Muffled Murmurs: Environmental effects in the LISA stochastic signal from stellar-mass black hole binaries

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Background

· Stellar-mass black hole binaries (sBBHs) that remain unresolved are expected to produce a stochastic gravitational-wave background (SGWB) detected by LISA [1,2].

· Astrophysical environmental effects [3,4], such as **gas dynamical friction** and **accretion**, can induce additional energy dissipation and leave detectable imprints on the background.

· How can environmental effects be modeled and analyzed using Bayesian methods?

· Can environmental effects be measured and distinguished from vacuum?

· Is it possible to probe a sub-population of sBBHs undergoing environmental effects?

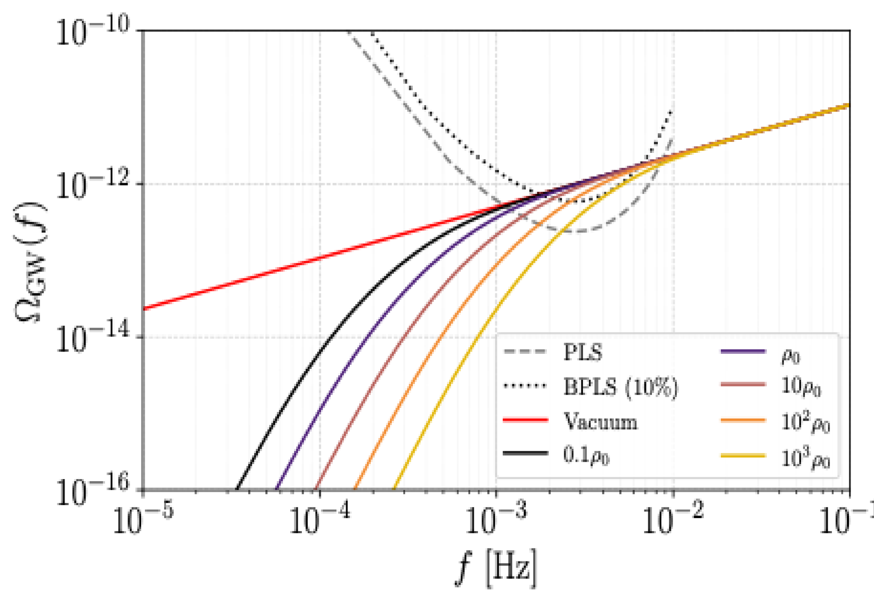
Environmental-effects imprint on the SGWB

Assumptions:

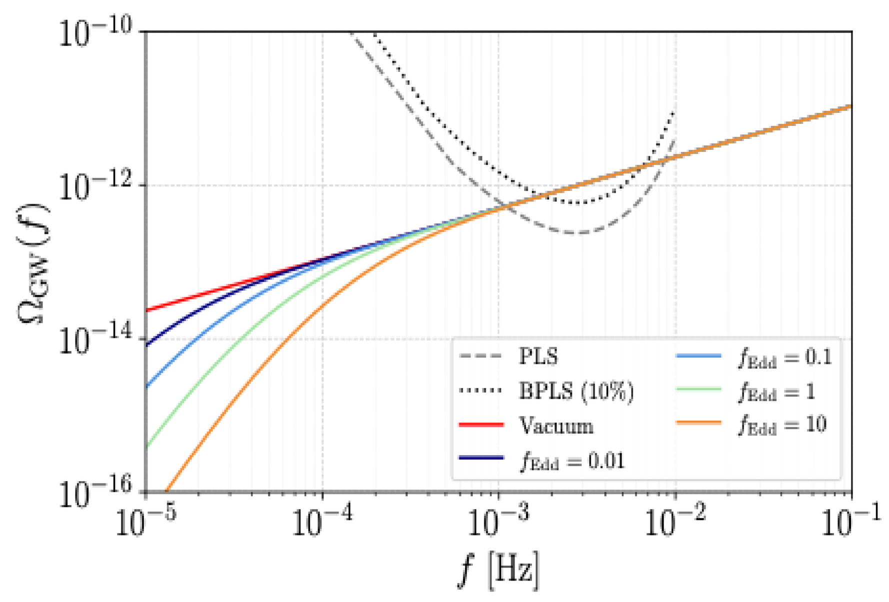
· sBBHs form in gaseous environment (such as accretion disk of AGNs).

· The SGWB is Gaussian, isotropic, Unpolarized, and stationary.

Dynamical friction (-5.5PN)



Eddington accretion (-4PN)



Dynamical friction induces a turning point in the optimally sensitive part of the LISA band, while accretion does not.

Phenomenological parametric

· Rational Power-Law (RPL model)

The RPL model is constructed based on the asymptotic behavior of background spectrum in low and high frequency regimes.

$$\Omega_{\rm RPL} = \frac{A_{\rm vac} f^{\gamma}}{1 + A_{\rm m}\alpha f^{\beta}[\ln(f/1{\rm Hz})]^{\kappa}}$$

Mapping to dynamical friction and accretion:

Parameter	Dynamic Friction	Accretion
α	ρ	$(5+3\xi)\, f_{\rm Edd}/\tau$
β	$-11/3$	$-8/3$
κ	1	0

· Rational Power-Law + Peak (RPLP model)

To improve accuracy of the RPL model at intermediate frequencies, we introduce a Gaussian correction as follows:

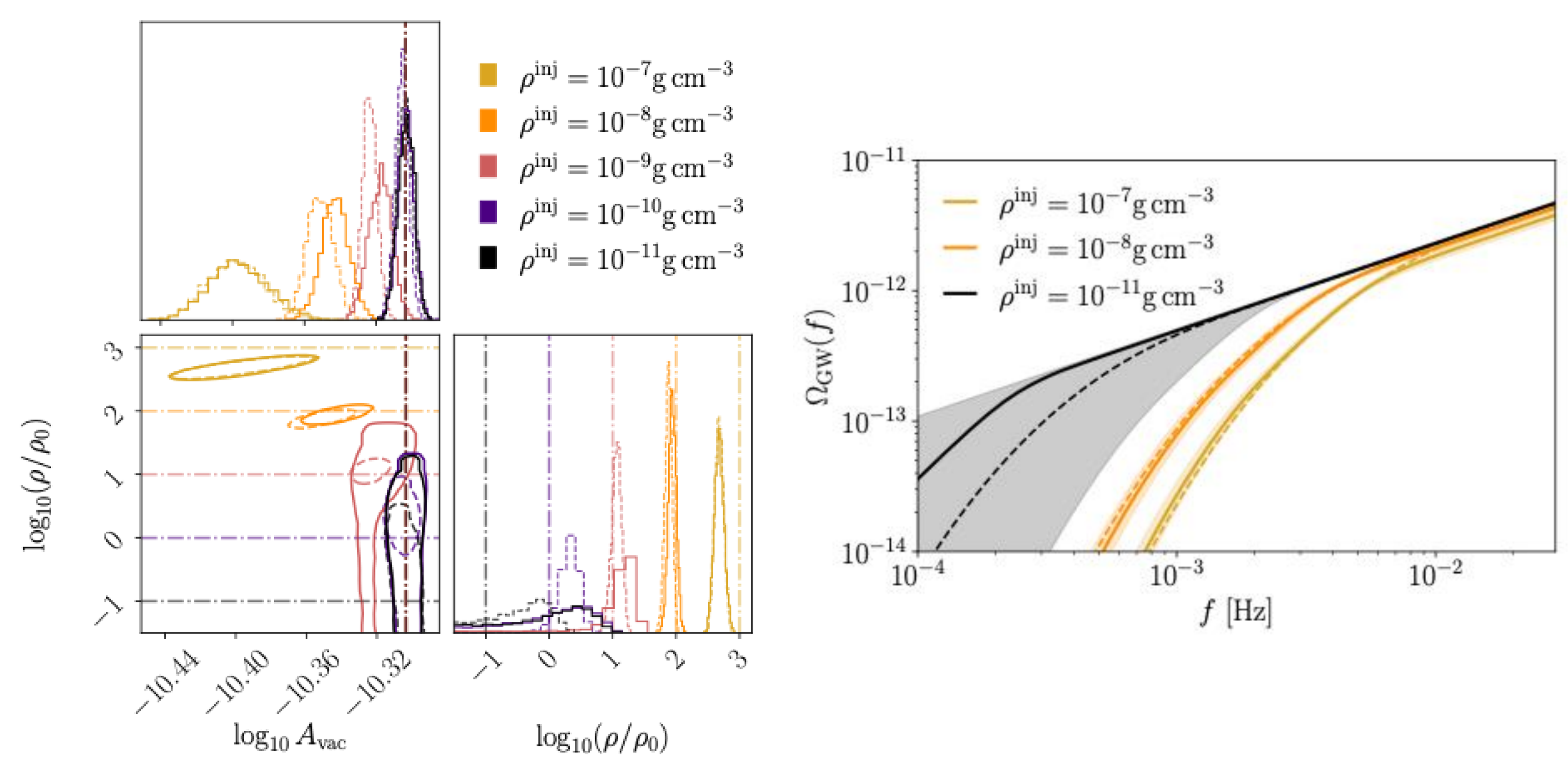
$$\Omega_{\rm RPLP} = \frac{\Omega_{\rm RPL}}{1 + \mathcal{G}(f, \alpha)}$$

Detection and Parameter estimation

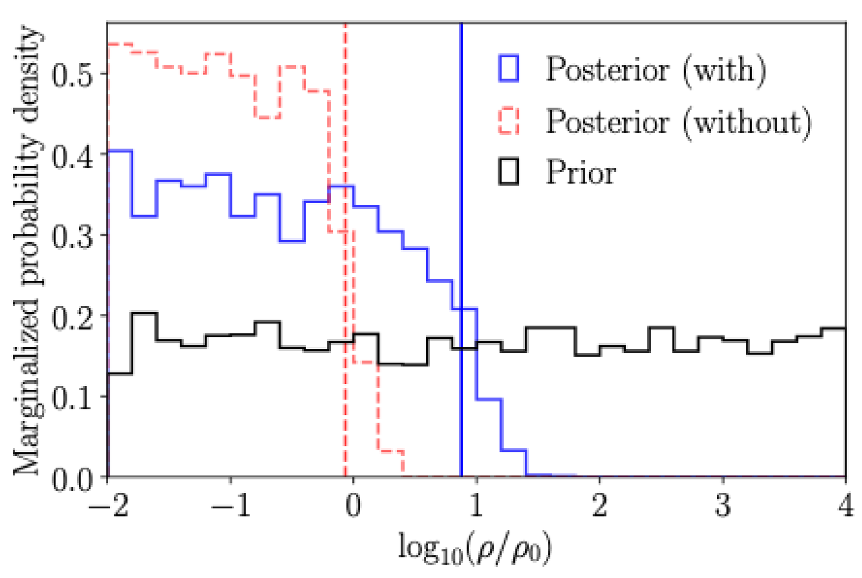
We perform injection–recovery studies to assess the detectability of environmental effects using model templates and the public codebase **Bahamas** [5].

To isolate the impact of the Galactic foreground, we run a separate analysis assuming its parameters are perfectly known.

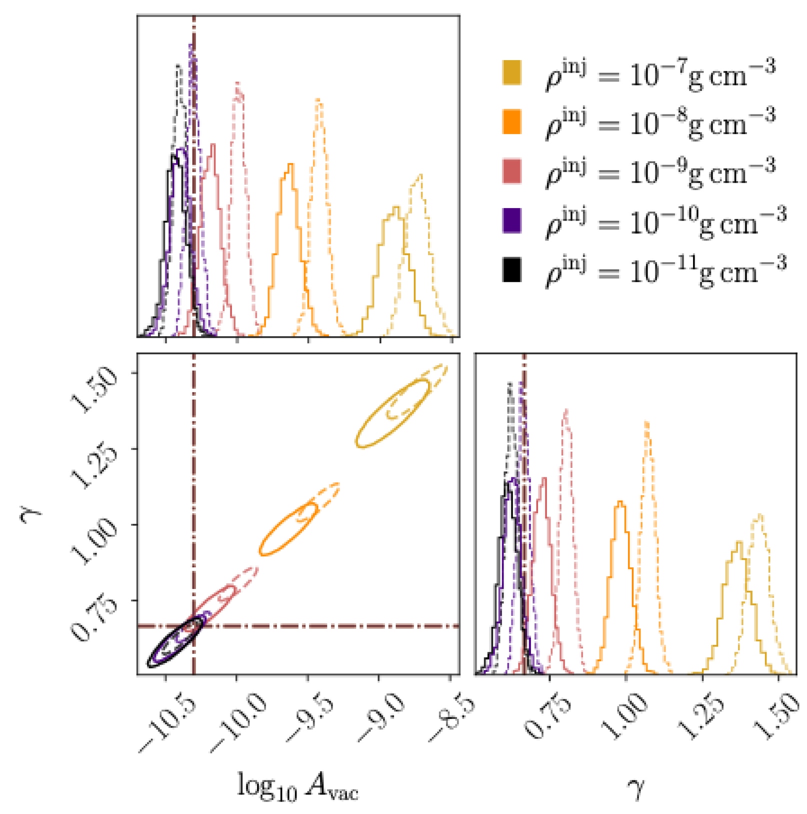
Parameter estimation using RPLP model



Upper bound on density from vacuum SGWB



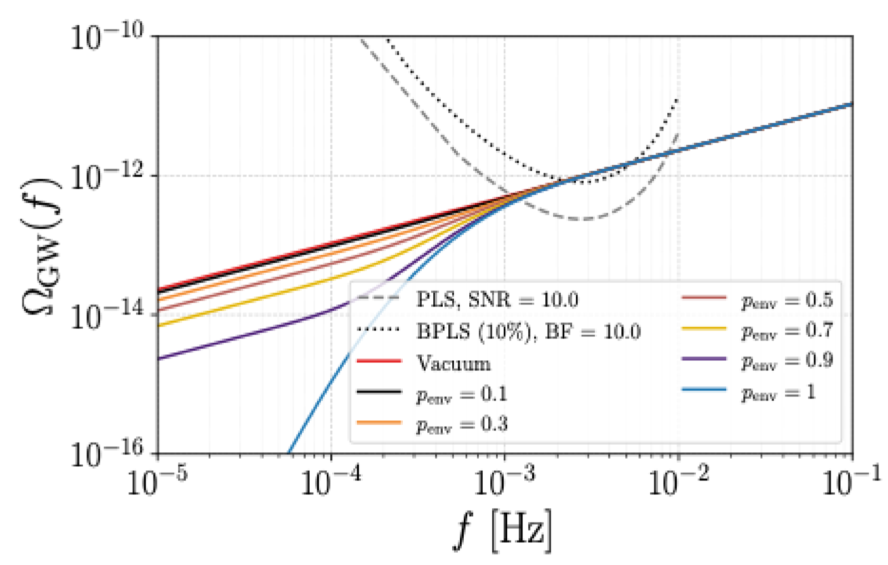
Systematic biases by neglecting environmental effects

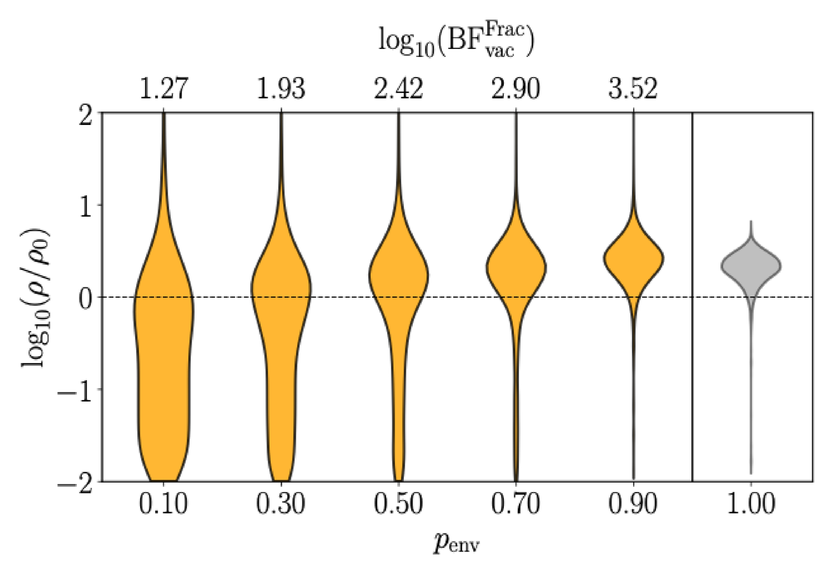


Sub-population investigation

Only a fraction of sBBHs may form in gaseous environments.

A phenomenological mixture model to capture the environmental imprint from this sub-population: $\Omega_{\rm Frac} = p_{\rm env}\Omega_{\rm env} + (1 - p_{\rm env})\Omega_{\rm vacuum}$





Conclusion

· Environmental effects can be modeled with a parametric template and inferred using Bayesian methods in LISA band.

· Dynamical friction is measurable and distinguishable from vacuum for $\rho \sim 10^{-10} - 10^{-9} g/cm^3$, with Bayes factors up to ~60.

· LISA can constrain environmental effects for a sub-population of sBBHs forming in thin accretion disks around AGNs.

References

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