The landscape of MBH spectroscopy with LISA and the ET

Phys.Rev.D 105 (2022) 12, 124063
e-print: 2201.00023

Costantino Pacilio, with E. Barausse, S. Bhagwat, P. Pani

costantino.pacilio@uniroma1.it

GR 23 — JULY 6 2022

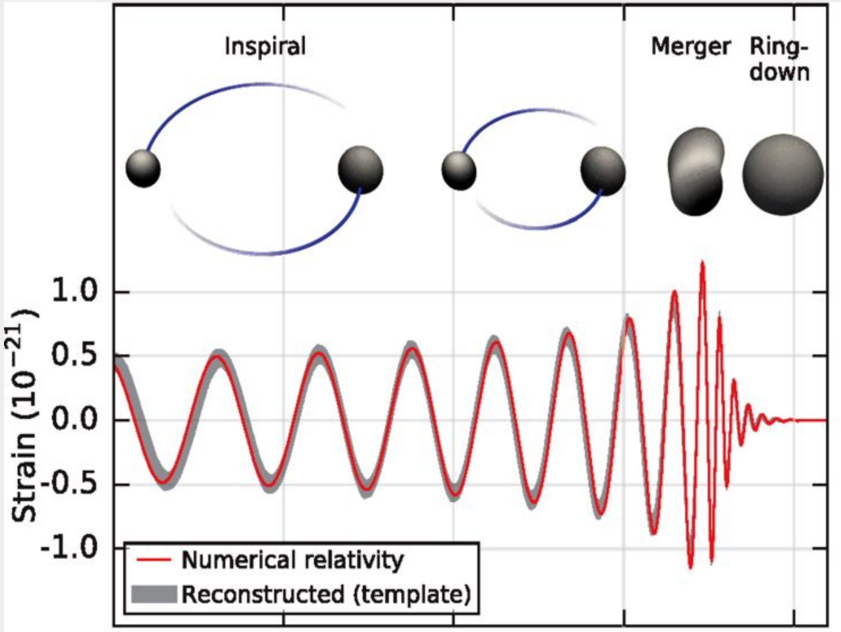
What is a black hole ringdown

Black hole ringdown is the signal that originates from a distorted black hole

It consists of a superimposition of quasi-normal modes

It is a good description at intermediate times after the merger of two black holes

$$h \sim \sum_{lmn} A_{lmn} e^{-t/\tau_{lmn}} e^{-i2\pi f_{lmn} t}$$



GW150914 https://arxiv.org/abs/1602.03837

BH uniqueness

Presently accepted facts

GR is the correct theory of gravitation

BHs settle down to the Kerr metric at equilibrium after they form

Consequences

1. BH perturbation theory is governed by Teukolsky's equation
2. The QNM spectrum of oscillations depends only on the mass and spin of the BH

Teukolsky (1410.2130)

BH spectroscopy

Main idea:

You have an infinite tower of QNMs but they only depend on two independent parameters (mass and spin)

You can test mutual consistency among the QNMs, i.e. that they all lie on the same codim-2 surface in the space of the QNMs

Dreyer et al. (gr-qc/0309007)

In practice …

QNMs are countably infinite and indexed by (l,m,n) indices: angular l, azimuthal m, overtone n, *Berti et al.* (0905.2975)

$$\omega_{lmn} = 2\pi f_{lmn} - i/\tau_{lmn}$$

The fundamental mode is (2,2,0)

Only a subset of subdominant modes is measurable for reasonable SNRs, the loudest candidates being typically (3,3,0), (2,1,0), (4,4,0)

Kamaretsos et al. (*1107.0854*)

Practical route to BH spectroscopy:

1. Use the dominant (2,2,0) frequency and damping time to invert for mass and spin
2. Map mass and spin into the frequencies and damping times of the measurable subdominant modes
3. Check consistency between predictions and measurements for the subdominant modes

You need to measure *at least* three frequencies/damping times

Kamaretsos et al.
Gossan et al. (1111.5819)

Requirements for BH spectroscopy

Resolvability You must be able to discriminate frequencies OR damping times of two distinct QNMs

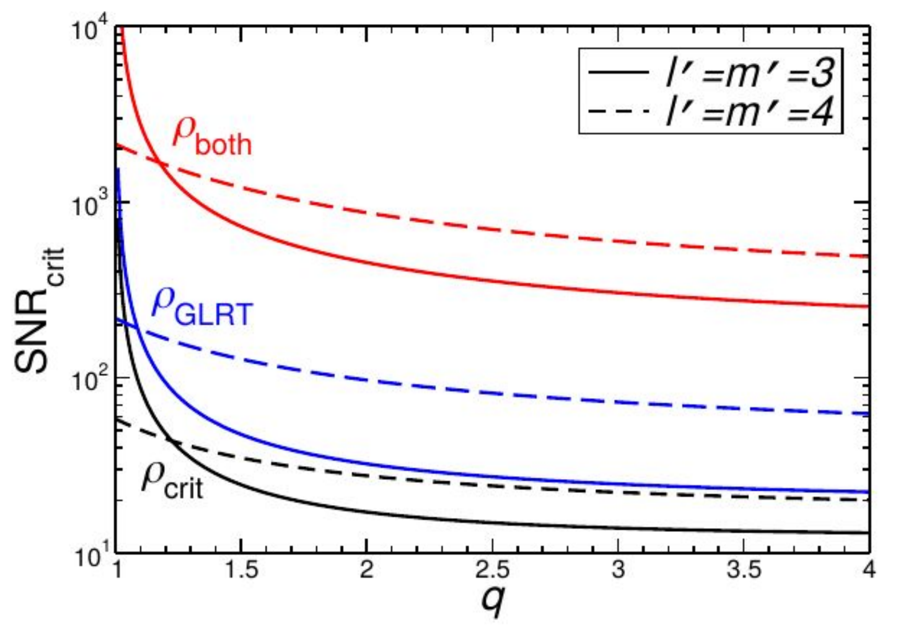
$$\frac{\max(\sigma_{f_1},\ \sigma_{f_2})}{|f_1 - f_2|} < 1$$

$$\frac{\max(\sigma_{\tau_1}, \sigma_{\tau_2})}{|\tau_1 - \tau_2|} < 1$$

GRLT criterion Resolvability of the amplitudes of the subdominant QNMs from noise

Berti et al. (gr-qc/0512160)
Berti et al. (0707.1202)

Criteria translate to minimum SNRs



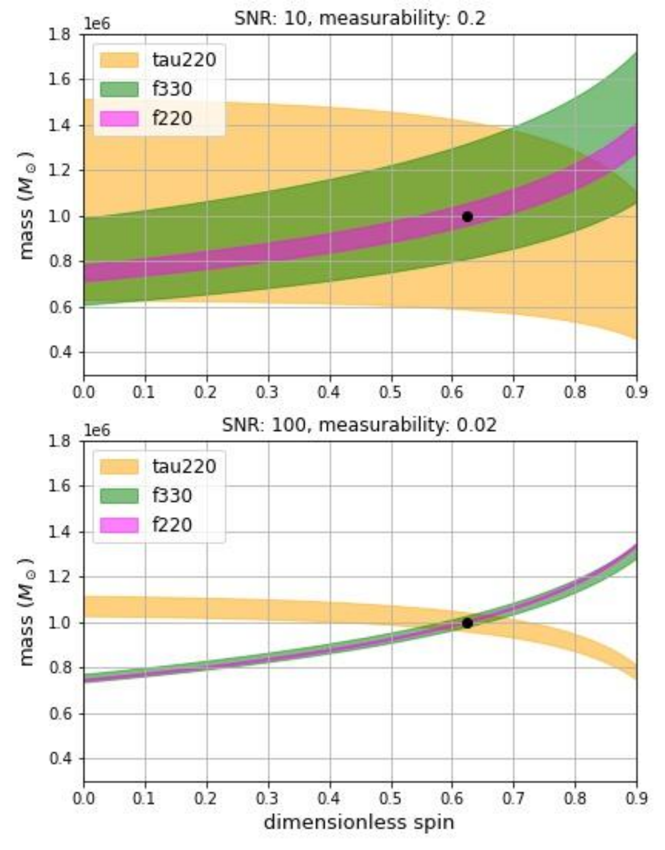
Requirements for BH spectroscopy

Measurability Maximum fractional uncertainty over the frequencies and damping times

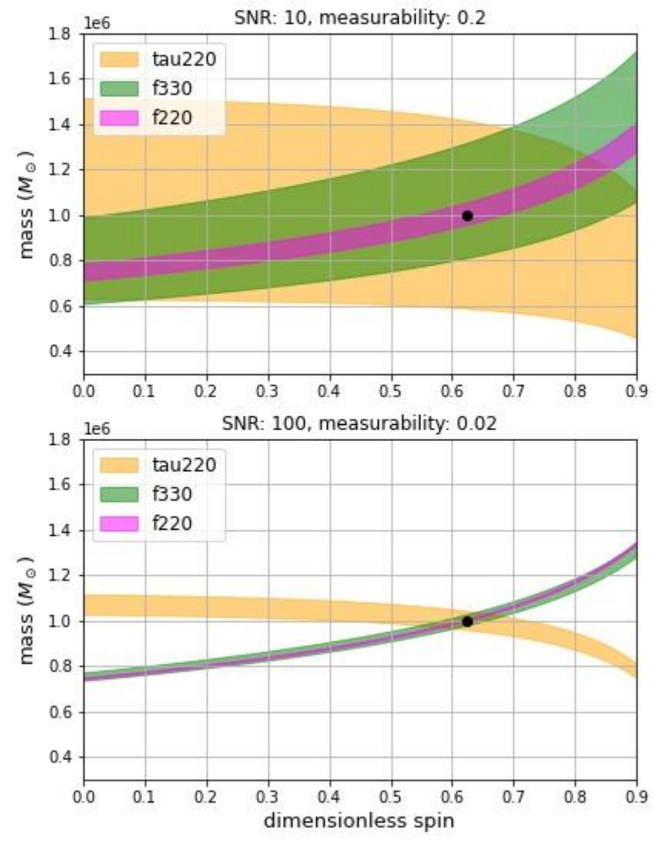
$$\max\left\{ \delta f_i / f_i ,\ \delta\tau_i / \tau_i \right.$$
$$\left. \text{for} \quad i = (2,2,0), (3,3,0), \text{etc.} \right\}$$

Bhagwat et al. (1910.08708)

If fractional uncertainties are large enough, you can accommodate GR but also modified QNMs from non-GR perturbations and/or non-Kerr background



Methodological detour: Fisher formalism



We compute errors on frequencies and damping times with a numerical code based on the Fisher approach in Berti et al. (gr-qc/0512160)

Amplitudes and phases are treated as independent variables

The SNR and covariance matrix are averaged over sky position and inclination angle

Relative excitations of the subdominant modes w.r.t. (2,2,0) are modelled following Baibhav et al. (1710.02156)

Why populations matter

As far as ringdown is concerned, a population model provides distributions for:

- Total number of events
- Detector-frame masses
- Mass-ratios
- Luminosity distances
- Spins of the progenitors

All these factors impact

- The total SNR
- The value of the dominant ringing frequency

Population model for MBHs

MHBs population is presently uncertain

We use a population model tracks the evolution of MBHs in their galactic hosts and the formation of MBH binaries

Main ingredients to bracket uncertainties:

1. Light seeds vs Heavy seeds
2. Supernova feedback vs *no-SN*
3. *Delays* vs *short-Delays*: delay between merger of galaxies and their MBHs

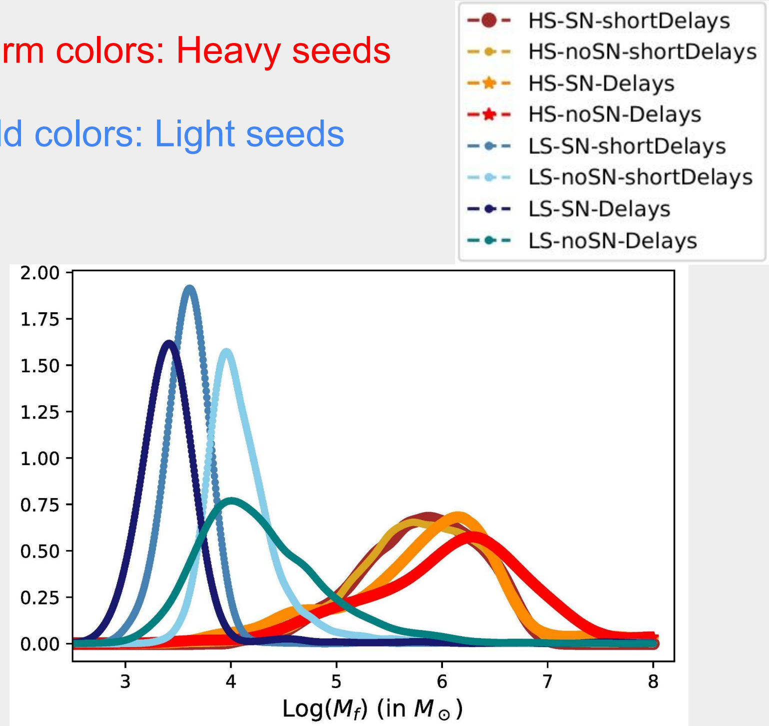
Barausse (1201.5888)

Barausse & Lapi (2011.01994)

Light seeds vs Heavy seeds

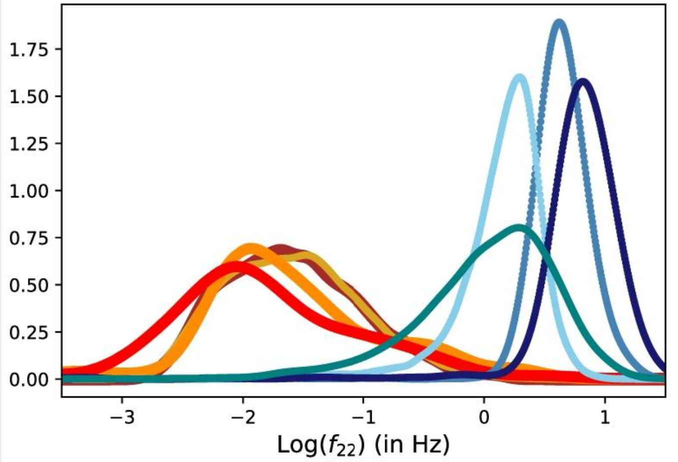
Warm colors: Heavy seeds

Cold colors: Light seeds



Heavy seeds are optimal for being detected by Lisa

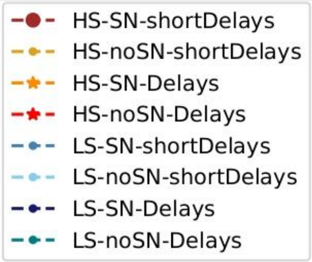
Light seeds can be (marginally) detected in the low frequency band of ET



Light seeds vs Heavy seeds

Warm colors: Heavy seeds

Cold colors: Light seeds



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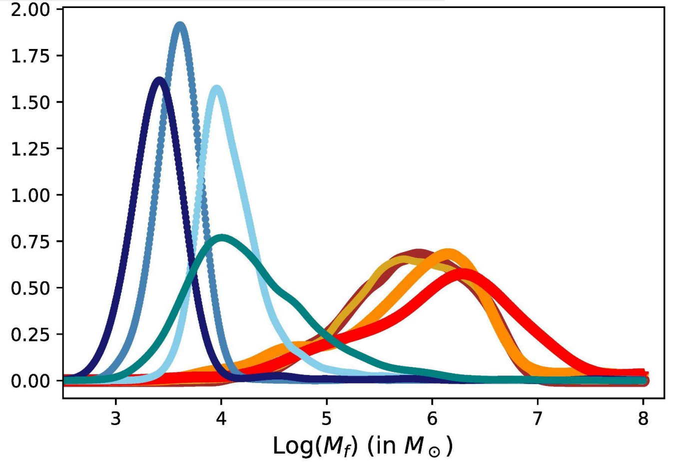
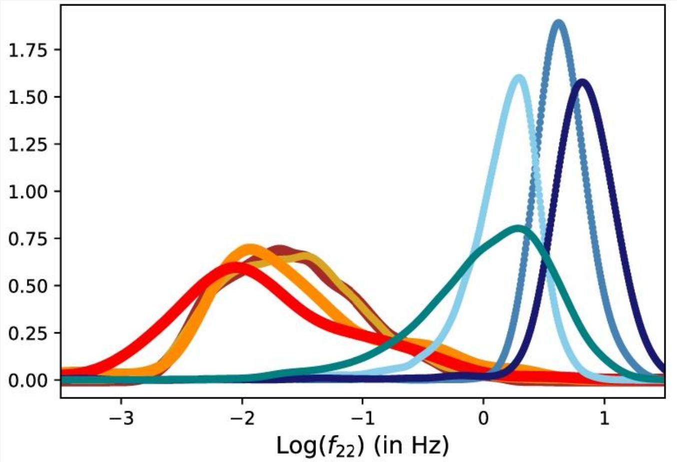




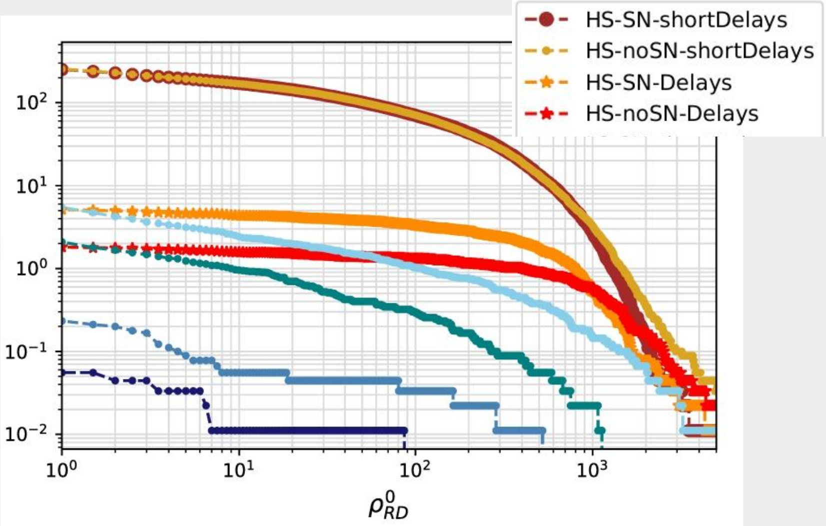
Hereafter I focus mainly on heavy seeds

Intrinsic rate vs Cumulative SNR of events

Intrinsic rate of BBH events

POPULATION MODEL	BBH EVENTS PER YEAR
SN Delays	~ 6
no-SN Delays	~ 2.5
SN short-Delays	~ 317
no-SN short-Delays	~ 322

Cumulative SNR of events per year



- *Delays*: most event have SNR O(1000)
- *short-Delays*: SNR spreads across [1,1000]

Measurability of HS with LISA

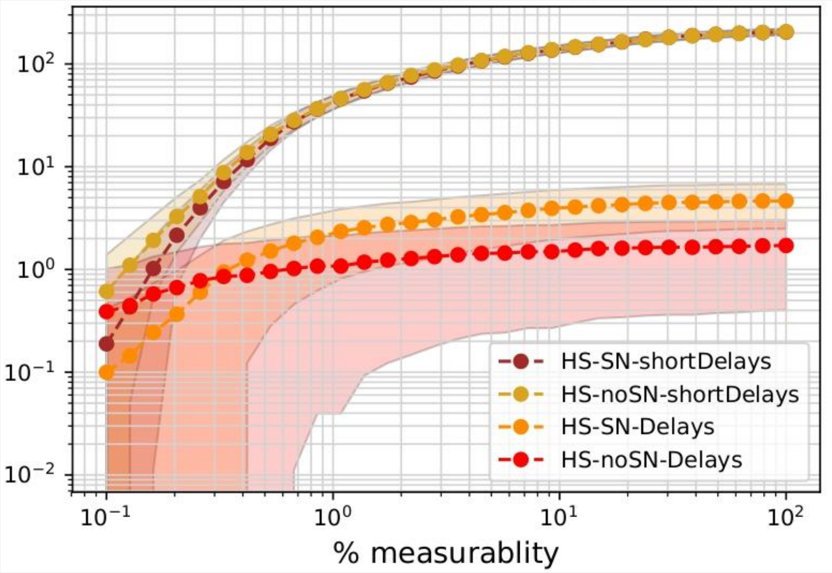
We require that:

1. at least one triplet of frequencies and/or damping times is measured
2. distinct frequencies/damping times are resolvable from each other

We select the triplet with the best measurability

Average over 100 realizations of 1 yr

Cumulative measurability of events per year



Measurability of HS with LISA

NOTE

For low measurability you require high SNR.

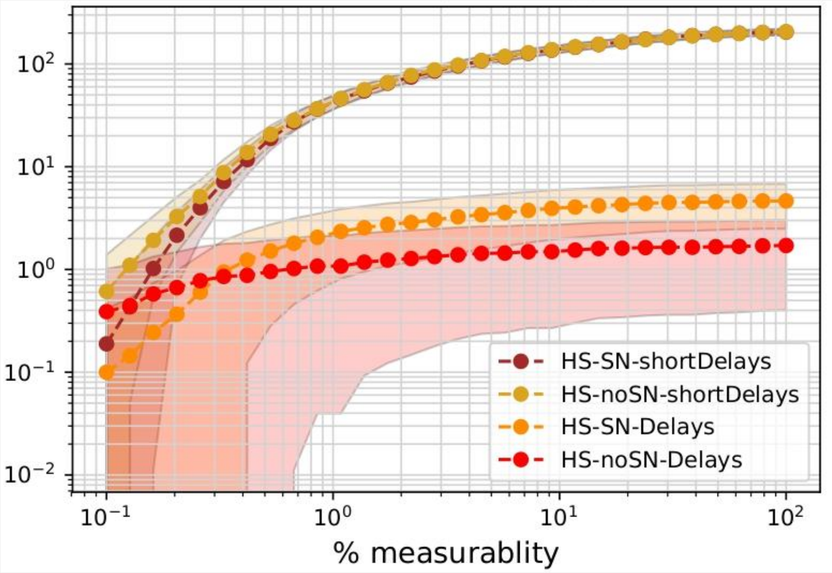
Only few events with O(0.1%) because:

1. *Delays* models have few intrinsic events all with high SNR
2. *short-Delays* models have many intrinsic events but only few at high SNR

TAKE AT HOME (1)

The ability of LISA to perform MBH spectroscopy with individual events is restricted to O(1%) measurability

Cumulative measurability of events per year



Measurability of HS with LISA

You might want to use stacking to improve your constraining power

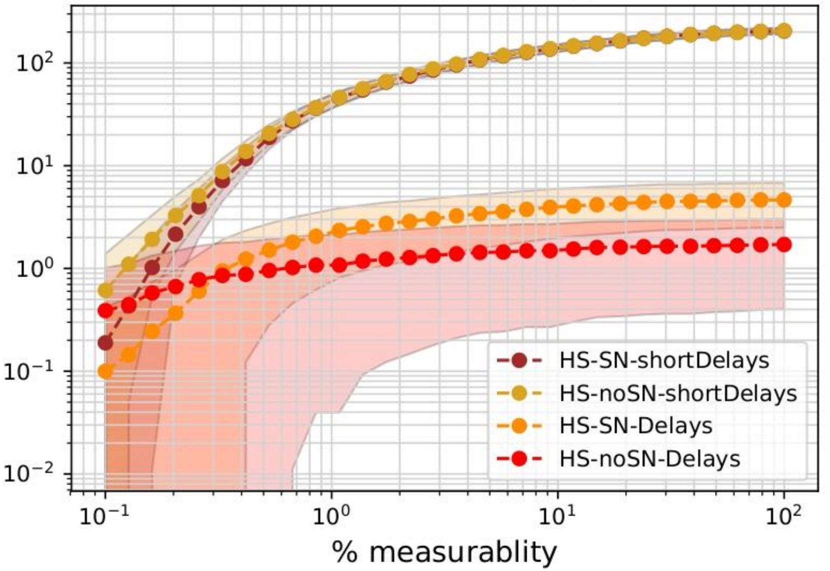
However … Events are not many!

TAKE AT HOME (2)

Stacking of BH spectroscopy events with LISA is limited by the number of useful events per year even in the most favorable case.

In the optimistic scenarios, you can stack O(1%) measurements to reach O(0.1%) stacked measurability

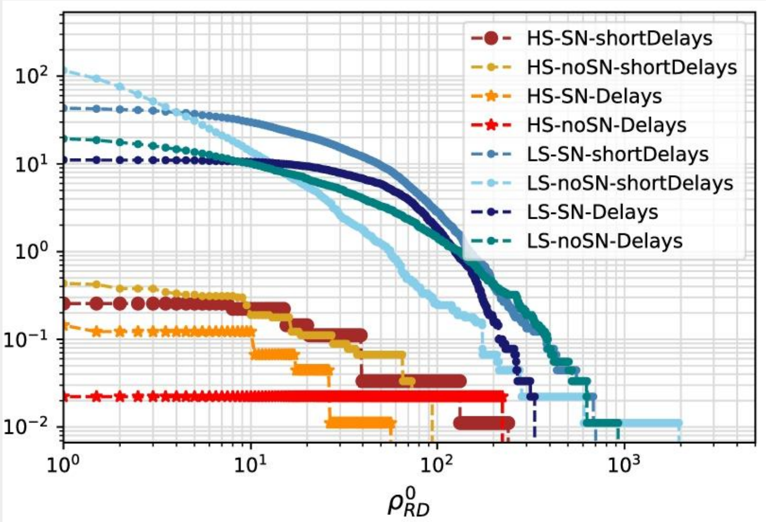
Cumulative measurability of events per year



Light Seeds with the Einstein Telescope

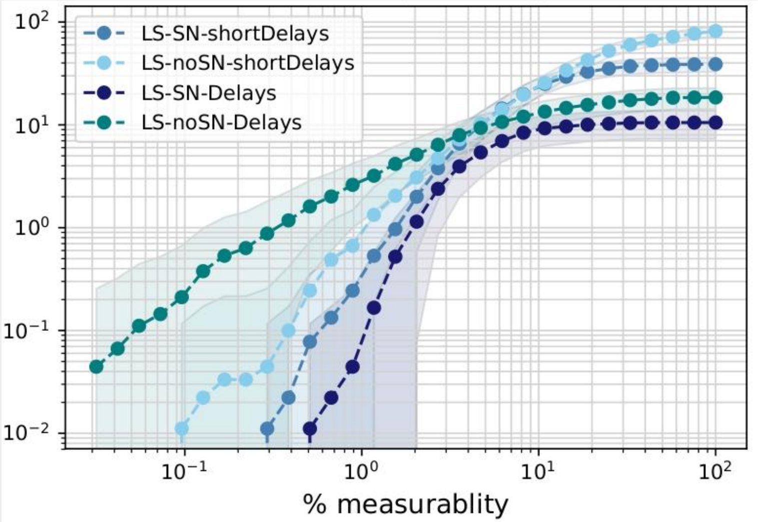
Cumulative SNR of events per year

We might have events with SNR ~100



Cumulative measurability of events per year

Only O(10%) is possible for individual events



Conclusions

- MBH spectroscopy with LISA has the potential to perform tests at O(1%) measurability for individual events and O(0.1%) measurability for stacked events, in the most favorable cases (*HS short-Delays*)

- In the least favorable cases (*HS Delays*) LISA is limited by O(1%) even after stacking is considered

- The ET has the potential to detect a fraction of light seeds MBHs with O(10%) measurability for most individual events

- It is possible (if not expectable) that both light seeds and heavy seeds exist, therefore the two scenarios are not mutually exclusive

- If light seeds exist, best prospect for MBH spectroscopy would result from light seeds detected by a deci-Hz detector (e.g. DECIGO)

THANK YOU!