Not-Quite-Continuous Gravitational Waves

Challenges and Opportunities

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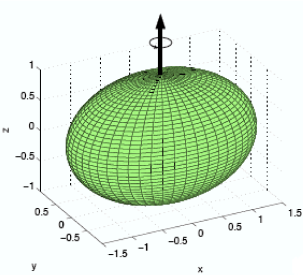
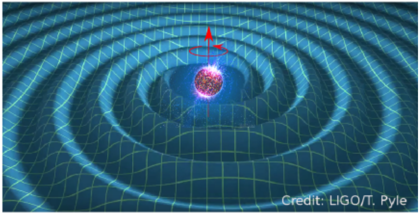
Recap: Continuous Gravitational Waves (CWs)





deformed (ϵ) spinning NS ☞ periodic GWs at $f = 2 \times f_{\rm spin}$

Strain amplitude h_0 on Earth

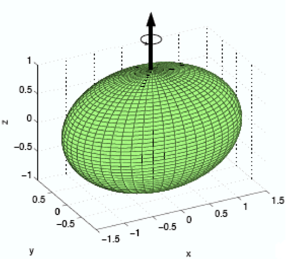
$$h_0 \approx 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I}{10^{38}\,\mathrm{kg\,m^2}}\right) \left(\frac{f_{\rm spin}}{50\,\mathrm{Hz}}\right)^2 \left(\frac{100\,\mathrm{pc}}{\text{distance}}\right)$$

CW phase model@NS ☞ low-order Taylor model $\{f, \dot{f}, (\ddot{f})\}$:

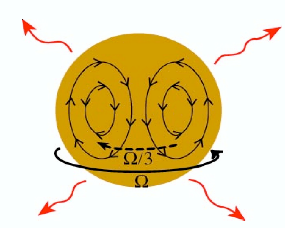
$$\phi(t) = 2\pi \left(f\,t + \frac{1}{2}\dot{f}\,t^2 \;\; (+\frac{1}{6}\ddot{f}\,t^3) \right)$$

Recap: Potential CW Emission Mechanisms

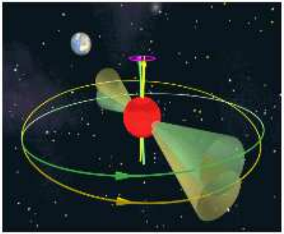
"Mountains" $f = 2 \times f_{\text{spin}}$



r-modes $f \approx \frac{4}{3} \times f_{\text{spin}}$



Precession $f \sim f_{\text{spin}}, \sim 2 \times f_{\text{spin}}$



Accretion $f \sim 2 \times f_{\text{spin}}$ or $\frac{4}{3} \times f_{\text{spin}}$

What Could Go Wrong? [Brainstorming Laundry List]

Fragile assumptions: 1) always-on 2) Taylor spindown $\{f, \dot{f}, \ddot{f}\}$

1. intrinsically-transient CW emission
   [larger non-axisymmetry ϵ ☞ shorter timescales?]

   - mountains, r-modes: triggered by NS glitches?
     (post-glitch relaxation $\mathcal{O}$ (days-months))
   - r-mode instability window
   - transient accretion
   - other? (asteroid-impact?, BNS post-merger?)

2. non-Taylor phase evolution: (☞ apparent transient-CW)

   - glitching-CWs: sudden change in $\{f, \dot{f}\}$
   - "timing noise": randomly drifting $\{f, \dot{f}\}$
     ☞ isolated pulsars (as seen in EM)
     ☞ accretion spin-drift in LMXBs
   - very young object (high f) ☞ power-law spindown $\dot{f} = -\kappa f^n$
   - other? (eg missed binary-orbital evolution)

Some Recent Suggestions for Not-Quite-CWs

- transient-CWs from post-glitch Ekman-flow
  [van Eysden, Melatos (2008), +Bennett (2010), Singh (2017)]
- inter-glitch r-mode spindown ($n = 7$) in J0537-6910?
  [Andersson+(2017)]
- CW-driven spindown during accretion in PSR J1023-0038?
  [Haskell&Patruno (2017)]
- GW170817 post-merger: HMNS $\sim 1\mathrm{s}$, SMNS $\sim 10 - 10^4\mathrm{s}$ transient CW from bar-mode-, magnetar-instability
  [LVC (2017)], ☞ Paul Lasky's talk
- …

Search Methods I: Coherent Matched Filtering

Optimal matched filtering

$$(\text{data}|\text{template}) \equiv \frac{1}{S_n} \int_0^{T_{\rm obs}} \text{data}(t)\, \text{template}(t)\, dt$$

☞ coherent Signal-to-Noise ratio: $\mathrm{SNR} = (s|s) \propto \frac{h_0}{\sqrt{S_n}} \sqrt{T_{\rm obs}}$

amplitude $h_0 \lesssim 10^{-25}$, noise $\sqrt{S_n} \sim 10^{-23}\mathrm{Hz}^{-1/2}$ ☞ $T_{\rm obs} \gtrsim \mathcal{O}\,(\mathrm{days})$

BUT: larger $T_{\rm obs}$ ☞ increases parameter-space resolution

Uncertainties $\Delta(\text{sky}, f, \dot{f}, \ldots)$ ☞ need template bank

$$\left.\begin{aligned} \mathrm{Cost}(\Delta f) &\propto T_{\rm obs} \\ \mathrm{Cost}(\Delta\{f, \dot{f}\}) &\propto T_{\rm obs}^3 \\ \mathrm{Cost}(\Delta\{\text{sky}, f, \dot{f}\}) &\propto T_{\rm obs}^5 \\ &\ldots \end{aligned}\right\}$$

☞ limits coherence time $T_{\rm obs} \lesssim \mathcal{O}\,(\text{days})$

☞ optimal in principle, but not if cannot afford to analyse all the data

+ larger $T_{\rm obs}$ ☞ more “fragile” to phase-model deviations

Search Methods II: Semi-Coherent Methods

Split T_{obs} into segments $N_{\text{seg}} \times T_{\text{seg}}$ + “incoherently” combine (eg sum)

"Cost $\to \infty$" — Fully Coherent Search

Cost $= C_0$ { Coherent + Coherent + Coherent + Coherent + Coherent
Fully Coherent Search

less sensitive for same amount of data, but much faster!

☞ more sensitive at fixed computing cost (typically $\times 2$)

+ smaller T_{seg} ☞ more robust to phase-model deviations

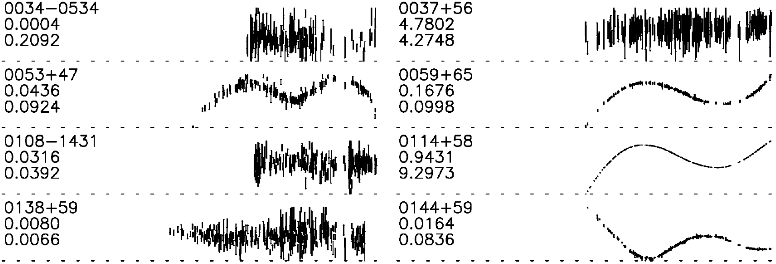
- insensitive to arbitrary phase jumps between segments
- coarser frequency- and spindown resolution:

$$df \propto \frac{1}{T_{\text{seg}}}, \quad d\dot{f} \propto \frac{1}{T_{\text{obs}}\,T_{\text{seg}}}, \quad \ldots$$

BUT: follow-up interesting candidates ☞ increase $T_{\text{seg}} \to T_{\text{obs}}$

Timing Noise (in Non-Accreting Pulsars)

Examples of timing residuals wrt Taylor spindown (over 38y):



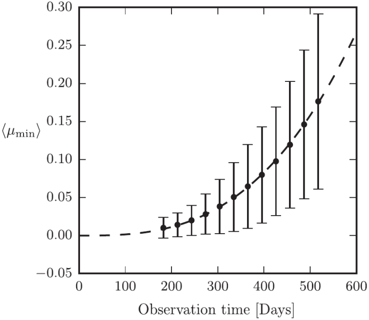
[Hobbs, Lyne, Cramer (2010)]

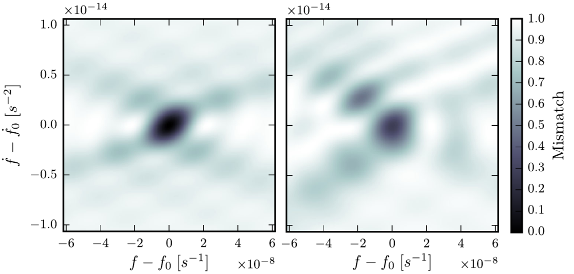
☞ What relation of EM-timing noise to CWs? [Jones (2004)]

- Use observed timing noise in Crab-template [Pitkin&Woan (2004)]
- Impact on wide-parameter-space searches [Ashton, Jones, Prix (2015)]

Effect of Timing Noise on CW searches [Ashton, Jones, Prix (2015)]

- Generate CW signal with Crab timing noise
- Search over $\{f, \dot{f}\}$ using Taylor spindown with varying T_{obs}
- measure mismatch $\mu \equiv$ relative SNR-loss wrt to optimum
- Slide observation window to average mismatch $\langle\mu\rangle \pm \mathrm{std}[\mu]$





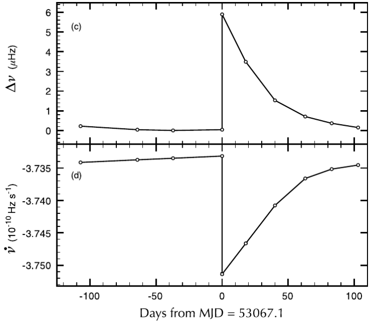
(a) Signal without timing noise (b) Signal with timing noise

☞ Crab-level timing noise not very problematic

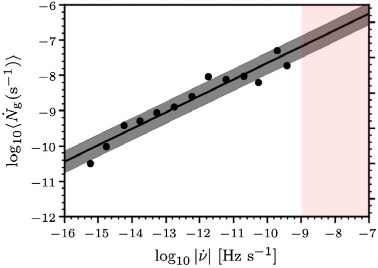
BUT: timing noise seems to increase with $\dot{f}$ [Hobbs, Lyne, Cramer (2010)]

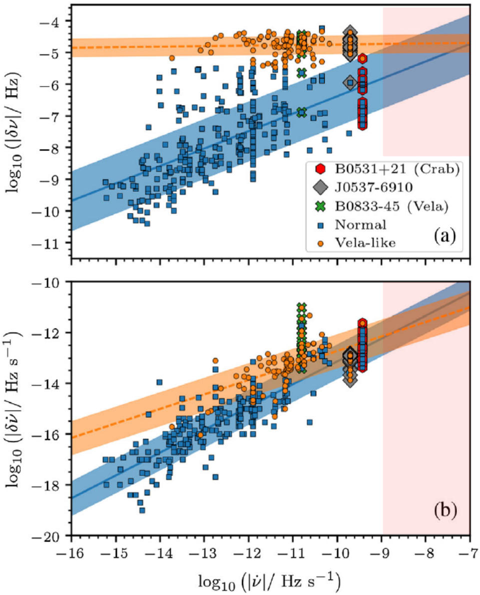
$\dot{f}_{\mathrm{Crab}} \sim 7 \times 10^{-10}\,\frac{\mathrm{Hz}}{\mathrm{s}}$ ☞ CW searches go up to $\dot{f} \sim (10^{-9} - 10^{-7})\,\frac{\mathrm{Hz}}{\mathrm{s}}$

Effect of Glitches on CWs: Extrapolate Pulsar Sample



[Espinoza+(2011)]

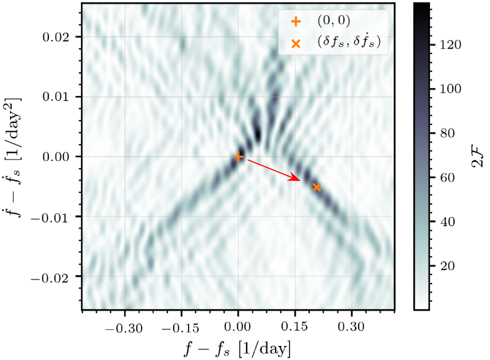




[Ashton, Prix, Jones (2017)]

Effect of Glitches on CWs

glitch: signal “jumps” in $\{f, \dot{f}\}$ space



[Ashton+, in prep.]

☞ 2 transient-CWs $[0, t_g]$, $[t_g, T_{\mathrm{obs}}]$

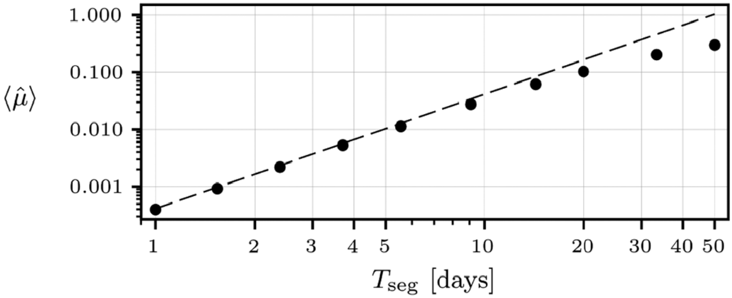
\+ interference, shifted maximum!

☞ maximal loss of SNR bounded by longest “transient-CW”

Glitching CWs: Impact on Searches and Follow-Up

Glitch $\delta f = 5 \times 10^{-7}\,\mathrm{Hz}$, search: $T_{\mathrm{seg}} = 1\mathrm{d}$, $T_{\mathrm{obs}} = 100\,\mathrm{d}$

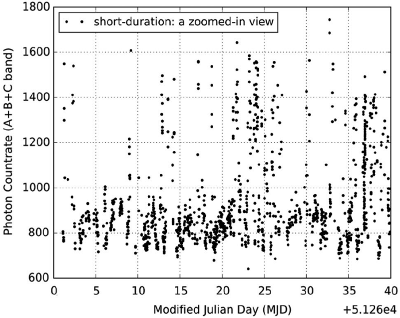
☞ follow-up: increase $T_{\mathrm{seg}} = 1 \rightarrow T_{\mathrm{obs}}$

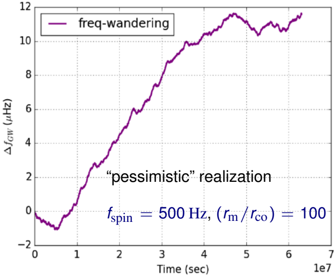


	$\min(\dot{f}_s)$ [nHz/s]	T_{seg} [hrs]	N_{seg}	T [days]	Ref.	Normal population $\langle N_g\rangle$	$P_{N_g\geq 1}$	$\langle\hat{\mu}^{(0)}\rangle_{N_g\geq 1}$	$\langle\tilde{\mu}^{(0)}\rangle_{N_g\geq 1}$	Vela-like population $\langle N_g\rangle$	$P_{N_g\geq 1}$	$\langle\hat{\mu}^{(0)}\rangle_{N_g\geq 1}$	$\langle\tilde{\mu}^{(0)}\rangle_{N_g\geq 1}$
S6 E@H all-sky	−2.7	60	90	255	[47]	1.1	68%	0.16 (0.35)	0.40 (0.54)	0.5	39%	0.18 (0.29)	0.34 (0.47)
S6 E@H all-sky HFU*	−2.7	280	22	257	[23]	1.1	68%	0.27 (0.36)	0.44 (0.53)	0.5	39%	0.26 (0.31)	0.39 (0.47)
S6 E@H Cas. A	−106.0	140	44	257	[20]	6.3	100%	0.64 (0.63)	0.93 (0.84)	2.7	93%	0.44 (0.45)	0.76 (0.66)
O1 E@H all-sky	−2.6	210	12	105	[48]	0.5	37%	0.17 (0.33)	0.25 (0.46)	0.2	18%	0.17 (0.30)	0.25 (0.43)
O1 E@H Cas. A	−144.0	245	12	122.5	[48]	3.5	97%	0.54 (0.54)	0.77 (0.71)	1.5	78%	0.38 (0.40)	0.59 (0.56)
O1 E@H Vela Jr.	−67.9	369	8	123.0	[48]	2.5	91%	0.47 (0.49)	0.66 (0.64)	1.1	65%	0.35 (0.39)	0.51 (0.52)
O1 E@H G357.3	−29.7	489	6	122.25	[48]	1.7	81%	0.41 (0.46)	0.59 (0.58)	0.7	51%	0.34 (0.39)	0.50 (0.49)

[Ashton, Prix, Jones (2017)]

Spin Wandering in Accreting Pulsars [Mukherjee, Messenger, Riles (2018)]





variable X-ray flux $\sim (\times 2 - \times 3)$

(model as a stochastic process with measured spectrum)

- mass accretion $\dot{M}(t)$
- torque (via I, $(r_{\rm m}/r_{\rm co})$, $f_{\rm spin}$)
- drift $|\dot{f}(t)| \in [3, 500] \times 10^{-7}\,\frac{\rm Hz}{\rm s}$

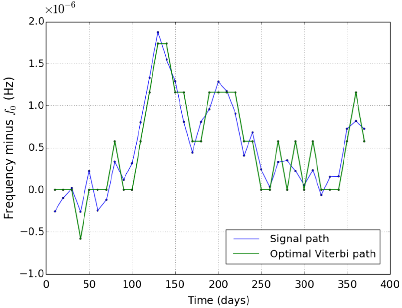
- limits $\max T_{\rm seg} \lesssim [5, 80]\,{\rm d}$
- limits sensitivity (semi-coh.)
- Viterbi: increase $\max T_{\rm seg}$
- unclear how to go to a "coherent" follow-up?

Outline

1. Why this might be an issue
2. How bad could it be? (timing noise, glitches, spin-wandering)
3. How can we deal with this?

Search Methods: Spin-Wandering / Timing Noise

- Use inherent robustness of semi-coherent methods constrains $T_{\mathrm{seg}} \lesssim \max T_{\mathrm{seg}}$ [Messenger+ (2015), Whelan+ (2015), LVC ApJ (2017)]
- Viterbi: can track spin-drift, allows larger $\max T_{\mathrm{seg}}$ [LVC PRD (2017)]



[Suvorova+ (2016)]

- Follow-up: how to increase sensitivity beyond $\max T_{\mathrm{seg}}$?

Search Methods: Glitching- & Transient CWs

- Bayesian transient-CW (+line robust) semi-coherent odds:

  $O_{\mathrm{tS/GL\,tL}}(\mathrm{data}) \equiv \dfrac{P(\mathrm{tS}|\mathrm{data})}{P(\mathrm{G\ or\ L\ or\ tL}|\mathrm{data})}$ [Keitel (2016)]

- explicit transient-CW coherent $\mathcal{F}$-statistic$(\mathrm{sky}, f, \dot{f}, \underbrace{t_{\mathrm{start}}, \tau})$

  [Prix, Giampanis, Messenger (2011)]

  additional search parameters: computationally infeasible for wide-parameter-space searches

  ☞ target interesting sources and/or follow-up candidates

  - L. Fesik+ @AEI: inter-glitch r-modes in J0537-6910
  - D. Keitel+: efficient GPU implementation, search post-glitch

- Glitching-CW MCMC follow-up method

  [Ashton&Prix (2018), Ashton+ (in prep.)], ☞ Greg Ashton's talk

- transient-CW MCMC search method [Keitel,Ashton,?]
- Viterbi: can track general non-Taylor spin evolution (e.g. power-law spindown, glitches) [Suvorova+ (2016), Sun+ (2018)]

Conclusions

Summary:

- Challenges:
  - ☞ easier to miss
  - ☞ might need more computing cost
  - ☞ confident detection? (especially for transient-CWs)
- Searches: robustness $\leftrightarrow$ dedicated searches/follow-up
- Opportunity: Signals carry more information than CWs!

Outlook:

- better astrophysical priors?
- improved / robust search methods:
  MCMC, $O_{\mathrm{tS/GL\,tL}}$, transient-CW $\mathcal{F}$-statistic, Viterbi, …
- Deep Neural Networks?
  generalize well + only need examples!