Neutron star gravitational waves emission

Fundamental physics and searches

Francesca Attadio, 11th April, 2024

Presentation outline

- **Gravitational waves** (GWs) and standard categorization of GWs signals with a focus on modeled signals
- **Neutron stars** (NSs), pulsars and magnetars,
- **GWs emitted by NSs**, amplitude and relevant parameters
- Different kind of **searches** and time frequency maps
- **Machine learning** approach
- **Conclusions**

Gravitational waves

Gravitational-Waves (GW) are **ripples in the space-time fabric** produced by **huge astrophysical catastrophes**, such as the coalescence of compact binary (two black holes and/or neutron stars).

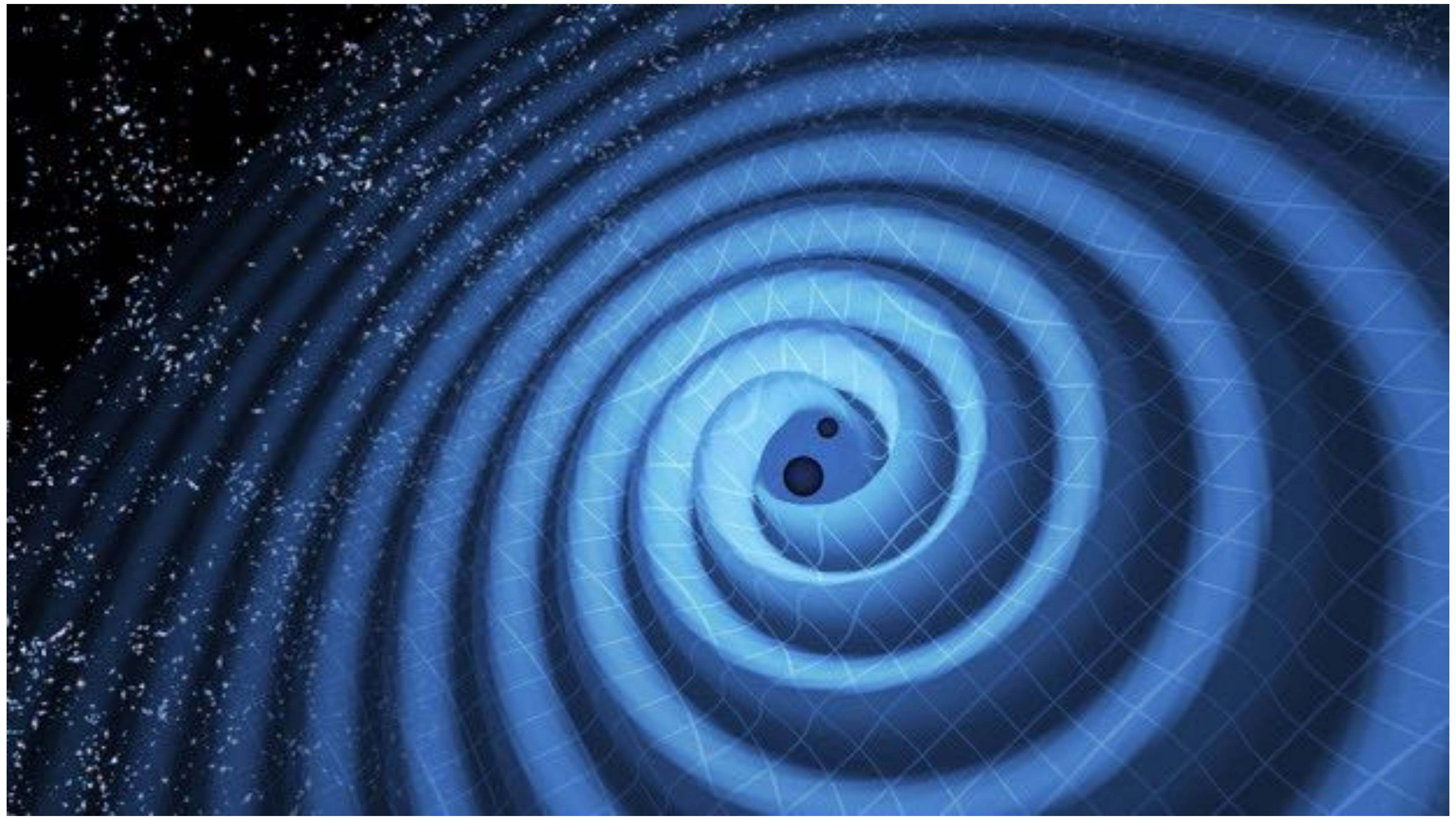


Image credit: LIGO/T. Pyle

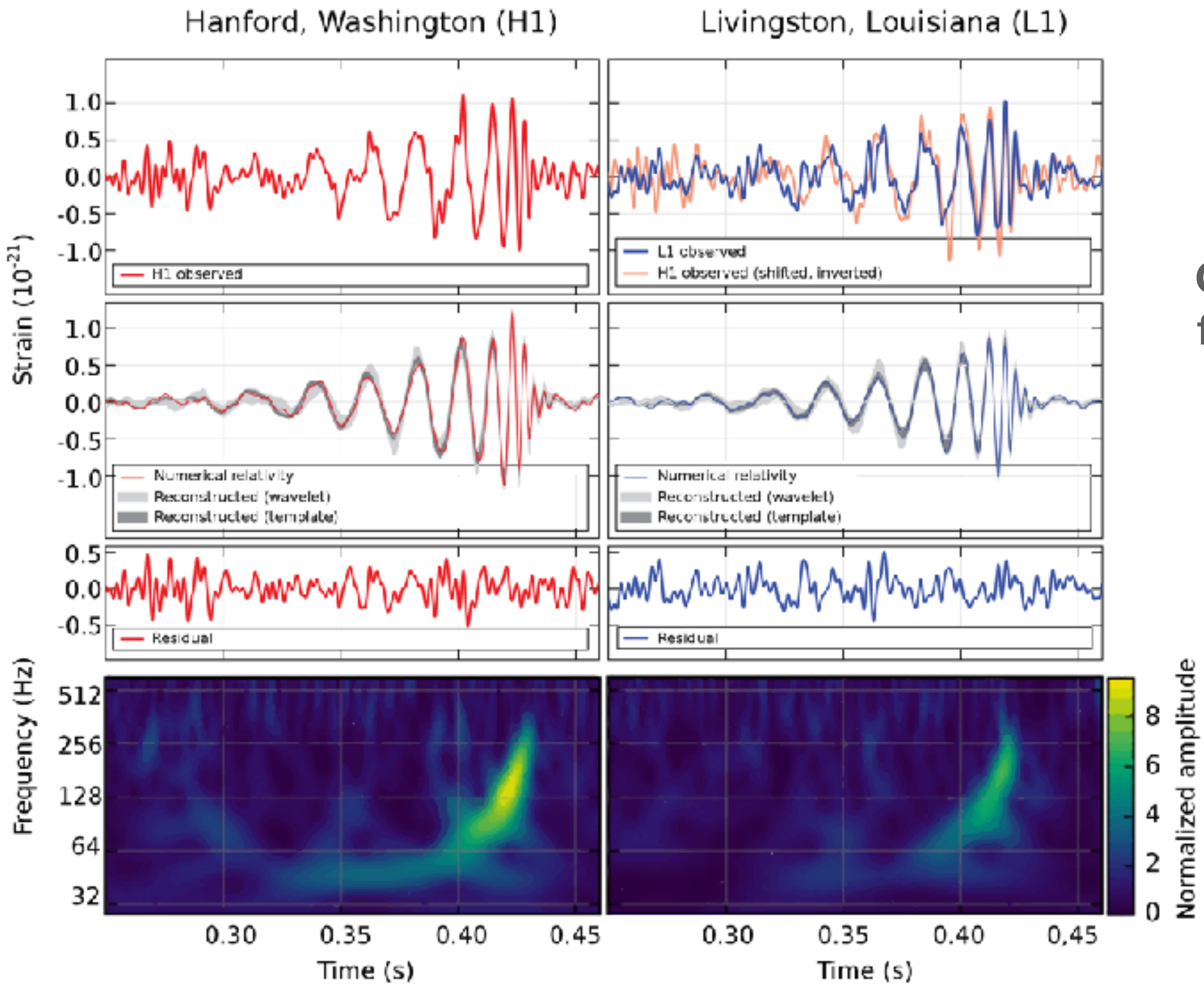


Image credit: **Observation of Gravitational Waves from a Binary Black Hole Merger** LIGO collaboration, Virgo collaboration

The **first direct detection is dated 14th September 2015**, a century after their prediction by Einstein (1916), within the General Relativity framework.

Standard categorization of GWs signals

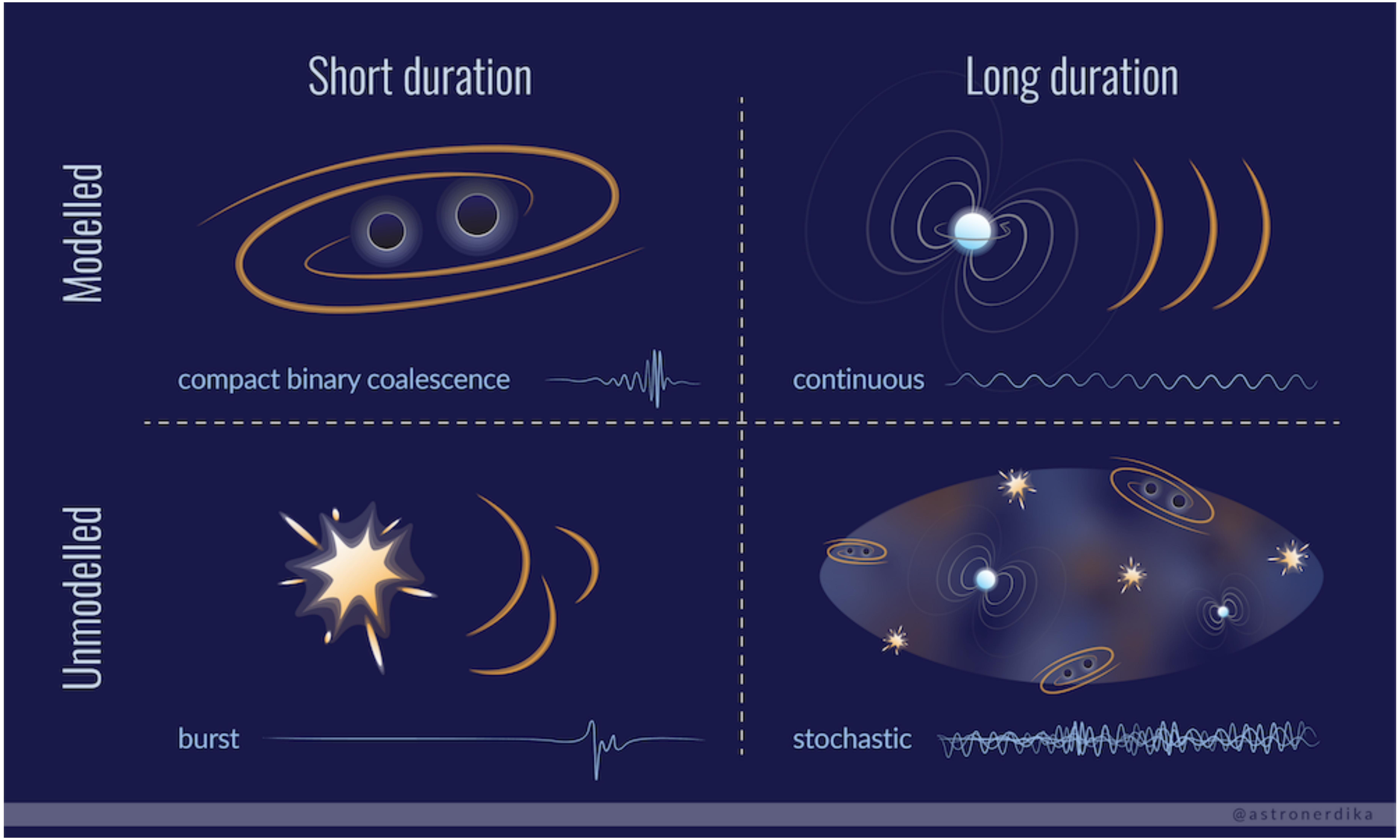
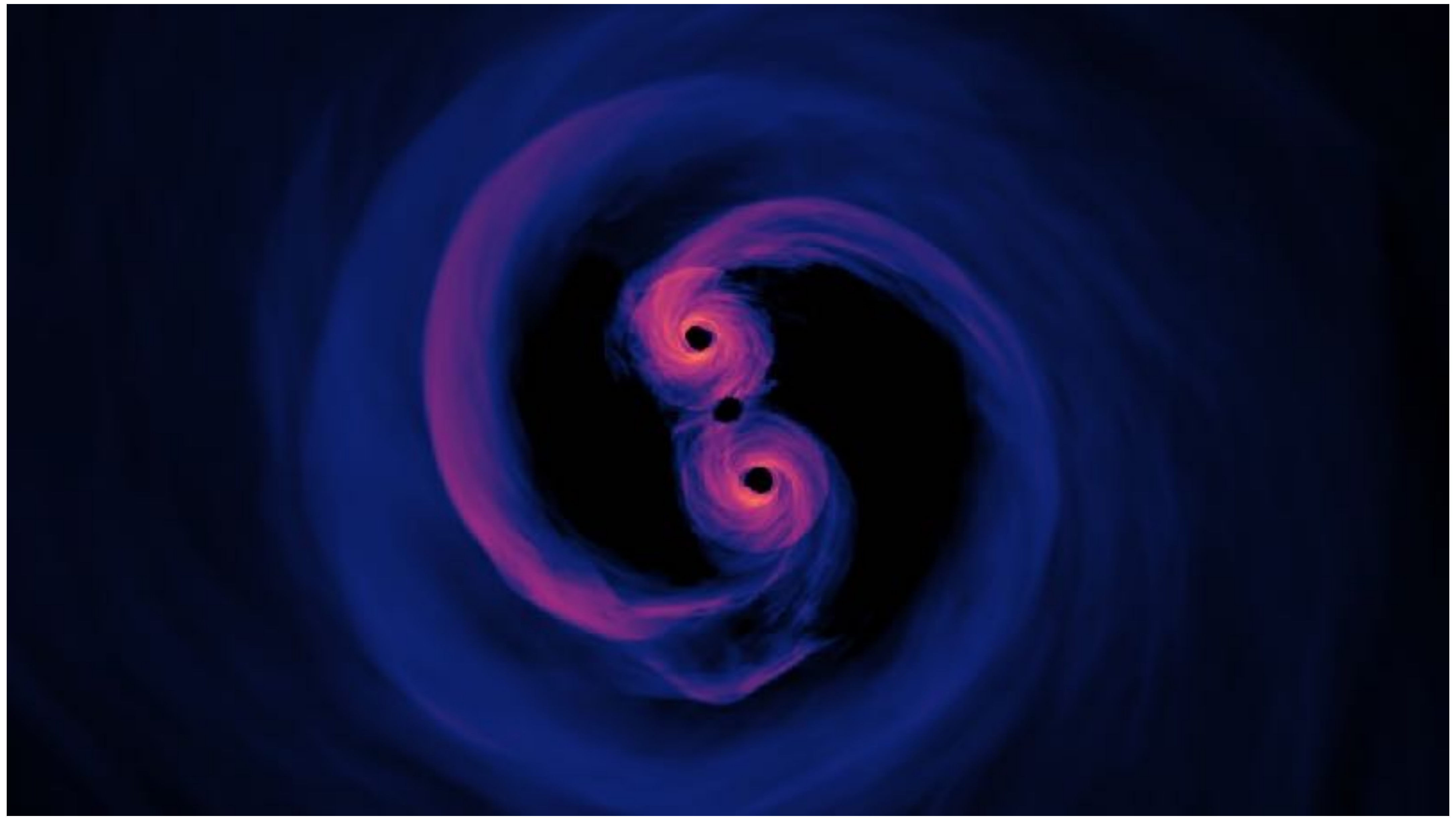


Image credit: Shanika Galaudage

Modeled signals

Transient signals



Duration: 0.1 to 100 seconds

Sources: Compact binary coalescence (CBC), supernova explosions.

→ Detected

Continuous waves

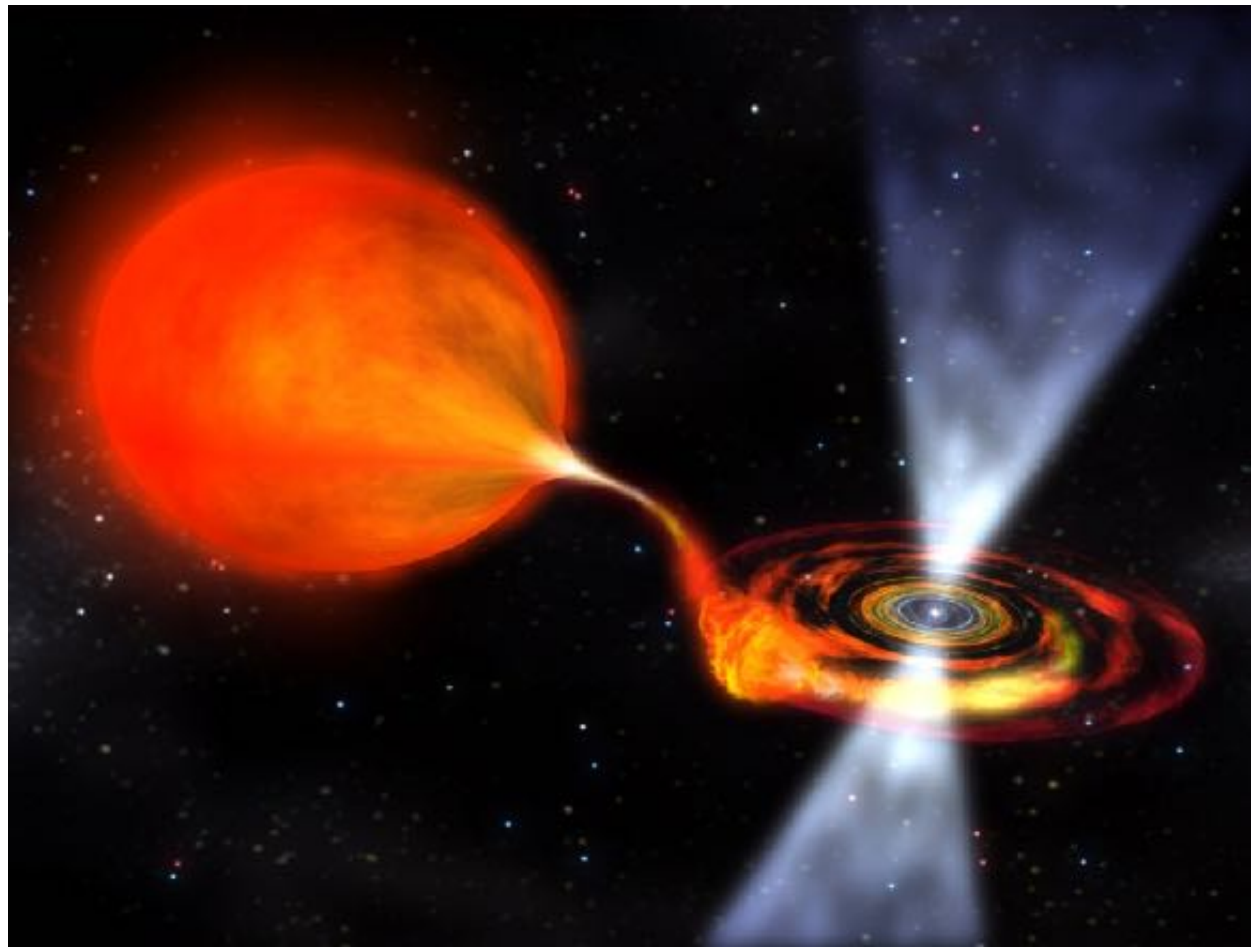


Image credit: NASA, Dana Berry

Duration: hours to years

Sources: Isolated neutron stars, low mass x ray binary

→ Not detected

Neutron stars (NSs)

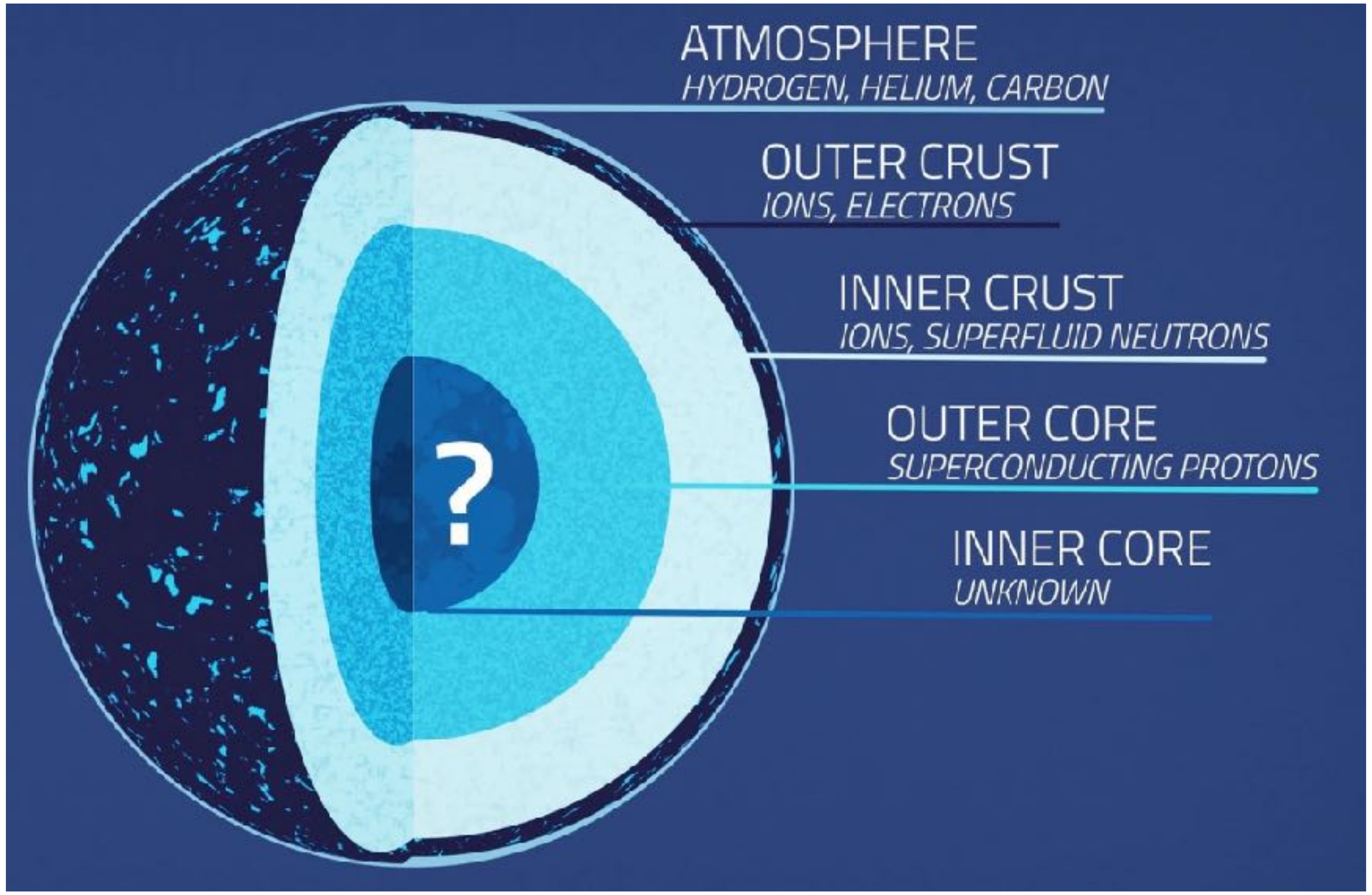
Final stage of stars with an initial mass between 8 and 30 solar masses.

Main characteristics:

- Mass: 1.25-2.15 solar masses
- Radius: 10-12 km
- Density: $\rho \leq 10^{15} \frac{\text{g}}{\text{cm}^3}$

It is impossible to reach on earth this kind of densities

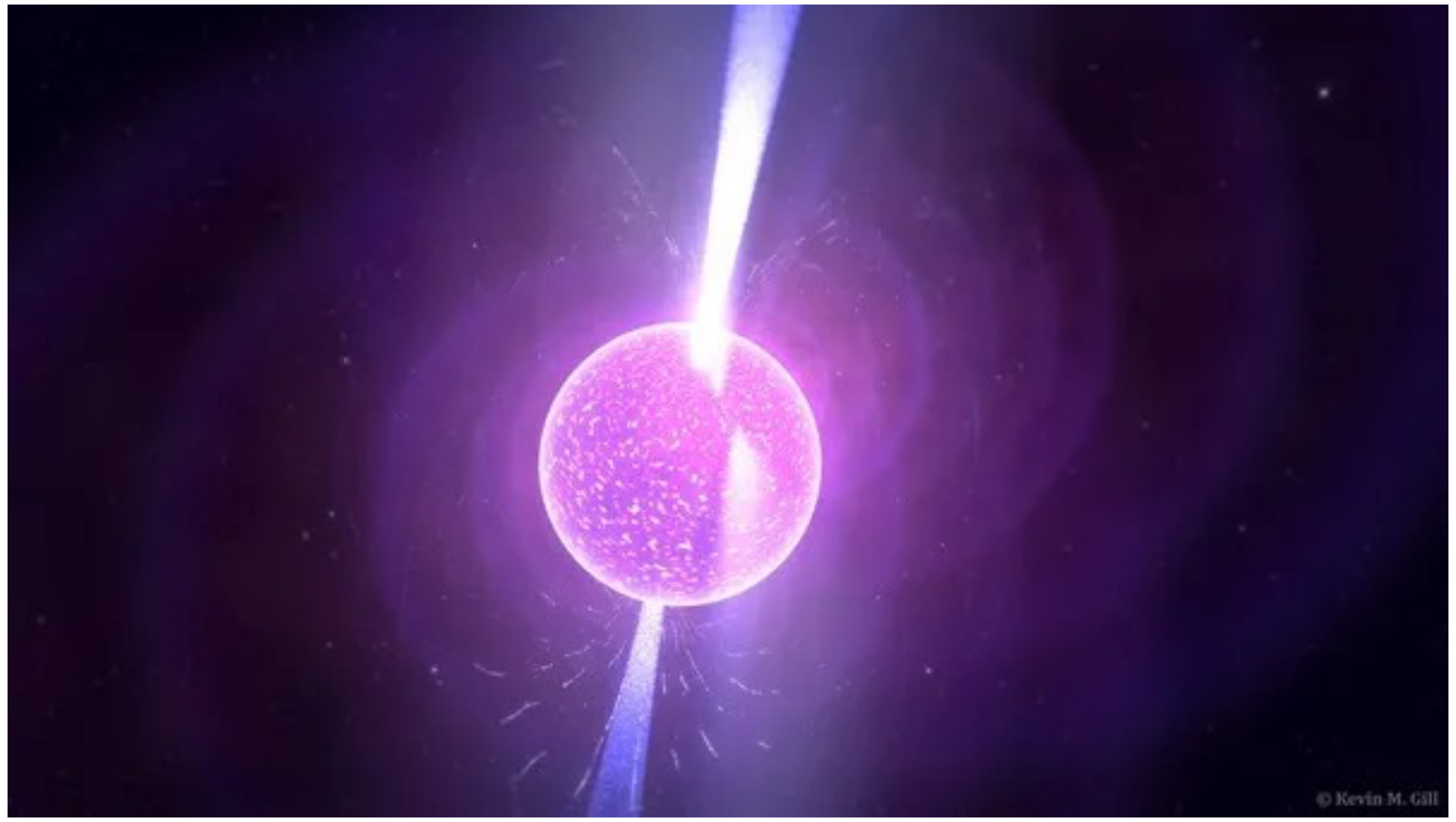
→ NSs are cosmic laboratory



Credit: NASA's Goddard Space Flight Center/Conceptual Image Lab

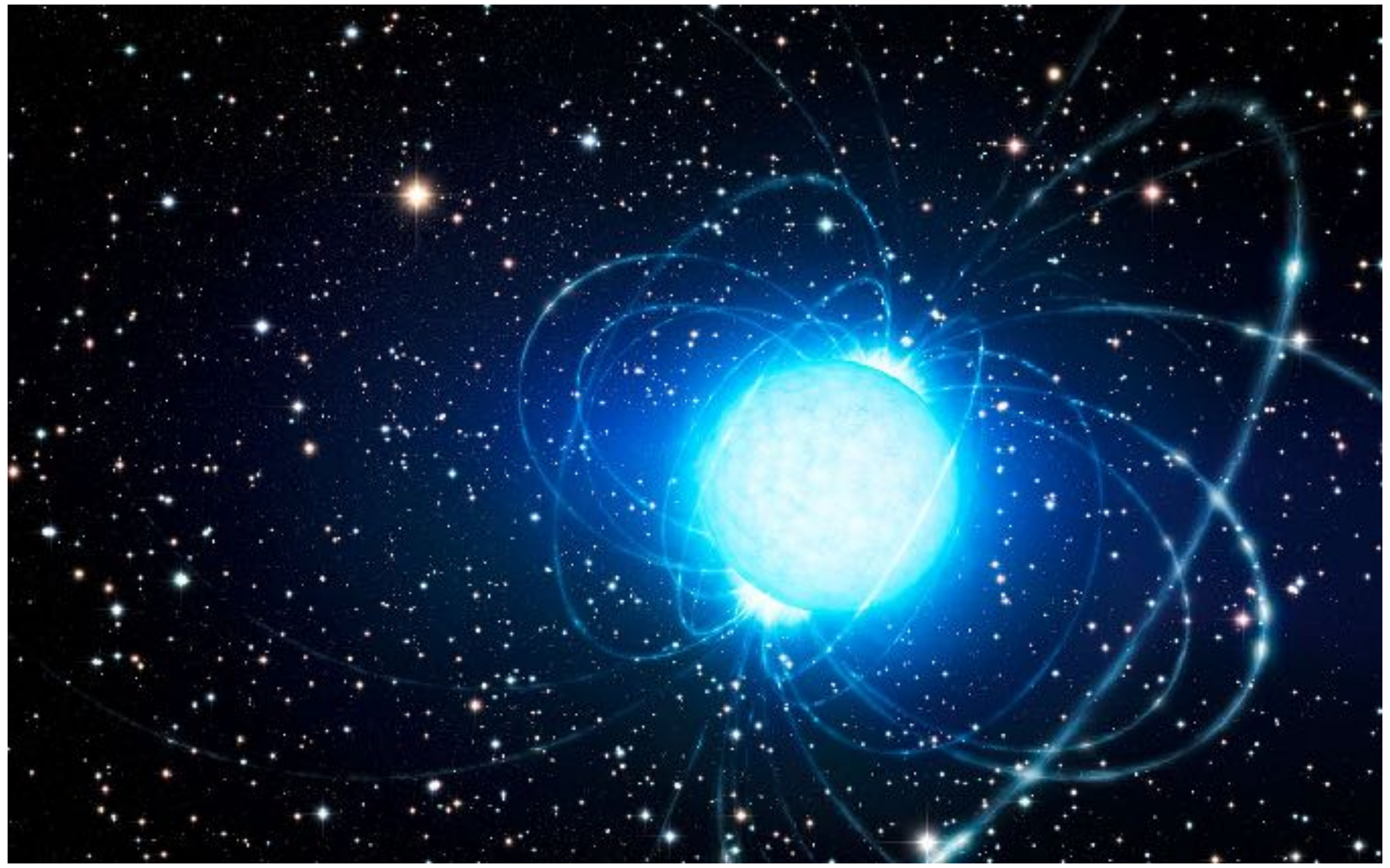
Different kind of NSs

Pulsar



- $B \sim 10^9 - 10^{14}$ G
- $f_{rot} \sim 0.1 - 740$ Hz
- $\epsilon < 10^{-5}$

Newly born Magnetars



- $B \sim 10^{15} - 10^{16}$ G
- $f_{rot} \sim 250 - 1000$ Hz
- $\epsilon \sim 10^{-5} - 10^{-3}$

Gravitational waves

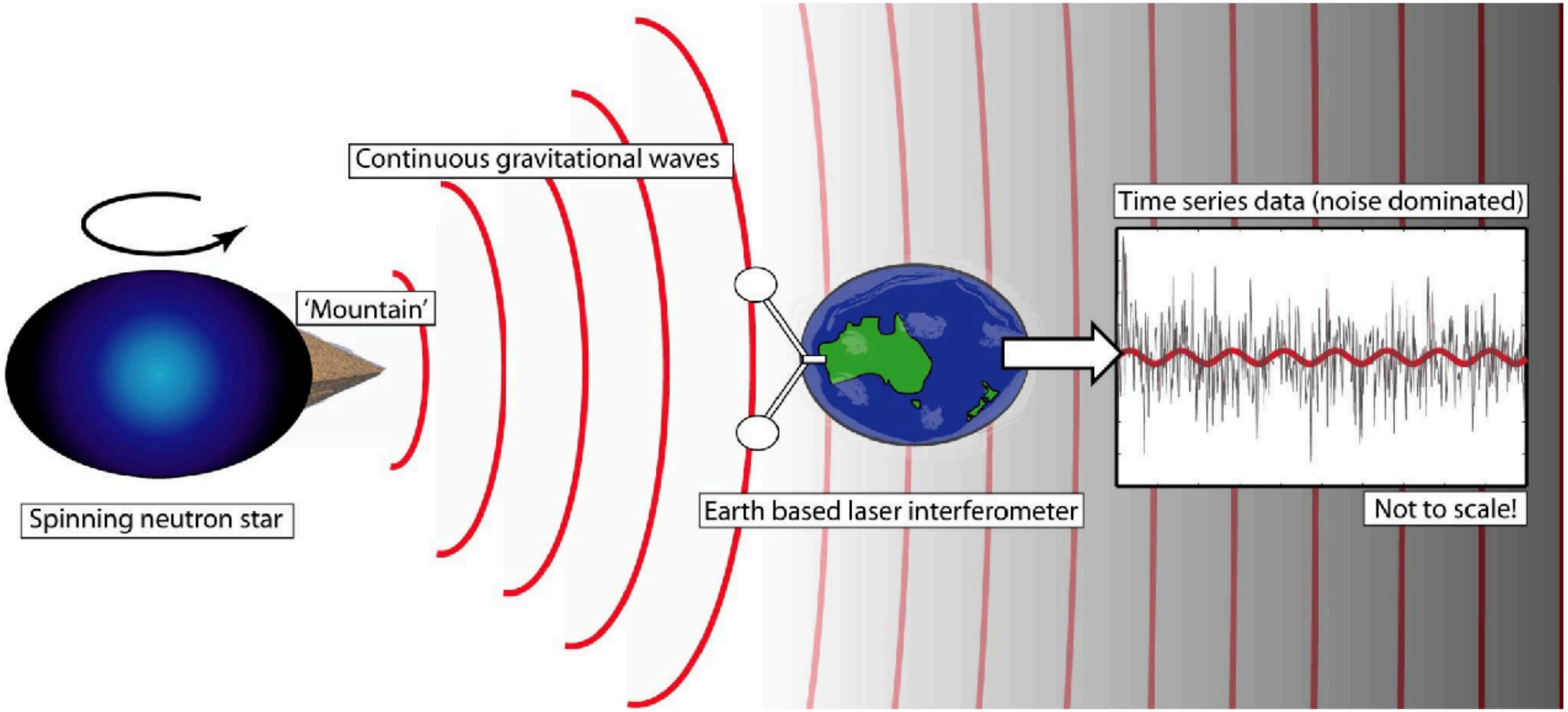


Image credit: Graham Woan

Isolated NSs spinning with a non axis-symmetric asymmetry emit GWs

GW amplitude $$h_0(t) = \frac{4\pi^2 G}{c^4} \frac{I\, f(t)^2}{d} \epsilon$$

GW frequency

Ellipticity

Distance of the source

Spin down equation

The rotational energy of the star is used to emit GWs and electromagnetic radiation

$$\dot{f}_{\mathrm{rot}} = -k f_{\mathrm{rot}}^{n}$$

$$f_{\mathrm{GW}} = 2 f_{\mathrm{rot}} \equiv \underline{f}$$

n: Braking index

k: Constant

They depends on the kind of emission

Rotational parameters: $\mathbf{f}, \dot{\mathbf{f}}, \ldots$

Ellipticity (Oblateness)

The measure of the asymmetry is the ellipticity (ϵ)

$$\epsilon \sim 10^{-5} - 10^{-3} \rightarrow 0.1 - 10 \text{ m}$$

Possible cause of asymmetry:

- Mountains
- R-modes
- Magnetic field

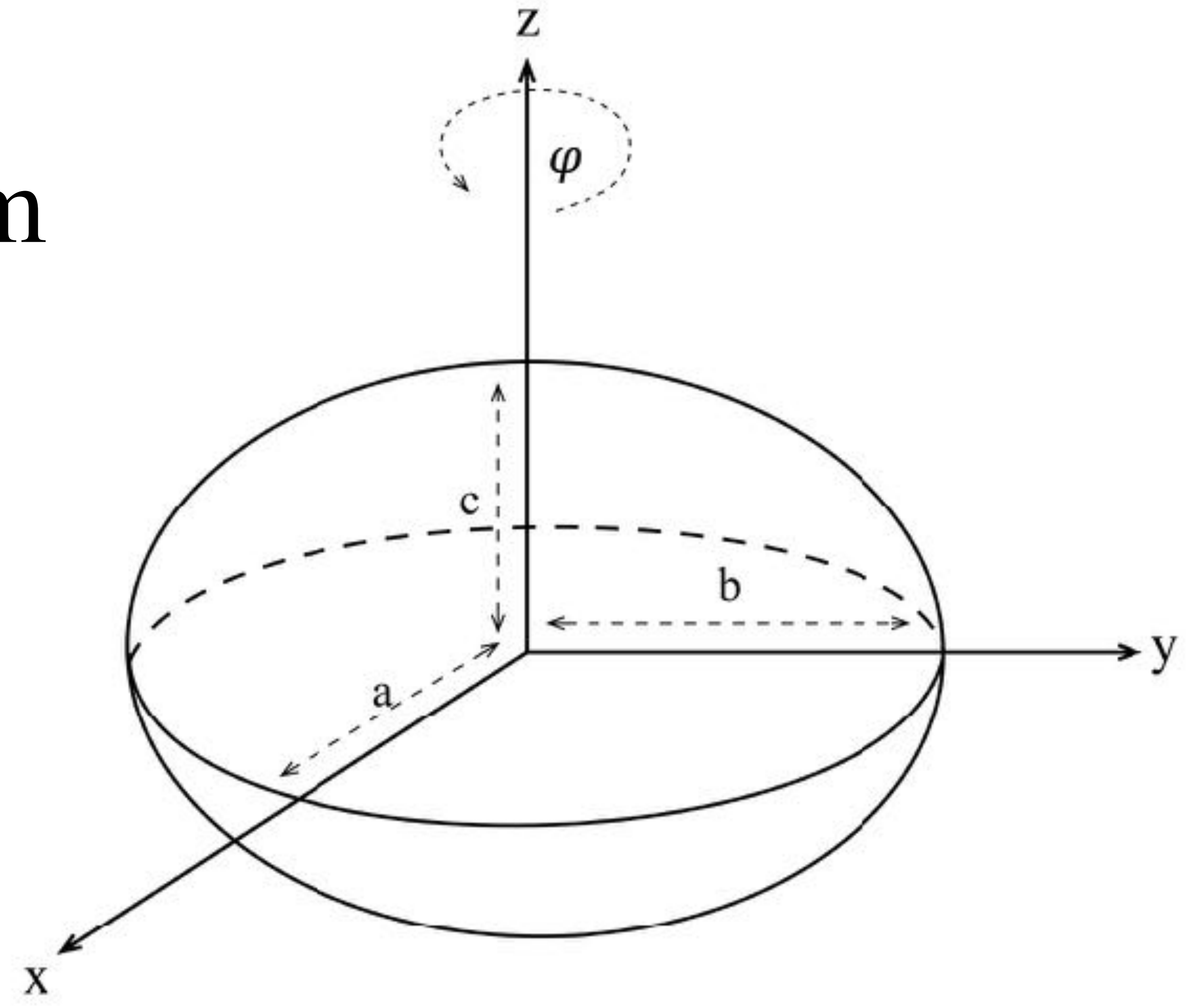
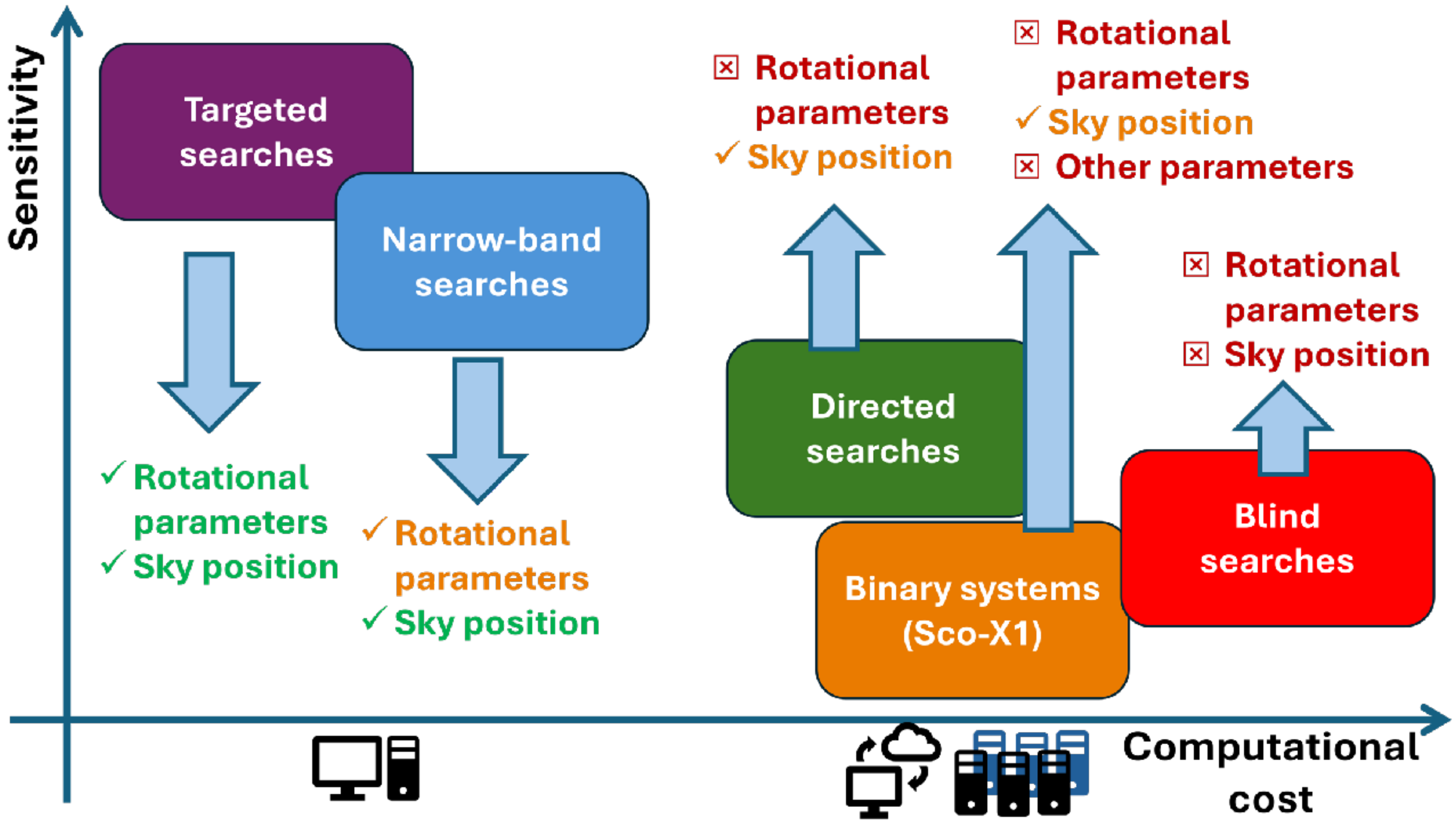


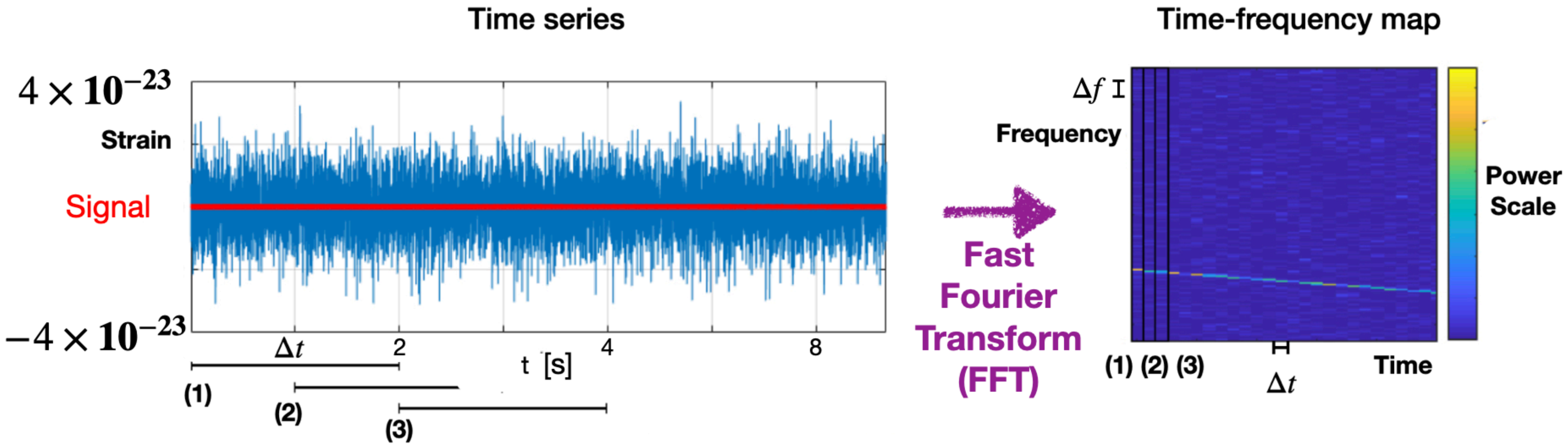
Image credit: General relativity and its application, Ferrari, Gualtieri, Pani

We do not have a measure of ellipticity for known NSs

Different kind of searches



Time-frequency maps



Machine learning

Dataset

- Training set
- Validation set
- Test set

Loss function

→ It estimates the distance from the current output and the desired output

→ Our goal during the training is to minimize this function

→ The choice of the loss function depends on the choice of the ML model

Dataset preparation

↓

Definition of the model structure

↓

Training

↓

Testing

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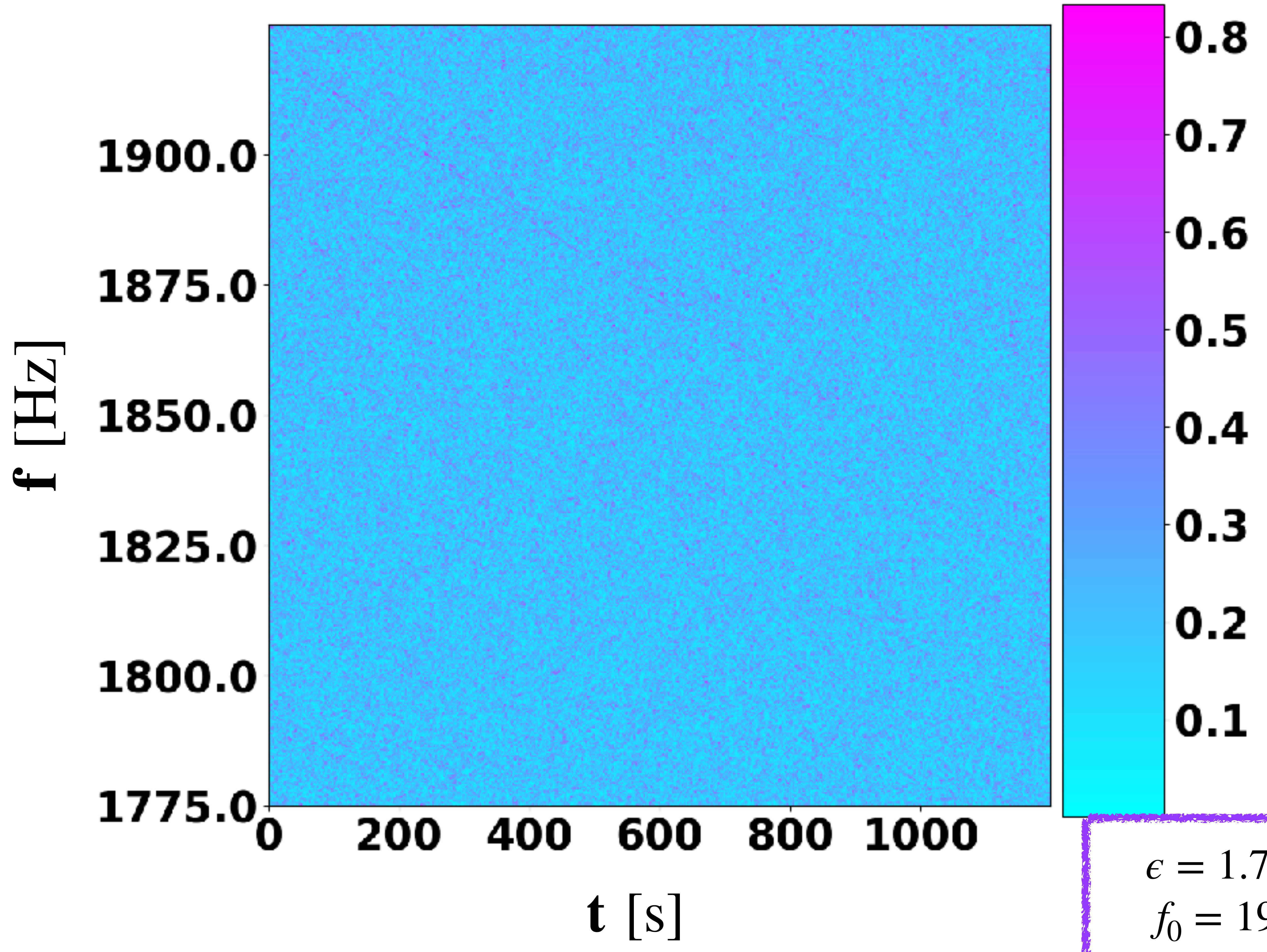
I have developed two ML models, a **denoiser** and a **classifier**

Classifier

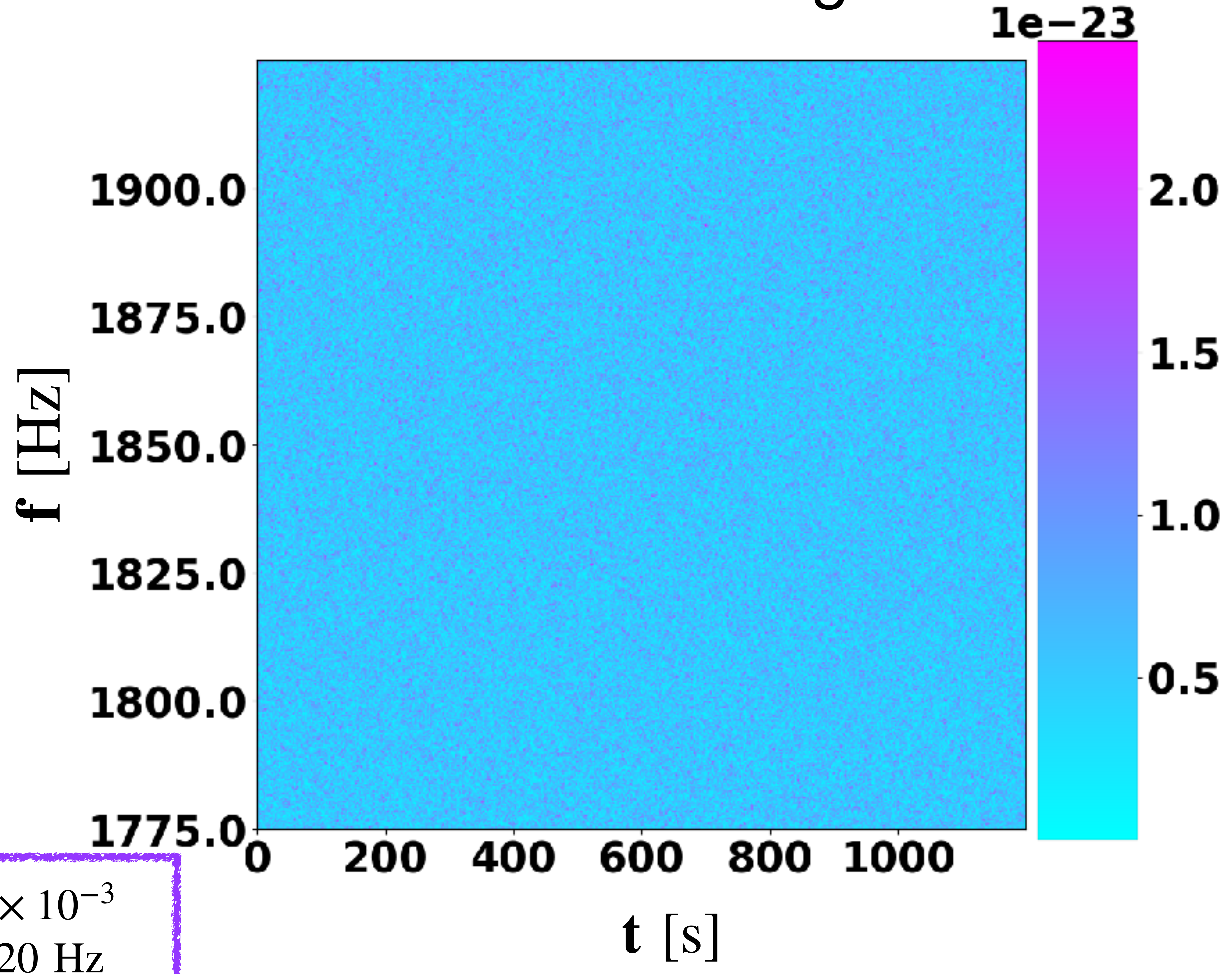
Classification of time-frequency maps

Presence of signal



$\epsilon = 1.7 \times 10^{-3}$
$f_0 = 1920$ Hz

Absence of signal



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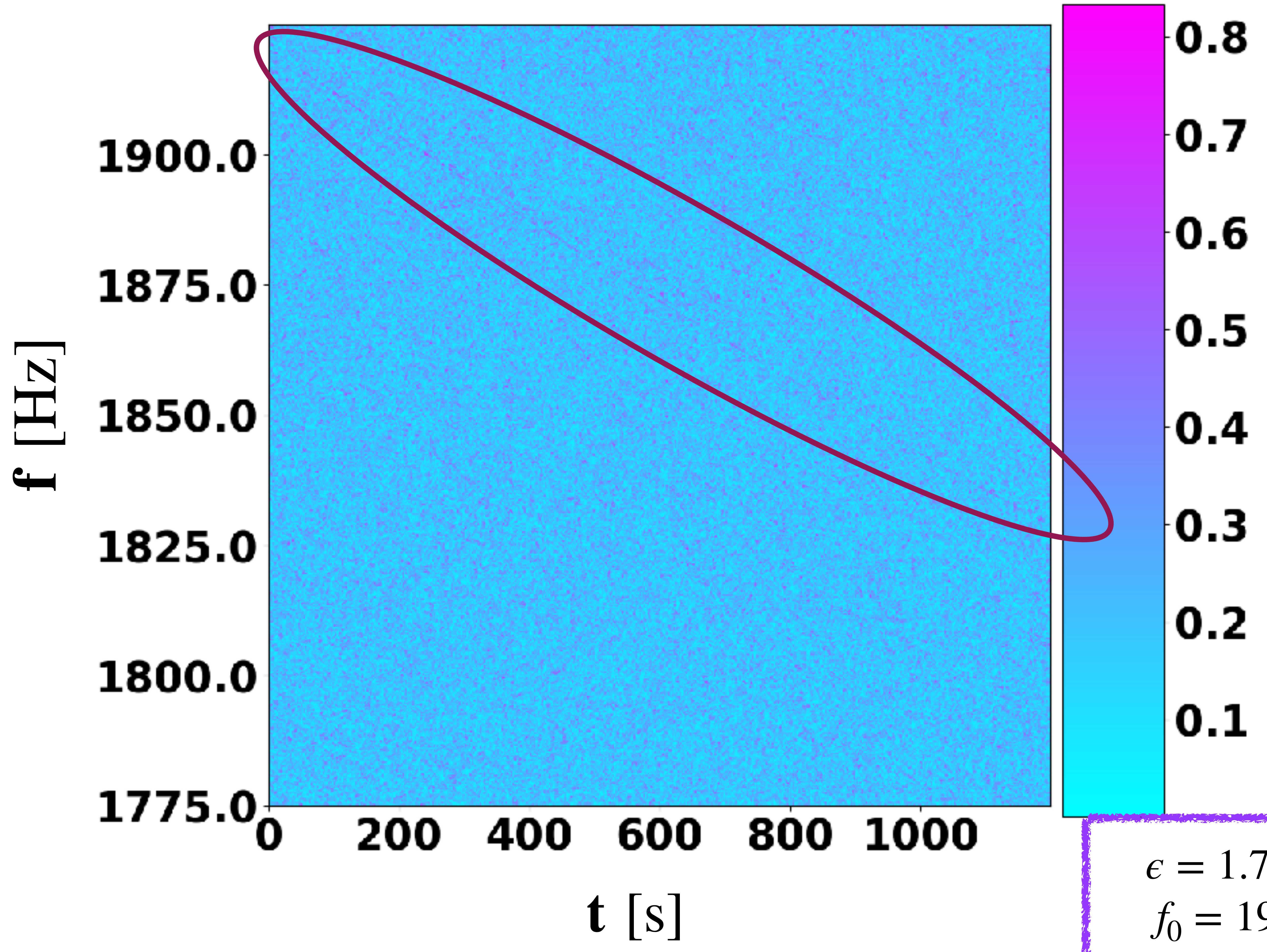
Classification of time-frequency maps

Presence of signal



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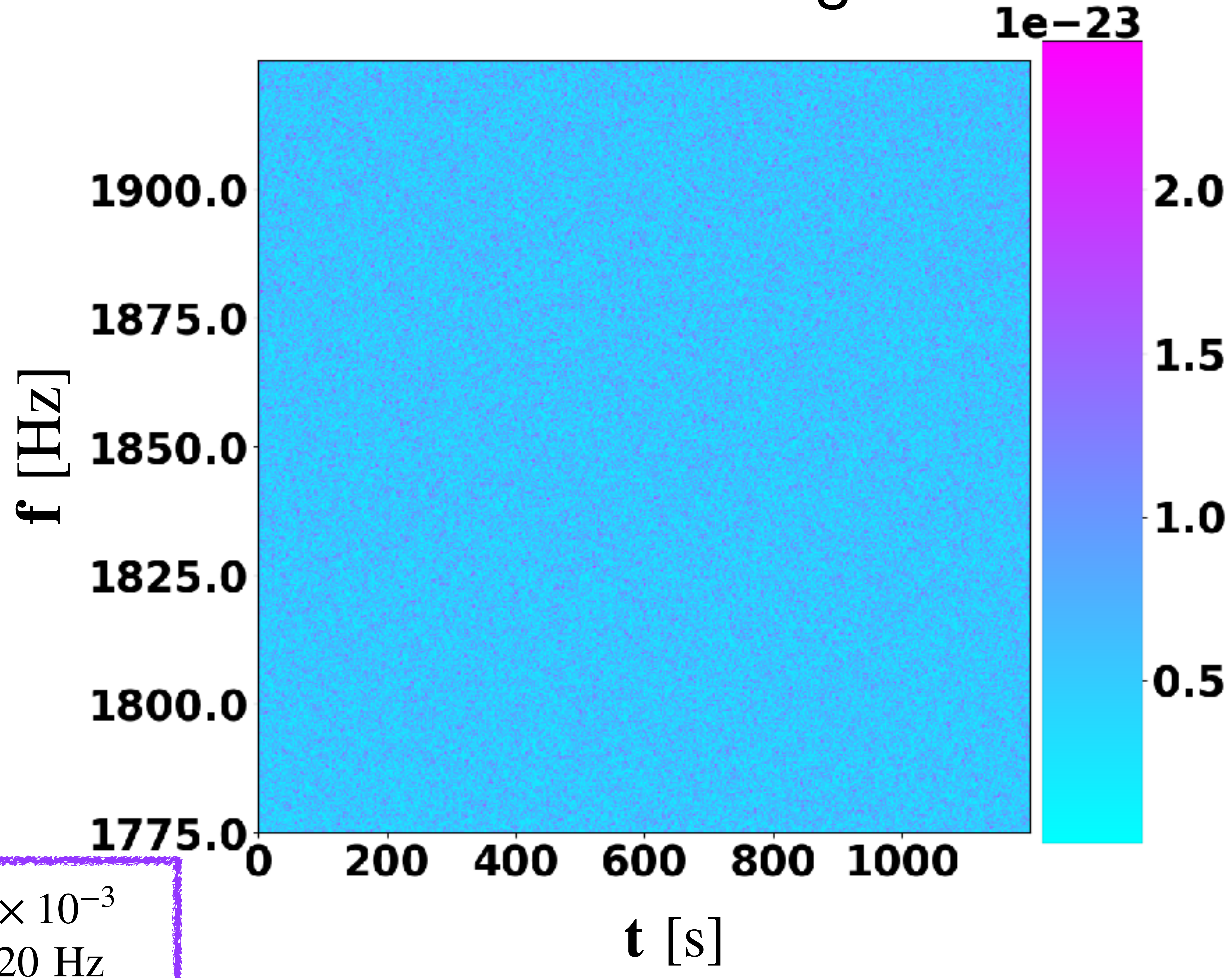
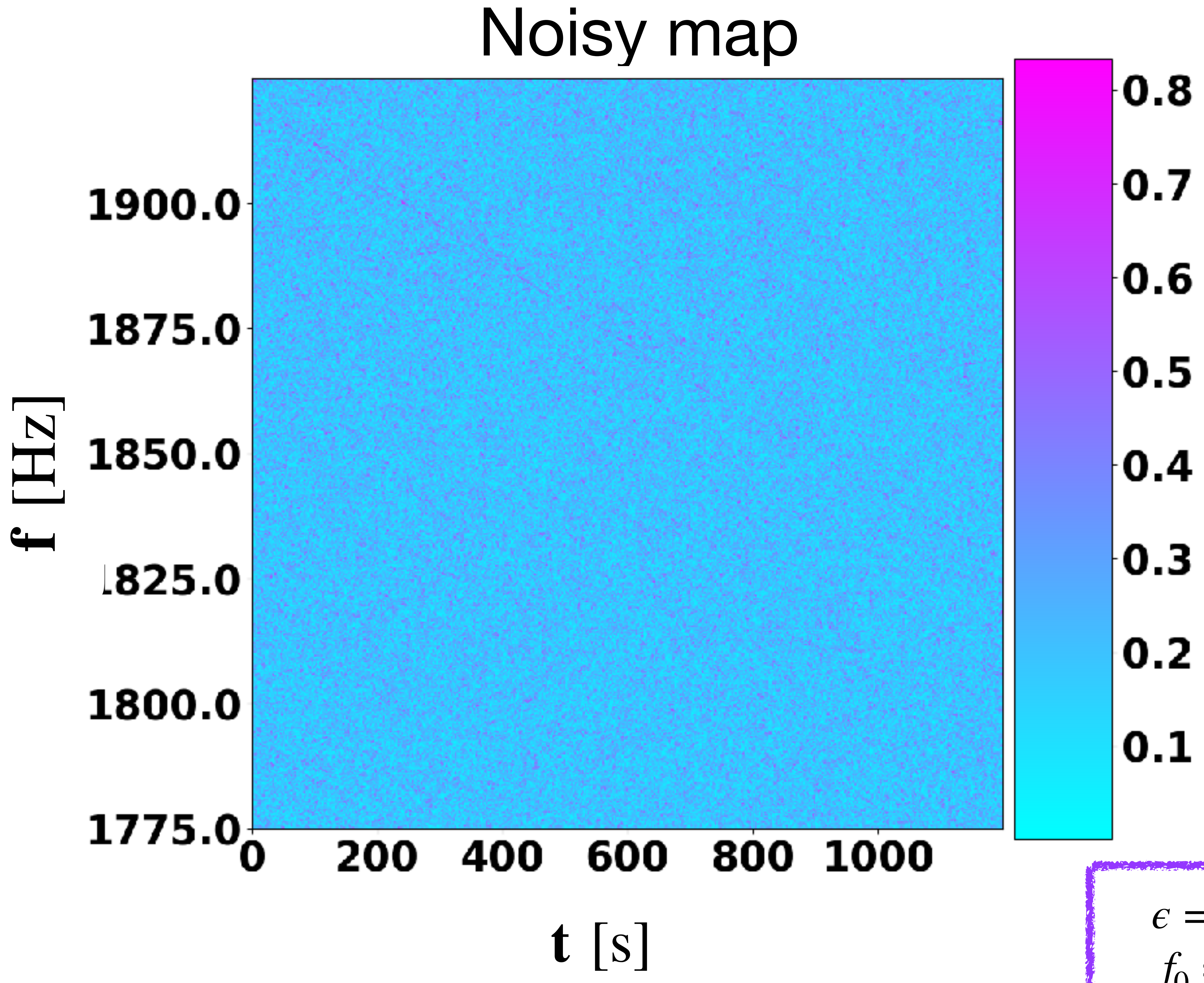


Denoiser

It reduces the noise level of the image while preserving a significant fraction of the signal



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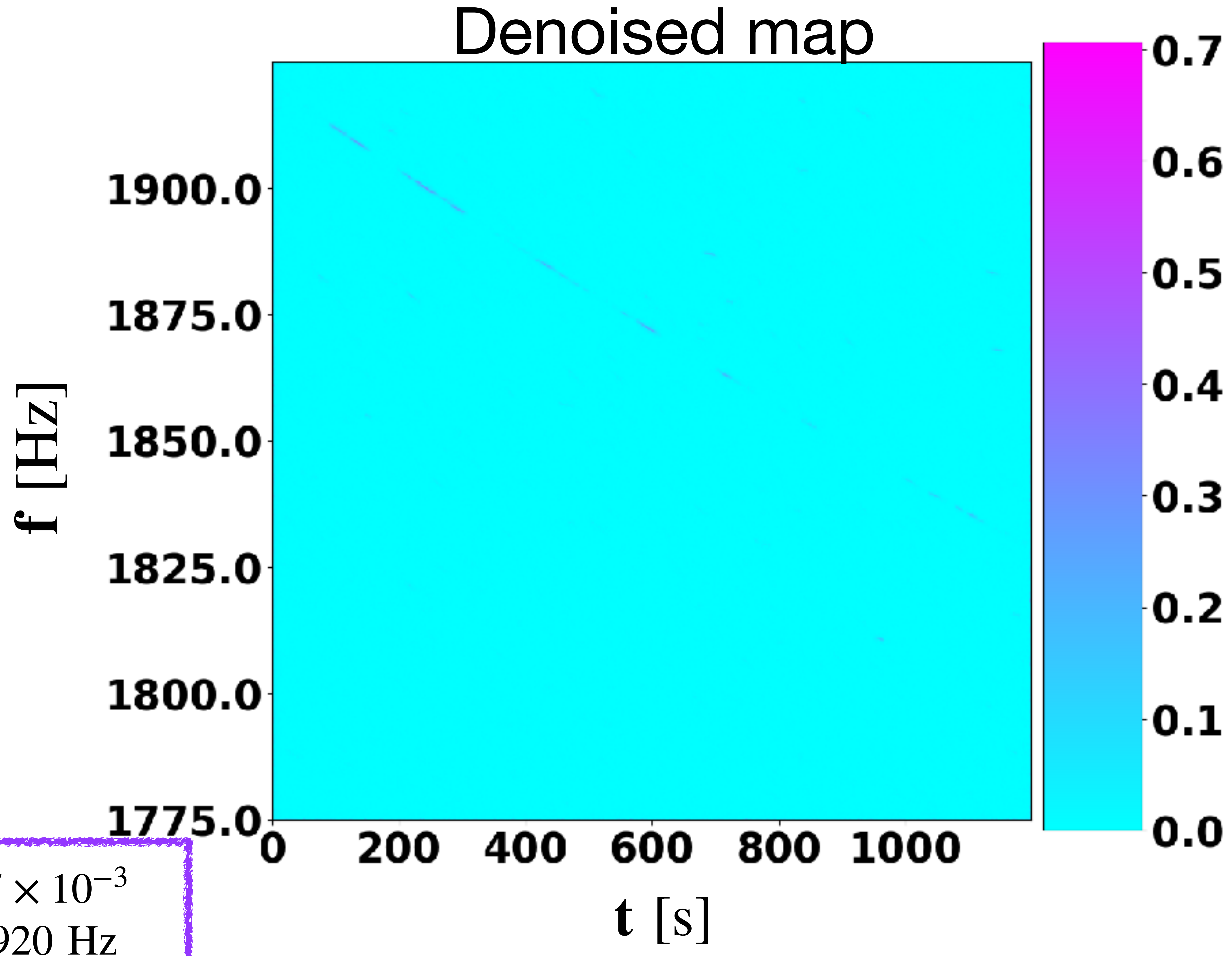

Conclusions

It is important to detect GWs emitted by NSs in order to understand how matter behaves in such extreme conditions

→ It is an open research field

→ We are studying frontier physics

What is next?

→ Improve the already existing data analysis techniques

→ Develop new techniques

→ New generation interferometers

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THANK YOU FOR YOUR ATTENTION

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