THE DETECTION OF CONTINUOUS GW

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INTRODUCTION

Neutron stars (*NS*) are one of the densest objects in the universe, with $\rho_{NS} \sim 4 \cdot 10^{17} kg/m^3$, diameter $d \sim 10km$, mass $M \sim 1{-}2M_\odot$. Rough estimations give a billion *NS* in our universe, but only about 1900 *NS* have been detected. Moreover, the inner structure of *NS* could not yet been well explained. *NS* are a source of gravitational waves (*GW*) and with the beginning of *GW* astronomy, researchers aim to detect new spinning *NS*. The *GW* carries information on: the rotation frequency ($f_{GW} = 2f_s$), and amplitude (localisation). Astronomers hope to gain more insides into the equation of state (EOS) of these astronomical objects and *GW* emitting processes.

CONTINUOUS GW

NS are a key source of GW. Continuous *GW* (CW) from *NS* are very difficult to detect. Firstly, the nature of the signal is very weak. Secondly, *CW* extremely hard to separate from the noise. They have a roughly constant frequency in the range of 100-800 Hz. Asymmetries required to produce *CW* imply deformations at the star. This deformation can be caused by elastic stresses, magnetic fields or matter accretion. *NS CW* systems include: 1) *Low mass X-ray binaries* (LMXBs), 2) *milli-second pulsars* (MP), and 3) *unstable oscillation modes* (r-modes). Beyond standard *NS*, exotic objects like quark stars, hybrid stars or strange stars could be found out there with deformations exceeding those of *NS*.

SEARCHES

There are 3 main types of *CW* searches:

- *Targeted searches*. Known sky location, frequency f and frequency rate $\dot{f}$ from electromagnetic (EM) counterparts. For example: Crab or Vela pulsars.
- *Directed searches*. Know sky location, but f and frequency rate $\dot{f}$ are unknown. For instance, SN 1987A, Sco X-1, globular clusters.
- *All sky searches*. Unknown pulsar or *NS* searches. Computationally challenging, it can be handled with distributed computing like Einstein@home.

EM counterparts of the *CW* sources are important. Even when direct GW could provide the *EOS*, tests of nuclear and relativistic theories for *NS* or similar compact objects, *EM* can: 1) identify the source better, 2) connect to transient phenomenology, 3) constraint models, 4) improve parameter estimation or detections, 5) cross-correlate with other types of searches.

THEORETICAL CALCULATIONS

For accreting *NS*, we require a multipole Q_{22} to balance the accretion spin torque $\dot{J}$.

$$Q_{22} \approx 4.5 \cdot 10^{37} g \cdot cm^2 \left(\frac{\dot{M}}{10^{-9} M_\odot yr^{-1}}\right)^{1/2} \left(\frac{300Hz}{f_s}\right)^{5/2} \tag{1}$$

where $\dot{M}$ is the accretion rate and f_s is the spin frequency. The maximum Q_{22} is about $1.2 \cdot 10^{38} g \cdot cm^2$, and that produces a GW amplitude ($\Omega = 2\pi f_s$). :

$$h_0 \approx \frac{16}{5}\left(\frac{\pi}{3}\right)^{1/2} \frac{GQ_{22}\Omega^2}{dc^4} \approx 10^{-27} \tag{2}$$

Reference: Ushomirsky G. , Cutler C. and Bildsten L. 2000, *Deformations of accreting neutron star crusts and gravitational wave emission*. Mon. Not. R. Astron. Soc. 319, 902-32.

DATA ANALYSIS

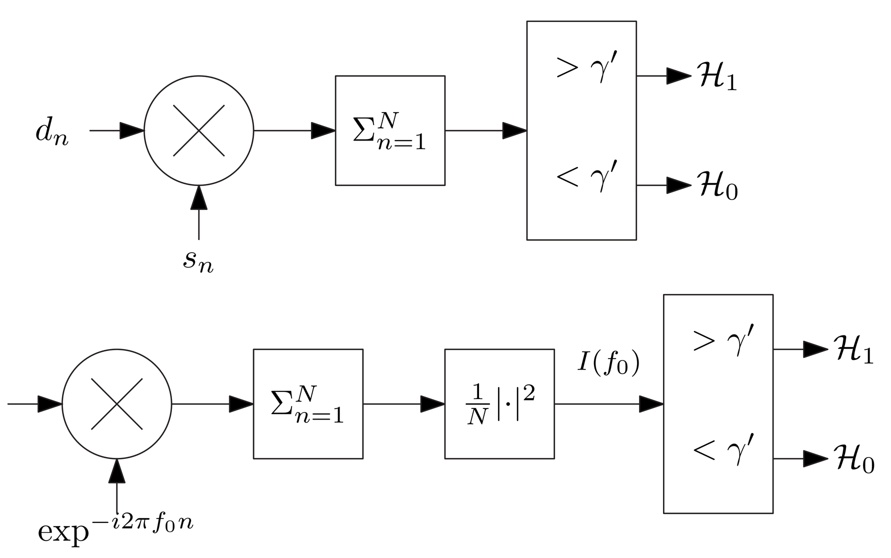
Problem: choosing among (at least) two competing hypotheses

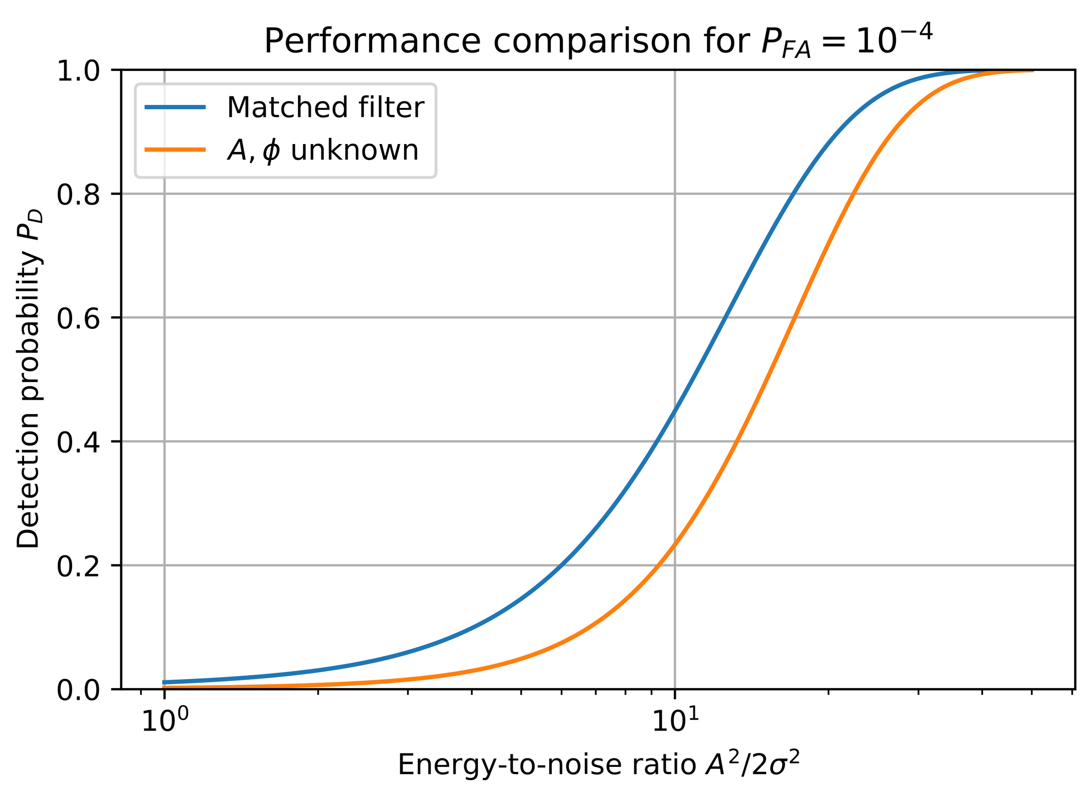
$$\mathcal{H}_0 : d_n = w_n$$
$$\mathcal{H}_1 : d_n = w_n + A\sin(2\pi f_0 n + \phi)$$

If the signal is known, Neyman-Pearson gives us the optimal strategy. What if we do not known A, ϕ? Two options:

- **Frequentist** Estimate them! → GLRT
- **Bayesian** Marginalize over them!

Both cases lead to performance losses and/or expensive computations. For example, the generalized likelihood ratio (GLRT) test does the following





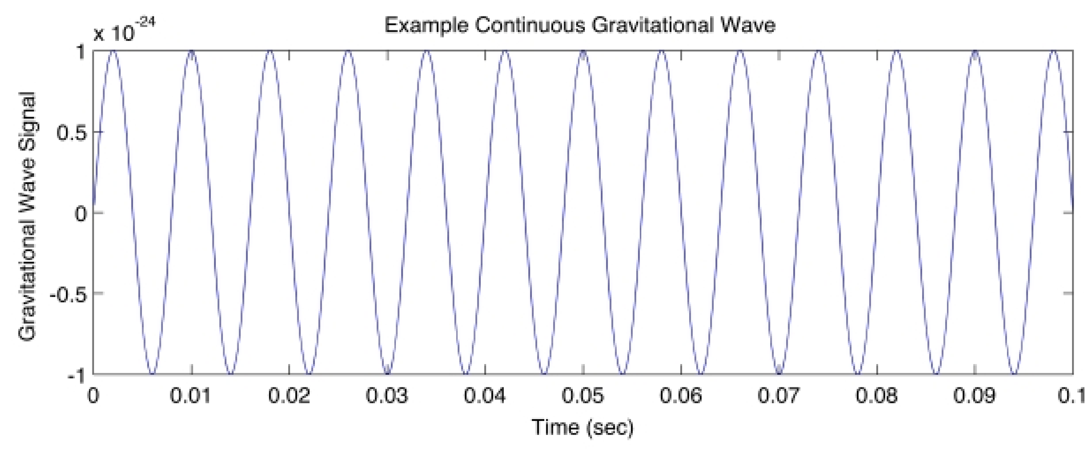
⇒ **Computationally expensive!**⇐

- Hybrid: nested sampling on large space → narrow GLRT searches.
- LMP: nested sampling on large space → narrow search with *locally most powerful* detectors.

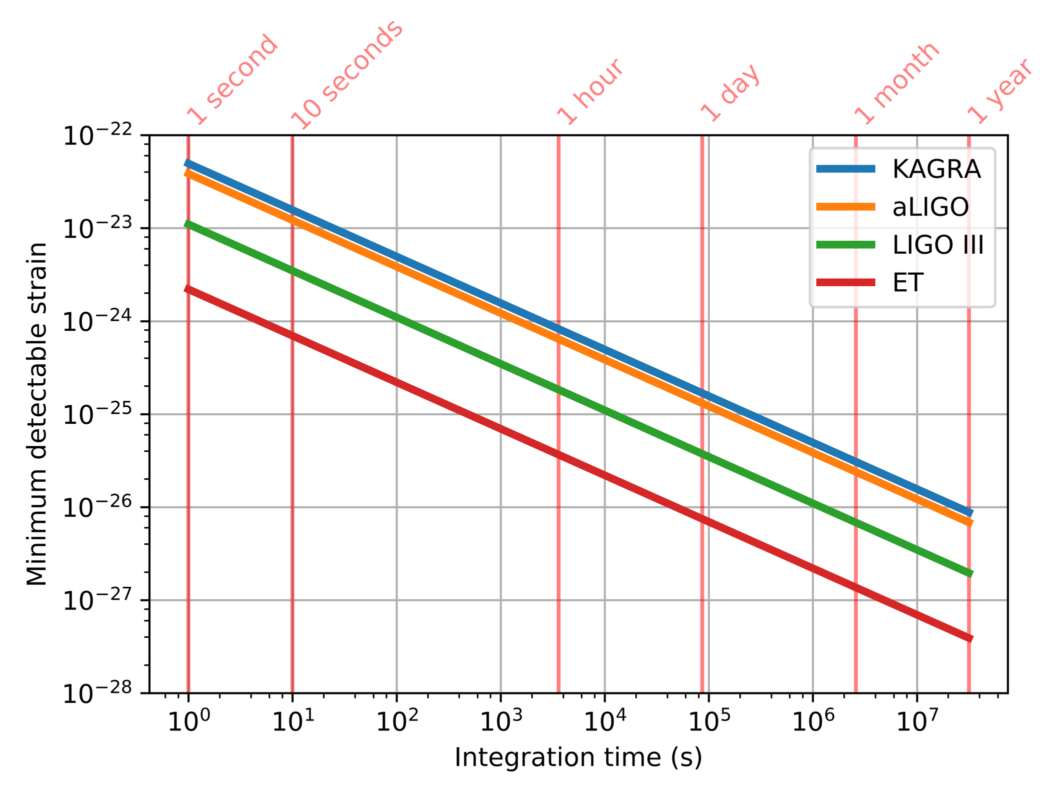
Reference: *Fundamentals of Statistical Signal processing*, vol. 2.

STRAIN AND TIME.

CW have a fairly constant frequency, and a periodic, persistent quasi-monochromatic signal:



NS must have asymmetries in order to generate continuous *GW*. The *SNR* (signal-to-noise ratio) of a detection scales with the square root of integration time. Due to their low amplitude, *CW* signals require long integration times to be detected. An approximation of the minimum strain h_{min} that can be detected for a given integration time T and spectral noise density S can be derived. This assumes a false alarm probability of 1% and false dismissal probability of 10%, $h_{\text{min}} \approx 11(\frac{S}{T})^{1/2}$. A plot of the minimum detectable strain vs integration time for four detectors at 300 Hz:



Given a signal strain of $h_0 \sim 10^{-25}$ (typical for a *NS*), aLIGO data would need to be integrated over a timescale of months/years to achieve detection, the Einstein telescope (ET) would need to be integrated for hours. Targeted searches are more likely to be detected, thus, in 3rd generation *GW* detectors.

Reference: *Searches for continuous gravitational wave signals and stochastic backgrounds in LIGO and VIRGO data, arXiv:1201.3176*