

A Cross-Correlation Technique to Search for Periodic Gravitational Waves

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Outline

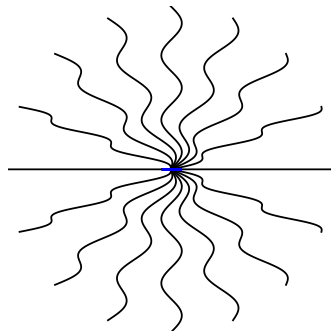
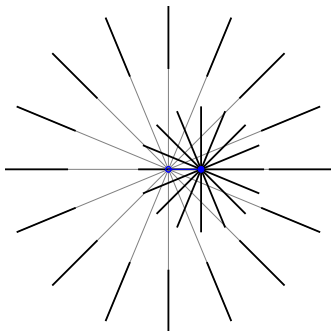
- 1 Searches for Gravitational Waves
 - Crash Course in Gravitational Wave Physics
 - Gravitational-Wave Sources & Signals
 - Gravitational-Wave Observations & Detectors
- 2 Cross-Correlation Method
 - Application to Stochastic Background
 - Application to Quasiperiodic Gravitational-Wave Signals
 - Tuning Search by Choice of Data Segments to Correlate
- 3 Applications and Outlook
 - Directed Search for Young Neutron Stars
 - Accreting Neutron Stars in Low-Mass X-Ray Binaries
 - Summary

Adapted from Amaldi talk [LIGO-G0900536](#)
by JTW, Chung, Krishnan, Melatos, Peralta

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Motivation



- In **Newtonian gravity**, force dep on distance btwn objects
- If massive object suddenly moved, grav field **at a distance** would change **instantaneously**
- In relativity, **no** signal can travel faster than light
→ time-dep grav fields must propagate like light waves

Gravity as Geometry

- Minkowski Spacetime:

$$ds^2 = -(dx^0)^2 + (dx^1)^2 + (dx^2)^2 + (dx^3)^2$$

$$= \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix}^{\text{tr}} \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} = \eta_{\mu\nu} dx^\mu dx^\nu$$

- General Spacetime:

$$ds^2 = \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix}^{\text{tr}} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} = g_{\mu\nu} dx^\mu dx^\nu$$

Gravitational Wave as Metric Perturbation

- For GW detection, spin-2 “graviton tensor” $h_{\mu\nu}$ is difference btwn actual metric $g_{\mu\nu}$ & flat metric $\eta_{\mu\nu}$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

($h_{\mu\nu}$ “small” in weak-field regime, e.g. for GW detection)

- E.g. Plane wave propagating in z direction

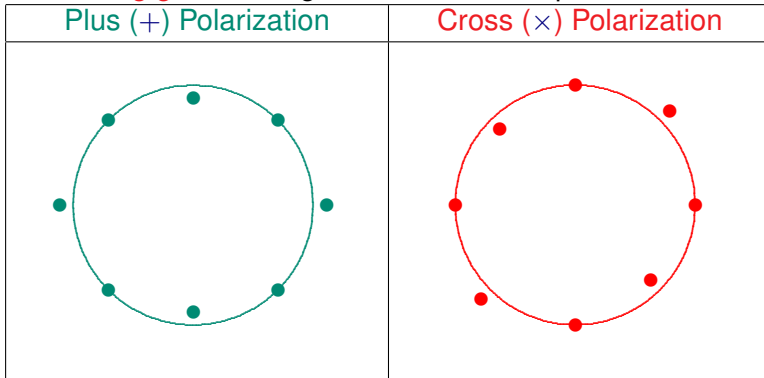
$$\{h_{\mu\nu}\} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} e^{i2\pi f(z-t)}$$

h_+ and h_\times are amplitudes of “plus” and “cross” pol states.

$$\vec{h} = [h_+ \vec{e}_+ + h_\times \vec{e}_\times] e^{i2\pi f(\hat{k} \cdot \vec{r} - t)}$$

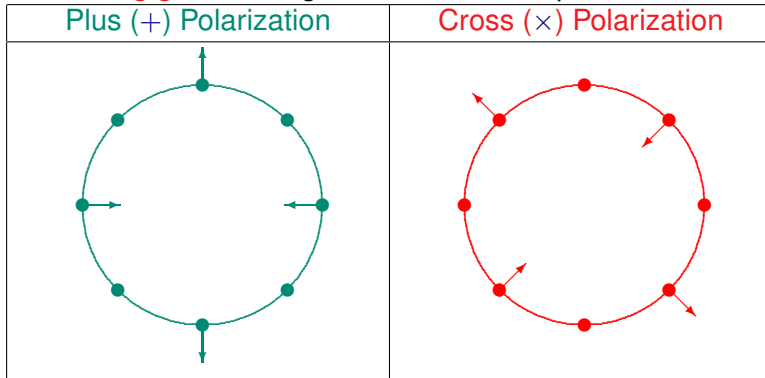
Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:



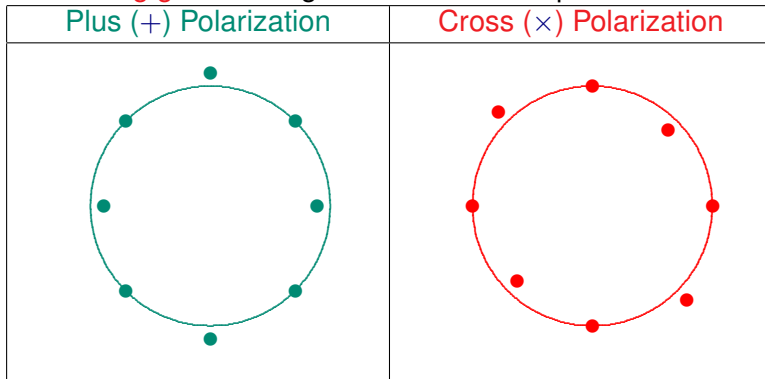
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Effects of Gravitational Wave

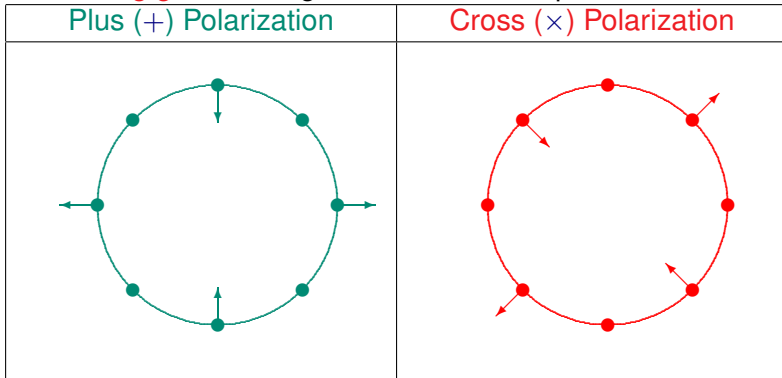
Fluctuating geom changes distances btwn particles in free-fall:





Effects of Gravitational Wave

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Effects of Gravitational Wave

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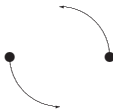
Plus (+) Polarization				
Cross (x) Polarization				

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Gravitational Wave Generation

- Generated by **moving/oscillating** mass distribution
- Lowest **multipole** is **quadrupole**
- Classic example: orbiting **binary** system



(e.g., **Binary Pulsar** 1913+16

– **Observed** energy loss agrees w/**GW** prediction)

Classification of GW Signals

In LIGO band (10s-1000s of Hz), natural division of sources:

	modelled	unmodelled
long	Periodic Sources (e.g., Rotating Neutron Star)	Stochastic Background (Cosmological or Astrophysical)
short	Binary Coalescence (Black Holes, Neutron Stars)	Bursts (Supernova, BH Merger, etc.)

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Measuring GWs w/Laser Interferometry

Interferometry: Measure GW-induced distance changes

- Measure small change in

$$\begin{aligned} L_x - L_y &= \sqrt{g_{11}} L_0^2 - \sqrt{g_{22}} L_0^2 \\ &= \sqrt{(1 + h_{11})} L_0^2 - \sqrt{(1 + h_{22})} L_0^2 \\ &\approx L_0 \frac{h_{11} - h_{22}}{2} \sim L_0 h_+ \end{aligned}$$

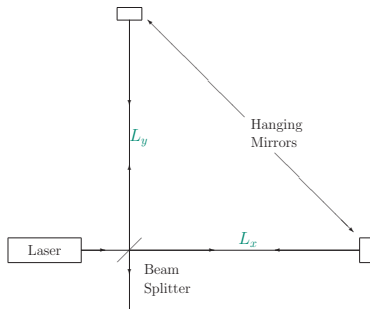
- More gen,

$$(L_1 - L_2)/L_0 = \vec{h} : \vec{d}$$

with “response tensor”

$$\vec{d} = \frac{\hat{n}_1 \otimes \hat{n}_1 - \hat{n}_2 \otimes \hat{n}_2}{2}$$

(also when \hat{n}_1 & \hat{n}_2 not \perp)



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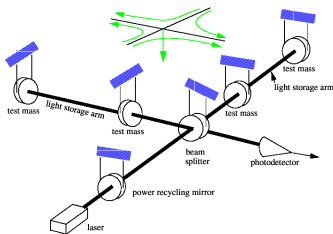
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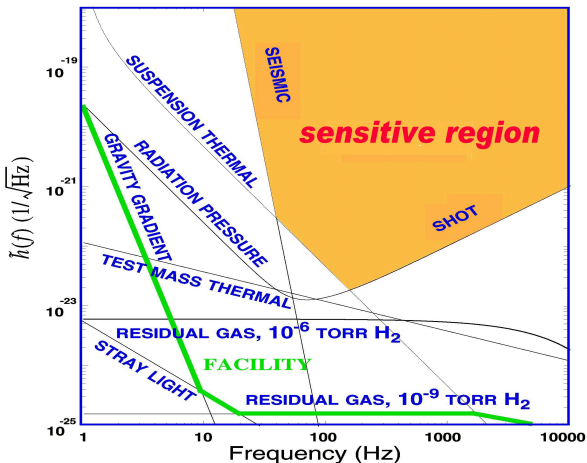
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LIGO's Sensitive Frequency Band



Rogues' Gallery of Ground-Based Interferometers



LIGO Hanford (Wash.)



LIGO Livingston (La.)



GEO-600 (Germany)



Virgo (Italy)

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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)

$$\langle \tilde{x}_1^*(f) \tilde{x}_2(f') \rangle = \langle \tilde{h}_1^*(f) \tilde{h}_2(f') \rangle = \vec{d}_1 : \langle \tilde{h}_1^*(f) \otimes \tilde{h}_2(f') \rangle : \vec{d}_2$$

- For stochastic backgrounds

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

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

Detection Statistic

- Optimally filtered cross-correlation statistic

$$Y = \int df \tilde{x}_1^*(f) Q(f) \tilde{x}_2(f)$$

- Filter encodes expected **spectrum** & **spatial distribution** (isotropic, pointlike, spherical harmonics . . .)

$$Q(f) \propto \frac{\gamma_{12}^*(f) S_{\text{gw}}^{\text{exp}}(f)}{S_{n1}(f) S_{n2}(f)}$$

- “Radiometer” search for **ptlike srcs** incl targeting **Sco X-1**: known sky location, unknown frequency
Ballmer, **CQG 23**, S179 (2006); LSC, **PRD 76**, 082003 (2007)

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Gravitational Waves from Quasiperiodic Sources

- Sco X-1 is Low-Mass X-Ray Binary:
accreting **neutron star** in orbit w/companion
- 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 :

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

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

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

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

Doppler Modulation in Cross-Correlation Searches

- Max **Doppler shift** from **Earth's rotation**: $\frac{|\vec{v}_{\oplus \text{rot}}|}{c} \lesssim 1.5 \times 10^{-6}$
Doppler shift at **2000 Hz** is $\lesssim 0.003 \text{ Hz}$.
- Max **Doppler shift** from **Earth's orbit**: $\frac{|\vec{v}_{\oplus \text{orb}}|}{c} \lesssim 1.0 \times 10^{-4}$
Doppler shift at **2000 Hz** is $\lesssim 0.2 \text{ Hz}$.
- Stochastic searches use FTs of e.g., **120 s** duration, so

$$\delta f \approx 0.0083 \text{ Hz}$$

Cross-correlation between detectors uses same freq bin

- Stochastic search combines fine bins into coarse bins of

$$\Delta f = 0.25 \text{ Hz}$$

Cross-corr power collected in single bin for most freqs

- Correlating detectors at different times, or with longer FTs means including Doppler effects

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 \rightarrow **fine resolution** in freq etc
 \rightarrow need **too many templates** \rightarrow **computationally impossible**

$$\text{e.g.} \quad N_{\text{tplts}} \sim \frac{1}{\Delta f} \frac{1}{\Delta f} \frac{1}{\Delta \text{sky}} \sim T \cdot T^2 \cdot (fT)^2$$

- Most CW searches **semi-coherent**: deliberately limit **coherent integration time** & **param space resolution** to keep **number of templates** manageable

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Tuning the Cross-Correlation Search

- Computational considerations limit coherent time, i.e., possible time lag between correlated segments
- Detectable signal goes like

$$h_0 \propto N_{\text{pairs}}^{-1/4} T_{\text{sft}}^{-1/2}$$

(T_{sft} is duration of fourier transformed data segment)

- If all data used, $N_{\text{pairs}} \sim N_{\text{sft}}^2$, so

$$h_0 \propto (N_{\text{sft}} T_{\text{sft}})^{-1/2}$$

like coherent search of duration $N_{\text{sft}} T_{\text{sft}}$

- If only simultaneous SFTs correlated, $N_{\text{pairs}} \sim N_{\text{sft}}$, so

$$h_0 \propto N_{\text{sft}}^{-1/4} T_{\text{sft}}^{-1/2}$$

like semi-coherent search w/ N_{sft} coherent segs of T_{sft} each

- Can “tune” sensitivity vs comp time by choosing SFT pairs



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



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



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

Only consider “diagonal” auto-correlations



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

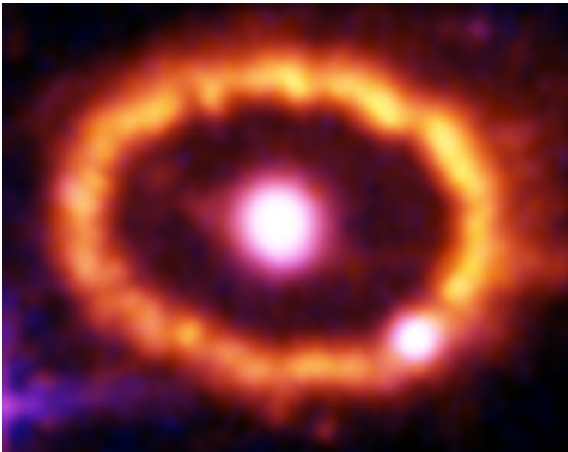
	$x_1(t_0)$	$x_2(t_0)$	$x_1(t_1)$	$x_2(t_1)$	$x_1(t_2)$	$x_2(t_2)$	$x_1(t_3)$	$x_2(t_3)$
$x_1(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_2(t_0)$	Y	Y	Y	Y	N	N	N	N
$x_1(t_1)$	Y	Y	Y	Y	Y	Y	N	N
$x_2(t_1)$	Y	Y	Y	Y	Y	Y	N	N
$x_1(t_2)$	N	N	Y	Y	Y	Y	Y	Y
$x_2(t_2)$	N	N	Y	Y	Y	Y	Y	Y
$x_1(t_3)$	N	N	N	N	Y	Y	Y	Y
$x_2(t_3)$	N	N	N	N	Y	Y	Y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

“Sliding” semi-coherent search

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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** $\propto f^{\approx 3}$

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

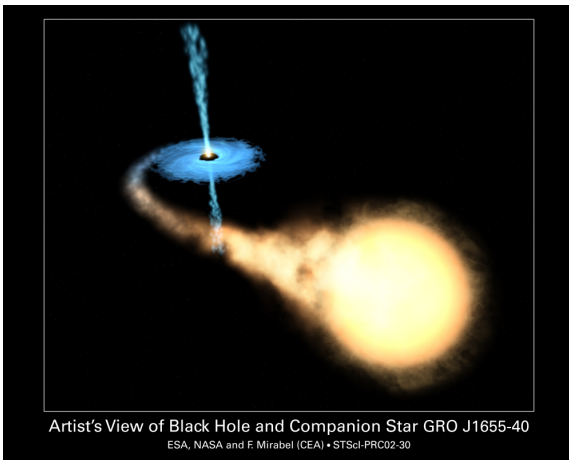
Search over $f_0, Q_{\text{GW}}, Q_{\text{EM}}, n$

- PhD thesis by Christine Chung (Uni Melbourne)

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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)