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Status and Prospects for Gravitational-Wave Astrophysics

16th International Conference on Interconnections between Particle Physics and Cosmology (PPC 2023)

Tjonnie Li (on behalf of the LVK Collaboration)

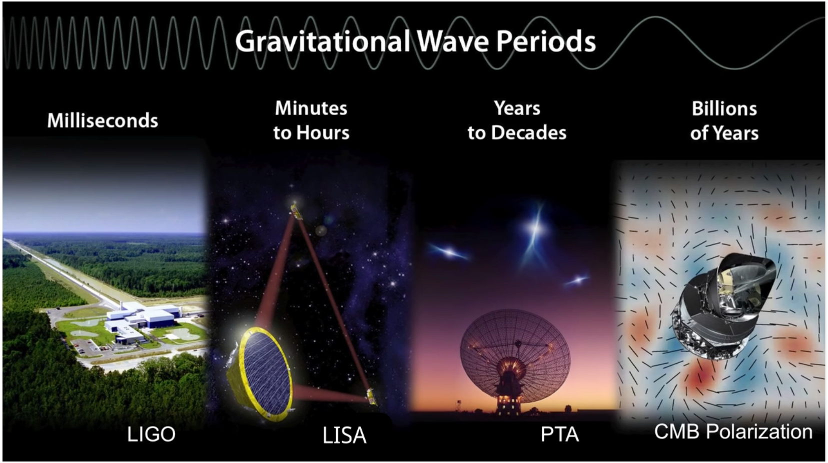
KU Leuven

14 June 2023

0 Outline

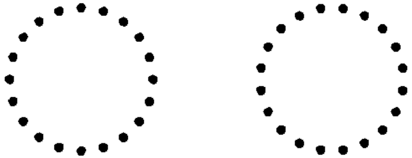
1 Outline

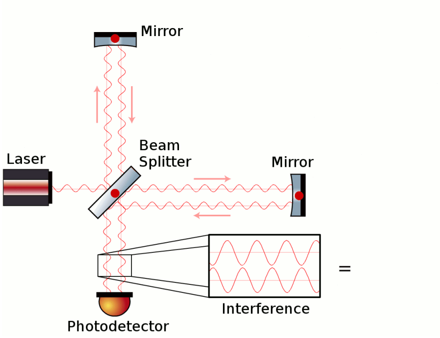
1 Gravitational Waves & Detectors



1 Laser Inferrometry for Detecting Gravitational Waves

- Measure strain through *laser interferometry*
- Gravitational waves changes the length of the arms
- Measure the change in light intensity





1 Gravitational-wave Detectors

Figure: credit: EGO

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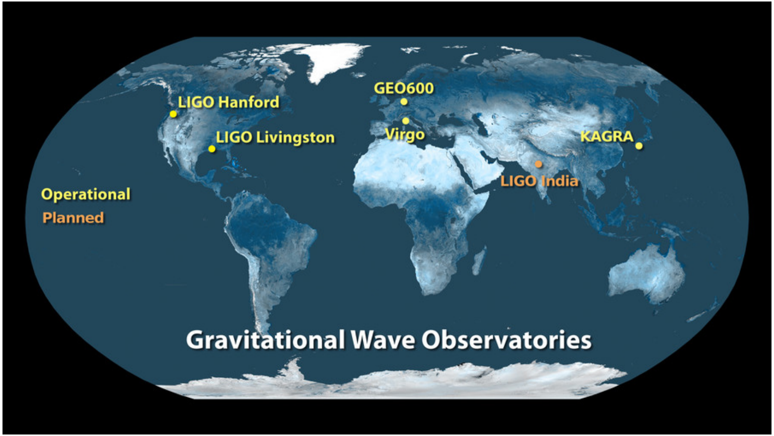

Figure: credit: LIGO Laboratory

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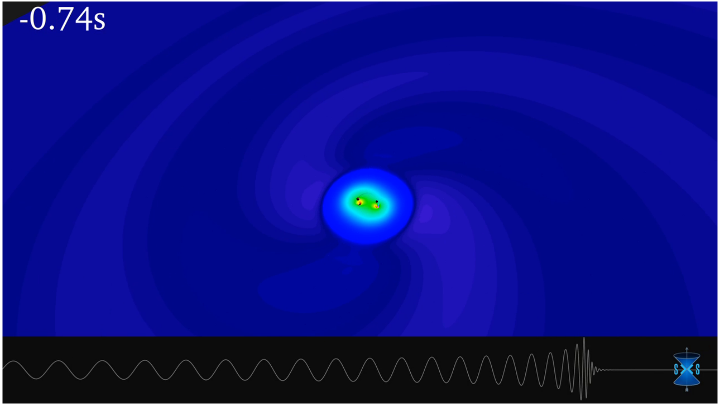
2 Outline

1. Gravitational Waves & Detectors
2. Detections So Far
3. Notable Results
4. Future Prospects (not exhaustive)

2 GW150914 Simulation



credit: SXS Collaboration

2 Searching for gravitational-wave signals

Modelled

- Search with waveform predicted by general relativity
- Optimal matched filter

Unmodelled

- Coincident excess power in time-frequency plane
- Minimal assumptions on signal morphology

Ranking candidates

- Candidates are assigned detection-statistic value (likelihood)
- Compare to noise background value

2 Unmodelled search – measuring cross power

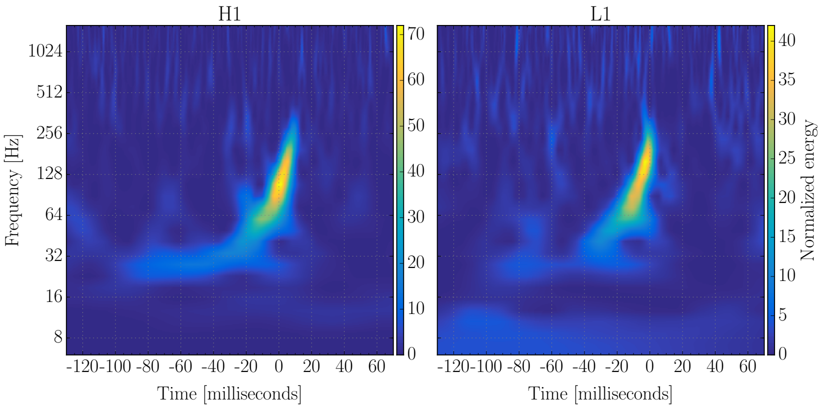
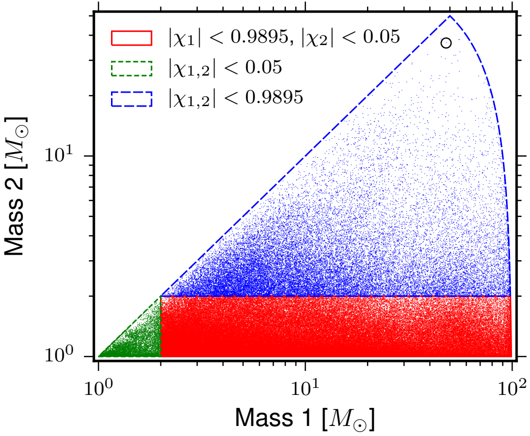


Figure: B. P. Abbott et al. *Phys. Rev. D* 93.12, 122003 (2016)

2 Modelled search – templates



- Component mass 1 to $99 M_\odot$
- Total mass $< 100 M_\odot$
- Dimensionless spinn < 0.99

$\Rightarrow$ $> 1 \times 10^5$ templates

B. P. Abbott et al. *Phys. Rev. D* 93.12, 122003 (2016)

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2 Search Result Example

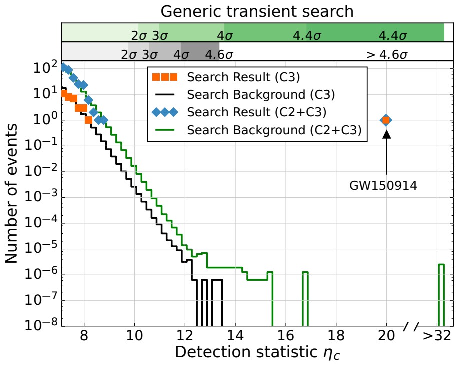

Figure: B. P. Abbott et al. *Phys. Rev. D* 93.12, 122003 (2016)

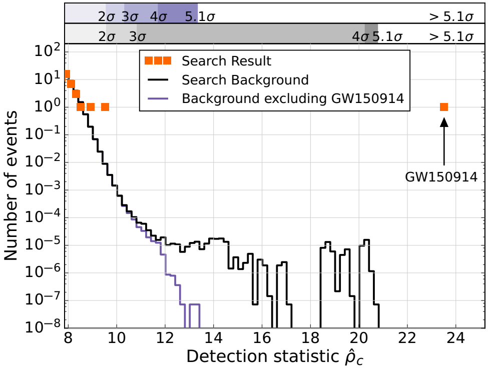

Figure: B. P. Abbott et al. *Phys. Rev. Lett.* 116.6, 061102 (2016)

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2 Measuring Properties

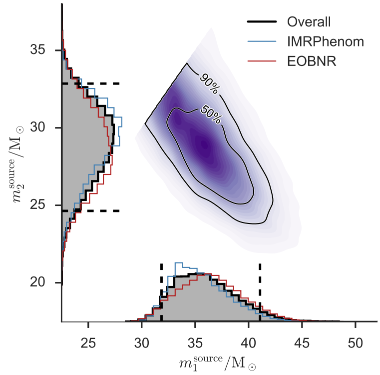
- Want to infer the properties of source from data
- Bayesian inference

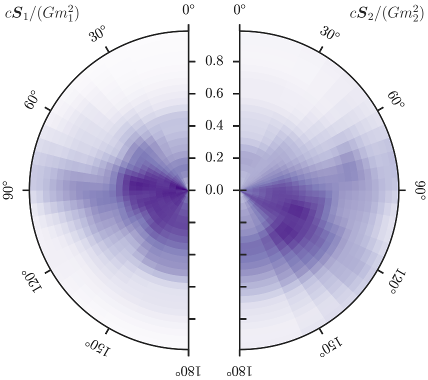
$$\Pr(\vec{\theta} \mid d) = \frac{\Pr(d \mid \vec{\theta}) \Pr(\vec{\theta})}{\Pr(d)} \tag{1}$$

- $\vec{\theta} \in \{m_1, m_2, \mathbf{S_1}, \mathbf{S_2}, D_L, \ldots\}$
- $\Pr(\vec{\theta} \mid d)$: Posterior
- $\Pr(d \mid \vec{\theta})$: Likelihood
- $\Pr(\vec{\theta})$: Prior
- $\Pr(d)$: Evidence/Marginal likelihood

Use Markov-Chain-Monte-Carlo methods to sample the posterior

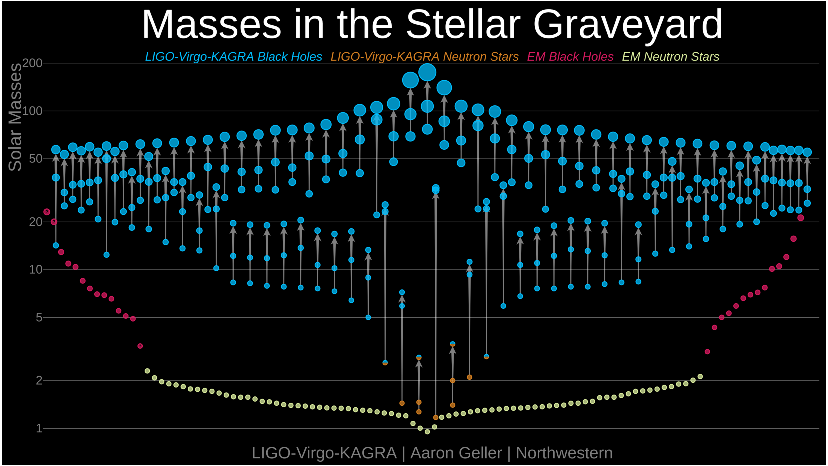
2 Properties of GW150914





B. P. Abbott et al. *Phys. Rev. Lett.* 116.24, 241102 (2016)

2 Compact Binary Mergers Observed by LIGO and Virgo

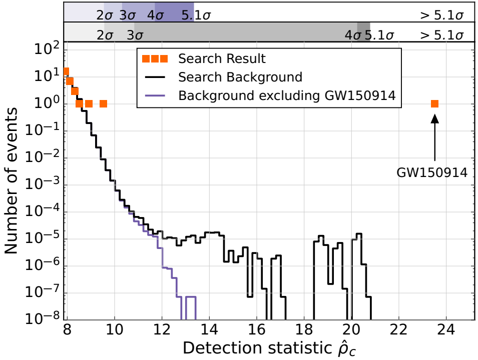


3 Outline

1. Gravitational Waves & Detectors
2. Detections So Far
3. Notable Results
4. Future Prospects (not exhaustive)

3 Notable Results (not exhaustive)

- GW150914
  - Detection of GW
  - Dynamical nature of spacetime
- GW170608
  - Black holes in EM range



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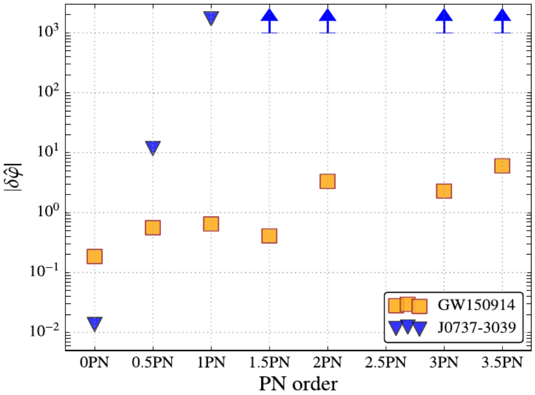

B. P. Abbott et al. *Phys. Rev. Lett.* 116.22, 221101 (2016)

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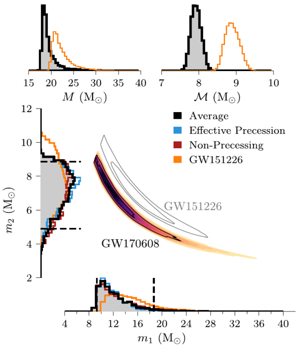
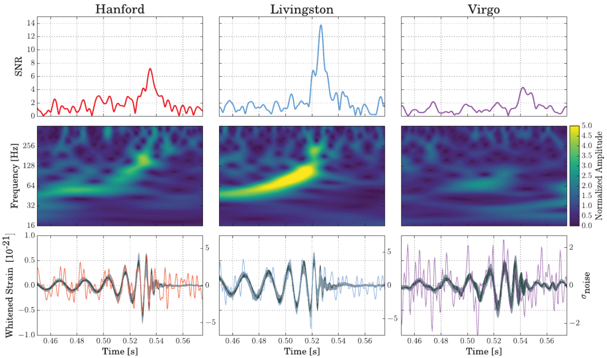


B. P. Abbott et al. *ApJ* 851.2, L35 (2017)

3 Notable Results (not exhaustive)

- GW170814
  - Three-detector network
- GW170817
  - Binary neutron stars
  - γ-ray burst and kilonova
  - Nuclear equation of state
  - Hubble constant
  - Speed of light vs gravity



B. P. Abbott et al. *Phys. Rev. Lett.* 119.14, 141101 (2017)

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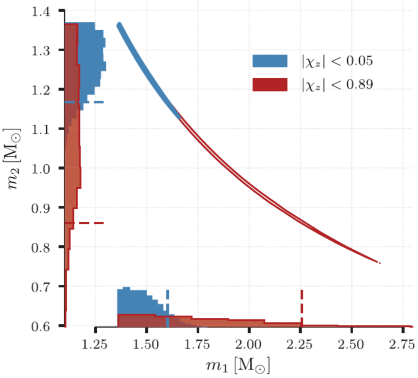

B. P. Abbott et al. *Phys. Rev. Lett.* 119.16, 161101 (2017)

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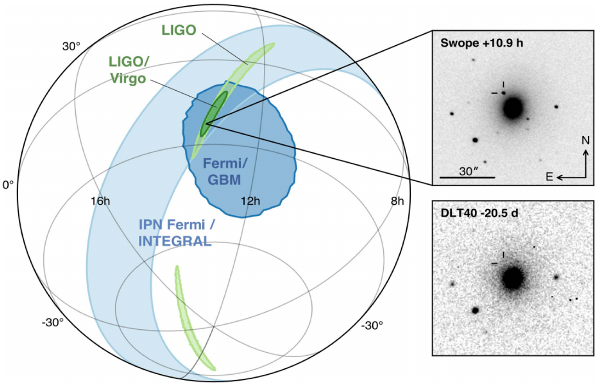

B. P. Abbott et al. *ApJ* 848.2, L12 (2017)

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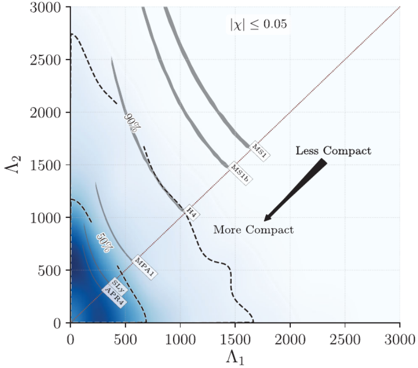

B. P. Abbott et al. *Phys. Rev. Lett.* 121.16, 161101 (2018)

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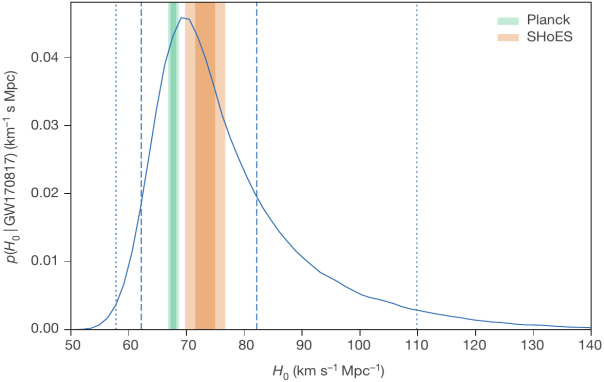

B. P. Abbott et al. *Nature* 551.7678 (2017)

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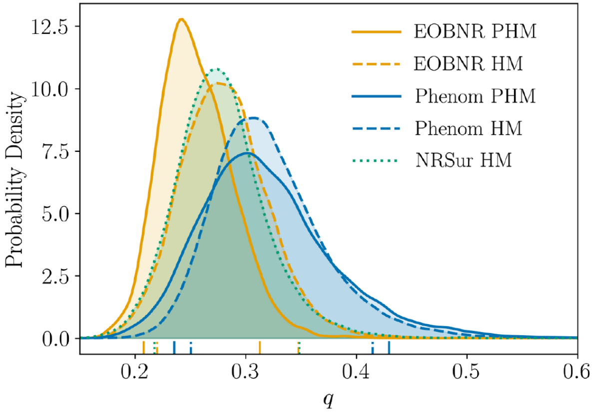
$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}.$$

B. P. Abbott et al. *Phys. Rev. Lett.* 123.1, 011102 (2019)

3 Notable Results (not exhaustive)

- GW190412/GW190814
  - Asymmetric masses
  - Subdominant $(3, 3)$ mode
- GW190521
  - High mass: At least one mass in PI mass gap
  - Observable in space-based detectors
- GW200105/GW200115
  - NSBH?



R. Abbott et al. *Phys. Rev. D* 102.4, 043015 (2020)

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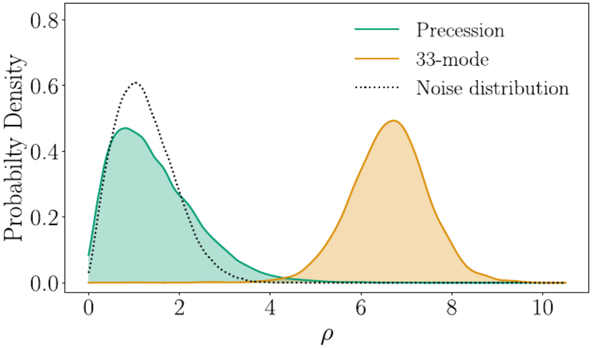

R. Abbott et al. *ApJ* 896.2, L44 (2020)

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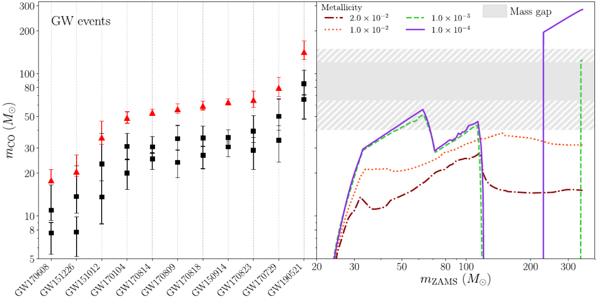

R. Abbott et al. *Phys. Rev. Lett.* 125.10, 101102 (2020)

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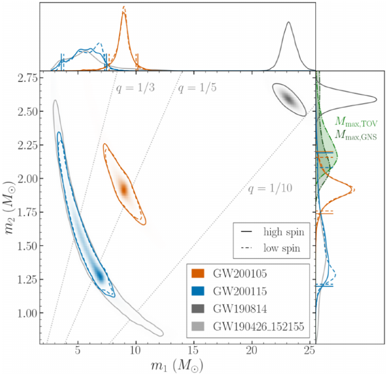

R. Abbott et al. *ApJ* 915.1, L5 (2021)

4 Outline

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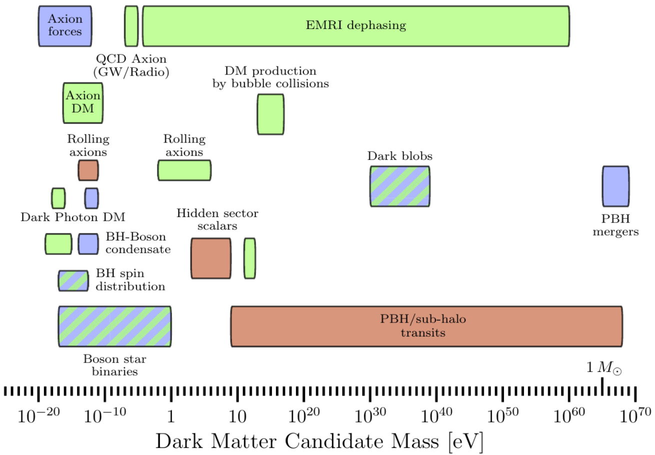
4 Dark Matter imprints on Gravitational Waves



Potential constraints from gravitational waves

- Current interferometers (blue)
- Future interferometers (green)
- Pulsar Timing Arrays (red).

G. Bertone et al. *arXiv e-prints*, arXiv:1907.10610 (2019)

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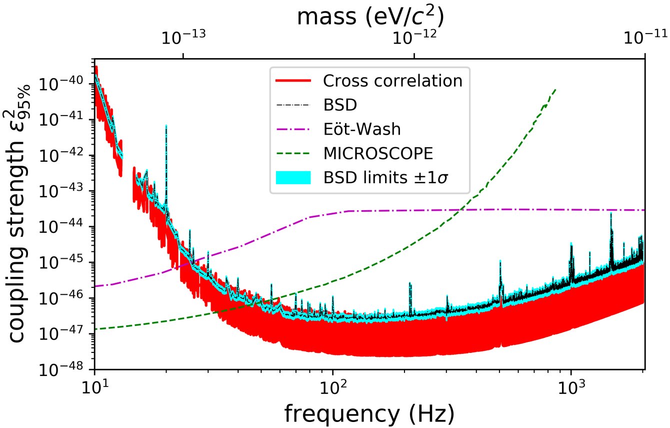
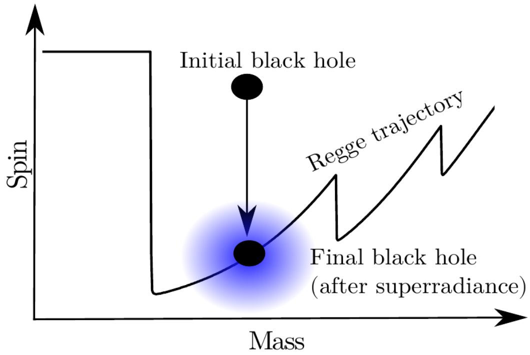
4 Search for Dark Photon Dark Matter

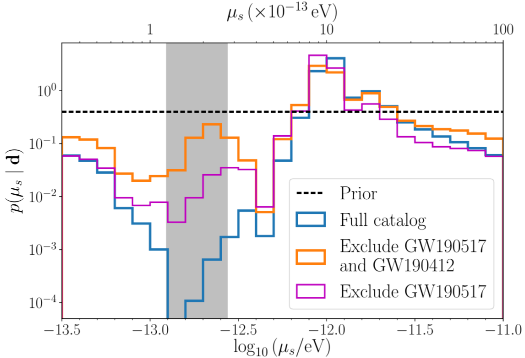


- Dark photon dark matter coupling into interferometers
- Cross-correlation of strain channels
- Excess power in the strain channels

R. Abbott et al. *Phys. Rev. D* 105.6, 063030 (2022)

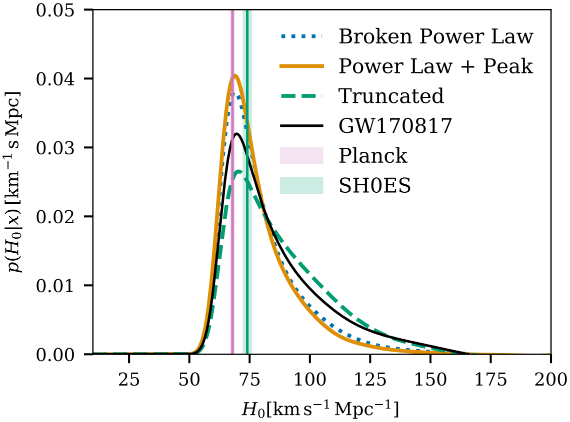
4 Ultra-light Bosons from Populations





K. K. Y. Ng et al. *Phys. Rev. Lett.* 126.15, 151102 (2021)

4 Better Measurements of Cosmological Parameters



- Estimate Hubble parameter $H(z)$ from 47 gravitational-wave detections
- Luminosity distance from gravitational-wave signal
- Redshift from
  1. Redshifted masses
  2. Galaxy catalogues

R. Abbott et al. *ApJ* 949.2, 76 (2023)

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4 Gravitational Lensing of Gravitational Waves

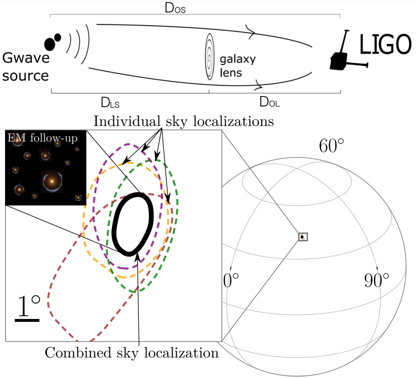
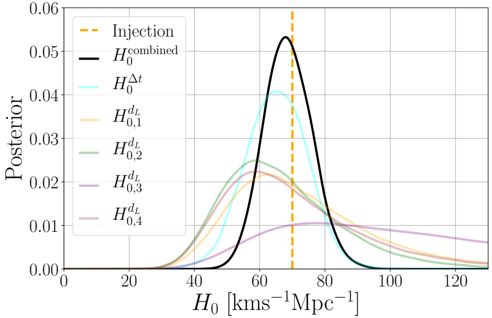


Figure: O. A. Hannuksela et al. *MNRAS* 498.3 (2020)



- See also The LIGO Scientific Collaboration et al. *arXiv e-prints*, arXiv:2304.08393 (2023)

Thank you!

4 Acknowledgements

“This material is based upon work supported by NSF’s LIGO Laboratory which is a major facility fully funded by the National Science Foundation”

Appendices

4 References I

[1] B. P. Abbott et al. "GW150914: First results from the search for binary black hole coalescence with Advanced LIGO". *Phys. Rev. D* 93.12, 122003 (2016), p. 122003. arXiv: 1602.03839 [gr-qc].

[2] B. P. Abbott et al. "Observation of Gravitational Waves from a Binary Black Hole Merger". *Phys. Rev. Lett.* 116.6, 061102 (2016), p. 061102. arXiv: 1602.03837 [gr-qc].

[3] B. P. Abbott et al. "Properties of the Binary Black Hole Merger GW150914". *Phys. Rev. Lett.* 116.24, 241102 (2016), p. 241102. arXiv: 1602.03840 [gr-qc].

[4] B. P. Abbott et al. "Tests of General Relativity with GW150914". *Phys. Rev. Lett.* 116.22, 221101 (2016), p. 221101. arXiv: 1602.03841 [gr-qc].

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[6] B. P. Abbott et al. "GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence". *Phys. Rev. Lett.* 119.14, 141101 (2017), p. 141101. arXiv: 1709.09660 [gr-qc].

[7] B. P. Abbott et al. "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral". *Phys. Rev. Lett.* 119.16, 161101 (2017), p. 161101. arXiv: 1710.05832 [gr-qc].

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[15] R. Abbott et al. "Observation of Gravitational Waves from Two Neutron Star-Black Hole Coalescences". *ApJ* 915.1, L5 (2021), p. L5. arXiv: 2106.15163 [astro-ph.HE].

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