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

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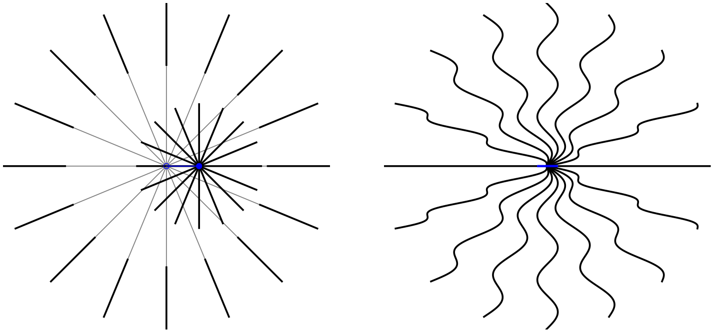
Motivation



- 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
  $\longrightarrow$ 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 $\Longrightarrow$ 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,

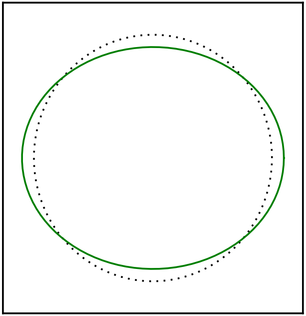
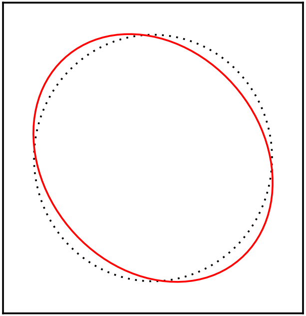
$$\{k_i\} \equiv \boldsymbol{k} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \qquad \{h_{ij}\} \equiv \mathbf{h} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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

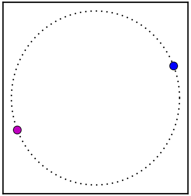
Effects of Gravitational Wave

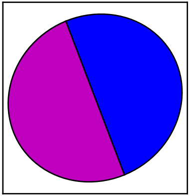
Fluctuating geom changes distances btwn particles in free-fall:

Plus (+) Polarization	Cross (×) 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.
  Note since gravity couples so weakly,
  only have to worry about lowest harmonic;
  No complicated "pulse profile"
- Other sources: compact binary inspiral, bursts (supernova etc), stochastic backgrounds...

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Methods for Measuring Gravitational Waves

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

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

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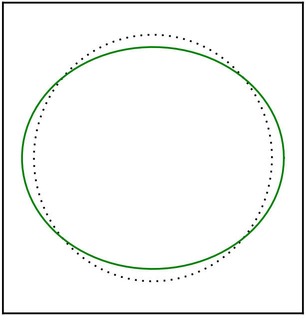
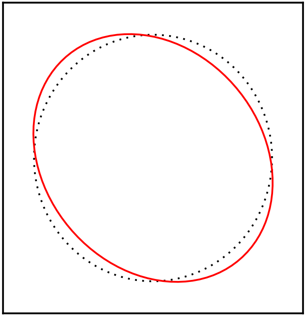
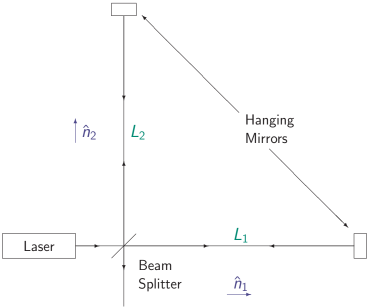
	

Measuring GWs w/Laser Interferometry

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: $h \lesssim 10^{-20}$
$\rightarrow$ need L_0 very big!
- For LIGO, $L_0 = 4\,\mathrm{km}$

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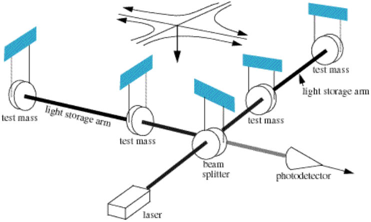

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- Plausible signals: $h \lesssim 10^{-20}$ $\rightarrow$ need L_0 very big!
- For LIGO, $L_0 = 4\,\mathrm{km}$

Rogues' Gallery of Ground-Based Interferometers

LIGO Hanford
(Washington, USA)

GEO-600 (Germany)

LIGO Livingston
(Louisiana, USA)

Virgo (Italy)

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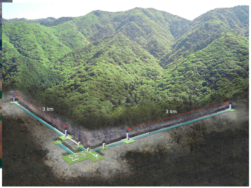
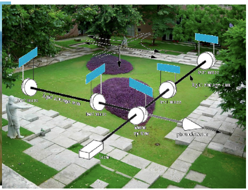


KAGRA (Japan)

LIGO Livingston (Louisiana, USA)

Virgo (Italy)



LIGO India

GW Observatory Network

- "Initial Detector Era" for large ground-based interferometers $\sim$ 2002 – 2011
- "Advanced Detector Era" starts this year
  - 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 Fall 2015
  - 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

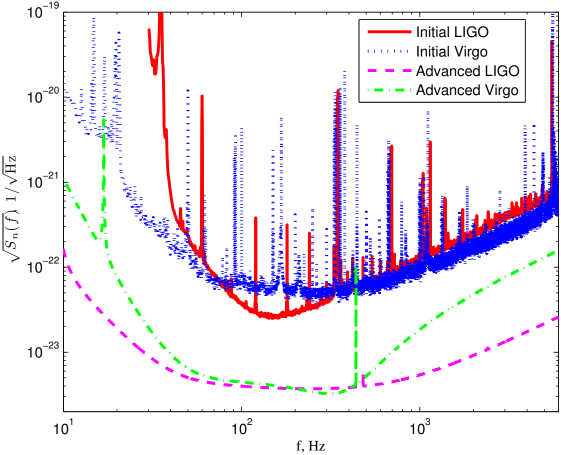


figure from *CQG* **27**, 173001 (2010)

A Few Words About Collaborations

- LIGO Scientific Collaboration LSC: hundreds of researchers at dozens of institutions world-wide working on instrument science, data analysis, astrophysics, etc.
  - LSC scientists operate LIGO & GEO detectors
  - GEO 600 and indigo consortium are LSC members
- VIRGO Collaboration operates Virgo (Italy) and includes institutions in Italy, France, Netherlands, Poland & Hungary
  - LIGO & Virgo conduct data analysis jointly
- KAGRA: 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 ≈ 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	$-15^\circ 38' 25''$	$0''.06$
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, Sundaresan, 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: $\lambda \equiv \{\alpha, \delta, f_0, \dot{f}_0, \ldots\}$ + orb params
- Jaranowski, Królak, Schutz *PRD* **58**, 063001 (1998) showed signal linear in $\{\mathcal{A}^\mu\}$ (fcns of amplitude params)

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

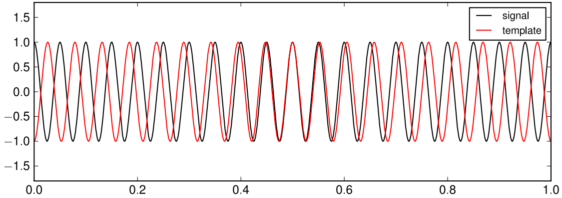
  template waveforms $h_\mu(t)$ depend on Doppler params λ
- Optimal[1] detection statistic is maximized log-likelihood ratio

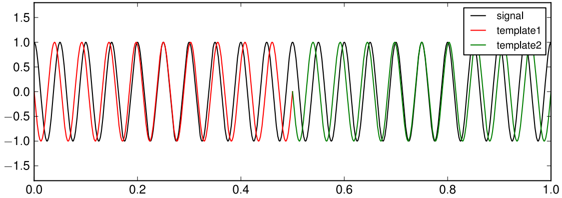
$$\mathcal{F} = \frac{1}{2} x_\mu(\lambda) \mathcal{M}^{\mu\nu}(\lambda) x_\nu(\lambda)$$

  where $\{x_\nu(\lambda)\}$ are four projections of the data
- Problem: long coherent searches need to try many λ values

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

Coherent vs Semi-Coherent Searches

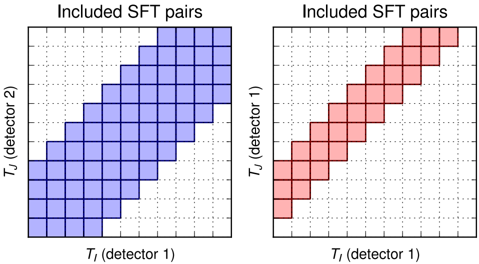




Most CW searches semi-coherent: deliberately limit coherent integration time & param space resolution to keep number of templates (λ points) manageable

Motivation for Cross-Correlation Method

- $\mathcal{F}$-stat quadratic in data; cross-terms combine all times $\longrightarrow$ need too many templates
- "Radiometer" method (stochastic cross-correlation search) only combines data from different detectors at same time; $\longrightarrow$ 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, Sundaresan, Zhang & Peiris *PRD* **91**, 102005 (2015)

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

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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 $E\left[z_K\right] = \mu_K$ and $E\left[(z_K - \mu_K)(z_L - \mu_L)^*\right] = \delta_{KL}$
- Construct quadratic statistic $\rho = z_K^* W_{KL} z_L$ with $W_{KL} \sim \mu_K \mu_L^*$ if $|T_K - T_L| \leq T_{\max}$, 0 otherwise.
- Normalized so that $\mathrm{Var}\,\rho = 1$ and

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

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Metric for Cross-Correlation Search

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

- Consider dependence of ρ on parameters $\boldsymbol{\lambda} \equiv \{\lambda_i\}$
- Parameter space metric $g_{ij} = -\frac{1}{2}\frac{E[\rho_{,ij}]\big|_{\boldsymbol{\lambda}=\boldsymbol{\lambda}_{\text{true}}}}{E[\rho^{\text{true}}]}$ 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, Sundaresan, Zhang & Peiris *PRD* **91**, 102005 (2015)

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

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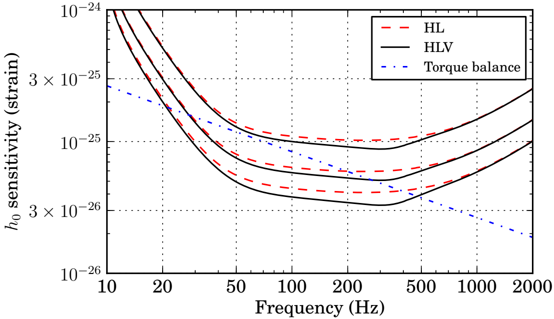
Sensitivity Estimates

- 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)

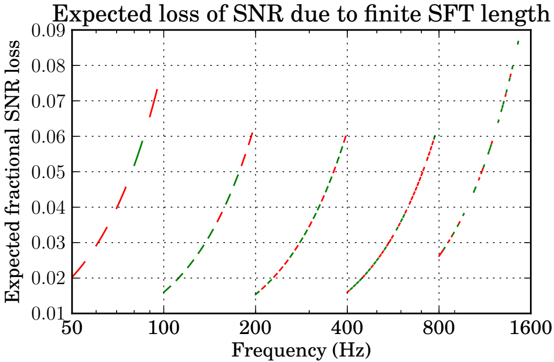
- “Apples-to-apples” comparison of search methods
- One year simulated white gaussian LIGO (2 sites) & Virgo noise, with gaps, $(S_n)^{1/2} = 4 \times 10^{-24}\,\mathrm{Hz}^{-1/2}$ (advanced design)
- 100 simulated signals
  (50 “open” w/published parameters, 50 “closed”)
  injected into specified 5 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

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



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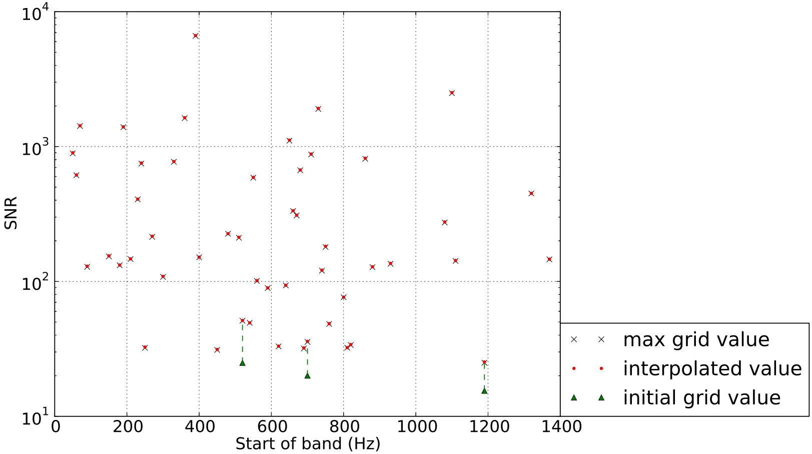
50–100 Hz	100–200 Hz	200–400 Hz	400–800 Hz	800–1450 Hz
900 s	600 s	420 s	300 s	240 s

- 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 $N_{\text{pair}} N_{\text{tmplt}} \leq 5 \times 10^{14}$ [$\mathcal{O}(500)$ 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

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)

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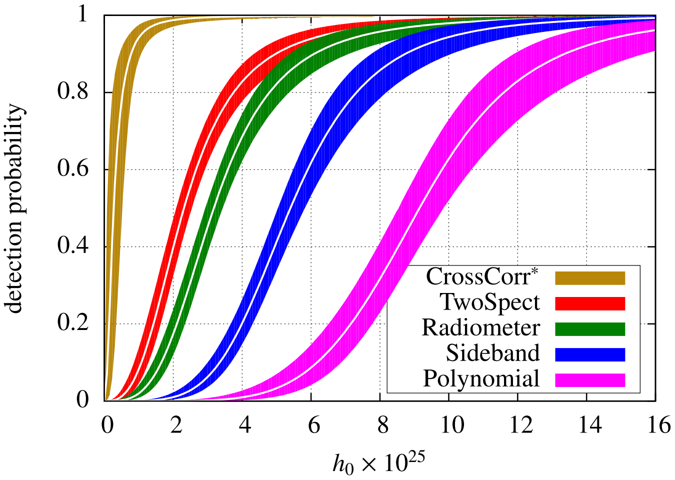
Comparison of Detection Efficiencies

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

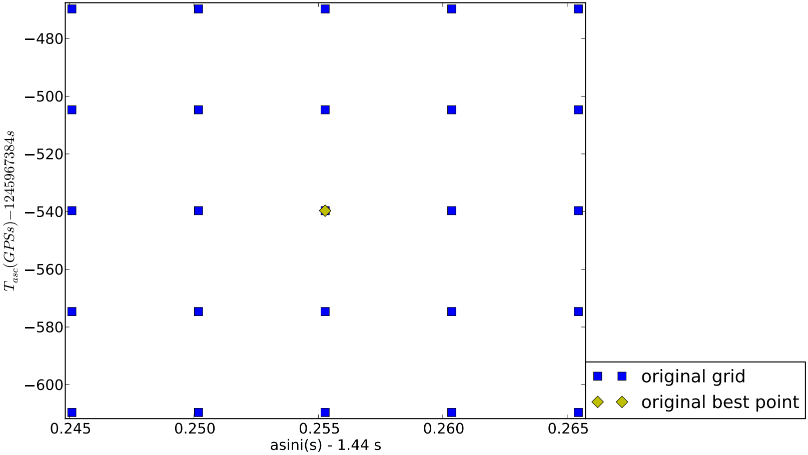


Messenger et al *PRD* **92**, 023006 (2015)

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

Original Search Grid (excerpt)



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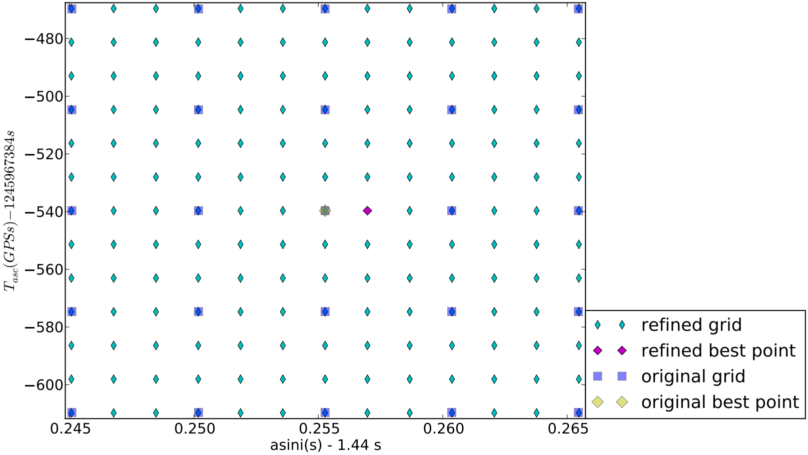
Refined Grid (same $T_{\max}$)



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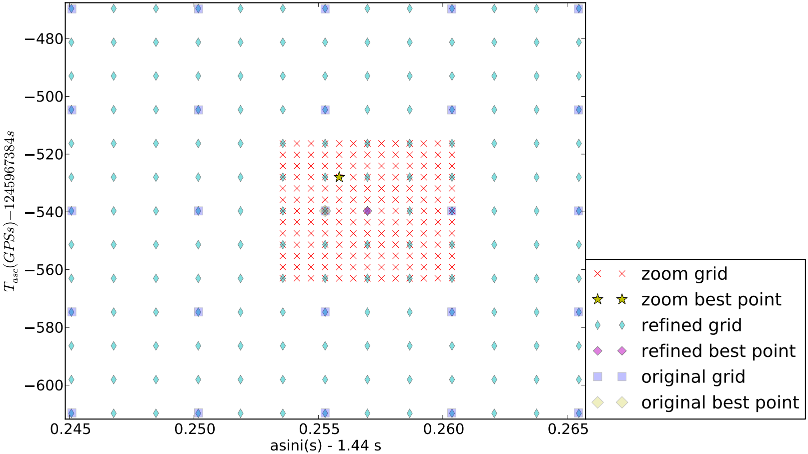
Zoomed Grid (increase $T_{\max}$ if desired for followup)



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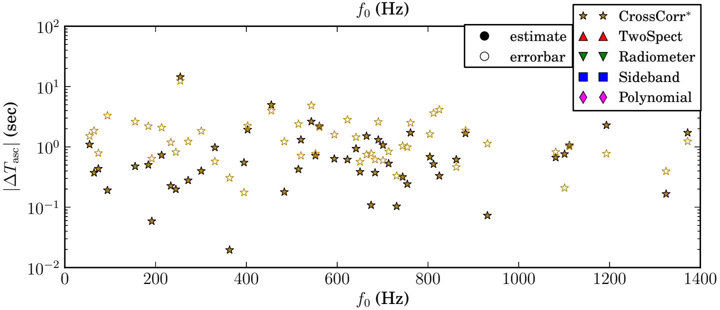
CrossCorr Parameter Estimation

- 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 $\rho(\boldsymbol{\lambda})$
  - ☞ 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 $t_{\rm asc}$
- Errors consistent w/errorbars
  (after high-SNR empirical correction based on open data)

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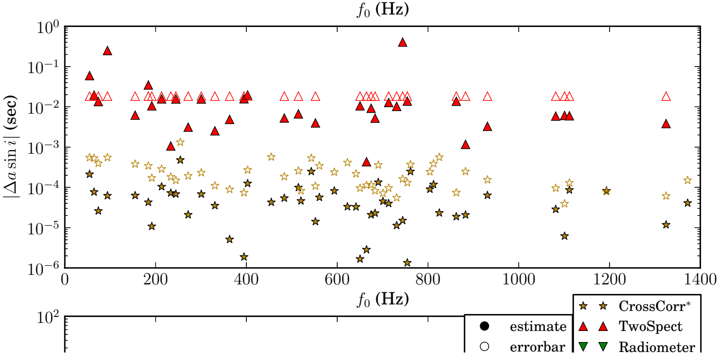
Parameter Estimation: Projected Semimajor Axis



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

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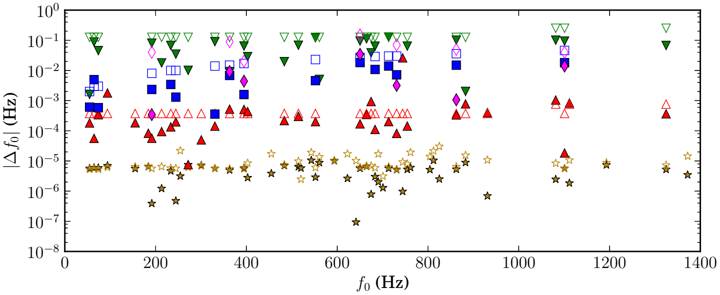
Parameter Estimation: Frequency



- Systematic error dominant
- Interpolation allows very precise f_0 estimate

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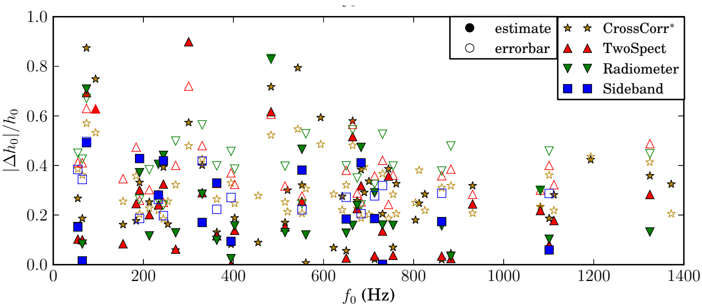
Parameter Estimation: Amplitude



- Dominant error from unknown spin inclination (for everyone)

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Summary and Future Outlook

- Advanced Gravitational Wave detectors about to begin 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 and computing cost via semicoherent analysis
- Advanced detector era sensitivity should reach torque balance prediction
- Validated by recent Sco X-1 Mock Data Challenge
- Note: proposed stacked $\mathcal{F}$-stat search (Leaci and Prix *PRD* **91**, 102003 (2015)) has similar sensitivity scaling; aims to achieve longer coherence time