A directed search for gravitational waves from Scorpius X-1 with initial LIGO
(LIGO-P1400094)

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Overview

- ## Scorpius X-1 (Sco X-1)
  - » Neutron star in binary system
  - » Most luminous extra solar X-ray source
  - » GW emission estimated by torque balance limit
  - » Unknown spin frequency

- ## Sideband algorithm
  - » Existing coherent F-statistic (matched filter)
  - » Orbital motion modulates signal frequency
  - » Sum of frequency modulated F-statistic sidebands

- ## S5 search
  - » Pilot study
  - » observation time-span limited to 10 days because of spin wandering
  - » 50-550 Hz search band

http://www.ralf-schoofs.de/galerien/astronomie/scorpius-x1/
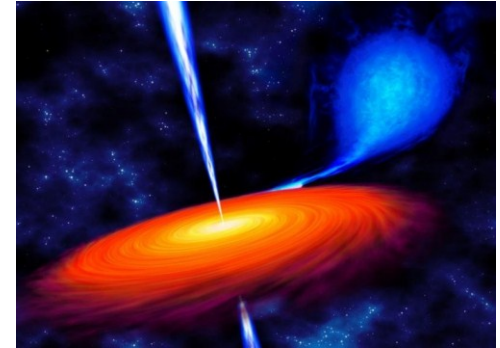
Torque balance limit

- ## Approximate upper bound on h_0
  - » Assume angular momentum gained from accretion is balanced by angular momentum lost via gravitational wave emission

$$h_0^{EQ} \approx 7 \times 10^{-26} \left(\frac{F_X}{F_X^{ScoX1}} \right)^{1/2} \left(\frac{R}{10 \text{km}} \right)^{3/4} \left(\frac{1.4 M_\odot}{M} \right)^{1/4} \left(\frac{150 \text{Hz}}{f_{GW}} \right)^{1/2}$$

- ## Current best h_0 LIGO upper limit from S5 radiometer search (at 150 Hz):

$$h_0^{95} \approx 2 \times 10^{-24}$$

Method

1. S. M. Ransom, et. al., Ap. J., 589, 911 (2003)
2. C. Messenger and G. Woan, CQG, 24, 469 (2007)
3. L. Sammut, et al., Phys. Rev. D, 89, 043001 (2014)

- **Existing software**
  - » Coherent F-statistic (matched filtering)
  - » Eg. Cas A, Supernovae remnants search

- **Sideband method**[1,2,3]
  - » Incoherent sum of frequency modulated F-statistic sidebands
  - » C-statistic = convolution of F-statistic with sideband template

F-statistic $\otimes$ Sideband Template $=$ C-statistic

Frequency   Frequency   Frequency
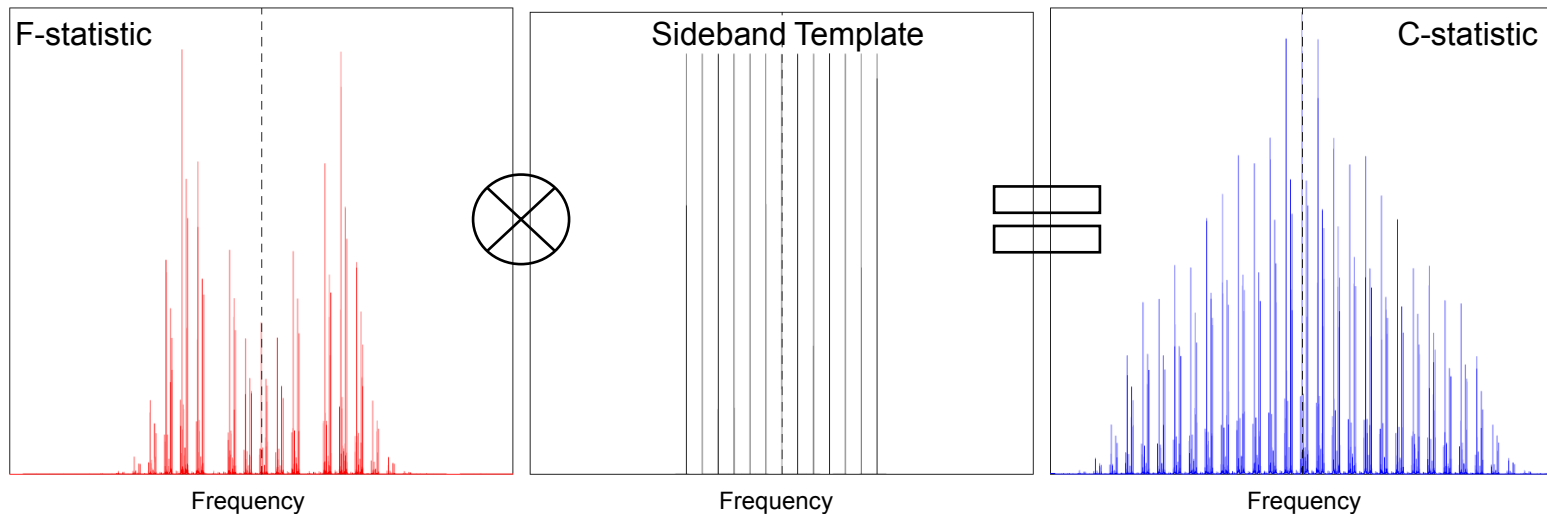
Results

- ## Signal-based veto
  - » Designed to remove non-Gaussian outliers
  - » Reduced 24 outliers to 8 candidates

- ## Manual inspection
  - » Reduced 8 candidates to 3 after visual inspection
  - » Consistent with noise at a 1% level

- ## Candidate follow-up
  - » 3 remaining candidate bands followed up in 2 other 10-day observations
  - » No significant candidates in other observations
  - » Combined C-statistic not significant (combined P-values ≥ 0.6)

- ## No detection

Upper Limits

- ## 95% ULs on GW strain for 50-550 Hz band

  - » Range of ULs for each 1-Hz search band

  - » Median UL provides robust and representative estimate of the sensitivity of the search

  - » $h_0^{95} \approx 1.3 \times 10^{-24}$ and 8×10^{-25} for the standard and angle-restricted searches respectively, at 150 Hz.

- ## Improve on previous results

  - » 10-day coherent observation time and minimal computational expense

  - » 1.4 and 2.3 improvement on previous Sco X1 directed UL at 150 Hz

    - – S5 radiometer search returned a most sensitive median 95% strain upper limit at of $h_0^{95} \approx 2 \times 10^{-24}$ at 150 Hz[J. Abadie et al., Physical Review Letters, 107, 271102 (2011)]

Summary

- ## Sideband Search
  - » Pilot study, 10 days of S5 data, 50-550 Hz band
  - » Demonstrates use of sideband method on LIGO data
  - » Beats previous upper limits across search band
    - – factors of 1.4 (standard) and 2.3 (angle restricted) at 150 Hz

- ## Upper limits
  - » Constrained GW strain amplitude of NS in Sco X-1 system
  - » Significant sensitivity improvement over previous Sco X-1 searches

- ## Search and paper draft extensively reviewed
  - » Procedure validated
  - » Panel review, CW review
  - » Paper presented to DAC and posted to LVC for comments

- ## Intend to submit to PRD

Acknowledgements
Review panel: Eric Thrane, Alberto Vecchio (and Teviet Creighton)
CW internal reviewers: Karl Wette and Holger Pletch
Keith Riles and the CW group
Bruce Allen and the AEI

Sco X-1 system parameters

- Sky position, binary orbital parameters, orientation angles, NS spin frequency

TABLE II: Sco X-1 system parameters required for the sideband search. Directly observable parameters are presented in the top half of the table. The bottom half, separated by the horizontal line, displays search limits and constraints derived from these.

Parameter	Symbol	Value	Units	Uncertainty	References
Right Ascension	α	$16^h 19^m 55^s.0850$	mas	± 0.3	[71]
Declination	δ	$-15°38'24.9''$	mas	± 0.3	[71]
Proper motion	μ	14.1	mas yr^{-1}		[71]
Parallax	π_β	0.36	mas	± 0.04	[71]
Moment of inertia	I	10^{38}	kg m^2		[71]
Accretion rate	$\dot{M}$	1.23×10^{15}	kg s^{-1}		[71]
Bolometric X-ray flux	F_X	40×10^{-8}	erg cm^{-2}s^{-1}		[28]
Projected semi-major axis light travel time	a	1.44	s	± 0.18	[72]
Orbital Period	P	68023.82	s	± 0.06048	[73]
NS spin inclination angle	ι	44	deg	± 6	[74]
GW polarization angle	ψ	234	deg	± 3	[74]
Time of periapse passage (SSB)	t_p	614638484	s	± 400	[72, 75]
Strain amplitude (at $\nu_s = 300$ Hz)	h_0^{300}	3.5×10^{-26}			Eq. 7
Spin limited observation timespan	T_s^{spin}	13	days		Eq. 55

unknown GW frequency → wideband search

L. Sammut, C. Messenger, A. Melatos, and B. J. Owen, Phys. Rev. D, 89, 043001 (2014)

Results
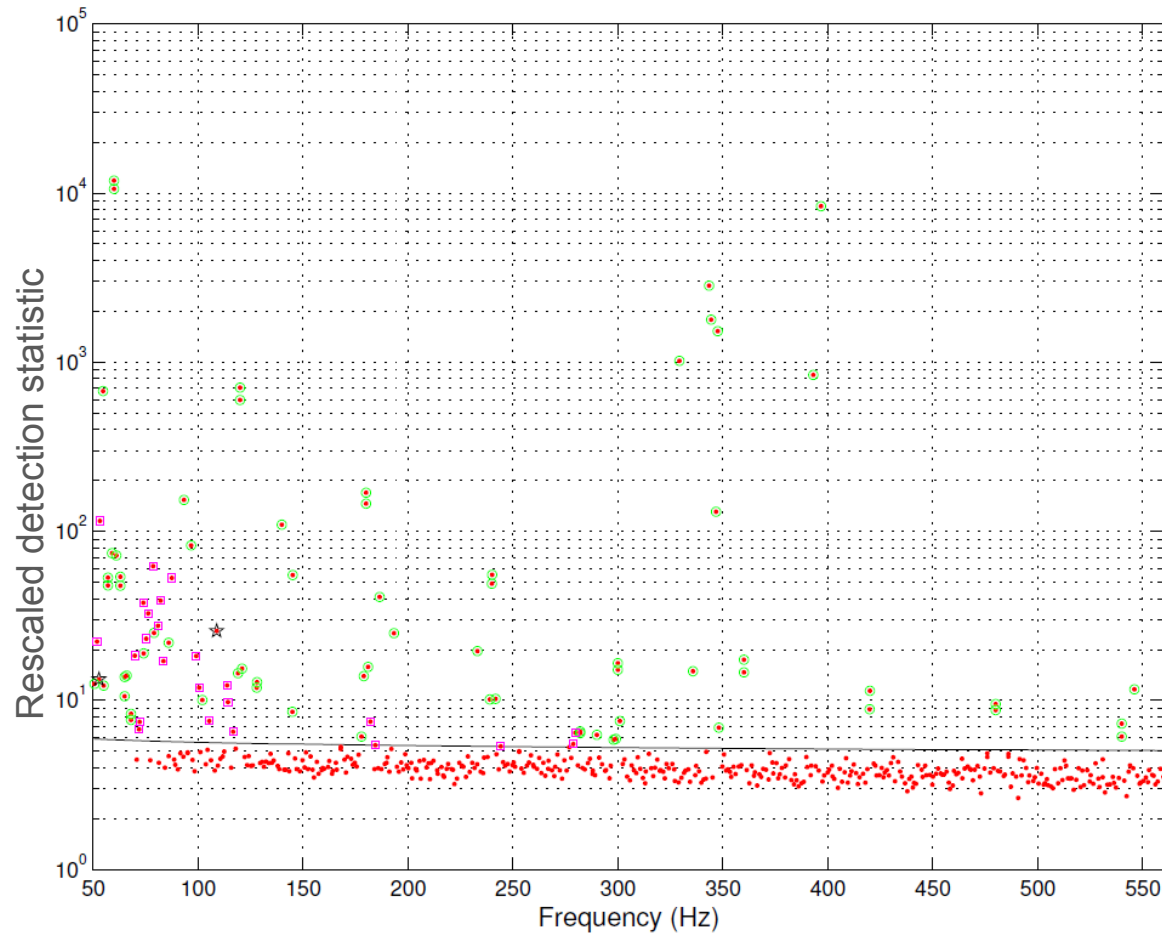
Black curve: 1% multiple trial false alarm threshold

Red points: data

Black stars: isolated hardware injections

Green circles: known noise lines

Pink squares: outliers not consistent with noise

**24 outliers above 1% false alarm rate, expect only O(5) in Gaussian noise.**

Candidates

TABLE IV. Maximum C-statistic from each Hz sub-band exceeding the detection threshold C_N^* for N trials after removing isolated pulsar injections and candidates in bands contaminated by known noise lines. The first column lists the frequency f_{max} at which the maximum C-statistic C_{max} occurs. C_{max} and C_κ^* are listed in the second and third columns, respectively, for comparison.

f_{max} (Hz)	$C_{max}(\times 10^3)$	$C_\kappa^*(\times 10^3)$
51.785819	5.66	4.22
53.258119	14.0	4.38
69.753009	6.88	5.6
71.879543	5.87	5.75
72.124267	6.02	5.82
73.978239	9.23	5.91
75.307963	7.90	6.06
76.186649	9.00	6.13
78.560484	12.3	6.28
80.898939	8.82	6.43
82.105904	10.2	6.58
83.585249	7.93	6.66
87.519459	12.3	6.96
99.113480	9.41	7.87
100.543741	8.72	7.94
105.277878	8.58	8.31
113.764264	9.80	8.91
114.267062	9.55	8.99
116.686578	9.29	9.14
182.150449	14.4	14.1
184.392065	14.3	14.2
244.181829	18.7	18.7
278.712575	21.3	21.2
279.738235	21.5	21.3

TABLE V. Candidates surviving the $4M$ veto. The table lists the start frequency of the 1-Hz sub-band containing the candidate, the expected C-statistic value $4M$, the $P_{a|N} = 1\%$ threshold C_κ^*, and the fraction of C-statistics below $4M$ and above C_κ^* in the range $|f - f_{max}| < M/P$ centred at the bin f_{max} returning C_{max}. The $*$ marks the bands containing the candidates that survive the final, manual veto.

f_{band} (Hz)	$4M$	C_κ^*	$\% < 4M$	$\% > C_\kappa^*$
69	5036	5596	15.3	52.5
71	5180	5746	1.04	1.97
105	7644	8314	1.17	4.02
116	8436	9135	1.34	1.34
184*	13356	14208	27.0	0.0204
244*	17700	18662	33.2	0.00723
278*	20164	21182	14.7	0.0365
279	20236	21255	4.71	4.5

Signal based veto

LIGO-G1401272
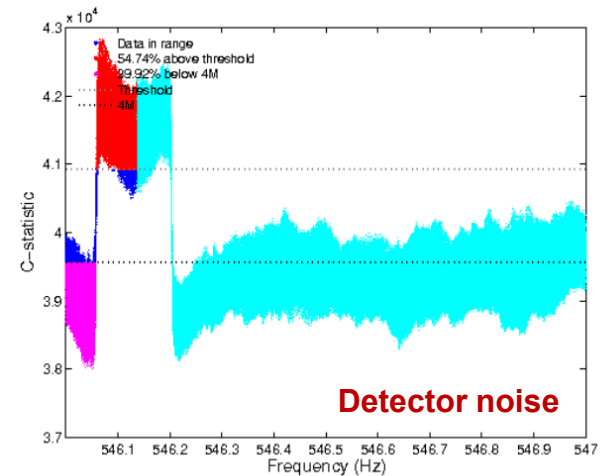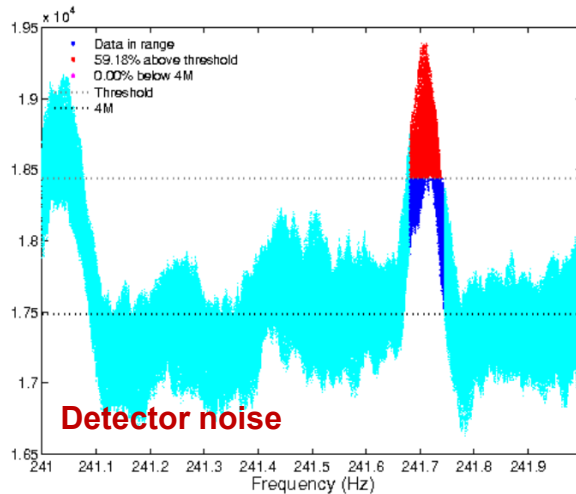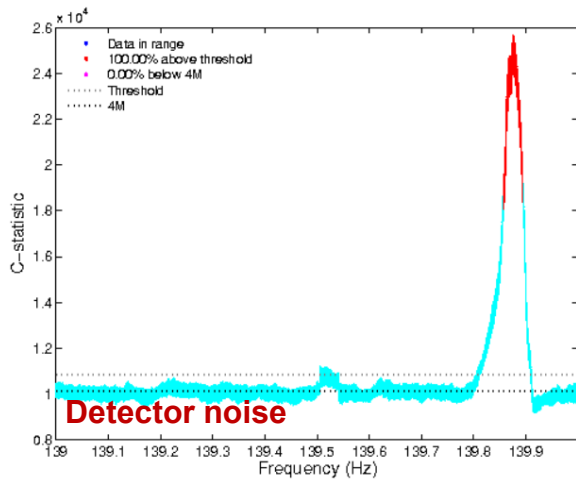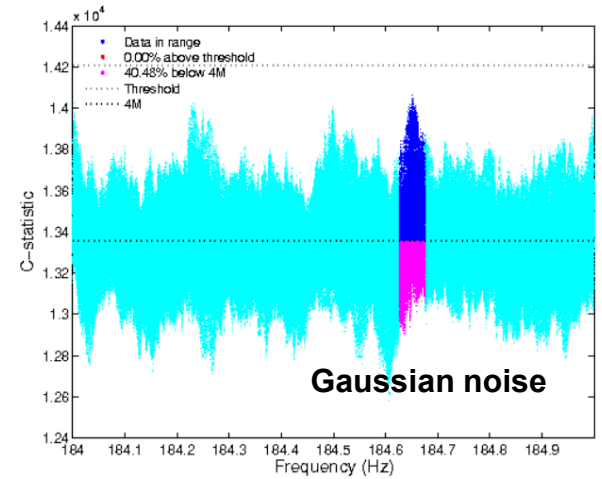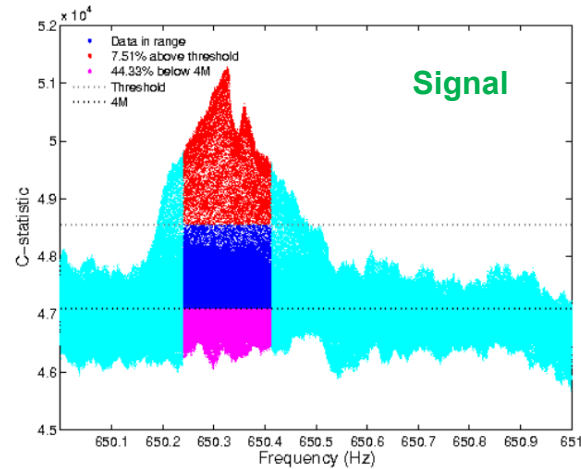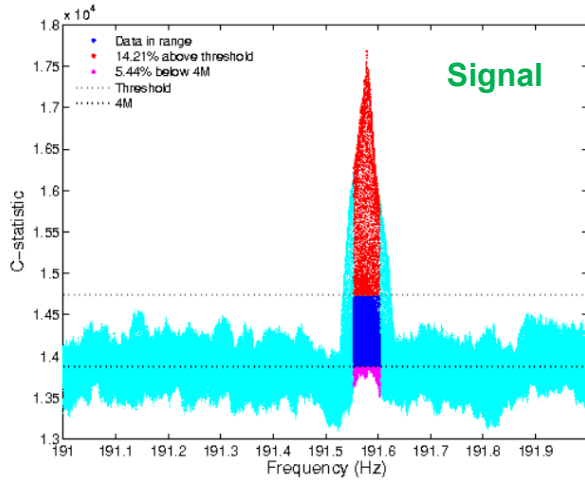
Follow-up

TABLE VI. Results from candidate follow-up for each observation timespan at each Hz frequency band. The fractional percent above C_κ^* and below $4M$ are taken from the expected signal region indicated by the original candidate (which includes a sideband width centred at the candidate, plus the maximum effects of any spin wandering). The P-value is calculated for the maximum C-statistic value in this region. A combined P-value for each candidate is displayed at the bottom of the table.

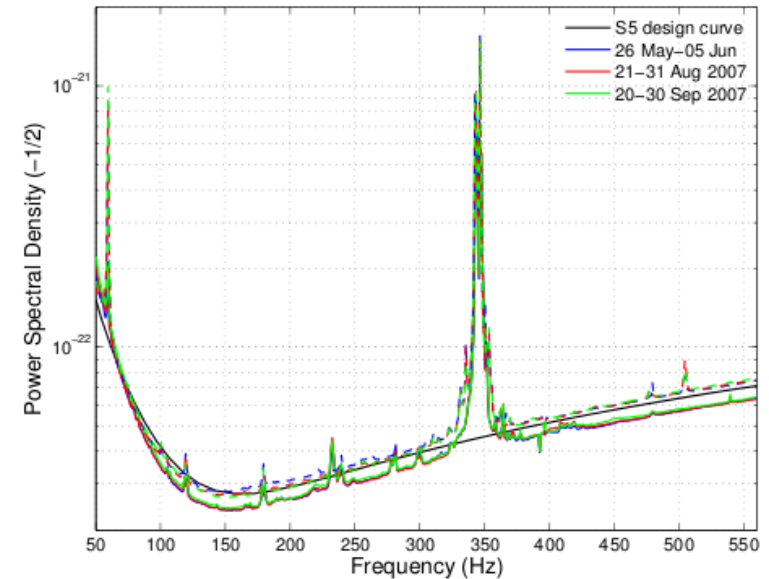| Timespan		184 Hz	244 Hz	278 Hz
21–31 Aug 2007 (original)	% above C_κ^*	0.02	0.01	0.04
	% below $4M$	27.02	33.22	17.72
	P-value	1.03×10^{-5}	1.12×10^{-5}	5.36×10^{-6}
20 – 30 Sep 2007 (follow-up)	% above C_κ^*	0.00	0.00	0.00
	% below $4M$	32.46	46.69	33.54
	P-value	0.92	0.27	0.36
26 May – 05 Jun 2007 (follow-up)	% above C_κ^*	0.00	0.00	0.00
	% below $4M$	41.44	49.27	63.38
	P-value	0.50	0.47	0.15
Combined	P-value	0.99	0.75	0.60

FIG. 8. (colour online) S5 design curve (black) compared to power spectral density of both H1 (solid, lower) and L1 (dashed, upper) detectors during the selected 10 day data stretch (red), which ran from 21–31 August 2007, and the other two stretches used for follow-up (26 May – 05 Jun 2007 indicated in blue, and 20 – 30 Sep 2007 in green).
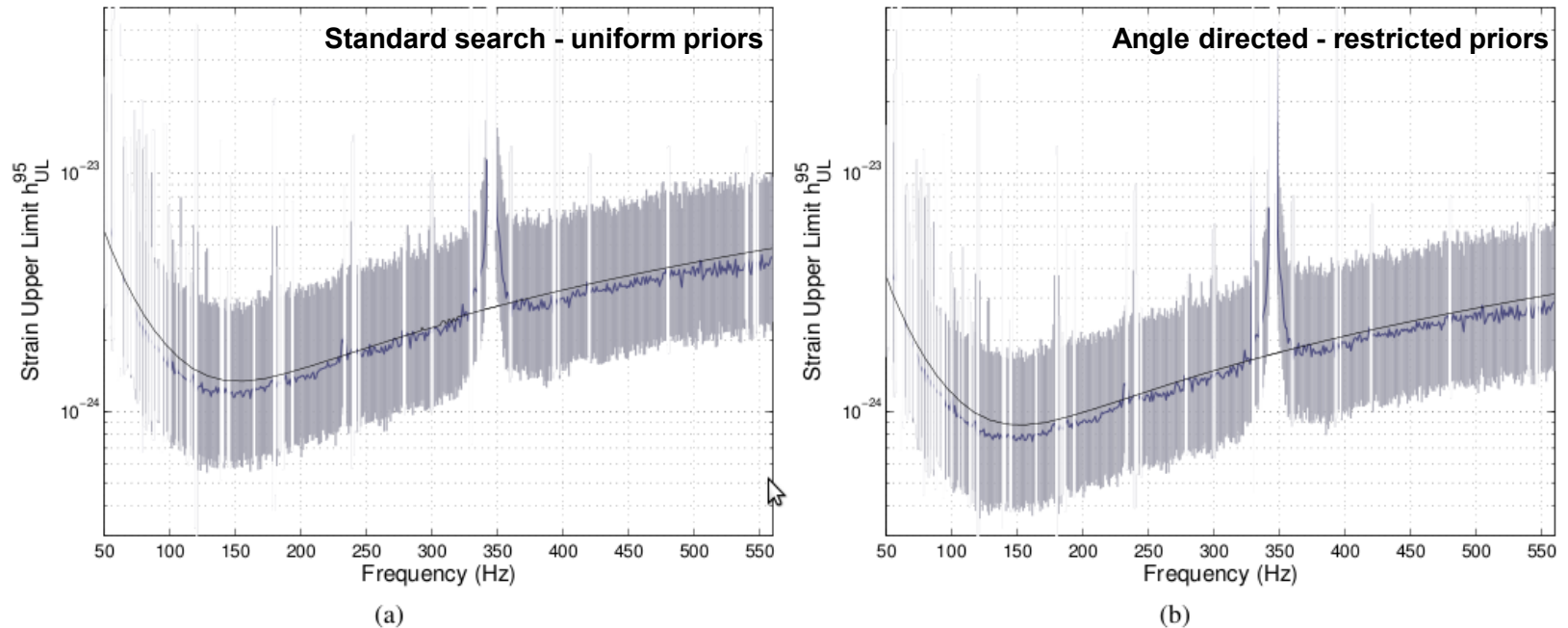
FIG. 4. Gravitational wave strain 95% upper limits for H1L1 data from 21–31 Aug 2007 for (a) the standard search with flat priors on $\cos\iota$ and ψ (left panel) and (b) the angle-directed search with $\iota = 44° \pm 6°$ and $\psi = 234° \pm 4°$ (right panel). The grey region extends from the minimum to the maximum upper limit in each 1-Hz sub-band. The median upper limit for the selected data span is indicated by a solid, thick, blue-grey curve. The expected upper limit for Gaussian noise at the S5 design sensitivity is shown for comparison (solid, thin, black curve). Whited regions of the grey band indicate bands that have been excluded (due to known contamination or vetoed out bands). No upper limits are quoted in these bands.