Multi-band gravitational wave cosmology with stellar origin black hole binaries

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December 10, 2021

Laboratoire des 2 Infinis, L2IT Toulouse

IRAP-L2IT Symposium

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4.4σ discrepancy!

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Aim of the project

Provide an independent measure for cosmological parameters

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Cosmological distances

EM waves $\rightarrow$ Standard Candles

- Luminosity distance $F = \frac{L}{4\pi d_L^2}$
- Redshift $z = \frac{\lambda - \lambda_0}{\lambda_0}$

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GWs $\rightarrow$ **Standard Sirens**

- Luminosity distance $A_{gw} \propto \mathcal{M}^{5/3} d_L^{-1} f_{gw}^{2/3}$
- Redshift generally unknown

Probabilistic approach to bypass the unidentified redshift

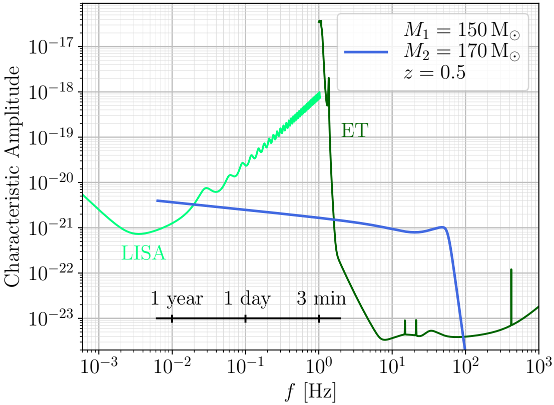
Multi-band approach

Multi-band sources:
Heavy stellar black hole binaries (SBHBs)

Detectors:

1. LISA $\rightarrow \Delta\Omega$
2. ET $\rightarrow \Delta d_L$

Waveform:
IMR PhenomD



Parameter estimation - Fisher Matrix Formalism

The Fisher Matrix is defined as:

$$\Gamma_{ij} = (\partial_i h | \partial_j h)$$

and the Correlation Matrix:

$$\Sigma_{ij} = (\Gamma^{-1})_{ij}$$

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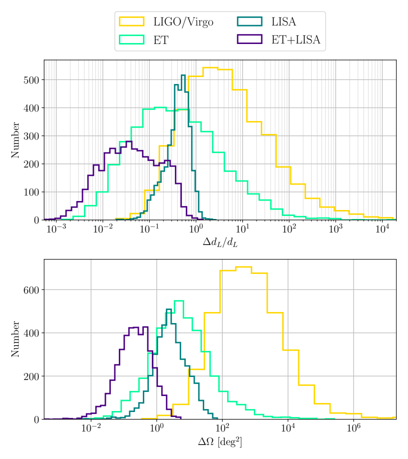
Included parameters

1. Luminosity distance d_L
2. Sky position (θ, ϕ)
3. BH masses M_1 e M_2
4. BH spins χ_1 e χ_2
5. Inclination ι

Errorbox - Construction



$$\Gamma_{\text{ET+LISA}} = \Gamma_{\text{ET}} + \Gamma_{\text{LISA}}$$

$$\downarrow$$

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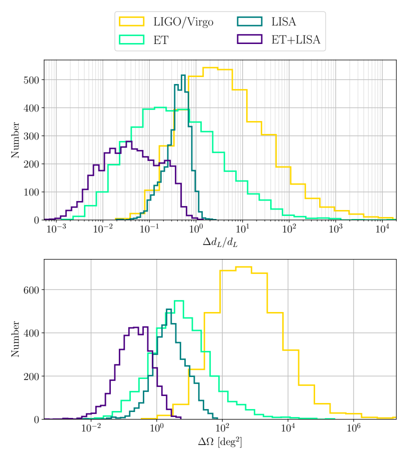

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$$d_L \pm \Delta d_L \rightarrow [z^- - \Delta z_{pv},\ z^+ + \Delta z_{pv}]$$

Errorbox - Peopling from the Millennium simulation

Peopling the error-box

1. We fix a cosmology (i.e. the Millennium one):
    - $H_0 = 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$
    - $\Omega_m = 0.25$
    - $\Omega_\Lambda = 0.75$

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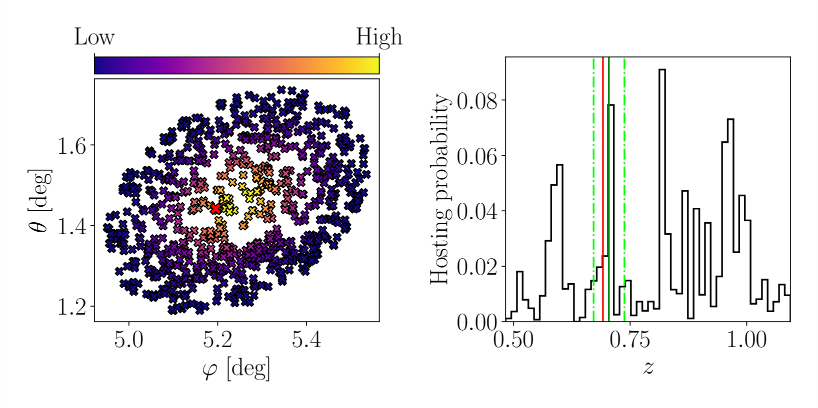
2. We search for galaxies in the $z \pm \Delta z$ consistent with $d_L \pm \Delta d_L$
3. We randomly select a galaxy within this volume and label it as the true host
4. We then consider all the galaxies within the volume defined by

$$\Delta\Omega \times [z^- - \Delta z_{pv}, z^+ + \Delta z_{pv}]$$

Errorbox - Example



Bayesian inference
Prior knowledge on cosmological parameters

We consider the set of cosmological parameters $\mathcal{S} \equiv \{h, \Omega_m\}$, where

$$h = \frac{\mathrm{H}_0}{100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}}.$$

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We assume flat prior distributions:

$$h \in [0.6, 0.86], \qquad \Omega_m \in [0.04, 0.5]$$

We rely on the ***cosmolisa***[5] public software package to infer $\mathcal{S}$.

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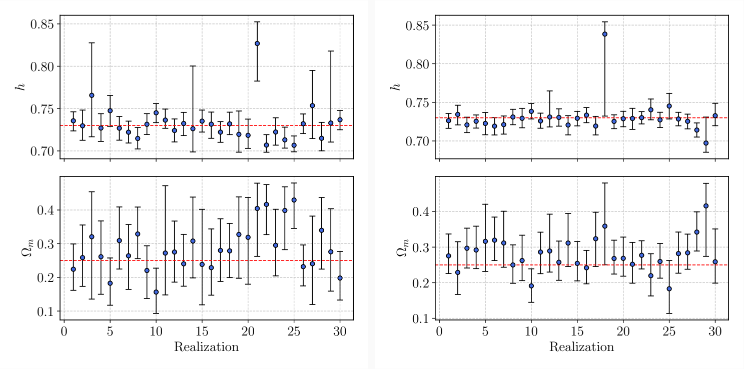
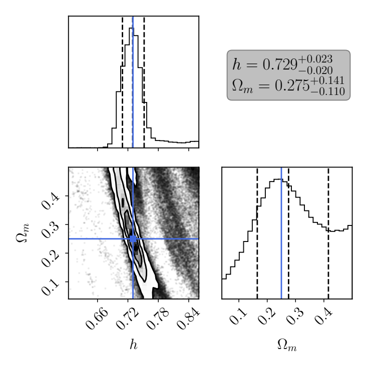
Results

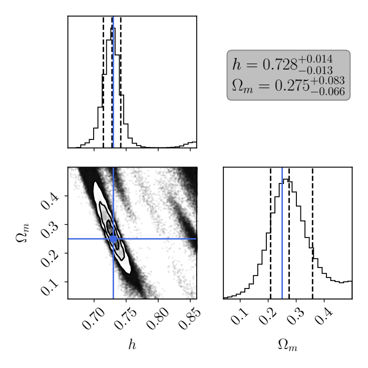
30 independent realizations assuming 4 (left) and 10 (right) years of LISA mission time



Results

Averaged joint posterior distributions assuming 4 (left) and 10 (right) years of LISA mission time





$< \frac{\Delta h}{h} > \simeq 2.9\%$ $< \frac{\Delta h}{h} > \simeq 1.8\%$

Conclusion

Multi-band observations of massive SBHBs can provide great measurements of the cosmological parameters $\mathcal{S}$.

4 **years:**

- $\frac{\Delta h}{h} \simeq 1.6\%$
- $\frac{\Delta \Omega_m}{\Omega_m} \simeq 26.2\%$

10 **years:**

- $\frac{\Delta h}{h} \simeq 1.1\%$
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Future Improvements

1. Likelihood expression
2. Prior shape
3. Design of the simulation

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Thank you for your attention.
Further information on ArXiv: Muttoni et al., 2021

Appendix - Inner product

The inner product is defined as

$$(A|B) = 4\,\mathrm{Re} \int_0^{+\infty} df \, \frac{\tilde{A}^*(f)\tilde{B}(f)}{S_n(f)}$$

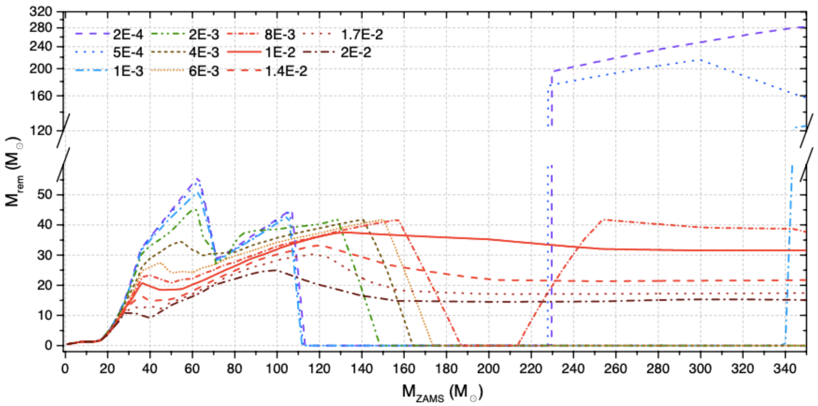
where $S_n(f)$ represents the detector's PSD. In particular, the S/N is given by

$$\left(\frac{S}{N}\right) = (h|h)^{1/2}$$

Appendix - Single GW event likelihood

$$\mathcal{L}(d_i|H) \propto \int_{z_{\min}}^{z_{\max}} dz \, \exp\left[-\frac{1}{2}\left(\frac{d_L(z,\mathcal{S}) - \langle d_L \rangle}{\sigma_{d_L}}\right)^2\right] \times$$
$$\times \sum_{j=1}^{K} w_j \exp\left[-\frac{1}{2}\left(\frac{z_j - z}{\sigma_{pv}}\right)^2\right]$$

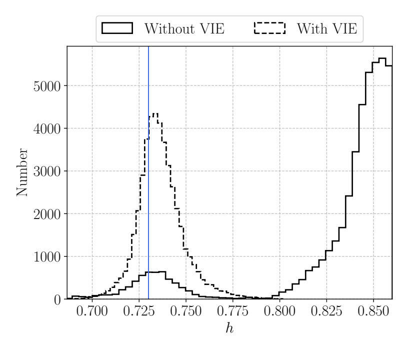
Appendix - Above-gap SBHBs (Spera and Mapelli, 2017)



Meaning of the second mode

Two tests to assess the meaning of the bimodal distribution:

1. Add a Very Informative Event (VIE) to the problematic realizations



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2. Repeat the inference with different prior bounds