Gravitational Waves from Scorpius X-1:
Comparisons of Search Methods and Prospects for Detection with Advanced Detectors

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8th International Conference on Gravitation and Cosmology
IISER Mohali, Punjab, India
2015 December 17 LIGO-G1501206-v3

Outline

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 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)
  Galloway et al *ApJ* **781**, 14 (2014)

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

Parameter		estimate	error
RA	α	$16^{\mathrm{h}}19^{\mathrm{m}}55^{\mathrm{s}}$	$0''.06$
dec	δ	$-15°38'25''$	$0''.06$
distance	d	2.8 kpc	0.3 kpc
orb period	P_{orb}	68023.70 s	0.04 s
time of ascension	t_{asc}	2008-Jun-17 16:06:20 UTC	100 s
proj semimajor axis	a_p	1.44 lt−s	0.18 lt−s
eccentricity	e	0	0.02

Param uncertainty means optimal coherent search unfeasible!

GW Searches for Sco X-1

- Fully coherent $\mathcal{F}$-statistic search
  Jaranowski, Królak & Schutz *PRD* **58**, 063001 (1998)
  ☞ w/6 hours of 2003 LIGO data LSC *PRD* **76**, 082001 (2007)
- Directed stochastic ("radiometer") search
  Ballmer *CQG* **23**, S179 (2006)
  ☞ w/2005 LIGO data LSC *PRD* **76**, 082003 (2007)
  ☞ w/2005-2007 LIGO data LVC *PRL* **107**, 271102 (2011)
- Sideband search Messenger & Woan *CQG* **24**, S469 (2007)
  ☞ w/2005-2007 LIGO data LVC *PRD* **91**, 062008 (2015)
- TwoSpect search Goetz & Riles *CQG* **28**, 215006 (2011)
  ☞ w/2009-2010 LIGO/Virgo data LVC *PRD* **90**, 062010 (2014)
- Model-based cross-correlation search

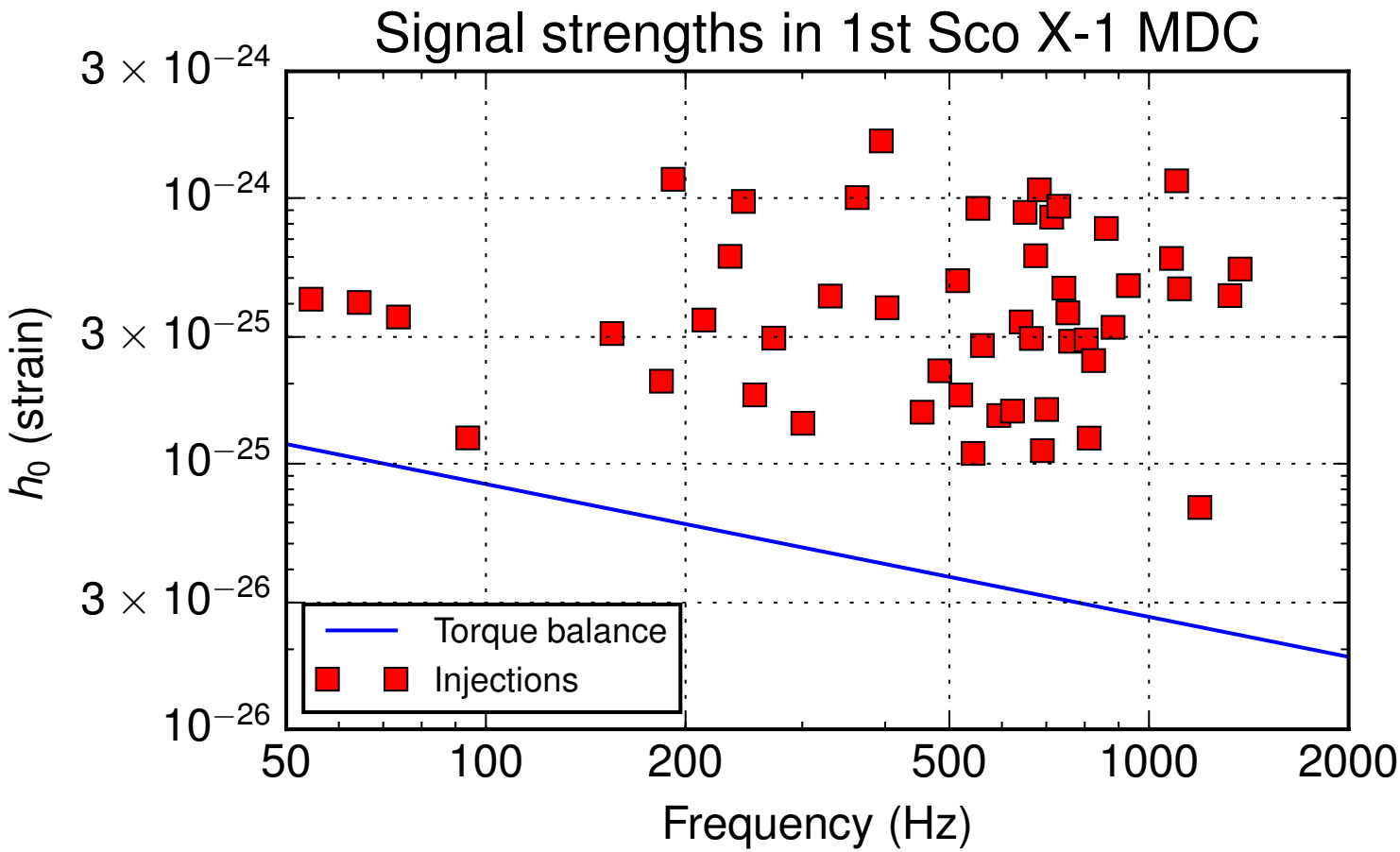
Dhurandhar, Krishnan, Mukhopadhyay & JTW *PRD* **77**, 082001 (2008)
JTW, Sundaresan, Zhang & Peiris *PRD* **91**, 102005 (2015)

Mock Data Challenge

Messenger et al *PRD* **92**, 023006 (2015)

- "Apples-to-apples" comparison of search methods
- 1 yr simulated white gaussian LIGO (2 sites) & Virgo noise, with gaps, $(S_n)^{1/2} = 4 \times 10^{-24}\,\mathrm{Hz}^{-1/2}$ (advanced design)
- 100 simulated signals
  (50 "open" w/published parameters, 50 "closed")
  injected into specified 5 Hz bands from 50-1450 Hz
- Log-normal distribution of $6 \times 10^{-26} \lesssim h_0 \lesssim 2 \times 10^{-24}$
  Mostly above torque-balance level; chosen for detectability
- Participants: Radiometer*, Sideband*, TwoSpect*, Polynomial, CrossCorr*
  * has been used in LSC/LVC observational paper
  * "late entrant" in self-blinded mode

Injected (Closed) Signal Strengths



All signals above torque balance prediction

but note some amplitudes at torque bal level corresponding to lower freqs

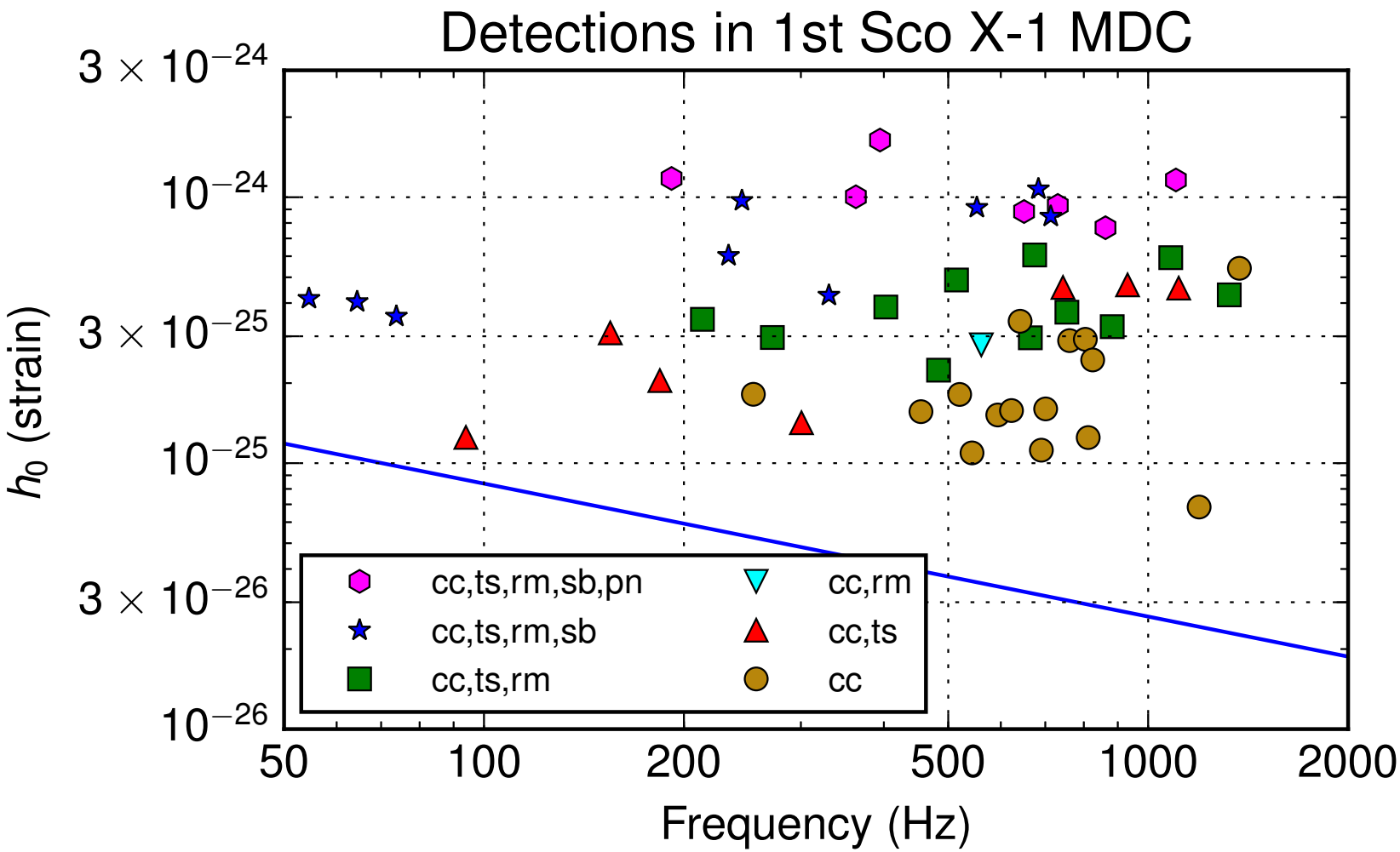
Comparison of Detection Efficiencies

Out of 50 closed signals:

- CrossCorr: found 50 with $h_0 \gtrsim 6.8 \times 10^{-26}$
- TwoSpect: found 34 with $h_0 \gtrsim 1.3 \times 10^{-25}$
- Radiometer: found 28 with $h_0 \gtrsim 2.2 \times 10^{-25}$
- Sideband: found 16 with $h_0 \gtrsim 3.6 \times 10^{-25}$
- Polynomial: found 7 with $h_0 \gtrsim 7.7 \times 10^{-25}$

Messenger et al *PRD* **92**, 023006 (2015)

Signal Strengths of Detections



Messenger et al *PRD* **92**, 023006 (2015)

Plans for Followup MDC(s)

- Limitations of first MDC:
  - white Gaussian noise
  - unrealistically loud signals
  - circular binary orbit
  - Intrinsic frequency constant,
    but participants told to pretend there was "spin wandering"
    $\dot{f}_0 \lesssim 10^{-12}\,\mathrm{Hz/s}$ varying on timescales $\sim 10^6\,\mathrm{s}$
- Second MDC under development with enhancements:
  - iLIGO/iVirgo instrumental noise recolored to aLIGO/adV spectrum
  - plan "early aLIGO" MDC concurrent with O1 analyses;
    "design aLIGO/adV" MDC later in 2016
  - simulations to include spin wandering
  - weaker signals, related to torque balance level
  - some signals may include eccentricity
    and/or be drawn from broader orbital priors

Prospects for Signal Detection

- So far, only CrossCorr has shown it can detect signals down to $h_0 \lesssim 10^{-25}$ level predicted by torque balance
- TwoSpect & Radiometer working on improvements; coherence time still limited to Fourier transform scale.
  Main utility[1] is robustness/speed if signal has unexpected properties
- Proposed semicoherent stacked $\mathcal{F}$-stat search
  Messenger *PRD* **84**, 083003 (2011);
  Leaci & Prix *PRD* **91**, 102003 (2015)
  could acieve longer coherence time & better sensitivity using resampling & Fourier methods
  Patel, Siemens, Dupuis & Betzwieser *PRD* **81**, 084032 (2010)
- Work underway to use resampling to speed up CrossCorr and allow longer coherence time as well

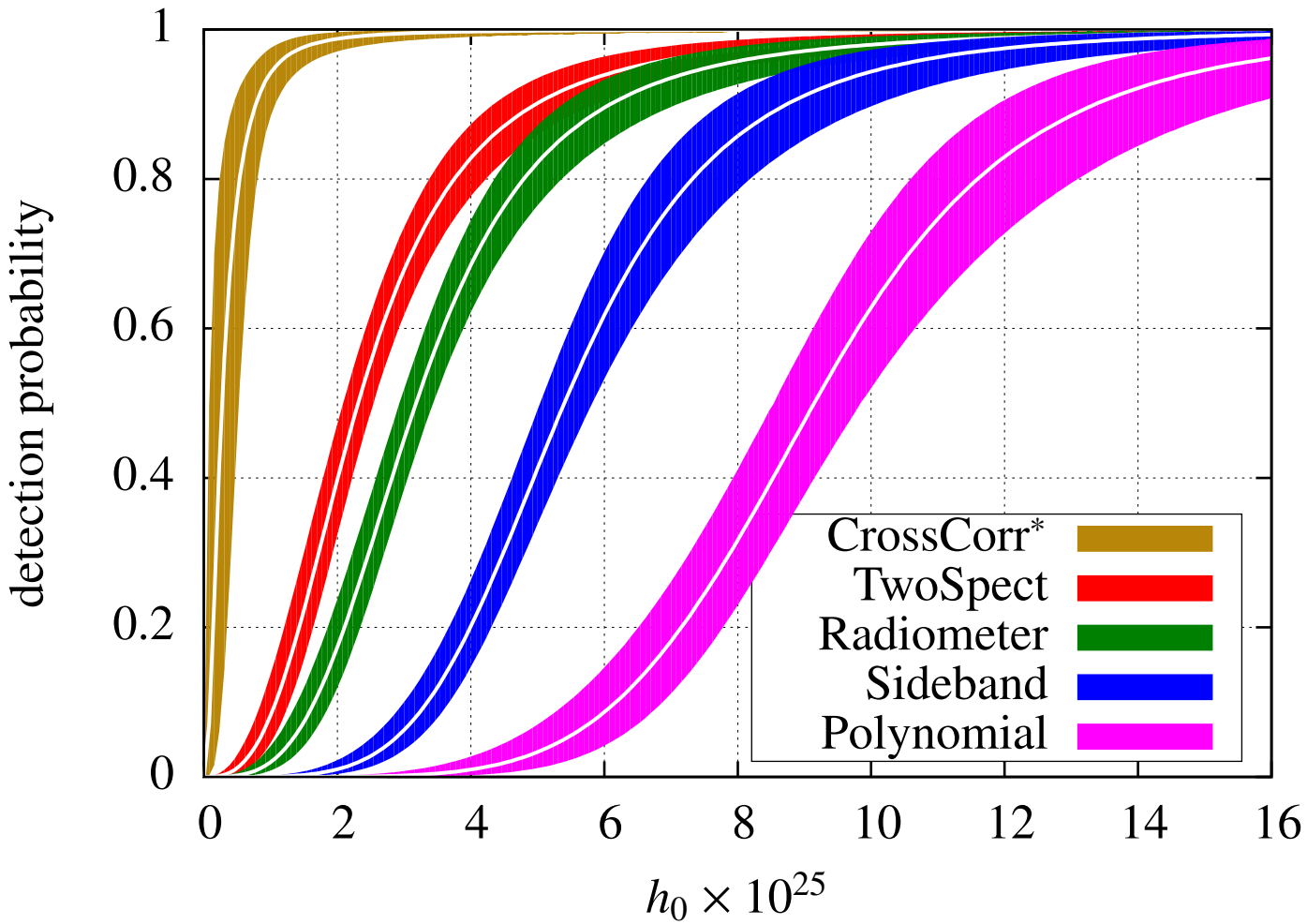
[1] Note: Radiometer, TwoSpect & Polynomial designed for all-sky searches

Summary

- Sco X-1 is a promising continous GW source for aLIGO/aVirgo
- Semicoherent methods needed to handle param uncertainties
- Mock Data Challenges ongoing to compare search methods
- Current methods sensitive to expected signal strength at some frequencies, given a year of design-sensitivity data

EXTRA SLIDES

Comparison of Detection Efficiencies



Messenger et al *PRD* **92**, 023006 (2015)

Parameter Estimation

Median parameter error bars:

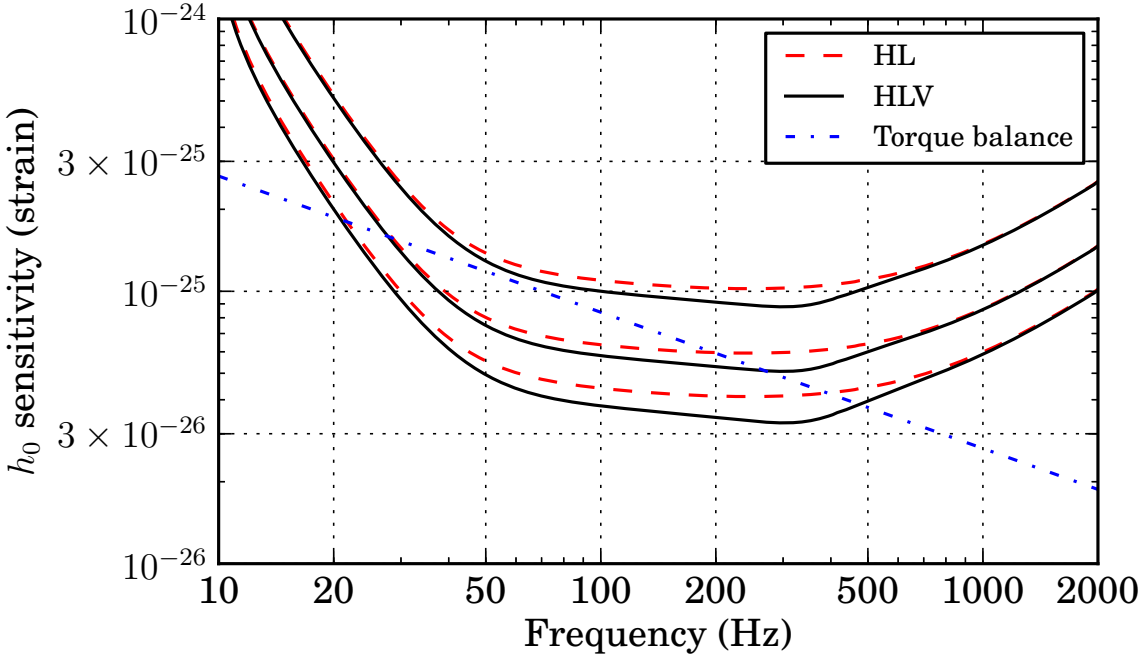
Search	σ_{f_0} (Hz)	σ_{a_p} (lt-sec)	$\sigma_{t_{\rm asc}}$ (sec)
CrossCorr*	6.9×10^{-6}	1.8×10^{-4}	1.2
TwoSpect	3.7×10^{-4}	1.8×10^{-2}	N/A
Radiometer	1.2×10^{-1}	N/A	N/A
Sideband	1.6×10^{-2}	N/A	N/A
Polynomial	5.0×10^{-2}	N/A	N/A

Note: CrossCorr parameter accuracy partly due to interpolation

Messenger et al *PRD* **92**, 023006 (2015)

CrossCorr Sensitivity Estimates

- Sensitivity of search $h_0 \propto (S_n)^{1/2}(T_{\rm obs}\,T_{\rm max})^{-1/4}$
- Expected signal strength from torque balance $h_0 \propto f_0^{-1/2}$
- Compare for 1 yr advanced detector data w/$T_{\rm max} = 6, 60, 600$ min (Single-template false alarm prob 5×10^{-10})



JTW, Sundaresan, Zhang & Peiris *PRD* **91**, 102005 (2015)