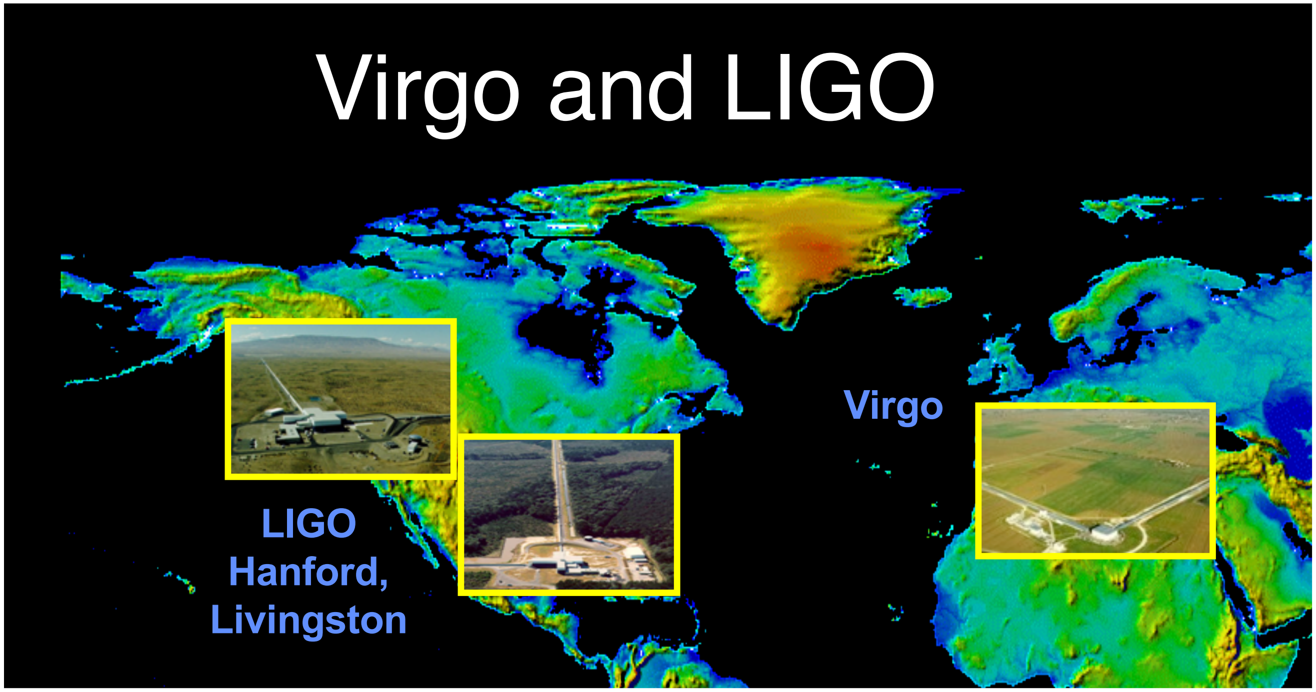
Gravitational Waves Detected:
The physics behind the detection,
The physics we observed

Séminaire Poincaré
3 December 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



Virgo and LIGO built new observatories in the 90's

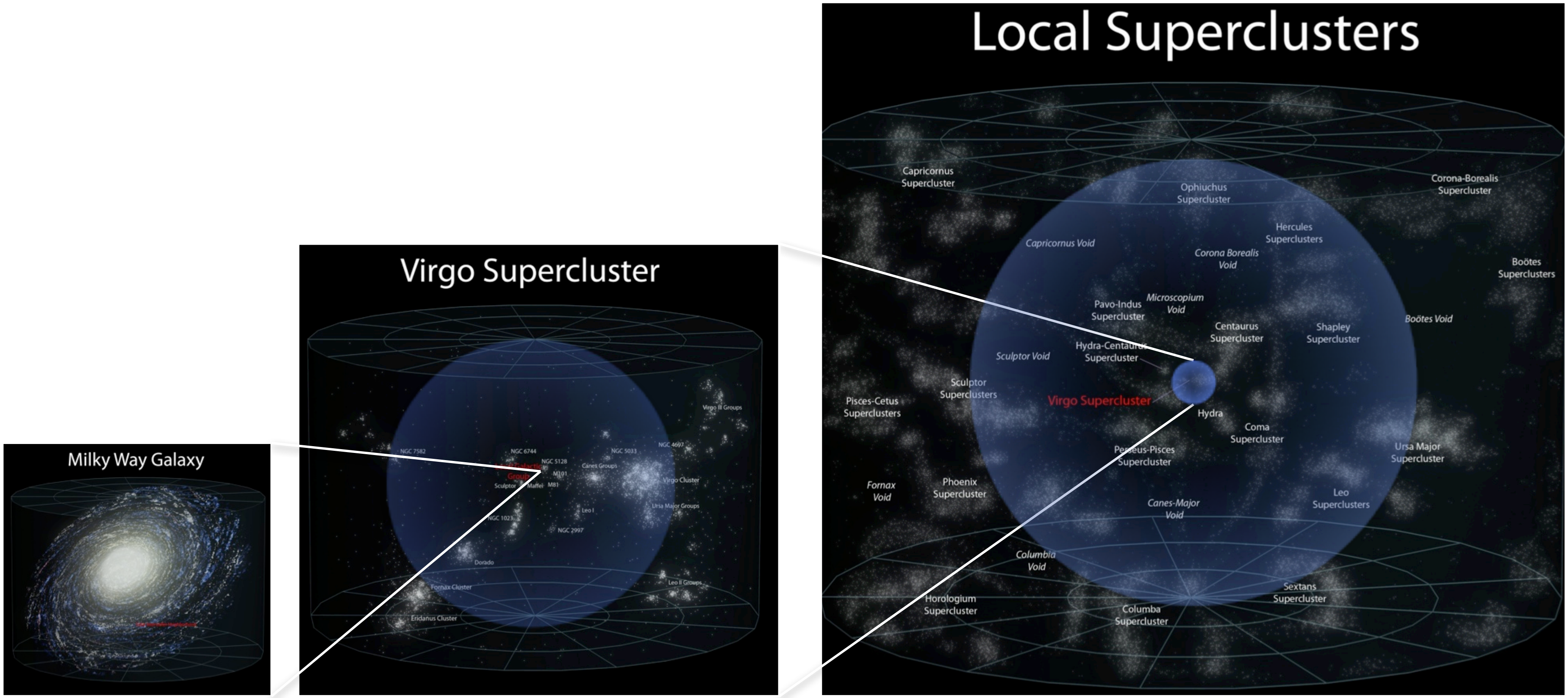
…and Observed with the initial detectors
2005-2011,
and saw **no signals**

(with some interesting non-detections)

Advanced Detectors:
a *qualitative* difference

- While observing with initial detectors, parallel R&D led to better concepts
- Design for 10x better sensitivity

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



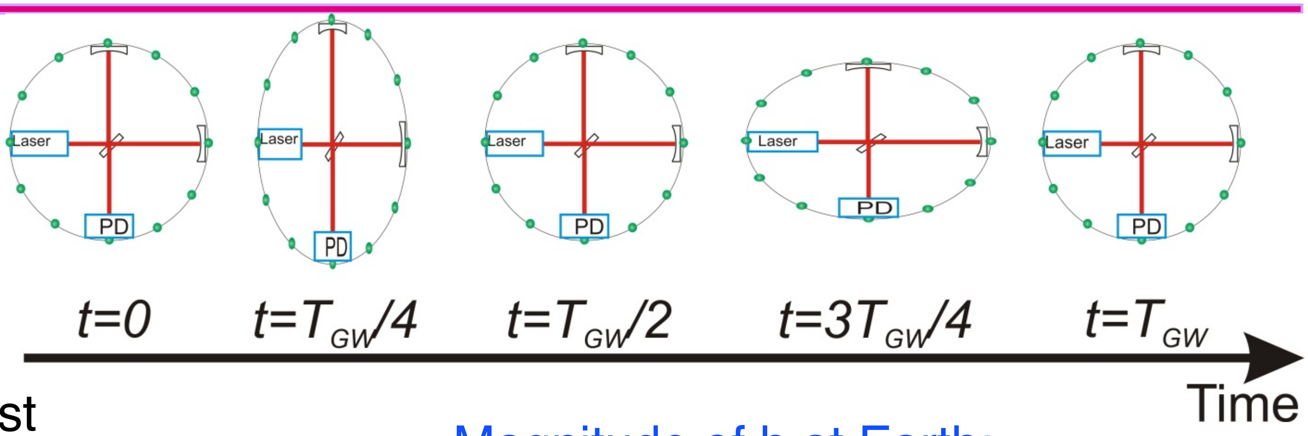
M. Evans

Initial Reach

Advanced Reach

What is our 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….



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

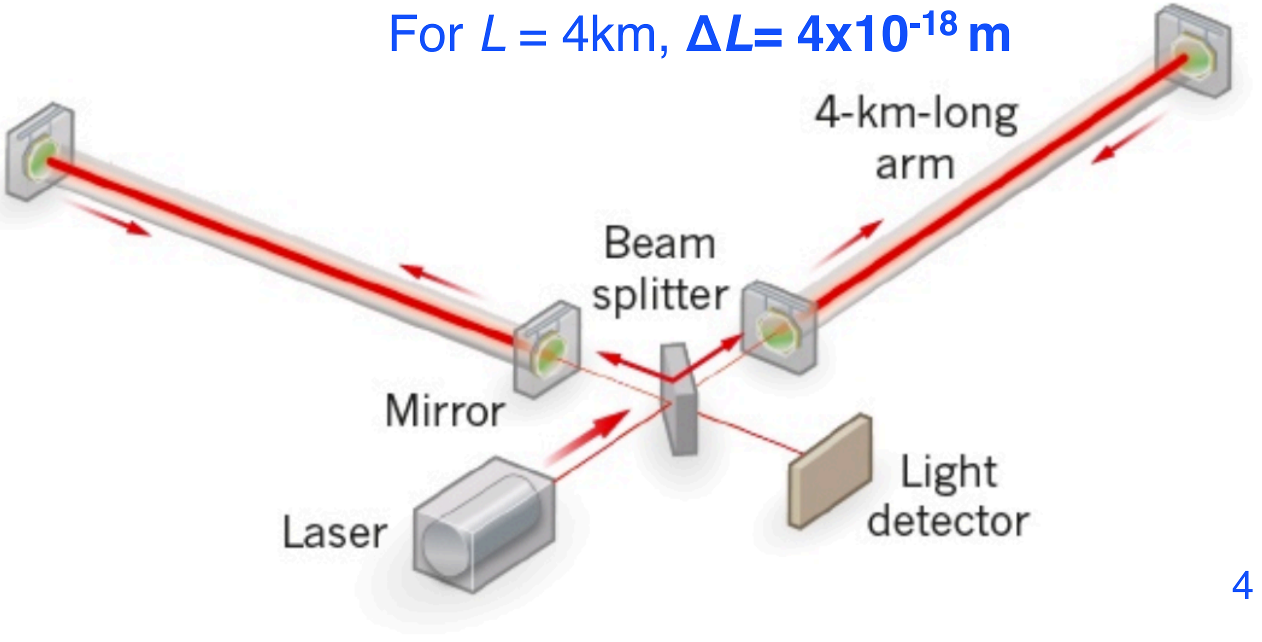
Magnitude of h at Earth:

Largest signals h ~ 10^{-21}

(1 hair / Alpha Centauri)

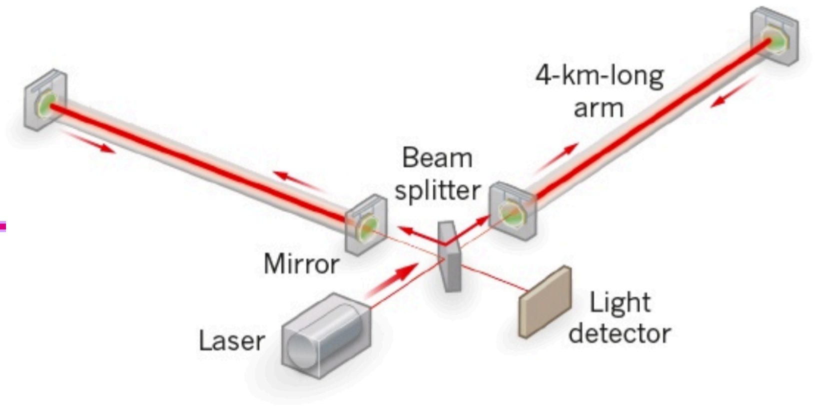
For L = 1 m, $\Delta L = 10^{-21}$ m

For L = 4km, **$\Delta L = 4\mathrm{x}10^{-18}$ m**



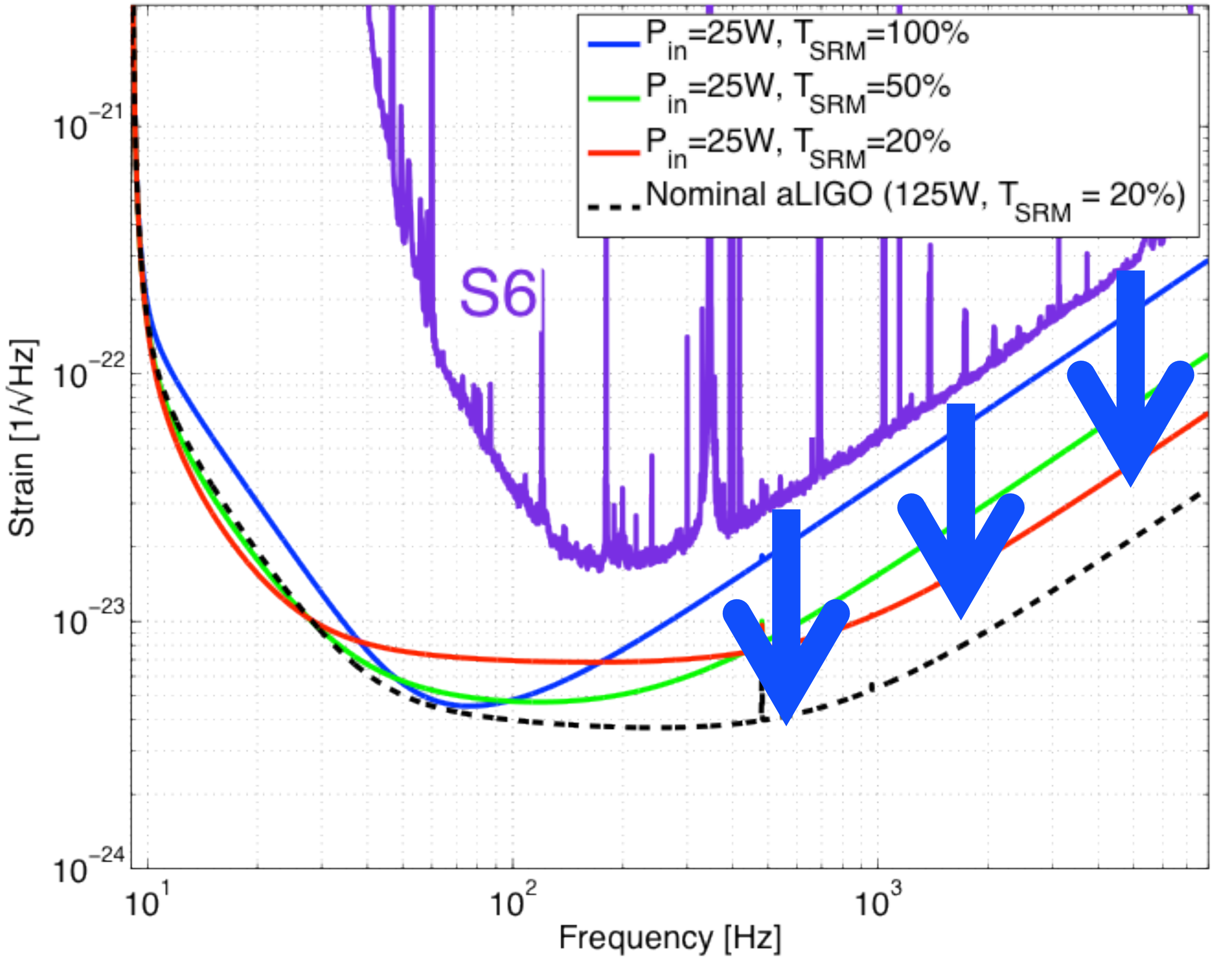
Measuring Δ*L*= 4x10^{-18} m

Readout

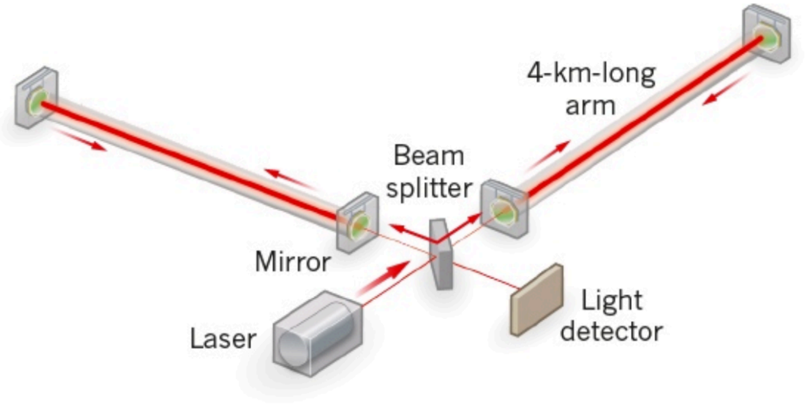


- **Shot noise** – ability to resolve a fringe shift due to a GW (counting statistics)
- *Zum gegenwärtigen Stand des Strahlungsproblems*, A. Einstein, 1909
- Fringe Resolution at high frequencies improves as as (laser power)$^{1/2}$

$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$



Measuring $\Delta L = 4\mathrm{x}10^{-18}$ m
Readout

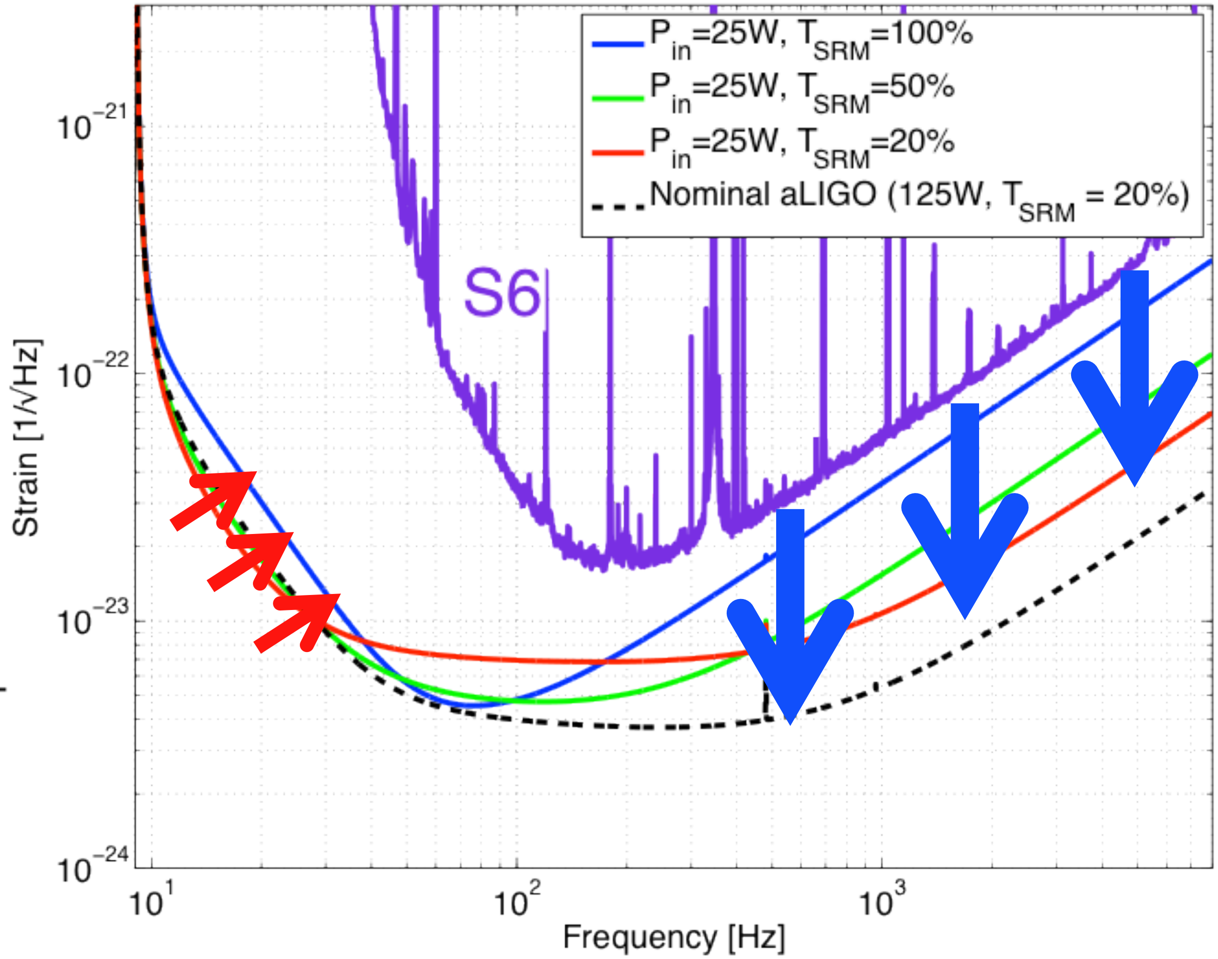


- Shot noise – ability to resolve a fringe shift due to a GW (counting statistics)

$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

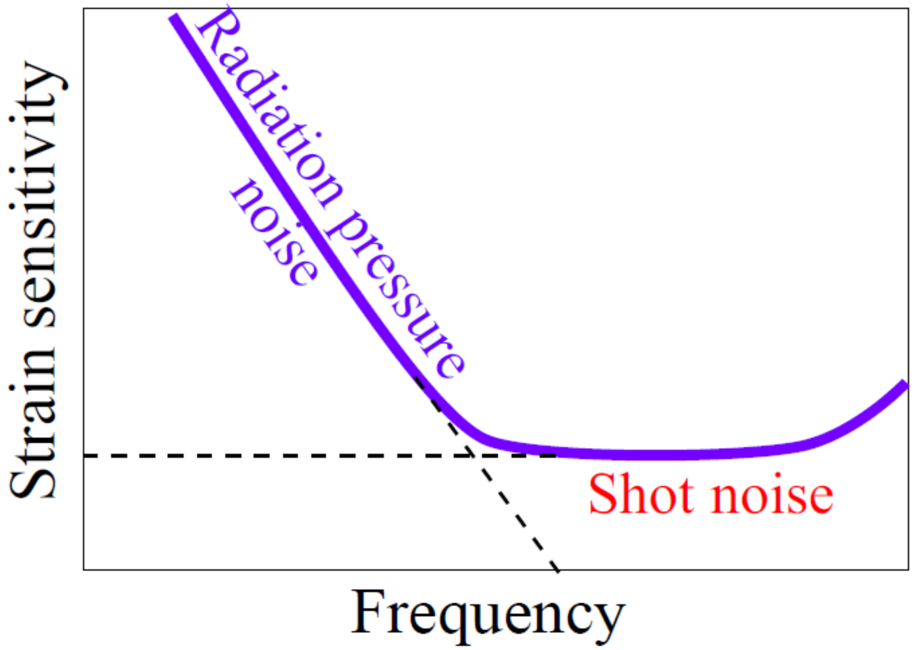
- **Radiation Pressure noise** – Point of diminishing returns when buffeting of test mass by photons increases low-frequency noise – use heavy test masses!

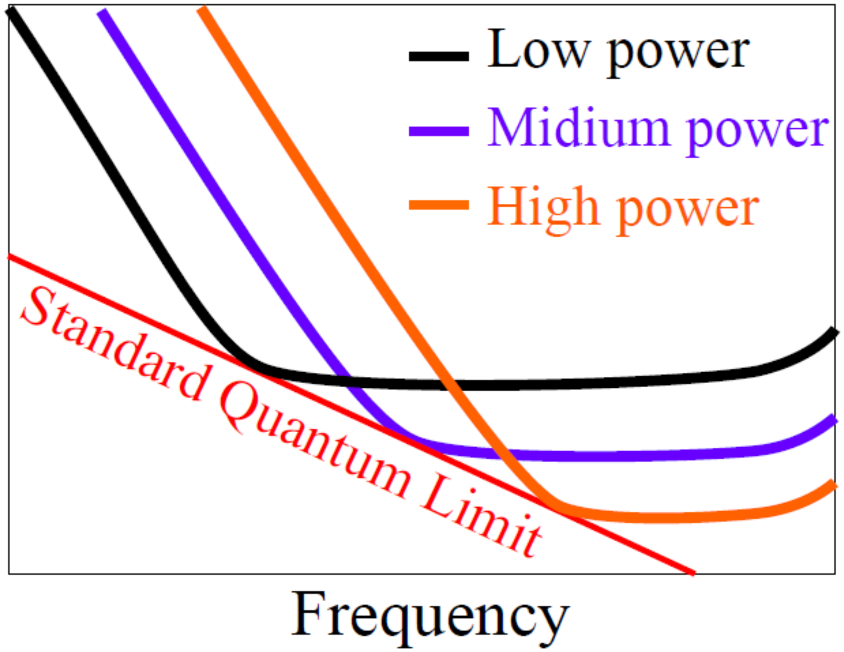
$$h_{\mathrm{rp}}(f) = \frac{1}{mf^2L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$



Standard Quantum Limit

- For a simple model of the instrument, one can choose the frequency of the best compromise between the two effects

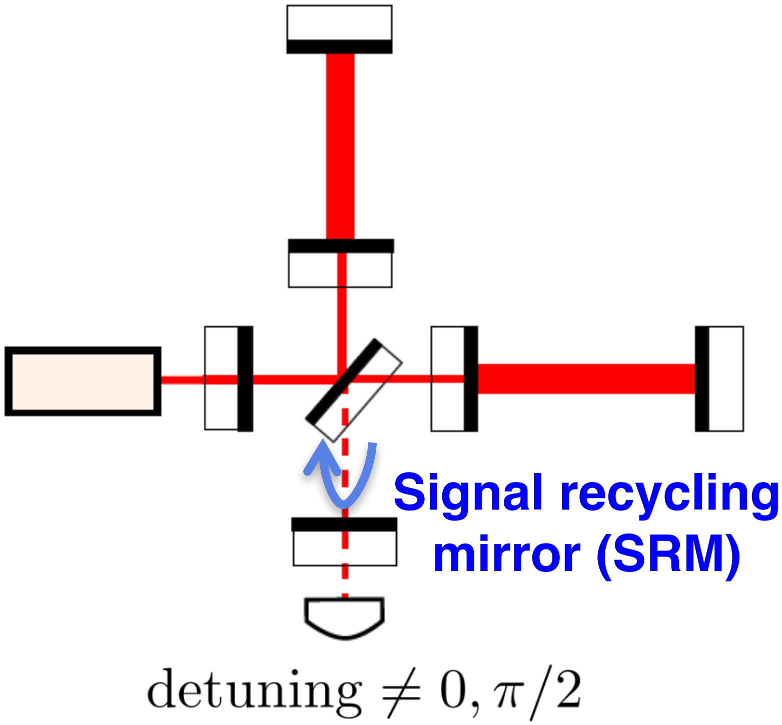




Figures: Miao

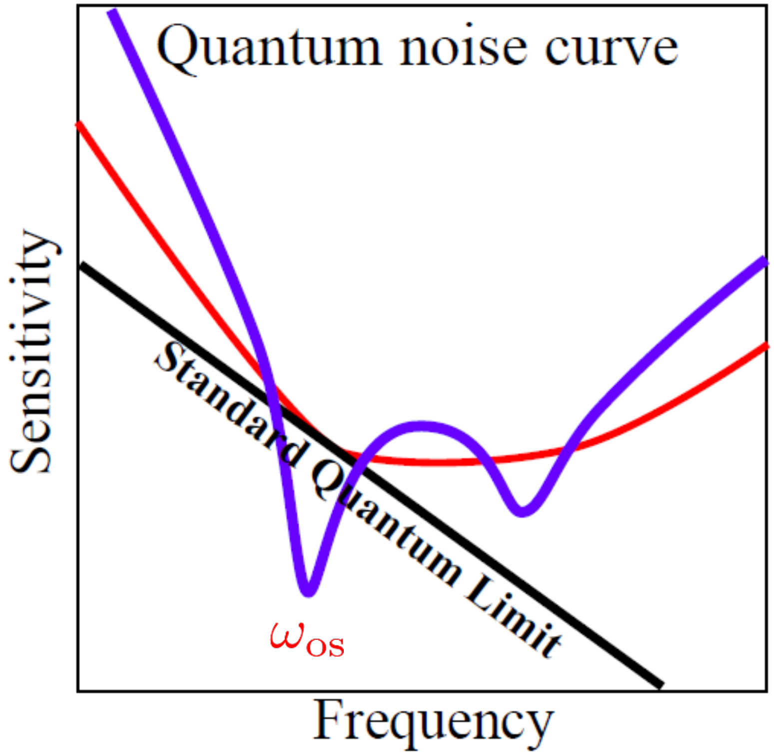
Detuned signal recycling (SR)

- In fact, in Advanced LIGO the signal recycling mirror couples phase and amplitude, and there is pondermotive squeezing of the light



Signal recycling mirror (SRM)

detuning $\neq 0, \pi/2$



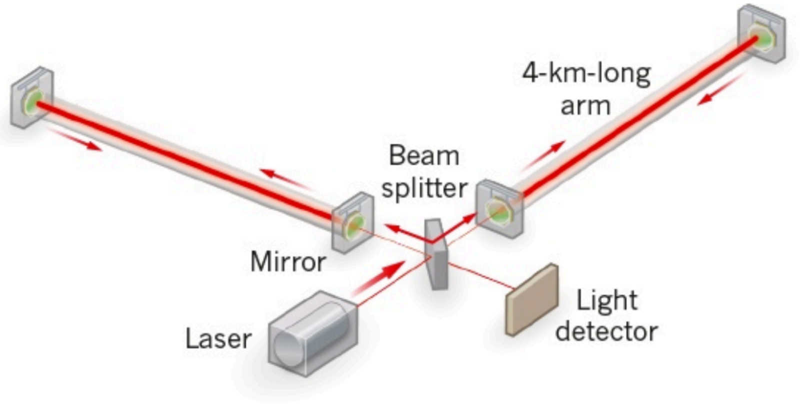
One interpretation: optical spring effect

$$M\ddot{x}(t) = F_{\mathrm{GW}}(t) \quad \Rightarrow \quad M\ddot{x}(t) = -M\omega_{\mathrm{os}}^2 x(t) + F_{\mathrm{GW}}(t)$$

[1] A. Buonanno and Y. Chen. *Signal recycled laser-interferometer gravitational-wave detectors as optical springs*, PRD **65**, 042001 (2002). Slide: H. Miao

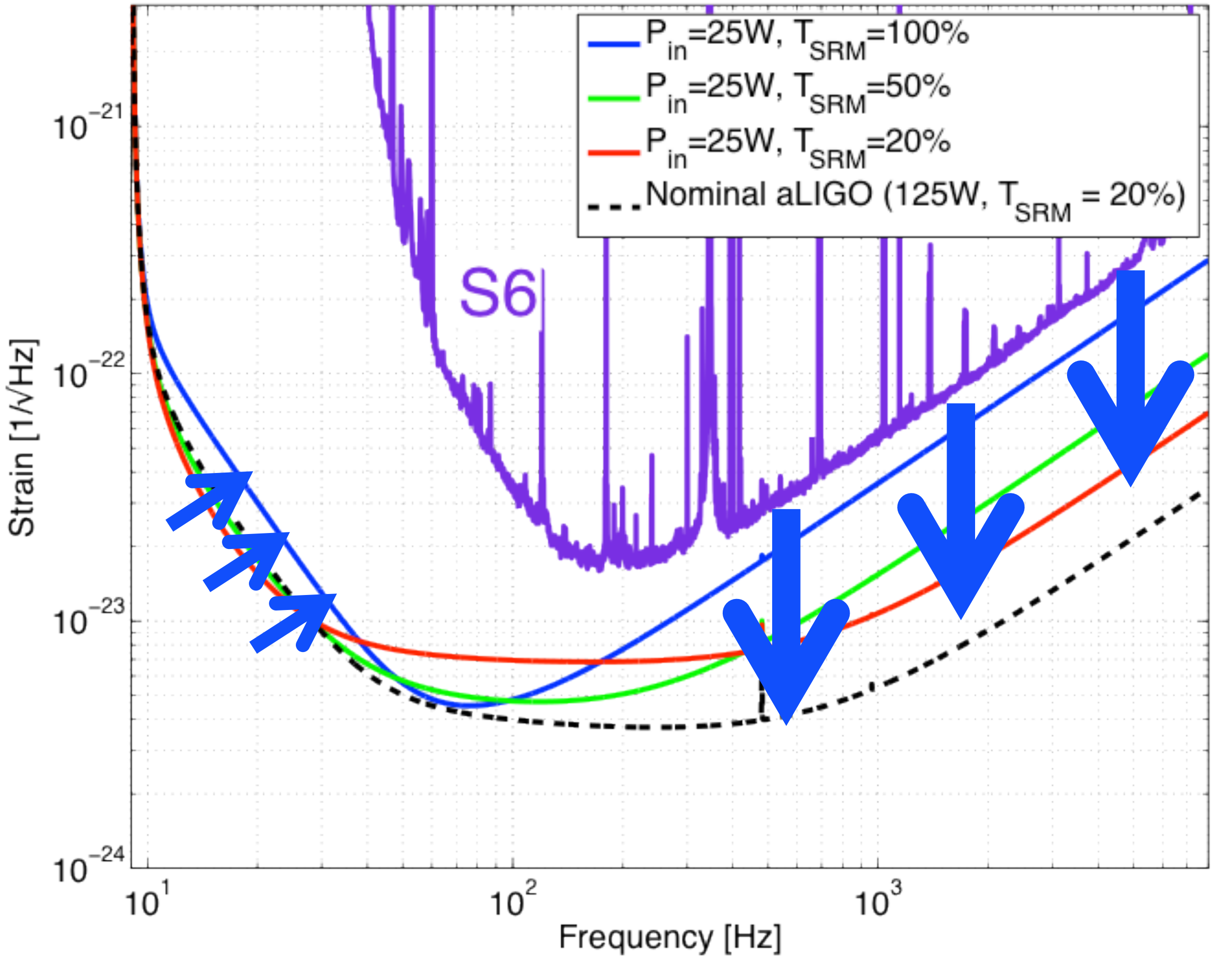
Measuring $\Delta L = 4\times10^{-18}$ m

Readout



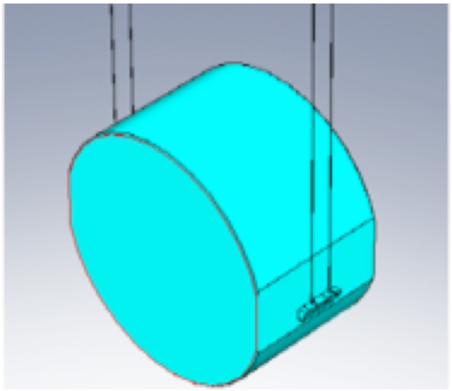
- Advanced LIGO is expected to operate in this pondermotive regime with its **200W laser, 40 kg test masses**

- …not yet, though (only see shot noise to date)



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

Internal motion

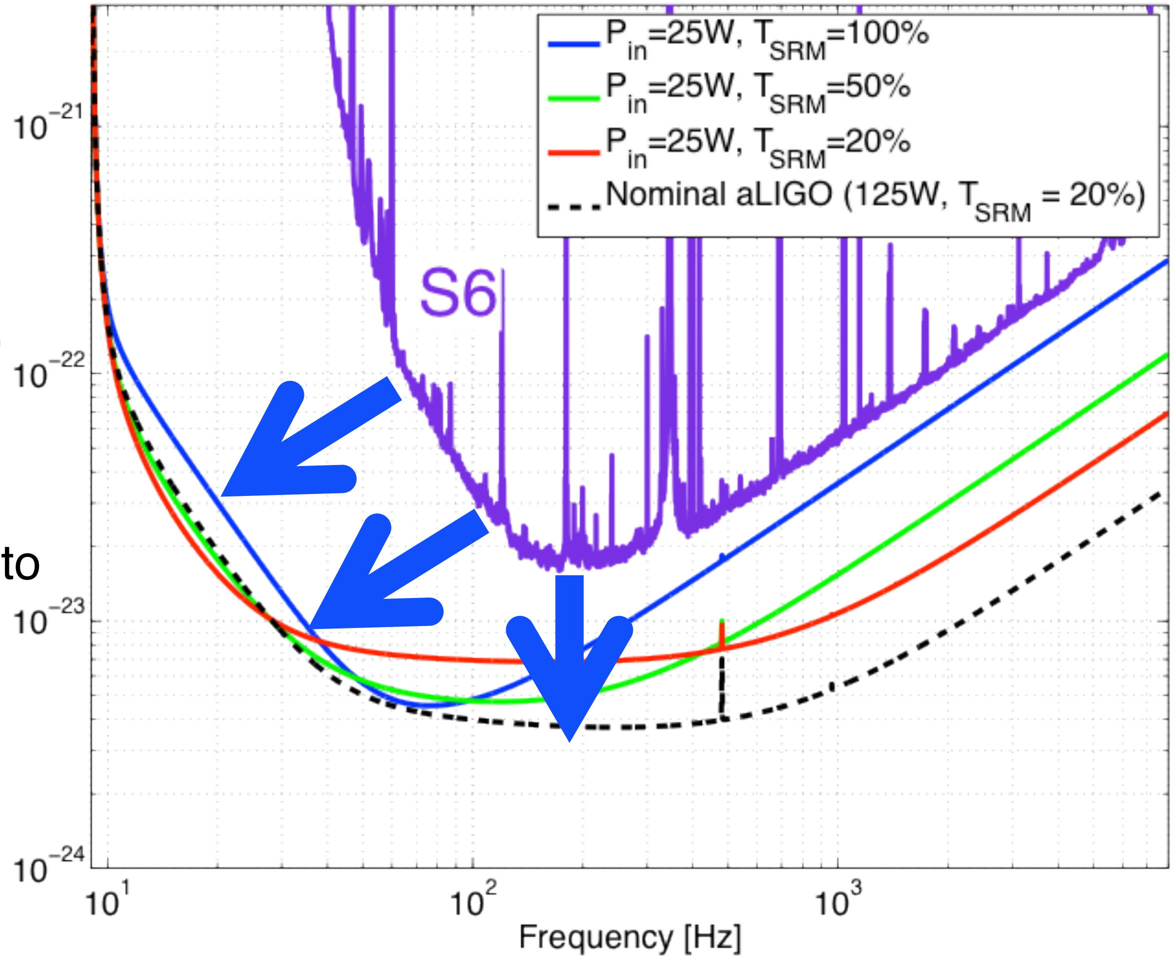


- **Thermal noise** – kT of energy per mechanical mode
- *Über die von der molekularkinetischen Theorie der Wärmegeforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen,* A. Einstein, 1905
- Simple Harmonic Oscillator:

$$x_{rms} = \sqrt{\left\langle (\delta x)^2 \right\rangle} = \sqrt{k_B T / k_{spring}}$$

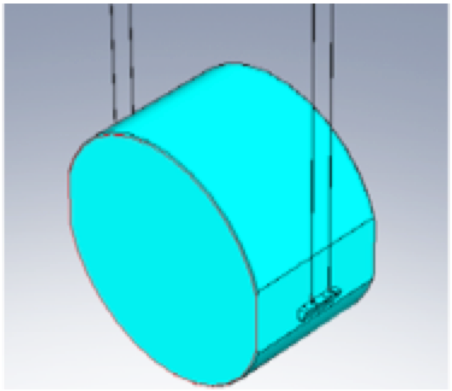
- Distributed in frequency according to real part of impedance $\Re(Z(f))$

$$\tilde{x}(f) = \frac{1}{\pi f}\sqrt{\frac{k_B T}{\Re(Z(f))}}$$

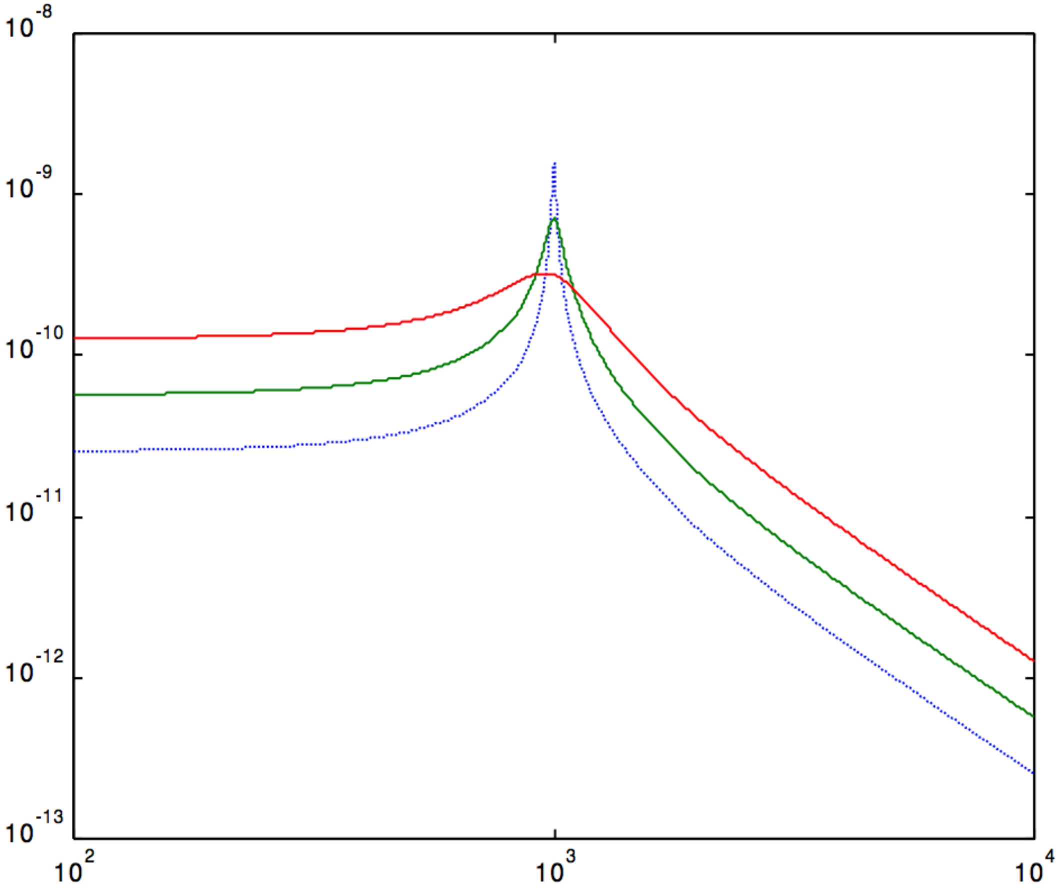


Measuring Δ*L*= $4x10^{-18}$ m

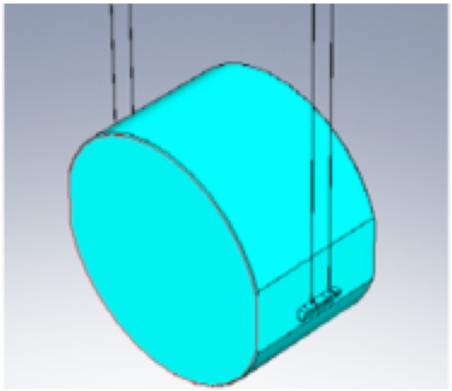
Internal motion



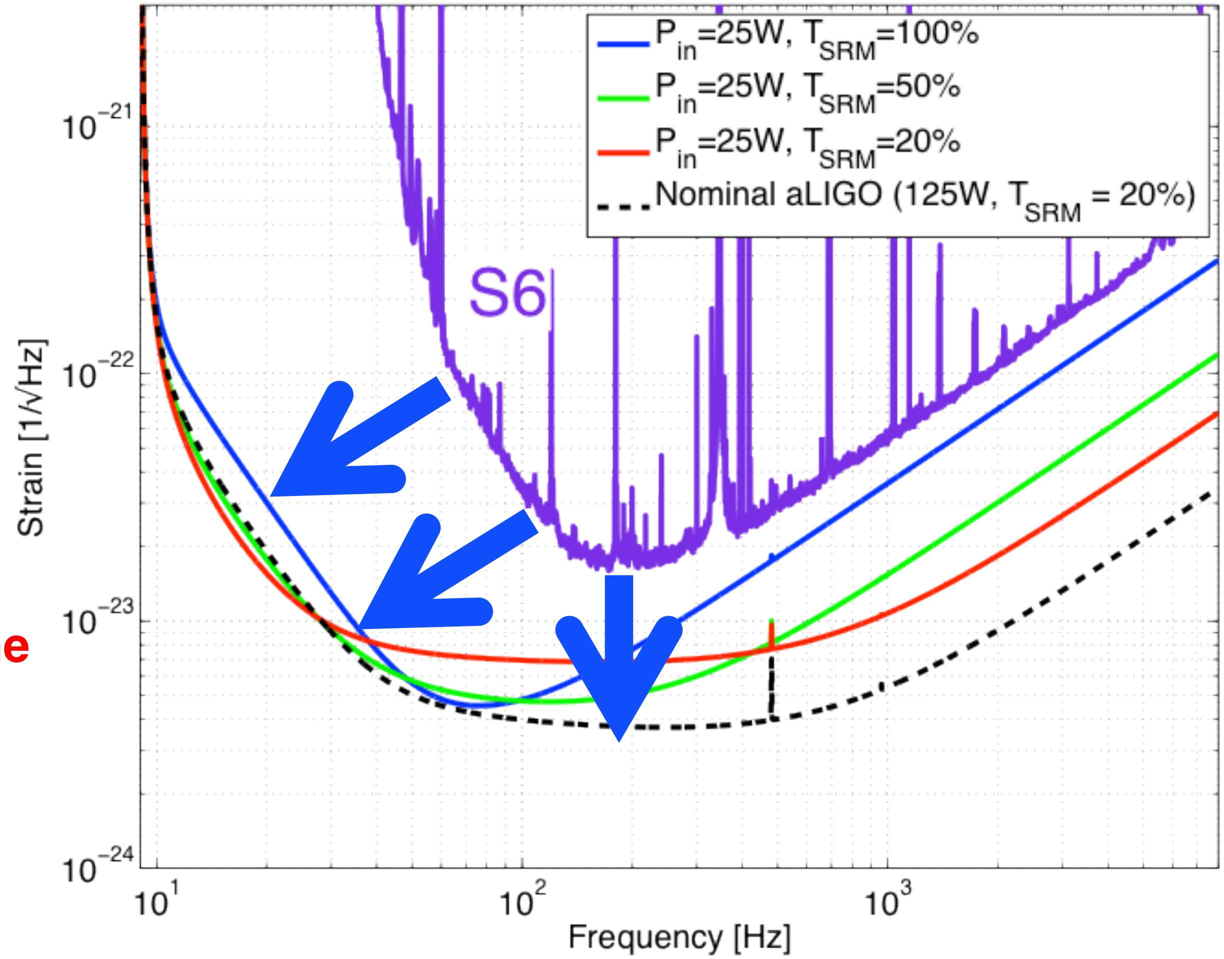
- **Thermal noise** – kT of energy per mechanical mode
  - » This is the integral under the curve of motion…
- Fluctuation-dissipation theorem gives motion as a function of frequency
- Low mechanical loss materials gather this motion into a narrow peak at resonant frequencies
  - » Lower noise above and below the peak



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

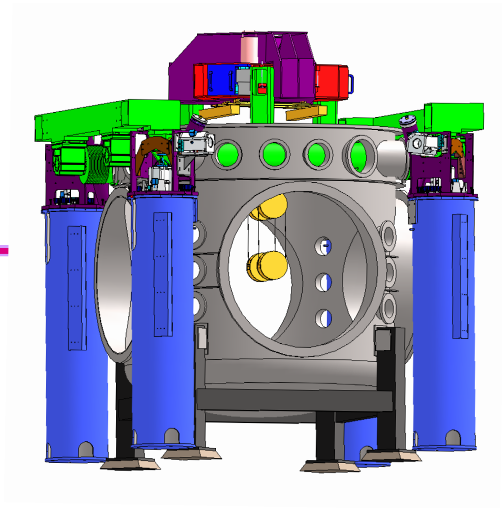


- In Advanced LIGO, the optical coating is the dominant loss
  - » ~100µm thick
- Fused silica components have losses of order 10^{-6} – 10^{-8}
- Sputtered optical coatings have losses of order 10^{-4}
- **And** the lossy coating is the interface to the laser beam
- **This is the dominant limit in the critical 10-200 Hz band**
- A focus of research!

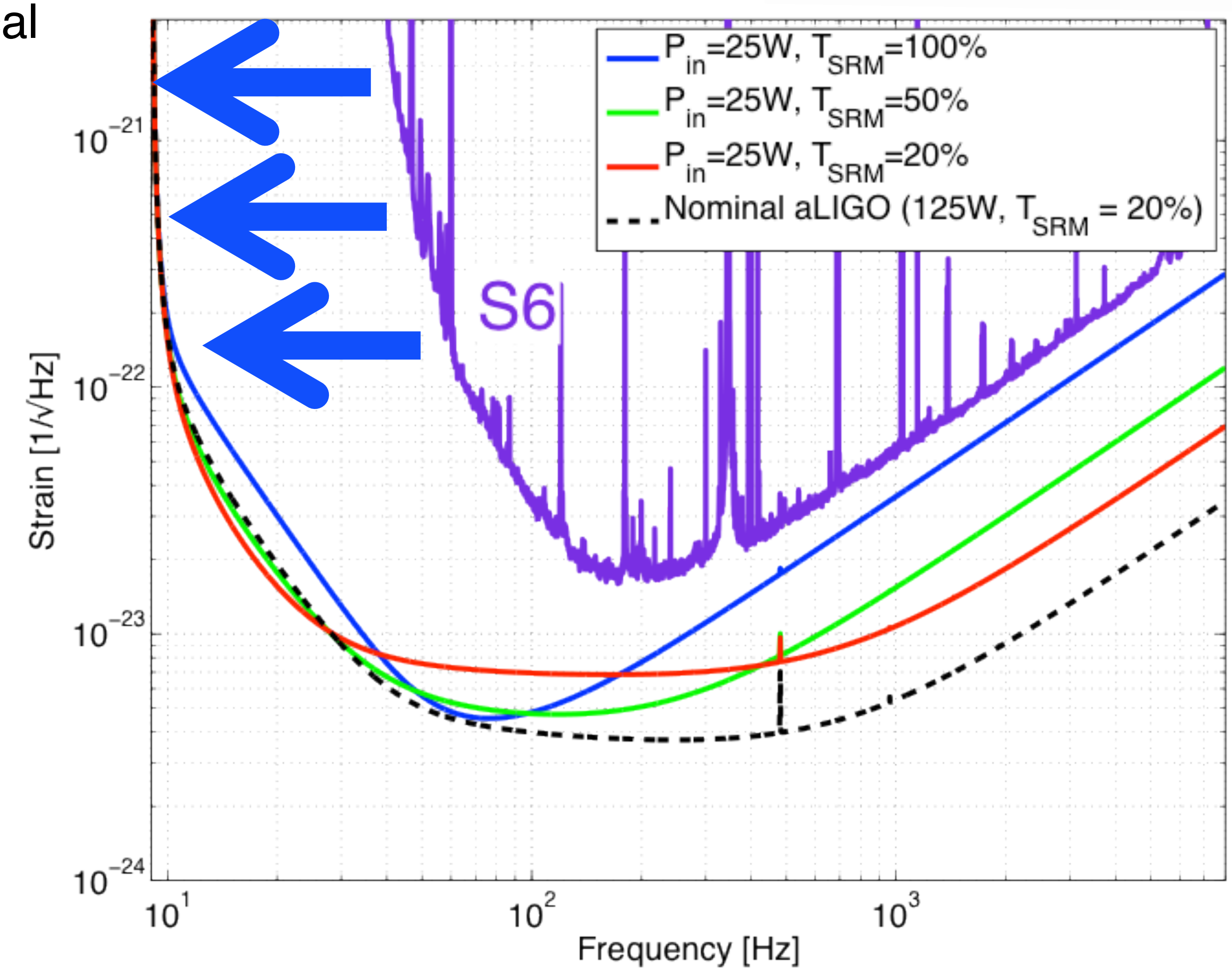


Measuring ΔL= 4x10^{-18} m

Forces on test mass

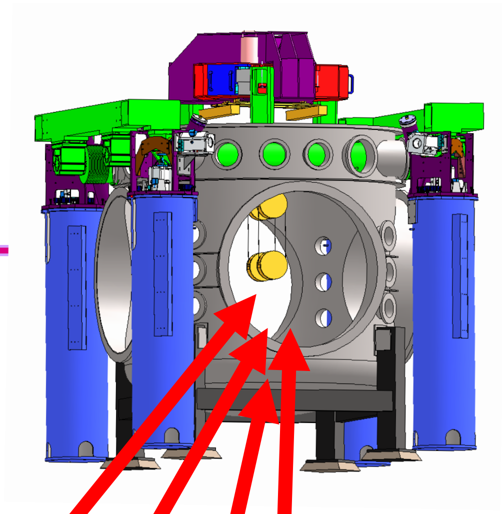


- **Seismic noise** – must prevent masking of GWs, enable practical control systems
- *(did Einstein work on seismic motion…?)*
- Motion from waves on coasts…and people moving around
- GW band: 10 Hz and above – direct effect of masking
- Control Band: below 10 Hz – forces needed to hold optics on resonance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



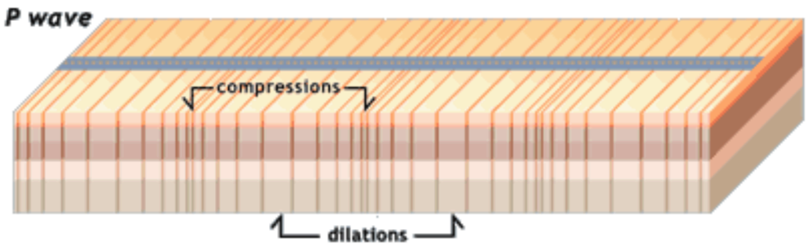
Measuring $\Delta L = 4\mathrm{x}10^{-18}$ m

Forces on test mass

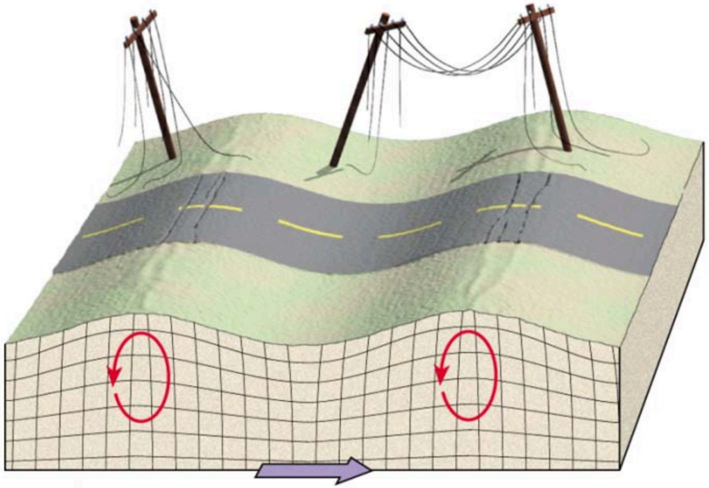


- Ultimate limit on the lowest frequency detectors on- or under-ground:
- Newtownian background – wandering net gravity vector; a limit in the 10-20 Hz band

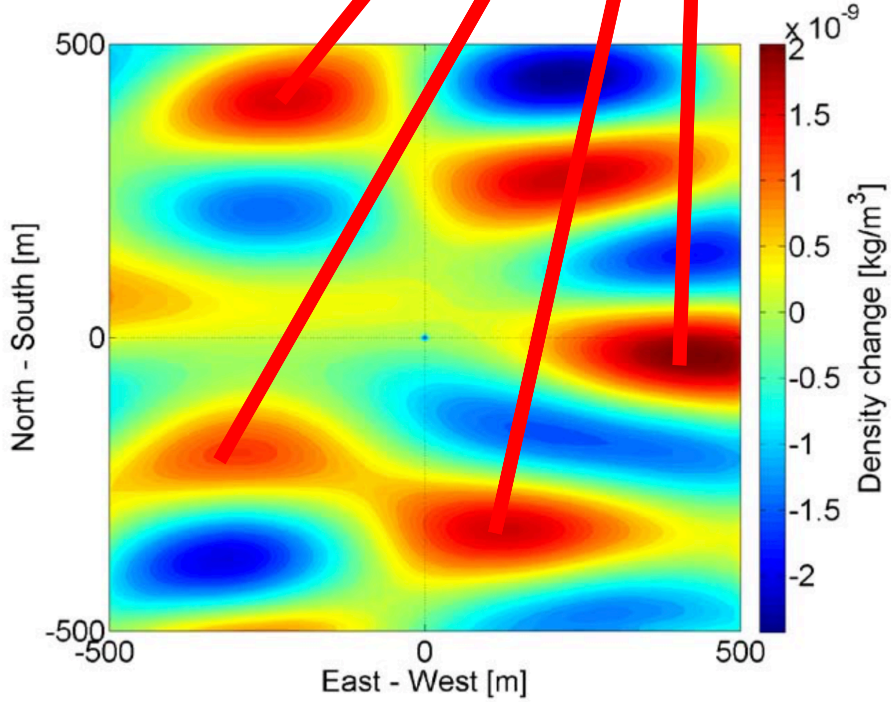
Body waves



Rayleigh waves



Density perturbation

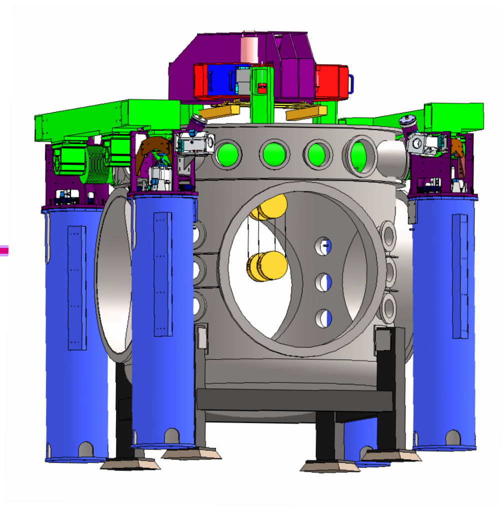


Density perturbations cause gravity perturbations.

Images: J. Harms

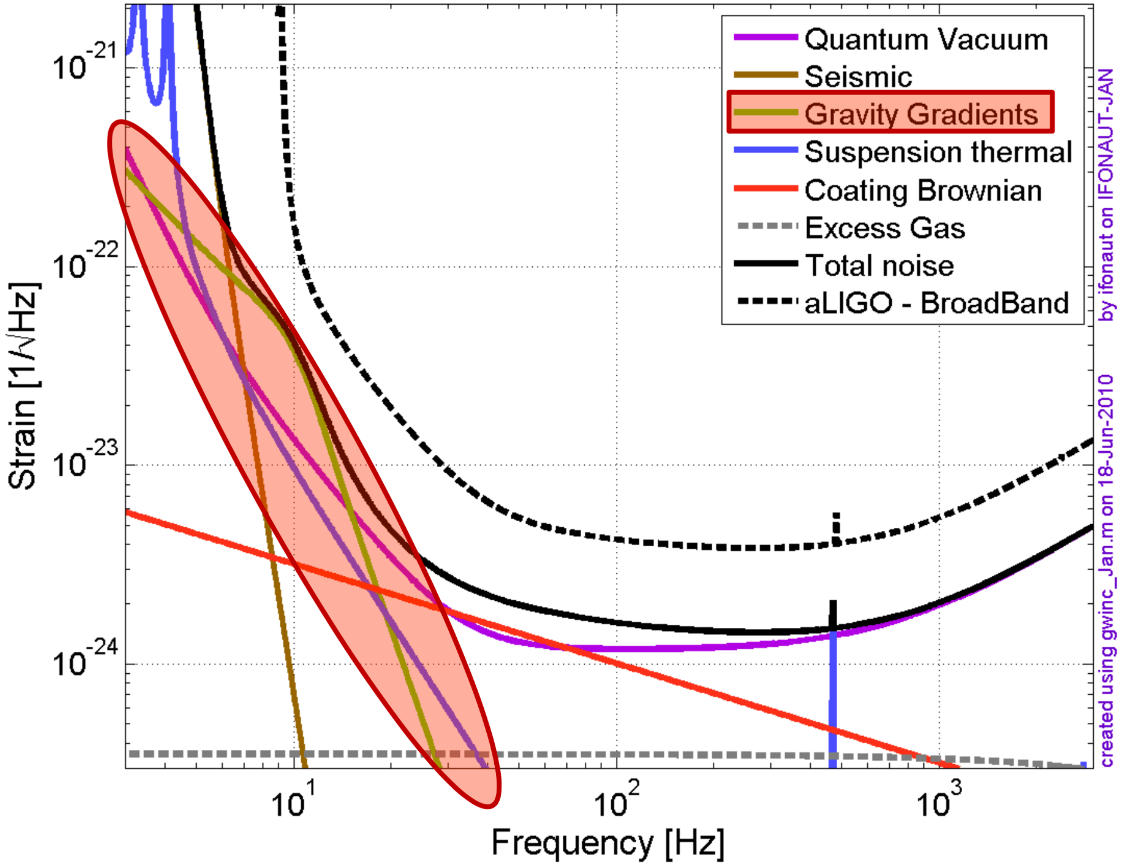
Measuring ΔL= 4x10^{-18} m

Forces on test mass



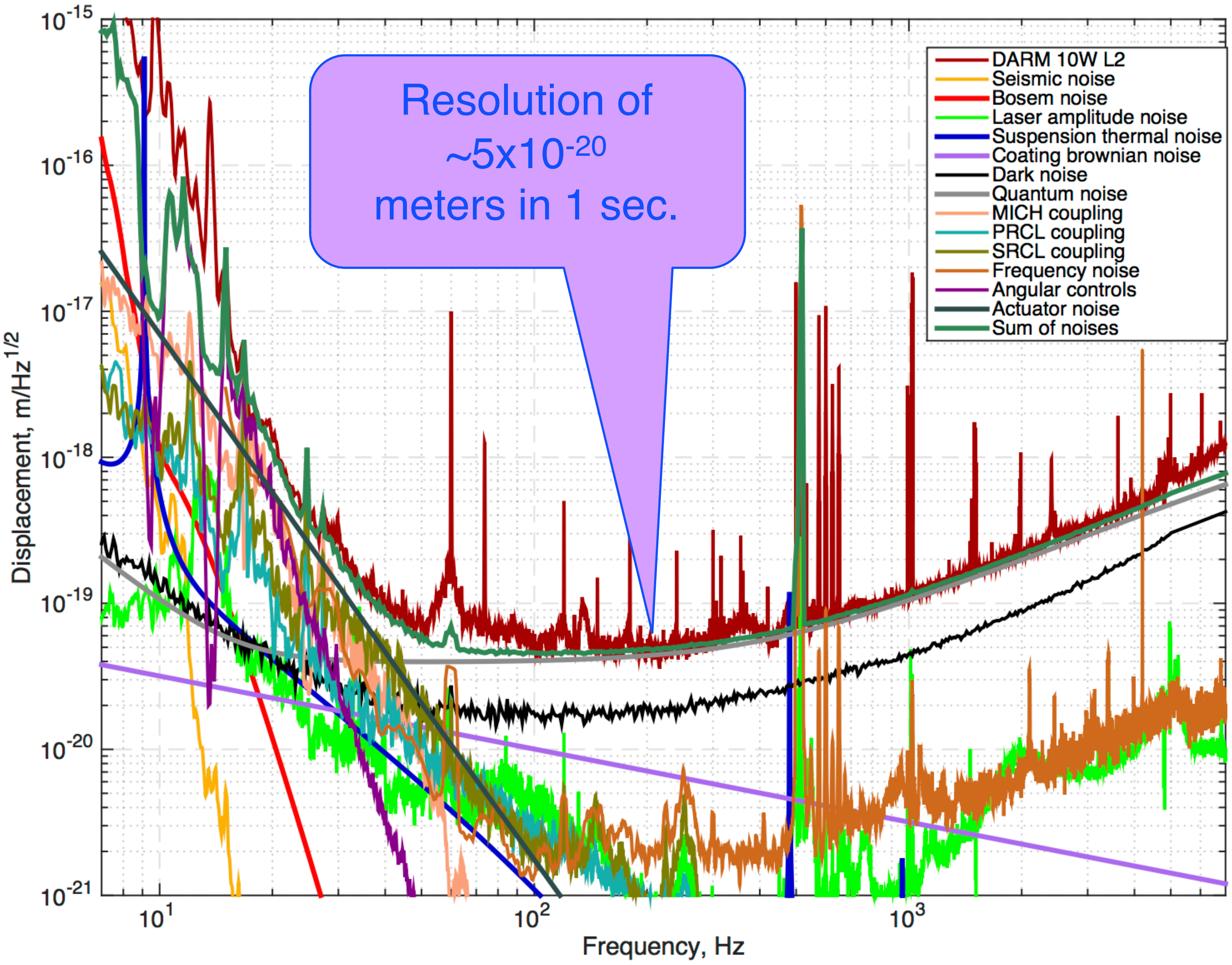
- Advanced LIGO (and Virgo) expect to be limited by this noise source –
  - After all technical noise sources beaten down
  - At low optical power (no radiation pressure noise)
  - In the 10-30 Hz range

- We would *love* to be limited only by this noise source!



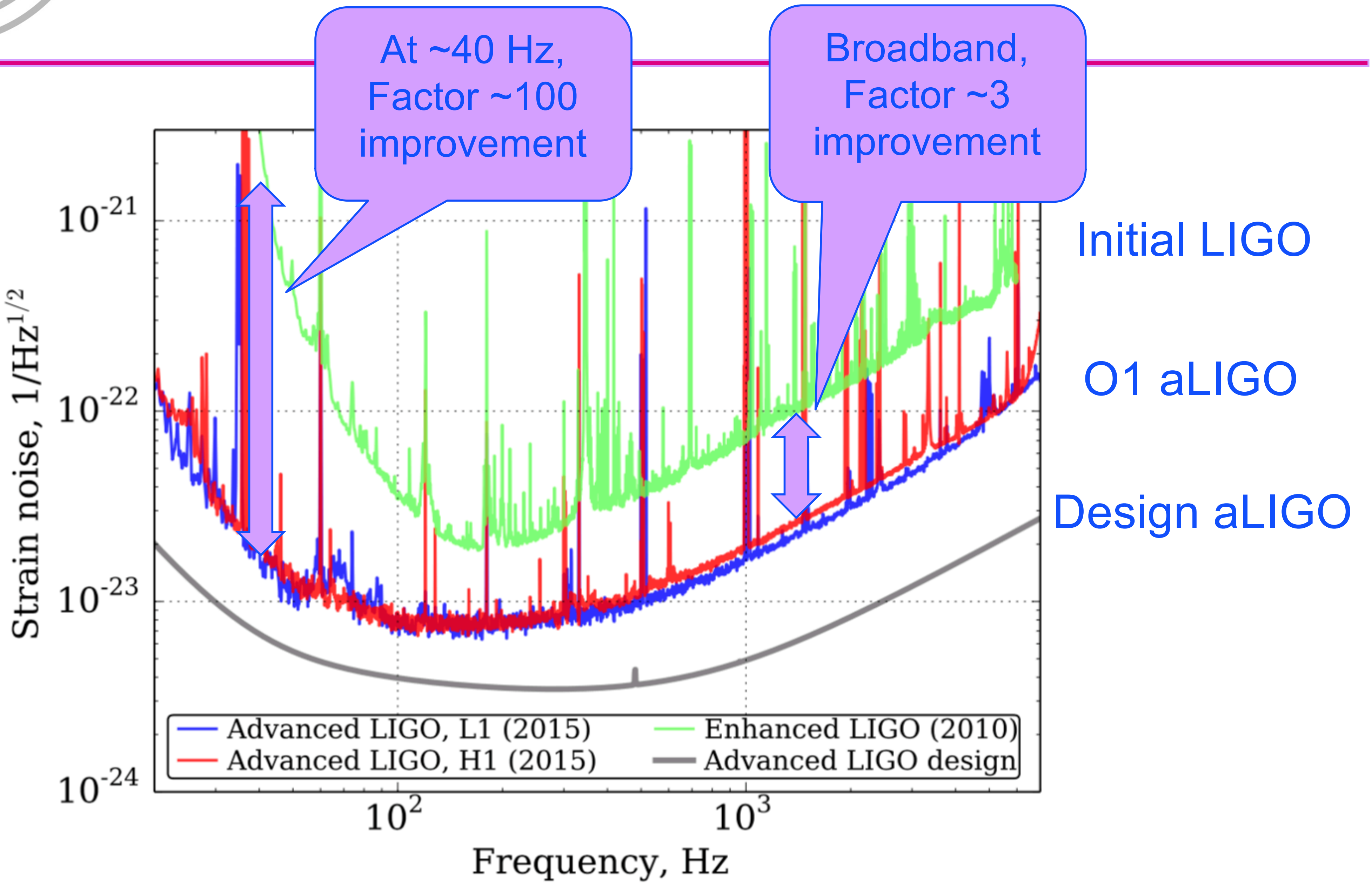
Images: J. Harms

Then there are the technical noise sources….



Resolution of ~5x10^{-20} meters in 1 sec.

Sensitivity for first Observing run



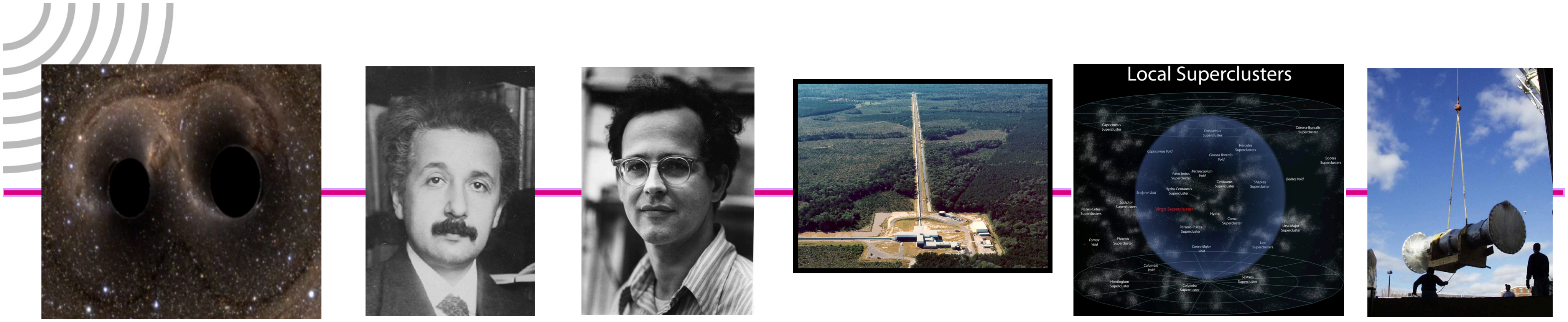
At ~40 Hz, Factor ~100 improvement

Broadband, Factor ~3 improvement

Initial LIGO

O1 aLIGO

Design aLIGO



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...

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

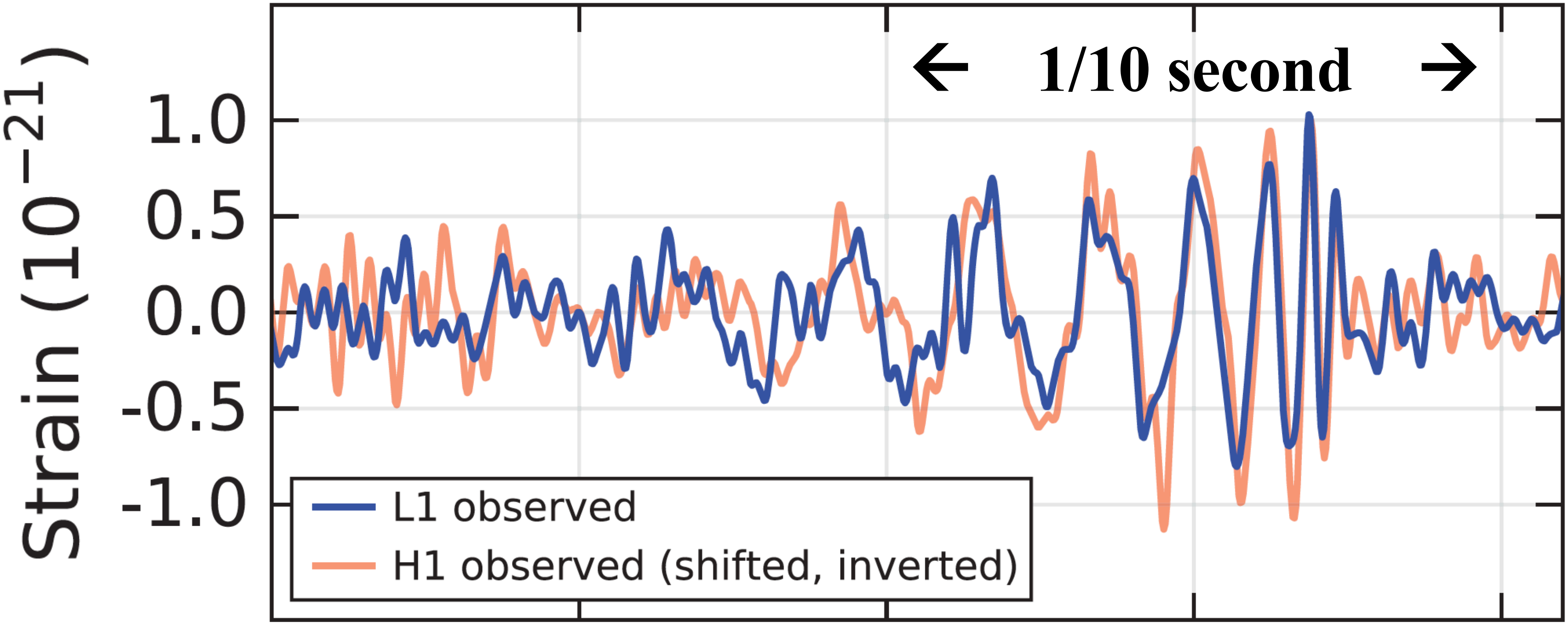
10 years after Advanced LIGO got the ok...

6 months after starting detector tuning...

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

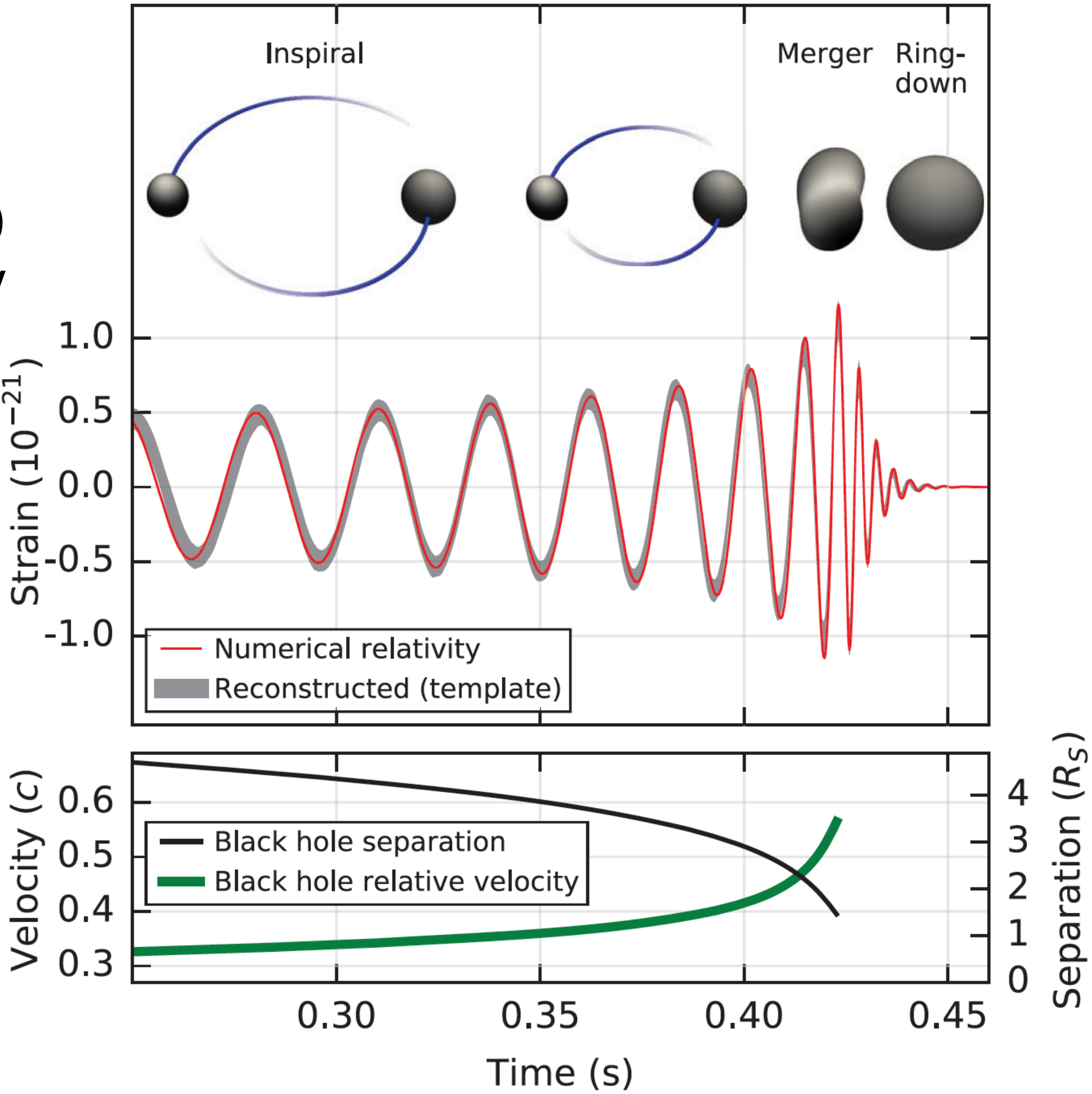
The first signal

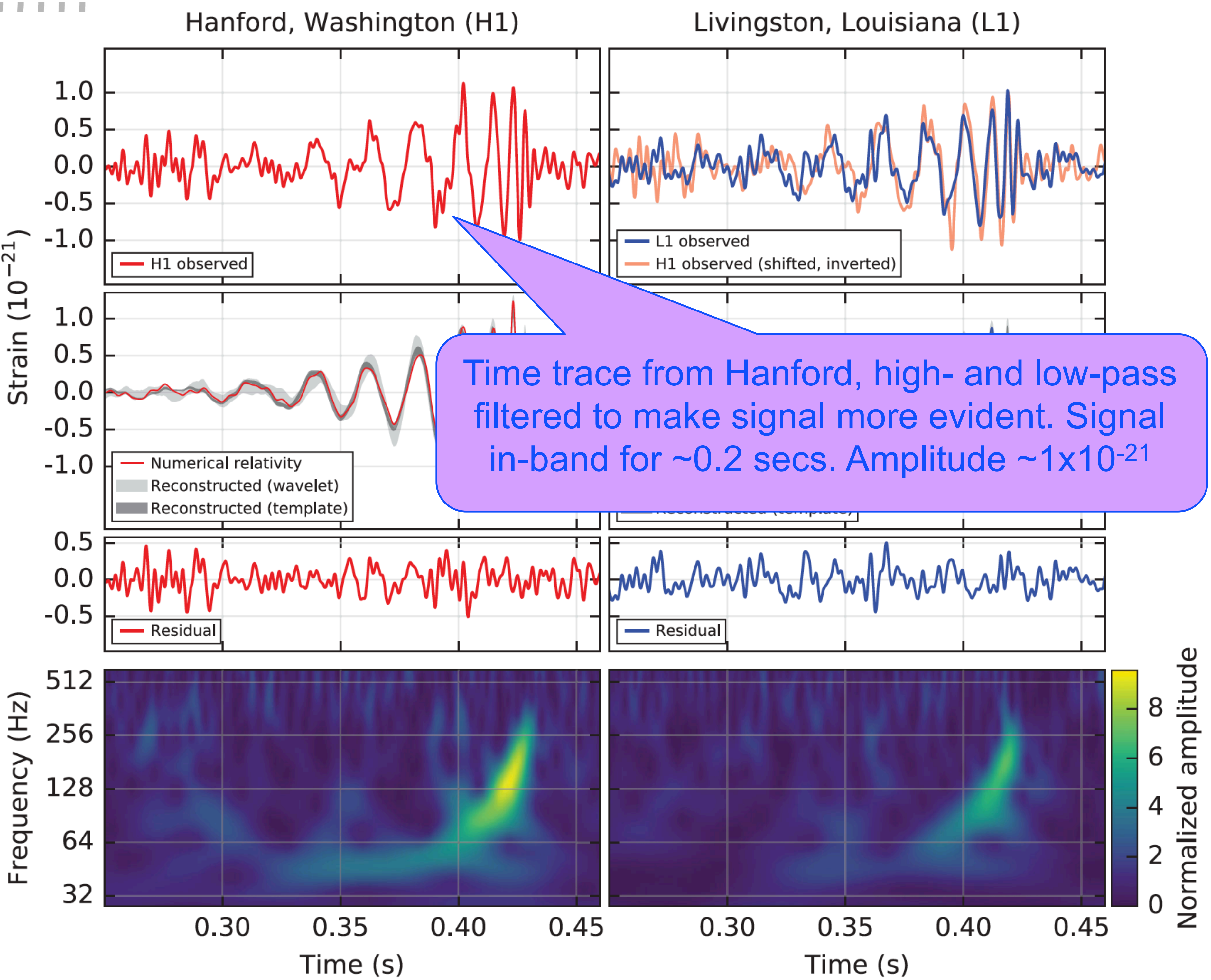
On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory observed a transient gravitational-wave signal



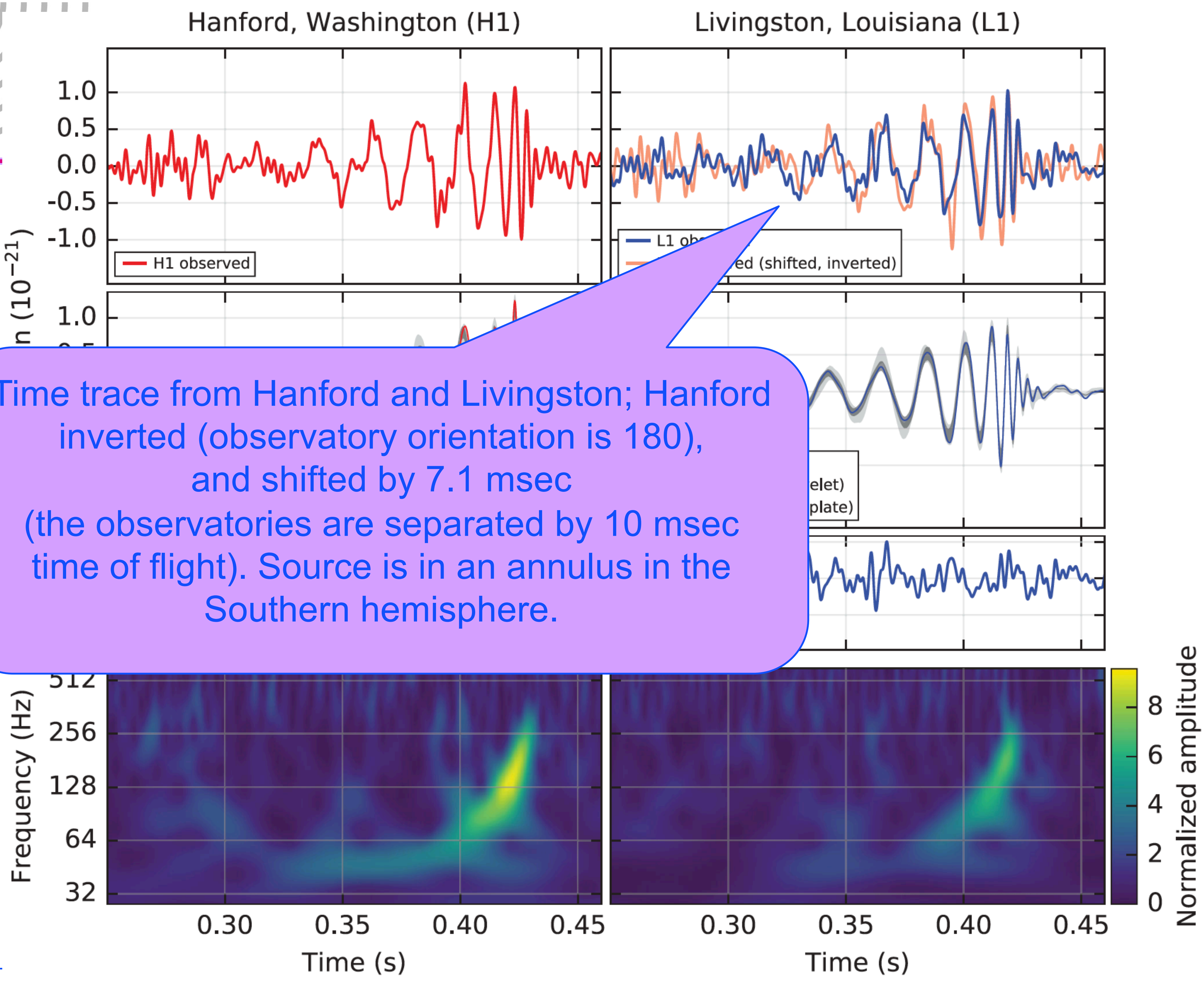
We measure *h(t)* – think ‘strip chart recorder’

- 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
  - radiation of gravitational waves confirmed to *remarkable* precision for 0th post-Newtonian
- **LIGO can actually measure the change in distance between our own test masses, due to a passing space-time ripple**
  - Instantaneous amplitude rather than time-averaged power
  - Much richer information!

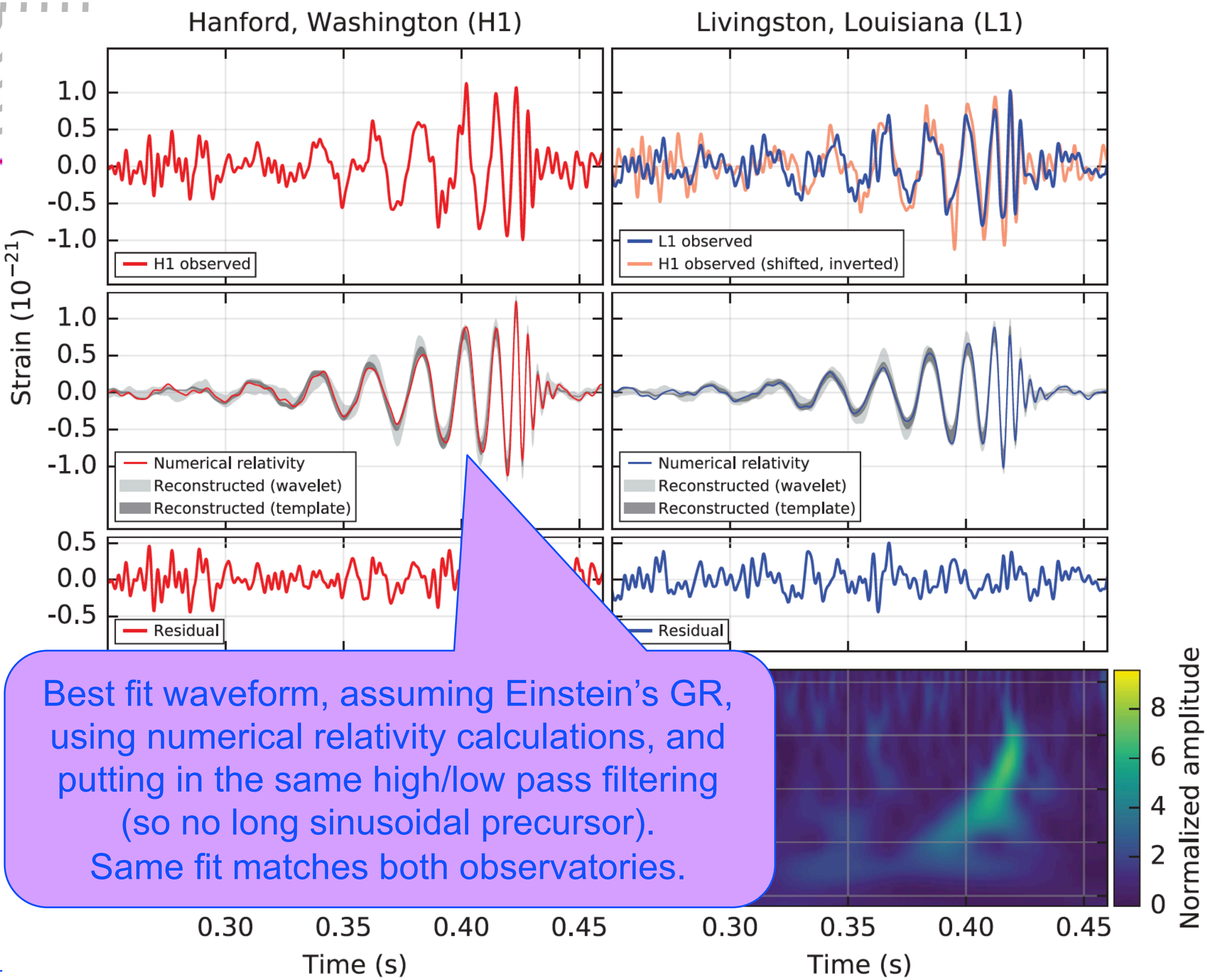




Time trace from Hanford, high- and low-pass filtered to make signal more evident. Signal in-band for ~0.2 secs. Amplitude ~1×10^{-21}

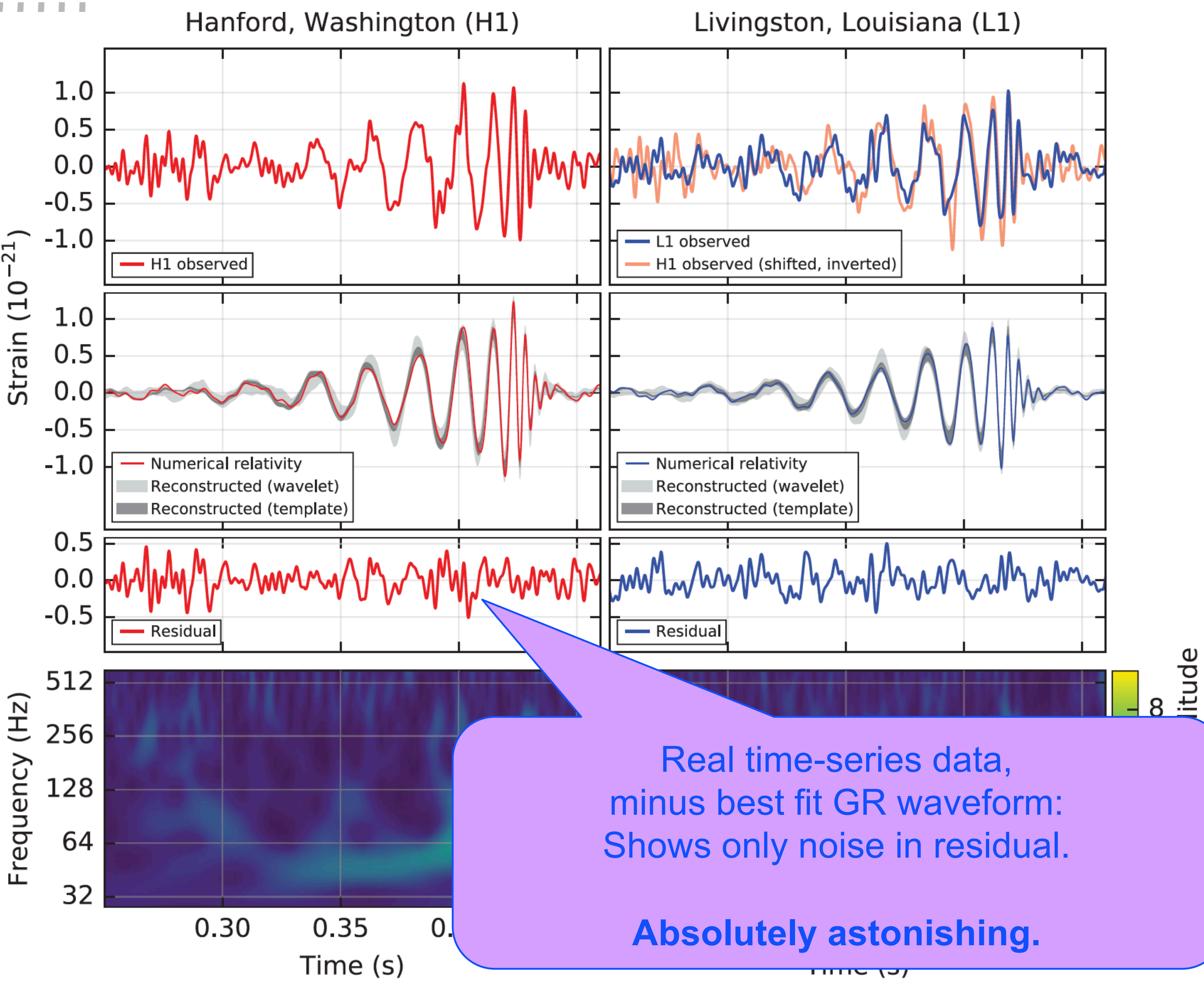


Time trace from Hanford and Livingston; Hanford inverted (observatory orientation is 180), and shifted by 7.1 msec (the observatories are separated by 10 msec time of flight). Source is in an annulus in the Southern hemisphere.



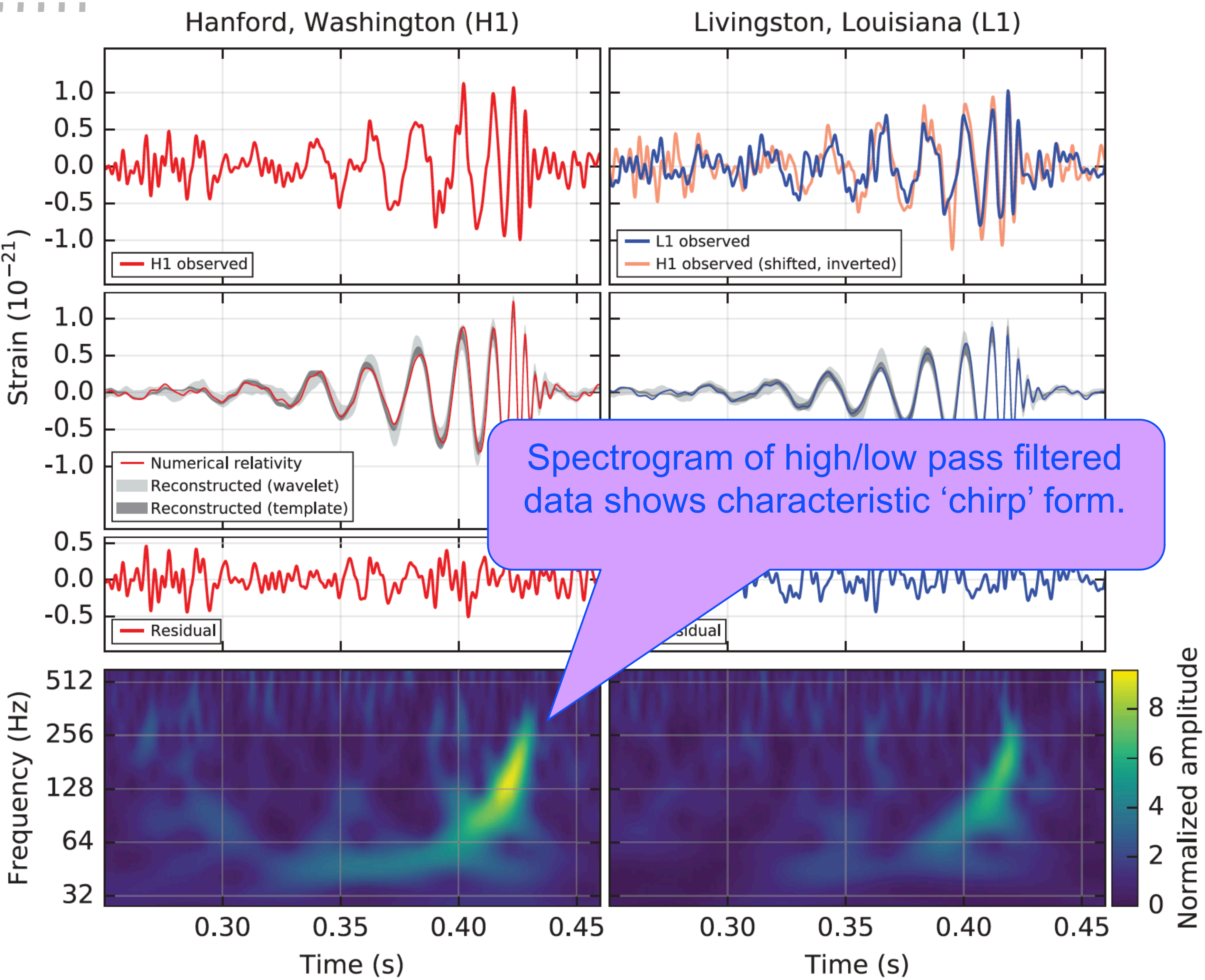
Best fit waveform, assuming Einstein's GR, using numerical relativity calculations, and putting in the same high/low pass filtering (so no long sinusoidal precursor).

Same fit matches both observatories.

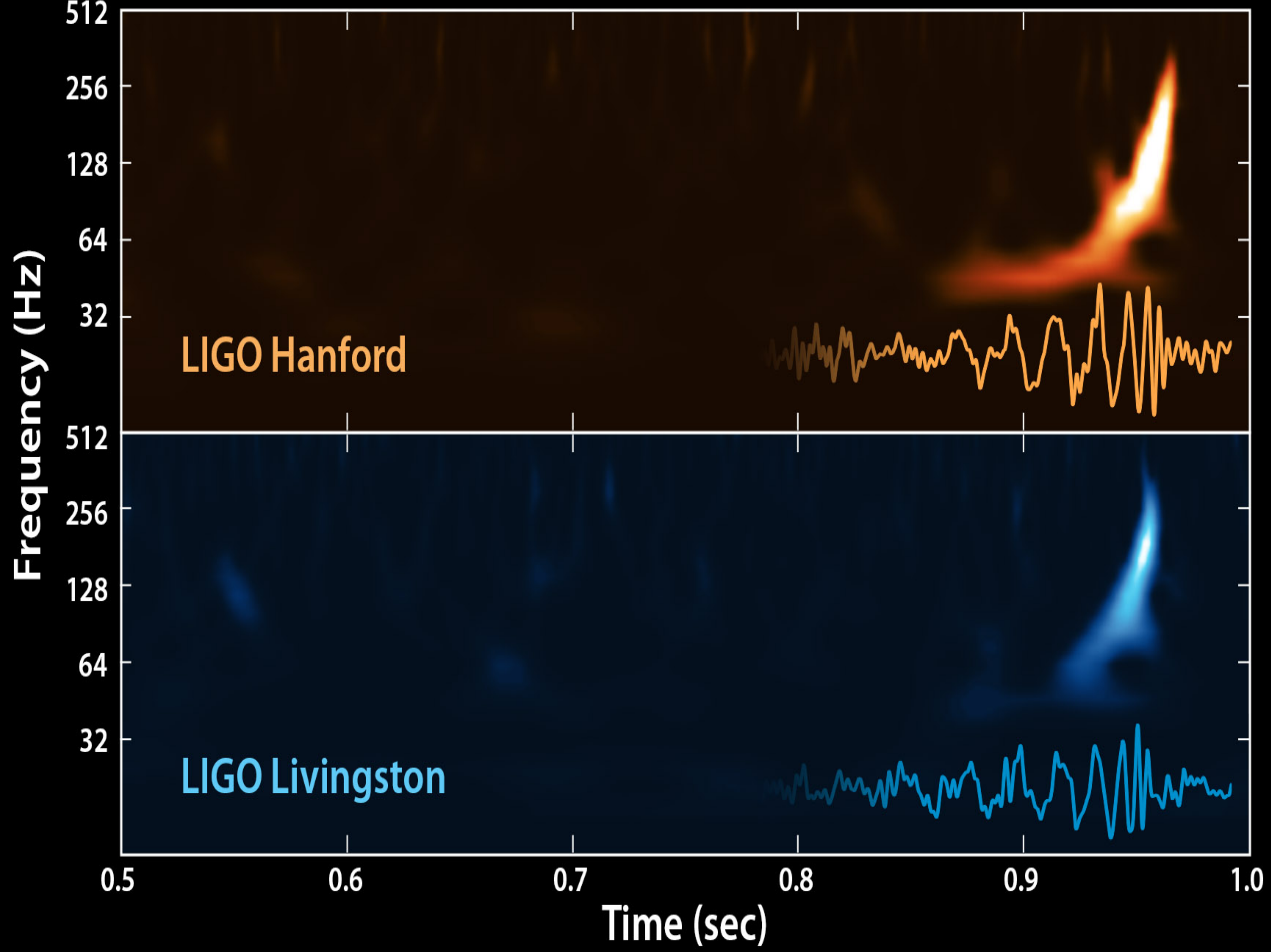


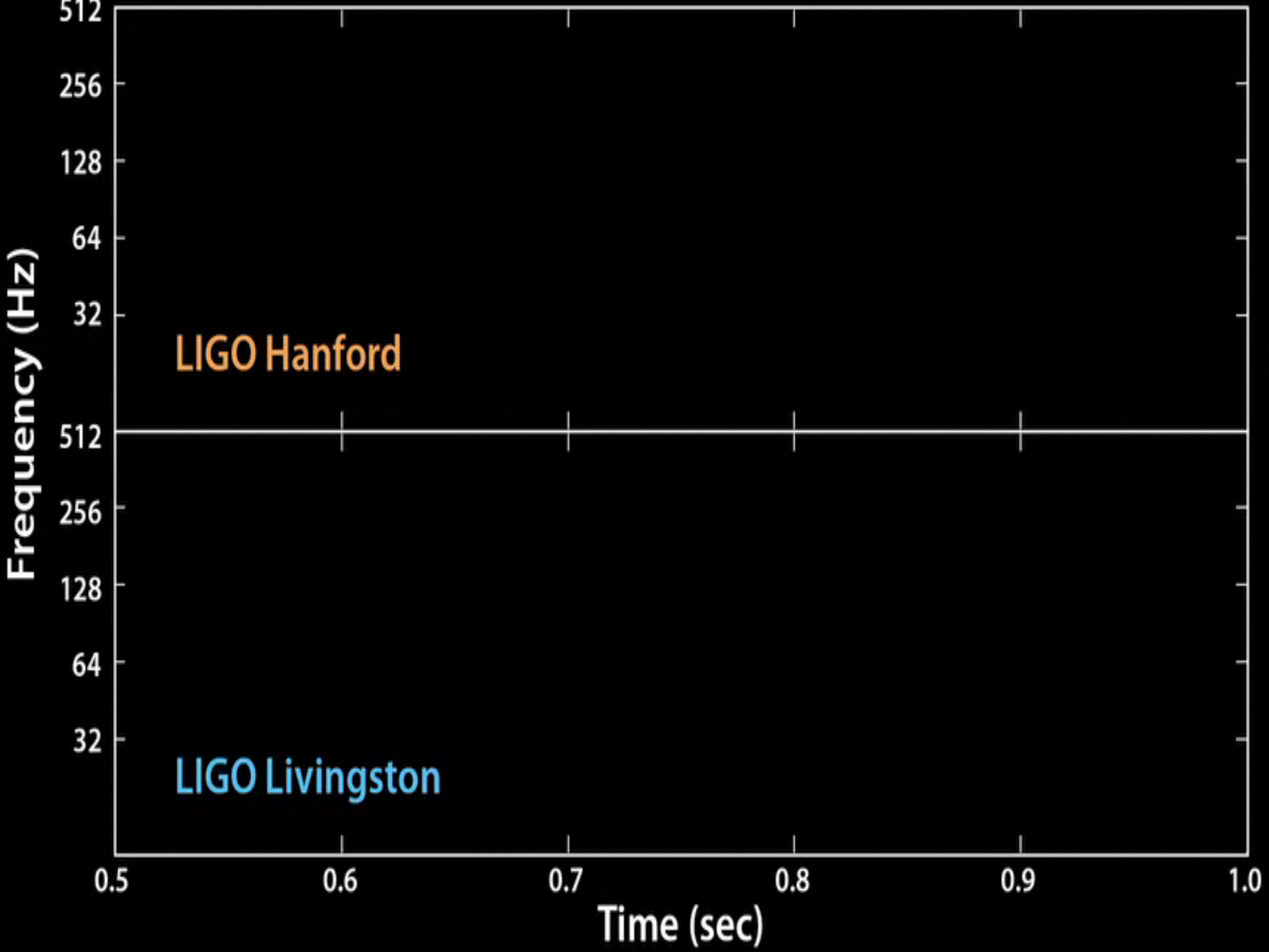
Real time-series data,
minus best fit GR waveform:
Shows only noise in residual.

Absolutely astonishing.



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


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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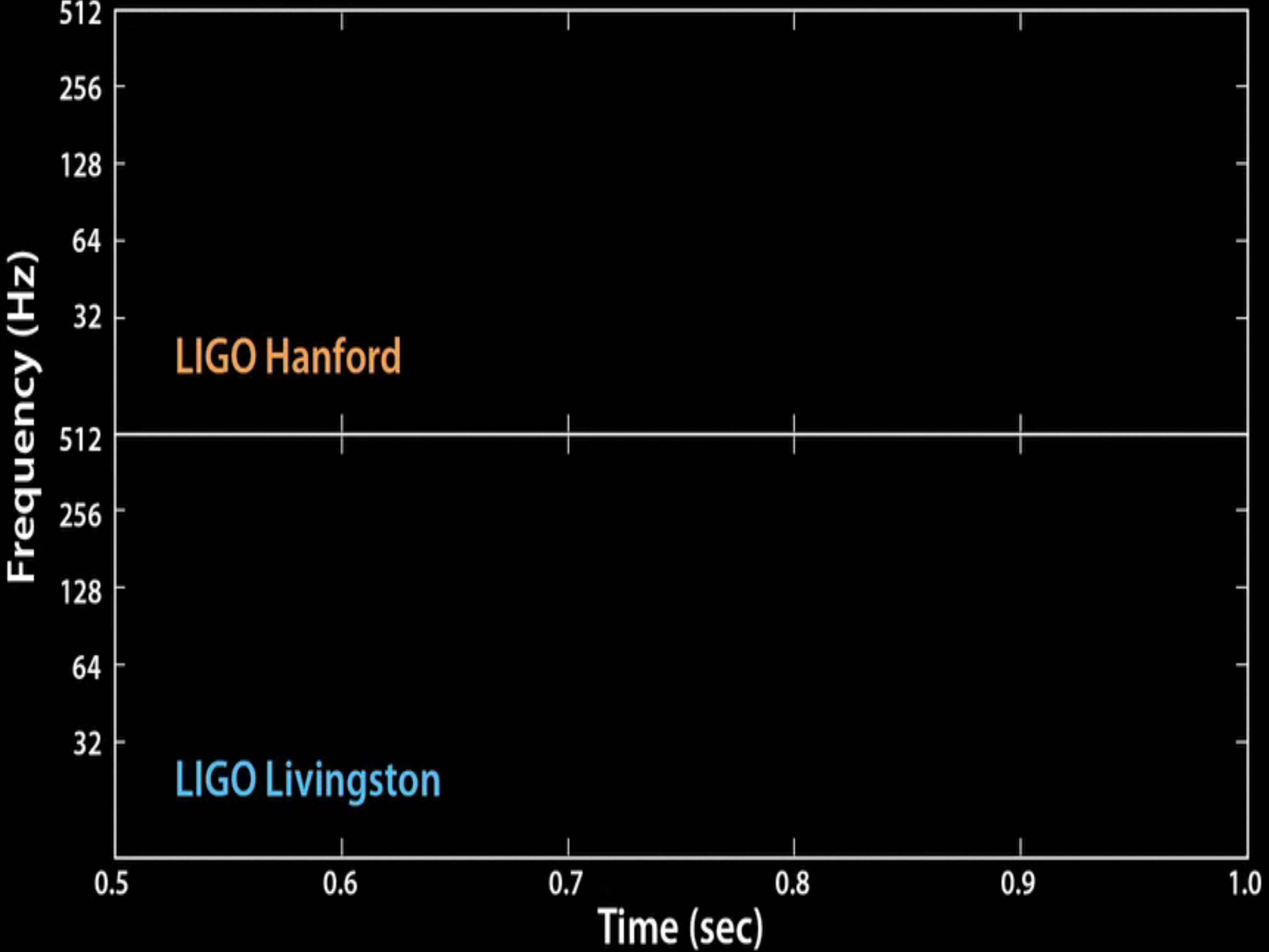
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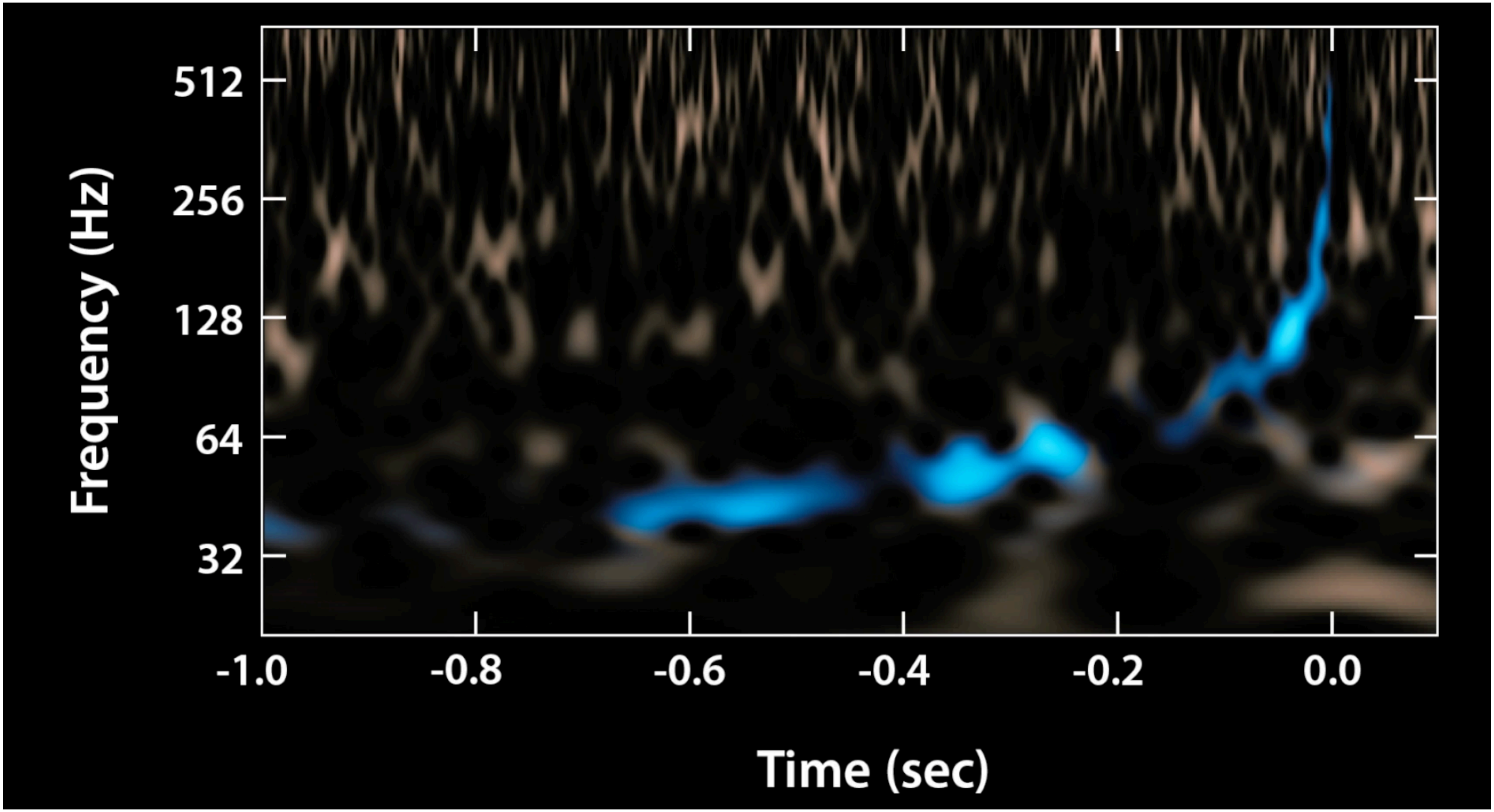
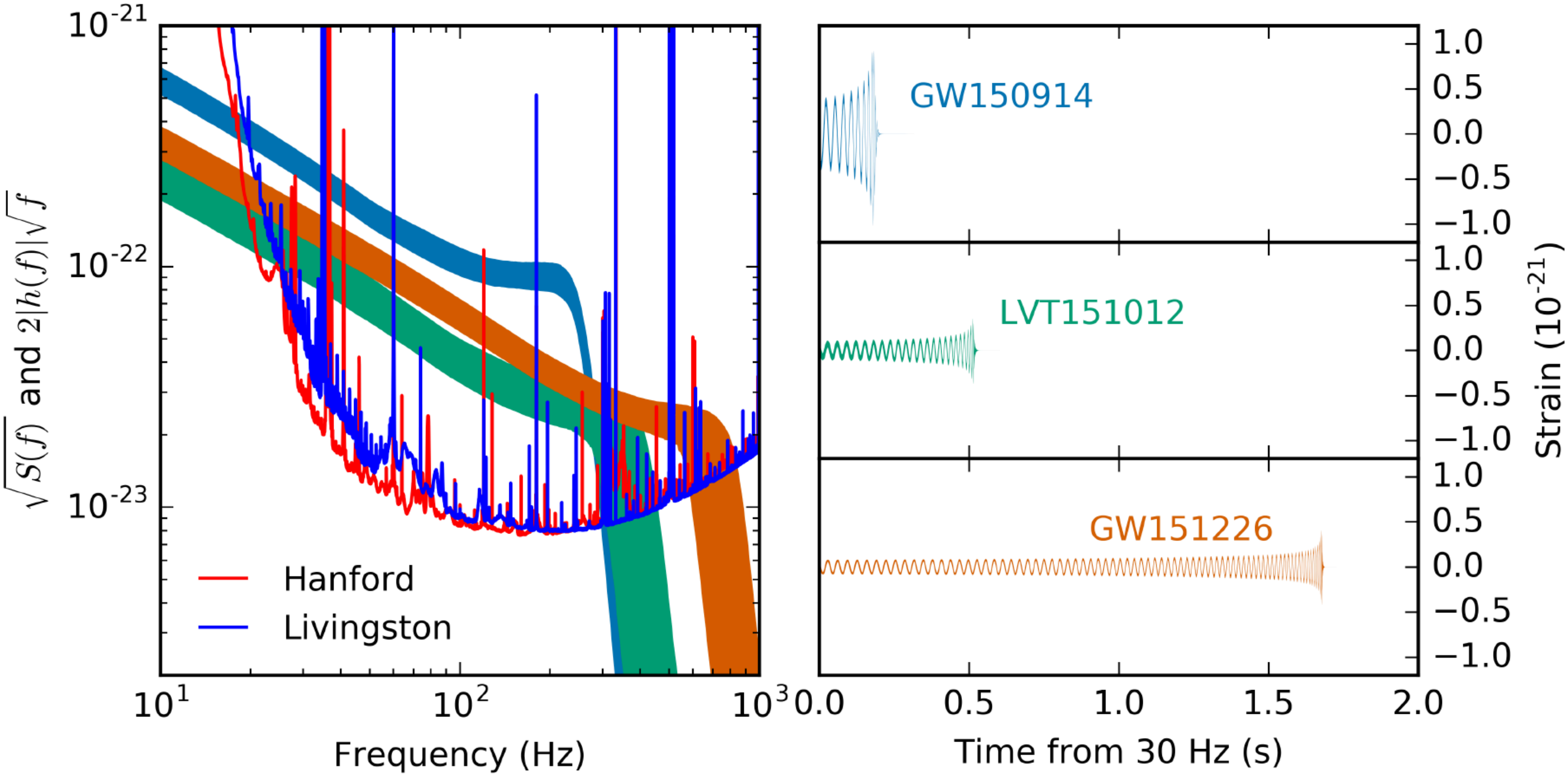
0.7
0.8
0.9
1.0
Time (sec)

One event…was it real?

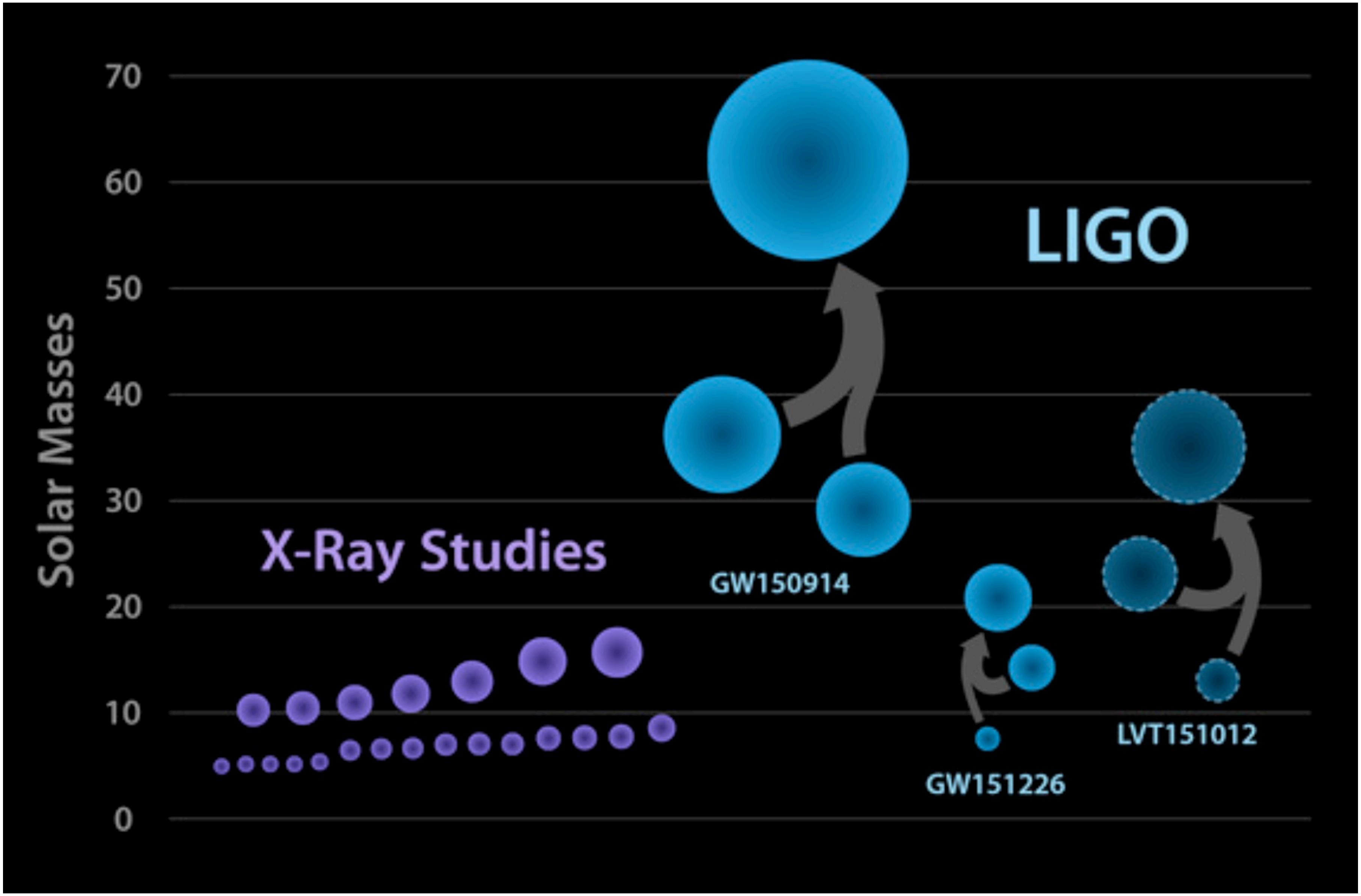
Our second signal, 26 December 2015 – the SNR we *thought* we would be working with



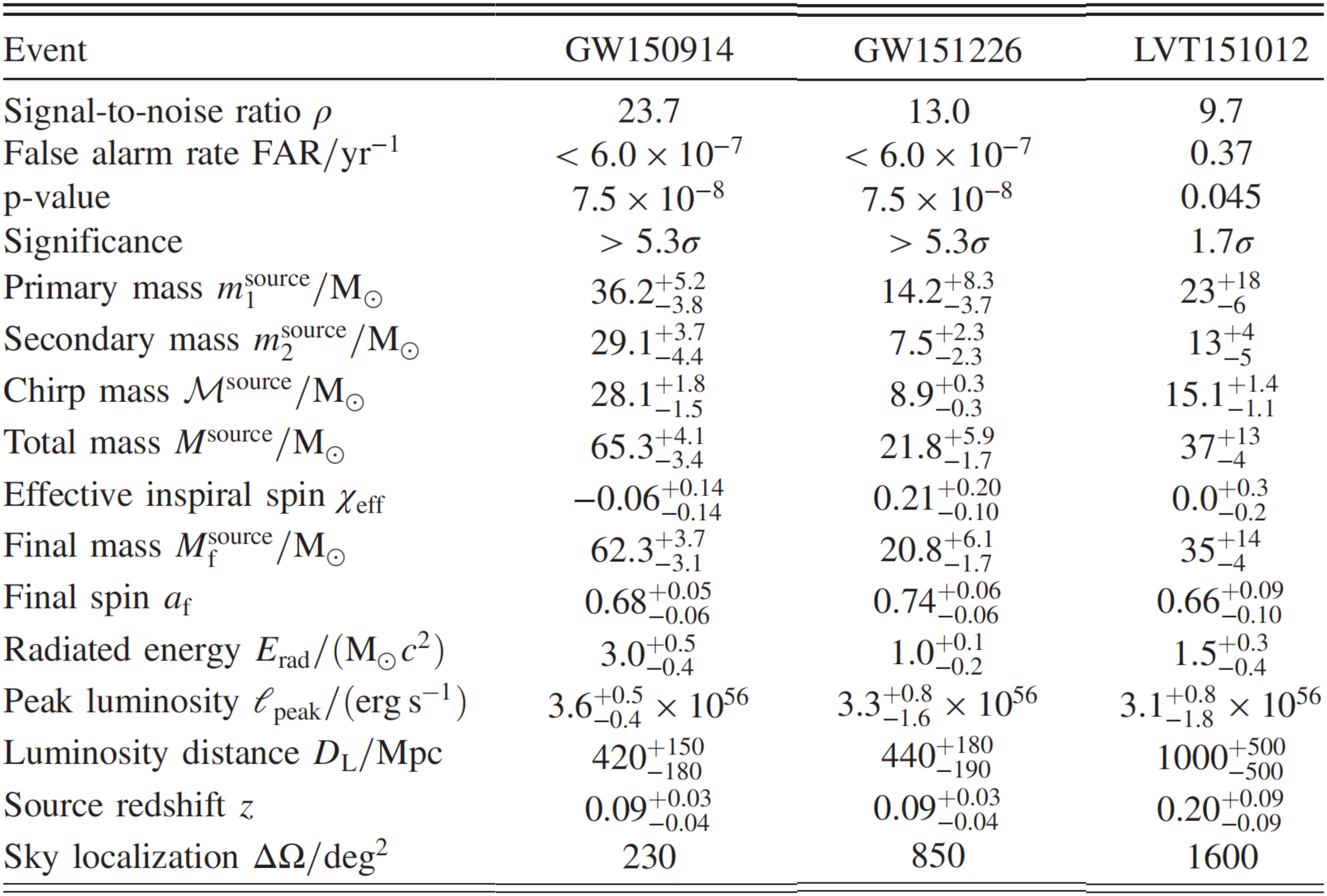
Our 2+1 signals to date



Black holes seen to date



Gravitational-wave astrophysics

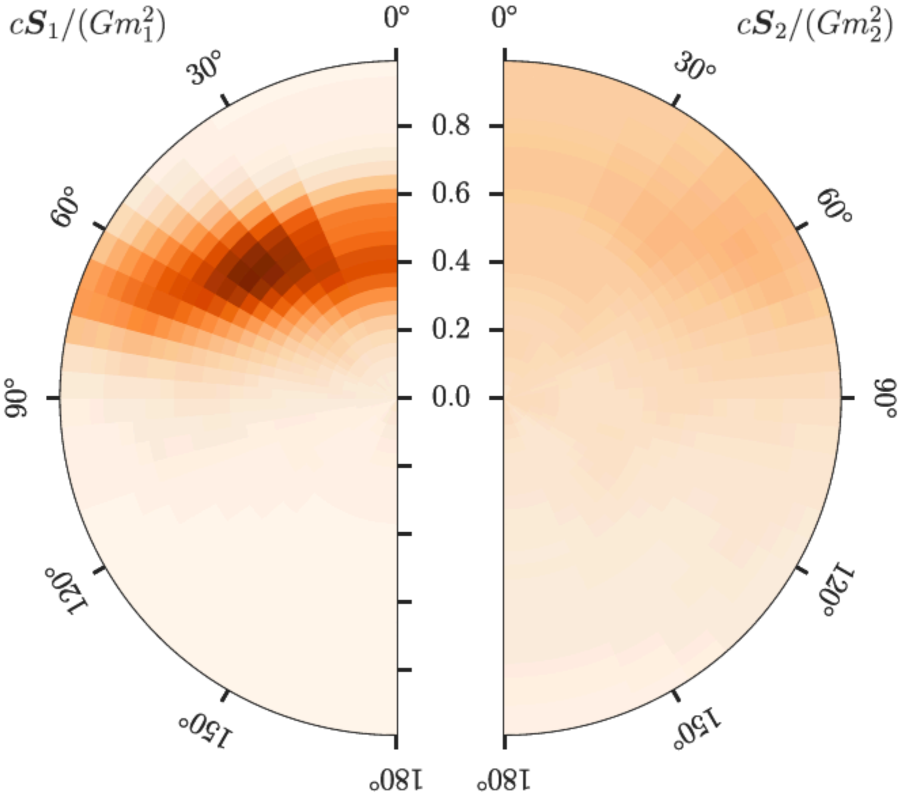


Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR}/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\mathrm{L}}/\mathrm{Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

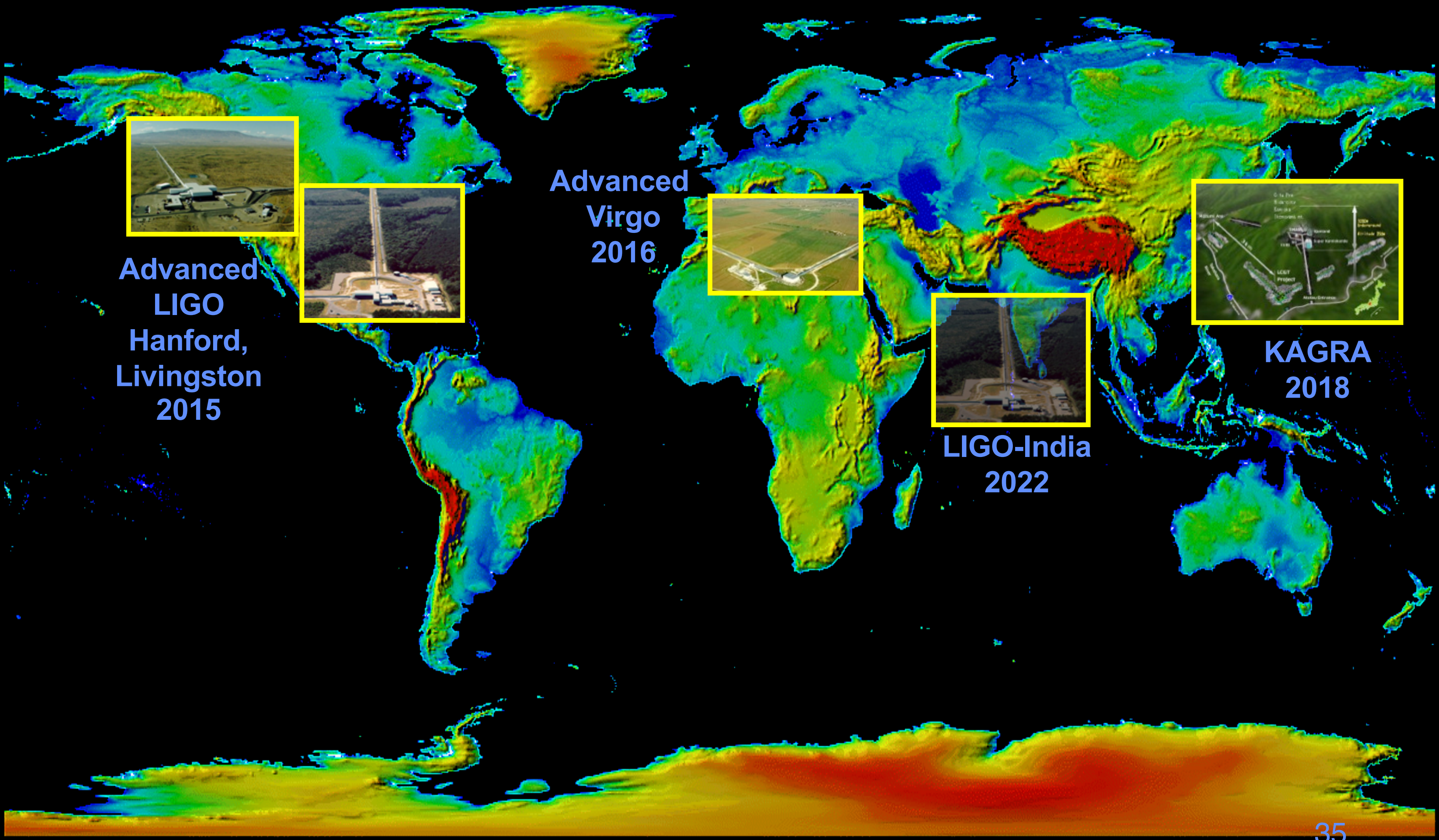
Spins of component BH

- Would like to make inferences about origins based on spin
- For all but one component BH, no statistical deviation from zero spin (face-on, so not a good measure)
- For one component of GW151226, spin of 0.2 – so probably not the result of a merger (→ primordial BH?)

- Plot of probability distribution of spin, BH#1 left, BH#2 right



The advanced GW detector network



Advanced LIGO
Hanford,
Livingston
2015

Advanced
Virgo
2016

LIGO-India
2022

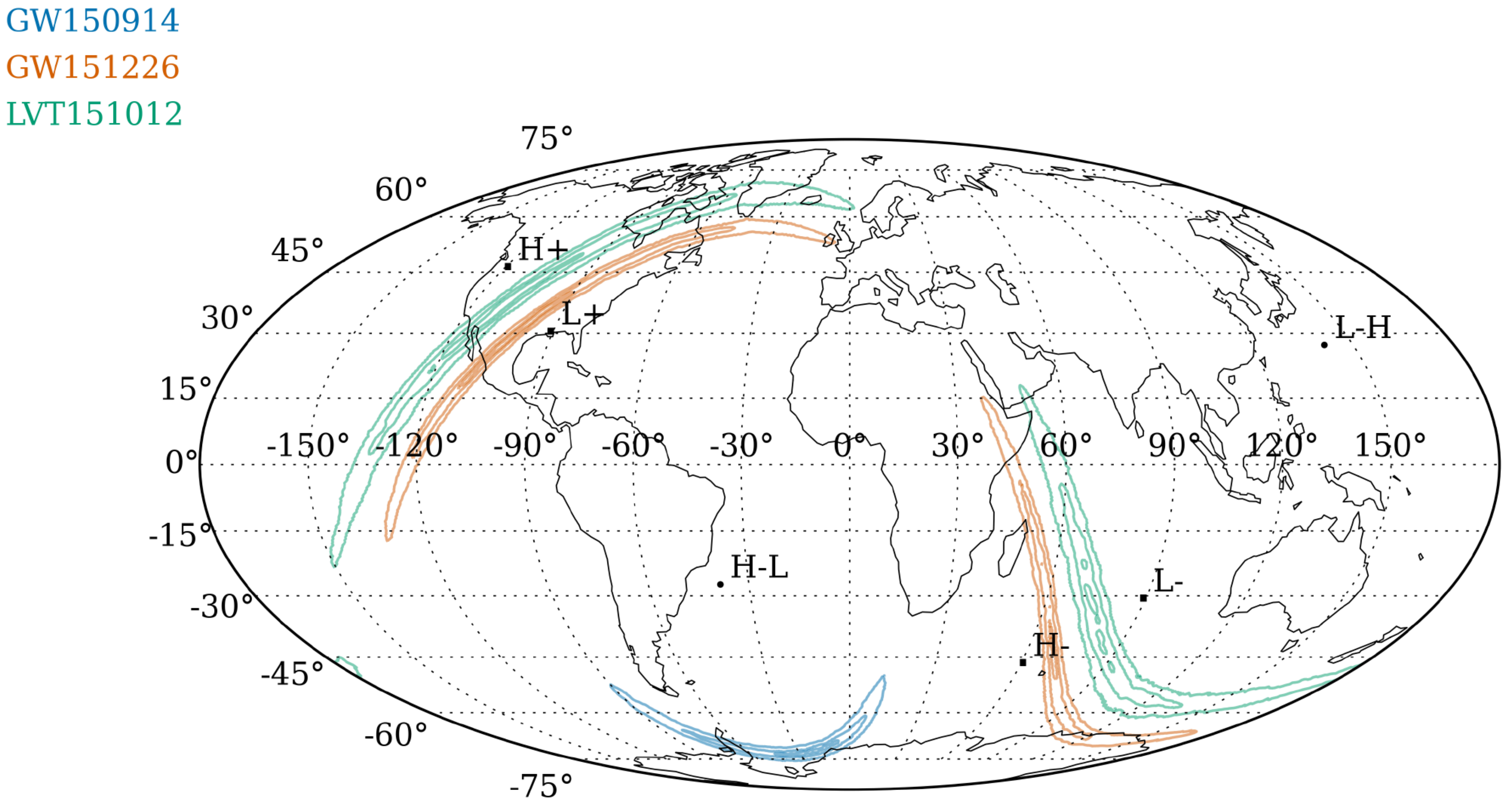
KAGRA
2018

What does the future hold?

LIGO First Detection Sensitivity/configuration:

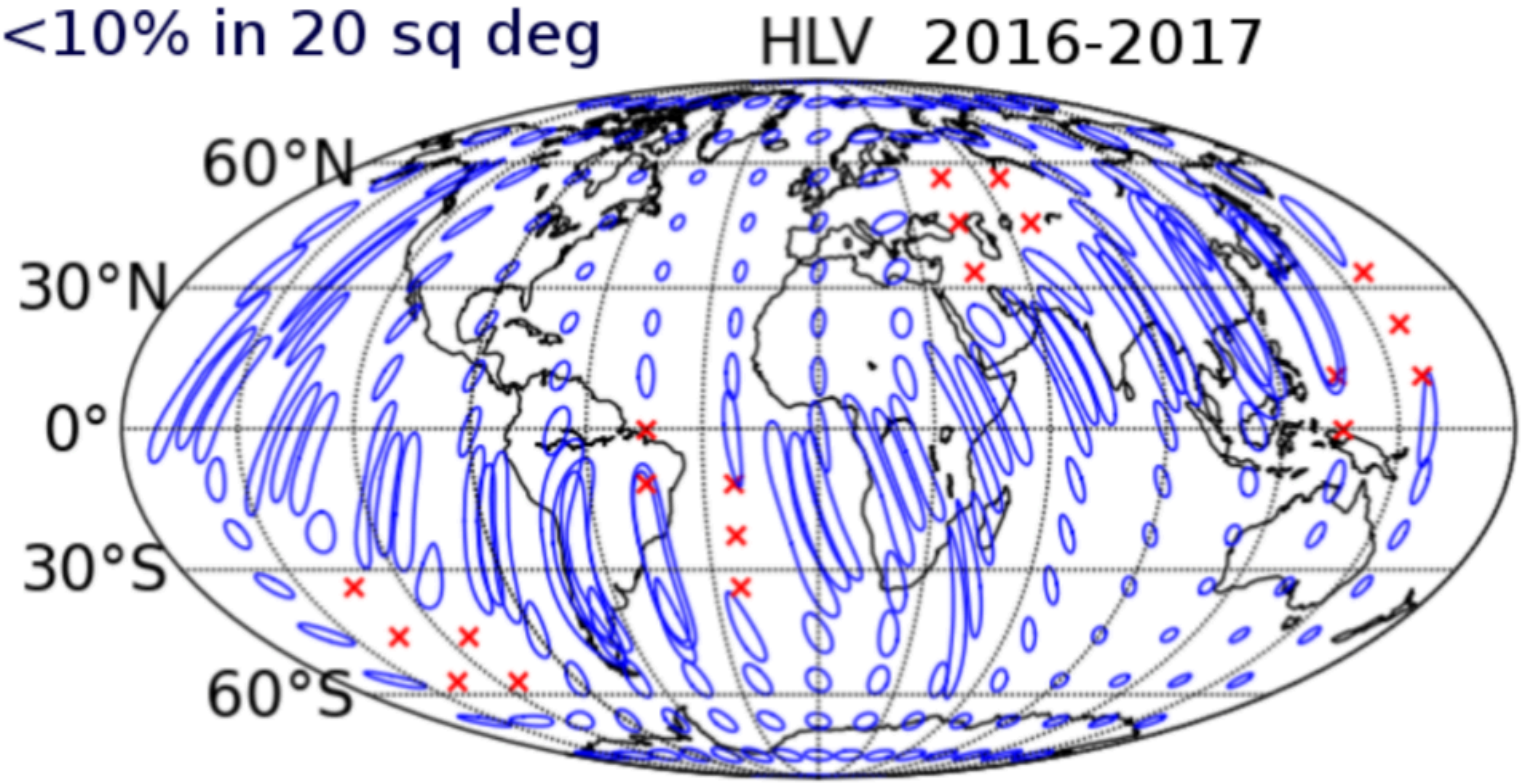
2 detectors, 1/3 goal sensitivity

~3 signals in 4 months of observation



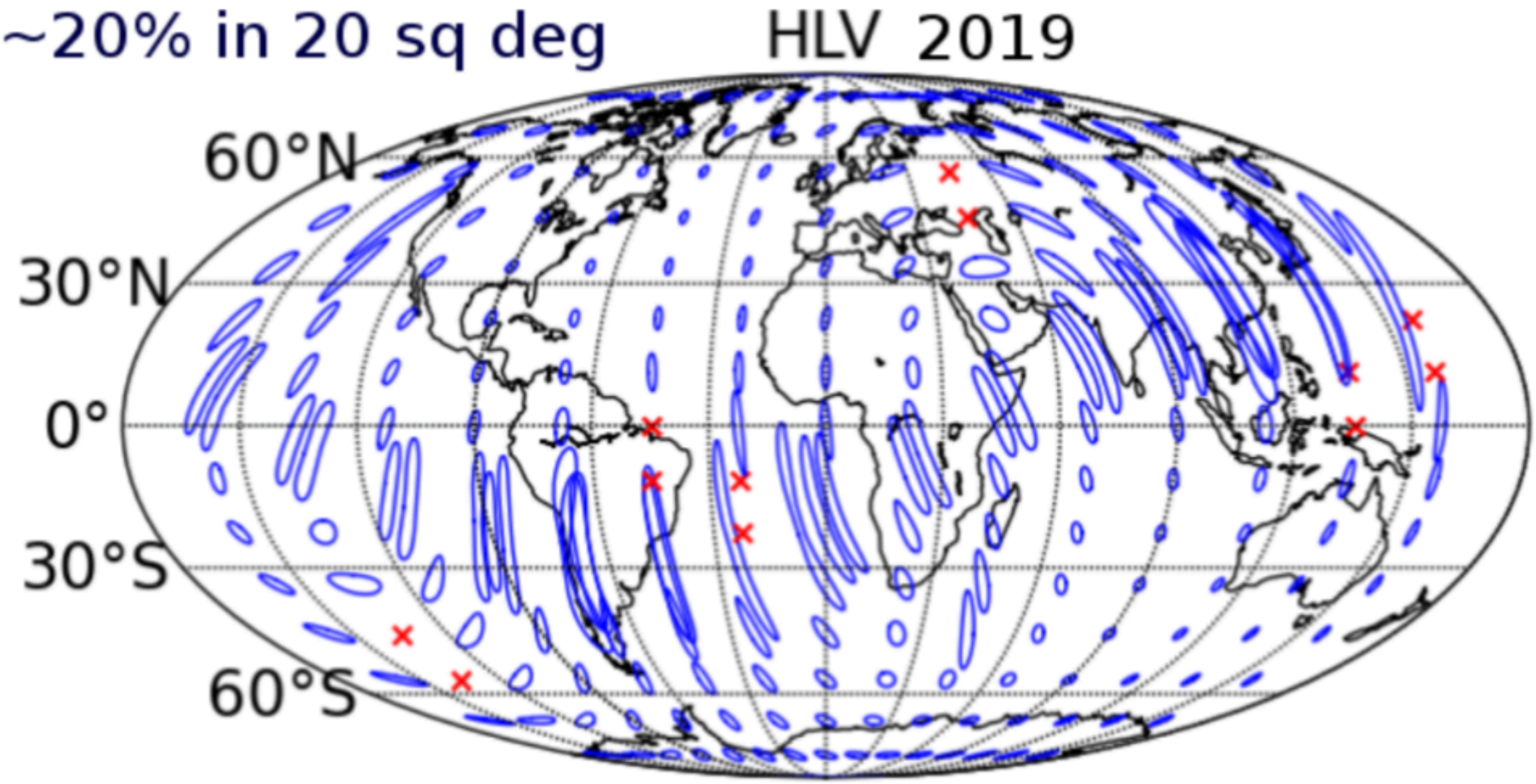
2017 Sensitivity/configuration:

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



2018-19 Sensitivity/configuration:

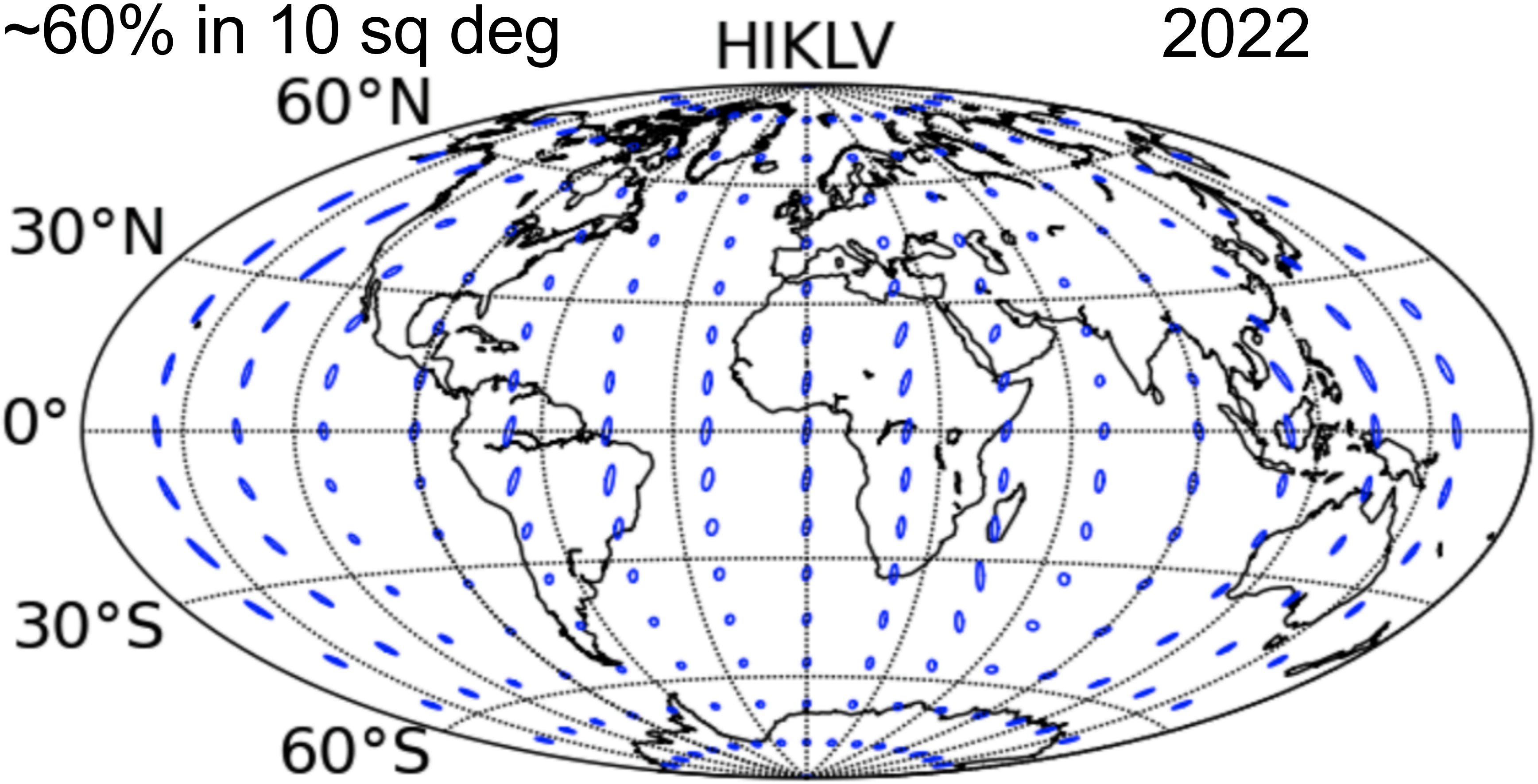
3 detectors, **full goal sensitivity**
~1 signal *per day*



2022 Sensitivity/configuration:

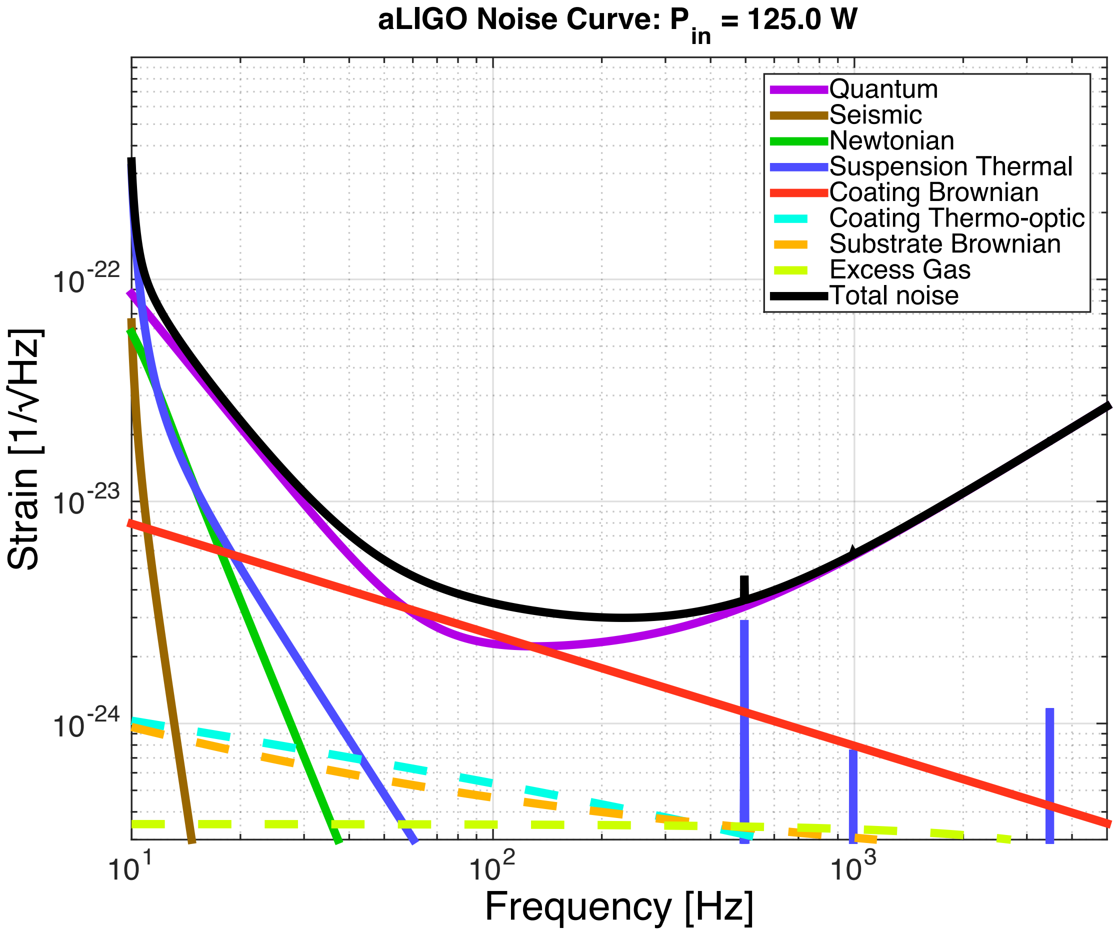
5 detectors (add India and Japan)
far improved source localization

~60% in 10 sq deg



aLIGO operating at full power

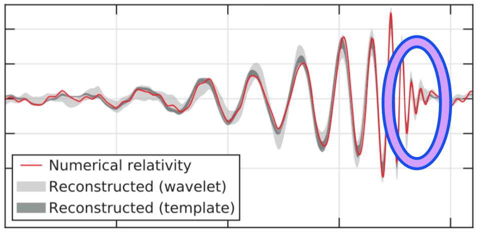
Planned for 2018-19



BNS reach: 191 Mpc

BBH reach: 1366 Mpc

QNM SNR ~21
(for an event like
GW150914)



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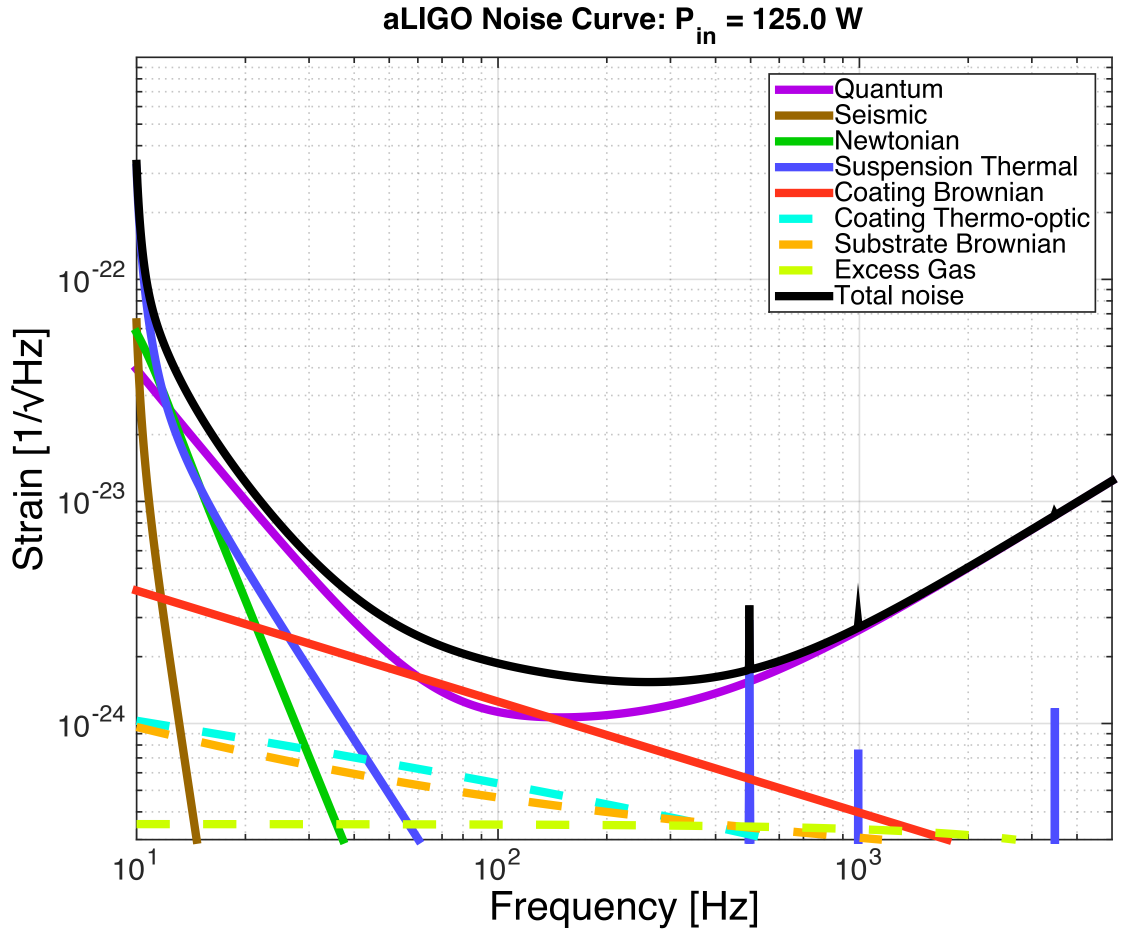
aLIGO with the addition of frequency-dependent squeezing and lowered optical coating thermal noise

Could be operating mid-2022

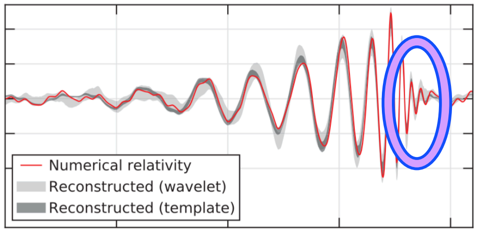


A+

BNS reach: 510 Mpc

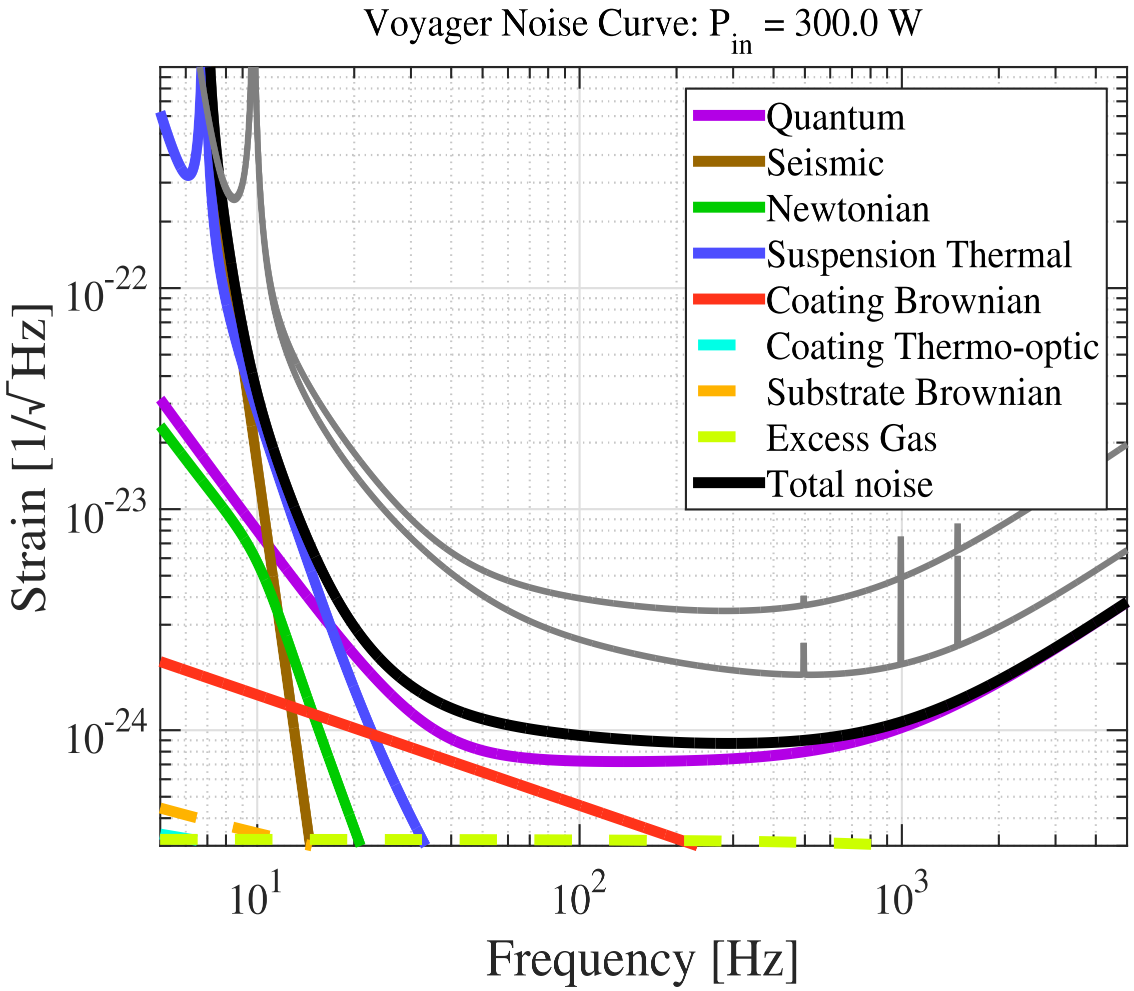
BBH reach: 3700 Mpc
(z = 1.1)

QNM SNR ~35
(for an event like
GW150914)



aLIGO with: Si optics, > 100 kg; Si or AlGaAs coatings; 'mildly' Cryogenic; λ~2 μm, 300 W

Could be operating late 2020's

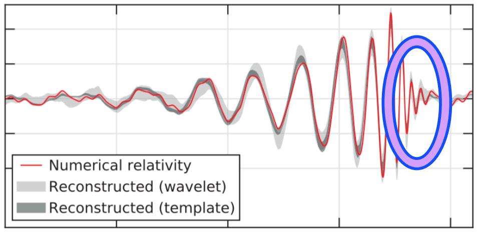

Voyager Noise Curve: P_{in} = 300.0 W

Voyager

BNS reach: 800 Mpc

BBH reach: z ~ 5

QNM SNR ~80 (for an event like GW150914)



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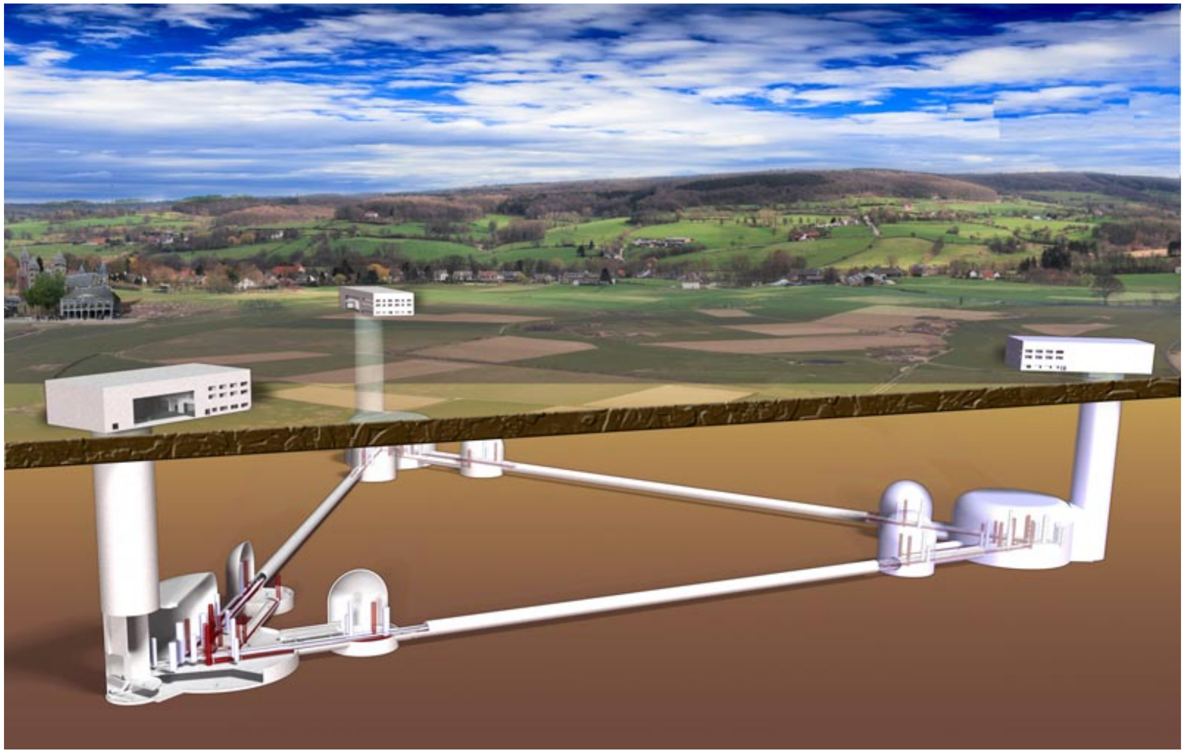
Further Future Improvements: The 3rd generation

- European Concept: Einstein Telescope
- Significant design study undertaken for both Facility and Instruments
- Underground construction proposed to reduce Newtonian Background
  - (and be compatible with densely-populated Europe)
- Triangle – LISA-like – with 10km arms
- Multiple instruments in a ‘Xylophone’ configuration
  - Allows technical challenges for low- and high-frequency to be separated
- Designed to accommodate a range of detector topologies and mechanical realizations
  - Including squeezing and cryogenics

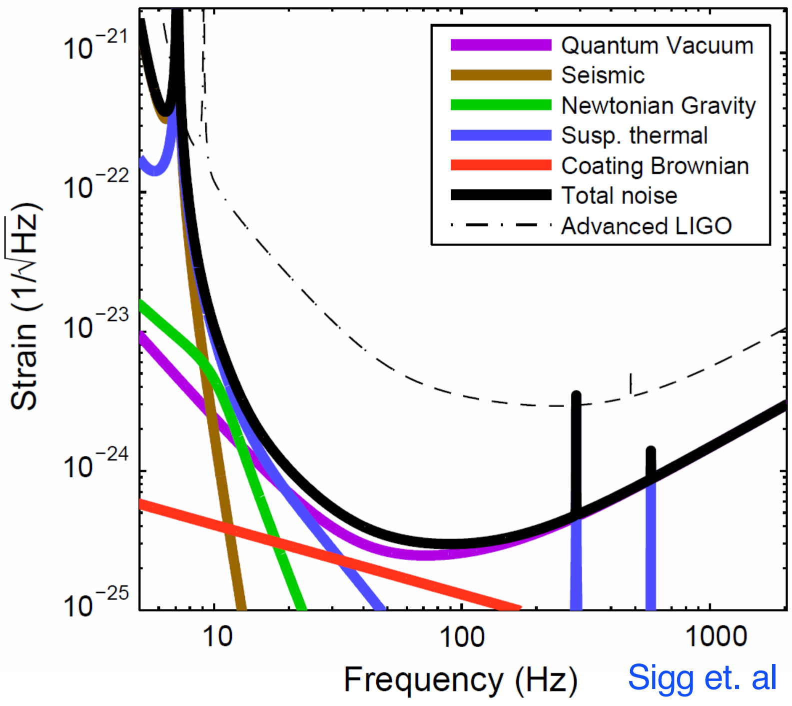


US Concept:
Make Advanced LIGO 10x longer,
10x more sensitive

Signal grows with length – ***not*** most noise sources

- Thermal noise, radiation pressure, seismic, Newtonian unchanged
- Coating thermal noise improves faster than linearly with length
- 40km surface Observatory ‘toy’ baseline
  - can still find sites, earthmoving feasible; costs another limit…
- Concept offers sensitivity without new measurement challenges; could start at room temperature, modest laser power, etc.

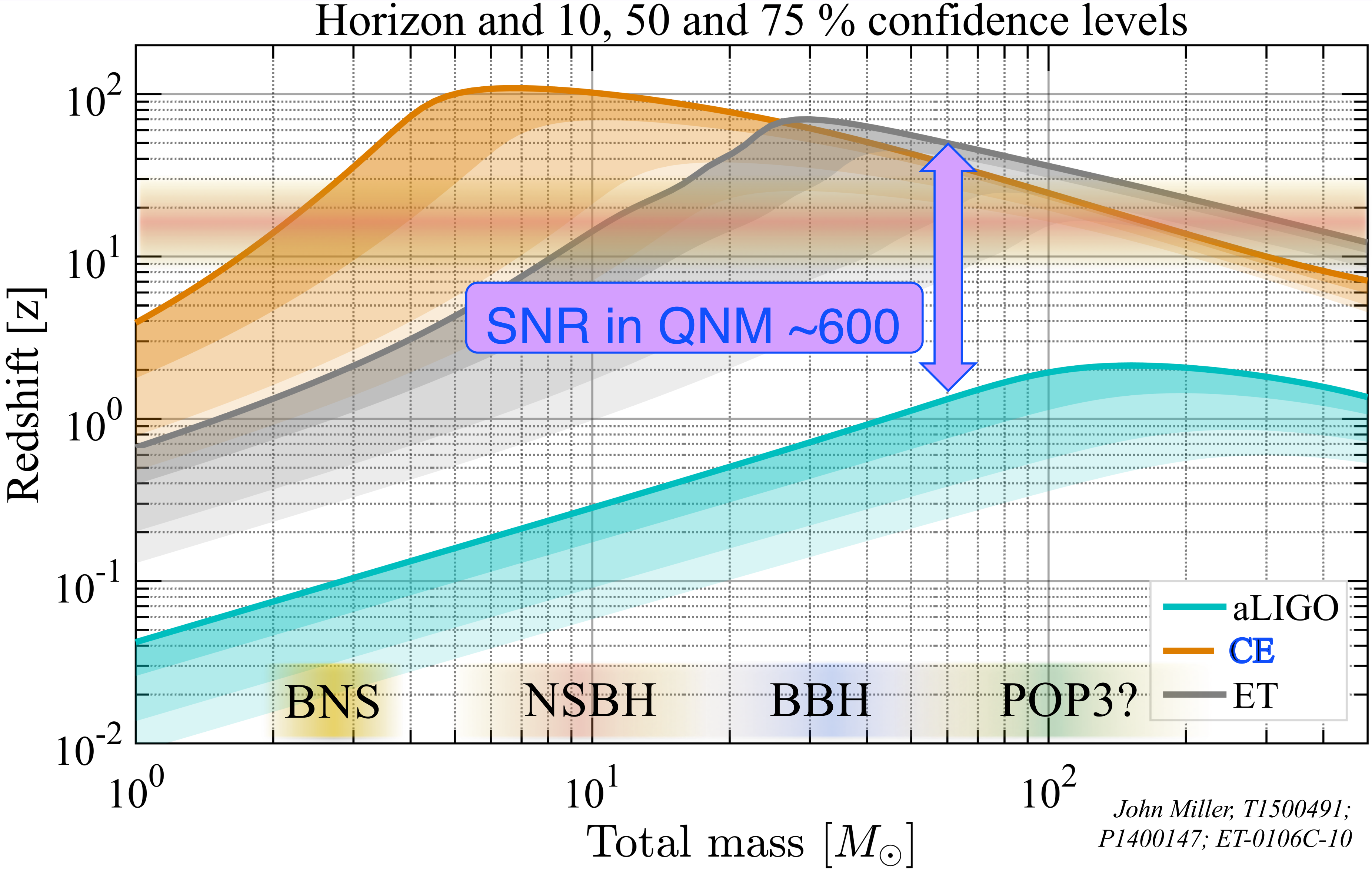
	Adv. LIGO	**40 km LIGO**
Arm length	4 km	40 km
Beam radius	6.2 cm	11.6 cm
Measured squeezing	none	5 dB
Filter cavity length	none	1 km
Suspension length	0.6 m	1 m
Signal recycling mirror trans.	20%	10%
Arm cavity circulating power	775 kW	
Arm cavity finesse	446	
Total light storage time	200 ms	2 s



Sigg et. al

Einstein Telescope, Cosmic Explorer

‘Green field’ multi-generation Observatories ~G$/G€



John Miller, T1500491; P1400147; ET-0106C-10

ZUCKER Sigg et. al

3rd Generation

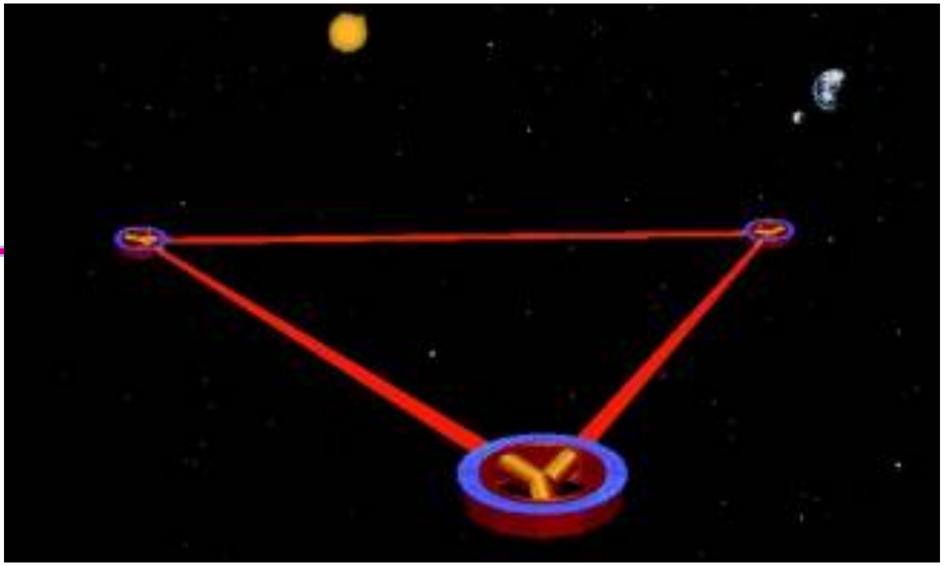
- When could this new wave of ground instruments come into play?
- Appears 15 years from *t*=0 is a feasible baseline
    - Initial LIGO: 1989 proposal, and at design sensitivity 2005
    - Advanced LIGO: 1999 White Paper, GW150914 in 2015
- Modulo funding, could envision…
    - **Einstein Telescope in the early 2030's**
    - **Cosmic Explorer in the mid-2030s**
- Should hope – and strive and plan – to have great instruments ready to 'catch' the end phase of binaries seen in LISA (ref. Sesana)

- **Crucial for all these endeavors: to expand the scientific community planning on exploiting these instruments far beyond the GR/GW enclave**
    - Costs are like TMT/GMT/ELT – needs a comparable audience

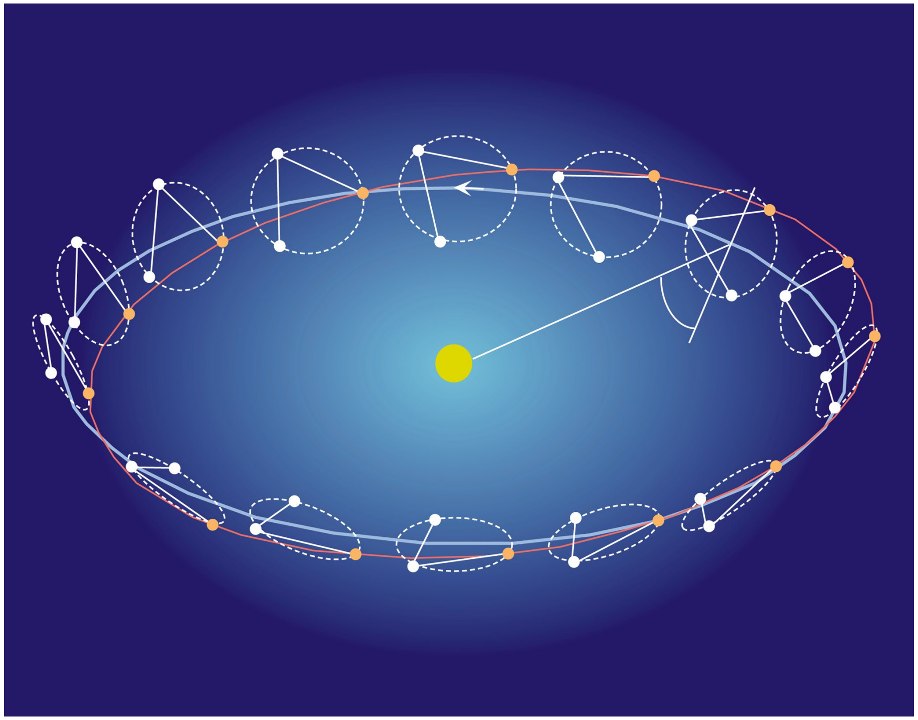
...and a detector in Space: **LISA**

- 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

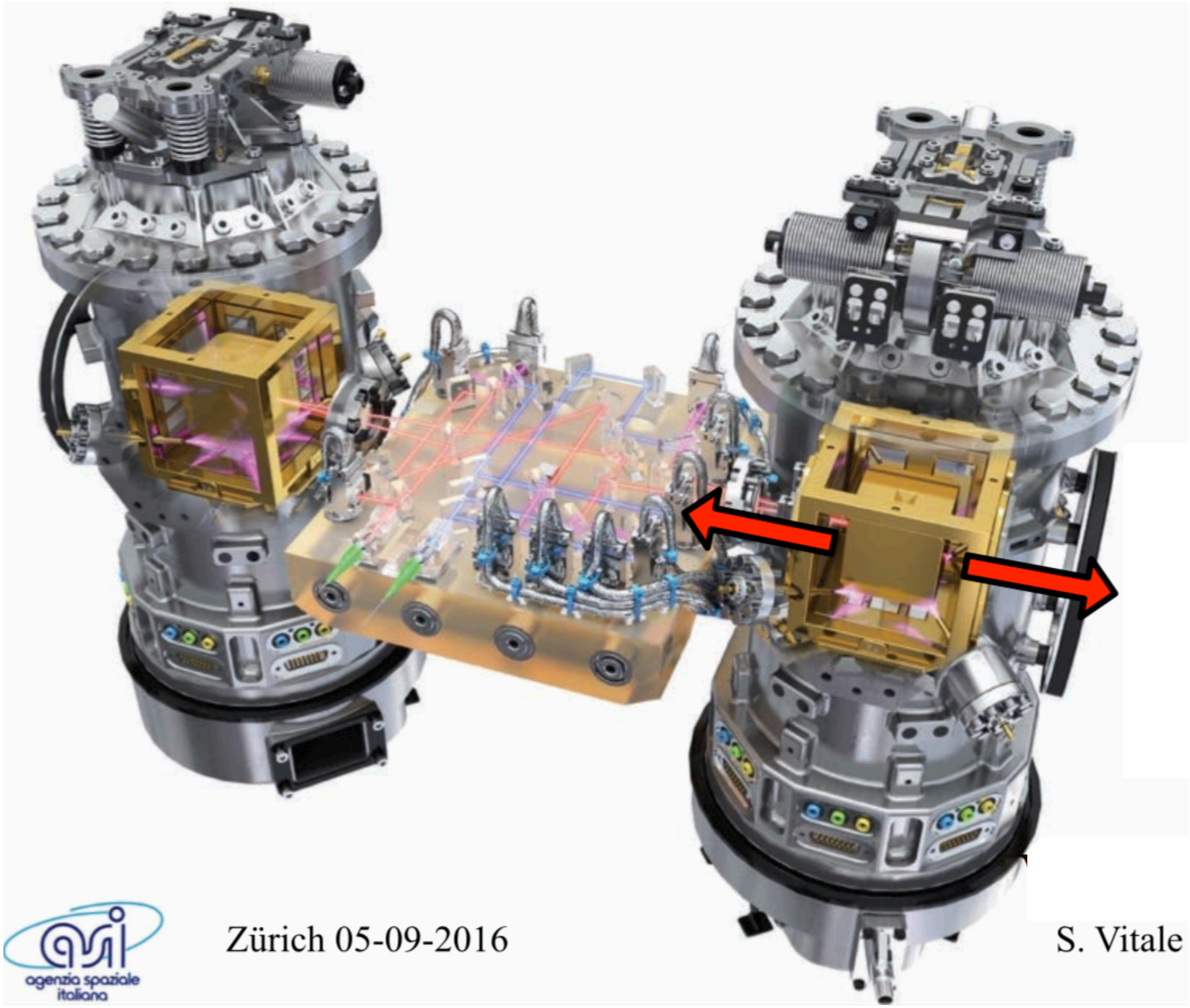
LISA



- Notion of a space-based interferometric detector dates from 1974
  - Rai Weiss and Peter Bender
- Basically a timing measurement between test masses in space
- Take advantage of vacuum in space: make very long arms
  - $h = \Delta L/L$; L can be $\sim 10^9$ m, making $\Delta L \sim 10^{-12}$ m (not LIGO's 10^{-19})
  - Also moves best sensitivity to milliHz region – explores much more massive objects
- Triangular configuration
- Sums and differences around the triangle
  - Allows both polarizations of the gravitational waves to be measured
  - Provides signals to remove laser frequency noise
- Earth-trailing orbit provides scan of the sky, provides sky localization

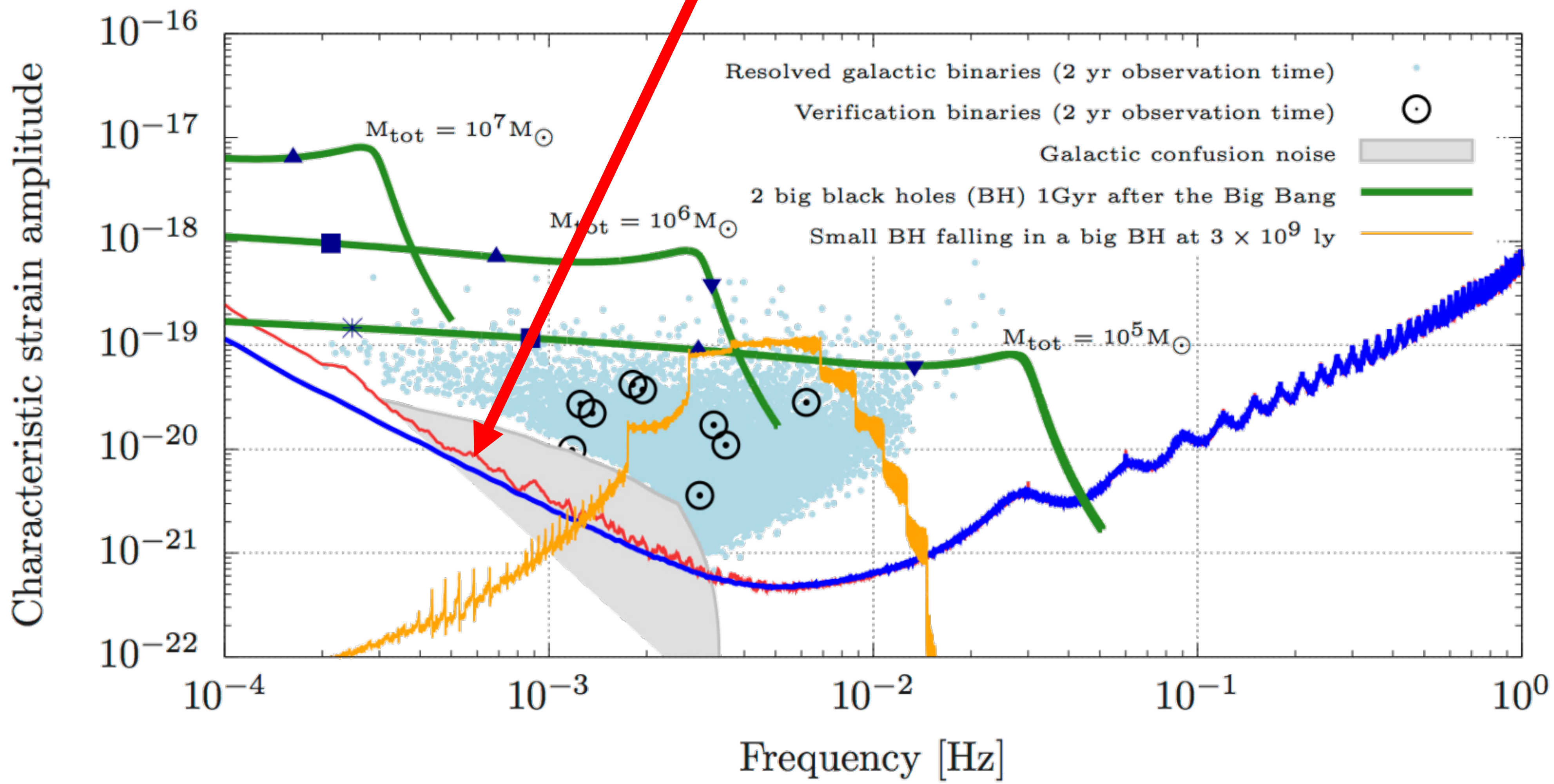


LISA Pathfinder test mission, now underway: interferometry between two LISA test masses


Zürich 05-09-2016

S. Vitale

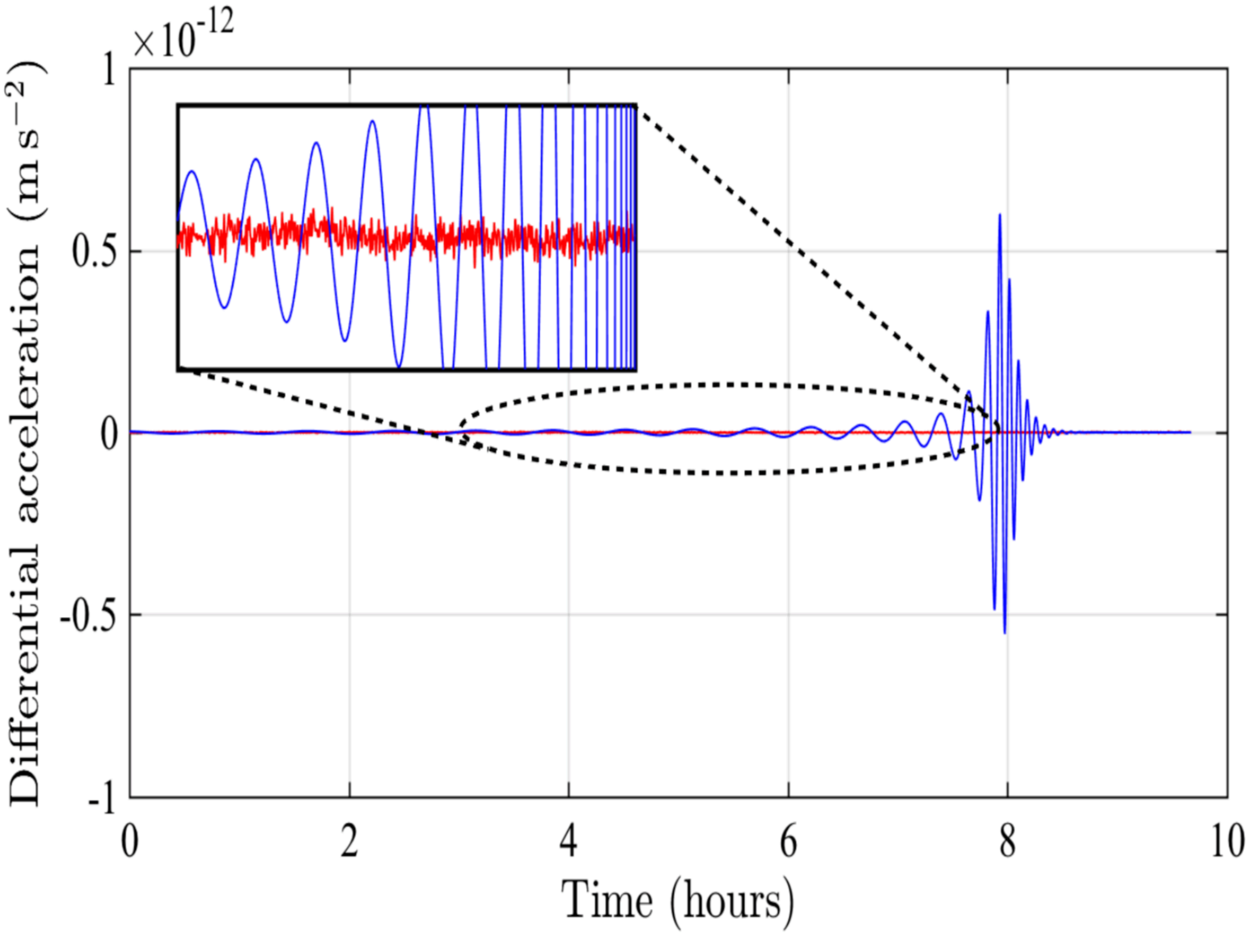
LISA Sensitivity, with current Pathfinder Performance



A. Petiteau 2016

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



Zürich 05-09-2016 S. Vitale

Blue: Simulated signal for inspiral of two 5×10^5 Black Holes inspiraling at z=5

Red: LISA Pathfinder interferometer performance