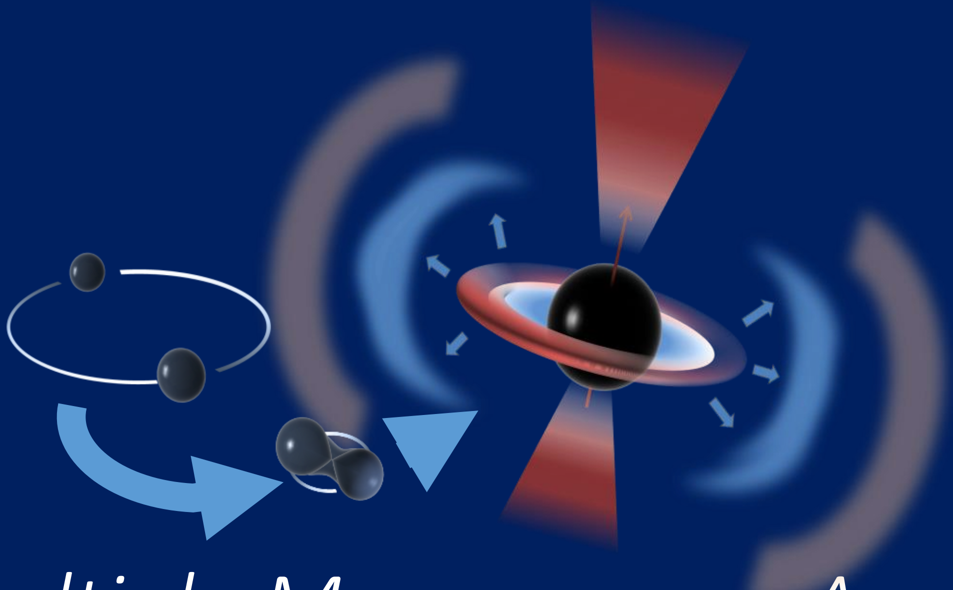


How to Search for Multiple Messengers—A General Framework Beyond Two Messengers

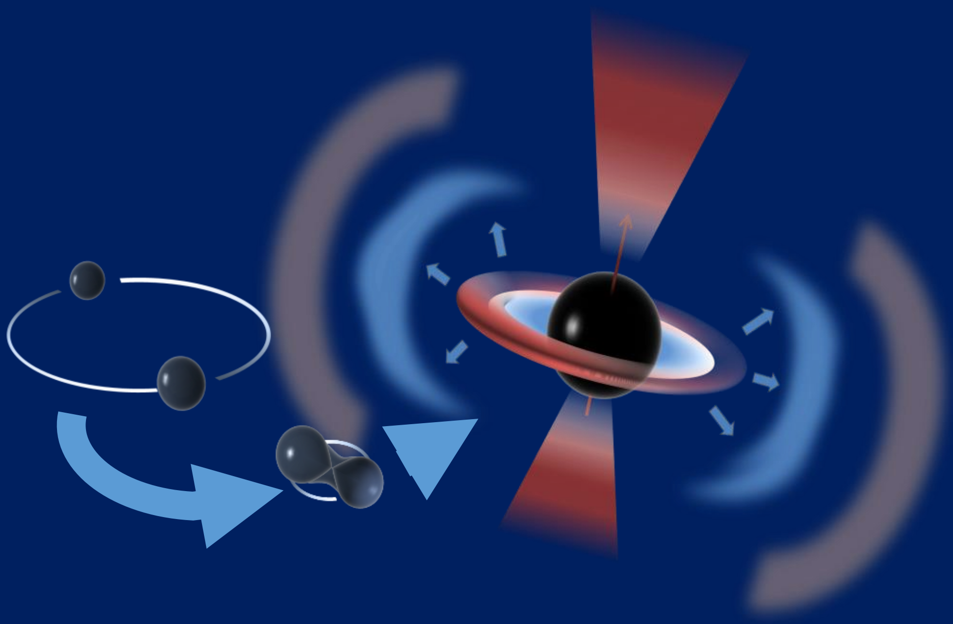
ZSUZSA MARKA
Columbia Experimental Gravity Group
Columbia University in the City of New York

Oct 5, 2022

"Pioneering MMA with GW for decades!"

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

GECo



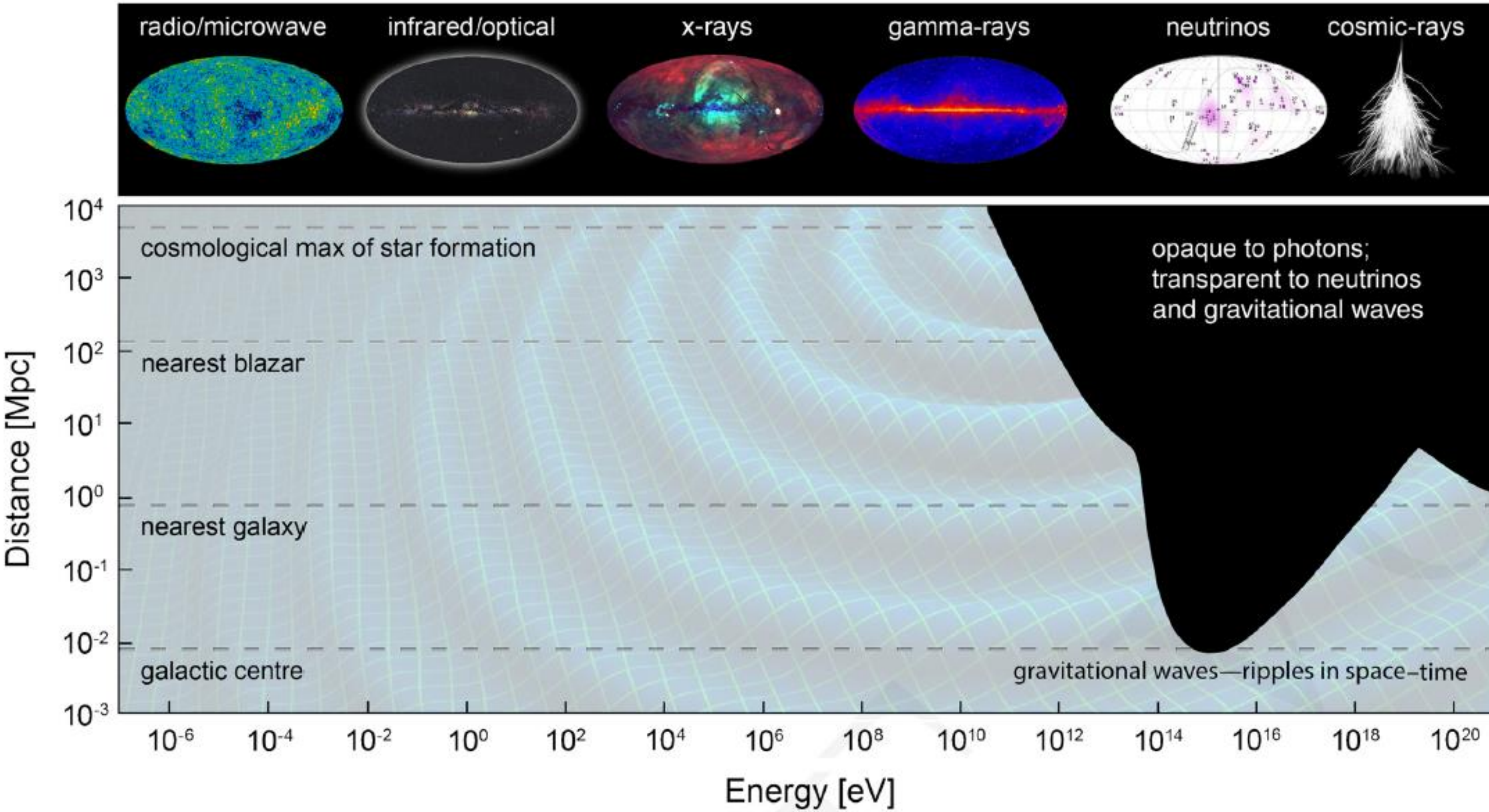
Multimessenger astronomy: “the exploration of the Universe through combining information from a multitude of cosmic messengers: electromagnetic radiation, gravitational waves, neutrinos and cosmic rays” **(Bartos and Kowalski, Multimessenger Astronomy , 2017)**

“Pioneering MMA with GW for decades!”

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

G
E
Co

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

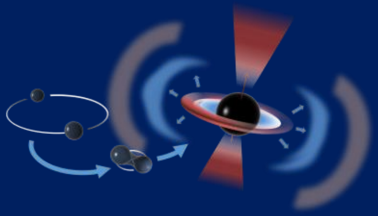
astrophysical system (an active galaxy, a soft-gamma repeater, ..)

in order to

DISCOVER new/more transients and emitting sources

uncover the physics of the multimessenger emission mechanism

The Multimessenger Astrophysics Search Landscape



History of MMA searches – GW data analysis centered

- MMA search methodologies (externally triggered, follow-up, joint search)

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)

Offline, real-time/ low-latency, early warning

Statistical Framework

Is their an optimal search? Is it real or chance coincidence?

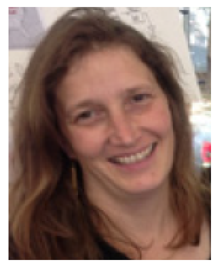
Beyond two messengers

Outlook

LIGO Magazine: https://www.ligo.org/magazine/LIGO-magazine-issue13.pdf

The Early Years: The Multi-Messenger Effort in LIGO

Zsuzsa Márka



is a long time LIGO member in the Columbia Experimental Gravity group, and works on timing diagnostics and multimessenger searches. She has 4 children, who are what she is the most proud of in her life.

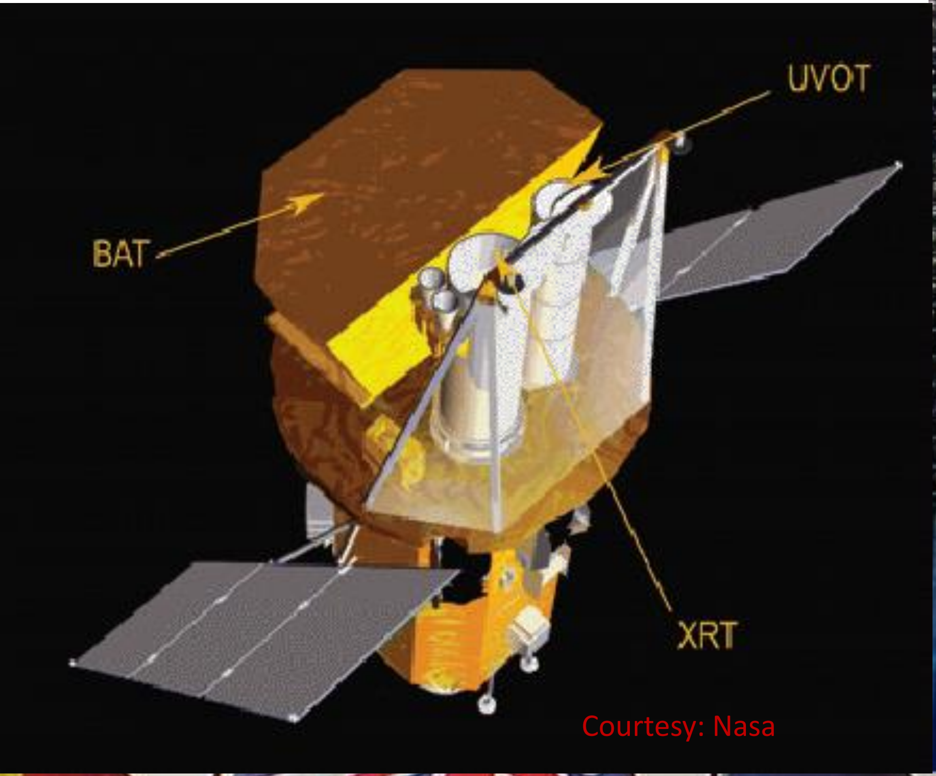
The first multimessenger astronomy discussion I remember took place during a dinner in Louisiana, and the topic was SN1987A. Soon after, Szabi Márka proposed LIGO multimessenger efforts to Barry Barish, who enthusiastically supported them. The LSC joined SNEWS, the SuperNova Early Warning System, and initiated multimessenger search related code development with vigor and enthusiasm.

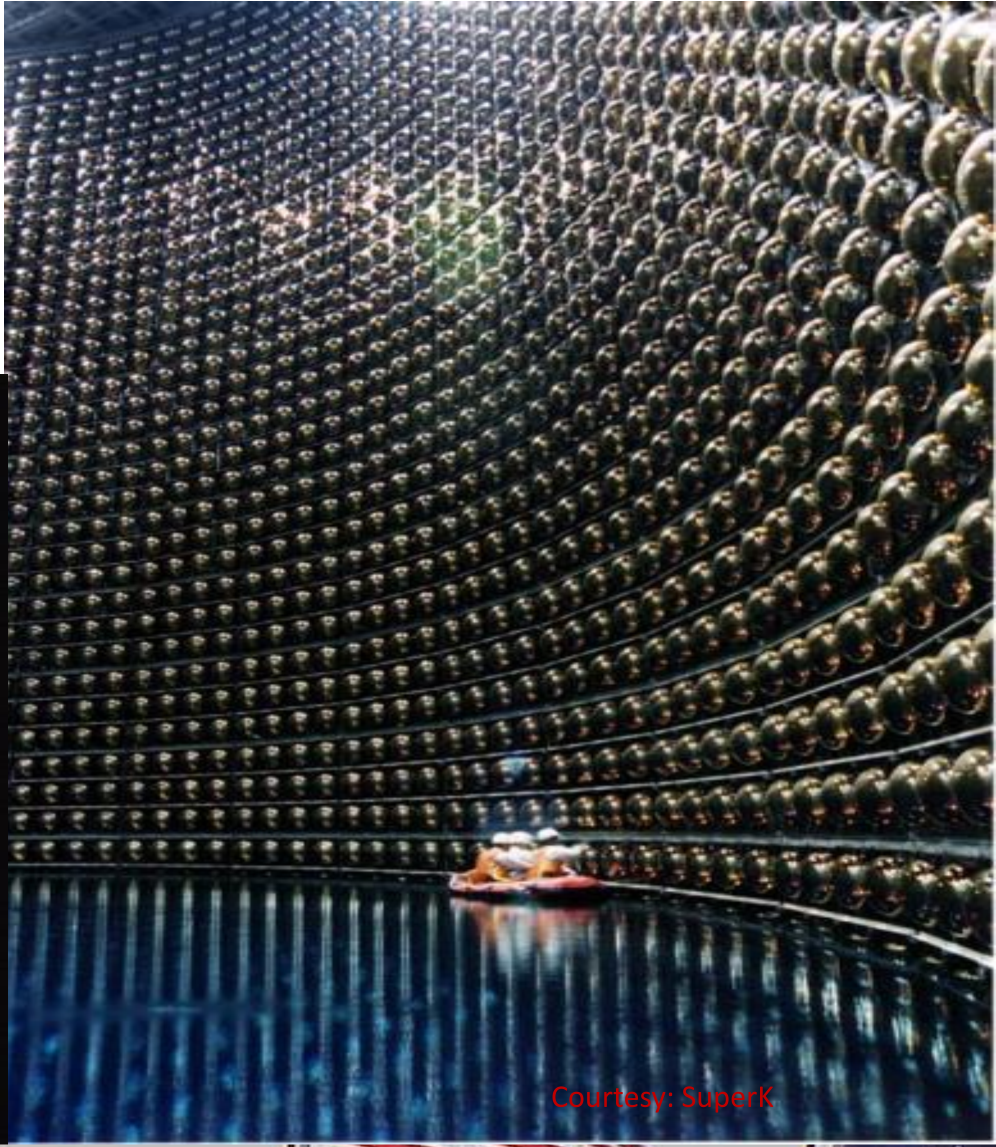
A joint detection from a supernova is still a long shot with current detector sensitivities, but definitely it is worth waiting for. On the other hand, gamma ray bursts (GRBs), especially the short kind, were excellent candidates. LIGO started to receive GCN circulars originally on an old Sun workstation that to be. Except for some innovative faculty, mostly postdocs and graduate students were the driving forces behind the vision. Virgo members also joined the effort. I vividly remember hearing Alessandra Corsi's voice over the phone as she talked about the hallmark Virgo-GRB analysis. Beyond GRB related submitted an abstract, with Yoichi Aso joining the team, for a poster for the upcoming Gravitational Wave Data Analysis Workshop. It was clear that a correlation analysis of gravitational wave data and IceCube events was promising and should be pursued further. As of writing, the latest news from IceCube was just announced: On September 22, 2017 the IceCube Neutrino Observatory detected its first multimessenger event, a high-energy neutrino associated with a flaring blazar. I was especially pleased to see that the so far missing 'holy grail', a GW/high-energy neutrino event (maybe with an electromagnetic counterpart) was highlighted as an ultimate goal at the press conference. Only nature can tell, we must keep searching.

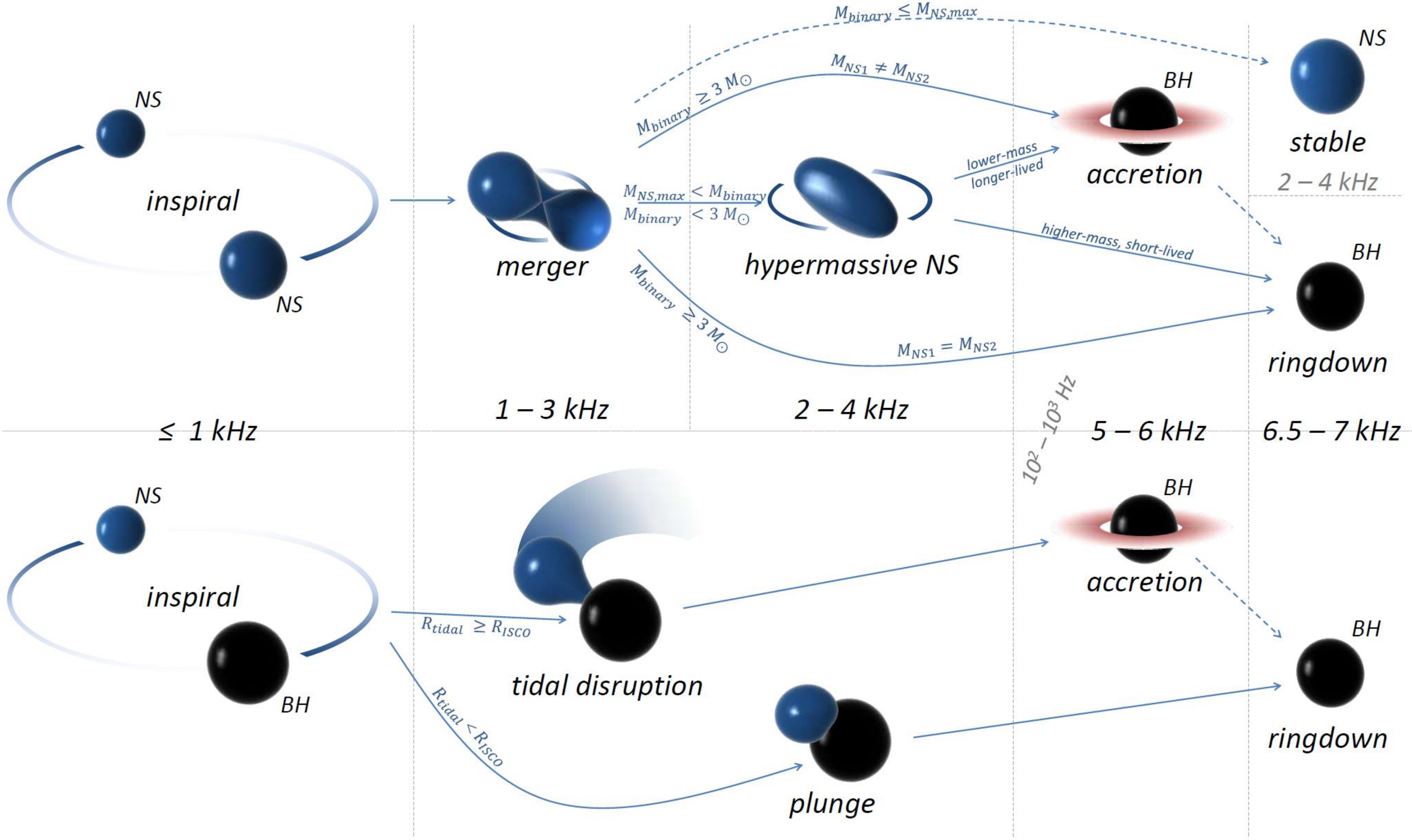
~ Early 2000s

- LIGO joins SNEWS, GCN, and IPN
- NDAS gets data from worldwide network

2001 http://gravity.physics.uwa.edu.au/amaldi/papers/NDAS.pdf







How Gravitational-wave Observations Can Shape the Gamma-ray Burst Paradigm?

Bartos, Brady, Marka – Topical Review – Editor's Highlght – CQG

Multimessenger searches for GWs with LIGO: GRBs

for review of topic see: Bartos I., Brady P., Marka S.; *"How Gravitational-wave Observations Can Shape the Gamma-ray Burst Paradigm"*; Class. Quantum Grav. 30, 123001, 2013 (CQG Highlights)

- GRB triggered searches method development until 2003
- First GRB multimessenger search published: GRB030329

B. Abbott et al. [LIGO Scientific Collaboration], "*A search for gravitational waves associated with the gamma ray burst GRB030329 using the LIGO detectors*", Phys. Rev. D 72, 042002, 2005

- S4, S5, S6 GRB triggered searches upper limits

- First astrophysically significant multimessenger result from LIGO:

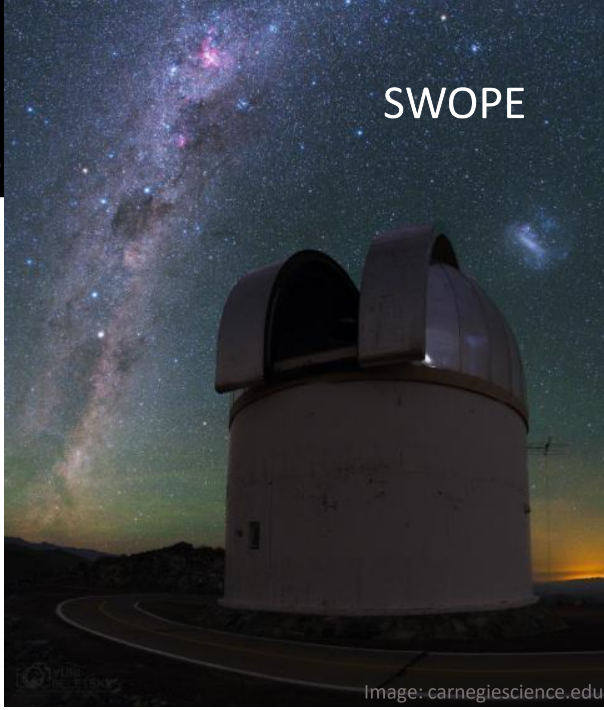
Non detection of GWs from direction of GRB070201 (Andromeda galaxy) contributed to the detection of the first extragalactic SGR hyperflare

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

- First coincident observation!

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A, Abbott et al., The Astrophysical Journal, 848, L13, 2017

Multimessenger searches for GWs with LIGO: EM follow-up program



- Since 2007 - pioneering study used SWOPE(!) and MDM telescope, real-time pipeline topology, and galaxy targeting

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

- Near-real time searches development, search program with ~10 MOU during the last weeks of initial LIGO era
- Large scale program with >70 partners by start of advanced LIGO, facilitated by preparations during and since initial LIGO as well as advancement in theory (Metzger)
- Result from O1
- NGC4993 –

GW170817 – GRB170817A

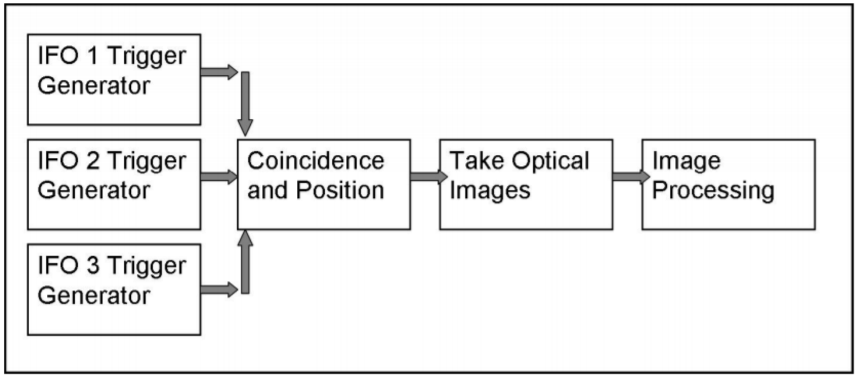
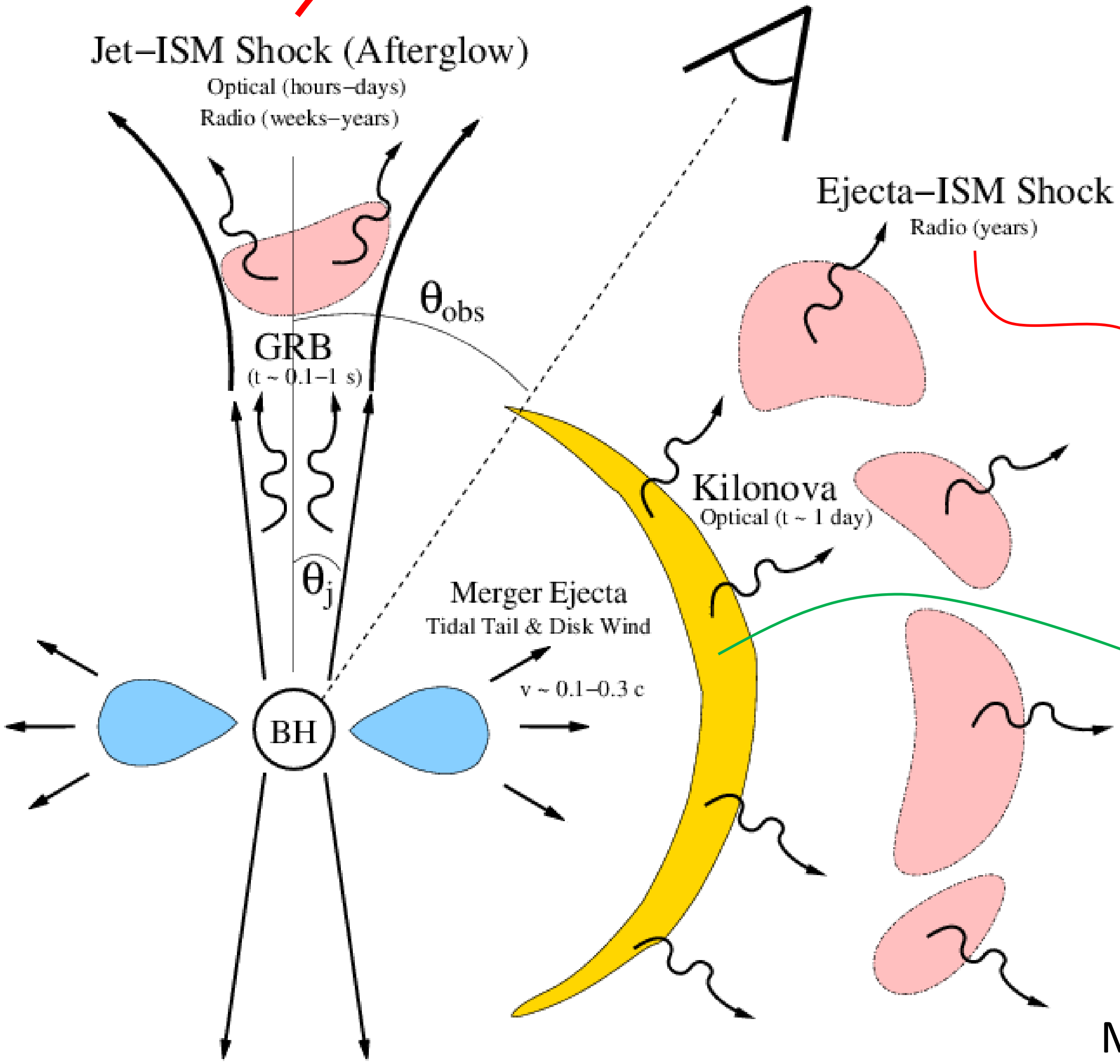


Figure 1. A schematic of the analysis. Triggers are identified in data from the three sites of the LIGO-Virgo network. The three trigger lists are then compared to find coincident events, labeled "candidate events." A sky region is assigned to each event candidate. The sky region is then imaged with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

Input from theory can guide observations



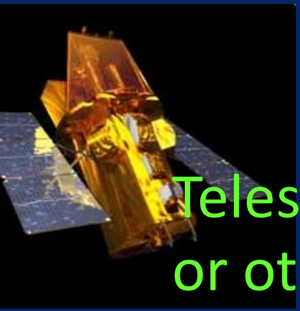
- Beamed
- Good gamma-ray FoV
- Gamma-ray long term?
- Follow-up difficult
- Off-axis light curves

- Isotropic
- Long-term -- easy follow-up
- Flux too small?

- Good time frame (~week)
- Isotropic
- Limited IR FoV / sensitivity

Metzger & Berger 2012

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

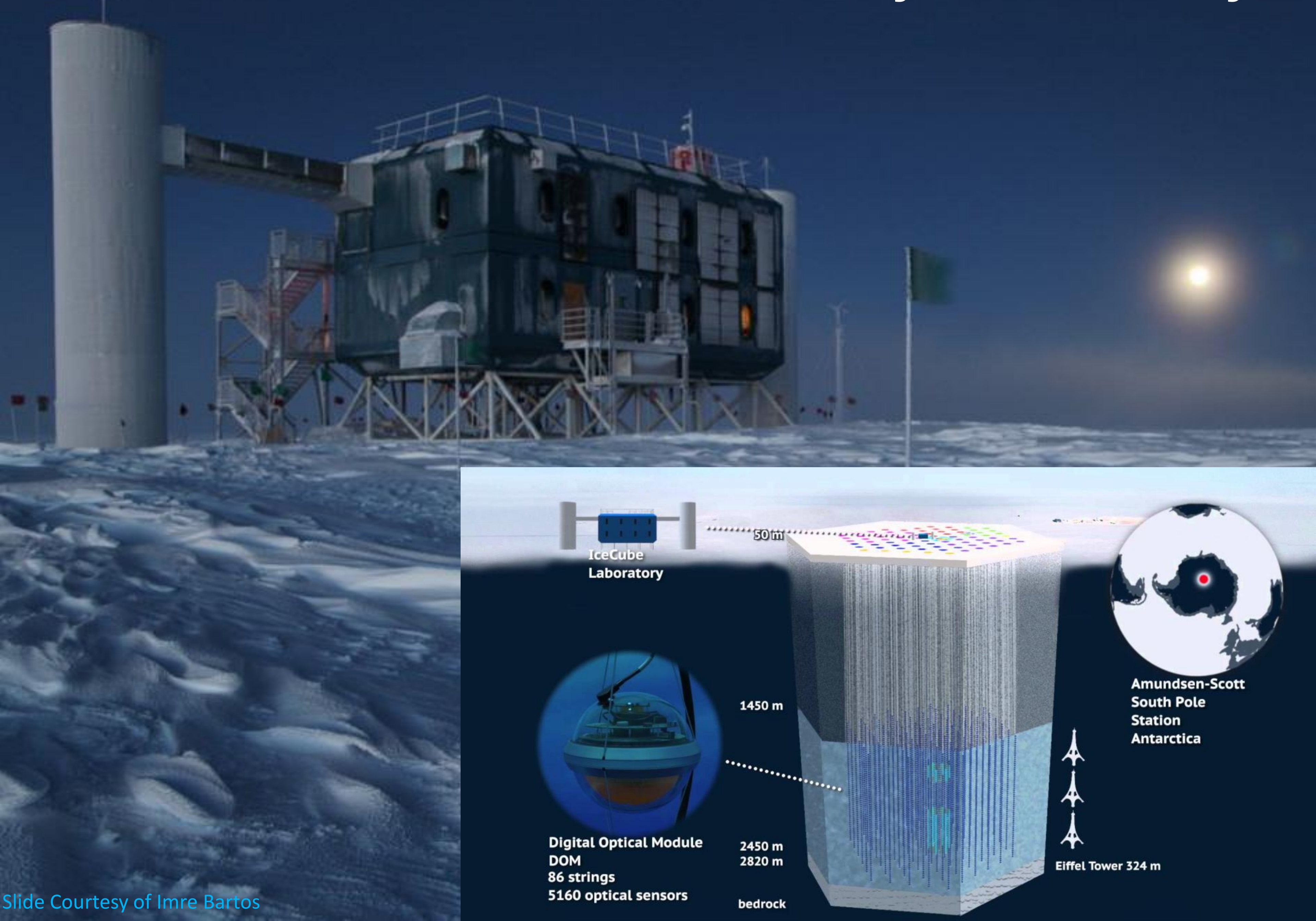
Low-latency pipeline development is essential

quick localization

subthreshold triggers?

large field of view is useful

Some detectors see the whole sky continuously

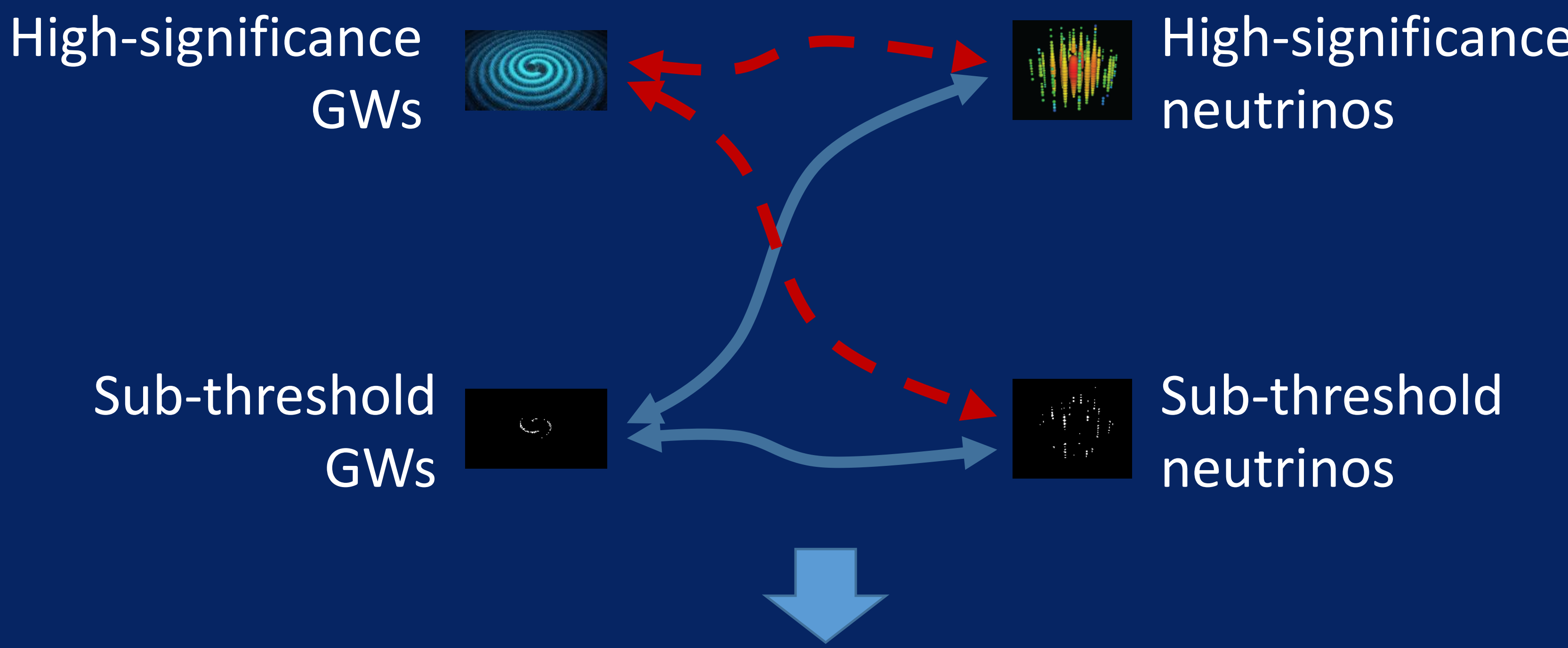


Slide Courtesy of Imre Bartos

Multimessenger Approaches

“Joint search” strategy:

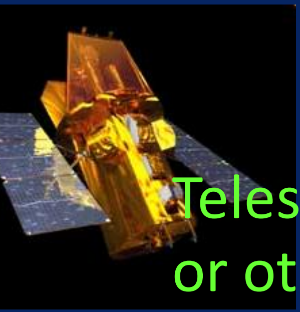
Multimessenger Search for GW+neutrino sources with complete neutrino and GW datastreams



Alert EM community of significant temporal+spatial overlaps

Basic Glossary: Multimessenger Approaches

"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:

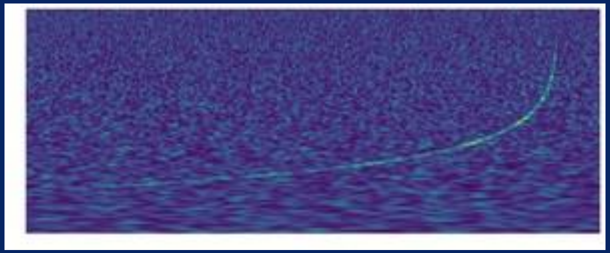
GW detector →
GRB detector →
HEN detector →
++ →

Low
Latency
Algorithm for
Multimessenger
Astrophysics

→

Two famous MMA events with new messengers:
GW170817 & IceCube-170922A

Similarities:

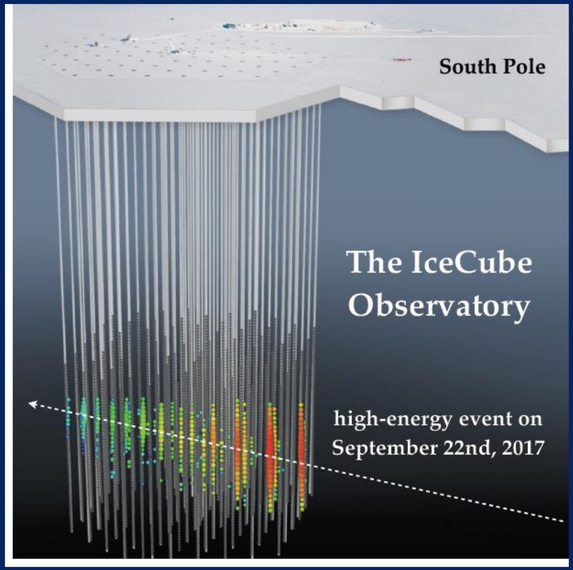


Significant events (high SNR / high–energy)

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:

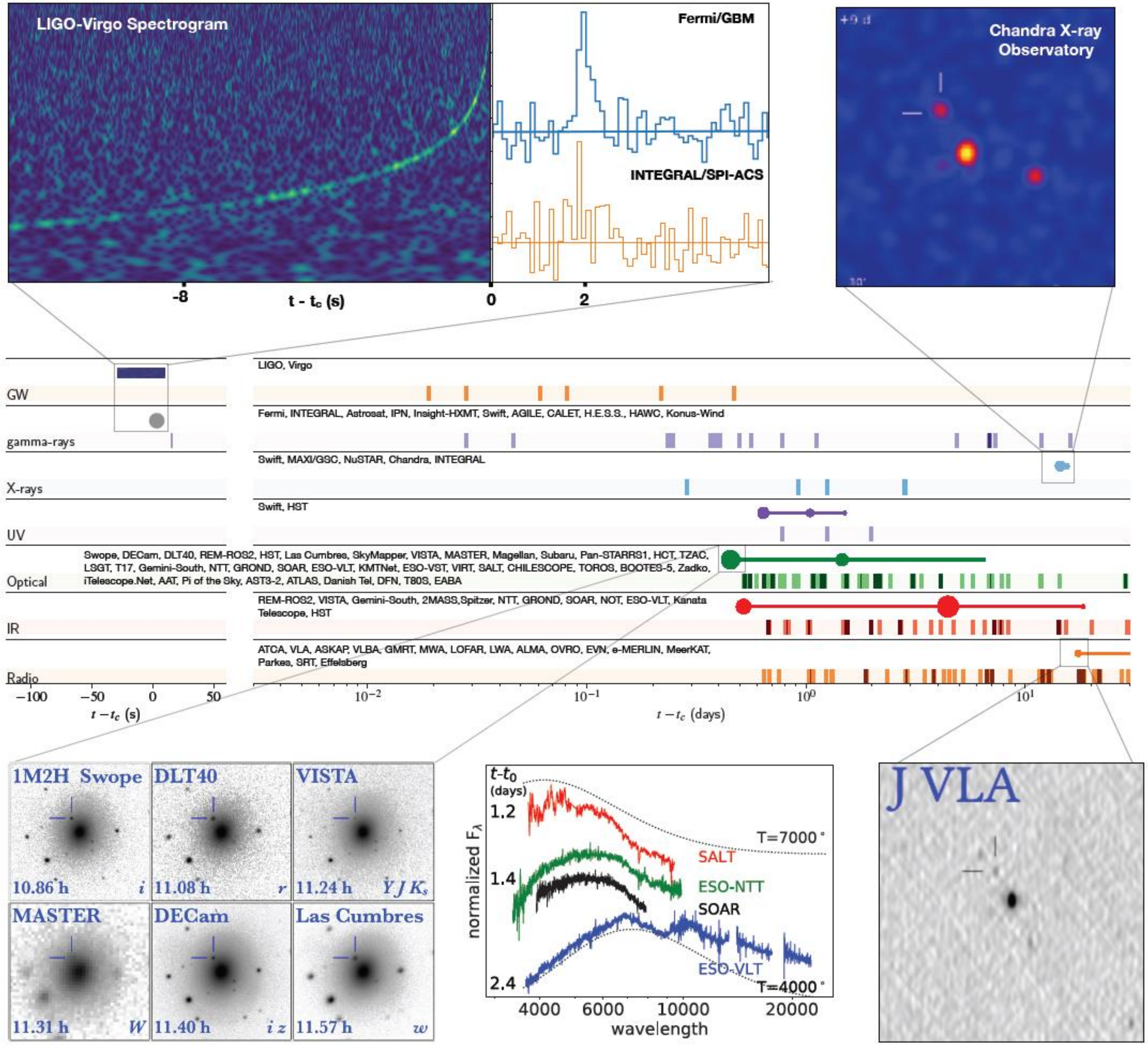
GW messenger has *extra attributes*:
inference on source type (BNS merger)
distance

Neutrinos provide more confined localization

=>Inference on MMA association

Images: ligo.org and Astro2020 IceCube paper

GW170817 - an MMA event



LIGO/Virgo and the EM-Follow-up partners, ApJL Oct 16, 2017

MMA event with neutrinos: IceCube-170922A

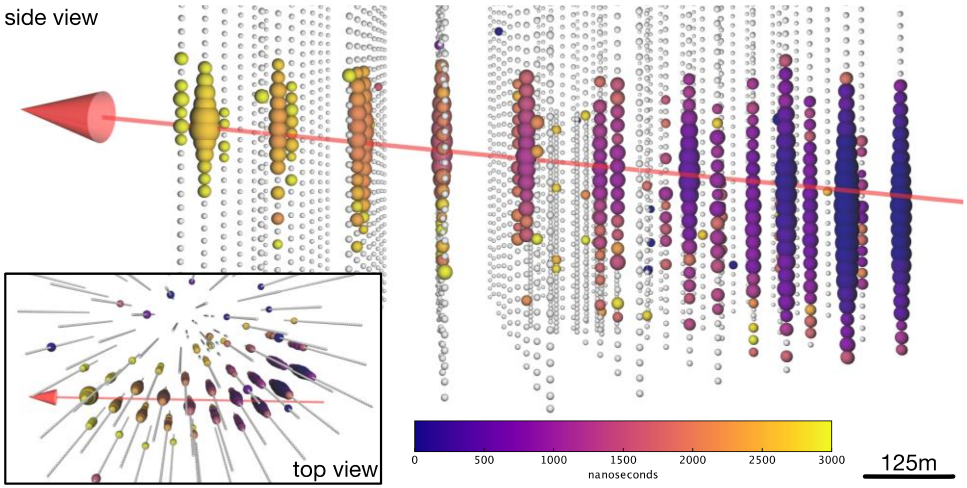
On Sept 22, 2017, IceCube detected a high-energy ν ≅ 290 TeV energy

Telescopes across the globe started observing its location asap

Swift observed 9 X-ray sources in its FoV with one source only 0.08° away

Fermi finds the source to be a flaring blazar: TXS 0506+056

An extensive multi-wavelength campaign started
MAGIC detected high-energy γ-rays > 100GeV from the blazar



Courtesy: IceCube

Courtesy: IceCube

IceCube-led papers:

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A
http://science.sciencemag.org/cgi/doi/10.1126/science.aat1378

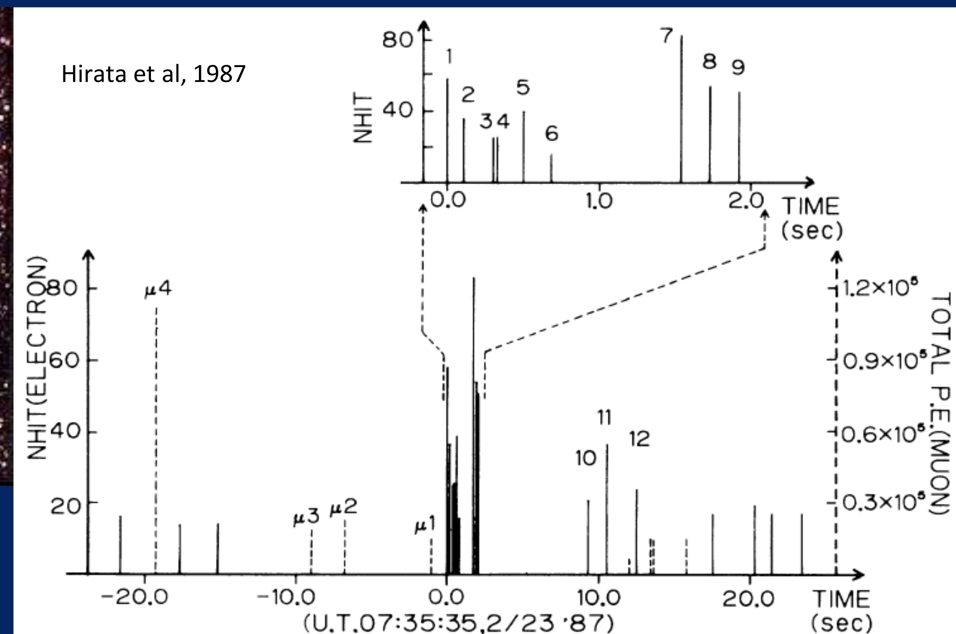
Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert
http://science.sciencemag.org/cgi/doi/10.1126/science.aat2890

3σ high-energy neutrino source association

Blazars maybe a source of high-energy neutrinos

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 ‘poissonianly’ rare source to be seen (with current sensitivities)

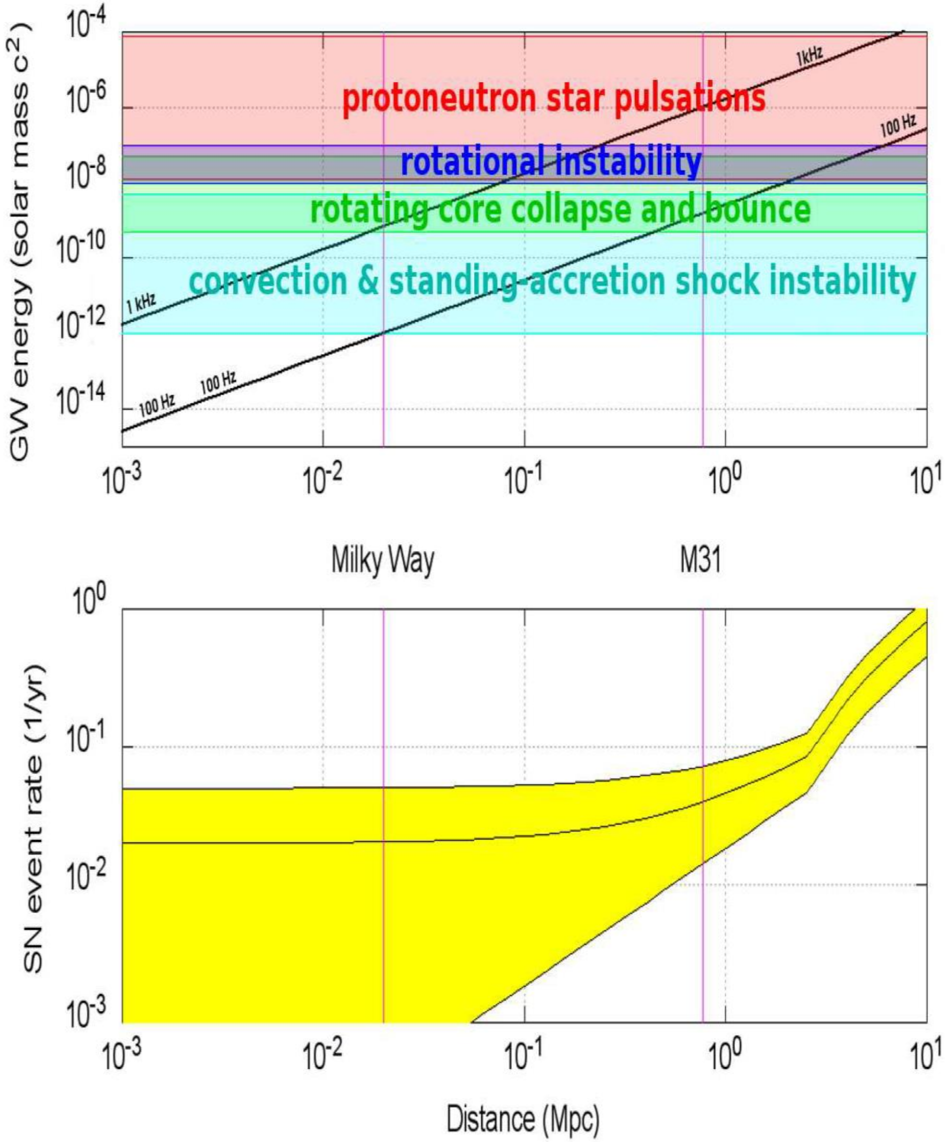
This will likely be a typical *exttrig type of search* from the both the EM and the GW point of view

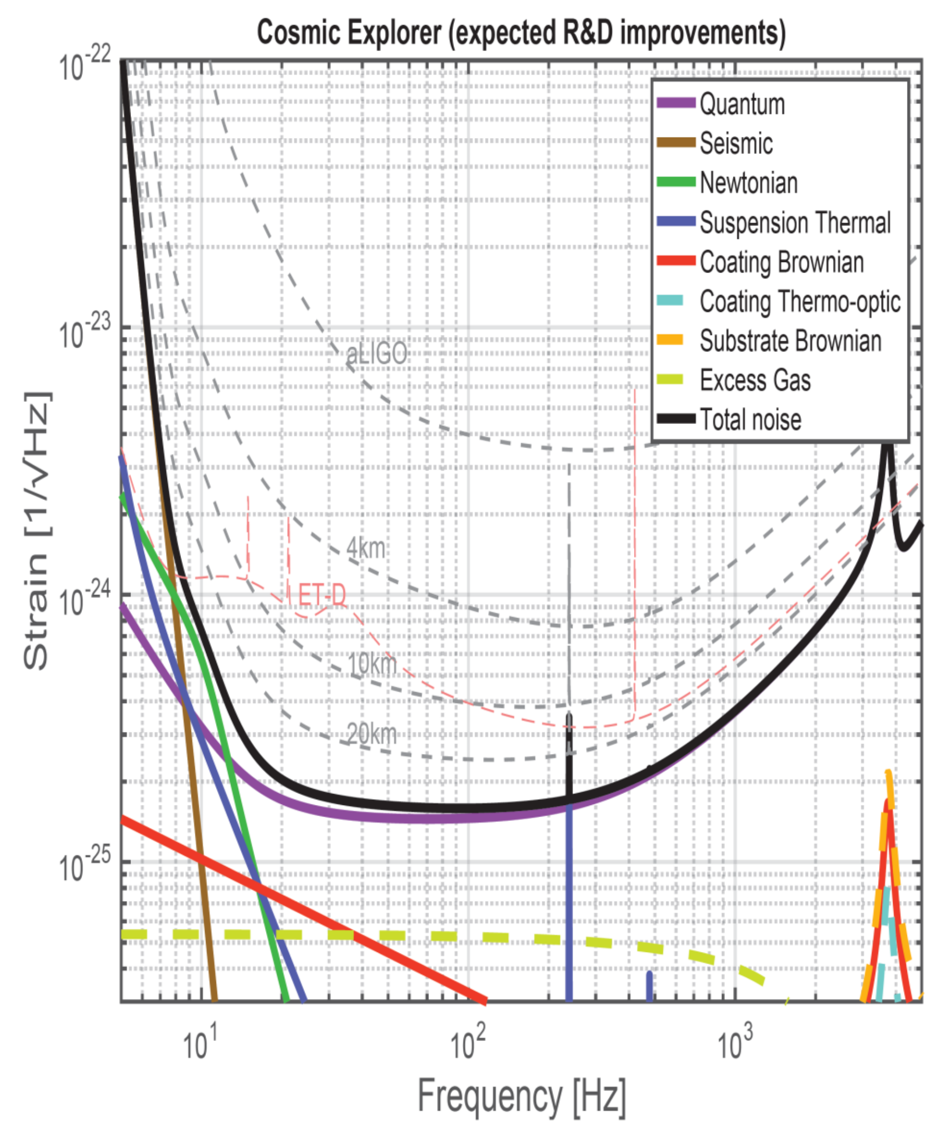
To ensure detection of GWs from core collapse: build 3G detector

https://dcc.ligo.org/LIGO-T1600119/public

Chasee-Motin, Hendry, Marka, Sutton GRG, 2010

Instrument Science White Paper





The missing combination

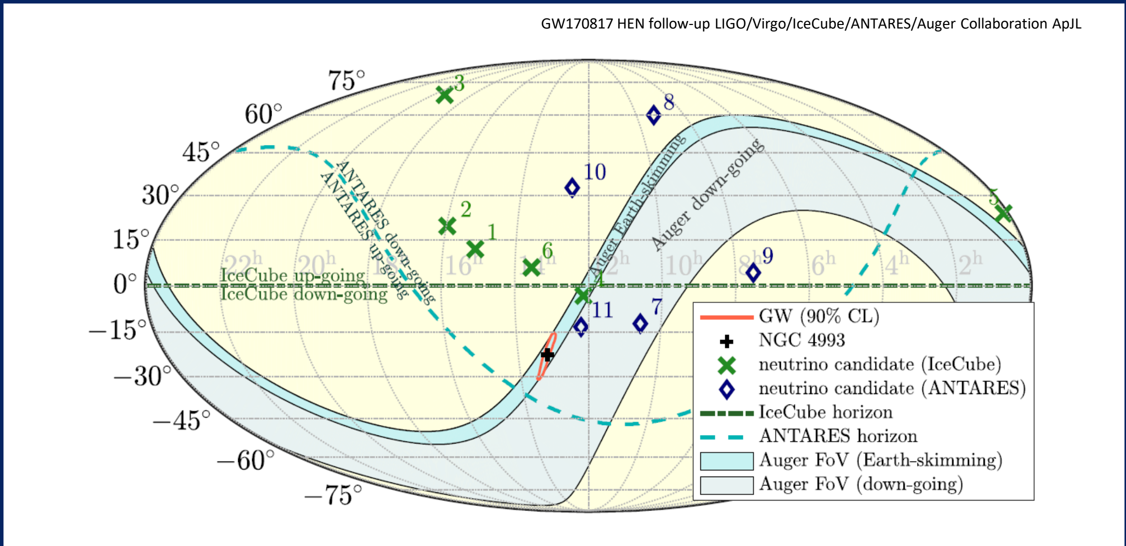
Gravitational waves and particle messenger
GW+HEN search example

Whole sky observation with localization information

Significant up-time

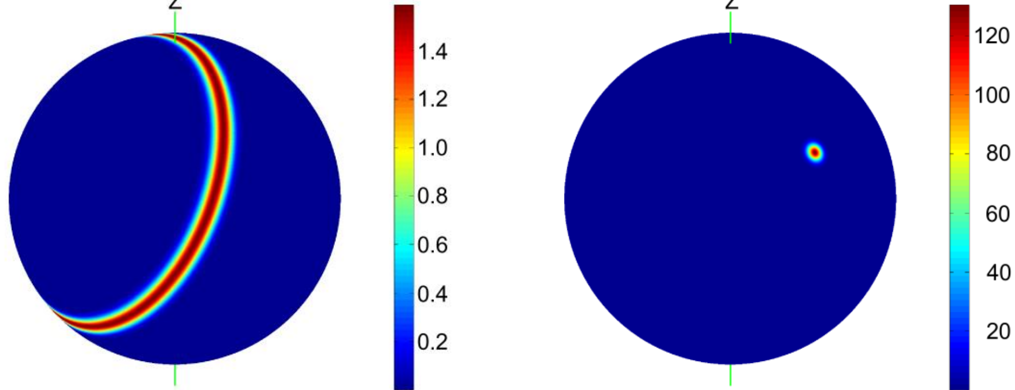
Are there joint sources?

Detect then alert the EM community of joint candidates or set limit on population of joint emitters



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

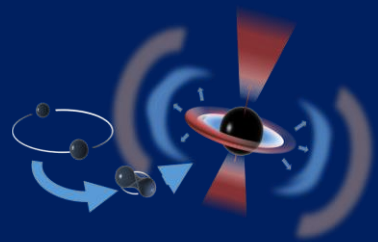
IceCube Search for Neutrinos Coincident with Compact Binary Mergers from LIGO-Virgo's First Gravitational-Wave Transient Catalog; The Astrophysical Journal Letters, 898, L10, 2020

IceCube search for neutrinos coincident with gravitational wave events from LIGO/Virgo run O3 https://arxiv.org/abs/2208.09532

Several dozens of GCNs during O2 and O3

GECo

Ingredients of an MMA search



Detector data for each messenger

Time of the transient

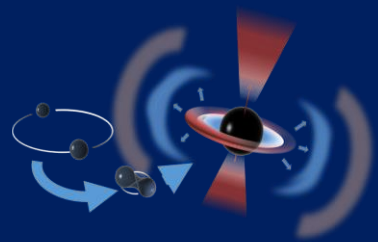
Localization of the transient

Find **spatial** and *temporal* overlap

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

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

Ingredients of an MMA search

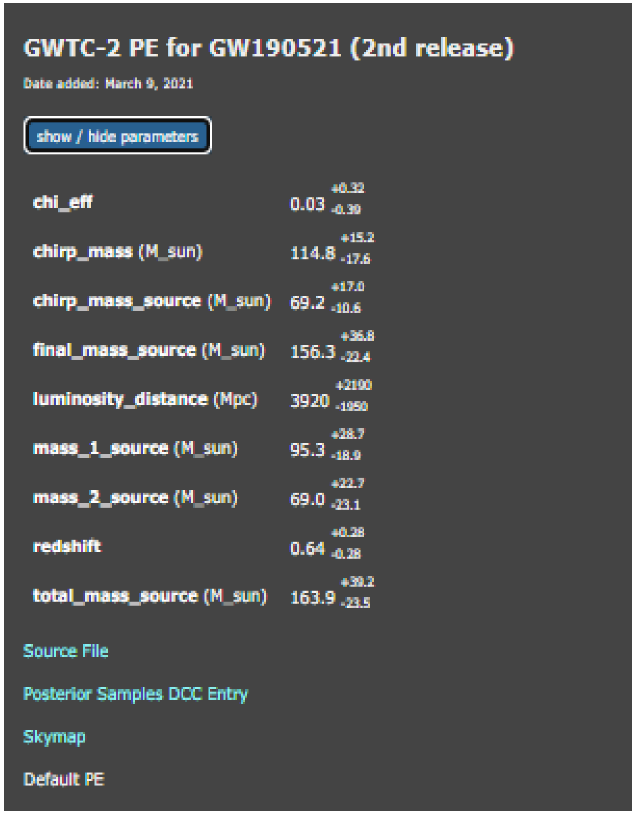


Source model

Search time window assumes a source model

Gravitational Wave Open Science Center

GW data - CBC interpretation provides rich information about the source



GWTC-2 PE for GW190521 (2nd release)

Date added: March 9, 2021

show / hide parameters

chi_eff	$0.03^{+0.32}_{-0.39}$
chirp_mass (M_sun)	$114.8^{+15.2}_{-17.6}$
chirp_mass_source (M_sun)	$69.2^{+17.0}_{-10.6}$
final_mass_source (M_sun)	$156.3^{+36.8}_{-22.4}$
luminosity_distance (Mpc)	3920^{+2190}_{-1950}
mass_1_source (M_sun)	$95.3^{+28.7}_{-18.9}$
mass_2_source (M_sun)	$69.0^{+22.7}_{-23.1}$
redshift	$0.64^{+0.28}_{-0.28}$
total_mass_source (M_sun)	$163.9^{+39.2}_{-23.5}$

Source File

Posterior Samples DCC Entry

Skymap

Default PE

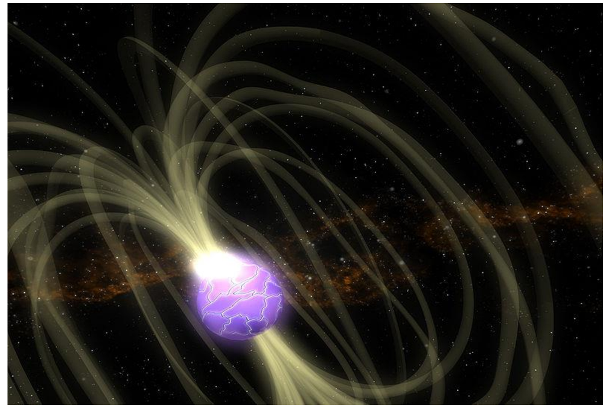
No model

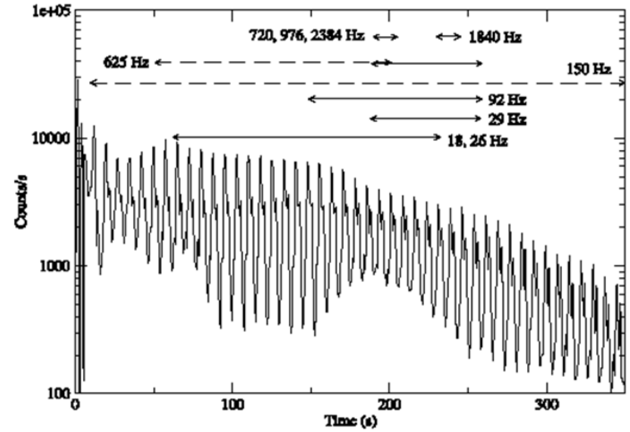
How background-like each trigger event is?

Observations guide source model for search or
source model enables interpretation of data from other messenger?

EM observations guide GW search

Multimessenger searches for GWs with LIGO: SGRs





- SGR related searches since 2004 (hyperflares, stacked searches)

  Targeting both initial transient and quasiperiodic oscillations in pulsating tail

Abbott B. et al., [LIGO Collaboration], "***Search for gravitational wave radiation associated with the pulsating tail of the SGR 1806 - 20 hyperflare of 27 December 2004 using LIGO***", Phys. Rev. D. 76:062003, 2007

P. Kalmus, R. Khan, L. Matone, S. Marka, *"Search method for unmodeled transient gravitational waves associated with SGR flares"*, Class. Quantum Grav. 24, 659, 2007

B. Abbott et al. [LIGO Collaboration], *"Search for Gravitational Wave Bursts from Soft Gamma Repeaters"*, Physical Review Letters 101, 211102, 2008

P. Kalmus, K.C. Cannon, S. Marka, B. Owen, "***Stacking Gravitational Wave Signals from Soft Gamma Repeater Bursts***", Physical Review D, 80, 042001, ArXiv e-prints, 0904.4906, 2009

Abbott et al., *"Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm"*, Astrophysical Journal, 701, L68, arXiv:0905.0005, 2009

Abadie et al., *"Search for Gravitational Wave Bursts from Six Magnetars"*, The Astrophysical Journal, 734, L35, 2011

Murphy D., Tse M., Raffai P., Bartos I., Khan R., Marka Z., Matone L., Redwine K., Marka S.; *"Detecting Long-Duration Narrow-Band Gravitational Wave Transients Associated with Soft Gamma Repeater Quasi-Periodic Oscillations"*; Phys. Rev. D 87, 103008, 2013

Searches for GWs from magnetars is on ongoing effort in LVK during the advanced detectors era.

Ingredients of an MMA search
GW+HEN example

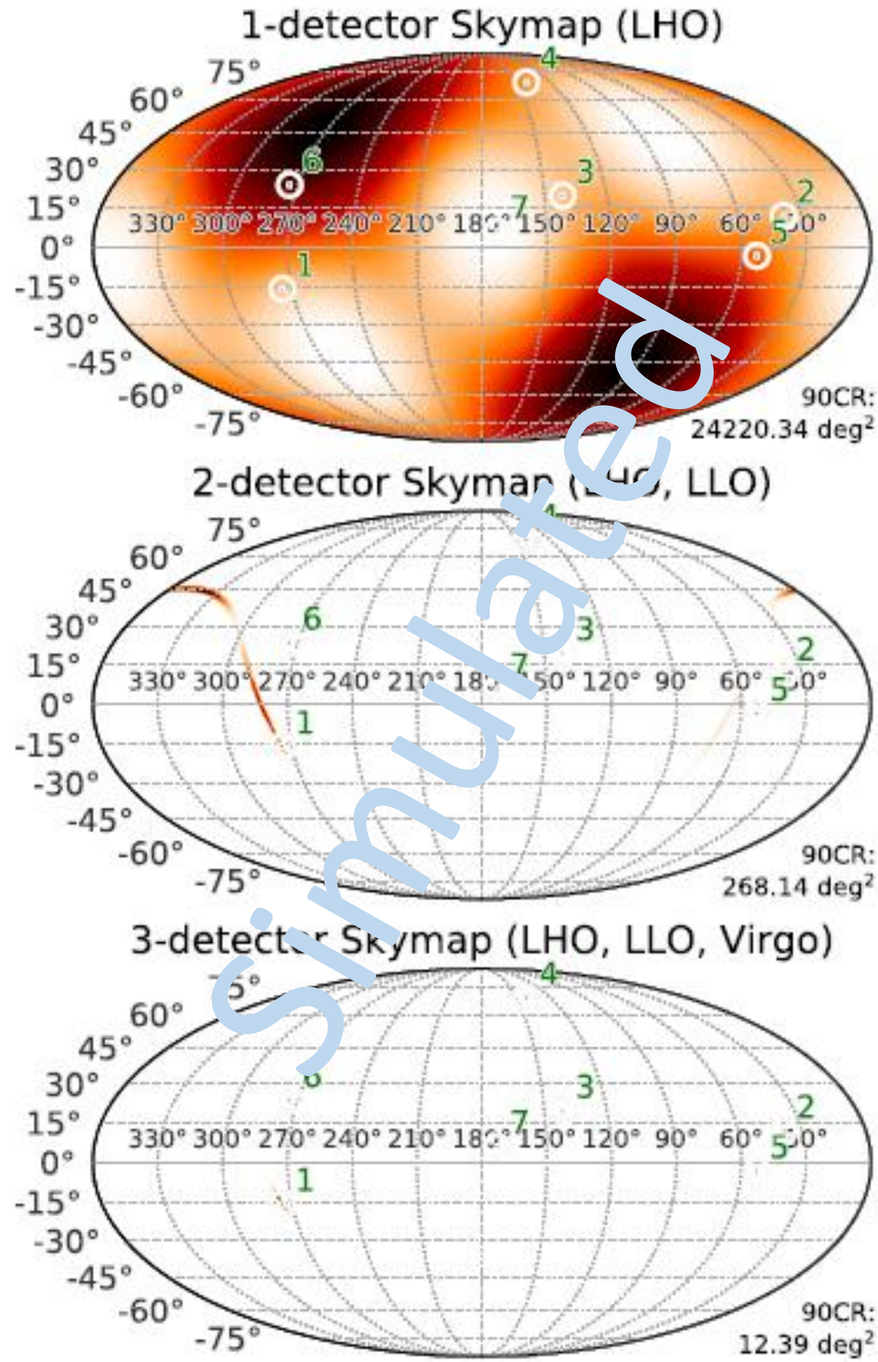
SEARCH INPUTS
(different for each multi-messenger trigger)

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

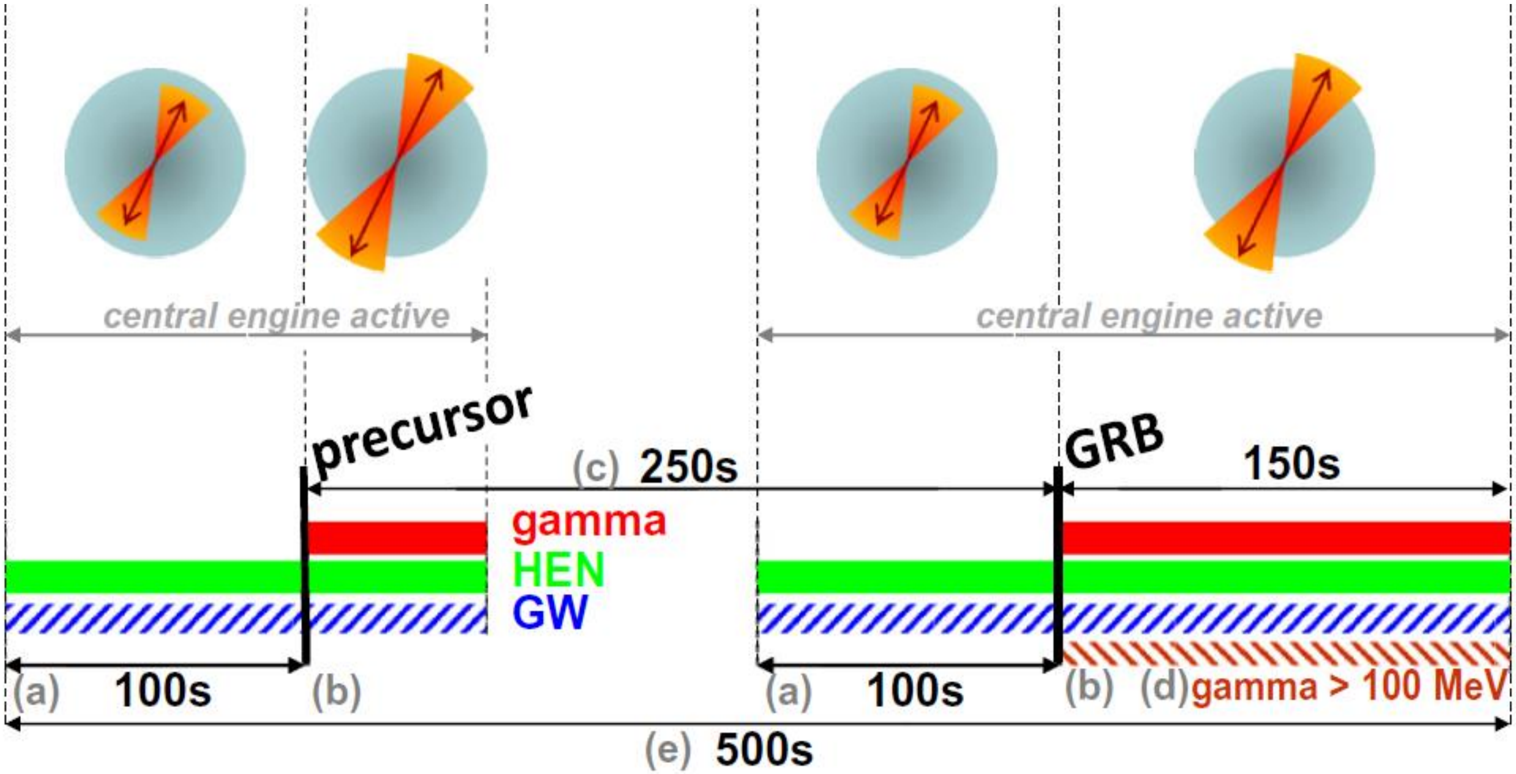
$$\theta = \{t_{\mathrm{s}}, r, \mathbf{\Omega}, E_{\mathrm{gw}}, E_\nu\}$$

e.g. log uniform source engines:

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

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

Search time window

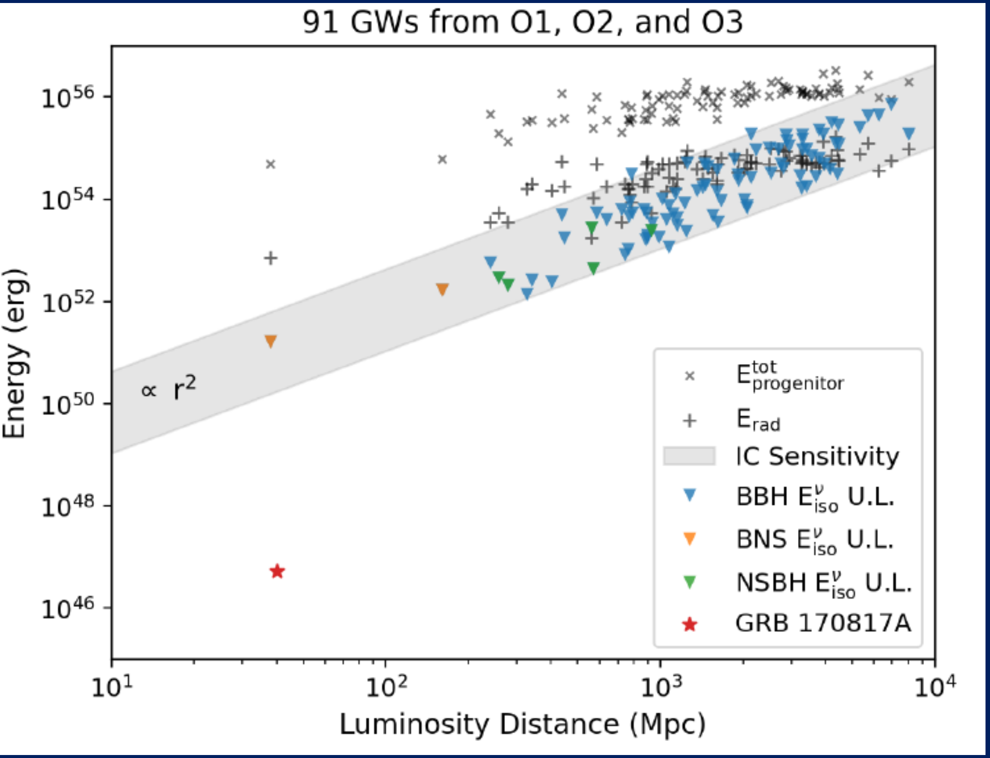


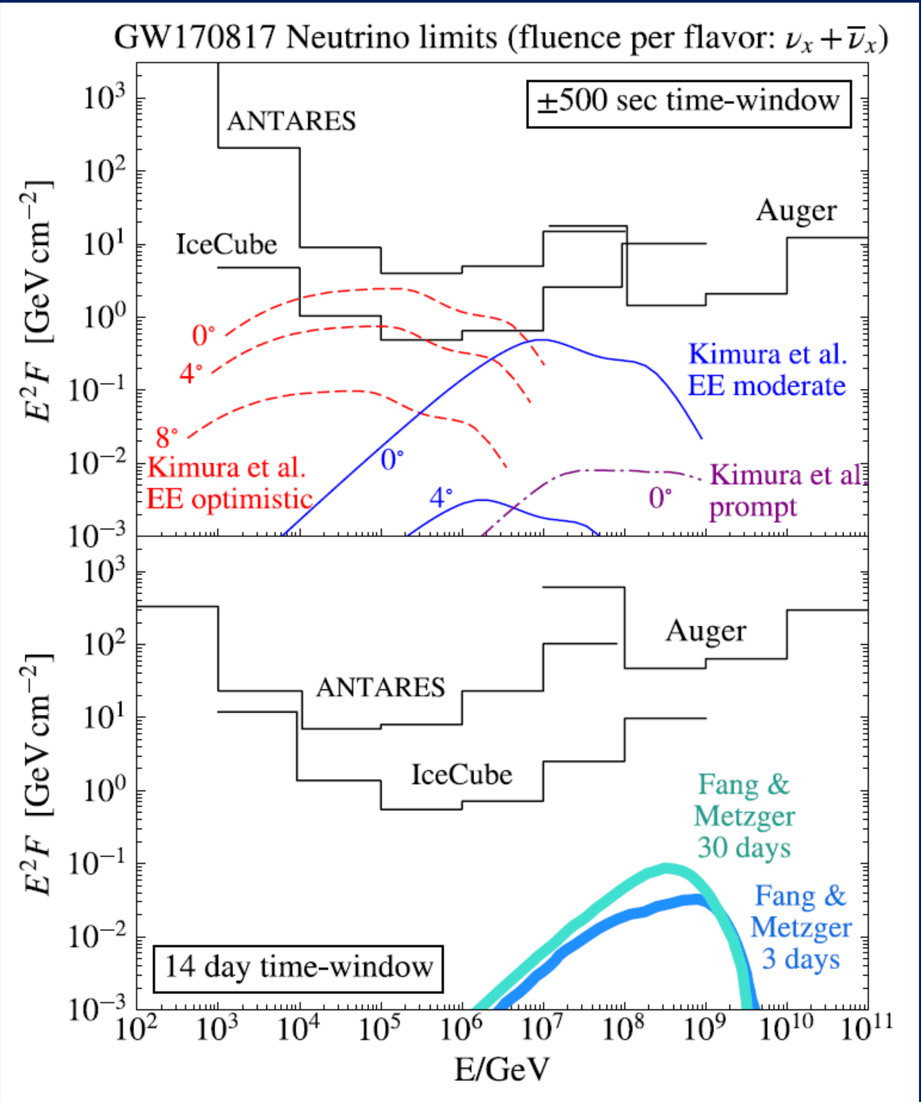
Overall, the considered processes allow for a maximum of 500 s between the observation of a HEN and a GW transient.

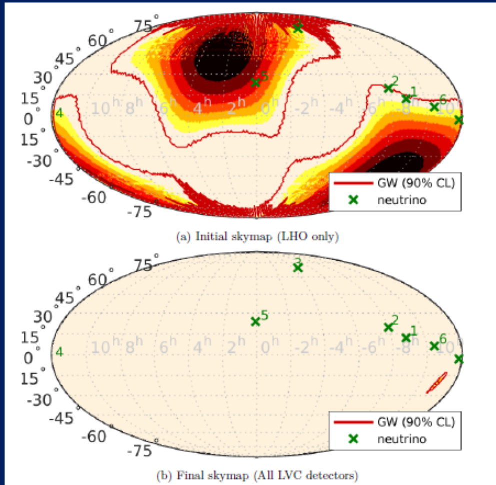
Search window: [-500 s, 500 s]

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

Offline Search example: GW+HEN







Online -> offline

Online Search example: Low-latency GW+HEN search aids EM follow-up

Rapid identification of candidate events is needed for timely EM follow-up observations

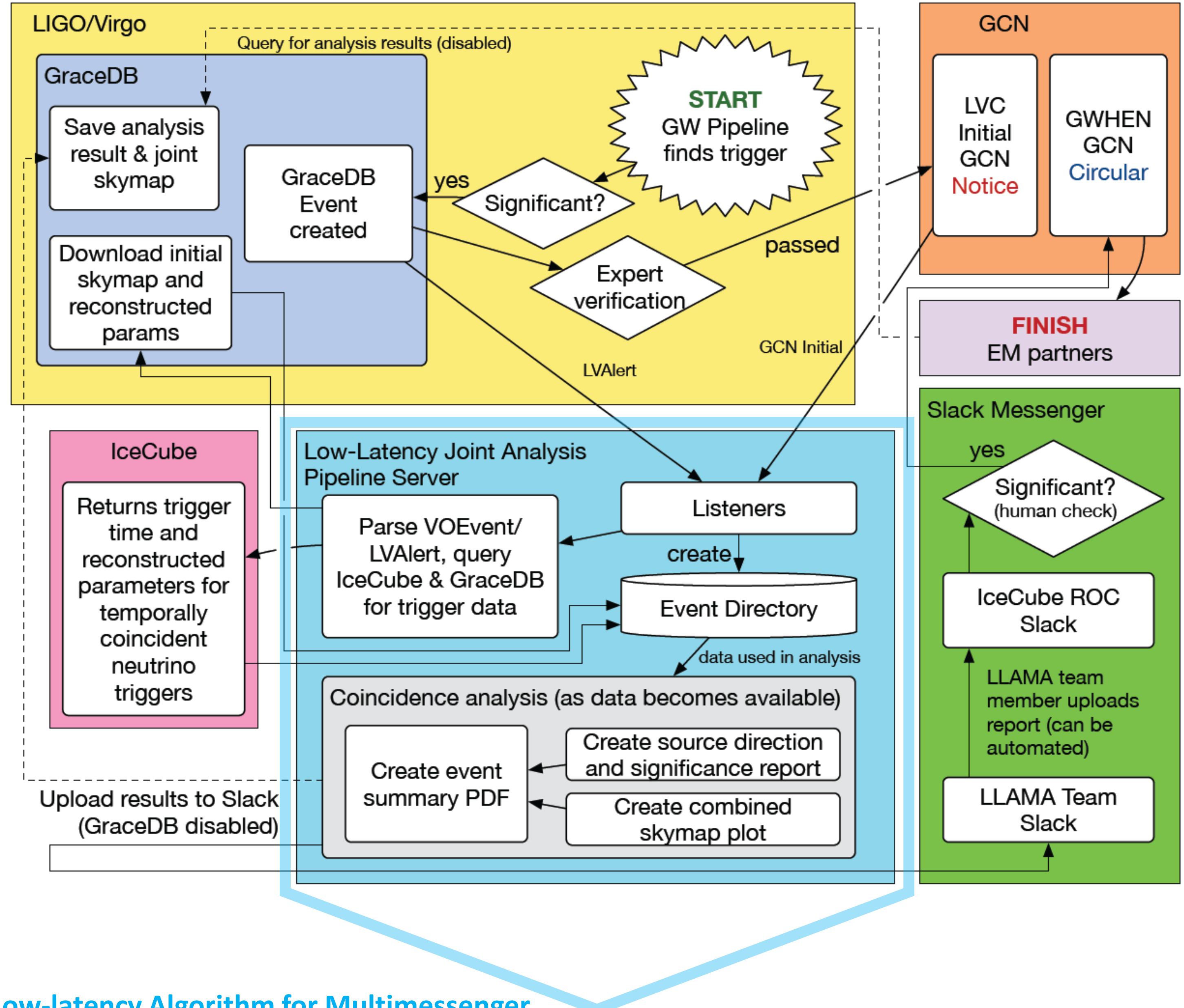
- Both GWs and HENs are typically emitted over a short time frame of seconds to minutes during the formation or evolution of compact objects
- Detectors searching for both messengers observe the whole sky continuously
- Joint skymap can be made rapidly available to guide follow-up electromagnetic surveys

Low-latency searches based on signals that could not individually be established as discoveries are promising => joint significance of an MMA candidate can rise above threshold

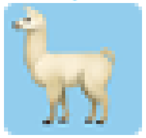
GW+HEN search is a prime motivation ***for joint subthreshold search*** strategy

Proper treatment of joint event significance is essential

O3 era pipeline partner flowchart

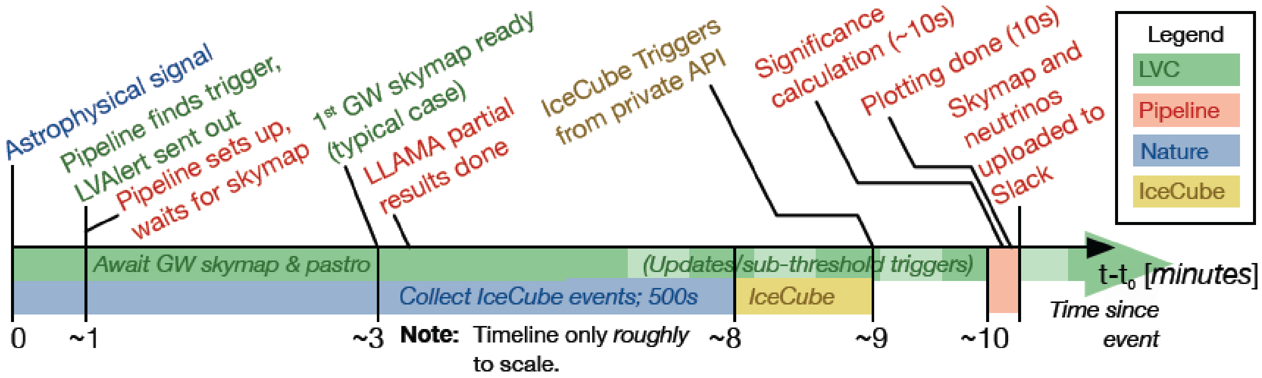


Low-latency Algorithm for Multimessenger Astrophysics (LLAMA) pipeline
multimessenger.science
Countryman et al.



Already operated and sent triggers in O2

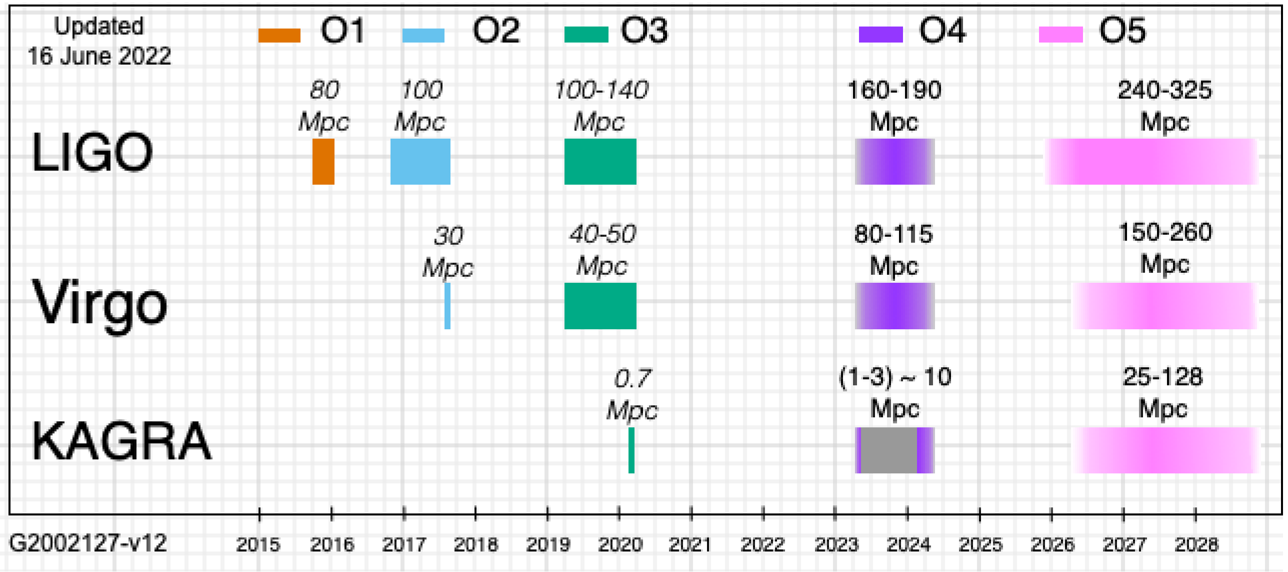
Low-latency Algorithm for Multimessenger Astrophysics (LLAMA) pipeline analysis timeline



O3 era example

Countryman et al.

O4 run



Minor changes to alert content (EM-bright, p-astro, multiorder skymaps)
NO masses, spins, eccentricities will be given, just basic classification (BBH, BNS, ..)

Multiple distribution channels for alerts
- GCN (legacy)-notices and circulars (as in O3)
- Kafka-based alerts with embedded skymap via SCiMMA and GCN network

visit scimma.org and hop.scimma.org

(1st, 2nd, …) EarlyWarning (fully automatic) alert as better/new localization is available NEW

(1st) Preliminary (fully automatic) alert (targeting < 30s)
(2nd) Preliminary alert (fully automatic) after search is completed by all the pipelines with updated localization (targeting < 3 minutes)

Data quality checks, RRT meeting and a human/rapid-PE evaluation typically within 4 hours for BNS or 1 day for vanilla BBH
An Initial/Update or Retraction alert will be sent.

An Initial/Update alert can contain improved localization and source classification.
Update alerts will be sent when improved PE results are available.

Statistical Framework in LLAMA
Our hypotheses

- 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

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

Bayes' rule

$$P(A \mid B) = \frac{P(B \mid A)\,P(A)}{P(B)}$$

- We want to find

P(This is a signal| parameters) or P(This is noise | parameters)

- $$\frac{\text{P(This is a signal| parameters)}}{\text{P(This is noise | parameters)}}$$ = Bayes' factor ,

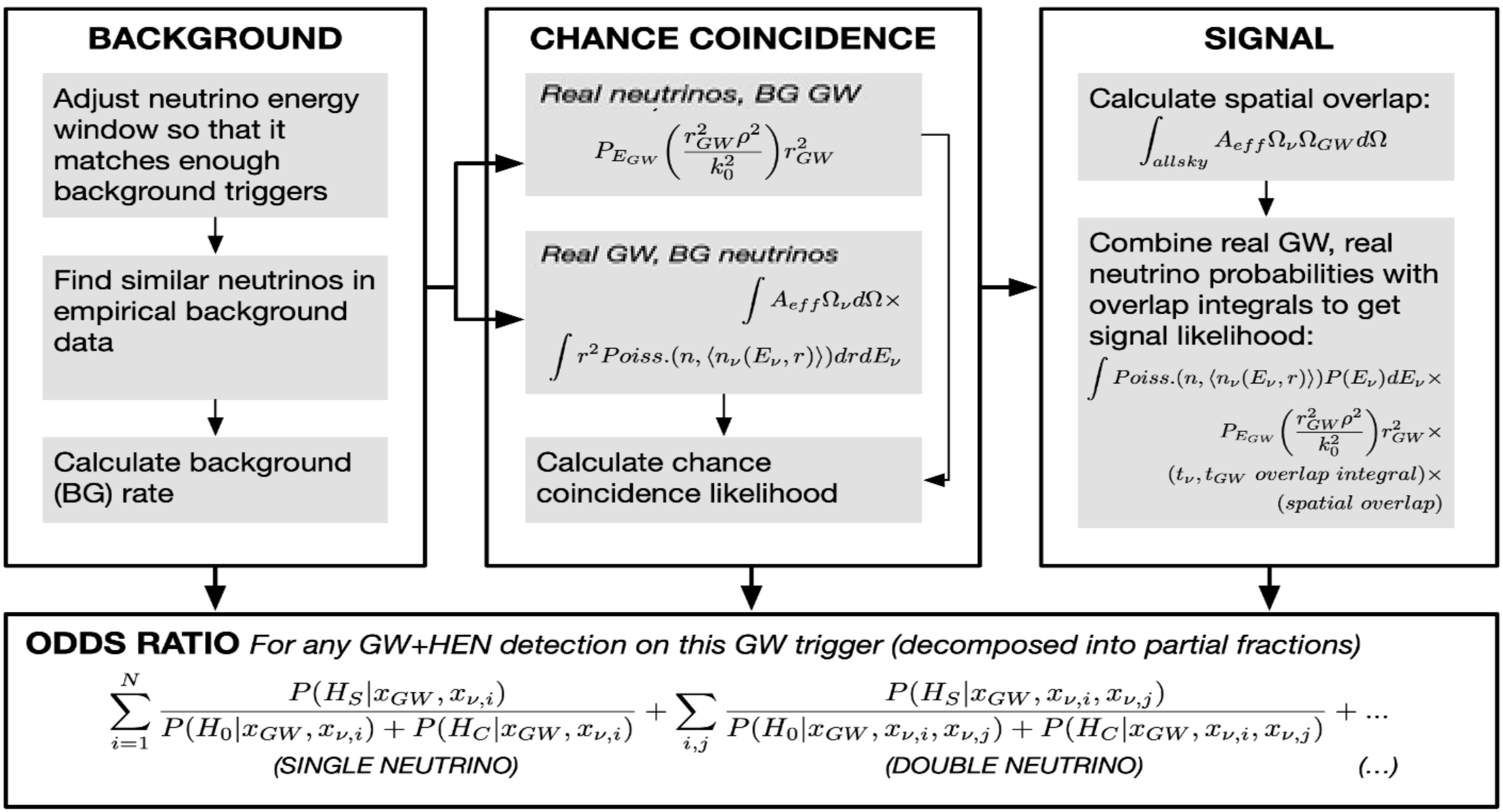
(we call it Odds ratio or TS)

- Odds ratio > signal threshold means we have a signal.

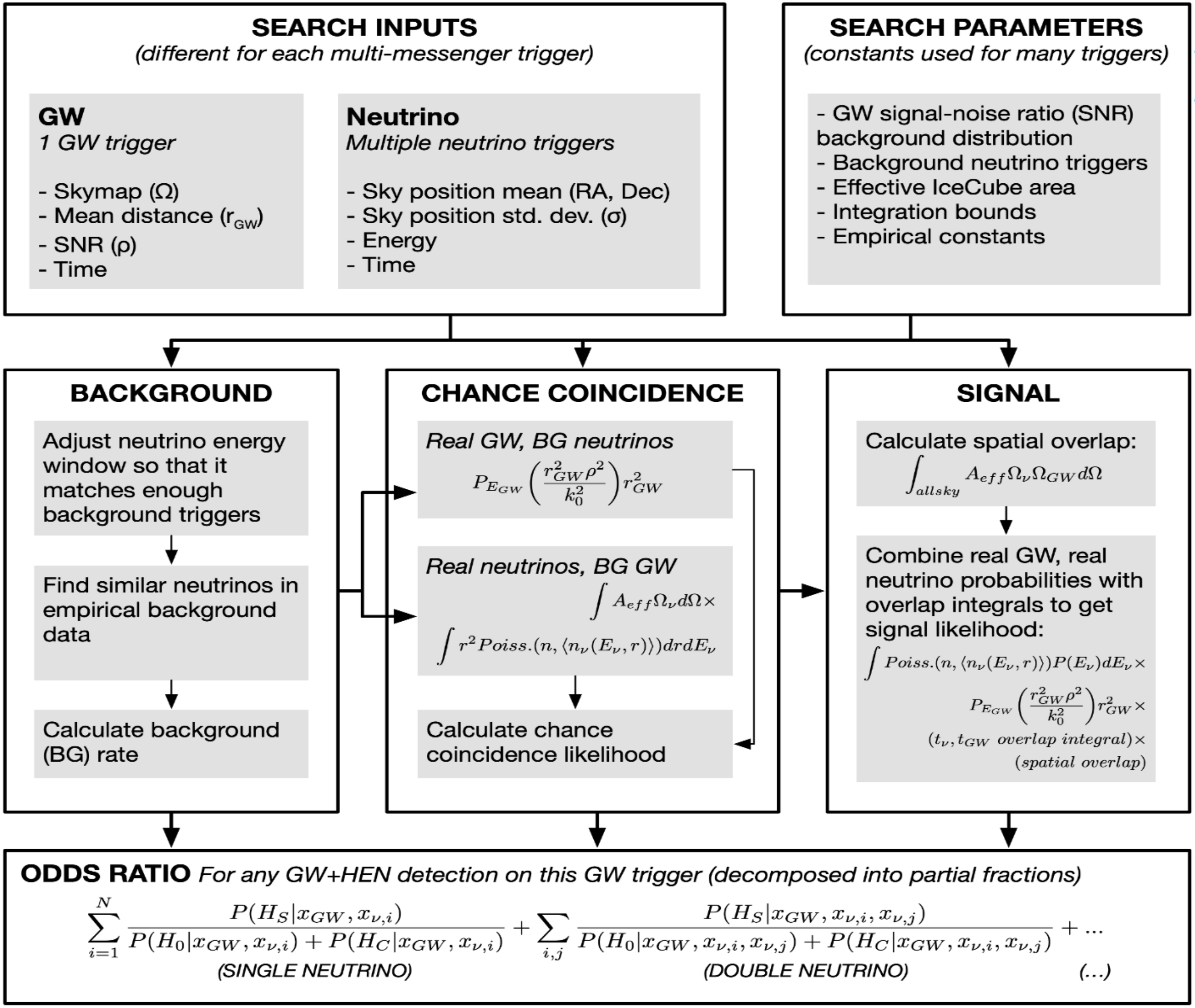
The signal threshold is determined in a frequentist manner from a background distribution.

Putting it all together
GW+HEN MMA search example

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



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

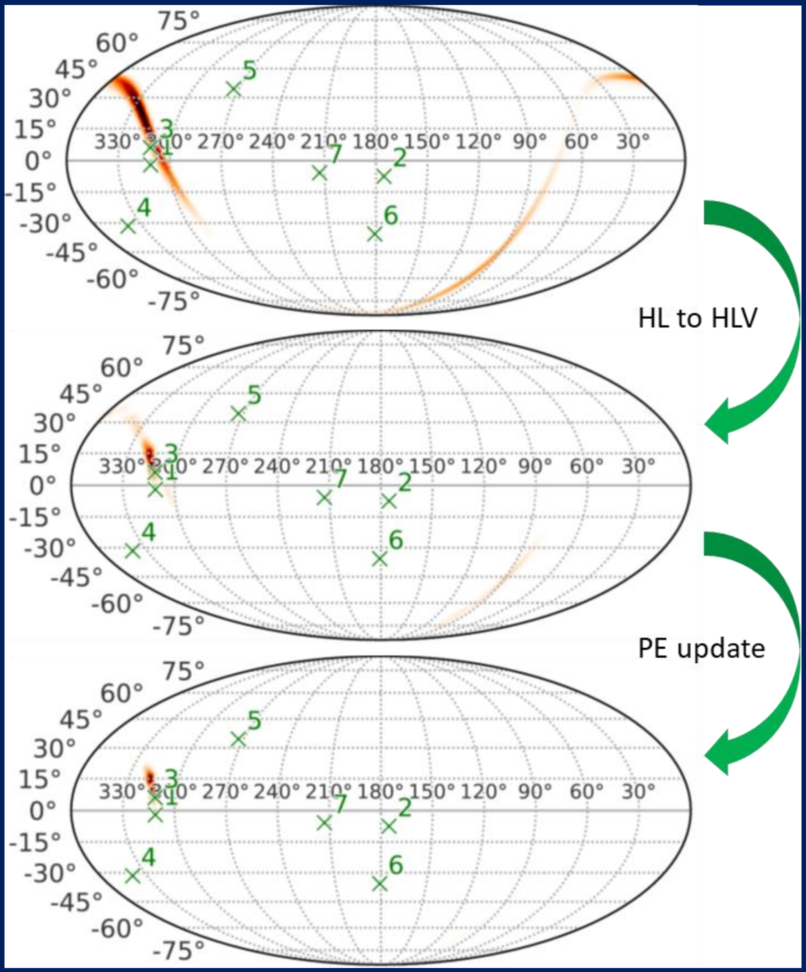
Upper Limit: Veske et al.; *Neutrino emission upper limits with maximum likelihood estimators for joint astrophysical neutrino searches with large sky localizations*; JCAP 2020

=> 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.

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

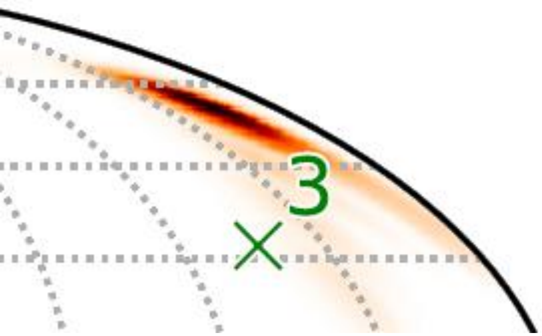
LVC Update Skymap, 07/28/19 20:29:15 UT
90% area: 104 deg^2

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 – on arxiv

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.

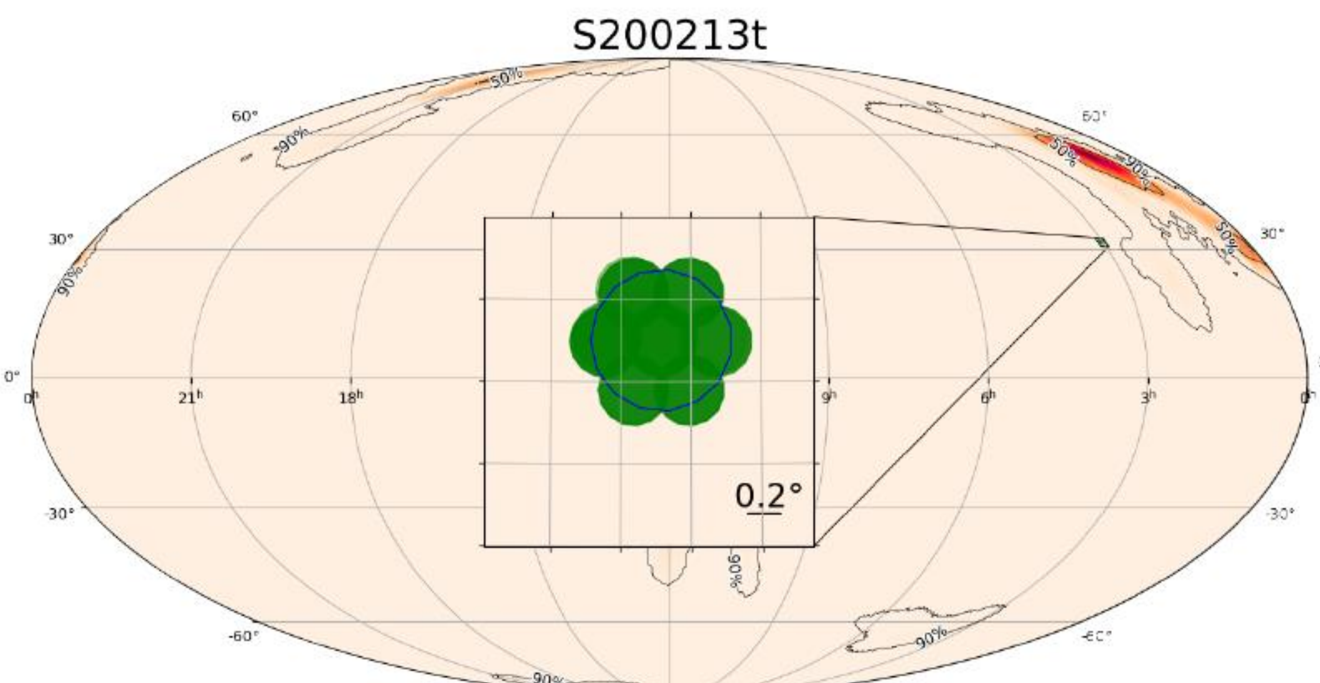
NUMBER: 27043
SUBJECT: LIGO/Virgo S200213t: 1 counterpart neutrino candidate from IceCube neutrino searches
DATE: 20/02/13 04:40:26 GMT

…..

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

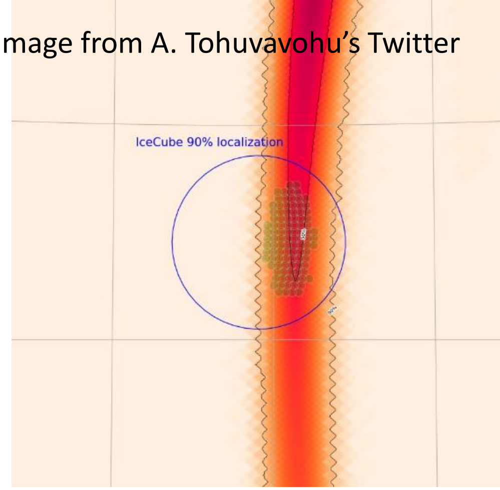
where: dt = Time offset (sec) of track event with respect to GW trigger. Angular uncertainty = Angular uncertainty of track event: the radius of a circle representing 90% CL containment by area. Pvalue = the pvalue for this specific track event from each search.



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



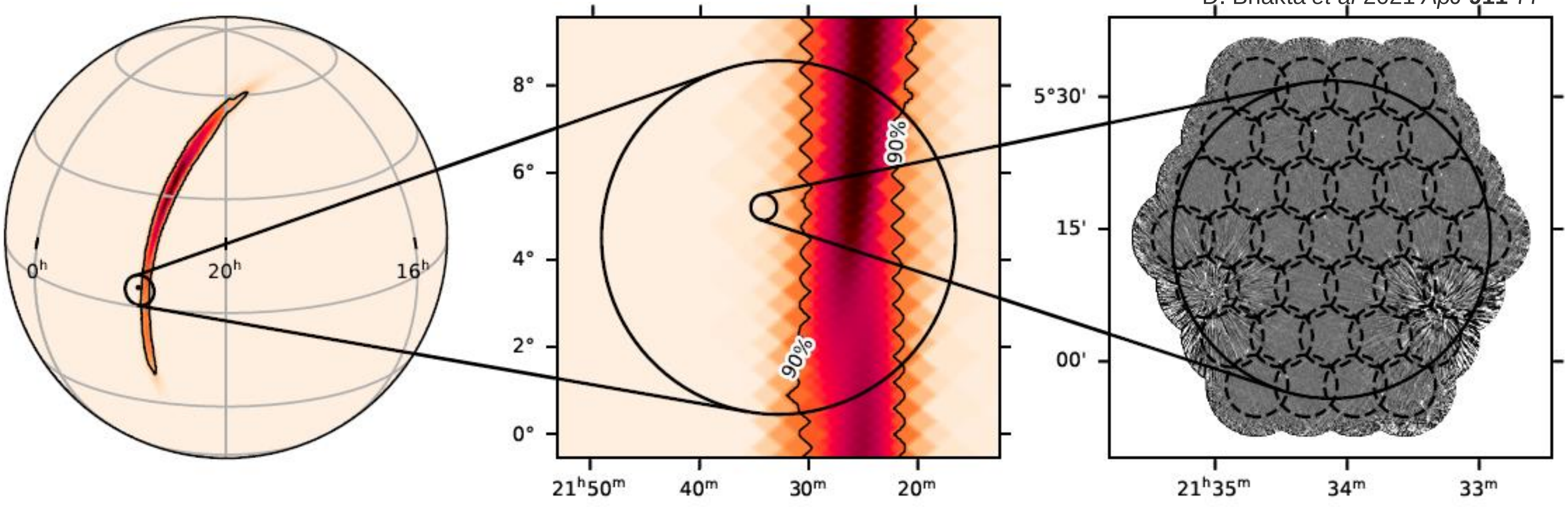
⇒ **GW candidate S191216ap by LIGO/Virgo**

⇒ 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!

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

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

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

Many messengers many hypotheses…

Astrophysical or noise

Related or unrelated

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

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

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)

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

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:

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

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

Conclusion

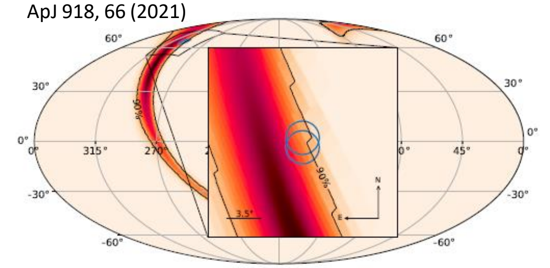


Figure 1. The localization probability map for sub-threshold LIGO BNS candidate C1 (2015-10-12T02_40_22; from Table 1) presented in equatorial coordinates with two VERITAS observations that overlap spatially and temporally overlaid.

MMA searches already produced significant discoveries

Discoveries were enabled by decades long pioneering work

Upgraded detectors, new instruments => transient event factories

Each messenger => subthreshold trigger lists

Joint analysis of subthreshold lists is already ongoing => e.g. GW + VERITAS search

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

New data streaming services are coming (SCiMMA, TACHS)

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