Science with gravitational waves in the era of LIGO-Virgo-KAGRA discoveries

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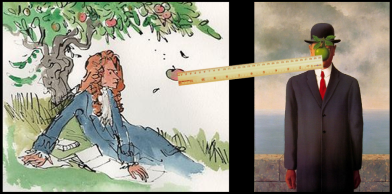
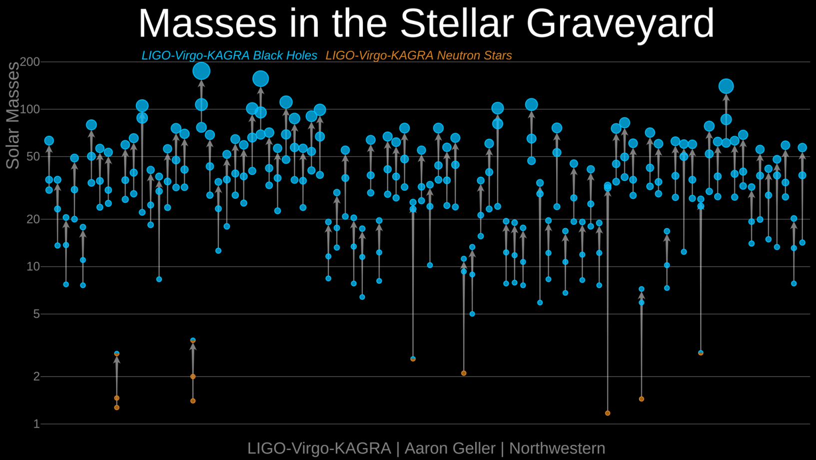
6.3.24

LIGO-Virgo(-KAGRA) global detector network

Very precise rulers: measuring distances between free-falling bodies with laser light.

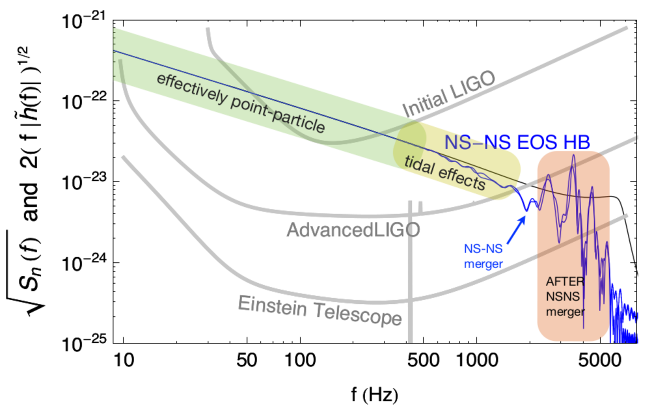


Compact objects population in GWTC-3 (O1, O2, O3)



$\sim$200 events until now (including O4), and counting...

GW spectrum of binaries (e.g., BBH, BNS)

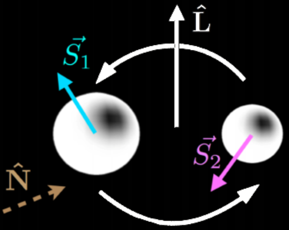


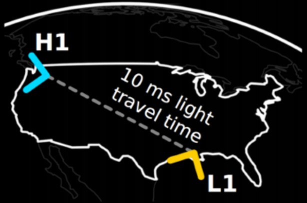
Phase evolution may differ from point-particle description because of extended-body interactions:

$$\Psi(f) = \Psi_{PP}(f) + \Psi_{tidal}(f)$$

Binary system waveform: 15+ parameters

- Intrinsic:
  - masses
  - spins
  - tidal deformability





Credit: LIGO/Virgo

- Extrinsic:
  - Inclination, distance, polarisation
  - Sky location
  - Time, reference phase

Astrophysically-interesting parameters

Intrinsic:

- ⋆ Chirp mass $\mathcal{M} = \left(\mu^3 M^2\right)^{1/5} = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$,
- ⋆ Mass ratio $q = m_2/m_1$ (at 1PN), alternatively $\nu = m_1 m_2/(m_1+m_2)^2$,
- ⋆ Spin-orbit and spin-spin coupling (at 2PN and 3PN, resp.) $\rightarrow$

$$\chi_{eff} = (m_1\chi_{1z} + m_2\chi_{2z})/(m_1+m_2)$$

  where χ_{iz} are spin components along system's total angular momentum,

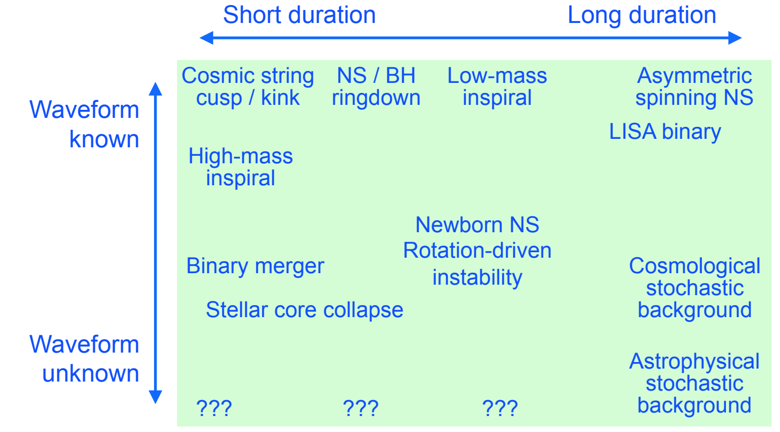
- ⋆ Tidal deformability Λ (at 5PN) $\rightarrow$

$$\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1}{(m_1+m_2)^5} + (1\leftrightarrow 2), \qquad \mathcal{R} = 2\mathcal{M}\tilde{\Lambda}^{1/5}$$

Extrinsic:

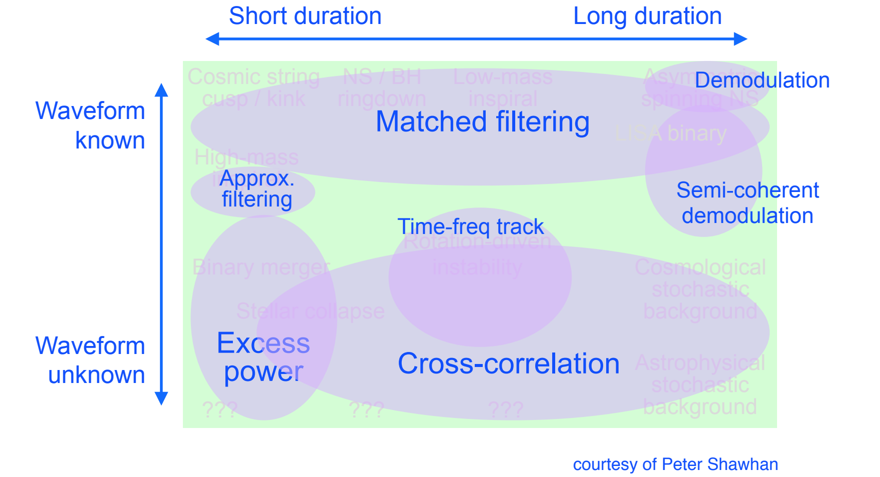
- ⋆ Direct "luminosity" ("loudness") distance: binary systems are "standard sirens".

Taxonomy of signal and search types

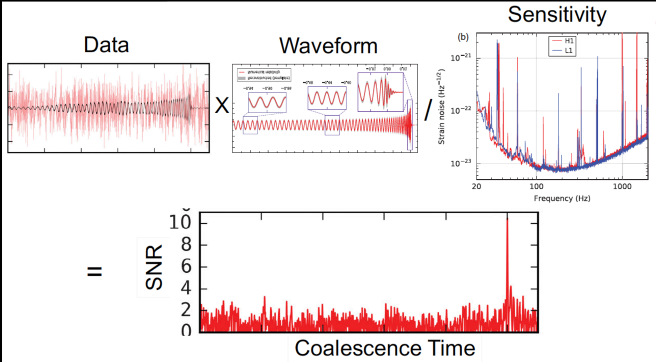


courtesy of Peter Shawhan

Taxonomy of signal and search types



Matched filter in pictures



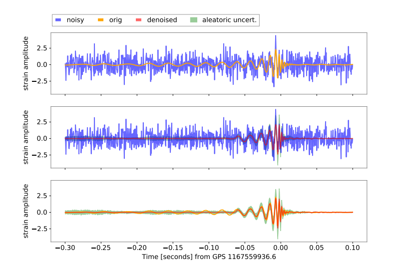
- ⋆ With the data $s(t) = n(t) + h(t)$,
- ⋆ signal template $h_t(t)$ and
- ⋆ one-sided amplitude spectral density of the noise $S_n(f)$, defined as $\langle \tilde{n}(f)\tilde{n}^\star(f')\rangle = \frac{1}{2} S_n(|f|)\delta(f-f')$,

the matched filter is an inner product

$$(s|h) = 2\int_{-\infty}^{\infty} \frac{\tilde{s}(f)\tilde{h}_t^\star(f)}{S_n(f)}\,df$$

Machine learning in GW astronomy

- ⋆ Signal detection and classification,
- ⋆ Parameter estimation,
- ⋆ Data cleaning (denoising),
- ⋆ Discovering relations and patterns in data,
- ⋆ Forecasting / prediction.

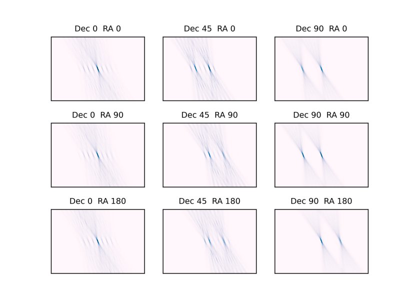


Data denoising using Denoising

AutoEncoders Neural Networks

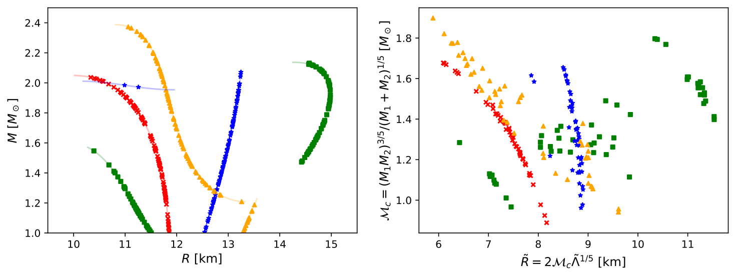
`arXiv:2205.13513`

Searching for long-duration signal patterns:



Machine learning in GW astronomy

Patterns in the EM observations of neutron stars $M(R)$, and GW $\mathcal{M}_c(\mathcal{R})$:

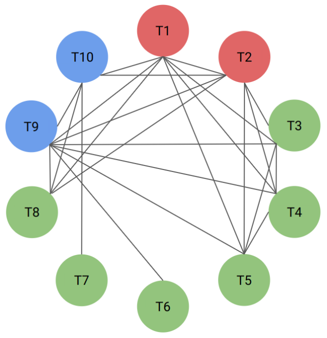


$\mathcal{M}_c(\mathcal{R})$, "binary system" analog to $M(R)$:

- ⋆ Chirp mass $\mathcal{M} = \left(\mu^3 M^2\right)^{1/5} = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$,
- ⋆ Mass-weighted tidal deformability
  $\tilde{\Lambda} = \frac{16}{13}(m_1 + 12 m_2) m_1^4 \Lambda_1/(m_1+m_2)^5 + (1 \leftrightarrow 2)$, $\qquad \mathcal{R} = 2\mathcal{M}\tilde{\Lambda}^{1/5}$

Science with gravitational waves in the era of LIGO-Virgo-KAGRA discoveries

Interplay between observations (data analysis, also using ML), theory (astrophysics) and computation (efficient computational methods).



1. Monitoring of sensor network and analysis of seismic and infrasound data
2. Monitoring of magnetic noise and its influence on gravitational wave detectors
3. Development of data analysis methods and search for long-duration signals in the all-sky survey
4. Development of a narrow-band search pipeline using the F-statistic and optimal grids
5. Search for gravitational waves from r-mode instabilities in pulsar J0537-6910
6. Methods to search for gravitational waves from postmerger stage of compact binary coalescences
7. Using LLM models for partial data-analysis automation of EM-GW observations
8. Measuring the core-collapse supernova engine dynamics with GWs
9. Models of extreme-matter GW sources as input to GW data analysis
10. Formation and properties of compact object binaries

Science with gravitational waves in the era of LIGO-Virgo-KAGRA discoveries

Future detectors (LIGO/Virgo+, ET, CE) will reach farther in distance, and broader in frequency:

- ⋆ long inspirals and post-merger signals,
- ⋆ unmodeled signal types,
- ⋆ weak/complicated/overlapping signals.

We design efficient ways to

- ⋆ improve long-duration GW searches: post-processing with ML,
- ⋆ searches for GWs with complicated signal morphology,
- ⋆ analyse population of GW signals to uncover details of the dense matter EOS,
- ⋆ calculate models of neutron stars with specific dense-matter features as components of GW sources.

If you are interested in GW astronomy, contact me

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