

Hunting the oxymoron: transient continuous waves from disturbed neutron stars

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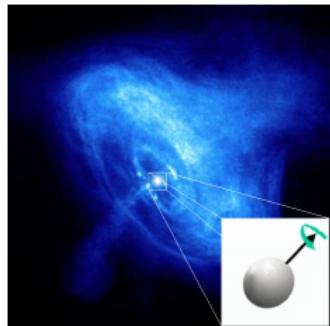
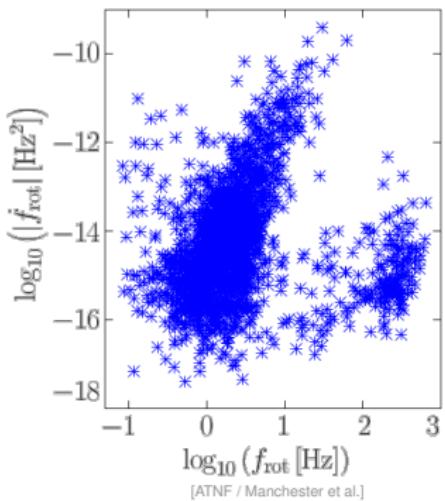
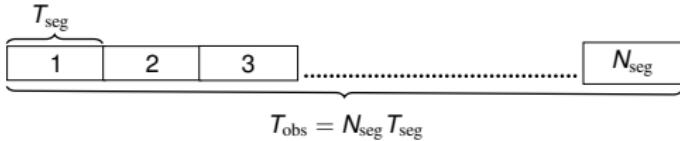


funded by
MSCA-IF action
704094 GRANITE

GWPAW 2017, Annecy
2017-06-01
LIGO-G1700712-v3

① Continuous Waves

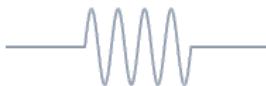
- Neutron Stars: dense, rapid spin
- non-axisymmetric deformations
⇒ GW emission!
- CW model: *quasi-monochromatic*, gentle spindown, coherent $\geq T_{\text{obs}}$
- Doppler-modulated by Earth's motion
- search strategy: *accumulate SNR over months of observation*
- optimal coherent matched-filter search for known pulsars only
- wide-parameter space searches:
semicoherent methods more efficient



② transient Continuous Waves (tCWs)

The oxymoron: What are tCWs?

- same signal morphology as CWs
- quasi-monochromatic
- but limited duration,
minutes to weeks
- $T \gg$ other GW transients (e.g. BBHs)

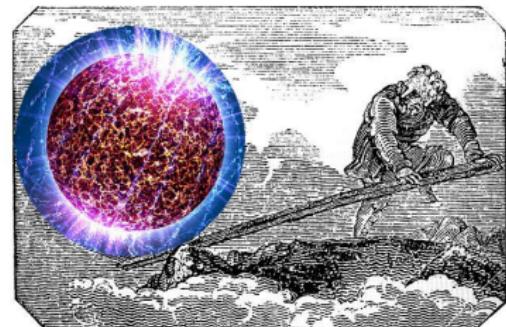


... strange beasts!



Why search for them?

- don't leave any stone
any Neutron Star unturned
- LIGO has opened a new
observational window
- we should check for all
signal morphologies

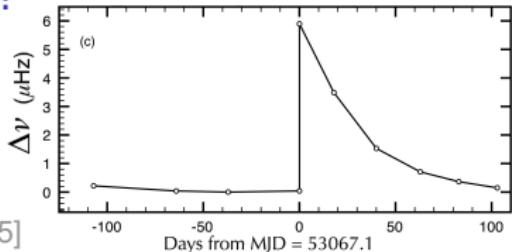


[Mechanics Mag. 1824 / C.Reed (PSU)]

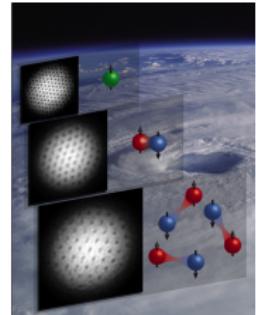
② transient Continuous Waves (tCWs)

'Real' astronomer: No, seriously, why?

- true CWs: only tiny asymmetries can be sustained long enough
- could have bigger, but short-lived, deformations [1, 2] or oscillations [3, 4, 5]
- how and when could these occur?
 - in very young NSs
 - by accretion in close binaries
 - after glitches [6, 7, 8]
(starquakes, vortex unpinning, ...)
- general quantitative predictions difficult, but some progress for specific models



[Espinoza et al. [9]]



[CompStar]

[1] Prix, Giampaolis, Messenger, *PRD* **84**, 023007 (2011)

[2] A. Singh, *PRD* **95**, 024022 (2017); [3] Levin, van Hoven, *MNRAS* **418**, 659 (2011);

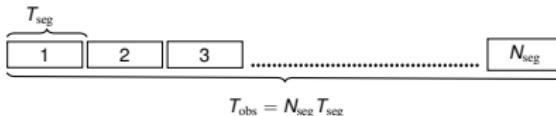
[4] Kashiyama, Ioka, *PRD* **83**, 081302 (2011); [5] N. Andersson, *APJ* **502**, 708–713 (1998);

[6] Melatos, Douglass & Simula, *APJ* **807**, 132 (2015); [7] van Eysden, Melatos, *CQG* **25**, 225020 (2008);

[8] Bennett, van Eysden, Melatos, *MNRAS* **409**, 1705 (2010); [9] Espinoza et al., *MNRAS* **414**, 1679–1704 (2011)

③ How to find tCWs?

- every CW search is also a (very suboptimal) tCW search:
instead of adding up, signal is averaged out
- 'add-on' search: check for time structure in data subdivisions
 - segments in a semicoherent search [10]



- arbitrary chunks of a targeted pulsar search (Pearlstone et al.)
- unmodeled long-transient search [11]
- dedicated search + templates for short, complex waveforms [12]
- extend matched-filter \mathcal{F} -stat [13] with tCW parameters: [1]
start time t_0 , duration τ_{tCW} , window function
⇒ increased sensitivity for low $\frac{\tau_{\text{tCW}}}{T_{\text{obs}}}$

[1] Prix, Giampaolis, Messenger, *PRD* 84,023007 (2011);

[10] D. Keitel, *PRD* 93,084024 (2016); [11] Thrane, Mandic, Christensen, *PRD* 91,104021 (2015);

[12] Coyne, Corsi, Owen, *PRD* 93,104059 (2016); [13] Jaranowski, Krolak & Schutz, *PRD* 58,063001 (1998);

③ How to find tCWs?

Three main scenarios:

- i post-glich transients from known (young) pulsars
- ii transient r -mode oscillations in perturbed fast rotators
- iii model-agnostic followup of candidates
from blind CW searches
(e.g. from Einstein@Home)

④ known-pulsar glitches

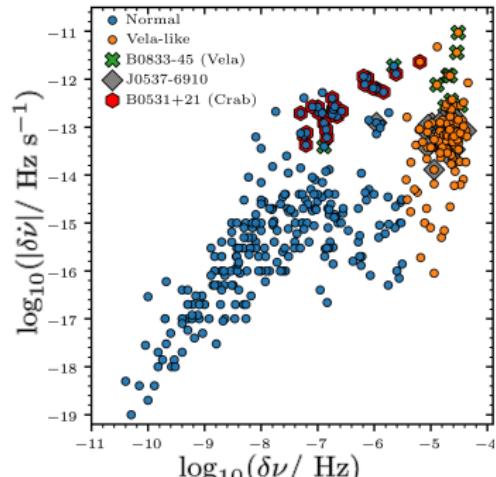
- observed population of glitching pulsars [9, 14]

- lots of models, two main classes:

- crust-reshaping 'starquake'
 - suprafluid re-coupling with crust

- optimistic scenarios, $E_{\text{tCW}} = E_{\max}$:

- 'dark glitch' directly excites GW-emitting modes without spinning up crust
 - normal glitch, full relaxation power goes into deformations and GWs



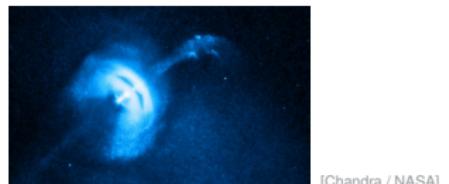
[Ashton, Prix & Jones arXiv:1704.00742]

- both simple starquake and two-fluid models [1]: $E_{\max} \propto I \nu \delta\nu$
- intrinsic strain amplitude $h_0 \propto \sqrt{E_{\text{tCW}}/\tau_{\text{tCW}}}/(f_{\text{GW}} d_{\odot|\text{NS}})$
- accumulating SNR $\propto \sqrt{T_{\text{obs}}}$ \Rightarrow detectable $h_0 \propto 1/\sqrt{T_{\text{obs}}}$

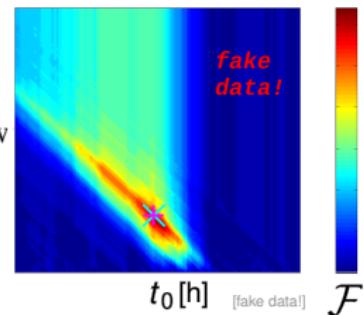
[9] Espinoza et al., MNRAS 414, 1679-1704 (2011); [14] Lyne, Shemar, Smith, MNRAS 315, 534 (2000);
[15] Ashton, Prix & Jones arXiv:1704.00742; [1] Prix, Giampaiani, Messenger, PRD 84, 023007 (2011)

④ known-pulsar glitches

- exciting example: Vela glitch 2016/12/12, at the start of LIGO O2! [16]
- optimistically: $\delta\nu/\nu \sim 10^{-6}$, $\tau_{\text{tCW}} \sim 10 \text{ d}$
 $\Rightarrow E_{\text{max}} \sim 10^{42} \text{ erg}$, $h_0 \sim \text{a few} \cdot 10^{-24}$
- O1 CW upper limit: $h_0 \lesssim 3 \cdot 10^{-25}$ [17]
- *EM-triggered* \Rightarrow fully coherent search
- methods (almost) ready to go:
 - grid-based \mathcal{F} -statistic search [1, 13, 18, 19]
 - emcee \mathcal{F} -statistic search [20]
 - Bayesian Blocks targeted search [slide9]
- challenges:
 - search setup optimization
 - non-Gaussian detector background
(unmodeled searches can help!)



[Danieljr1992, WMC,
CC BY-SA 3.0]



[16] J. Palfreyman, ATel #9847 (2016/12/12); [17] Abbott et al. (LVC), *APJ* 839, 12 (2017)

[18] Santiago-Prieto et al., *J. Phys. Conf. Ser.* 363, 012042 (2012); [19] R.I. Santiago-Prieto, PhD thesis (2014);

[20] G. Ashton, <https://gitlab.aei.uni-hannover.de/GregAshton/PyFstat>

Bayesian blocks and reduced Bayesian blocks

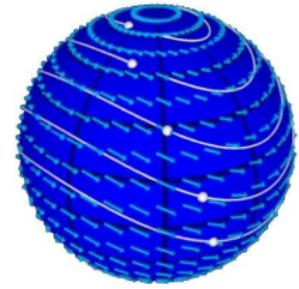
- Need a way to make sure that CW signal are **continuous**
- Robust against detector noise and flexible to tCWs
- Use as a late follow-up on targeted/all sky search candidates
- Use to determine if there is transient nature in signal
 - If not transient, can use to check $\text{SNR} \sim t^{1/2}$
- Look to Bayesian blocks [21, 22]
 - But it's expensive!
- Build a new analysis around BB (\rightarrow bonus slides)
 - Resamples data (Reduces number od data samples D)
 - Small D \rightarrow Sets limit on number of changepoints N_{CP}
 - Each data sample d_i contributes more SNR
 - Can ask a different question:
 - Is there a signal that fits a given transient on/off times



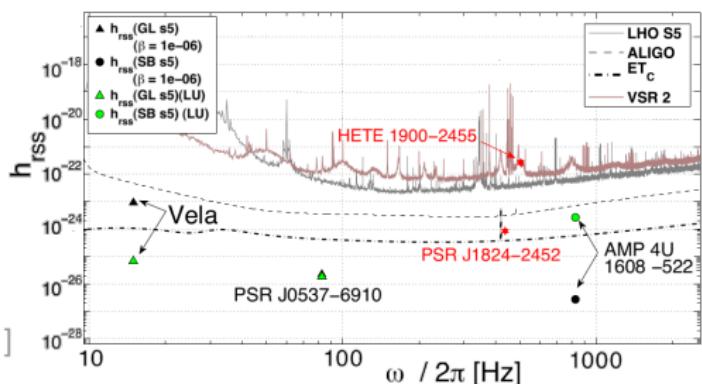
[Brynley Pearlstone's PhD project]

5 transient r -modes

- r -modes: toroidal oscillations with Coriolis restoring force [23]
- current (not mass) quadrupole dominates GW emission
- r -mode frequency $f_{\text{GW},r} \approx \frac{4}{3}f_{\text{rot}}$, uncertain to $\sim \pm 10\%$ [24]
- could get impulsively excited e.g. by glitch or X-ray burst
- fast rotators better: [18, 19] MSP μ -glitches, AMXPs
- \mathcal{F} -statistic transient search [1]



[Lamb et al., CTA, U. Illinois]



[R.I. Santiago-Prieto, based on LU model [25], PRELIMINARY!]

[18] Santiago-Prieto et al., *J. Phys. Conf. Ser.* **363**, 012042 (2012); [19] R.I. Santiago-Prieto, PhD thesis (2014);
 [23] Papaloizou & Pringle, *MNRAS* **182**, 423–442 (1978); [24] Idrisy et al., *PRD* **91**, 024001 (2015);
 [1] Prix, Giannopoulos, Messenger, *PRD* **84**, 023007 (2011); [25] Levin & Ushomirsky, *MNRAS* **324**, 917 (2001)

⑥ candidate follow-up

- reminder: every CW search is a suboptimal tCW search
- simple add-ons can enhance tCW performance
- blind searches: semicoherent methods better



- example: distributed Einstein@Home search [26] on aLIGO O1 data: 20–100 Hz all-sky CW analysis [27]
- add-on tCW search: per-segment CW signal likelihood
⇒ semicoherent line-robust Bayes factor [10]
- $T_{\text{obs}} = 4 \text{ months}$, 12 segments ⇒ tCW timescale $\sim 10 \text{ days}$

[26] einsteinathome.org; [27] S. Walsh, talk at this conference; [10] D. Keitel, *PRD* 93,084024 (2016)

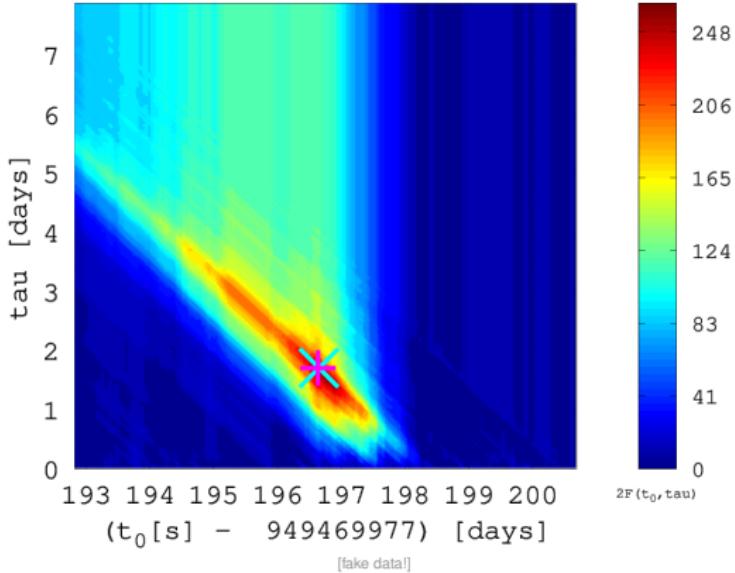
⑥ candidate follow-up

- semicoherent line-robust tCW detection statistic: (\rightarrow bonus slides)

$$\widehat{B}_{\text{IS/GLtL}}(\mathbf{x}) \propto \frac{P(\square\square|\mathbf{x}) + P(\square\square|\mathbf{x})}{P(\square\square|\mathbf{x}) + P(\square\square|\mathbf{x}) + P(\square\square|\mathbf{x}) + P(\square\square|\mathbf{x}) + P(\square\square|\mathbf{x}) + P(\square\square|\mathbf{x}) + P(\square\square|\mathbf{x})}$$

- fake data example
with old S6 setup:
 $T_{\text{obs}} \sim 1 \text{ yr}, T_{\text{seg}} = 60 \text{ h}$

- semicoherent search candidates: identify highest- \mathcal{F} segment
- coherent follow-up:
small search box
and several segments
around candidate



- ongoing: full sensitivity estimate in simulated Gaussian noise,
background studies with LIGO open data

Conclusions and perspectives

transient Continuous Waves (tCWs)

- a simple signal model allowing pragmatic searches
- several possible emission mechanisms from perturbed neutron stars

multi-messenger perspective

- majority of NS not seen as pulsars:
CW or tCW detection \Rightarrow radio+Xray+optical follow-up
- good sky localization, though T_{obs} - dependent

fundamental physics with tCWs and NSs

- powerful probes of NS dynamic interiors
- e.g. equation-of-state constraints from r -modes [28, 29]

[28] Link, Epstein & vanRiper, *Nature* **359**, 616–618 (1992); [29] Mytidis et al., *APJ* **810**, 27 (2015)

Thanks for
your attention!

Questions very welcome!



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 704094 (MSCA-IF action GRANITE).

*Thanks to R. Prix, G. Ashton, K. Wette, H.B. Eggenstein, B. Machenschalk
for various aspects of code development!*

References

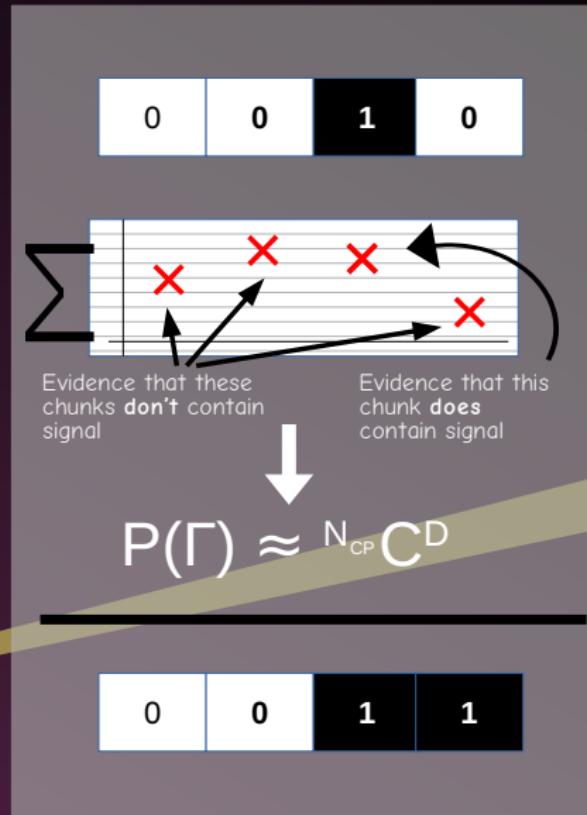
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- [5] N. Andersson, *APJ* **502**,708–713 (1998)
- [6] Melatos, Douglass & Simula, *APJ* **807**,132 (2015)
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- [8] Bennett, van Eysden, Melatos, *MNRAS* **409**,1705 (2010)
- [9] Espinoza et al., *MNRAS* **414**,1679-1704 (2011)
- [10] D. Keitel, *PRD* **93**,084024 (2016)
- [11] Thrane, Mandic, Christensen, *PRD* **91**,104021 (2015)
- [12] Coyne, Corsi, Owen, *PRD* **93**,104059 (2016)
- [13] Jaranowski, Krolak & Schutz, *PRD* **58**,063001 (1998)
- [14] Lyne, Shemar, Smith, *MNRAS* **315**,534 (2000)
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- [16] J. Palfreyman, ATel #9847 (2016/12/12)
- [17] Abbott et al. (LVC), *APJ* **839**,12 (2017)
- [18] Santiago-Prieto et al., *J. Phys. Conf. Ser.* **363**,012042 (2012)
- [19] R.I. Santiago-Prieto, PhD thesis (2014)
- [20] G. Ashton, <https://gitlab.aei.uni-hannover.de/GregAshton/PyFstat>
- [21] J.D. Scargle, *APJ* **504**,405–418 (1998)
- [22] Scargle et al., *APJ* **764**,167 (2013)
- [23] Papaloizou & Pringle, *MNRAS* **182**,423–442 (1978)
- [24] Idris et al., *PRD* **91**,024001 (2015)
- [25] Levin & Ushomirsky, *MNRAS* **324**,917 (2001)
- [26] einsteinathome.org
- [27] S. Walsh, talk at this conference
- [28] Link, Epstein & vanRiper, *Nature* **359**,616–618 (1992)
- [29] Mytidis et al., *APJ* **810**,27 (2015)
- [30] Prix & Krishnan, *CQG* **26**(20),204013 (2009)
- [31] Keitel et al., *PRD* **89**,064023 (2014)

BONUS SLIDES

RBB - The procedure

(c) B. Pearlstone

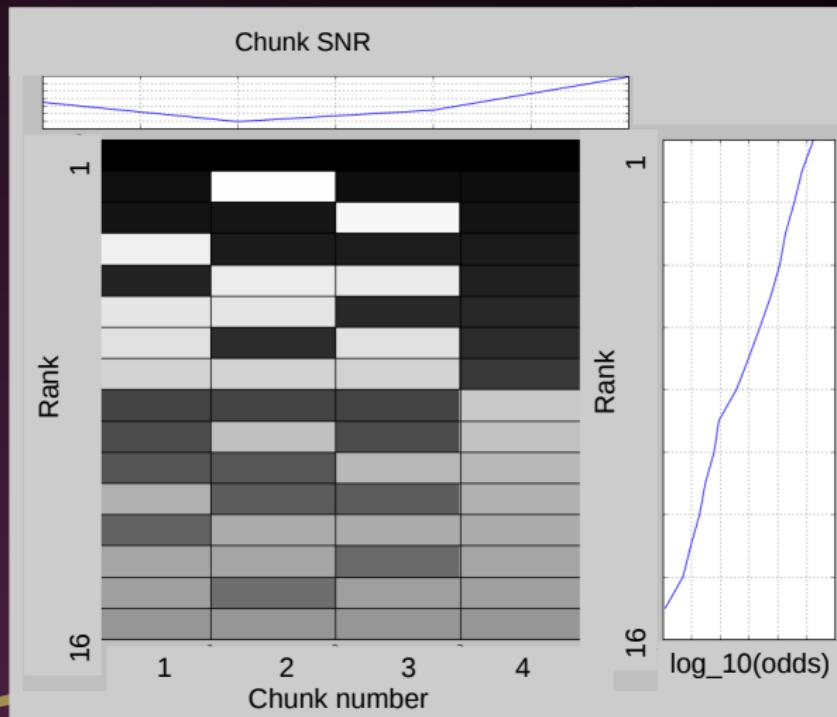
- Chunk up data into (4) chunks
- Overhead: Perform long analysis on chunks
- Pick configuration $\Gamma = \{\gamma_i\}$
 - Black $\gamma_i = 1$, white $\gamma_i = 0$
- Read in data $\{d_i\}$ for each chunk
- Do analysis on $\{d_i\}$
 - Sum evidence for γ_i over i
 - Multiply by prior on Γ
 - Prior flat over N_{CP}
 - Proportional to binomial coefficient
- Repeat for next configuration
- Devil in the details!
 - Consecutive $\gamma_i = 1$ – treat as a single longer chunk
 - Prior on Γ a function of N_{CP} intrinsic property of Γ



RBB - Barcode plot

(c) B. Pearlstone

- Take odds ratio for each Γ_j
- Toplist of most favoured configuration
- Order from highest to lowest, top to bottom
- Greyscale – greyer, worst fitting model
- Top diagram – SNR (signal evidence divided by noise evidence) for each chunk
- Right – log-evidence for each Γ_j , sorted in the same order
- Centre – Barcode
- Easy way to diagnose. Go down barcode, does the order make sense?



6 semicoherent tCW search

simplest example of a semicoherent search

2 detectors $X = 1, 2$ and 2 segments $\ell = 1, 2$

\square : pure Gaussian noise in (X, ℓ) \blacksquare : signal or disturbance

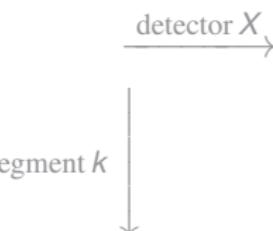
1 persistent
signal [13, 30]



2 transient signal [10]



↑ detect ↑



3 persistent line [31]



4 transient line [10]



↑ suppress ↑

[13] Jaranowski, Krolak & Schutz, *PRD* 58,063001 (1998); [30] Prix & Krishnan, *CQG* 26(20),204013 (2009);
[10] D. Keitel, *PRD* 93,084024 (2016); [31] Keitel et al., *PRD* 89,064023 (2014)

⑥ semicoherent tCW search

standard matched-filter \mathcal{F} -statistic [13, 30] for CWs:

$$\hat{B}_{S/G}(\mathbf{x}) \propto e^{\hat{\mathcal{F}}(\mathbf{x})} \propto \frac{P(\begin{array}{|c|c|} \hline \blacksquare & \blacksquare \\ \hline \end{array} | \mathbf{x})}{P(\begin{array}{|c|c|} \hline \square & \square \\ \hline \end{array} | \mathbf{x})}$$

detector X
segment $k \downarrow$

line-robust CW detection statistic [31]:

$$\hat{B}_{S/GL}(\mathbf{x}) \propto \frac{P(\begin{array}{|c|c|} \hline \blacksquare & \blacksquare \\ \hline \end{array} | \mathbf{x})}{P(\begin{array}{|c|c|} \hline \square & \square \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \blacksquare & \square \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \square & \blacksquare \\ \hline \end{array} | \mathbf{x})}$$

tCW detection statistic [10]:

$$\hat{B}_{tS/GLtL}(\mathbf{x}) \propto \frac{P(\begin{array}{|c|c|} \hline \blacksquare & \blacksquare \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \square & \square \\ \hline \end{array} | \mathbf{x})}{P(\begin{array}{|c|c|} \hline \square & \square \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \blacksquare & \square \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \square & \blacksquare \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \blacksquare & \blacksquare \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \blacksquare & \square \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \square & \blacksquare \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \blacksquare & \square \\ \hline \end{array} | \mathbf{x}) + P(\begin{array}{|c|c|} \hline \square & \blacksquare \\ \hline \end{array} | \mathbf{x})}$$

[13] Jaranowski, Krolak & Schutz, *PRD* 58,063001 (1998); [30] Prix & Krishnan, *CQG* 26(20),204013 (2009);
[10] D. Keitel, *PRD* 93,084024 (2016); [31] Keitel et al., *PRD* 89,064023 (2014)