Review of the transient non-CBC searches
Rencontres de Moriond - Gravitation
March 27, 2017

F. Salemi, Albert-Einstein Institut – Hannover
for the LIGO Scientific Collaboration and Virgo Collaboration
Motivation for an unmodeled GW searches

New Worlds, New Horizons (2010)
Page 201

“It would be unprecedented in the history of astronomy if the gravitational radiation window … (omissis) ...does not reveal new, enigmatic sources.”
Generic transient (burst) analysis

- Searches for gravitational-wave bursts do not require knowledge about the phase evolution (waveform) of the expected signal
- Burst searches aim to cover a broad parameter space which can overlap with well-modelled signals (e.g., binary black holes)
- Potential for discovering new sources of gravitational waves
- Steps of a typical generic burst search:
  - Weight data by the noise at each frequency (whitening)
  - Make time-frequency representation of the data
  - Identify correlated excess power in multiple detectors
- Some burst searches target GWs expected from particular sources or are informed by non-GW observations of astrophysical phenomena
Simplified representation of a GW un-modeled pipeline

H1 Multiresolution time-frequency transforms

Select pixels above threshold

For each sky location
maximum likelihood
Is used to extract the
signal from noise

L1 Multiresolution time-frequency transforms

Time delay

$h_{f0} = F_{+}^{f0} h_+ + F_{x}^{f0} h_x$

H1 & L1 Synthesis

Reconstructed Signal H1

Reconstructed Signal L1

waveform parameters

detections statistic

$\eta_c = \text{SNR} \cdot \text{Coherence}$

Credits to G. Vedovato

The sky location with highest probability is used to reconstruct signal & its detection statistic
Gravitational-Wave (GW) Bursts sources

- Sources include core-collapse supernovae, the merger phase of binary compact objects, neutron star instabilities, accretion disk instabilities, fallback accretion, cosmic string cusps/kinks, and the unexpected!

- Waveform morphologies for many of the potential sources are either unknown or too poorly known for optimal filtering to be used

- Short duration:
  - Short-lived signals, lasting only a few cycles within the frequency band of the instruments: typically lasting a few milliseconds to a few seconds and with frequency content in the 10 Hz – few kHz range

- Long duration:
  - Signals lasting from ~10s to days; they bridge short bursts and stochastic/CW searches
Burst searches

- All-sky search for ‘unmodelled’ GW transients
- Search for transients with short durations (up to a few seconds) and long durations (~10-500s, see following talk)
- Short transient searches also run in low-latency mode
- Search for intermediate-mass black holes binaries (IMBHB) and eccentric binary black holes (eBBH)
- Search for GWs from cosmic strings kinks and cusps
- Transient searches associated with
  - high-energy neutrinos (HEN)
  - GRBs
  - nearby optical supernovae
- Fast Radio Bursts
  - Search previously performed on FRBs detected by Green Bank Telescope and Parkes between 2007 and 2013 ([arXiv:1605.01707], PRD 93, 122008 (2016))
All-sky unmodeled (burst) search pipelines

  - Multi-resolution time-frequency map of data is obtained through wavelet decomposition
  - Triggers are analyzed coherently to estimate signal waveform, polarization, source location, using a constrained likelihood method (maximised over sky position)

- Omicron+LIB (oLIB) (arXiv:1511.05955)
  - Data is decomposed using sine-gaussian templates to form time-frequency map; triggers within 100 ms with same central frequency and quality factor are clustered
  - Coincident triggers analyzed using Bayesian parameter estimation and model selection algorithm (with single sine Gaussian template)

- cWB+BayesWave (Phys. Rev. D 91, 084034 (2015))
  - Bayesian model selection using a linear combination of sine Gaussian templates (optimized using a reversible jump Markov chain Monte Carlo). Posterior distributions for estimation parameters and waveform reconstruction
Search for generic gravitational wave transients using all data from O1 (Phys. Rev. D 95, 042003 (2017))

- GW energy in short pulses, detectable with 50% efficiency for standard-candle sources emitting at 10 kpc

\[ E = \frac{\pi^2 c^3}{G} r_0^2 f_0^2 h_0^2 \]

- False Alarm Rate < 1/100yr
- Able to detect gravitational wave energy of just over \(10^{-9}M_{\odot}c^2\) at 10 kpc around 100 Hz
- E.G. sensitive to galactic supernovae:
  - \(~10^{45}\) ergs @ 10 kpc
  - \(~10^{51}\) ergs @ 10 Mpc
All-sky burst O1 BBH sensitivity

FIG. 3. A comparison of the sensitive luminosity radii \cite{7} in Mpc, as a function of the total redshifted masses in the detector frame, among the three algorithms. The radii are binned according to mass ratio $q$ (from left to right $q = 1, 0.5, 0.25$) and effective spin $\chi_{\text{eff}}$, defined in \cite{7}. The three ranges of spin refer to aligned ($0.33 < \chi_{\text{eff}} < 1$), non-spinning ($-0.33 < \chi_{\text{eff}} < 0.33$), anti-aligned ($-1 < \chi_{\text{eff}} < -0.33$).
Rate Density on Non-Binary-Black-Hole Sources

- We give 90% classical confidence intervals on rate density, assuming $\text{EGW} = 1 \, M_\odot c^2$.
- At the S6 False-Alarm Rate of $1/8 \, \text{yr}$, the O1 rates are stricter by an order-of-magnitude.
- In light of actual GW detections, we have set rates at a False-Alarm Rate of $1/(100 \, \text{yr})$. 

False-Alarm Rate $= 1/(100 \, \text{yr})$
Searches for CBC sources: burst role

- We just started exploring the GW sky
- So far BBHs in the ~20-60 Msun mass range have been detected
- No evidence yet for sources outside of the current template banks: no strong precession, eccentricity, deviations from GR, etc ….
- Just starting to explore astrophysical implications from our detections
- Goal: characterize BHs populations and various BH formation channels
- One of the Burst group goals:
  - complement existing CBC template searches by extending the parameter space of binary sources.
IMBHB and eBBH burst searches

- Motivation for **IMBHB**: finding an IMBHB would be ground-breaking
- The burst search can potentially extend the IMBHB parameter space searched by current CBC searches to higher total masses and to IMBHB sources for which higher order modes and precession play an important role
- O1 paper on a joint CBC+burst search almost ready for submission
- Motivation for **eBBH**: there are various astrophysical models which predicts significant residual eccentricity for the BBH systems till late inspiral and merger. A single detection of such a source can enrich our understanding about the BH formation in dense stellar environments
- The circular template banks are not a good match for the binaries having eccentricity $> 0.05$ [Huerta, E. A. and Brown, Duncan A. PRD (2013)]
- This study was performed for BNS systems, we are now extending this to BBH to understand in which part of the parameter space the contribution of the un-modelled searches will be significant
- The waveforms to do these studies are being explored
- An O1+O2 eBBH burst search is currently being investigated
Search for cosmic strings

- GW bursts are produced by “cusp” features propagating on oscillating loops
- “Kinks” are also expected to radiate GWs but with lower amplitudes


- Stochastic background by cross-correlating data streams can also limit cosmic string cusps (S. Ölmez, V. Mandic, and X. Siemens Phys. Rev. D 81, 104028 (2010))
Cosmic for cosmic strings (2)

- Search sensitivity → constraints on cosmic string model parameters:
  - $G\mu$: string tension
  - $\varepsilon$: string loop size parameter
  - $p$: reconnection probability
- Upper limit is astrophysically competitive for “small-loop” scenarios and low reconnection probabilities
- O1 cosmic string search paper, presenting both the burst and stochastic results
GW triggered HEN searches

- Binary mergers that result in a black hole with accretion disks can drive relativistic outflows that may have high energy neutrino components.
- Searched for neutrino events coincident with the GW detections (BBH) in IceCube and Antares data.
- It basically correlates GW times and sky location with IceCube and Antares events.
- No temporal & directional coincidence.
- Derived upper limits on the spectral fluence and total energy radiated into neutrinos.
GW triggered HEN searches (2)

- Searched for HENs associated with GW150914 (arXiv:1602.05411, PRD 93, 122010 (2016))

  GW150914: three neutrinos were detected by IceCube within a ±500s window with no detections by ANTARES. No spatial coincidence.

- Search for neutrinos coincident with GW151226 or LVC151012 with IceCube and ANTARES (arXiv:1703.06298)

  3+4 temporally coincident neutrinos found – consistent with background

- No temporal & directional coincidence.

- A coincident neutrino for LVT151012 could have boosted the significance of the joint trigger to make it a discovery.
Gamma-ray bursts and Gravitational waves

Matched filtering (short GRBs)

Generic burst time-frequency mapping (all GRBs)
Triggered search parameter space

- **Modeled search (CBC search)**
  - Covers NS-NS and NS-BH systems with
  - \(1 \, M_\odot < M_{\text{NS}} < 2.8 \, M_\odot\) and \(1 \, M_\odot < M_{\text{comp}} < 25 \, M_\odot\)
  - Maximal spin 0.999 for BH and 0.05 for NS
  - Only search for NS-BH masses that create a remnant accretion torus

- **Unmodeled search (Burst search)**
  - Covers GW transients in 16-500 Hz (16-1000 Hz online), without assuming prior knowledge of signal waveforms
GRB Sample in Advanced LIGO First Observing Run  

arXiv:1611.07947 (accepted by APJ)

O1: Sep 12, 2015 - Jan 19, 2016

- GRB sample: total 114
  - Swift, Fermi (GCN) + IPN (27) ~20% short
- GW data processed: 42
- GRB 150906B Sep 06, 2015 at 08:42:20 UTC, detected by IPN
  - “Short-duration/hard-spectrum”
  - GRB lies close to the local galaxy NGC 3313, which has a redshift of 0.0124 at a luminosity distance of 54 Mpc
    - Levan et al. 2015; Dálya et al. 2016
- Only Hanford detector was operational at that time
- RAVEN: Coincidence between events in low latency GW searches and GRB alerts
GRB Triggered search results

- No coincidences from RAVEN
- Triggered searches
  - No GW was detected in coincidence with a GRB

**Modeled search**

**Unmodeled search**
90% confidence exclusion regions

- Extrapolation: 2 years of operation @ Advanced LIGO sensitivity (factor $\sim 3$ better than the first observing run)
- With 2 years of observation at design sensitivity, Advanced LIGO will probe the observed redshift distribution
Waiting for the next nearby CCSN

- Gravitational waves, like neutrinos, are the only direct probes of the supernova engine.
- Several mechanisms may give rise to gravitational wave emission from core-collapse supernovae:
  - rotating collapse and bounce $5 \times 10^{-10} - 5 \times 10^{-8} \, M$
  - post-bounce convection and SASI $1 \times 10^{-12} - 5 \times 10^{-9} \, M$
  - rotational instability $1 \times 10^{-8} - 1 \times 10^{-7} \, M$
  (Ott in Class. Quant. Grav. 26 063001, 2009)
- Only our own Milky Way and the Magellanic Clouds could be within our range. The expected event rate is very low and estimated to $2 - 3$ CCSNe/100 yr
- Collaborative efforts between the GW and neutrino communities for joint searches are under way–will assist in identifying stellar core structure, rotation state, and explosion mechanism
- Published paper on initial GW detectors (see following slide)
  - aims to exclude emissions models
- O1 analysis is on-going
Initial LIGO, Virgo and GEO: CCSN triggered search

- Initial LIGO and Virgo data, 4 nearby (<11Mpc) supernovae considered.

Only SN 2007gr and SN 2011dh were used for detection statements.

SN 2008ax/bk were excluded from detection statements because of high False Alarm Rate.
Initial LIGO, Virgo and GEO: CCSN triggered search (2)

- No gravitational wave candidates.
- Results: detection efficiency, upper limits and model exclusion statements.