Searching for New Compact Objects with Gravitational Waves

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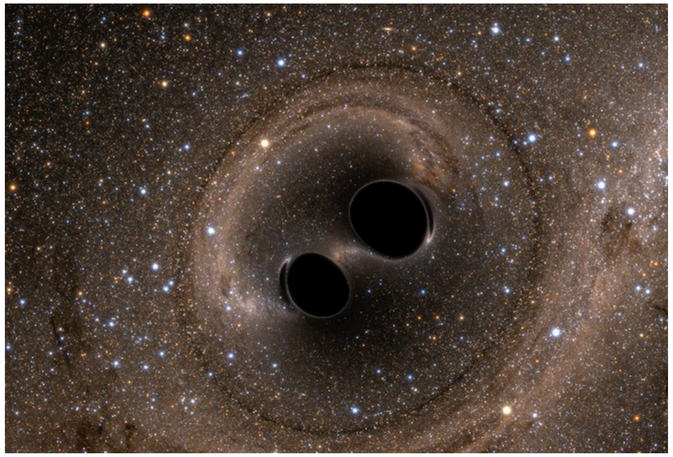
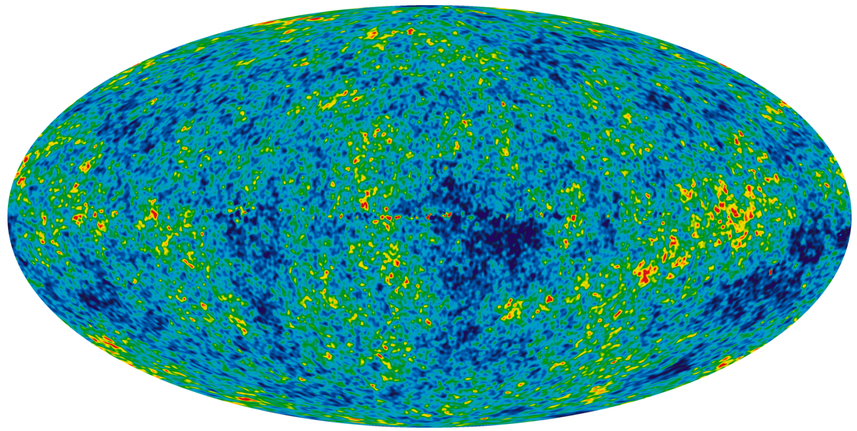
Richard George, Cody Messick, Christian Setzer, Christoph Weniger, & Aaron Zimmerman

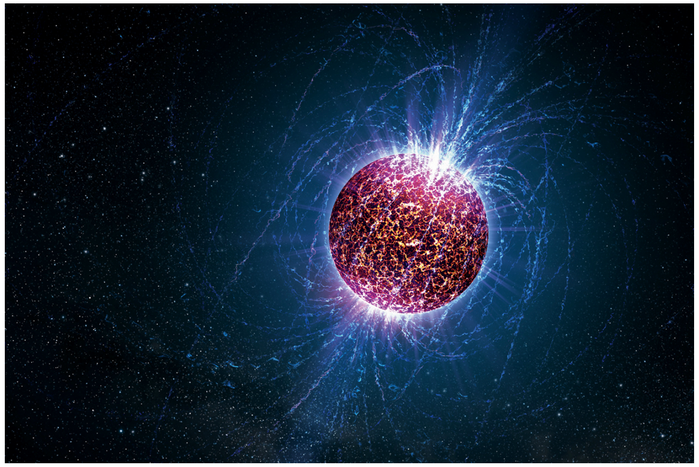
Sources of Gravitational Waves



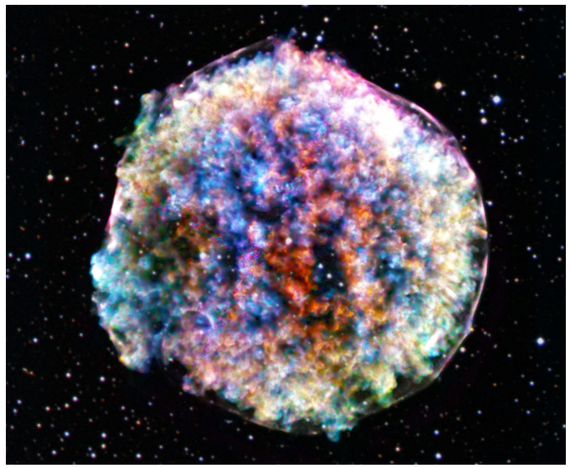
Compact Binary Coalescence



Stochastic Background



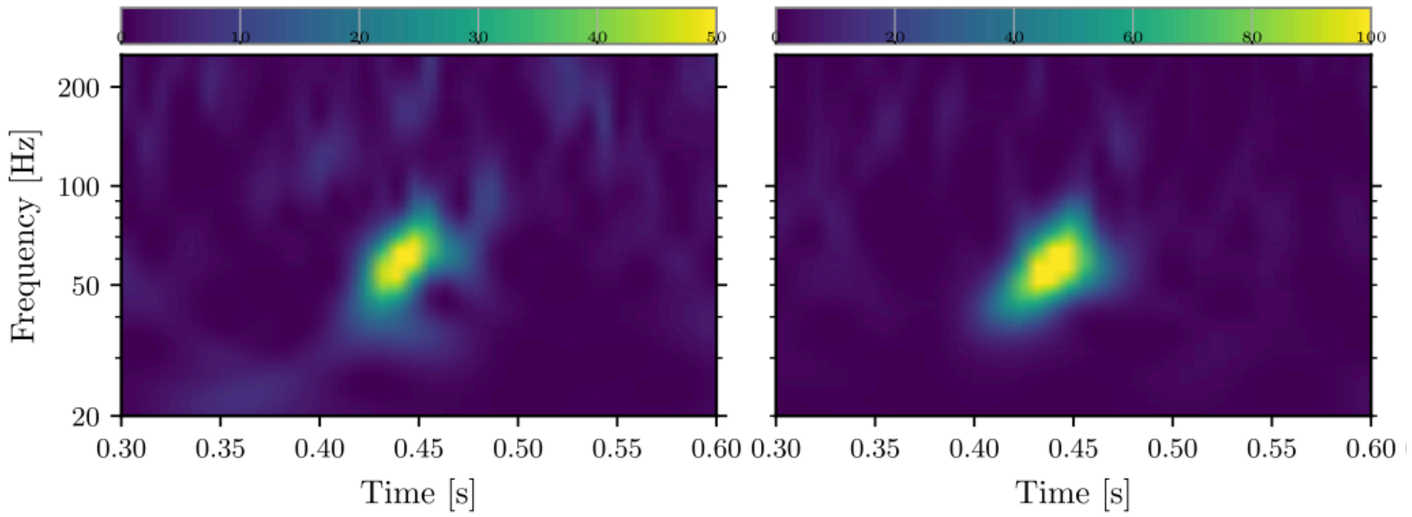
Continuous (Neutron Stars)



Bursts (Supernovae)

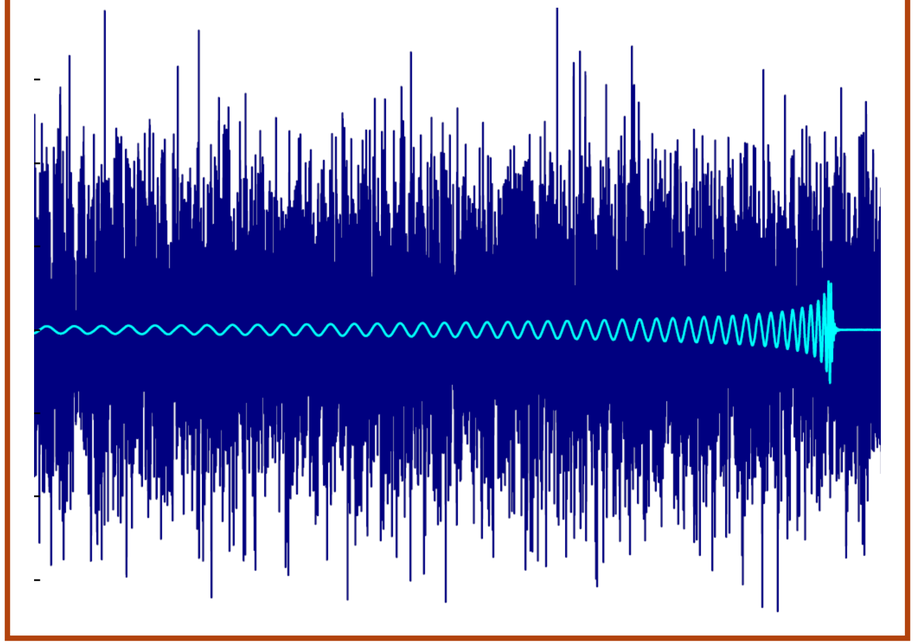
Offline Search Methods

Coherent Burst Searches

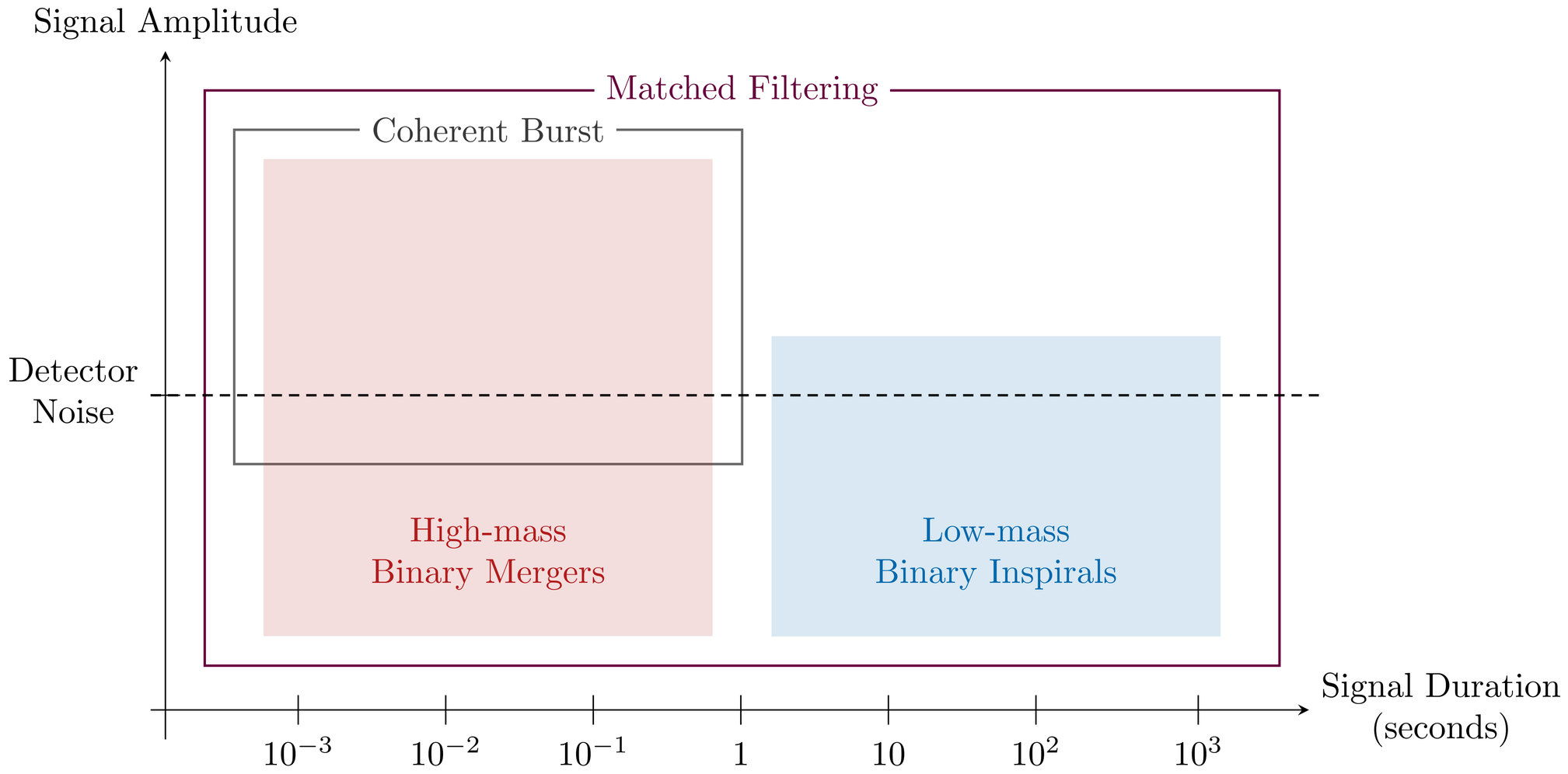


[LVC: 2009.01075, LVC: 2009.01190]

Matched Filtering Searches



Searching for Signals in GW data



[**TE**, Chia (JCAP): 2004.06729]

Overview:

1. Searches may be insensitive to new compact objects
2. How to perform a search for these new compact objects

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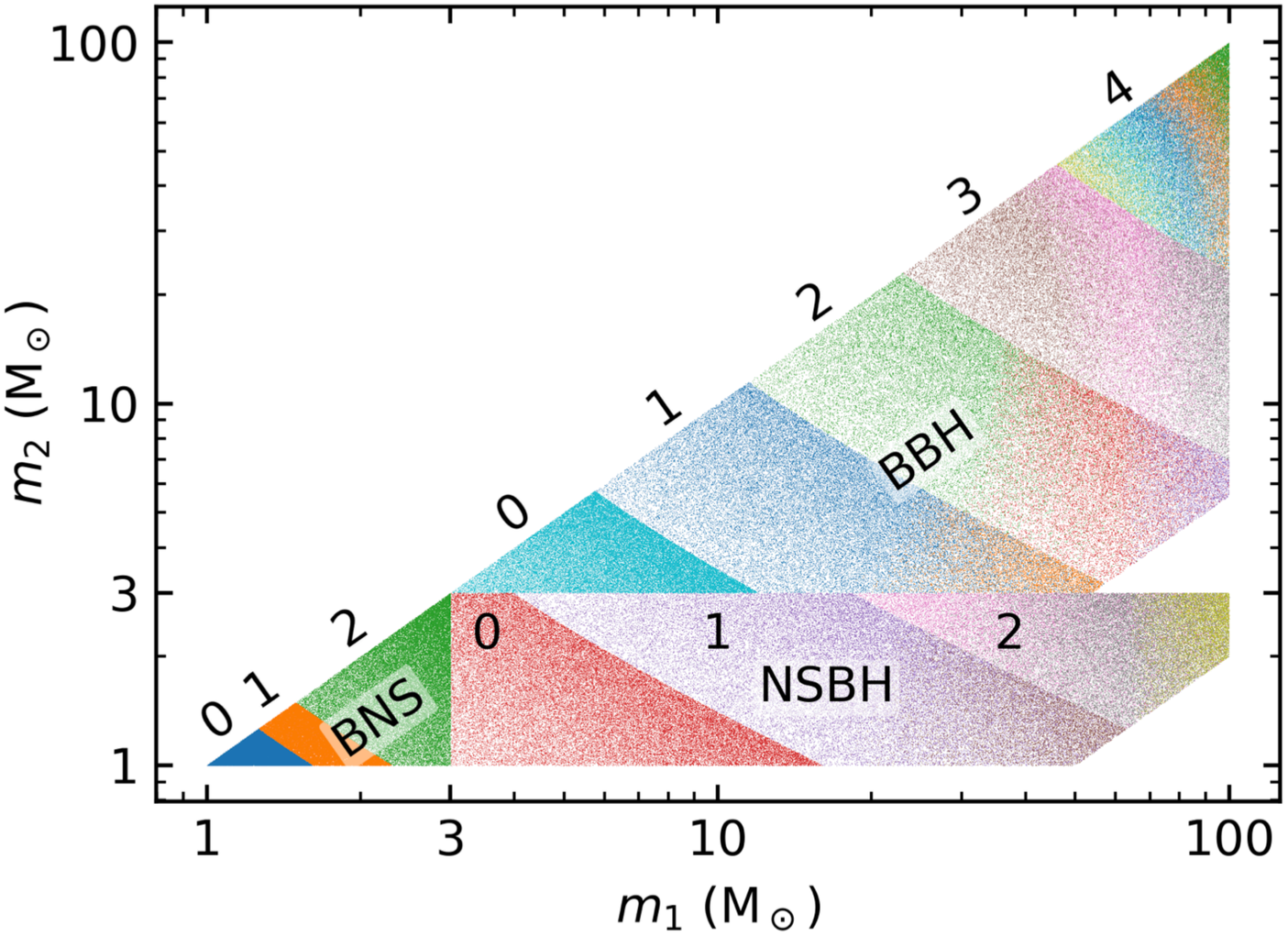
Template Banks and Effectualness

A priori, we don't know what signals will appear in the data — must construct **template banks**

Use the *effectualness* to create template banks

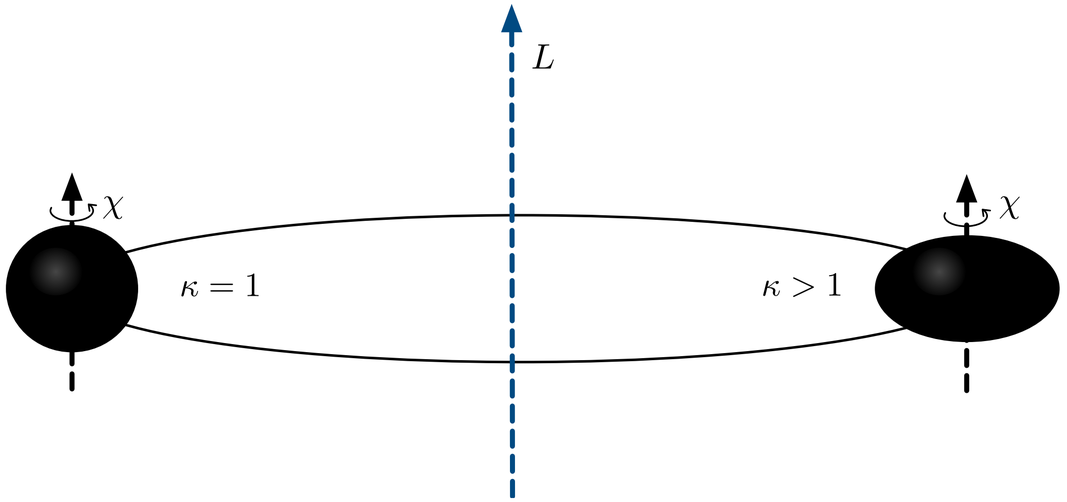
$$\frac{\mathrm{SNR}_{\mathrm{recovered}}}{\mathrm{SNR}_{\mathrm{true}}} = \varepsilon \qquad \varepsilon > 0.97$$

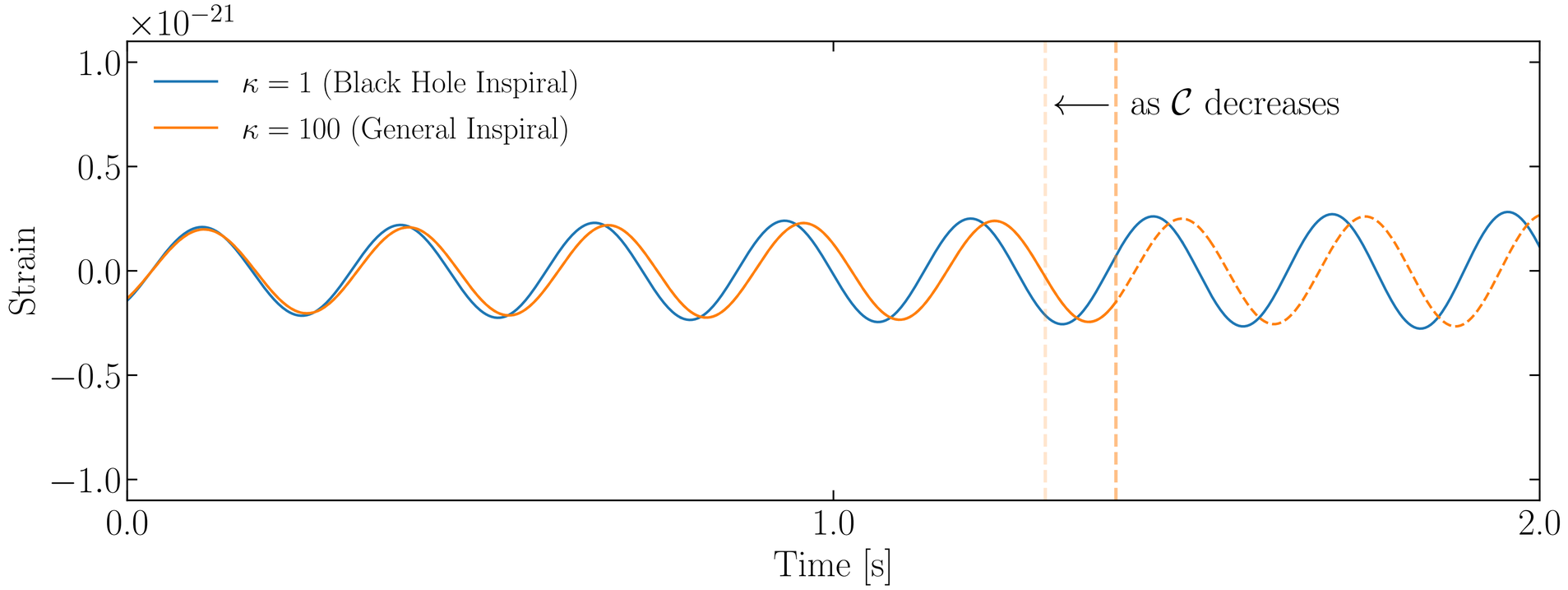
[Roulet et al.: 1904.01683]



Spin-Induced Quadrupoles

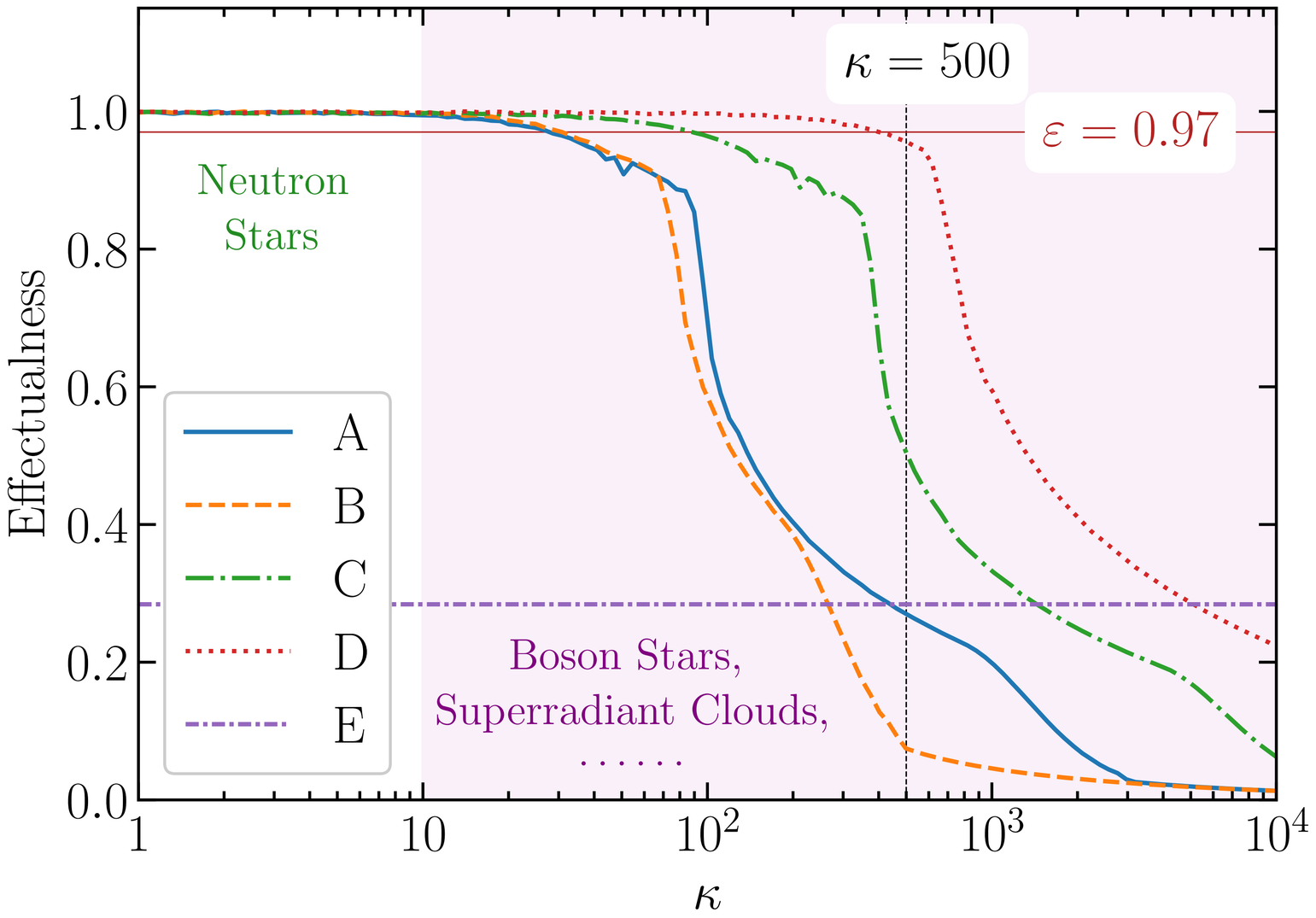
Kappa controls the axisymmetric response of an object to spin *i.e.*, how oblate it becomes





Missing Signals - Variable Kappa

[**TE**, Chia (JCAP): 2004.06729]



Scenario	$m_1\,[\mathrm{M}_\odot]$	$m_2\,[\mathrm{M}_\odot]$	χ_1	χ_2	$\mathcal{C}$
A	2.0	2.0	0.7	0.7	0.1
B	2.8	2.8	0.7	0.7	0.1
C	3.0	1.0	0.7	0.7	0.1
D	2.0	2.0	0.2	-0.2	0.1
E	2.0	2.0	0	0	0.01

1. For NSs, it is safe to set k = 1 when searching for signals

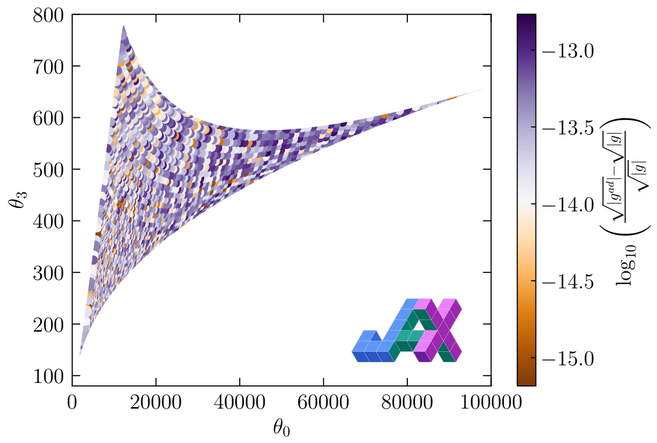
2. For highly spinning objects, k > 20 starts to significantly degrade the effectualness

Overview:

1. Searches may be insensitive to new compact objects
2. How to perform a search for these new compact objects

Enabling Searches

Quickly generating template banks



[Coogan, **TE**, Chia, George, Freese, Messick, Setzer, Weniger, Zimmerman: 2112.XXXX]

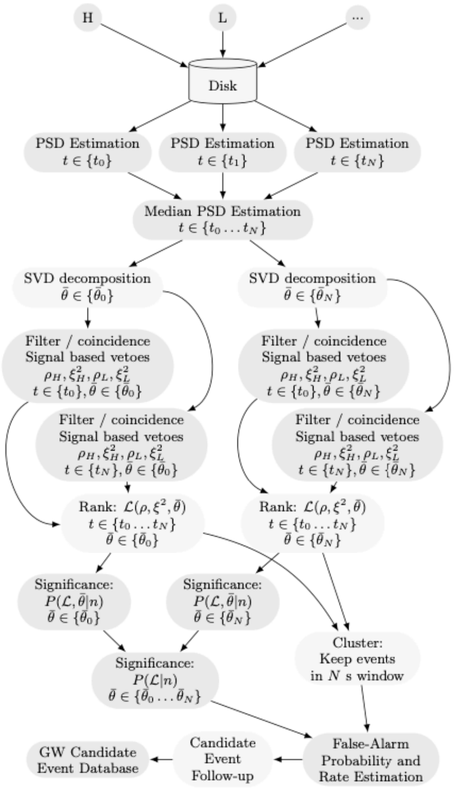
Dimensionally reducing the waveform parameter space

$$\{m_1\, m_2, \chi_1, \chi_2, \kappa_1, \kappa_2\}$$

$$\rightarrow \{m_1\, m_2, \chi, \kappa_{\rm eff}^{\rm 2PN}\}$$

[Chia, George, Coogan, **TE**, Freese, Messick, Setzer, Zimmerman: 2112.XXXX]

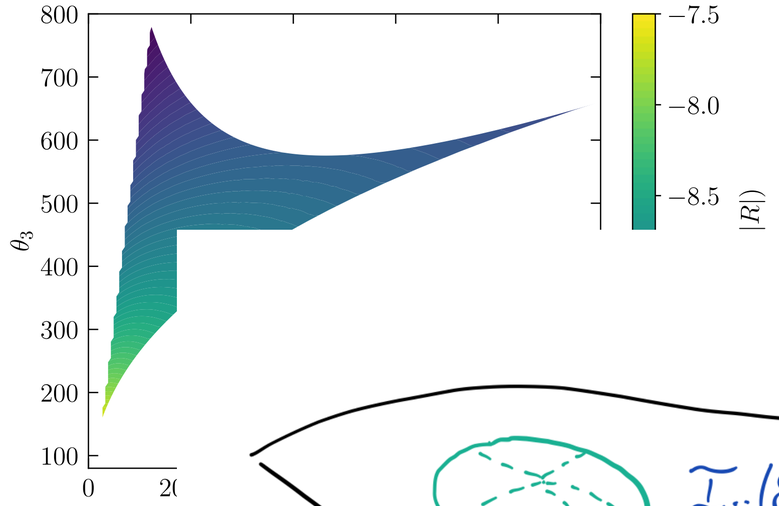
Using *Gstlal* to search for these signals



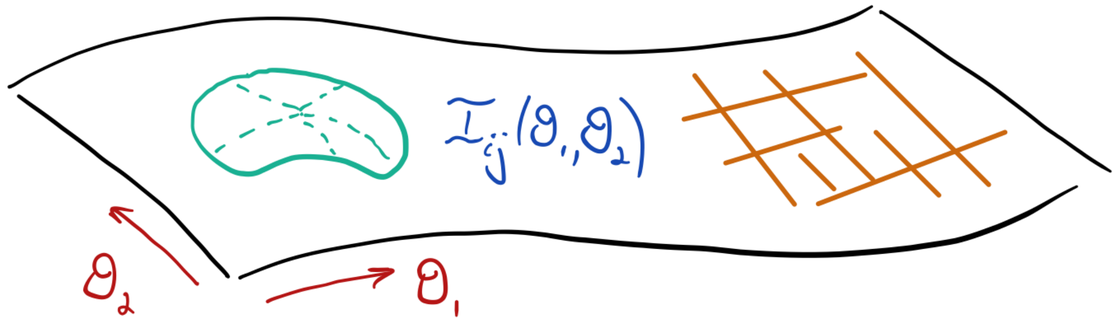
[Messick, Coogan, Chia, **TE**, George, Freese, Setzer, Zimmerman: 2112.XXXX]

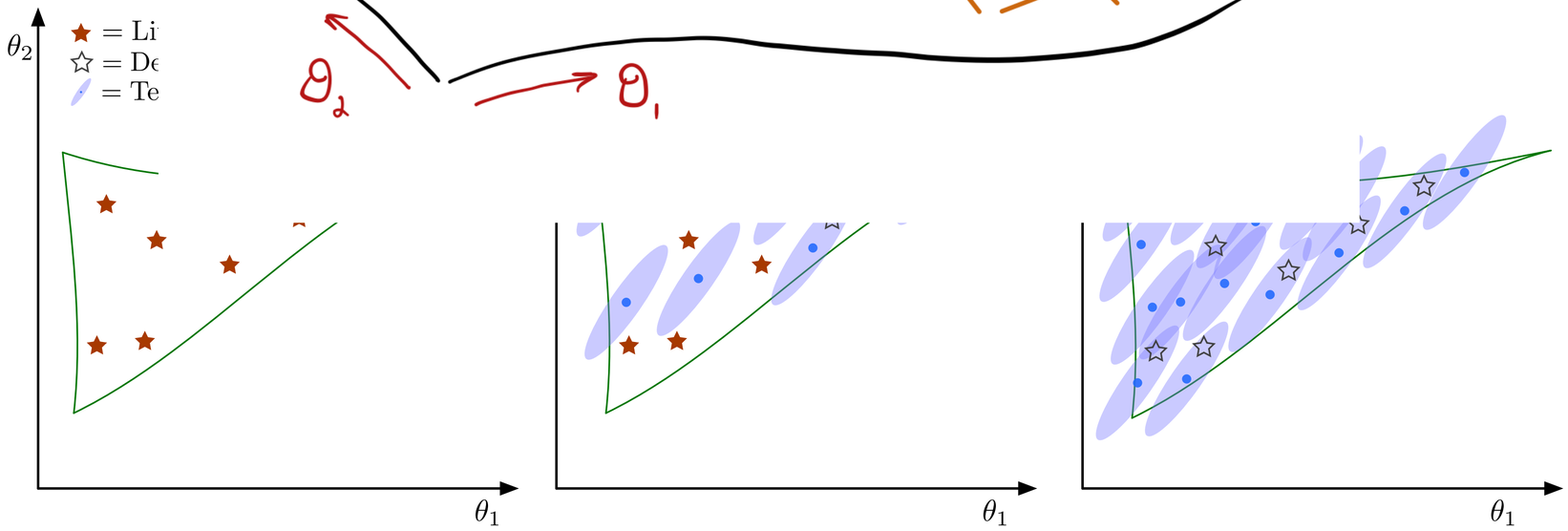
Building Template Banks

Preliminary!



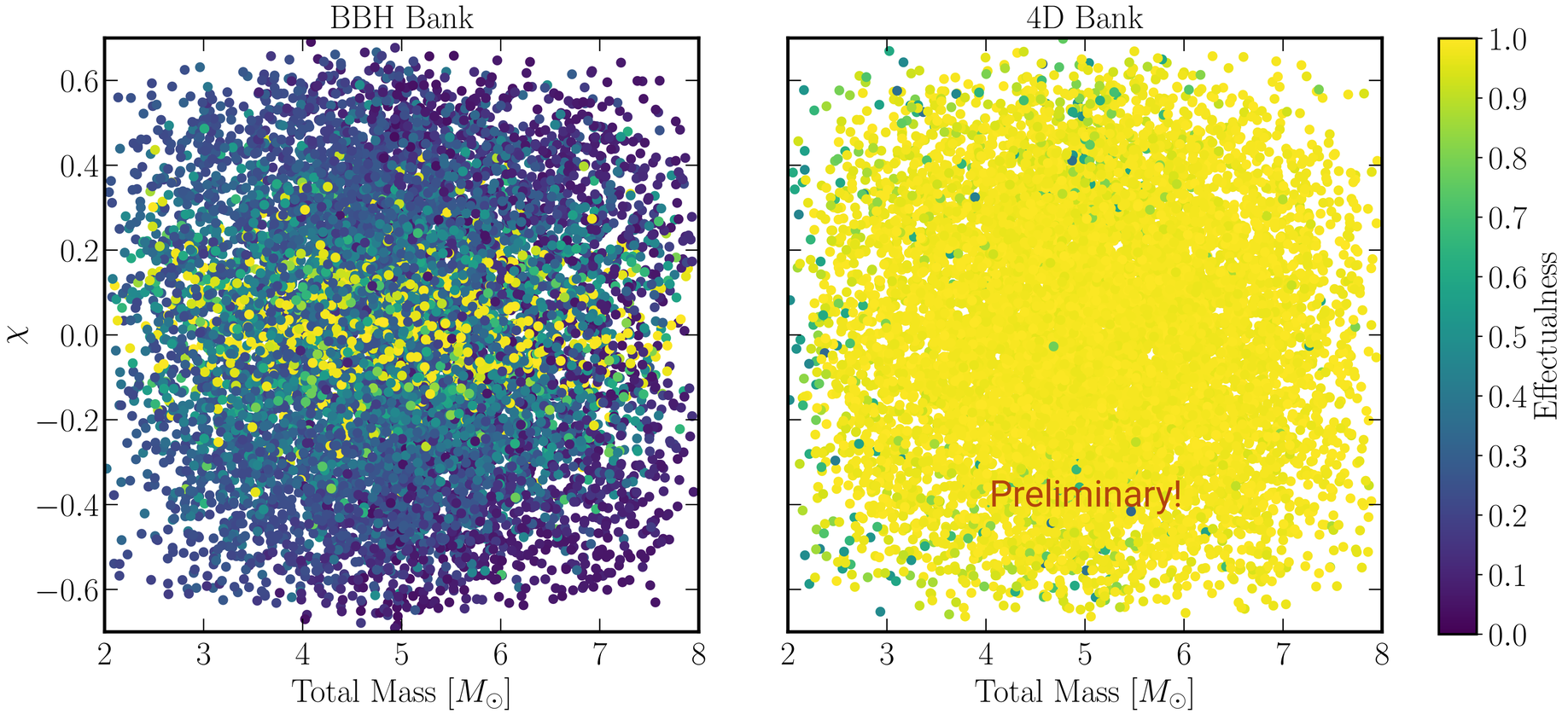
Name	$n_{\text{templates}}$	T_{gen}
		s
		37 s
		. s





[Messenger: 0809.5223]

Dimensionally Reducing Waveforms



$$\{m_1\, m_2, \chi_1, \chi_2, \kappa_1, \kappa_2\}$$

$$\rightarrow \{m_1\, m_2, \chi, \kappa_{\rm eff}^{\rm 2PN}\}$$

$$\chi := \left(1 - \frac{76}{113}\nu\right)\chi_s + \delta\chi_a$$

$$\chi_a = (\chi_1 - \chi_2)/2$$

$$\chi_s = (\chi_1 + \chi_2)/2$$

[Ajith et al: 1210.6666]

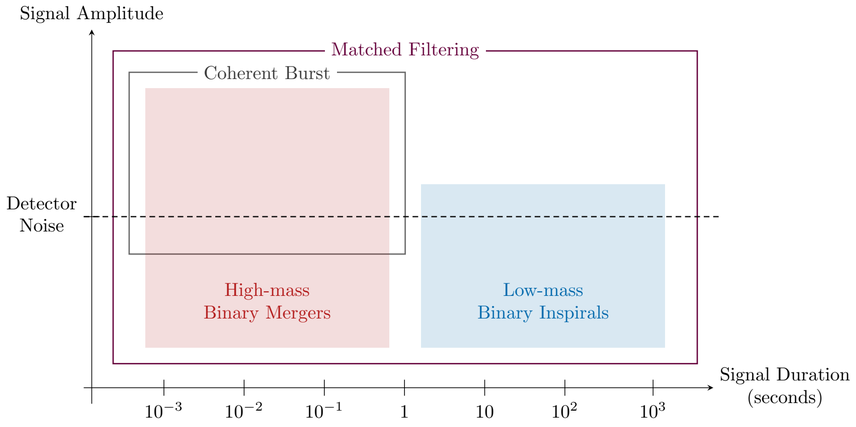
Searching for New Signals in the Public Data

Name	Inst.	MBTA			GstLAL			PyCBC			PyCBC-BBH		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}
GW190403_051519	HL	--	--	--	--	--	--	--	--	--	7.7	8.0	0.61
GW190408_181802	HLV	8.7×10^{-5}	14.4	1.00	$< 1.0 \times 10^{-5}$	14.7	1.00	2.5×10^{-4}	13.1	1.00	$< 1.2 \times 10^{-4}$	13.7	1.00
GW190412	HLV	$< 1.0 \times 10^{-5}$	18.2	1.00	$< 1.0 \times 10^{-5}$	19.0	1.00	$< 1.1 \times 10^{-4}$	17.4	1.00	$< 1.2 \times 10^{-4}$	17.9	1.00
GW190413_052954	HL	--	--	--	--	--	--	*170*	*8.5*	*0.13*	0.82	8.5	0.93
GW190413_134308	HLV	0.34	10.3	0.99	*39*	*10.1*	*0.04*	*21*	*9.3*	*0.48*	0.18	8.9	0.99
GW190421_213856	HL	1.2	9.7	0.99	0.0028	10.5	1.00	5.9	10.1	0.75	0.014	10.1	1.00
GW190425	LV	--	--	--	$0.034^{\dagger}$	12.9	0.78	--	--	--	--	--	--
GW190426_190642	HL	--	--	--	--	--	--	--	--	--	4.1	9.6	0.75
GW190503_185404	HLV	0.013	12.8	1.00	$< 1.0 \times 10^{-5}$	12.0	1.00	0.038	12.2	1.00	0.0026	12.2	1.00
GW190512_180714	HLV	0.038	11.7	0.99	$< 1.0 \times 10^{-5}$	12.2	1.00	1.1×10^{-4}	12.4	1.00	$< 1.1 \times 10^{-4}$	12.4	1.00
GW190513_205428	HLV	0.11	13.0	0.99	1.3×10^{-5}	12.3	1.00	*19*	*11.6*	*0.49*	0.044	11.8	1.00
GW190514_065416	HL	--	--	--	*450*	*8.3*	*0.00*	--	--	--	2.8	8.4	0.76
GW190517_055101	HLV	0.11	11.3	1.00	0.0045	10.8	1.00	0.0095	10.4	1.00	3.5×10^{-4}	10.3	1.00
GW190519_153544	HLV	7.0×10^{-5}	13.7	1.00	$< 1.0 \times 10^{-5}$	12.4	1.00	$< 1.0 \times 10^{-4}$	13.2	1.00	$< 1.1 \times 10^{-4}$	13.2	1.00
GW190521	HLV	0.042	13.0	0.96	0.20	13.3	0.79	0.44	13.7	0.96	0.0013	13.6	1.00
GW190521_074359	HL	$< 1.0 \times 10^{-5}$	22.2	1.00	$< 1.0 \times 10^{-5}$	24.4	1.00	$< 1.8 \times 10^{-5}$	24.0	1.00	$< 2.3 \times 10^{-5}$	24.0	1.00
GW190527_092055	HL	--	--	--	0.23	8.7	0.85	--	--	--	*19*	*8.4*	*0.33*
GW190602_175927	HLV	3.0×10^{-4}	12.6	1.00	$< 1.0 \times 10^{-5}$	12.3	1.00	0.29	11.9	0.98	0.013	11.9	1.00
GW190620_030421	LV	--	--	--	$0.011^{\dagger}$	10.9	0.99	--	--	--	--	--	--
GW190630_185205	LV	--	--	--	$< 1.0 \times 10^{-5}$	15.2	1.00	--	--	--	0.24	15.1	1.00
GW190701_203306	HLV	35	11.3	0.87	0.0057	11.7	0.99	0.064	11.9	0.99	0.56	11.7	1.00
GW190706_222641	HLV	0.0015	11.9	1.00	5.0×10^{-5}	12.5	1.00	3.7×10^{-4}	11.7	1.00	0.34	12.6	1.00
GW190707_093326	HL	0.032	12.6	1.00	$< 1.0 \times 10^{-5}$	13.2	1.00	$< 1.0 \times 10^{-5}$	13.0	1.00	$< 1.9 \times 10^{-5}$	13.0	1.00
GW190708_232457	LV	--	--	--	$3.1 \times 10^{-4\dagger}$	13.1	1.00	--	--	--	--	--	--
GW190719_215514	HL	--	--	--	--	--	--	--	--	--	0.63	8.0	0.92
GW190720_000836	HLV	0.094	11.6	1.00	$< 1.0 \times 10^{-5}$	11.5	1.00	1.4×10^{-4}	10.6	1.00	$< 7.8 \times 10^{-5}$	11.4	1.00
GW190725_174728*	HLV	3.1	9.8	0.59	--	--	--	0.46	9.1	0.96	2.9	8.8	0.82
GW190727_060333	HLV	0.023	12.0	1.00	$< 1.0 \times 10^{-5}$	12.1	1.00	0.0056	11.4	1.00	2.0×10^{-4}	11.1	1.00
GW190728_064510	HLV	7.5×10^{-4}	13.1	1.00	$< 1.0 \times 10^{-5}$	13.4	1.00	$< 8.2 \times 10^{-5}$	13.0	1.00	$< 7.8 \times 10^{-5}$	13.0	1.00
GW190731_140936	HL	6.1	9.1	0.80	0.33	8.5	0.78	--	--	--	1.9	7.8	0.83
GW190803_022701	HLV	77	9.0	0.96	0.073	9.1	0.94	*81*	*8.7*	*0.17*	0.39	8.7	0.97
GW190805_211137	HL	--	--	--	--	--	--	--	--	--	0.63	8.3	0.95
GW190814	LV	$< 2.0 \times 10^{-4}$	20.4	1.00	$< 1.0 \times 10^{-5}$	22.2	1.00	0.17	19.5	1.00	--	--	--
GW190828_063405	HLV	$< 1.0 \times 10^{-5}$	15.2	1.00	$< 1.0 \times 10^{-5}$	16.3	1.00	$< 8.5 \times 10^{-5}$	13.9	1.00	$< 7.0 \times 10^{-5}$	15.9	1.00
GW190828_065509	HLV	0.16	10.8	0.96	3.5×10^{-5}	11.1	1.00	2.8×10^{-4}	10.5	1.00	1.1×10^{-4}	10.5	1.00
GW190910_112807	LV	--	--	--	$0.0029^{\dagger}$	13.4	1.00	--	--	--	--	--	--
GW190915_235702	HLV	0.0055	12.7	1.00	$< 1.0 \times 10^{-5}$	13.0	1.00	6.8×10^{-4}	13.0	1.00	$< 7.0 \times 10^{-5}$	13.1	1.00
GW190916_200658*	HLV	6.9×10^{3}	8.2	0.66	*12*	*8.2*	*0.09*	--	--	--	4.7	7.9	0.64
GW190917_114630	HLV	--	--	--	0.66	9.5	0.77	--	--	--	--	--	--
GW190924_021846	HLV	0.0049	11.9	0.99	$< 1.0 \times 10^{-5}$	13.0	1.00	$< 8.2 \times 10^{-5}$	12.4	1.00	8.3×10^{-5}	12.5	1.00
GW190925_232845*	HV	*100*	*9.4*	*0.35*	--	--	--	*73*	*9.0*	*0.02*	0.0072	9.9	0.99
GW190926_050336*	HLV	--	--	--	1.1	9.0	0.54	--	--	--	*87*	*7.8*	*0.09*
GW190929_012149	HLV	2.9	10.3	0.64	0.16	10.1	0.87	*120*	*9.4*	*0.14*	*14*	*8.5*	*0.41*
GW190930_133541	HL	0.34	10.0	0.87	0.43	10.1	0.76	0.018	9.8	1.00	0.012	10.0	1.00

44 high significance candidates candidates found so far in the O3a data

Our search is complete and we are currently confirming the background model before unblinding

Summary



→ Current search pipelines can easily signals from new compact objects

→ We developed all the necessary tools to search for a variety of new signatures. Our first search for objects with enhanced spin-induced quadrupoles is nearly complete