LIGO-Virgo Searches for Gravitational Waves from Scorpius X-1

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on behalf of the LIGO Scientific Collaboration
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Outline

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Gravitational Waves from Low-Mass X-Ray Binaries

- LMXB: compact object (neutron star or black hole) in binary orbit w/companion star
- If NS, accretion from companion provides "hot spot"; rotating non-axisymmetric NS emits gravitational waves
- Bildsten *ApJL* **501**, L89 (1998) suggested GW spindown may balance accretion spinup; GW strength can be estimated from X-ray flux
- Torque balance would give ≈ constant GW freq
- Signal at solar system modulated by binary orbit

Scorpius X-1

- 2nd brightest persistent X-Ray source in the sky, after the Sun
- Favored model is $1.4M_\odot$ NS + $0.42M_\odot$ companion
  Steeghs & Casares *ApJ* **568**, 273 (2002)

Parameters (see Messenger et al *PRD* **92**, 023006 (2015) for refs)

Parameter		estimate	1σ error
right ascension	α	$16^h19^m55^s$	$0''.06$
declination	δ	$-15°38'25''$	$0''.06$
distance	d	2.8 kpc	0.3 kpc
eccentricity	e	0	0.02
orbital inclination	i	44°	6°

Signal phase affected by uncertain parameters

- Frequency f_0 ($2\times$ spin freq; unknown)
- Proj semimajor axis a_p, time of ascension t_{asc}, orb period P_{orb}

☞ Fully coherent search infeasible

Sco X-1 Orbital Parameters

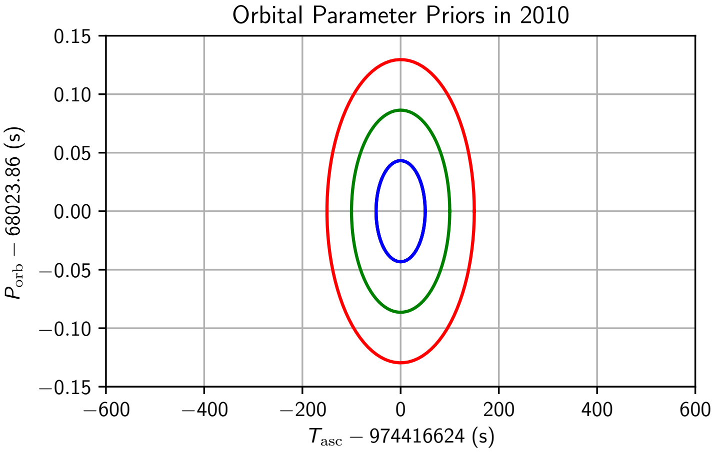
Best observational constraints from Wang et al *MNRAS* **478**, 5174 (2018)

- $a_p \in [1.45, 3.25]$ light-seconds (**not** Gaussian)
- $P_{\text{orb}} = 68023.86 \pm 0.04\,\text{s}$ (1σ) ($\approx 18.9\,\text{hr}$)c
- $t_{\text{asc}} = 974416624 \pm 50\,\text{s}$ (1σ) (2010-Nov-21 23:16:49 UTC)

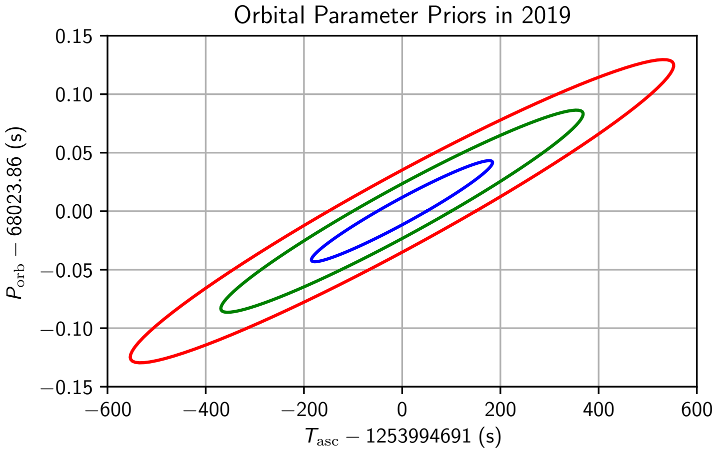
Note:

- P_{orb} estimate consistent w/Gottlieb et al *ApJL* **195**, L33 (1975); estimate from Galloway et al *ApJ* **781**, 14 (2014) marginally inconsistent
- P_{orb} & t_{asc} uncertainties uncorrelated **but** redefining $t'_{\text{asc}} = t_{\text{asc}} + nP_{\text{orb}}$ introduces correlations

Joint Prior in Orbital Period and Phase



Joint Prior in Orbital Period and Phase



Torque Balance Level

- Estimate equilibrium GW strength needed to balance accretion torque (inferred from X-ray flux)
- Optimistic prediction or significant benchmark
- For Sco X-1, level is[1]

$$h_0 \approx 3.4 \times 10^{-26} \left(\frac{f_0}{600\,\mathrm{Hz}} \right)^{-1/2} .$$

Watts, Krishnan, Bildsten & Schutz *MNRAS* **389**, 839 (2008)

- Most searches sensitive to $(h_0^{\mathrm{eff}})^2 = h_0^2 \frac{[(1+\cos^2\iota)/2]^2+[\cos\iota]^2}{2}$
  Quote h_0 sensitivity/upper limit assuming $\cos\iota$ value, e.g.:
  - $\cos\iota = \pm 1 \equiv$ circular polarization (best case)
  - $\cos\iota = 0 \equiv$ linear polarization (worst case)
  - Assume NS spin inclination $\iota \approx$ orbit inclination $i \approx 44^\circ$
  - Marginalize over ι or quote $(h_0^{\mathrm{eff}})^2$

[1] Assuming accretion torque at NS surface $R_* \approx 10\,\mathrm{km}$; assuming Alfvén radius R_A gives more optimistic estimate by ~ 2.56.

Outline

Radiometer Method

Ballmer *CQG* **23**, S179 (2006)

- Directional stochastic search; cross-correlate data from different detectors at same time, phase-shifting for GW from one sky position.
- Sco X-1 is one “interesting” direction considered
- O1 results paper LVC *PRL* **118**, 121102 (2017)
- O1+O2 results paper LVC *PRD* **100**, 062001 (2019)

Cross-Correlation Method

Dhurandhar, Krishnan, Mukhopadhyay & JTW *PRD* **77**, 082001 (2008)
JTW, Sundaresan, Zhang & Peiris *PRD* **91**, 102005 (2015)

- Construct quadratic cross-correlation statistic ρ which combines all data segments w/ $|T_K - T_L| \leq T_{\text{max}}$
- Tunable semicoherent search: freedom to choose T_{max}
  Increasing T_{max} improves sensitivity, increases cost
- Potential speedup w/resampling
  Meadors et al *PRD* **97**, 044017 (2018)
- For O1, search $f_0 \in [25, 2000]$ & orbital parameters
  T_{max} ranged from 240–25920 s across parameter space
- Followed up candidates by increasing T_{max}
- O1 results paper LVC *ApJ* **847**, 47 (2017)

Viterbi Method

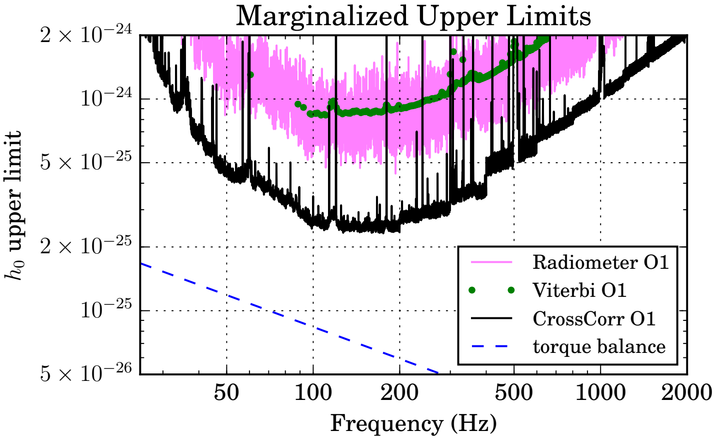
- Sideband method Messenger & Woan *CQG* **24**, S469 (2007) Sammut, Messenger, Melatos & Owen *PRD* **89**, 043001 (2014)
  - Resolves orbital Doppler modulation of signal into sidebands
  - Very sensitive to frequency;
    slight "spin wandering" could disrupt signal after $\sim 10\,\mathrm{days}$.
- Viterbi 1.0 Suvorova et al, *PRD* **93**, 123009 (2016)
  - Use hidden Markov model to follow possible evolution of f_0
  - Computationally efficient ($\lesssim 3000$ CPU-hr for O1)
  - O1 results paper LVC *PRD* **95**, 122003 (2017)
- Viterbi 2.0 Suvorova et al, *PRD* **96**, 102006 (2017)
  - Doppler-modulated $\mathcal{J}$-statistic includes orbital phase
  - Improved sensitivity, but now depends on t_{asc}, a_p, f_0 (& P_{orb})
  - Cost still manageable ($\mathcal{O}(10^6)$ CPU-hr for O2)
  - O2 results paper LVC *PRD* **100**, 122002 (2019)

Outline

Searches for Sco X-1 in Advanced LIGO Data

- Advanced LIGO's first observing run (O1) Sep 2015-Jan 2016
  Second observing run (O2) Dec 2016-Aug 2017
  (CW analyses usually run after all the data taken)
- O1 papers
  - Radiometer LVC *PRL* **118**, 121102 (2017)
  - Viterbi 1.0 LVC *PRD* **95**, 122003 (2017)
  - CrossCorr LVC *ApJ* **847**, 47 (2017)
- O2 papers
  - Radiometer LVC *PRD* **100**, 062001 (2019)
  - Viterbi 2.0 LVC *PRD* **100**, 122002 (2019)

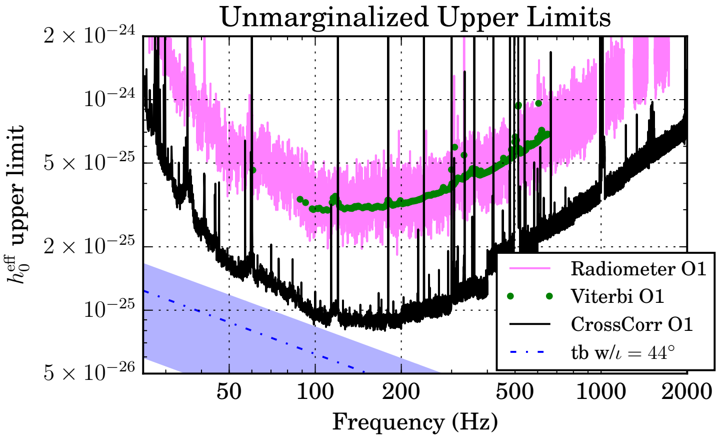
O1 Upper Limits (95% CL)



LVC *ApJ* **847**, 47 (2017)

3.4× higher than torque balance

O1 Upper Limits (95% CL)

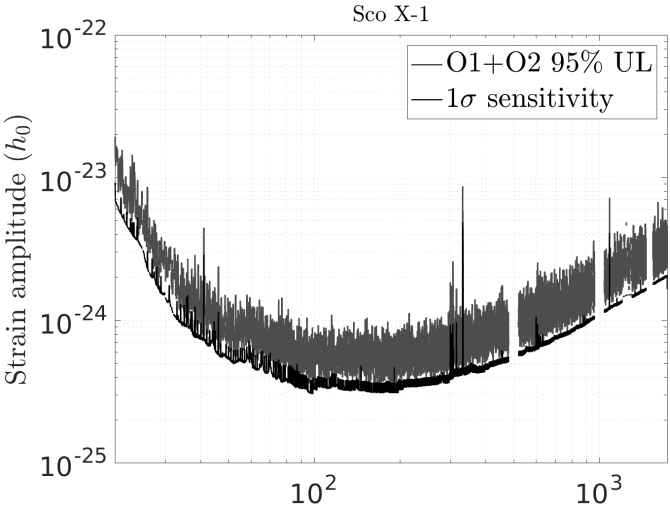


$\cong$ circular pol UL; $\times 2.83$ gives linear pol UL; $\times 1.35$ gives UL for $\iota = 44°$

1.2–3.5$\times$ higher than torque balance, depending on ι assumption

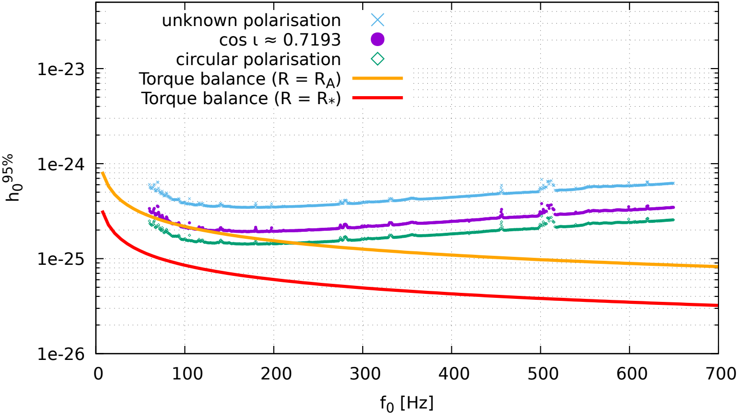
O1+O2 Radiometer Upper Limits (Marginalized)

LVC *PRD* **100**, 062001 (2019)



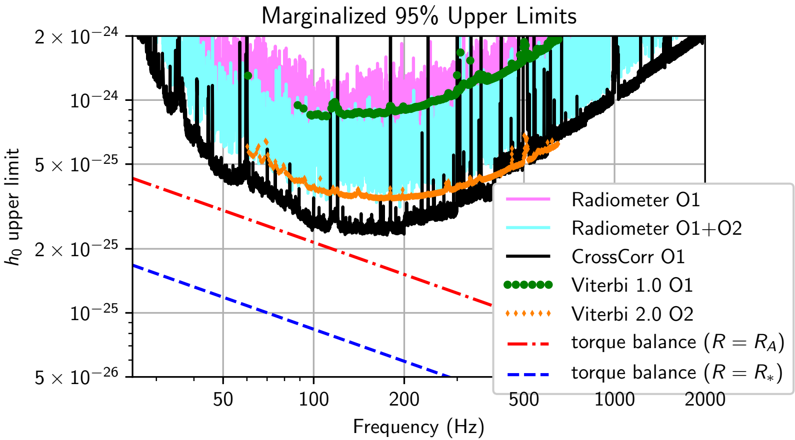
O2 Viterbi 2.0 Upper Limits

LVC *PRD* **100**, 122002 (2019)

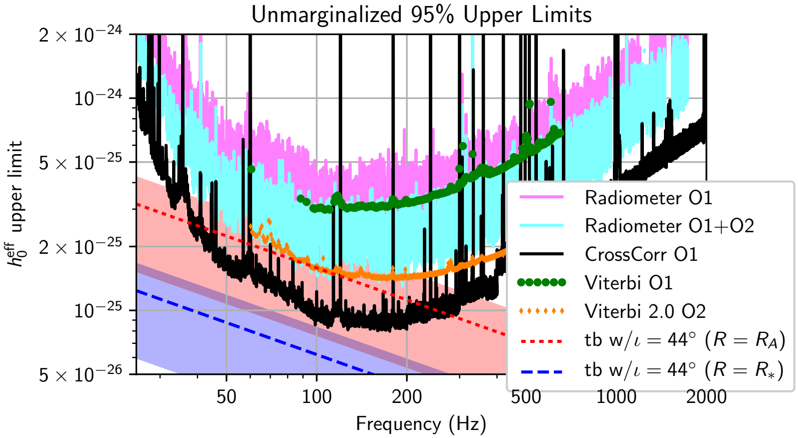


Most sensitive results designed to be robust against spin wandering

Combined O1 & O2 Upper Limits



Combined O1 & O2 Upper Limits



Conclusions/Outlook

- Scorpius X-1 is a prime target for directed LIGO/Virgo searches
- Current (O1+O2) limits reach 0.5-1.2-3.5 of torque balance level depending on polarization & lever arm assumptions
- Multiple searches w/varying robustness to parameter assumptions & spin wandering
- O3's longer observing time & better strain sensitivity
  ☞ Sco X-1 sensitivity crossing into torque balance regime