



Young Astronomers Meeting
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Data analysis of long duration gravitational wave sources

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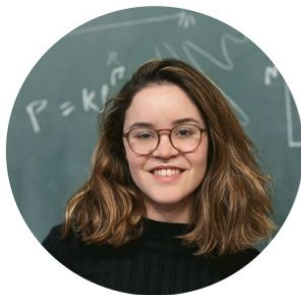


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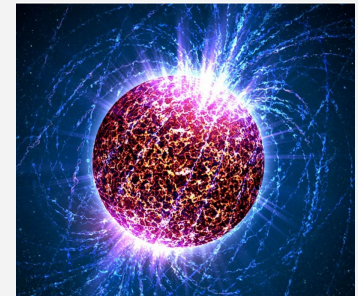
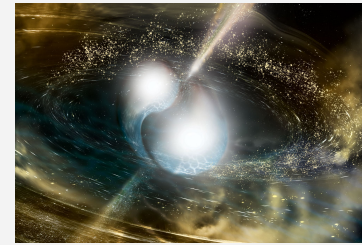
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Gravitational Waves sources

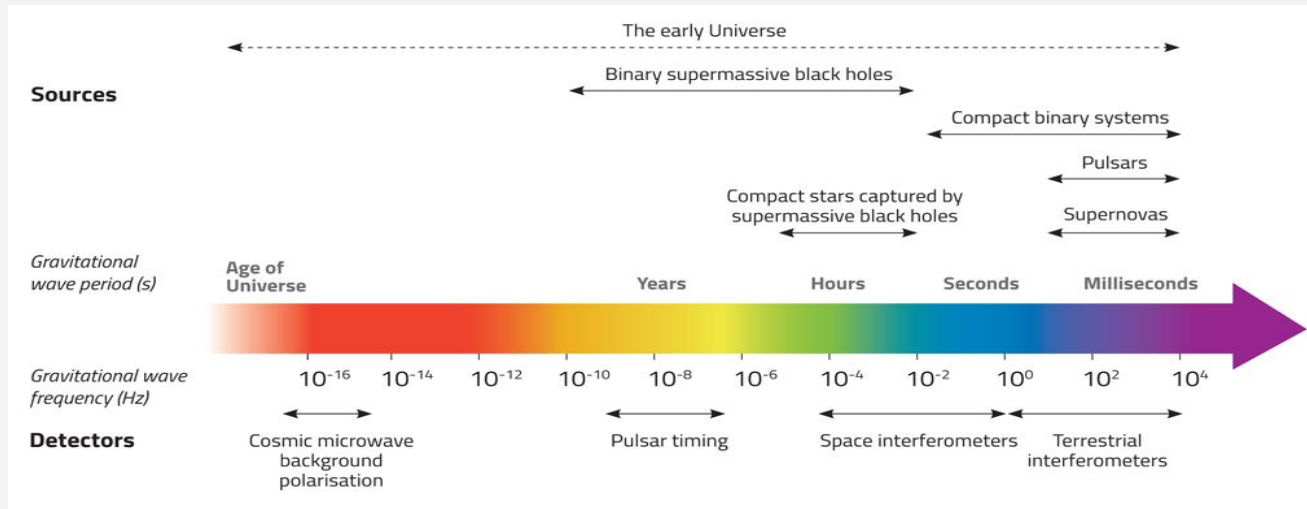
- Gravitational waves are produced by accelerating masses.
 - They are waves propagating in spacetime.
- There are numerous sources of gravitational waves.
 - Binary black holes
 - Binary neutron stars
 - Isolated neutron stars
 - Supernovae bursts
- These sources happen at a wide range of frequencies.



How long is long enough?

- When antenna patterns become important in search and parameter estimation, we call these long duration gravitational waves.

$$h(t) = \mathbf{F}_\times(\alpha, \delta, t) h_\times(t) + \mathbf{F}_+(\alpha, \delta, t) h_+(t)$$



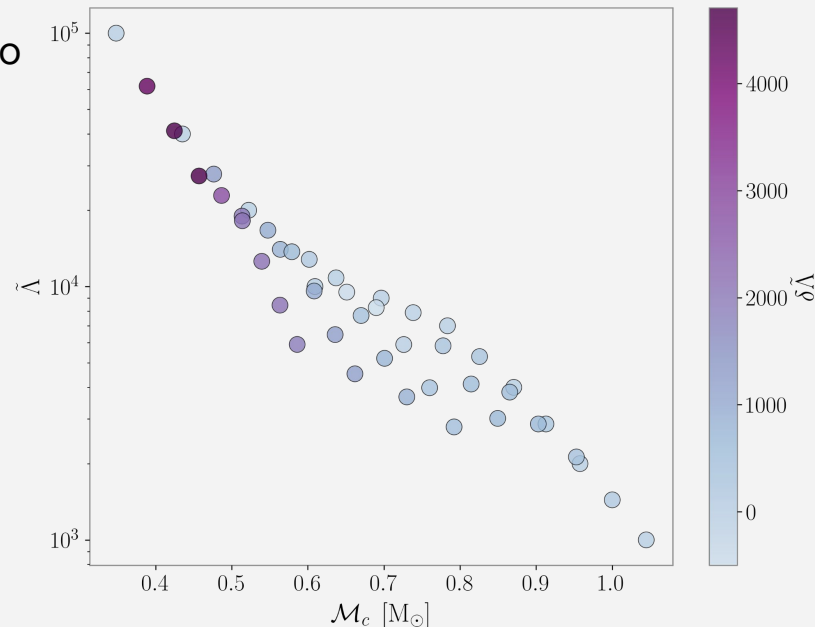
Source - 1: Sub solar mass binaries

- They span **few hours** in the frequency band, 30 - 1024 Hz.
- Why is it interesting?
 - New physics...
 - **Primordial black holes, sub-solar neutron stars and exotic stars like boson stars, strange stars.**
- Non Confident detections like **SSM200308, S250818k, S251112cm** also indicates the possible detection of sub-solar mass events in the future. [Alexander H. Nitz et al. 2022, Gonzalo Morrás et al. 2023, LVK Circular 2025]

What do we do?

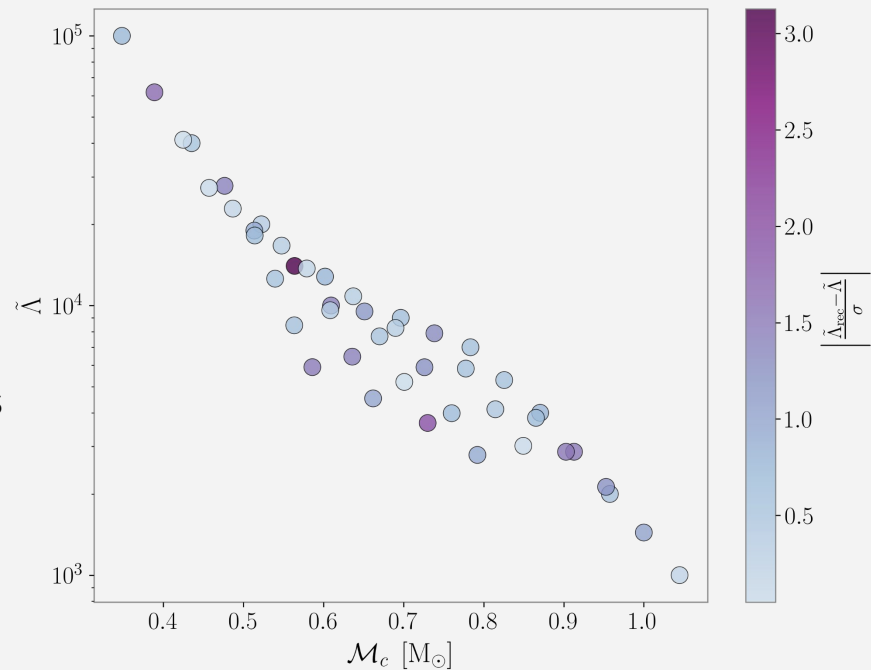
- We inject multiple sub-solar mass binaries and try to recover their parameters like masses and tidal deformability.
- For tidal deformabilities, we work with **prof. J. L. Zdunik** on using **strange star model** to solve Tolman–Oppenheimer–Volkoff equation.
- We understand how our constraints can get better over detectors like Einstein Telescope, Cosmic Explorer and also through distances.

$$P(\rho) = \frac{1}{3} a(\rho - \rho_0) c^2$$



Can we actually constraint them?

- **Yes!!**, we can constrain them considering we recover long enough signal with high SNR.
- Masses are recovered the best.
- In terms of tidal deformability, we recover the combined tidal deformability better.
 - Individual tidal deformabilities constraints still need an improvement.
- These recoveries **needs to be tested with different SNRs!**

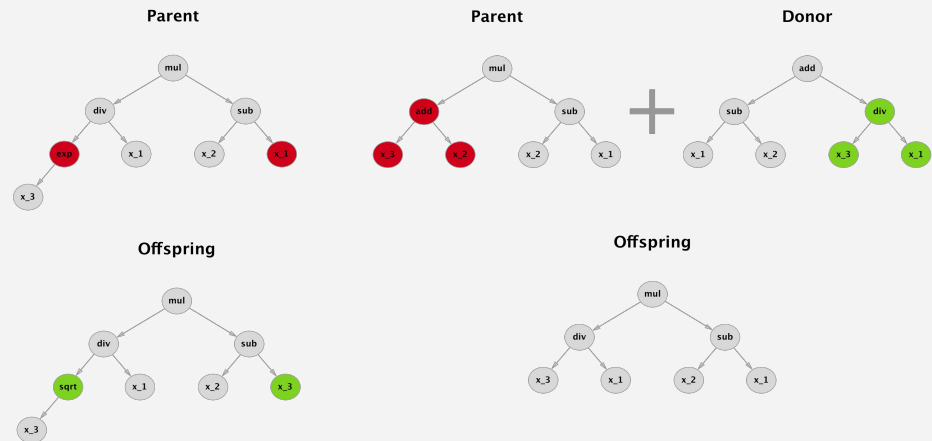
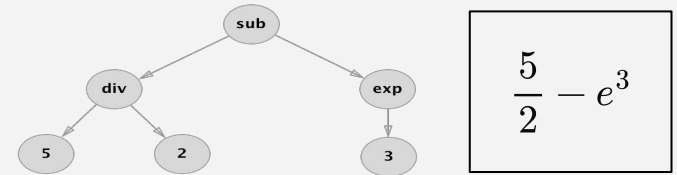


What can we do with it?

- Currently we try to constrain the **equation of state parameters** using the gravitational wave observations using
 - Machine learning models like **Symbolic regression.**

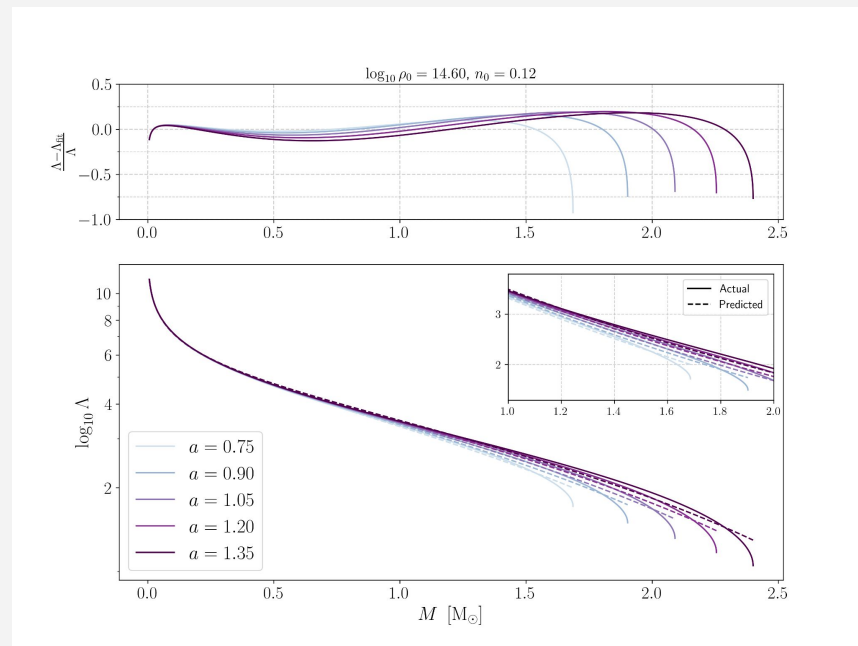
What is it?

It's a machine learning model looks for a best analytical expression that fits your data.



What can we do with it?

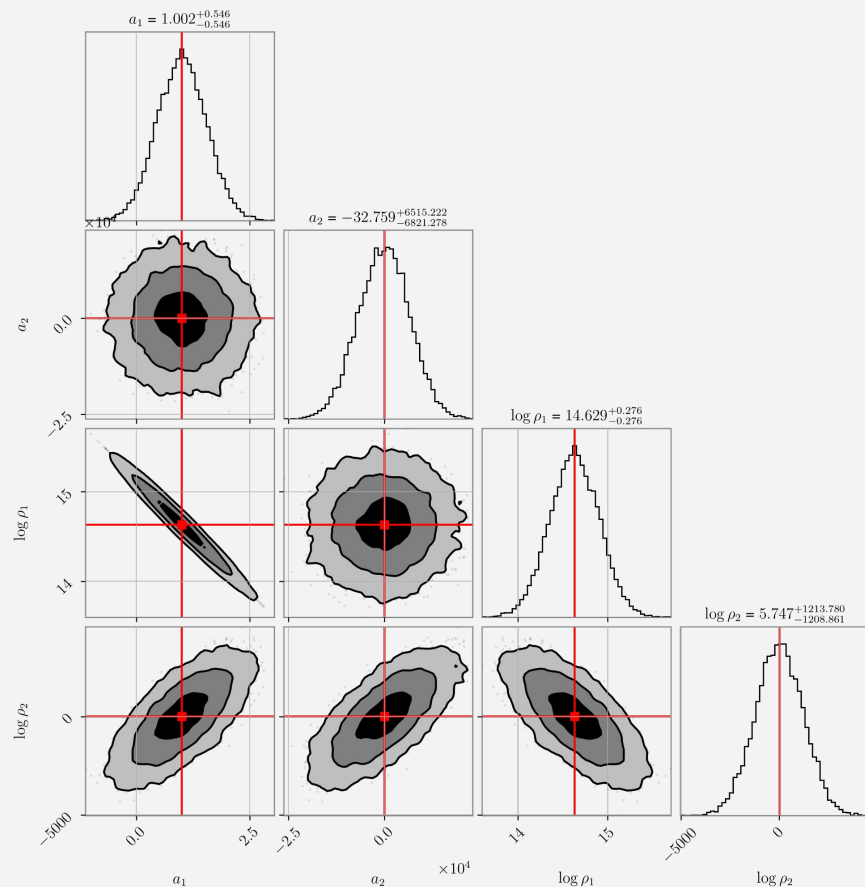
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$$\log_{10} \rho_0 = 14.61$$

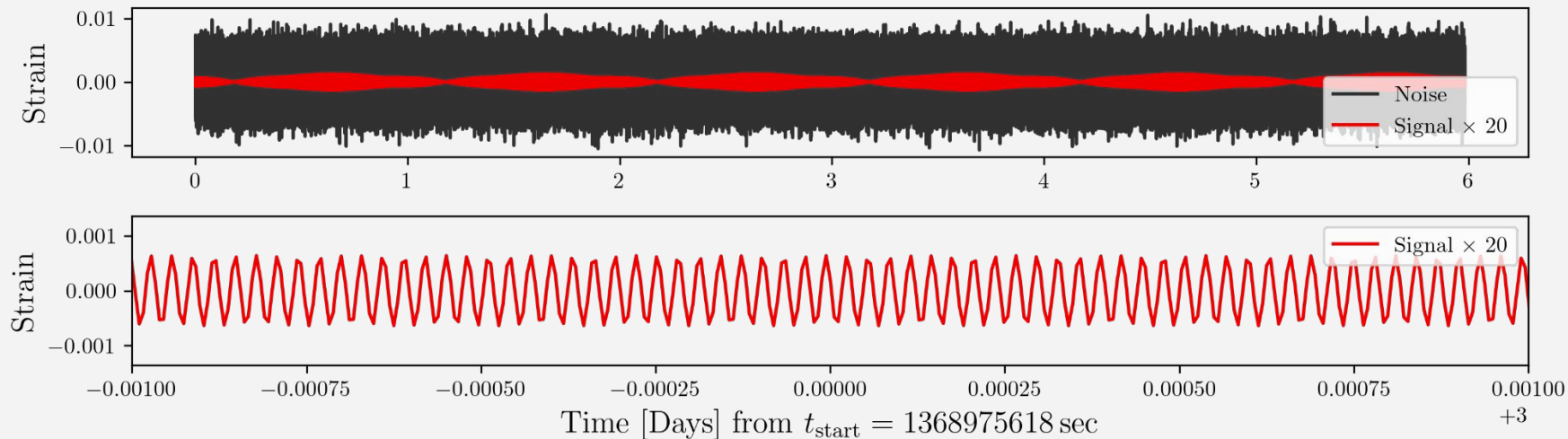
What can we do with it?

- Currently we try to constrain the **equation of state parameters** using the gravitational wave observations using
 - Machine learning models like **Symbolic regression**.
- We can understand degeneracies of tidal deformabilities with other GR effects.
- Searching for sub-threshold events through lensing of GWs.



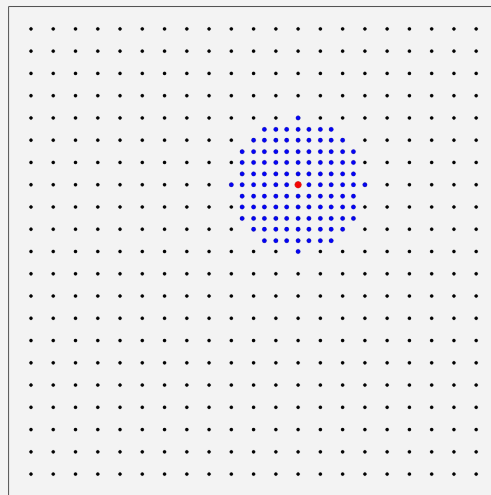
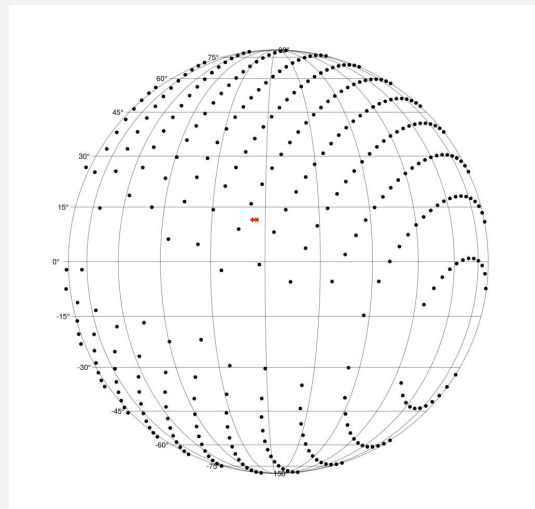
Source - 2: Continuous GWs from isolated neutron stars

- Gravitational waves produced by asymmetric isolated neutron stars.
- These signals are **emitted over years**.
It emits at a **given frequency** and **spin down** (very small....)



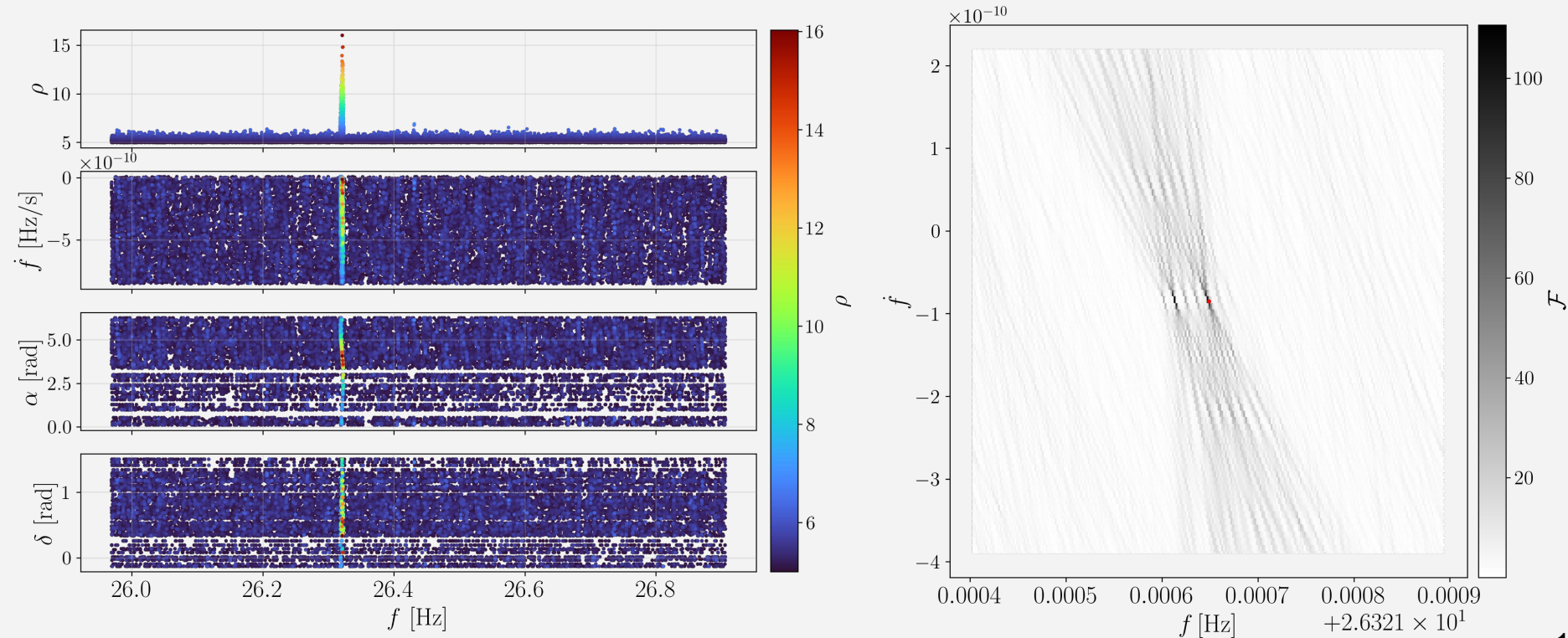
How do we search for these signals?

- We use **Time Domain F Statistic (TDFstat)** pipeline, to search for continuous gravitational waves.
 - We at CAMK are the major developers of this pipeline.
 - All sky searches, directed searches
- This pipeline uses a **4-dimensional grid in frequency, spin down and sky positions** to compute templates and calculate **signal to noise ratio and F statistic**.



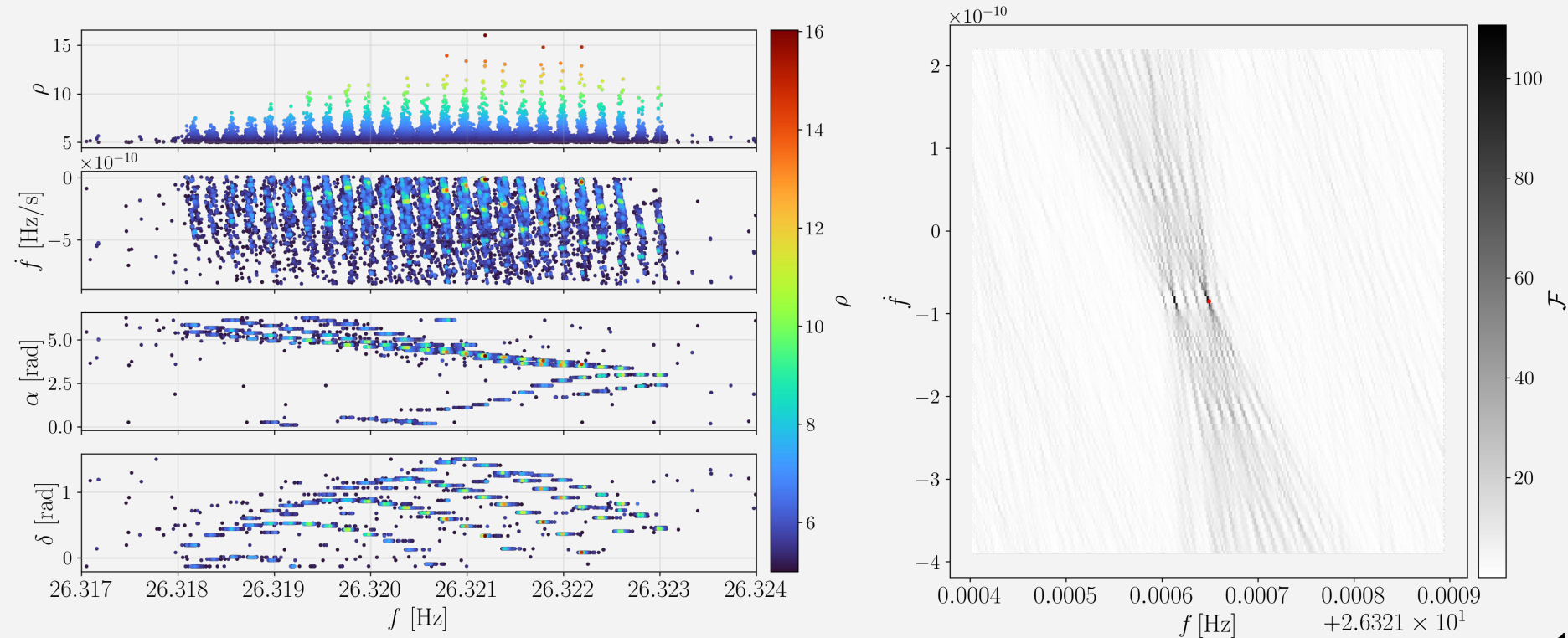
How does the recovered F statistic look like?

$$\rho = \sqrt{2\mathcal{F} - 4}$$

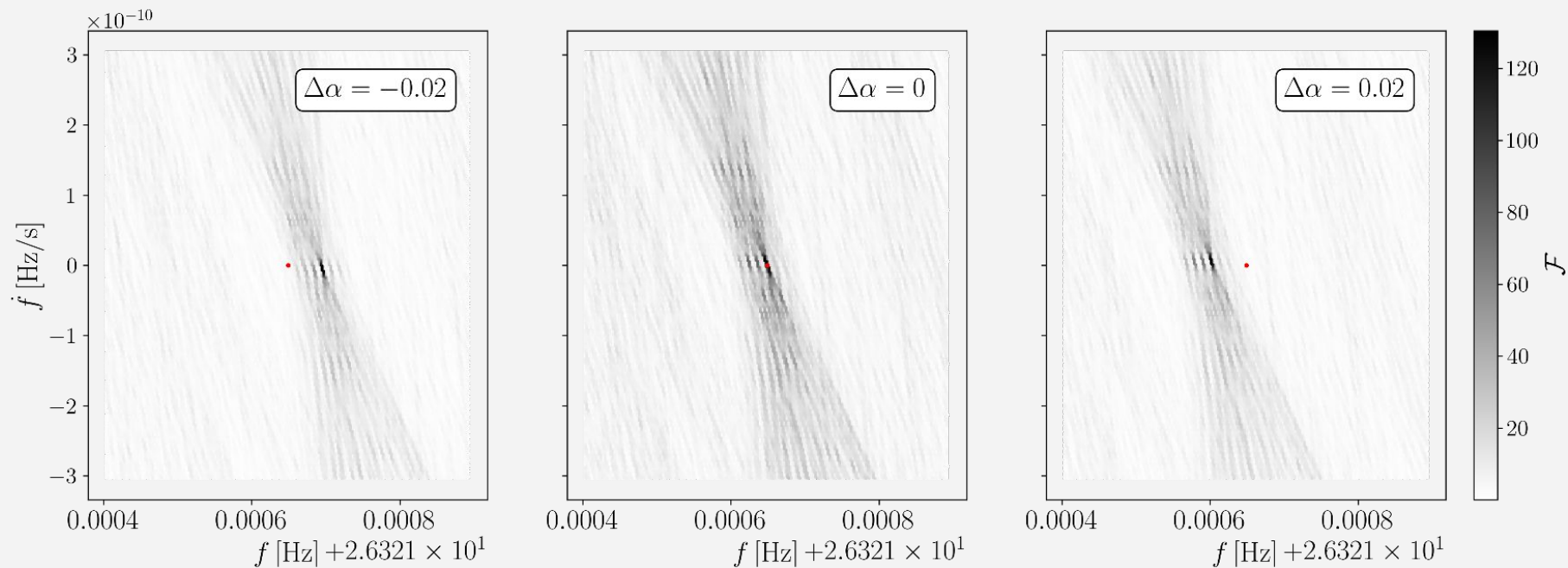


How does the recovered F statistic look like?

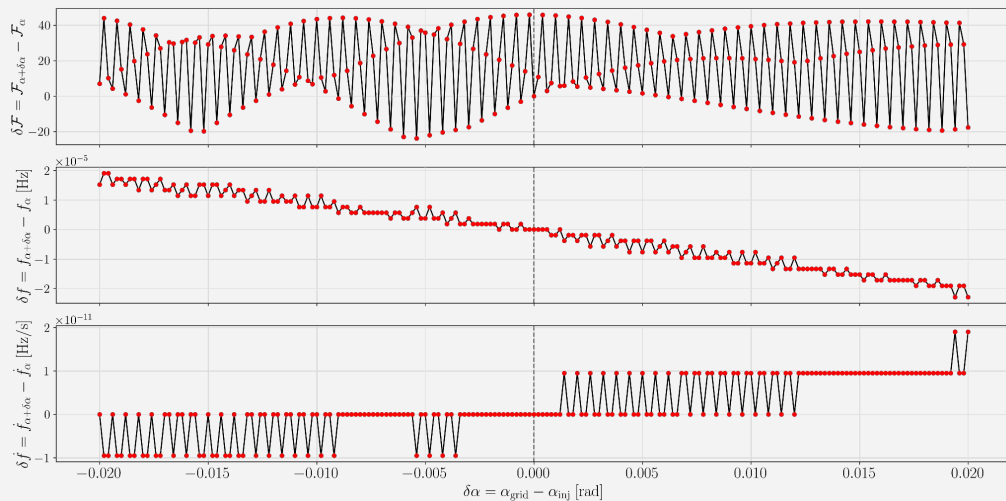
$$\rho = \sqrt{2\mathcal{F} - 4}$$



What happens when we look at it in a different direction?



What happens when we look at it in a different direction?

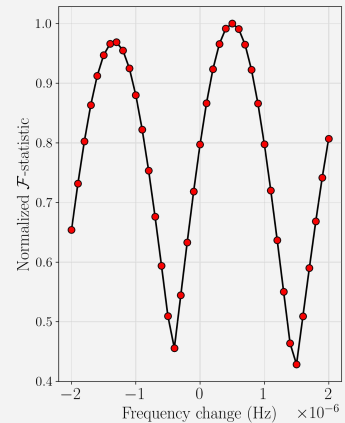


$\dot{j} \approx \mathcal{O}(1 \text{ grid})$

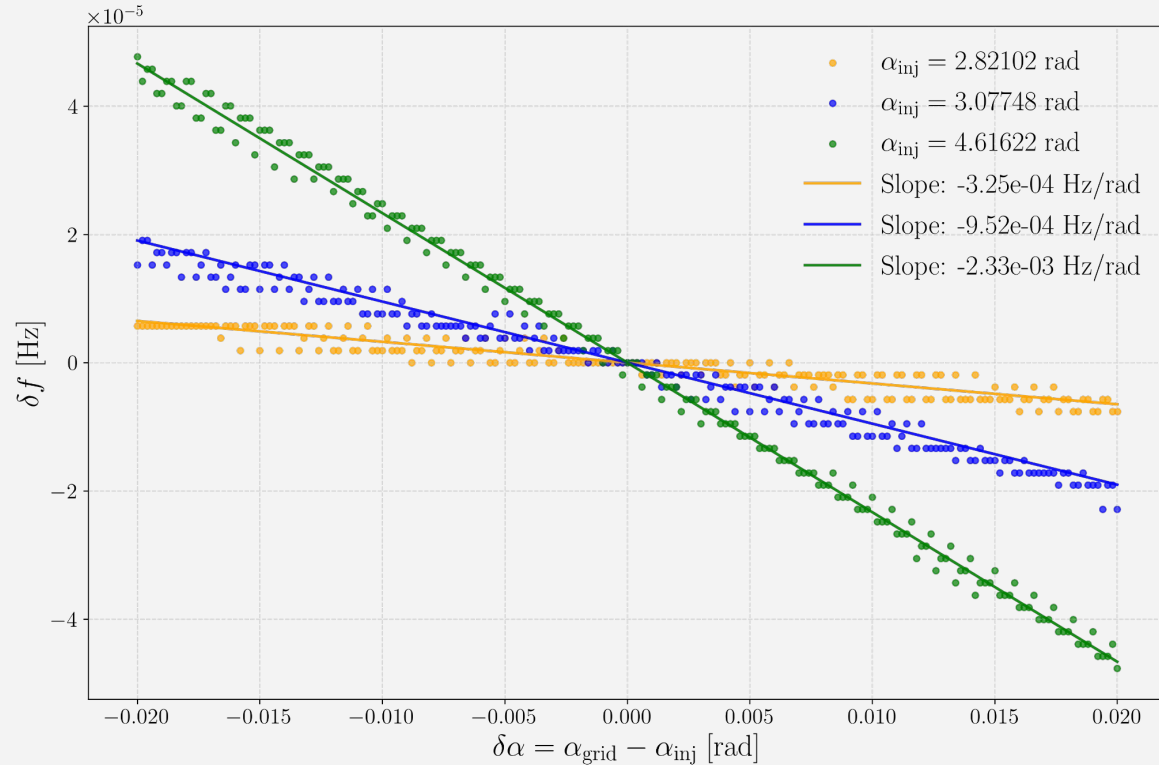
$$\Delta f = h(\alpha, \delta, \Delta\alpha, \Delta\delta)$$

$$\Delta \mathcal{F} = ?$$

- F statistic drops are due
- Change in sky-position
 - SNR loss due to FFT binning



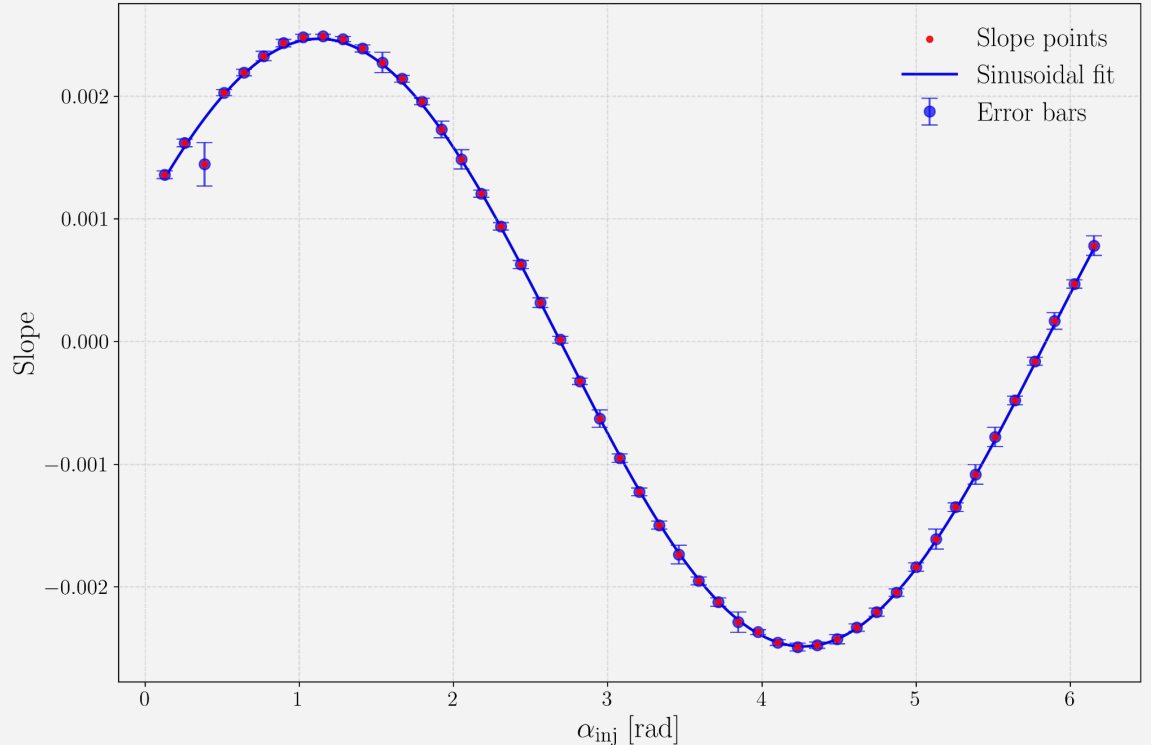
Linear profile of change in frequency



Overall change of slope w.r.t to right ascension

$$\text{slope} = A \sin [\alpha + \phi] + c$$

$$A = (2.4770 \pm 0.0117) \times 10^{-3},$$
$$\phi = (4.4433 \pm 0.0048) \times 10^{-1} \text{ rad},$$
$$c = (-8.9260 \pm 8.3617) \times 10^{-6}.$$



What else can we do with TDFstat?

- We also work on using machine learning models to understand the F statistic shapes
 - Przemysław Figura and Michał Bejger
- With the current directed search methods, we can use known pulsars and look for continuous wave signals.
- Developments to improve detection of candidate triggers or improve veto procedures.
- Doing searches for signals in real data, that's why TDFstat was built :)

Summer Projects

- **Lensing of sub-solar mass binaries,**

dr. Sree Kanth Hari Kumar and Anirudh Nemmani

Due to lensing, the gravitational wave signals can be magnified or demagnified. One can use this advantage to dig out sub-threshold sub-solar mass events.

- **Degeneracies between tidal deformability and lensing,**

dr. Sree Kanth Hari Kumar and Anirudh Nemmani

Sub-solar mass compact stars are expected to have high tidal deformability.

- **Want to work with us on continuous waves and TDFstat (Lot of ideas....) & Symbolic Regression**

dr hab. Michał Bejger and Anirudh Nemmani

More on **machine learning** next by **Valéria Carvalho**

Thank you