Distinguishing transient signals and instrumental disturbances in semi-coherent searches for continuous gravitational waves with line-robust statistics

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Overview

1. Introduction and Context
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3. Persistent Single-Detector Line Artifacts ■ □ / ■ □
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simplest example case:
2 detectors $X = 1, 2$ and 2 segments $k = 1, 2$
□ : pure Gaussian noise in (X, k) ■ : signal or disturbance

❶ intro: continuous waves

- non-axisymmetric rotating neutron stars emit quasi-monochromatic gravitational waves
- long-duration *continuous wave* (CW) signals: one of the main LIGO/Virgo/KAGRA targets
- many first-stage CW search methods susceptible to false alarms from *instrumental artifacts*
- usually treated with ad-hoc *vetoes*, and sometimes with expensive follow-up methods

❶ intro: line-robust statistics

- CW searches (e.g. Einstein@Home) return limited *toplists*
  $\Rightarrow$ post-processing useless if toplists swamped by artifacts
  $\Rightarrow$ use robust statistics!
- Bayesian hypothesis testing: improve robustness with explicit model of *persistent single-detector disturbances*
- Keitel, Prix, Papa, Leaci, Siddiqi, *PRD* **89**,064023 (2014)

❶ intro: transients in semi-coherent searches

- long data sets and wide parameter spaces:
  semi-coherent searches, split data into short *segments*

- many outliers in semi-coherent searches of LIGO data caused by *transient disturbances* ($\sim$ hours $\leq T_{\mathrm{seg}}$)

- neutron stars could emit transient CW-like signals (*tCWs*)
- pragmatic alternative to specialized tCW searches: make standard semi-coherent CW searches more tCW-sensitive

❷ persistent astrophysical signals

- standard case of CW data analysis:
  quasi-stationary signals in Gaussian noise
- almost-optimal detection statistic: the $\mathcal{F}$-statistic [1, 2]
- corresponds to a Bayes factor [3]

$$B_{\mathrm{S/G}}(d) = \frac{P(\text{ signal }|\,\text{data})}{P(\text{Gaussian}|\,\text{data})} = \frac{P\left(\begin{matrix} \blacksquare & \blacksquare \\ \blacksquare & \blacksquare \end{matrix}\middle|\, d\right)}{P\left(\begin{matrix} \square & \square \\ \square & \square \end{matrix}\middle|\, d\right)} \propto \mathrm{e}^{\mathcal{F}(d)}$$

(notation reminder for 2-detector, 2-segment example matrix: signals ■ , pure noise □)

[1] Jaranowski, Królak, Schutz, *PRD* **58**,063001 (1998); [2] Cutler, Schutz, *PRD* **72**,063006 (2005)
[3] Prix, Krishnan, *CQG* **26**,204013 (2009)

❸ persistent single-detector line artifacts

- such artifacts look like signals to the $\mathcal{F}$-statistic
- explicit line hypothesis $\Rightarrow$ modified detection statistic: [4]

$$
B_{\mathrm{S/GL}}(d) = \frac{P\left(\begin{matrix}\blacksquare & \blacksquare \\ \blacksquare & \blacksquare\end{matrix}\,\middle|\, d\right)}{P\left(\begin{matrix}\square & \square \\ \square & \square\end{matrix}\,\middle|\, d\right) + P\left(\begin{matrix}\blacksquare & \square \\ \blacksquare & \square\end{matrix}\,\middle|\, d\right) + P\left(\begin{matrix}\square & \blacksquare \\ \square & \blacksquare\end{matrix}\,\middle|\, d\right)}
$$

$$
\propto \frac{\mathrm{e}^{\mathcal{F}(d)}}{\mathrm{const.} + \sum_X o^X_{\mathrm{L/G}}\, \mathrm{e}^{\mathcal{F}^X(d)}}
$$

- detection efficiency: matches $\mathcal{F}$ in quiet data
  and improves over it in disturbed data [4]
- generalizes *$\mathcal{F}$-stat consistency veto* [5, 6, 7]

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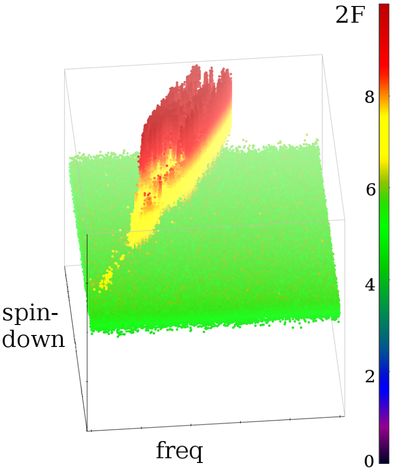
[4] Keitel, Prix, Papa, Leaci, Siddiqi, *PRD* **89**,064023 (2014); [5, 6, 7] LSC/LVC PRD **76**,082001, **87**,042001, **88**,102002

❹ transient single-detector line artifacts

- transient single-detector disturbances in LIGO often limited to single segment: $\sim$ hours [7, 8]
- simulated data with transient disturbance: 1 of 2 detectors, 1 of 90 segments
- search setup similar to Einstein@Home S6Bucket search [9]



[7] Aasi et al., *PRD* **88**,102002 (2013); [8] O. Piccinni, master thesis, U. Roma La Sapienza (2014)
[9] H.B. Eggenstein, talk later today

❹ transient single-detector line artifacts

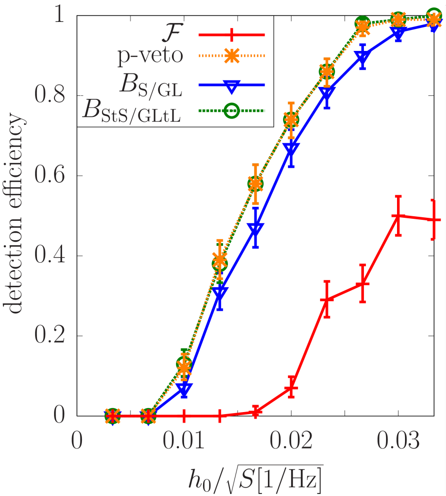
- extend noise model:
  sum over transient lines of length T_{seg}, in any single (X, k)

$$B_{\mathrm{S/GLtL}}(d) = \frac{P\left(\begin{smallmatrix}\blacksquare & \blacksquare \\ \blacksquare & \blacksquare\end{smallmatrix} \,\middle|\, d\right)}{P\left(\begin{smallmatrix}\square & \square \\ \square & \square\end{smallmatrix} \,\middle|\, d\right) + P\left(\begin{smallmatrix}\blacksquare & \square \\ \blacksquare & \square\end{smallmatrix} \,\middle|\, d\right) + P\left(\begin{smallmatrix}\square & \blacksquare \\ \square & \blacksquare\end{smallmatrix} \,\middle|\, d\right) + P\left(\begin{smallmatrix}\blacksquare & \square \\ \square & \square\end{smallmatrix} \,\middle|\, d\right) + \ldots}$$

- can be tuned to *safety* for CW signals in Gaussian noise …
- … while improving detection efficiency in transient-disturbed data

❹ transient single-detector line artifacts

- injecting persistent CW signals into disturbed data (1 of 90 segments)
- search setup similar to Einstein@Home S6Bucket [9]
- transient-robust statistic $B_{\mathrm{S/GLtL}}$ as efficient as multi-detector permanence veto (*p-veto*) [7, 10]



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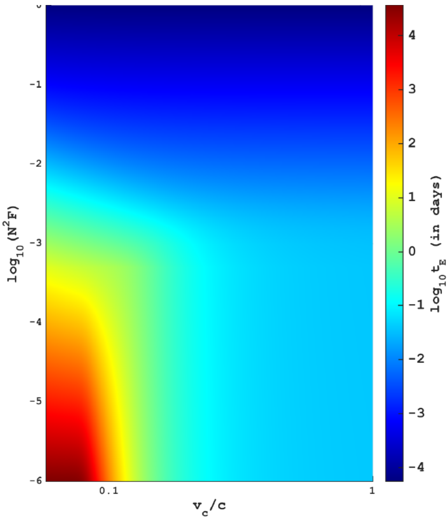
[9] H.B. Eggenstein, talk later today

[7] Aasi et al., *PRD* **88**,102002 (2013); [10] Behnke, Papa, Prix, *PRD* **91**,064007 (2015)

❺ transient astrophysical signals

- but what about tCWs (*transient CW-like signals*), which the p-veto would kill . . . ?
- Neutron stars can emit tCWs by various mechanisms [11, 12]
- for Ekman flow model, see talk by A. Singh (Fri 15:00, Source Modelling session)



[11] Prix, Giampanis, Messenger, *PRD* **84**,023007 (2011); [12] R.I.Santiago Prieto, PhD thesis, Glasgow (2014)

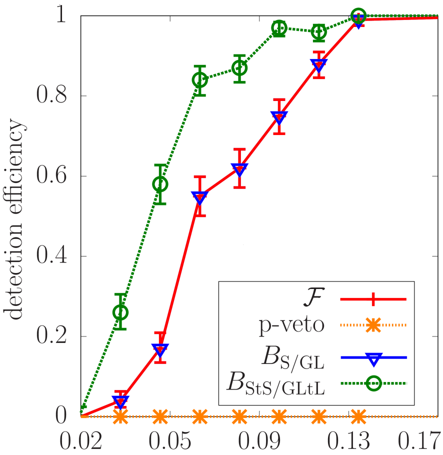
❺ transient astrophysical signals

- improve over semi-coherent $\mathcal{F}$ or $B_{\mathrm{S/GL}}$ by including hypothesis for tCW signals of duration $T_{\mathrm{tCW}} = T_{\mathrm{seg}}$
- $\Rightarrow$ extend signal model, sum over tCWs (both detectors, any single segment):

$$B_{\mathrm{StS/GLtL}}(d) = \frac{P\left(\begin{smallmatrix}\blacksquare & \blacksquare \\ \blacksquare & \blacksquare\end{smallmatrix} \middle| d\right) + P\left(\begin{smallmatrix}\blacksquare & \blacksquare \\ \square & \square\end{smallmatrix} \middle| d\right) + P\left(\begin{smallmatrix}\square & \square \\ \blacksquare & \blacksquare\end{smallmatrix} \middle| d\right)}{P\left(\begin{smallmatrix}\square & \square \\ \square & \square\end{smallmatrix} \middle| d\right) + P\left(\begin{smallmatrix}\blacksquare & \square \\ \blacksquare & \square\end{smallmatrix} \middle| d\right) + P\left(\begin{smallmatrix}\square & \blacksquare \\ \square & \blacksquare\end{smallmatrix} \middle| d\right) + P\left(\begin{smallmatrix}\blacksquare & \square \\ \square & \square\end{smallmatrix} \middle| d\right) + \ldots}$$

❺ transient astrophysical signals

- injecting tCW signals into Gaussian noise
- duration $T_{\mathrm{tCW}} = T_{\mathrm{seg}}$
- search setup similar to Einstein@Home S6Bucket [9]
- same tuning as for CW safety: $B_{\mathrm{StS/GLtL}}$ improves tCW sensitivity



[9] H.B. Eggenstein, talk later today

❻ conclusions

- with appropriate tuning, $B_{\mathrm{StS/GLtL}}$ is ...
  ... *robust against transient or persistent disturbances*
  ... *sensitive to transient or persistent CW-like signals*
- disturbances or signals within a single segment:
  only need *loudest* single-segment $\mathcal{F}_k$, $\mathcal{F}_k^X$
- easy to modify existing searches, not much extra memory or computations needed
- $\Rightarrow$ cheap transient search as "add-on" to semi-coherent CW search such as Einstein@Home [6, 9]
- no dedicated transient-CW searches done so far

[6] Aasi et al., *PRD* **87**,042001 (2013); [9] H.B. Eggenstein, talk later today

❻ outlook

- further improvements through $B_{\mathrm{StS/GLtL}}$-ordered toplists, instead of recomputing from results sorted by $\mathcal{F}$ and $B_{\mathrm{S/L}}$
- applications on real LIGO data, e.g. Einstein@Home post-processing . . . ? [9]
- compare transient-CW detection efficiency with dedicated coherent search [11] or stochastic search [13]
- possible generalization: Bayesian blocks [14, 15]

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[9] H.B. Eggenstein, talk later today

[11] Prix, Giamp., Messenger, *PRD* **84**,023007 (2011); [13] Thrane, Mandic, Christensen, *PRD* **91**,104021 (2015)

[14] Scargle, *APJ* **504**,405 (1998); [15] Scargle et al., *APJ* **764**,167 (2013)

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- [2] Cutler, Schutz, *PRD* **72**,063006 (2005)
- [3] Prix, Krishnan, *CQG* **26**,204013 (2009)
- [4] Keitel, Prix, Papa, Leaci, Siddiqi, *PRD* **89**,064023 (2014)
- [5] Abbott et al., *PRD* **76**,082001 (2007)
- [6] Aasi et al., *PRD* **87**,042001 (2013)
- [7] Aasi et al., *PRD* **88**,102002 (2013)
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- [9] H.B. Eggenstein, later today
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- [13] Thrane, Mandic, Christensen, *PRD* **91**,104021 (2015)
- [14] Scargle, *APJ* **504**,405 (1998)
- [15] Scargle, Norris, Jackson, Chiang *APJ* **764**,167 (2013)