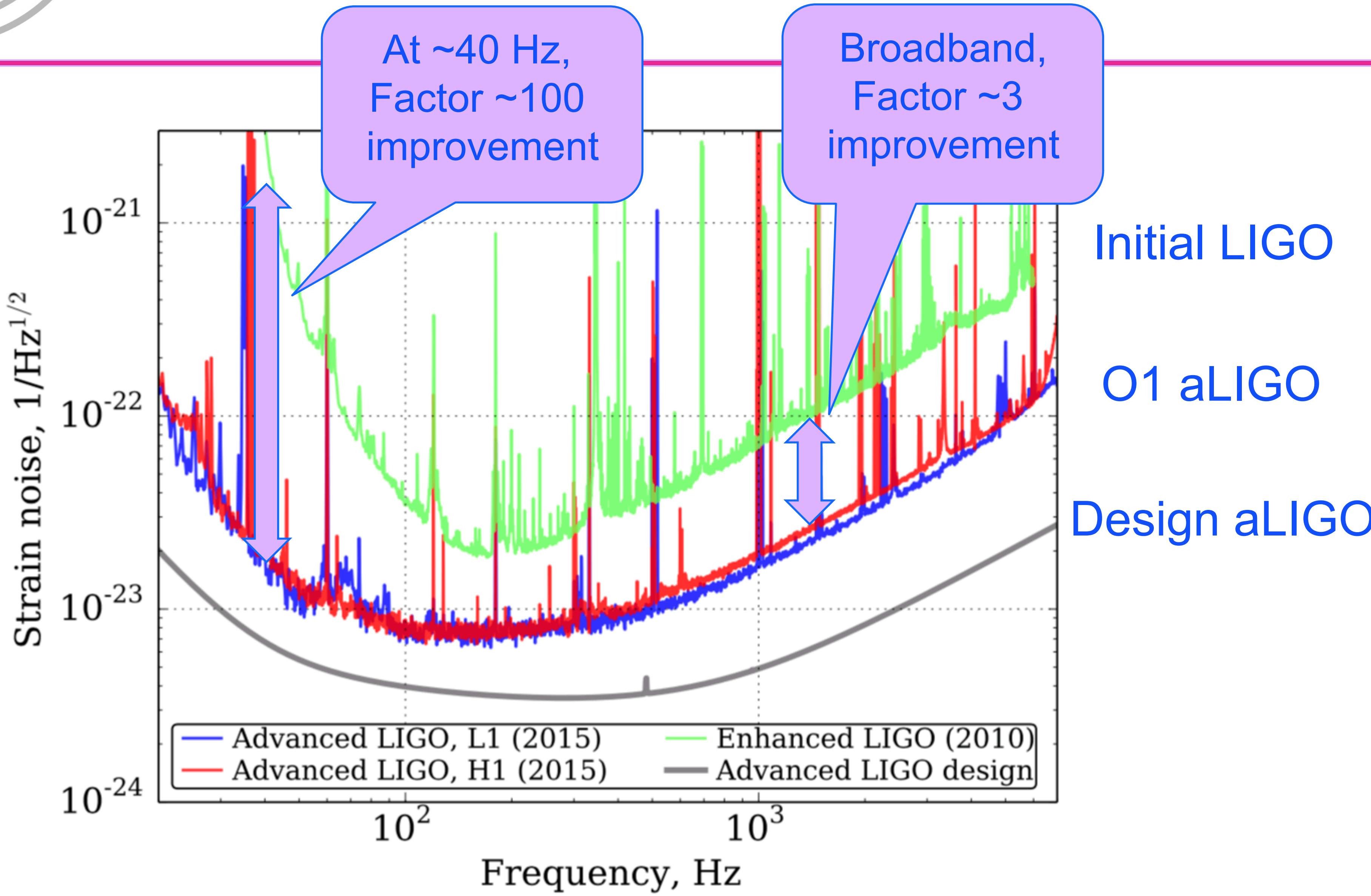
- Quadruple pendulum suspensions for the main optics; second 'reaction' mass to give quiet point from which to push
- Create quasi-monolithic pendulums using GPB star-tracking telescope techniques; Fused silica fibers to suspend 40 kg test mass
  - » VERY Low thermal noise!



Sensitivity Commissioning of aLIGO after completion of installation



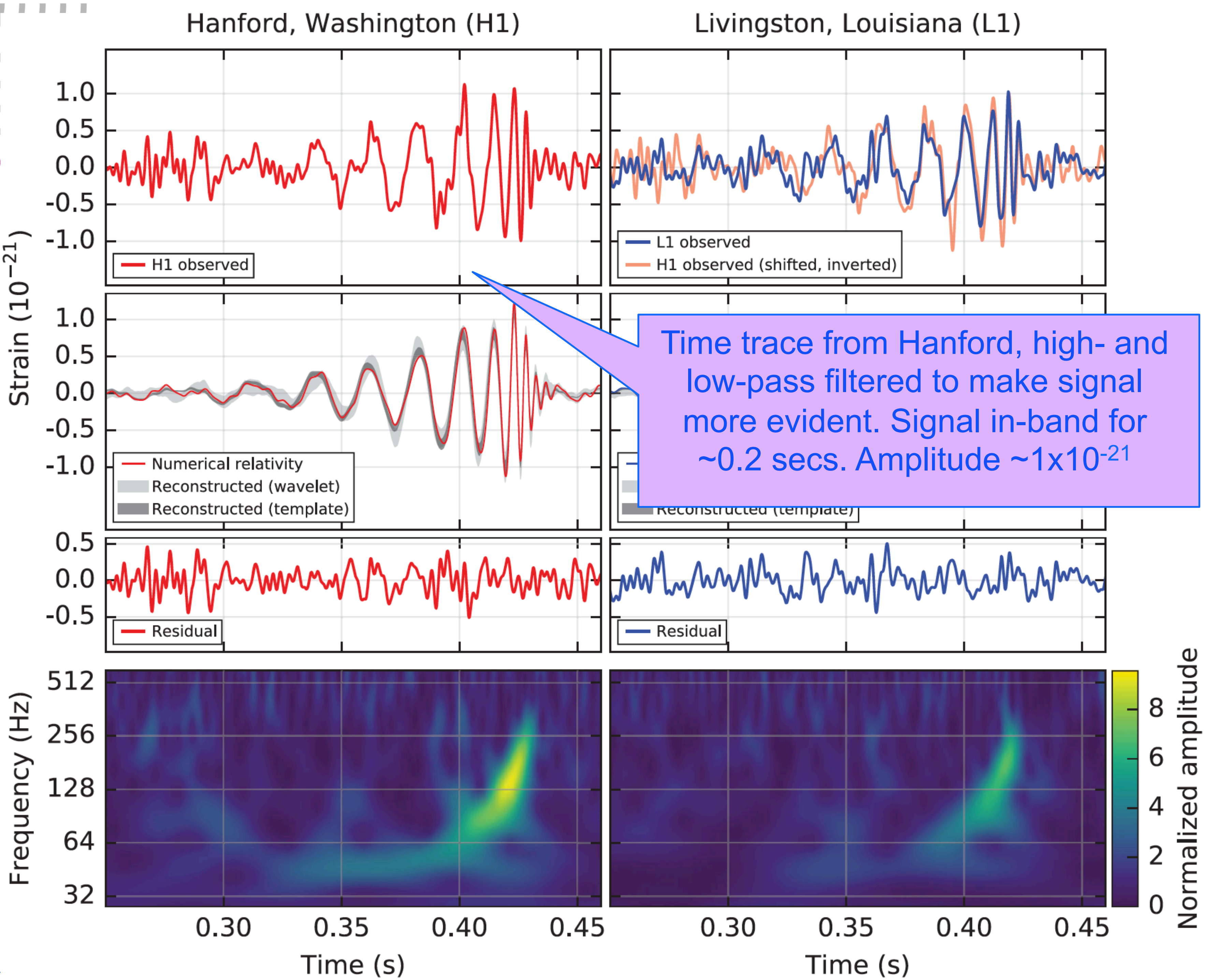
Sensitivity for first Observing run

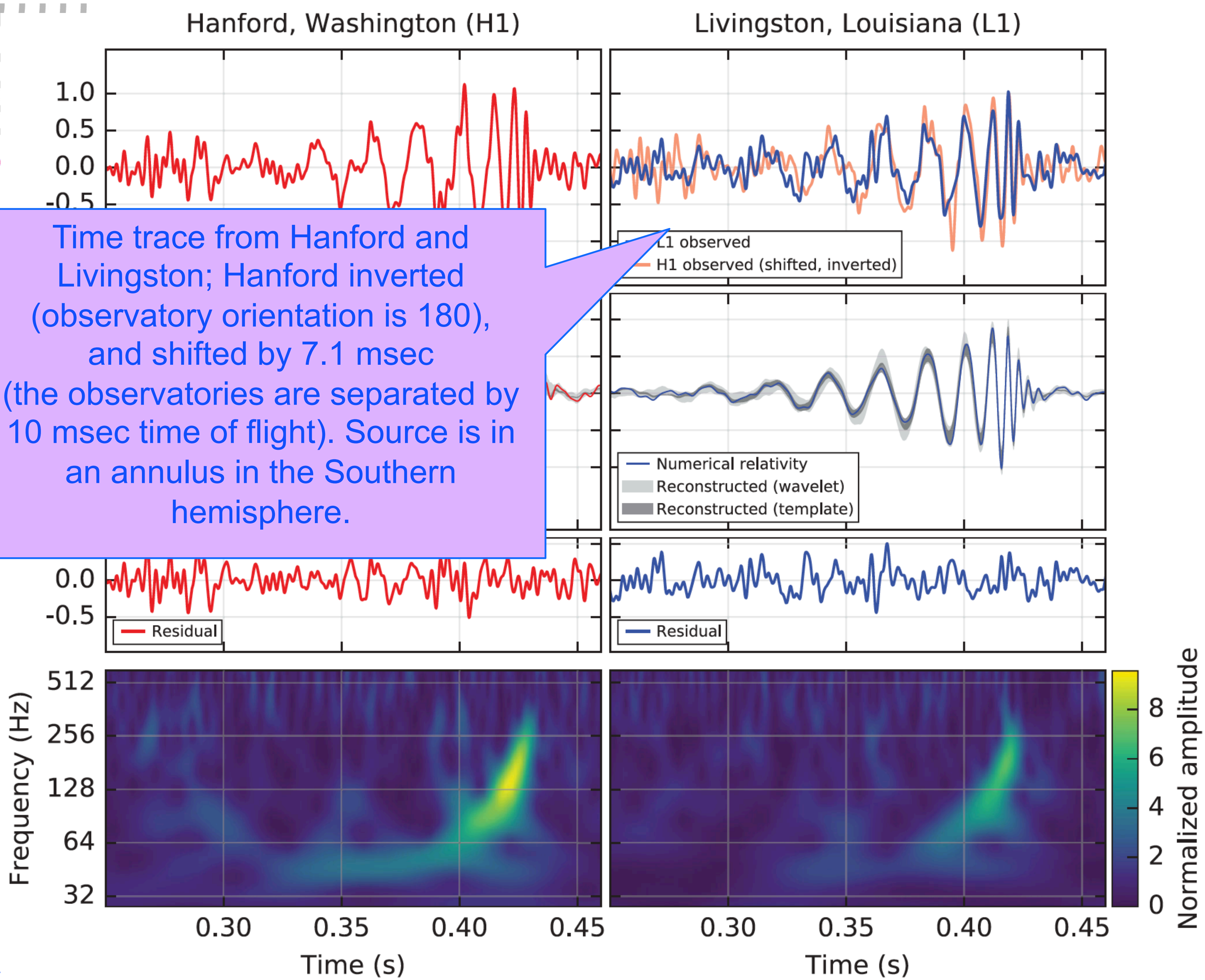


Non-stationary Noise; Detector Characterization

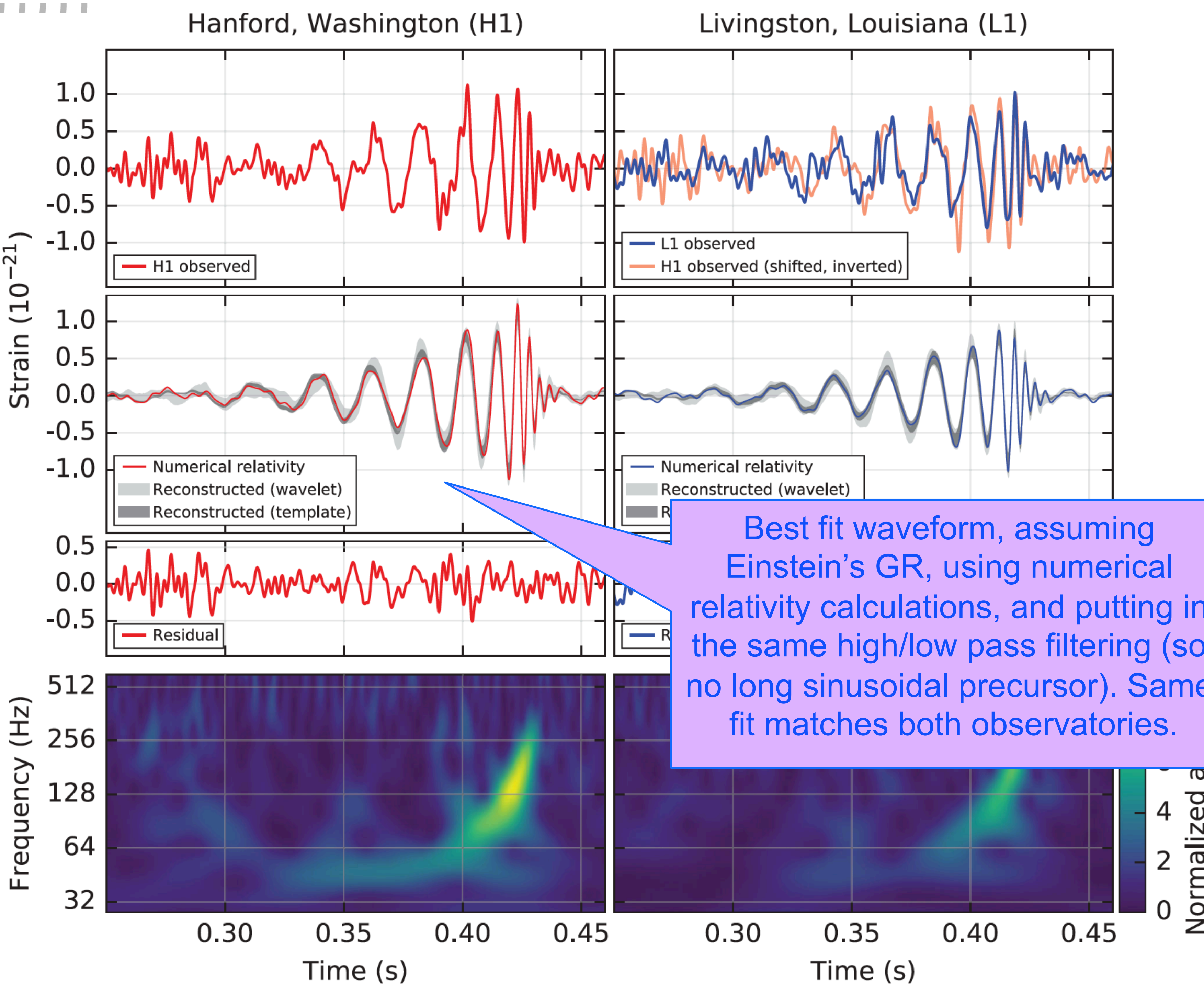
- Develop vetoes of transient events through study of correlations between *h(t)* and ~100,000 channels of auxiliary data
  - » Signals within the ~10,000 interferometer control systems
  - » Signals from ~1,000 microphones, seismometers, magnetometers, electric field receivers, etc.
- Measure coupling from all external sources to *h(t)*, develop estimates of safety, find significant margin at the time of the signal
- For GW150914, the false-alarm probability was not significantly affected by these data quality vetoes.
  - » **GW150914 was the loudest recovered event during the analysis period of 16 days**
  - » (Duty cycle for the two interferometers running in coincidence was about 50%, so took ~32 days to accumulate these data)
  - » significantly louder than every background event even without data quality products applied.

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

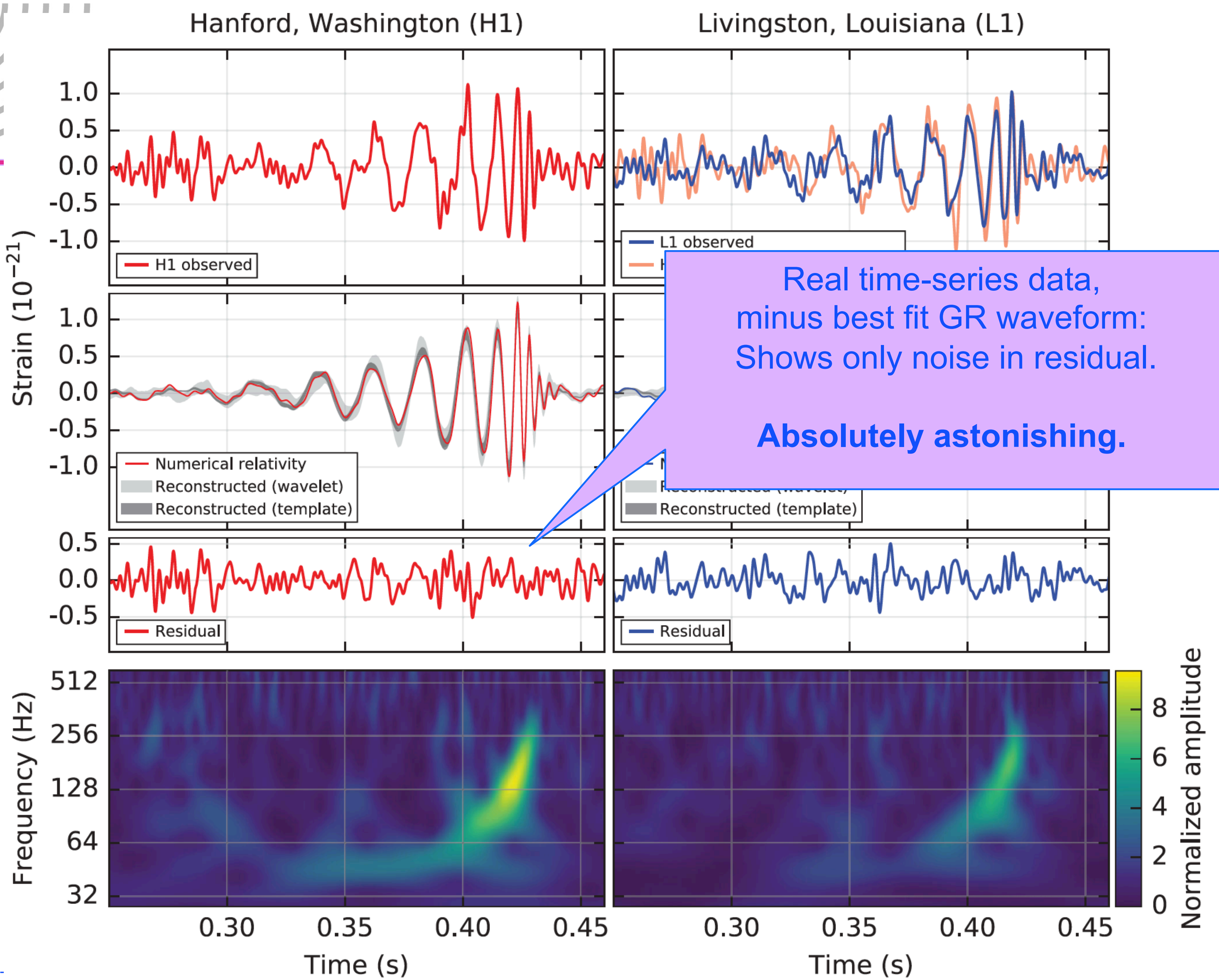

Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10⁻²¹)
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Residual
Frequency (Hz)
Time (s)
Time (s)
Normalized amplitude
Time trace from Hanford, high- and low-pass 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.

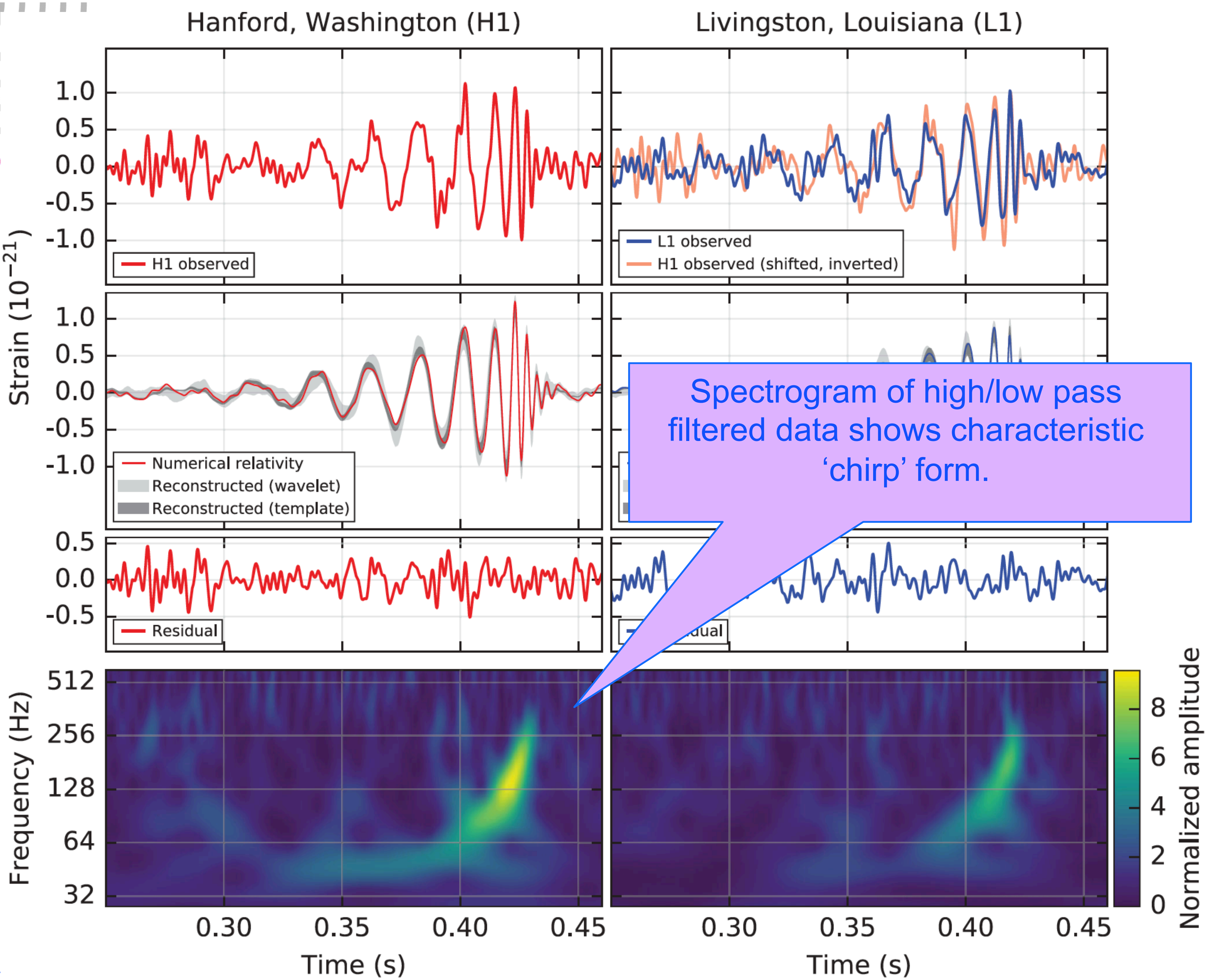


Best fit waveform, assuming Einstein's GR, using numerical relativity calculations, and putting in the same high/low pass filtering (so no long sinusoidal precursor). Same fit matches both observatories.



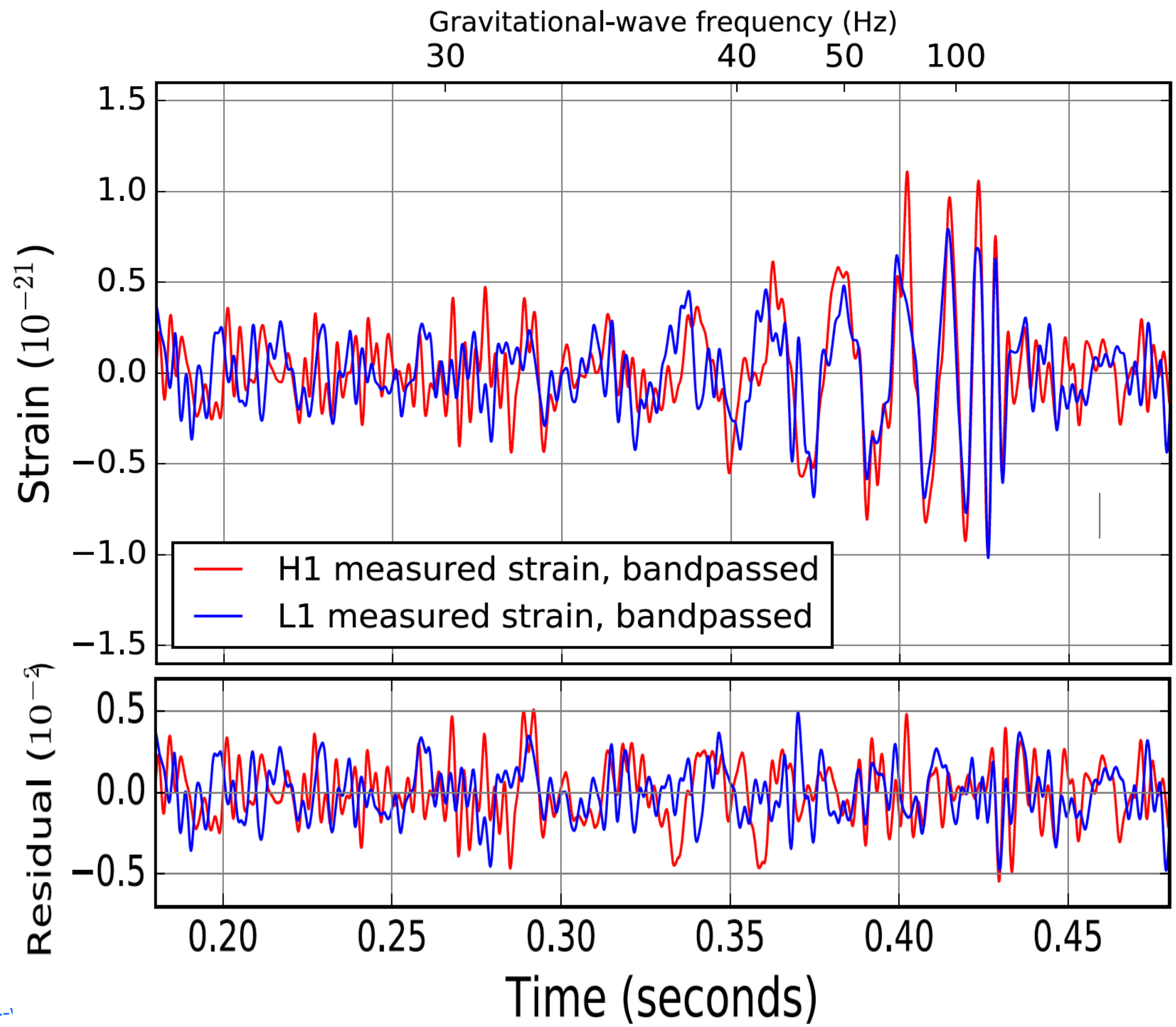
Real time-series data,
minus best fit GR waveform:
Shows only noise in residual.

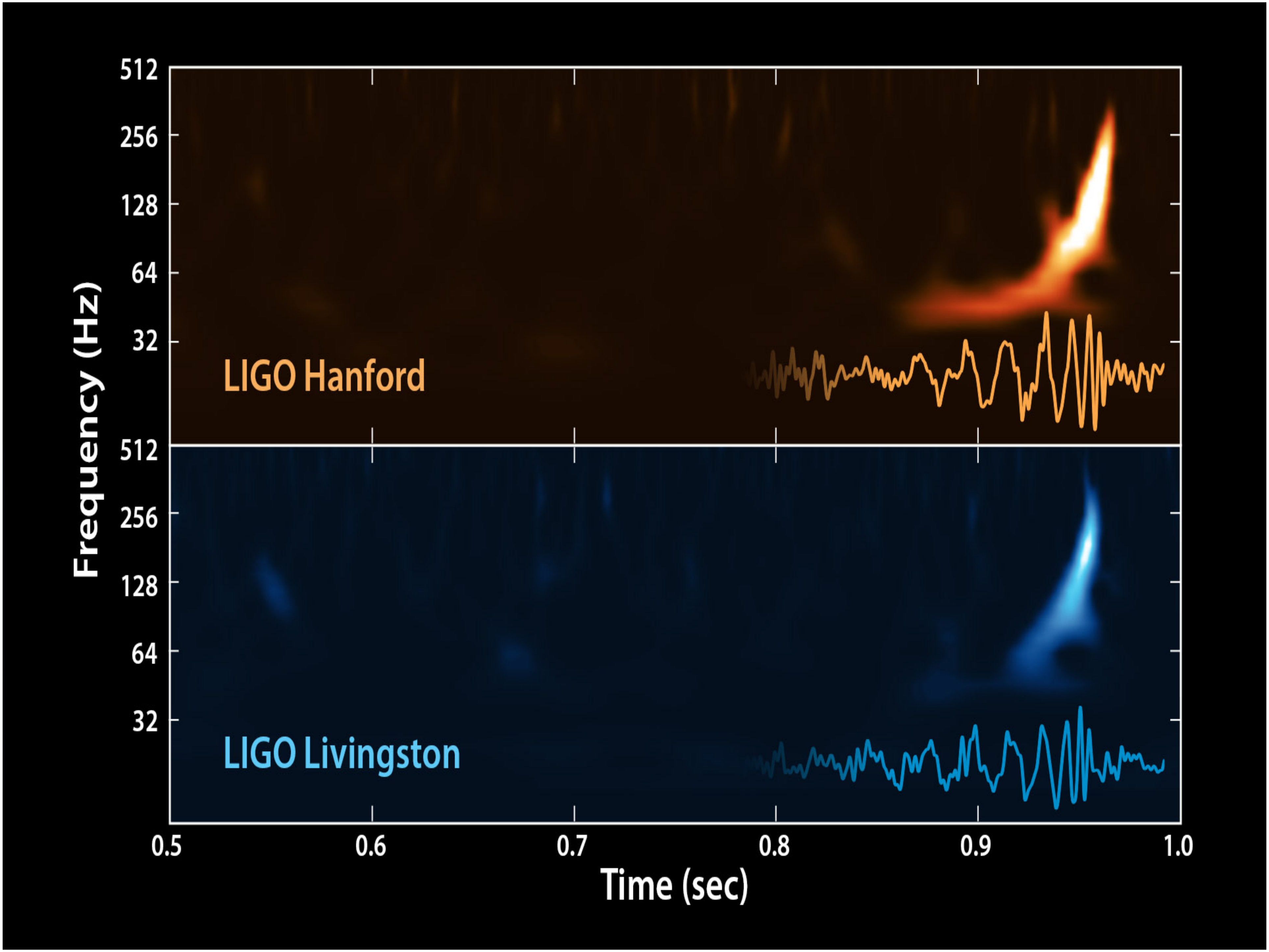
Absolutely astonishing.



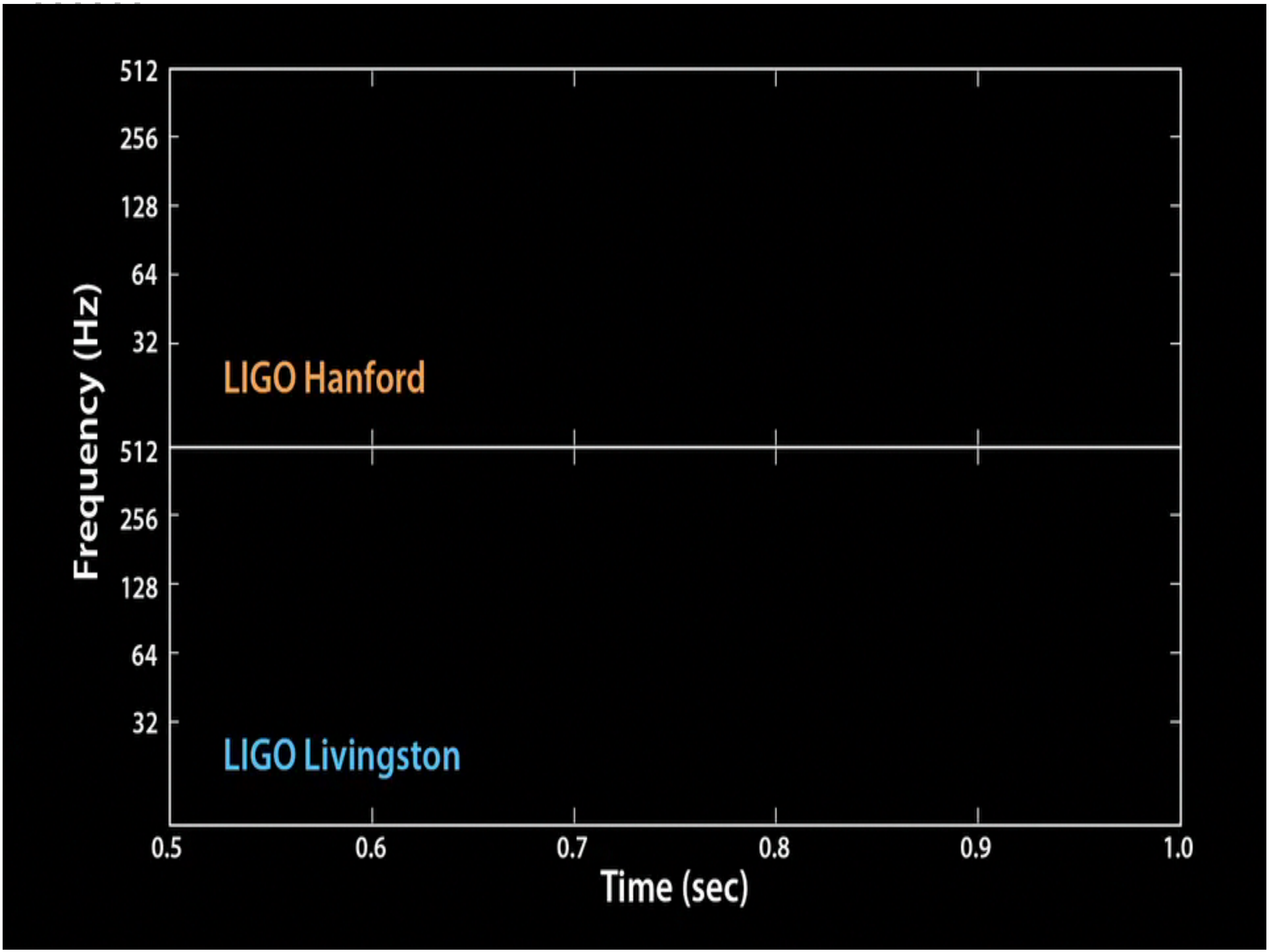
Spectrogram of high/low pass filtered data shows characteristic 'chirp' form.

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





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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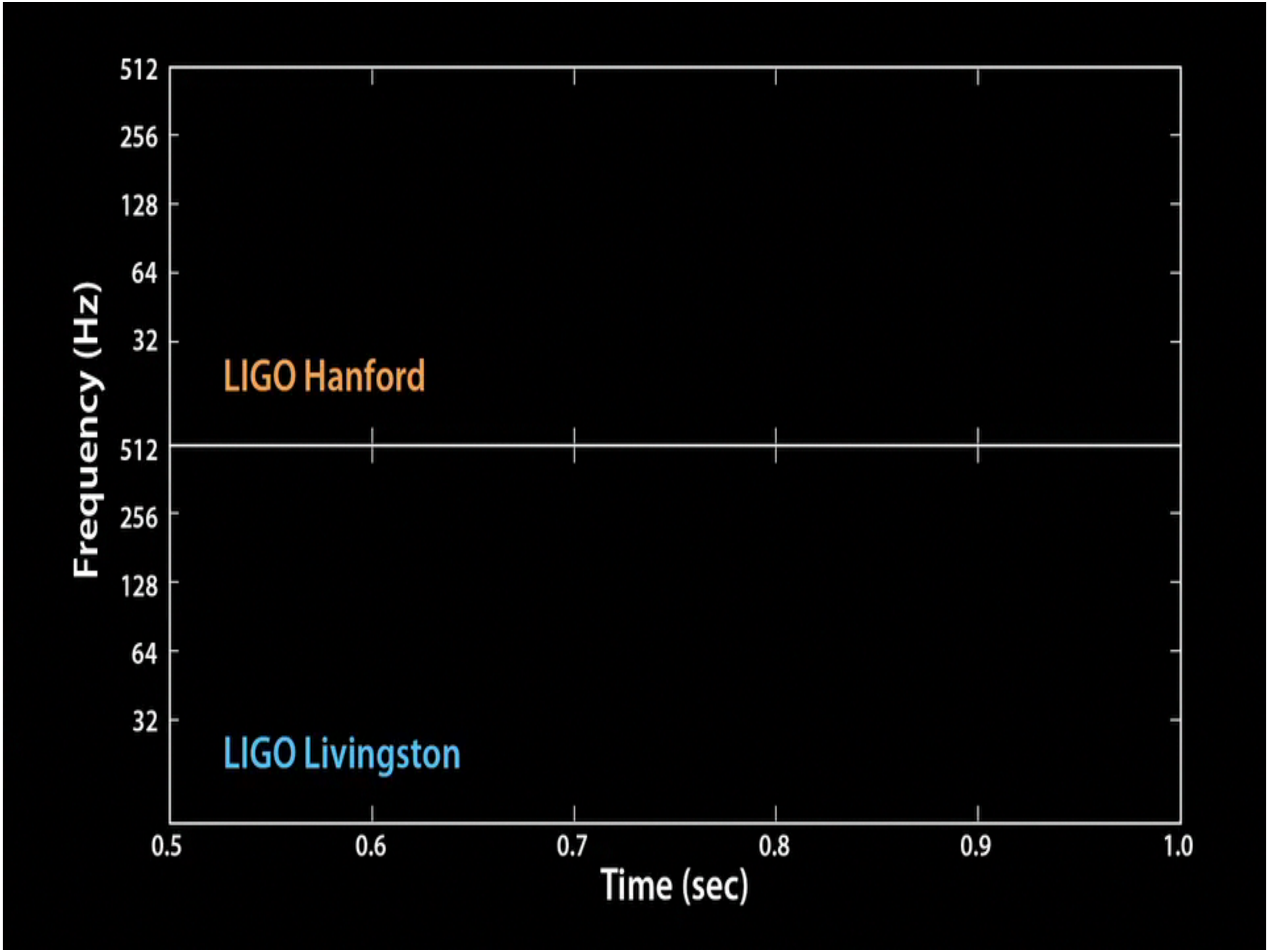
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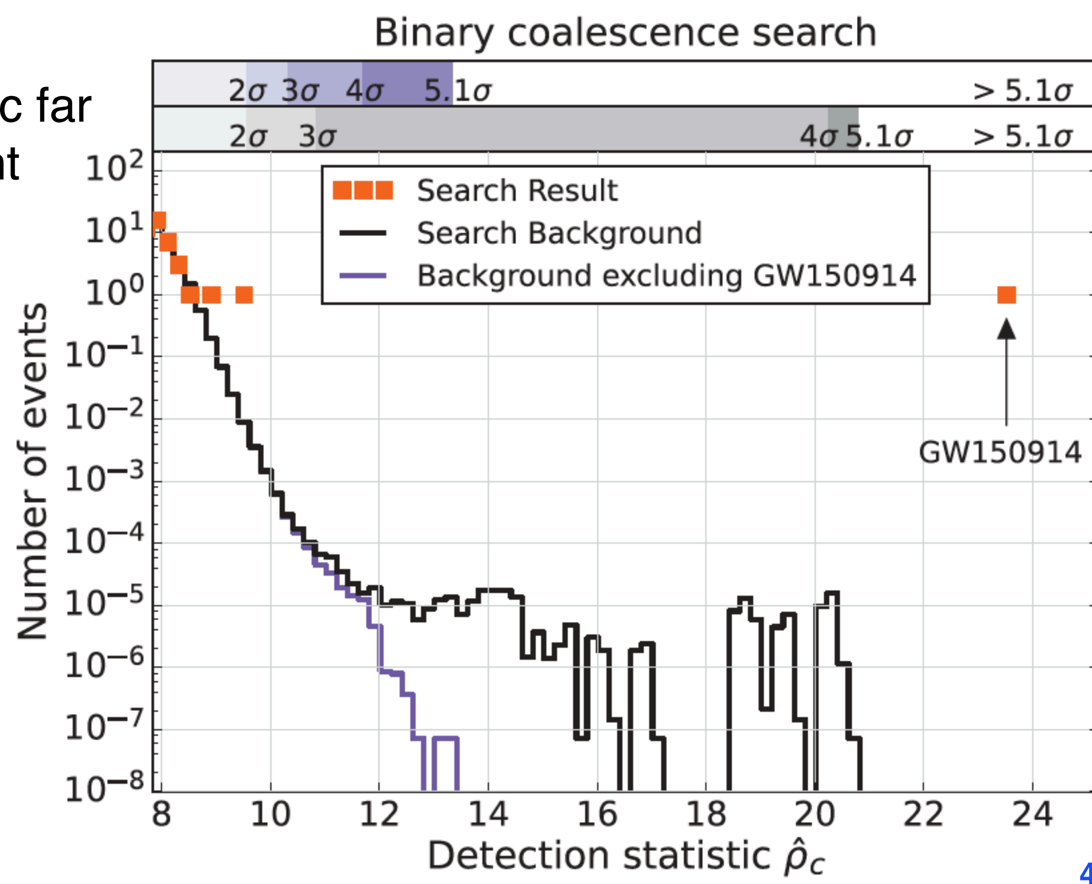
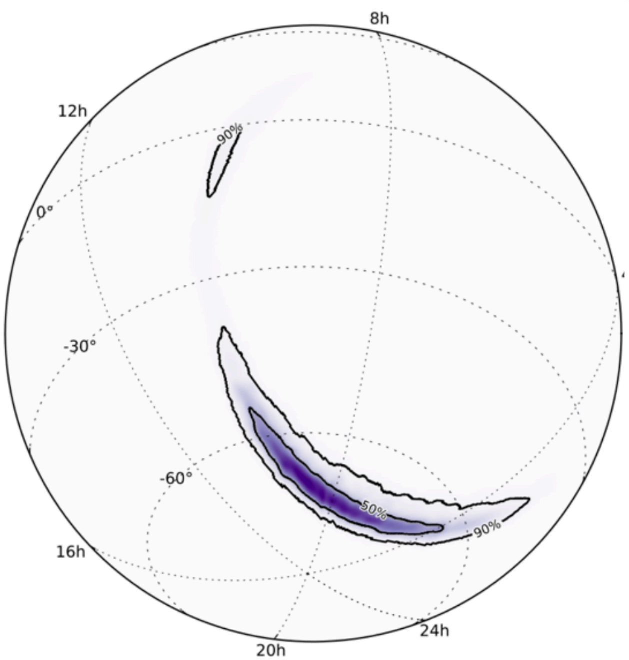
Detection Confidence

- First seen with a 'burst' on-line detection system, but best statistical confidence measure obtained with a template search based on GR, and numerical solutions
- 'Off-source' background built up using non-physical time slides (>10 msec)
- Equivalent of 600,000 years of background used
- GW150914 had detection statistic far larger than any background event
- False Alarm rate <1/203,000 years, corresponding to 5.1σ.
- A very large SNR in quiet data.
- **Yes: we got lucky.** (…for the timing and nature of our first event. It took more than luck to build the instrument and analyze the data)



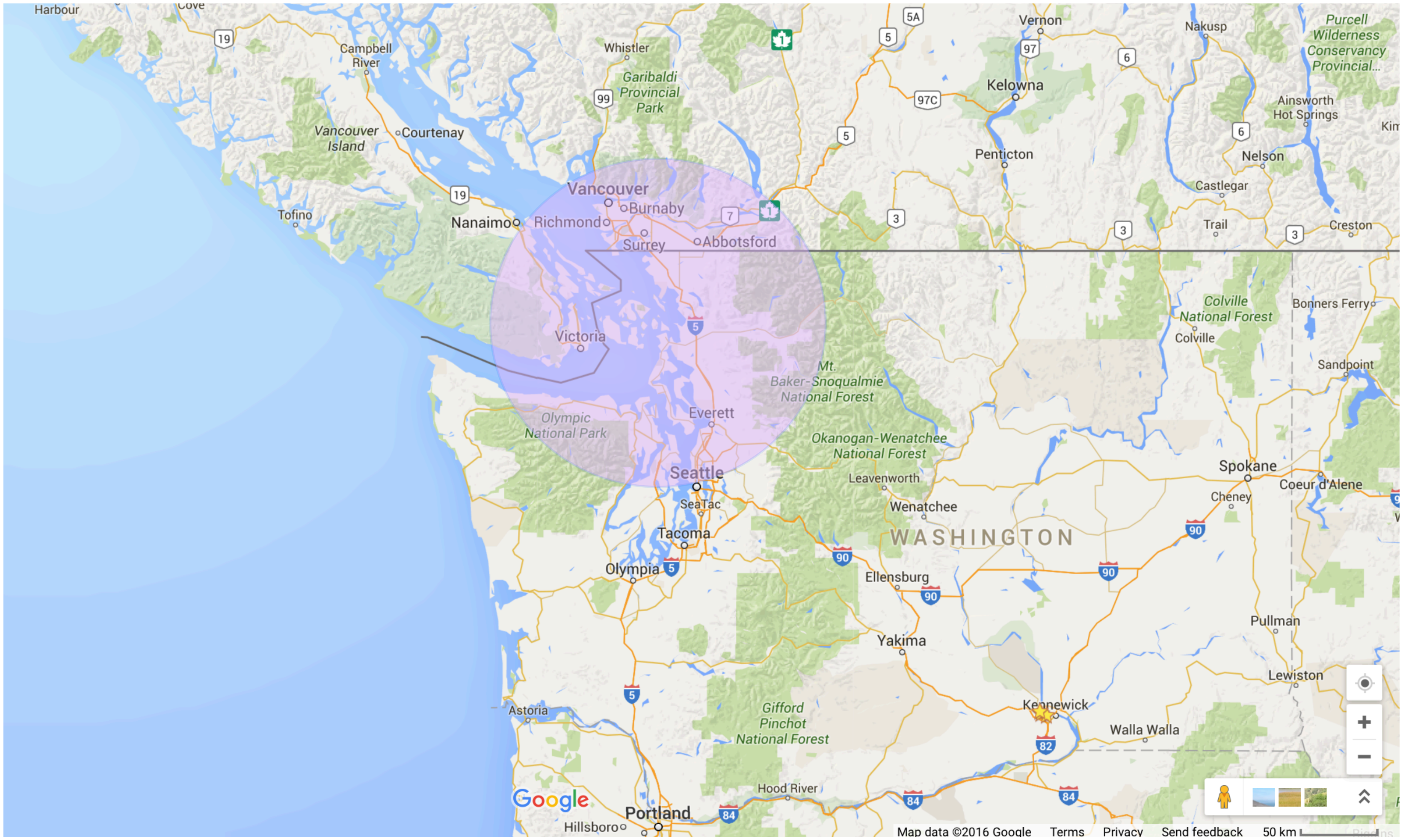
Source characteristics

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	$0.09^{+0.03}_{-0.04}$



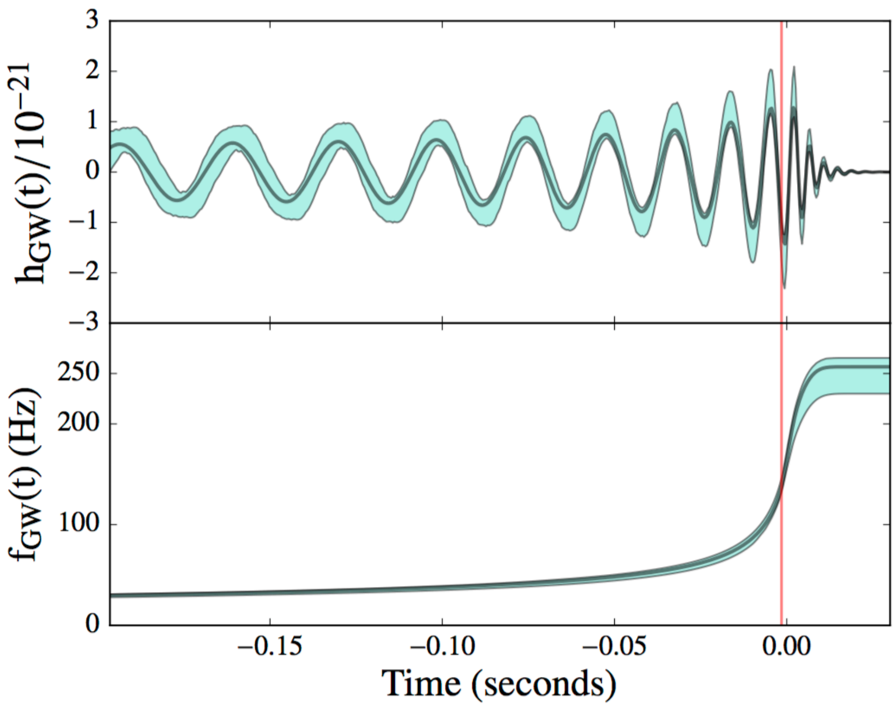
- 3 $M_\odot$ radiated in GWs;
  36 + 29 = 62....+3
- Initial spins not well constrained ('face off' position)
- Degeneracy in position and distance (only 2 detectors… need Virgo!)
  - In the Southern Hemisphere, an annulus with some preference in angle
- Can determine a rich set of conclusions due to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

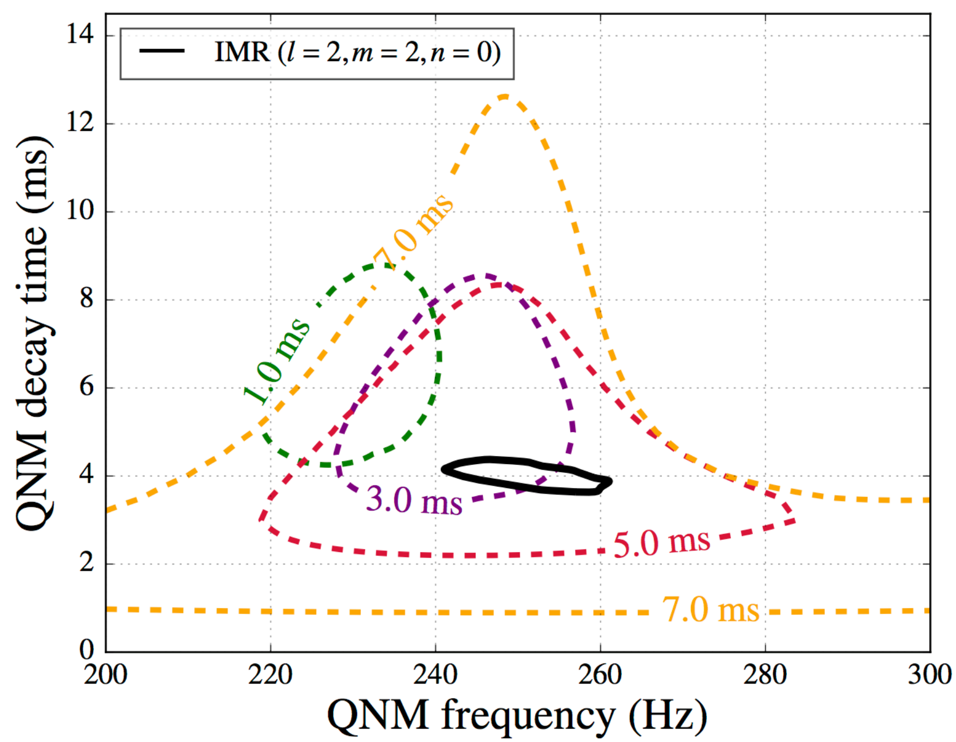
For scale: The event horizon of a 36 $M_{\odot}$ black hole

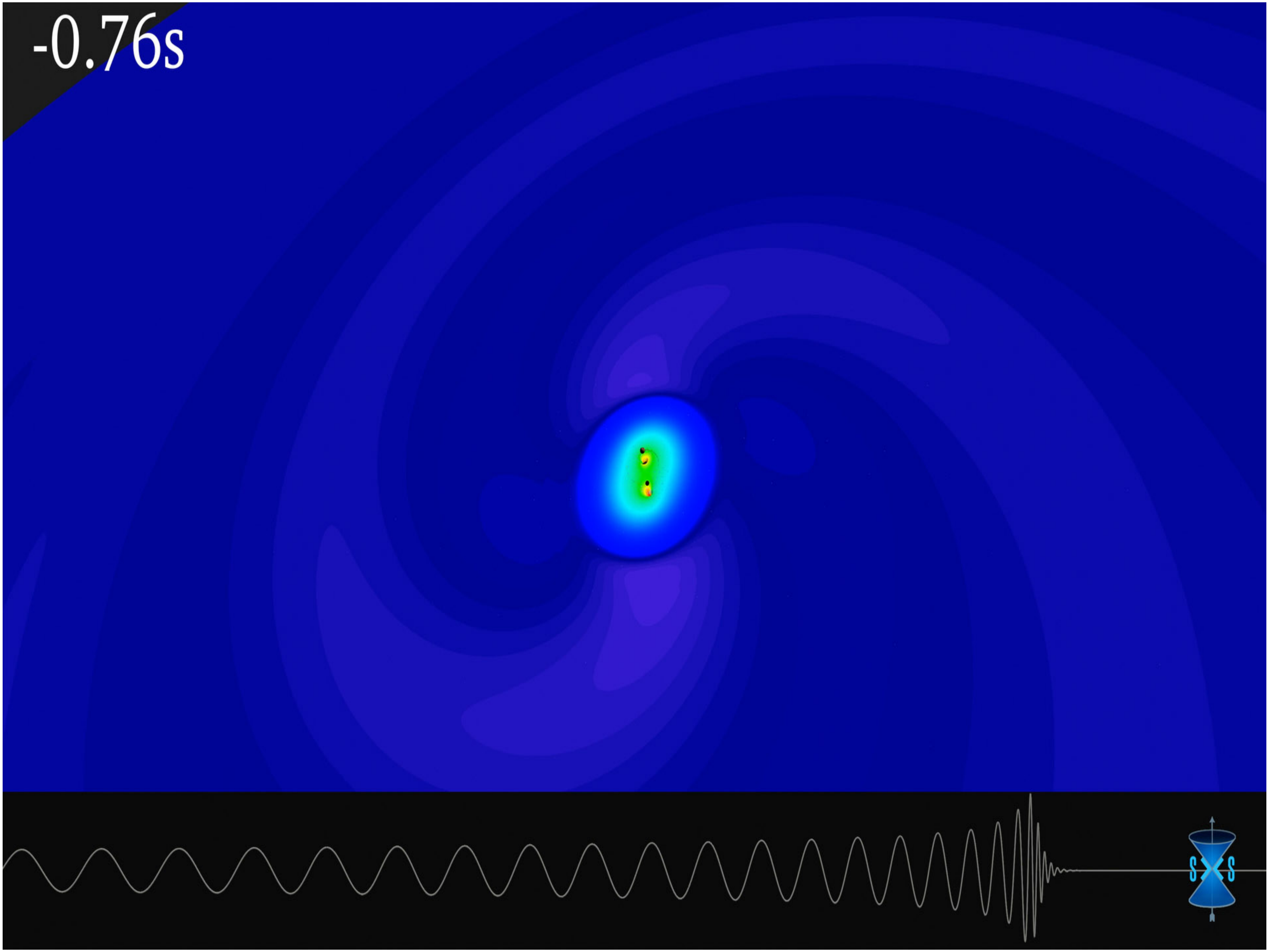


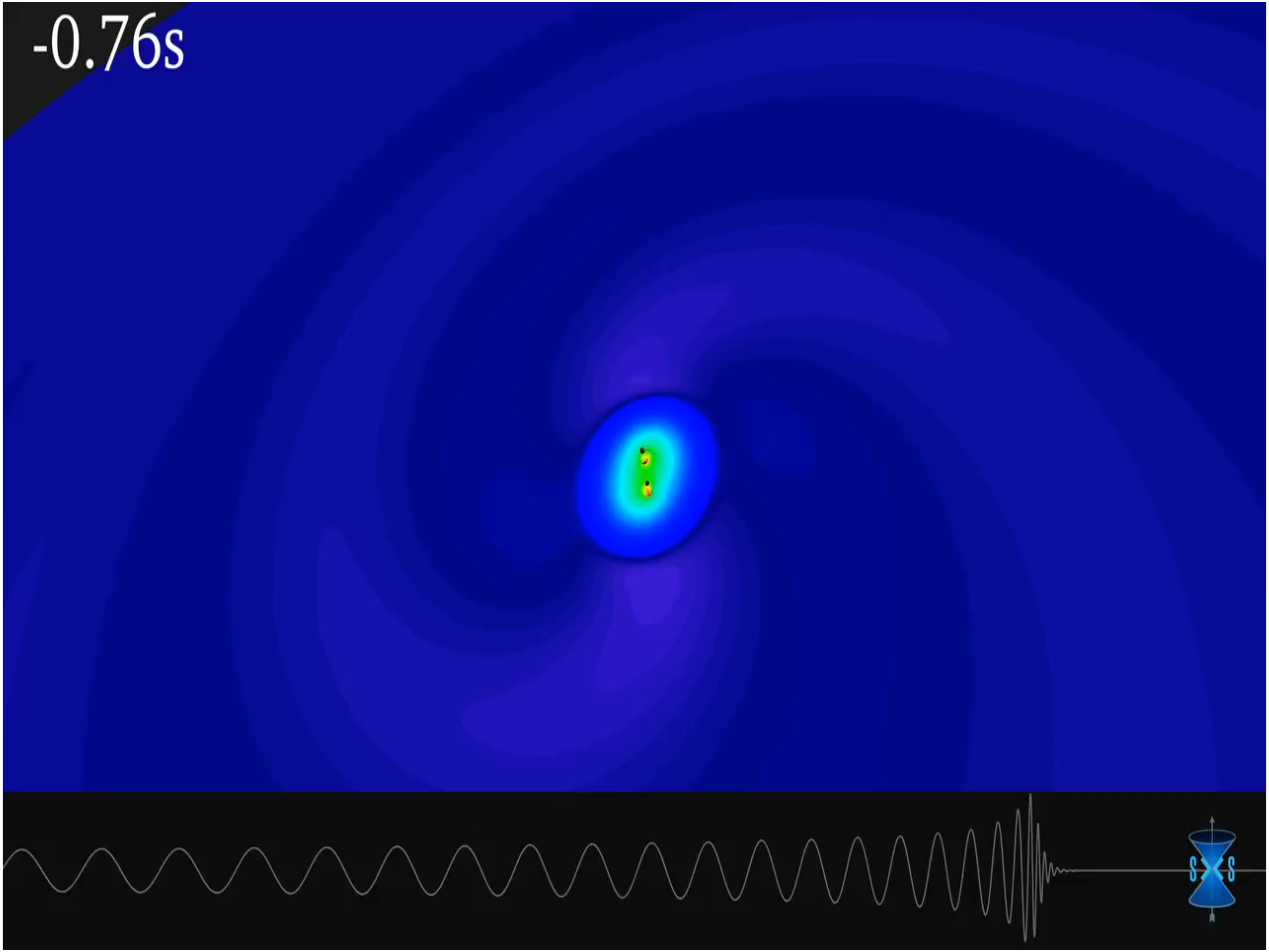
Testing GR

- Effects due to GR-violations in GW150914 are limited to less than 4%
- Ringdown of final BH interesting; f_{QNM} = 251 ± 8 Hz and τ_{QNM} = 4.0 ± 0.3 ms at 90% confidence, but a struggle to pull out from data
- Will need to observe higher SNR signals, and/or multiple signals, to be more confident






-0.76s

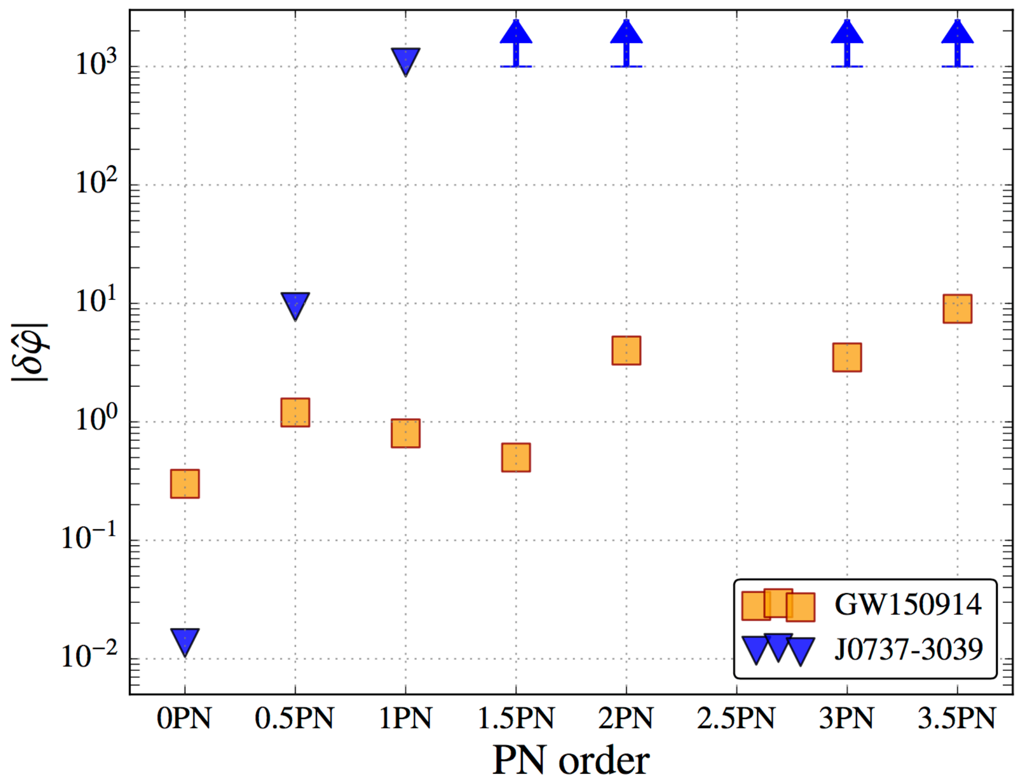

-0.76s

Testing GR

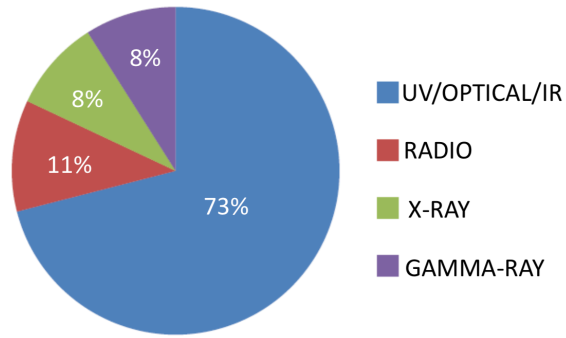
- New constraints on higher-order post-Newtonian coefficients
- Pulsar timing of dP_{orb}/dt , of the double pulsar J0737- 3039, is still by far the best constraint on 0th post-Newtonian coeff.
  - thanks to the long observation time (~ 10 years against ~ 0.4 s for GW150914).

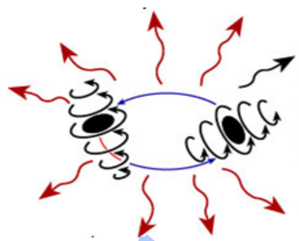
- Our measurement far more constraining on higher-order terms
- No significant deviation at any order seen

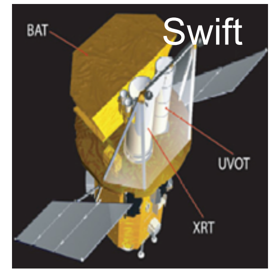
- Our papers in **arXiv**; search on title **GW150914** with **LIGO** as author



Start of multi-messenger astronomy with gravitational waves







X-ray, γ-ray follow-up

- 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….

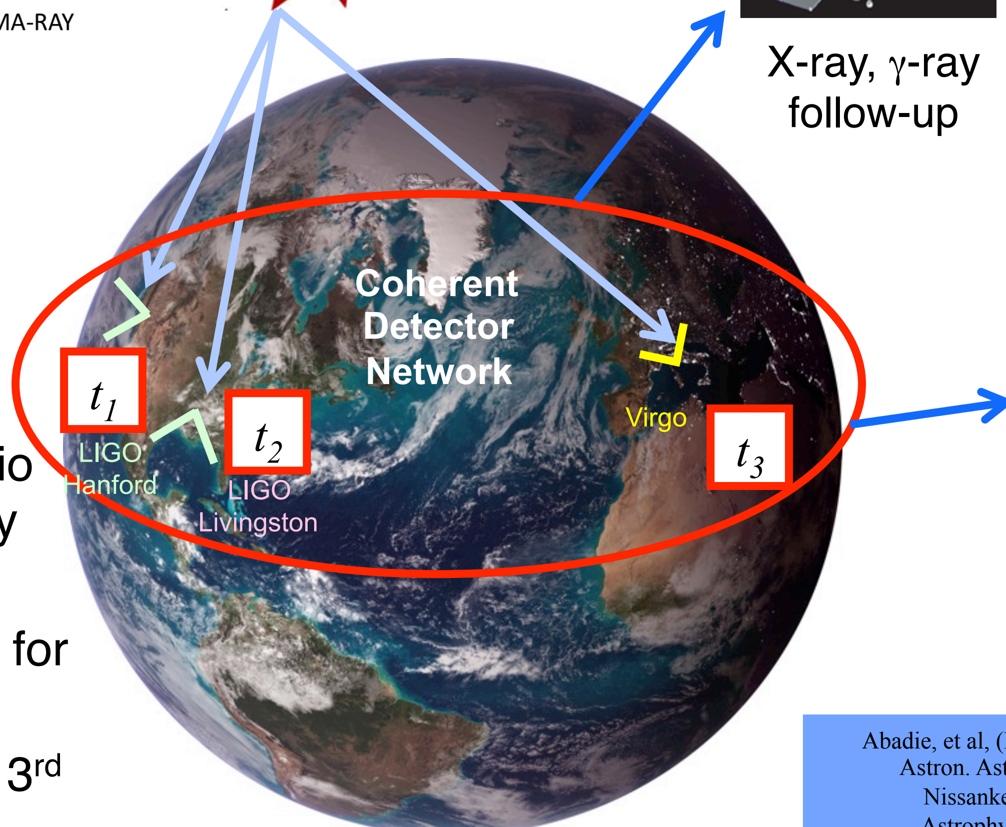


Image: http://earthobservatory.nasa.gov/

Optical follow-up

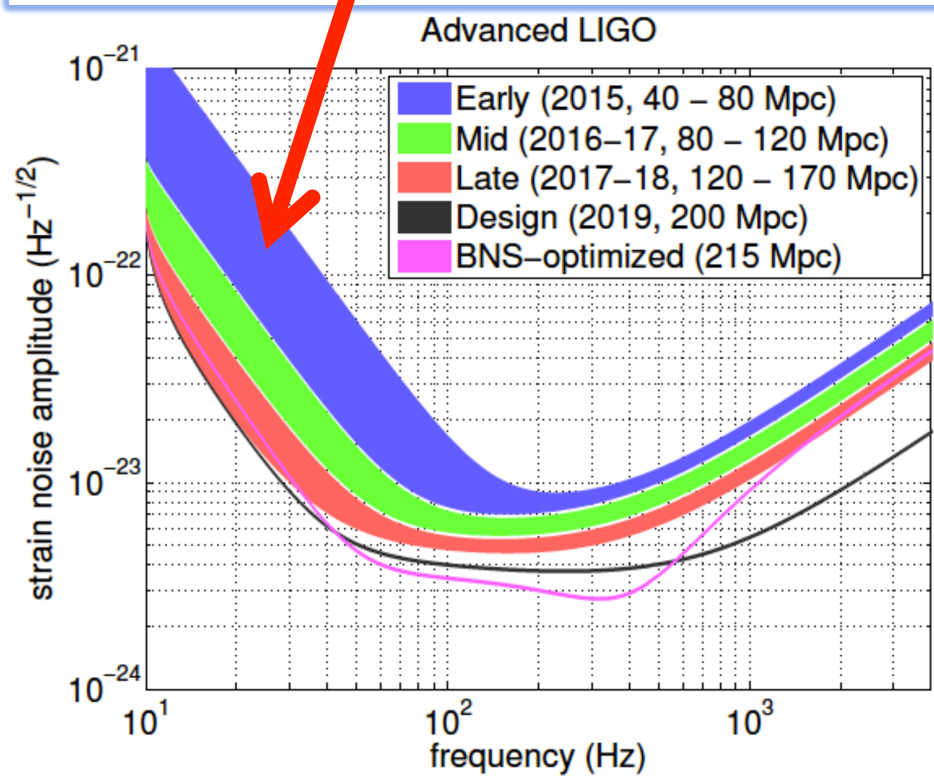
Abadie, et al, (LSC & Virgo Collaborations) Astron. Astrophys. 541 (2012) A155.
Nissanke, Kalsiwal, Georgieva, Astrophysical J. 767 (2013) 124.
Singer, Price, et al., Astrophysical J., 795 (2014) 105.

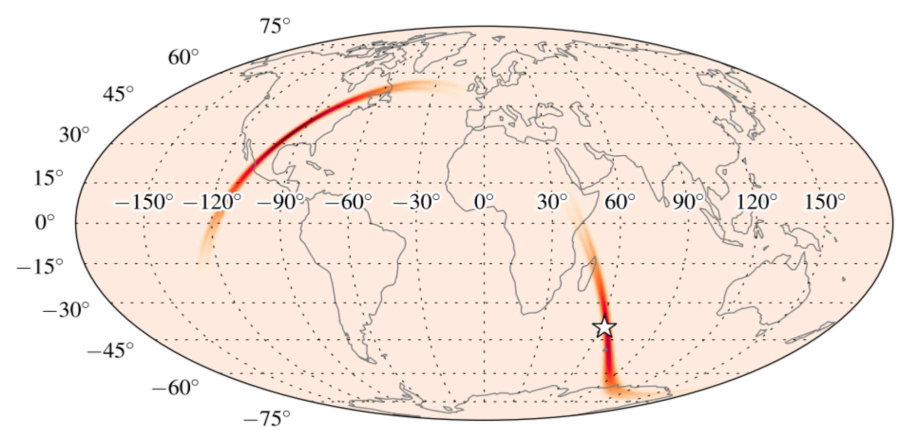
What does the future hold?

Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		$5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48





Localization of source,
Hanford and Livingston LIGO detectors,
First science run at end 2015

Observing Scenario, focus on NS-NS Binaries

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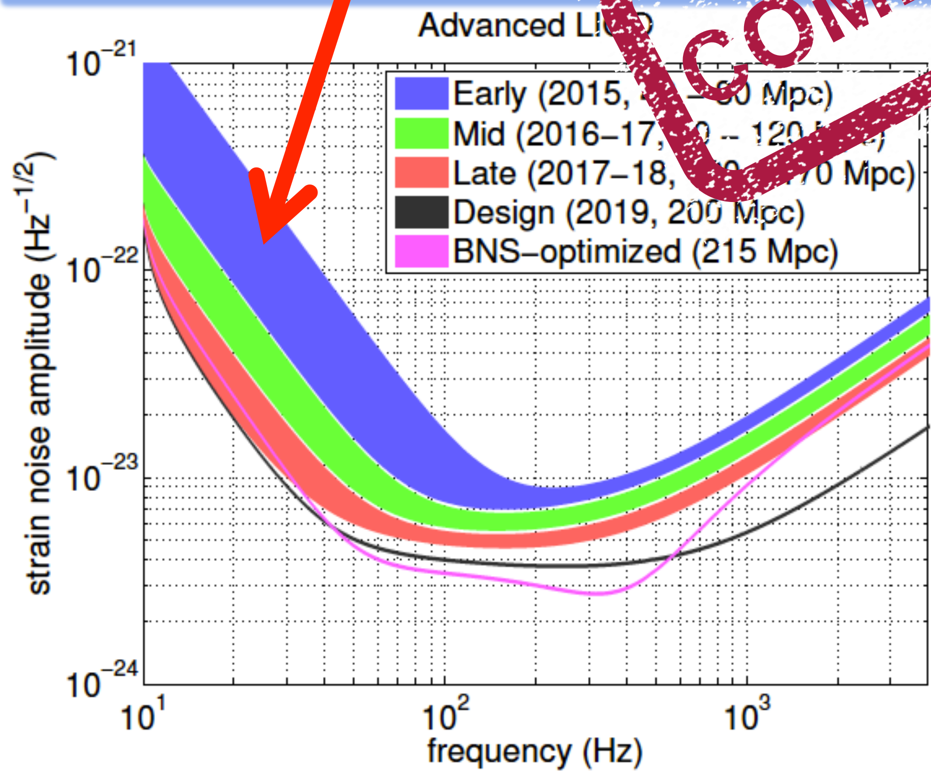
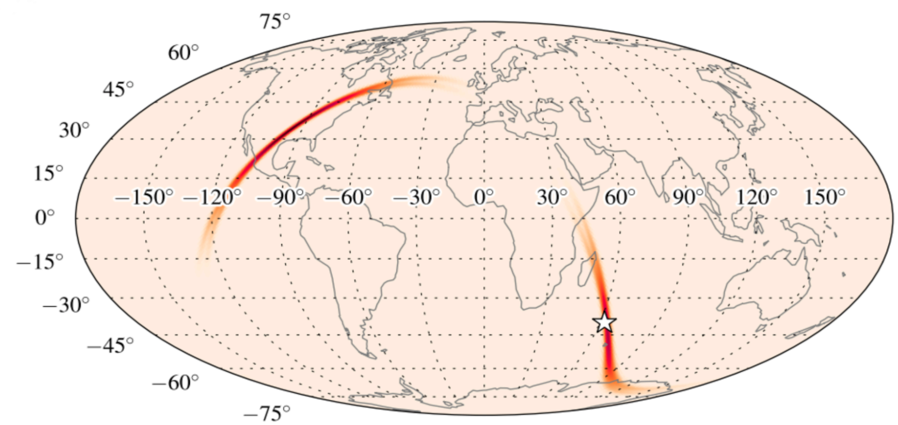
2016–17	6 months	60 – 75	20 – 40	[illegible] – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	[illegible]	0.4 – 400	17	48

COMPLETED





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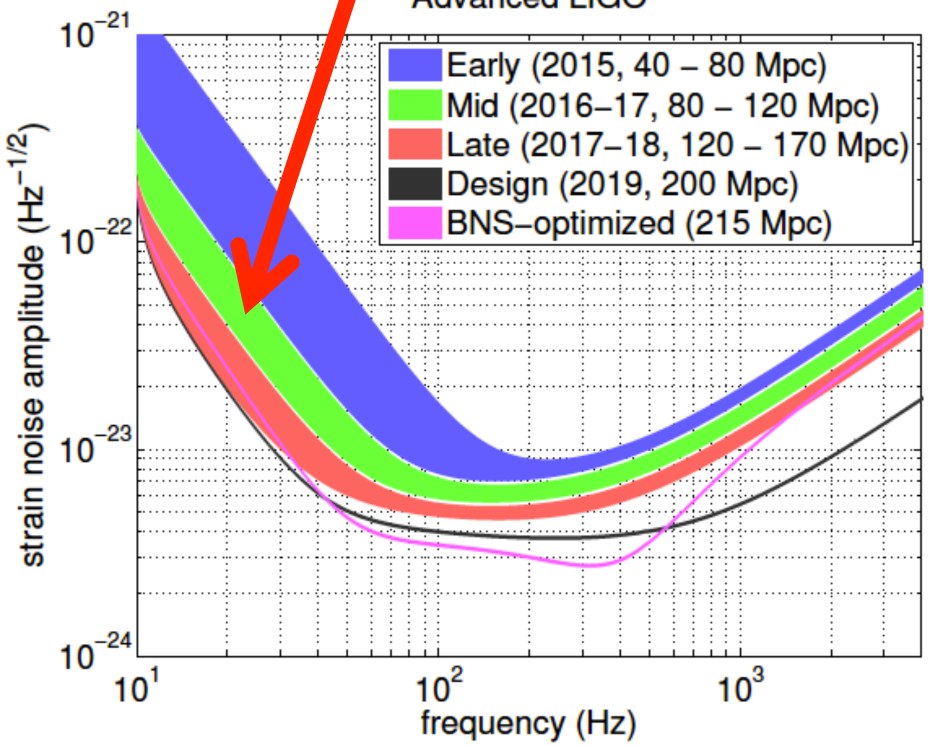

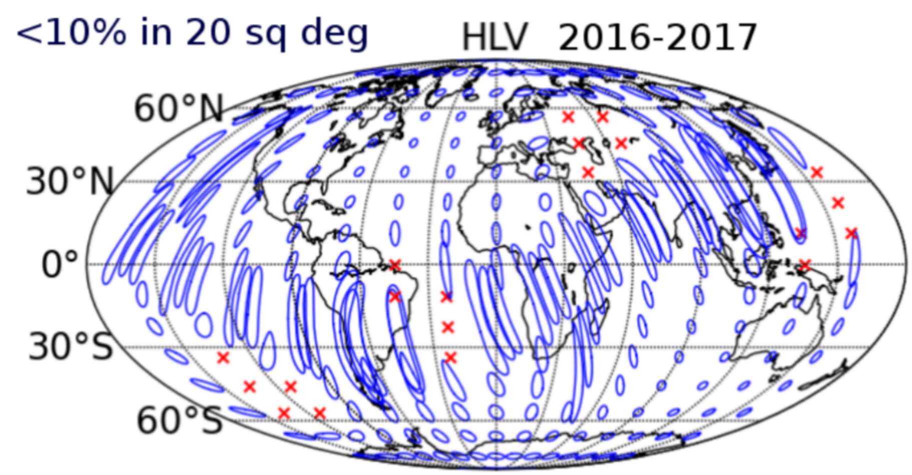

Localization of source,
Hanford, Livingston and Virgo detectors,
Observing 2016-17

Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
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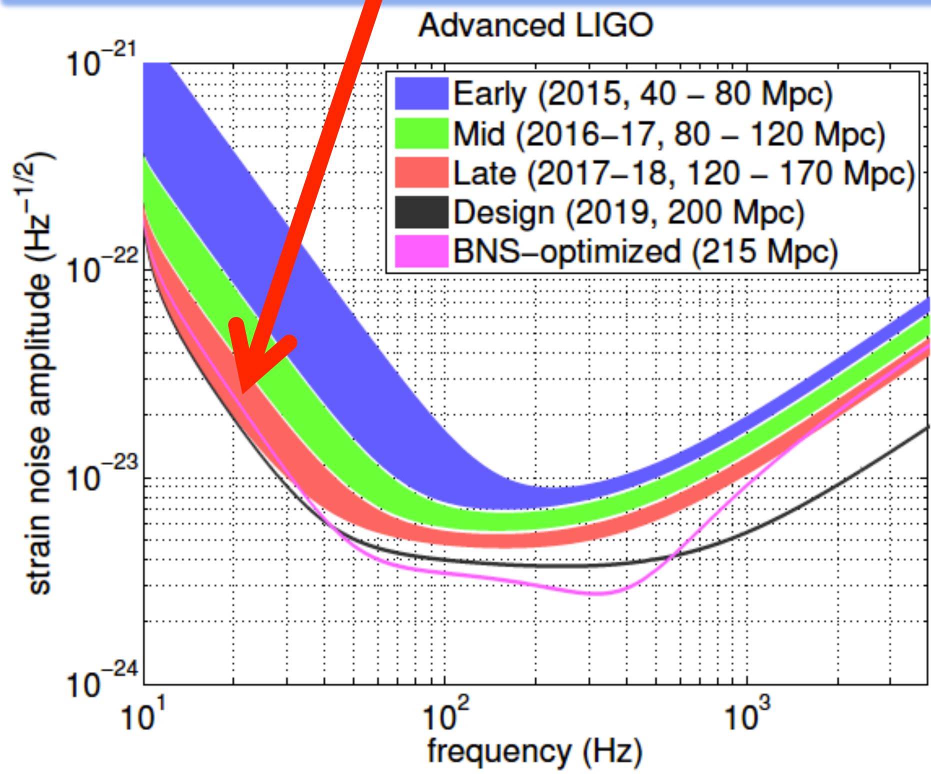

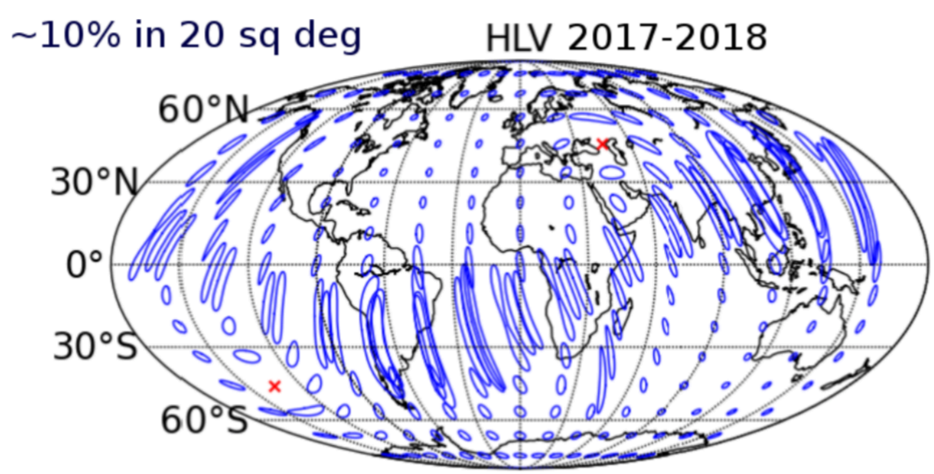

Localization of source,
Hanford, Livingston and Virgo detectors,
Observing 2017-18

Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
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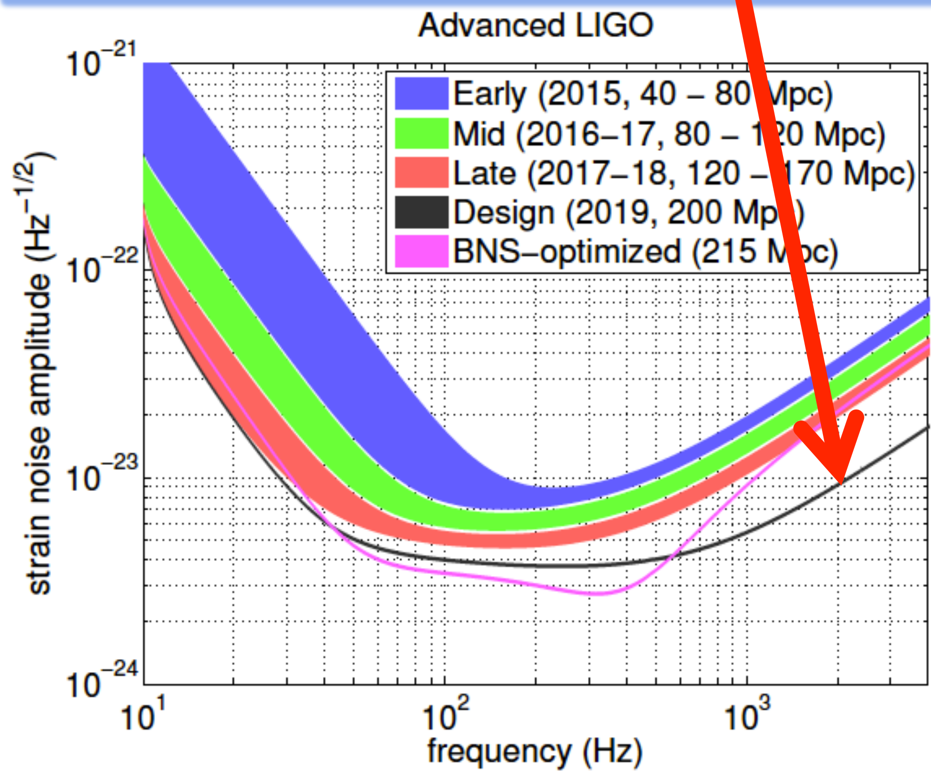

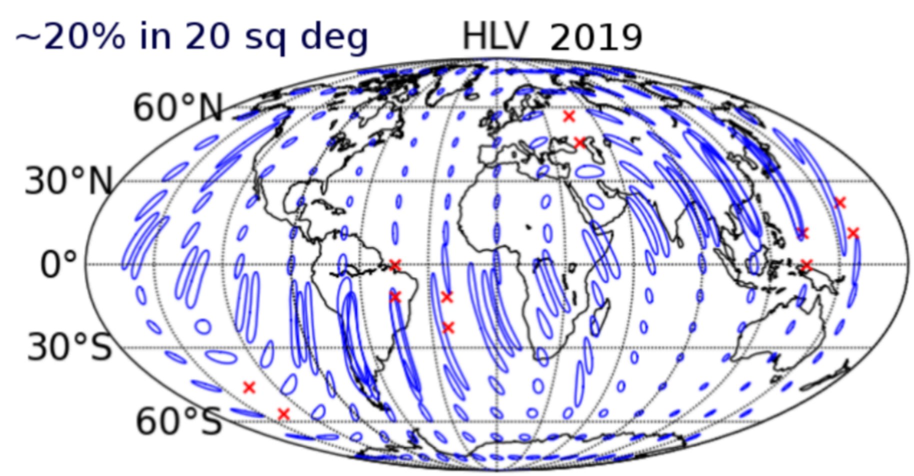

Localization of source,
Hanford, Livingston and Virgo detectors,
Observing 2019

Observing Scenario, focus on NS-NS Binaries

http://arxiv.org/abs/1304.0670

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg²	20 deg²
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
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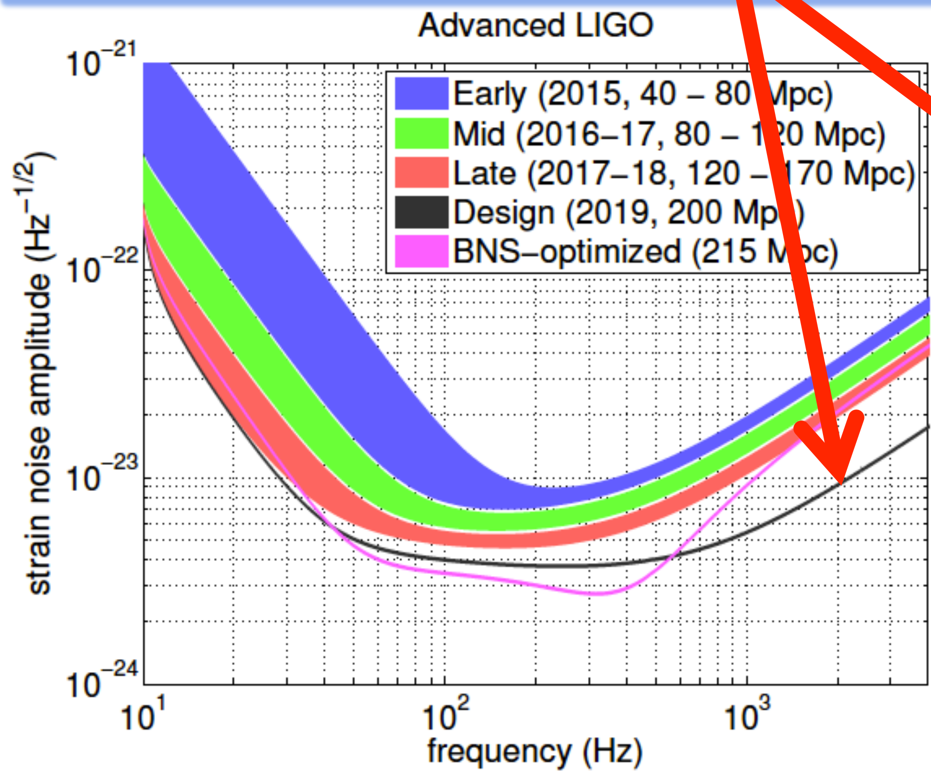
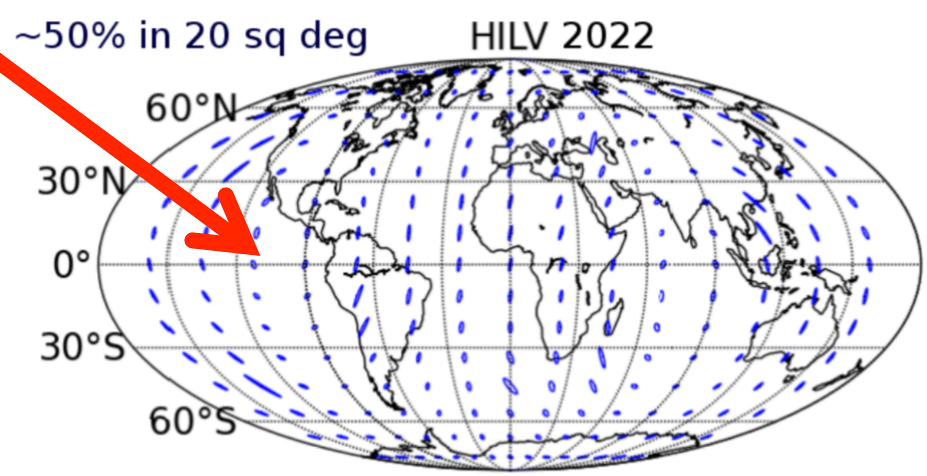
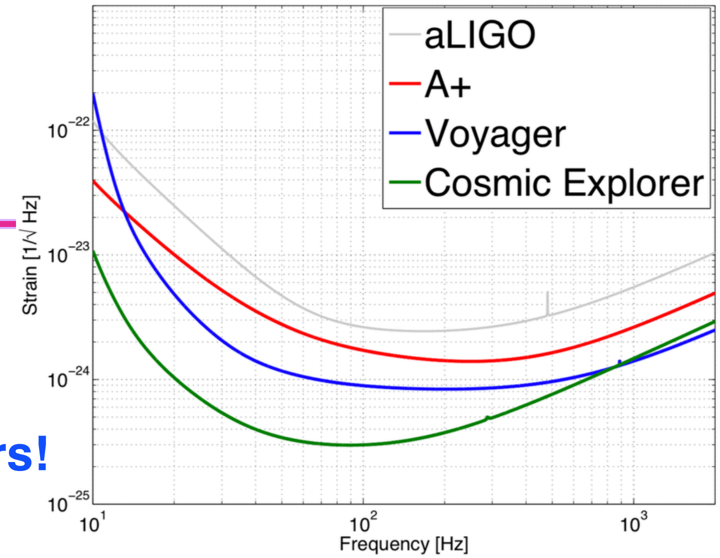


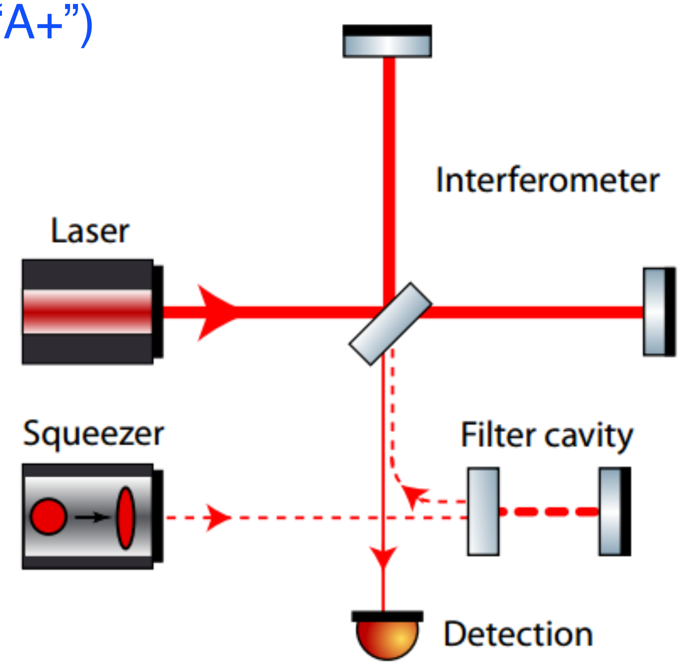


Localization of source,
Hanford, Livingston, Virgo, India detectors,
Observing 2022

Future Improvements: Reaching even further

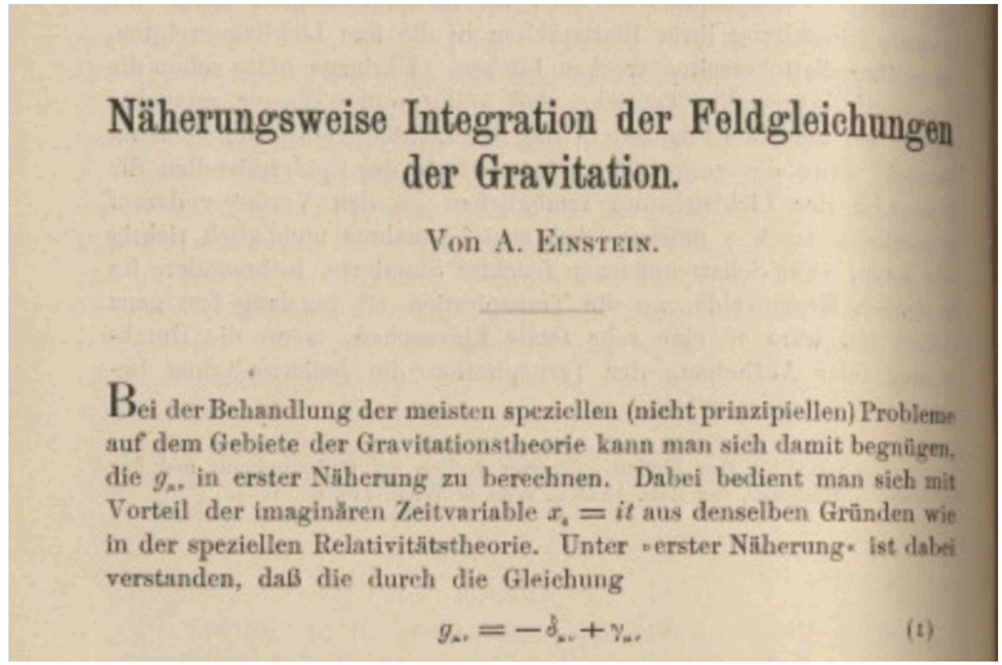
- Want to fully exploit the instrument we designed
- **But then we will all want more sensitive detectors!**
- R&D continuing; see sensible paths to yet better sensitivity near-term and longer-term
- Factor ~1.7 in sensitivity: possible as early as 2018 ("A+")
  - Would give increase in event rate of ~5
- Use of squeezed light expected (and demonstrated)
- Factor 10: perhaps by 2035 ("Cosmic Explorer")
  - One approach would be a longer baseline – say, 40km instead of 4km
  - Almost all noise sources stay constant – but signal grows a factor of 10
  - Models indicate feasibility
  - Requires global cooperation to succeed





The last page

- Einstein made his first publication on gravitational waves in 1916
- I gave a talk in mid 2015; I said I thought we had a *chance* to make a detection in 2016…



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

Here's hoping for many happy returns!