Targeted and Directed Searches for Periodic Gravitational Waves

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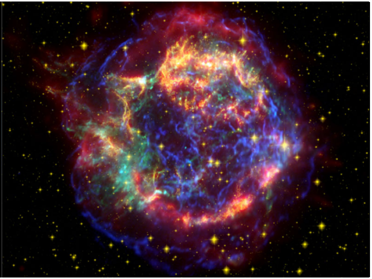


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Outline

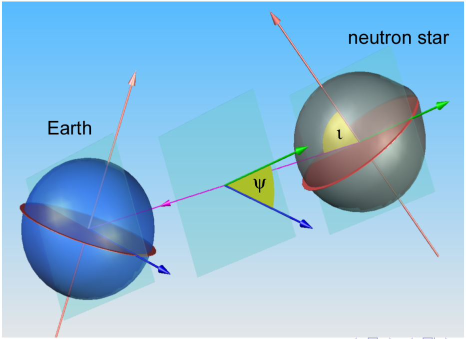
Periodic Gravitational Waves

- Groud-based detectors (LIGO, Virgo, etc) sensitive to GWs w/frequencies of 10s-1000s of Hz
- Source for periodic GWs: deformed rotating neutron stars
  - Non-axisymmetric deformation
    $\rightarrow$ periodically varying quadrupole moment
- Classify situation by what we know about the neutron star:
  - **Blind search** (aka all-sky): M. A. Papa's talk looking for GW from unknown neutron star
  - **Directed search**: location of neutron star known or inferred (supernova remnant, low-mass X-ray binary, galactic ctr. . .) but rotation rate unknown
  - **Targeted search**: neutron star seen as pulsar sky position, frequency & frequency evolution known

Continuous Wave Signals

- Rotating NS w/deformation or long-lived oscillation emits nearly sinusoidal signal

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



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  - $\Phi(\tau) \equiv$ phase evolution in inertial frame: f, $\dot{f}$, $\ddot{f}$, ...
  - $\tau(t) \equiv$ Doppler modulation from detector motion (& binary orbit)
- Templates parameterized by phase params (intrinsic) f, $\dot{f}$, sky position (α, δ), orbital params (if NS in binary)
- Don't need to search over amplitude params (extrinsic) $h_0 = \frac{4\pi^2 G|I_1 - I_2| f_{\text{gw}}^2}{c^4 d}$, spin orientation ($\iota$, ψ), ϕ_0 (can analytically maximize likelihood over them)

Computing Cost Motivates Search Strategies

All-sky coherent search of full phase param space infeasible:
# of templates skyrockets w/increasing integration time
E.g, for all-sky search with one spindown,

$$N_{\text{tmplts}} \sim \frac{1}{\Delta f} \frac{1}{\Delta \dot{f}} \frac{1}{\Delta \text{sky}} \sim T \cdot T^2 \cdot (fT)^2 \propto T^5$$

Different strategies depending on knowledge of object:

- Unknown objects: need to use semi-coherent methods for **All-Sky Search** (Preceding talk by Maria Alessandra Papa)
- Known pulsars: all phase parameters known, can do fully coherent **Targeted Search**
  Note $f_{\text{gw}} = 2f_{\text{rot}}$ for triaxial ellipsoid rotating about principal axis
- Known objects not seen as pulsars (e.g., SN remnants, LMXBs): can do **Directed Search** but need to cope w/uncertain remaining phase parameters

Searching for Known Pulsars

- Phase params (rotation, sky pos [& binary params]) known
  Pulsar ephemerides (timing) detail phase evolution
- Can search over amplitude params (h_0, ι, ψ, ϕ_0);
  search cost NOT driven by observing time
- Different options for amplitude parameters:
  - Maximize likelihood analytically ($\mathcal{F}$-statistic)
  - Marginalize likelihood numerically ($\mathcal{B}$-statistic)
    (Poster by Reinhard Prix)
  - Get posterior prob distribution w/Markov-Chain Monte Carlo
  - Use astro observations to constrain spin orientation (ι & ψ)
- Spindown produces indirect upper limit
  - GW emission above limit $\longrightarrow$ more spindown than seen
  - Pulsars w/rapid spindown have “more room” for GW
  - LIGO/Virgo have surpassed spindown limit for Crab & Vela

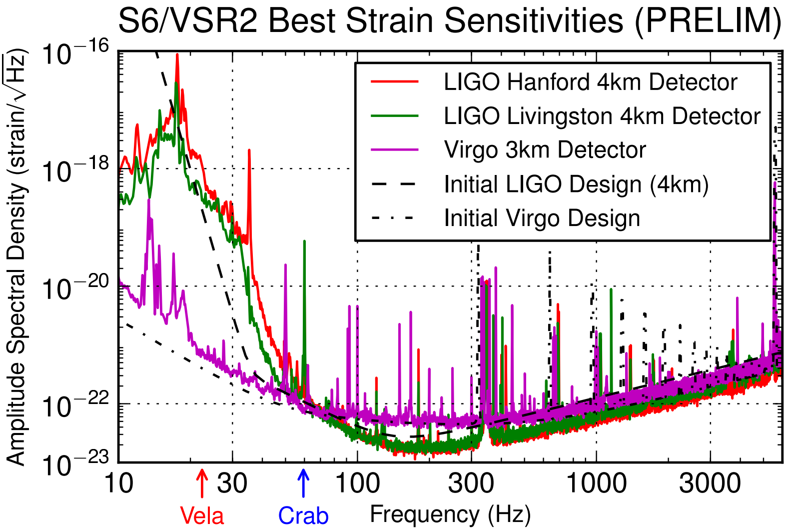
Crab Pulsar Upper Limit

- Pulsar in Crab Nebula
- Created by SN 1054
- $\sim 2\,\text{kpc}$ away
- $f_{\text{rot}} = 29.7\,\text{Hz}$
- $f_{\text{gw}} = 59.4\,\text{Hz}$

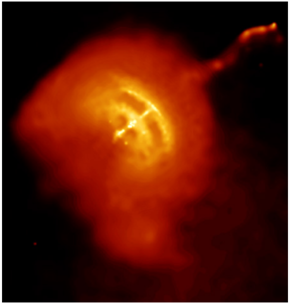
Image credit: Hubble/Chandra

- Initial LIGO (S5) upper limit beats spindown limit
- Abbott et al (LSC) *ApJL* **683**, L45 (2008)
- Abbott et al (LSC & Virgo) + Bégin et al *ApJ* **713**, 671 (2010)
- No more than 2% of spindown energy loss can be in GW

Initial Virgo Targets the Vela Pulsar



Vela Pulsar Upper Limit



- Pulsar in Vela SN remnant
- Created ~ 12,000 years ago
- ~ 300 pc away
- $f_{\mathrm{rot}} = 11.2\,\mathrm{Hz}$
- $f_{\mathrm{gw}} = 22.4\,\mathrm{Hz}$

Image credit: Chandra

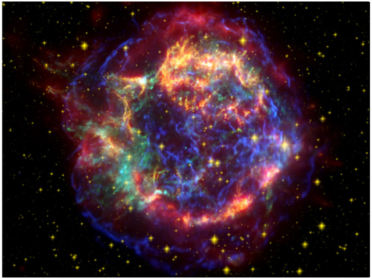
- GW frequency below initial LIGO "seismic wall"
- Virgo has better low-frequency sensitivity
- VSR2 upper limit beats spindown limit
- No more than 10% of spindown energy loss can be in GW

Abadie et al (LSC & Virgo) + Buchner et al *ApJ* **737**, 93 (2011)

Directed Searches for NS at Known Sky Positions

- Known or suspected neutron stars not seen as pulsars
- Knowledge of sky position reduces parameter space
- Can do fully coherent search on short stretch of data using $\mathcal{F}$-statistic method
(Jaranowski, Królak, Schutz *PRD* **58**, 063001 (1998)):
  - Search over remaining phase params (freq & orbit)
  - Analytically maximize likelihood ratio over amp params
  - Use maximized likelihood as detection statistic
- To use all available data instead,
need to combine coherent sub-searches incoherently

Cassiopeia A Upper Limit



- Cas A SN remnant
- $\sim$ 2 kpc away
- $\sim$ 300 yr old
- central compact object seen in x-rays; spin period unknown

Image: Spitzer/Hubble/Chandra

- Indirect limit on GW emission from age of neutron star
- Sky position known, can search over f, $\dot{f}$, $\ddot{f}$ param space using $\mathcal{F}$-stat on 12 days of LIGO S5 Data upper limit surpasses indirect limit below 300 Hz

Abadie et al (LSC & Virgo) *ApJ* **722**, 1504 (2010)

Gravitational Waves from Low-Mass X-Ray Binaries

- LMXB: compact object (neutron star or black hole) in binary orbit w/companion star
- If NS, accretion from companion provides “hot spot”; rotating non-axisymmetric NS emits gravitational waves
- Bildsten *ApJL* **501**, L89 (1998) suggested GW spindown may balance accretion spinup; GW strength can be estimated from X-ray flux
- Torque balance would give ≈ constant GW freq
- Signal at solar system modulated by binary orbit

Brightest LMXB: Scorpius X-1

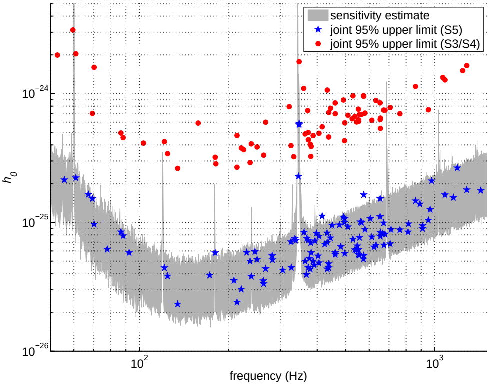
- Scorpius X-1
  - $1.4 M_\odot$ NS w/$0.4 M_\odot$ companion
  - unknown params are f_0, $a \sin i$, orbital phase
- LSC/Virgo searches for Sco X-1:
  - Coherent $\mathcal{F}$-stat search w/6 hr of S2 data
    Abbott et al (LSC) *PRD* **76**, 082001 (2007)
  - Directed stochastic ("radiometer") search (unmodelled)
    Abbott et al (LSC) *PRD* **76**, 082003 (2007)
    Abbott et al (LSC) arXiv:1109.1809
- Proposed directed search methods:
  - Look for comb of lines produced by orbital modulation
    Messenger & Woan, *CQG* **24**, 469 (2007)
  - Cross-correlation specialized to periodic signal
    Dhurandhar et al *PRD* **77**, 082001 (2008)
- Promising source for Advanced Detectors

Summary

- Ground-based GW detectors sensitive to periodic signals from rotating neutron stars
- Can search for unknown or known/inferred neutron stars
- Targeted searches use timing info from known pulsars
  - LIGO & Virgo have beat indirect “spindown limit” for Crab & Vela pulsars
- Directed searches use known sky position; no spin info
  - Cas A supernova remnant: beat indirect spindown age limit
  - Sco X-1 LMXB: binary orbital params complicate search; could be detectable by Advanced LIGO/Virgo
  - Other directions include SN1987A & galactic center

EXTRA SLIDES

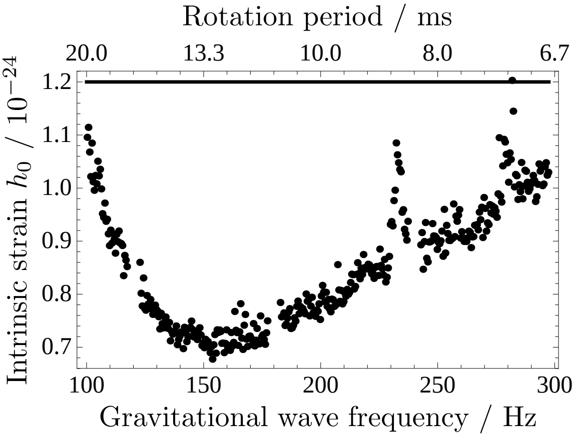
Limits set on 116 pulsars w/rotation freq $> 20\,\mathrm{Hz}$ ($f_{gw} > 40\,\mathrm{Hz}$)



Abbott et al (LSC & Virgo) + Bégin et al *ApJ* **713**, 671 (2010)

Cas A Upper Limits

LIGO upper limit surpasses indirect limit below 300 Hz



Also set limit on strength of r-mode oscillation of Cas A CCO