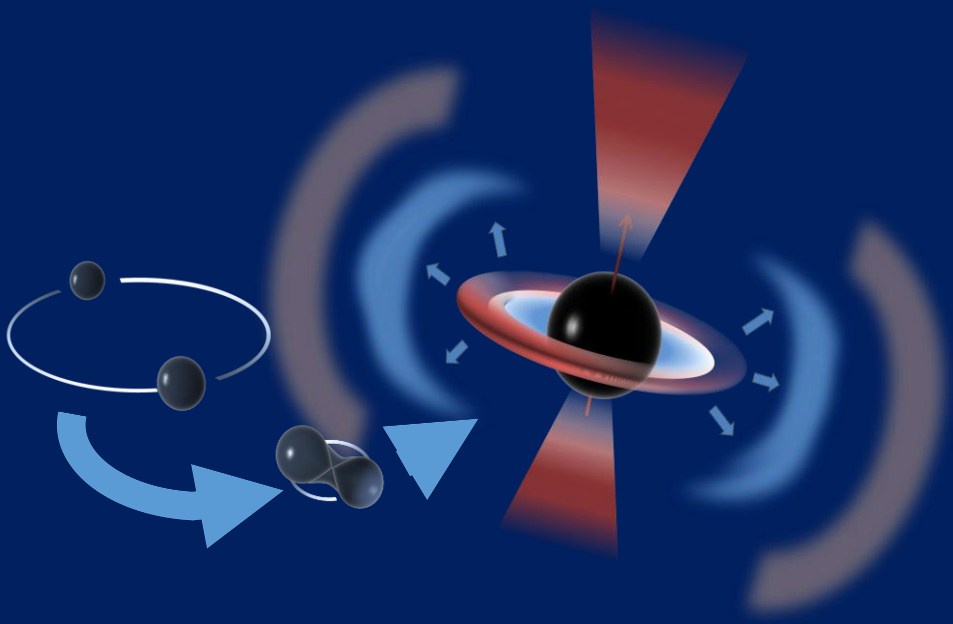


Observational-data-rich future in multimessenger astrophysics

ZSUZSA MARKA
Columbia University in the City of New York

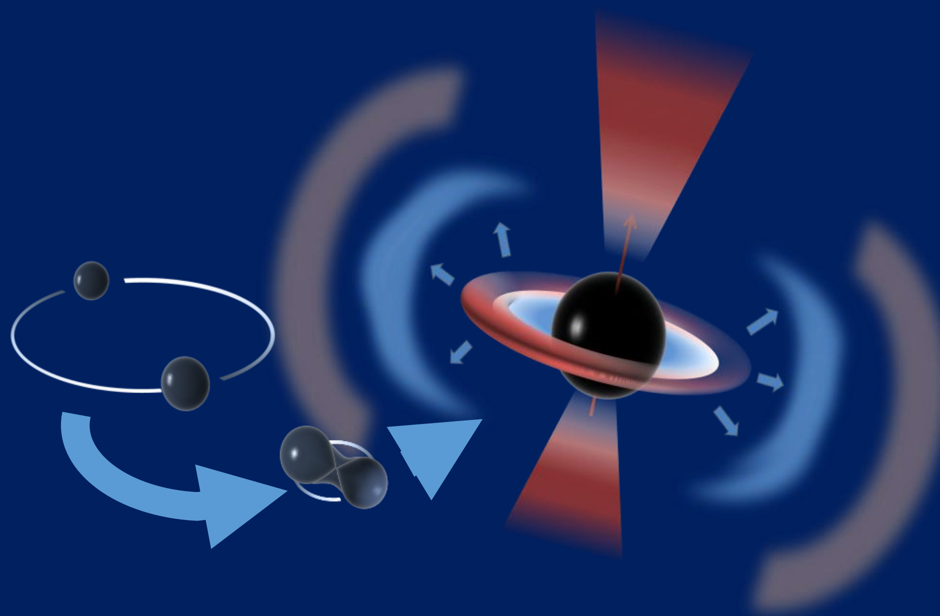
July 8, 2024

MG17, Pescara

"Pioneering MMA with GW for decades!"

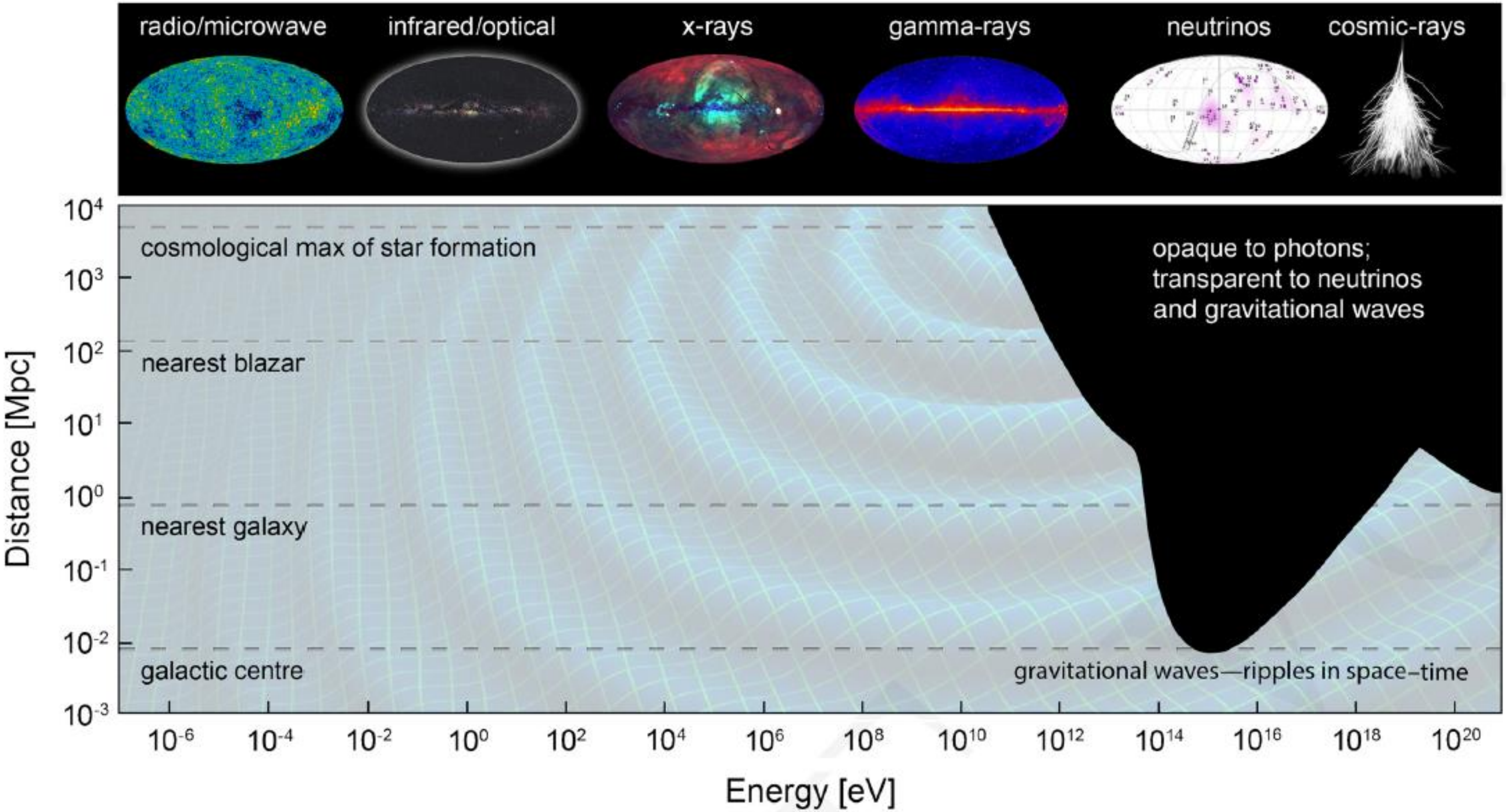
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

GECo



Multimessenger astronomy: “the exploration of the Universe through combining information from a multitude of cosmic messengers: electromagnetic radiation, gravitational waves, neutrinos and cosmic rays” **(Bartos and Kowalski, Multimessenger Astronomy , 2017)**

The multimessenger energy-distance scale



Bartos and Kowalski

Multimessenger Astrophysics

connecting different kinds (EM, GW, particle) of observations of the same

astrophysical event (e.g. a supernova, a binary merger, ..)

or

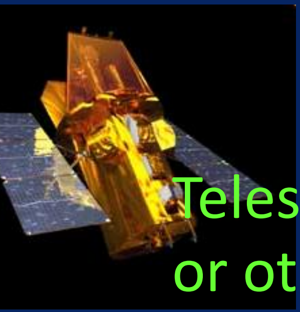
astrophysical system (an active galaxy, a soft-gamma repeater, ..)

in order to

DISCOVER new/more transients and emitting sources

uncover the physics of the multimessenger emission mechanism

Multimessenger Approaches



"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

GW
Data

"Follow-up" strategy:

Flow of trigger information →

Telescopes, Satellites
or other external entities

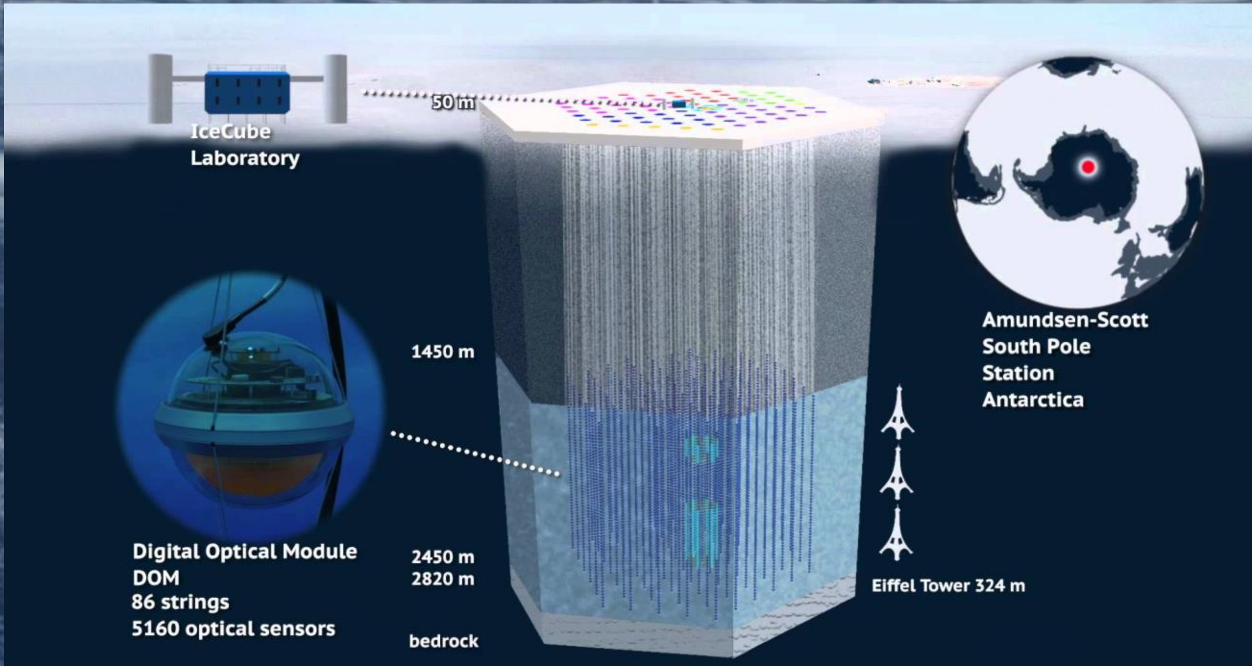
Low-latency pipeline development is essential

quick localization

subthreshold triggers?

large field of view is useful

Some detectors see the whole sky continuously

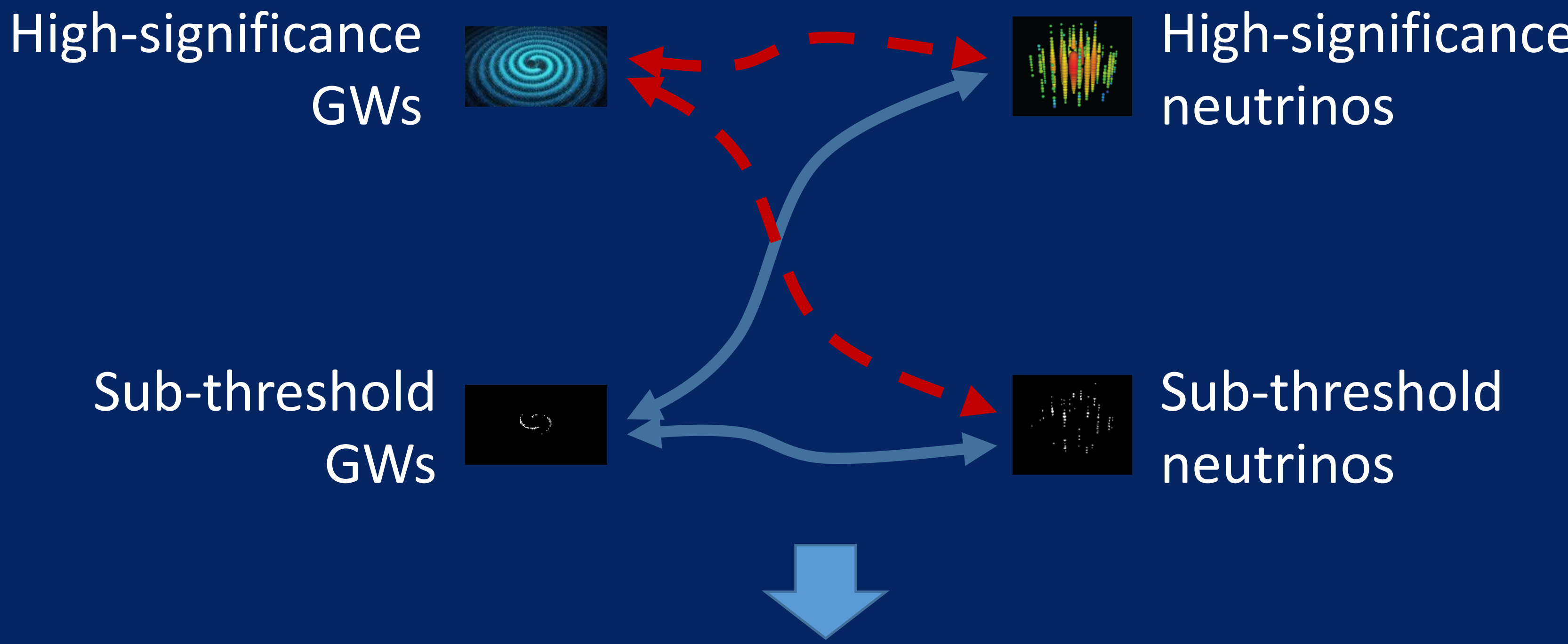


Slide Courtesy of Imre Bartos

Multimessenger Approaches

"Joint search" strategy:

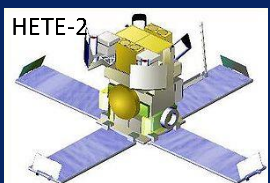
Multimessenger Search for GW+neutrino sources with complete neutrino and GW datastreams



Alert EM community of significant temporal+spatial overlaps

Basic Glossary: Multimessenger Approaches

Two decades of MMA searches with GWs



"ExtTrig" strategy:

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

First exttrig search GRB030329

"Follow-Up" strategy:

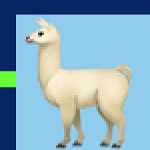
GW Data → Flow of trigger information → Telescopes, Satellites or other external entities

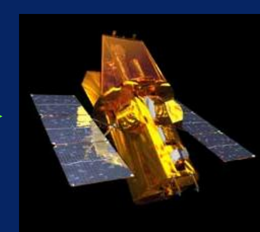
First EM follow campaign: summer 2007 pilot project

"joint search" strategy:

GW detector →
(GRB detector) →
HEN detector →
++ →

Low
Latency
Algorithm for
Multimessenger
Astrophysics





First search concept: 2006 in ***low-latency*** since O2 (2017)

Two famous MMA events with new messengers:

GW170817 & IceCube-170922A

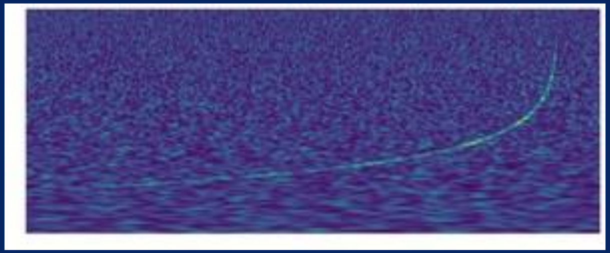
Similarities:

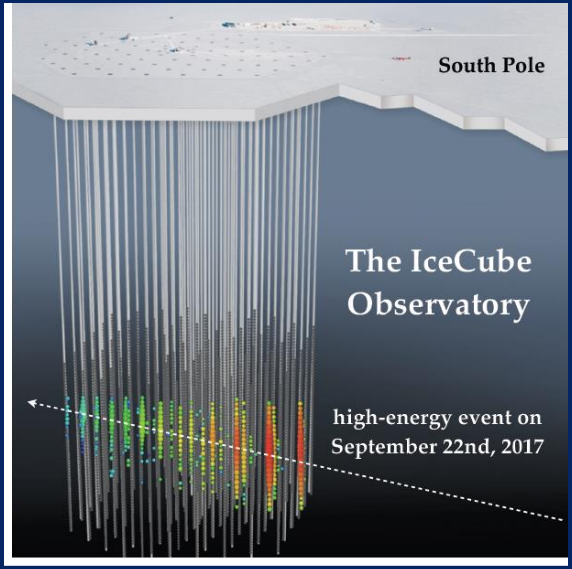
Significant events (high SNR / high–energy)

Localization is available in relatively low-latency / real-time

Method to disseminate alerts is available and well-tested

Sizable and experienced EM follow-up community – previous alert periods - willingness to receive alerts that may be retracted





Differences:

GW messenger has *extra attributes*:
inference on source type (BNS merger)
distance

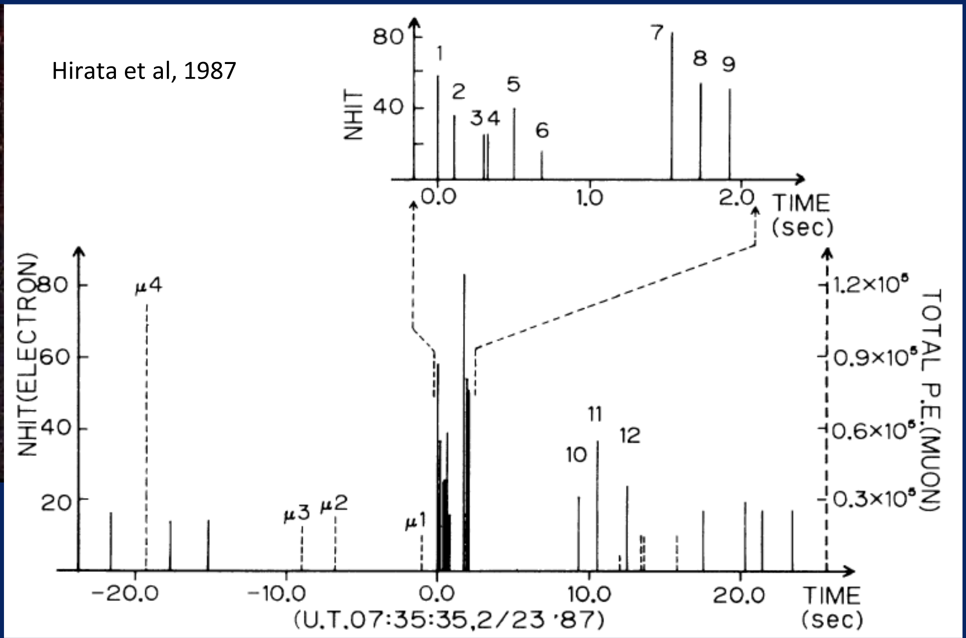
Neutrinos provide more confined localization

=>Inference on MMA association

Images: ligo.org and Astro2020 IceCube paper

The missing combination

Gravitational waves and particle messenger:
The supernova case



We have SNEWS!

Whole sky observation with localization information

Significant up-time

Supernova is a rare source (with current sensitivities)

This will likely be a typical *exttrig type of search* from the both the EM and the GW point of view

The missing combination

Gravitational waves and **high-energy neutrino** messenger
GW+HEN search example

GWs and HENs as messengers

- Detectors searching for these messengers observe the whole sky continuously
- Joint skymap can be made rapidly available to *guide follow-up electromagnetic surveys*

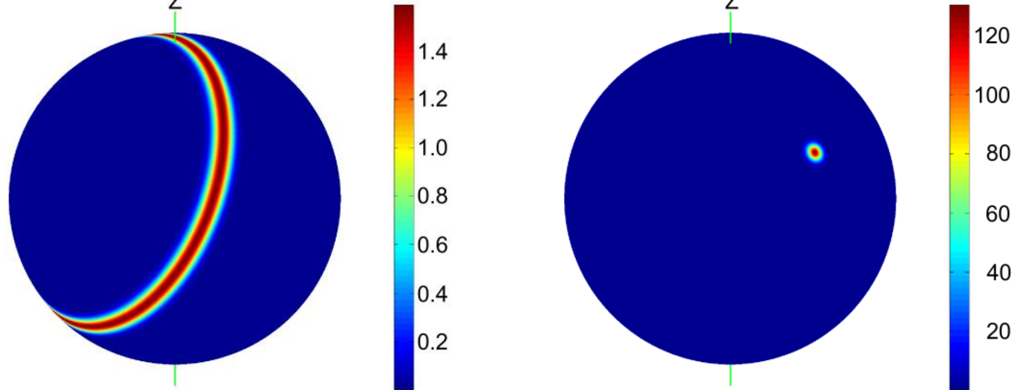
GWHEN sources may include binary neutron stars (a potential kilonova), neutron star-black hole binaries, binary black holes with an accretion disc, core collapse supernovae, …

Search Science Goals

Discovery of common source of gravitational waves (GW) and high-energy neutrinos (HEN) (offline and low-latency)
In case of non-detection, constrain upper limit event-by-event or the GW+HEN joint source population

Multimessenger searches with GWs and 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

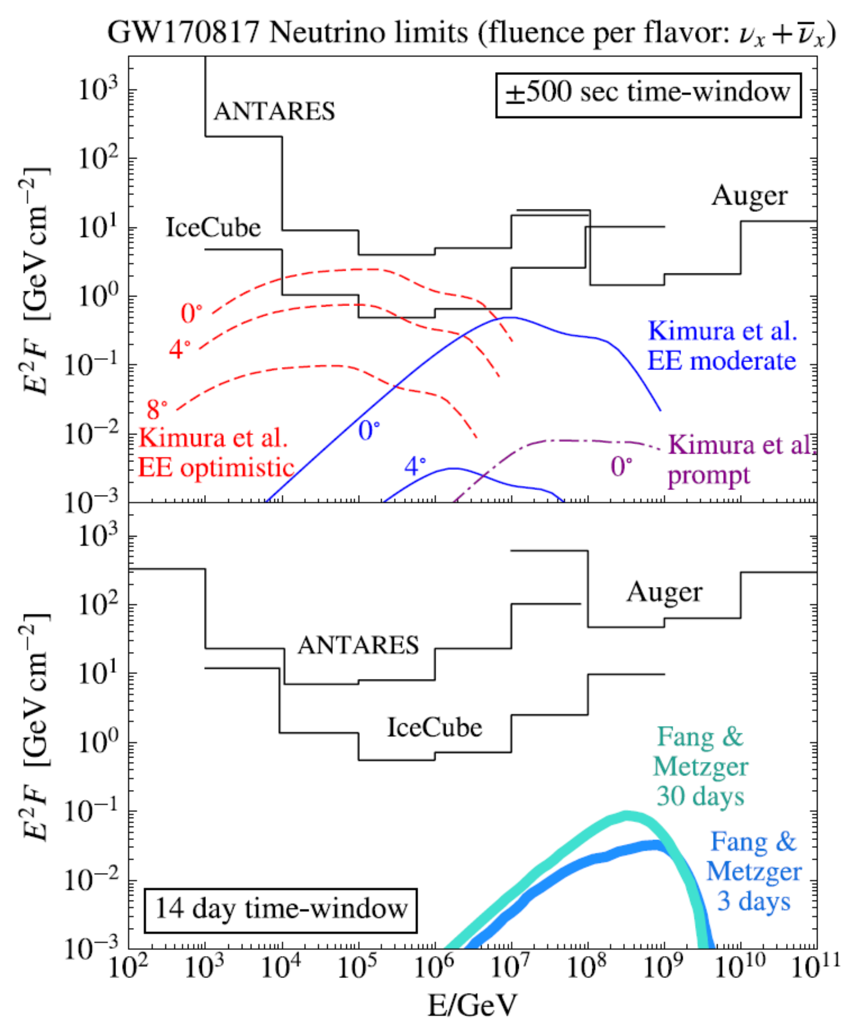
IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-Wave Transient Catalog; The Astrophysical Journal Letters, 898, L10, 2020

IceCube search for neutrinos coincident with gravitational wave events from LIGO/Virgo run O3 ApJ 944 (2023) 80

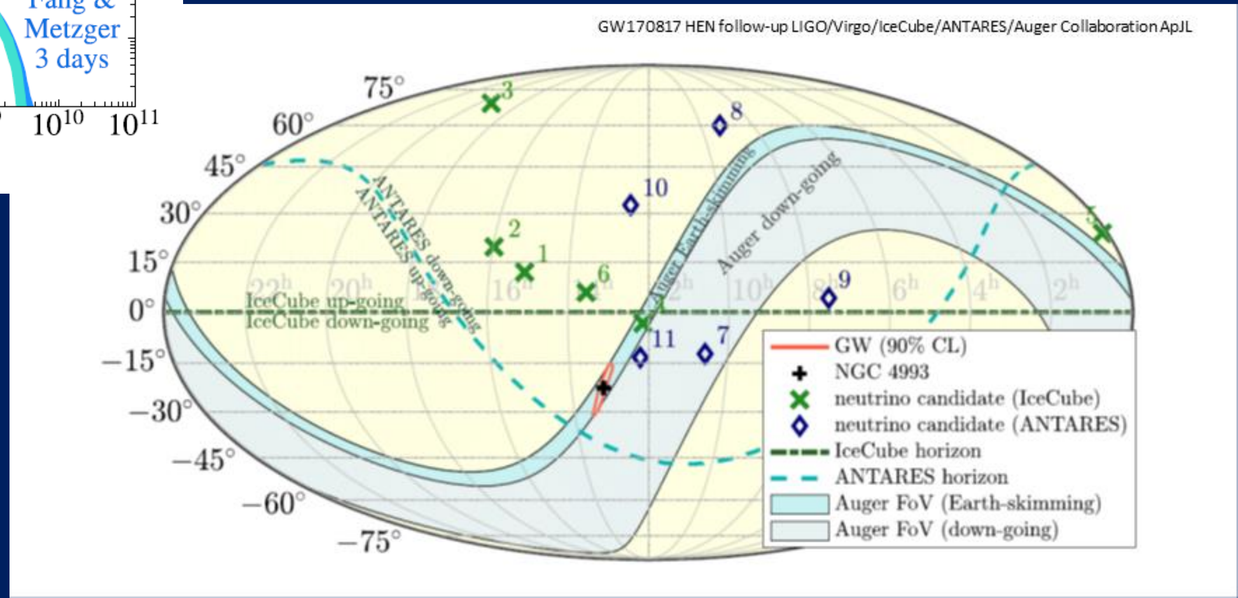
Several dozens of GCNs during O2 and O3 and NOW in O4!!!

IceCube LVK Alert Nu Track Search, topic = gcn.notices.icecube.lvk_nu_track_search (https://gcn.nasa.gov/missions/icecube)

GW170817



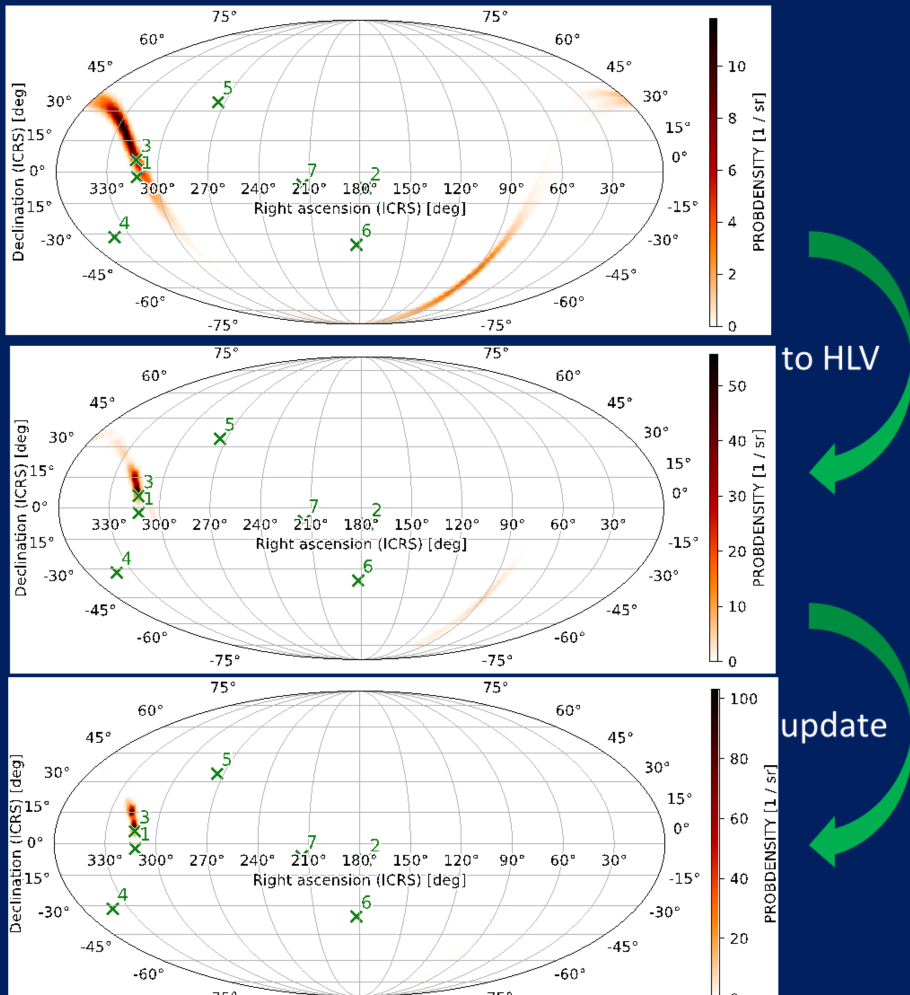
GW170817 Neutrino limits (fluence per flavor: $\nu_x + \bar{\nu}_x$)
±500 sec time-window
ANTARES
IceCube
Auger
Kimura et al. EE moderate
Kimura et al. EE optimistic
Kimura et al. prompt
0°
4°
8°
14 day time-window
ANTARES
IceCube
Auger
Fang & Metzger 30 days
Fang & Metzger 3 days
E^2F [GeV cm^{-2}]
E/GeV



GW170817 HEN follow-up LIGO/Virgo/IceCube/ANTARES/Auger Collaboration ApJL
ANTARES down-going
ANTARES up-going
Auger Earth-skimming
Auger down-going
IceCube up-going
IceCube down-going
GW (90% CL)
NGC 4993
neutrino candidate (IceCube)
neutrino candidate (ANTARES)
IceCube horizon
ANTARES horizon
Auger FoV (Earth-skimming)
Auger FoV (down-going)

Realtime search during O3

Evolution of the localization skymap for S190728q and the associated follow up results



LVC Preliminary, 07/28/19 06:59:31 UT
90% area: 977 deg^2

p-value (Maximum Likelihood): 0.17
p-value (LLAMA): 0.092

LVC Initial Skymap, 07/28/19 07:50:45 UT
90% area: 543 deg^2

p-value (Maximum Likelihood): 0.039
p-value (LLAMA): 0.013

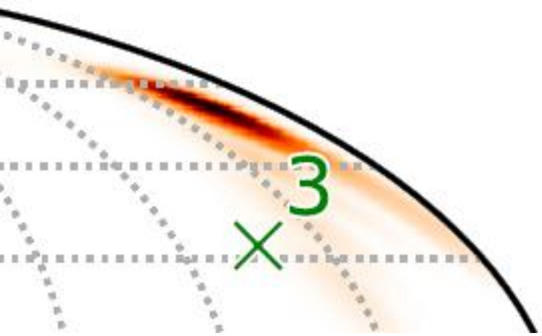
LVC Update Skymap, 07/28/19 20:29:15 UT
90% area: 104 deg^2

p-value (Maximum Likelihood): 0.016
p-value (LLAMA): 0.010

As the localization is refined, the p-values from both pipeline become more significant

IceCube search for neutrinos coincident with gravitational wave events from LIGO/Virgo run O3 ApJ 944 (2023) 80

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.

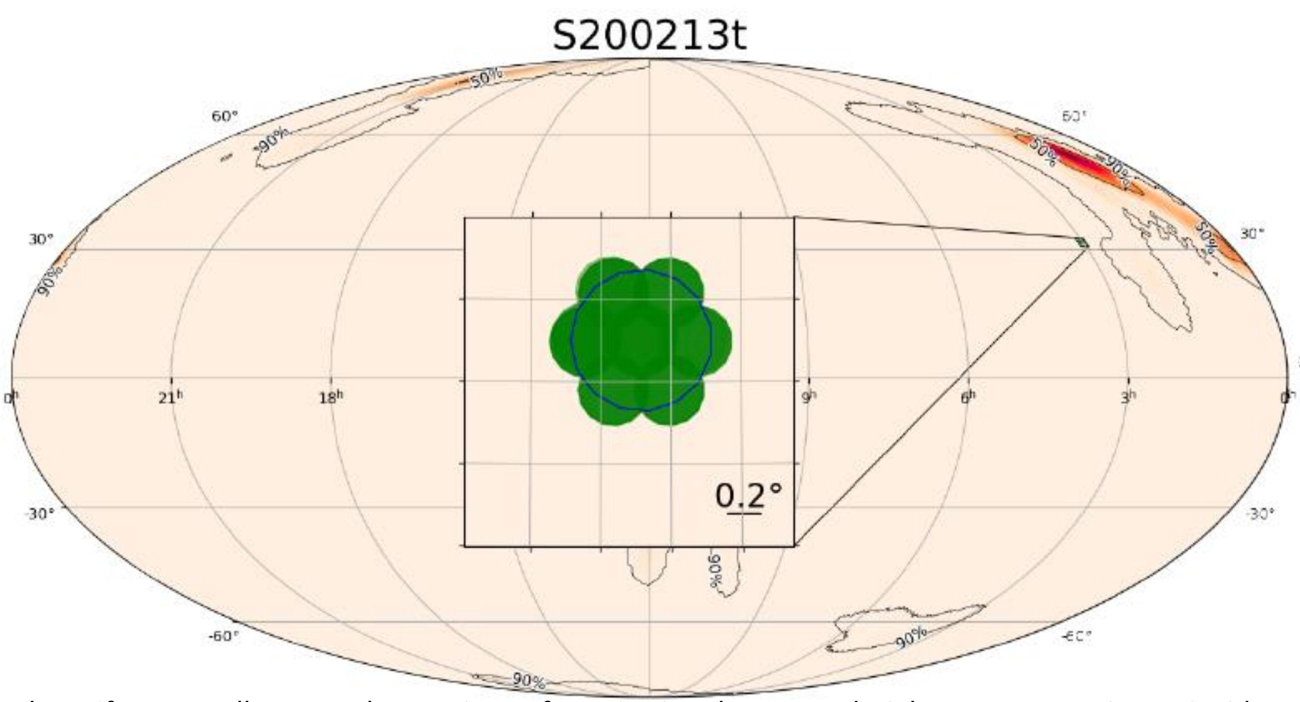
NUMBER: 27043
SUBJECT: LIGO/Virgo S200213t: 1 counterpart neutrino candidate from IceCube neutrino searches
DATE: 20/02/13 04:40:26 GMT

…..

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)

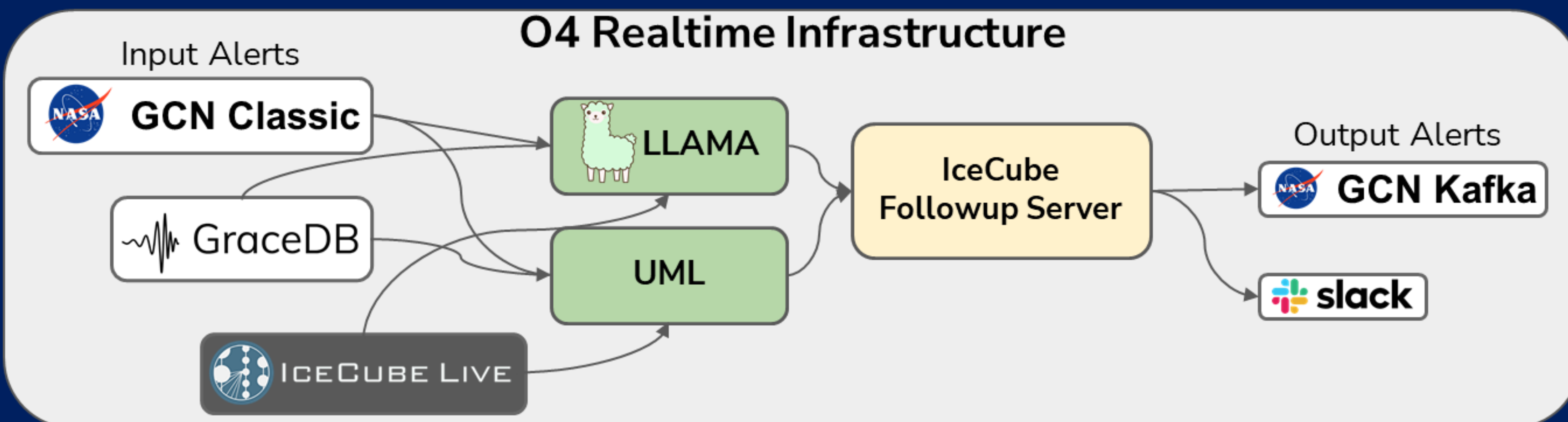
Ongoing O4 run: Searches in Realtime

Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA)

Test statistic calculates odds ratio for a common source by including astrophysical emission priors in order to use the distance information from the GW detection

Unbinned Maximum Likelihood (UML) *Hussain et al., ICRC Proceedings 2019*

Test statistic uses the best fit for the signal neutrino count and spectral index

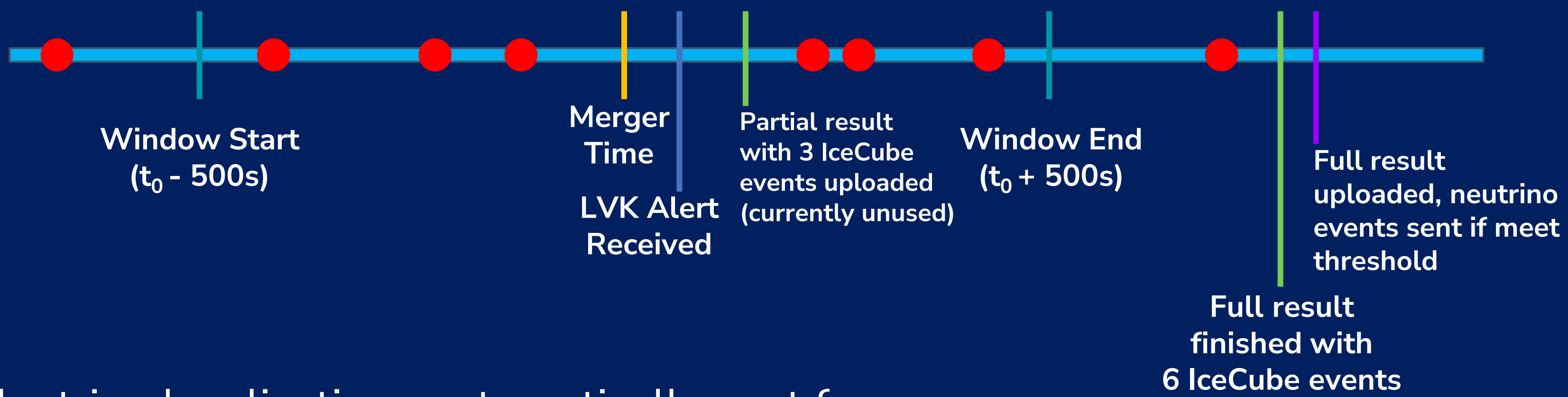


- Both analyses look for neutrinos ±500s around the GW event.
- LLAMA uses all publicly announced GW triggers, including the subthreshold ones
- At the end a frequentist p-value is found
  - Background distributions for UML are calculated for each skymap
  - LLAMA uses pre-computed background distributions for different source types

O4 joint analysis is ongoing in realtime

1000s GFU event window centered around merger time

- Partial result is generated as soon as possible with available events
    - Not sent out, but provides data for evaluating delay
- Final result generated after an event from *after* the window is received



Neutrino localizations automatically sent for coincidences with $p < 0.1$ (either UML or LLAMA)

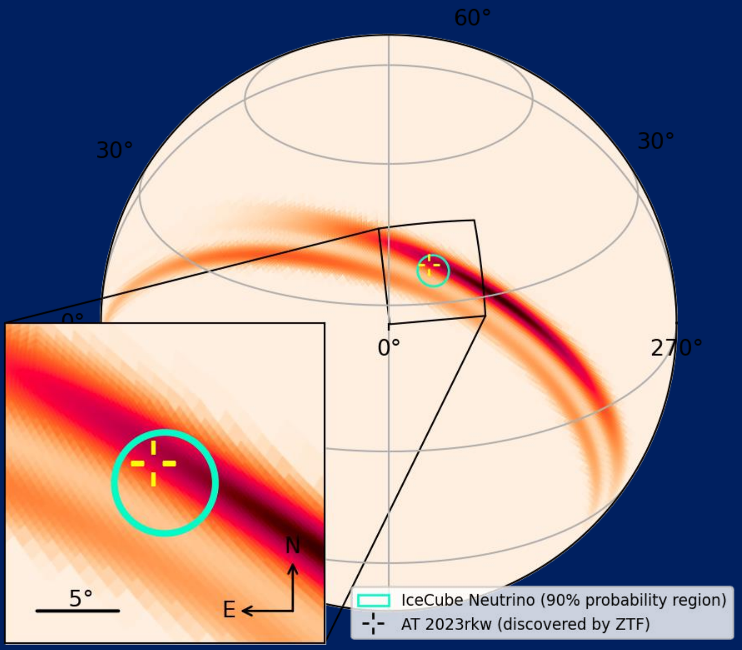
GCN Circular sent for coincidences with $p < 0.01$, after manual review

Slide credit, Albert Zhang, AAS talk 2024

GWHEN search is limited by neutrino detector sensitivity => **focus on detector upgrades**

LLAMA in Action: S230904n

- Within 12 minutes of the event, LLAMA found **1 coincident track** (teal circle) with *p*=0.004 and an automated GCN Notice was sent. UML found *p*=0.12. After manual vetting, we reported the event in GCN Circular 34616 later that day.
- After observing the IceCube sky localization, the Zwicky Transient Facility (**ZTF**) announced **AT 2023rkw** as a possible optical counterpart (Circulars 34688, 34717)
- Follow-up spectroscopy revealed AT 2023rkw was likely a type Ia supernova and unrelated to the GW event (Circular 34751)



Slide credit, Albert Zhang, AAS talk 2024

Future of MMA: rich in observational data

- More sensitive detectors across all messenger types

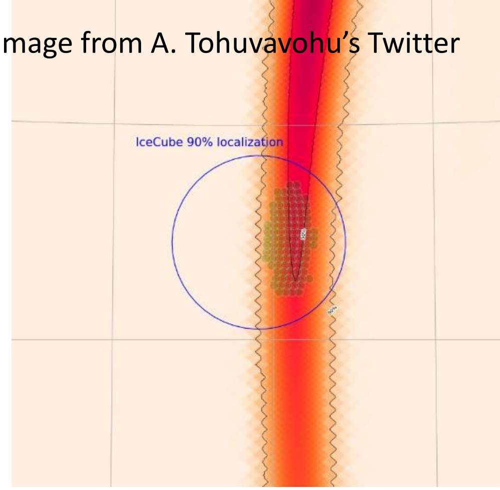
- Proliferation of open science
  - Realtime public data for multiple observatories
  - Multitudes of open-source software

- Proliferation of real-time analysis capabilities
  - Receive information from MMA cyberinfrastructures
  - Multitudes of open-source software
  - Even subthreshold triggers are released publicly

=>Coincident observation of triggers for two or more messengers (gravitational-waves, electromagnetic, neutrinos) will become increasingly frequent

Beyond Two Messengers

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



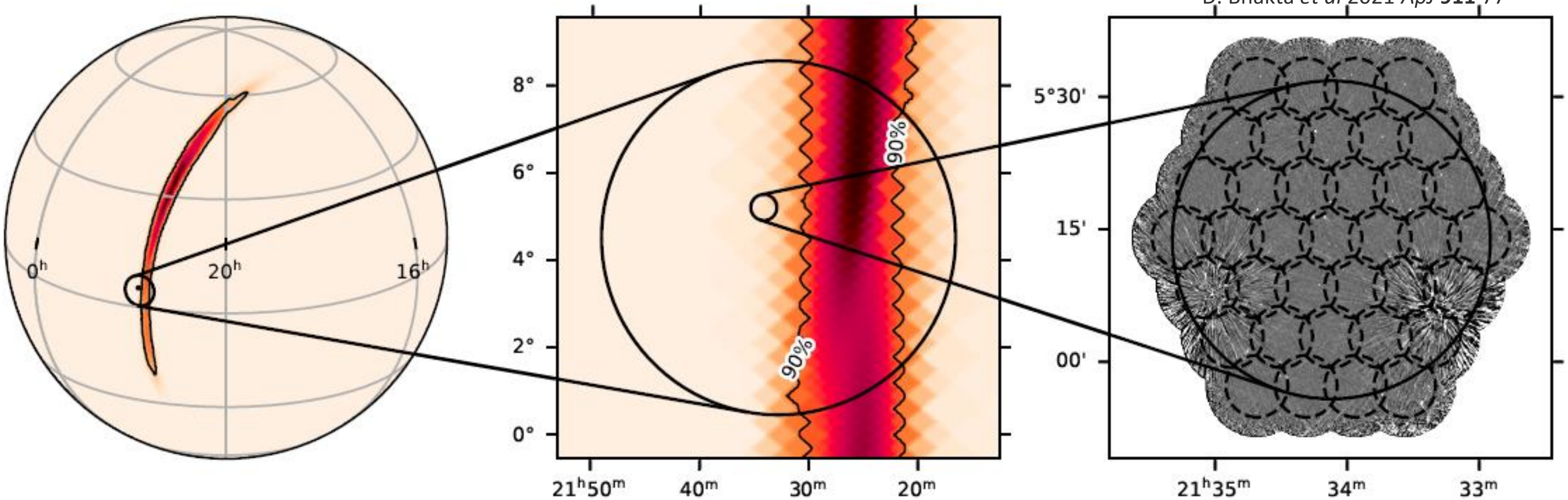
⇒ **GW candidate S191216ap by LIGO/Virgo**

⇒ 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!

Beyond two Messengers

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

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

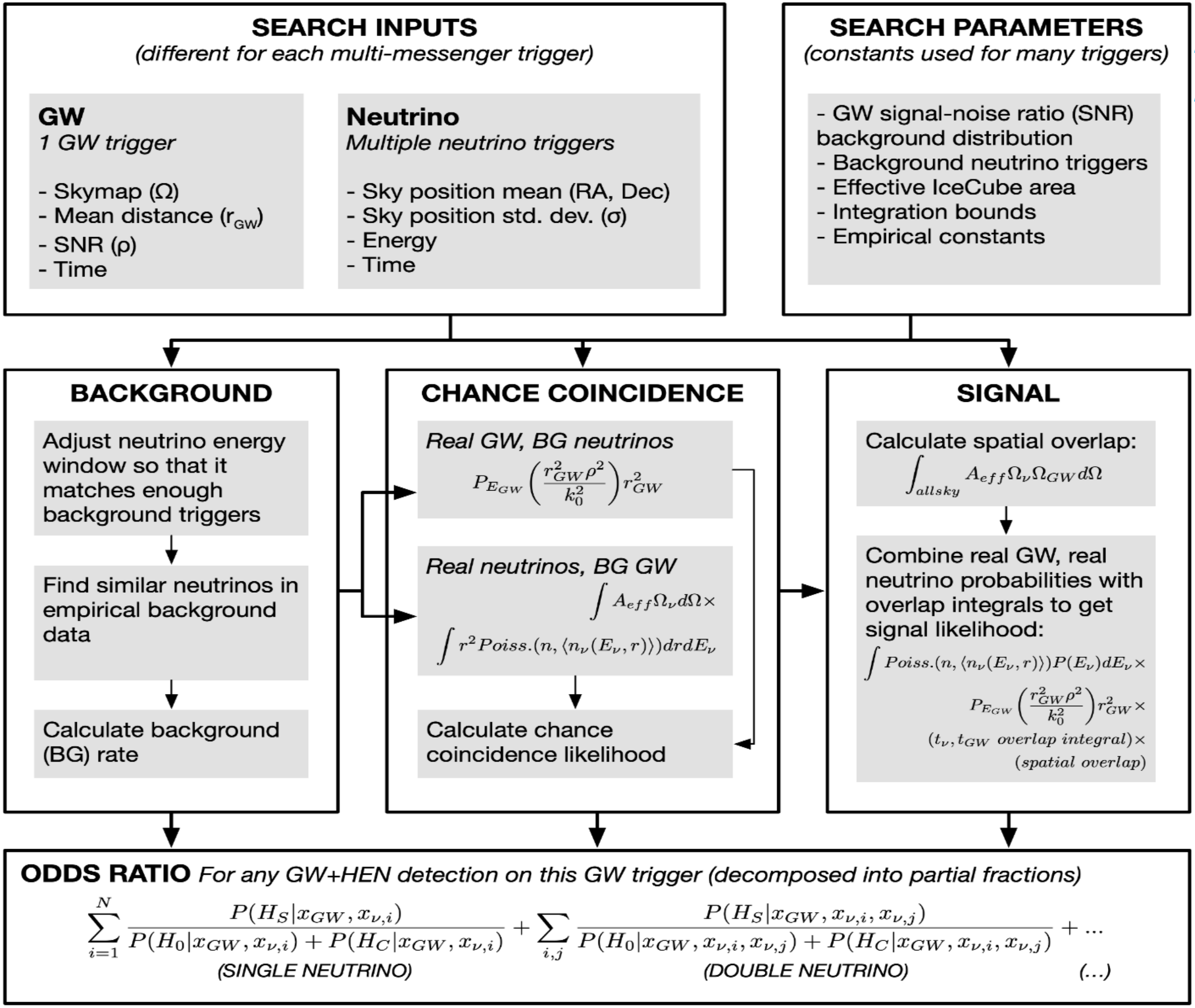
Doğa Veske[1], Zsuzsa Márka[2], Imre Bartos[3], and Szabolcs Márka[1]
[1] Department of Physics, Columbia University in the City of New York, New York, NY 10027, USA; dv2397@columbia.edu

What is LLAMA?
Low-Latency Algorithm for Multimessenger Astrophysics

Flexible Python library for MMA.
Originally developed by Stefan Countryman (Columbia PhD 2023) for O2, has been sending low-latency GWHEN alerts since 2017.

LLAMA is also a statistical framework for MMA

- Features:
  - Batch processing tools for offline analyses
  - Alert listeners and upload handlers for online analysis
  - ipywidgets-based Jupyter interface
  - Easy orchestration and portability with Docker Compose
- LLAMA is extendable for beyond two-messengers



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

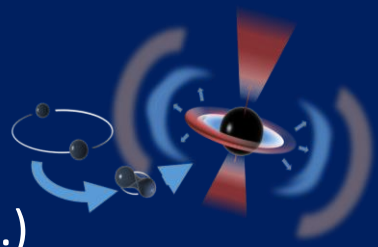
Upper Limit: Veske et al.; *Neutrino emission upper limits with maximum likelihood estimators for joint astrophysical neutrino searches with large sky localizations*; JCAP 2020

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

=> In online analysis, 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.

Ingredients of an MMA search



- detector data for each messenger (arrival time, localization ..)
- understanding the detector's behavior (sensitivity – distance reach, noise trigger rate ..)

- source model (emission delay between messengers, distribution of sources in the Universe, source energetics) or no model (unknown unknown)

Time of the transient

Localization of the transient

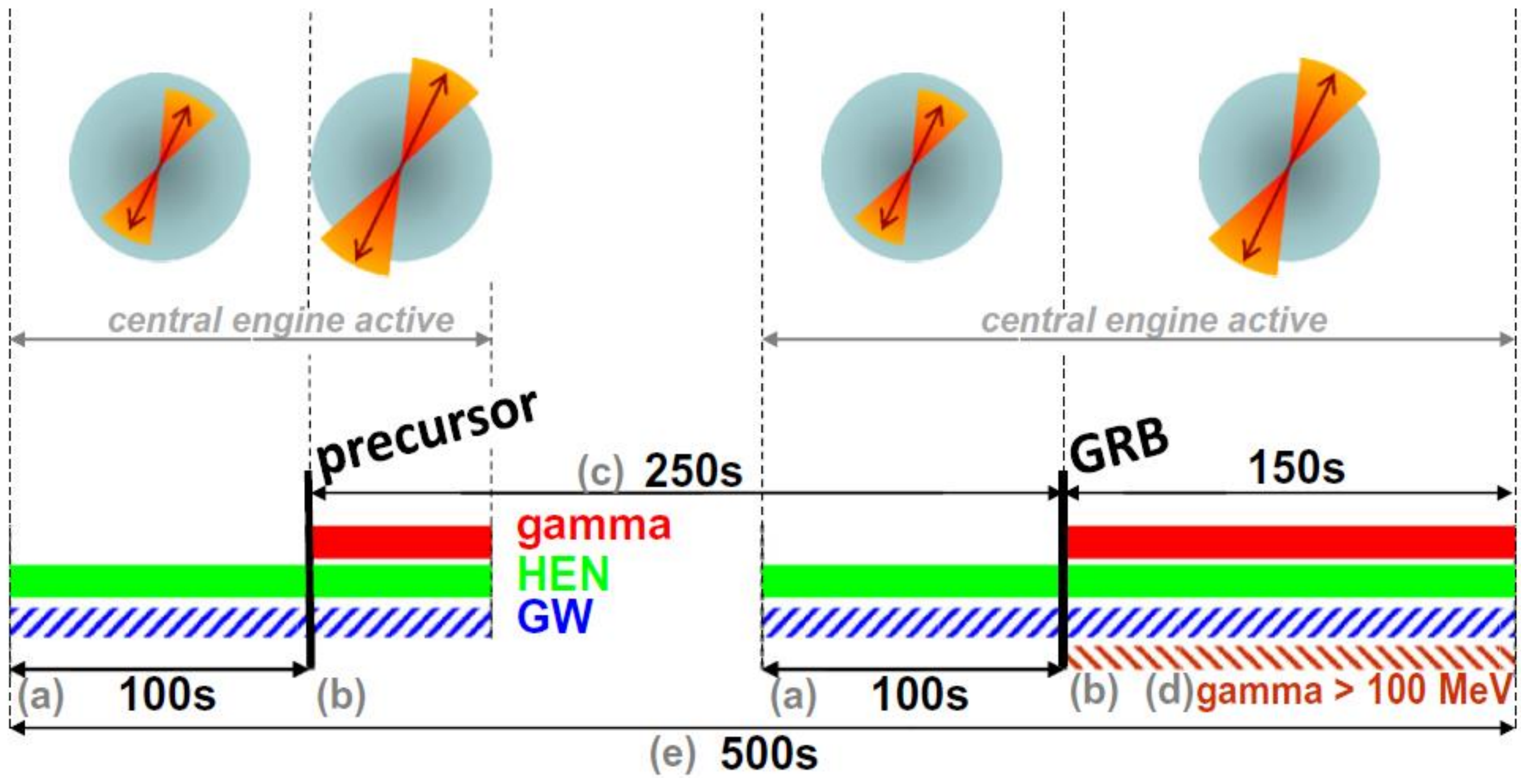
Find **spatial** and *temporal* overlap

Energetics of the observed excess
-signalness of GW trigger candidate
-neutrino energy

Understand the detectors' behavior (sensitivity – distance reach, noise trigger rate ..)

Ingredients of an MMA search
GW+HEN example

Search time window



Overall, the considered processes allow for a maximum of 500 s between the observation of a HEN and a GW transient.

Search window: [-500 s, 500 s]

Bounding the time delay between high-energy neutrinos and gravitational-wave transients from gamma-ray bursts, Baret et al, 2011

Ingredients of an MMA search
GW+HEN example

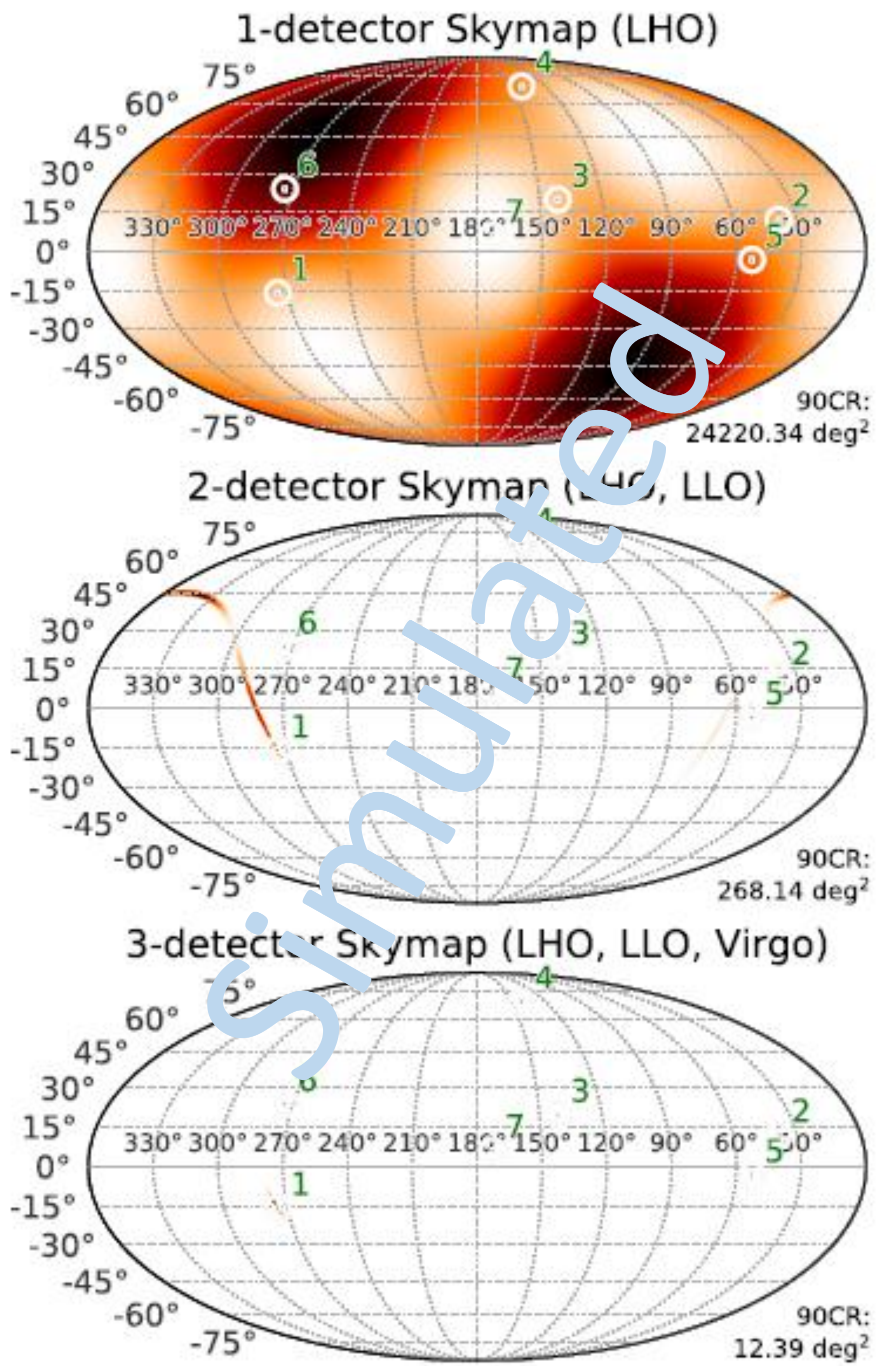
SEARCH INPUTS
(different for each multi-messenger trigger)

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



Ingredients of an MMA search
GW+HEN example

SEARCH PARAMETERS
(constants used for many triggers)

- GW signal-noise ratio (SNR) background distribution
- Background neutrino triggers
- Effective IceCube area
- Integration bounds
- Empirical constants

from timeslides

assume a uniform distribution of sources in the universe

SOURCE PARAMETERS

$$\theta = \{t_s, r, \Omega, E_{gw}, E_\nu\}$$

e.g. log uniform source engines:

$$P(E_{gw}, E_\nu | H_s) = P(E_{gw}|H_s)P(E_\nu|H_s)$$
$$= \left(E_{gw}E_\nu \log\left(\frac{E_{gw}^+}{E_{gw}^-}\right)\log\left(\frac{E_\nu^+}{E_\nu^-}\right)\right)^{-1}$$

time of a relevant astrophysical event delayed by the travel time of information to Earth at the speed of light

Is it a real or event or..?
Statistical Inference

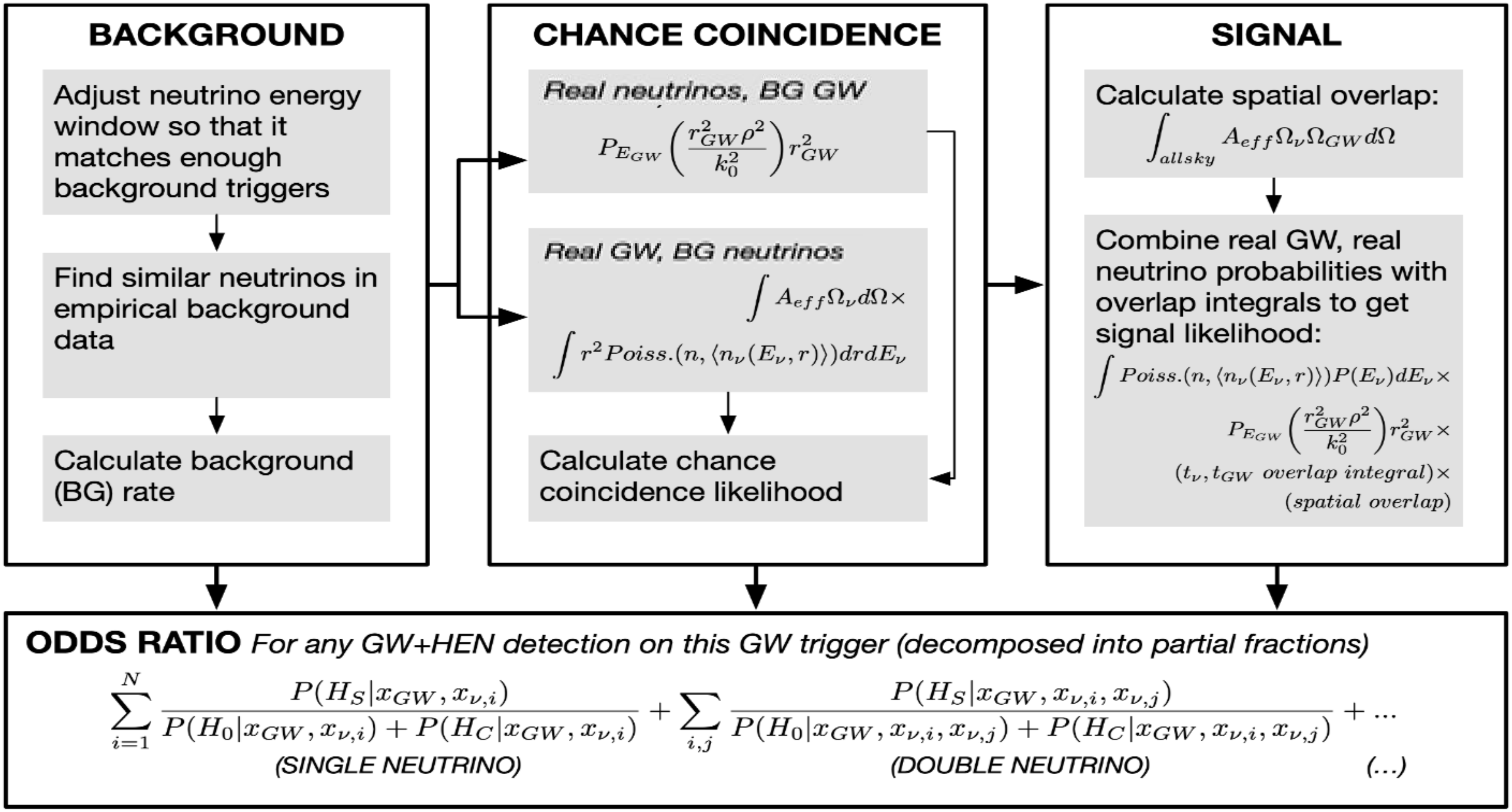
Hypotheses in the GW+HEN case:

- Signal hypothesis (H_s) , we have a GW and at least one neutrino signal coming from the same source
- Null hypothesis (H_0), both GW and neutrino signals are background
- Chance coincidence hypothesis (H_c), only one of GW or neutrino signal is background and the other one is not.
- Negligible contribution: both signals are not background but they come from different sources

Putting it all together
GW+HEN MMA search example

Ingredients of an MMA search
GW+HEN example

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



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

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

e.g. 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:

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

Combined signal hypothesis

Model dependent prior probability

Independent of **x**

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

Takeaways

GWHEN search is limited by neutrino detector sensitivity => **focus on detector upgrades**

Upgraded detectors, new instruments => transient event factories

Each messenger => subthreshold trigger lists

Some of the triggers become public ‘immediately’ => enables low-latency / real time MMA searches => already sending alerts to include additional observations

The future is rich in observational data!

Approach: joint analysis of trigger lists, including subthreshold triggers in real-time (and offline)

Multiple coincidences are inevitable

⇩

Best statistical inference for the coinciding multiple messengers is a REQUIREMENT

DATA that becomes available is a *metadata* – interpretation of any MMA candidate will require *knowledge of the detectors involved*

Interactions between experts in different messenger data streams is highly desirable

Input from the theory community is critically needed ‘yesterday’ - MMA discoveries are interpreted on the basis of source model