Cross-Correlation Searches for Periodic Gravitational Waves

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Outline

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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

Cross-Correlation Search for Stochastic Background

- Noisy data from GW Detector:
  $x(t) = n(t) + h(t) = n(t) + \overleftrightarrow{h}(t) : \overleftrightarrow{d}$
- Correlate data btwn detectors (Fourier domain)

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

  $S_{\mathrm{gw}}(f)$ encodes spectrum; $\gamma_{12}(f)$ encodes geometry
- Optimally filtered cross-correlation statistic

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

  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

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

  - $\Phi(\tau)$: 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:

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

  - $\tilde{h}_I(f)$ 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

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

Dhurandhar, Krishnan, Mukhopadhyay & JTW *PRD* **77**, 082001 (2008)

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

Outline

Supernova 1987A Remnant

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

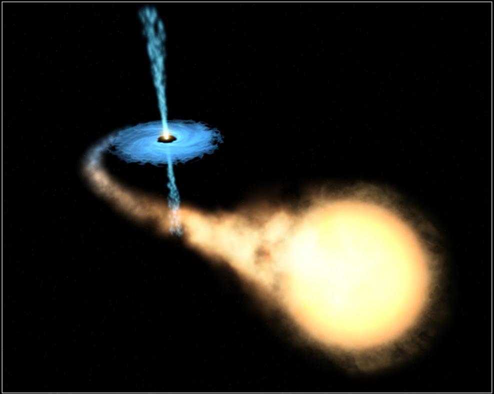
Searching for Young Neutron Stars

- Young ($\lesssim 100\,\text{yr}$) 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 $f, \dot{f}, \ddot{f}, \ldots$
  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_{GW}, Q_{EM}, n

Low-Mass X-Ray Binary



Artist's View of Black Hole and Companion Star GRO J1655-40
ESA, NASA and F. Mirabel (CEA) • STScI-PRC02-30

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)] $\longrightarrow$ 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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Summary

- 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)