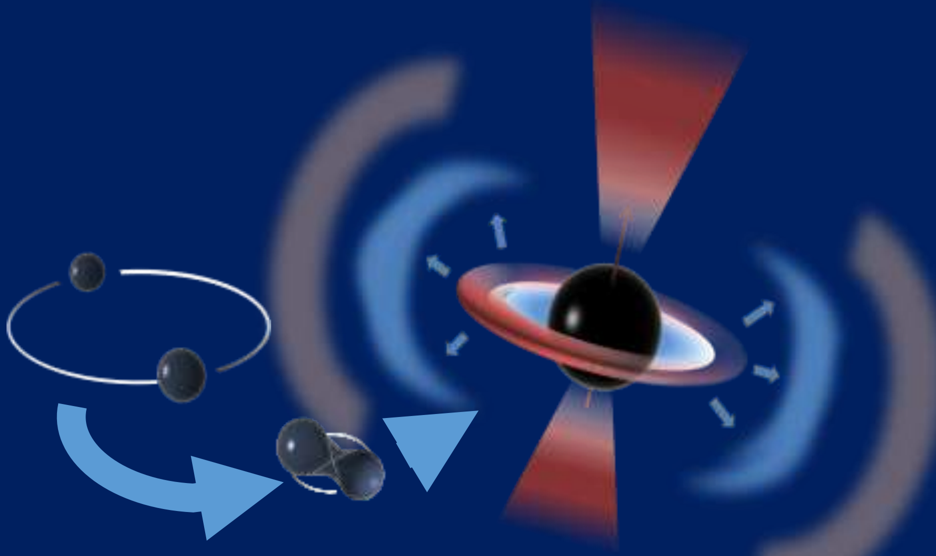


Statistical Inference for Multimessenger Astrophysics

ZSUZSA MARKA
Columbia Experimental Gravity Group
Columbia University in the City of New York,

and the GWHEN team

January 18, 2022

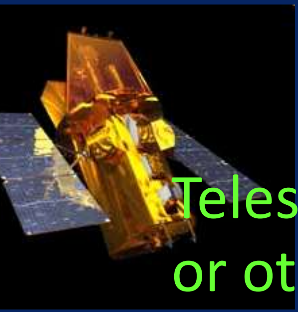
"Pioneering MMA with GW for decades!"

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

G
E
Co

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

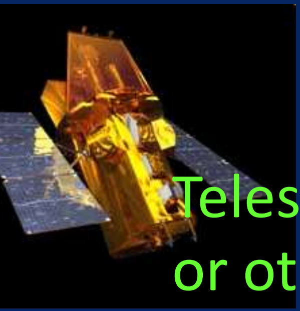
First astrophysically significant multimessenger result from LIGO:

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

B. Abbott et al. [LIGO Collaboration], *"Implications for the Origin of GRB 070201 from LIGO Observations",* ApJ., 681, 1419, 2008

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

We can always go back to the collected data and analyze later

Multimessenger Approaches: Follow-up strategy

GW Data

Flow of trigger information

Telescopes, Satellites or other external entities

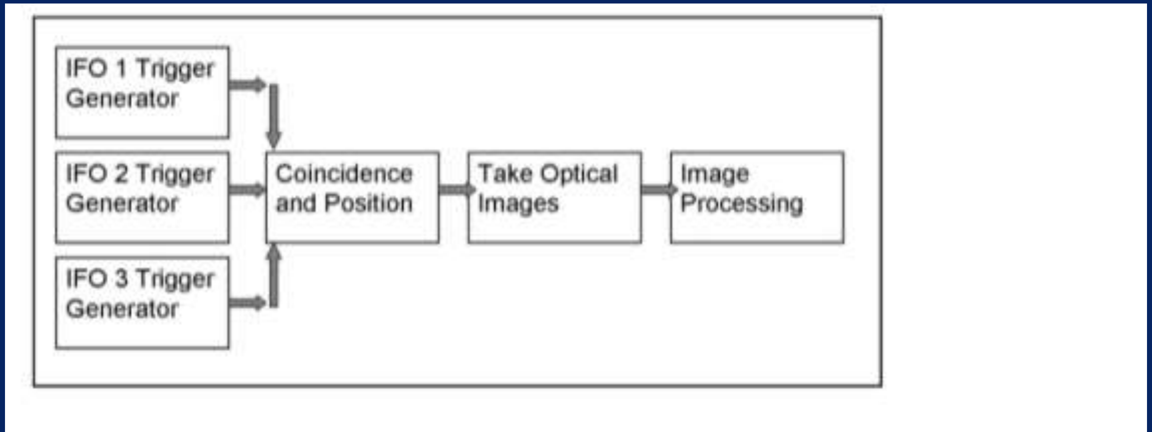
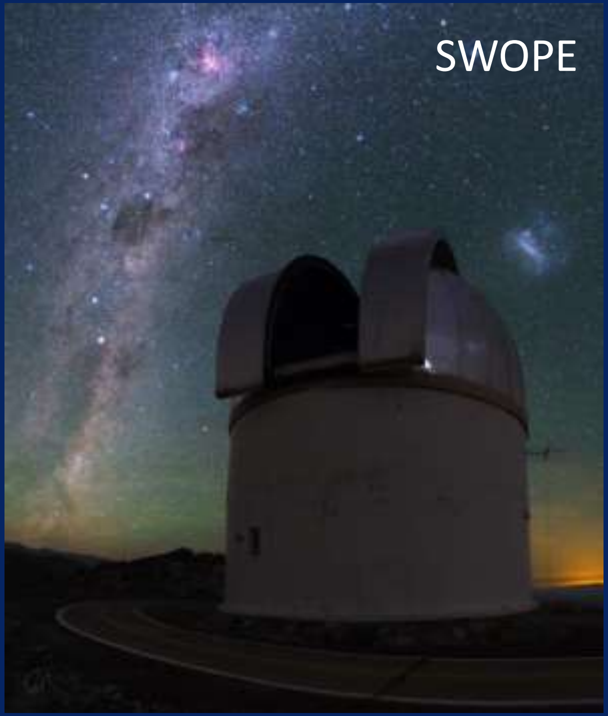


Figure 1. A schematic of the analysis. Triggers are identified in data from the three sites of the LIGO-Virgo network. The three trigger lists are then compared to find coincident events, labeled "candidate events." A sky region is assigned to each event candidate. The sky region is then imaged with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



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

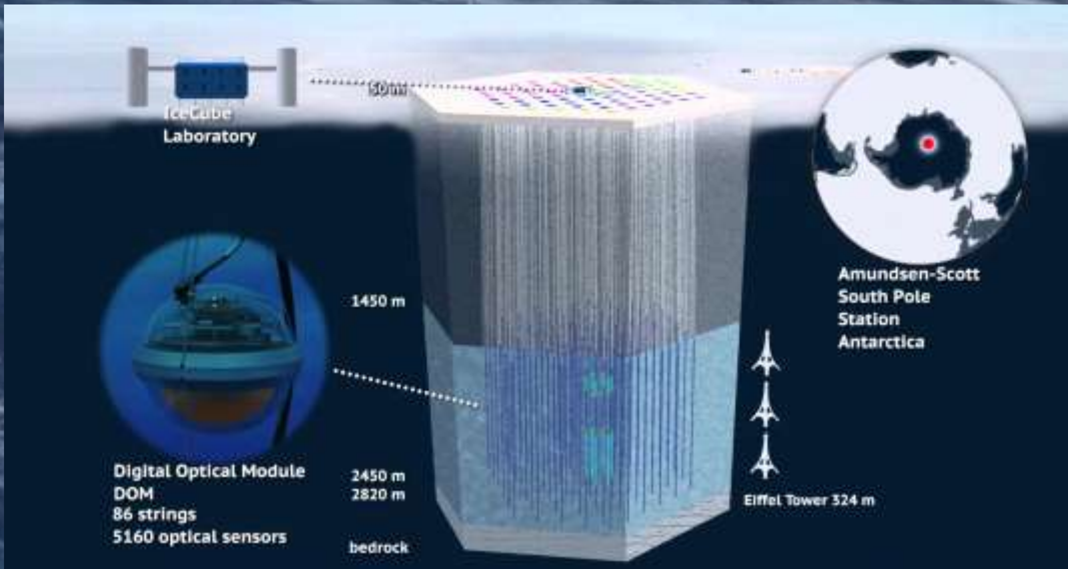
Multimessenger Approaches

“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



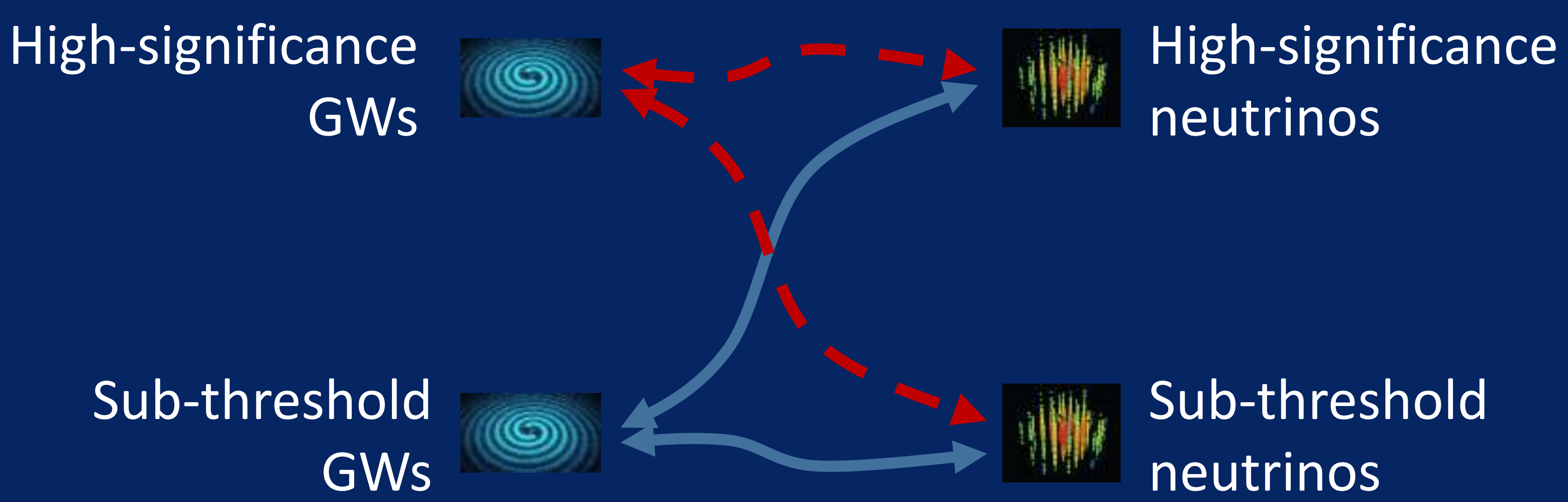
Slide Courtesy of Imre Bartos

Multimessenger Approaches

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

"Joint search" strategy:

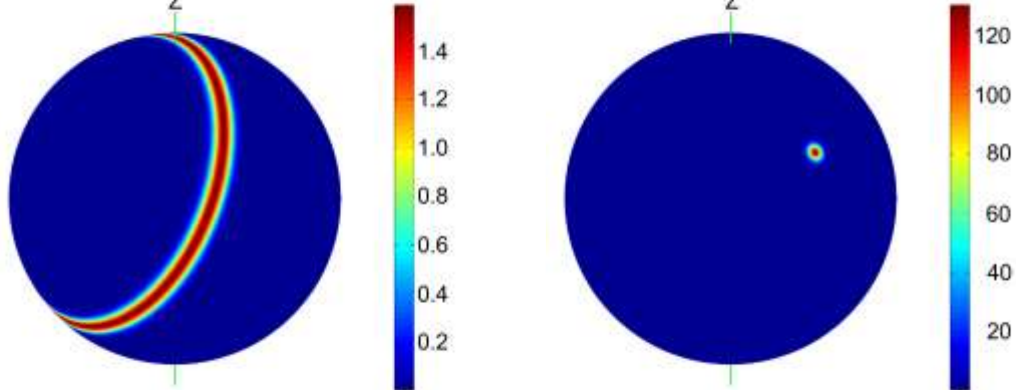
Multimessenger Search for GW+neutrino sources with complete neutrino and GW datastreams



courtesy of Imre Bartos

Multimessenger searches for GWs with LIGO: HENs

High-energy neutrino – GW multimessenger studies since 2006



"Search method for coincident events from LIGO and IceCube detectors" Class. Quantum Gravity, 25, 114039, 2008

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

Bartos et al., ***"Observational Constraints on Multimessenger Sources of Gravitational Waves and High-Energy Neutrinos"***, Physical Review Letters, 107, 251101, 2011

Baret et al., *"Multimessenger Science Reach and Analysis Method for Common Sources of Gravitational Waves and High-energy Neutrinos"*, Physical Review D, 85, 103004, 2012

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

High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube, Antares Collaboration, IceCube Collaboration, LIGO Scientific Collaboration, Virgo Collaboration, arXiv:1602.05411, 2016

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 High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory, Albert et al., The Astrophysical Journal, 850, L35, 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

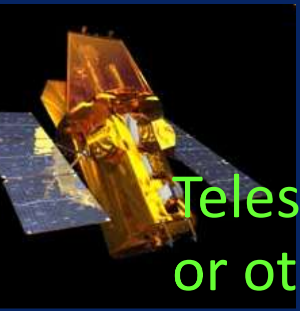
GW+HEN search is a prime motivation ***for joint subthreshold search*** strategy

- 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:

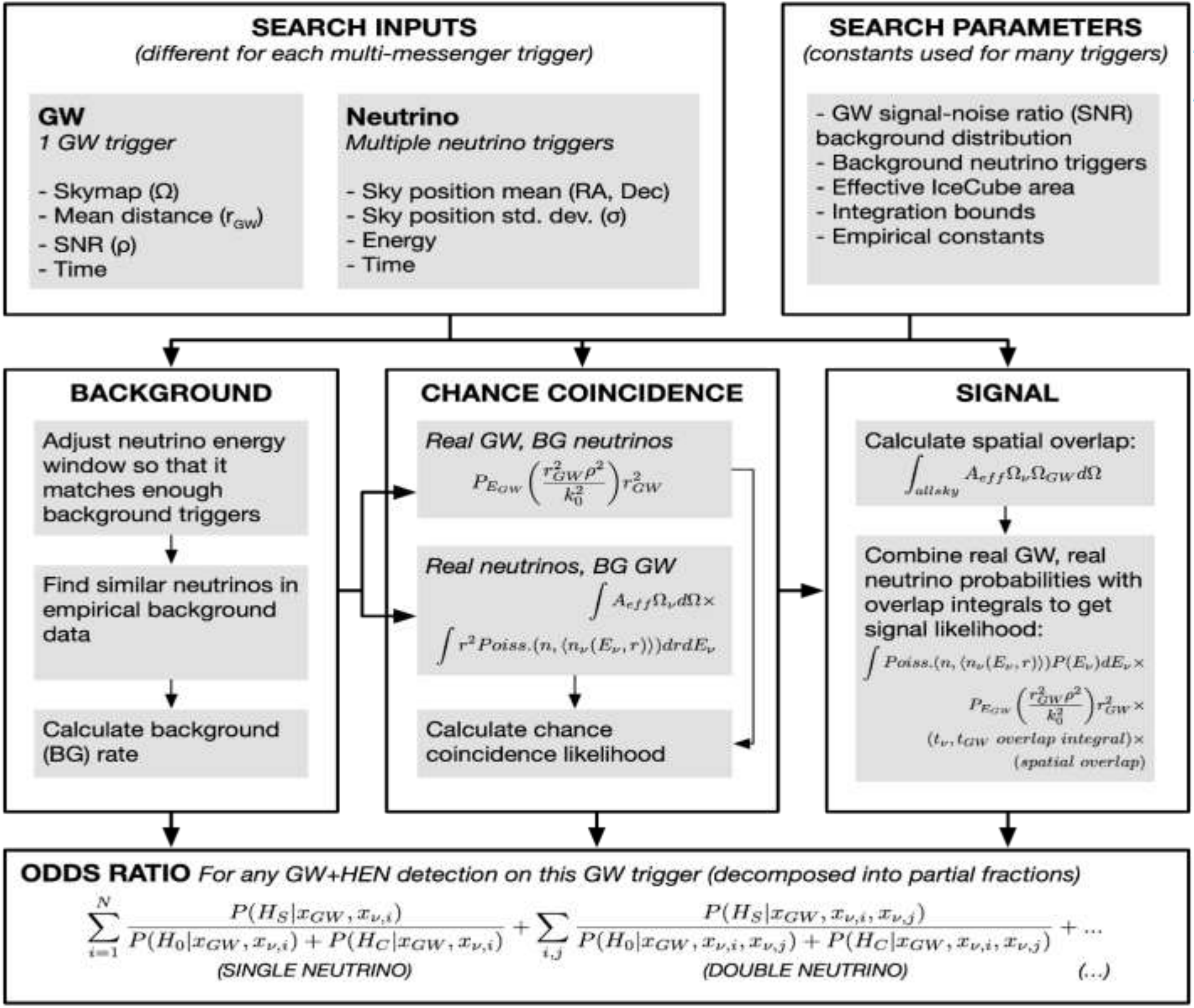
GW Data → (Flow of trigger information) → Telescopes, Satellites or other external entities

"*Low-latency* joint search" strategy:

GW detector →
GRB detector →
HEN detector →
++ →

Low
Latency
Algorithm for
Multimessenger
Astrophysics

→



LLAMA Employs Bayesian Method

O2 online: Countryman et al.; *Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA) with Gravitational-Wave and High-Energy Neutrino Candidates*; arXiv:1901.05486, 2019

O3 online: Keivani et al.; *Multi-messenger Gravitational-Wave + High-Energy Neutrino Searches with LIGO, Virgo and IceCube*, ICRC2019, 36, 930, 2019

ESSENCE: Bartos et al.; *Bayesian multimessenger search method for common sources of gravitational waves and high-energy neutrinos*; Physical Review D, 100, 083017, 2019

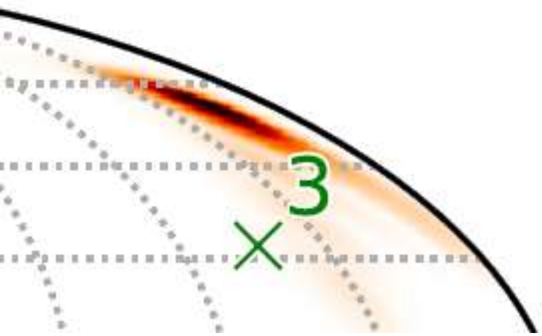
Upper Limit: Veske et al.; *Neutrino emission upper limits with maximum likelihood estimators for joint astrophysical neutrino searches with large sky localizations*; JCAP 2020

=> Odds ratio is used as a test statistic and we perform a frequentist significance assignment

=> If **p-value > threshold**, the of 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)



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

Typical event besides one p-value.

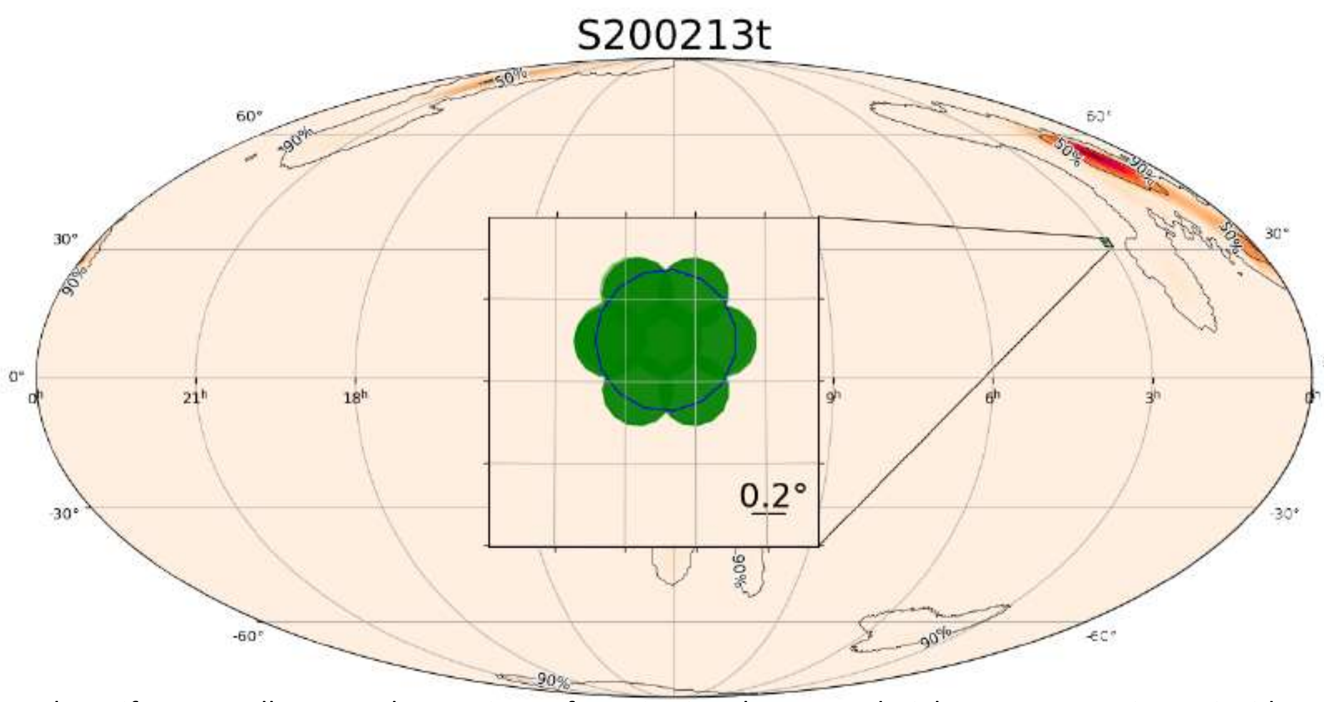
NUMBER: 27043
SUBJECT: LIGO/Virgo S200213t: 1 counterpart neutrino candidate from IceCube neutrino searches
DATE: 20/02/13 04:40:26 GMT

…..

Properties of the coincident events are shown below.

dt	ra	dec	Angular Uncertainty(deg)	p-value(generic transient)	p-value(binary merger)
-175.94	45.21	31.74	0.43	0.003	0.017

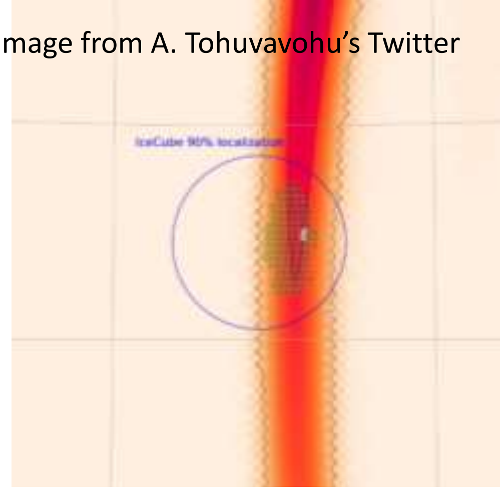
where: dt = Time offset (sec) of track event with respect to GW trigger. Angular uncertainty = Angular uncertainty of track event: the radius of a circle representing 90% CL containment by area. Pvalue = the pvalue for this specific track event from each search.



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

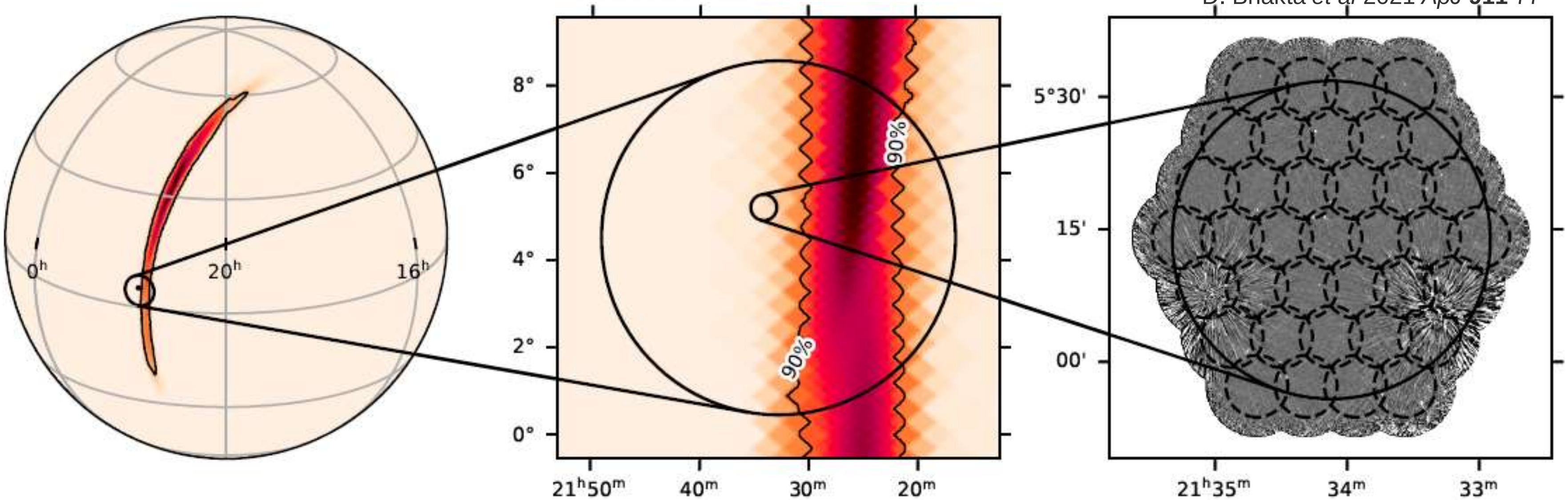
Beyond Two Messengers

Swift follow-up of S191216ap —image from A. Tohuvavohu's Twitter



- ⇒ **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

D. Bhakta *et al* 2021 *ApJ* **911** 77



Need a statistical treatment for multiple messengers for such multiple coincidences!

Many messengers many hypotheses…

Veske et al., The Astrophysical Journal (2021), Volume 908, Number 2, 216

Astrophysical or noise

Related or unrelated

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

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

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_o, null)

What is the optimal test statistic for this case?

Veske et al., The Astrophysical Journal (2021), Volume 908, Number 2, 216

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:

Combined signal hypothesis

Model dependent prior probability

Independent of **x**

$$\mathrm{TS}(\mathbf{x}) = \frac{P(\mathbf{x}|H_s)}{P(\mathbf{x}|H_n)} = \frac{\sum_i P(\mathbf{x}|H_s^i)P(H_s^i)}{\sum_j P(\mathbf{x}|H_n^j)P(H_n^j)} \times \frac{\sum_j P(H_n^j)}{\sum_i P(H_s^i)}$$

Detection outcomes

Combined null hypothesis

Sub-hypothesis likelihoods

SEARCH INPUTS

(different for each multi-messenger trigger)

GW
1 GW trigger

- Skymap (Ω)
- Mean distance (r_{GW})
- SNR (ρ)
- Time

Neutrino
Multiple neutrino triggers

- Sky position mean (RA, Dec)
- Sky position std. dev. (σ)
- Energy
- Time

GRB
1 GRB trigger

- Sky position
- Angular uncertainty
- Time
- Duration, Significance, Fluence

Common source relation through a source parameter:

$$P(\mathbf{x}|H_a^b) = \int P(\mathbf{x}|\boldsymbol{\theta}, H_a^b)P(\boldsymbol{\theta}|H_a^b)d\boldsymbol{\theta}$$

Future Outlook

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.

The Astrophysical Journal, 908:216 (7pp), 2021 February 20 https://doi.org/10.3847/1538-4357/abd542

CrossMark

How to Search for Multiple Messengers—A General Framework Beyond Two Messengers

Doğa Veske[1], Zsuzsa Márka[2], Imre Bartos[3], and Szabolcs Márka[1]
[1] Department of Physics, Columbia University in the City of New York, New York, NY 10027, USA; dv2397@columbia.edu