



Model-Based Cross-Correlation Search for Gravitational Waves from Scorpius X-1

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Outline

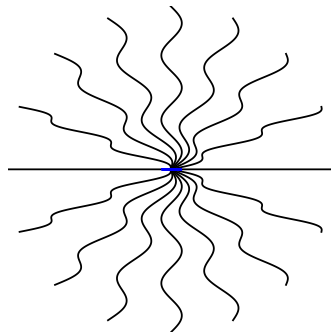
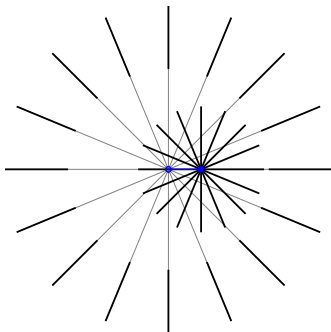
- 1 **Searches for Gravitational Waves**
 - Crash Course in Gravitational Wave Physics
 - Gravitational-Wave Observations & Detectors
 - Gravitational Waves from Low-Mass X-Ray Binaries
- 2 **Cross-Correlation Search**
 - Fundamentals of Periodic GW Searches
 - Parameter Space Search
 - Sensitivity Estimates
- 3 **Scorpius X-1 Mock Data Challenge**
 - Detection of Sco X-1 MDC Signals
 - Parameter Estimation
 - Summary and Future Outlook



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Motivation



- In **Newtonian gravity**, force dep on distance btwn objects
- If massive object suddenly moved, grav field **at a distance** would change **instantaneously**
- In relativity, **no** signal can travel faster than light
 → time-dep grav fields must propagate like light waves



Gravity as Geometry

- Minkowski Spacetime:

$$ds^2 = -c^2(dt)^2 + (dx)^2 + (dy)^2 + (dz)^2$$
$$= \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix}^{\text{tr}} \begin{pmatrix} -c^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} dt \\ dx \\ dy \\ dz \end{pmatrix} = \eta_{\mu\nu} dx^\mu dx^\nu$$

- General Spacetime:

$$ds^2 = \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix}^{\text{tr}} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} = g_{\mu\nu} dx^\mu dx^\nu$$

Metric tensor $\{g_{\mu\nu}(\{x^\lambda\})\}$ determined by masses via Einstein's equations. (10 non-linear PDEs!)

Gravitational Wave as Metric Perturbation

- For GW propagation & detection, work to **1st order** in $h_{\mu\nu} \equiv$ difference btwn actual metric $g_{\mu\nu}$ & flat metric $\eta_{\mu\nu}$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

($h_{\mu\nu}$ “small” in weak-field regime, e.g. for GW detection)

- $h_{\mu\nu}$ analogous to electromagnetic potential $\{A_\mu\} = \{\varphi, \vec{A}\}$
- Small coord changes induce “**gauge transformation**” on $h_{\mu\nu}$
 Convenient choice of gauge is **transverse-traceless**:
 In this gauge:

- Vacuum Einstein eqns \implies **wave equation** for $\{h_{ij}\}$:

$$\left(-\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{ij} = 0$$

- Test particles w/constant coords are **freely falling**



Gravitational Wave Polarization States

- Far from source, GW looks like plane wave prop along \hat{k}
TT conditions mean, in convenient basis,

$$\{k_i\} \equiv \mathbf{k} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad \{h_{ij}\} \equiv \mathbf{h} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where $h_+ \left(t - \frac{x^3}{c}\right)$ and $h_\times \left(t - \frac{x^3}{c}\right)$ are components in “plus” and “cross” polarization states

- EM (spin-1 massless photon) & grav (spin-2 massless “graviton”) waves both have two polarization states



Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:

Plus (+) Polarization	Cross (\times) Polarization



Gravitational Wave Generation

- Generated by **moving/oscillating** mass distribution
- Lowest **multipole** is **quadrupole**

- Rotating neutron star w/**non-axisymmetric** perturbation gives sinusoidally-varying **quadrupole moment**.
- Other sources: compact binary inspiral, bursts (supernova etc), stochastic backgrounds. . .



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Methods for Measuring Gravitational Waves

- Cosmic Microwave Background Perturbations ($f_{\text{gw}} \sim H_0 \sim 10^{-18}$ Hz)
- Pulsar Timing Arrays (10^{-9} Hz $\lesssim f_{\text{gw}} \lesssim 10^{-7}$ Hz)
- Laser Interferometers
 - Space-Based (10^{-3} Hz $\lesssim f_{\text{gw}} \lesssim 10^{-1}$ Hz)
 - ⇒ Ground-Based (10^1 Hz $\lesssim f_{\text{gw}} \lesssim 10^3$ Hz)
- Resonant-Mass Detectors (narrowband, $f_{\text{gw}} \sim 10^3$ Hz)

Note, observable GW freq cover **20** orders of magnitude, similar to EM radiation, but the frequencies are much lower (10^3 Hz $\lesssim f_{\text{em}} \lesssim 10^{23}$ Hz)



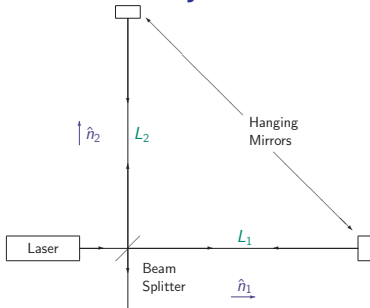
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Measuring GWs w/Laser Interferometry

Interferometry: Measure GW-induced distance changes

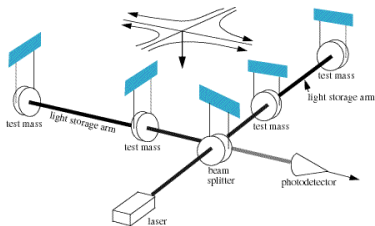


- Measure small change in

$$L_1 - L_2 \approx L_0 \frac{h_{11} - h_{22}}{2} \sim L_0 h_+$$
- Plausible signals: $h \lesssim 10^{-20}$
 → need L_0 very big!
- For LIGO, $L_0 = 4 \text{ km}$

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Rogues' Gallery of Ground-Based Interferometers



LIGO Hanford
 (Washington, USA)



GEO-600 (Germany)



LIGO Livingston
 (Louisiana, USA)



Virgo (Italy)

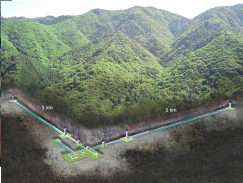
Rogues' Gallery of Ground-Based Interferometers



LIGO Hanford
 (Washington, USA)



GEO-600
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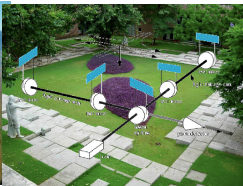
KAGRA (Japan)



LIGO Livingston
 (Louisiana, USA)



Virgo (Italy)



LIGO India



GW Observatory Network

- “Initial Detector Era” for large ground-based interferometers ~ 2002 – 2011
- “Advanced Detector Era” started September 2015
 - Germany: **GEO-600** (600m) used for technology development (laser power, squeezed light, . . .) & “**astrowatch**” in case a **transient event** occurs when other detectors **offline**.
 - USA: **LIGO Hanford** & **LIGO Livingston** (4km)
First observing run (“O1”) Sept 2015-Jan 2016
 - Italy: **Virgo** (3km)
Expected to start observing 2016
 - Japan: **KAGRA** (formerly LCGT)
(3km, underground, cryogenic, under construction)
 - India: **LIGO India** (4km, planned)

Detectors distributed on the Earth useful
for **sky localization** of transient signals



Sensitivity of Initial & Advanced Detectors

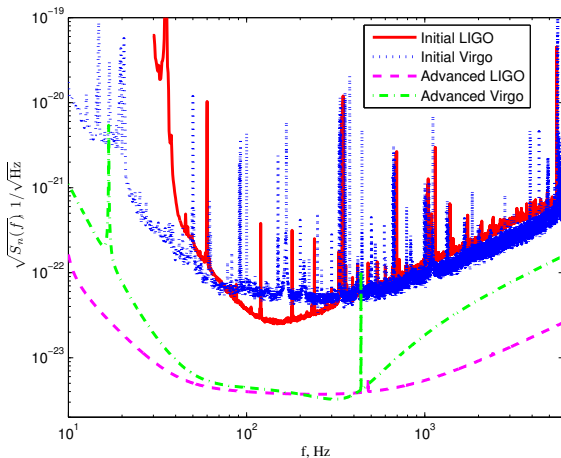


figure from [CQG 27, 173001 \(2010\)](#)



A Few Words About Collaborations

- LIGO Scientific Collaboration : hundreds of researchers at dozens of institutions world-wide working on instrument science, data analysis, astrophysics, etc.
 - LSC scientists operate  & GEO detectors
 -  and  consortium are LSC members
-  Collaboration operates Virgo (Italy) and includes institutions in Italy, France, Netherlands, Poland & Hungary
 - LIGO & Virgo conduct data analysis jointly
- : Japanese collaboration constructing detector in Kamioka mine



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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 \approx 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	$16^{\text{h}}19^{\text{m}}55^{\text{s}}$	$0''06$
dec	δ	$-15^{\circ}38'25''$	$0''06$
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



Note on Inclination Angles

- Inclination i of binary orbit to line of sight
 - Projected semimajor axis $a_p = a \sin i$ (in light seconds)
 - Amplitude of orbital Doppler modulation $\frac{2\pi a_p}{P_{\text{orb}}}$
- Inclination ι of neutron star spin to line of sight
 - Amplitudes of GW polarizations:
 $A_+ = h_0 \frac{1+\cos^2 \iota}{2}$ & $A_\times = h_0 \cos \iota$
 - Many searches sensitive to $A_+^2 + A_\times^2$ rather than just h_0^2
 h_0 is amplitude of GW strain at the solar system
- Generally don't assume i and ι are related



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* **24**, S469 (2007)

☞ 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, Sundaesan, Zhang & Peiris *PRD* **91**, 102005 (2015)



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Coherent Maximum-Likelihood Search (\mathcal{F} -statistic)

- Divide signal parameters into
 - **amplitude params:** $\{h_0, \iota, \psi, \phi_0\}$ (amp, orientation etc)
 - **Doppler params:** $\lambda \equiv \{\alpha, \delta, f_0, \dot{f}_0, \dots\}$ + orb params
- Jaranowski, Królak, Schutz *PRD* **58**, 063001 (1998)
 showed signal linear in $\{\mathcal{A}^\mu\}$ (fncs of **amplitude params**)

$$h(t; \mathcal{A}, \lambda) = \mathcal{A}^\mu h_\mu(t; \lambda) \quad (\text{assume } \sum_{\mu=1}^4 = 1)$$

template waveforms $h_\mu(t)$ depend on **Doppler params** λ

- Optimal¹ detection statistic is maximized log-likelihood ratio

$$\mathcal{F} = \frac{1}{2} x_\mu(\lambda) \mathcal{M}^{\mu\nu}(\lambda) x_\nu(\lambda)$$

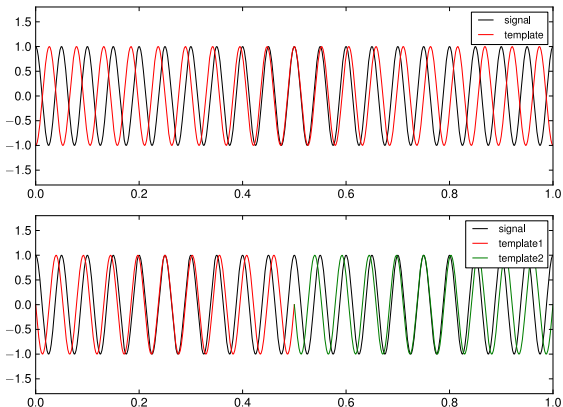
where $\{x_\nu(\lambda)\}$ are four projections of the data

- **Problem:** long coherent searches need to try many λ values

¹But see Prix & Krishnan *CQG* **26**, 204013 (2009)
 and JTW, Prix, Cutler & Willis *CQG* **31**, 065002 (2014)



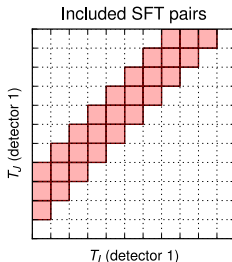
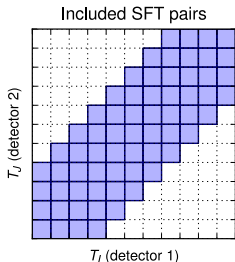
Coherent vs Semi-Coherent Searches



Most CW searches **semi-coherent**: deliberately limit
coherent integration time & **param space resolution**
to keep **number of templates** (λ points) manageable

Motivation for Cross-Correlation Method

- \mathcal{F} -stat quadratic in data; cross-terms combine all times
 → need too many templates
- “Radiometer” method (stochastic cross-correlation search)
 only combines data from different detectors at same time;
 → fast but much less sensitive.
- Construct quadratic cross-correlation statistic which
 combines all data segments w/ $|T_K - T_L| \leq T_{\max}$





Basics of Cross-Correlation Method

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



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

- [BTW, other targets include SN1987A supernova remnant; see Chung, Melatos, Krishnan & JTW *MNRAS* **414**, 2650 (2011)]



Basics of Cross-Correlation Method

Dhurandhar, Krishnan, Mukhopadhyay & JTW *PRD* **77**, 082001 (2008)

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

- Divide data into segments of length T_{sft} & take “short Fourier transform” (SFT)
 K labels SFT, i.e., detector & time
- Parameters λ tell us which Fourier component should contain signal in a given SFT; z_K is that component, normalized by noise PSD $S_n^{(K)}(f_0)$,
so $E[z_K] = \mu_K$ and $E[(z_K - \mu_K)(z_L - \mu_L)^*] = \delta_{KL}$
- Construct quadratic statistic $\rho = z_K^* W_{KL} z_L$
with $W_{KL} \sim \mu_K \mu_L^*$ if $|T_K - T_L| \leq T_{\text{max}}$, 0 otherwise.
- Normalized so that $\text{Var } \rho = 1$ and

$$E[\rho] \propto h_0^2 \frac{\sqrt{T_{\text{obs}} T_{\text{max}}}}{\langle S_n(f_0) \rangle}$$



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Metric for Cross-Correlation Search

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

- Consider dependence of ρ on parameters $\lambda \equiv \{\lambda_i\}$
- Parameter space metric $g_{ij} = -\frac{1}{2} \frac{E[\rho_{,ij}]|_{\lambda=\lambda_{\text{true}}}}{E[\rho^{\text{true}}]}$ from

$$\frac{E[\rho] - E[\rho^{\text{true}}]}{E[\rho^{\text{true}}]} = -g_{ij}(\Delta\lambda^i)(\Delta\lambda^j) + \mathcal{O}([\Delta\lambda]^3)$$

- Assume dominant contribution to $E[\rho_{,ij}]$ is from variation of $\Delta\Phi_{KL} = \Phi_K - \Phi_L$; get phase metric

$$g_{ij} = \frac{1}{2} \sum_{KL} \Delta\Phi_{KL,i} \Delta\Phi_{KL,j} |W_{KL}|^2 \equiv \frac{1}{2} \langle \Delta\Phi_{KL,i} \Delta\Phi_{KL,j} \rangle_{KL}$$

- If you ignore that weighting factor you get back usual metric

$$\langle \Phi_{I,i} \Phi_{I,j} \rangle_I - \langle \Phi_{I,i} \rangle_I \langle \Phi_{J,j} \rangle_J$$



Computing Cost Scaling

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

- Resolution is $\Delta f_0 \propto T_{\max}^{-1}$, $\Delta a_p \propto \frac{P_{\text{orb}}}{f_0 T_{\max}}$, $\Delta t_{\text{asc}} \propto \frac{P_{\text{orb}}^2}{a_p f_0 T_{\max}}$
(if $T_{\max} \ll P_{\text{orb}}$)
- Number of templates $\propto f_0^2 T_{\max}^3$
(for Sco X-1, P_{orb} well constrained observationally)
- Number of pairs of data segments $\propto \frac{T_{\text{obs}} T_{\max}}{T_{\text{sft}}^2}$
- Note: need $T_{\text{sft}} \propto (f_0)^{-1/2}$ to avoid signal loss from Doppler phase acceleration
- Rough cost scaling $\propto f_0^2 T_{\max}^4$
- Work in progress on algorithmic improvements e.g. resampling à la Patel, Siemens, Dupuis & Betzwieser *PRD* **81**, 084032 (2010)

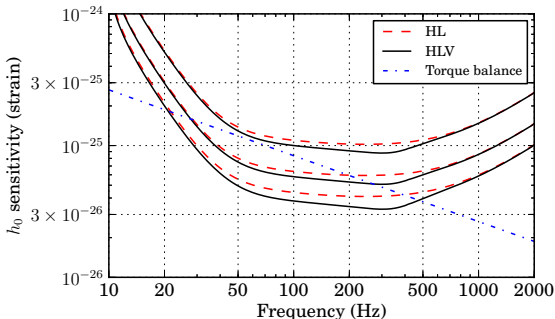


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Sensitivity Estimates

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



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



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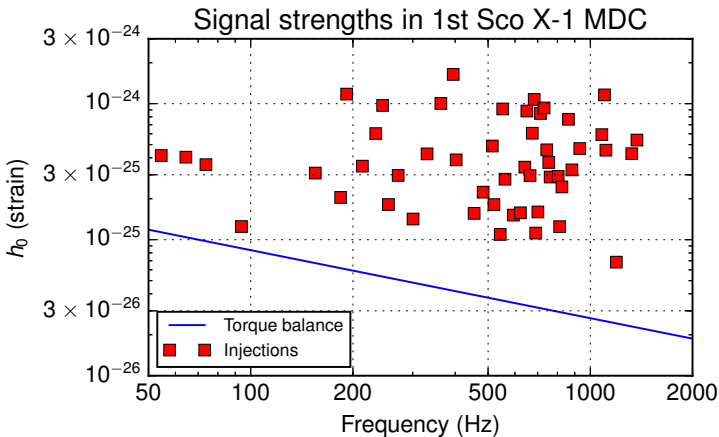


Mock Data Challenge

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, $(S_n)^{1/2} = 4 \times 10^{-24} \text{ Hz}^{-1/2}$ (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

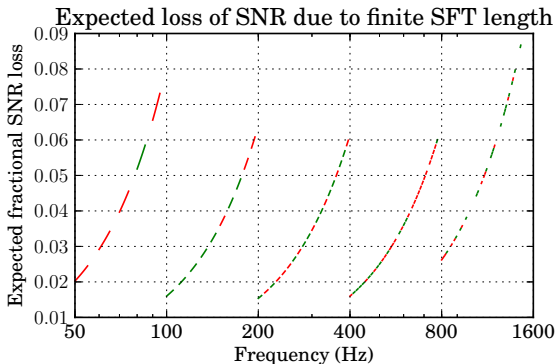
but **note** some amplitudes at torque bal level corresponding to lower freqs

Cross-Correlation Configuration

Zhang, JTW & Krishnan *in preparation*

- SFT length varied with frequency (Doppler acceleration)

50–100 Hz	100–200 Hz	200–400 Hz	400–800 Hz	800–1450 Hz
900 s	600 s	420 s	300 s	240 s



Cross-Correlation Configuration

Zhang, JTW & Krishnan *in preparation*

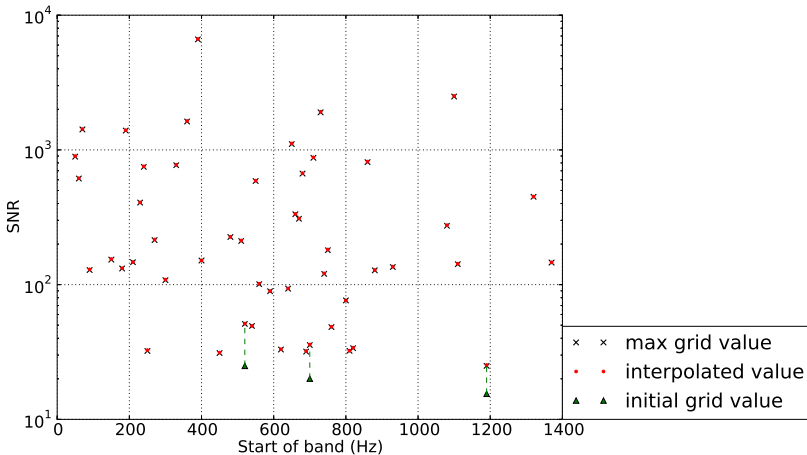
- SFT length varied with frequency (Doppler acceleration)

50–100 Hz	100–200 Hz	200–400 Hz	400–800 Hz	800–1450 Hz
900 s	600 s	420 s	300 s	240 s

- Search $\pm 3\sigma$ in a_p and t_{asc}
- Adjust T_{max} to keep cost per 5 Hz band roughly constant
- Consider budget per band of $N_{pair} N_{tmplt} \leq 5 \times 10^{14}$
[$\mathcal{O}(500)$ CPU-days on AEI atlas cluster]
- Choose two different T_{max} values for each freq octave
(deeper search within 1.5σ of most likely orb params)

50–100 Hz	100–200 Hz	200–400 Hz	400–800 Hz	800–1450 Hz
5400 s	2400 s	2100 s	1140 s	780 s
3600 s	1200 s	840 s	840 s	540 s

Detection of Closed Signals: 50 for 50!



Zhang, JTW & Krishnan *in preparation*



Comparison of Detection Efficiencies

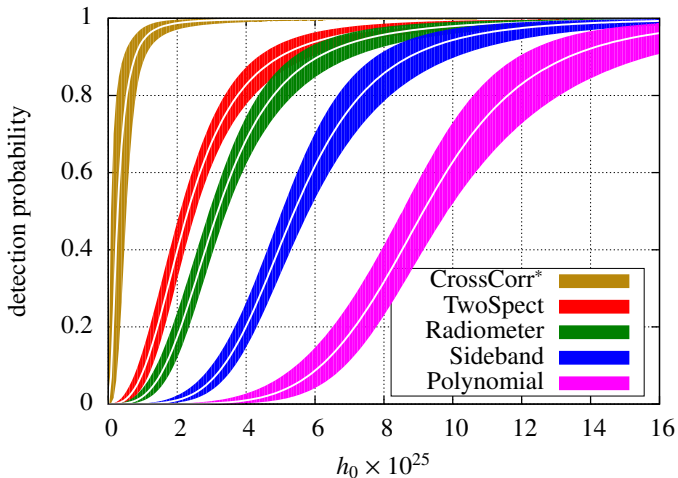
Out of 50 closed signals:

- **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)

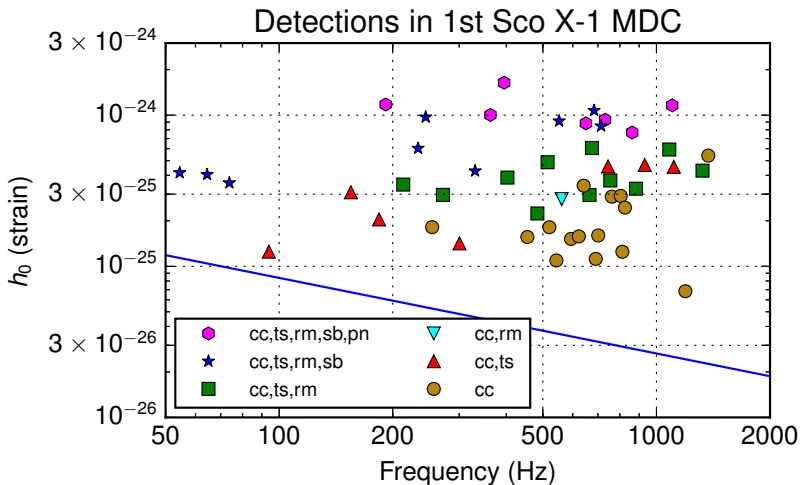


Comparison of Detection Efficiencies



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

Signal Strengths of Detections



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



Detection: Open and Closed

- All closed signals were detected with $\rho > 15.4$
 - Detectable without zoom followup
(Did it on 3 quietest anyway to increase SNR)
 - Could in principle use followup to improve param est;
Limited by “spin wandering” (imperfect torque balance)
- Open signals more interesting:
 - 48 of 50 detected with $\rho > 11$
 - One signal (in 960 Hz band, with $h_0 = 4.96 \times 10^{-26}$) had $\rho = 6.7$;
zoom followup brought this to $\rho = 14.7$
 - One signal (in 490 Hz band, with $h_0 = 3.85 \times 10^{-26}$) **not** detected
Loudest ρ (not at signal point) was 6.07; zoom brought to 5.02
(ρ at true signal params was 3.5)

Zhang, JTW & Krishnan **in preparation**



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 - Detecton of Sco X-1 MDC Signals
 - **Parameter Estimation**
 - Summary and Future Outlook



Parameter Estimation

Median parameter error bars:

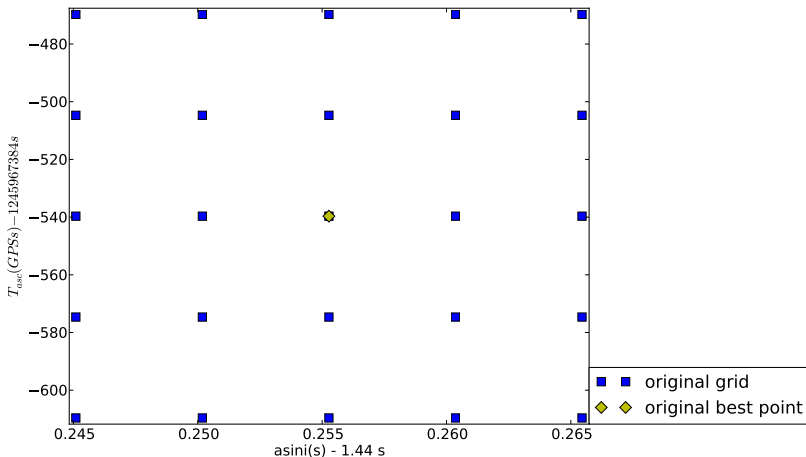
Search	σ_{f_0} (Hz)	σ_{a_p} (lt-sec)	$\sigma_{t_{asc}}$ (sec)
CrossCorr*	6.9×10^{-6}	1.8×10^{-4}	1.2
TwoSpect	3.7×10^{-4}	1.8×10^{-2}	N/A
Radiometer	1.2×10^{-1}	N/A	N/A
Sideband	1.6×10^{-2}	N/A	N/A
Polynomial	5.0×10^{-2}	N/A	N/A

Note: CrossCorr parameter accuracy partly due to interpolation

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



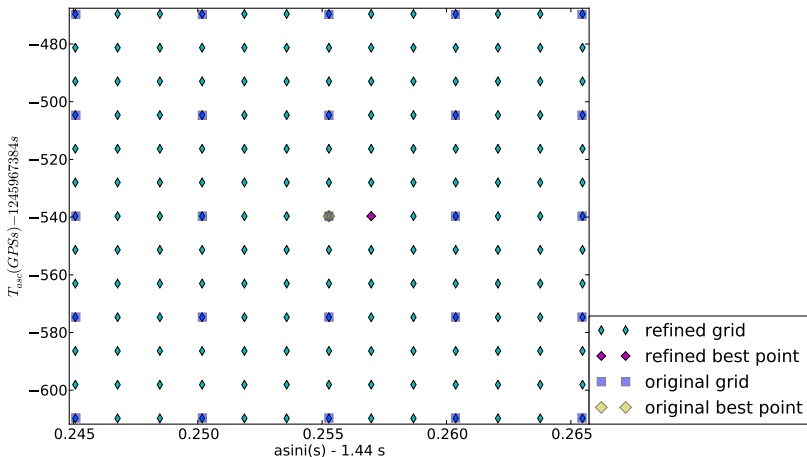
Original Search Grid (excerpt)



Zhang, JTW & Krishnan in preparation

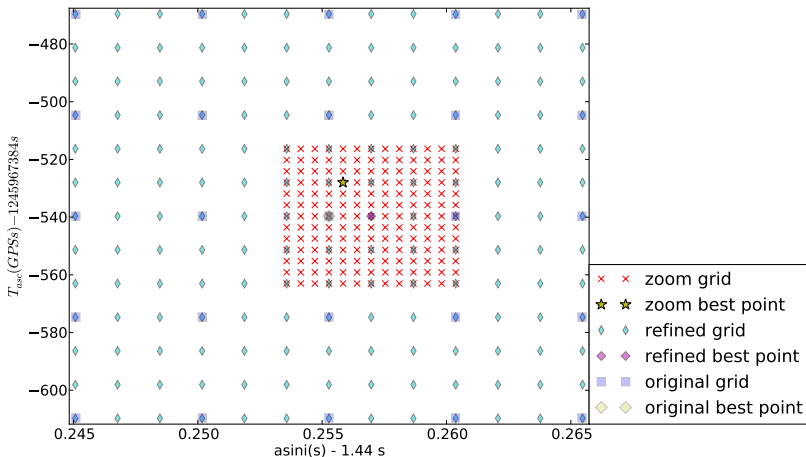


Refined Grid (same T_{\max})



Zhang, JTW & Krishnan in preparation

Zoomed Grid (increase T_{\max} if desired for followup)



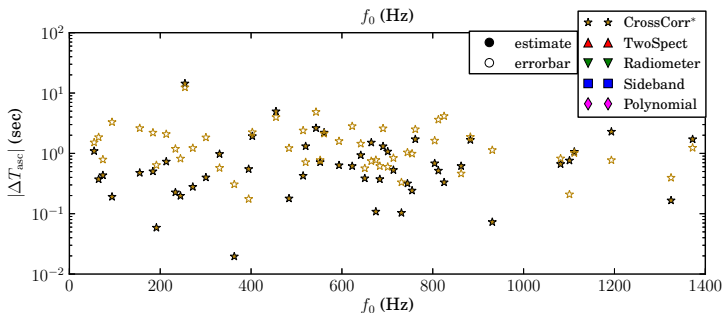
Zhang, JTW & Krishnan in preparation



CrossCorr Parameter Estimation

- In 1 year Gaussian noise $\rho \gtrsim 8$ means false alarm $< 10^{-13}$
☞ with trials factor $\sim 10^8$, still $\lesssim 10^{-5}$
- For such “detections”, can estimate parameters:
 - h_0 from ρ value and noise level
dominant error is unknown inclination of NS spin
 (“could” estimate, but we didn’t for MDC)
 - f_0 , a_p , t_{asc} from values around best-fitting template
- In $3 \times 3 \times 3$ box around “best” point, fit parabola to $\rho(\lambda)$
☞ allows resolution below grid spacing
- Sources of error:
 - Systematic: unknown inclination means max CC stat not at true param values, even without noise
 - Statistical: noise fluctuations offset max CC stat
 - Interpolation: determination of sub-grid

Parameter Estimation: Time of Ascension

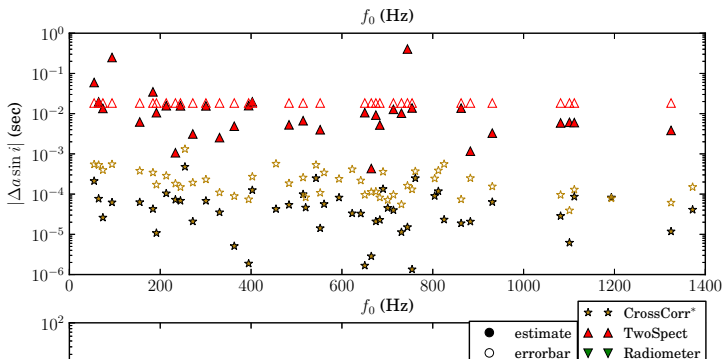


- No one else estimated t_{asc}
- Errors consistent w/errorbars
(after high-SNR empirical correction based on open data)

Messenger et al [PRD 92, 023006 \(2015\)](#)



Parameter Estimation: Projected Semimajor Axis

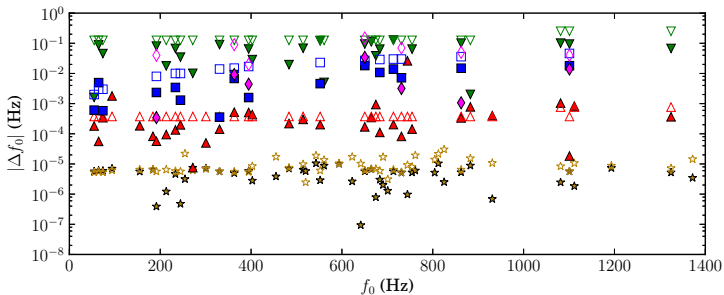


- Removed systematic bias at low frequencies (high-SNR empirical correction based on open data)
- Even w/conservative errorbars, most precise a_p measurement

Messenger et al [PRD 92, 023006 \(2015\)](#)



Parameter Estimation: Frequency

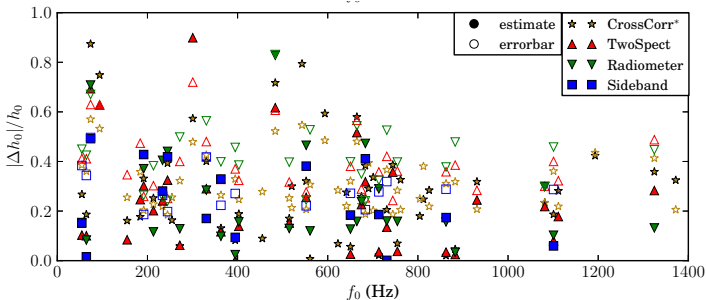


- Systematic error dominant
- Interpolation allows very precise f_0 estimate

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



Parameter Estimation: Amplitude



- Dominant error from unknown spin inclination (for everyone)

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



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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**”
 $f_0 \lesssim 10^{-12}$ Hz/s varying on timescales $\sim 10^6$ 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 utility² 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 achieve **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

²Note: **Radiometer**, **TwoSpect** & **Polynomial** designed for **all-sky** searches



Summary and Future Outlook

- Advanced **Gravitational Wave** detectors have begun observing in 10-4000 Hz band
- Promising target is the low-mass X-ray binary **Scorpius X-1**
- **Cross-correlation method** adapted for **CW signals** allows balance of sensitivity & computing cost via semicoherent analysis
- Current analysis sensitive to expected signal strength **at some frequencies**, given a year of design-sensitivity data
- Validated by recent Sco X-1 Mock Data Challenge