Tracking of continuous gravitational waves with spin wandering: selected results using O3 LIGO data

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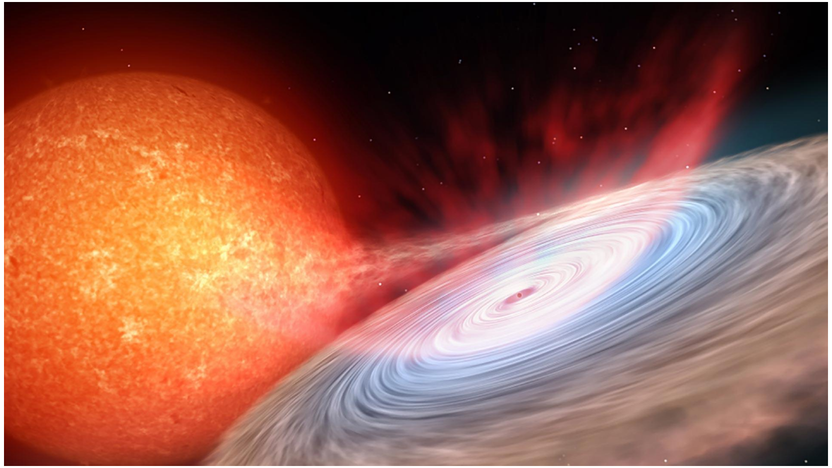
GW and spin wandering

Continuous gravitational Waves (CW) are *expected* to be produced at a multiple of the spin frequency $f_{\mathrm{GW}} = \eta f_{\star}$, with $\eta = 1, 2, 4/3, \ldots$ given by the emission mechanism.

Yet, either by internal (e.g. *crust-superfluid couplings*) or external (e.g. *accretion*) processes of the neutron star, its spin frequency may wander with time. This is called spin wandering.

This is a challenge for tracking CW searches, as they must accommodate for a signal possibly wandering in some time-scale.



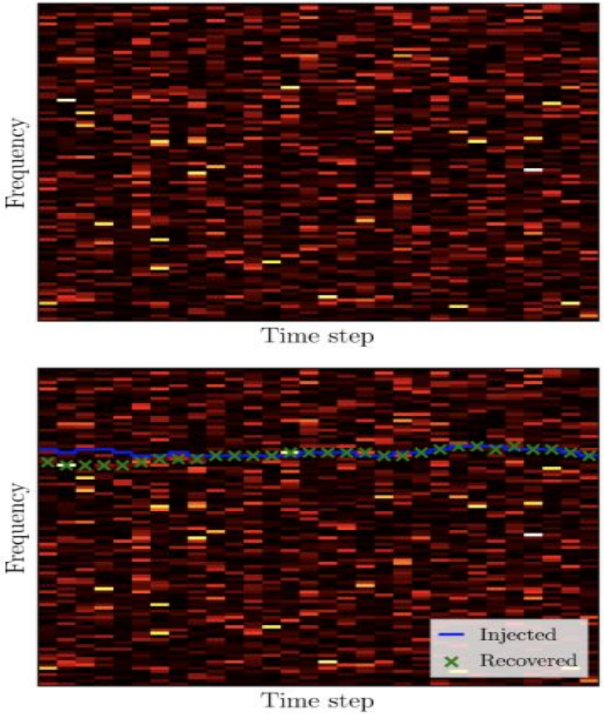
(*Artistic representation of a neutron star accreting matter from its companion's envelope. Credit: Gabriel Pérez Díaz.*)

Pipeline: the HMM search

This pipeline considers hidden parameters as steps of a Markov chain related to the observable states through a probability.

The hidden GW frequency, f(t), is tracked through a trellis of log-like values calculated using a statistic on blocks of duration T_{drift}.

Assuming f(t) can vary at most a frequency bin per T_{drift} block, the Viterbi algorithm is used to efficiently track the most probable path.

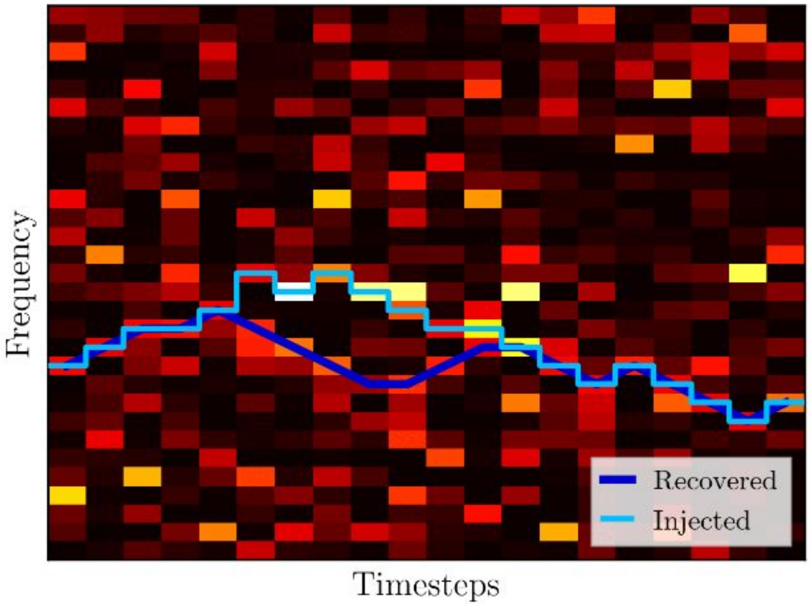


(HMM Tracking. Image made by Julian Carlin)

Pipeline: the HMM search

Simplified workflow:

- The data is divided into $N_T = T_{obs} / T_{drift}$ segments.
- T_{drift} sets the resolution in frequency space: Δf .
- The frequency space is split into sub-bands of width $\Delta f_{band} = 2^n \Delta f$. We calculate the $\mathcal{J}$-statistic for every T_{drift} segments.
- The search is repeated for all possible "templates" of the orbital parameters.



(HMM Tracking. Image made by Julian Carlin and Hannah Middleton.)

Thresholds

For each template within a sub-band the algorithm returns the summed log-likelihood of the best path: $\mathcal{L}$. We save the path of highest summed log-likelihood for all templates in the sub-band: $\max(\mathcal{L})$.

We set a threshold for a given sub-band, $\mathcal{L}_{\mathrm{th}}$, through realisations of pure Gaussian noise. This threshold accounts for the total number of templates per sub-band.

Historically, the HMM search method sets the probability of false alarm to (PFA) = 1 % per sub-band.

Vetoes

For all candidates with $\max(\mathcal{L})$ > $\mathcal{L}_{\mathrm{th}}$, we apply the following two vetoes:

A. **Lines Veto:** removes any candidate that is close with a known noise line.

B. **Single interferometer veto:** removes any candidate that is consistent with noise lines located in a single detector, or louder in the less-sensitive detector.

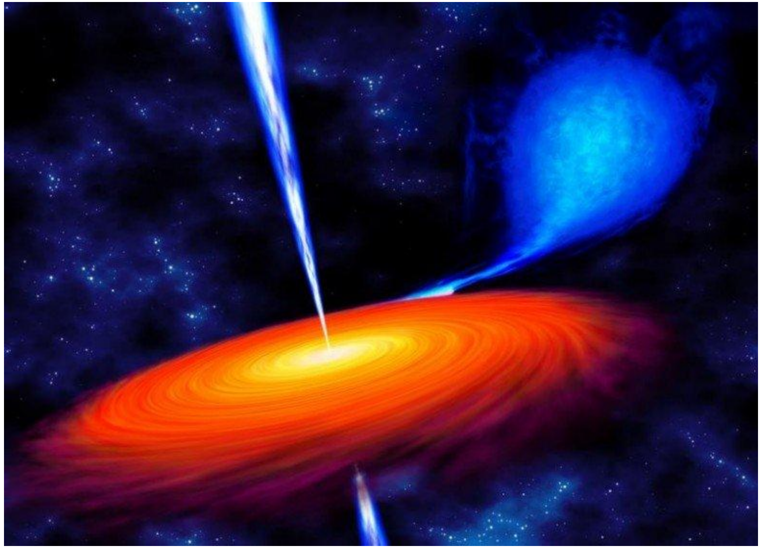
Search for gravitational waves from Scorpius X-1 in the data from Advanced LIGO O3 observing run with a hidden Markov model

R. Abbott et al. Phys. Rev. D **106**, 062002

Scorpius X-1 (Sco X-1)

LMXBs, such as Sco X-1, are binaries systems composed by a *donor* which accretes matter unto its companion, generally a compact object.

$$\text{(Torque Balance)} \sim \text{(GW strain)} \sim \sqrt{\text{(X-ray flux)}}$$



Sco X-1 is the brightest LMXB in X-rays, making it the highest priority target

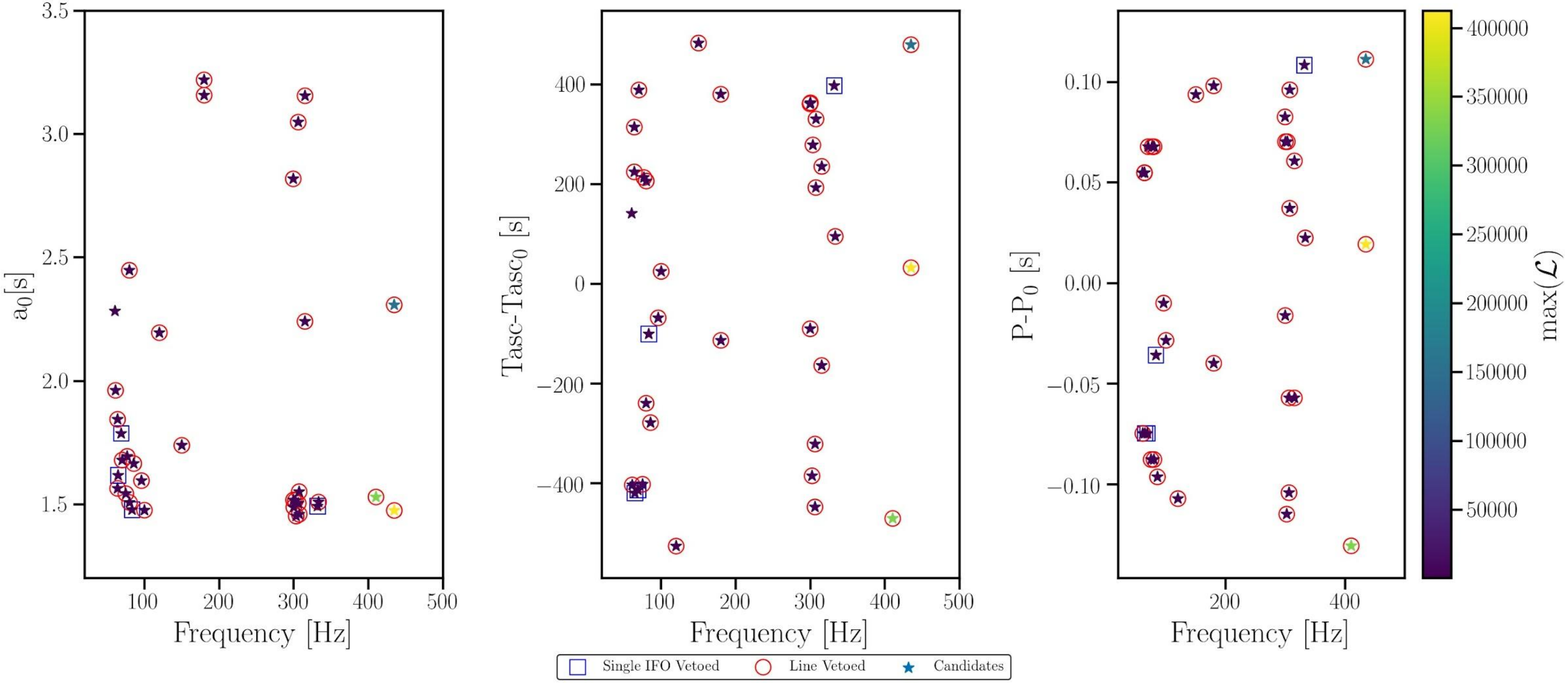
The perks of searching for Sco X-1

Continuous gravitational Waves (CW) are *expected* to be produced at a multiple of the spin frequency $f_\star$

Yet there are no electromagnetic measurements of Sco X-1 spin frequency to guide any CW search

Also the spin frequency of an LMXB wanders stochastically making the search more difficult!
For Sco X-1 the timescale for the frequency wandering has been estimated to be: $\geq\ 10\ \mathrm{days}$

Results

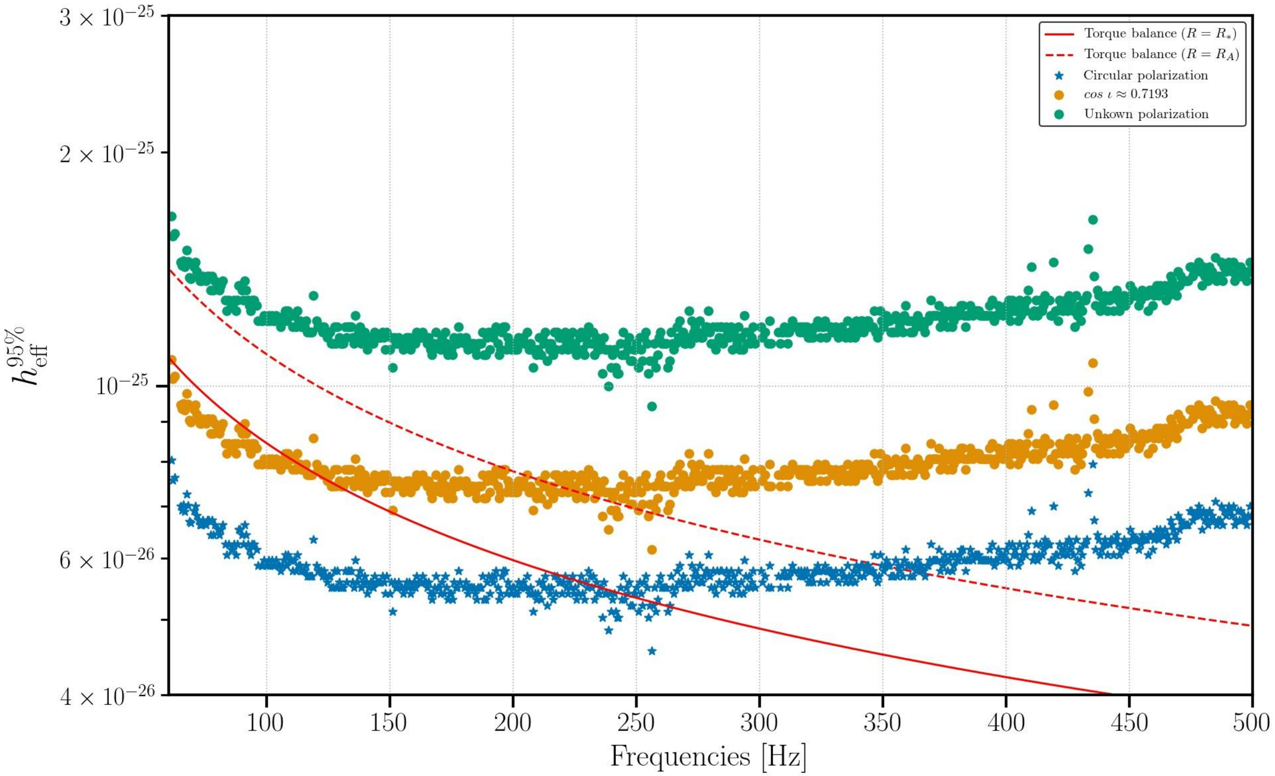


(FIG 3. in paper)

Upper Limits

All sub-bands with no candidates are used to generate upper limits detectable at 95% confidence h_0.

We do this by injecting signals, with varying h_0 and random parameters, until it is no longer detectable.



(FIG 4. in paper)

Summary of the search

We did a broad-band search for CW from Sco X-1 using the O3 LIGO data from Hanford and Livingston.

We obtain 35 candidates with a (PFA)=1%.

One candidate remains after vetoes. This candidate disappears when using the 60 Hz subtracted data.

Upper limits are obtained for all sub-bands without a candidate. This is the first time a Sco X-1 HMM search dips under the torque-balance line.

Other Sco X-1 O3 searches

As Sco X-1 is a promising candidate, there are more pipelines actively searching for it!

For instance:

- The CrossCorr pipeline, see: R.Abbott et al. ApJL **941** L30 (2022)
- The Radiometer search, see: R.Abbott et al. Phys. Rev. D **104**, 022005

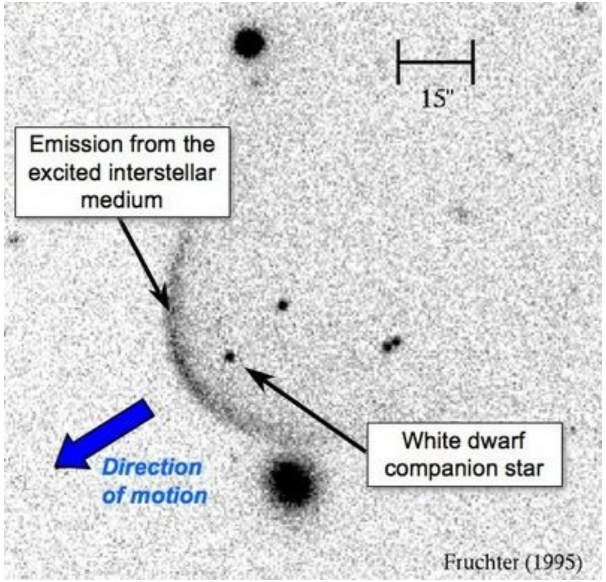
Search for continuous gravitational waves from PSR J0437-4715 with a hidden Markov model in O3 LIGO data

A. Vargas and A. Melatos. Phys. Rev. D **107**, 064062

Why this target?

PSR J0437-4715 is an interesting target as:

- It is nearby and the GW strain, h_0, scales $\propto D^{-1}$
- It spins rapidly and $h_0 \propto f_*^2$.
- Radiation at $\{1,2,4/3\}f_*$ far from main LIGO instrumental lines.
- The orbital elements are known to high accuracy!



(Optical image of the binary system containing PSR J0437-4715. Image by Andrew S. Fruchter)

PSR J0437-4715 is a constant target for GW searches!

Motivation

There are several scenarios a {1,2, 4/3}f_* - search is *insensitive* to. For example:

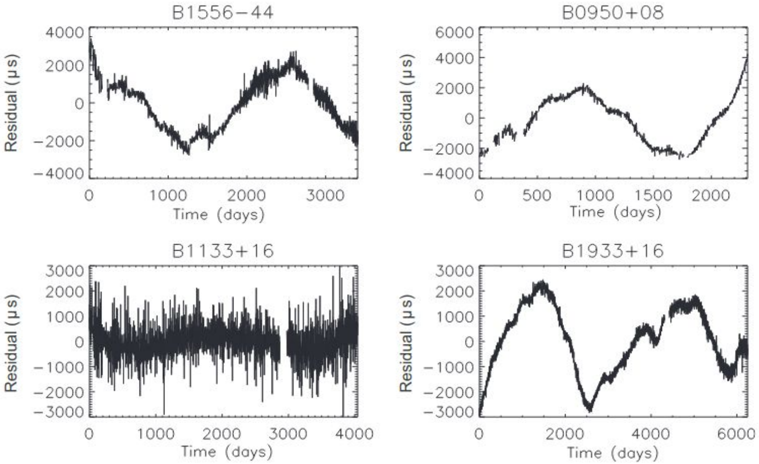
- *What if* the GW-emitting quadrupole is not locked to the crust?
- *What if* the GW signal frequency wanders stochastically with time.
- *What if* the r-modes emit far from 4/3 f_* due to complicated microphysics?

Our work cover the above considerations by searching over a broad frequency range using a hidden Markov model (HMM).

Considerations: T_{drift}

In the absence of a GW detection, from millisecond pulsars, there is no way to predict T_{drift}!

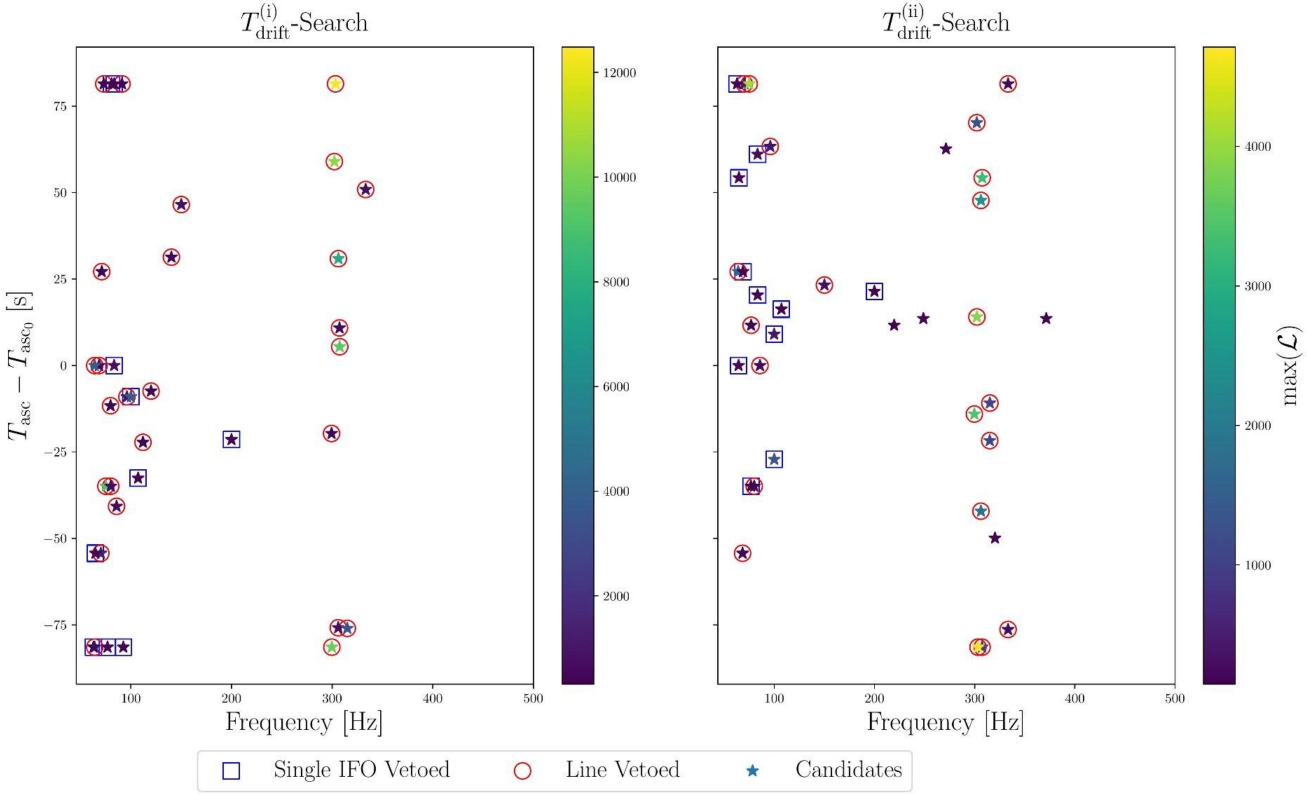
The time-scale for deviations from the long-term secular evolution of a rotating NS is estimated to be ~ 10 - 20 days.



(Timing residuals for four pulsars. From S. Price et al. 2012)

Exploiting the speed of the HMM algorithm we conduct two analysis with $T_{\mathrm{drift}}^{(i)}$ = 10 days and $T_{\mathrm{drift}}^{(ii)}$ = 30 days.

Results



(Figure 1. In paper)

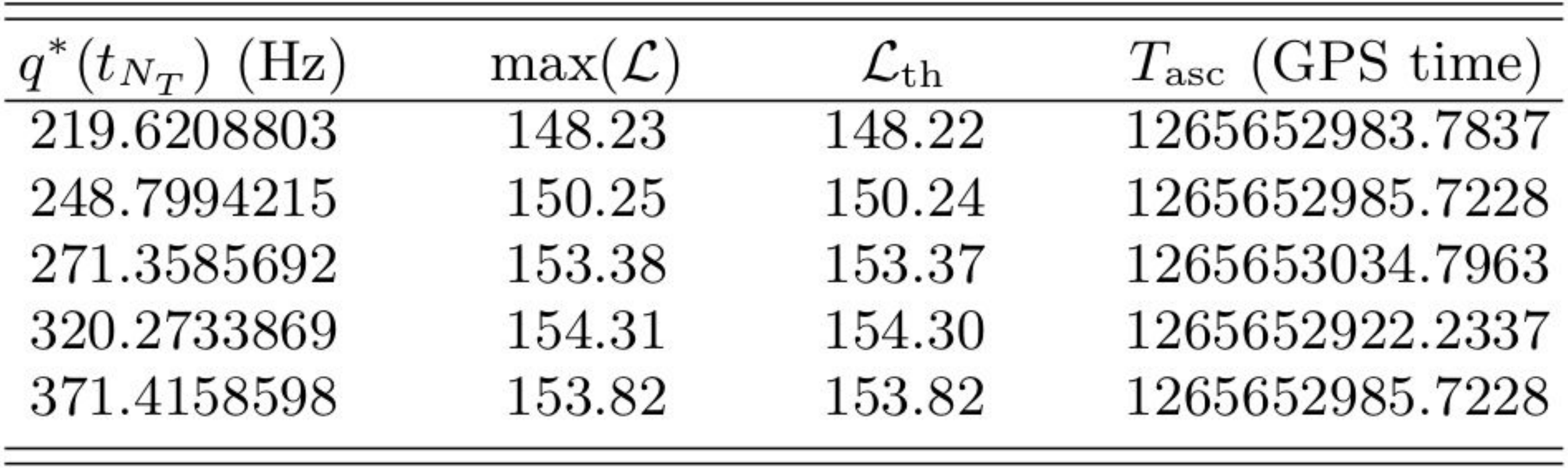
Results

A closer look:

- $T_{\text{drift}}^{(i)}$ search: No candidates survives the vetoing procedure.
- $T_{\text{drift}}^{(ii)}$ search: **five** candidates survive the vetoing procedure. This is consistent with the expected number of false alarms (~11).
    - All five survivors belong to *outcome 4* of the Single IFO veto, i.e. data from both detectors are needed to get $\max(\mathcal{L})$ > $\mathcal{L}_{\text{th}}$.
    - All survivors follow $q^*(t_N) \neq \eta f_\star$, with $\eta \in \mathbb{Q}$.
    - Two of the survivors share the same T_{asc} template.

Results

Table of survivors:



$q^*(t_{N_T})$ (Hz)	$\max(\mathcal{L})$	$\mathcal{L}_{\mathrm{th}}$	T_{asc} (GPS time)
219.6208803	148.23	148.22	1265652983.7837
248.7994215	150.25	150.24	1265652985.7228
271.3585692	153.38	153.37	1265653034.7963
320.2733869	154.31	154.30	1265652922.2337
371.4158598	153.82	153.82	1265652985.7228

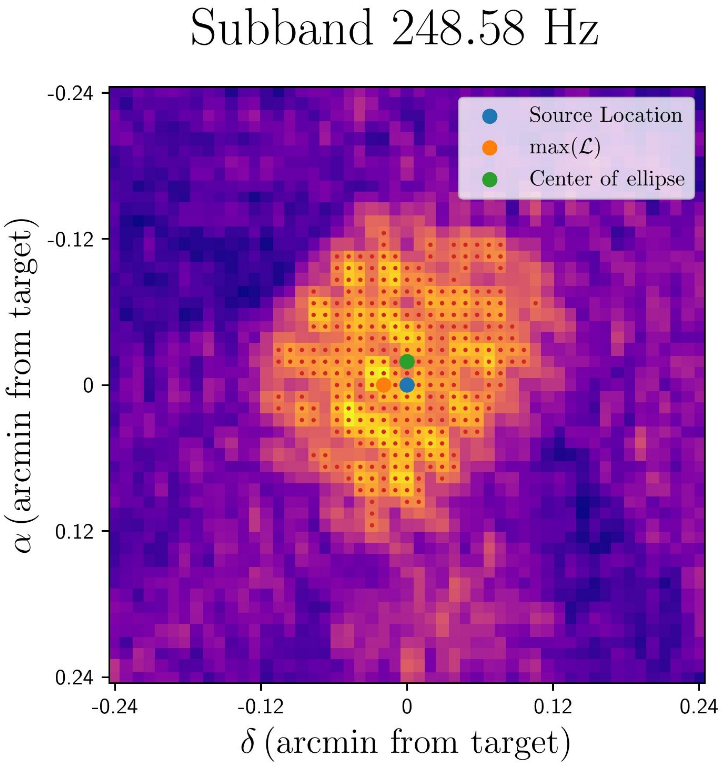
(Table 5. In paper)

Results: Sky maps

We follow up the survivors by plotting how the detection statistic varies with the sky position of the search.

We calculate $\mathcal{L}$ for a uniform ($\boldsymbol{\alpha}$,$\boldsymbol{\delta}$)-grid of 2601 pixels around the source position.

In general an astrophysical candidate's $\mathcal{L}$ should diminish when pointing away from the source, forming elliptical contours of constant $\mathcal{L}(\boldsymbol{\alpha},\boldsymbol{\delta})$.



(Figure 2. In paper)

Summary of the search

We search for CW from PSR J0437-4715, in the band $60\text{ Hz} \leq f \leq 500\text{ Hz}$, to catch any possible signal with $f(t) \neq f_*(t)$.

We conduct two distinct analysis with $T_{\text{drift}}^{(i)} = 10$ days and $T_{\text{drift}}^{(ii)} = 30$ days.

No candidates survive the veto procedure for the $T_{\text{drift}}^{(i)}$ analysis, while five candidates survive the $T_{\text{drift}}^{(ii)}$ analysis, two of which share the same T_{asc} and are in the frequency ratio 1.493. The number of survivors is consistent with the expected number of false alarms.

Sky maps of $\mathcal{L}(\boldsymbol{\alpha},\boldsymbol{\delta})$ versus search position do not reveal clear signatures of instrumental artifacts or an astrophysical origin.

All five survivors appear in sub-bands not covered by previous analysis.

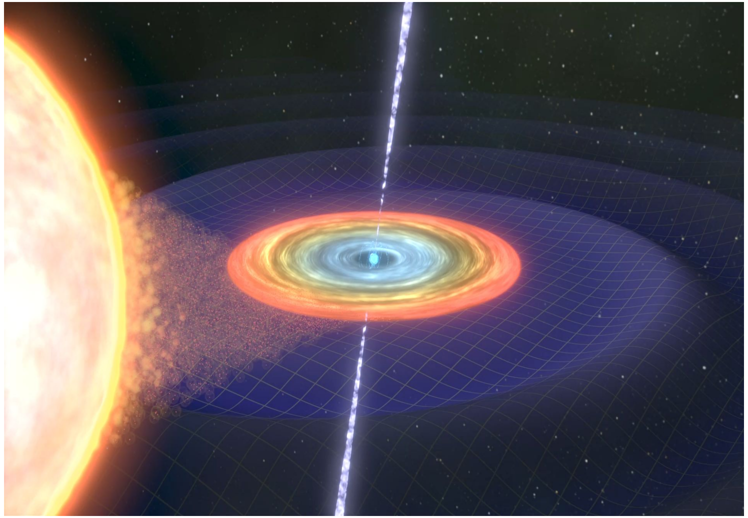
Search for continuous gravitational waves from 20 accreting millisecond x-ray pulsars in O3 LIGO data.

R. Abbott et al. Phys. Rev. D **105**, 022002

Why these targets?

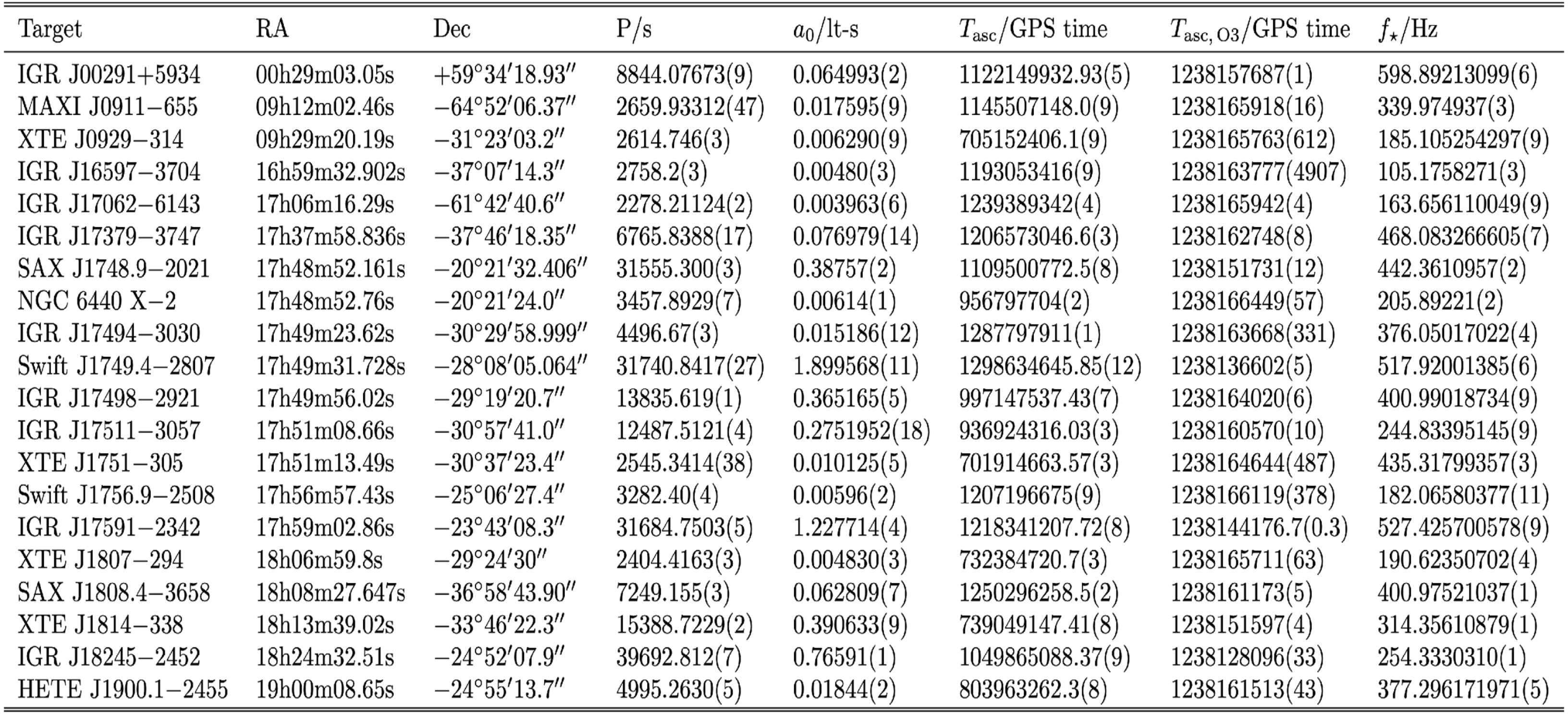
Accreting millisecond X-ray pulsars (AMXPs) are interesting targets as they:

- Binary accreting systems composed of a NS and a low-mass companion.
- Active accretion could create mountains or excite r-modes.
- Orbital elements and f_* are known to high accuracy, i.e. very computationally cheap HMM search.



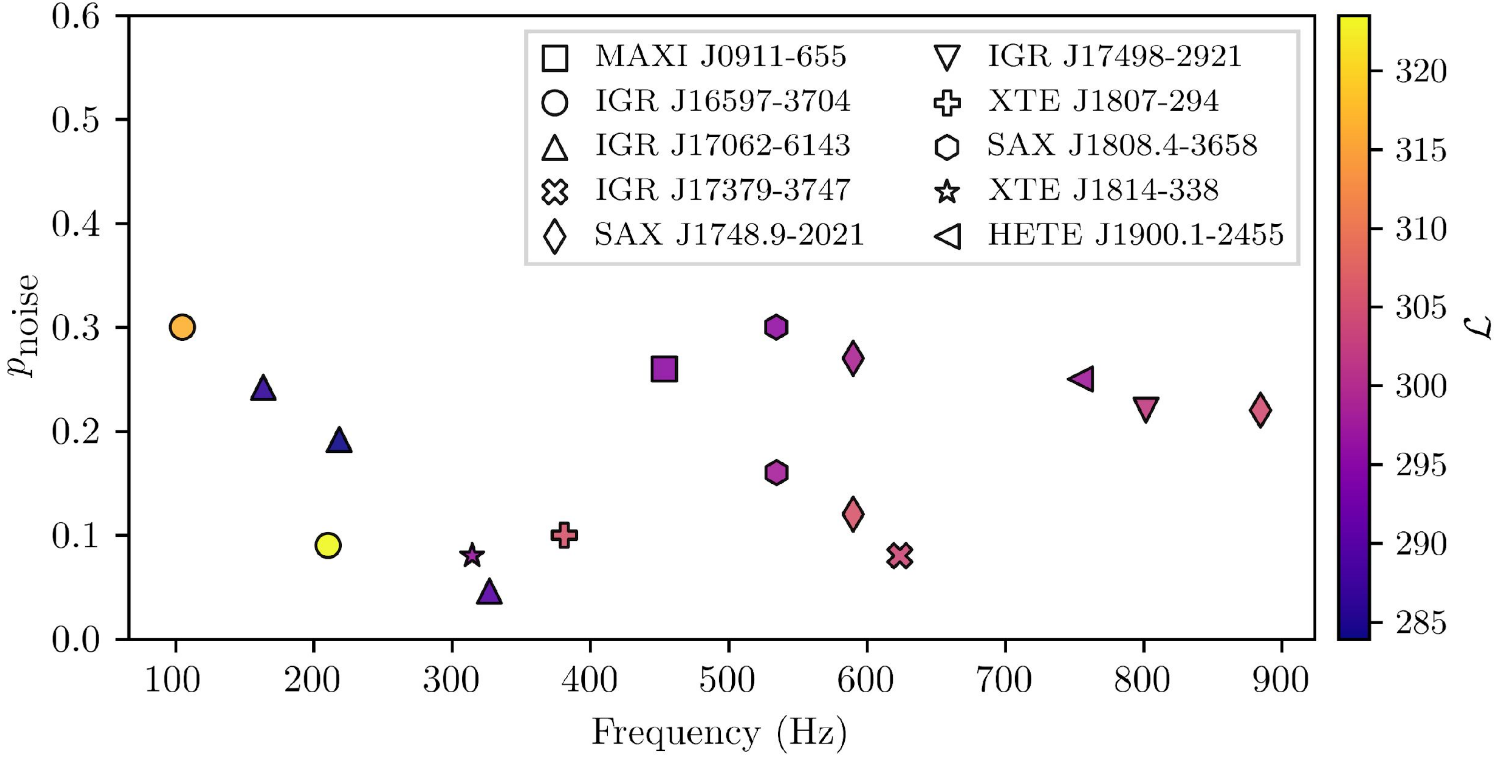
(Mark Myers, Ozgrav-Swinburne University)

Targets



Target	RA	Dec	P/s	a_0/lt-s	T_{asc}/GPS time	$T_{\mathrm{asc,\,O3}}$/GPS time	$f_\star$/Hz
IGR J00291+5934	00h29m03.05s	+59°34′18.93″	8844.07673(9)	0.064993(2)	1122149932.93(5)	1238157687(1)	598.89213099(6)
MAXI J0911−655	09h12m02.46s	−64°52′06.37″	2659.93312(47)	0.017595(9)	1145507148.0(9)	1238165918(16)	339.974937(3)
XTE J0929−314	09h29m20.19s	−31°23′03.2″	2614.746(3)	0.006290(9)	705152406.1(9)	1238165763(612)	185.105254297(9)
IGR J16597−3704	16h59m32.902s	−37°07′14.3″	2758.2(3)	0.00480(3)	1193053416(9)	1238163777(4907)	105.1758271(3)
IGR J17062−6143	17h06m16.29s	−61°42′40.6″	2278.21124(2)	0.003963(6)	1239389342(4)	1238165942(4)	163.656110049(9)
IGR J17379−3747	17h37m58.836s	−37°46′18.35″	6765.8388(17)	0.076979(14)	1206573046.6(3)	1238162748(8)	468.083266605(7)
SAX J1748.9−2021	17h48m52.161s	−20°21′32.406″	31555.300(3)	0.38757(2)	1109500772.5(8)	1238151731(12)	442.3610957(2)
NGC 6440 X−2	17h48m52.76s	−20°21′24.0″	3457.8929(7)	0.00614(1)	956797704(2)	1238166449(57)	205.89221(2)
IGR J17494−3030	17h49m23.62s	−30°29′58.999″	4496.67(3)	0.015186(12)	1287797911(1)	1238163668(331)	376.05017022(4)
Swift J1749.4−2807	17h49m31.728s	−28°08′05.064″	31740.8417(27)	1.899568(11)	1298634645.85(12)	1238136602(5)	517.92001385(6)
IGR J17498−2921	17h49m56.02s	−29°19′20.7″	13835.619(1)	0.365165(5)	997147537.43(7)	1238164020(6)	400.99018734(9)
IGR J17511−3057	17h51m08.66s	−30°57′41.0″	12487.5121(4)	0.2751952(18)	936924316.03(3)	1238160570(10)	244.83395145(9)
XTE J1751−305	17h51m13.49s	−30°37′23.4″	2545.3414(38)	0.010125(5)	701914663.57(3)	1238164644(487)	435.31799357(3)
Swift J1756.9−2508	17h56m57.43s	−25°06′27.4″	3282.40(4)	0.00596(2)	1207196675(9)	1238166119(378)	182.06580377(11)
IGR J17591−2342	17h59m02.86s	−23°43′08.3″	31684.7503(5)	1.227714(4)	1218341207.72(8)	1238144176.7(0.3)	527.425700578(9)
XTE J1807−294	18h06m59.8s	−29°24′30″	2404.4163(3)	0.004830(3)	732384720.7(3)	1238165711(63)	190.62350702(4)
SAX J1808.4−3658	18h08m27.647s	−36°58′43.90″	7249.155(3)	0.062809(7)	1250296258.5(2)	1238161173(5)	400.97521037(1)
XTE J1814−338	18h13m39.02s	−33°46′22.3″	15388.7229(2)	0.390633(9)	739049147.41(8)	1238151597(4)	314.35610879(1)
IGR J18245−2452	18h24m32.51s	−24°52′07.9″	39692.812(7)	0.76591(1)	1049865088.37(9)	1238128096(33)	254.3330310(1)
HETE J1900.1−2455	19h00m08.65s	−24°55′13.7″	4995.2630(5)	0.01844(2)	803963262.3(8)	1238161513(43)	377.296171971(5)

Results



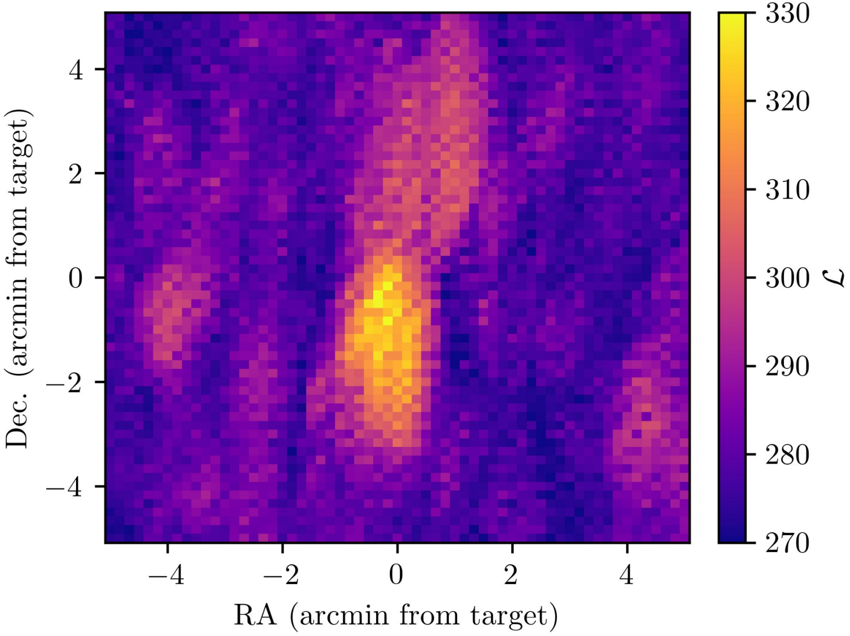
(Figure 1. In paper)

Results: Sky maps

Rigorous follow-up of the candidates do not yield any astrophysical information.

Only the sky map for IGR J16597-3704 (right diagram) show high log likelihoods in the target's position vicinity.

The highest $\mathcal{L}$ is not centered in the diagram to the right.



(Figure 6. In paper)

Thank you!

Summary of the search

Most comprehensive (in scope and sensitivity) search of CW from AMXPs.

No candidates remain after vetoes, if PFA = 1% .

16 Candidates remain after vetoes, if PFA=30%.

After extensive follow-up procedure no convincing evidence that any are a true astrophysical signal.

Upper limits are set and used to constraint ellipticity and r-mode amplitude.

The strictest are $\epsilon^{95\%} = 3.1\times10^{-7}$ and $\alpha^{95\%} = 1.8\times10^{-5}$ respectively

Extra Slides:

Sco X-1 search setup for O3

We expect the frequency to wander every T_{drift}=10 days. So in Fourier space we have a resolution of $\Delta f_{\mathrm{drift}} = 1/(2T_{\mathrm{drift}}) \approx 5.787037 \times 10^{-7}\,\mathrm{Hz}$

We will divide the data in blocks of 10 days, so in total there are: $N_T = \lceil T_{\mathrm{obs}}/T_{\mathrm{drift}} \rceil = 36$, of these. We assume for each block the signal can 'jump' at most $\Delta f_{\mathrm{drift}}$.

The search was done in sub-bands of width: $\Delta f_{\mathrm{band}} = 2^{20}\Delta f_{\mathrm{drift}} = 0.6068148\mathrm{Hz}$ in total the search consist of 725 sub-bands.

Additionally neither a_0, P or T_{asc} are well constrained. So the frequency search must be expanded to include an additional search over possible "*templates*" of these parameters.