中国科学院大学
University of Chinese Academy of Sciences

Gravitational Lensing of Gravitational Waves

(A statistical perspective)

Shun-Sheng Li

Collaborators: Shude Mao, Yuetong Zhao, and Youjun Lu

National Astronomical Observatories
Chinese Academy of Sciences

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Outline

Gravitational waves

GW Spectrum

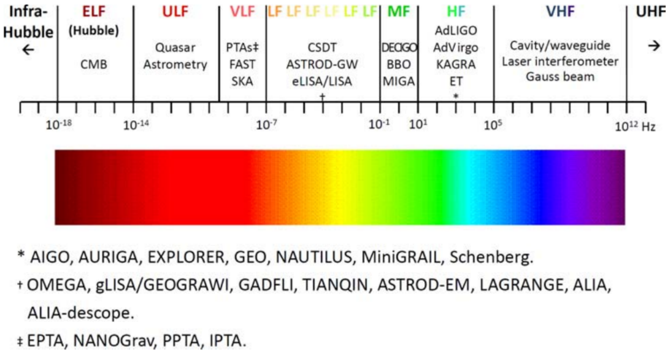


Figure: adopted from K. Kuroda et al. 2015.

HF Sources

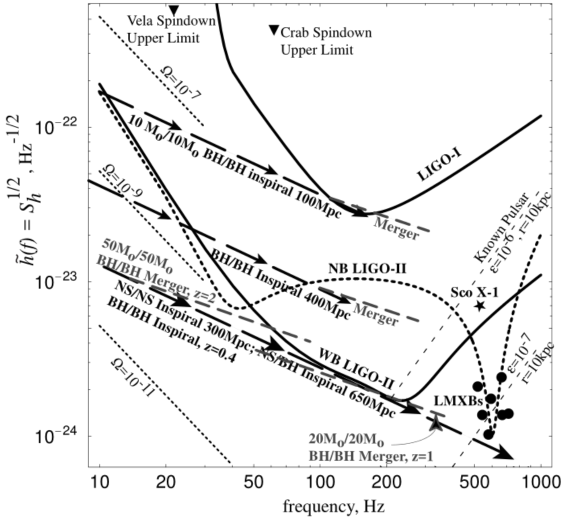


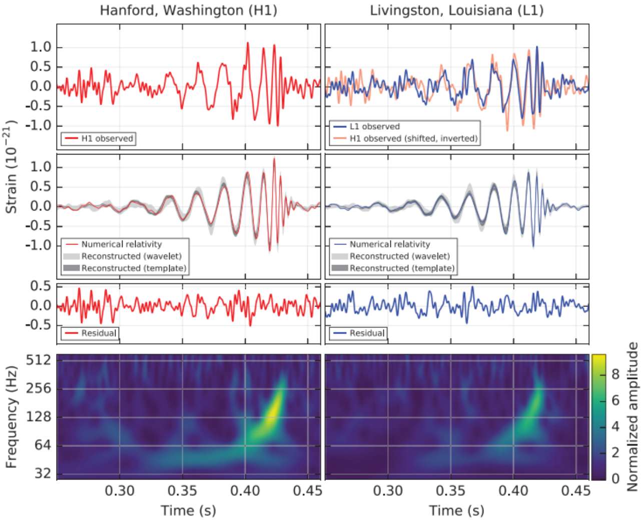
Figure: adopted from C. Cutler & K. Thorne 2015.

Detections

- O1 (2015.09.12—2016.09.19)
  - GW150914 (First detection)
  - LVT151012
  - GW151226
- O2 (2016.11.30—2017.08.25)
  - GW170104
  - GW170814
  - GW140817 (First BNS detection)
  - GW170608
- O3 (early 2019)

GW150914

The debut of gravitational-wave astronomy



GW150914 Timeline-1

Figure: adopted from LIGO magazine, issue 8, 3/2016.

GW150914 Timeline-2

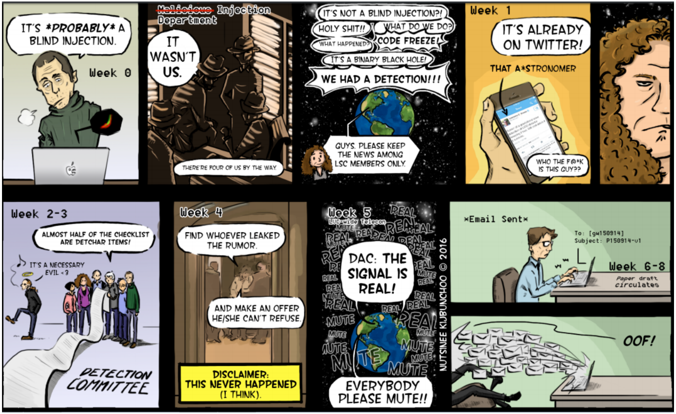


Figure: adopted from LIGO magazine, issue 8, 3/2016.

GW150914 Timeline-3

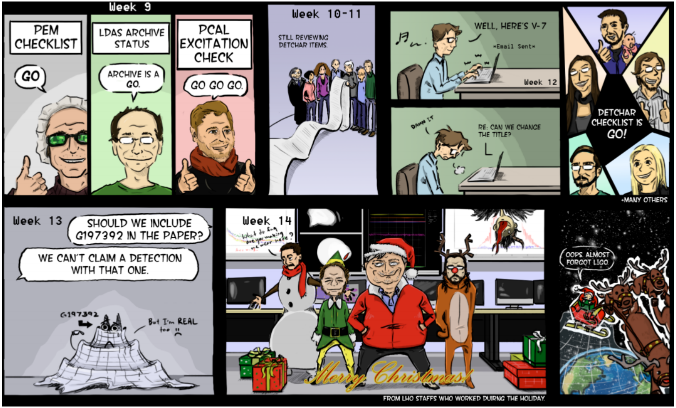


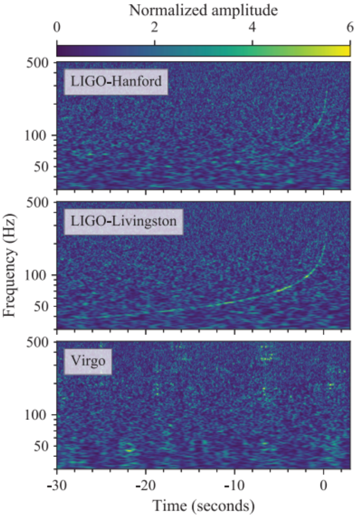
Figure: adopted from LIGO magazine, issue 8, 3/2016.

GW150914 Timeline-4

Figure: adopted from LIGO magazine, issue 8, 3/2016.

GW170817

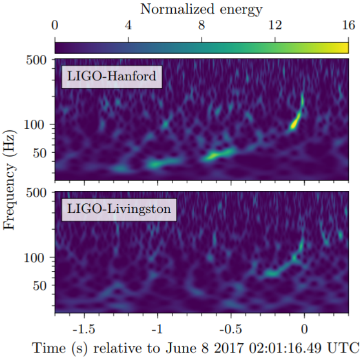
The dawn of multi-messenger astronomy



- First observation of a BNS inspiral.
- First joint gravitational and electromagnetic observation.
- First direct evidence of the source of short γ-ray burst.

GW170608

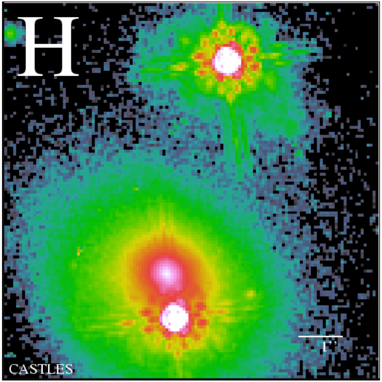
The regular detection of gravitational waves



- The lightest black hole binary so far.
- The “humblest” GW event so far.

Gravitational lensing

Lensed Quasar



- Q0957+561: The first extragalactic gravitational lens system (source: CASTLES).
- The most promising source of lensing system (> 100 documented by CASTLES Survey).

Lensed Galaxy

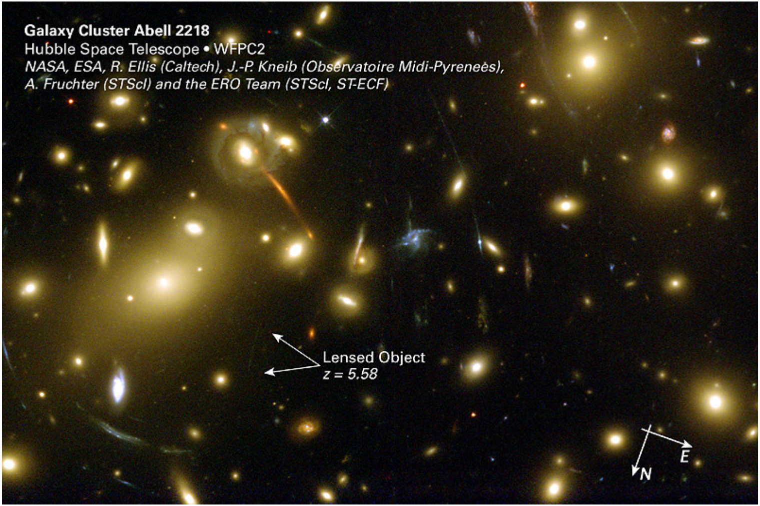


Figure: Abell 2218: A rich galaxy cluster containing seven multiple systems (source: NASA/STScI).

Lensed Supernova

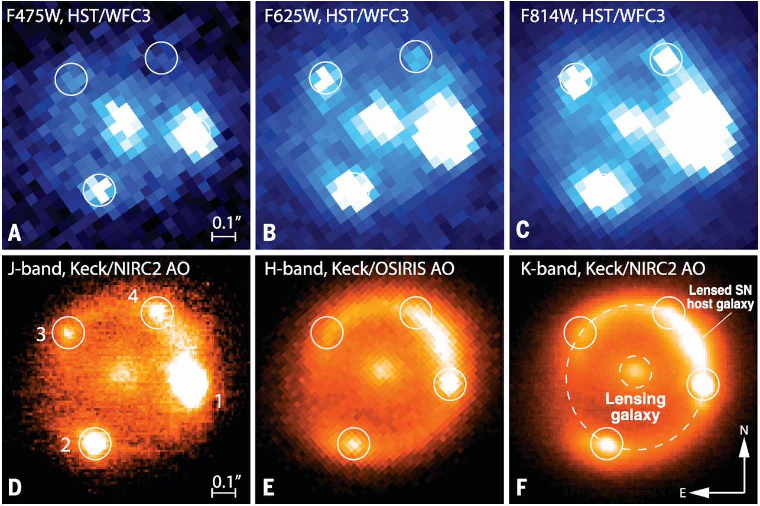


Figure: iPTF16geu: the first lensed SN Ia with high-spatial-resolution imaging (Goobar et al. 2017).

Gravitational lensing of gravitational waves

GL of GWs

- Wang et al. (1996) first proposed the possibility.
- Nakamura (1998) first considered the diffraction effect.
- Cao et al. (2014) and Dai & Venumadhav (2017) discussed the waveform distortion.
- Collett & Bacon (2017) and Fan et al. (2017) addressed the potential for studying basic physics.
- Sereno et al. (2011) and Wei & Wu (2017) investigated the application in exploring cosmology.
- ...

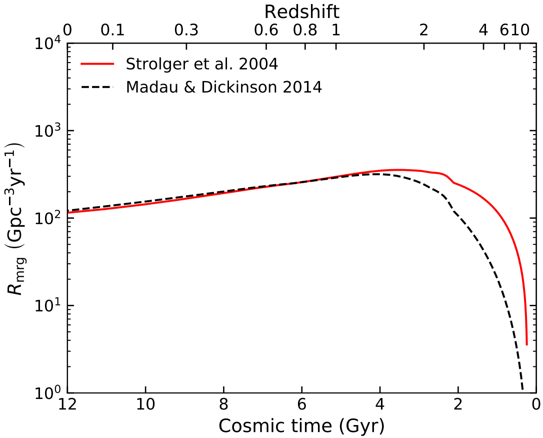
The statistics of lensed GW events

Sketch

- Predecessors:
  - Wang et al. (1996): aLIGO; neutron star binaries.
  - Sereno et al. (2010): LISA; massive black hole binaries.
  - Biesiada et al. (2014): ET; double compact objects.
- Improvements:
  - More sophisticated lens model.
  - More accurate estimate of sources.
- Goals:
  - A general strategy of statistical calculation
  - A prediction of lensed event rates.

Theoretical model

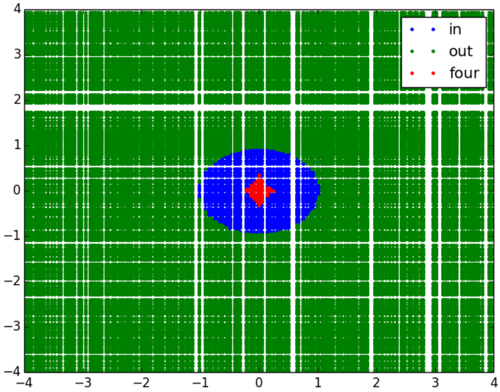
GW modelling



- Stellar binary black holes (Cao et al. 2017).
- The theory of GW detection (Finn 1996).

Lens modelling

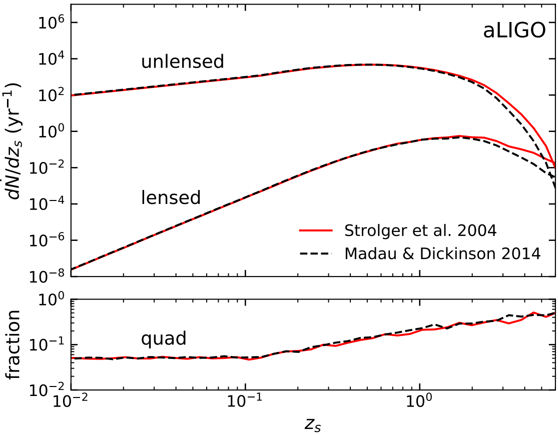
singular isothermal ellipsoid with external shear



Results

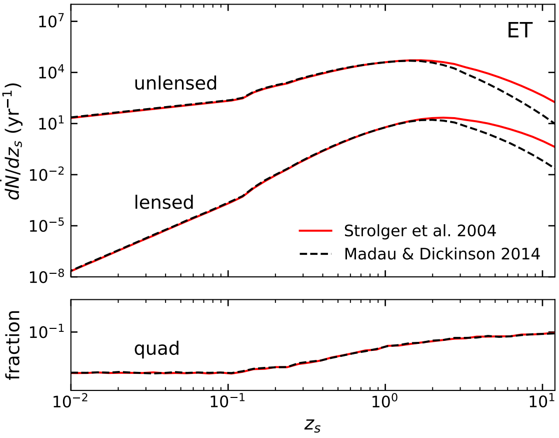
Lensing rate

aLIGO at its design sensitivity



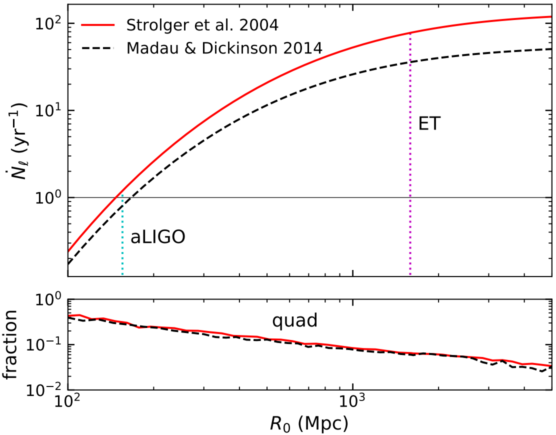
Lensing rate

Proposed Einstein Telescope

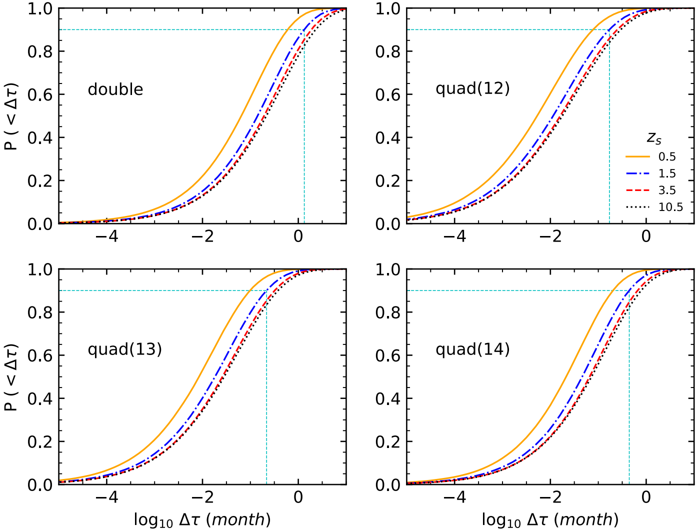


Lensing rate

General GW detectors



Distribution of time delays



Conclusions

- For aLIGO at its design sensitivity, once per year (quadruple fraction $\sim 30\%$).
- For proposed Einstein Telescope, $40 \sim 80$ per year (quadruple fraction $\sim 6\%$).
- Selection bias due to the finite survey duration is insignificant.
- Technical details: arXiv:1802.05089