DeepCW: using Deep Learning to find Continuous Gravitational Waves (CW)

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Continuous Gravitational Waves from Spinning Neutron Stars (NSs)

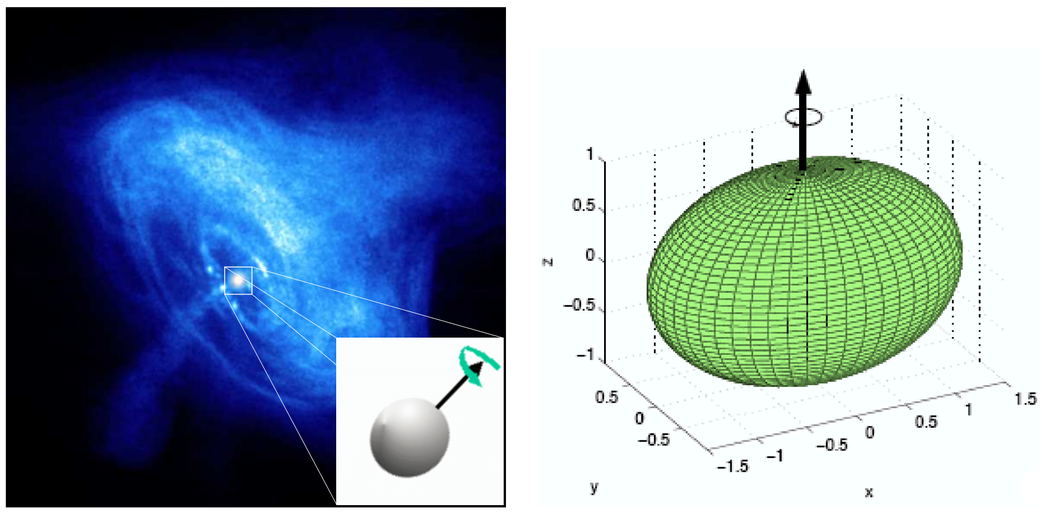


Figure 1: Spinning non-axisymmetric NSs emit CWs of frequency f = twice the NS rotation rate.

- a spinning neutron star (distance d, rotation rate ν, eccentricityϵ, moment of inertia I_{zz}) emits continuous gravitational waves (CWs).
- expected to be located in supernova remnants
- the strain amplitude h_0 on Earth would be

$$h_0 = 4 \times 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I_{zz}}{10^{45}\,\mathrm{g\,cm^2}}\right) \left(\frac{\nu}{100\ \mathrm{Hz}}\right)^2 \left(\frac{100\,\mathrm{pc}}{d}\right) ,$$

☞ **Extremely weak signals!**

Detector Data

- Detector data is a time series of strain $h(t) = h_{\mathrm{noise}}(t) + h_{\mathrm{signal}}(t)$
- CWs have nearly constant frequency
  ☞ **Analysis in Fourier domain**
- Doppler shifts broaden the signal (see Fig.2 right)
- With unkown parameters we have to search a frequency band (see Fig.2 left)

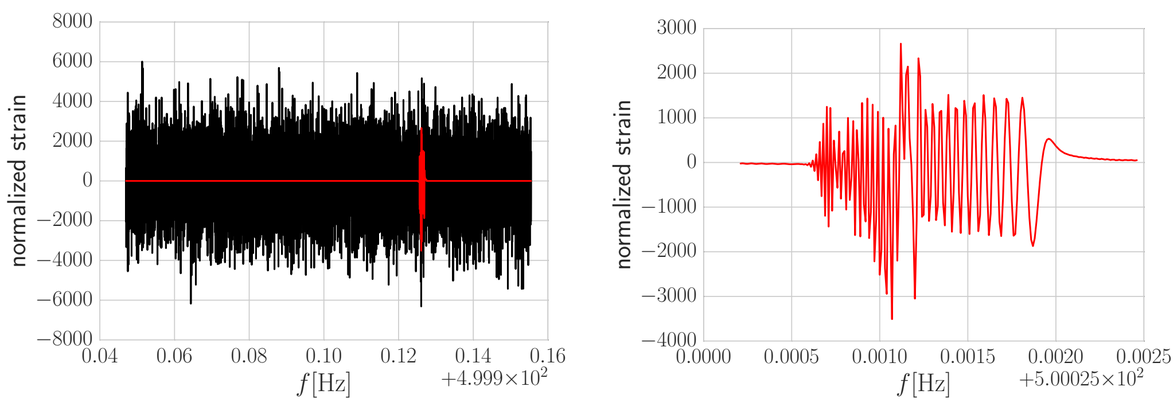


Figure 2: Signals in frequency domain:
Left: signal (red) and signal + noise (black), Right: signal template

- we define signal strength as ratio of the power spectral density (PSD) and the strain amplitude h_0 (giving the depth $\mathcal{D}$):

$$\mathcal{D} = \frac{\sqrt{\mathrm{PSD}}}{h_0}$$

Matched Filtering

Template search:

- create templates for many different signal parameters (e.g. f, $\dot{f}$, sky-position).
- compare every template against the detector data
  ☞ **detection statistic**
- Does the statistic cross a certain threshold corresponding to a fixed p-value?

Properties of matched filtering:

- optimal method if a template matches a signal perfectly
- **but** in general loss of sensitivity due to mismatch
- in principle: just use as many templates as possible.
- **but** computational cost limits the number of templates and hence the sensitivity
- distributed computing project Einstein@Home (https://einsteinathome.org/)

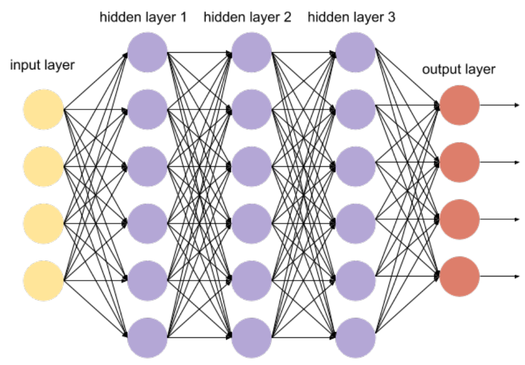
References

[1] Gabbard, Hunter, et al. "Matching matched filtering with deep networks for gravitational-wave astronomy." Physical Review Letters 120.14 (2018): 141103.

[2] George, D. and Huerta, E. "Deep neural networks to enable real-time multimessenger astrophysics" Physical Review D, APS, 2018, 97, 044039

Deep Learning

- Machine learning: algorithms learning from examples
- artificial neural network with many layers
- convolutional neural networks (CNN): not every neuron is connected with every neuron in the next layer but they form local filters
- has been tested for searches for signals from merging black holes [1]



Our Approach: use CNN to find CWs

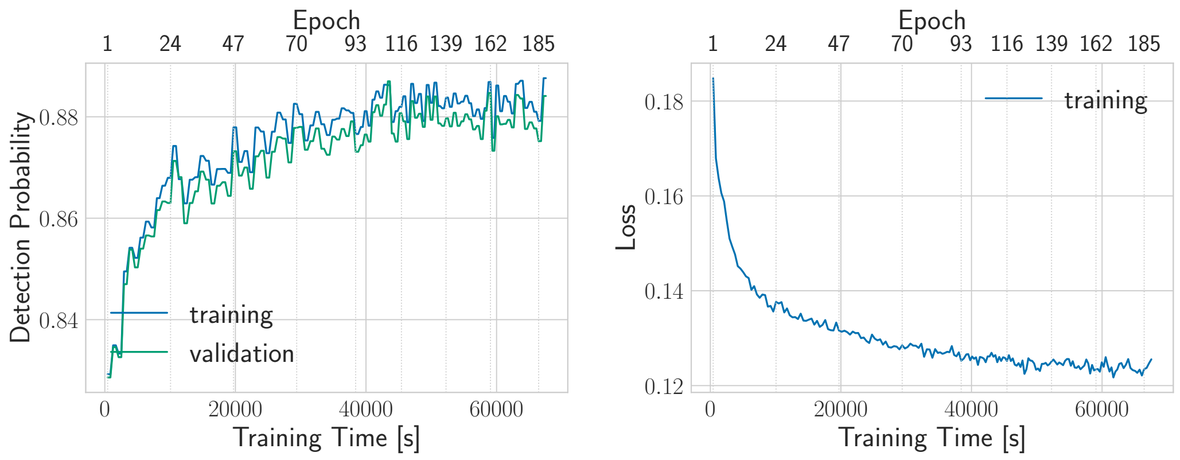
Input layer:

- fourier transformed time series of the normalized strain $\tilde{h}(f)$
- **training set**: signals are generated with random parameters and
- is placed in generated Gaussian noise (see Fig. 2 left)

Output layer:

- probability that the input contains a signal or not
- can be interpreted as detection statistic to calculate a threshold for given p-value
- calculate detection (threshold crossing) probability
- compare to matched filtering performance

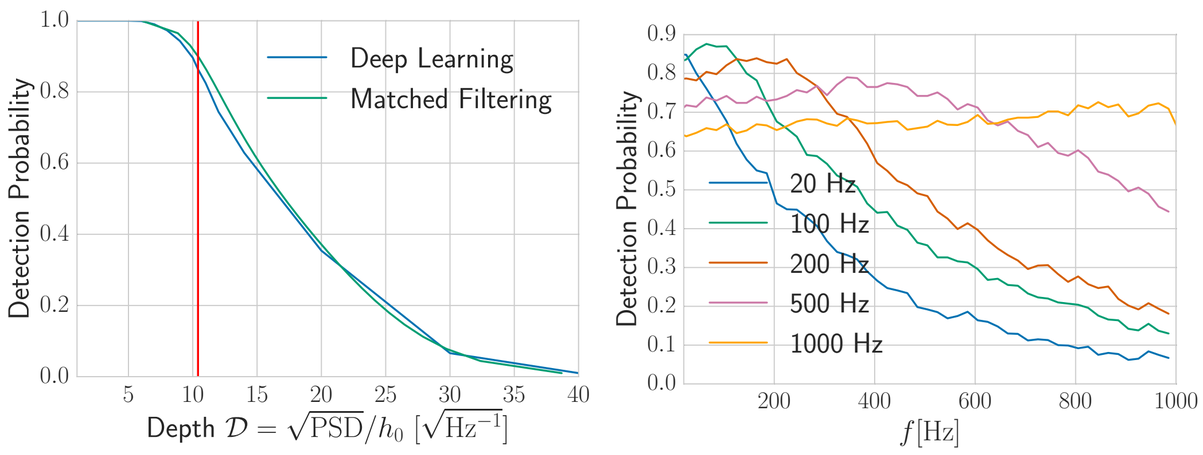
Training Example: 100 Hz signals



- Here matched filtering achieves a detection probability of 90% at a fixed false alarm rate of 1% and a fixed signal strength $\frac{\sqrt{\mathrm{PSD}}}{h_0} = 10.4\,\sqrt{\mathrm{Hz}^{-1}}$.
- The network trained at a frequency of 100 Hz reaches about 88%.

Generalisation in signal strength and frequency

- Testing the network at different signal parameters than trained (given by red line and legend)



- different signal strength: similar performance to matched filtering
- maintains sensitivity over $\gtrsim 100$ Hz
  ☞ only a couple of networks needed to cover wide frequency range

Future Work

- current approach does not contain parameter estimation
  ☞ change output, locating the signal in frequency
- testing the network with real noise
- proper optimization of hyper parameters
- setting up a full scale all sky search (e.g. $f = [20, 1000]$ Hz)

Astronomical Data Analysis Software & Systems 2018, College Park, Maryland, 11th to 15th November 2018