Search for long GWs using HEN triggers

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Outline

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Gamma Ray Bursts (GRBs)

- GRBs are considered the most energetic phenomena in the recent Universe.
  - Distribution extends to cosmological distances.
- They are broadly classified into two categories i) Long and ii) short GRBs and mainly arise from
  - Collapse of massive stars and
  - Merger of BNS
- Even though they are copious emitters of photons, they are also expected to emit\(^1\),
  - High Energy Neutrinos (HENs) of \(\sim 10^{11}\) eV – \(10^{16}\) eV
  - Gravitational waves (GWs)

A relatively popular, fireball model of GRBs predict both photons and HENs originating inside the jet.

**Photons**
- Synchrotron by electron ($\geq 100$ MeV)
- Inverse Compton and $p\gamma \rightarrow \pi^0 \rightarrow \gamma\gamma$ (GeV and TeV)

**HENs**
- The dominant process is $p\gamma \rightarrow \pi^+ \rightarrow \nu_\mu e^+\nu_e\bar{\nu}_\mu$ (TeV, PeV, EeV)
- Neutrinos carry $\sim 5\%$ of the energy of the proton.

**GWs**
- Various instabilities in the progenitor and the accretion disc around it.
The past decade has seen the advent of new detectors that look for GWs and HENs from astrophysical sources like GRBs.
- GW detectors - LIGO, VIRGO, GEO etc.,
- Neutrino detectors - IceCube, ANTARES
Till now there has been no direct detection of GWs or HENs from GRBs.
- Upper limit constraints on the GW$^2$ and HEN emission from GRBs.$^3$
Even though the individual detectors haven’t seen anything yet, coincidence analyses offer better prospects for such a detection.
In this talk I describe the search for long duration GWs in LIGO-VIRGO data in coincidence with HEN candidates from IceCube.

Choked GRBs and low luminous GRBs

Accretion disc instabilities (ADI)

Accretion disc or torus surrounding the inner core in CCSNe or central engine in Collapsar can fragment into clumps. Depending on the mass of central core and the dynamics connecting the core and disc, the clump can be as big as $\sim M_{\odot}$.

GW strain $h \sim 10^{-23} \left( \frac{f}{1000 \text{Hz}} \right)^{2/3}$ for a source at a distance of 100 Mpc; duration of $\sim 100$ secs.

Simple ADI model\textsuperscript{6}

\begin{itemize}
  \item \( f_{GW} = \frac{1}{\pi} \sqrt{\frac{G M_{BH}}{(r_0+R_{ISCO})^3}} \)
  \item \( r_0 \sim 100\text{km} \) (const) and \( R_{ISCO} = f(J_{BH}, M_{BH}) \)
  \item Formation of clumps requires larger disc or outer envelope.
\end{itemize}

\textsuperscript{6} C Ott and L Santamaria, \textit{LIGO document T1100093 (2011)}.
Detection strategy

- Select HEN triggers from the periods when both IceCube and LIGO detectors were on.
  - IceCube’s 22-string run overlaps with last six months of LIGO’s S5 run (\(\sim\) May 2007 - Oct 2007).
- Select a time window around each of those triggers to look for GW signal in LIGO data consistent with the HEN direction.
  - Time window of 1500 sec (-600 sec to +900 sec around the trigger); accounts for various GW production mechanisms\(^7,^8\).
  - 100-1200 Hz band in LIGO data (most sensitive band).
  - Since angular errors of the IceCube triggers (\(\sim 3^\circ\)) are larger than that of the GW search (\(\sim 1^\circ\)), grid the sky patch of each trigger and pick the hottest grid point in the GW search.

GW search algorithm

- Cross-correlation based GW analysis, involving two LIGO GW detectors.
- Frequency-time (ft)-maps are produced using the cross-correlated data from the two detectors.
- Look for clusters of bright pixels in the ft-map using clustering algorithms.
  - GW signals will show up as clusters of high SNR pixels in the map.
  - Have to take care non-stationarity and glitches in the data\textsuperscript{9}.
- For sensitivity studies and upper limit calculations, use simplified model of ADI waveforms

\textsuperscript{9} T Prestegard et. al., \textit{Class. Quantum Grav.} \textbf{29} 095018 (2012).
Detection statistics

- A complete description of the method and quantitative details of the GW pipeline is already published\(^\text{10}\).

- Estimators for GW power \(\hat{Y}\) and its variance \(\hat{\sigma}_Y^2\) are given by
  - \(\hat{Y}(t; f) = 2\text{Re}[\tilde{Q}_{IJ}(t; f)s^*_I(t; f)s_J(t; f)]\)
    where \(s_I(t) = n_I(t) + h_I(t)\).
  - \(\hat{\sigma}_Y^2 = \frac{1}{2}|\tilde{Q}_{IJ}(t; f)|^2P_I(t; f)P_J(t; f)\)
    where \(P_I(f) = 2|s_I|^2\)
  - Filter function \(\tilde{Q}(t; f) = \frac{e^{2\pi if\Omega \cdot \Delta x_{IJ}/c}}{\sum_A F^A_I(t; f)F^A_J(t; f)}\)

- \(\hat{\Omega}\) is the direction of the source
- \(\Delta x_{IJ}\) is the distance vector connecting the two interferometers I and J
- \(F^A\)'s are the response functions of interferometers for GW polarization \(A\); we sum over + and \(\times\) polarizations.

- For multiple pixels, combine \(\hat{Y}\)'s with \(\hat{\sigma}^{-2}\) as weights.

An example injection and recovery (ADI at 10 Mpc)
Background distribution
Conclusions

- GRBs are considered one of the strongest candidates for first detection of GW signal.
- Coincidence analyses of GWs with HEN and EM triggers offer better prospects for the detection of GWs from GRBs using current and next generation of interferometric GW detectors.
  - With HEN triggers, we can look for GRBs which are optically faint or dark, like low luminous and choked GRBs.
- From the sensitivity studies using simple ADI waveforms, we find that the current planned search for long GWs can potentially reach up to $\sim 10 - 100$ Mpc for optimistic models.
  - This is within the range of nearby GRBs observed electromagnetically.
  - Potentially there may be more that lack EM observations.