Overview of Advanced LIGO and future methods of noise reduction

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In collaboration with LSC and Virgo

The LIGO interferometers

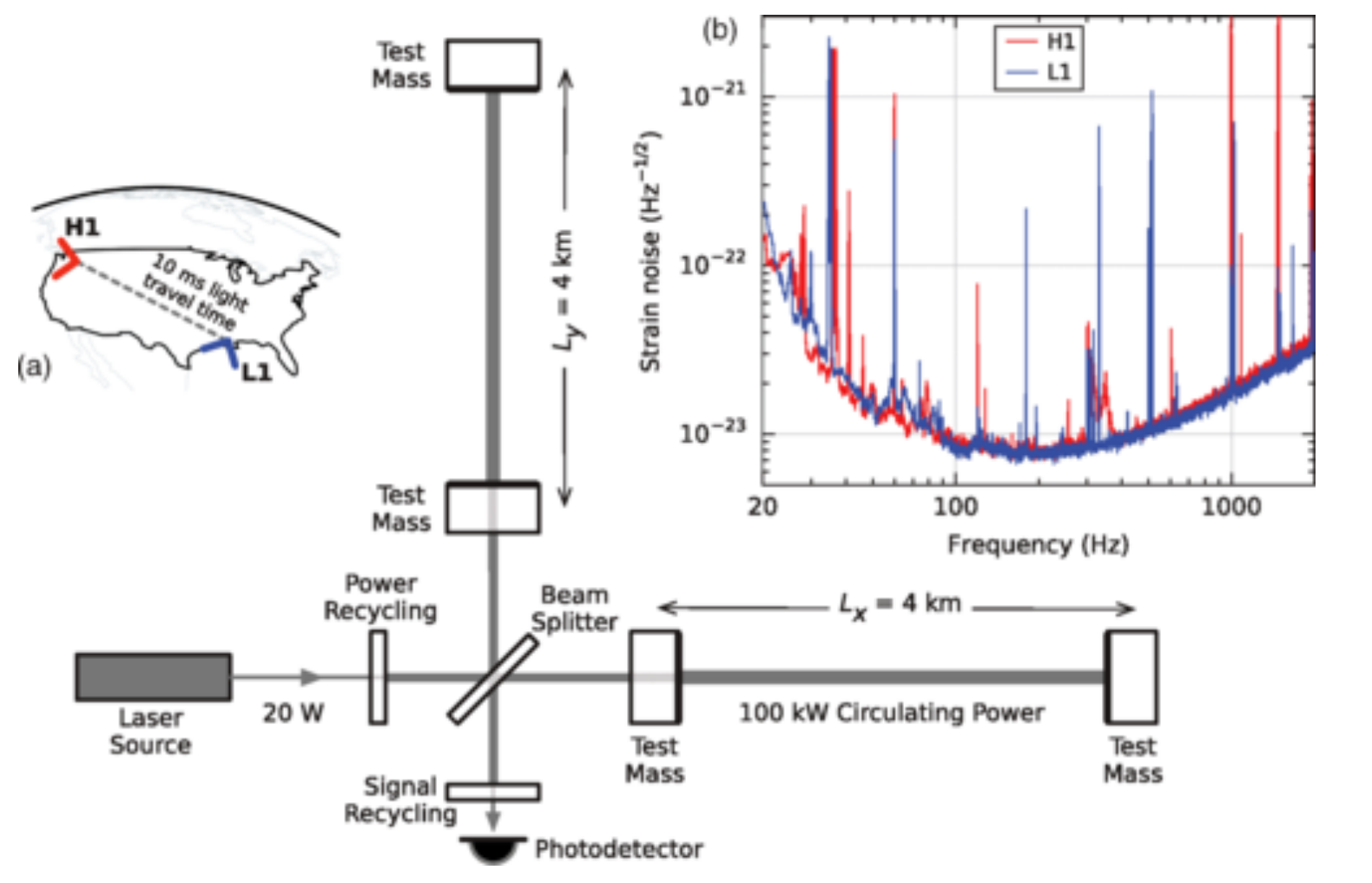

Fig. 1 – Simplified interferometer diagram [1].

- 2 Michelson Interferometers (in Louisiana and Washington).
- Mirrors of 40 kg each.
- Arms of 4 km.
- aLIGO target: input power of 125 W (~1 MW circulating).
- Limited by quantum shot noise.
- Current strain sensitivity of 10^{-21} Hz^{-2} at 100 Hz.
- Spectrum shown is at 25 W and is shot noise limited above ~150 Hz.

First detection

- Binary black hole merger detected by Advanced LIGO on 09/14/2015.
- Resulting black hole of over 60 solar masses.
- Both signals are matched accounting for GW travel time between interferometers and the relative positioning of both.
- Signal goes through template matching.
- 2017 Physics Nobel Prize awarded to Rainer Weiss (MIT), Kip Thorne (Caltech) and Barry Barish (Caltech) for this detection.

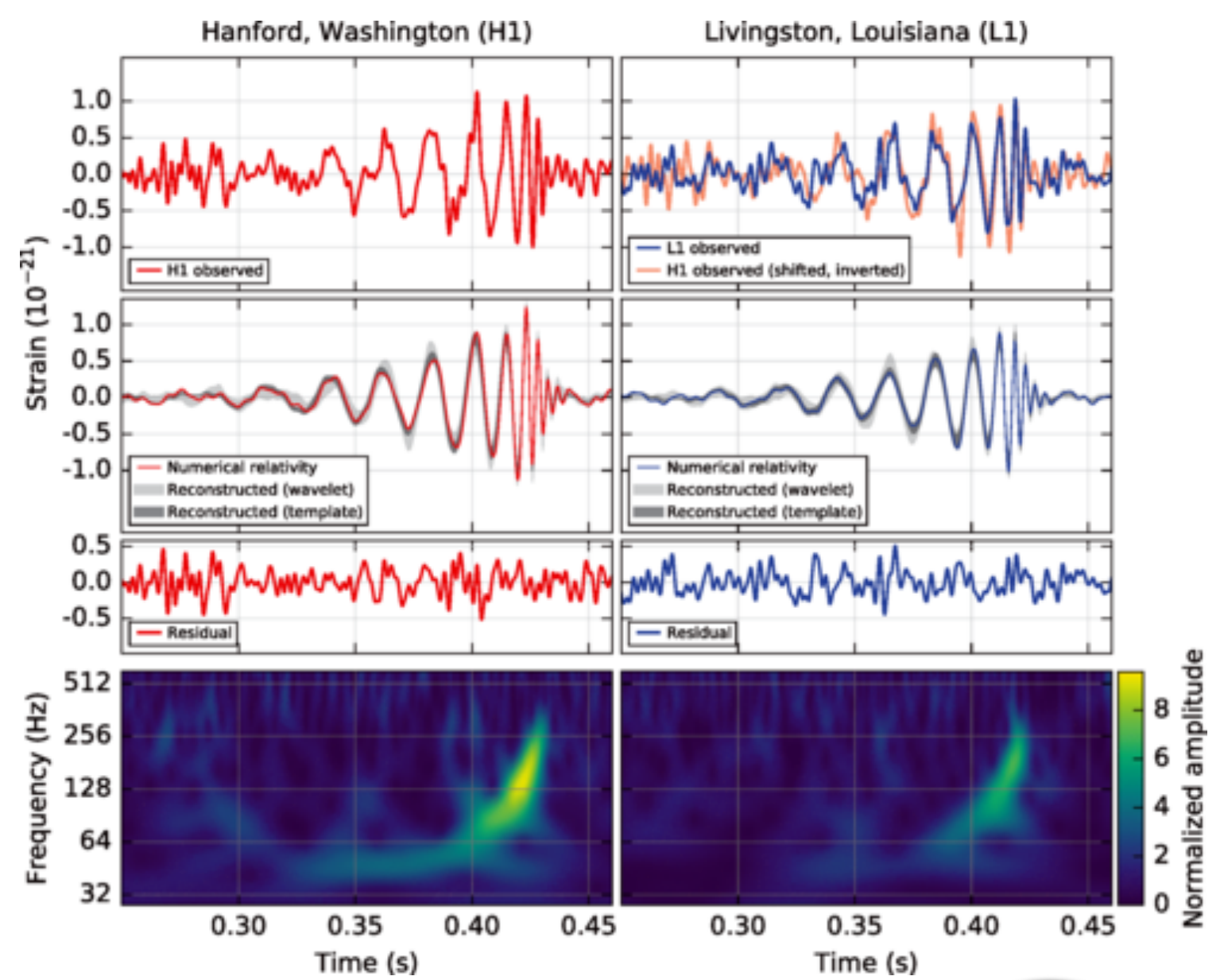

Fig. 2 – Matching black hole merger signals from both interferometers [1].

Subsequent detections

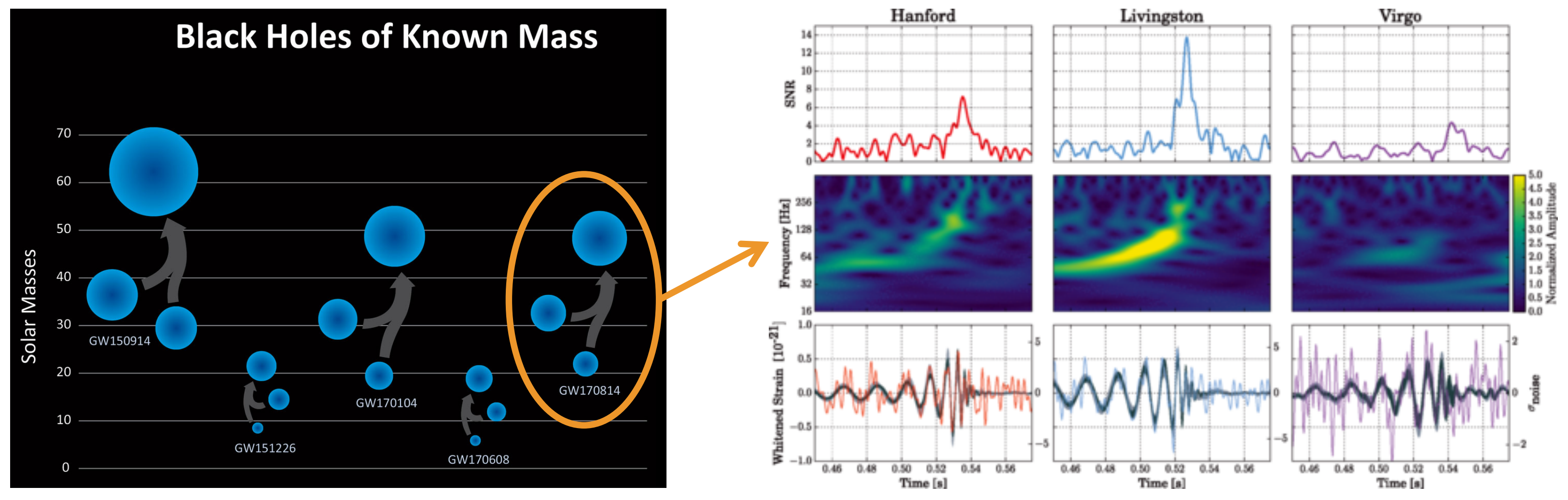

Fig. 3 – List of black hole merger detections (left) [2] and signal from first detection with Virgo (right) [3], which allows for better sky localization of GW source.

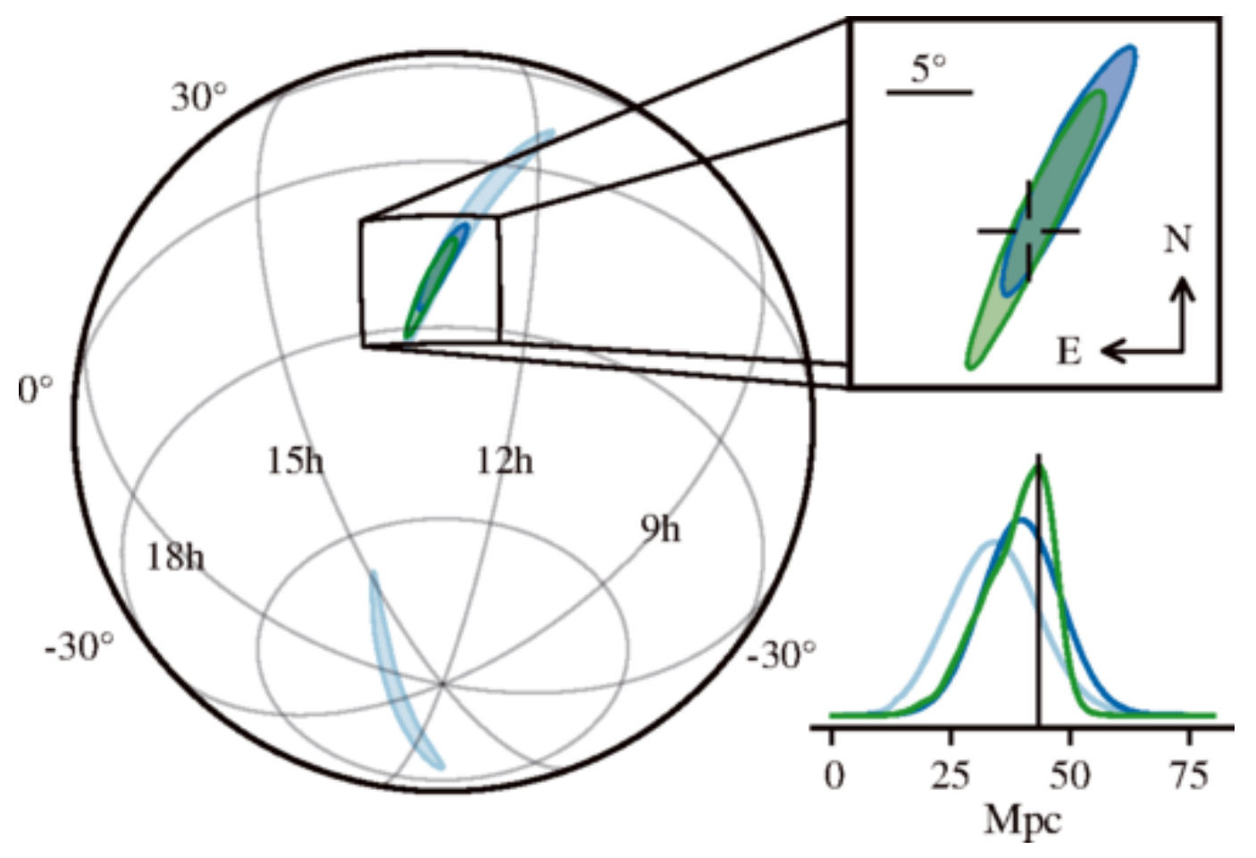

Fig. 4 – Sky localization based on LIGO (blue) and Virgo (green) binary neutron star merger detections [4].

- 1st binary neutron star merger detection 3 days after 1st detection with Virgo. [4]
- Having LIGO and Virgo allowed for better localization of the GW source.
- An alert was sent to dozens of collaborations that had follow-up observations of the source across the electromagnetic spectrum.
- Beginning of multi-messenger astronomy.

Squeezed light and the quantum limit

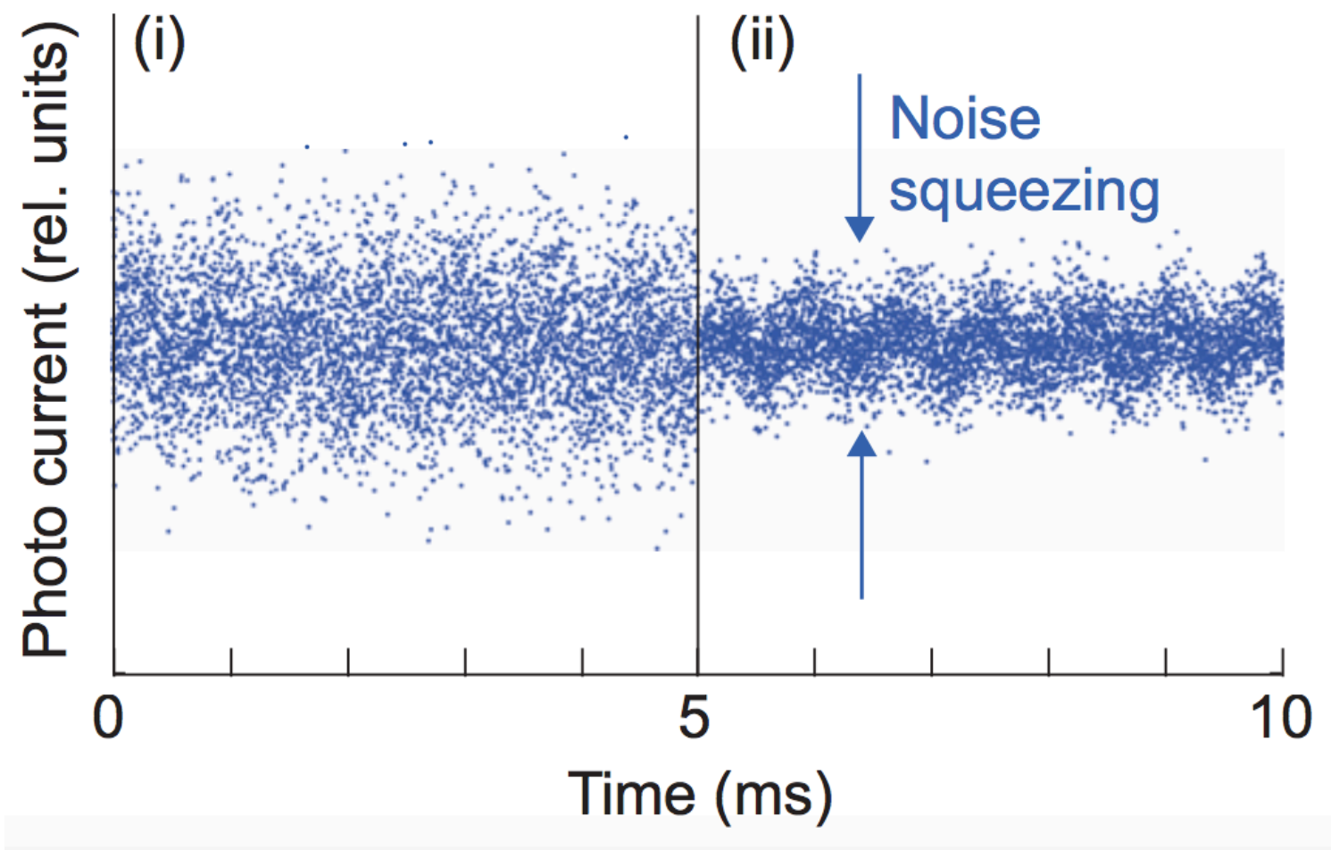

Fig. 5 – Simulation of squeezed photon data. Squeezing reveals a sinusoidal pattern [5].

- Heisenberg uncertainty principle:

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

- Applies to phase and amplitude of light.
- Preference for phase or amplitude squeezing depends on frequency band.
- Squeeze in phase, allowing noise to be "concentrated" in amplitude. → go below the quantum limit!

What is shot noise?

- Classical picture: statistical uncertainty in photon counting. Did one photon hit, or two?
- Quantum theory: random fluctuations in vacuum, even when there is no light, called "zero-point fluctuations". Inherent to the quantum nature of light.

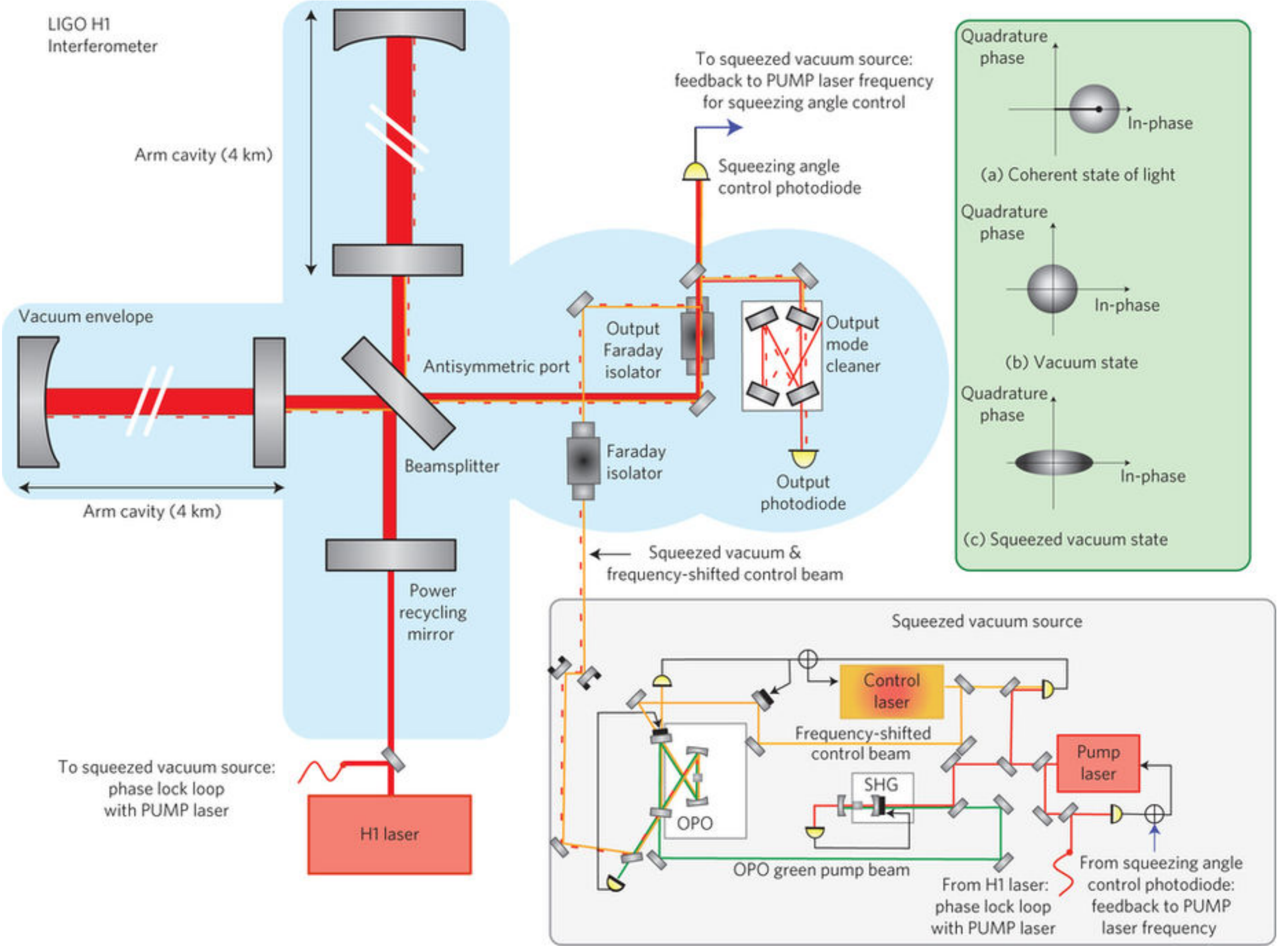

Fig. 6 – OPO "bowtie" cavity for generation of squeezed light [5].

- In-vacuum OPO cavity used to generate squeezed light.
- Complications: must be vacuum-compliant, overall noise must be very small in order to see sub-quantum limit benefit.
- Squeezed light from parametric down conversion (PDC) + cavity.
- Nonlinear crystal (PPKTP) down-converts a 532nm photon to two phase-entangled 1064nm photons.
- Cavity enhances effects of crystal through multiple passes.
- Phase-lock H1 (main) laser to pump laser of OPO, and inject squeezed vacuum into dark port → overall reduction in phase noise.

Optomechanics and squeezing

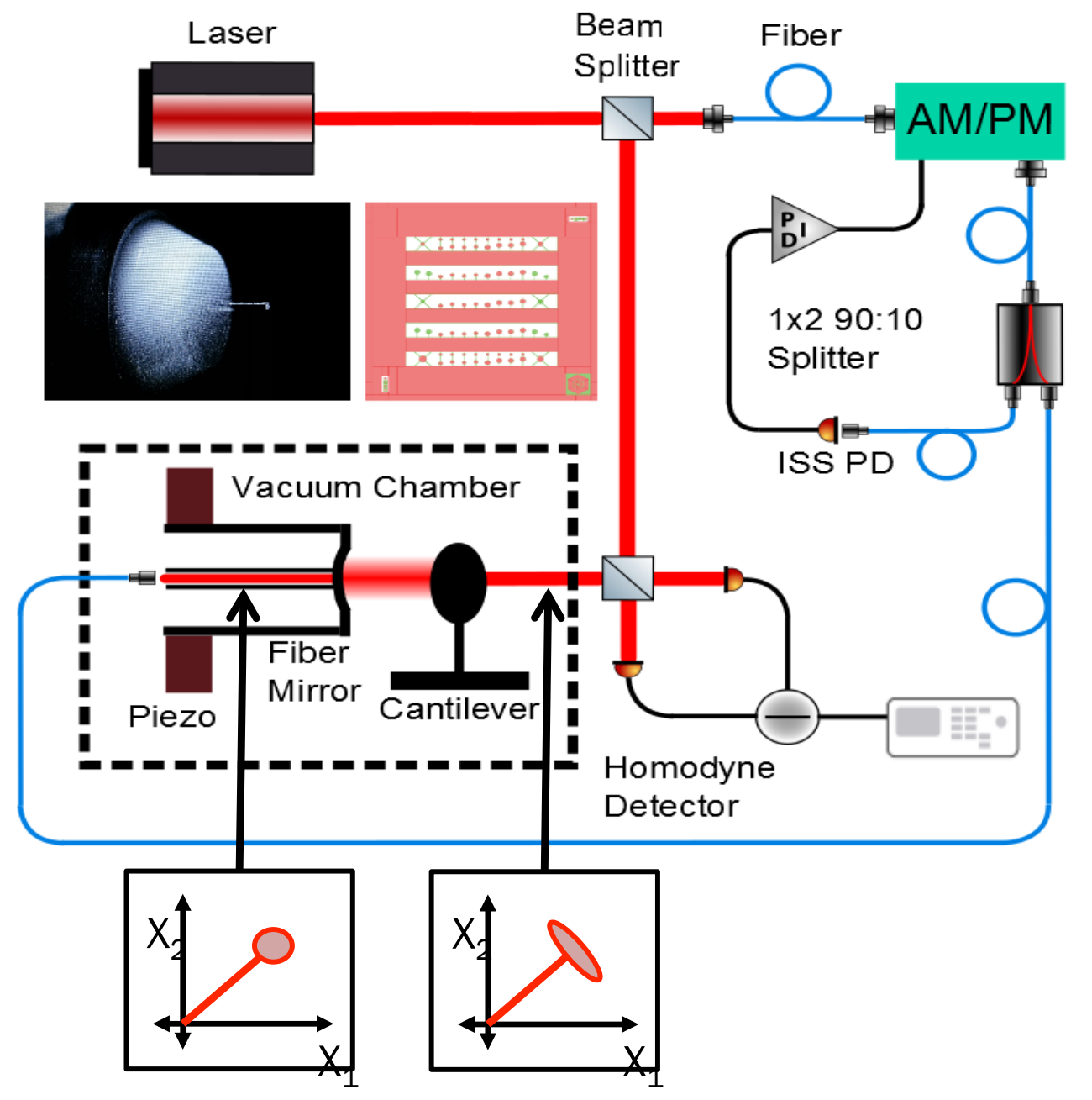

Fig. 7 – Diagram of optomechanical squeezing experiment. Credits for figure and information: Nancy Aggarwal, Robert Lanza, and Adam Libson.

- Squeezing in audio frequencies.
- Does not depend on laser wavelength.
- Optical fibers couple light to squeezer.
- Fiber mirror and micromechanical mirrors on a cantilever form an optical cavity.
- Can measure radiation pressure effects.

Noise reduction in the lab tabletop setup

Want to measure radiation pressure effects

Shot noise limit at a part in 10^8

Implement Intensity Stabilization Servo to reduce noise

Characterizing noise and photodetectors

We collected noise and transfer function data from the setup and PDs.

Simulating performance

We wrote a program in MATLAB that predicted the noise reduction using the ISS based on the collected data and different instrument specifications.

Implementing the ISS

Using the best PD, a fiber amplitude modulator and a signal amplifier, we are now implementing the ISS.

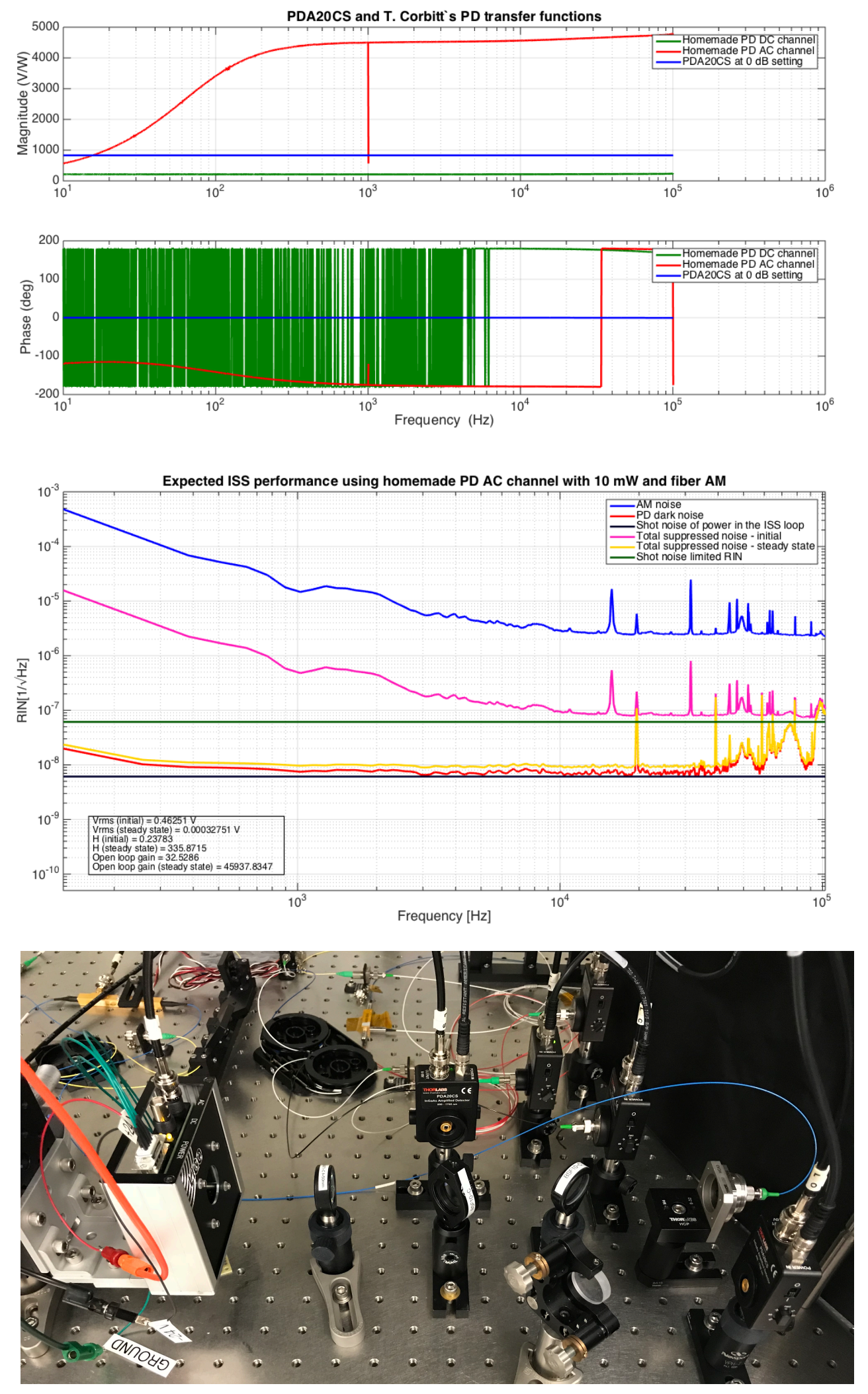

Fig. 8 – PD transfer functions (top), predicted ISS performance (center), ISS setup (bottom).

Acknowledgements

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References

[1] B.P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Phys. Rev. Lett. 116, 061102 (2016).
[2] Sky & Telescope. LIGO sees smallest black hole binary yet. Available at http://www.skyandtelescope.com/astronomy-news/ligo-sees-smallest-black-hole-binary-yet-1611201723/ (2017).
[3] B.P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Phys. Rev. Lett. 119, 141101 (2017).
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