# *Neutron star gravitational waves emission*

Fundamental physics and searches

**Francesca Attadio, 17th 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).

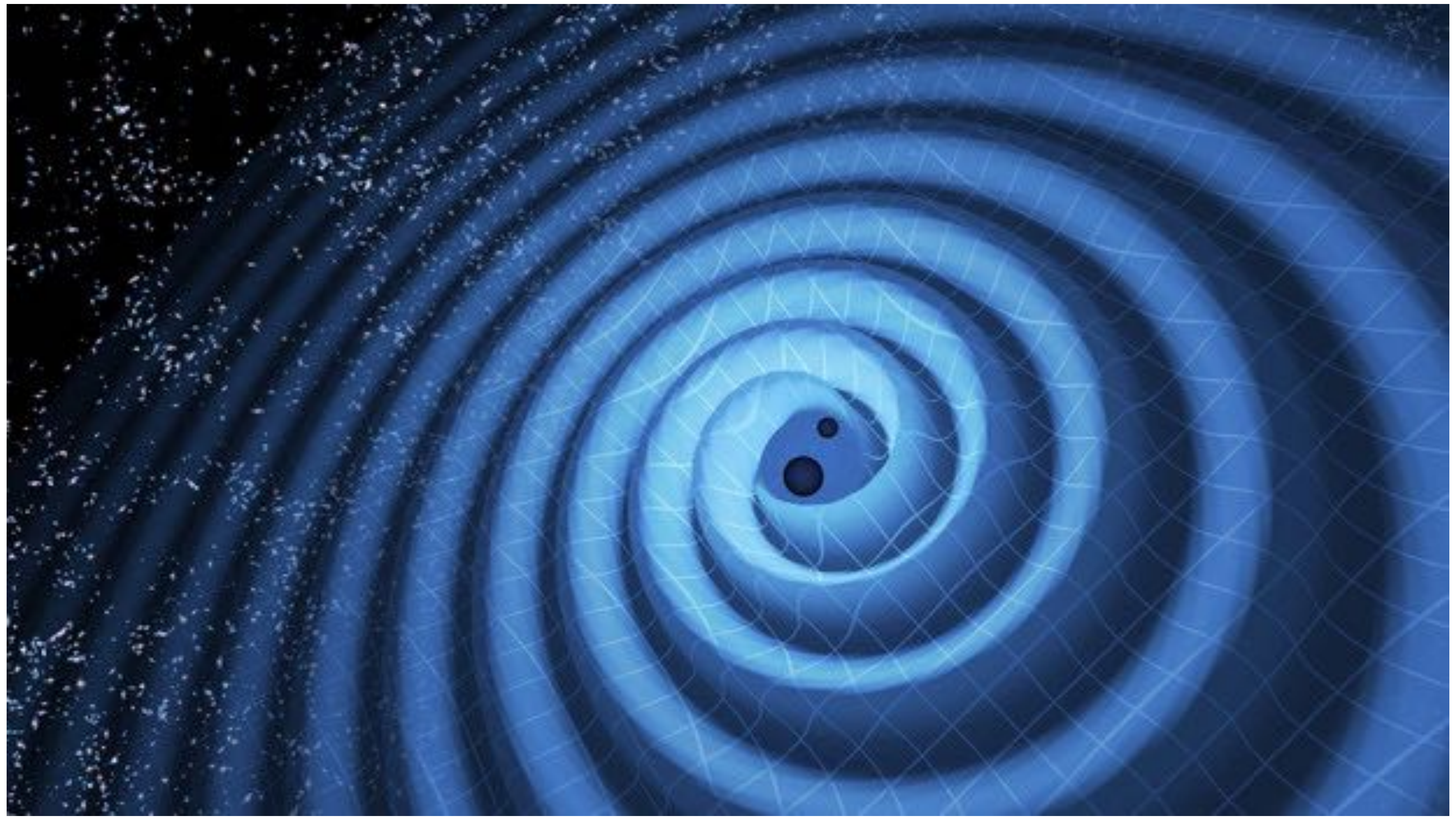


Image credit: LIGO/T. Pyle

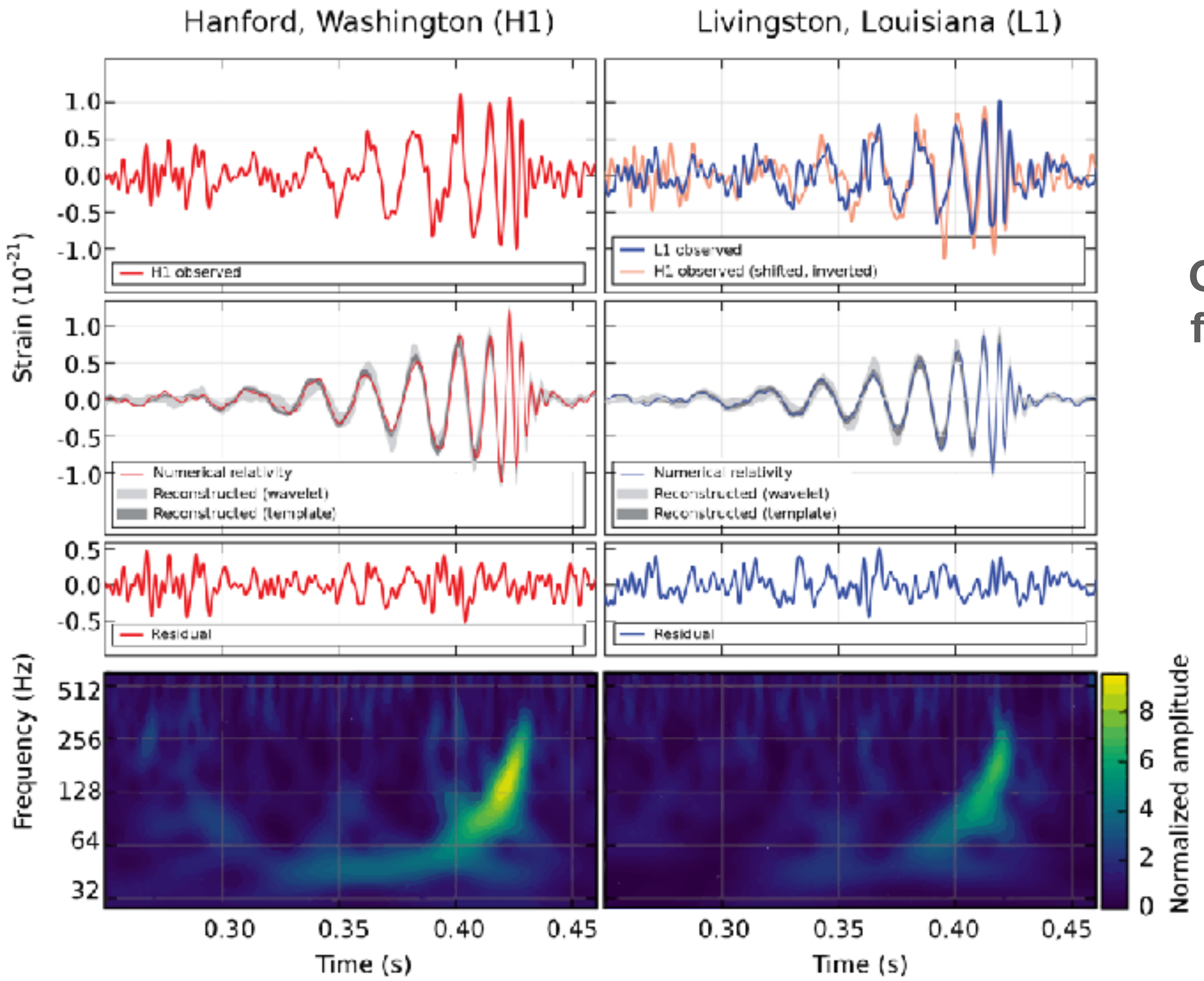



Image credit: **Observation of Gravitational Waves from a Binary Black Hole Merger** LIGO collaboration, Virgo collaboration

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

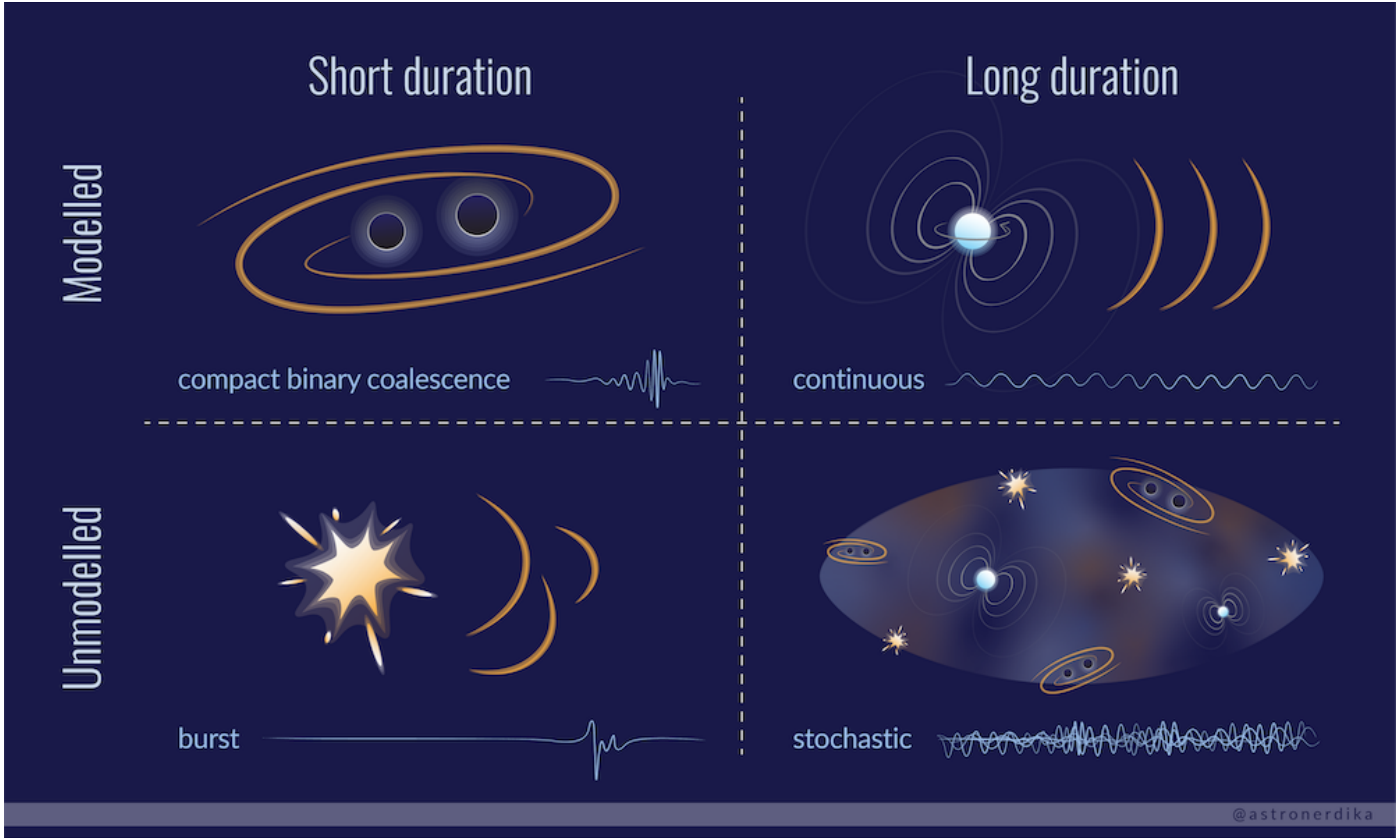
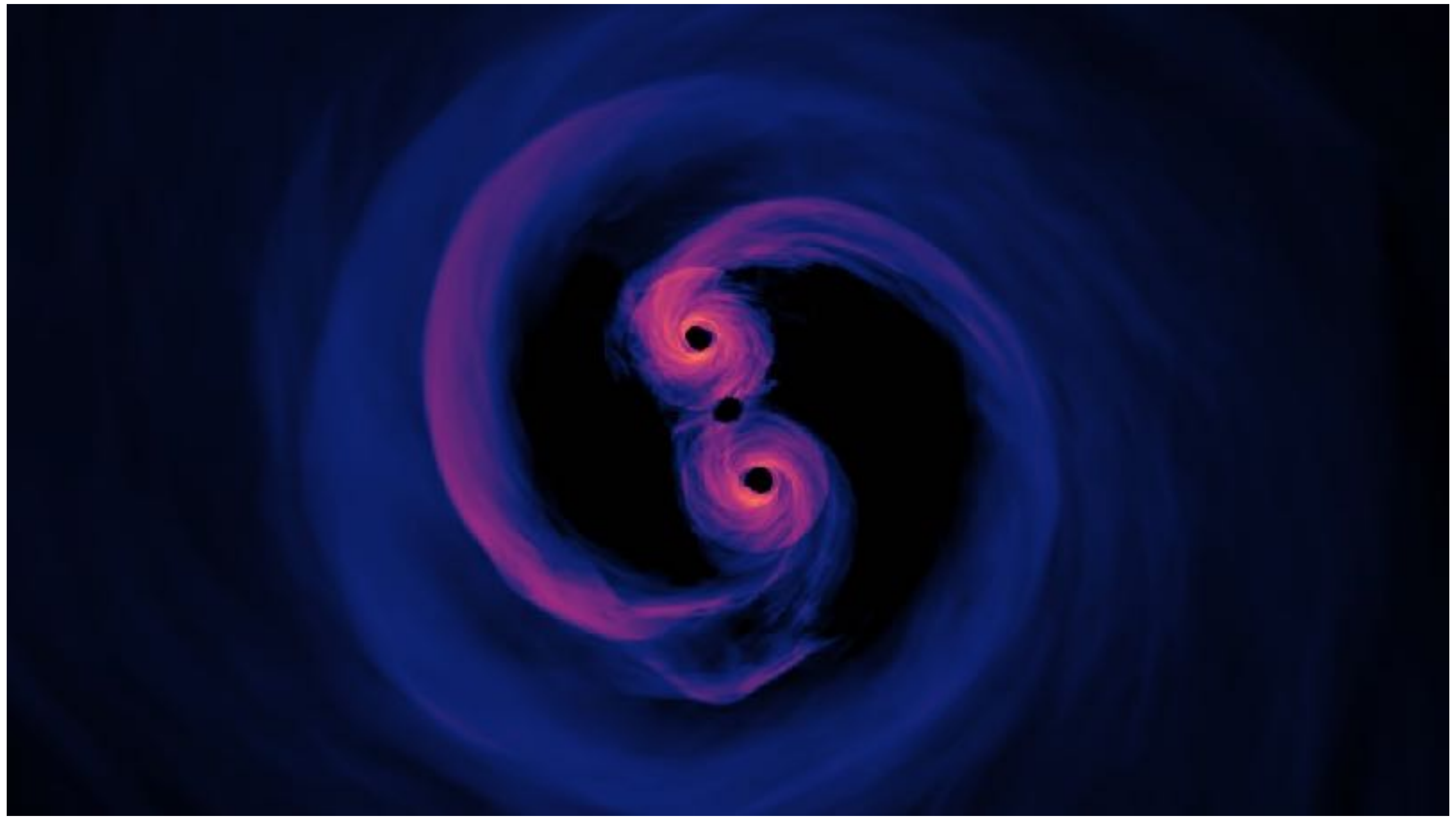



Image credit: Shanika Galaudage

# Modeled signals

## Transient signals



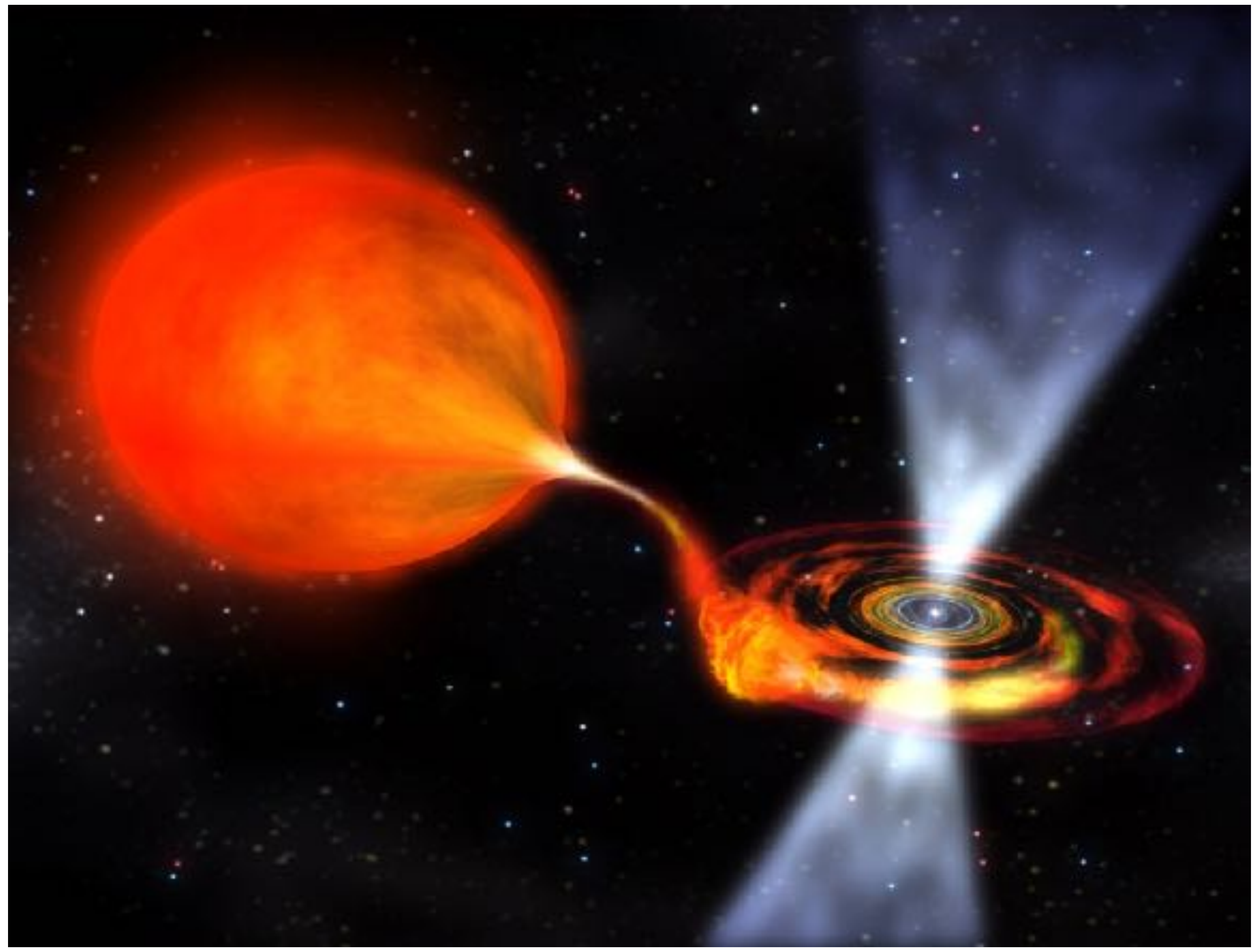
**Duration**: 0.1 to 100 seconds

Image credit: NASA's Goddard Space Flight Center/Scott Noble

**Sources**: Compact binary coalescence (CBC)

→ Detected

## Continuous waves



**Duration**: hours to years

Image credit: NASA, Dana Berry

**Sources**: Isolated neutron stars, low mass x ray binary

→ Not detected

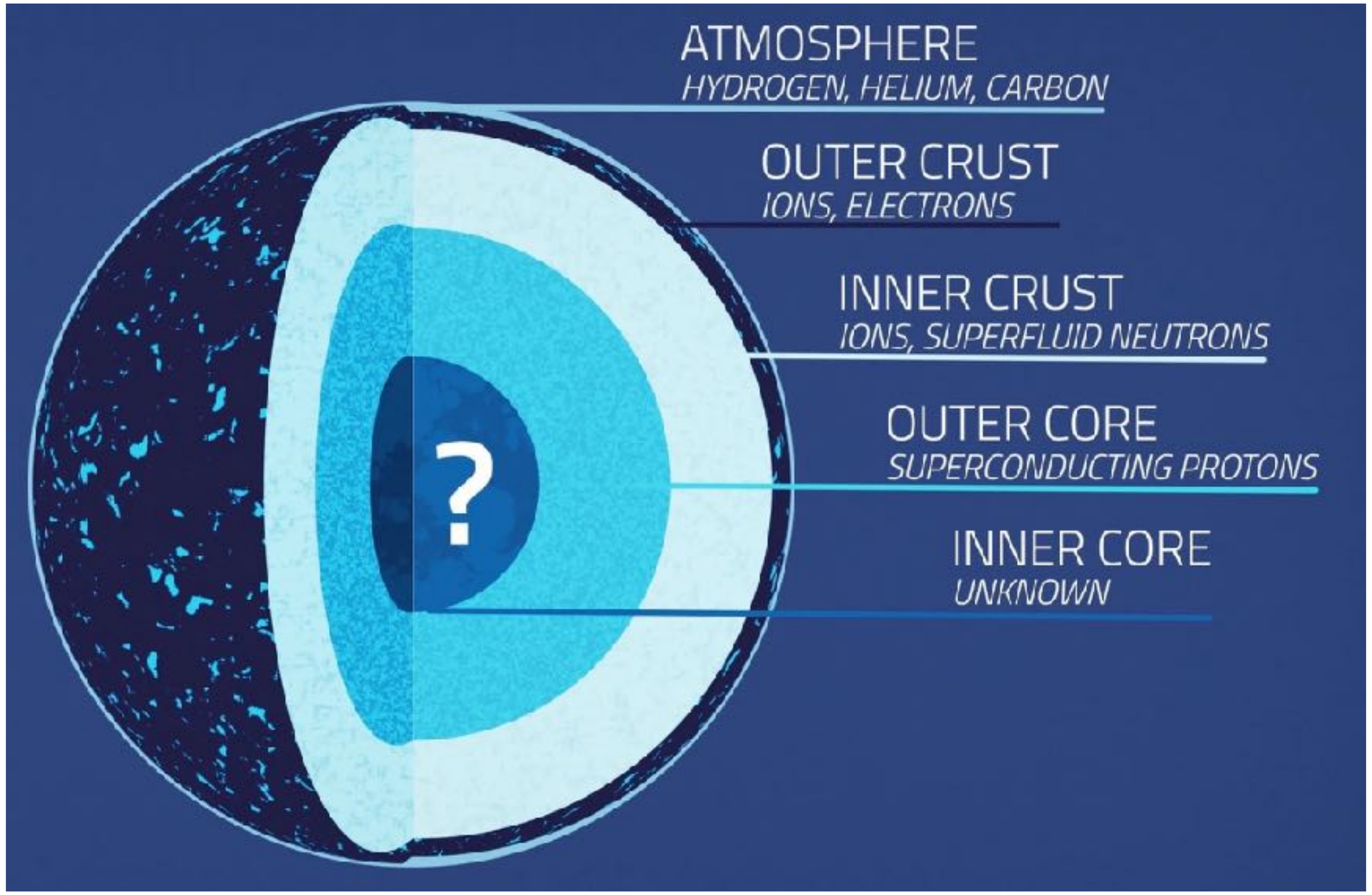
# Neutron stars (NSs)

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: $\rho \leq 10^{15} \frac{\mathrm{g}}{\mathrm{cm}^3}$

(From the crust to the core)




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

It is impossible to reach on earth this kind of densities

→ NSs are cosmic laboratory

# Gravitational waves

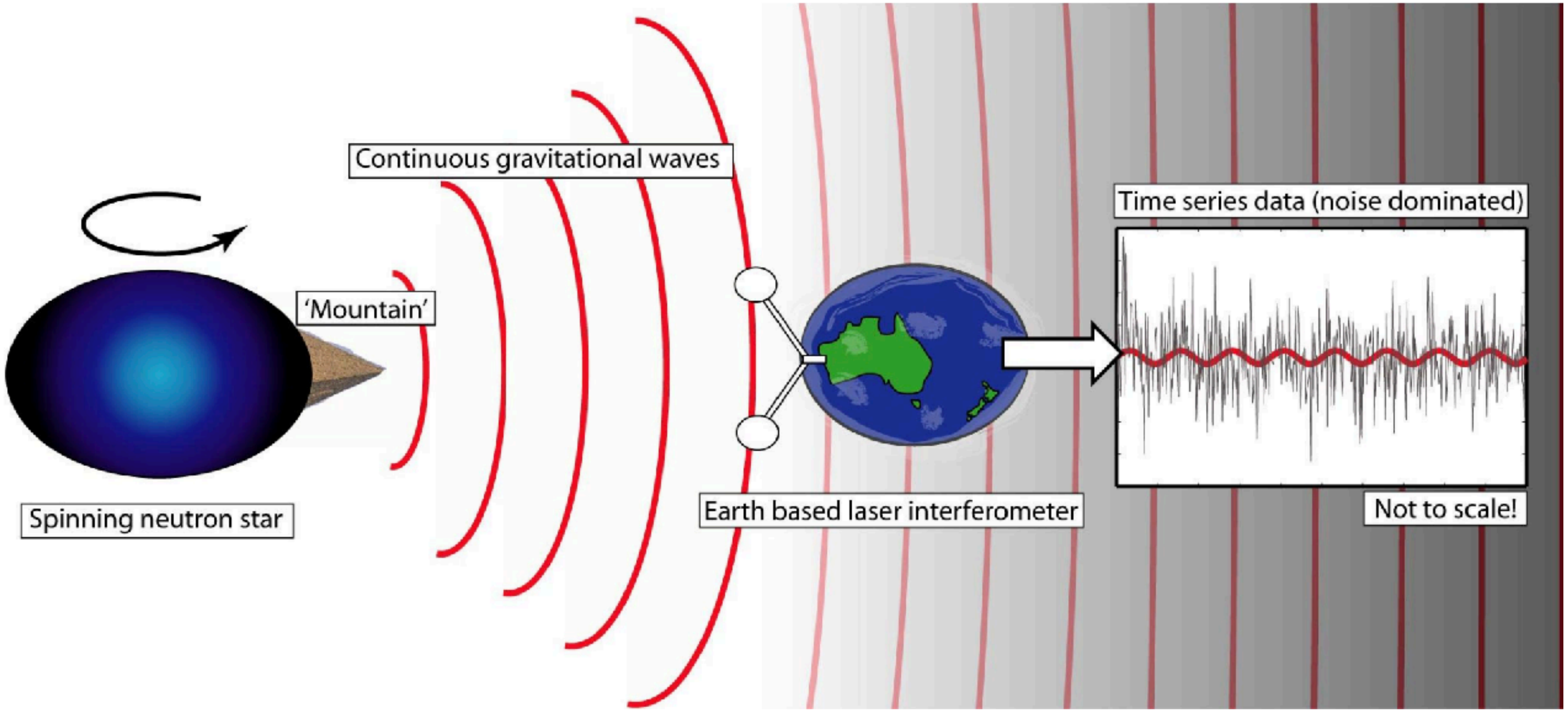



Image credit: Graham Woan

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

$$\dot{f}_{\rm rot} = -kf^n_{\rm rot}$$

n: Braking index

k: Constant

They depend on the kind of emission

$$f_{\rm GW} = 2f_{\rm rot} \equiv f$$

Star rotational parameters $\rightarrow \mathbf{f}, \dot{\mathbf{f}}, \ldots$

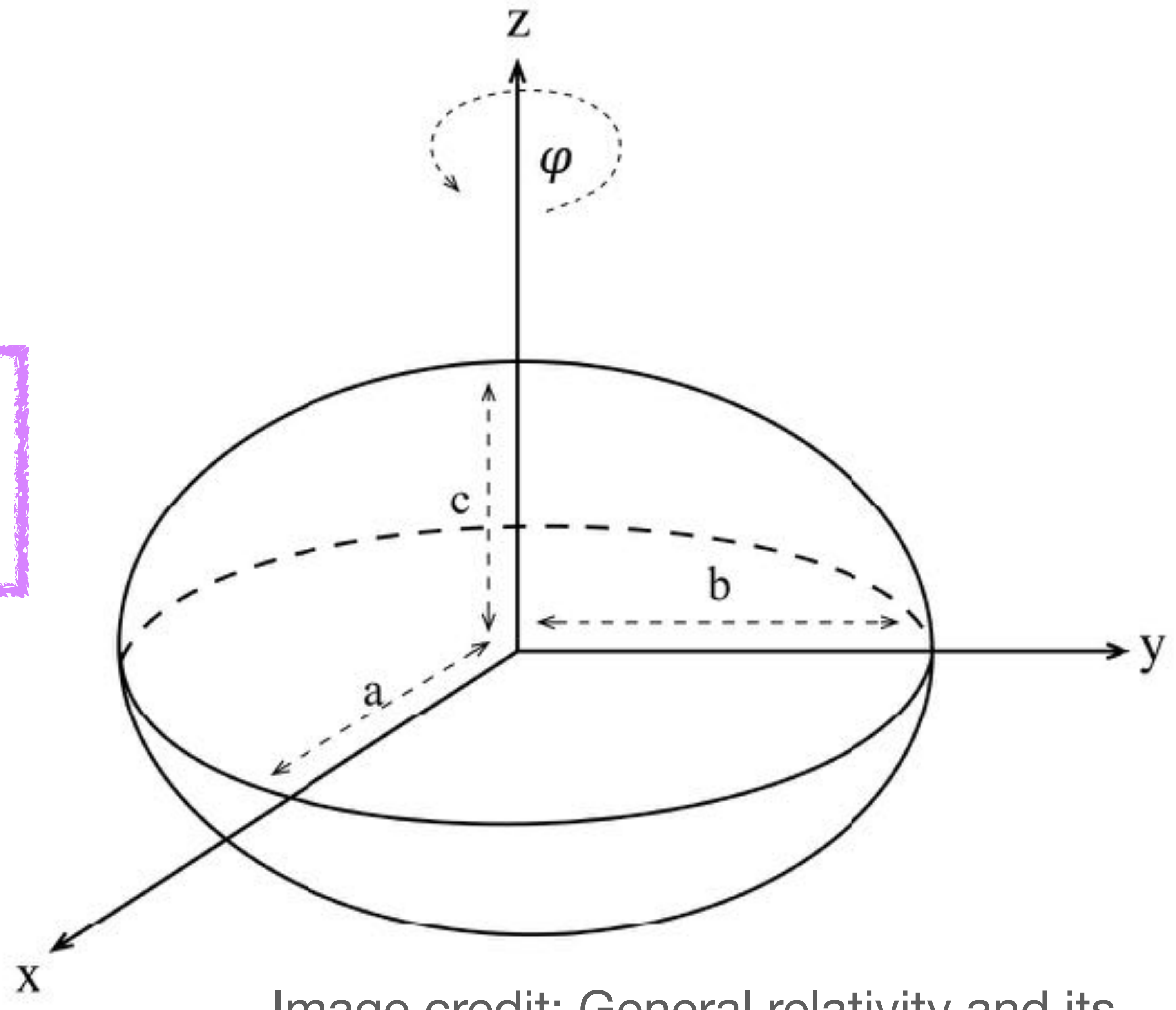



Image credit: General relativity and its application, Ferrari, Gualtieri, Pani

# Ellipticity (Oblateness)

The measure of the asymmetry is the ellipticity ($\epsilon$)

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

Possible cause of **asymmetry**:

- Mountains
- R-modes
- Magnetic field

We do not have a measure of ellipticity for known NSs

# Different kind of NSs

## Pulsar

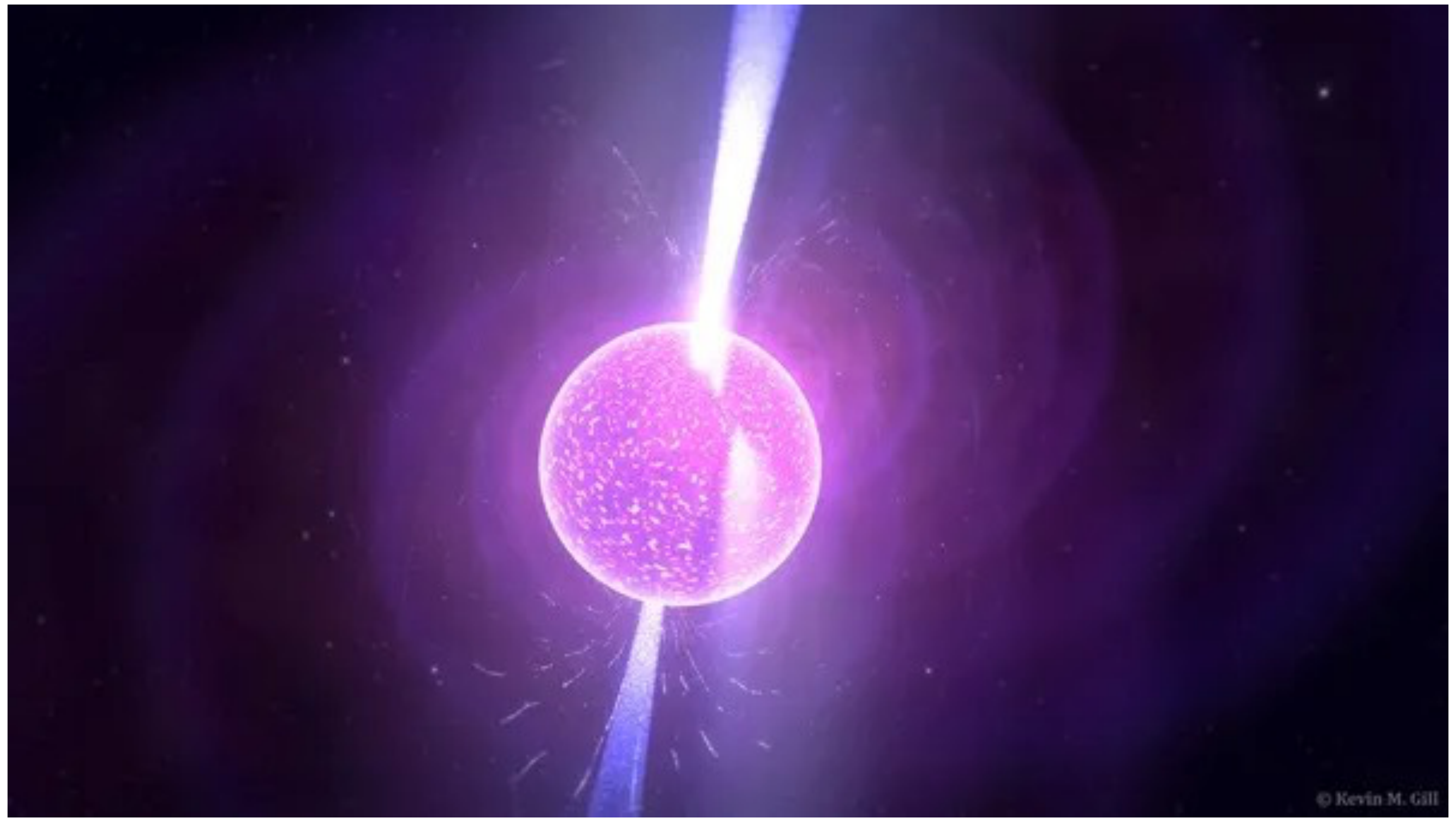



Image credit: Kevin Gill

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

## Newly born Magnetars

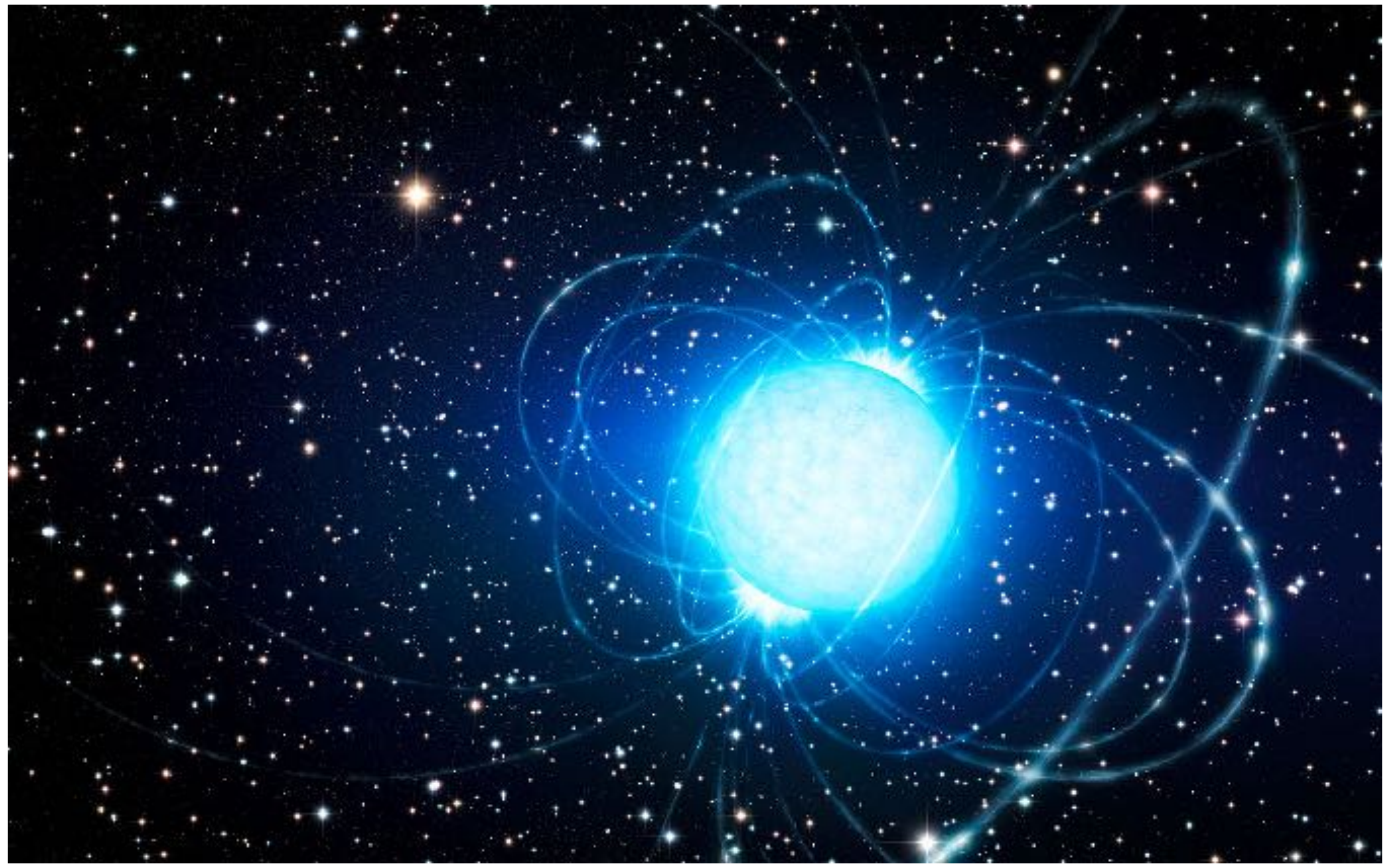


Image credit: ESO/L. Calçada

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

# Different kind of searches

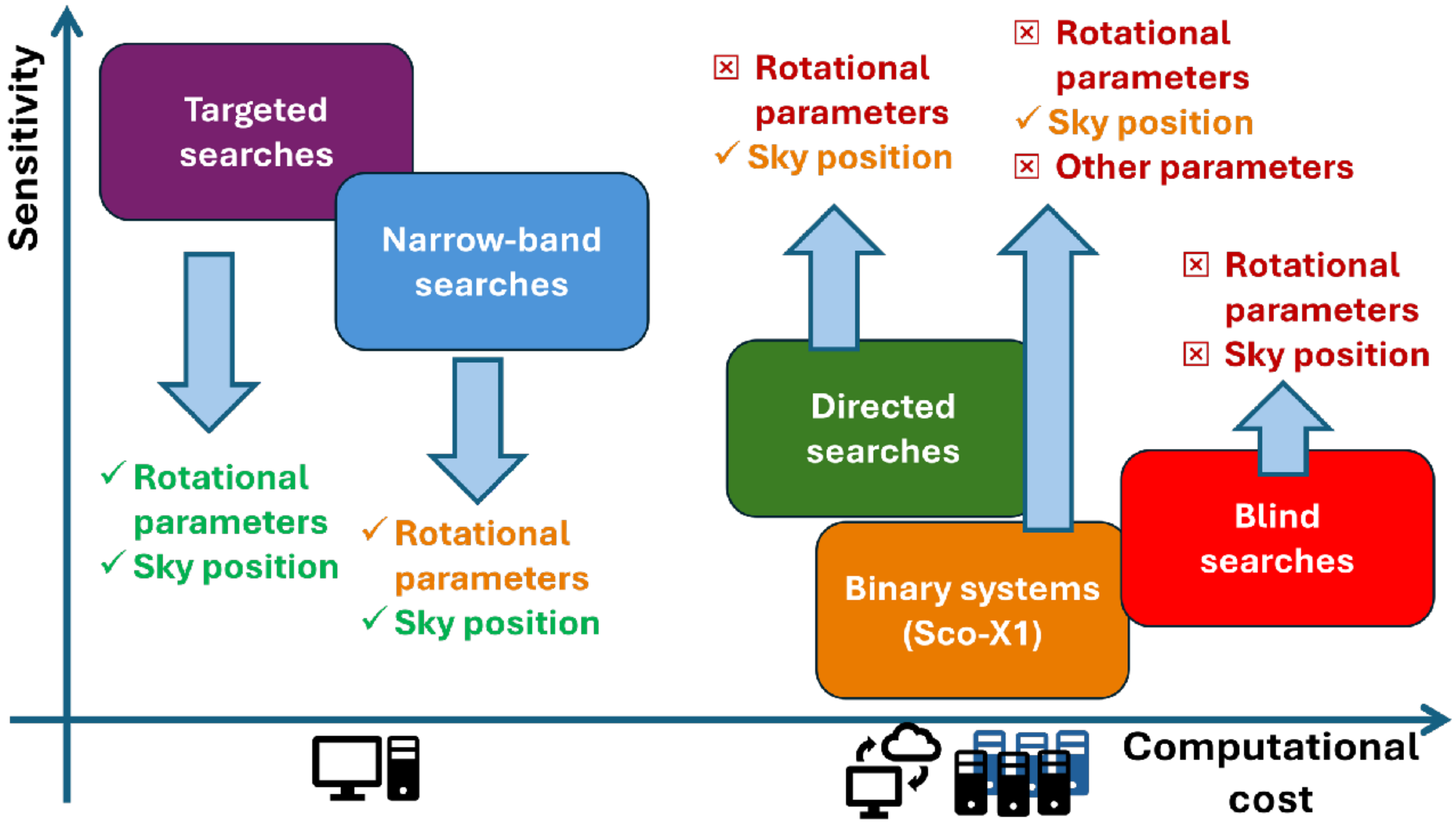



Image credit: Cristiano Palomba

# Time-frequency maps

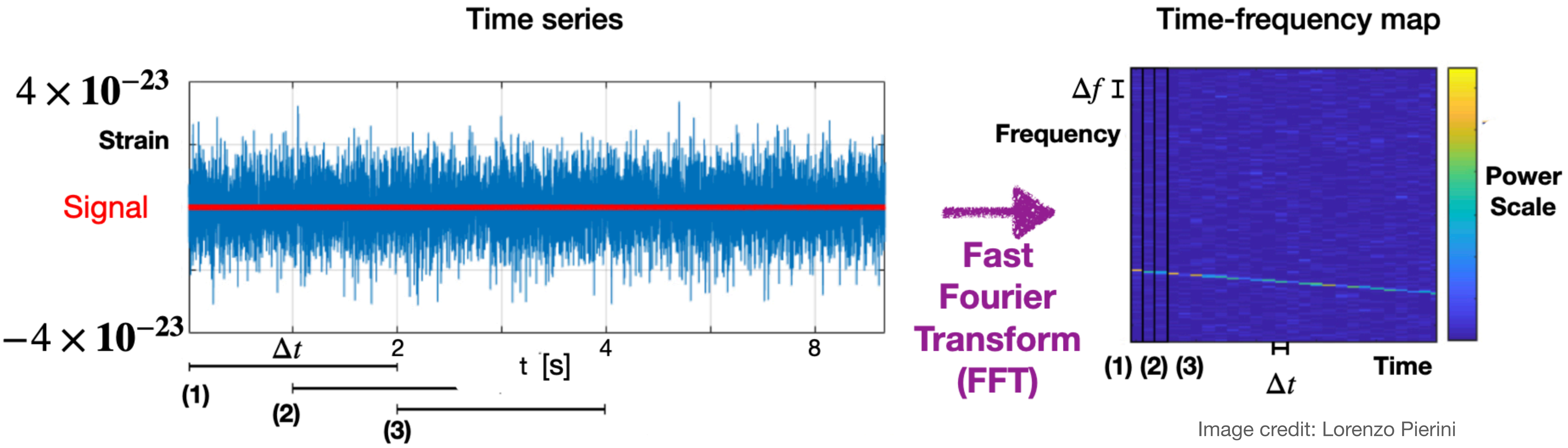



Image credit: Lorenzo Pierini

# 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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**Definition of the model structure**

↓

**Training**

↓

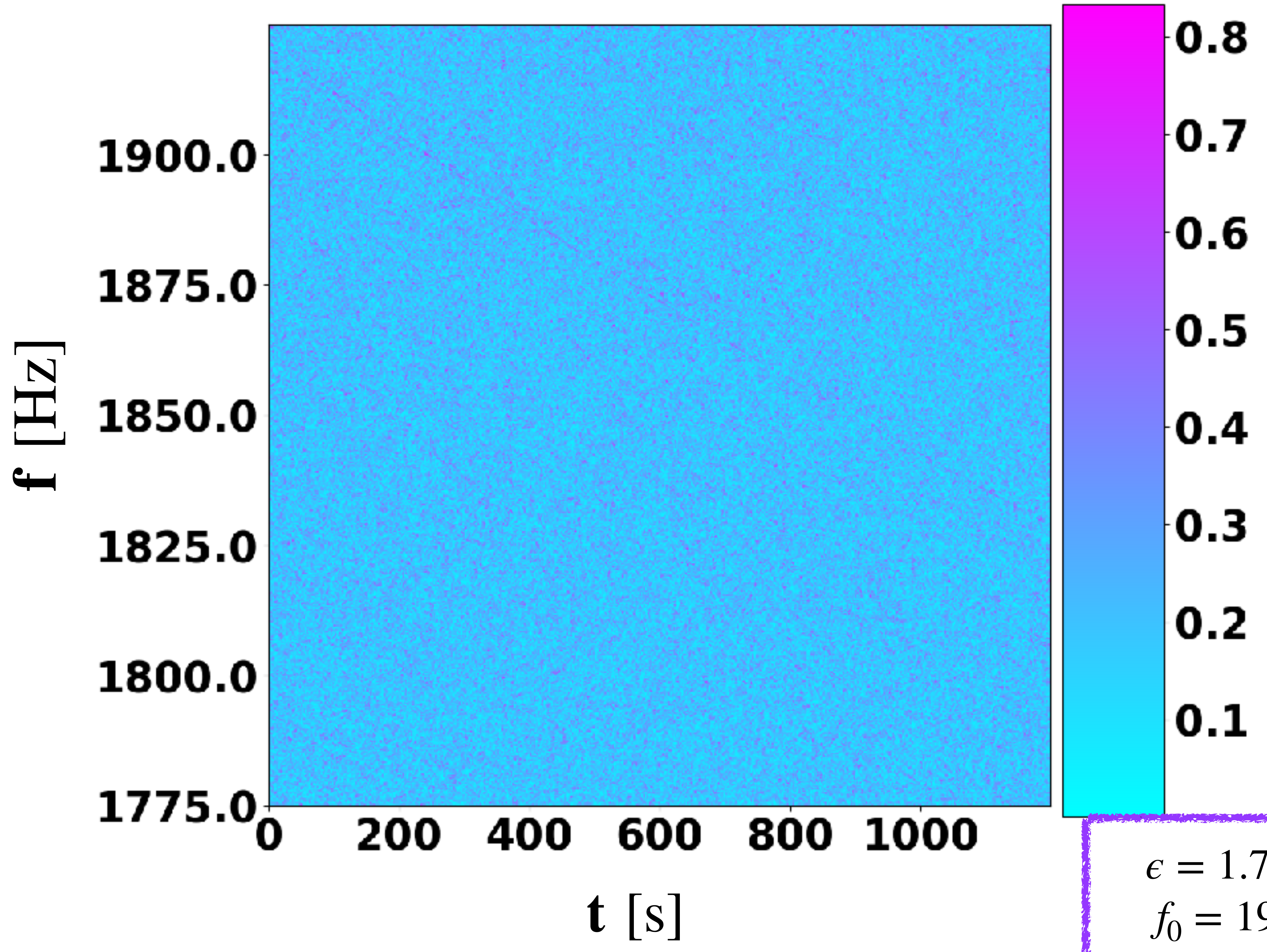
**Testing**

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

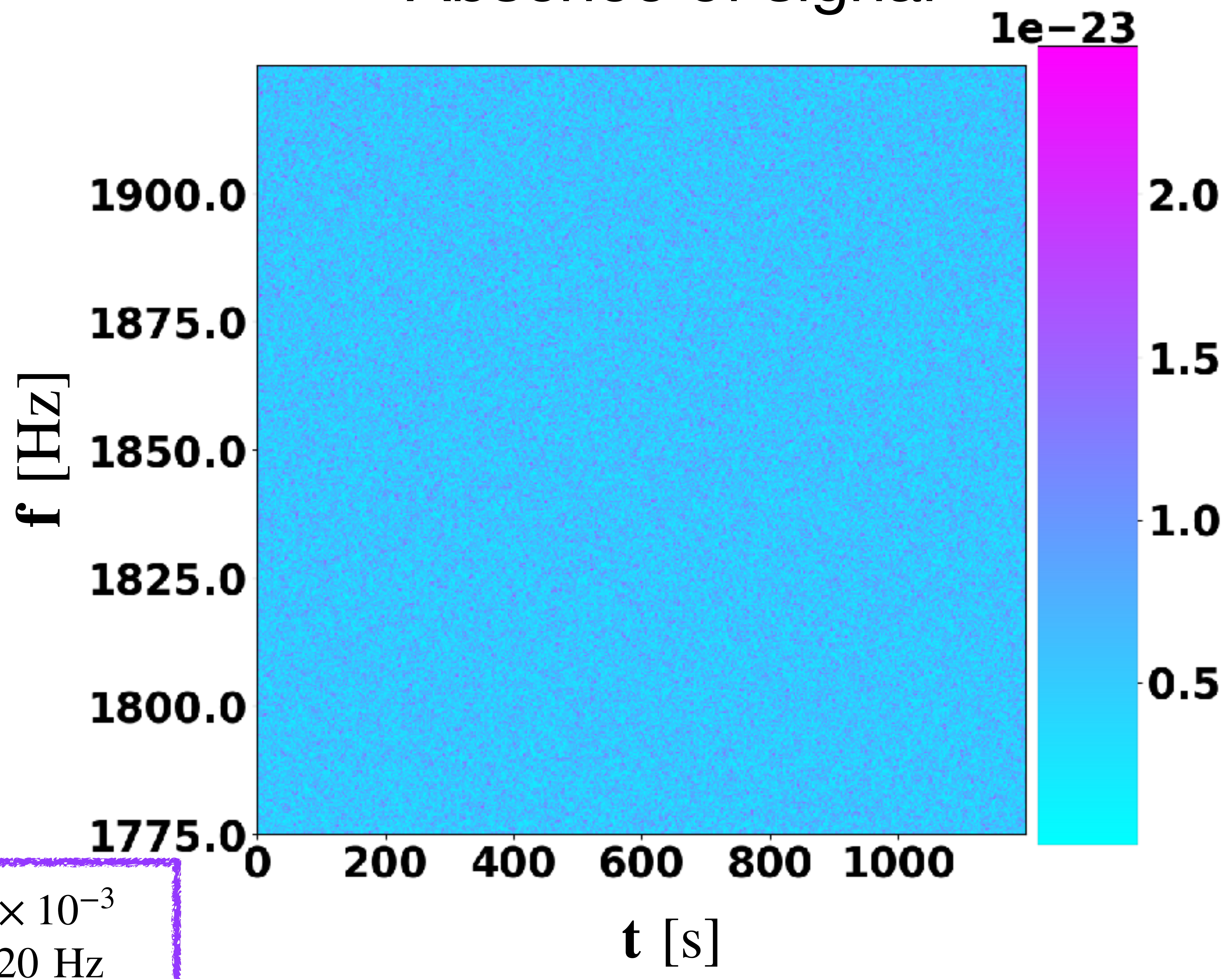
# Classifier

Classification of time-frequency maps

Presence of signal




Absence of signal

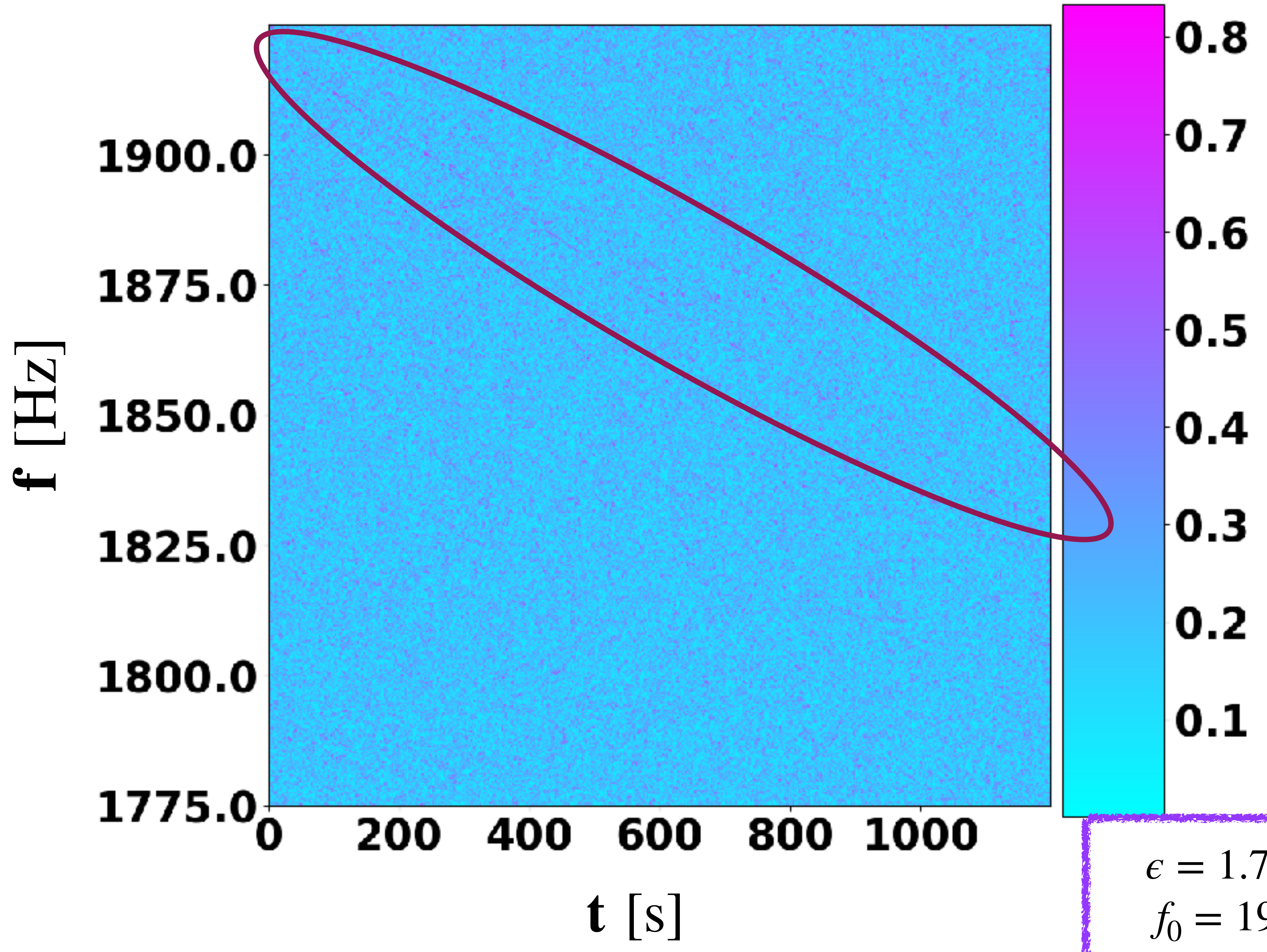



$\epsilon = 1.7 \times 10^{-3}$
$f_0 = 1920$ Hz

# Classifier

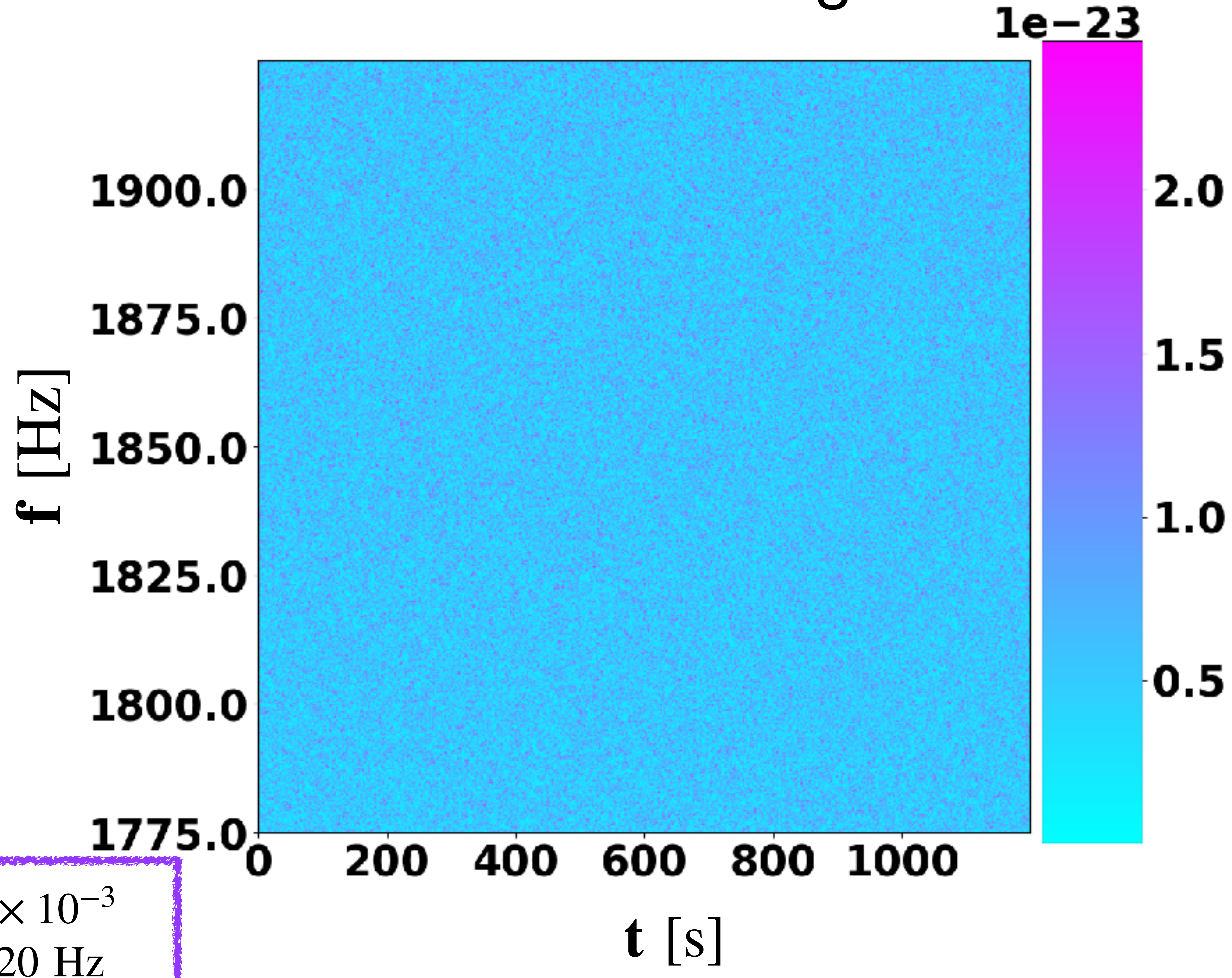
Classification of time-frequency maps

Presence of signal



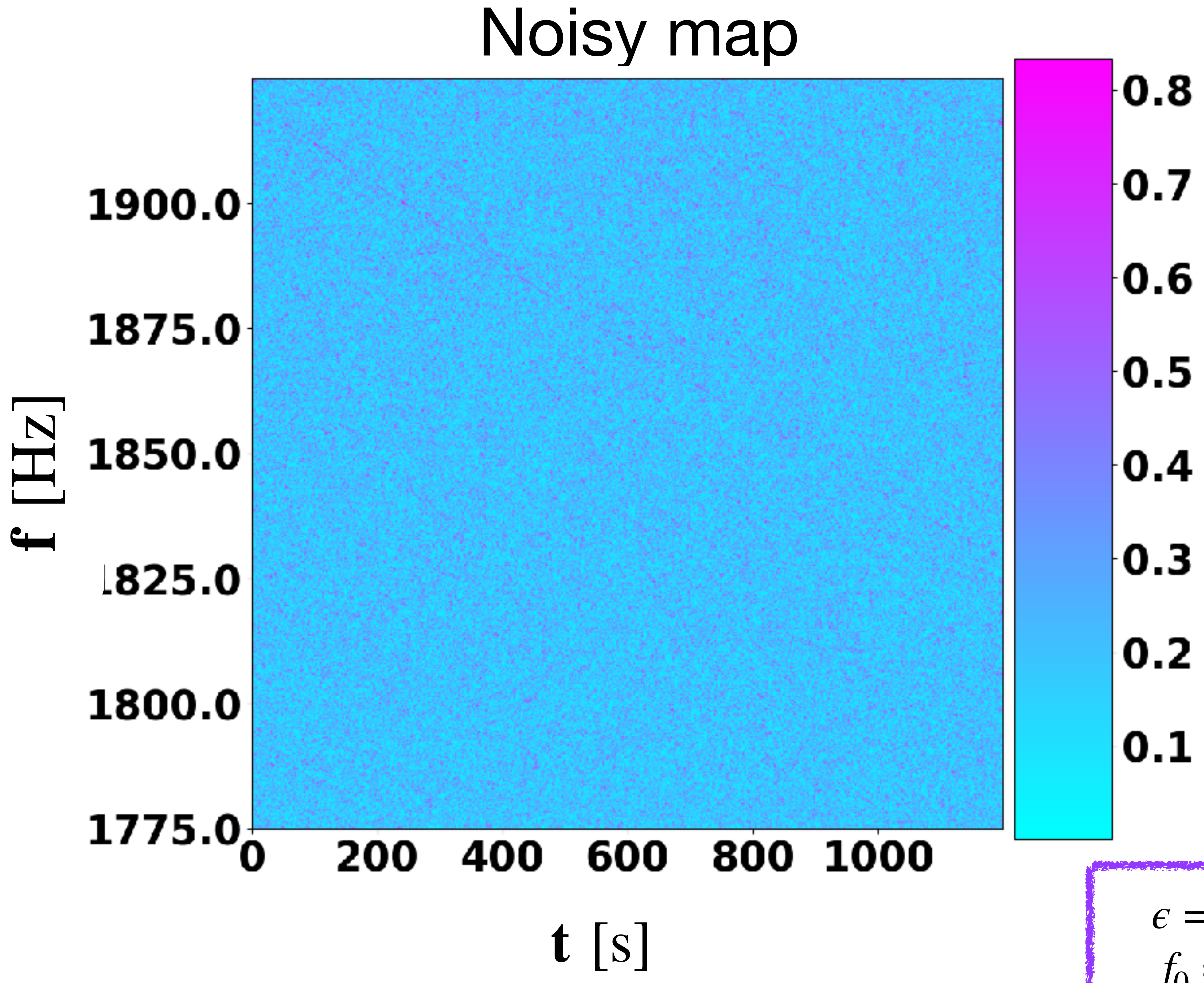

$\epsilon = 1.7 \times 10^{-3}$
$f_0 = 1920$ Hz

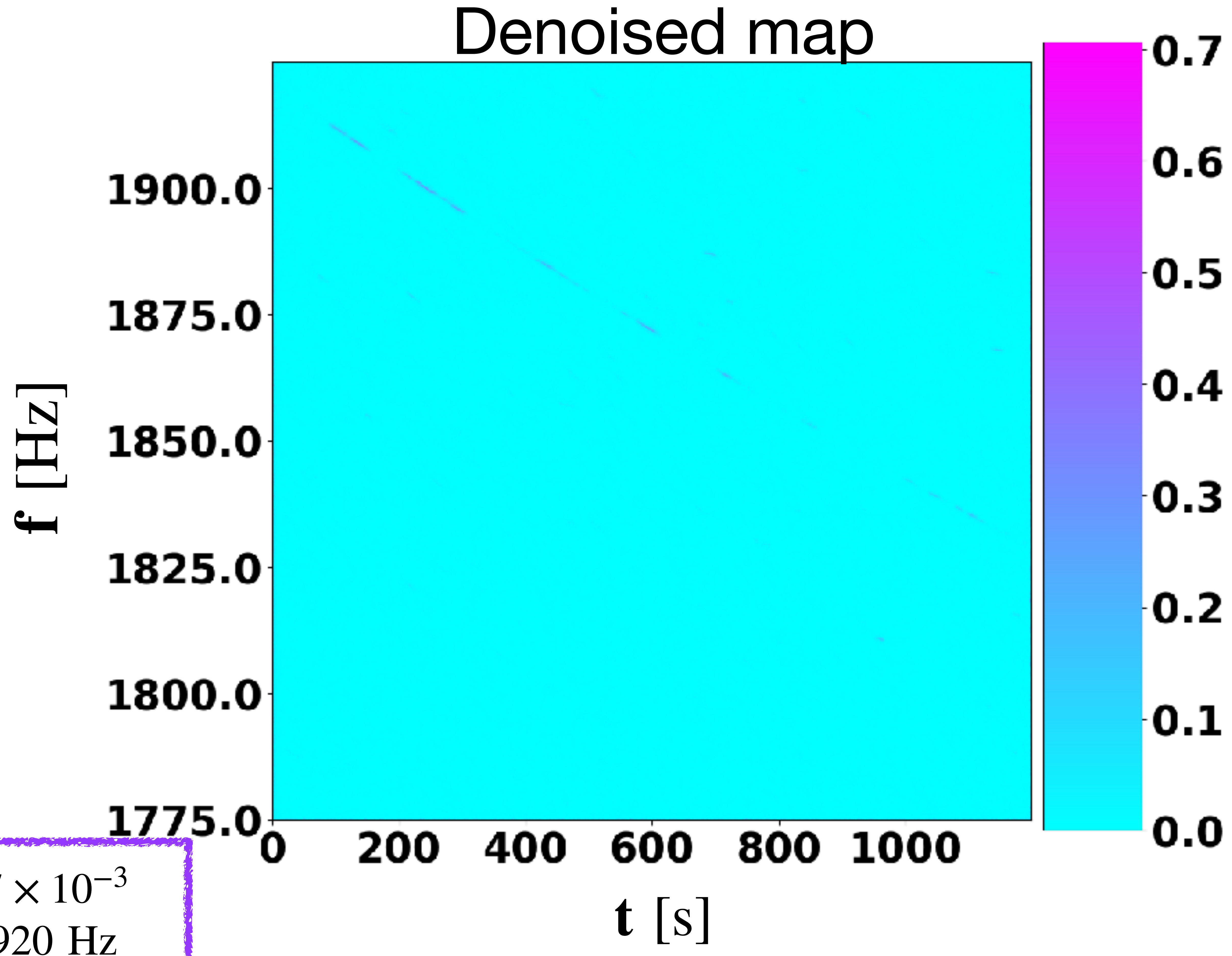
Absence of signal



# Denoiser

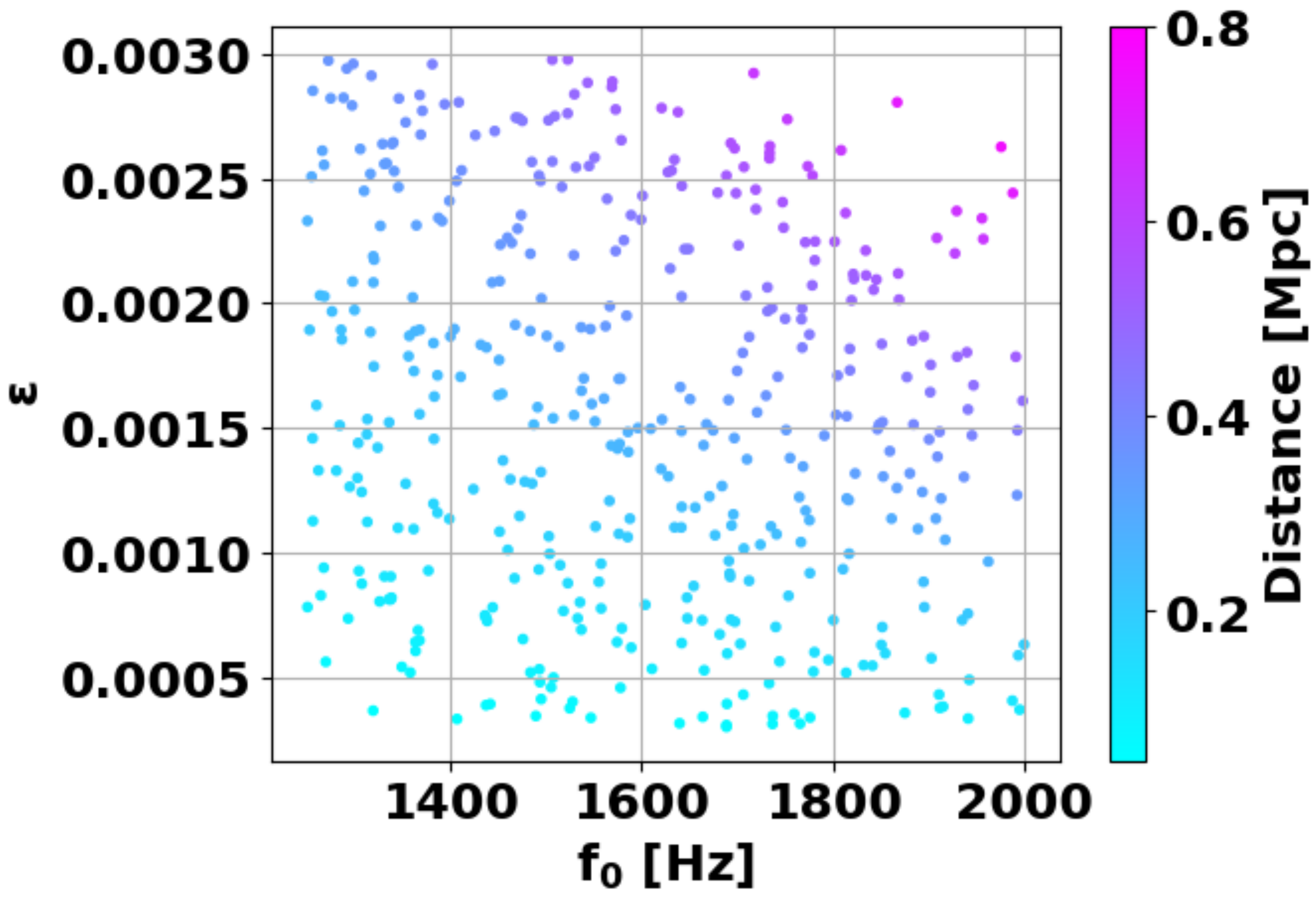
It reduces the noise level of the image while preserving a significant fraction of the signal

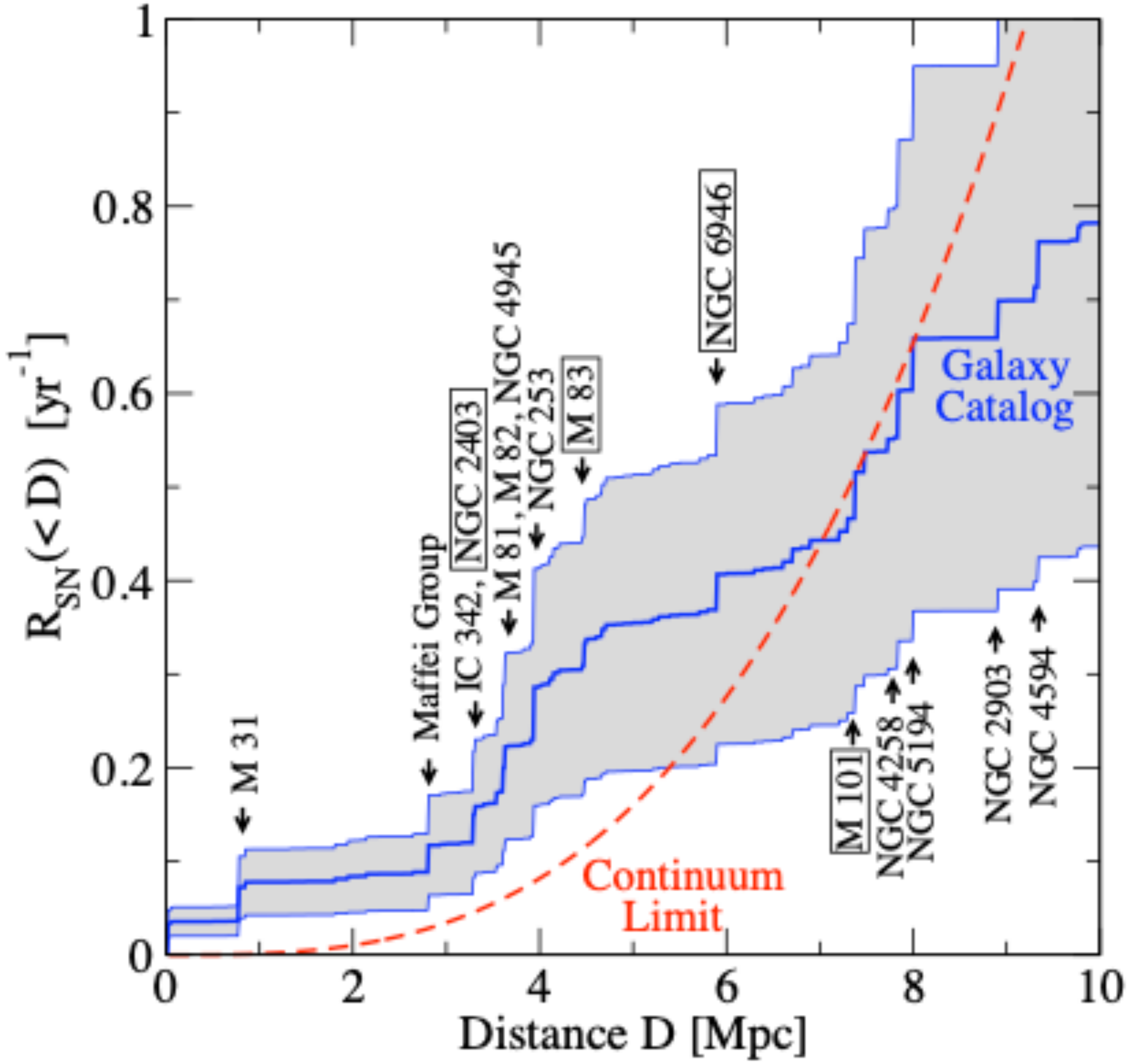



$\epsilon = 1.7 \times 10^{-3}$
$f_0 = 1920$ Hz

# Preliminary conclusions




Hyper-Kamiokande Proto-Collaboration et al. Hyper-Kamiokande *Design Report*

We need to reach higher distances to increase the probability to see an event

# 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

# 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

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THANK YOU FOR YOUR ATTENTION

**What is next?**

→ Improve the already existing data analysis techniques

→ Develop new techniques

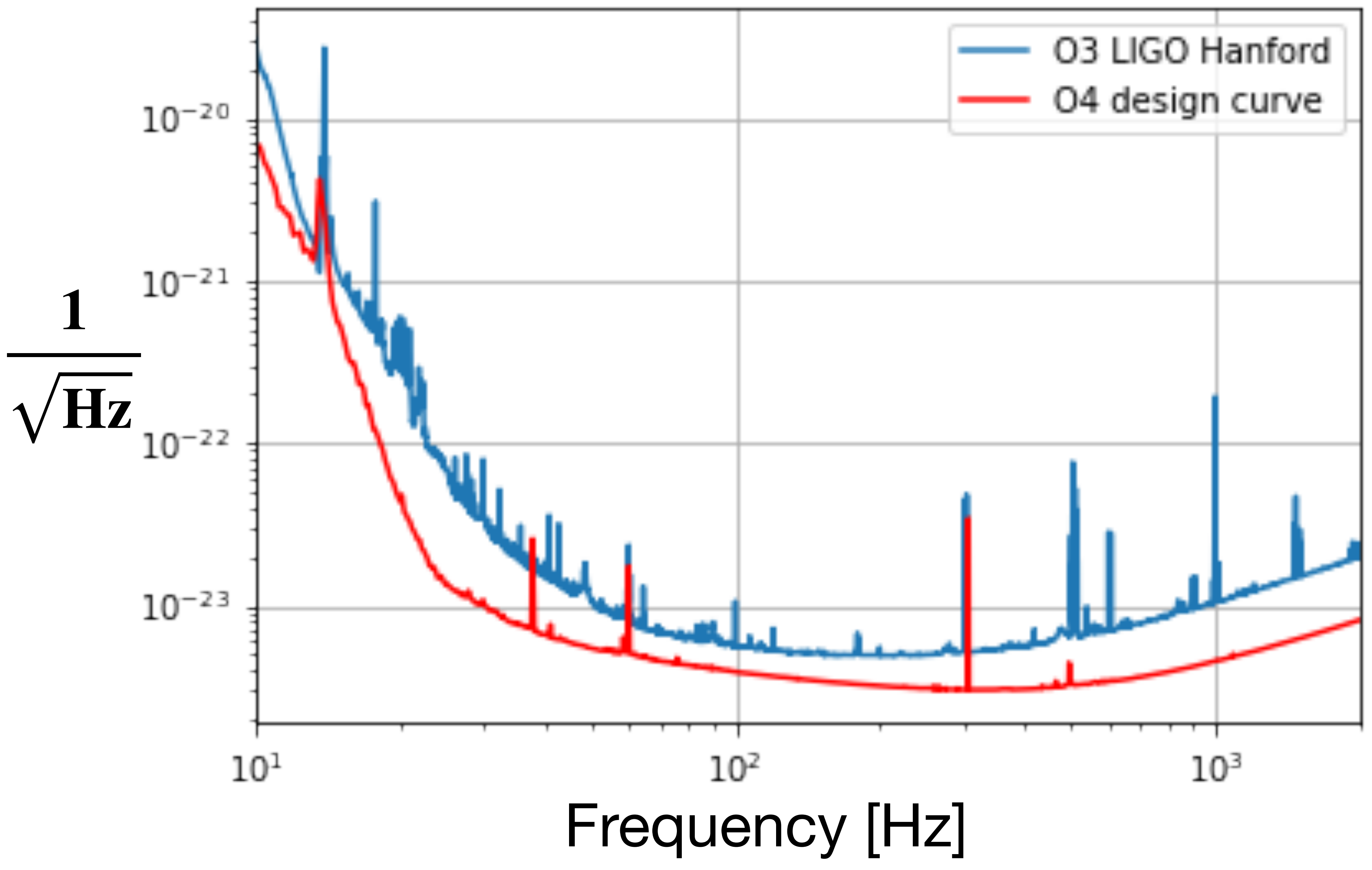
→ New generation interferometers

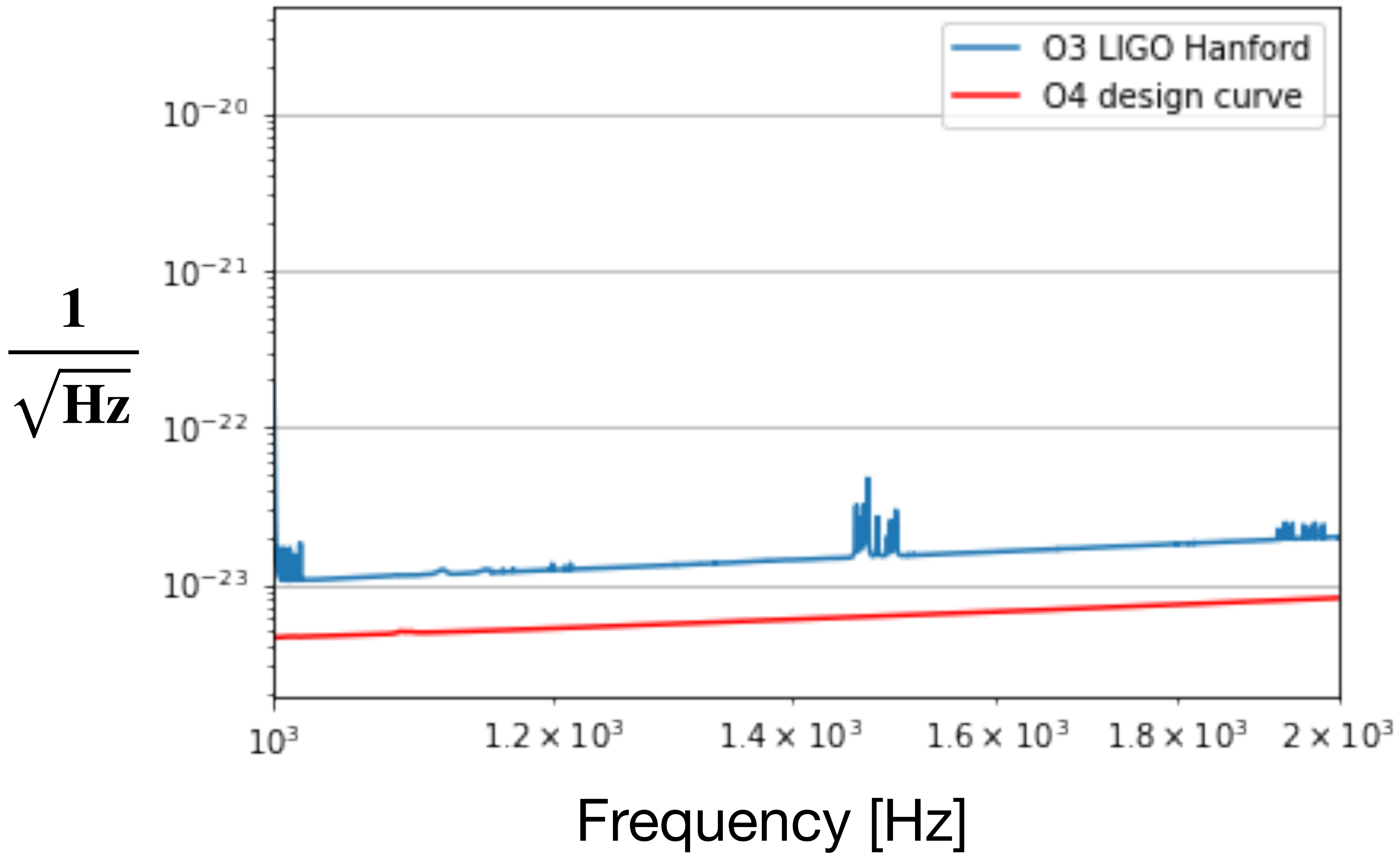
# Backup slides

# Noise

**Simulated data:**
Simulated noise according to the noise curve

**Gaussian frequency dependent noise**




*Noise curves used for Simulations in the update of the Observing Scenarios Paper*
LIGO Document T2000012-v2

# Signal

**GW amplitude**

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

Distance of the source

**Frequency variation**

$$\dot{f}(t) \sim -\epsilon^2 f(t)^5 \rightarrow f(t) = f_0 \left(1 + \frac{t\, \epsilon^2 f_0}{const}\right)^{-\frac{1}{4}}$$

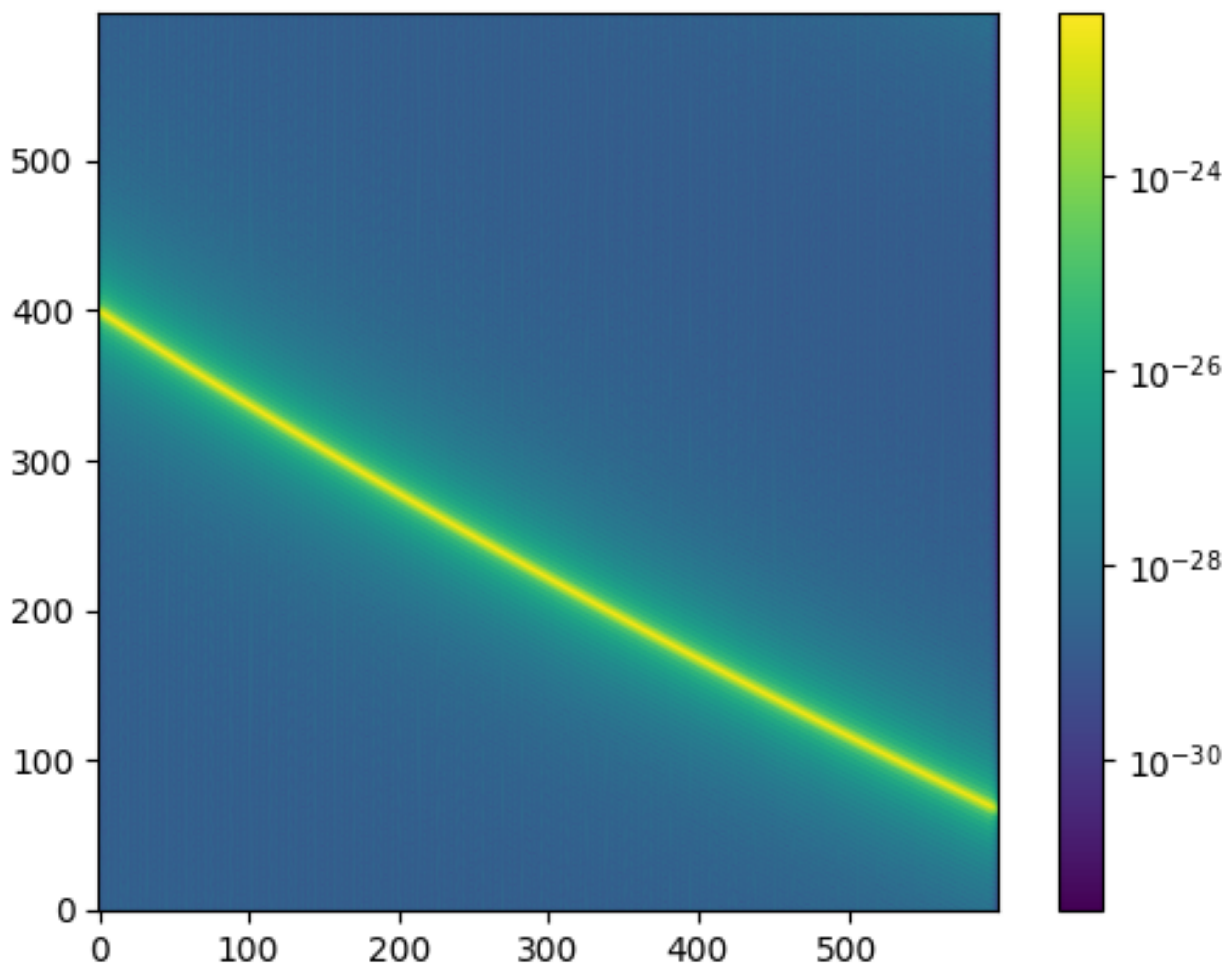
→ **Fixed initial amplitude :** $2 \times 10^{-23}$

→ **Fixed inclination angle:** $\iota \sim 56°$

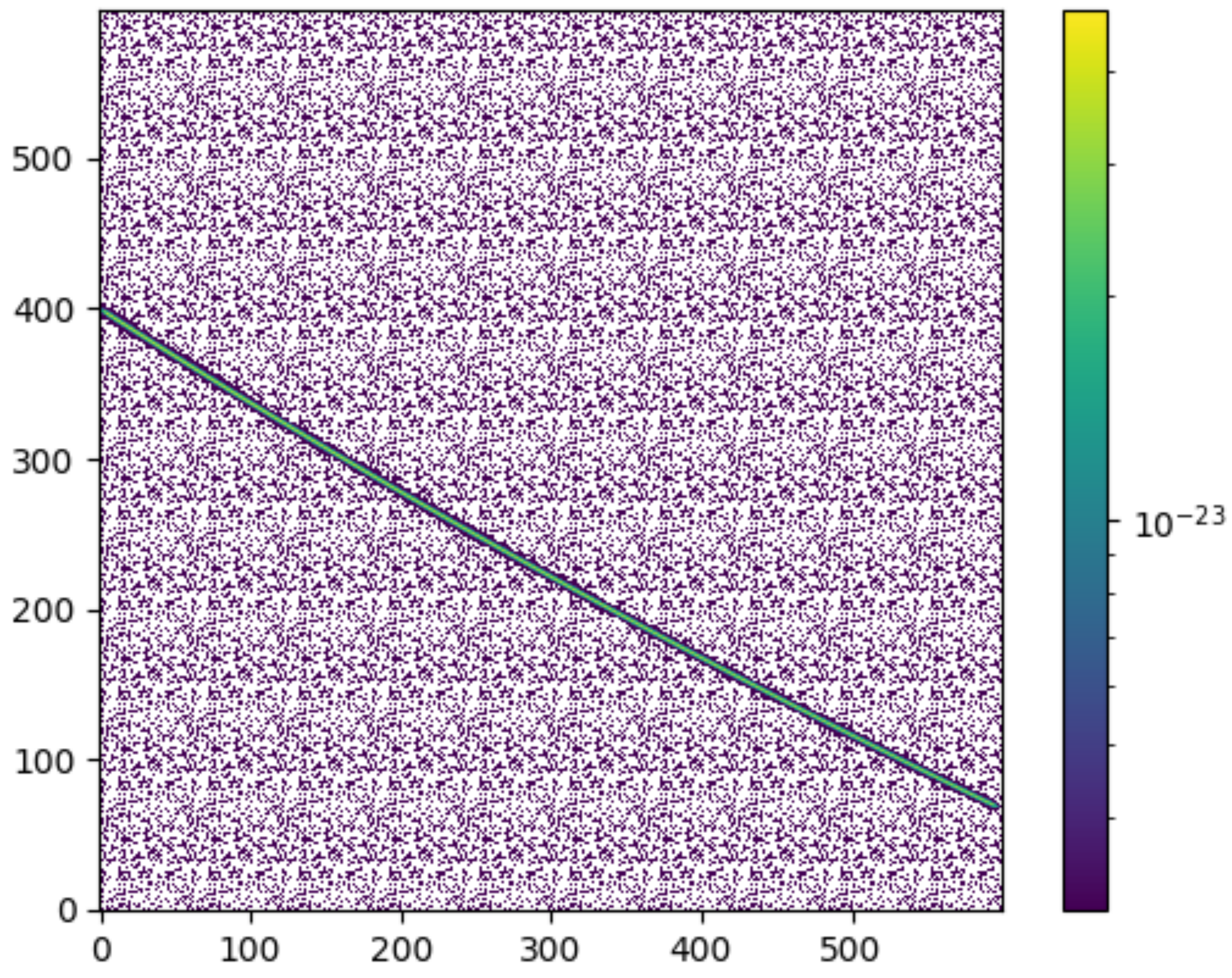
**Parameters range:** $\epsilon \in [3,30] \times 10^{-4}$ $f_0 \in [1.25,2.00]$ kHz

**We are not focusing on continuous signals**

# Artefacts



500
400
300
200
100
0
0
100
200
300
400
500
$10^{-24}$
$10^{-26}$
$10^{-28}$
$10^{-30}$

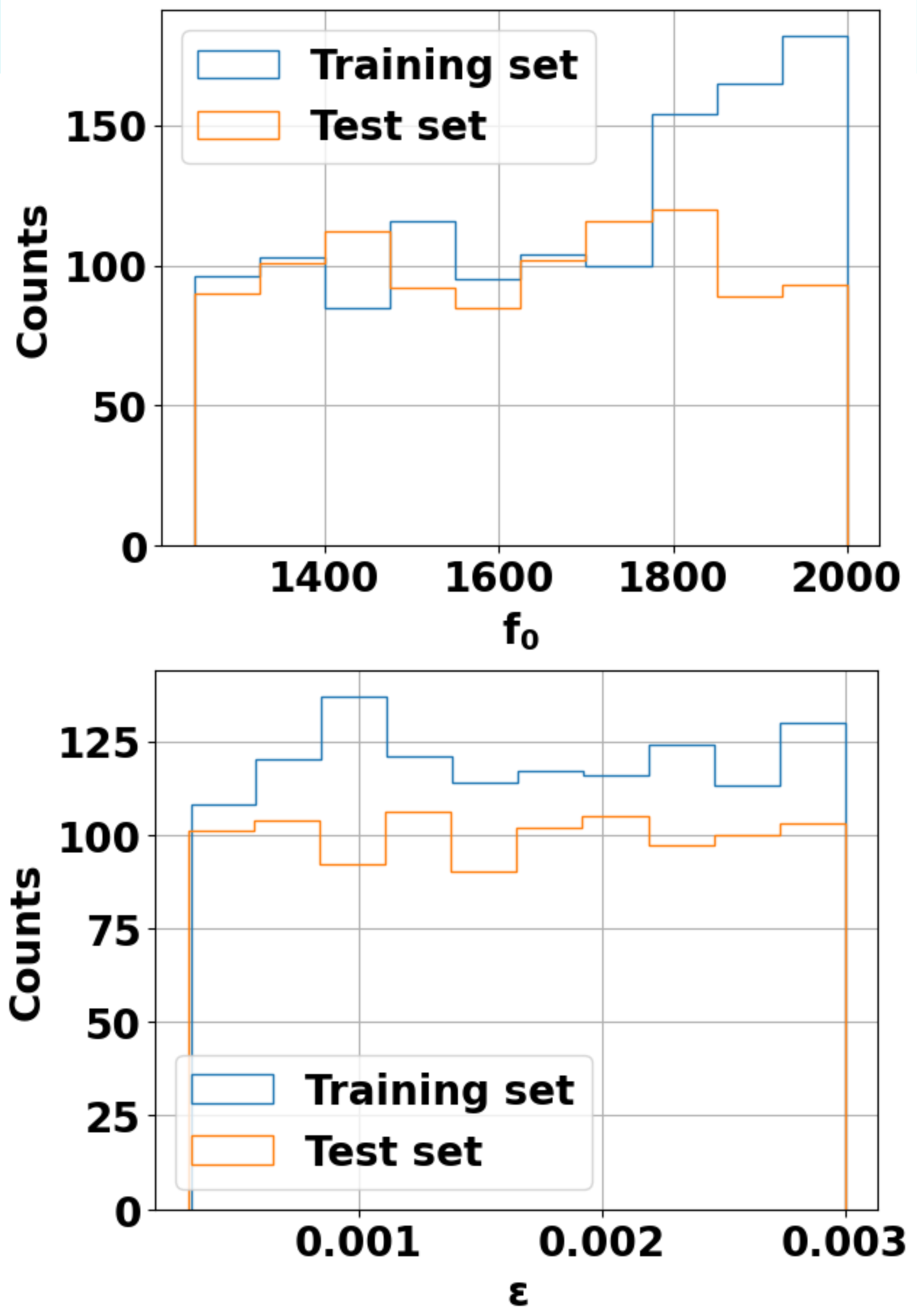



500
400
300
200
100
0
0
100
200
300
400
500
$10^{-23}$

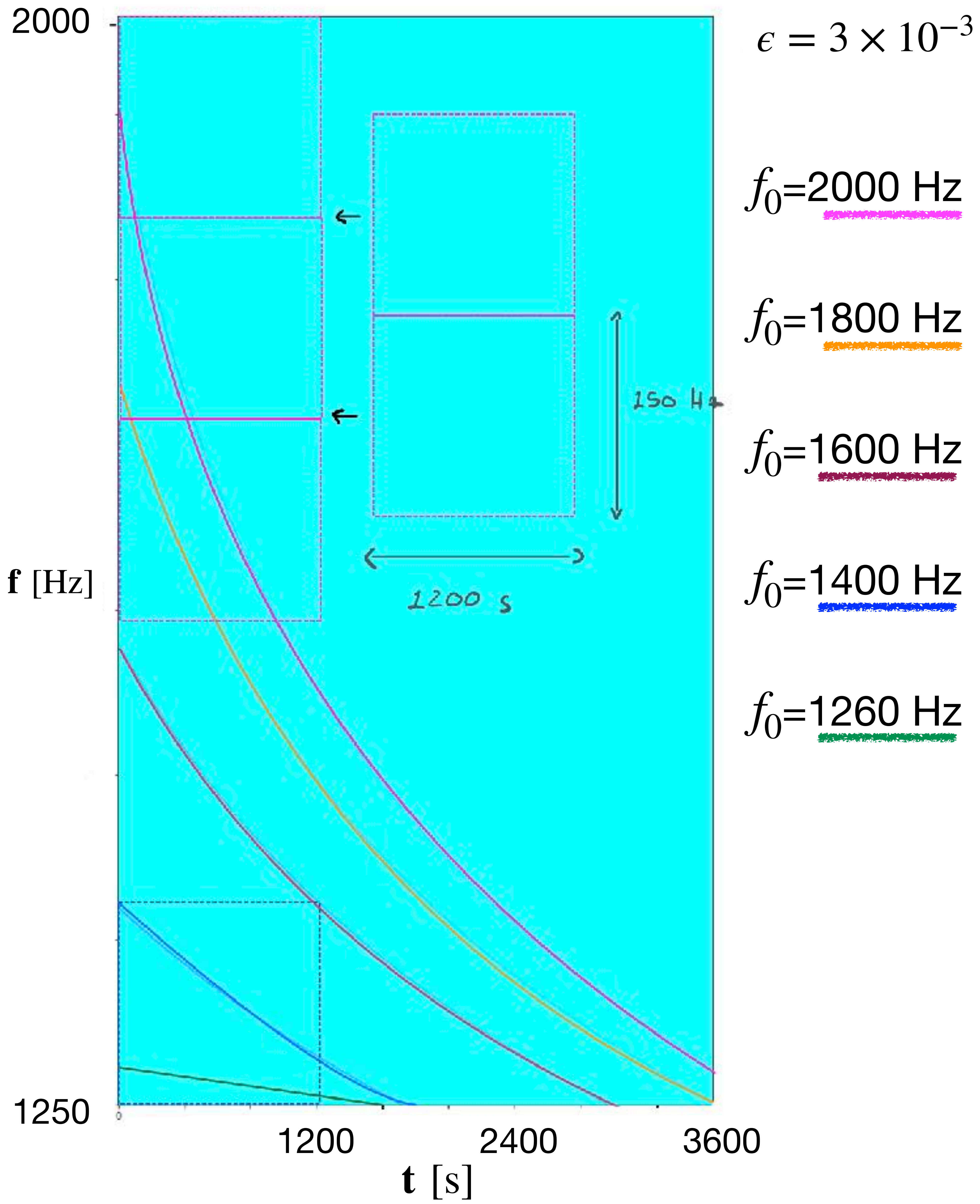
# Dataset

**Number of signals**:
1200 training, 1200 testing

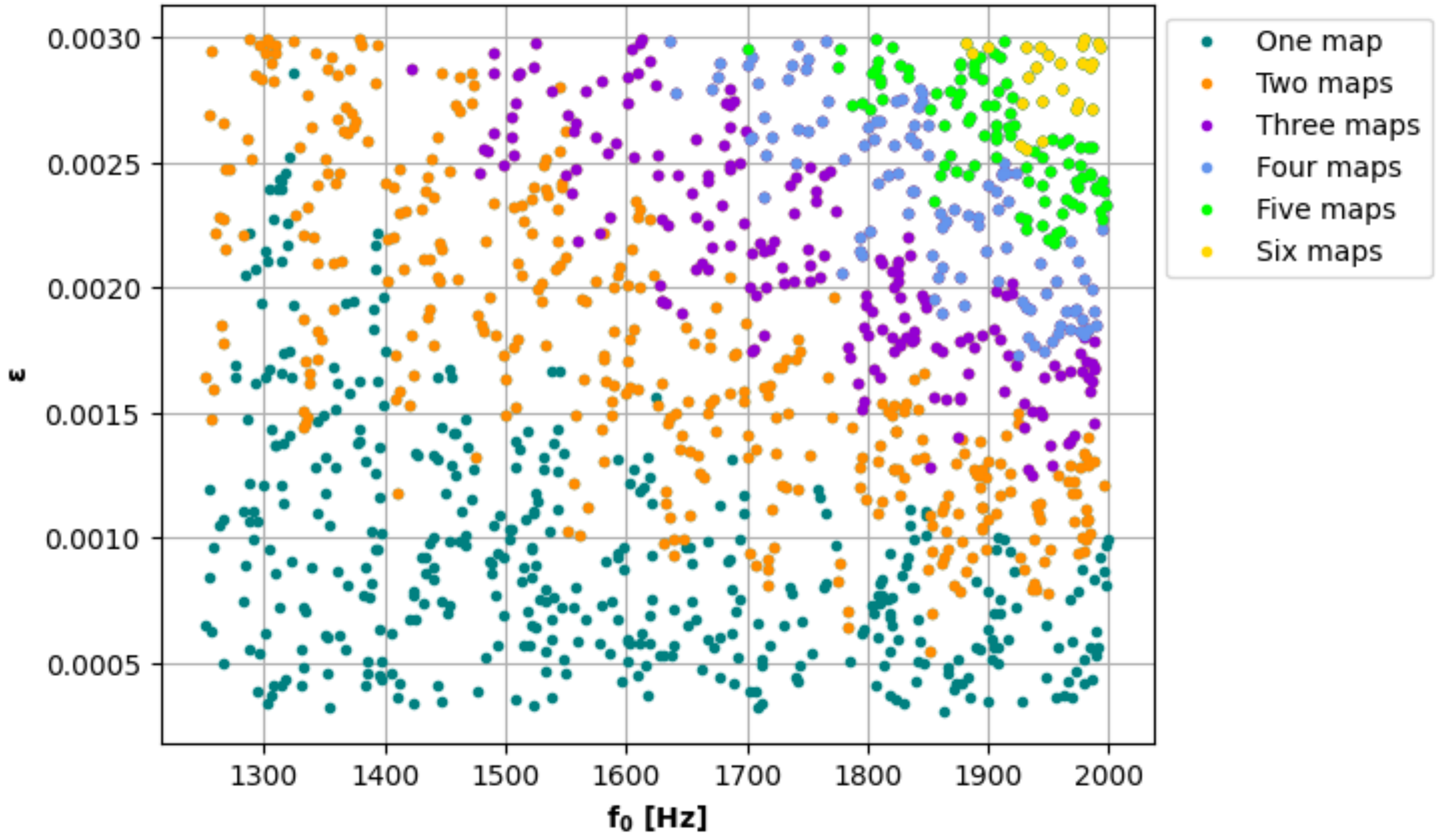
- **Training set**: 2226
- **Validation set**: 556
- **Test set**: 2177
- **Threshold** $\mathbf{10^{-23}} : 5 \times 10^{-25}$
- **Normalization**: maximum of noise and signal maps group



## Maps construction



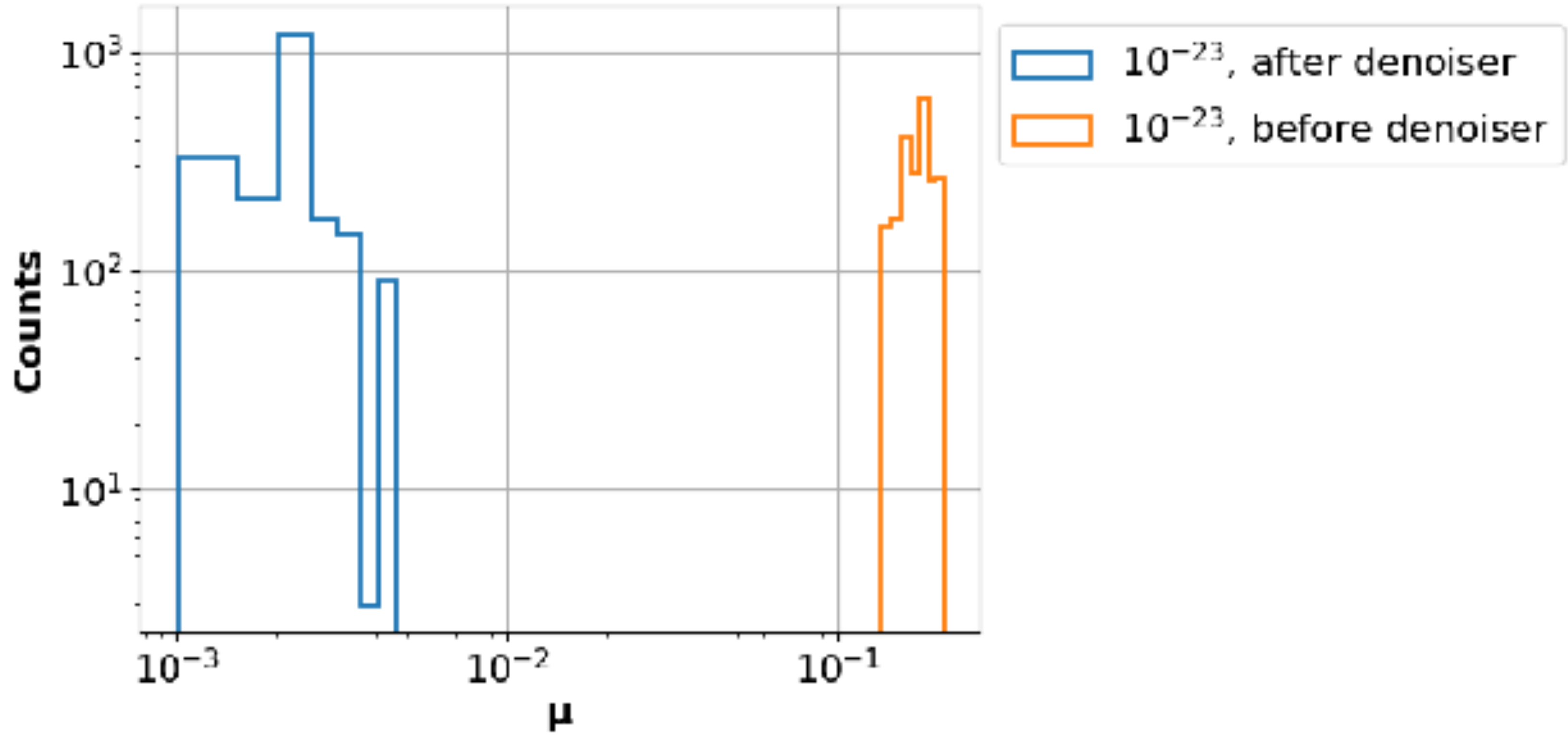

## Number of maps crossed by a signal



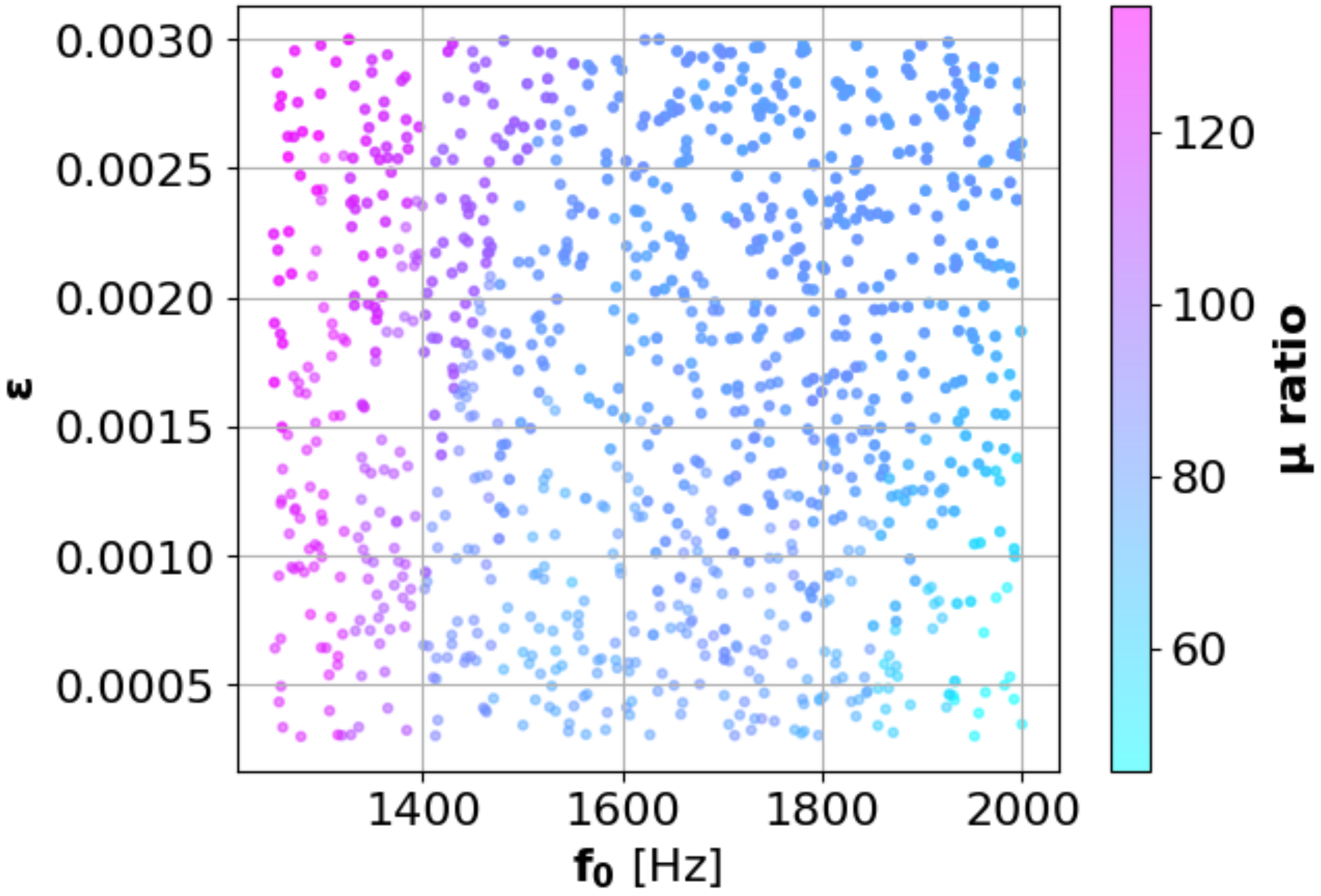

→ The number of maps per signal depends on the parameters

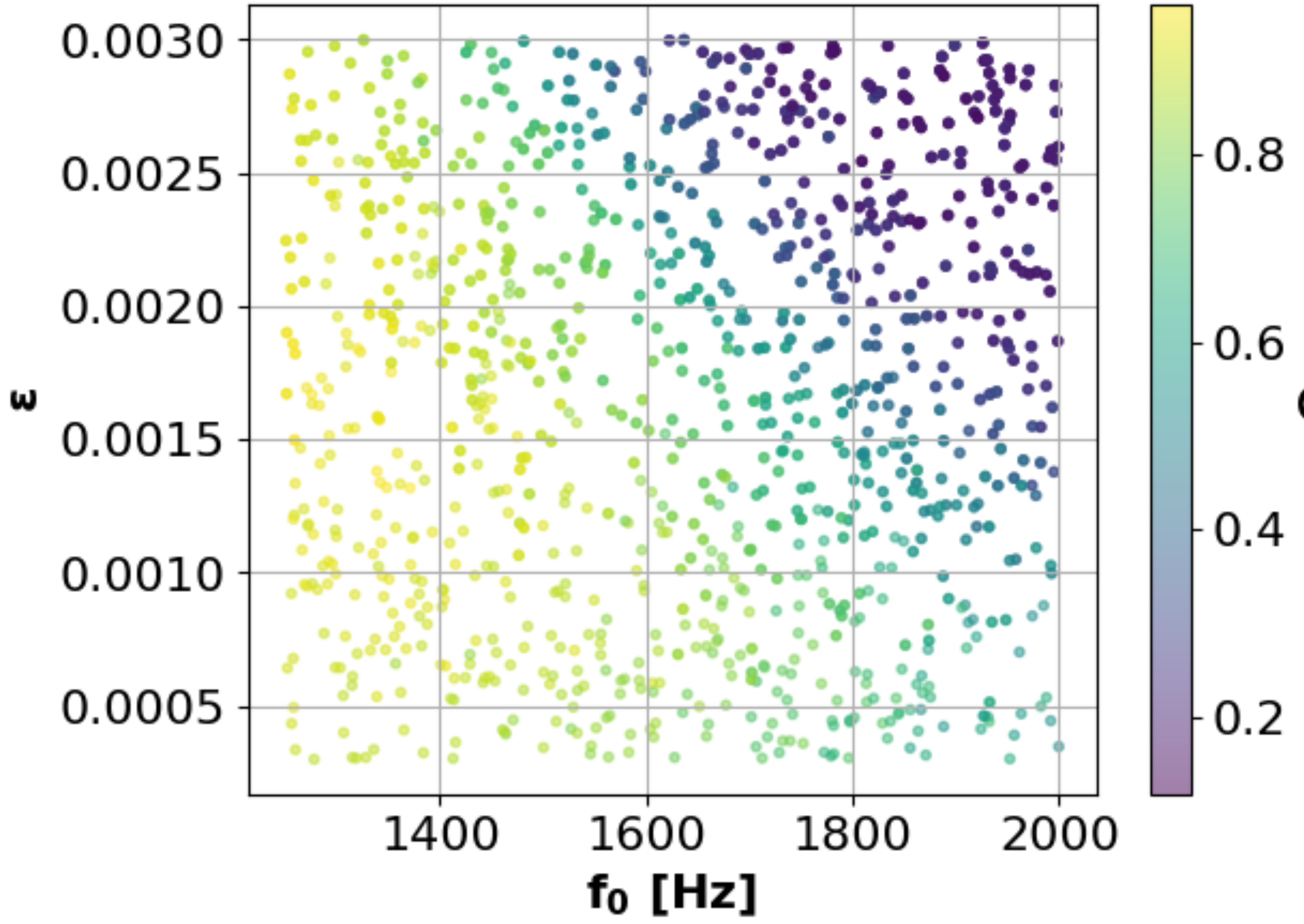
→ It is enough to tag right one map to have a trigger

# Denoiser




Removing noise



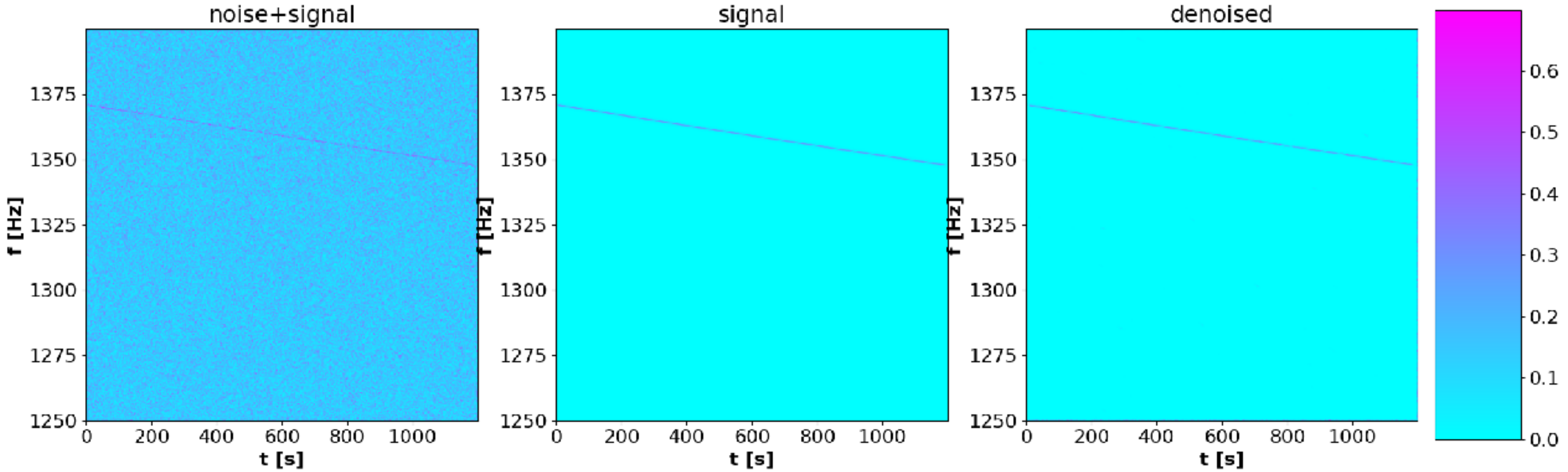




Preserving the signal

# Overlap

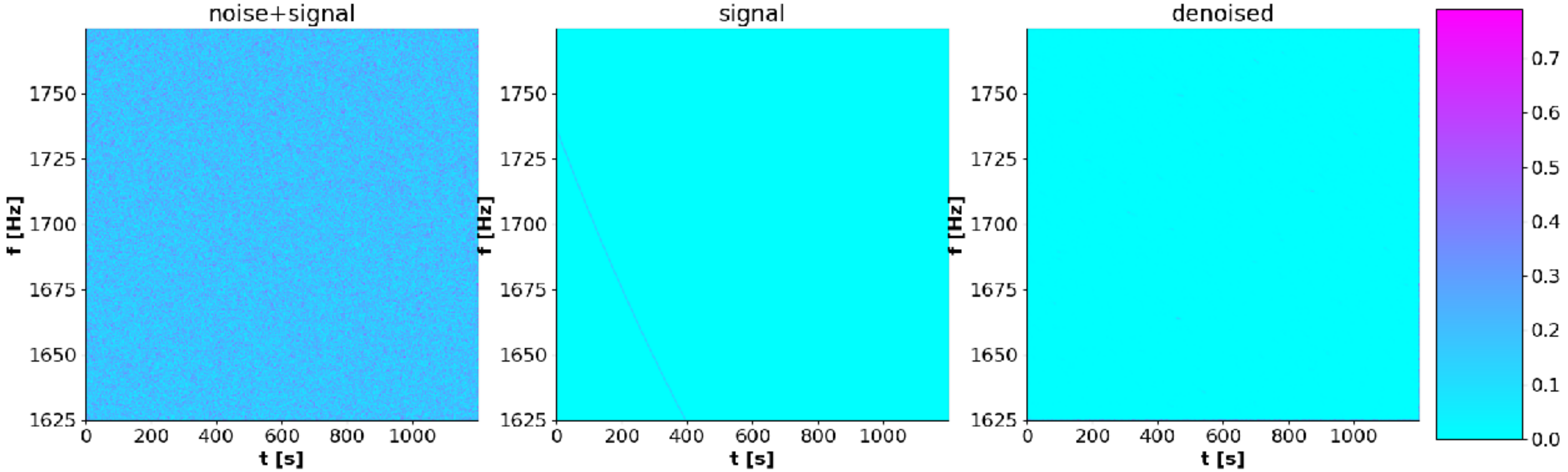
$\epsilon = 1.3 \times 10^{-3}$
$f_0 = 1370$ Hz

$\mathcal{O} = 0.96$

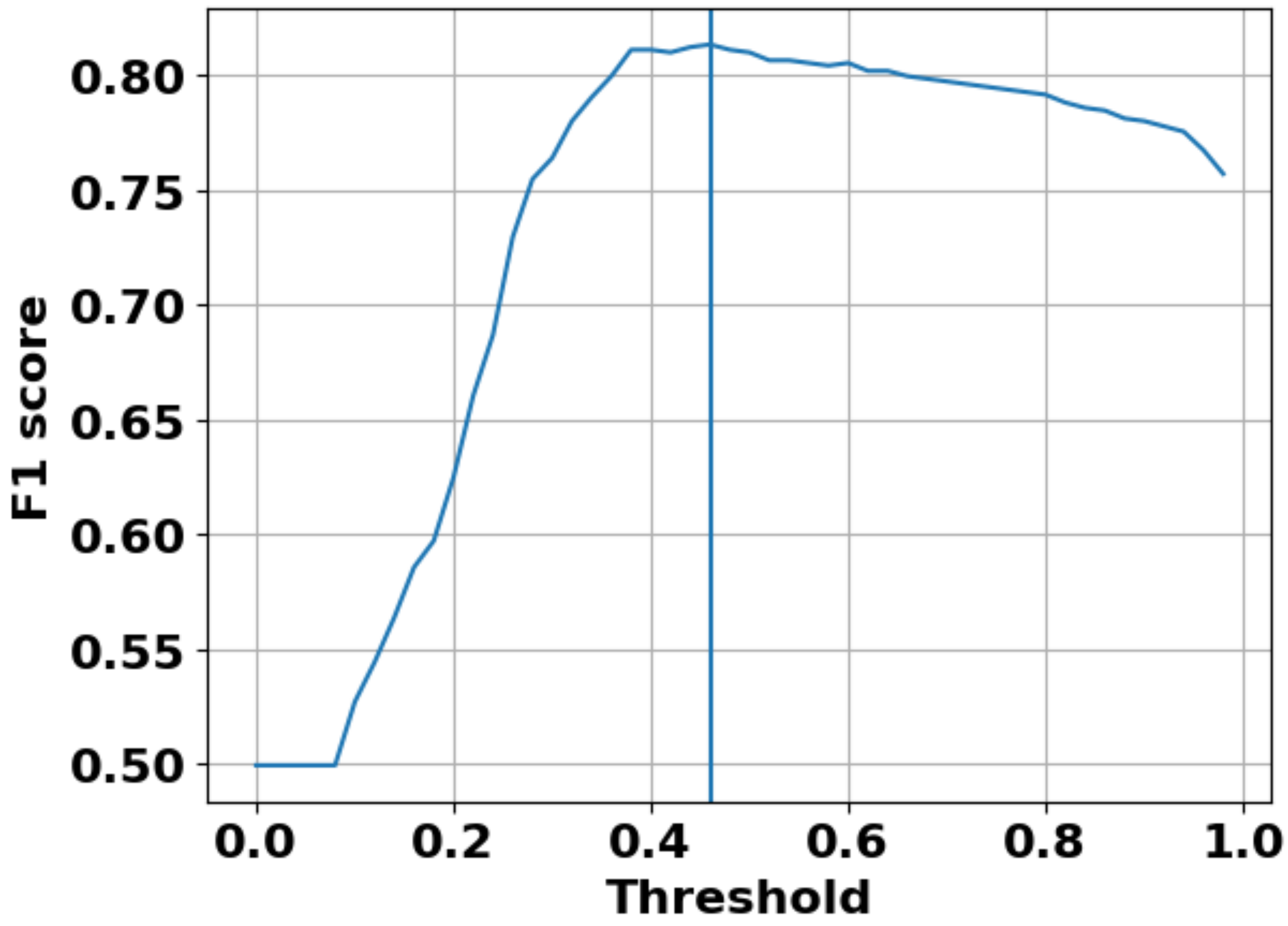



$\epsilon = 3 \times 10^{-3}$
$f_0 = 1737$ Hz

$\mathcal{O} = 0.11$



# F1 score

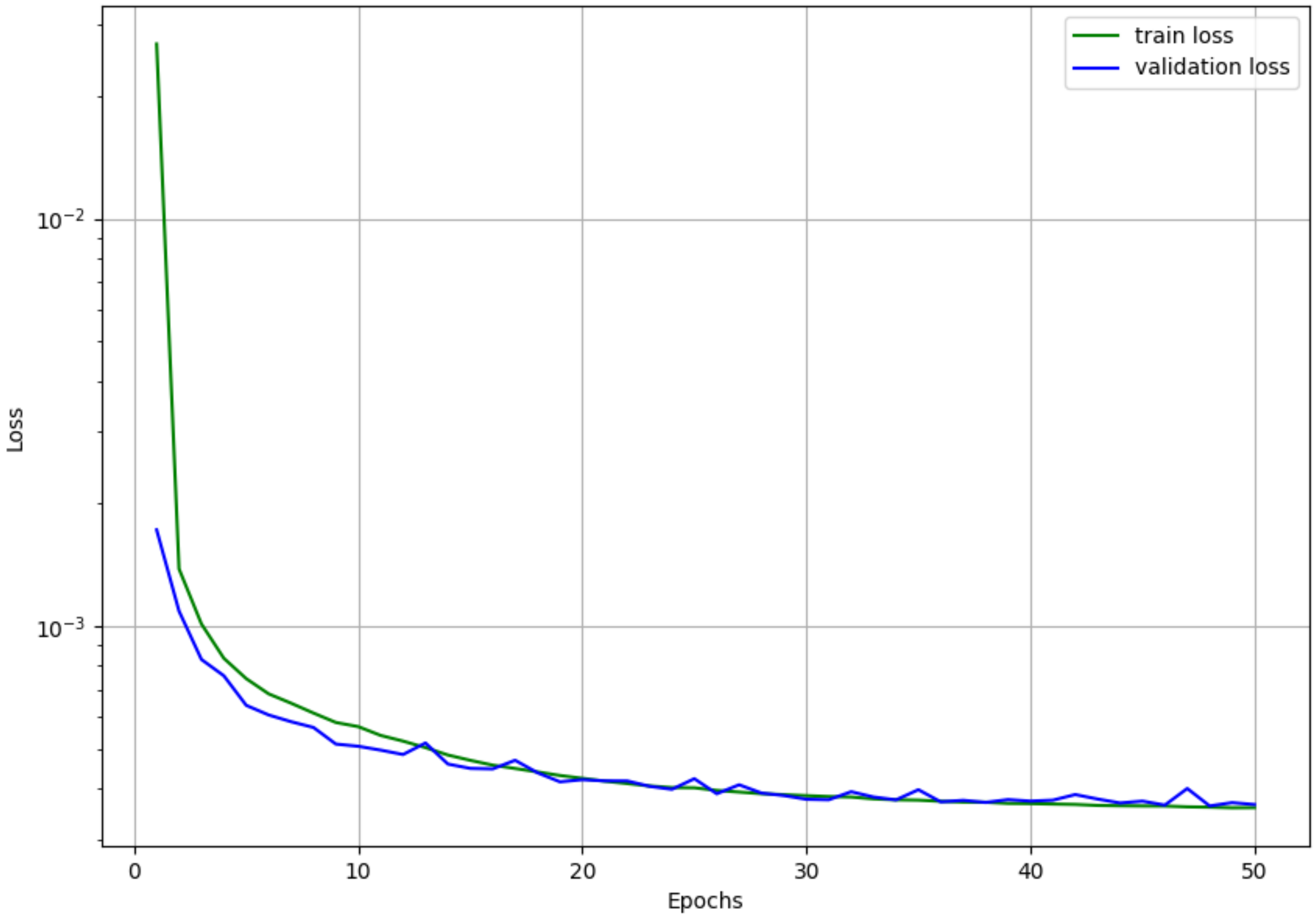



$$p = \frac{true\ positive}{predicted\ positive}$$

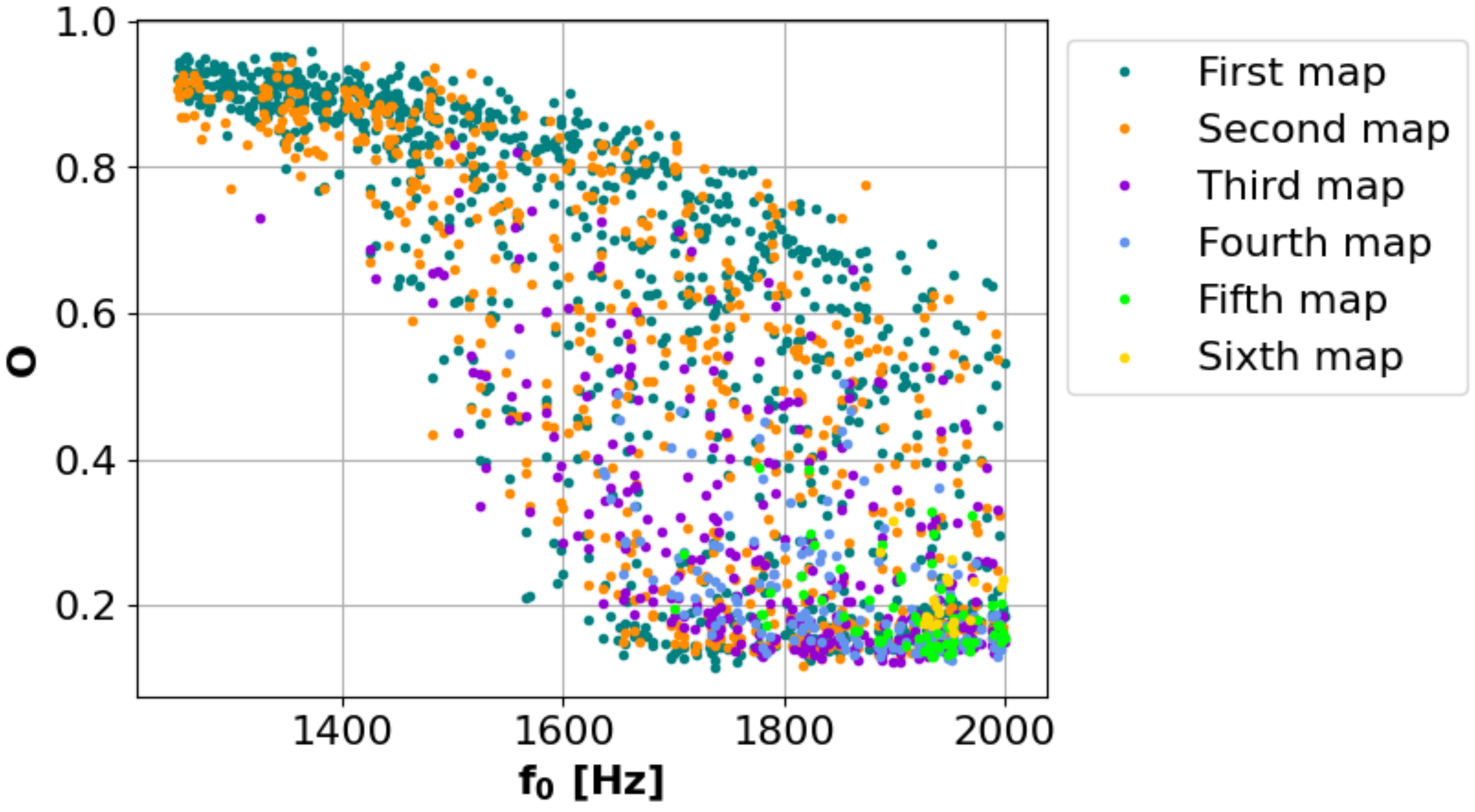
$$r = \frac{true\ positive}{true\ positive + \ false\ negative}$$

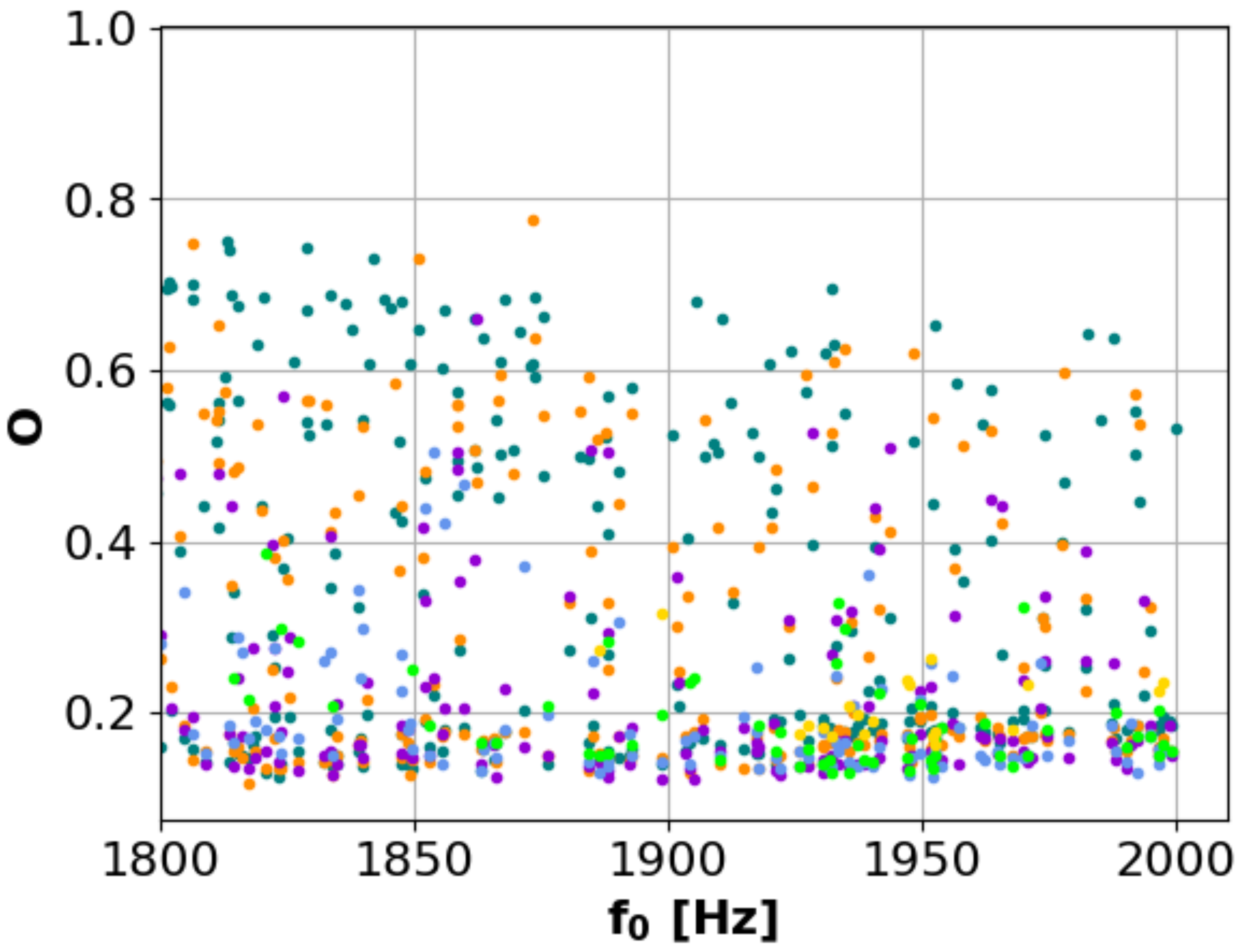
$$\mathrm{F}_1 = 2\frac{p \cdot r}{p + r}$$

# Loss function, denoiser



# Overlap vs #maps



# Efficiency and wrong tags

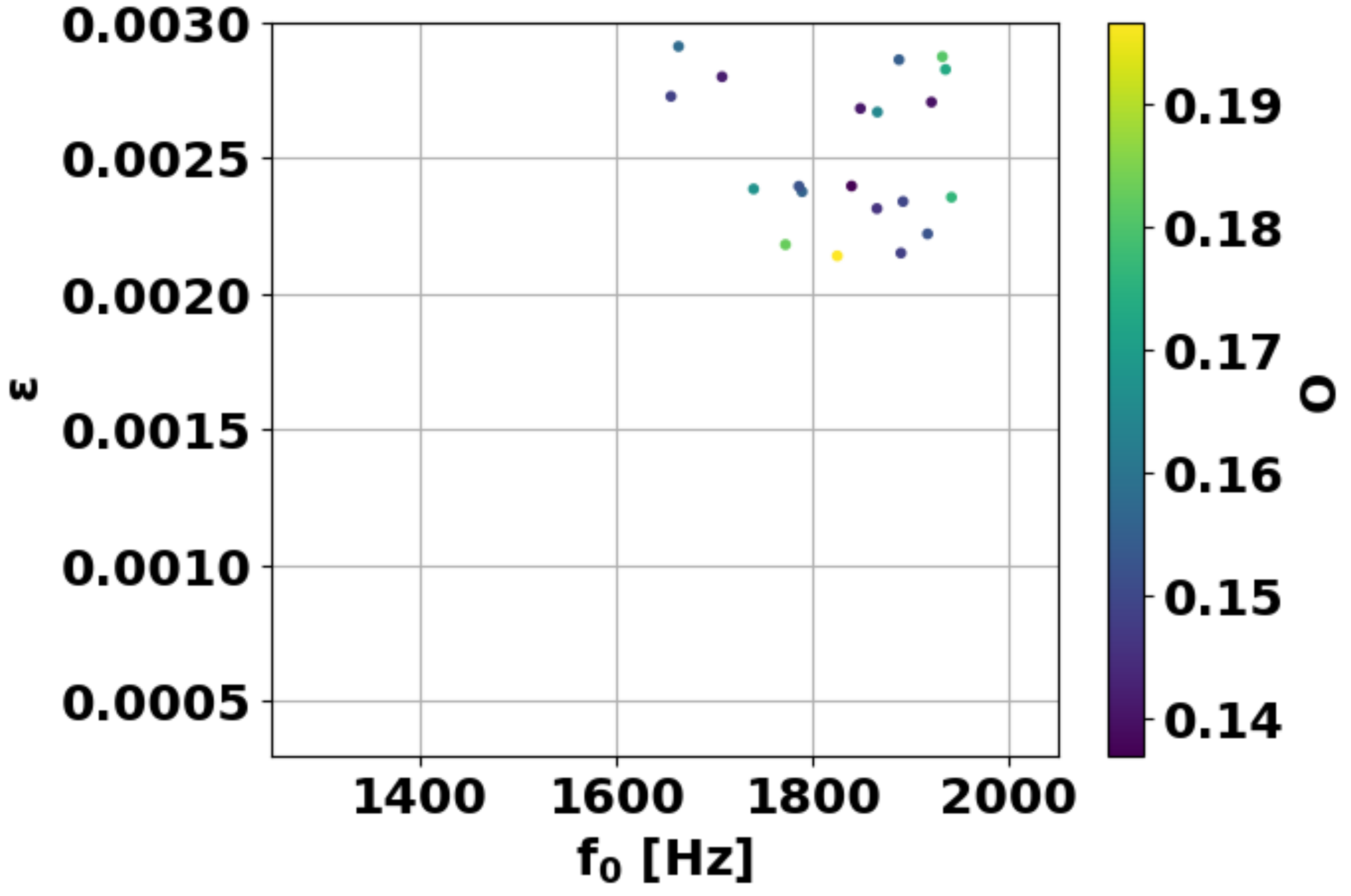
→ The frequency can vary rapidly in time and the signal can cross more maps

→ It is enough to tag right one map to have a trigger

**The efficiency of our method is 90%**

→ **Right tags**: 182 signals over a sample of 202

**Wrong tags**



# Comparison with other methods for long-transient signals

Collaboration paper: *Search for Gravitational Waves from a Long-lived Remnant of the Binary Neutron Star Merger GW170817, Abbott et al. 2019*

**Generalized FrequencyHough**

$\epsilon = 1.44 \times 10^{-3}$ $f_0 = 1740$ kHz $\Delta t = 2$ s $I = 4.34 \times 10^{38}$kg m$^2$ → $d_{FrH} = 0.242$ Mpc

**This method**

**Computational cost: 1 GPU for ∼3 hours, smaller than GFh**

$\epsilon = 1.77 \times 10^{-3}$ $f_0 = 1753$ kHz $\Delta t = 2$ s $I = 1.4 \times 10^{38}$kg m$^2$ → $d = 0.402$ Mpc

→ Detector sensitivity improved by a factor of 3 in the [1700,1800] frequency band

**We gained a factor of ∼2 in distance**