Advanced LIGO detectors and the birth of Gravitational-wave astronomy

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Overview

1. Gravitational waves
2. GW Detectors
3. LIGO
4. Recent discoveries and Future detectors

Gravitational Waves

Solutions to Einstein's Field equations

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1$$

Transverse Traceless gauge

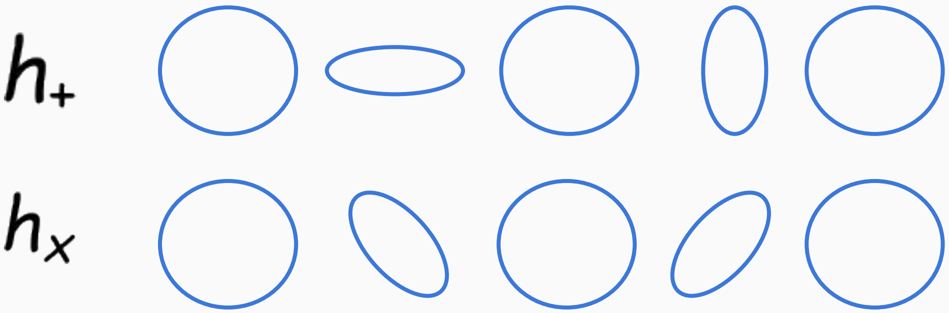
$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \cos(\omega(t - z/c))$$

Accelerating charges → EM waves

Accelerating masses → GW waves

GWs induce strain in space

$$\frac{h}{2} = \frac{\Delta L}{L}$$



Gravitational wave sources

- Binary Inspirals
    - Coalescence of binary black holes, neutron stars
    - Signal ~ we know what it will look like
    - Short duration signals detected by LIGO and Virgo GW detectors

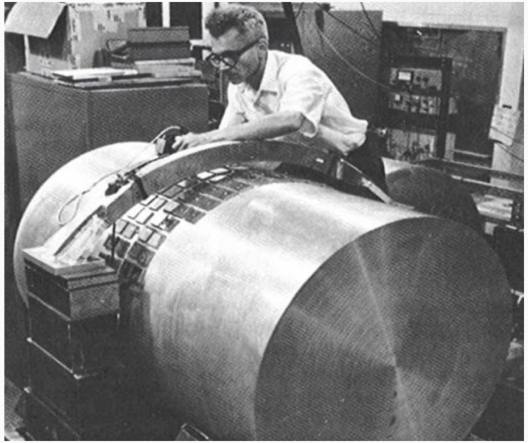
- Continuous wave
    - Spinning neutron stars and pulsars
    - Imperfections in spherical geometry
    - Long duration signals

- Stochastic
    - Superposition of many sources
    - Similar to CMB but goes back way further in time
    - Correlation between two or more detectors

Gravitational Wave Detectors

History of gravitational wave detectors

Resonant mass detectors



Weber's bar detector in 1960's
Vibrate like a tuning fork when a GW passes by

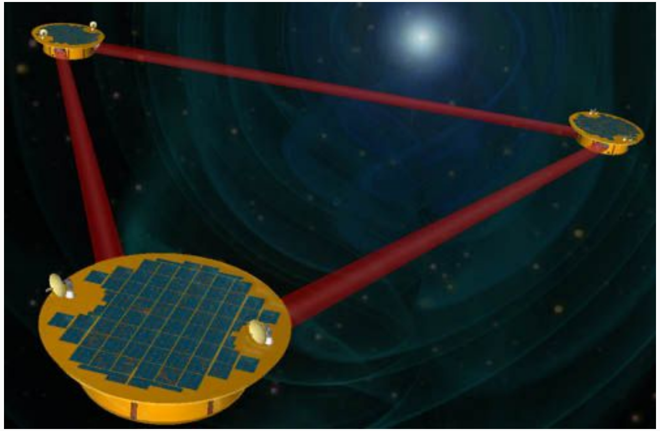
www.sciencemag.org

Ground based detectors

Two LIGO detectors in US
Virgo detector in Italy
Kagra in Japan
Upcoming LIGO detector in India

www.ligo.org

Space based detectors



Equilateral triangle with 2.5 million kms long arms
To detect low frequency GWs
Schedule launch in 2030's

www.lisa.nasa.gov

Gravitational wave detectors

Construction

- Installation and testing
- Ends with Acceptance ~ ifo can lock
- Short engineering runs
- aLIGO constructed completed in March 2015

Commissioning

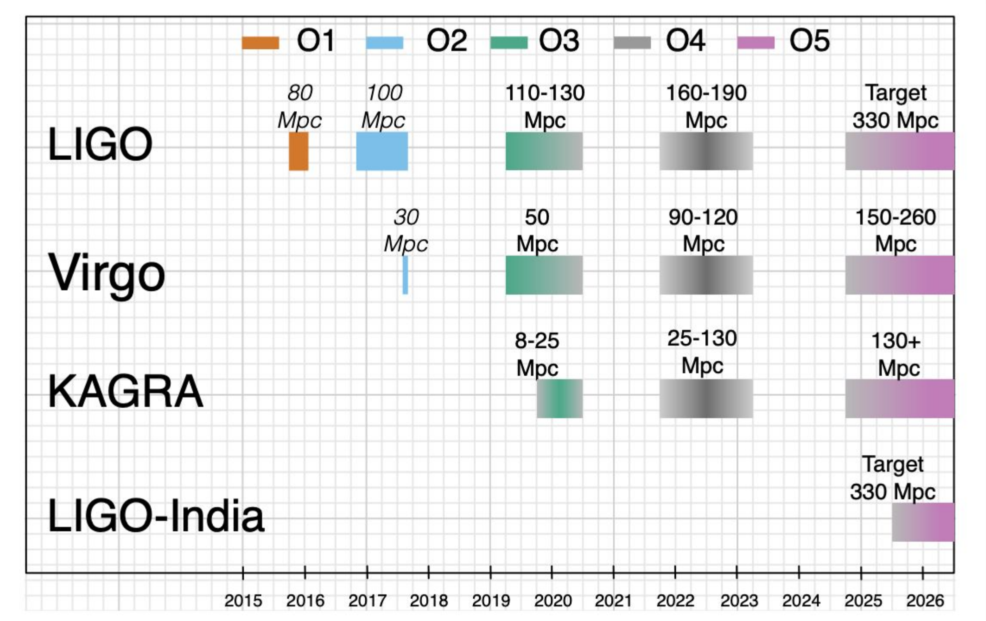
- Reach design sensitivity
- Engineering runs
- Scheduled checks and unexpected problems

Observing

- Maintain higher sensitivity
- Astrophysical results
- O1, O2 and O3

Prospects for Observing and Localizing GW Transients with aLIGO, AdV and KAGRA. B.P. Abbott et al

O1 to O5

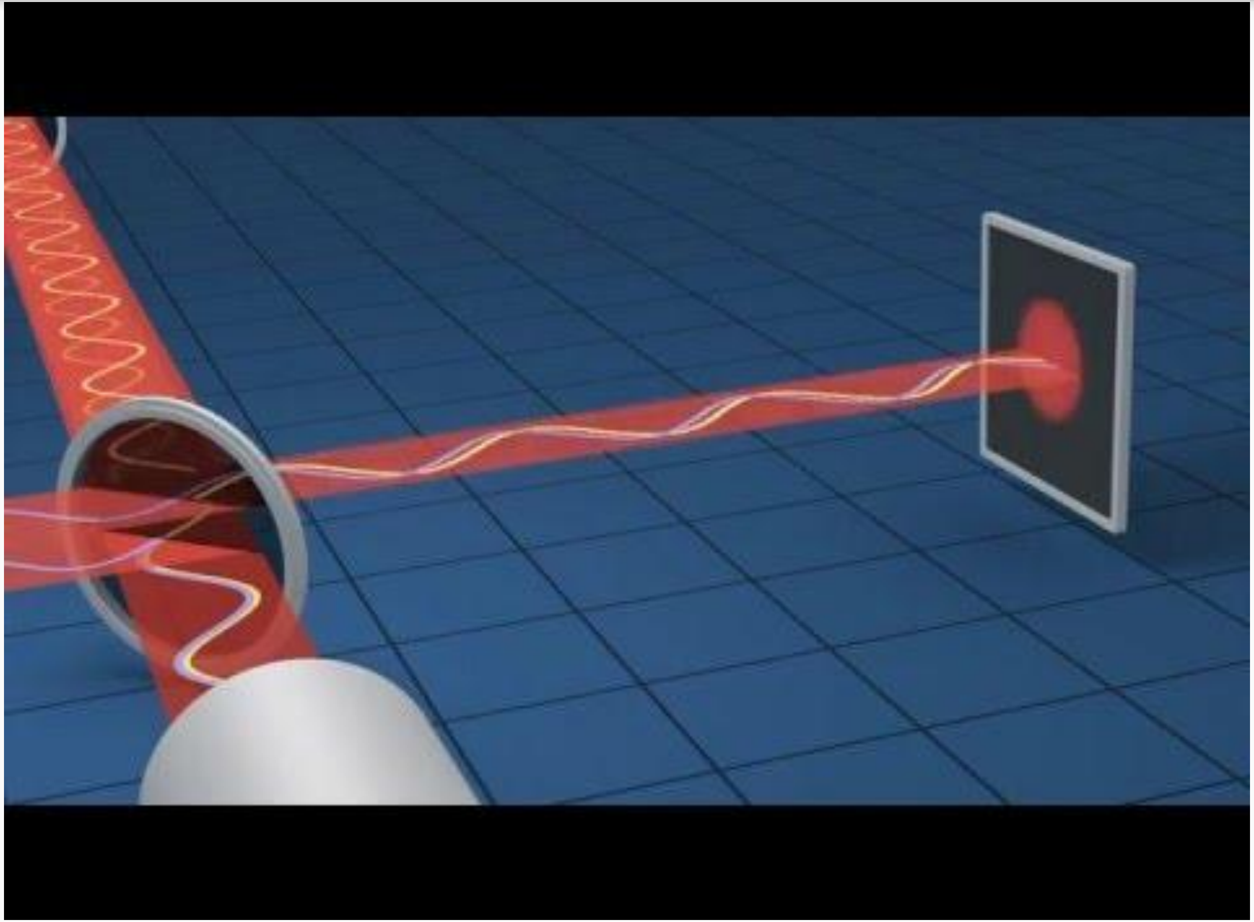


O1 and O2 → a total of 10 BBH and 1 Neutron star merger
O3 → 56 public alerts
O4 → Several detections per day predicted

Prospects for Observing and Localizing GW Transients with aLIGO, AdV and KAGRA. B.P. Abbott et al

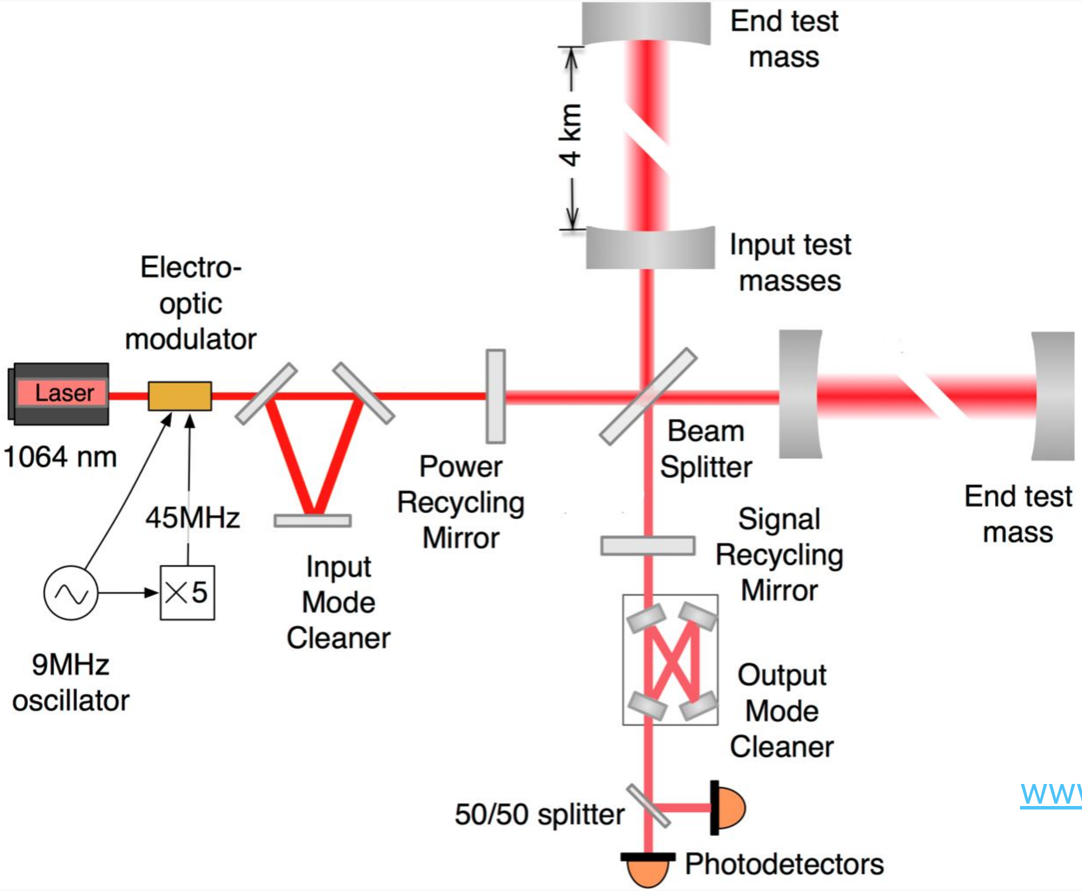
How does LIGO work?

LIGO animation



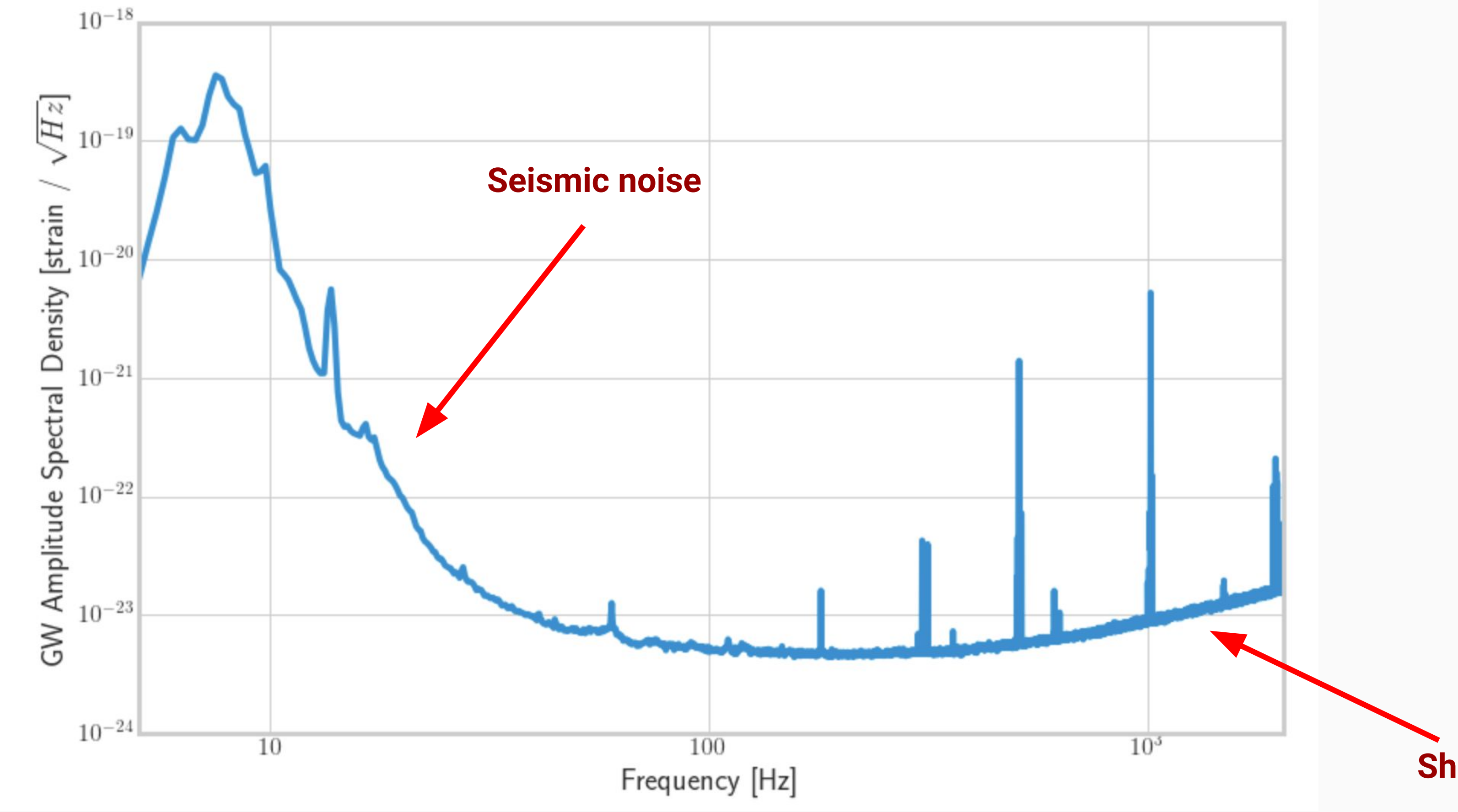
comunicazioneINFN

LIGO detector



www.ligo.org

Seismic and Shot noise

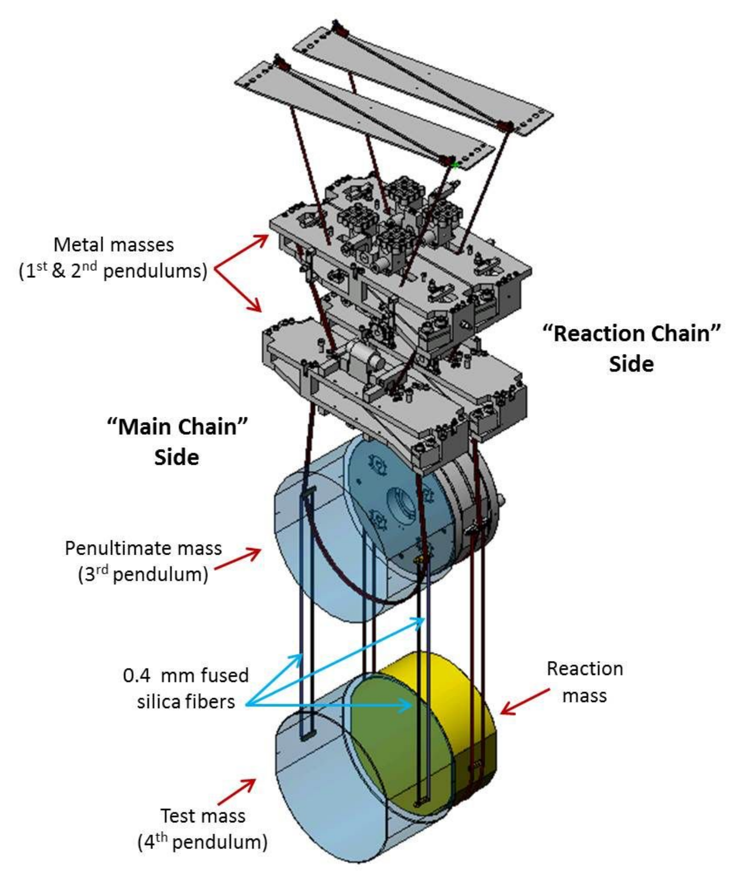


Seismic noise

Shot noise

Ground motion and Suspension

- Ground motion in the frequency band 0.01 Hz to 30 Hz
- Earthquakes
- Ocean waves, winds
- Human activity, logging
- Trains, thunderstorms



www.ligo.org

Quantum noise

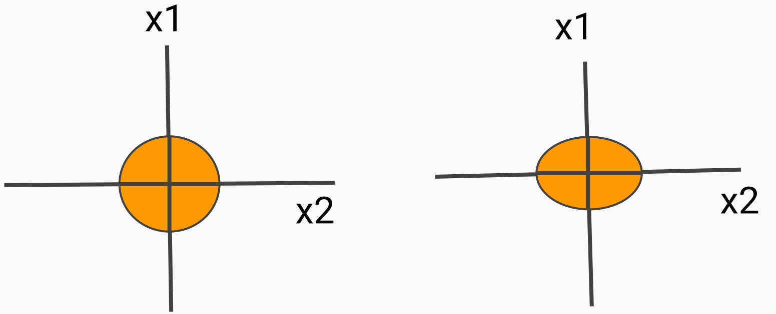
Shot noise

- Uncertainty in photon arrival time
- Variance in phase, high frequency noise
- Decreases with increase in Laser power

Radiation pressure noise

- Fluctuations in mirror position
- Variance in amplitude, low frequency noise
- Increases with increase in Laser power

Squeezing



Classical state **Squeezed state**

- Squeezing contributed to increase in sensitivity during O3 at higher frequencies
- Plans to include frequency dependent squeezing in O4

Recent Discoveries

Identification of GWs using Search pipelines

1. Match filter detector data with Template bank
    1. Template bank is a collection of waveforms generated using post-Newtonian approximations and numerical relativity
    2. The template bank covers a 4 dimensional space of masses and spins of the binaries

2. Identify coincident events between the detectors

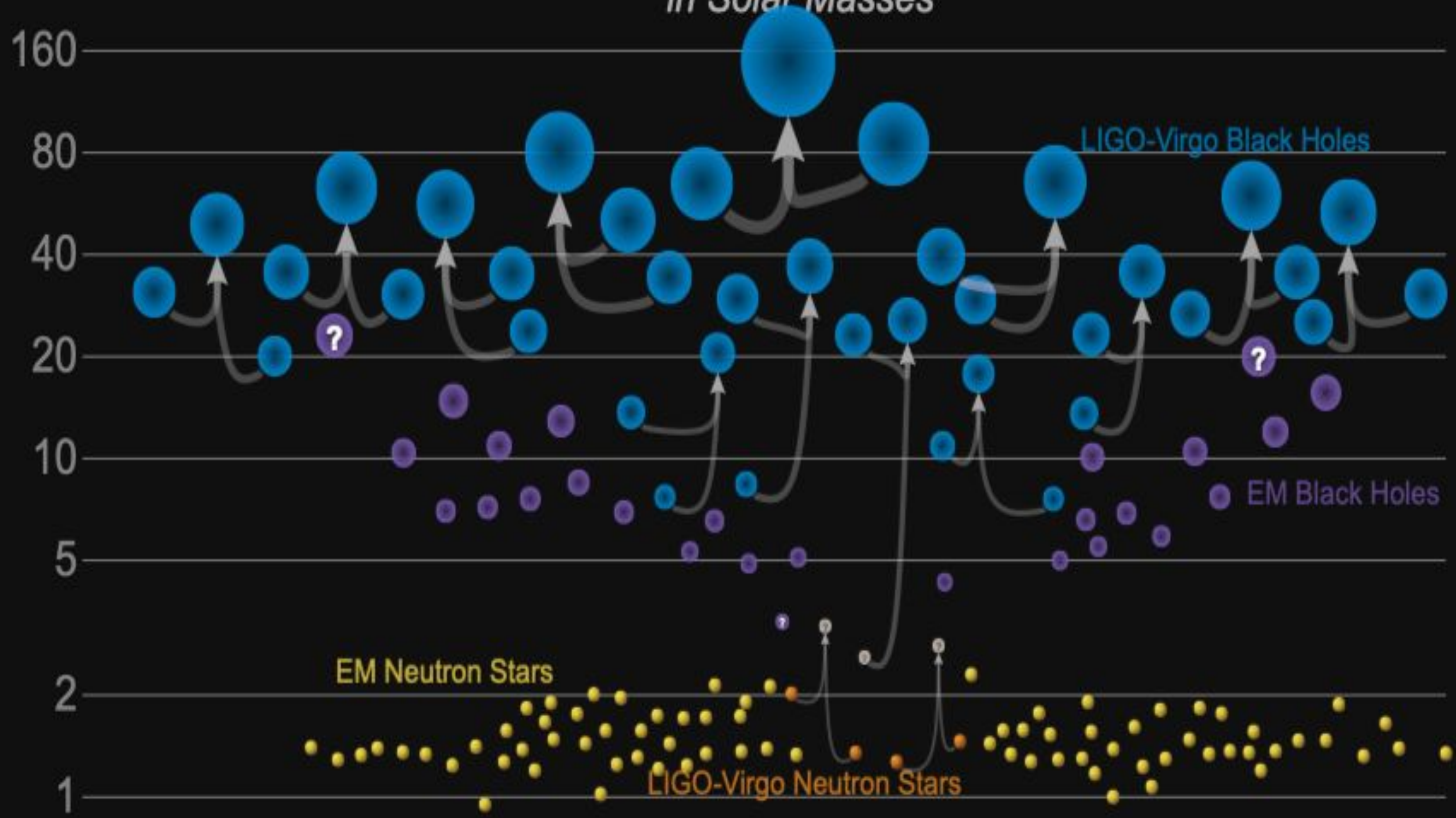
3. Calculate false alarm rate

4. Alerts are sent to the wider community

The PyCBC search for gravitational waves from compact binary coalescence. S Usman et al

Masses in the Stellar Graveyard

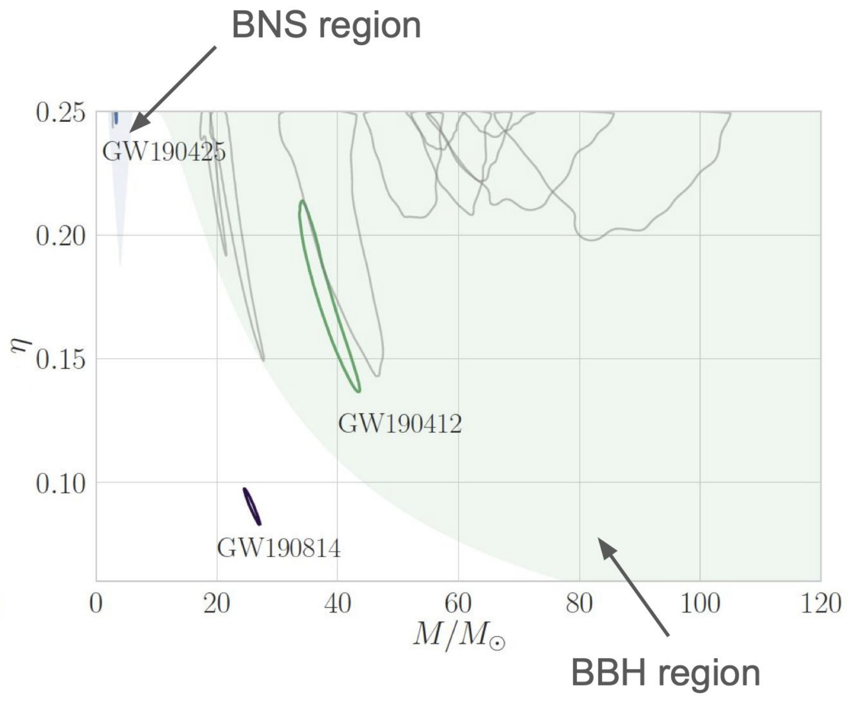
in Solar Masses



Updated 2020-09-02
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

GW190814

- Primary mass ~ 23.3 M⊙, secondary mass ~ 2.6 M⊙
- Lowest mass ratio measured of all the GW events
- First GW event with compact object mass in the range 2.5 - 3 M⊙
- The secondary object either the heaviest neutron star or lightest black hole ever discovered in the binary system
- No detection of EM counterpart
- Higher order multipoles observed with a high significance

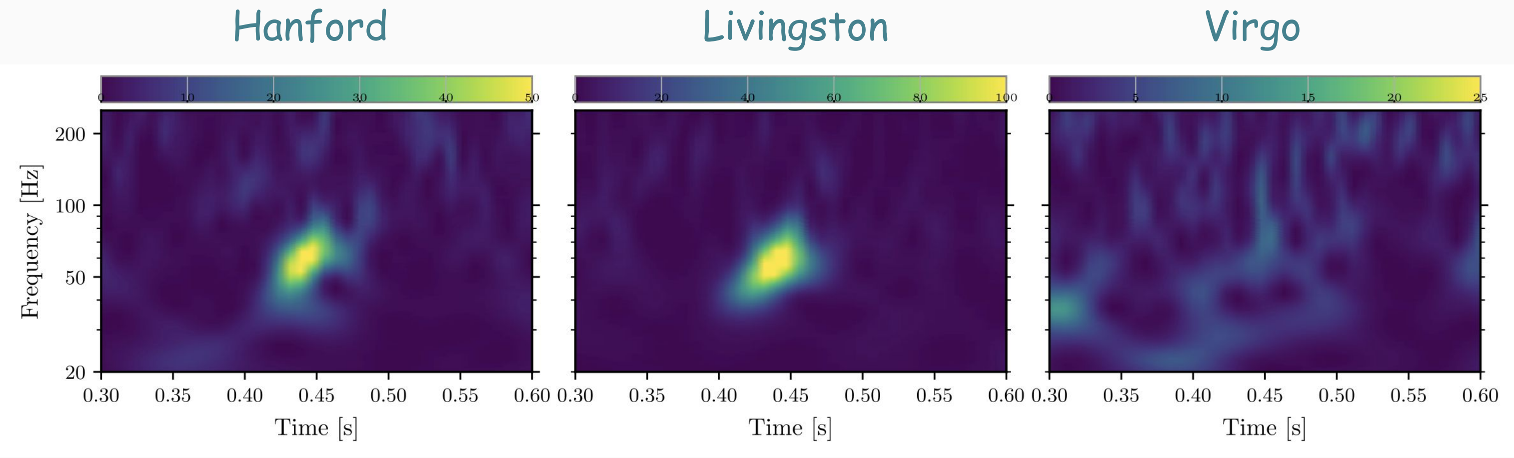


GW190814 discovery paper.

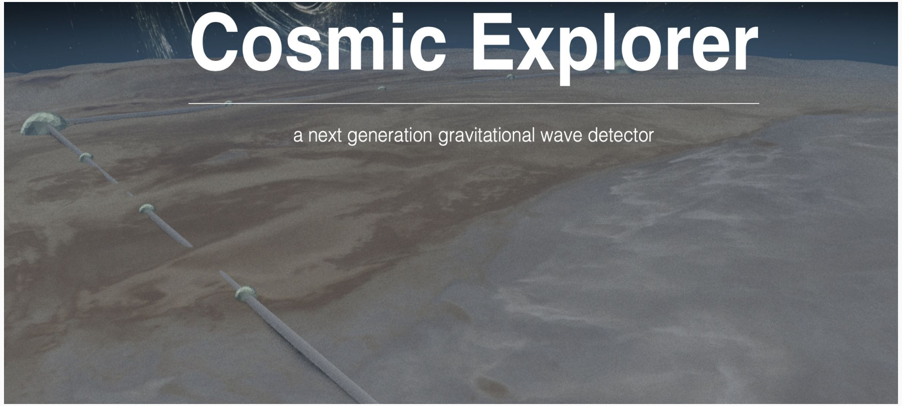
GW190521

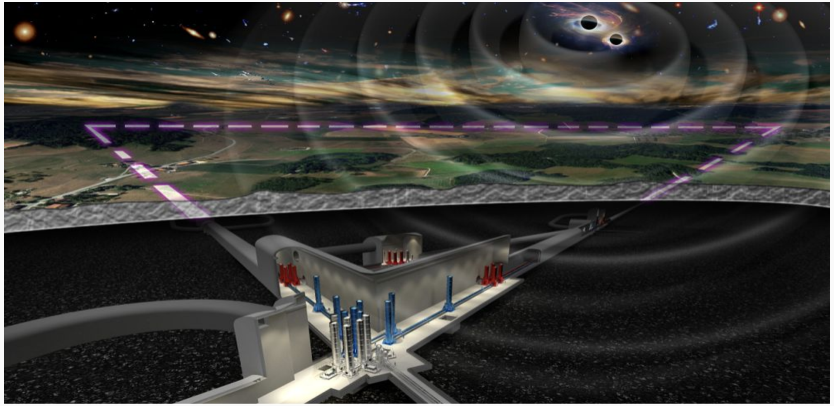
- Primary mass ~ 85 $M_\odot$ and secondary mass ~ 66 M
- Remnant mass ~ 142 $M_\odot$
- Peak frequency ~ 60 Hz
- Signal duration ~ 100 milliseconds

- Primary object in the upper mass gap
- Merger remnant is IMBH
- GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$



Future : Cosmic Explorer and Einstein Telescope



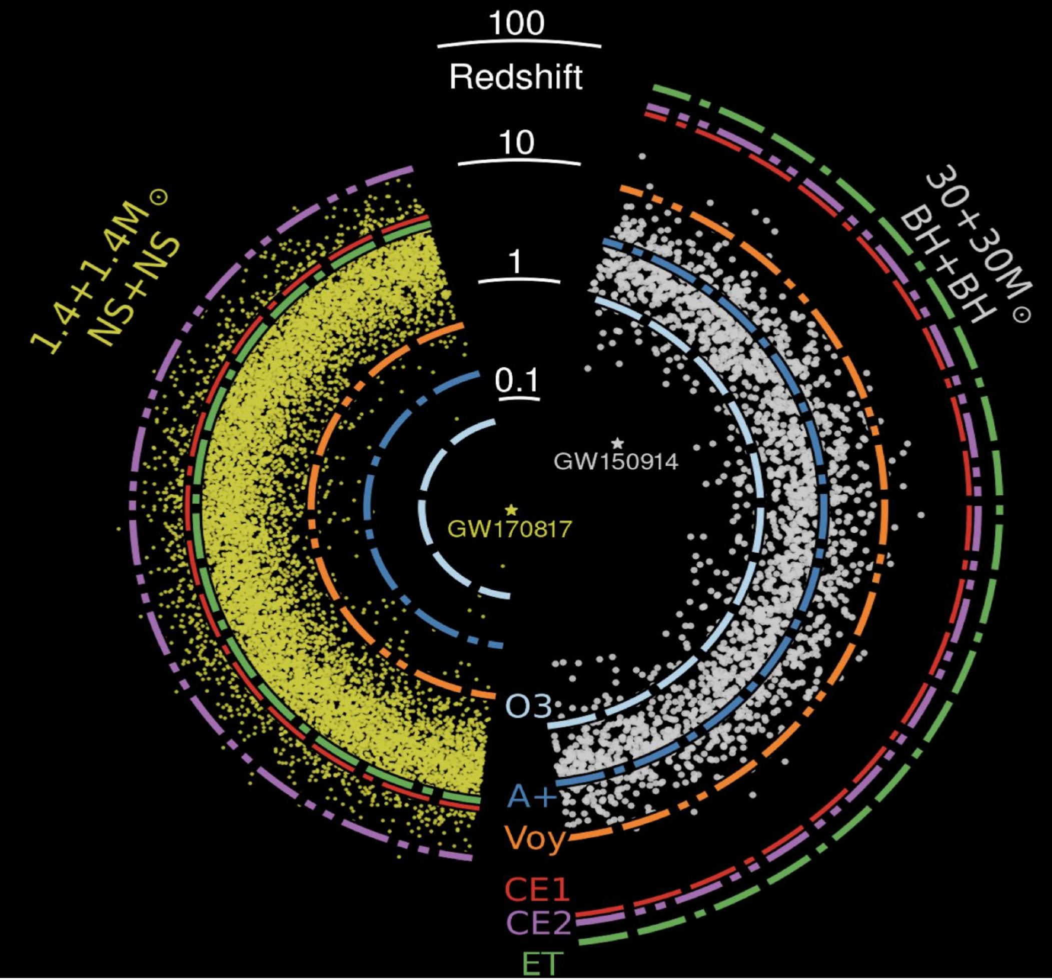


- 3rd generation ground based detector in US
- 40 Kms long L shaped arms
- 10 times more sensitive than Advanced LIGO and Virgo
- CE1 in 2030s and CE2 in 2040s

https://cosmicexplorer.org

- 3rd generation underground observatory in Europe
- 10 kms long arms
- Three triangularly nested detectors
- Construction in 2026, Observation in 2035

http://www.et-gw.eu



S. Vitale, E. Hall, MIT

COSMIC EXPLORER

[Cosmic Explorer : the proposed US contribution to 3rd generation GW detector network by Joshua Smith]

Thank You!
Questions and Comments

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