Realistic simulations of resolved binaries in pulsar timing array datasets

V Gravi-Gamma-nu workshop - October 9-11, 2024 - Bari

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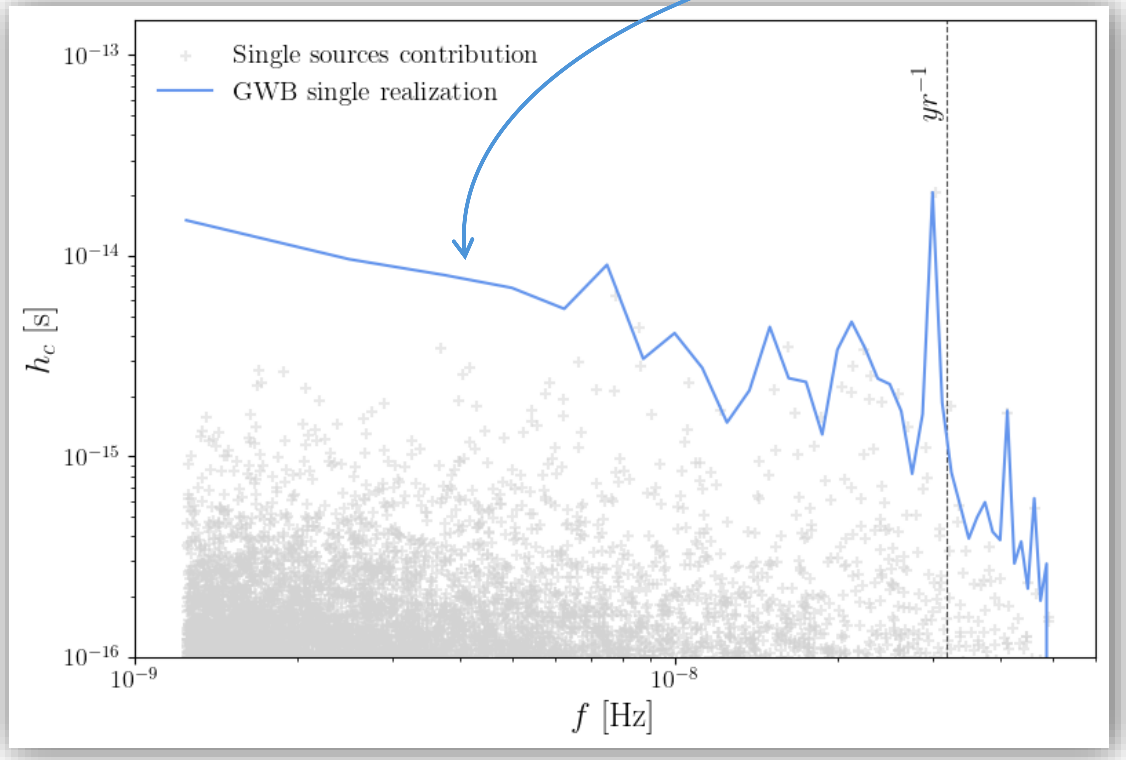
PTA signal from Super Massive Black Hole Binaries (SMBHBs)

- SMBHBs emit in the PTA band during the inspiral phase -> the signal is always present throughout the observation period
- Since many many SMBHBs are expected to populated our universe, we expect to see the incoherent superposition of their GW emissions

-> a Gravitational Wave Background (GWB)



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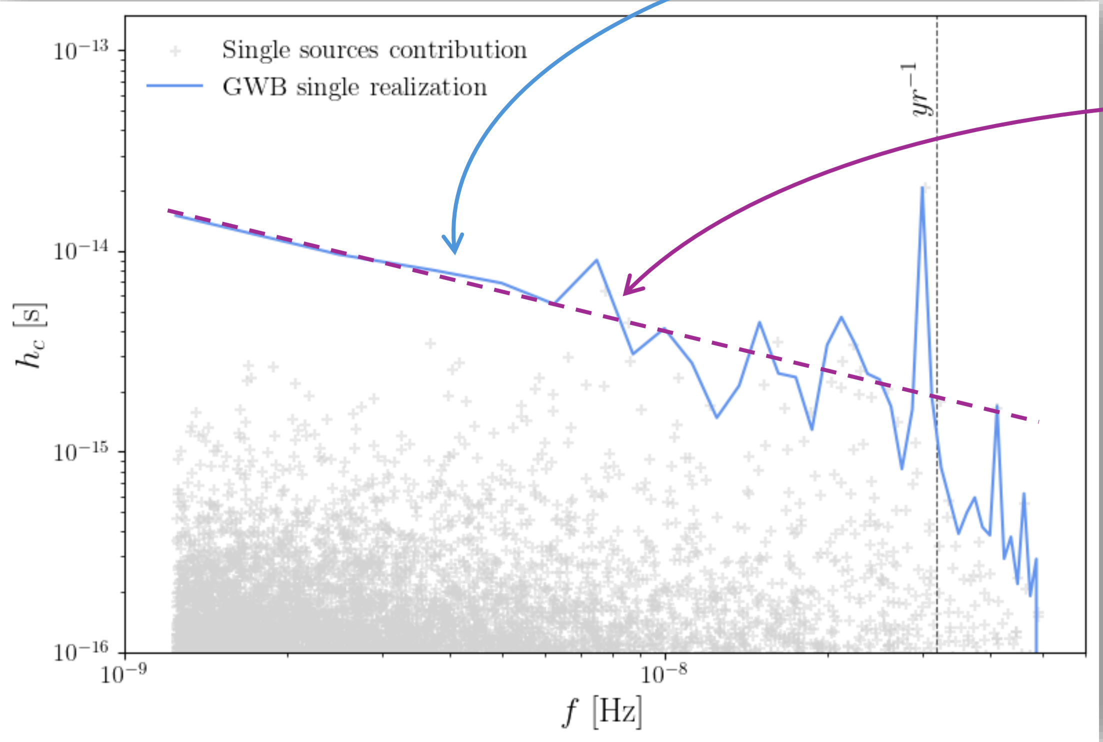

Modelled in the frequency domain as a **power-law spectrum**

$$h_c(f) = A_{\mathrm{GWB}} \left(\frac{f}{yr^{-1}}\right)^{-\alpha_{\mathrm{GWB}}}, \ \alpha_{\mathrm{GWB}} = 2/3$$

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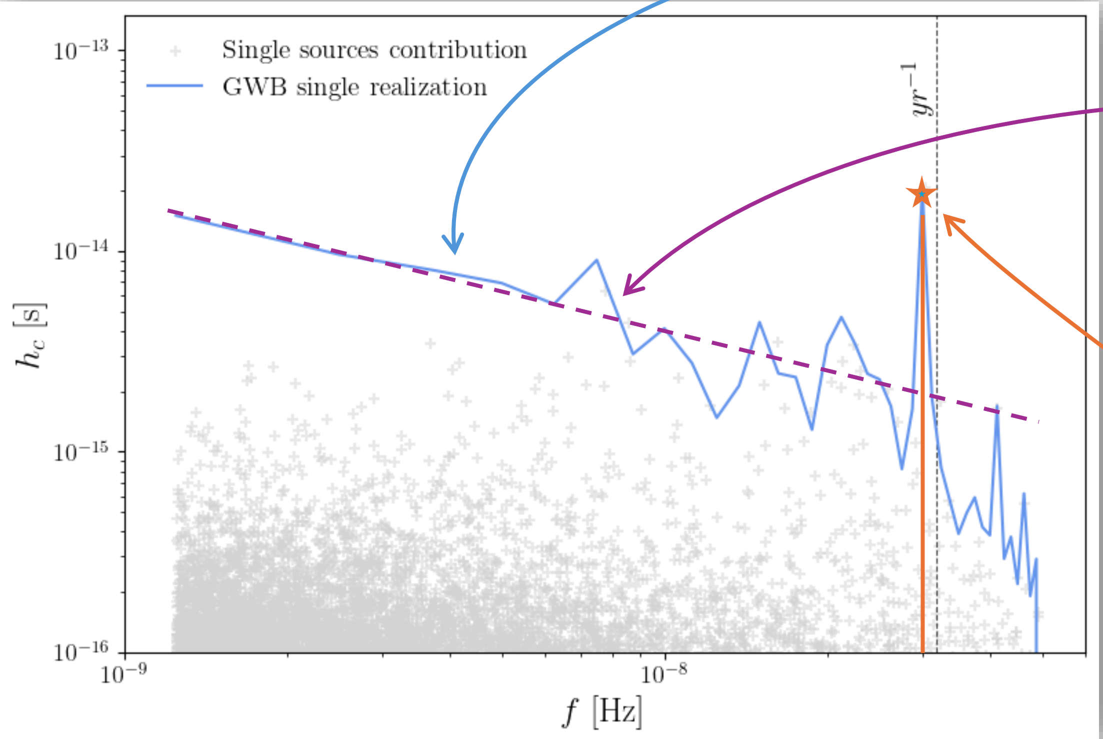

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Continuous Gravitational Wave (CGW)

= very massive and closeby sources that can be **singularly resolved**

-> **their template s(t) in the time domain is deterministic**

Continuous Gravitational Wave model

Pulsar term Earth term

$$s(t) = s_p(t_p) - s_e(t_e)$$

$$s_r(t) = F^+(\phi, \theta)s_+(t) + F^\times(\phi, \theta)s_\times(t)$$

$r = e, p$

$$s_+(t) = \frac{\mathcal{M}^{5/3}}{d_L \omega(t)^{1/3}}\left(-\sin(2\Phi(t))(1+\cos^2(\hat{\imath})\cos(2\psi) - 2\cos(2\Phi(t))\cos(\hat{\imath})\sin(2\psi)\right)$$

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The deterministic CGW model depends on 8 parameters which are related to the source

Sky location

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Chirp mass　Orbit's inclination angle　Polarization angle

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Chirp mass and luminosity distance are totally degenerate :(

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The degeneracy can be broken if we are sensitive to the frequency evolution :)

Current status and perspectives of CGW searches

Currently, PTA dataset show **no significant evidence** in favour of a single resolved source:

CGW present on top of the GWB → GWB + CGW

No CGW present → GWB

$$\text{Bayes factor}^{\,GWB + CGW}_{\,GWB} = \begin{matrix} 0.7 & \text{EPTA DR2 10yr} \\ 0.4 & \text{NANOGrav 15yr} \end{matrix}$$

Future PTA experiments, like **SKA**, should perform much better at high frequencies (above 10nHz), where the background is low and detecting single sources is easier!

Ex. **SKA 30yr with 200 pulsars**

~ **20-55 resolved sources**

(= single sources with SNR>5 above the GWB)

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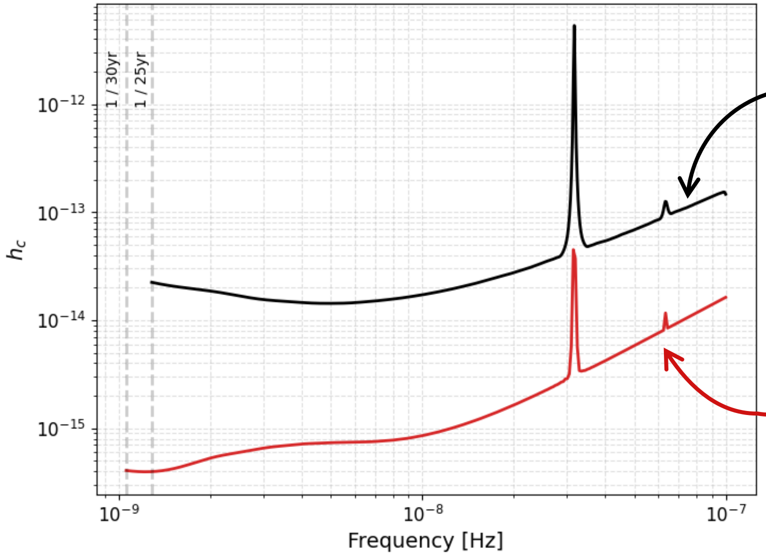

EPTA DR2 25yr, 25 pulsars

SKA 30yr, 200 pulsars

Realistic simulations of EPTA DR2 with single resolved sources

We performed some realistic simulations of PTA datasets with detectable single sources to test the performance of the current CGW analysis pipeline

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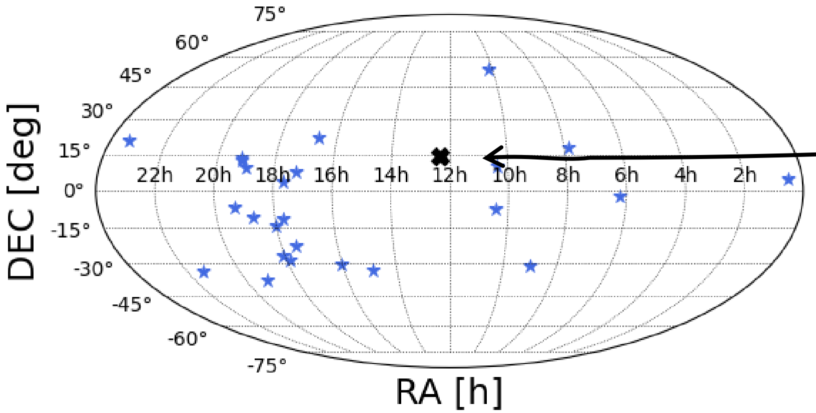
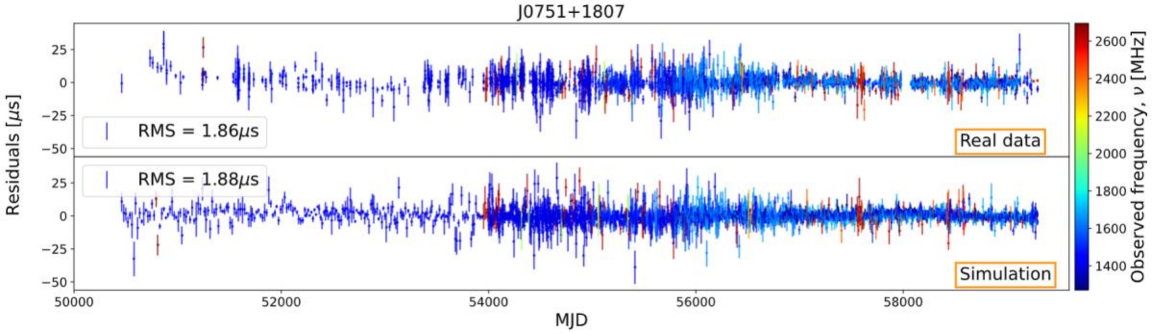
25 **pulsars** of EPTA DR2, 25yr



With the same observation time and the **same noise properties**



2 datasets are used with 2 different single sources:

Both sources are in the **Virgo cluster** and have **chirp mass of** $2 \cdot 10^9 M_\odot$

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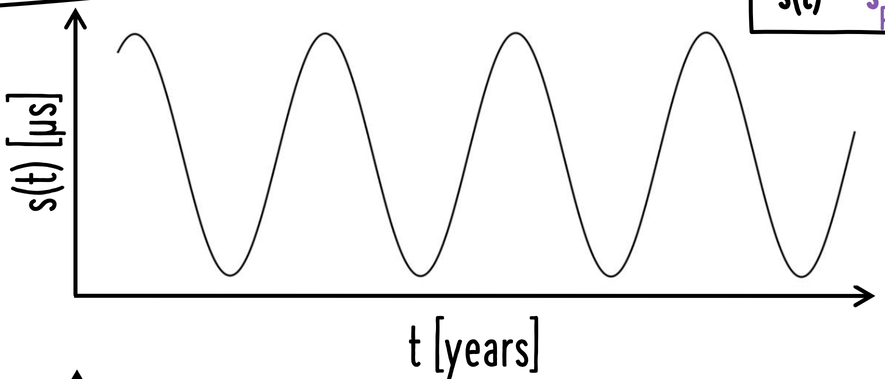
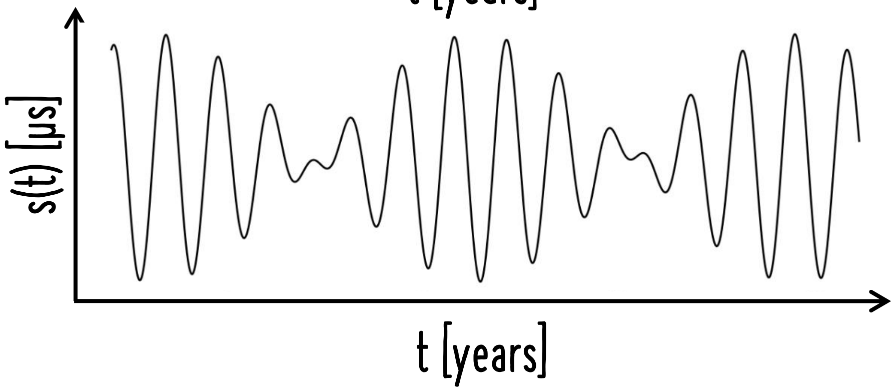


f = 5nHz

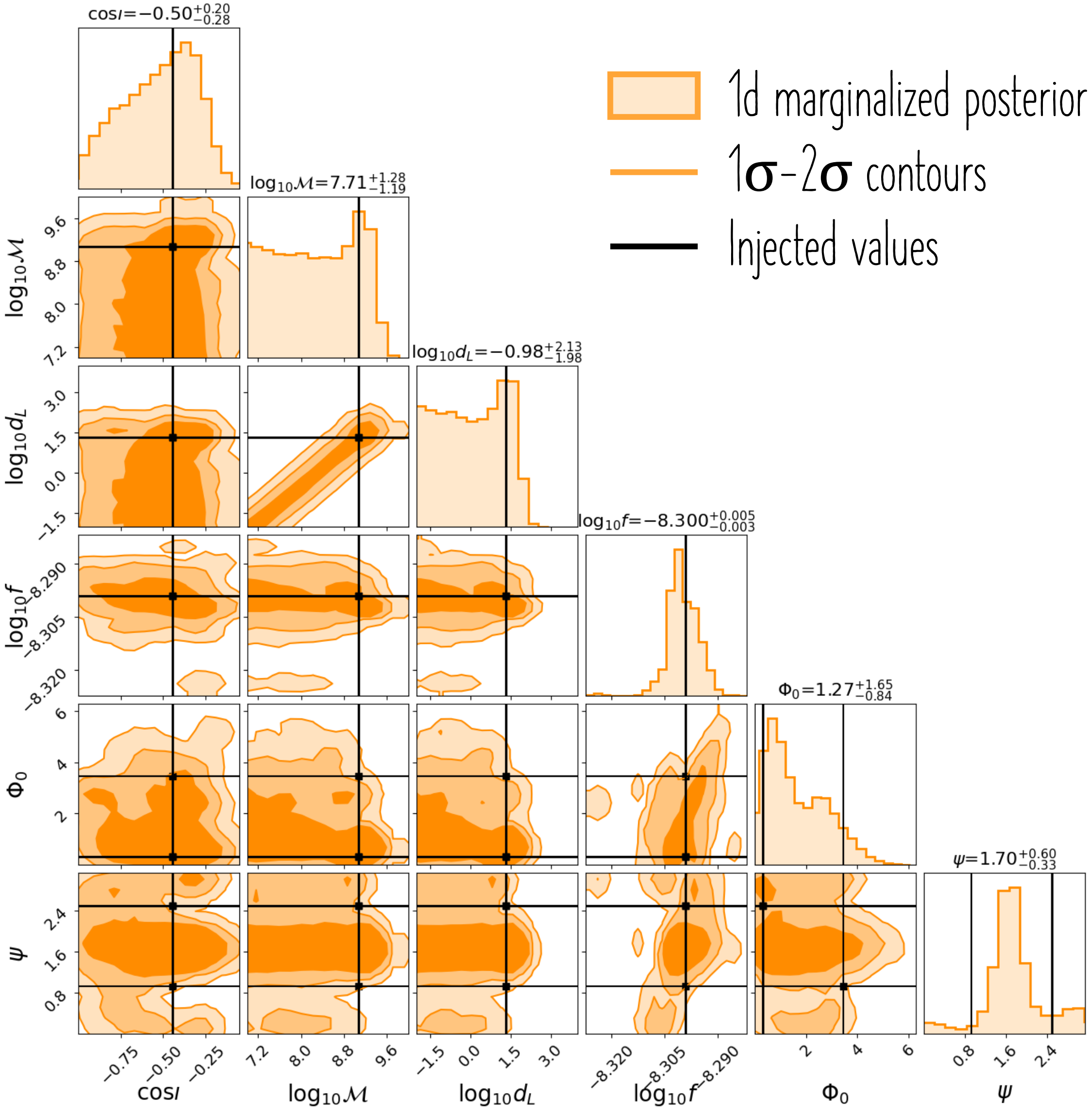
SNR ~ 7



f = 20nHz

SNR ~ 10

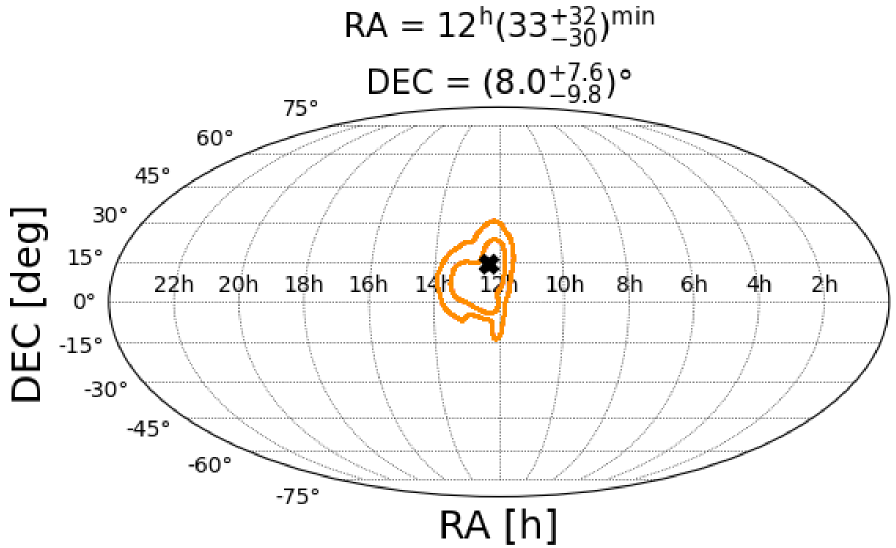
5nHz CGW simulations – results



1d marginalized posterior distributions

1σ-2σ contours

Injected values

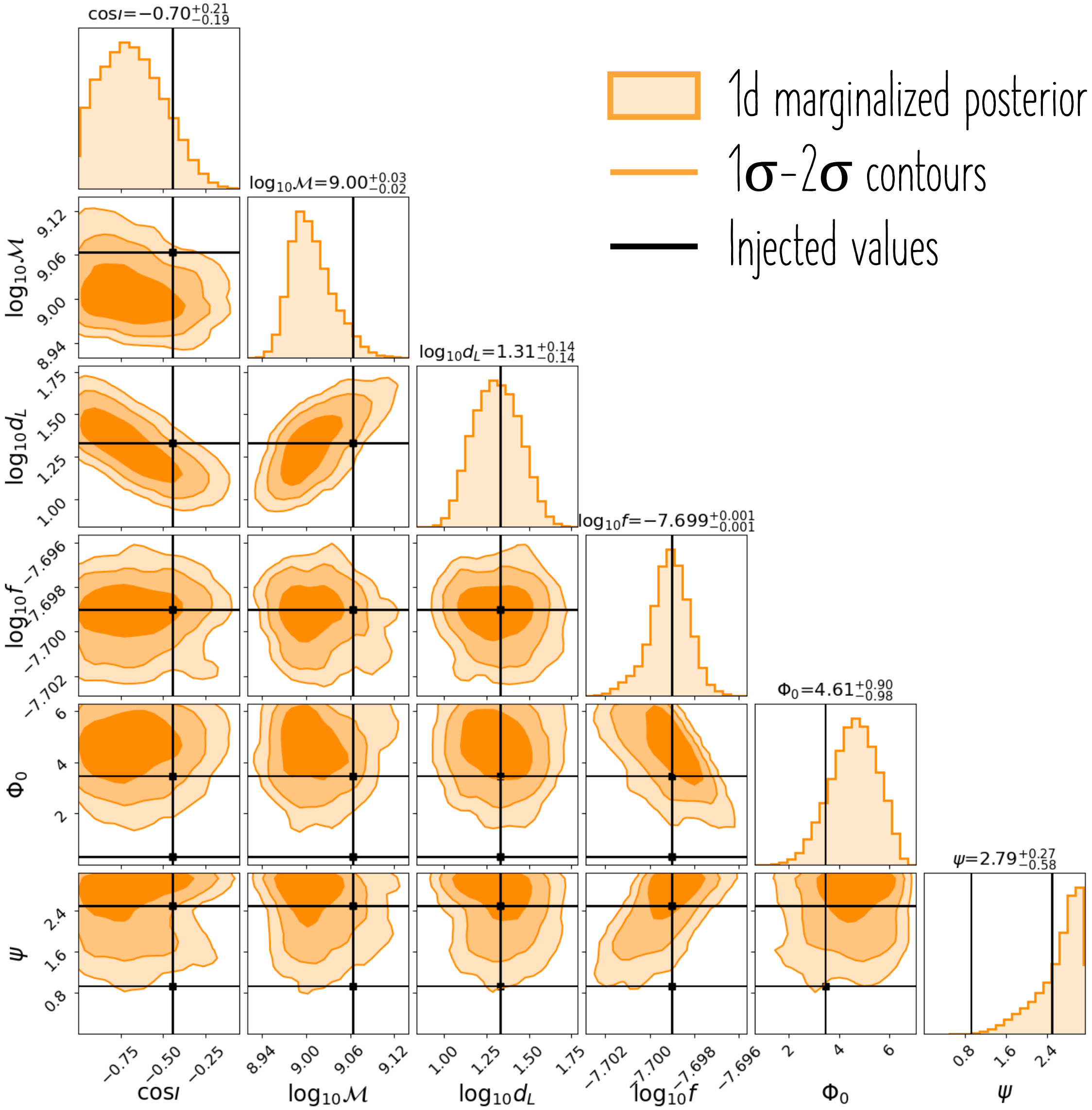


- **Parameters** are mostly recovered **unbiased**
- **Mass and luminosity distance are poorly constrained** because the frequency evolution is beyond the PTA resolution in frequency:

$$\Delta f = f(t_e) - f(t_p) = 0.01\text{nHz}$$

EPTA 25yr resolution = 1.3nHz

20nHz CGW simulations – results



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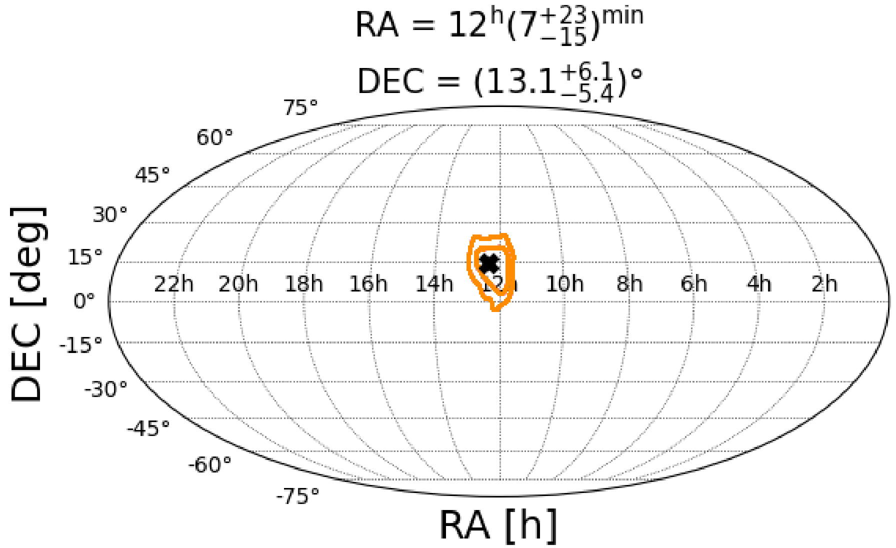

- **Parameters** are mostly recovered **unbiased**
- **Mass and luminosity distance are well constrained** because the frequency evolution is bigger than the PTA resolution in frequency:

$$\Delta f = f(t_e) - f(t_p) = 4\text{nHz}$$

EPTA 25yr resolution = 1.3nHz

CGW simulations - source localization and host galaxy identification

Size of the sky localization error box (68% C.I.):

f = 5nHz, SNR = 7 -> $\Delta\Omega \sim 442.6 \text{ deg}^2$

f = 20nHz, SNR = 10 -> $\Delta\Omega \sim 225.3 \text{ deg}^2$

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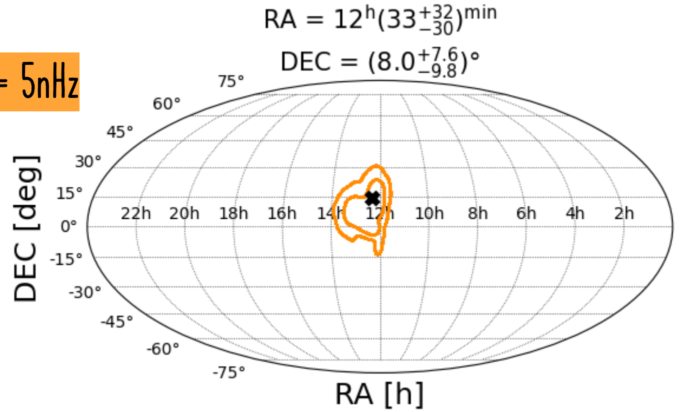

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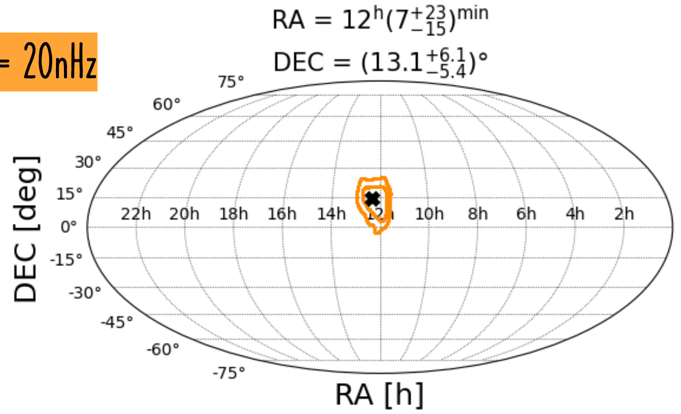

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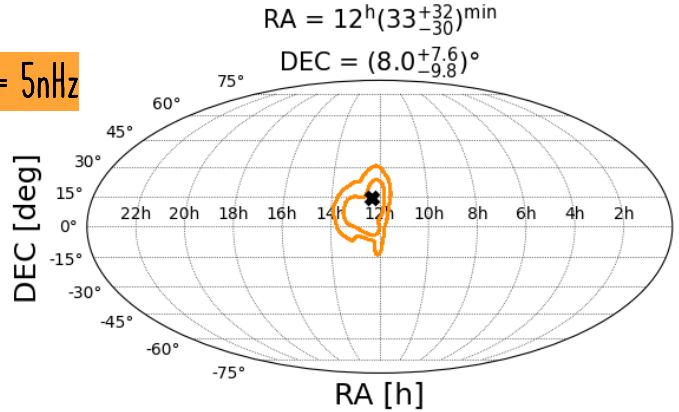

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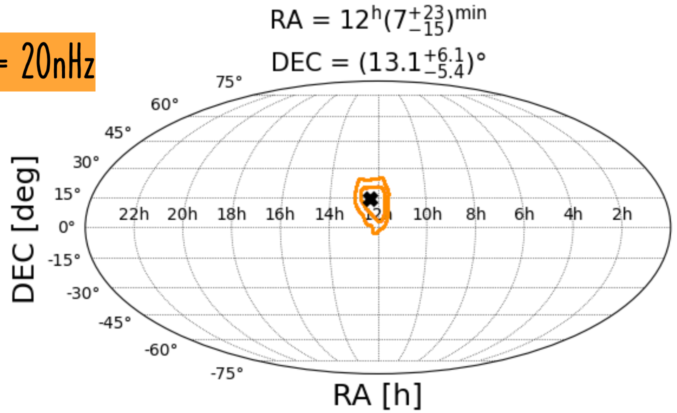

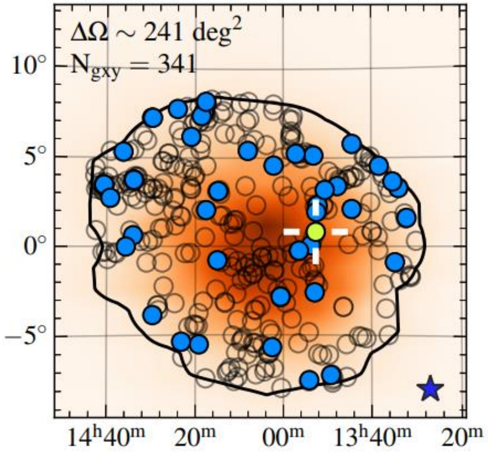

○ Host candidates within the error box

● Host candidates after cut in chirp mass and distance

$\Delta\Omega \sim 225.3$ deg^2

By comparing the error box with catalogs of massive galaxies at $z < 0.05$, we can estimate:

\# galaxies in the error box ~ 300-350

Using also the inference of the chirp mass and luminosity distance, # of possible hosts ~ 40-70

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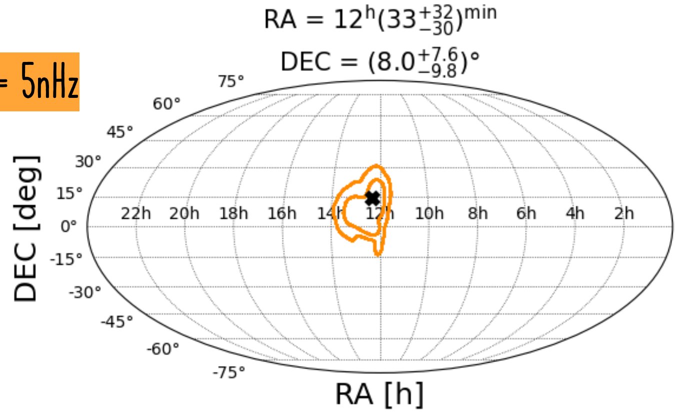

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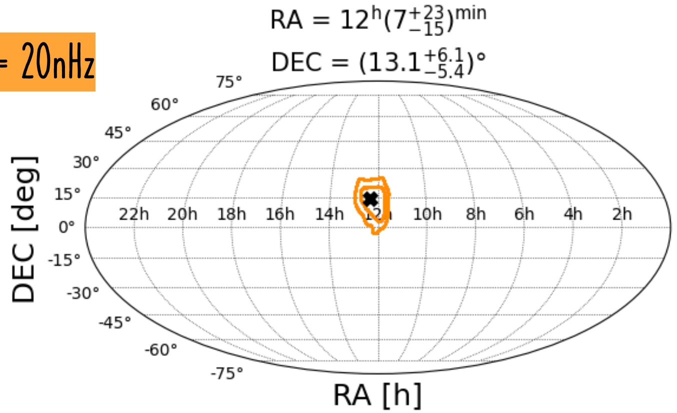

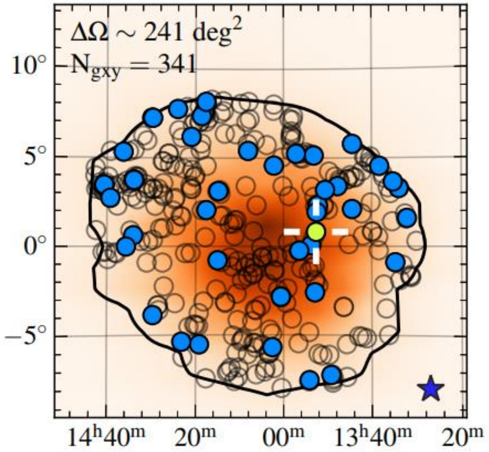

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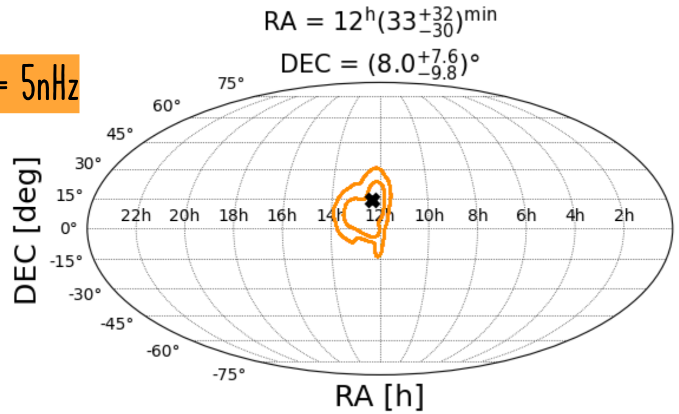

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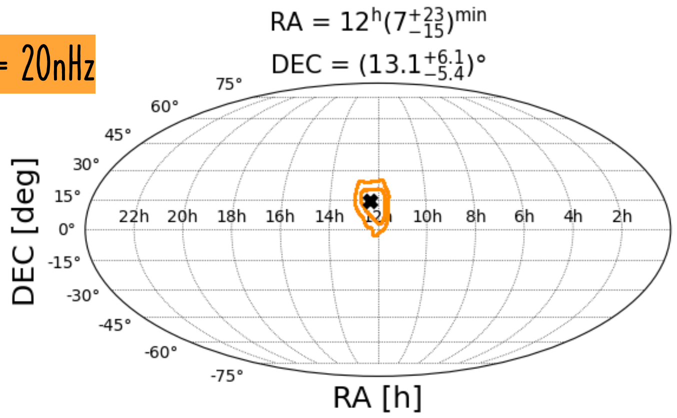

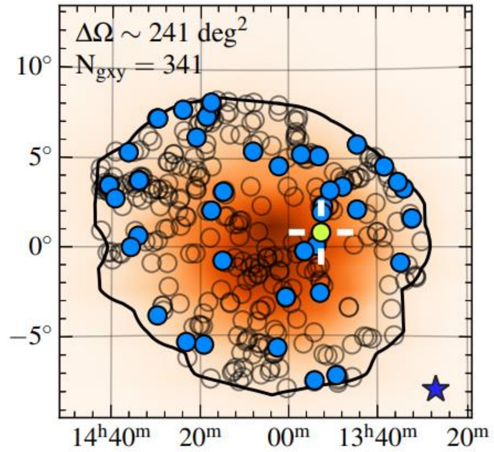

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Ex. SKA 30yr with 200 pulsars ~ 20-55 resolved sources

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Of these, **10% have SNR>15** -> **the error box** on the sky localization can go down to 80 - 1 deg^2

-> # of possible host galaxies can go down to 20 - 1 galaxies!

Summary

- Single resolved sources haven't yet be observed, but they are very likely to be detected on top of the stochastic GWB by future PTA experiments
- Since they can be localized in the sky, they are promising candidates to perform multimessenger observations
- Realistic simulations of PTA experiments have shown that **the models** currently used for CGW searches can estimate the source parameters without bias and with the precision expected from analytical studies
- Future PTA experiments are likely to have the opportunity to detect single sources with SNR > 15, allowing the identification of the host galaxy and thus opening the doors to the observation of electromagnetic counterparts

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THANK YOU!

Back-up slides

Continuous Gravitational Wave waveform