# Search for Gravitational Waves from Individual Supermassive Black Hole Binaries in MeerTime Data


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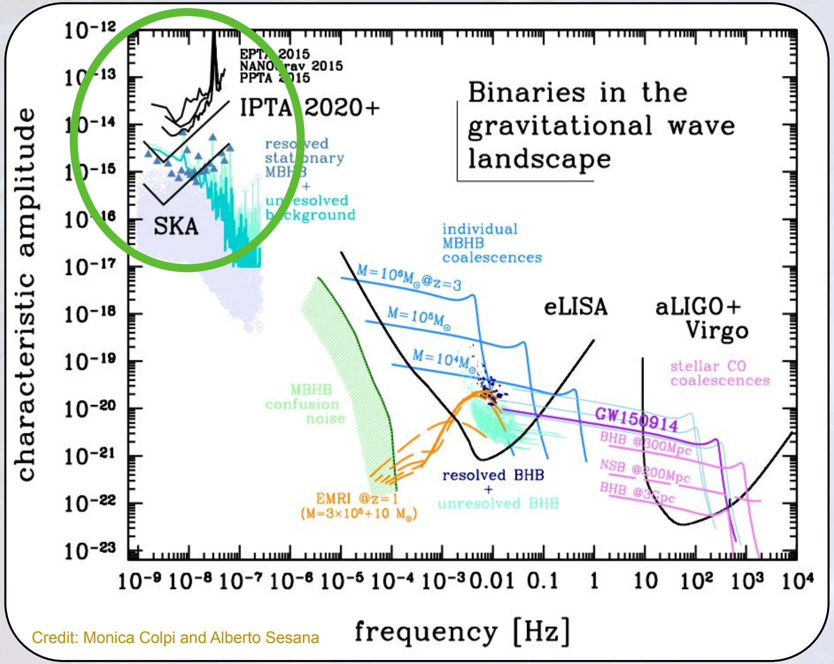
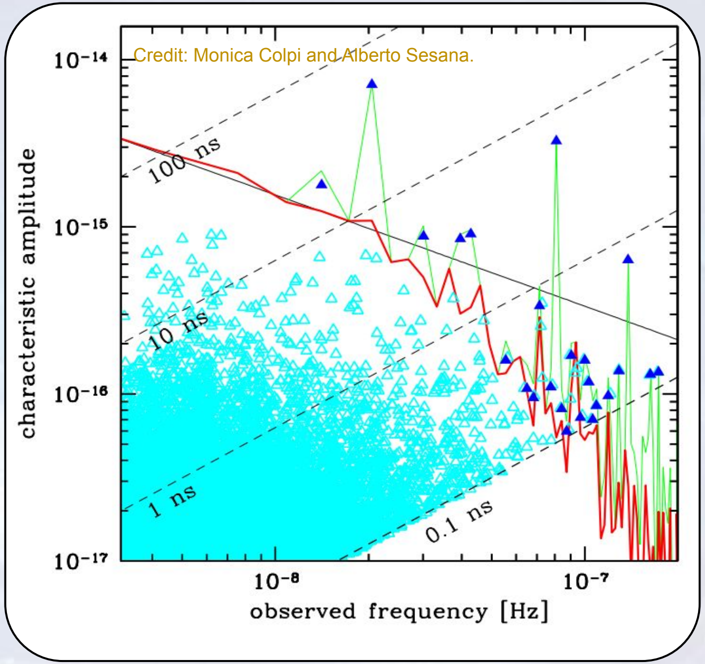
## V Gravi-Gamma-Nu Workshop, Bari
## 09/10/2024

# Sources of gravitational wave in PTA




- Confirm the **existence** of sub-parsec SMBHBs.
- Probe **dynamics** of SMBHBs.
- Provide **test** of fundamental physics.

- **Deterministic**: **continuous GW** (CGW) generated by inspiralling SMBHBs.
- **Stochastic**: superimposition of several CGWs or cosmic sources.

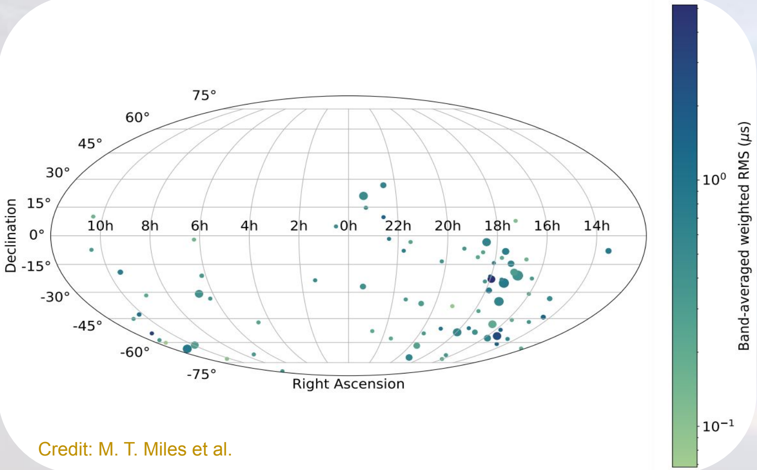
# MeerTime Pulsar Timing Array (MPTA)

**MeerTime** is a survey project of **MeerKAT.**

64 individual dish antennas with offset Gregorian configuration.

Dataset: ultra precise **88** MSPs (**DR2 4.5 yrs**).

MeerKAT operates in the range of **856 to 1712 MHz.**




Credit: M. T. Miles et al.

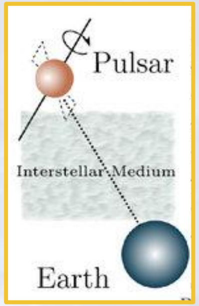

# Methods and SPNA

**Build custom models** composed of different noises:

- White noise (**WN**).
- Dispersion measure variation (**DM**).
- Free chromatic noise.
- Red noise (**RN**).
- Annual chromatic process.
- Solar Wind (**SW**).
- Gaussian chromatic bumps.

Systematic issues related to the **radiometer.**
During data collection: **folding** procedure.

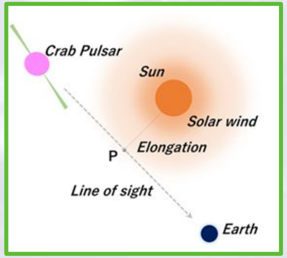
During the travel pulsar-Earth the light crosses **ionized material** in the interstellar medium. Chromatic noise.




Delay due to **intrinsic instabilities** such as a variation of the pulsar spin. Achromatic noise.

Electron density variations as the line of sight to the pulsar changes during the annual Earth motion **around the Sun**.

Presence of the Sun between pulsar and Earth. **Solar electron density.** Constant term + time-varying.

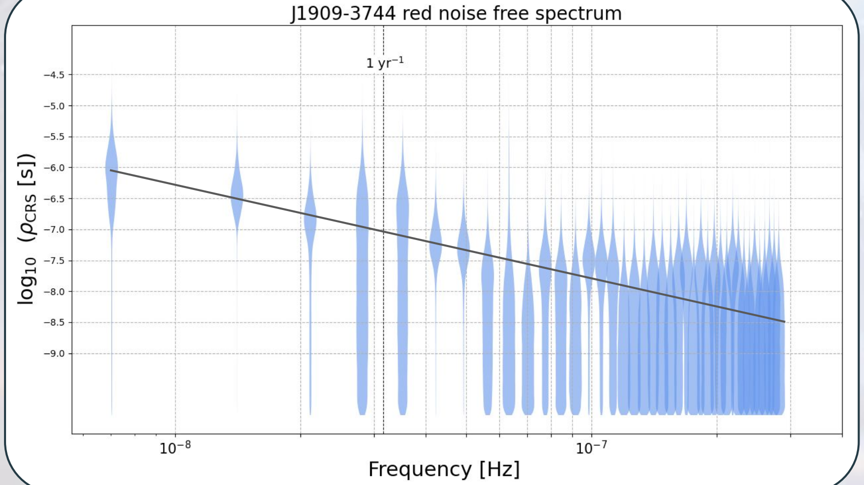



Used to model any deviations from noises.

# Methods and SPNA

**Optimization** of frequency bins in Fourier domain using method in **EPTA II [2023]**.

For **RN**, **DM** and **chromatic** noise.




$$P_{RN}(f) = \frac{A_{RN}^2}{12\pi^2} f_{yr}^{-3} \left(\frac{f}{f_{yr}}\right)^{-\gamma_{RN}}$$

$$P_{DM}(f) = \frac{A_{DM}^2}{12\pi^2} f_{yr}^{-3} \left(\frac{f}{f_{yr}}\right)^{-\gamma_{DM}} \left(\frac{1400MHz}{\nu}\right)^2$$

$$\mathbf{F}_j^{\text{chrom.}}(t_i) = \mathbf{F}(t_i) * \left(\frac{\nu_j}{1.4\ \text{GHz}}\right)^{-\chi}$$

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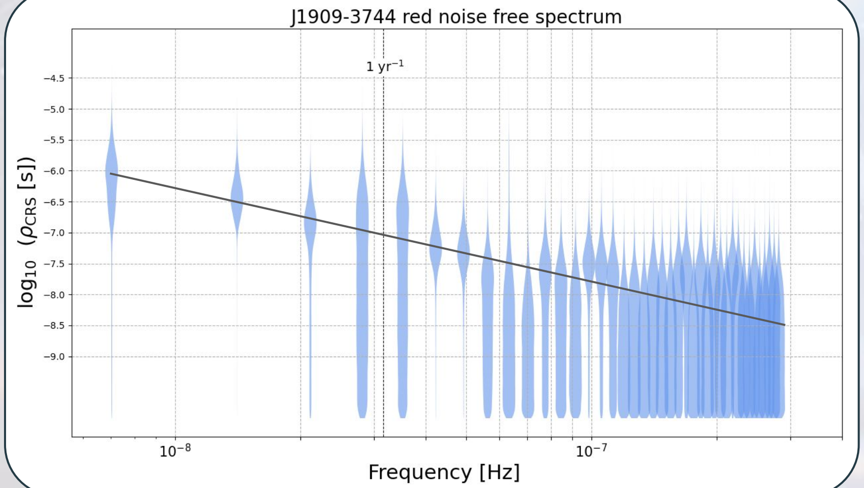


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**Why?**

**Falxa et al. 2023, Chalumeau et al. 2021.** Unmodelled high-frequency noise could conspire for CGW signal.

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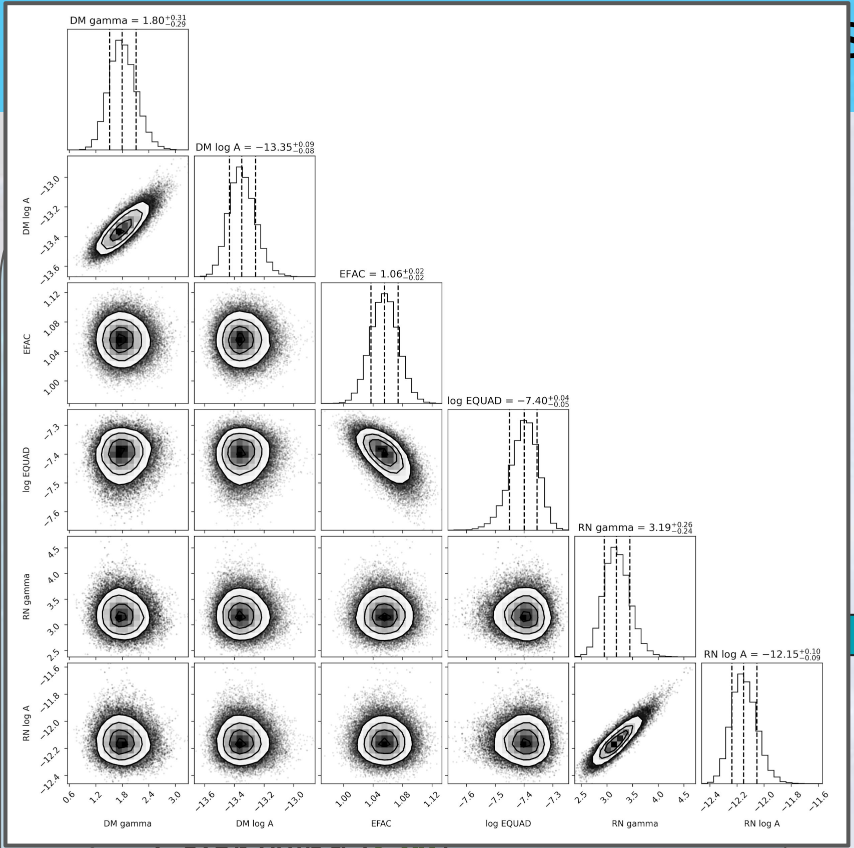
**Optimal model selection** between all models (higher **Bayes** factor, not always).

**Parameter estimation** with PTMCMC sampler of the optimal model.

**Check** the shape of posterior distributions and if noises are physically motivated (e.g. SW).

# s and SPNA

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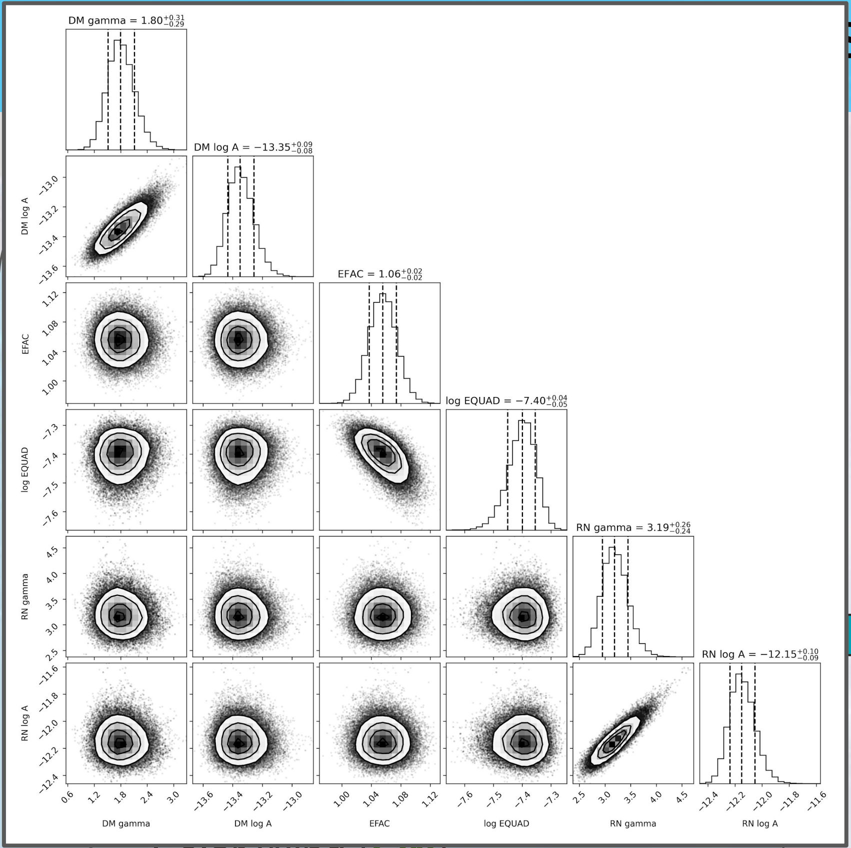


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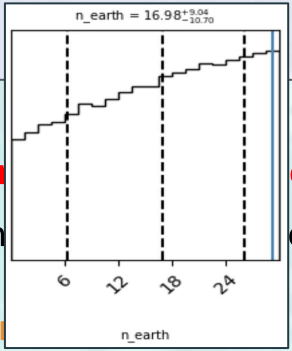


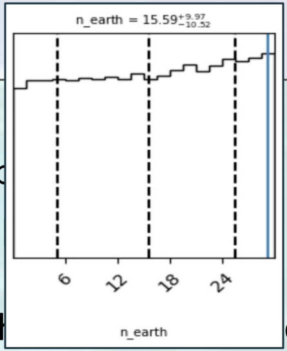


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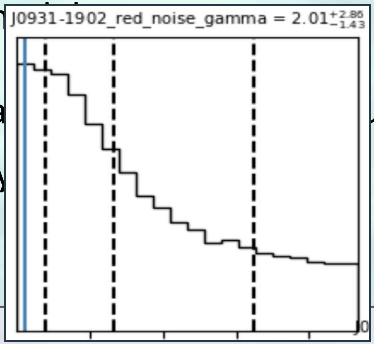



**Check** the sha… utions and if

noises are phy… SW).

# CGW search

**2 models** for CGW search.

CGW modeled using sine wave template.

$$r_a(t) = r_a^{\rm p}(t) - r_a^e(t)$$

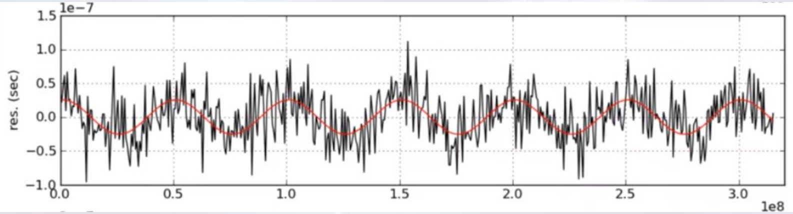
$$r_a^e(t) = \frac{\mathcal{A}}{\omega}\{(1+\cos^2\iota)F_a^+[\sin(\omega t+\Phi_0) - \sin\Phi_0] + 2\cos\iota F_a^\times[\cos(\omega t+\Phi_0) - \cos\Phi_0]\},$$

$$r_a^p(t) = \frac{\mathcal{A}_a}{\omega_a}\{(1+\cos^2\iota)F_a^+[\sin(\omega_a t+\Phi_a+\Phi_0) - \sin(\Phi_a+\Phi_0)] + 2\cos\iota F_a^\times[\cos(\omega_a t+\Phi_a+\Phi_0) - \cos(\Phi_a+\Phi_0)]\}.$$

$$\mathcal{A} = 2\frac{\mathcal{M}_c^{5/3}}{D_L}(\pi f)^{2/3}$$

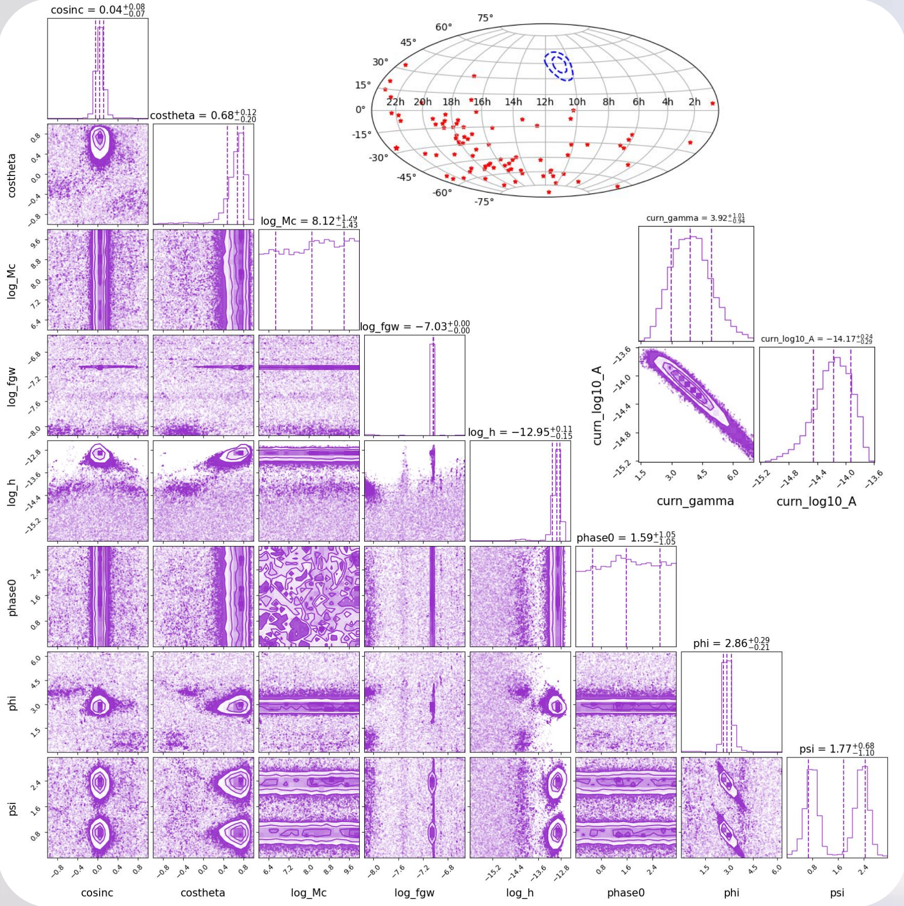
| CGW parameters | Range |
|---|---|
| cos $i$ | [-1, 1] |
| $\cos\theta$ | [-1, 1] |
| $\log_{10} M_c$ | [6.0, 10.0] |
| $\log_{10} dL$ | [-2.0, 4.0] |
| $\log_{10} f_{CGW}$ | [-8.097, -6.52] |
| $\phi_0$ | [0, $\pi$] |
| $\phi$ | [0, $2\pi$] |
| $\psi$ | [0, $\pi$] |

Compute the **Earth term**, no pulsar term.



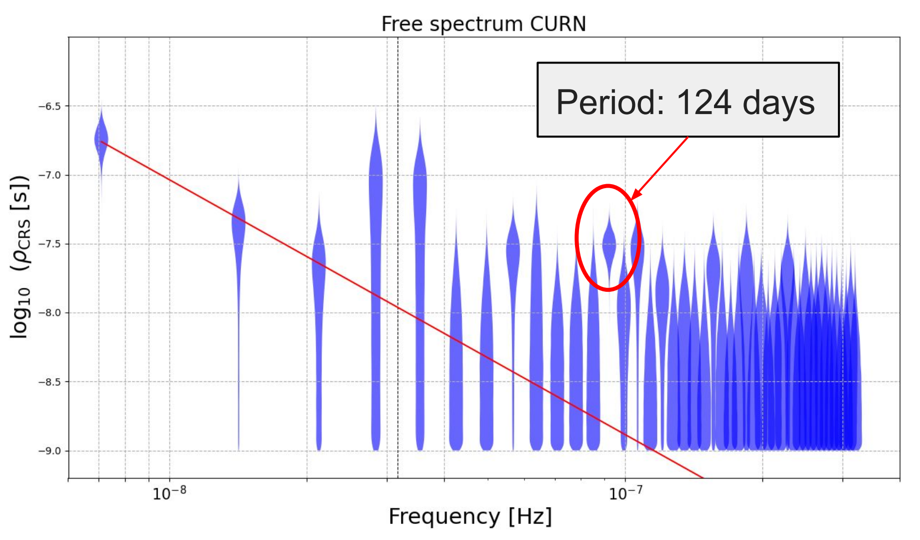
# Preliminary results

# CGW+CURN search




Preliminary results of MeerTime **DR2** using **advanced** model selection, **not custom**.

I search CGW in **all the sky, blindly**.



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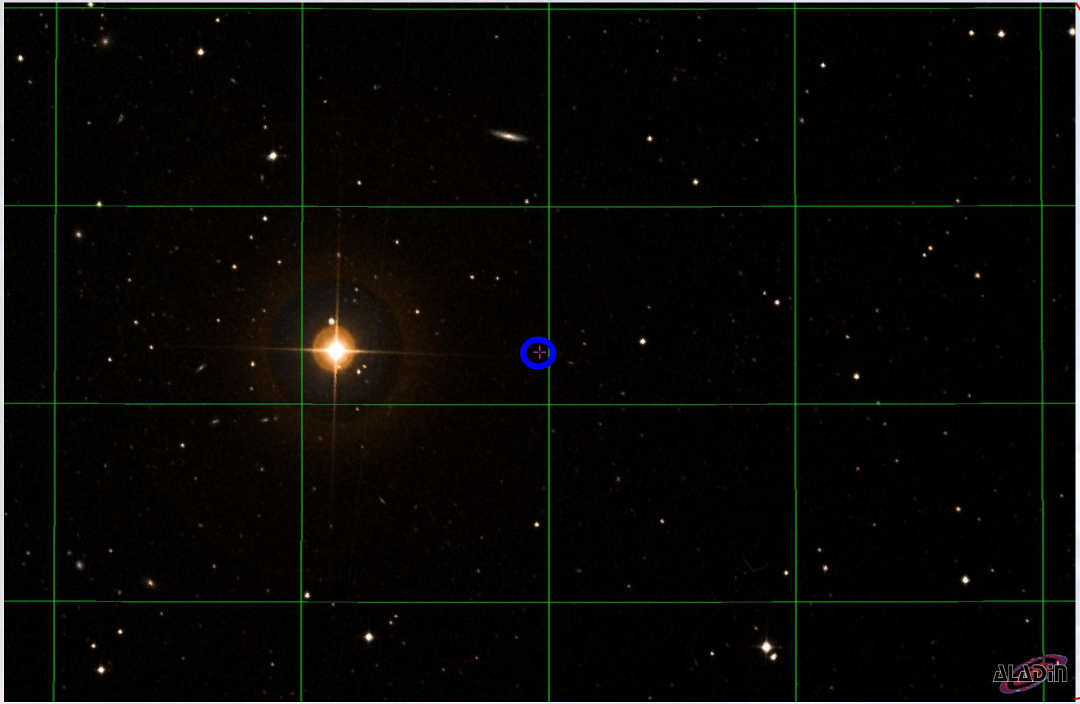
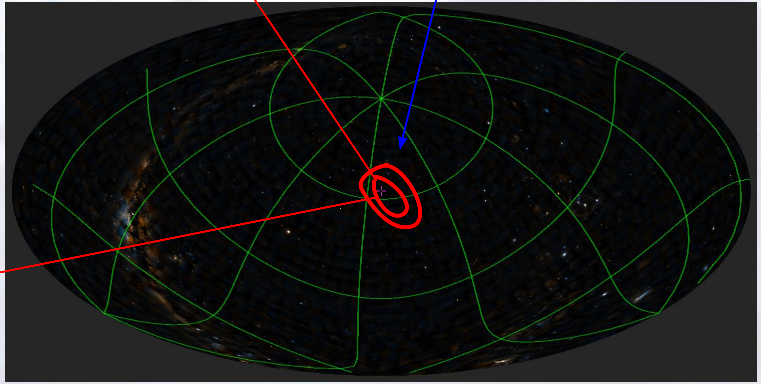
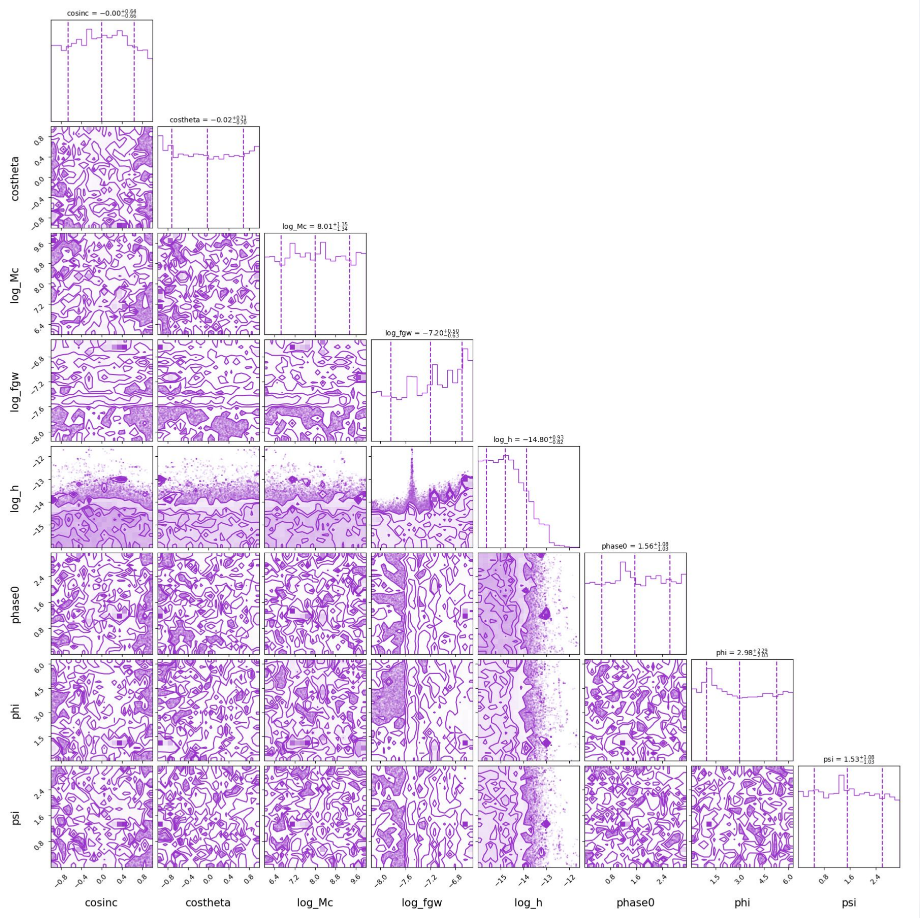



Survey: DSS colored

More than 500 galaxies in **VizieR** catalogues.



# CGW search

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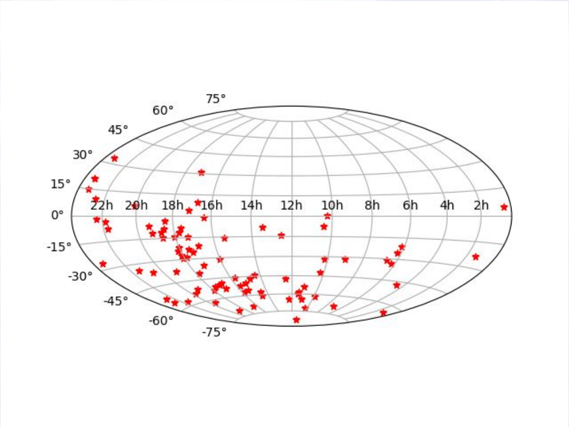
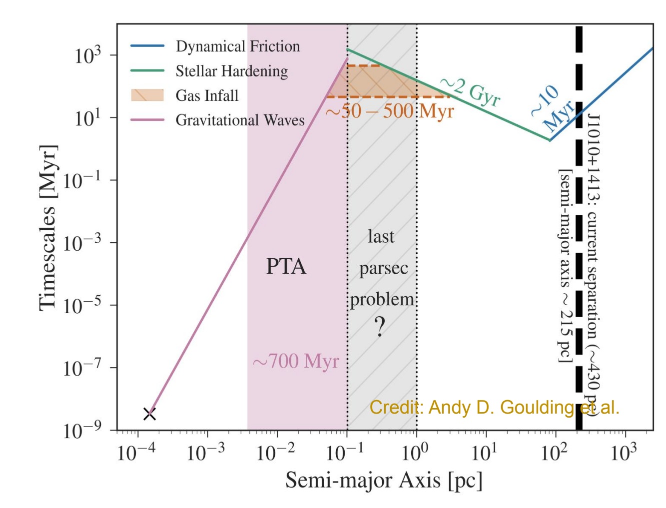


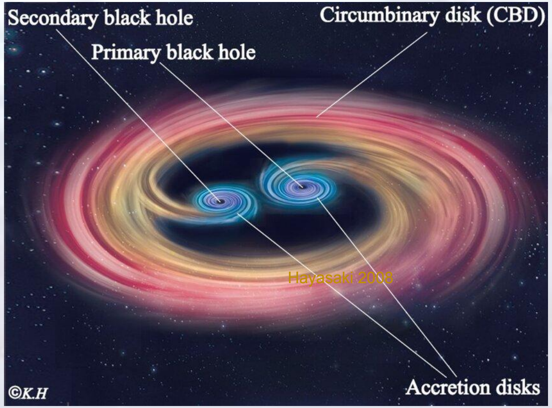
# Targeted search

SMBHs live at the center of the massive galaxies, galaxies merge, SMBHs travel toward the center through:

- **Dynamical friction**
- **Stellar hardening**
- **Gas torques**
- **GW emission**

Looking for **periodic light curves** in Active Galactic Nuclei (AGN). It traces the SMBHB activity and serve as **electromagnetic counterparts**.



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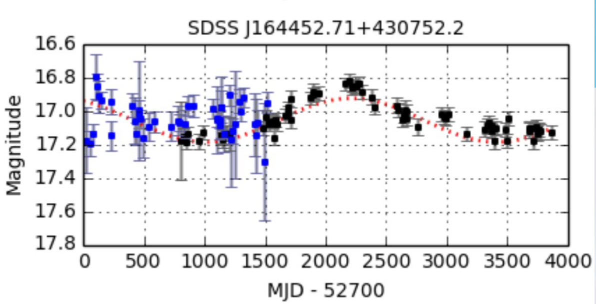


Looking for **periodic light curves** in Active Galactic Nuclei (AGN).

Build a **catalog** with the best candidates from Survey and literature:

- Catalina Real Time Transient Survey (**CRTS**, M. J. Graham et al. 2015). Used Sloan Digital Sky Survey (**SDSS**) spectra to compute masses of SMBHB
- Palomar Transient Factory (**PTF**)
- Panoramic Survey Telescope & Rapid Response System (**Pan-STARRS**)
- **SDSS J092712.65+294344.0** (M. Dotti et al. 2009)

| Object Name | RA | Dec | $f_{GW}$ [Hz] | $\log(M)$ [$M_\odot$] | strain $h_0$ |
|---|---|---|---|---|---|
| 3C66B* | 02 23 11.5 | +42 59 30 | 6.04E-08 | 9.08 | 7.2E-15 |
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| SDSS J133516.17+1833 | 13 35 16.1 | +18 33 41.8 | 1.34E-08 | 9.76 | 1.91E-16 |
| SDSS J140704.43+2735 | 14 07 04.5 | +27 35 56.3 | 1.48E-08 | 9.94 | 1.89E-16 |
| SDSS J134855.27-0321 | 13 48 55.3 | −3 21 41.4 | 1.62E-08 | 9.89 | 1.78E-16 |
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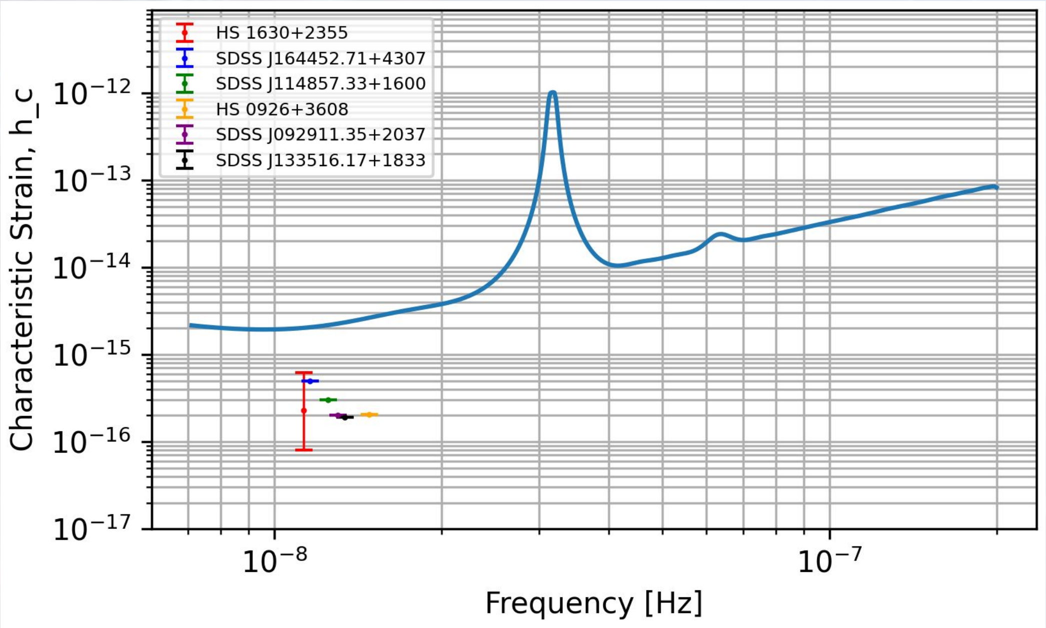
| SNU J13120+0641 | 13 12 04.7 | +06 41 07.6 | 1.55E-08 | 9.14 | 1.33E-16 |
| OJ287 | 08 54 48.9 | +20 06 31 | 5.82E-09 | 10.26 | 1.11E-16 |

Xin et al. 2021

# Targeted search

MPTA has a **short dataset,** so I consider sources with high frequency GW emission (not long period sources).




Once I finished the SPNA and the catalog is ready:

- I **fix** the candidate's **position** as a first approach.
- Depending on the results we will decide **next steps**:
  - ❖ Can we get any other constraints on parameters? Other check?
  - ❖ If useful, we can use other sky surveys for EM counterpart.

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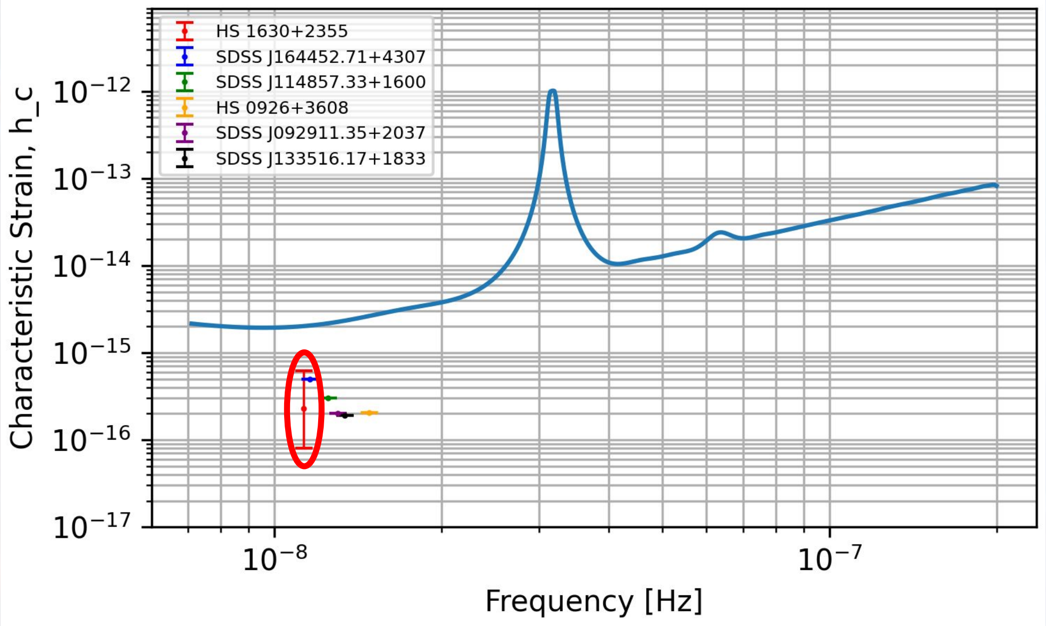


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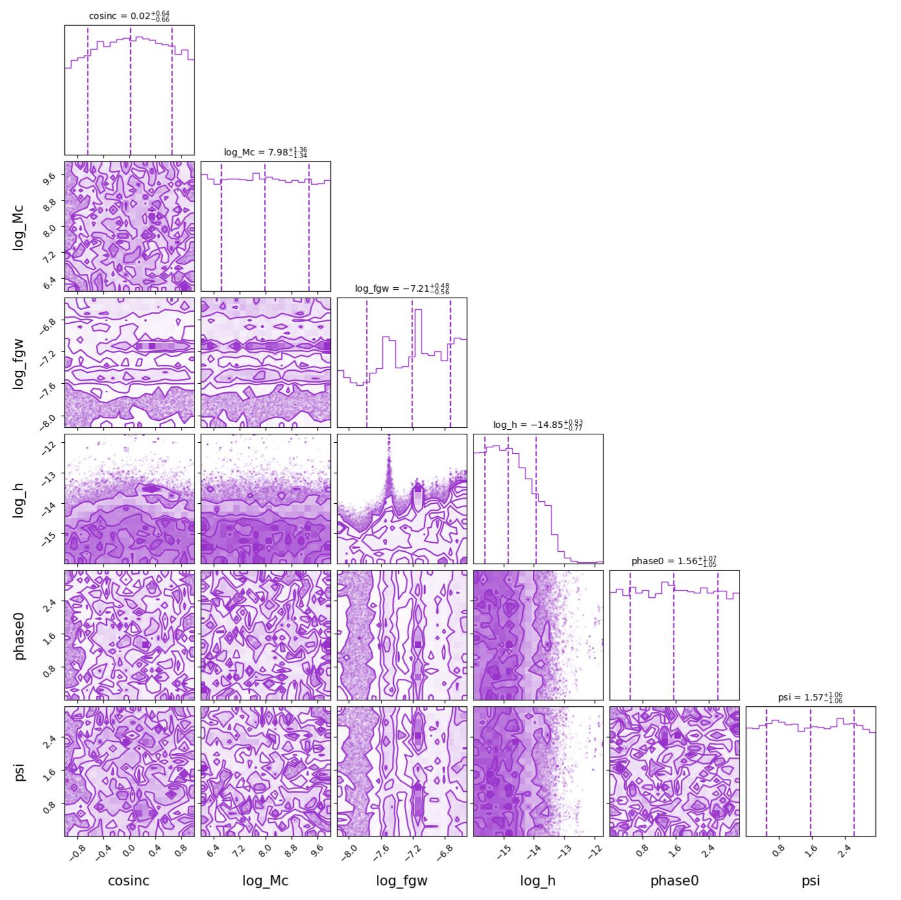


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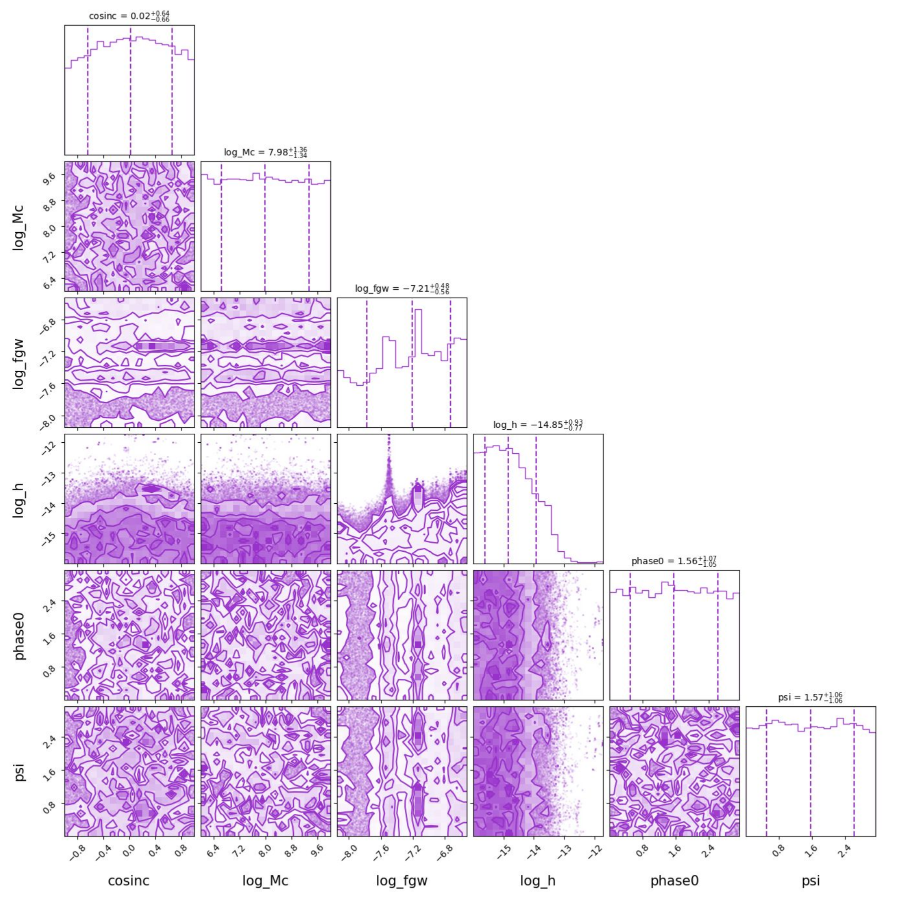


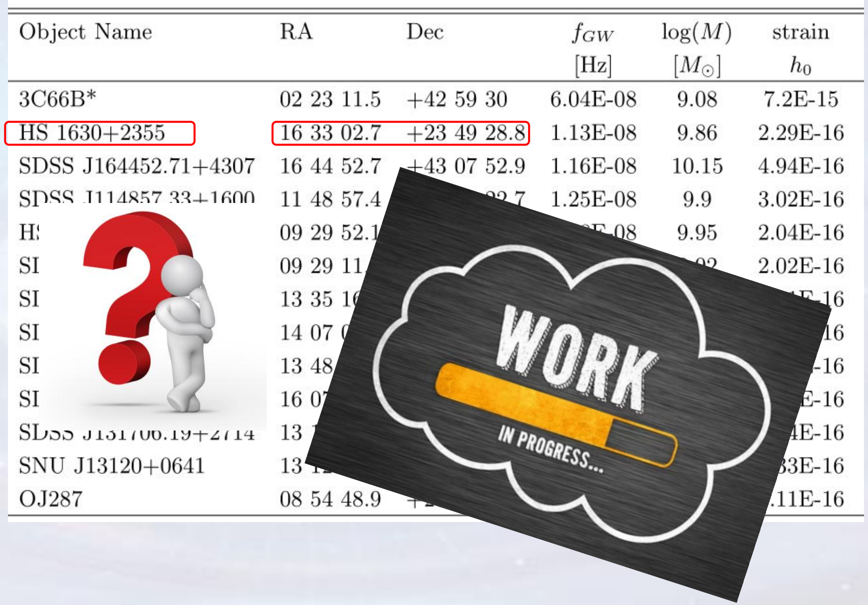

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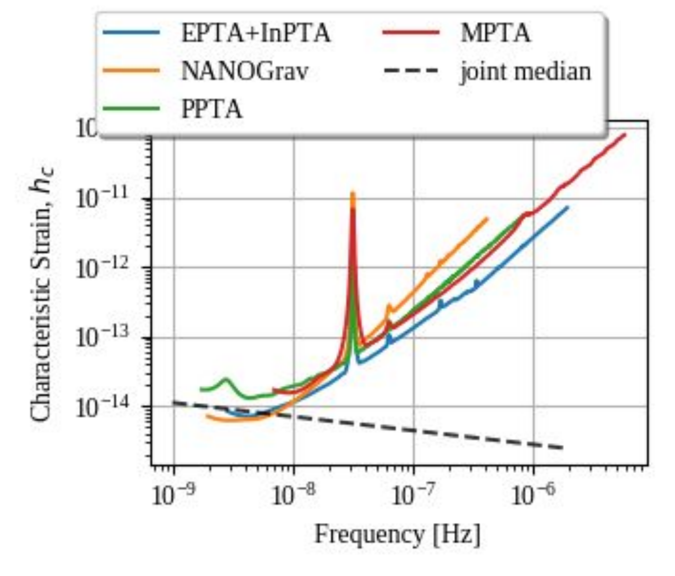
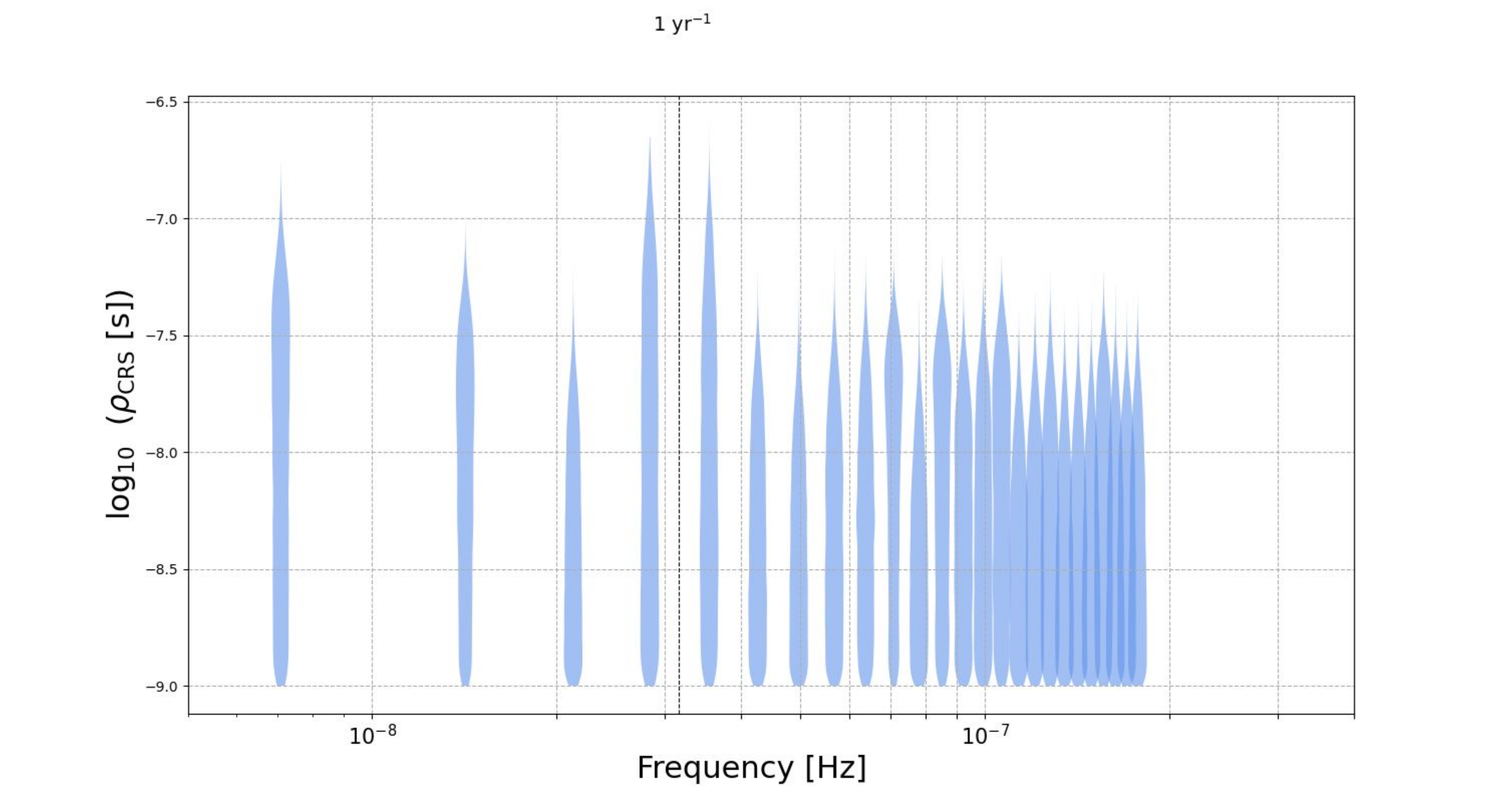
# Thank you!

# bk


EPTA+InPTA
NANOGrav
PPTA
MPTA
joint median
Characteristic Strain, $h_c$
$10^{-11}$
$10^{-12}$
$10^{-13}$
$10^{-14}$
$10^{-9}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
Frequency [Hz]


1 yr⁻¹
−6.5
−7.0
−7.5
−8.0
−8.5
−9.0
log10 (ρCRS [s])
10⁻⁸
10⁻⁷
Frequency [Hz]

# Papers for targeted search:

- Y. J. Chen et al. (2023)
- Ge et al. (2024)
- M. Minev et al. (2024)
- Saade et al. (2024)

# Bayes theorem

I used Bayesian techniques, a statistical approach used to analyze data.

In Bayesian framework, **parameters** are treated as random variables. so instead of considering parameters as **fixed** values, a prior probability distribution is assigned to them, which represents our knowledge before observing the data.

“The probability of an event can be estimated from our prior knowledge of conditions that might be related to the event”

$$p(\vec{\mu}|\vec{d},H) = \frac{L(\vec{d}|\vec{\mu},H)\pi(\vec{\mu}|H)}{p(\vec{d}|H)}$$

likelihood: $L(\vec{d}|\vec{\mu},H)$

prior probability: $\pi(\vec{\mu}|H)$

posterior probability: $p(\vec{\mu}|\vec{d},H)$

evidence: $p(\vec{d}|H)$

$H$ is the assumed model

$\vec{d}$ are the data $\vec{\mu}$ are parameters

# **Custom** SPNA

**Details:**

Chromatic index range [0,14]

Annual chromatic index range [0,14]

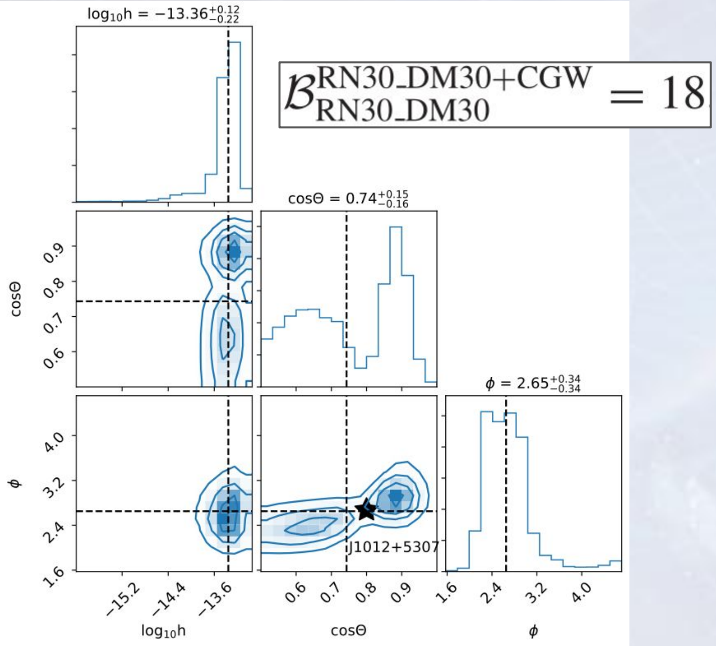
Then testing for chromatic noise with fixed index -4 (scattering)

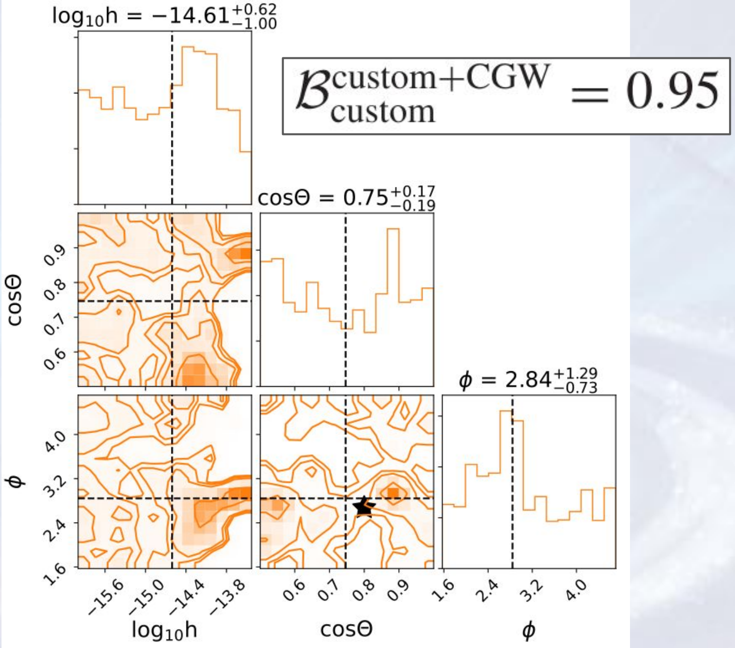
| Model | $E_Q+E_F+E_C$ | DM | RN | Chromatic noise | Annual chrom | Solar wind (det+stoc) |
|---|---|---|---|---|---|---|
| $M_0$ | ✓ | - | ✓ | - | - | - |
| $M_1$ | ✓ | ✓ | - | - | - | - |
| $M_2$ | ✓ | ✓ | ✓ | - | - | - |
| $M_3$ | ✓ | ✓ | - | ✓ | - | - |
| $M_4$ | ✓ | ✓ | ✓ | ✓ | - | - |
| $M_5$ | ✓ | - | ✓ | - | ✓ | - |
| $M_6$ | ✓ | ✓ | - | - | ✓ | - |
| $M_7$ | ✓ | ✓ | ✓ | - | ✓ | - |
| $M_8$ | ✓ | - | ✓ | - | - | ✓ |
| $M_9$ | ✓ | ✓ | - | - | - | ✓ |
| $M_{10}$ | ✓ | ✓ | ✓ | - | - | ✓ |
| $M_{11}$ | ✓ | - | - | ✓ | ✓ | - |
| $M_{12}$ | ✓ | - | ✓ | ✓ | ✓ | - |
| $M_{13}$ | ✓ | ✓ | - | ✓ | ✓ | - |
| $M_{14}$ | ✓ | ✓ | ✓ | ✓ | ✓ | - |
| $M_{15}$ | ✓ | - | ✓ | - | ✓ | ✓ |
| $M_{16}$ | ✓ | ✓ | - | - | ✓ | ✓ |
| $M_{17}$ | ✓ | ✓ | ✓ | - | ✓ | ✓ |
| $M_{18}$ | ✓ | - | - | ✓ | ✓ | ✓ |
| $M_{19}$ | ✓ | - | ✓ | ✓ | ✓ | ✓ |
| $M_{20}$ | ✓ | ✓ | - | ✓ | ✓ | ✓ |
| $M_{21}$ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $M_{22}$ | ✓ | - | - | - | - | - |
| $M_{23}$ | ✓ | - | - | - | ✓ | - |
| $M_{24}$ | ✓ | - | - | - | - | ✓ |
| $M_{25}$ | ✓ | - | - | - | ✓ | ✓ |

Data prefers the custom model

# Why **custom**?

Falxa et al. 2023




Using "standard" noise settings: **30** frequency bins for DM and RN. 51 nHz. 21 pulsars.

**Time-correlated noise** at high frequencies.

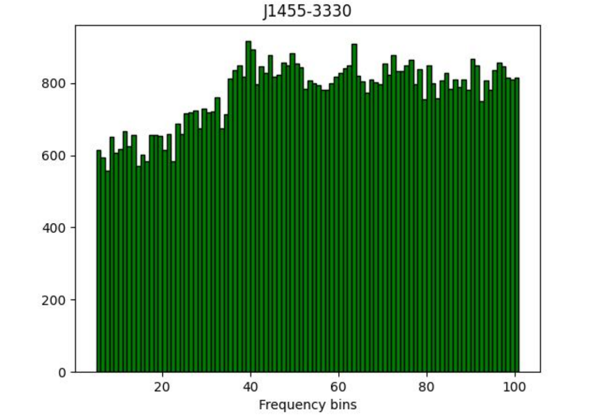
Using **custom** noise model for the six best EPTA pulsars (**from Chalumeau et al. 2021**).
Posterior distributions not anymore constrained.

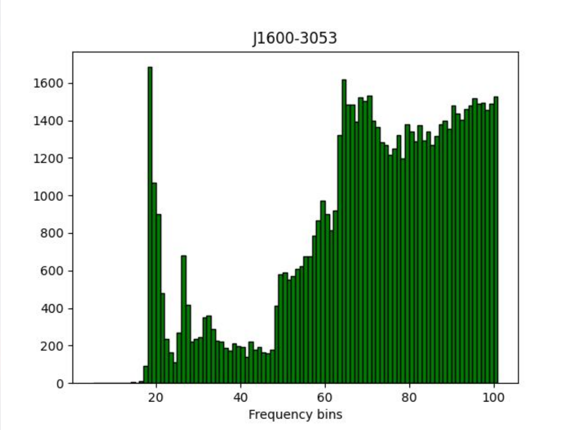
# SPNA: **custom** noise model

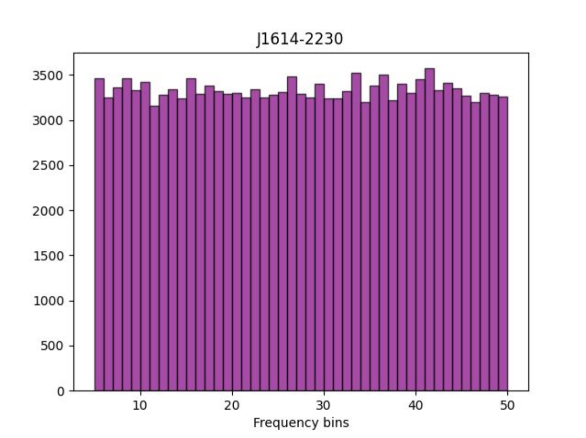
**Optimization** of frequency bins in Fourier domain using method in **EPTA II** [2023].

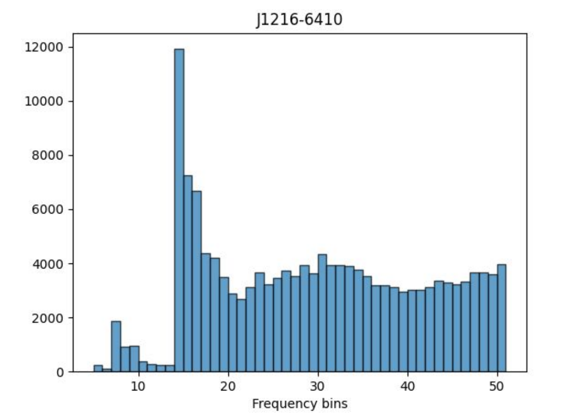
**Frequency range** for RN, DM and chromatic noise: from 5 to bin corresponding to 1/(2*cadence). 51 Models.

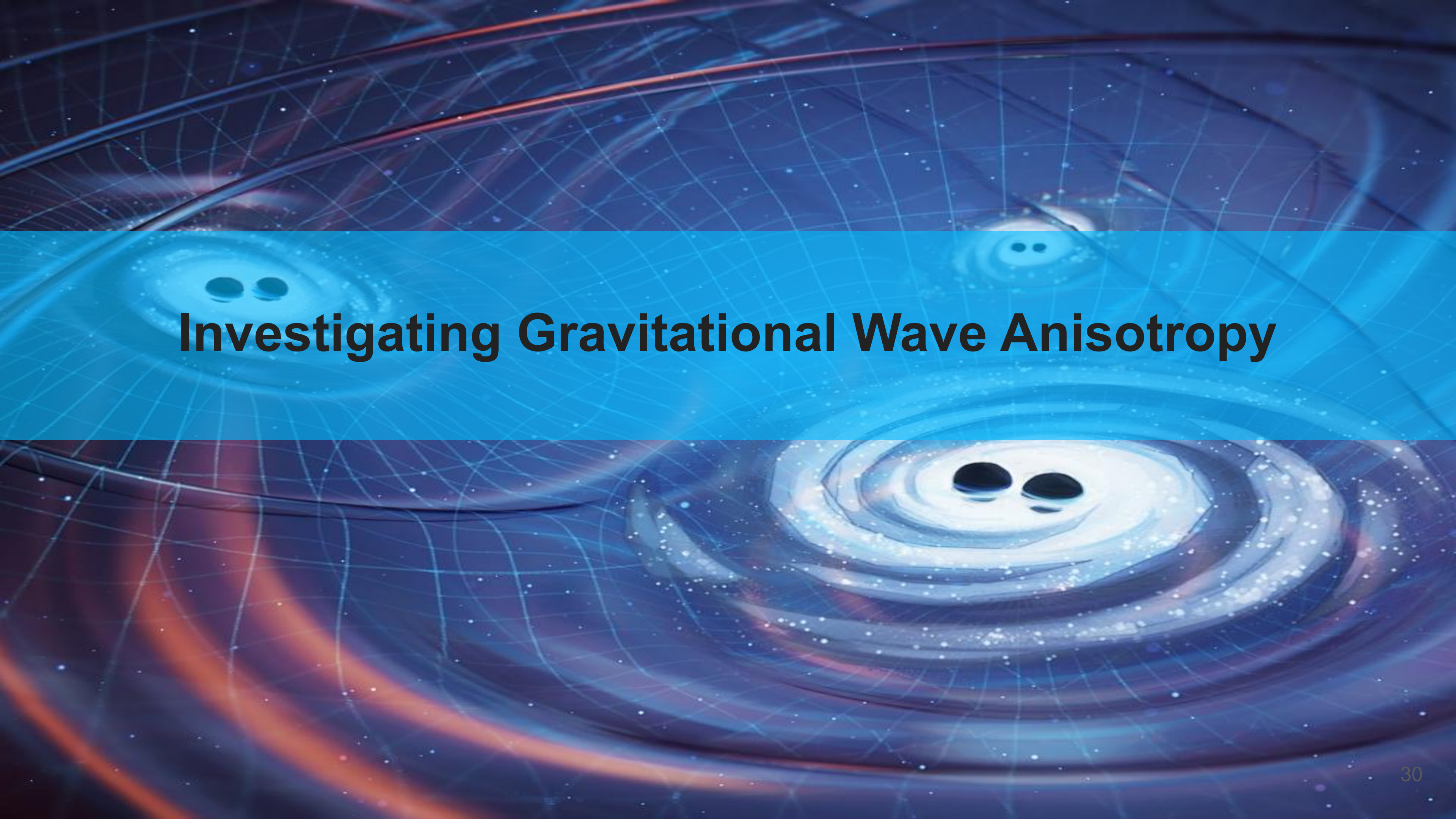
Example of posterior distributions, **code** in progress (thanks Aurélien).





# Investigating Gravitational Wave Anisotropy

# Different levels of anisotropy

**Sky maps** of the power spectral density of the GWB.

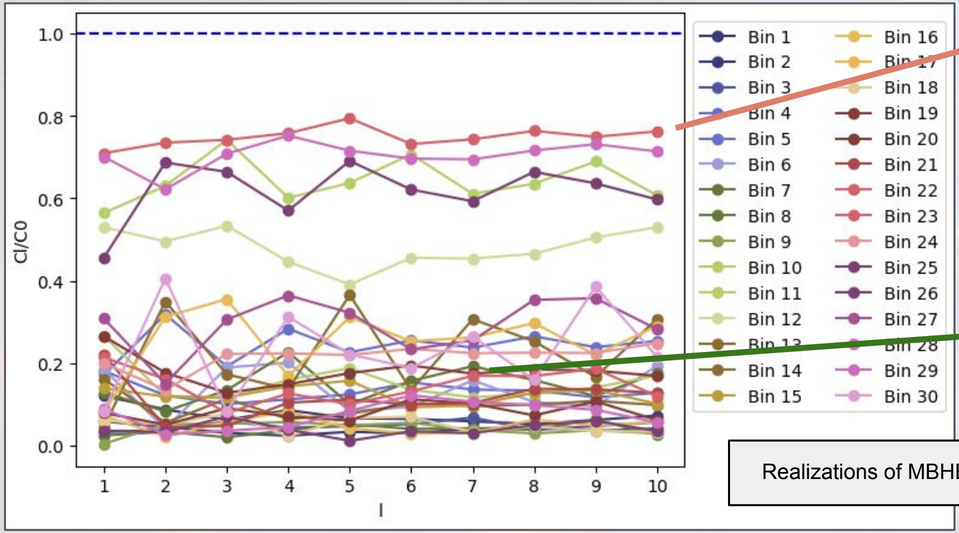
$$P_{GWB}(f) = \frac{h_c^2(f)}{12\pi^2 f^3}$$

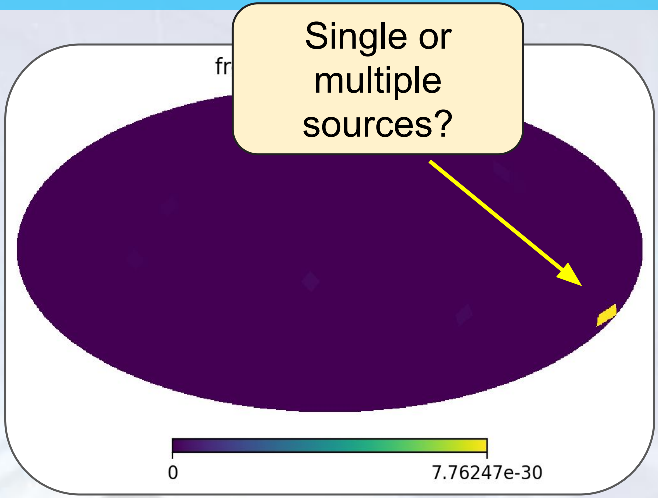
**Spherical-harmonics** decompositions.

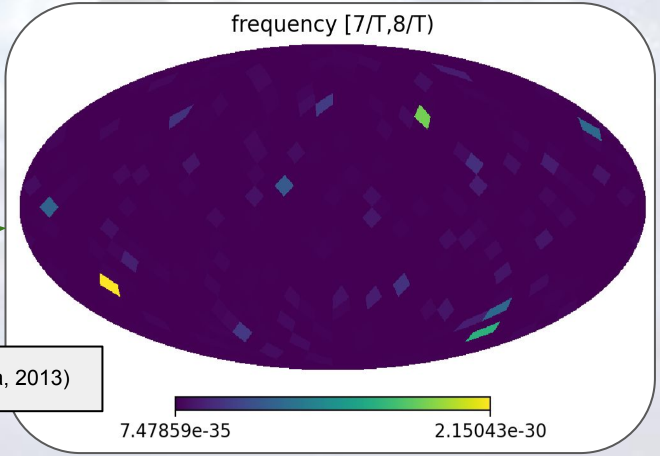
$$P(\Omega) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} c_{lm} Y_{lm}(\Omega)$$

Statistical fluctuations in the angular power of the GWB at different scales.

$$C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |c_{lm}|^2$$

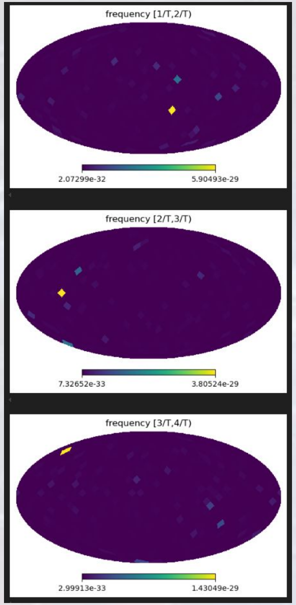


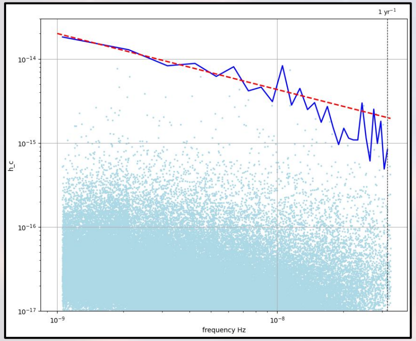



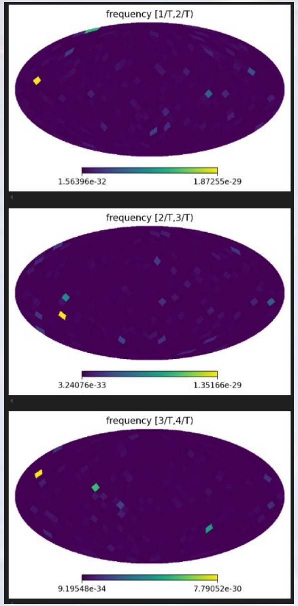

Realizations of MBHB population (Sesana, 2013)

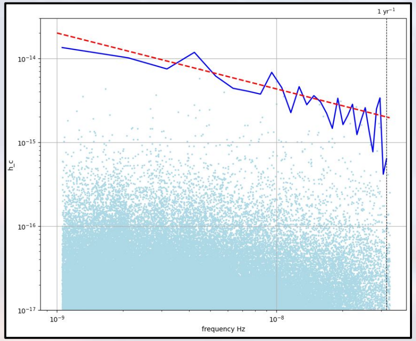
$e = 0.01$
$\rho = \rho^{fid}/10$



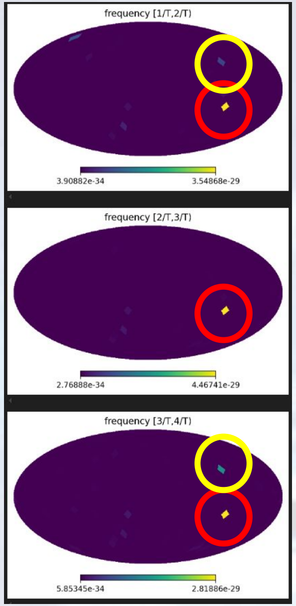



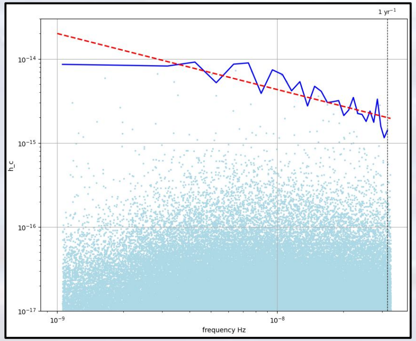

$e = 0.01$
$\rho = \rho^{fid}*10$




$e = 0.9$
$\rho = \rho^{fid}/10$




$e = 0.9$
$\rho = \rho^{fid}*10$