Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott, et al. (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. 116, 061102 (2016), arXiv: 1602.03837.

Alexander Beach, Bora Basa, Carina Baker, Shraddha Agrawal

December 7, 2018

ILLINOIS

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Geometrically, spacetime is the data $(M, g_{\mu\nu})$ with causal constraints (Lorentzian manifold). It is dynamical in the sense that $g_{\mu\nu}$ obeys the field equation

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathrm{Tr}_g R_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi T_{\mu\nu},$$

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  - The solutions of Einstein's equations correspond to the possible configurations of the Universe at large length scales.

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- A small metric perturbation is a gravitational wave that propagates at the speed of light!
  - It is generated by accelerating mass just as an electromagnetic vector potential is generated by accelerating charge.

[Tiec and Novak, 2017]

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  - Predicted by Einstein in 1916, **but** the amplitude is so small that *"detecting them is like measuring the distance to a star ten light-years away with a precision equivalent to the diameter of a strand of hair"*

    -Royal Swedish Academy of Sciences

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  - In the 1970's proposals for laser based interferometers were drafted
    - In the late 90's the first sets of interferometers were built, including TAMA 300, GEO 600, LIGO, and Virgo

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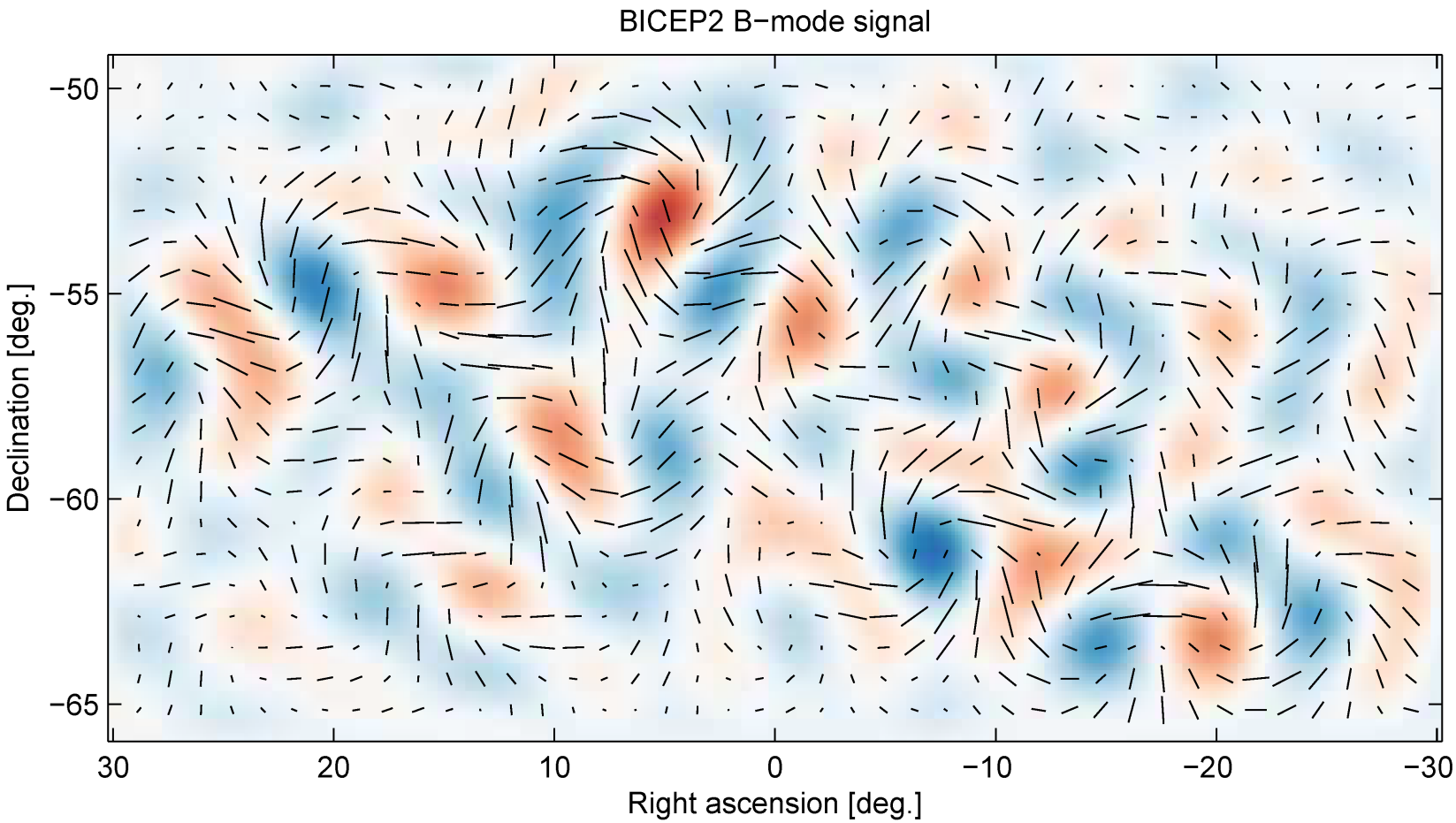
    - Ratio of observed to predicted orbital decay rate considering energy lost to gravitational waves is 0.997 ± 0.002

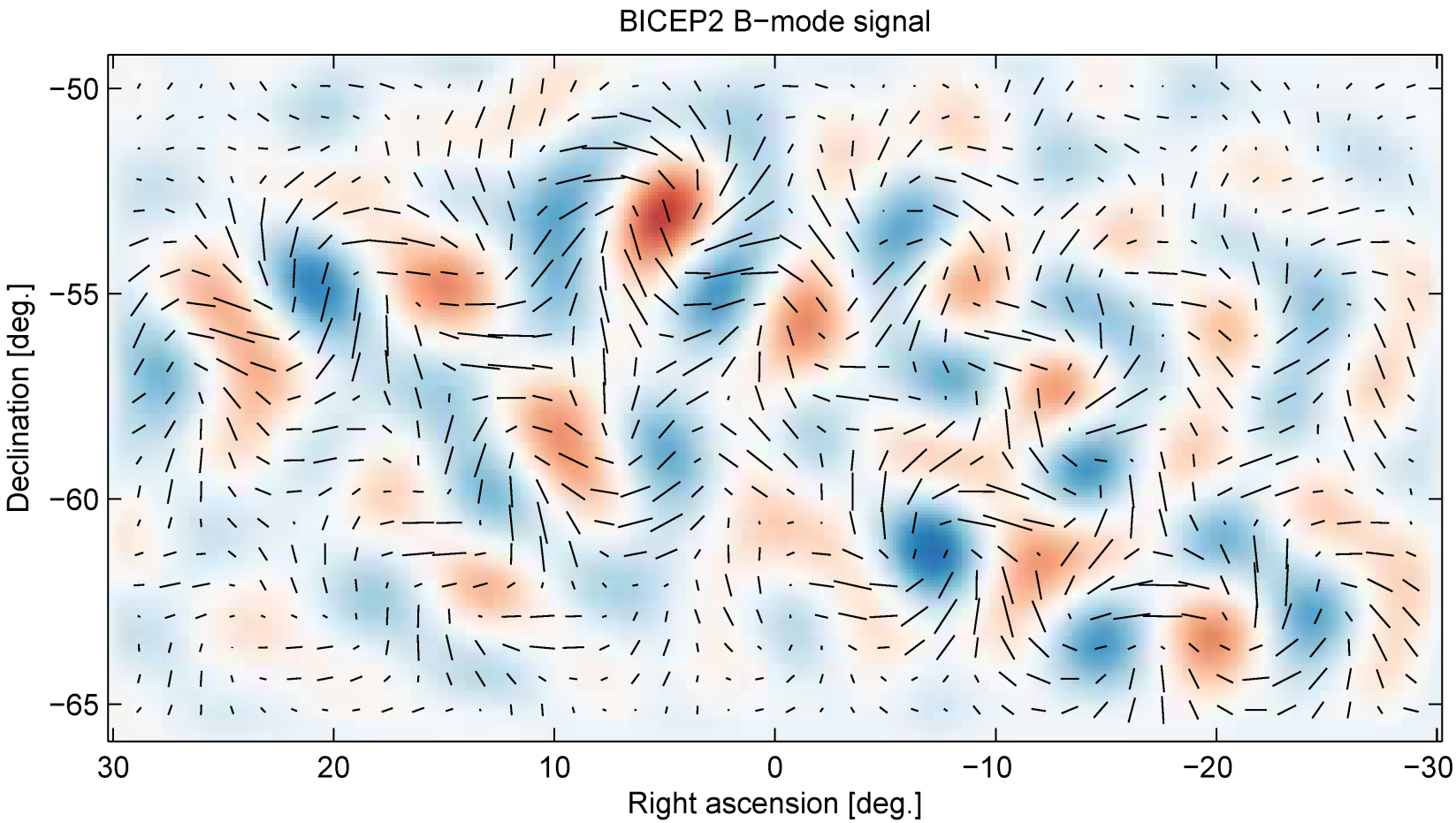
      [Weisberg et al., 2010]
    - In 2016 this was updated to 0.9983 ± 0.0016

      [Weisberg and Huang, 2016]

- BICEP2 – Gravitational Waves?
  - March 2014, BICEP 2 reported detection of B-mode primordial gravitational waves



- BICEP2 – Gravitational Waves?
  - It was just cosmic dust



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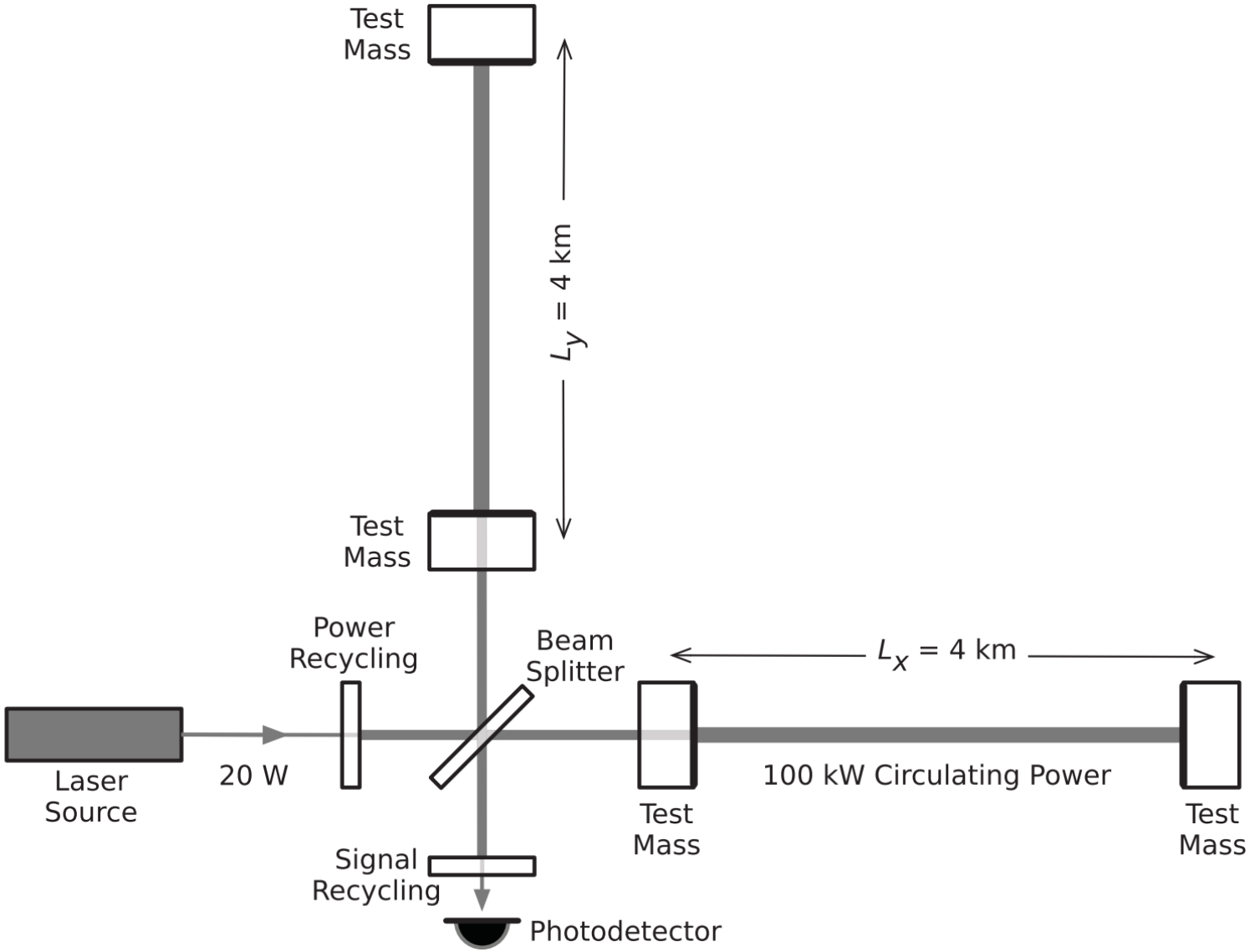
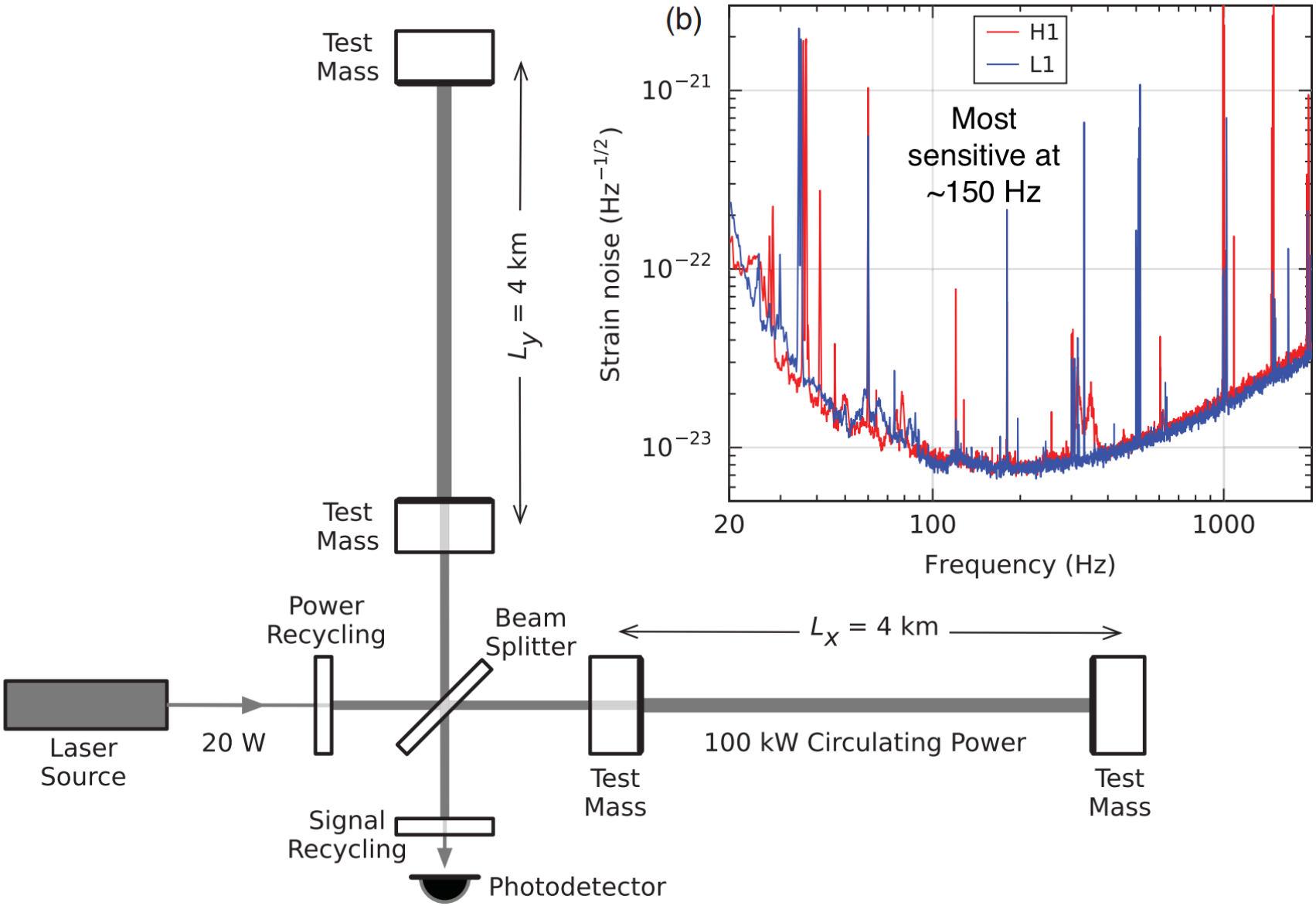
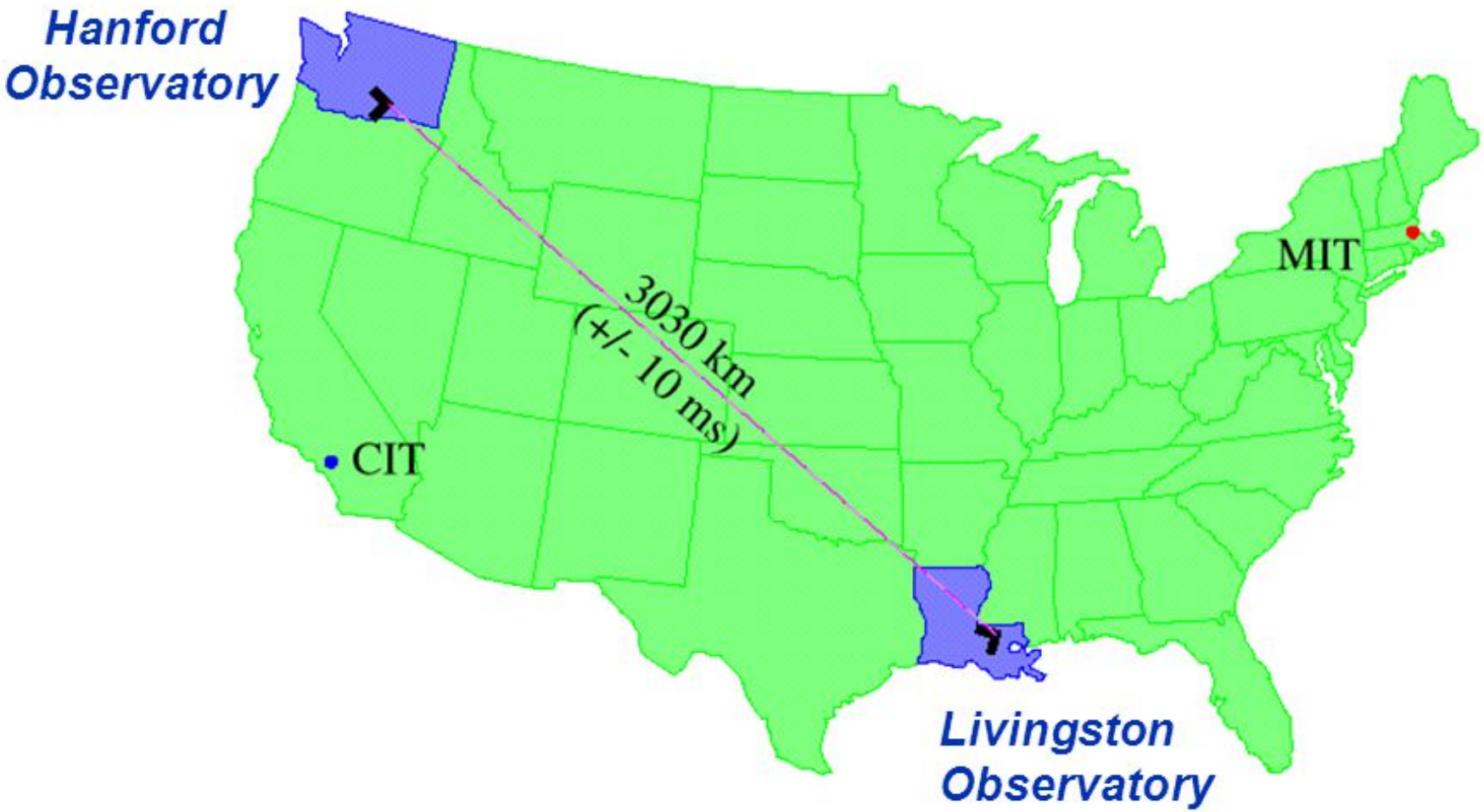

Test
Mass
L_y = 4 km
Test
Mass
Power
Recycling
Beam
Splitter
L_x = 4 km
Laser
Source
20 W
100 kW Circulating Power
Test
Mass
Test
Mass
Signal
Recycling
Photodetector

Sensitivity of Detector

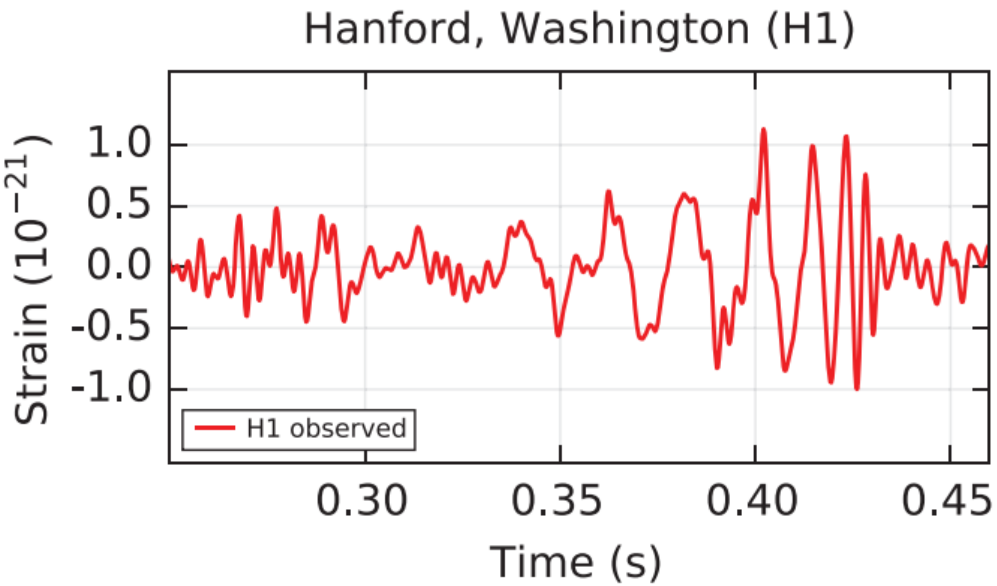



Hanford
Observatory
MIT
3030 km
(+/- 10 ms)
CIT
Livingston
Observatory

L1
Livingston, LA

H1
Hanford, WA

- September 14, 2015 Advanced LIGO detected a gravitational wave event



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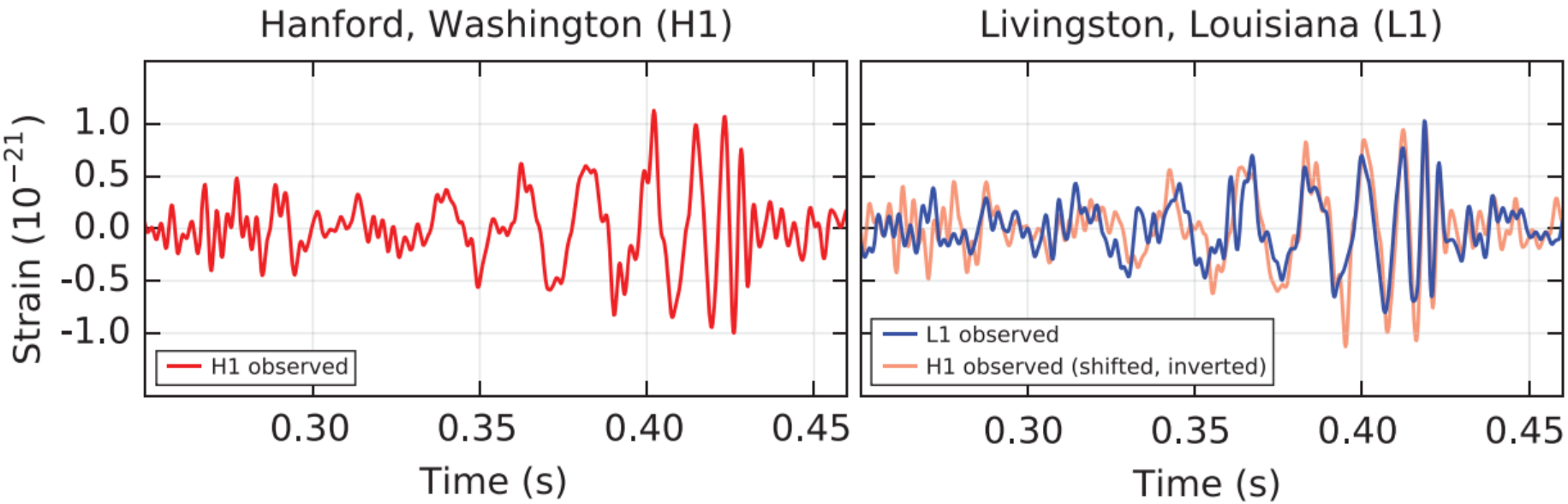

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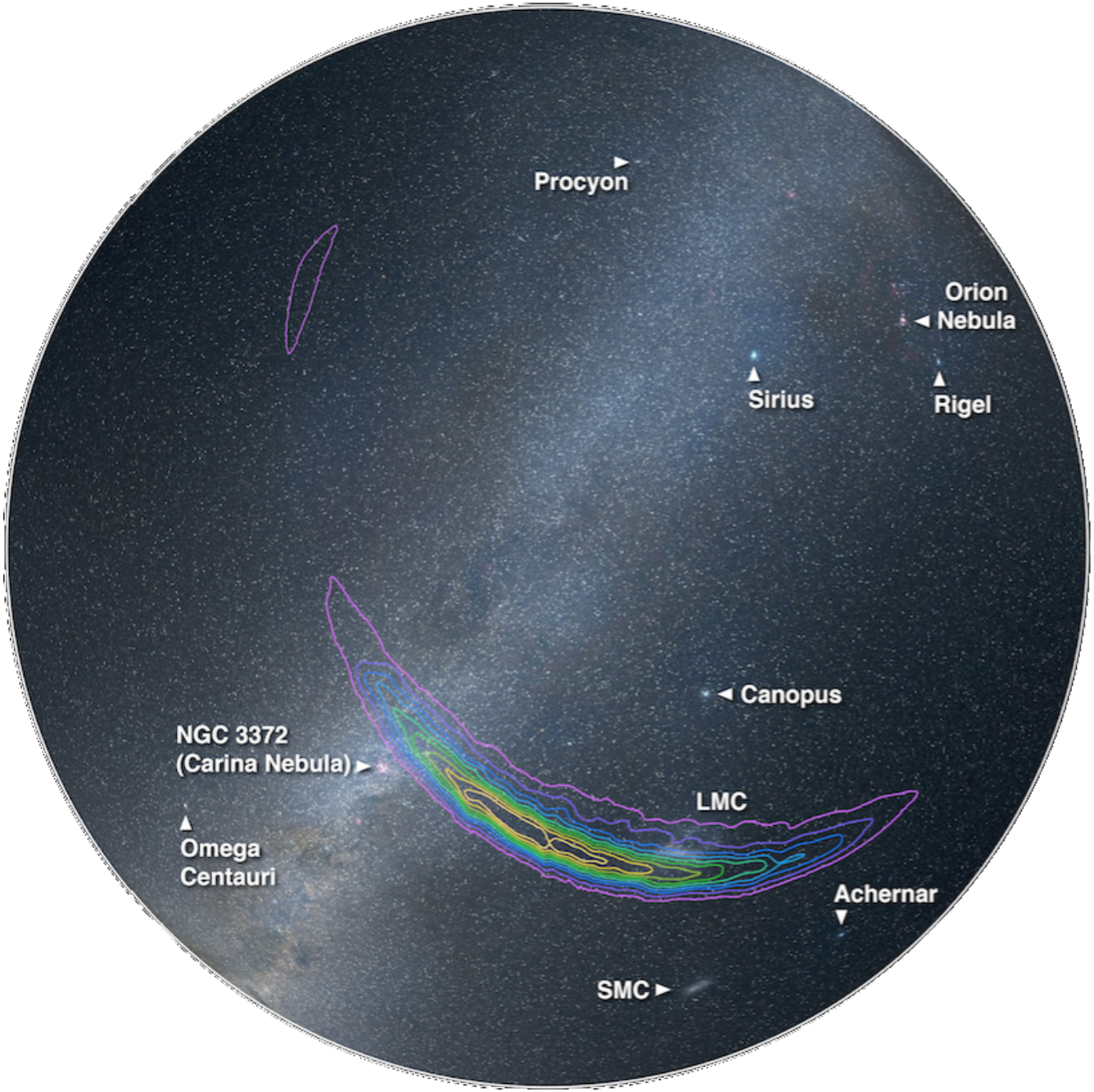
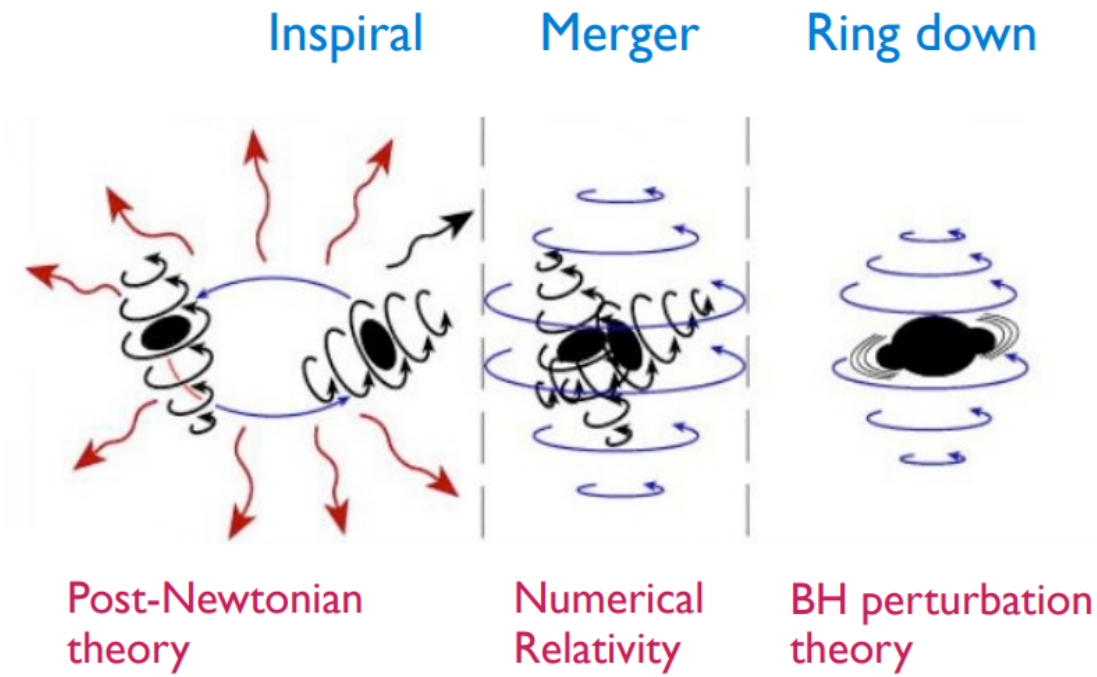

Procyon
Orion
Nebula
Sirius
Rigel
Canopus
NGC 3372
(Carina Nebula)
LMC
Omega
Centauri
Achernar
SMC

- Collision Parameters
  - Redshift of 0.09
  - Primary black hole mass 36 $M_\odot$
    - Spin 0.32
  - Secondary black hole mass of 29 $M_\odot$
    - Spin 0.44
  - Final black hole mass of 62 $M_\odot$
    - Spin 0.67

- Collision Waveform
  - Model merger event using combination of analytic and numerical techniques



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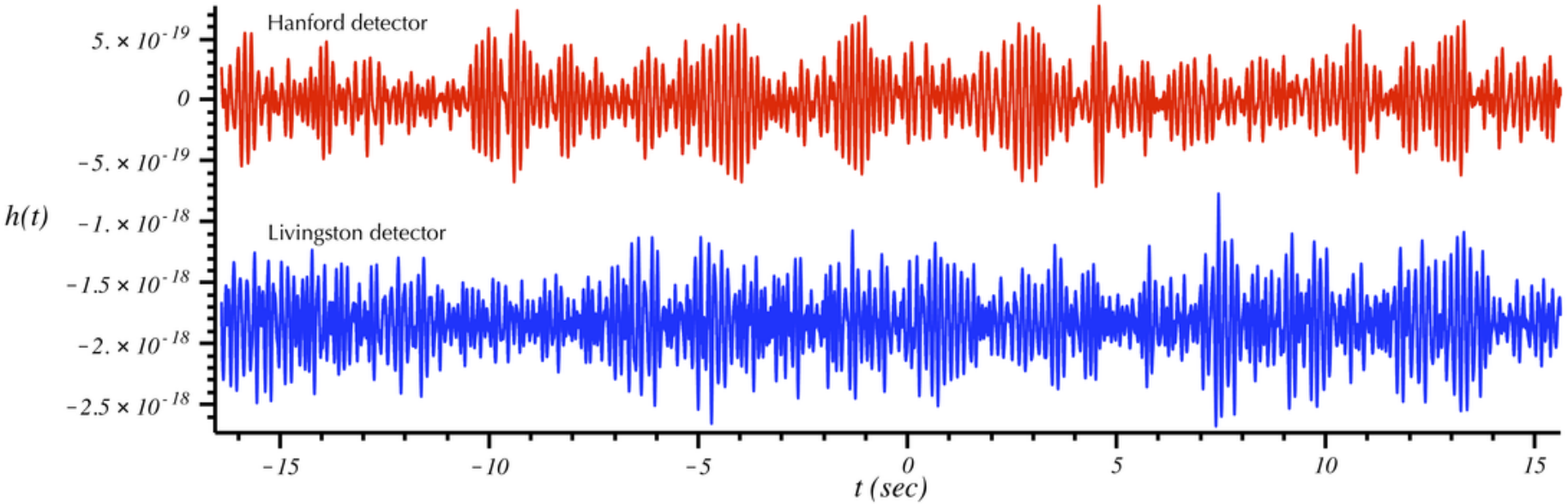
  - How do they know *this* was 2 black holes?



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  - For remaining signals, the background is re-estimated without the contribution of the signal

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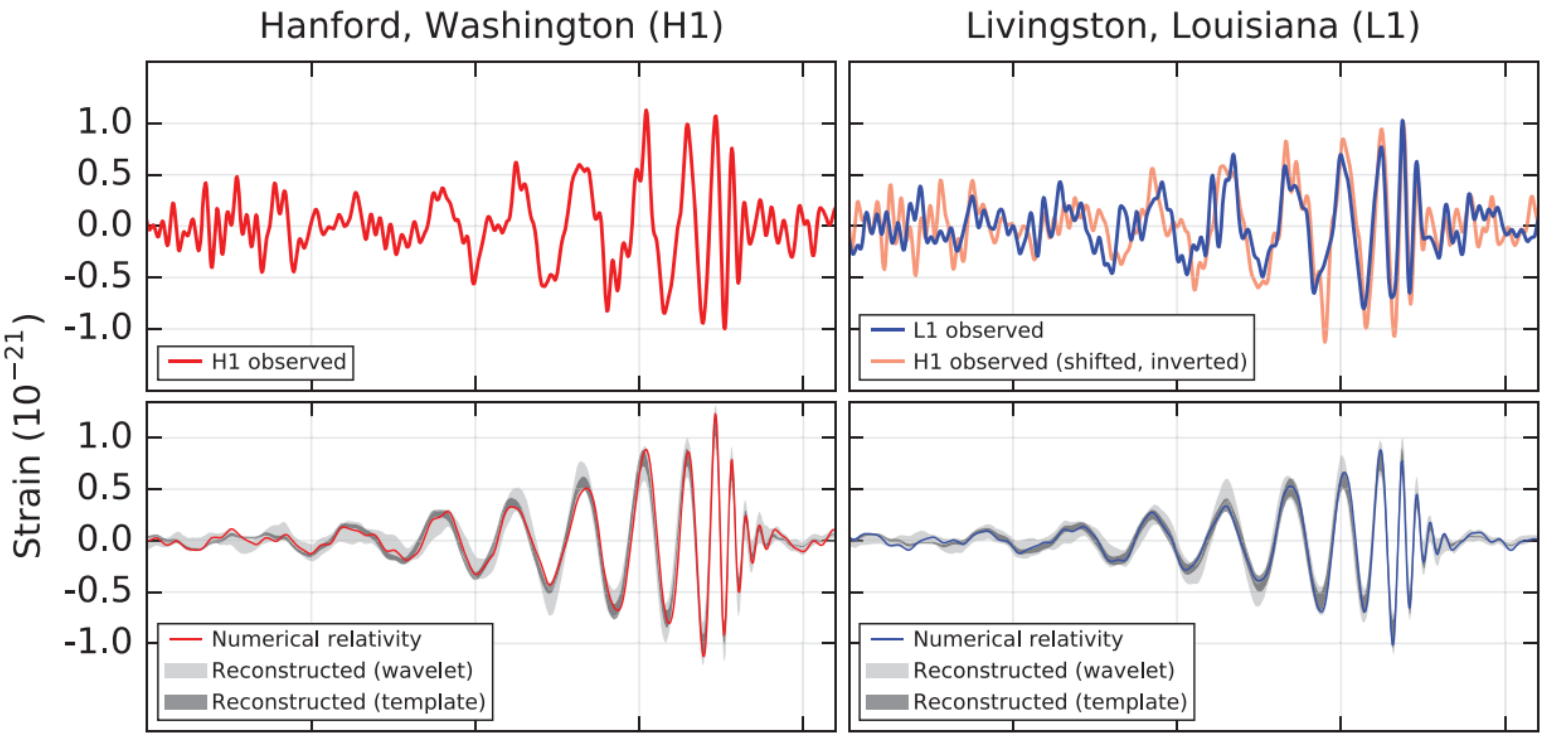

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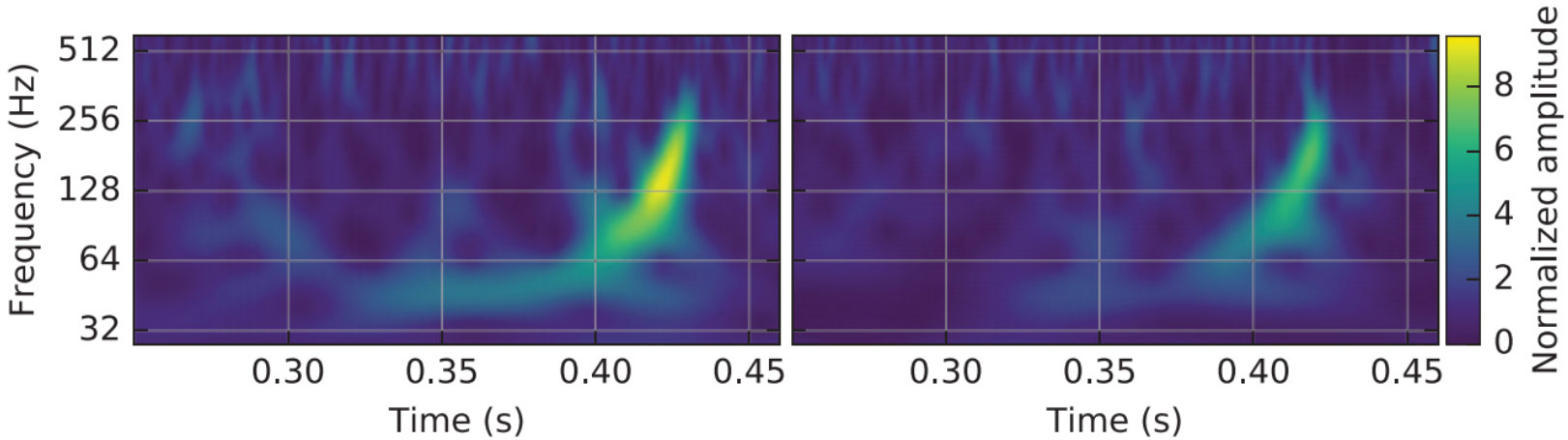

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  - Each site has seismometers, accelerometers, magnetometers, microphones, radio receivers, weather sensors, ac power line monitors, and cosmic ray detectors

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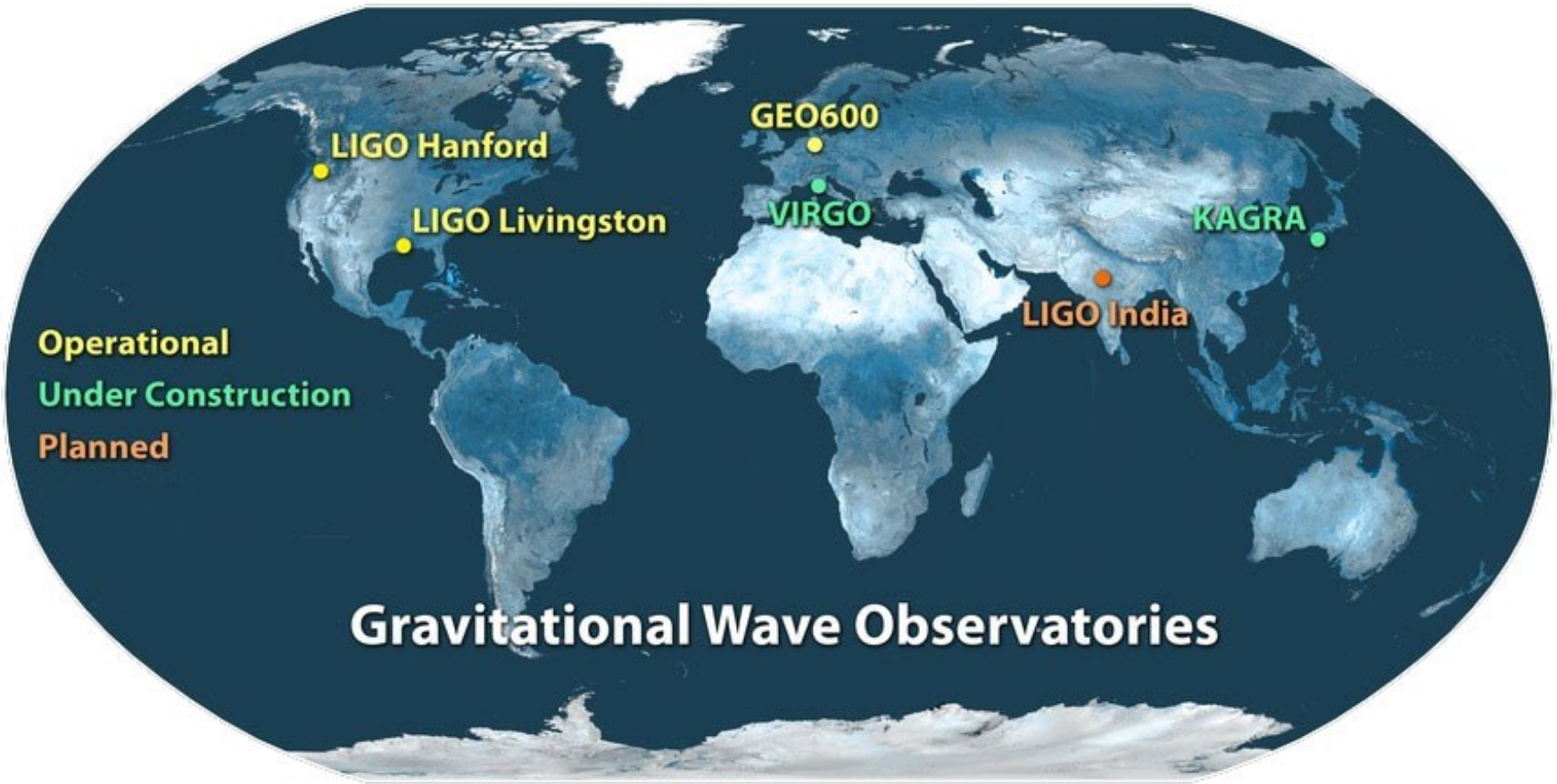
  - Improving the match filtering process
    - Better detection statistics
    - Expecting to see much higher frequency of events in the future


LIGO Hanford
LIGO Livingston
GEO600
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

- Future Plans
  - In 2034 the European Space Agency plans to begin launching a Laser Interferometer Space Antenna (LISA)
    - Vacuum of space is better than vacuum achievable in LIGO
    - Almost no noise from Earth
    - The interferometer arms can be much larger than on Earth

- Future Plans
  - Fermilab E-990 – *'Holometer'*
    - Most sensitive interferometer in the world
    - Meant to detect change in space-time due to quantum fluctuations
    - ▸ https://holometer.fnal.gov/faq.html#logo

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    - This correlation is maximised for both the signal and the noise, using the 6.9 ms time lag of the LIGO paper
- This paper is excellent in all other respects
  - Well written and unambiguous
  - Careful and thorough
  - Great example of international collaboration

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  - Carefully isolated from environmental noise

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    - Binary coalescence search looks for gravitational waves from binary systems in a specific mass range. Found the signal with false alarm probability of 5.1 σ.
  - Numerical models: mass and spin determined independently from the early stage and late stage agree.

- Why care?
  - Last piece of GR
  - New kind of astronomy

Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R. X., Adya, V. B., Affeldt, C., Agathos, M., Agatsuma, K., Aggarwal, N., Aguiar, O. D., Aiello, L., Ain, A., Ajith, P., Allen, B., Allocca, A., Altin, P. A., Anderson, S. B., Anderson, W. G., Arai, K., Arain, M. A., Araya, M. C., Arceneaux, C. C., Areeda, J. S., Arnaud, N., Arun, K. G., Ascenzi, S., Ashton, G., Ast, M., Aston, S. M., Astone, P., Aufmuth, P., Aulbert, C., Babak, S., Bacon, P., Bader, M. K. M., Baker, P. T., Baldaccini, F., Ballardin, G., Ballmer, S. W., Barayoga, J. C., Barclay, S. E., Barish, B. C., Barker, D., Barone, F., Barr, B., Barsotti, L., Barsuglia, M., Barta, D., Bartlett, J., Barton, M. A., Bartos, I., Bassiri, R., Basti, A., Batch, J. C., Baune, C., Bavigadda, V., Bazzan, M., Behnke, B., Bejger, M., Belczynski, C., Bell, A. S., Bell, C. J., Berger, B. K., Bergman, J., Bergmann, G., Berry, C. P. 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