



Cross-Correlation Searches for Periodic Gravitational Waves

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Outline

- 1 **Cross-Correlation Method**
 - Application to Stochastic Background
 - Application to Quasiperiodic Gravitational-Wave Signals
 - Choice of SFT Pairs for Correlation
- 2 **Search Targets**
 - Directed Search for Young Neutron Stars
 - Accreting Neutron Stars in Low-Mass X-Ray Binaries
- 3 **Summary**



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Cross-Correlation Search for Stochastic Background

- Noisy data from GW Detector:

$$x(t) = n(t) + h(t) = n(t) + \vec{h}(t) : \vec{d}$$

- Correlate data btwn detectors (Fourier domain)

$$\langle \tilde{x}_1^*(f) \tilde{x}_2(f') \rangle = \langle \tilde{h}_1^*(f) \tilde{h}_2(f') \rangle = \delta(f - f') \gamma_{12}(f) \frac{S_{\text{gw}}(f)}{2}$$

$S_{\text{gw}}(f)$ encodes spectrum; $\gamma_{12}(f)$ encodes geometry

- Optimally filtered cross-correlation statistic

$$Y = \int df \tilde{x}_1^*(f) Q(f) \tilde{x}_2(f) \quad Q(f) \propto \frac{\gamma_{12}^*(f) S_{\text{gw}}^{\text{exp}}(f)}{S_{n1}(f) S_{n2}(f)}$$

Filter encodes expected **spectrum** & **spatial distribution**

- isotropic: Allen & Romano *PRD* **59**, 102001 (1999)
- ptlike: Ballmer *CQG* **23**, S179 (2006)



Gravitational Waves from Quasiperiodic Sources

- Rotating NS w/deformation emits **nearly sinusoidal signal**

$$\vec{h}(t) = h_0 \left[\frac{1 + \cos^2 \iota}{2} \cos \Phi(\tau(t)) \vec{e}_+ + \cos \iota \sin \Phi(\tau(t)) \vec{e}_\times \right]$$

- $\Phi(\tau)$: phase evolution in rest frame;
- $\tau(t)$: Doppler mod from detector motion (& binary orbit)
- Features of **signal model** missing from stoch search:
 - **Doppler shift** @ each detector:
correlations peaked @ **different freqs**
 - **Long-term coherence**:
can correlate data @ **different times**



Cross-Correlation of Continuous GW Signals

- **Cross-correlation** of signal w/intrinsic frequency f_0 :

$$\begin{aligned}\langle \tilde{x}_I^*(f_I) \tilde{x}_J(f_J) \rangle &= \tilde{h}_I^*(f_I) \tilde{h}_J(f_J) \\ &= h_0^2 \tilde{G}_{IJ} \delta_{\Delta T}(f_0 - f_I - \delta f_I) \delta_{\Delta T}(f_0 - f_J - \delta f_J)\end{aligned}$$

- $\tilde{h}_I(f)$ is **Short Fourier Transform**, duration ΔT
- $\delta_{\Delta T}(f - f') = \int_{-\Delta T/2}^{\Delta T/2} dt e^{i2\pi(f-f')t}$
- \tilde{h}_I & \tilde{h}_J can be same or different times or detectors
- δf_I is relevant **Doppler shift**
- For given set of params, can add products of all **SFT pairs**

$$Y = \sum_{IJ} Q_{IJ} \tilde{x}_I^*(f_0 - \delta f_I) \tilde{x}_J(f_0 - \delta f_J) \quad Q_{IJ} \propto \frac{\tilde{G}_{IJ}^*}{S_{n,I}(f_0) S_{n,J}(f_0)}$$



Computational Costs and Frequency Resolution

- If freq, sky pos etc **known**, can do most sensitive **fully coherent search** (correlate **all data**)
- If some params **unknown**, have to search over them
- **Long coherent observation** → **fine resolution** in freq etc
→ need **too many templates** → **computationally impossible**
- Most CW searches **semi-coherent**: deliberately limit **coherent integration time** & **param space resolution** to keep **number of templates** manageable



Fully Coherent Search

	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
$x_1(t_0)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_2(t_0)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_1(t_1)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_2(t_1)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_1(t_2)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_2(t_2)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_1(t_3)$	Y	Y	Y	Y	Y	Y	Y	Y
$x_2(t_3)$	Y	Y	Y	Y	Y	Y	Y	Y

Combine **all SFT pairs**; as with standard \mathcal{F} -statistic,
quadratic combination of all SFTs



Semi Coherent Search

	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
$x_1(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_2(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_1(t_1)$	Y	Y	Y	Y	N	N	N	N
$x_2(t_1)$	Y	Y	Y	Y	N	N	N	N
$x_1(t_2)$	N	N	N	N	Y	Y	Y	Y
$x_2(t_2)$	N	N	N	N	Y	Y	Y	Y
$x_1(t_3)$	N	N	N	N	Y	Y	Y	Y
$x_2(t_3)$	N	N	N	N	Y	Y	Y	Y

Coherently combine within epochs



Lag-Limited Cross-Correlation Search

	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
$x_1(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_2(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_1(t_1)$	Y	Y	Y	Y	Y	Y	N	N
$x_2(t_1)$	Y	Y	Y	Y	Y	Y	N	N
$x_1(t_2)$	N	N	Y	Y	Y	Y	Y	Y
$x_2(t_2)$	N	N	Y	Y	Y	Y	Y	Y
$x_1(t_3)$	N	N	N	N	Y	Y	Y	Y
$x_2(t_3)$	N	N	N	N	Y	Y	Y	Y

“Sliding” semi-coherent search



Synchronous Cross-Correlation Search

	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
$x_1(t_0)$	N	Y	N	N	N	N	N	N
$x_2(t_0)$	Y	N	N	N	N	N	N	N
$x_1(t_1)$	N	N	N	Y	N	N	N	N
$x_2(t_1)$	N	N	Y	N	N	N	N	N
$x_1(t_2)$	N	N	N	N	N	Y	N	N
$x_2(t_2)$	N	N	N	N	Y	N	N	N
$x_1(t_3)$	N	N	N	N	N	N	N	Y
$x_2(t_3)$	N	N	N	N	N	N	Y	N

“Stochastic-style”: correlate data @ same time, diff detectors



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Supernova 1987A Remnant



Credit: NASA/ESA, P. Challis, R. Kirshner (Harvard-Smithsonian Center for Astrophysics), and B. Sugerman (STScI)





Searching for Young Neutron Stars

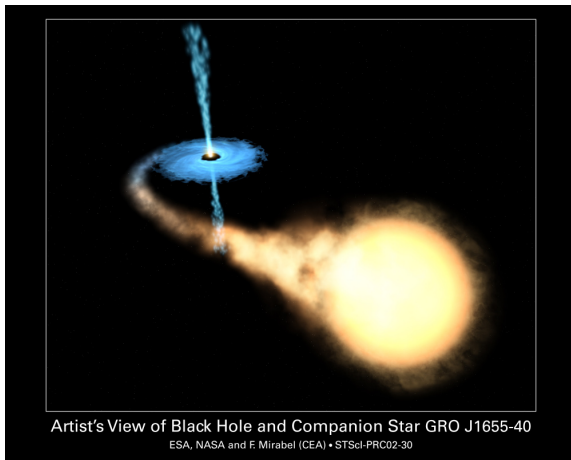
- **Young** ($\lesssim 100$ yr) NSs should be spinning rapidly
LIGO/Virgo band $50 \text{ Hz} \lesssim f_{\text{GW}} \lesssim 1500 \text{ Hz}$
- Look in **likely sky locations** for NSs not seen as pulsars:
SN1987A should have one; **galactic ctr** could have $\mathcal{O}(1)$
- **Spinning down rapidly**; inefficient to search over $f, \dot{f}, \ddot{f}, \dots$
Phase model: **GW spindown** $\propto f^5$; **EM spindown** $\propto f^{\approx 3}$

$$\frac{df}{d\tau} = Q_{\text{GW}} \left(\frac{f}{f_{\text{ref}}} \right)^5 + Q_{\text{EM}} \left(\frac{f}{f_{\text{ref}}} \right)^n$$

Search over $f_0, Q_{\text{GW}}, Q_{\text{EM}}, n$



Low-Mass X-Ray Binary



Compact object accreting mass from companion star



Searching for Neutron Stars in LMXBs

- LMXB: BH/NS/WD accreting mass from companion star
- Accretion spinup may be balanced by GW spindown [Bildsten *ApJL* **501**, L89 (1998)] \rightarrow no \dot{f}
- Scorpius X-1: $1.4M_{\odot}$ NS w/ $0.4M_{\odot}$ companion
unknown params are f_0 , $a \sin i$, orbital phase
- LSC searches for Sco X-1:
 - Coherent search w/6 hr of S2 data *PRD* **76**, 082001 (2007)
 - Directed stochastic cross-corr (“radiometer”) search w/simultaneous S4 H1 & L1 data *PRD* **76**, 082003 (2007)
- Can use improved cross-corr method to search including wider range of correlated segments



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- Cross-correlation method adapted to **periodic GWs**
- Tuning max **time-lag** between cross-correlated data allows tradeoff of **sensitivity** for **computing time**
- Can search for young NSs (e.g., **SN1987A**)
(search over f_0 & braking model params)
- Can search for LMXBs (e.g., **Sco X-1**)
(search over f_0 & binary orbit params)