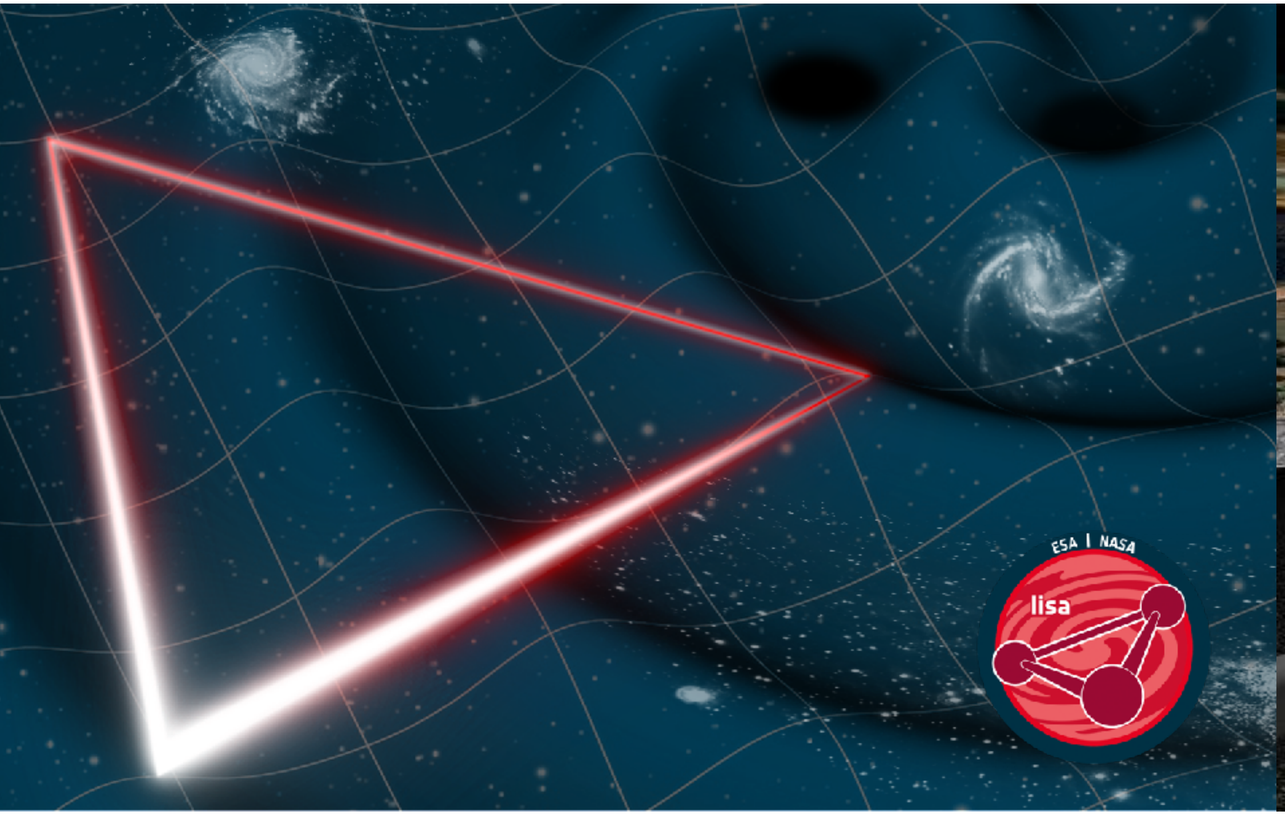
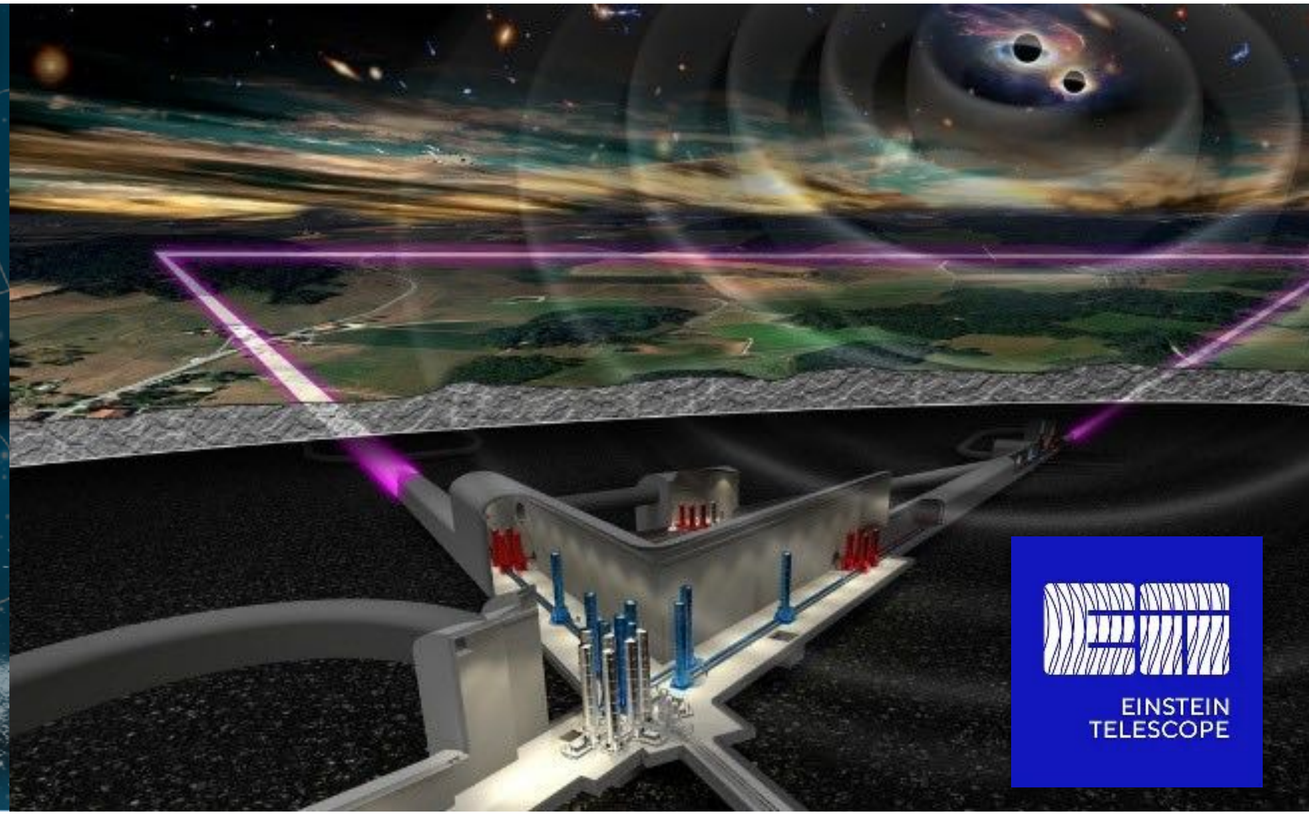
# A roadmap of gravitational wave data analysis

*The challenges of going to lower frequencies*




**Lorenzo Speri**

**Belgian-Dutch Gravitational Wave Meeting 2025**

# Motivation

The Science of the Einstein Telescope
https://arxiv.org/pdf/2503.12263

decade, we will be exploring the full GW spectrum from all sources. To maximise the scientific return, data analysis methods developed for other detectors (particularly LISA) could be highly relevant to ET, and vice versa. The synergy between different

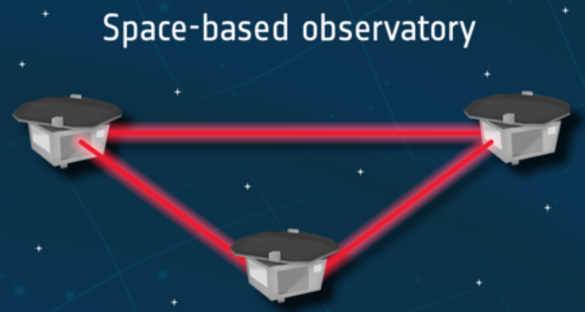
# THE SPECTRUM OF GRAVITATIONAL WAVES

esa

**Observatories & experiments**

Ground-based experiment

Space-based observatory



Pulsar timing array

Cosmic microwave background polarisation

**Timescales**

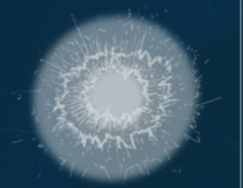
milliseconds | seconds | hours | years | billions of years

**Frequency (Hz)**

100 | 1 | $10^{-2}$ | $10^{-4}$ | $10^{-6}$ | $10^{-8}$ | $10^{-16}$

**Cosmic sources**

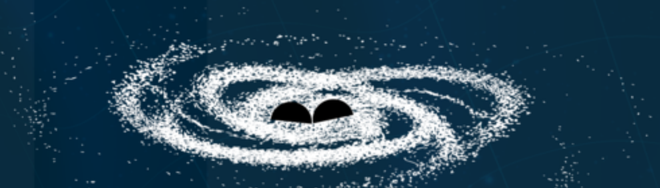
Cosmic fluctuations in the early Universe



Supernova

Pulsar

Compact object falling onto a supermassive black hole



Merging supermassive black holes

Merging neutron stars in other galaxies

Merging stellar-mass black holes in other galaxies

Merging white dwarfs in our Galaxy

#lisa

ESA | NASA lisa

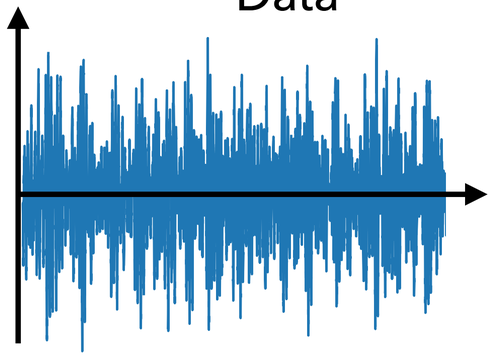
# Gravitational Wave Observatory Characteristics

| | LISA | ET |
|---|---|---|
| **Sampling rate** | 4 Hz | 10 kHz |
| **Duration** | 4+ years | 50 years |
| **Armlength** | $2.5 \times 10^6\,\mathrm{km}$ | $10\,\mathrm{km}$ |

# Gravitational wave data analysis

## Data Products

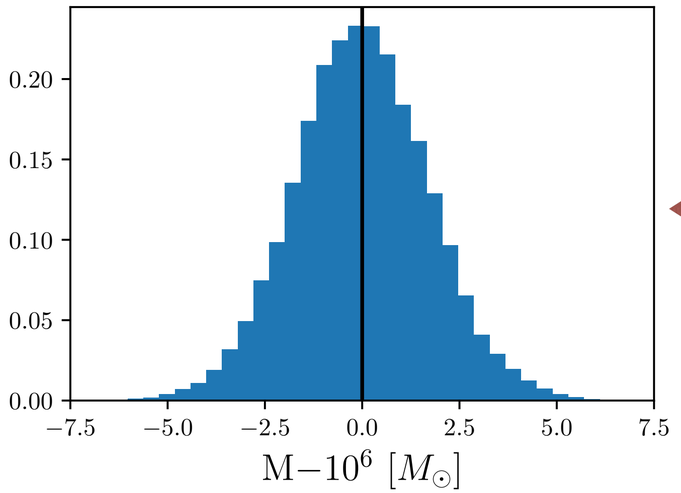
Data



DETECTION

INFERENCE

Posterior Distribution



# Gravitational wave data analysis

## Data Products

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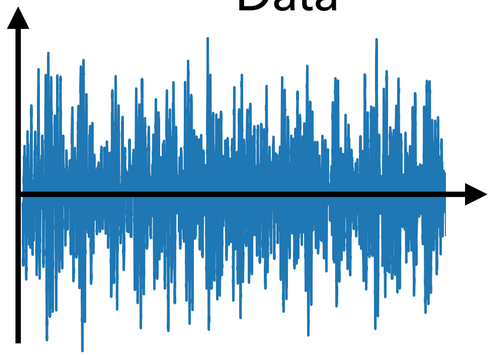

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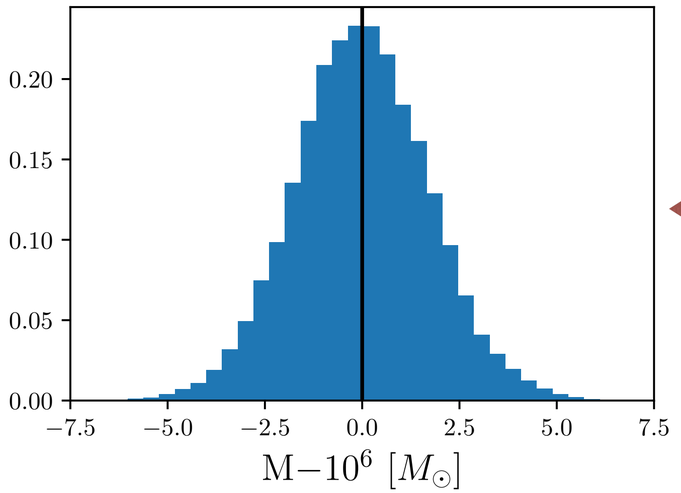
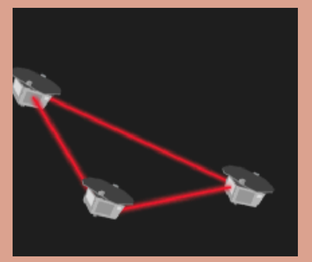



DETECTION

INFERENCE

## Models

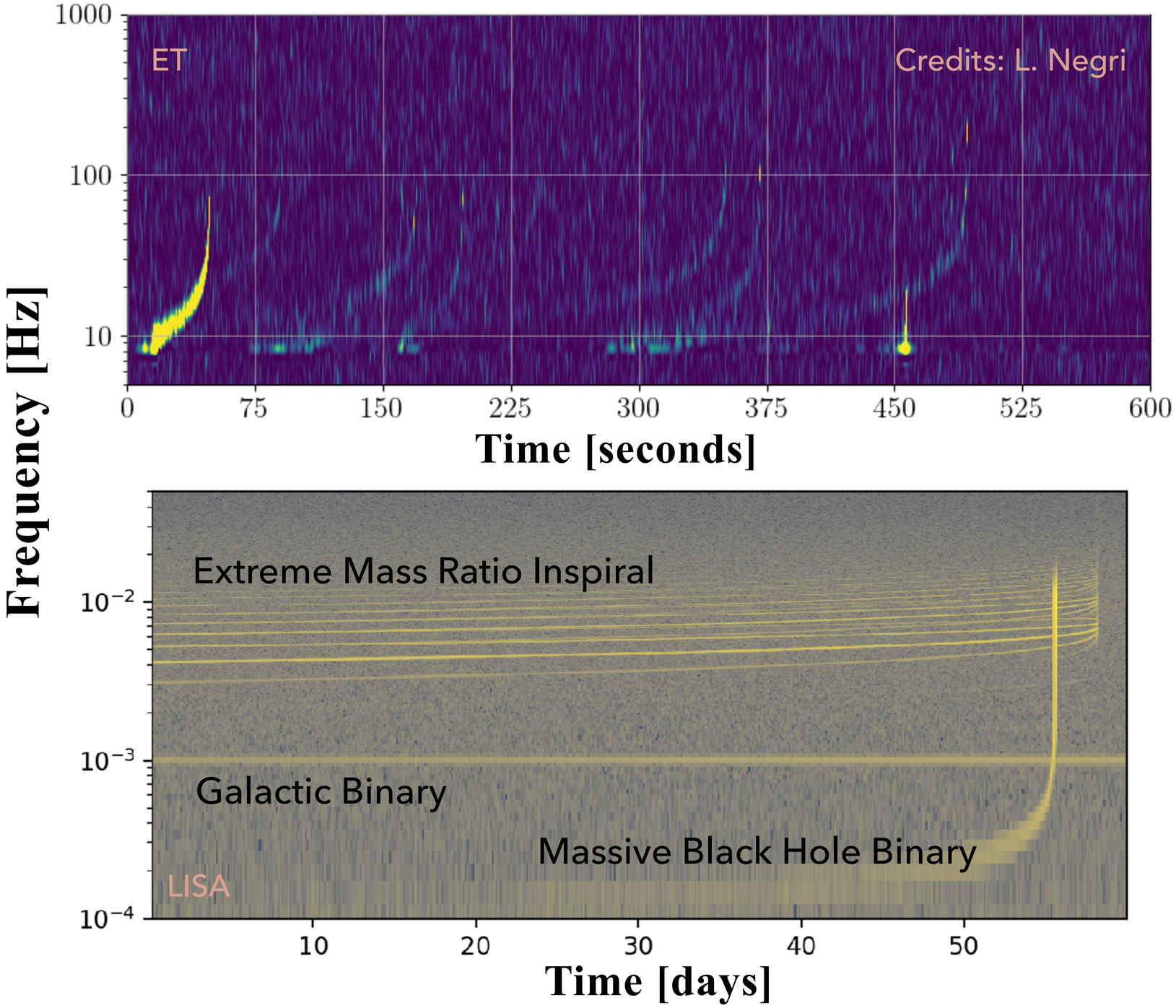
Detector



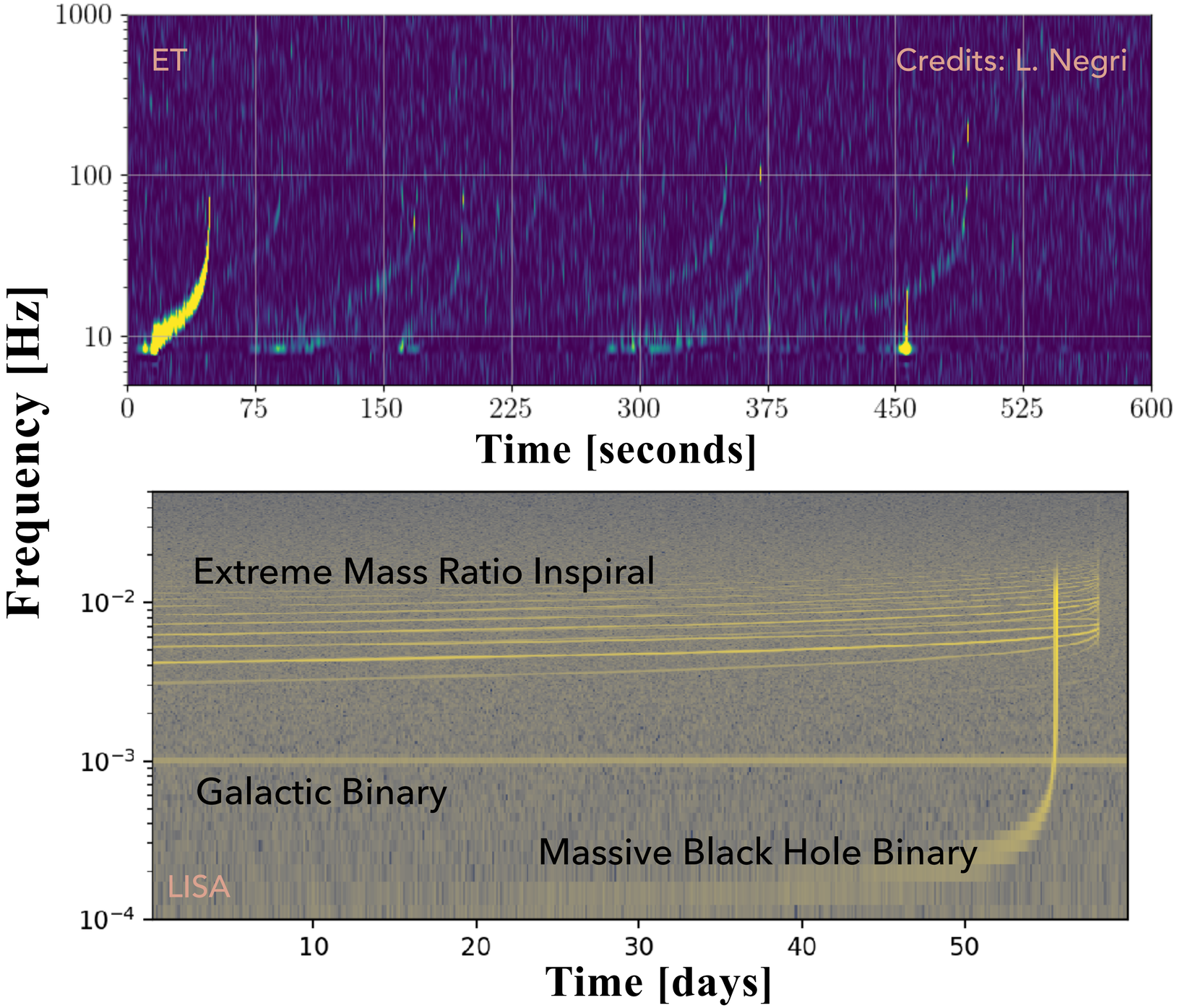
Waveform

# Overlapping sources

$$d = n + \sum_i h(\Theta_i)$$



# Overlapping sources



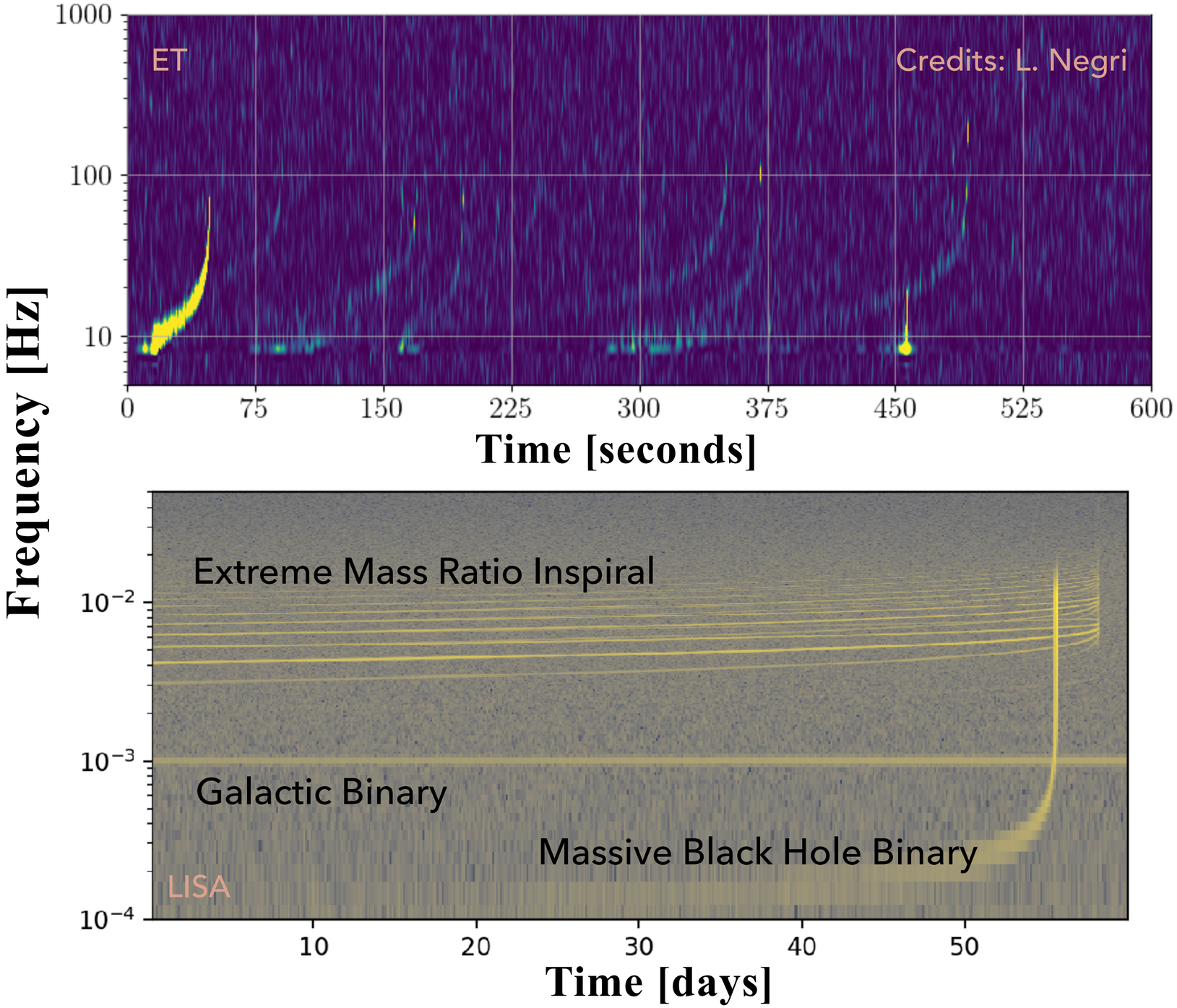

$$d = n + \sum_i h(\Theta_i)$$

- Hierarchical Subtraction

$$\mathrm{SNR}_1 > \mathrm{SNR}_{i>1}$$

$$d \approx n + h(\Theta_1)$$

$$d_{\mathrm{new}} = d - h(\Theta_1^*)$$

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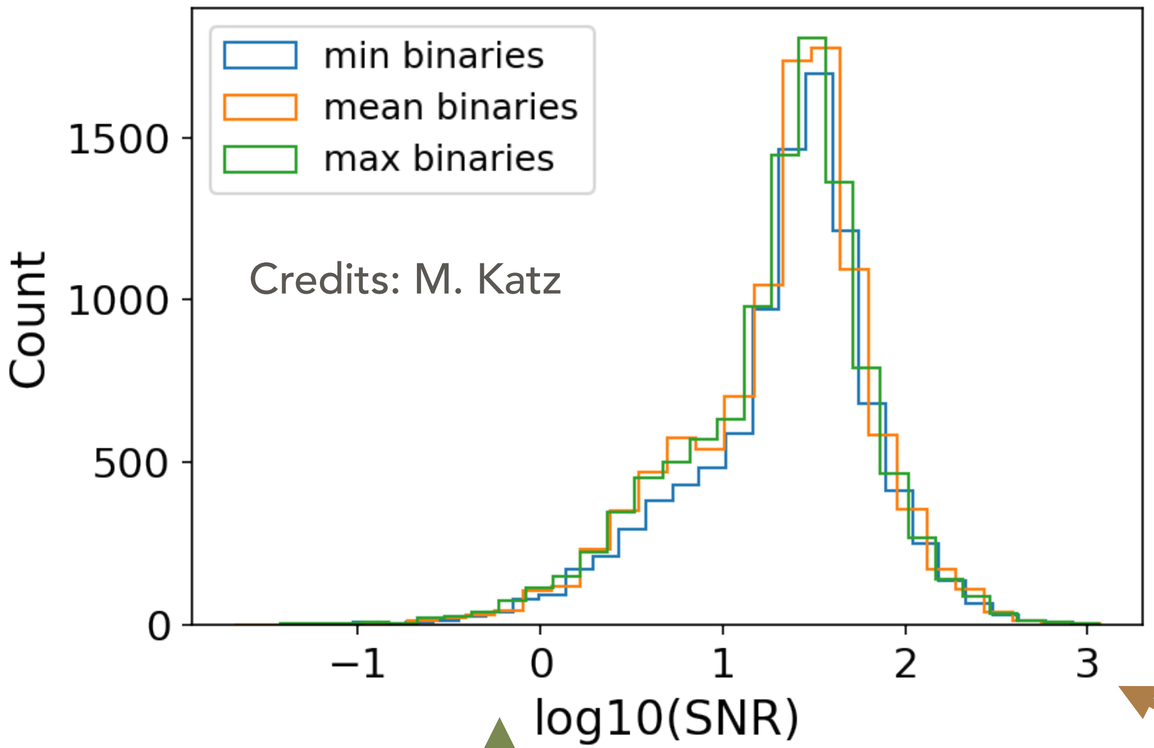
- Joint Parameter Estimation

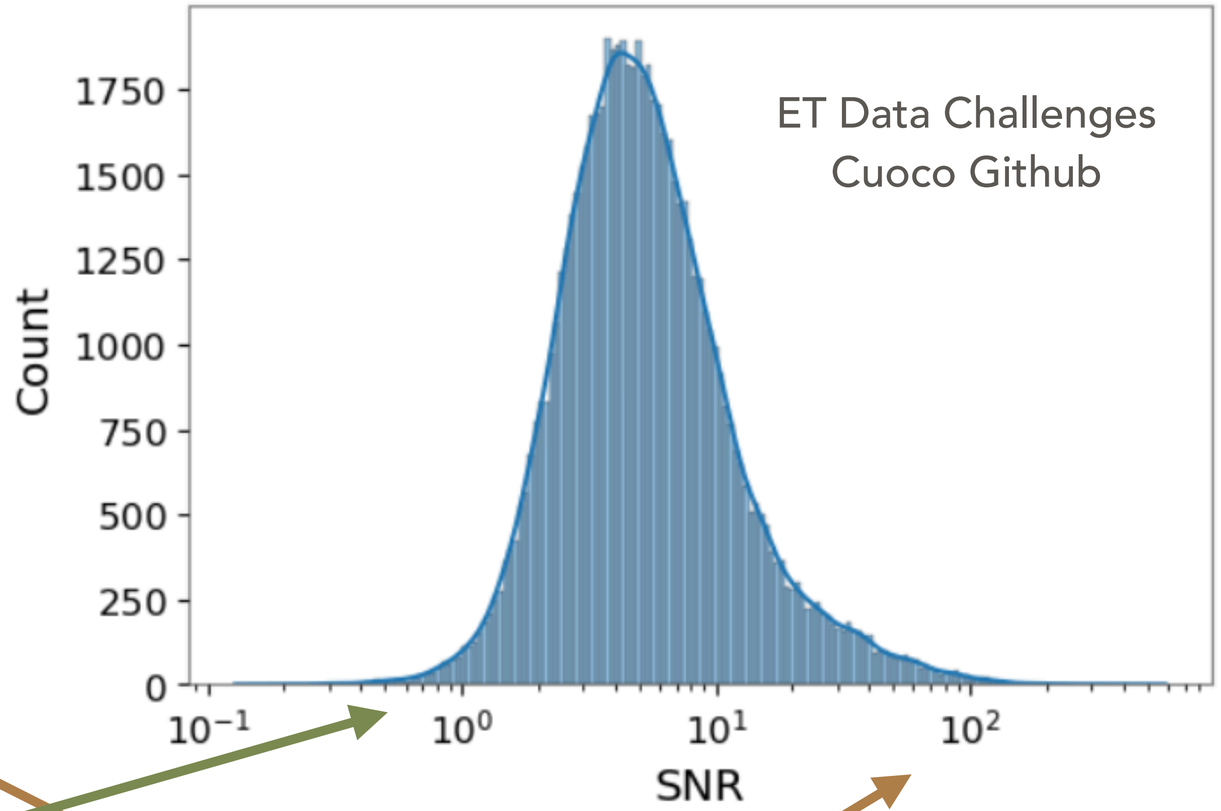
$$d = n + \sum_{i=1}^{N} h(\Theta_i)$$

# Signal to Noise Ratio

LISA




ET

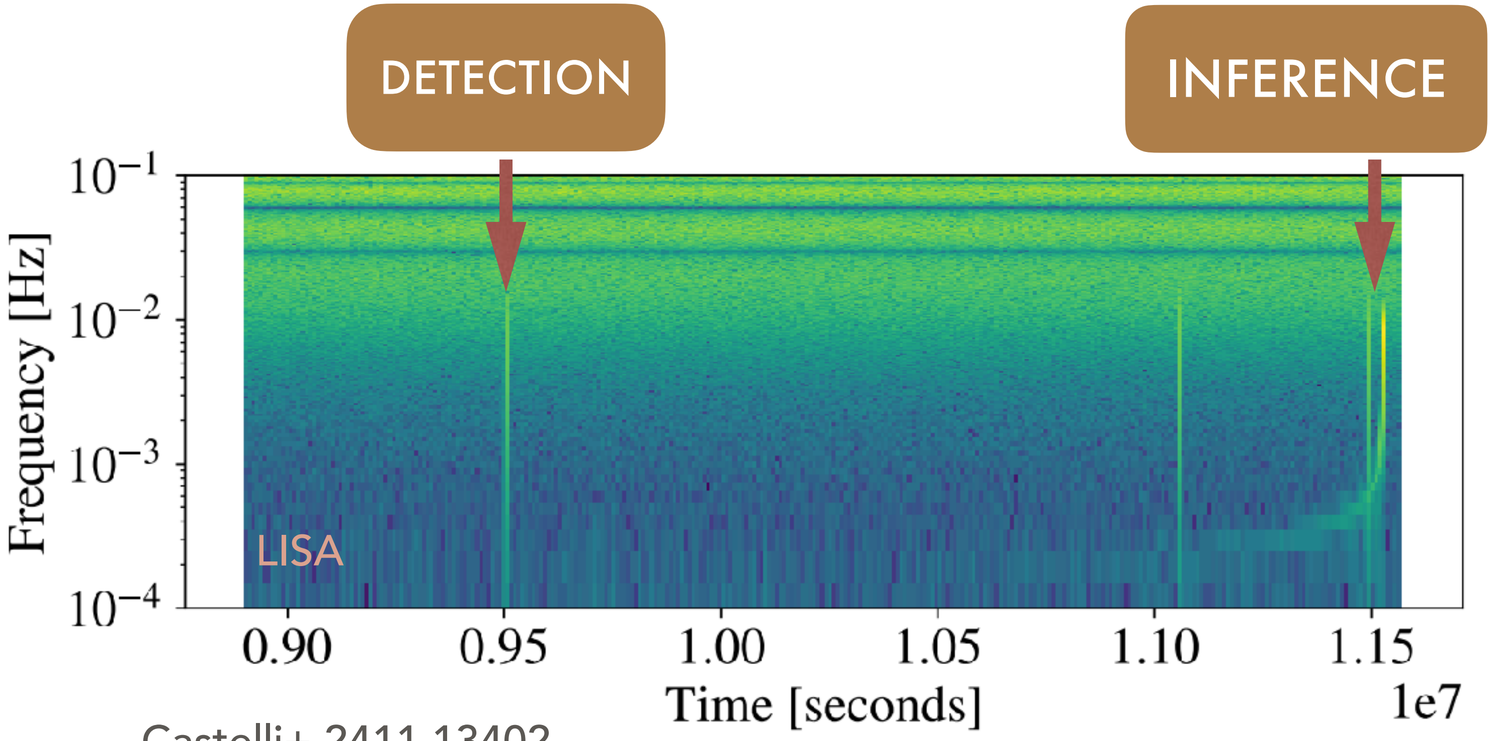



DETECTION

INFERENCE

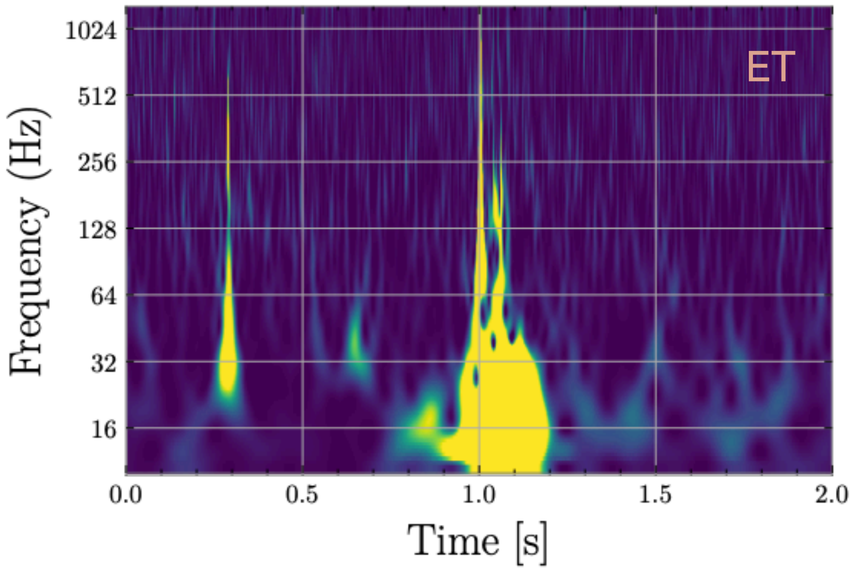
# Noise

- Additive noise $d = n + h$
- Gaussian noise
- Stationary: depends only on time differences
- Ergodic: time-averaged equal ensemble-averaged




Castelli+ 2411.13402

Dooney+ 2501.18423



# Ideas

- Define overlap and the target goal for future detectors
- Find parameters hierarchy or ordering, e.g. SNR, $t_c, f_0$
- Split strategy Search & PE depending on the parameter space
- Define non-stationary noise and detection threshold
- Machine Learning is useful if we can learn from data or speed up DA!


# Discussion

- Prompt: Where can we improve data analysis synergies between GW detectors?

1) Write down your ideas on the prompt (4 minutes)
2) Get together with a partner and share your ideas, noting similarities and differences (4 minutes)
4) Get together in groups of 4, share your results, note common themes, and start building a map (6 minutes)
All) Share ideas with the whole group (15 minutes)

# Discussion Guidance

- Defer judgement. You never know where a good idea is going to come from. The key is make everyone feel like they can say the idea on their mind and allow others to build on it.

- Encourage wild ideas. Wild ideas can often give rise to creative leaps. In thinking about ideas that are wacky or out there we tend to think about what we really want without the constraints of technology or materials or our current systems.

- Build on the ideas of others. Being positive and building on the ideas of others take some skill. In conversation, we try to use “and” instead of “but.”

- Stay focused on the topic. Try to keep the discussion on target, otherwise you can diverge beyond the scope of what we’re trying to achieve.

- One conversation at a time. Our group is far more likely to build on an idea and make a creative leap if everyone is paying full attention to whoever is sharing a new idea.

- Avoid interruptions. Allow group members to complete their thought before jumping in.

- Share the air. Respect each other’s speaking time and give everyone a chance to speak

# Summary of Data Analysis Idea

- Noise Estimation (Null channel, PSD estimation, glitches)
- Diagnostic tools
- Global Fit
- Instrument Response (CW example, LISA time-varying)
- Code sharing infrastructure
- Multi-band sources
- Sources overlapping
- Topical workshop Data Analysis ET & LISA & PTA
- Common Computing resources
- Learning resources for different levels e.g. Tutorials
- Machine Learning Tools


Animation by Nora Lützgendorf, LS