



Using Convolutional Autoencoders for Signal Detection of Extreme Mass Ratio Inspirals Detected by the LISA Mission

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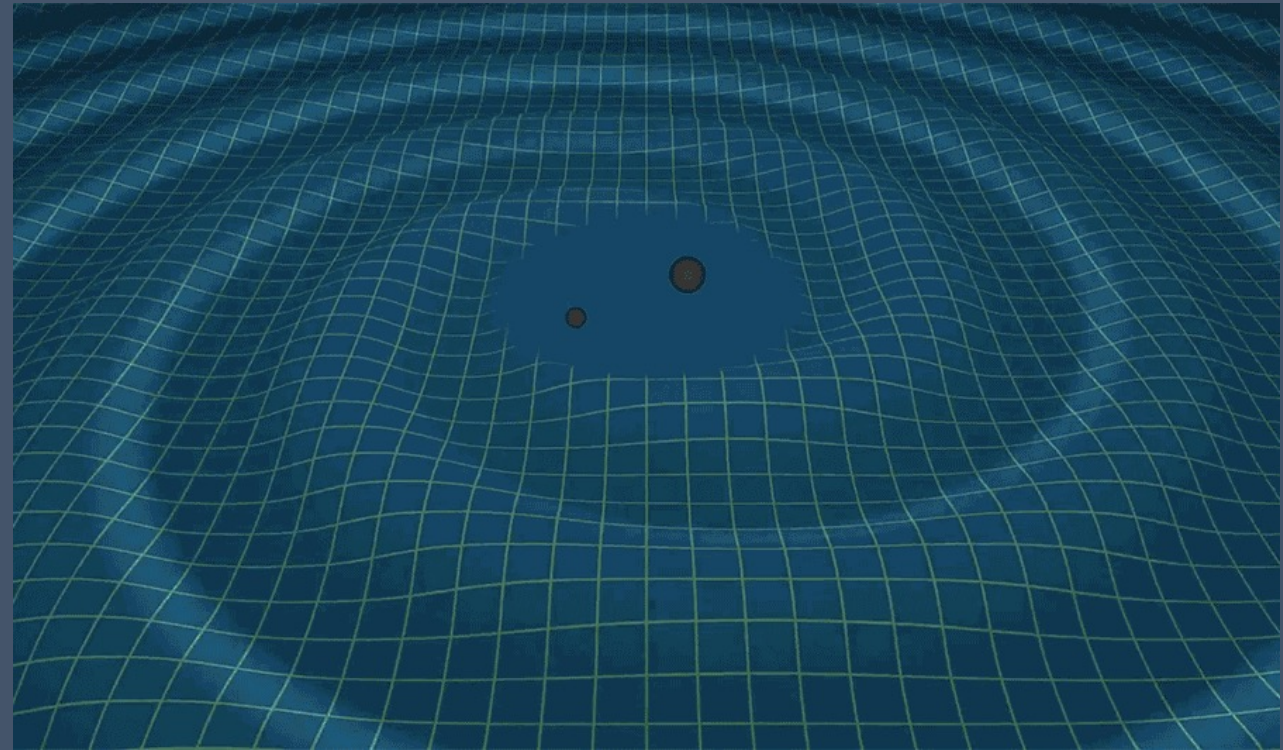
Some background on gravitational waves

Gravitational waves

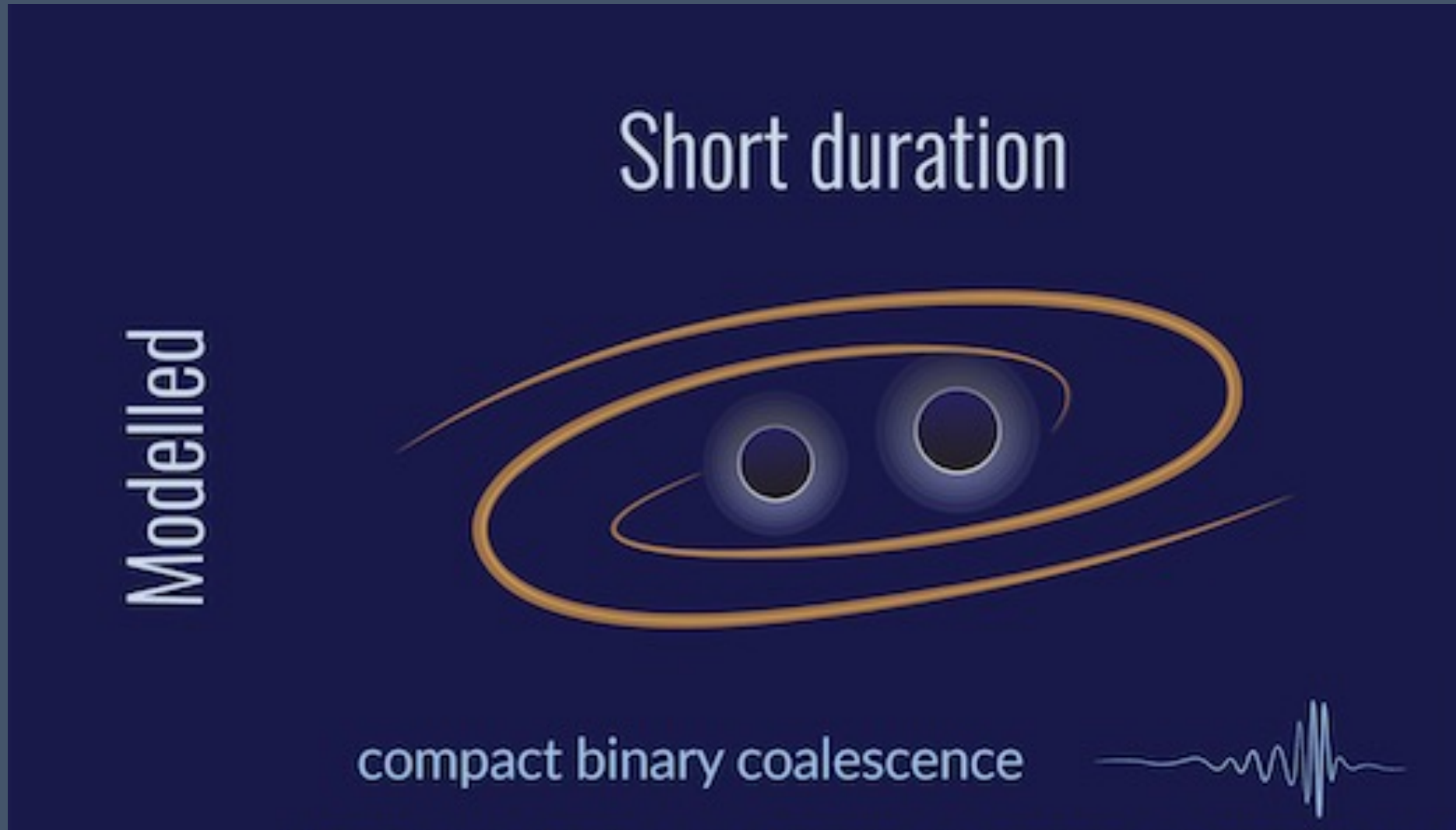
Definition: “ripples” in spacetime due to accelerating masses, as predicted by General Relativity

Properties:

- Light-speed propagation
- Two polarisations
- Extremely weak, $O(10^{-21})$

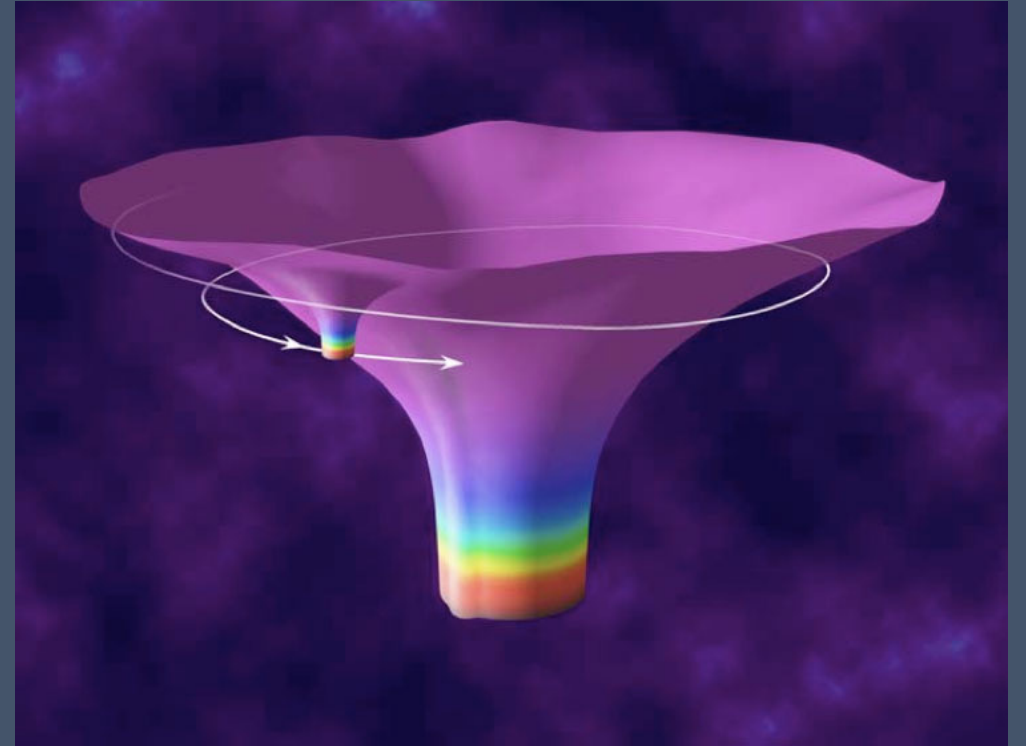


What category of GWs am I looking at?



Extreme mass-ratio inspirals (EMRI)

- Take a **black hole** and **neutron star** with masses M and μ
- $\frac{M}{\mu} > 10,000$
- The **black hole** captures the **neutron star** into its orbit, at the right distance
- The inspiral phase lasts from months to years ($\sim 10^4$ cycles)
- Low frequency GWs are emitted



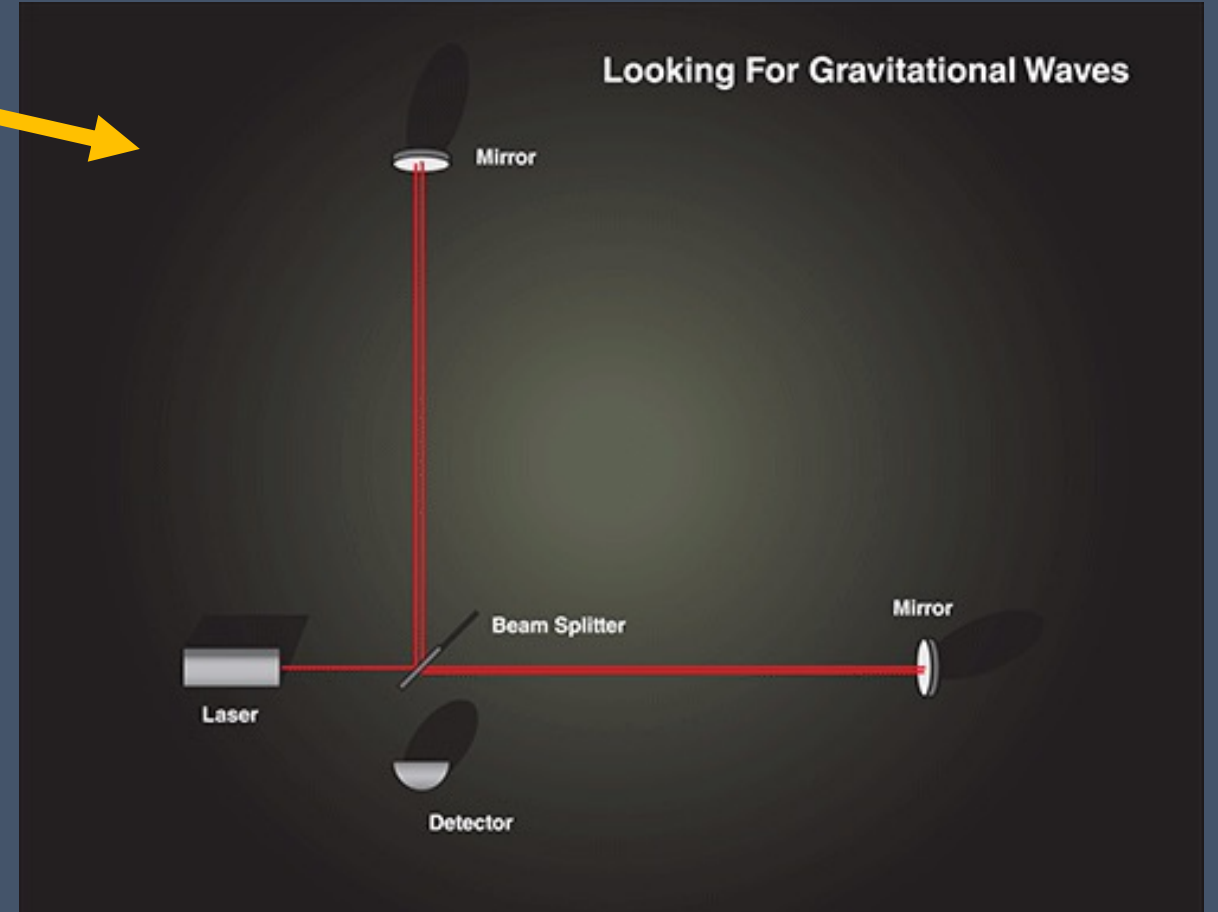
How to detect GWs

Detection apparatus: **Michelson interferometer**

To quantify GW amplitude ("strain"):

$$h(t) = \frac{L}{\delta L(t)}$$

For EMRIs, we need to take this detector to space!



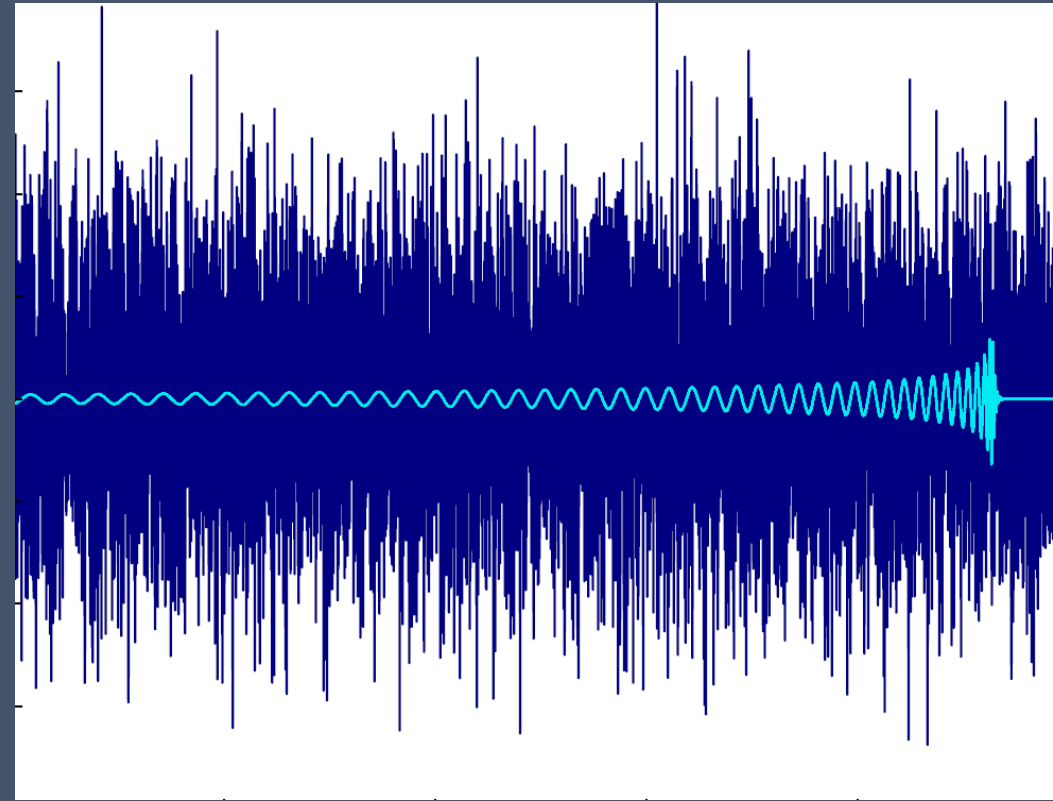
Modelling GW signals

GW source
emits this
event e.g.
EMRI

$$d(t) = h(t) + n(t)$$

GW detector
receives a
signal

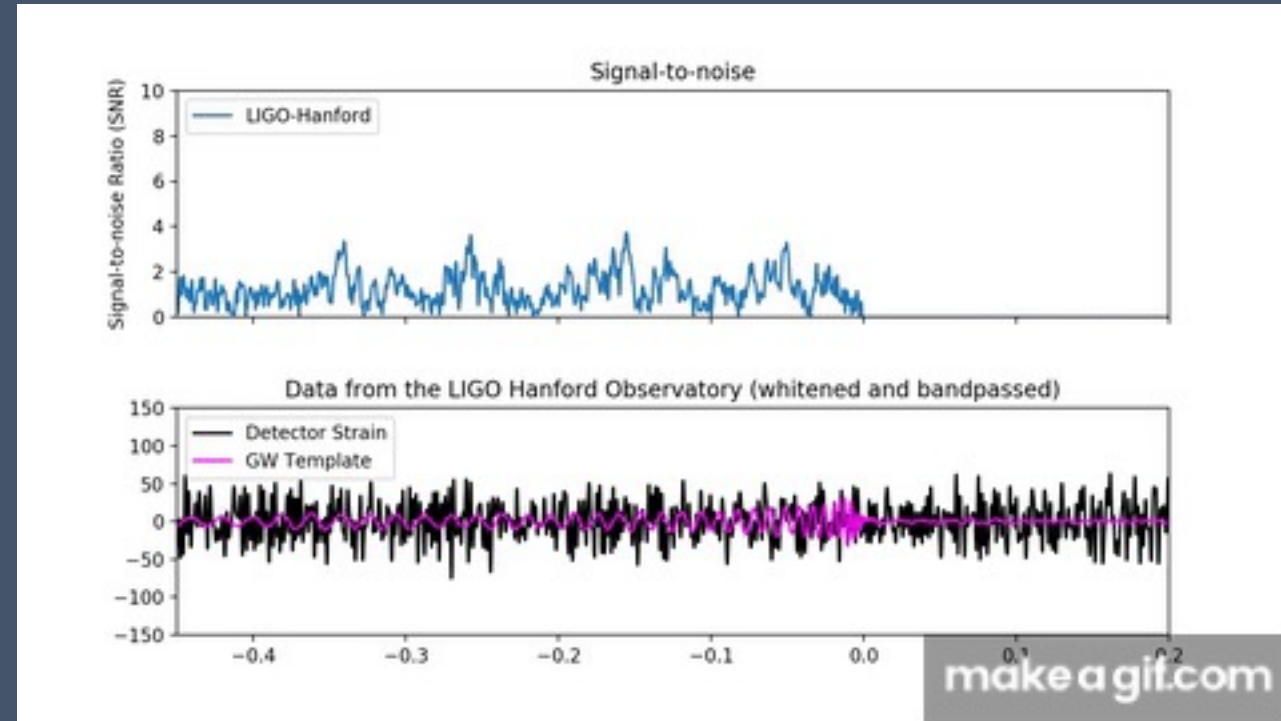
There is a
noise
background
too



Conventional signal detection of GWs

Analysis technique: **matched filtering**

- Generate a bank of template waveforms covering the entire parameter space
- Find the template waveform h that maximises the signal-to-noise ratio



Why matched filtering isn't suited to EMRIs

- 10^{40} templates needed
- Extremely long time to generate all templates
- Large template file size

Could machine learning techniques be an alternative?

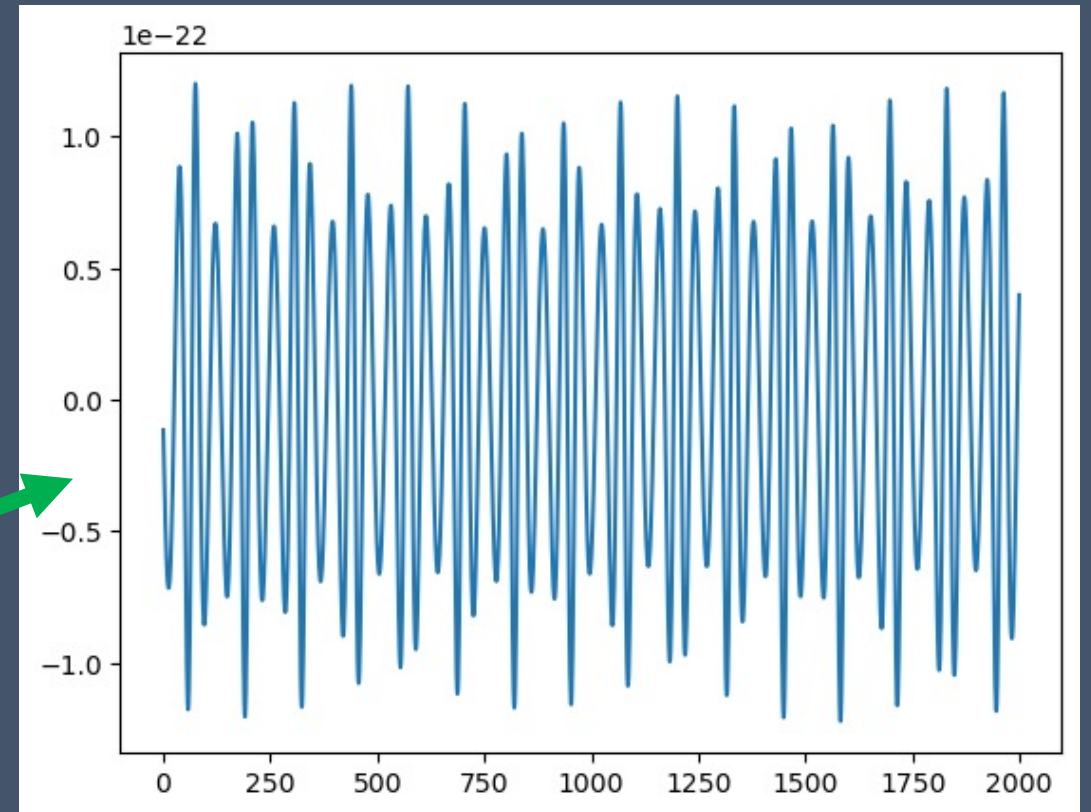
Why ML might be a good fit for EMRI data analysis

Trained ML models are:

- computationally *in*expensive
- process large amounts of data in short time
- “generalisable” in performance ?

Relevant application: **rapid generation of EMRI waveforms**

- Generates years-long signals in <1s



Some background on machine learning

What is ML?

Definition: Developing models and algorithms to perform a task without explicit instruction.

Applications:

- Image colorisation →
- Facial recognition
- Sentiment analysis
- Self-driving cars
- And many more!

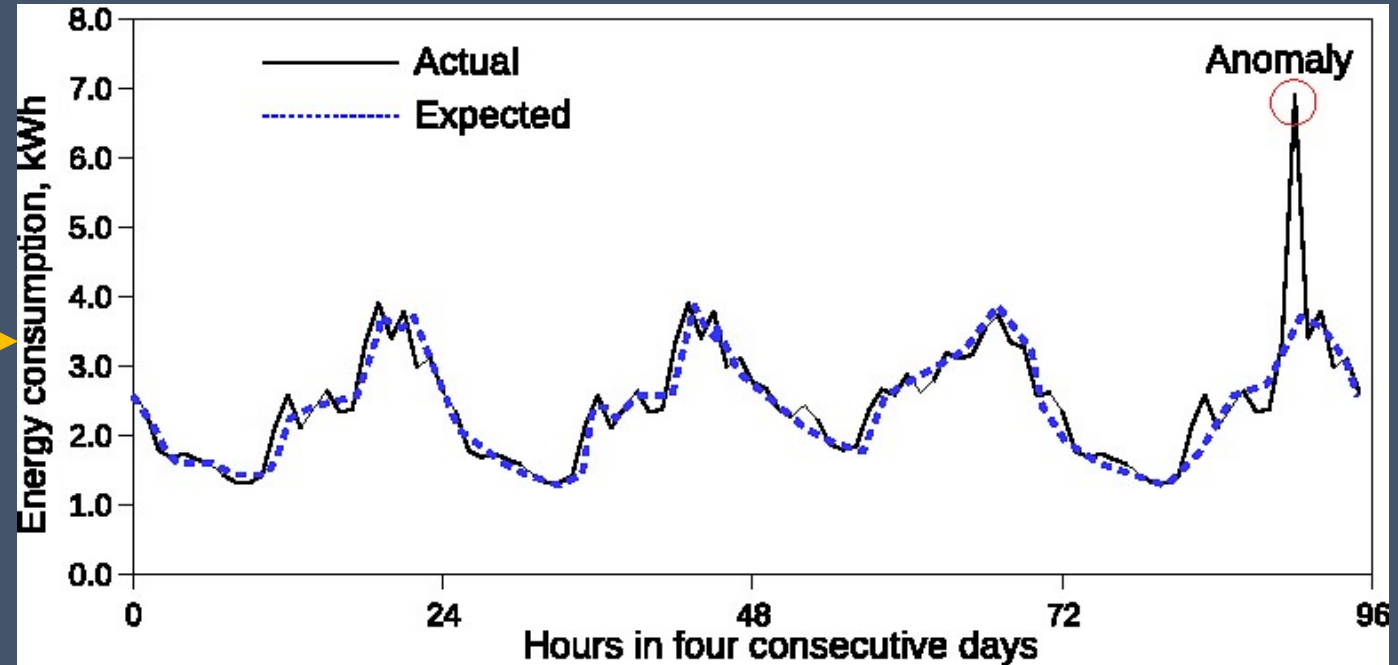


What type of ML model am I using?

- Convolutional autoencoder

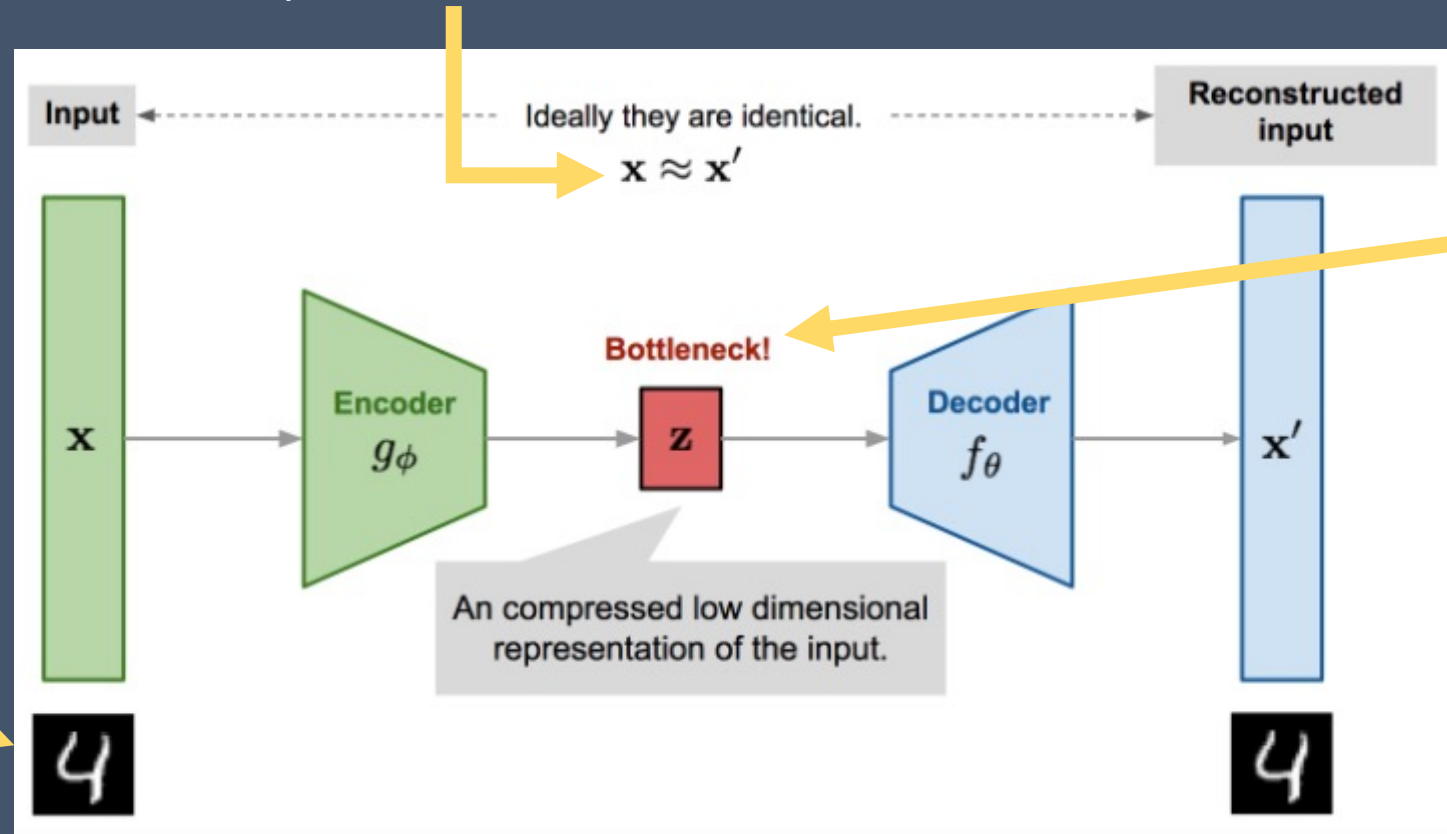
Common applications:

- **Anomaly detection** →
- Denoising
- Dimensionality reduction



Autoencoder

Quantify the reconstruction error in terms of a loss function



What if we gave it the number 5?

Model cannot learn the identity function

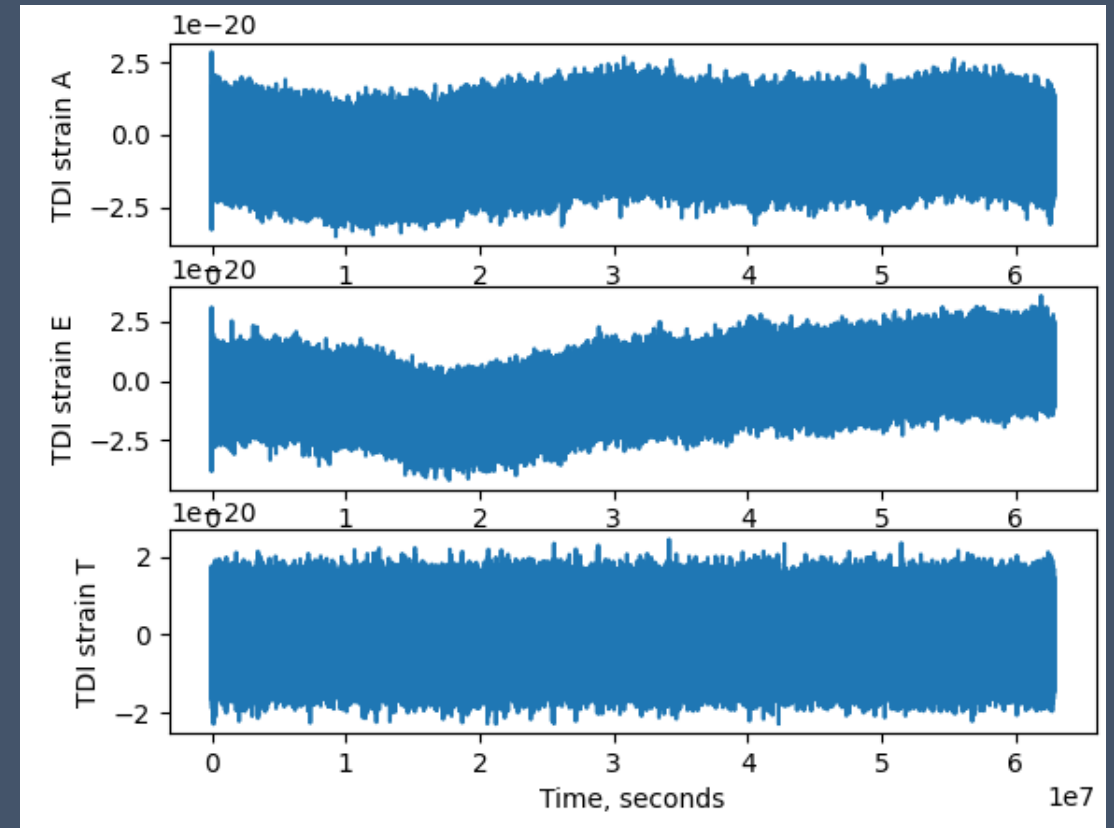
So let's train an autoencoder on EMRI signals.

Training the autoencoder

EMRI training dataset

Parameter	Quantity
Dataset size	1200
Time of signal	2 years
Sampling rate	1/15 Hz
Signal length	4194304
Number of channels	2 (A,E)

- EMRI waveform parameters randomised over astrophysically valid ranges
- Data = EMRI + Gaussian noise background
- Data is noise whitened



Training the autoencoder

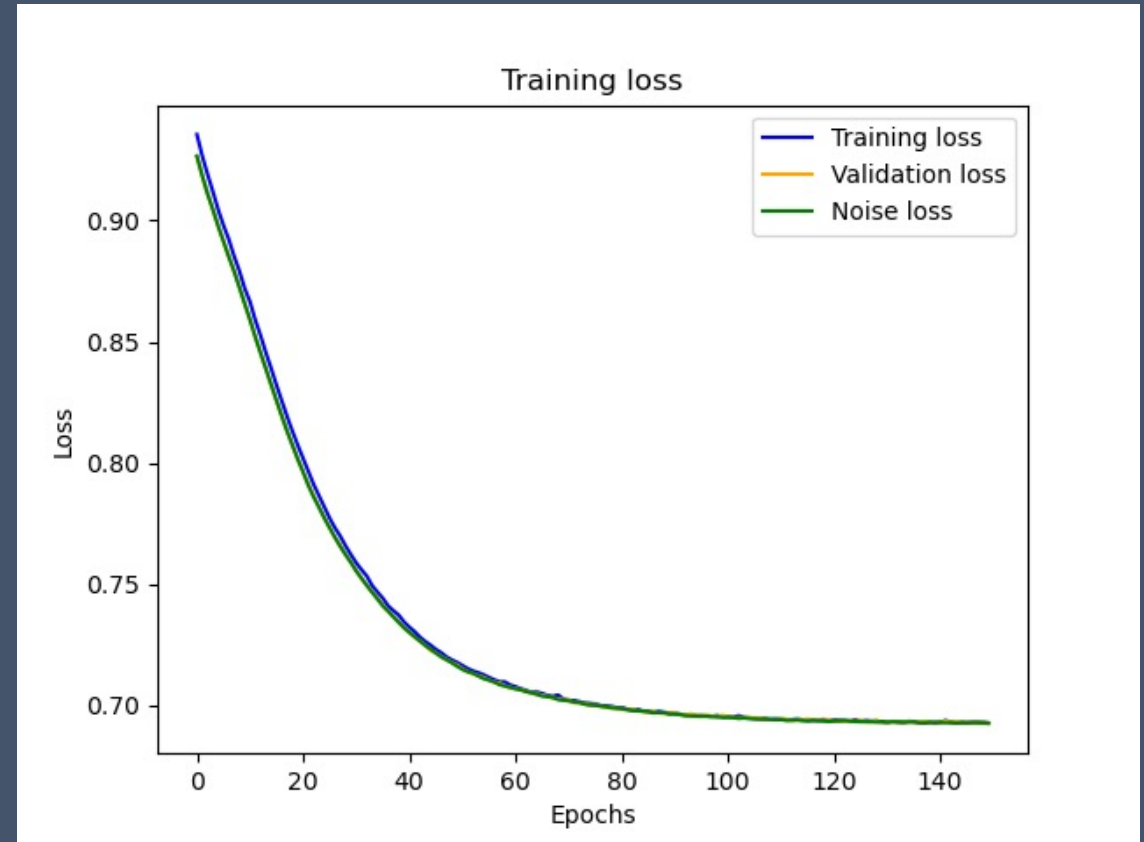
The loss function: mean squared error

Observations:

- Training converges to loss 0.7
- Noise is equally well reproduced as EMRIs



Why?

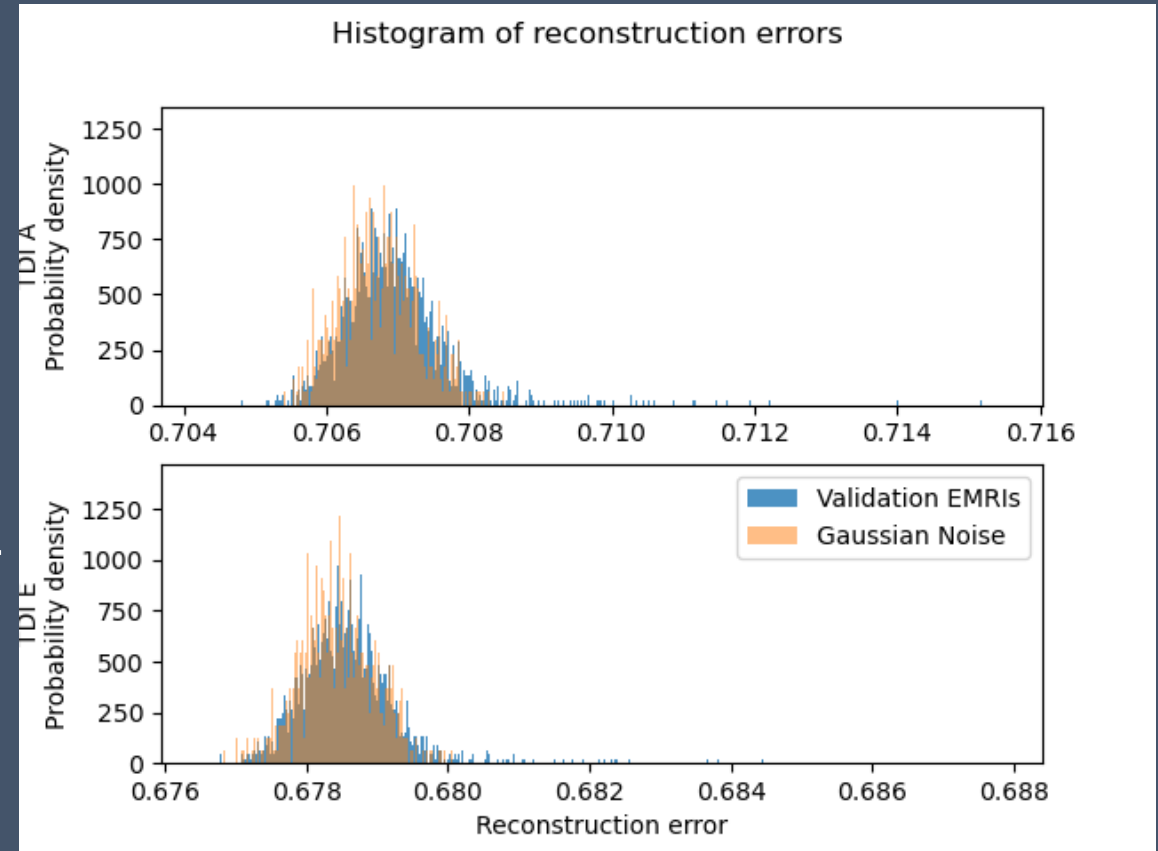


Evaluating the trained autoencoder

- Reconstruction error = loss function
- Histograms of EMRI and noise losses completely overlap

Ideally:

- Find the 95/98/99th percentile of EMRI losses
- This becomes our threshold loss when making predictions



Could this be an SNR issue?

- Random EMRI parameters lead to random SNRs
- But LISA is only sensitive to EMRIs at SNRs >30
- Generated EMRIs may be too low in SNR to be picked up by the model

So:

- The model instead learns the noise background



Moving on, I will fix the SNR issue and retrain.