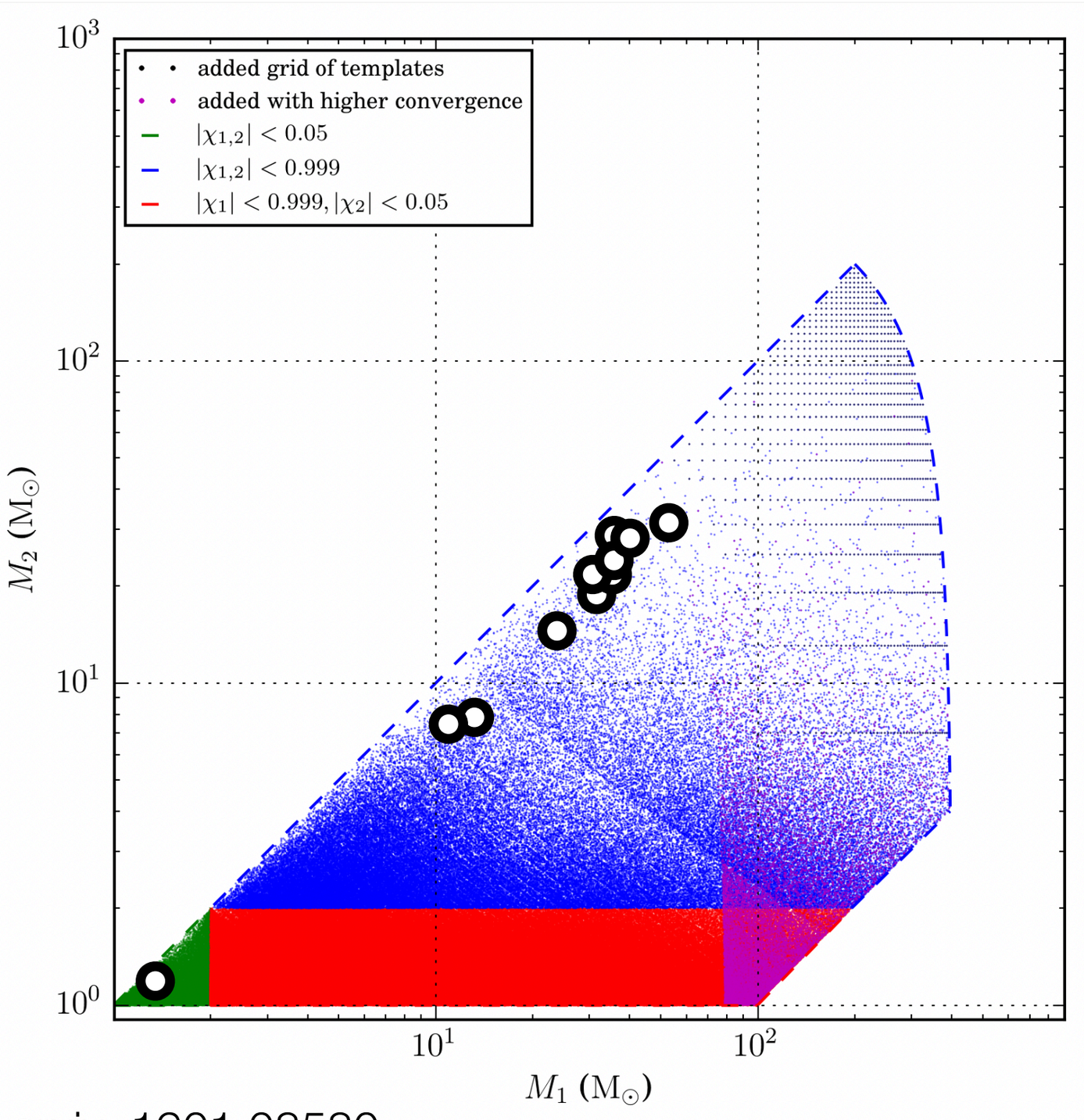
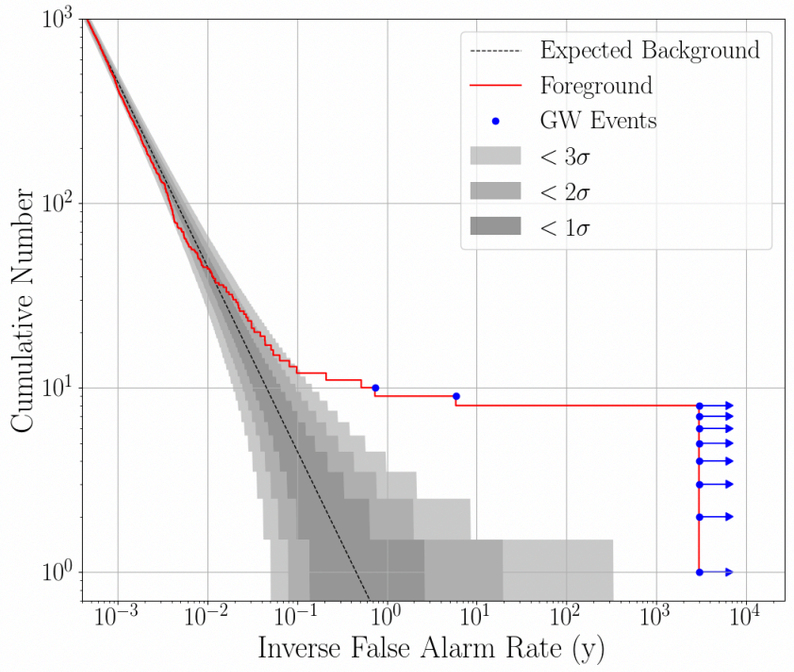
Astrophysics with GW sources

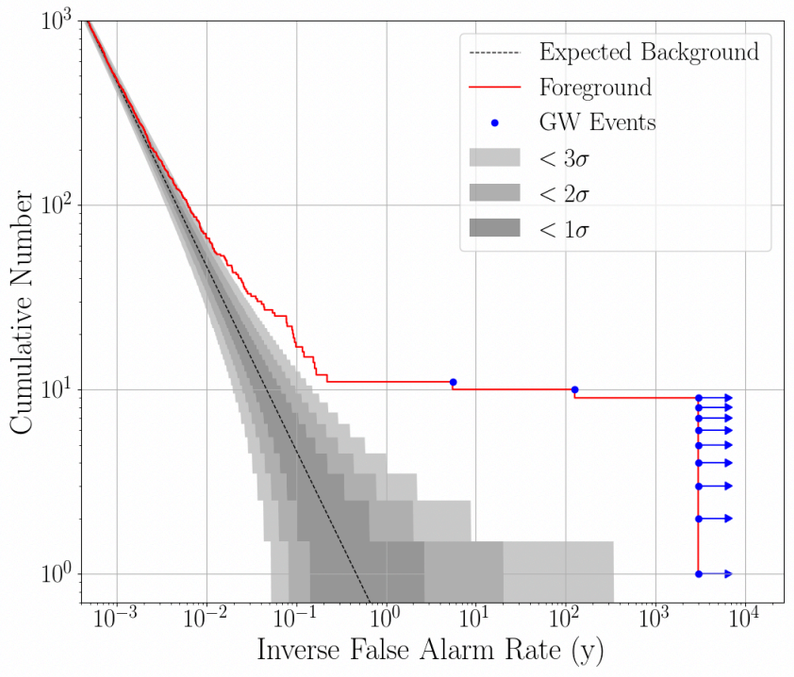
Tejaswi Venumadhav
Institute for Advanced Study, Princeton

GW Detections



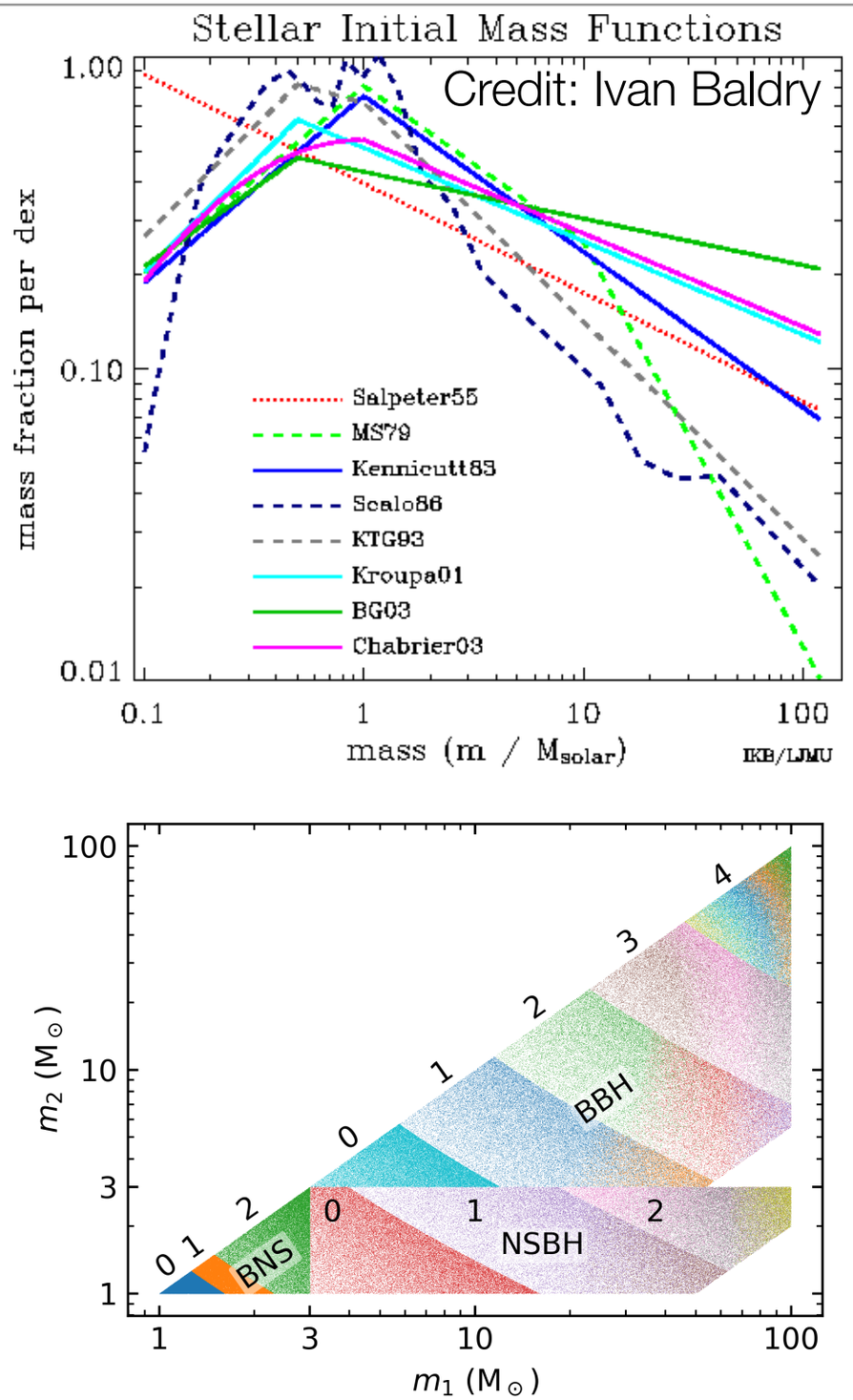
arxiv: 1901.08580



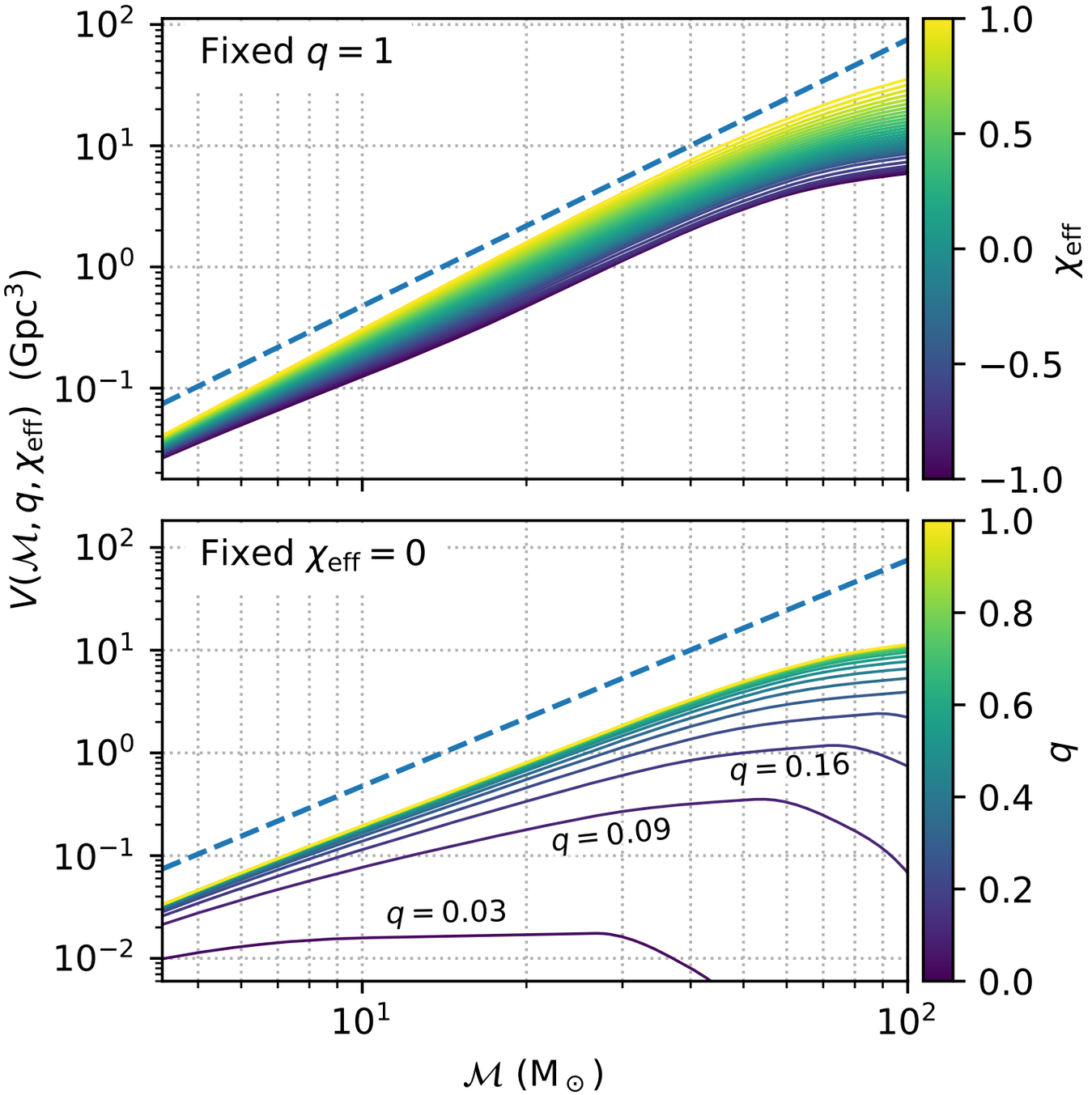


arxiv: 1811.12907

Our search: Accounting for Phase-space Density

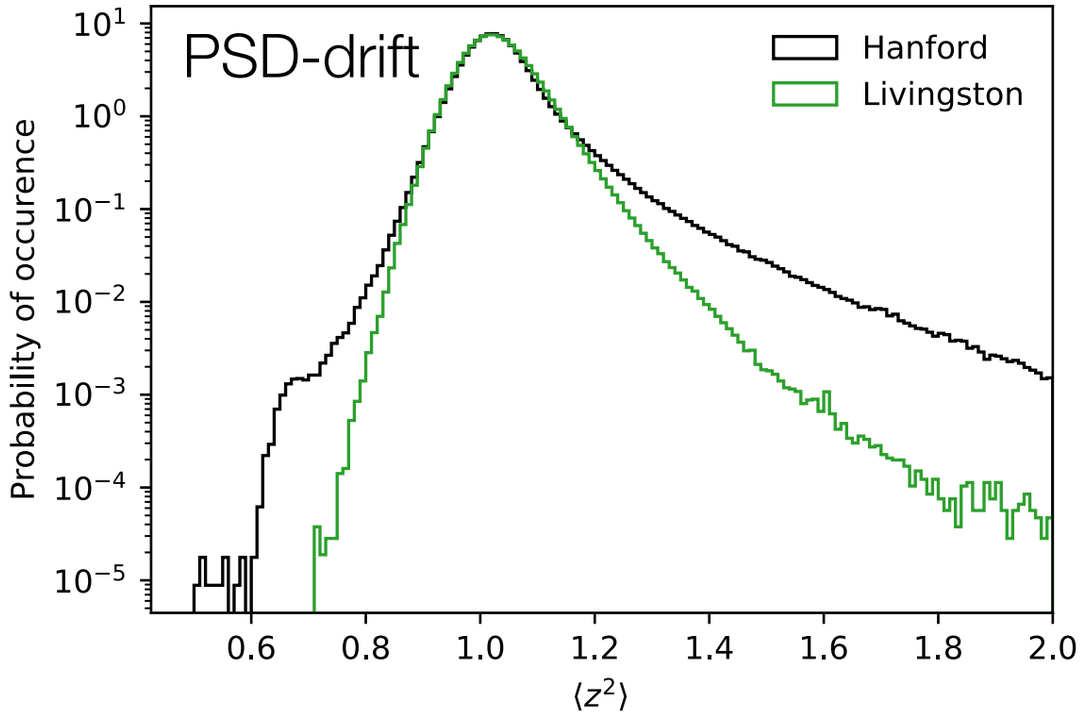


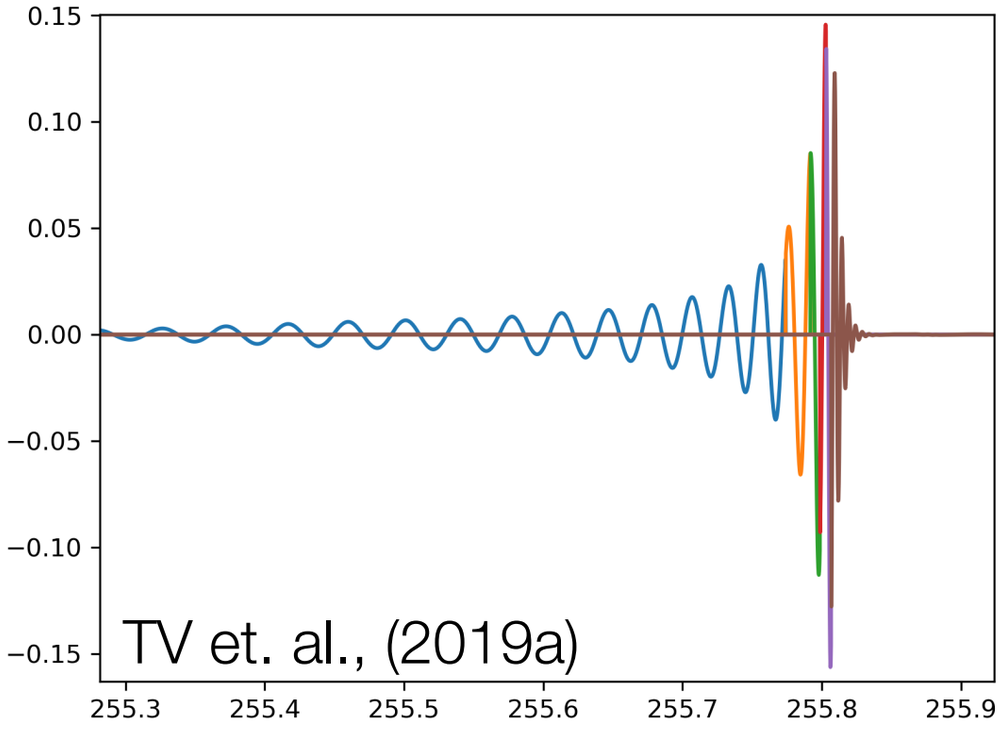
Roulet et. al. (2019)

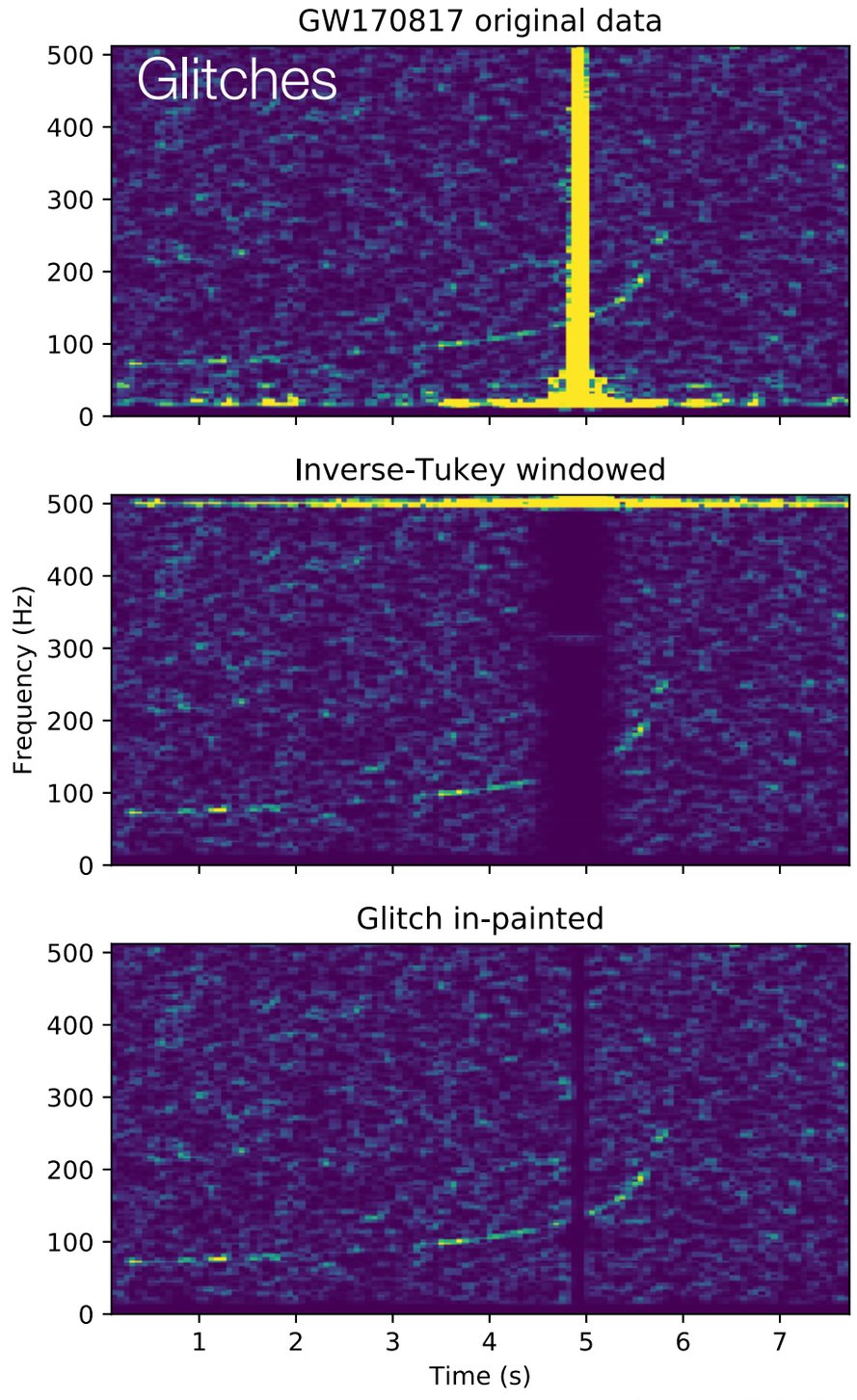


Roulet and Zaldarriaga (2018)

Our search: Accounting for Non-Gaussian Noise

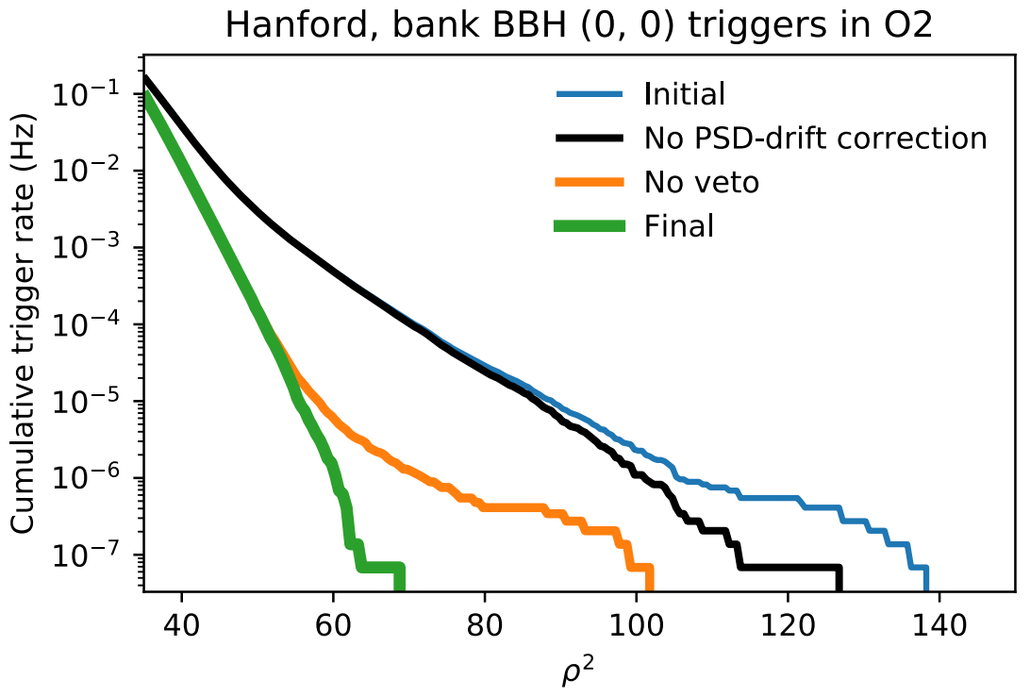




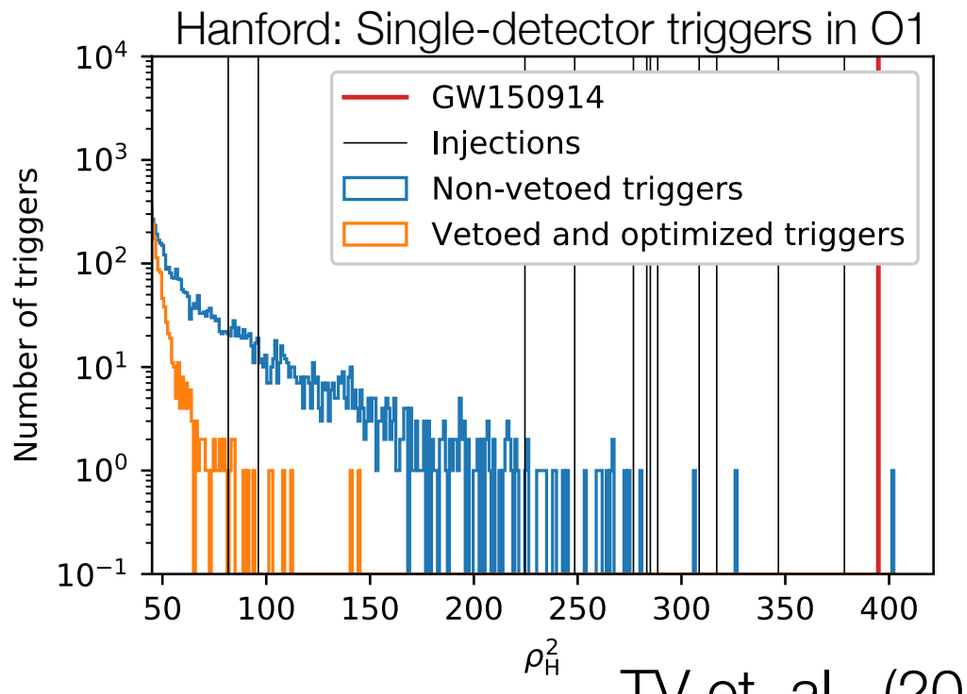


arxiv: 1908.05644

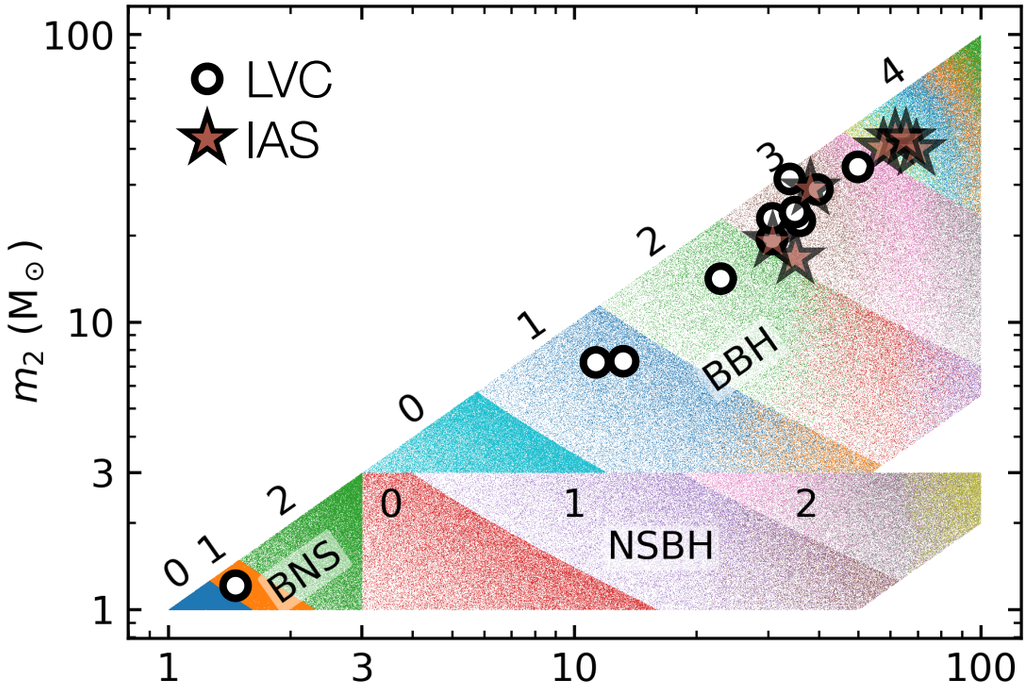
Our search: Overall Results



arxiv: 1908.05644

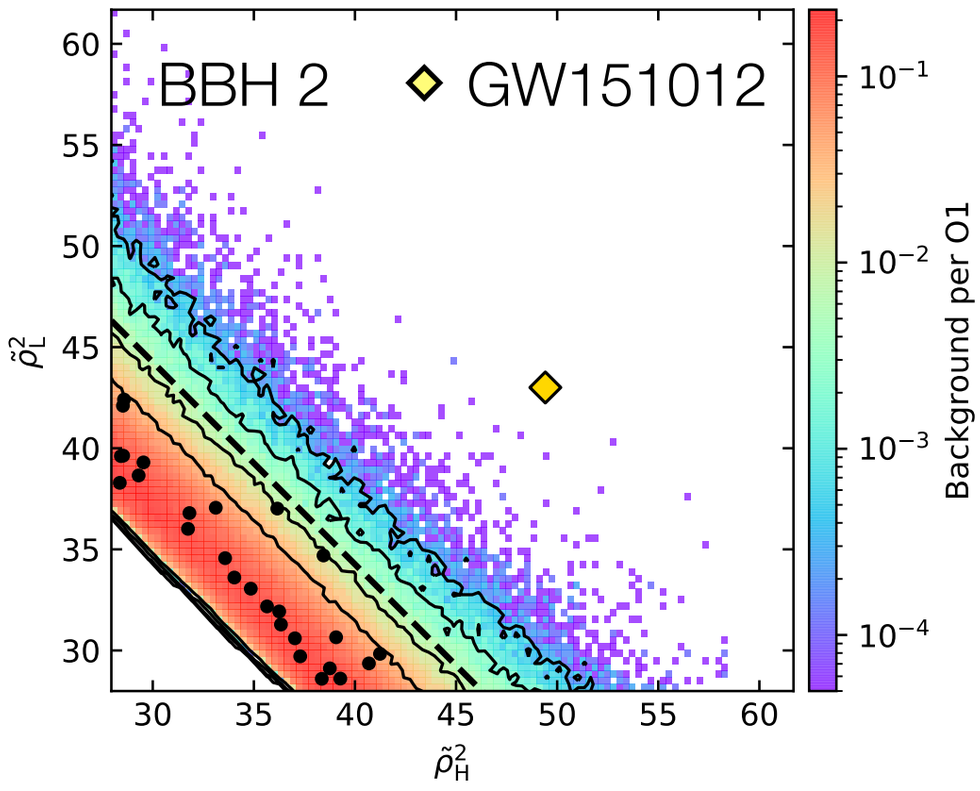


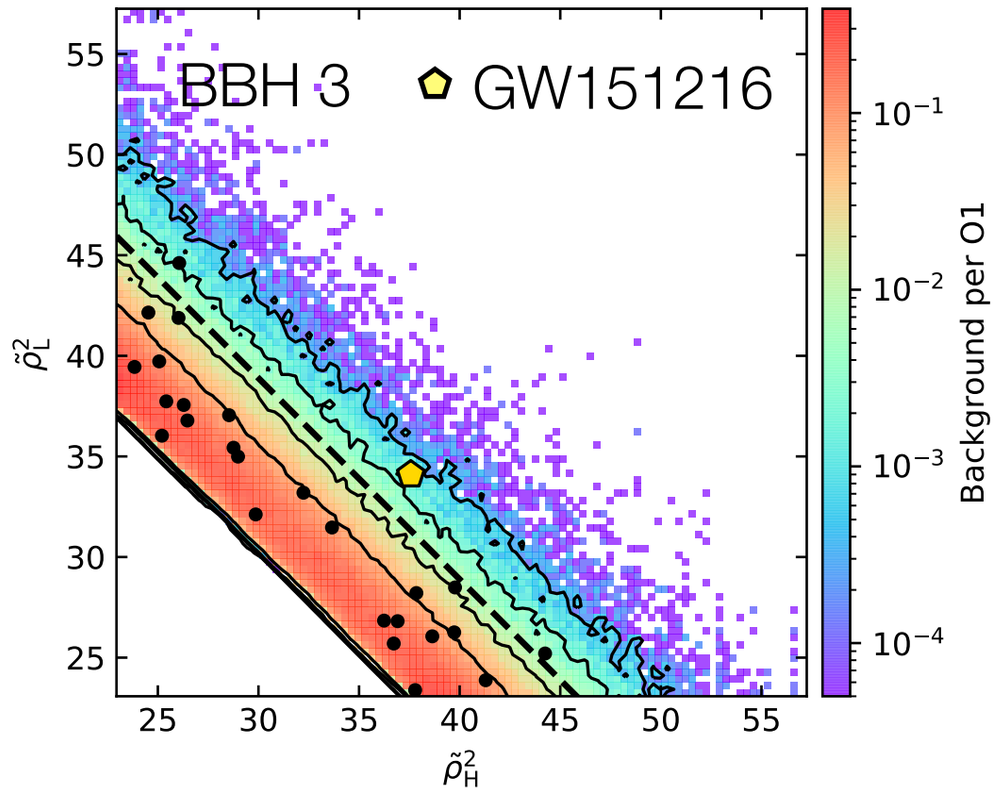
TV et. al., (2019a)



TV et. al., (2019b)

Our search: O1

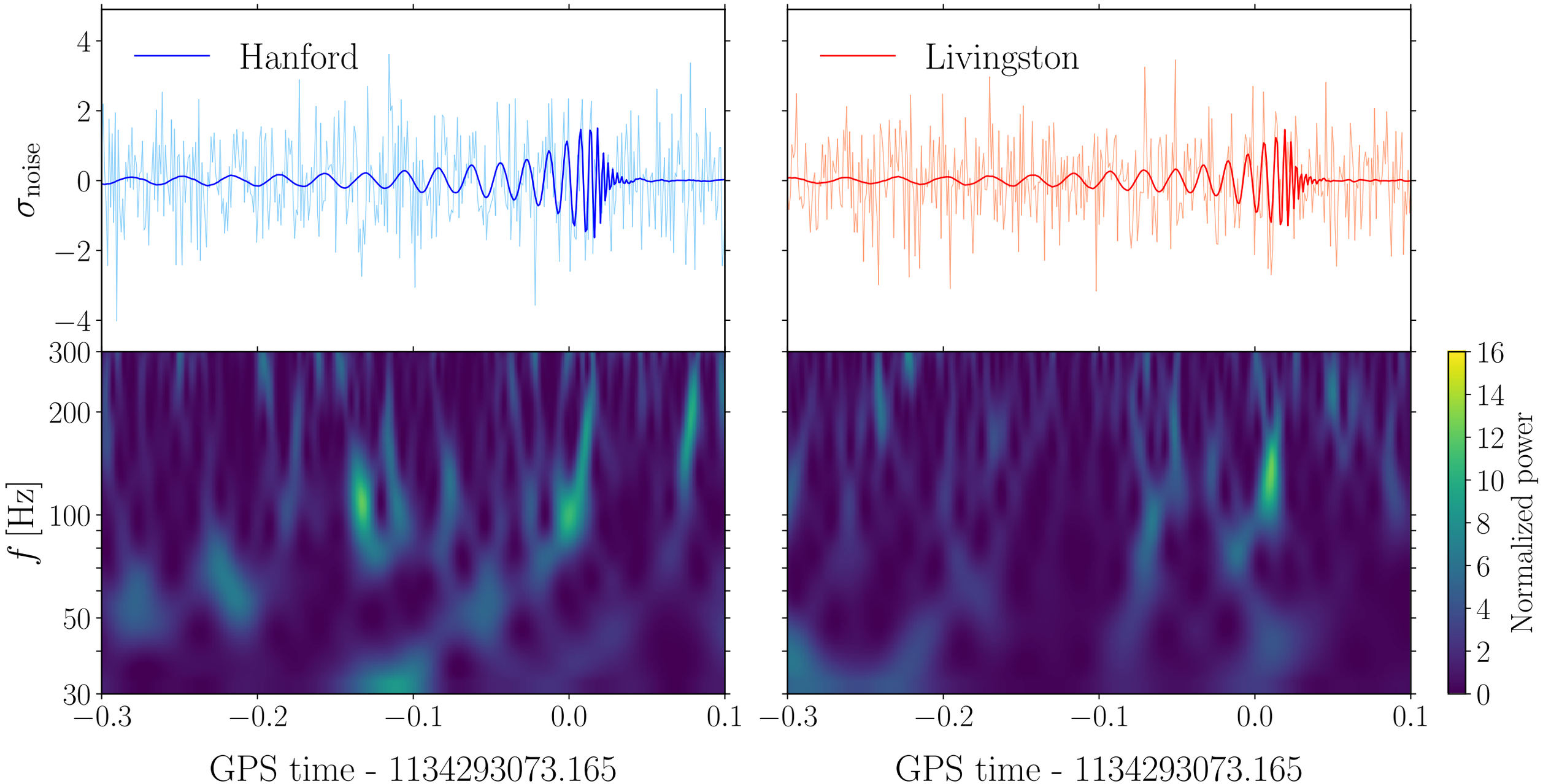




Name	Bank	$\mathcal{M}(M_\odot)$	GPS time[a]	ρ_H^2	ρ_L^2	FAR^{-1}(O1)[b]	$\frac{W}{\mathcal{R}(\text{event}\|H_0)}$ (days)	$\mathcal{R}_{>100}$(days^{-1})	p_{astro}
GW151226	BBH 1	9.74	1135136350.585	120.0	52.1	$> 20\,000$	–[c]	–	1[c]
GW151012	BBH 2	18	1128678900.428	55.66	46.75	$> 20\,000$	7×10^5 [d]	0.01	0.9998[d]
GW150914	BBH 3	28	1126259462.411	396.1	184.3	$> 20\,000$	–[c]	–	1[c]
GW151216[e]	BBH 3	29	1134293073.164	39.4	34.8	52	74 ± 2	0.033	0.71
151231	BBH 3	30	1135557647.145	37.5	25.2	0.98	5.4 ± 0.4	0.033	0.15
151011	BBH 4	58	1128626886.595	24.5	39.9	1.1	16 ± 1	0.01	0.14

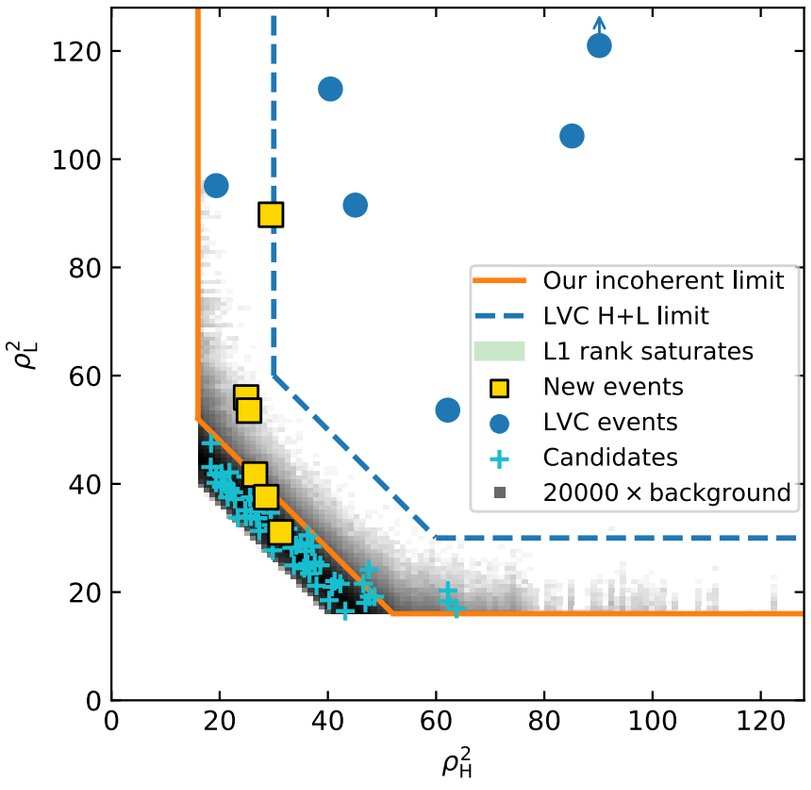
TV et. al., (2019a)

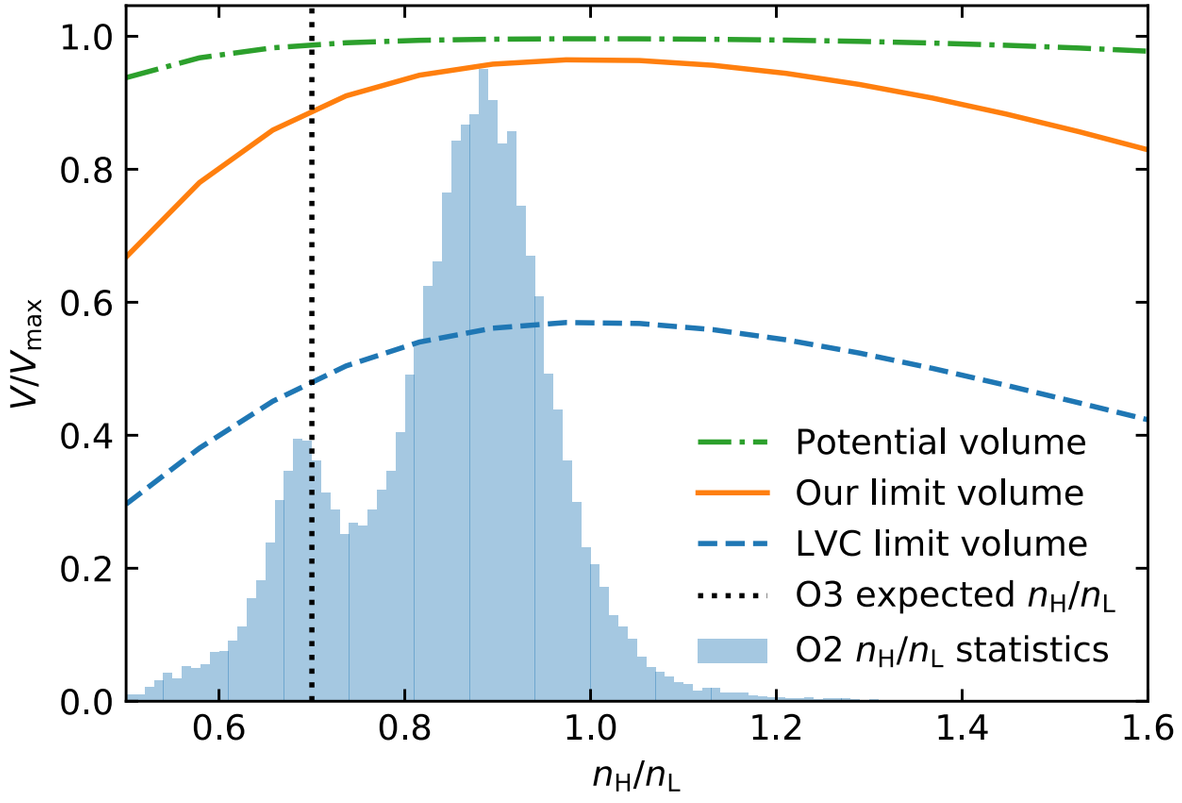
Our search: O1



Zackay et. al., (2019)

Our search: O2

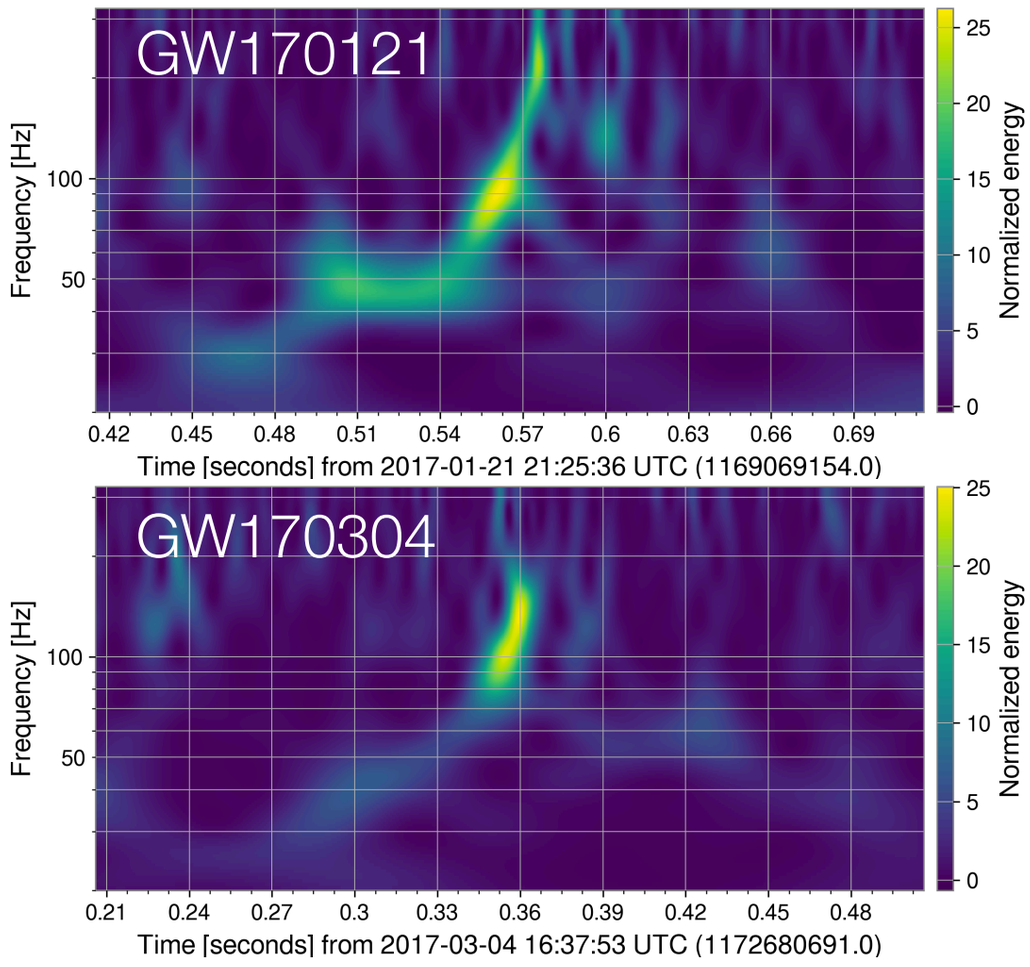


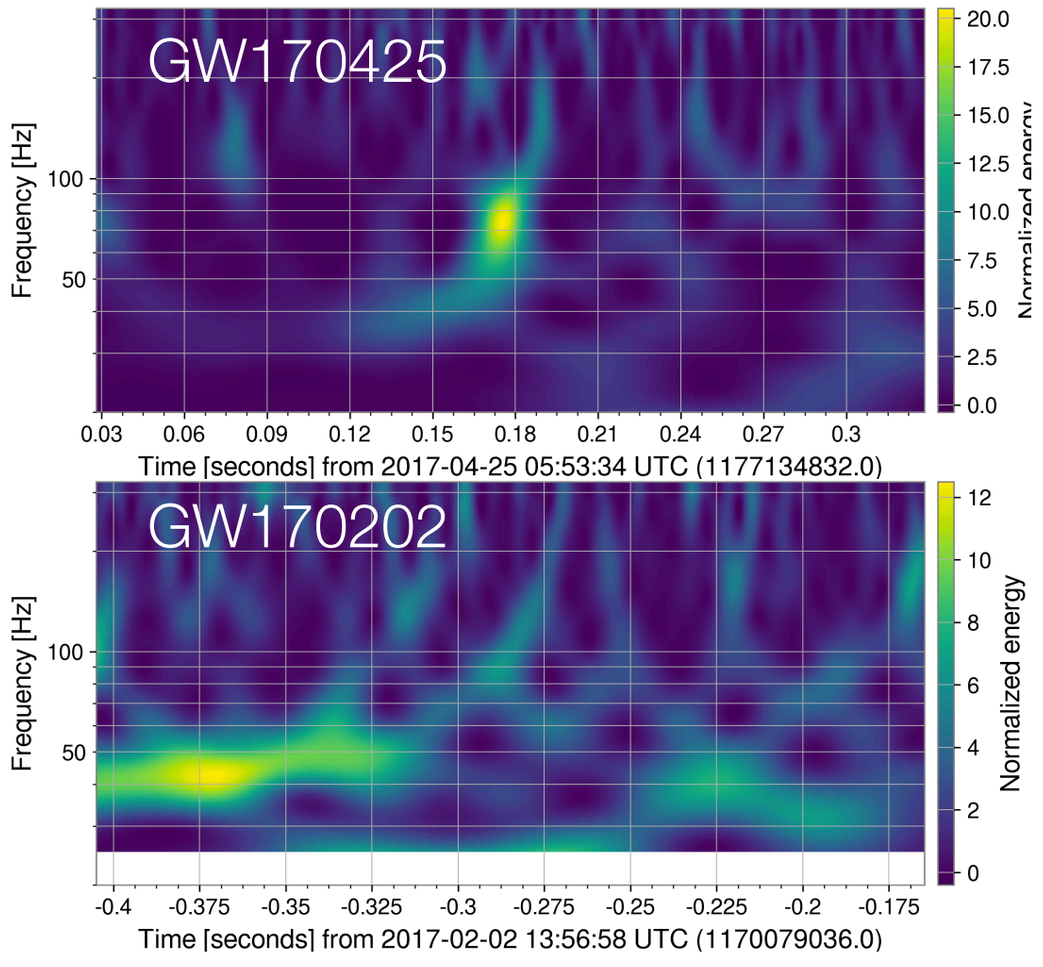


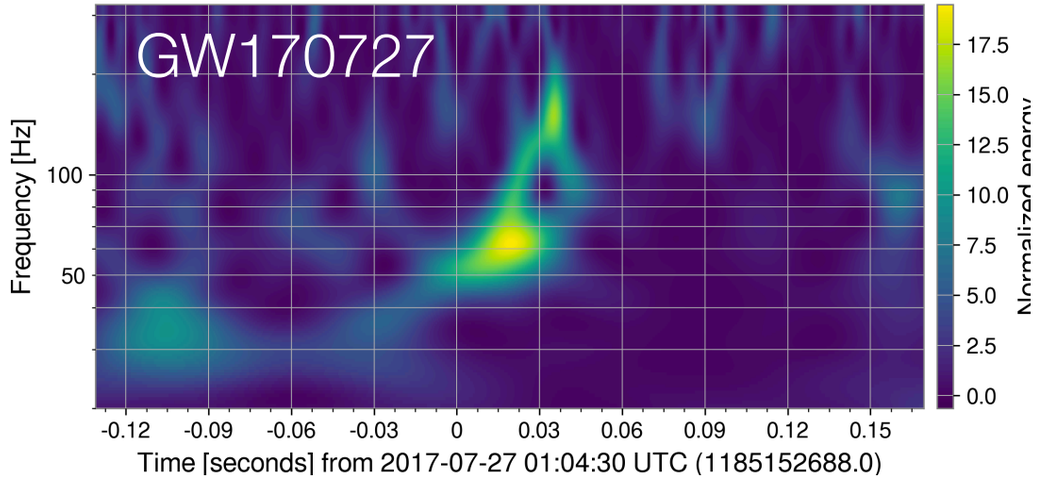
Name	Bank	$\mathcal{M}^{\rm det}(\mathrm{M}_\odot)$	$\chi_{\rm eff}$	z	GPS time[a]	$\rho_{\rm H}^2$	$\rho_{\rm L}^2$	$\mathrm{FAR}^{-1}(\mathrm{O2})$[b]	$\frac{W(\mathrm{event})}{\mathcal{R}(\mathrm{event}\|\mathcal{N})}$ (O2)	$p_{\rm astro}$
GW170121	BBH (3,0)	29^{+4}_{-3}	$-0.3^{+0.3}_{-0.3}$	$0.24^{+0.14}_{-0.13}$	1169069154.565	29.4	89.7	2.8×10^3	> 30	> 0.99
GW170304	BBH (4,0)	47^{+8}_{-7}	$0.2^{+0.3}_{-0.3}$	$0.5^{+0.2}_{-0.2}$	1172680691.356	24.9	55.9	377	13.6	0.985
GW170727	BBH (4,0)	42^{+6}_{-6}	$-0.1^{+0.3}_{-0.3}$	$0.43^{+0.18}_{-0.17}$	1185152688.019	25.4	53.5	370	11.8	0.98
GW170425	BBH (4,0)	47^{+26}_{-10}	$0.0^{+0.4}_{-0.5}$	$0.5^{+0.4}_{-0.3}$	1177134832.178	28.6	37.5	15	0.65	0.77
GW170202	BBH (3,0)	$21.6^{+4.2}_{-1.4}$	$-0.2^{+0.4}_{-0.3}$	$0.27^{+0.13}_{-0.12}$	1170079035.715	26.5	41.7	6.3	0.25	0.68
GW170403	BBH (4,1)	48^{+9}_{-7}	$-0.7^{+0.5}_{-0.3}$	$0.45^{+0.22}_{-0.19}$	1175295989.221	31.3	31.0	4.7	0.23	0.56

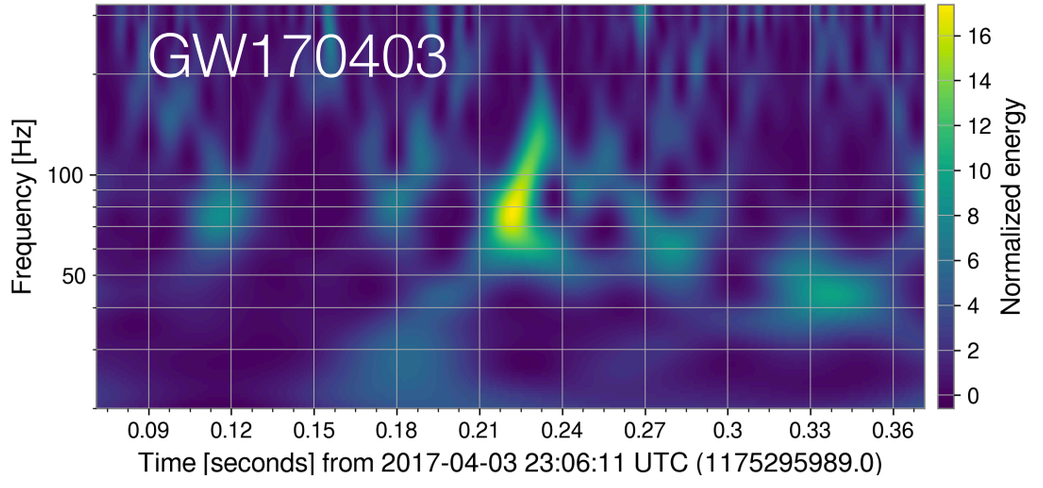
TV et. al., (2019b)

Our search: O2

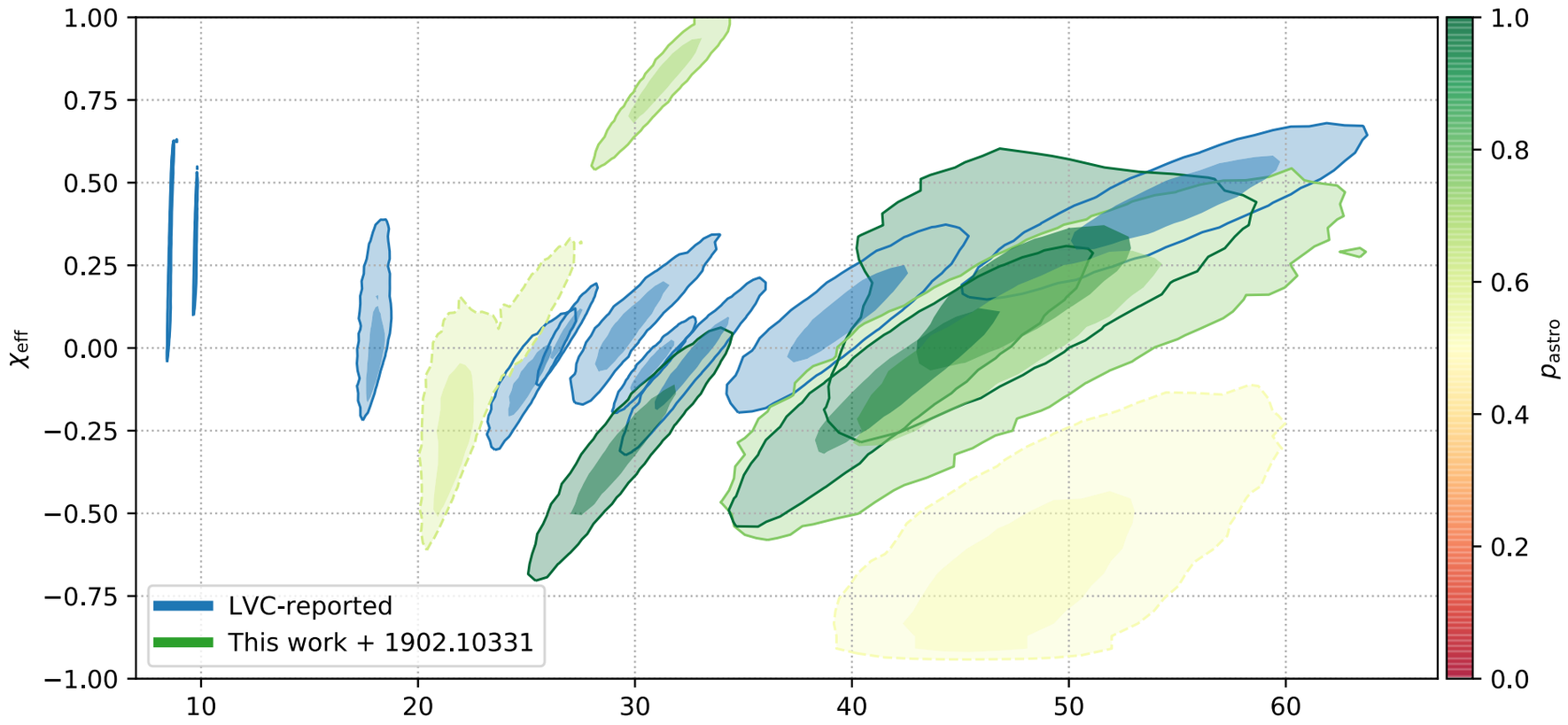


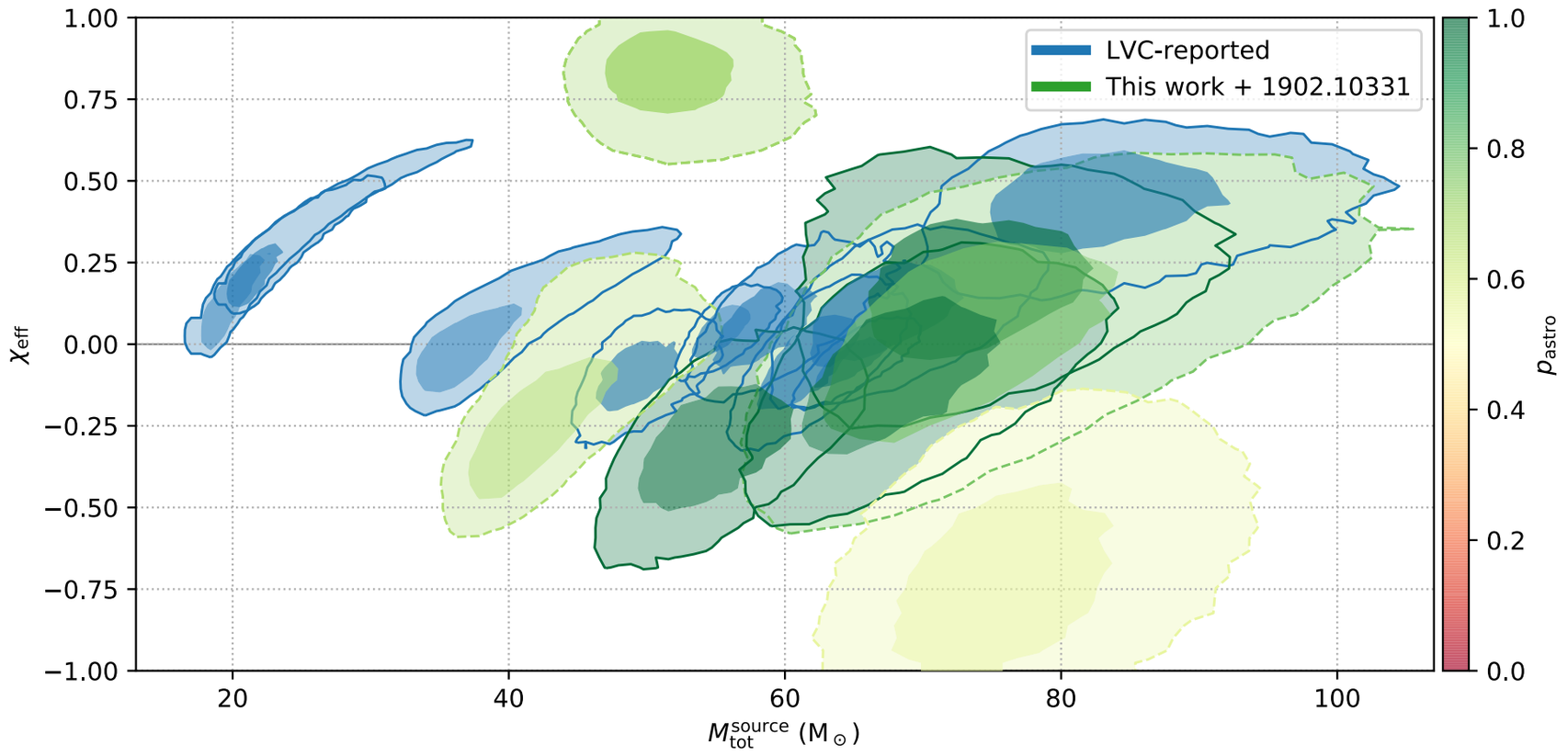






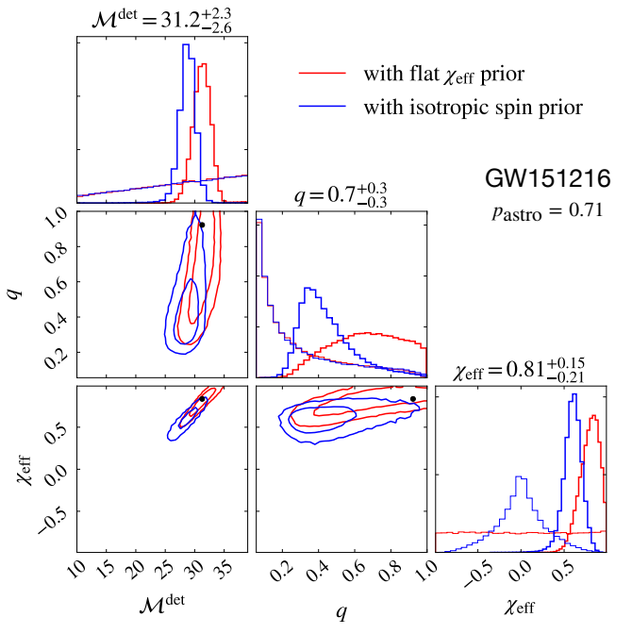
Parameters of the New Events

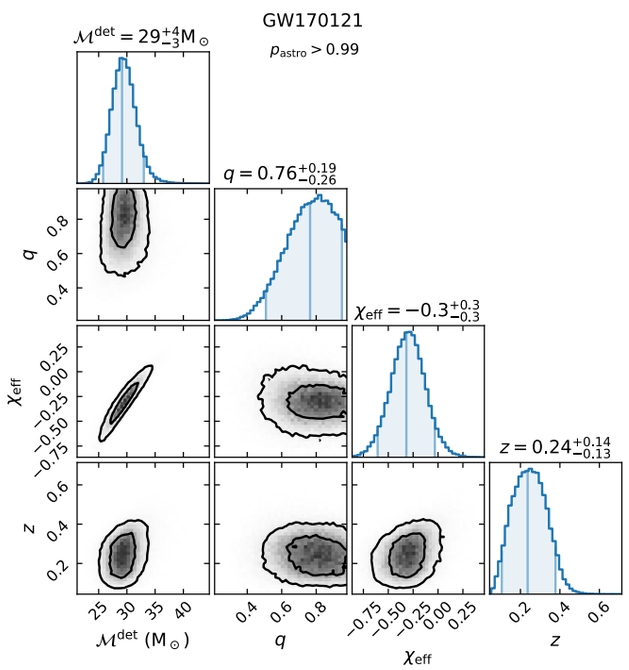


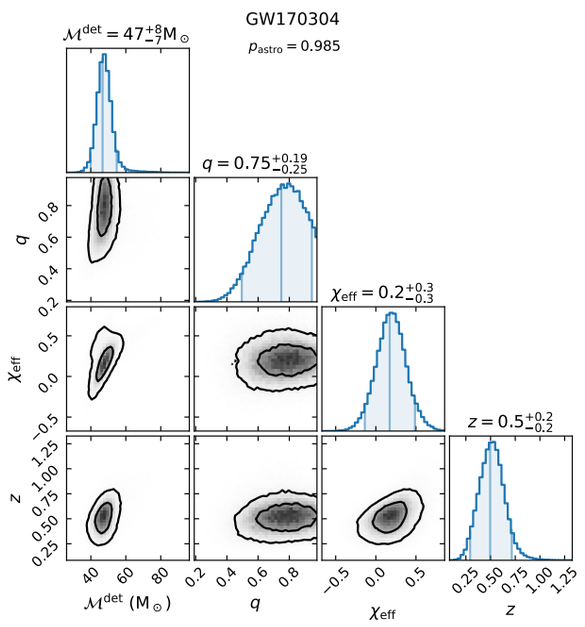


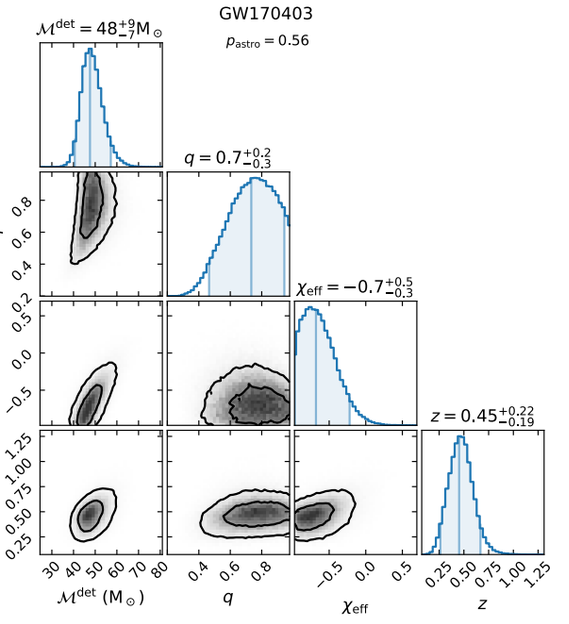
TV et. al., (2019b)

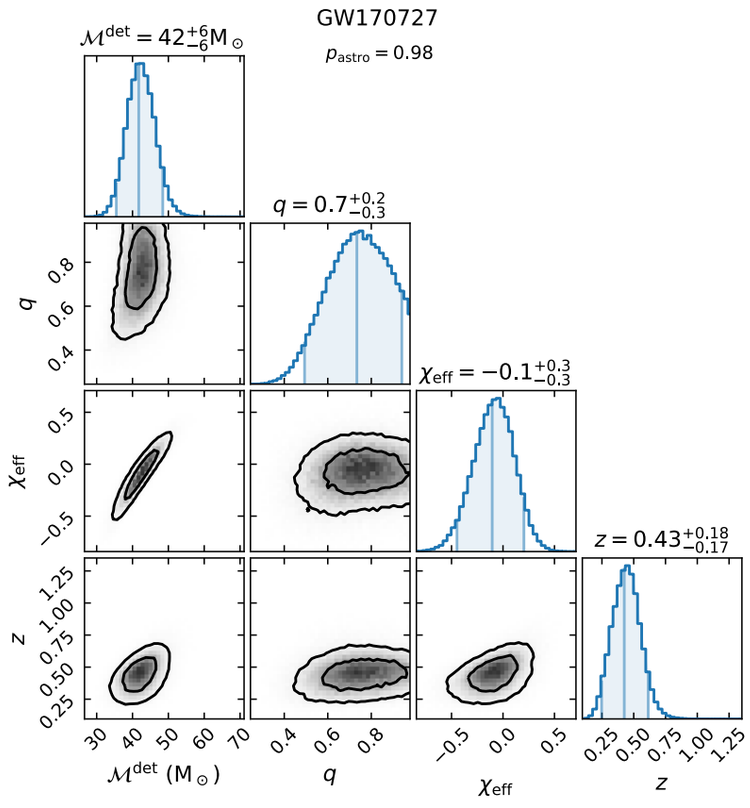
Parameters of the New Events

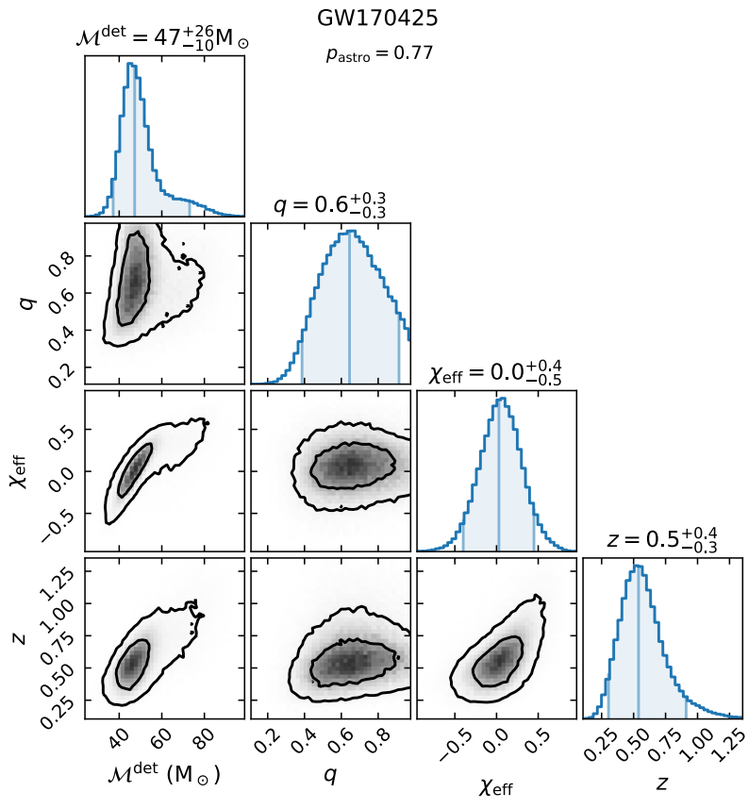


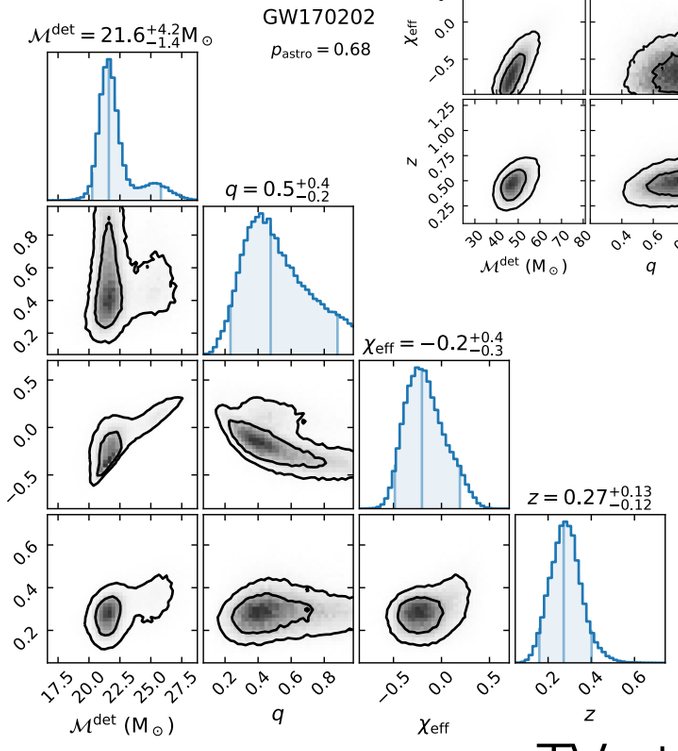






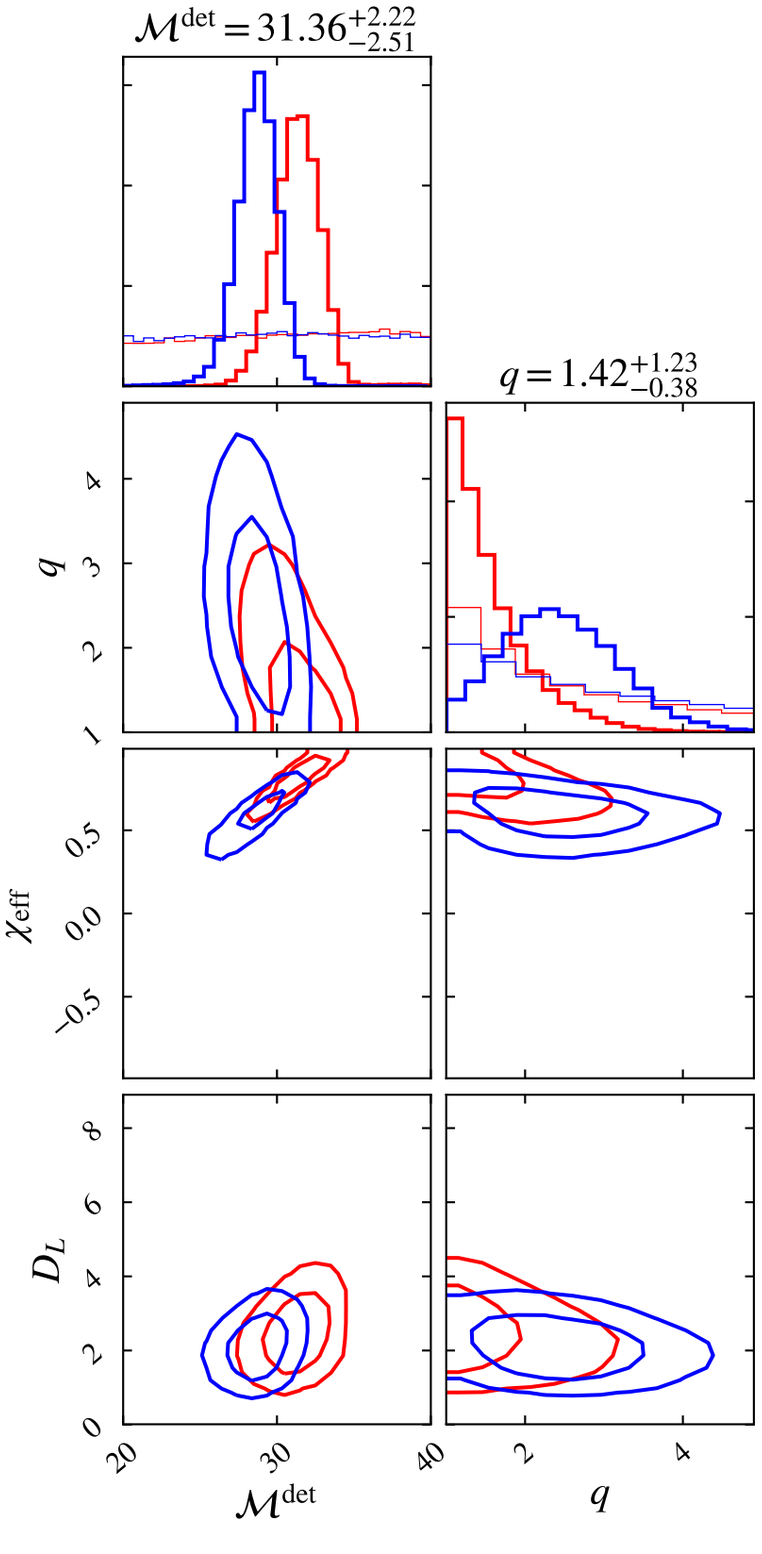


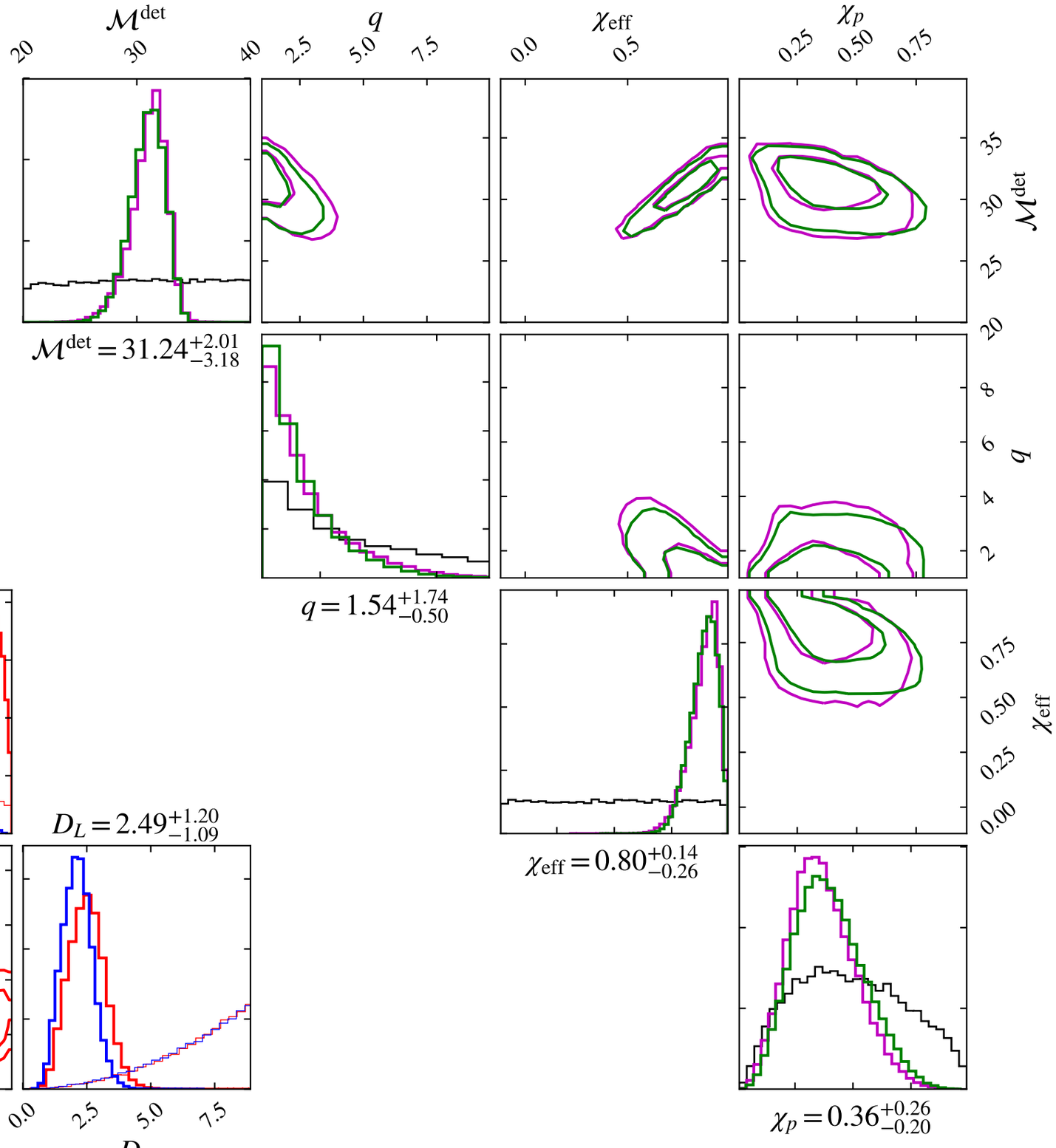




TV et. al., (2019b)

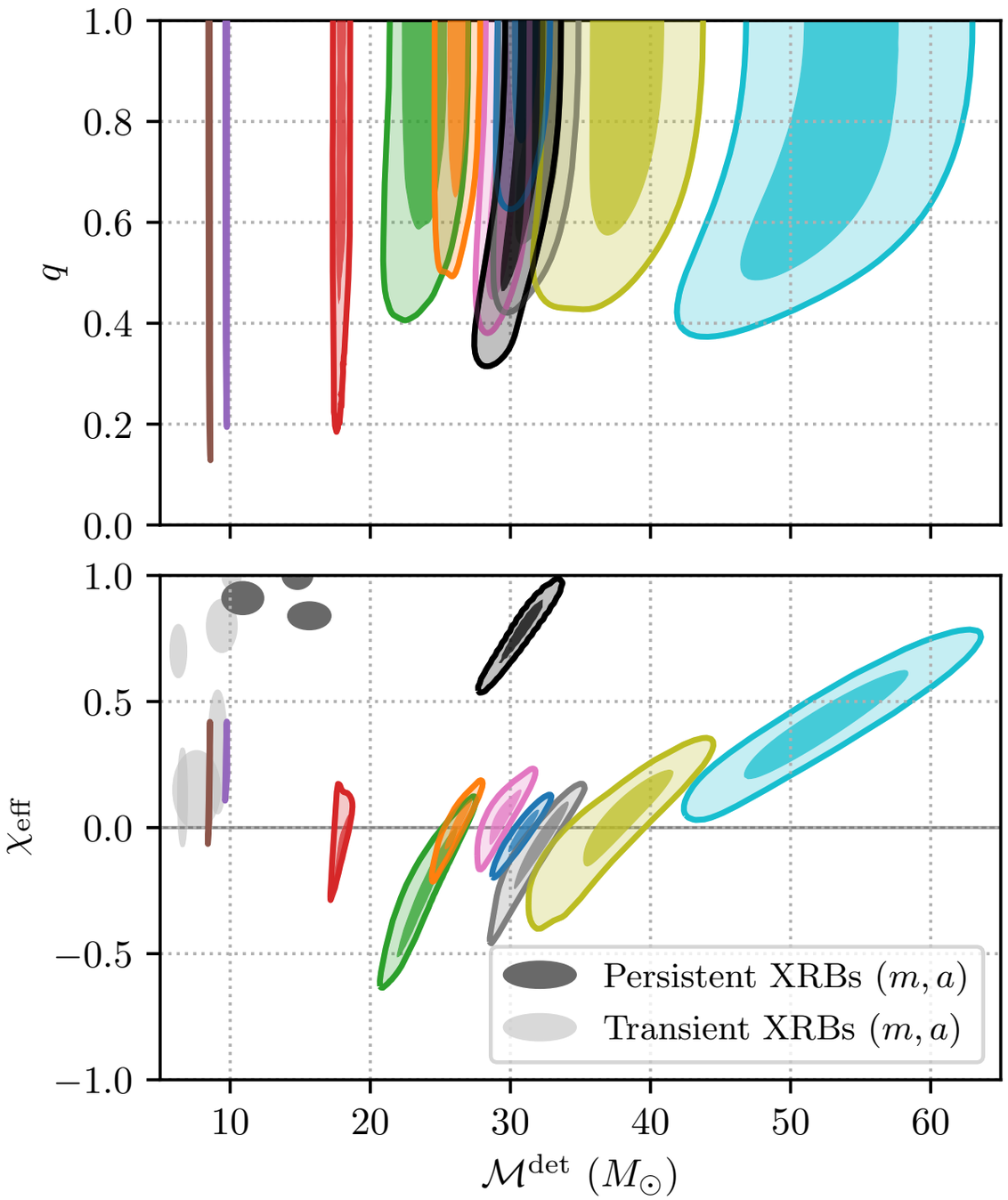
GW151216

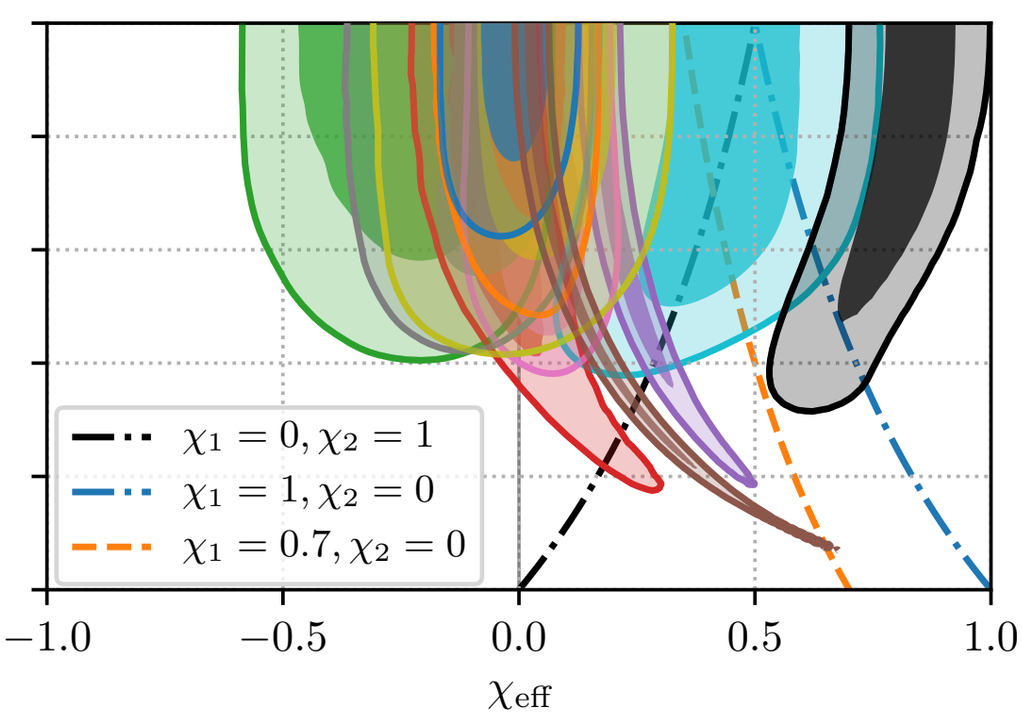




Zackay et. al., (2019)

GW151216





GW170608
GW151226
GW151012
GW170104
GW170814
GW170809
GW150914
GW170818
GW170823
GW170729
GW151216

$$\chi_{\rm eff} = \frac{\chi_1 + q\chi_2}{1 + q}$$

Zackay et. al., (2019)

Formation Scenarios for BBHs in the Literature

Field binaries (common envelope evolution)

Field binaries (chemically homogenous evolution)

Field triple systems

Few body interactions in: GCs, open clusters

Few body interactions + tides in: NSCs, GCs

Binaries in AGN disks

Population III stars

Primordial black holes

arxiv: 1811.12907

Formation Scenarios for BBHs in the Literature

Field binaries (C.E)

Field binaries
(Ch. homog. evol)

Field triple systems

Primordial black holes

Globular clusters

Open clusters

Nuclear star clusters

AGN disks

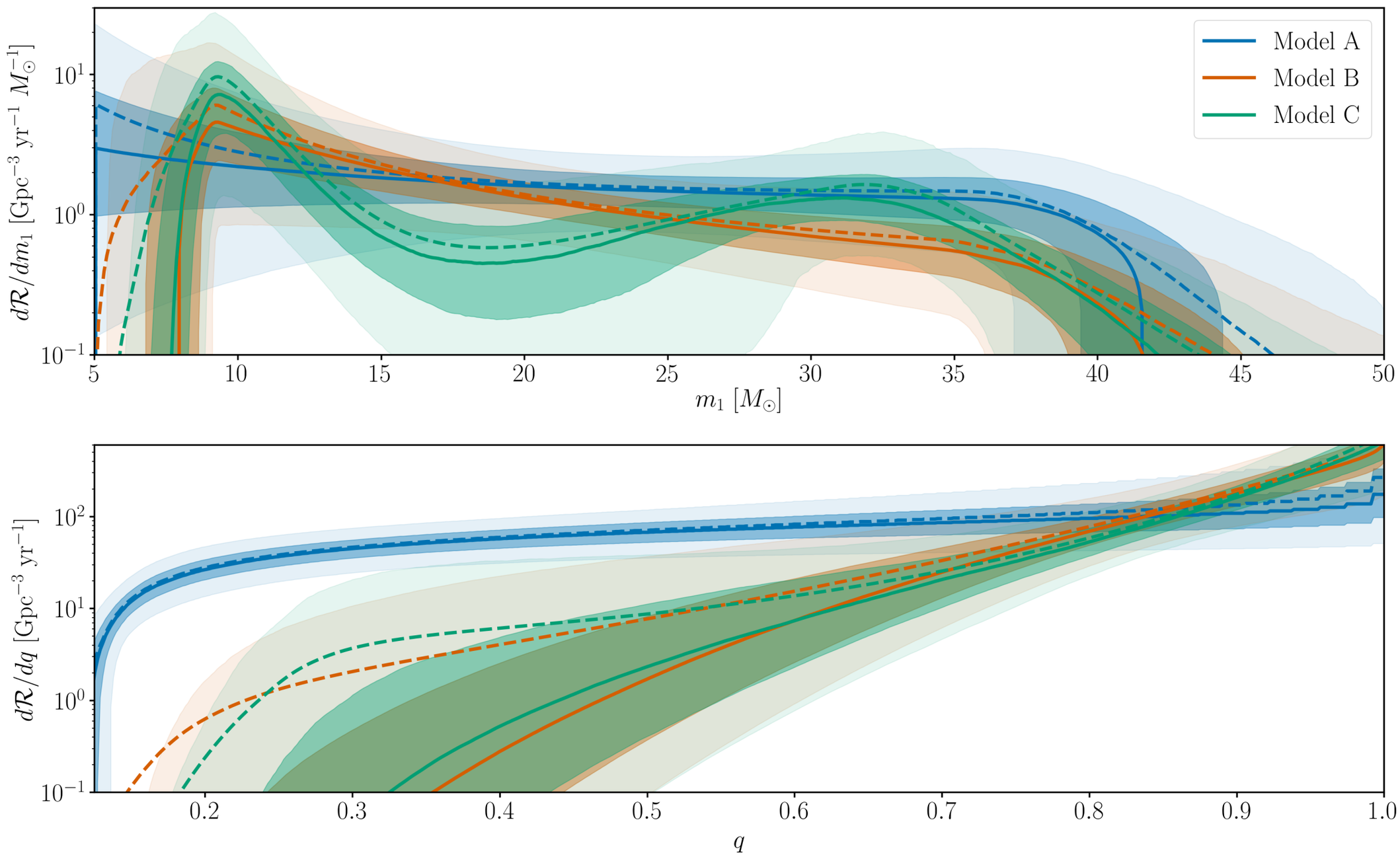
Pop. III stars

Abundant systems, with low merger efficiency

Known ingredients

Purely gravitational evolution to merger

LVC Rates



$$R = 53.2^{+58.5}_{-28.8}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

arxiv: 1811.12907

Parameter Distribution - caveats

- Isolated binaries have high and aligned spins due to tides? Natal kicks, winds and BBH formation at large merger times
  R. O'Shaughnessy et. al. (2017), Kushnir et. al. (2016)

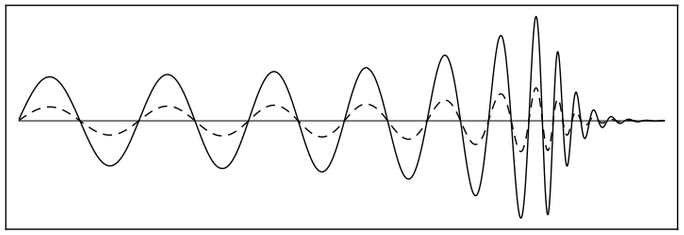
- Triples have randomly aligned spins? Highly hierarchical systems favor in-plane spins
  Liu et. al., (2018), Antonini et. al. (2018), Liu et. al., (2019)

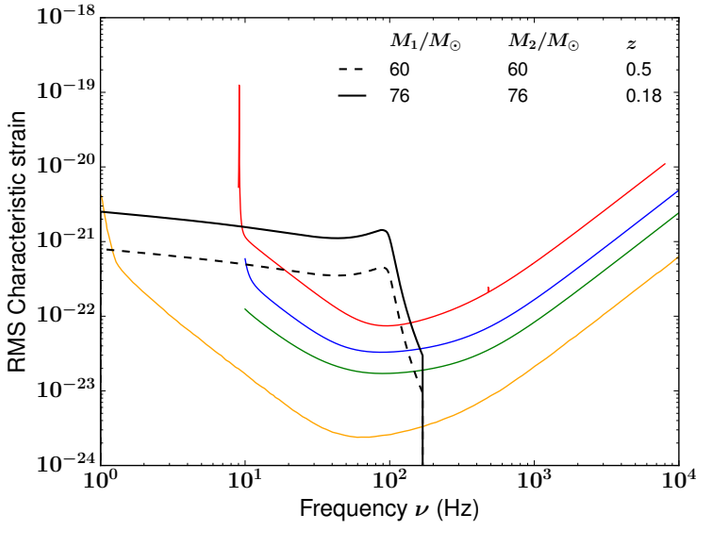
- Field binaries have no eccentricity in the LIGO band? Fortuitous natal kicks can lead to eccentricity
  Eldridge and Stanway (2016)

Strong Lensing of SN

Strong Lensing of GWs

Geometrical optics





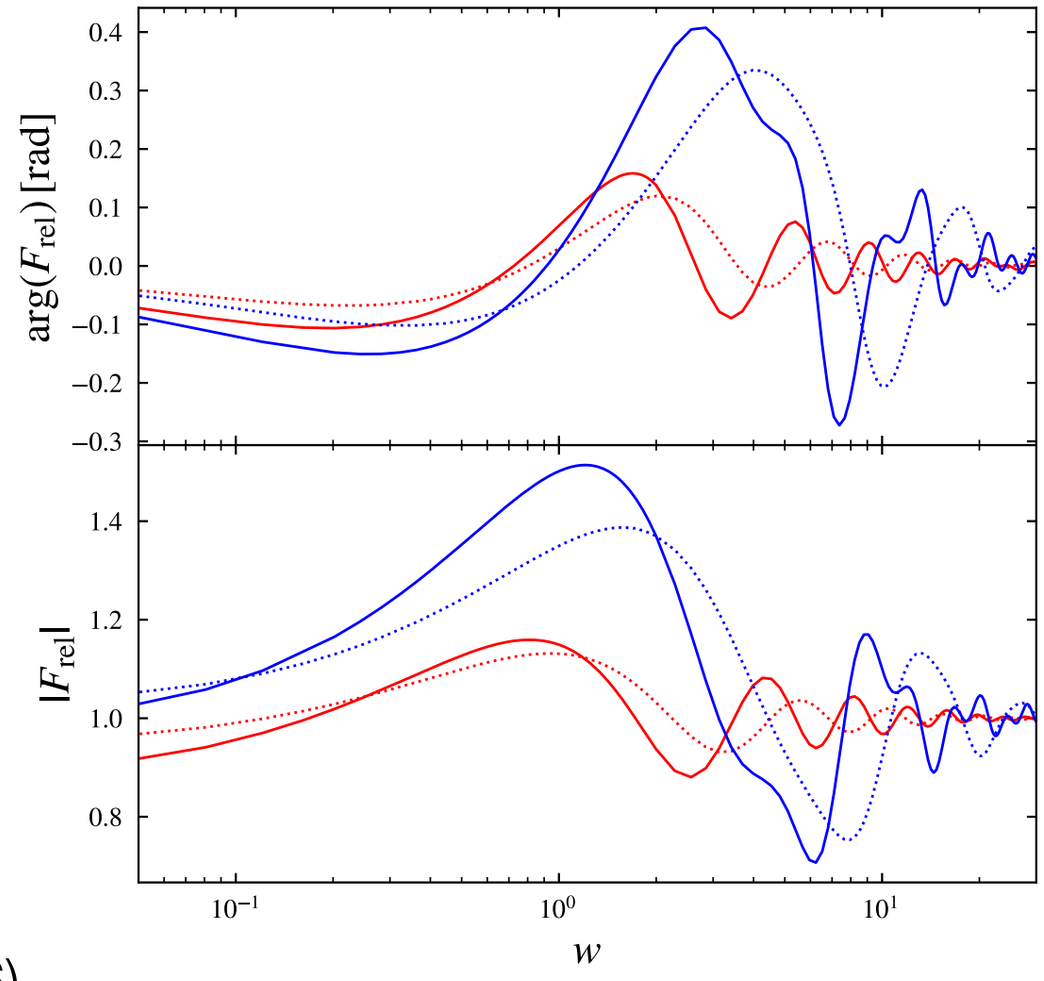
$$M(1+z) = \tilde{M}(1+\tilde{z})$$

$$d_L(\tilde{z}) = d_L(z)/\sqrt{\mu}$$

Dai et. al., (2016)

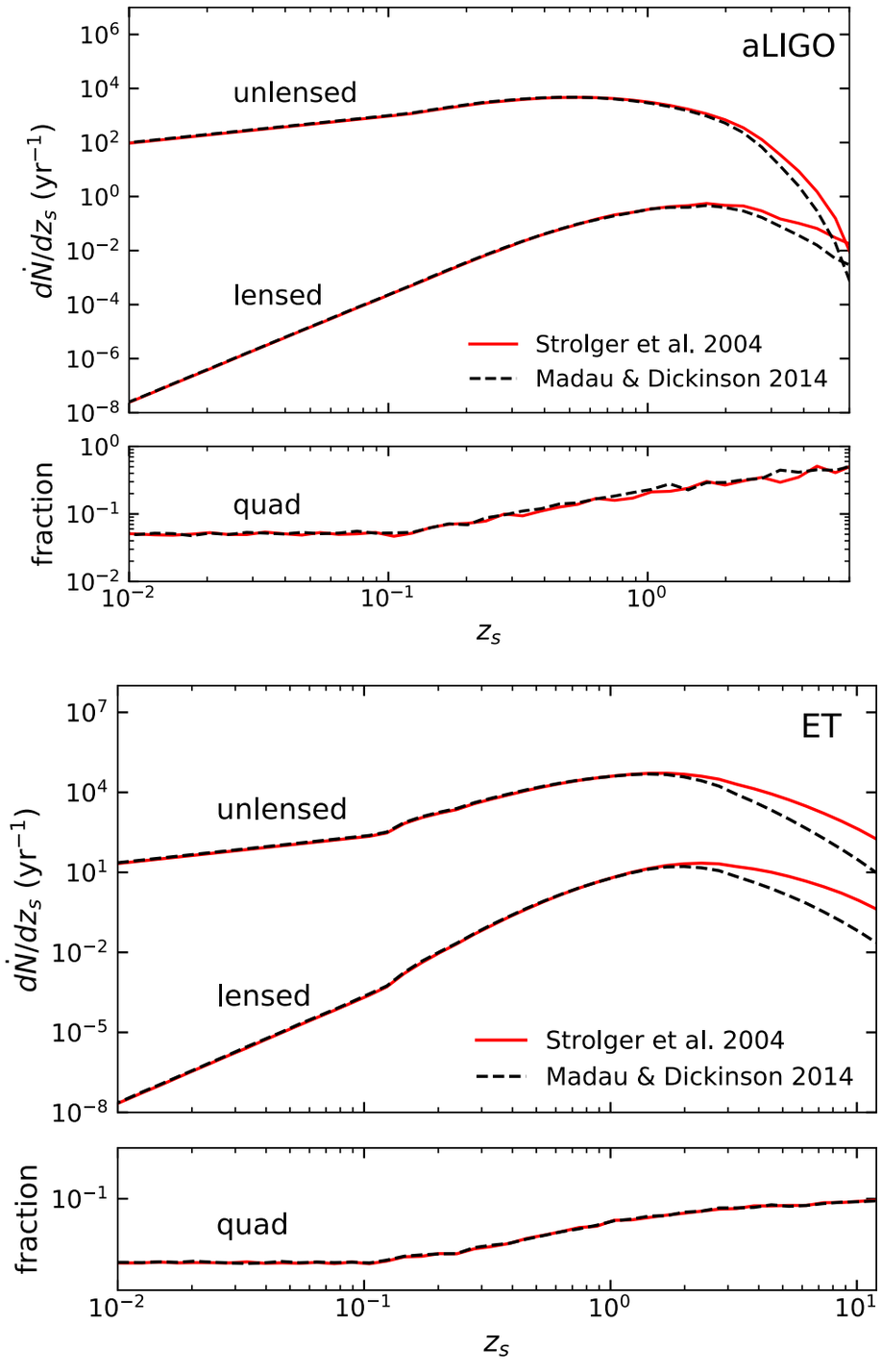
Wave optics

$$h_{\rm L}(f) = F(f)h(f)$$

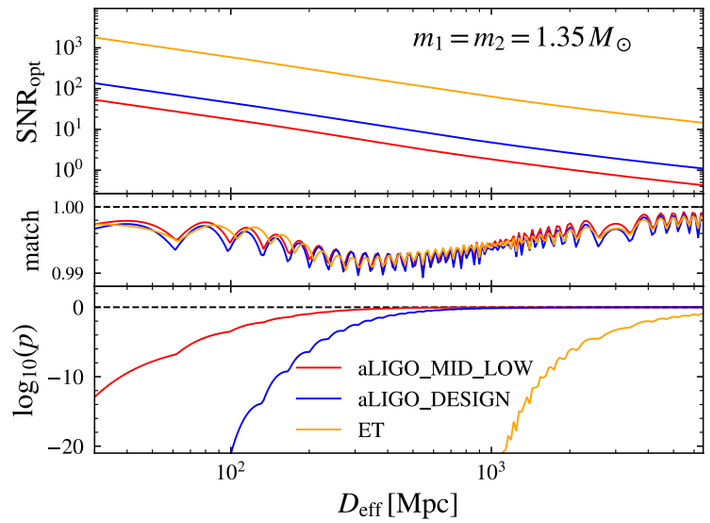


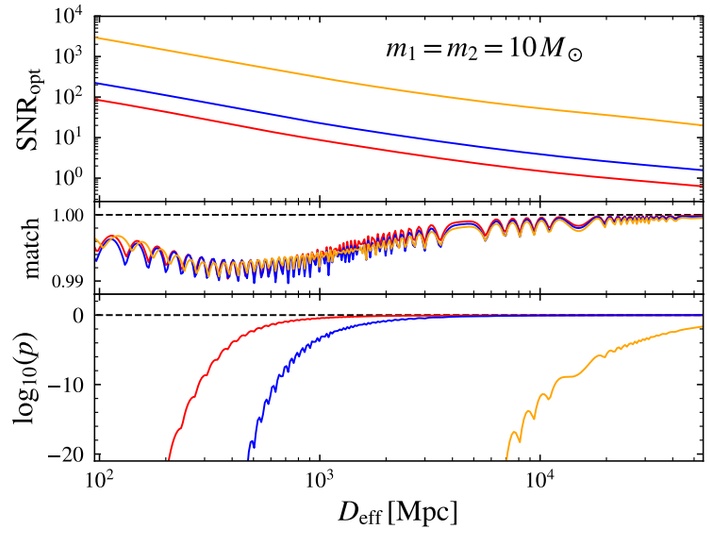
Takahashi (2004)

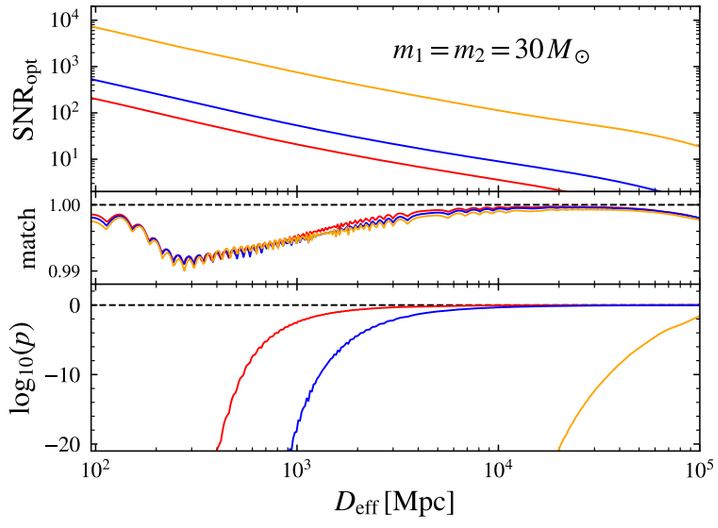
Strong Lensing of GWs



Mao et. al., (2018)





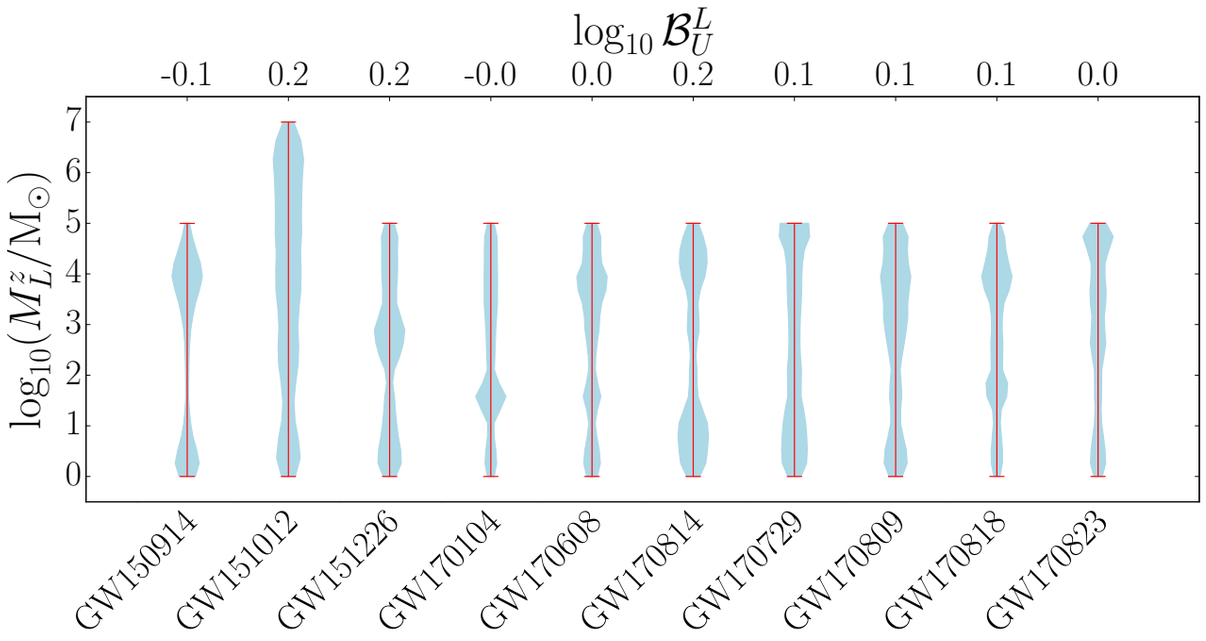


Dai et. al., (2016)

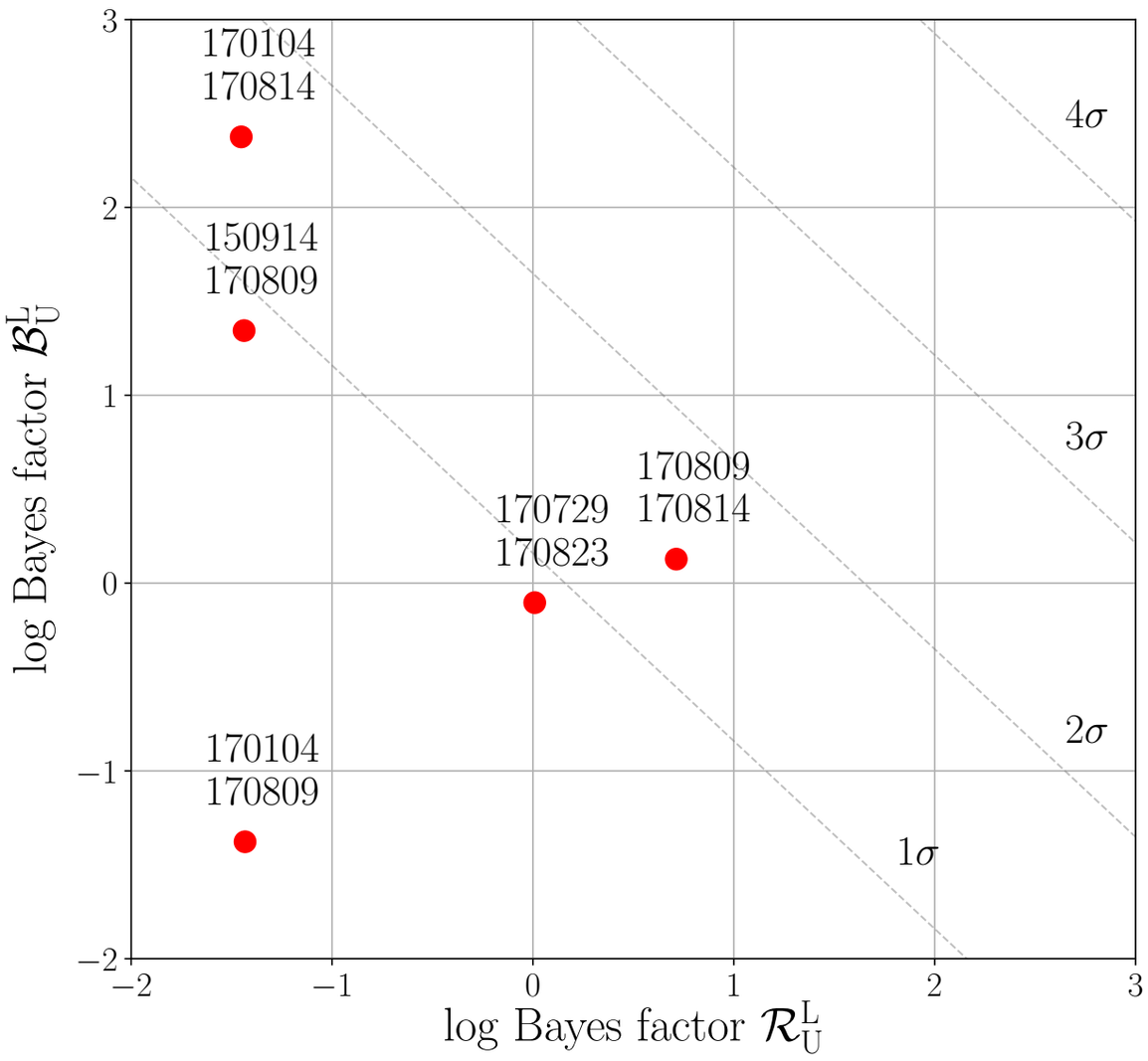
Analysis of O1+2 events

$$\mathcal{B}^{\mathrm{L}}_{\mathrm{U}} = \int d\boldsymbol{\theta}\, \frac{P(\boldsymbol{\theta}|d_1)\, P(\boldsymbol{\theta}|d_2)}{P(\boldsymbol{\theta})}$$

$$\mathcal{R}^{\mathrm{L}}_{\mathrm{U}} = \frac{P(\Delta t_0|\mathcal{H}_{\mathrm{L}})}{P(\Delta t_0|\mathcal{H}_{\mathrm{U}})}$$



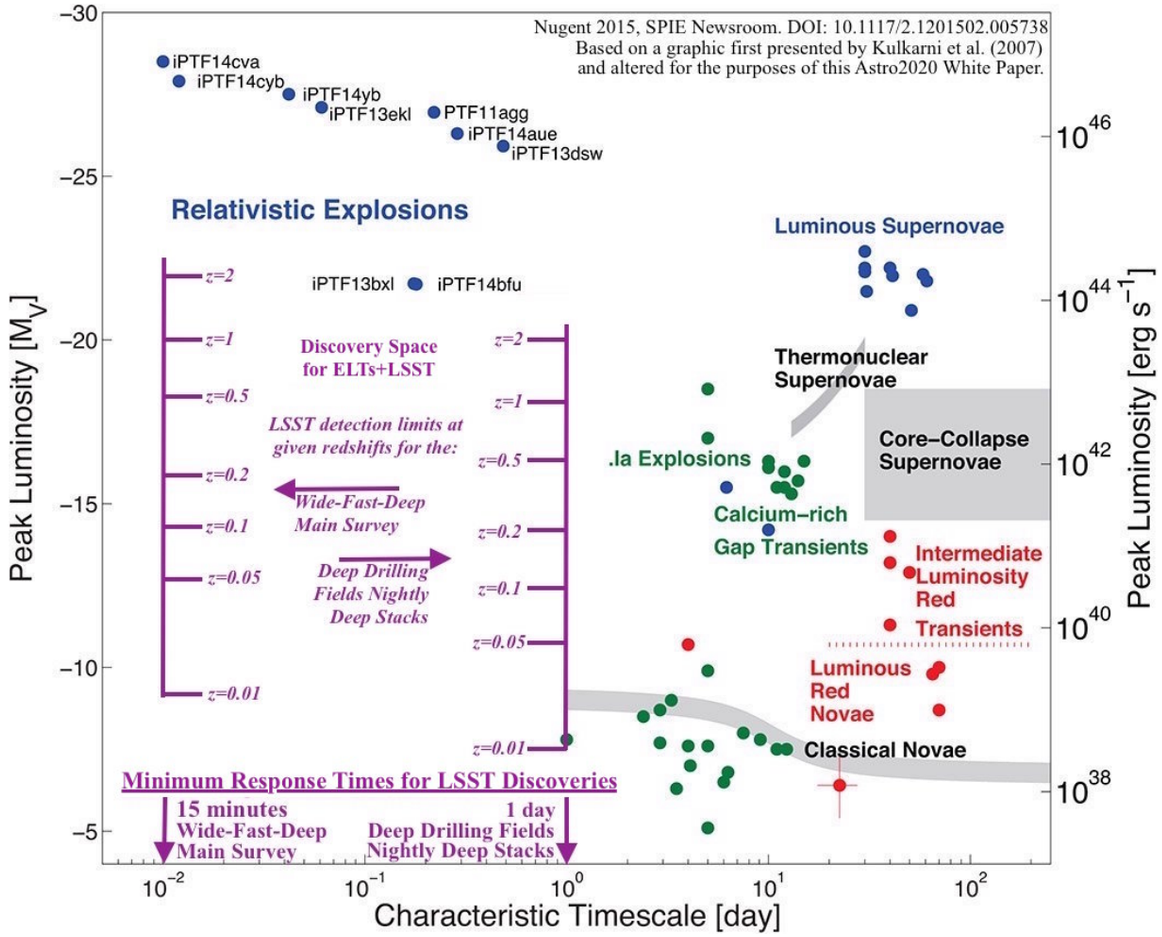
Wave optics

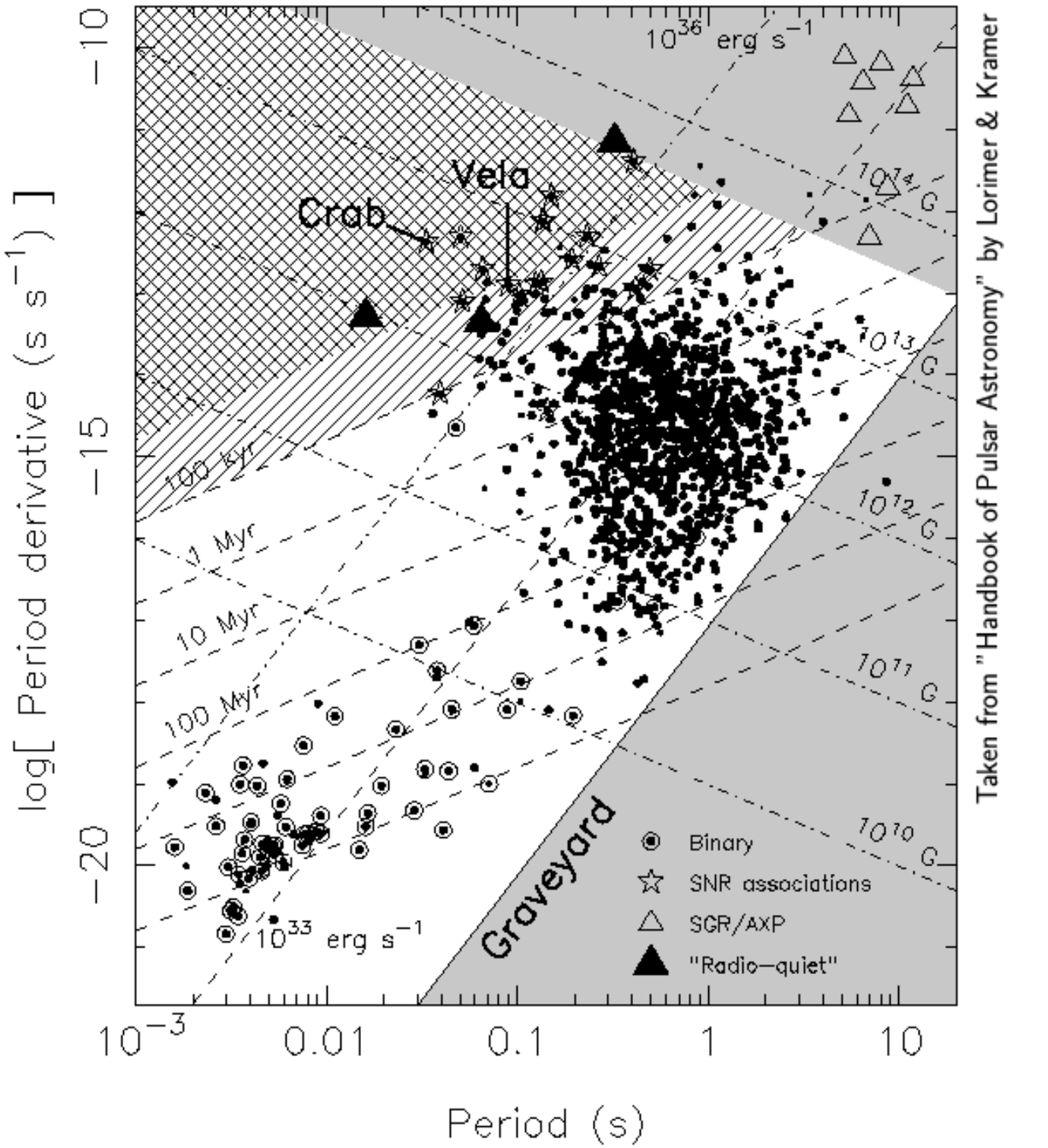


Geometrical optics

Hannuksela et. al. (2019)

Parameter Space and Population Modeling





arxiv: 1904.05957

`f-fdot' Diagram for GW Sources