Analysis of stellar-mass binaries in LISA data

10 years to LISA | Jet Propulsion Laboratory

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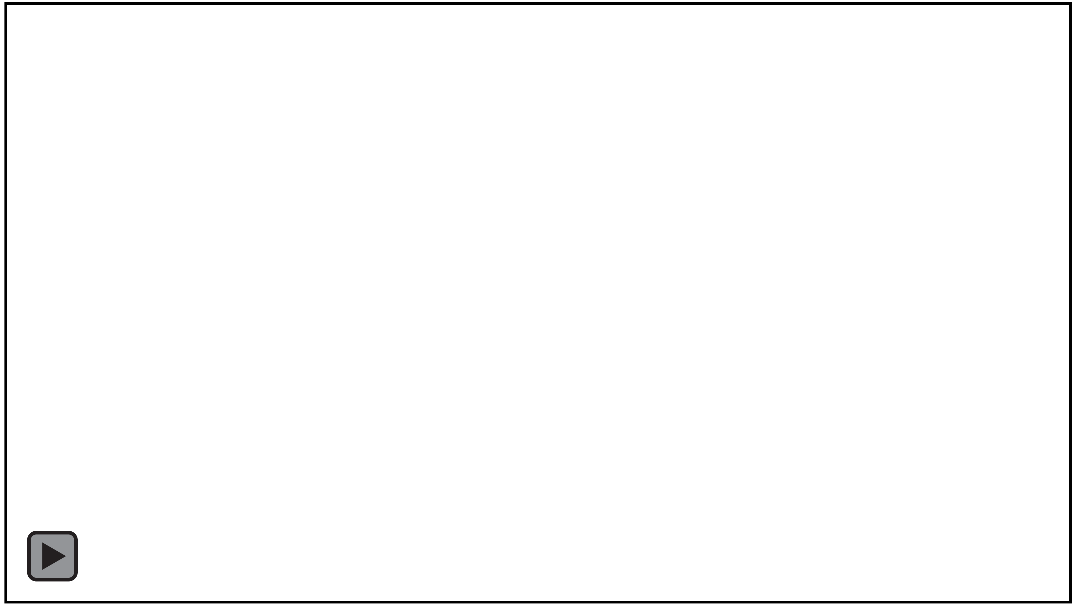
LVK binaries in their inspiral

Overview of sources

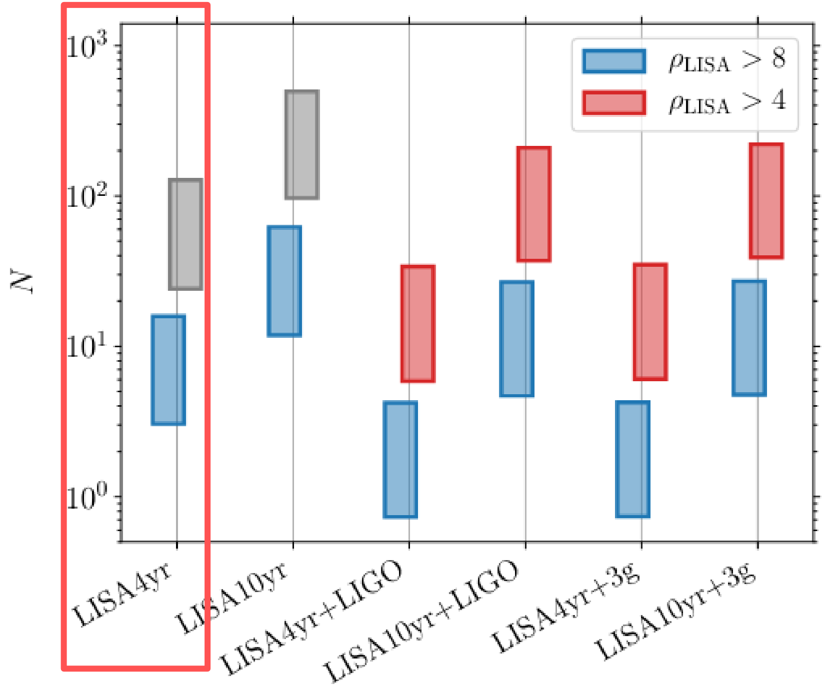
- Focusing on sources with chirp mass 5-100 solar masses.
- Stellar mass inspirals signals can chirp from 10^{-2} to 10^{-1} Hz.
- Qausi-monochromatic at low frequencies (10^{-3} Hz) and low masses.
- Exits the LISA frequency band usually months to weeks before merger.



Event rates

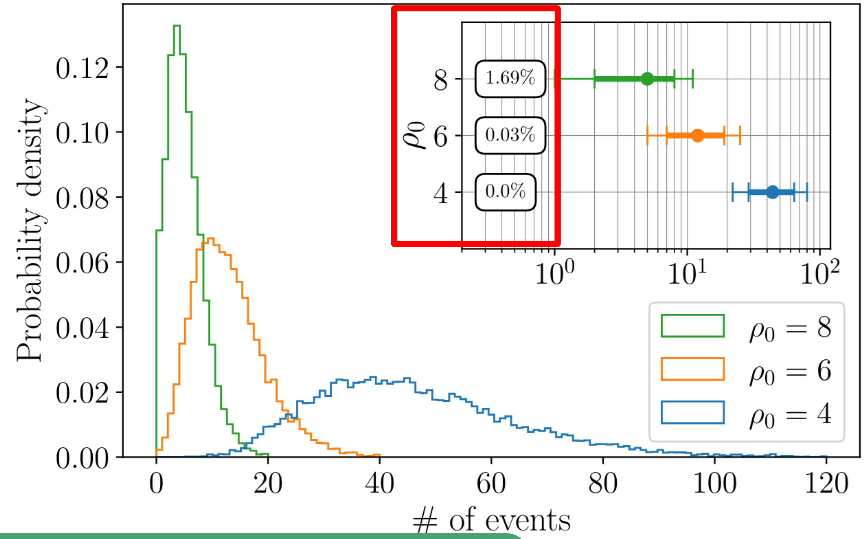
Multiband: **0-4** (ρ>8)
Total: **3-12** (ρ>8)

GWTC-1



Gerosa et al, 2019, arXiv:1902.0002

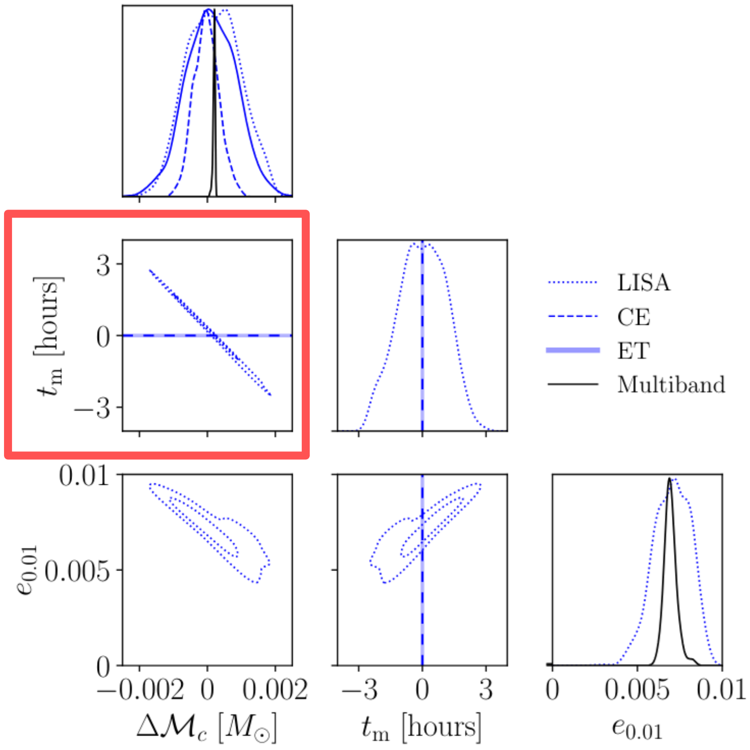
GWTC-3



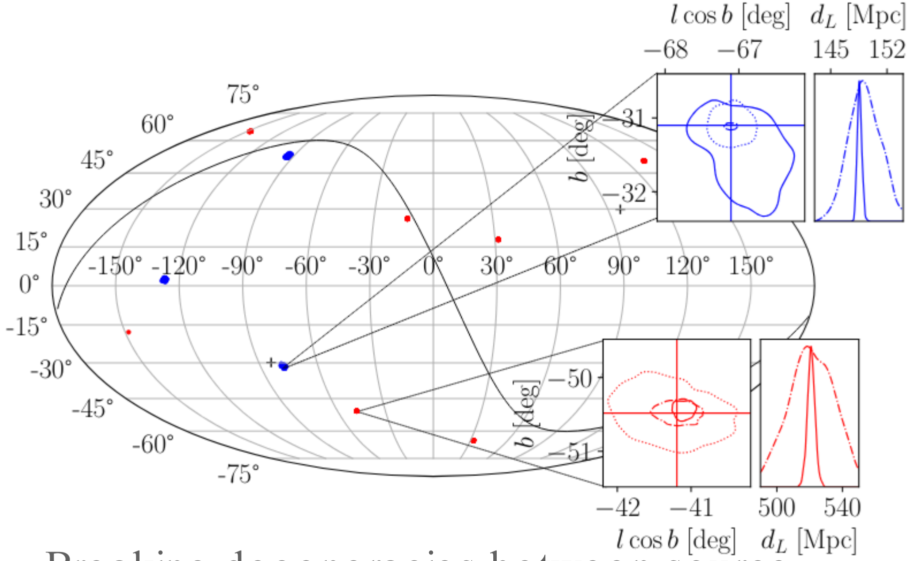
Multiband: **1-2** (ρ>8) **5-30** (ρ>4)
Total: **5** (ρ>8) **>20** (ρ>4)

Buscicchio et al, 2024, arXiv:2410.18171

Multiband observations



Klein et al, 2022, arXiv:2204.03423



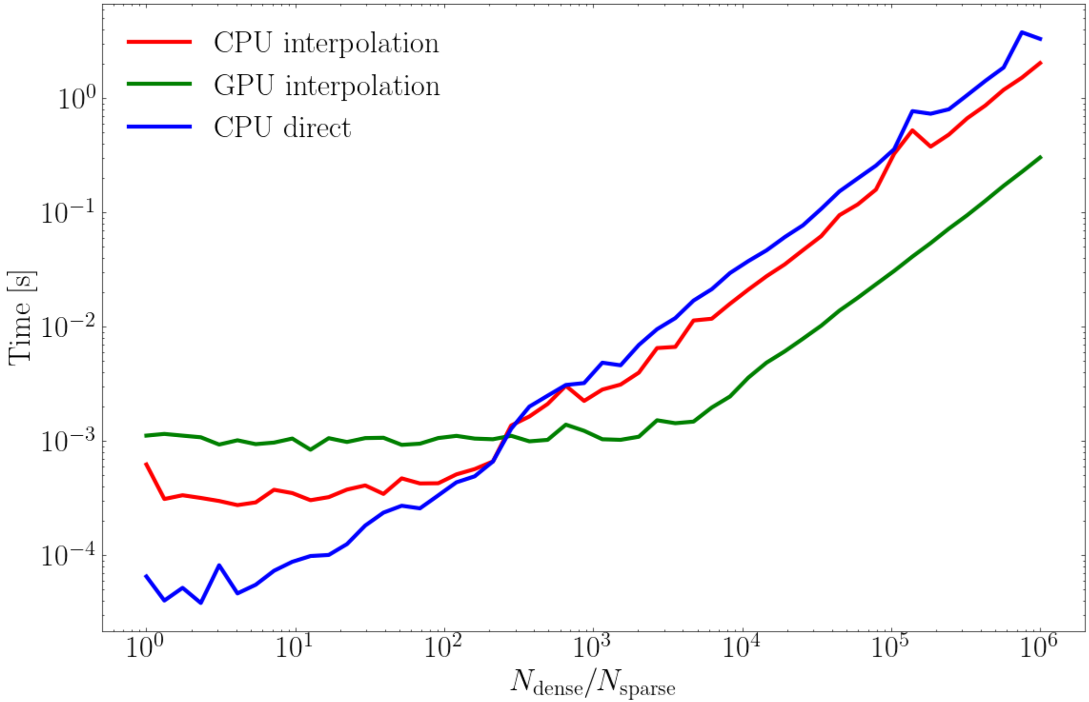
- Breaking degeneracies between source parameter in the posterior.
- Breaks multi-modality in sky position of 3G observations.
- Combining 3G distance precision, small localisation volume. Between 1 - 100 Mpc^3. Ideal as dark sirens (Muttoni et al, arXiv:2109.13934).

Practical cost of high frequency broadband sources

- Mission lifetime of at least 4 years, leads to a Fast-Fourier transform (FFT) grid with spacing 10^{-8} Hz, with $O(10^7)$ points. Both GW waveform and LISA instrument response needs to be computed over this grid.
- Why does this not affect MBHB analyses ?
  - MBHB merger signals are in the datastream for a much shorter timescale, i.e. small datastream →frequency spacing is larger.
  - Maximum GW frequency around 10^{-3} Hz, so the data can be downsampled significantly. Leads to an FFT grid of size $O(10^5)$ in the worst case.
- Why does this not affect DWD analyses?
  - Quasi-monochromatic narrowband source, only need small chunk of the full FFT grid with size $O(10^2 - 10^3)$.

Solutions?

- Interpolation in amplitude and phase!
  - Both amplitude and phase are **smooth functions** (of frequency and time). **Easy to interpolate!**
  - We need a device that is particularly good at interpolating onto a huge number of points: **GPUs**.
- Can also be applied to the instrument response!



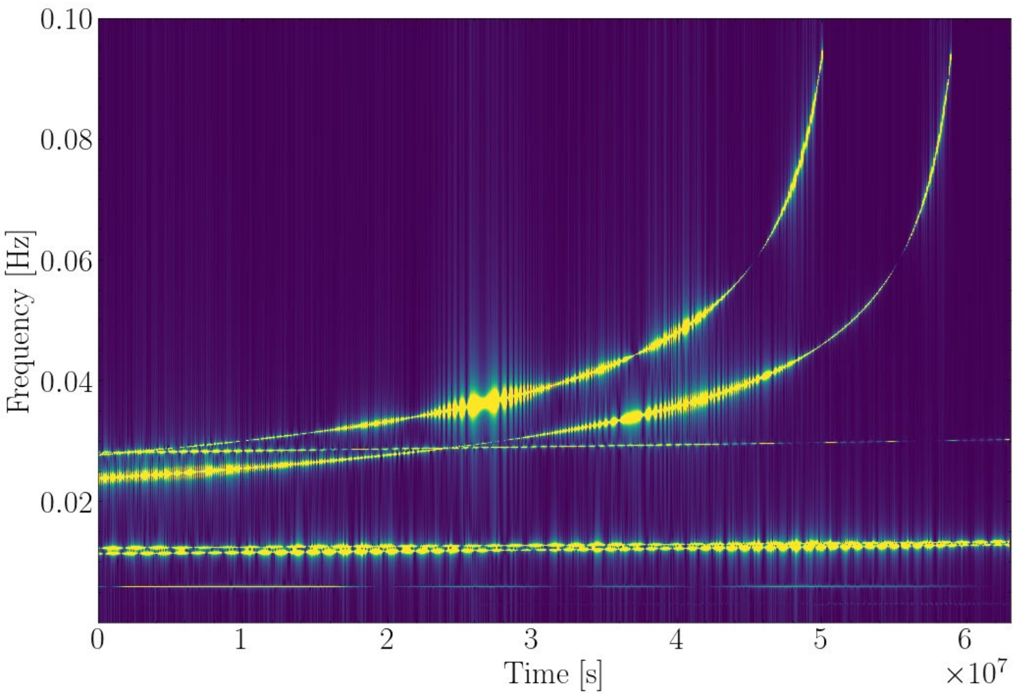
Similar approach is also often followed for Massive black hole binary analyses, see Katz et al, 2020, arXiv:2005.01827.

Generated on google collab for a simple sinusoidal test function, if we made the function more complicated the difference between the curves in the right of the plot would be more pronounced.

Solutions?

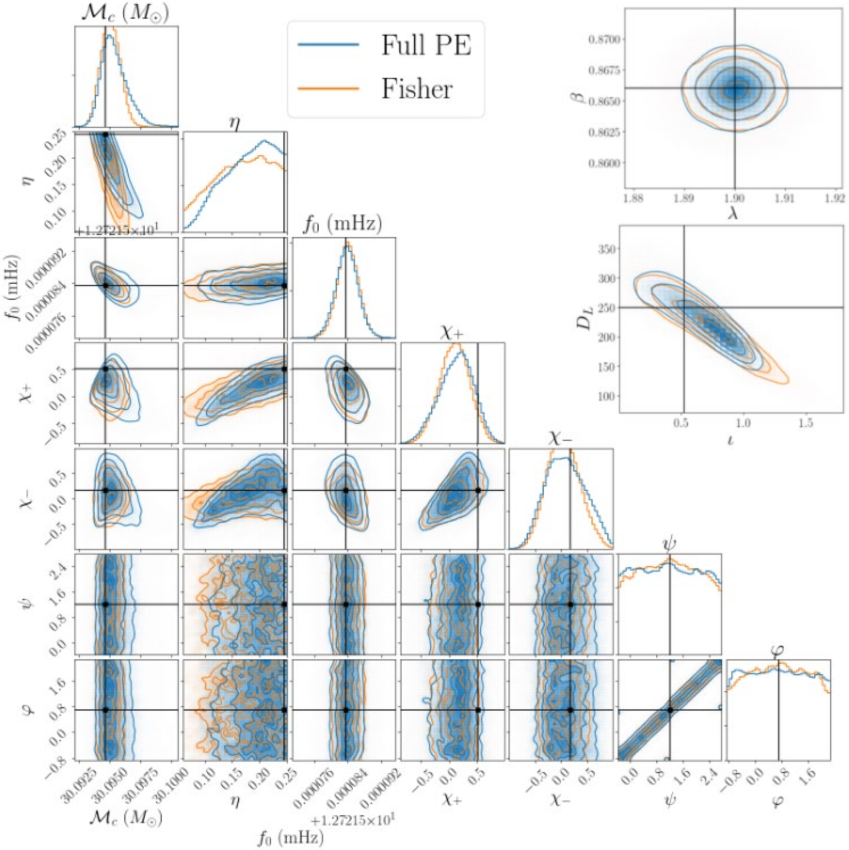
- Time-frequency instead of frequency
  - Stellar mass binary inspirals can be compactly represented in the wavelet/time-frequency domain.
  - Instead of $O(10^7)$ points in the FFT grid, the time-frequency grid contains $O(10^4)$ points (Digman et al, 2022, arXiv:2212:04600).
- Also more robust method for more complicated noise properties.

Elements of these two solutions can be combined!



Noiseless spectrogram for sources within the Yorsh LISA data challenge, will be discussed in more detail in later slides.

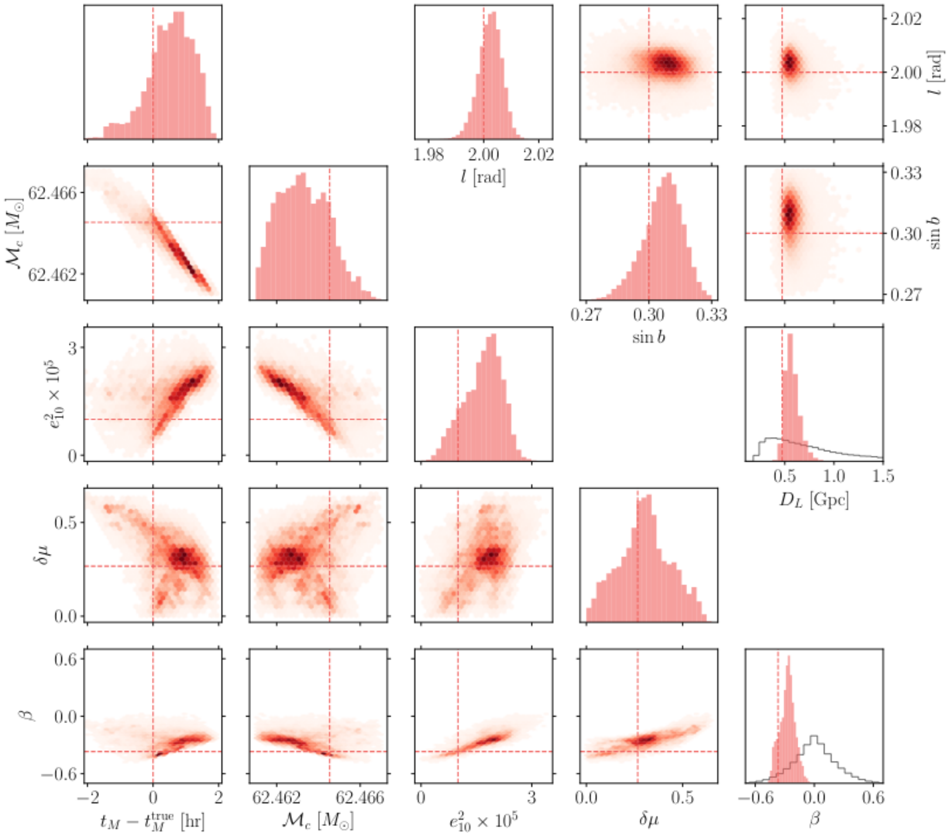
Parameter estimation



- Spin-aligned PhenomD waveform.
- Compared the use of the long wavelength instrument response to the full LISA instrument response.
- Considered the impact of a 4 vs 10 year LISA mission lifetime.
- Interpolated waveform and instrument response.
- Noiseless.

Toubiana et al, 2021, arxiv:2007.08544

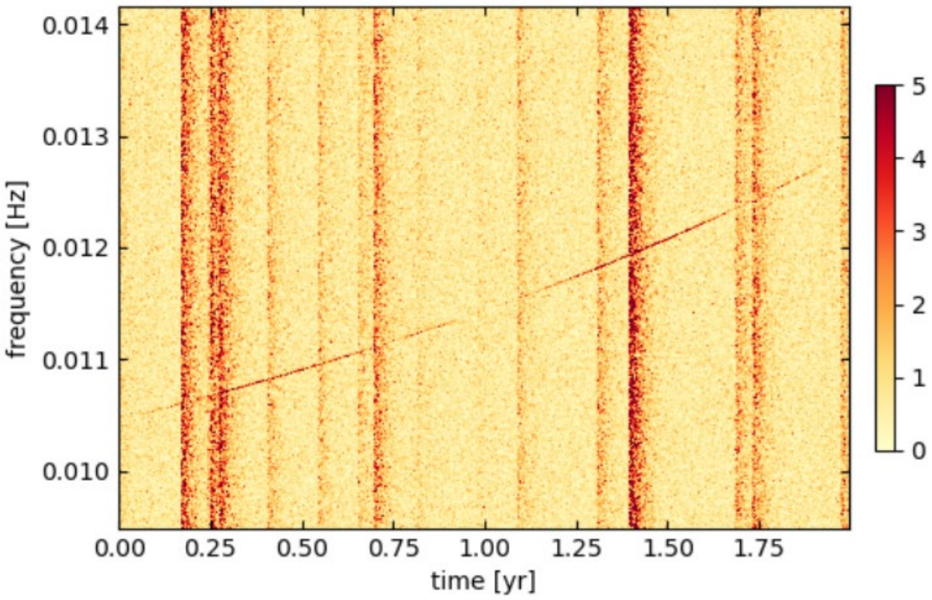
Parameter estimation



- Eccentric, spin aligned inspiral waveform.
- Uses Clenshaw-Curtis quadrature integration to approximate the likelihood.
- Noiseless.

Buscicchio et al, 2021, arXiv:2106.05259

Parameter estimation



- Time-frequency approach to the likelihood.
- Capable of dealing with non-stationary noise.
- $O(10^4)$ points over which waveform and response are evaluated, leads to cost of likelihood at $O(10^{-3})$ seconds.

Digman et al, 2022, arXiv:2212:04600

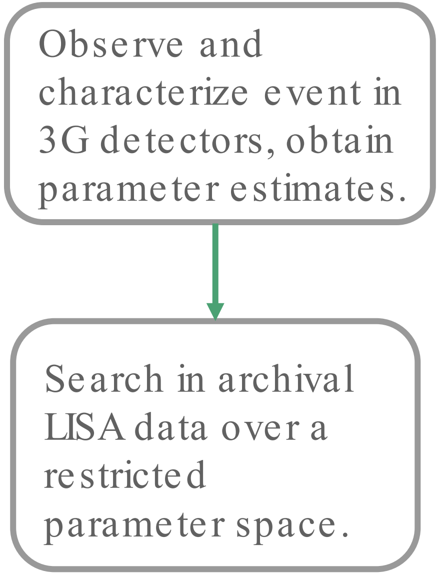
Search

- Current LVK searches for BHB mergers use $O(10^4\text{-}10^5)$ templates to search for the merger signals of these sources.
- Using a similar process to search the whole astrophysically reasonable parameter space for stellar mass binaries would need around 10^{41} templates (Moore et al, 2019, arXiv:1905.11998).
- Can either approach this problem with an archival search *(reduces the search space)* or a blind semi-coherent search *(trades lower computational expense for lower sensitivity)*.

Continuous wave-like problem

Archival search

- Archival searches can probe down to around SNR 4 (Wong et al, 2018, arxiv:1808.08247), likely much quieter than any blind search can reach. The quiet inspirals will very likely have to be handled by the archival search.
- See talk later by Shichao for a nice discussion of how this method will help us extract the low SNR signals that LISA will observe!
- The inclusion of eccentricity in the signals significantly increases the search cost (Han et al, 2023, arxiv:2304.10340).



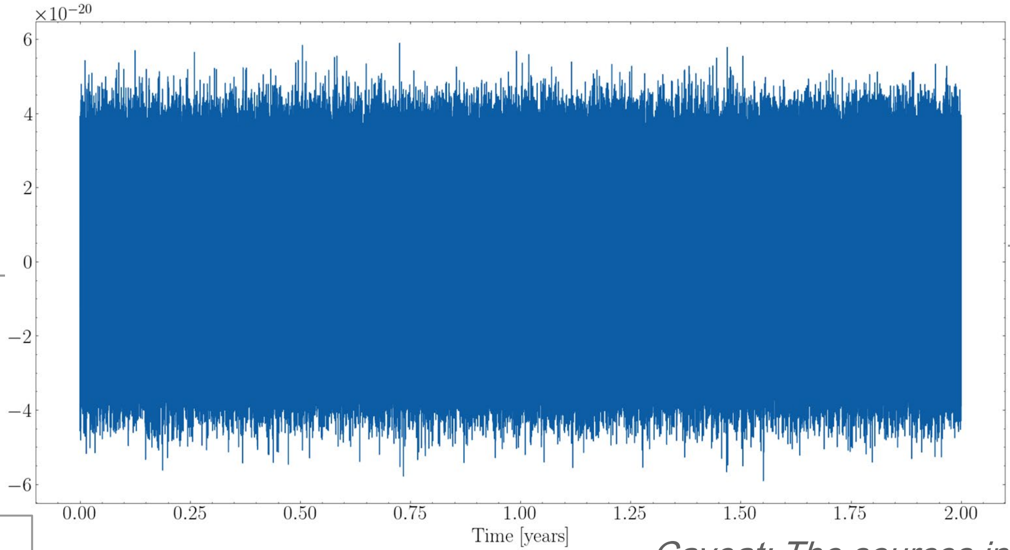
Blind (LISA only) search

- Early warning to both GW and EM observatories:
  - Time to merger estimates with constraints of **O(hours)**.
  - Sky localisation, down to **1 deg^2** in some cases. Helpful for electromagnetic observations!
- Informing maintenance windows for LVK/3G detectors.
- Early warnings for some of these multiband events can be **years ahead**!
- There can also be sources which are not multiband sources but still have $\rho>8$. Close by sources which are very mildly chirping.

The test bench: LISA data challenge ‘Yorsh’

8 simulated stellar mass binary signals

Realization of “realistic” noise time-series (includes unresolvable DWD forest)



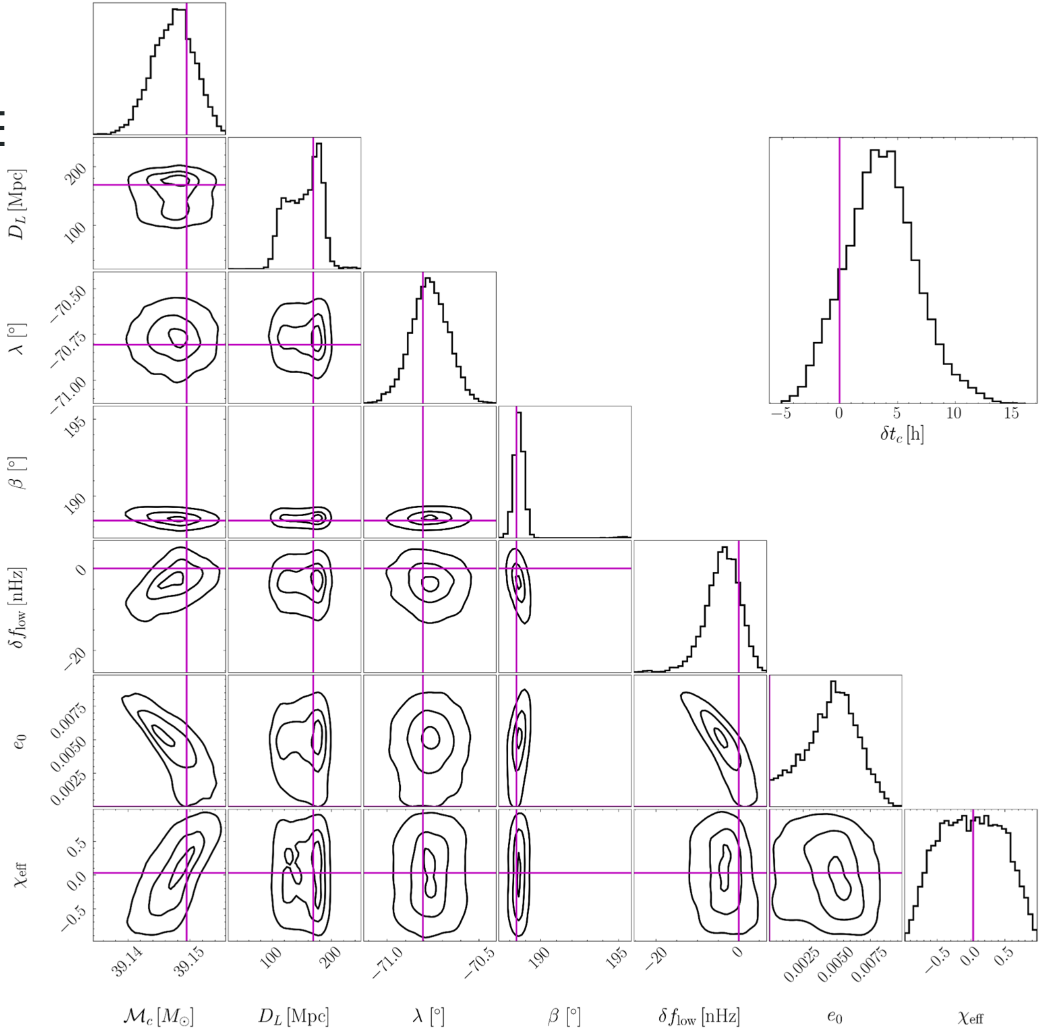
Search!

Caveat: The sources in Yorsh are not drawn from a ‘realistic’ population, but are rather cherry-picked by the LDC group to test analysis pipelines.

Semi-coherent blind search

Simplified Yorsh search seeded PE

- Search **seeded** parameter estimation.
- 1 deg^2 sky area.
- 10 hour posterior in time of merger.
- 4 out of 8 binaries in the data found (one example binary shown).
- **All this can be done upto 6 years before the binary merger is observed in the ground based detectors!** *(for this particular source)*

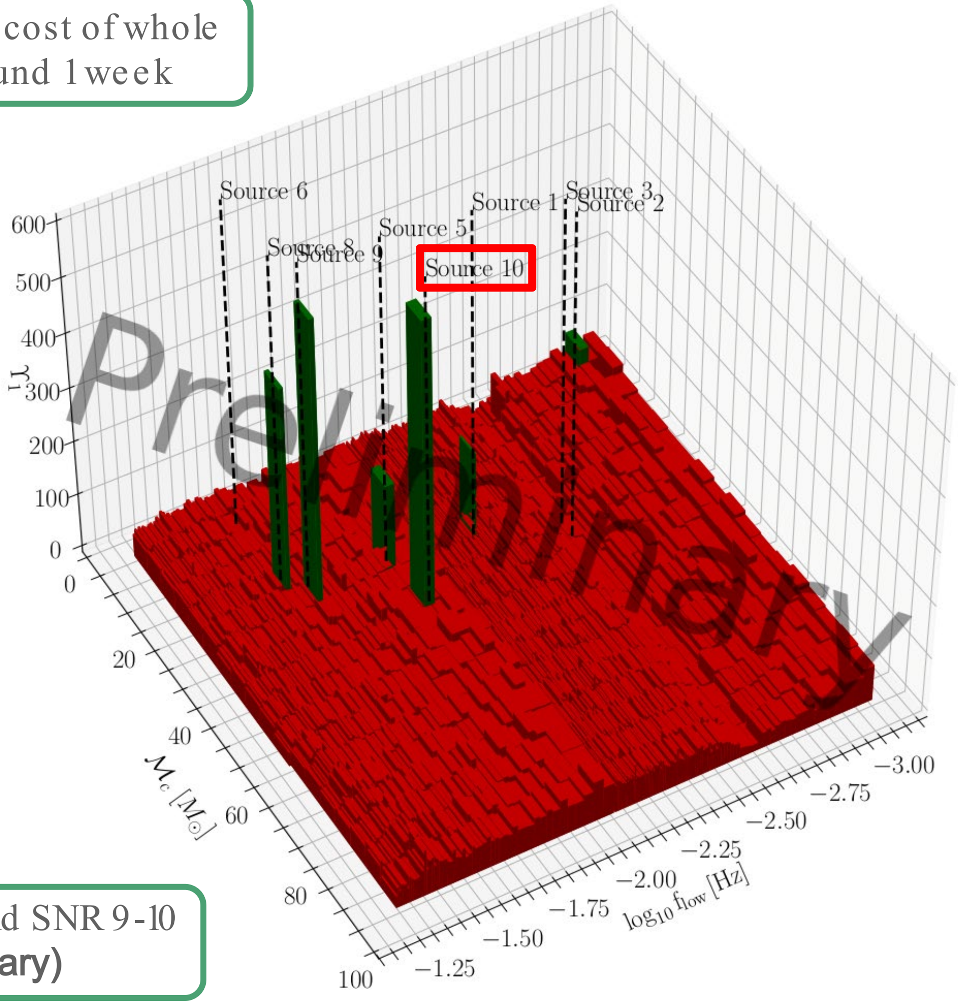


Bandopadhyay et al, 2024, arXiv:2412.10501

Yorsh 'full' search

(Unoptimized) cost of whole search around 1 week

- Injection (by LISA data challenge group):
  - Waveform: PhenomD
  - Response computed using LDC code + PyTDI
- Search (Independent pipeline):
  - Waveform: TaylorF2Ecc
  - Custom implementation of 0 order frequency domain response.
  - Using a time-frequency method, close to what will be described in Rodrigo's talk later using short fourier transforms!
  - Search statistic (likelihood) cost: O(10) **microseconds**.



Current threshold SNR 9-10 (Preliminary)

In prep

Connections to EMRI search

- Searching for an stellar mass binary inspiral GW signal is *kind of* like searching for one harmonic in an extreme mass ratio inspiral (EMRI).
- Common property between EMRI and stellar mass binary inspirals: incredibly compact posterior, even more compact for EMRIs.
- **If you want to be able to solve the EMRI search, you probably need something that can solve the stellar mass search first, as it is a simpler version of the same problem!**

Conclusions

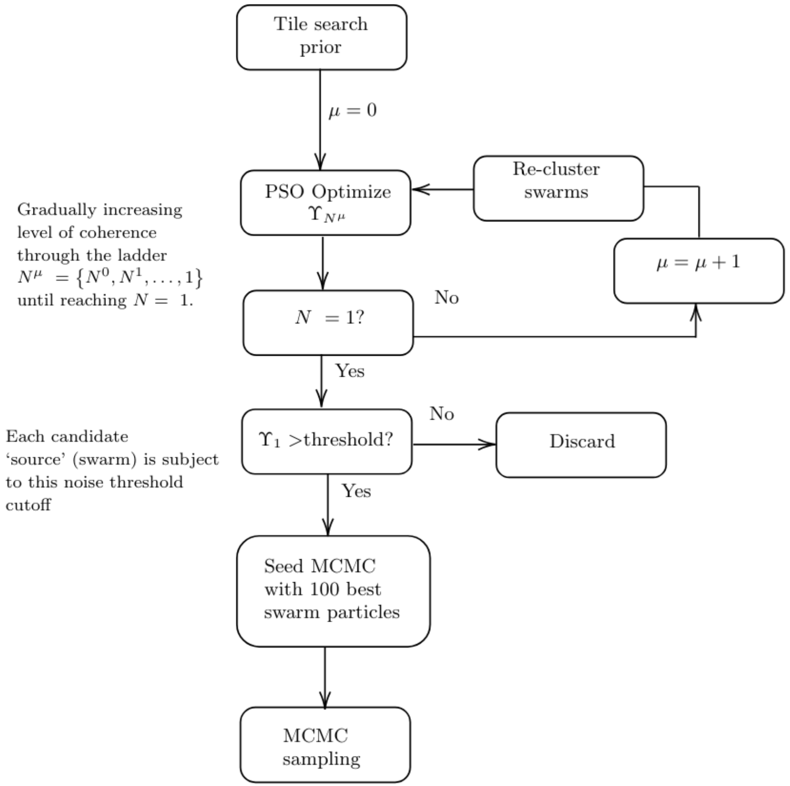
- We may get at least 1 multiband signal that can be detected by a blind search with associated early warning.
- Handful of stellar mass sources expected to be detected by archival searches from 3G observations.
- Things left to think about:
  - Need to start including gaps in the datastream, to make analysis more robust.
  - Data challenges should start containing eccentric signals.
  - Better characterization of the false alarm probability/FAR.
  - Archival search on 'Yorsh' dataset to ensure we can detect the quieter sources.
  - Translating this to the EMRI search.

Any questions?

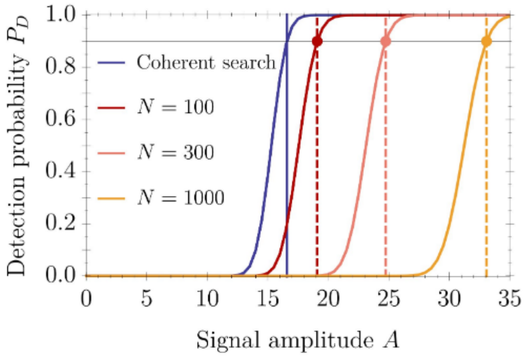
Not a realistic population! Max SNR sources from many catalog realisations from Buscicchio et al, 2024, arXiv:2410.18171

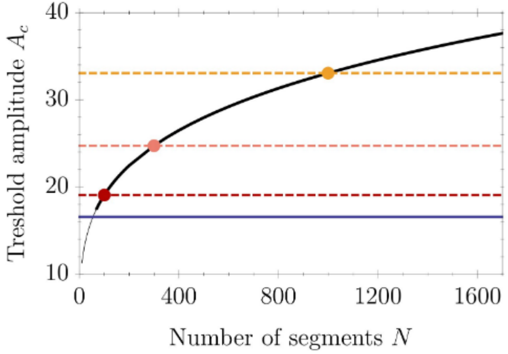
Extra slides

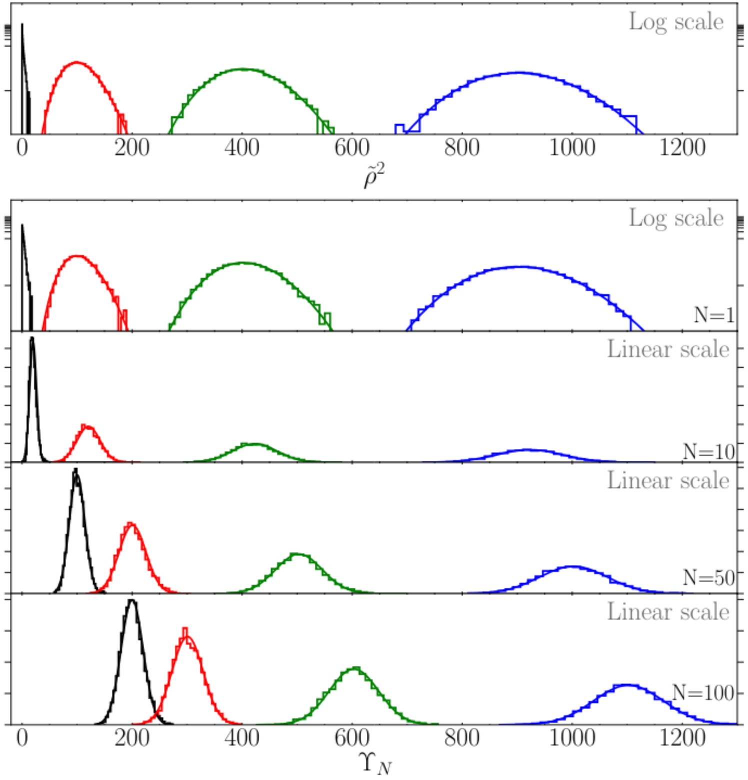
Blind search structure



What is the sensitivity cost you pay for introducing extra parameters and maximising?

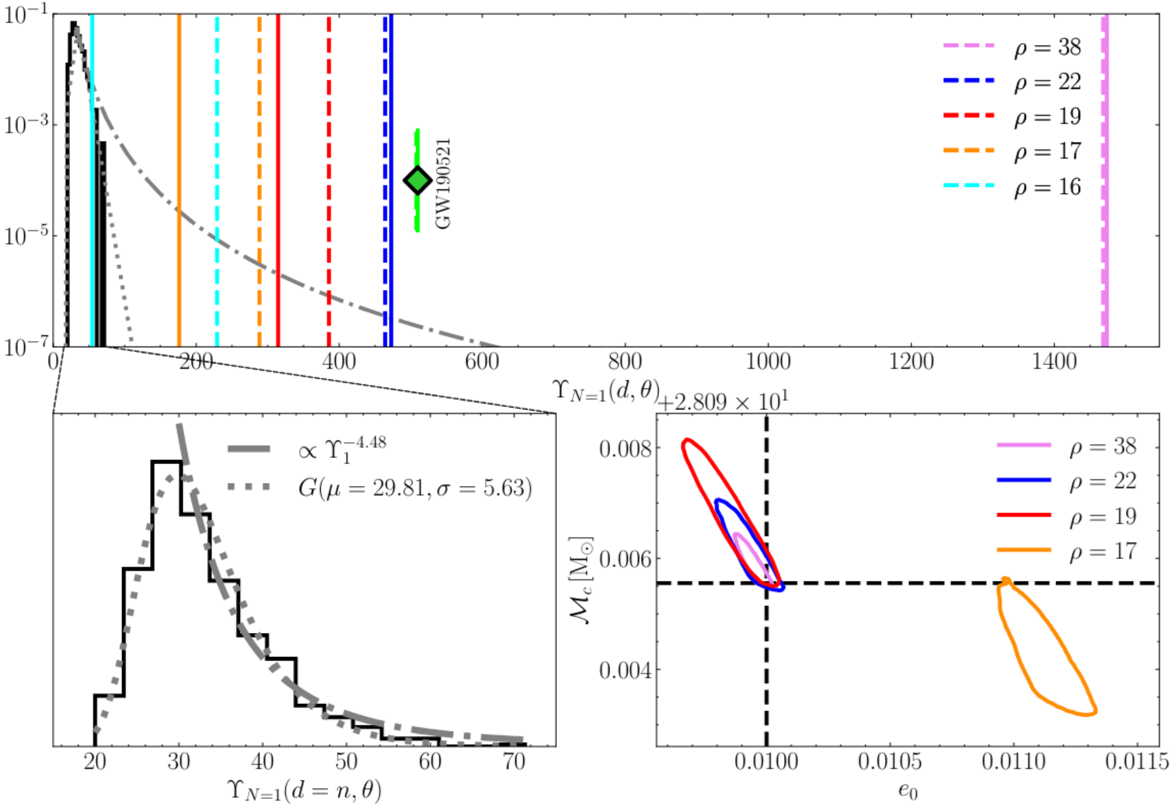






Chua et al, 2017, arXiv:1705.04259

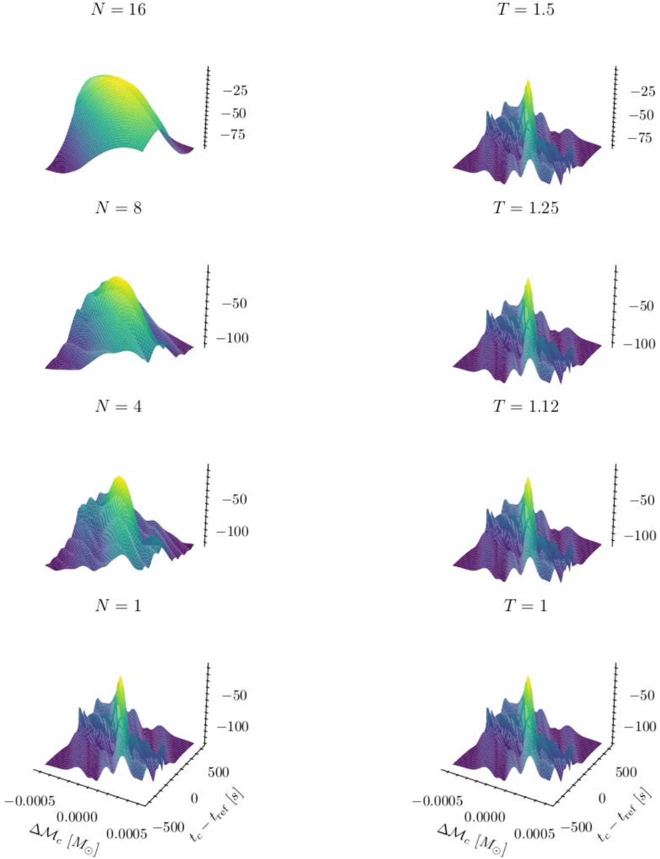
Significance of candidates from semi-coherent search



SNR ρ	FAP (lower)	FAP (upper)
16	7.4×10^{-2}	1.2×10^{-2}
17	1.3×10^{-3}	5.1×10^{-12}
19	1.6×10^{-4}	$< 10^{-12}$
22	4.1×10^{-5}	$< 10^{-12}$
38	7.8×10^{-7}	$< 10^{-12}$

Particle Swarm Optimisation

How is the semi-coherent stuff different to tempering?



$$T^{-1}\log L(d|\theta)$$

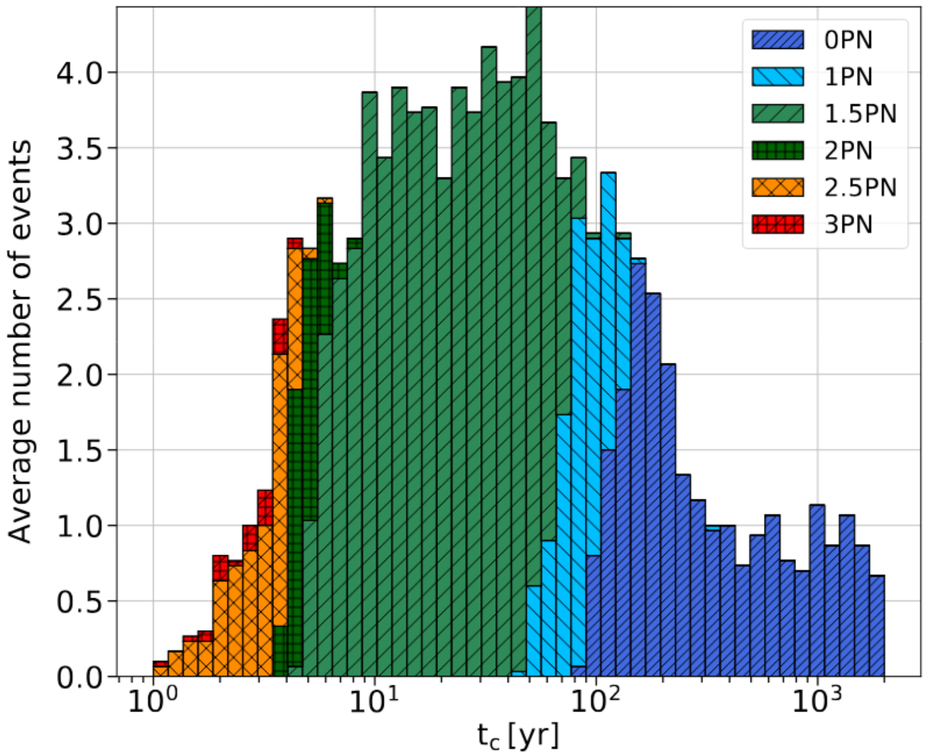
Yorsh search - Injections

ID	$\mathcal{M}_c^{\text{inj}}$ $[M_\odot]$	t_c^{inj} [years]	$f_{\text{low}}^{\text{inj}}$ [mHz]	d_L^{inj} [Mpc]	q^{inj}	$\chi_{\text{eff}}^{\text{inj}}$	ρ^{inj}
#1	29.34741587	65.9176	5.85830665	159.9	0.91	0.50	10.91
#2	38.04622881	252.7789	3.00851783	94.5	0.83	−0.06	4.07
#3	34.51216704	297.7712	3.00698596	47.0	0.58	0.10	9.88
#5	27.41970433	10.3457	12.24273032	168.3	0.83	−0.55	12.94
#6	7.007404972	11.0420	28.02352272	17.3	0.88	−0.17	14.30
#8*	22.40969304	1.6501	27.65438527	34.0	0.59	0.002	24.37
#9*	26.08583360	1.9185	23.76783772	85.5	0.95	0.10	23.08
#10	39.14942200	7.0604	11.31112717	168.9	0.88	0.03	24.65

Yorsh search - results

ID	SC_search-1				SC_search-1.5			
	Found	$\delta\mathcal{M}_c\,[M_\odot]$	$\delta t_c\,[s]$	$\rho_{\rm mf}$	Found	$\delta\mathcal{M}_c,\,[M_\odot]$	$\delta t_c[s]$	$\rho_{\rm mf}$
#1	×	-	-	-	×	-	-	-
#2	×	-	-	-	×	-	-	-
#3	×	-	-	-	×	-	-	-
#5	✓	0.0015	42482	12.2	✓	0.0004	40689.	11.60
#6	×	-	-	-	✓	0.0005	28031.	14.91
#8	×	-	-	-	✓	0.0001	611.	21.33
#9	×	-	-	-	✓	0.0020	1395.	23.53
#10	✓	0.0002	24297	26.54	✓	0.0006	22137.	25.77

Do we need a very complicated waveform?



Mangiagli et al, 2018, arXiv:1811.01805