Statistical Inference for Multimessenger Astrophysics

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Multimessenger Approaches

“Multi-messenger astrophysics”: connecting different kinds of observations of the same astrophysical event or system

“ExtTrig” strategy:

Telescopes, Satellites or other external entities → Flow of trigger information → GW Search

First astrophysically significant multimessenger result from LIGO:

Non detection of GWs from direction of GRB070201 (Andromeda galaxy) contributed to the detection of the first extragalactic SGR hyperflare

Multimessenger Approaches

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“ExtTrig” strategy:

Telescopes, Satellites or other external entities ➔ Flow of trigger information ➔ GW Search

We can always go back to the collected data and analyze later
Multimessenger Approaches: **Follow-up strategy**

![Image of telescopes and satellites]

**Flow of trigger information**

GW Data → Flow of trigger information → Telescopes, Satellites or other external entities

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**Figure 1.** A schematic of the analysis. Triggers are identified in data from the three sites of the LIGO-Virgo network. The three trigger lists are then compared to find coincident events, labeled “candidate events.” A sky region is assigned to each event candidate. The sky region is then imaged with an EM observatory. These images are searched for transients.

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J. Kanner, T. L. Huard, S. Márka, D. C. Murphy, J. Piscionere, M. Reed, P. Shawhan, “LOOC UP: locating and observing optical counterparts to gravitational wave bursts”, Classical and Quantum Gravity 25, 184034, 2008
Multimessenger Approaches

“Multi-messenger astrophysics”: connecting different kinds of observations of the same astrophysical event or system

“Follow-up” strategy:

GW Data → Flow of trigger information → Telescopes, Satellites or other external entities

Low-latency pipeline development is essential
Multimessenger Approaches

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“Joint search” strategy:

Multimessenger Search for GW+neutrino sources with complete neutrino and GW datastreams

High-significance GWs

Sub-threshold GWs

High-significance neutrinos

Sub-threshold neutrinos

courtesy of Imre Bartos
Multimessenger searches for GWs with LIGO: HENs

High-energy neutrino – GW multimessenger studies since 2006

Astrophysics, Theory development, Method and Team building: GWHEN <= LIGO, Virgo, Icecube, ANTARES

Y. Aso et al., “Search method for coincident events from LIGO and IceCube detectors” Class. Quantum Gravity, 25, 114039, 2008

Baret et al., "Bounding the time delay between high-energy neutrinos and gravitational-wave transients from gamma-ray bursts", Astroparticle Physics, 35,

Ando et al., "Colloquium: Multimessenger astronomy with gravitational waves and high-energy neutrinos", Rev. Mod. Phys. 85, 1401-1420, 2013


Aartsen et al., “Multimessenger search for sources of gravitational waves and high-energy neutrinos: Initial results for LIGO-Virgo and IceCube”, Physical Review D, 90, 102002, 2014 (Initial LIGO/Virgo era search)

Observational Result from O1/O2/O3


Search for high-energy neutrinos from gravitational wave event GW151226 and candidate LVT151012 with ANTARES and IceCube, Albert et al., Physical Review D, 96, 022005, 2017


Search for Multi-messenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during its first Observing Run, ANTARES and IceCube, ANTARES, IceCube,LIGO, Virgo Collaborations, Astrophys.J. 870, 134, 2019

IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo’s First Gravitational-Wave Transient Catalog; The Astrophysical Journal Letters, 898, L10, 2020

Several dozens of GCNs during O2 and O3
GW+HEN search in low-latency aiding EM follow-up

Rapid identification is needed for timely follow-up observations of transient emission

Low-latency searches based on signals that could not individually be established as discoveries are promising

GW+HEN search is a prime motivation for joint subthreshold search strategy

• Both are typically emitted over a short time frame of seconds to minutes during the formation or evolution of compact objects
• Detectors searching for both messengers observe the whole sky continuously
• Joint skymap can be made rapidly available to guide follow-up electromagnetic surveys

*Proper treatment of joint event significance is essential => LLAMA*
Basic Glossary: Multimessenger Approaches

“Multi-messenger astrophysics”: connecting different kinds of observations of the same astrophysical event or system

“ExtTrig” strategy:
Telescopes, Satellites or other external entities → Flow of trigger information → GW Search

“Follow-Up” strategy:
GW Data → Flow of trigger information → Telescopes, Satellites or other external entities

“Low-latency joint search” strategy:
GW detector → Low Latency Algorithm for Multimessenger Astrophysics
GRB detector
HEN detector
++
Odds ratio is used as a test statistic and we perform a frequentist significance assignment.

If p-value > threshold, the localization of the neutrino is sent out via GCN together with the p-value of the candidate joint GW+HEN event.

Otherwise and upper limit is set.
GW+HEN alert example (S200213t)

NUMBER: 27043
SUBJECT: LIGO/Virgo S200213t: 1 counterpart neutrino candidate from IceCube neutrino searches
DATE: 20/02/13 04:40:26 GMT

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Properties of the coincident events are shown below.

<table>
<thead>
<tr>
<th>dt</th>
<th>ra</th>
<th>dec</th>
<th>Angular Uncertainty(deg)</th>
<th>p-value(generic transient)</th>
<th>p-value(binary merger)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-175.94</td>
<td>45.21</td>
<td>31.74</td>
<td>0.43</td>
<td>0.003</td>
<td>0.017</td>
</tr>
</tbody>
</table>

where: dt = Time offset (sec) of track event with respect to GW trigger. Angular uncertainty = Angular uncertainty of track event: the radius of a circle representing 90% CL containment by area. Pvalue = the pvalue for this specific track event from each search.

LLAMA processed all Time coincident neutrinos (within +/-500 s of GW trigger) in 87 s.

Typical event besides one p-value.

Keivani et al., Swift X-ray Follow-Up Observations of Gravitational Wave and High-Energy Neutrino Coincident Signals (2021)
Beyond Two Messengers

- **GW candidate S191216ap by LIGO/Virgo**
- Potential neutrino counterpart from IceCube
- HAWC subthreshold gamma ray coinciding with the GW and the neutrino on the sky
- radio follow-up with VLA

Need a statistical treatment for multiple messengers for such multiple coincidences!
Many messengers many hypotheses...
Astrophysical or noise
Related or unrelated

For $n$ messengers, there are $f(n+1)$ hypotheses

$$f(n) = \sum_{i=0}^{n-1} \binom{n-1}{i} f(i), \quad f(0) = 1$$

GW+HEN+GRB case

We have 8 hypotheses (ignore unrelated two or more signal events)

- same source GW, HEN, GRB $\rightarrow$ Signal hypothesis 1
- same source GW, HEN, bg GRB $\rightarrow$ Signal hypothesis 2
- same source GW, GRB, bg HEN $\rightarrow$ Signal hypothesis 3
- same source HEN, GRB, bg GW $\rightarrow$ Signal hypothesis 4
- signal GW, bg HEN, bg GRB $\rightarrow$ BG hypothesis 1
- bg GW, signal HEN, bg GRB $\rightarrow$ BG hypothesis 2
- bg GW, bg HEN, signal GRB $\rightarrow$ BG hypothesis 3
- bg GW, bg HEN, bg GRB $\rightarrow$ BG hypothesis 4 ($H_0$, null)
What is the optimal test statistic for this case?

For two hypotheses, likelihood ratio is the optimal test statistic.

*Model independent optimal multimessenger search doesn’t exist!*

**Model dependent optimal test statistic with Bayesian statistics:**

\[
TS(x) = \frac{P(x|H_s)}{P(x|H_n)} = \frac{\sum_i P(x|H_s^i)P(H_s^i)}{\sum_j P(x|H_n^j)P(H_n^j)} \times \sum_i P(H_s^i)
\]

**SEARCH INPUTS**

*Different for each multi-messenger trigger*

- **GW**
  - 1 GW trigger
  - Skymap ($\Omega$)
  - Mean distance ($r_{gw}$)
  - SNR ($\rho$)
  - Time

- **Neutrino**
  - Multiple neutrino triggers
  - Sky position mean (RA, Dec)
  - Sky position std. dev. ($\sigma$)
  - Energy
  - Time

- **GRB**
  - 1 GRB trigger
  - Sky position
  - Angular uncertainty
  - Time
  - Duration, Significance, Fluence

Common source relation through a source parameter:

\[
P(x|H_a^b) = \int P(x|\theta, H_a^b)P(\theta|H_a^b)d\theta
\]

*Veske et al., The Astrophysical Journal (2021), Volume 908, Number 2, 216*
More and better quality data as a result of upgrades/new detectors
(LIGO/Virgo/KAGRA, IceCube Gen2, KM3NeT, Vera Rubin Observatory, Ultrasat, and more)

Multiple coincidences are inevitable

Statistical inference for the coinciding multiple messengers is a REQUIREMENT

We provide a proper generalized treatment for statistical inference for multiple coincident messengers.
It is adoptable by the Low-Latency Algorithm for Multimessenger Astrophysics pipeline (LLAMA) which is used for GW+HEN searches.