Archival Search for Neutron Star Mergers in Gravitational Waves and Very-High-Energy γ-rays

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Columbia Nevis REU Program, Summer 2023
VERITAS/CTA and GECo

Outline

1. Scientific Motivations
2. Gravitational Waves and LIGO
3. Gamma-ray Astronomy and VERITAS
4. Binary Neutron Star Mergers
5. Previous Search through O1 Data
6. VTS Observational Capability Filtering Criteria
7. Finding a Time-Window of Analysis
8. Analysis Results
9. Discussion
10. Future Directives

Scientific Motivations

1. To gain a deeper understanding of transient events in gravitational waves and very high energy astrophysics
2. Search through LIGO gravitational-wave subthreshold candidates from the 3rd run (O3) to find very high energy electromagnetic counterparts

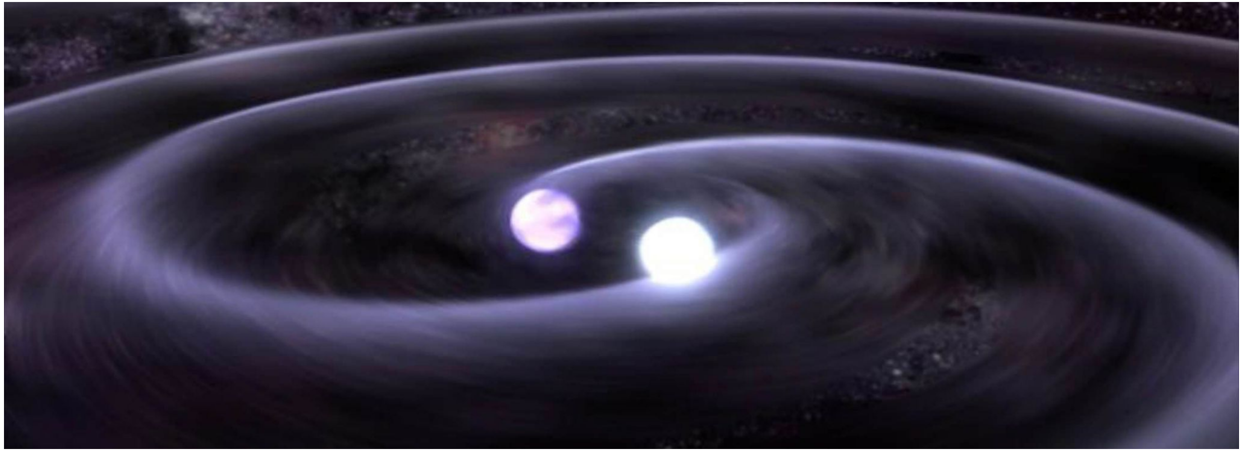


Image Credit: Dana Berry for NASA's Goddard Space Flight Center

Gravitational Waves

- ★ First theorized in Einstein's Theory of General Relativity (1916)
- ★ Ripples in spacetime caused by the acceleration of massive objects
- ★ Propagate at the speed of light

- ★ Where have they been found?
  - ○ Binary Black Hole Mergers (2015)
  - ○ Binary Neutron Star Mergers (2017)
  - ○ Neutron Star - Black Hole Mergers (2020)
  - ○ Gravitational Wave Background (2023)
    - ■ Low frequency GWs

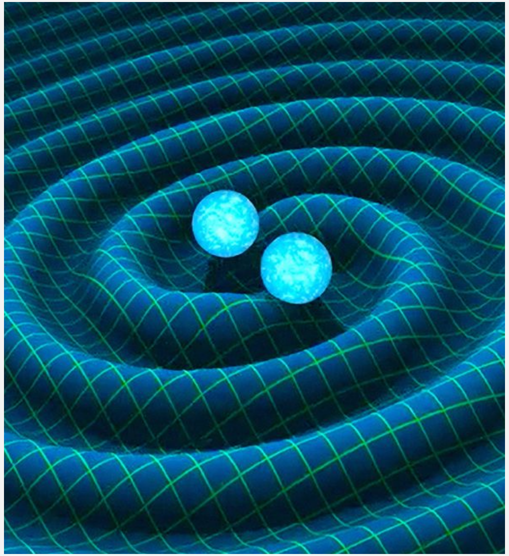


Image Credit: R. Hurt / Caltech-JPL

LIGO Detector

LIGO - Laser Interferometer Gravitational-wave Observatory

- ★ High frequency GWs
- ★ Einstein's Theory of General Relativity 1916
- ★ First detection of GWs in 2015 (from Binary Black Hole Merger)

LIGO Livingston

Image Credit Caltech/MIT/LIGO Lab

Interferometer set-up

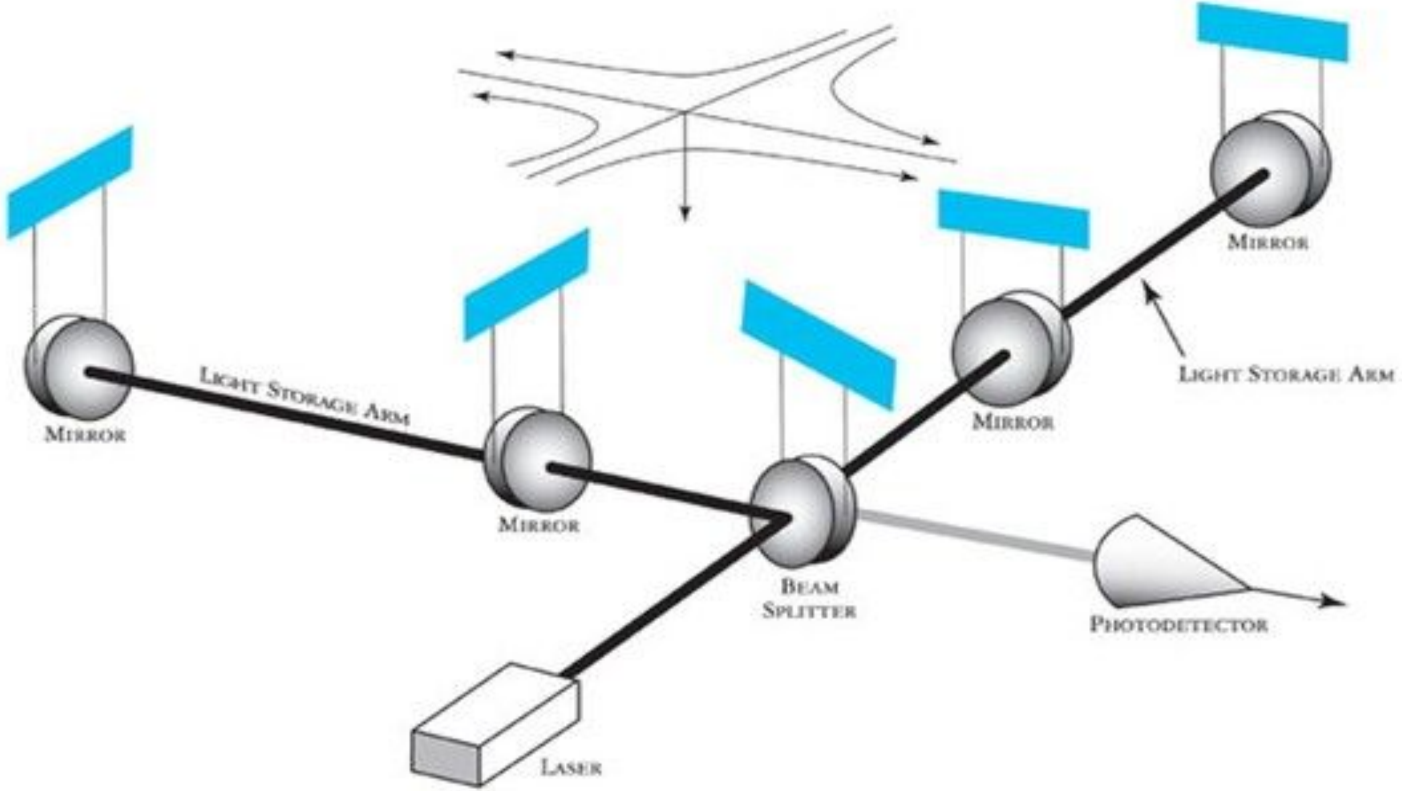


Image Credit(s): Caltech/MIT/LIGO Lab

Detector Noise and False Alarm Rate

$$FAR = \frac{N}{T_{bkg}}$$

N: # of detector background noise events with ranking statistic equal to or greater than of the candidate event.

T_bkg: Total duration of the background data

Ex) *GW150914* (first GW detection) - had a FAR of less than 1 in 203,000 years

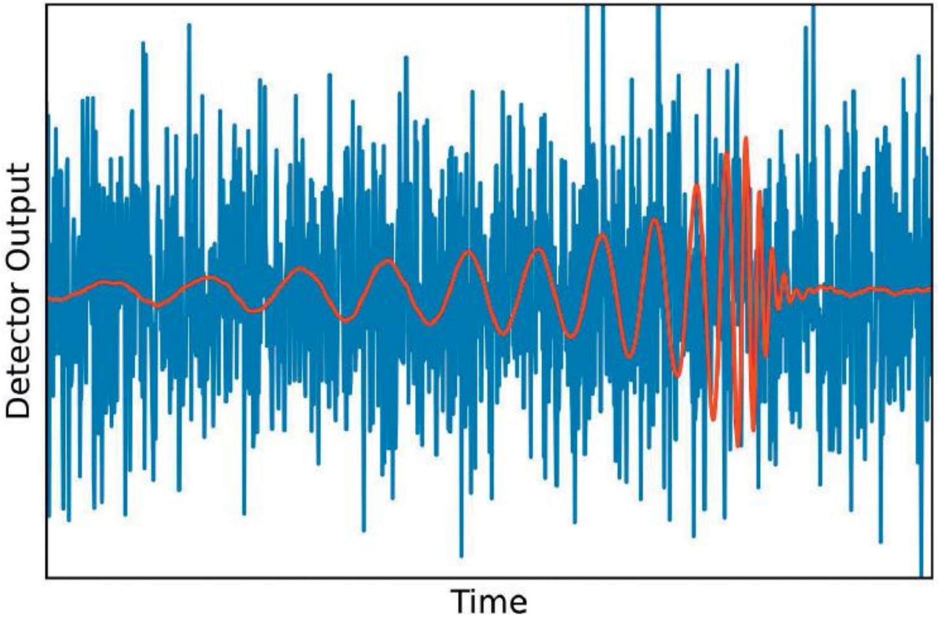


Figure: Typical gravitational-wave signal that is buried in detector noise.

Adapted from: Zheng et. al.

LIGO Analysis Pipelines

The following are certain pipelines LIGO filters its data through. They are based on some models that are assumed/placed onto the data.

Unmodeled Searches

cWB (coherent WaveBurst)

- ➢ Unmodeled Gravitational-wave data analysis
- ➢ Only gives a astrophysical and terrestrial probability

Modeled Searches (Latencies ≲ 1 min)

GstLAL (Gstreamer LAL), MBTA (Multi-Band Template Analysis), PyCBC (Python Compact Binary Coalescence) and PyCBC highmass

- ➢ Detailed information about the masses, spins, distances, and other parameters of mergers, allowing for detailed astrophysical studies

Pipeline Products (from modeled searches)

Masses:

- Chirp Masses

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

- Mass Ratio
- Individual Masses

Distances:

- Distance (in Mpc)
- Distance Uncertainty

Probabilities:

- BNS Probability
- BBH Probability
- NSBH Probability
- Astrophysical Probability
  - = BNS + BBH + NSBH Prob.
- Terrestrial Probability

Gamma-ray Astronomy

★ Highest energy window of the electromagnetic spectrum

★ Originate from non-thermal processes

  ○ Strong electromagnetic fields

  ○ Nuclear decay processes and interactions

Gamma-ray bursts (GRBs), 2 types:

★ Short GRBs: <2s

★ Long GRBs: >2s

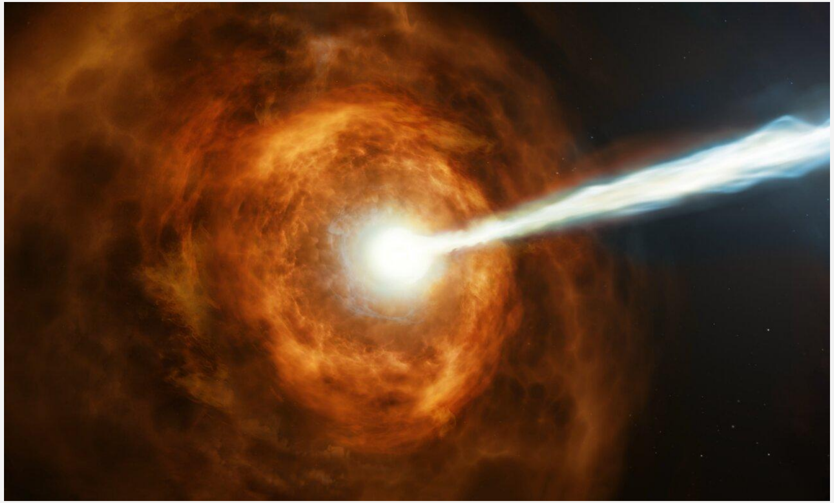


Image Credit: ESA/Hubble, M. Kornmesser

VERITAS

VERITAS - Very Energetic Radiation Imaging Telescope Array System

- ★ 4 IACTs
- ★ Ground based gamma-ray telescope
- ★ Explores 85 GeV to 30 TeV
- ★ Detects flashes of Cherenkov light

[VERITAS Array at FLWO]

Imaging Atmospheric Cherenkov Telescope (IACT)

➔ Gamma-rays are blocked by the upper atmosphere.

Cherenkov Radiation:

★ Flashes of electromagnetic radiation that propagate through a medium faster than the speed of light in that medium

★ Optical telescopes are used to detect the air-showers that are produced

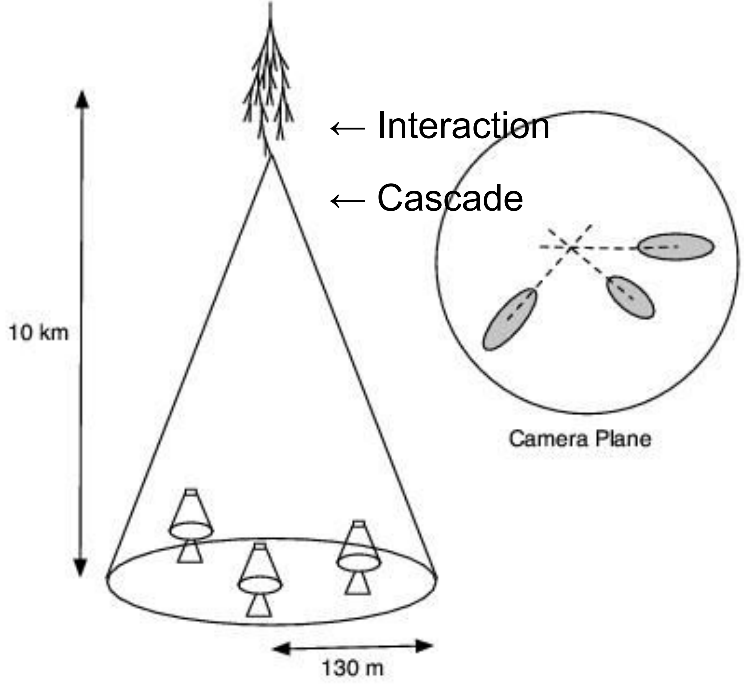


Image Credit: VERITAS

VEGAS - VERITAS Gamma-ray Analysis Suite

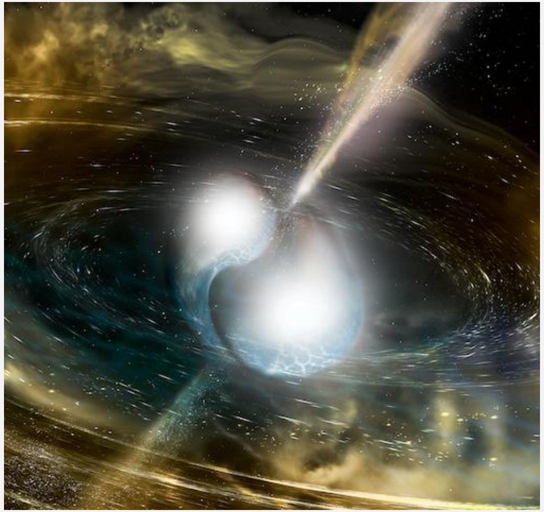
- **Stage 1:**
  - Raw input data gets calibrated
- **Stage 2/3:**
  - Subtracts out noise
  - Cleans the pixels and maps
- **Stage 4:**
  - Shower origin in sky, shower location on ground and other parameters are determined
  - Soft/medium/hard cuts are applied
- **Stage 5:**
  - Create .root files
- **Stage 6:**
  - Plots and skymaps are produced
  - Probability of a detection given by Li&Ma

Binary Neutron Stars

★ Neutron stars are thought to be born from collapse from cores of massive stars in supernovae

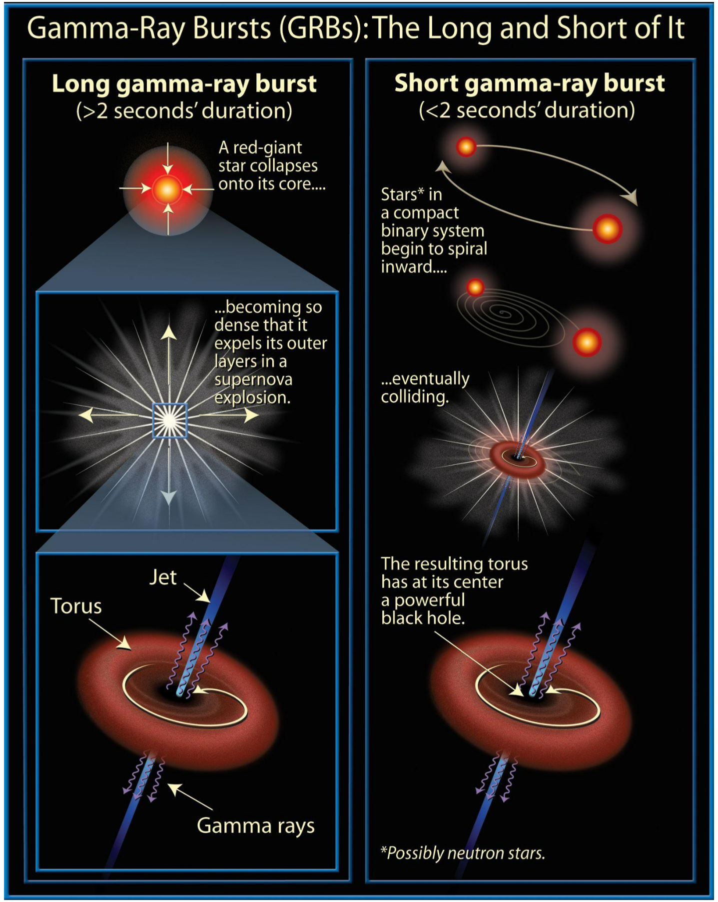
Why are BNS Mergers interesting?

➢ Gravitational radiation from the mergers (before and after the inspiral phase as well)
➢ Sources of electromagnetic and neutrino emission
➢ Responsible for production of the very heavy elements



NSF / LIGO / Sonoma State University / A. Simonnet

Source of Short GRBs



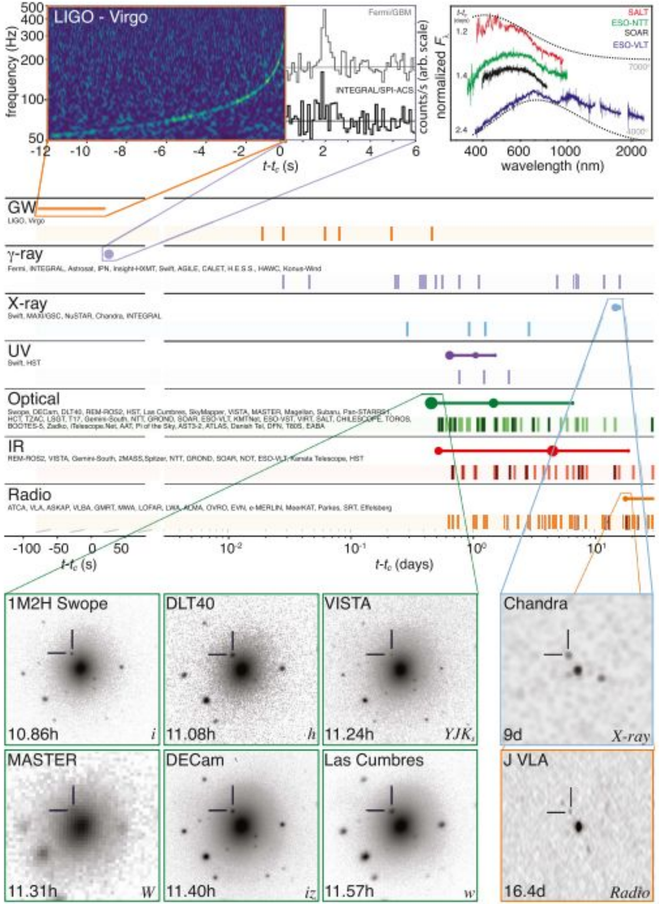
★ BNS Mergers long thought to be a source of short GRBs

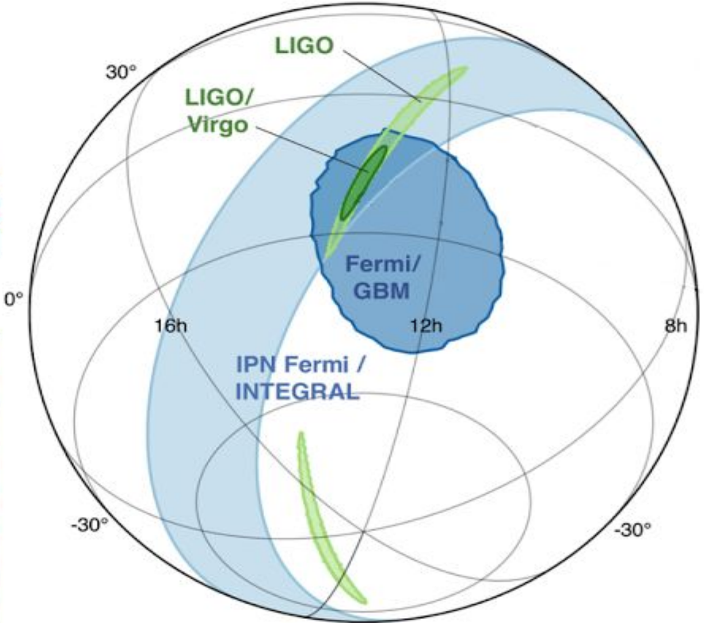
Stages of a merger

1) Inspiral phase
2) Merger phase
   a) Prompt emission
3) Post-merger phase
   a) Afterglow

Image Credit: NASA and A. Feild (STScI)

First Detection of a Binary Neutron Star Merger

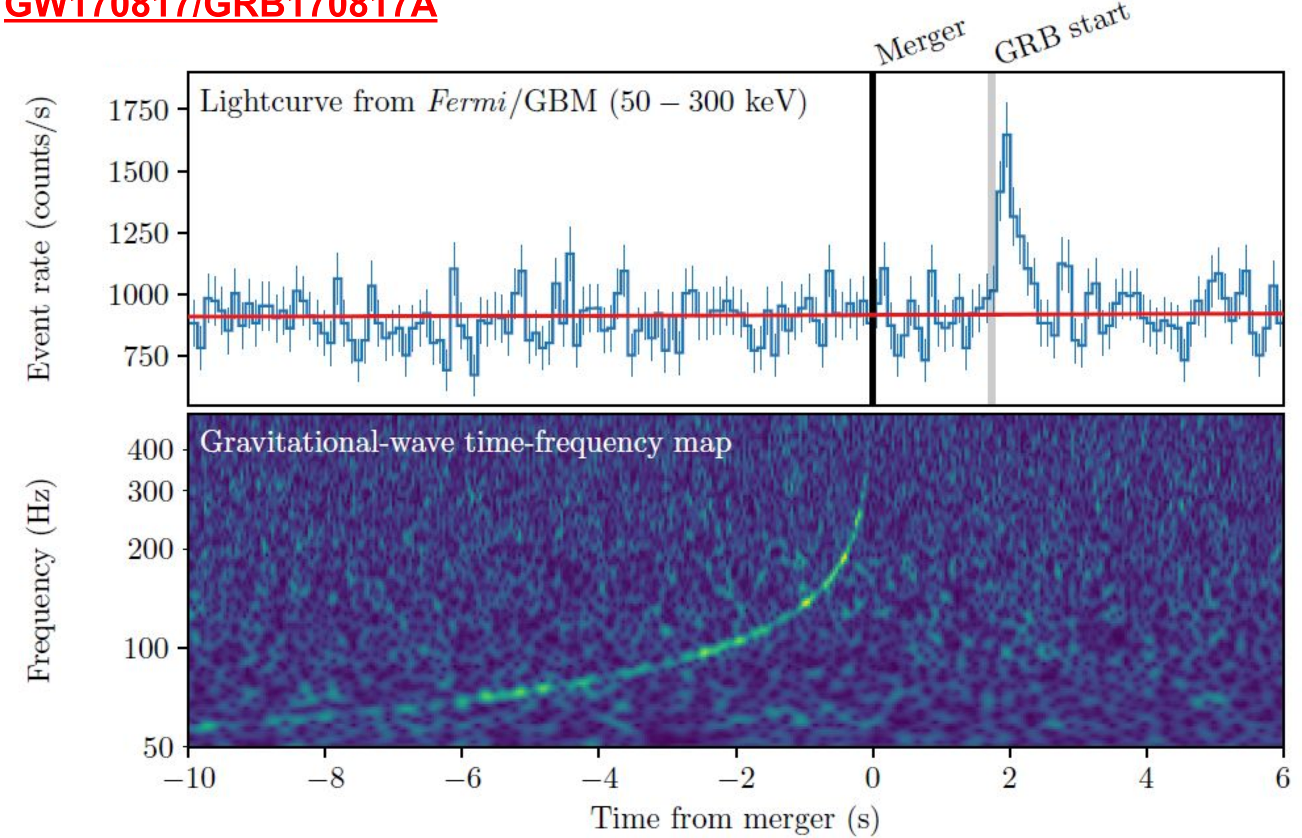




Adapted from Abbott+2017

First Detection of a Binary Neutron Star Merger

GW170817/GRB170817A



- ★ 1st Detection of a Binary Neutron Star Merger
- ★ Detection of EM signals coincident with GW from a BNS Merger

Adapted from Abbott+2017

Previous Search through LIGO Run O1 Data

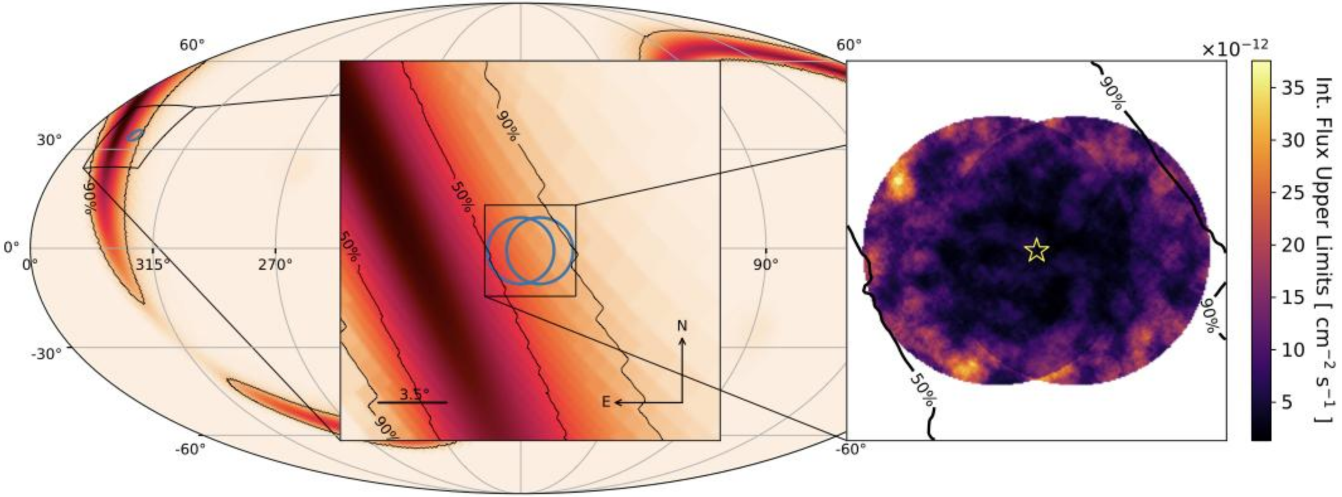


Fig: 90% Localization Probability Map of LIGO BNS Merger Candidate with the two overlapping VTS Observations

Of 103 LIGO subthreshold candidates from LIGO's O1 Run, 7 candidates were found to be spatially and temporally coincident (within -10 to 10,000s of LIGO event time) with 11 VERITAS archival observations

Adapted from [Adams et. al 2021.]

VERITAS Observational Capability Filtering Criteria

1000+ candidates from O3 passed the FAR (False Alarm Rate) test of <2 per day

Initial Filtering Criteria

1. Find VERITAS observations between -10 and 1,000s of the LIGO event time
2. Find VERITAS observations with a field of view within the 90% localization area of the LIGO skymap

Database: GWTC-3 Candidate Data Release

Produced from algorithm used in Adams et. al. 2021.

VERITAS Observational Capability Filtering Criteria

New Filtering Criteria:

1. Find candidates with any non-zero probability of being a BNS Merger
2. Find observations that overlap with LIGO event time
    a. Prompt Emission
3. Order them by VERITAS Field of View Integrated Probability

The Candidates

The 4 candidates that passed the filtering criteria

VTS Run #	LIGO Event	VTS Start Time	VTS End Time	LIGO Event Time (t_0)
95279	1263359288	1/18/2020 4:42	1/18/2020 5:13	1/18/2020 5:07
95396	1263888184	1/24/2020 7:22	1/24/2020 8:02	1/24/2020 8:02
95528	1264327620	1/29/2020 9:32	1/29/2020 10:07	1/29/2020 10:06
95667	1264747176	2/3/2020 6:14	2/3/2020 6:44	2/3/2020 6:39

VTS Run #	Astrophysical Prob.	BNS Prob.	NSBH Prob.	BBH Prob.	BNS & VTS Overlap Prob.
95279	0.000641204	0.000641204	0	0	1.94E-06
95396	0.002370415	0.000548151	0.001822264	0	2.75E-07
95528	4.90E-05	4.90E-05	0	0	2.41E-07
95667	2.00E-06	1.00E-06	0	0	1.25E-09

Finding time-window for analysis

Analyze a single run on a patch of sky where we don’t expect to see anything

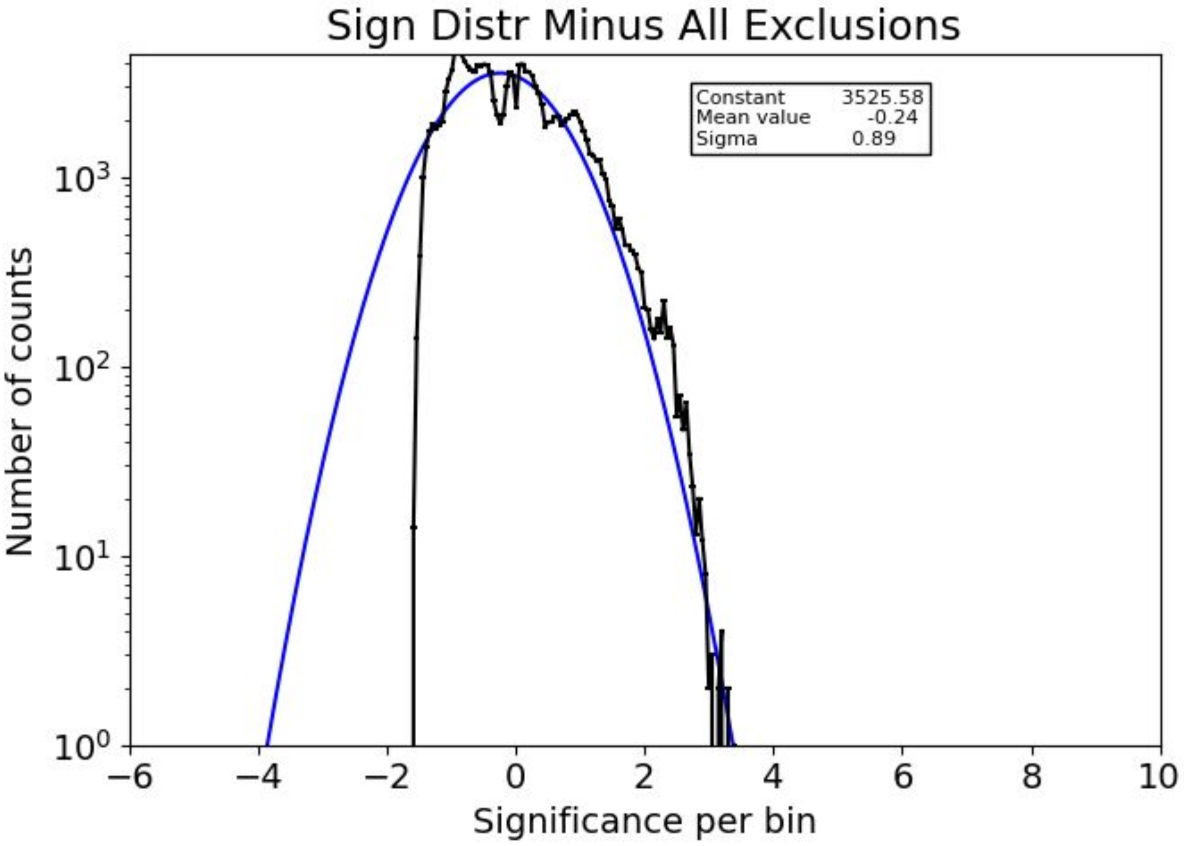
★ Source: Draco, Run # 77335, 30 minute run

Analyze this source for different timecuts (using VEGAS)

➔ Look at the histograms of the significance distributions to find the lowest analysis duration which gives us a good Gaussian distribution

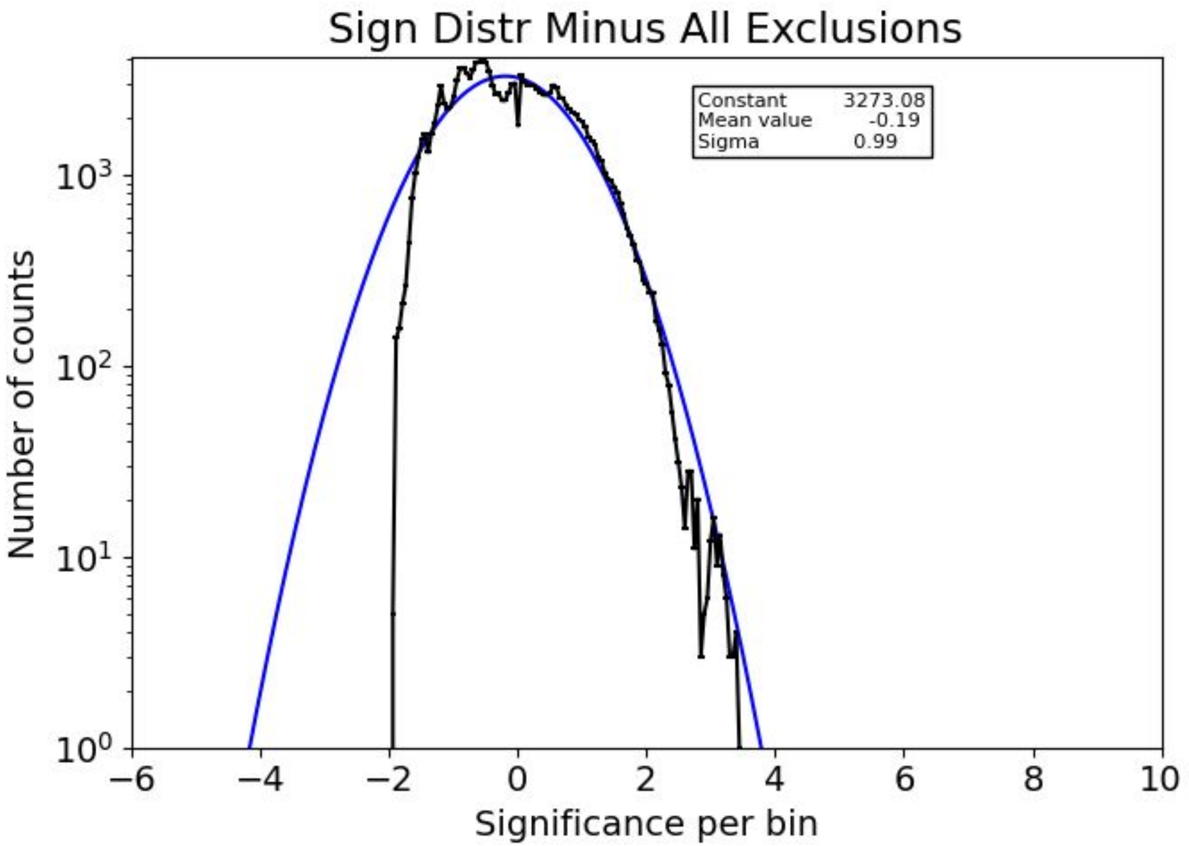
➔ We will then use that lowest analysis duration for our BNS analysis

2.5 Minutes

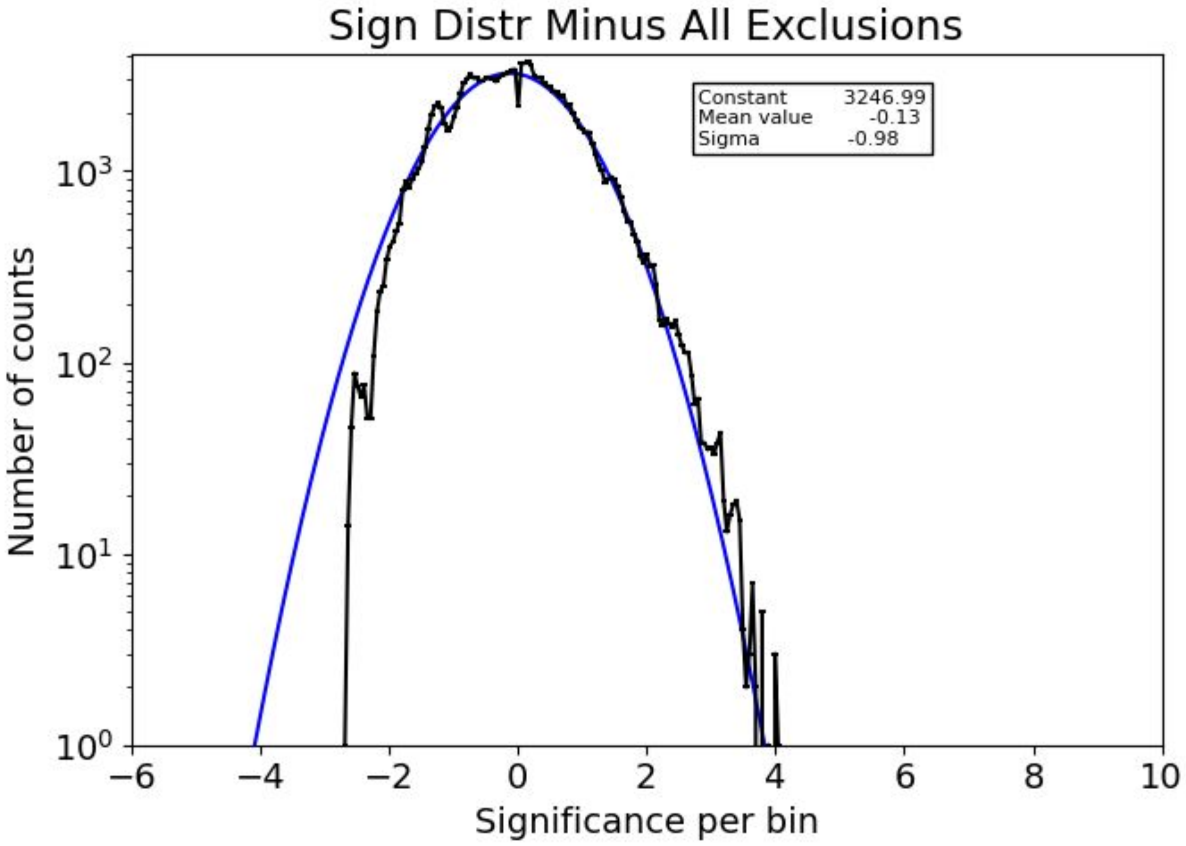


Sign Distr Minus All Exclusions
Constant 3525.58
Mean value -0.24
Sigma 0.89
Number of counts
10^0
10^1
10^2
10^3
−6
−4
−2
0
2
4
6
8
10
Significance per bin

5 Minutes

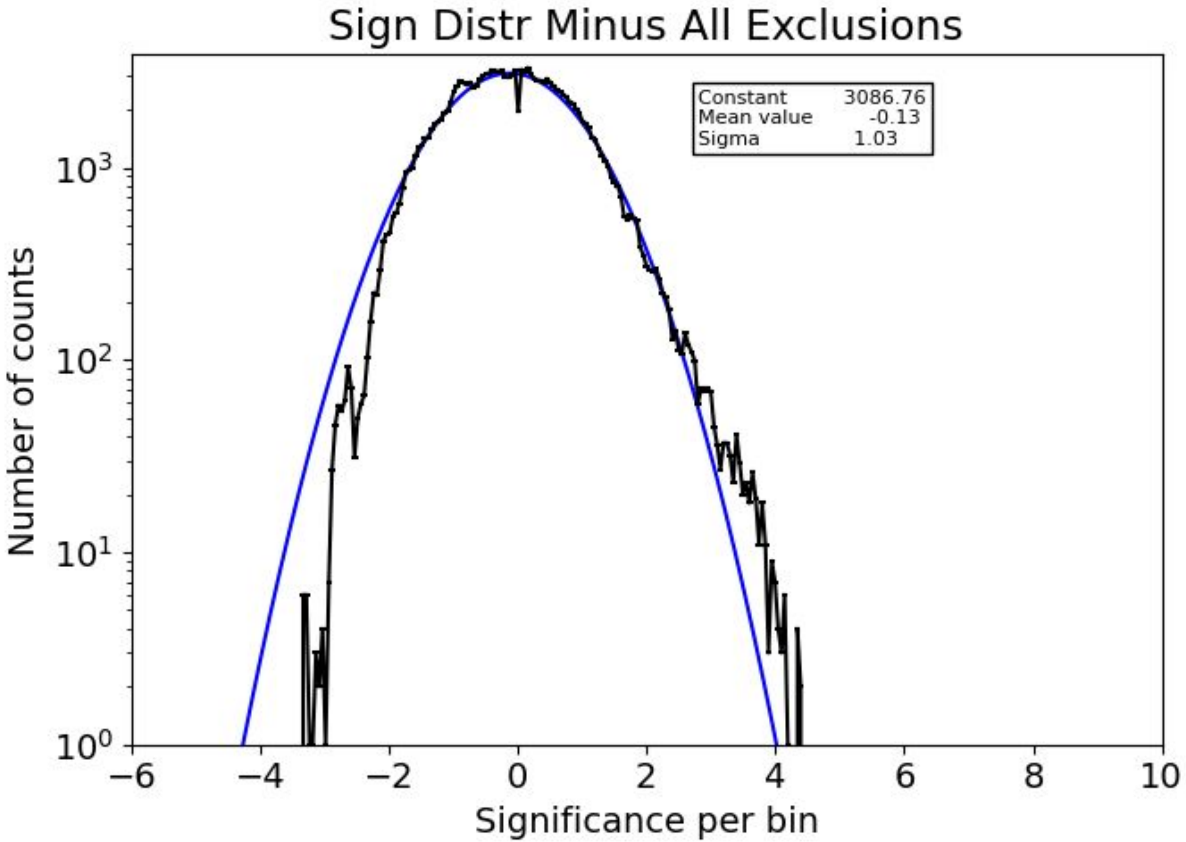

Sign Distr Minus All Exclusions
Constant 3273.08
Mean value -0.19
Sigma 0.99
Number of counts
Significance per bin
10^3
10^2
10^1
10^0
−6
−4
−2
0
2
4
6
8
10

10 Minutes



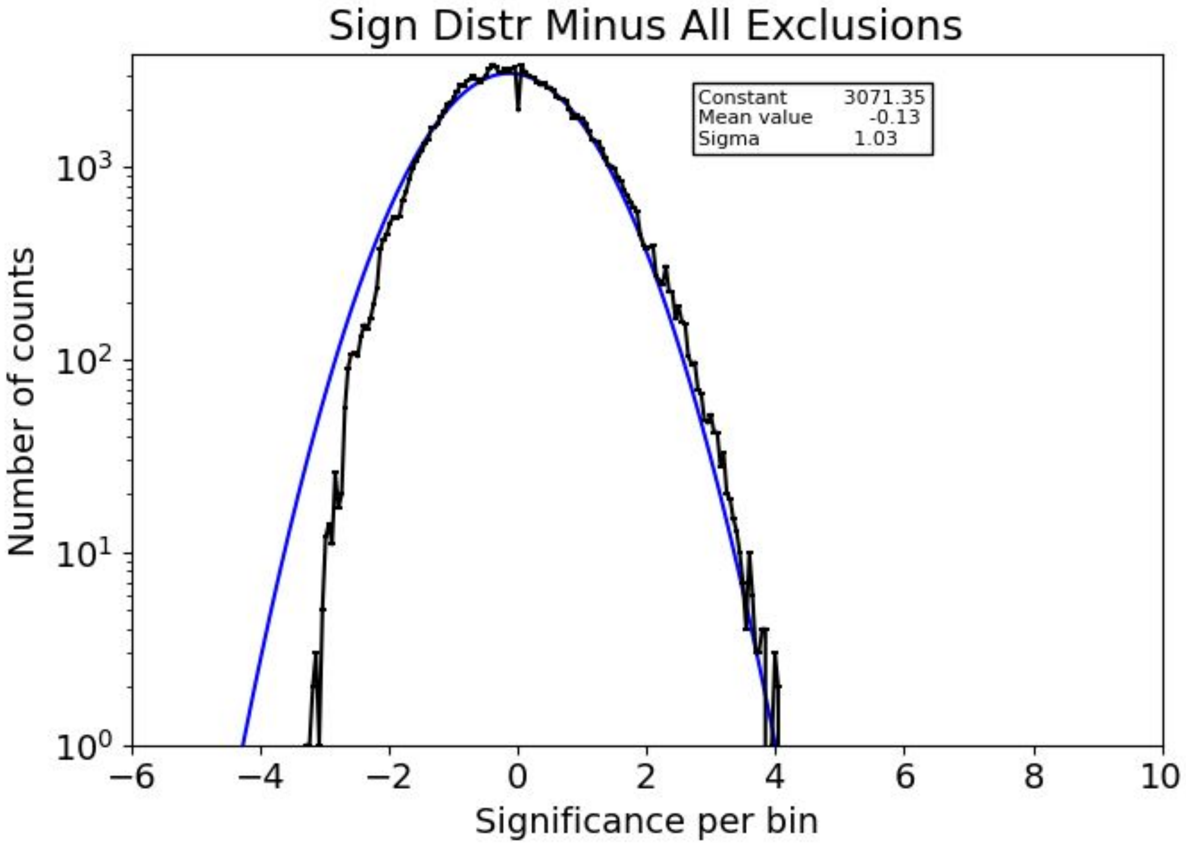
Sign Distr Minus All Exclusions
Constant 3246.99
Mean value -0.13
Sigma -0.98
Number of counts
10^3
10^2
10^1
10^0
−6
−4
−2
0
2
4
6
8
10
Significance per bin

15 Minutes



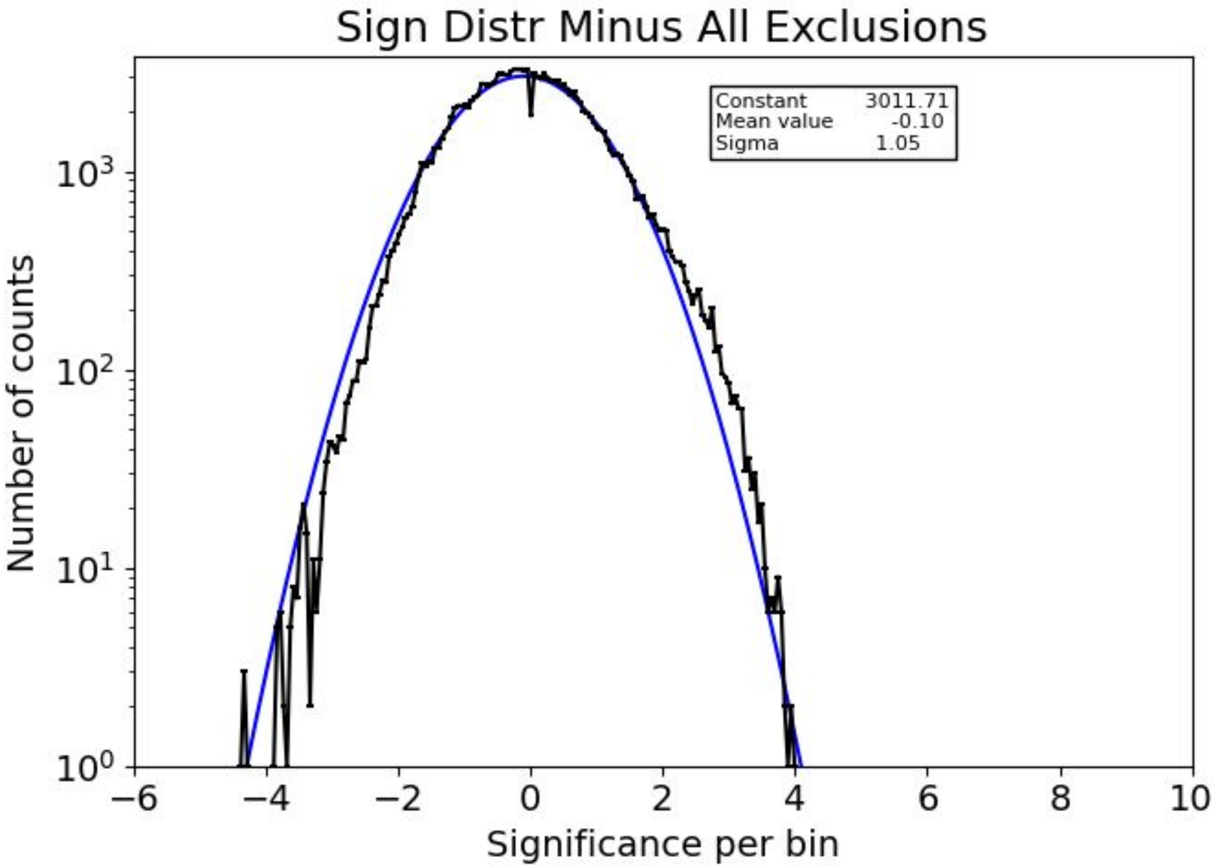
Sign Distr Minus All Exclusions
Constant 3086.76
Mean value -0.13
Sigma 1.03
Number of counts
10^3
10^2
10^1
10^0
−6
−4
−2
0
2
4
6
8
10
Significance per bin

20 Minutes



Sign Distr Minus All Exclusions
Constant 3071.35
Mean value -0.13
Sigma 1.03
Number of counts
10^0
10^1
10^2
10^3
−6
−4
−2
0
2
4
6
8
10
Significance per bin

30 Minutes



Sign Distr Minus All Exclusions
Constant 3011.71
Mean value -0.10
Sigma 1.05
Number of counts
10^0
10^1
10^2
10^3
−6
−4
−2
0
2
4
6
8
10
Significance per bin

Time Window Considerations

➔ Our method found the time window to be about 20 minutes

➔ This becomes an issue for our candidates that temporally overlap closely to the LIGO event time

➔ VERITAS candidates could be of these different types:

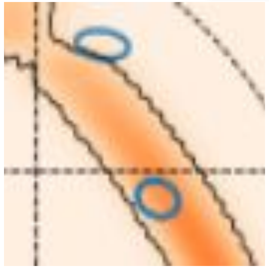
  a) 2 observations that don’t overlap

  b) Only 1 observation

  c) 2 observations that overlap

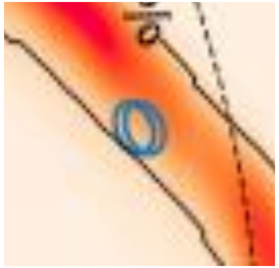
★ We will only look at observations that are overlapping!

a)



b)

c)



Run #: 95279, LIGO Event ID: 1263359288

- ➢ VERITAS observing time: 1/18/2020 4:42 UTC to 1/18/2020 5:13 UTC
- ➢ LIGO event time: 1/18/2020 5:07 UTC

Pipeline: PyCBC Allsky

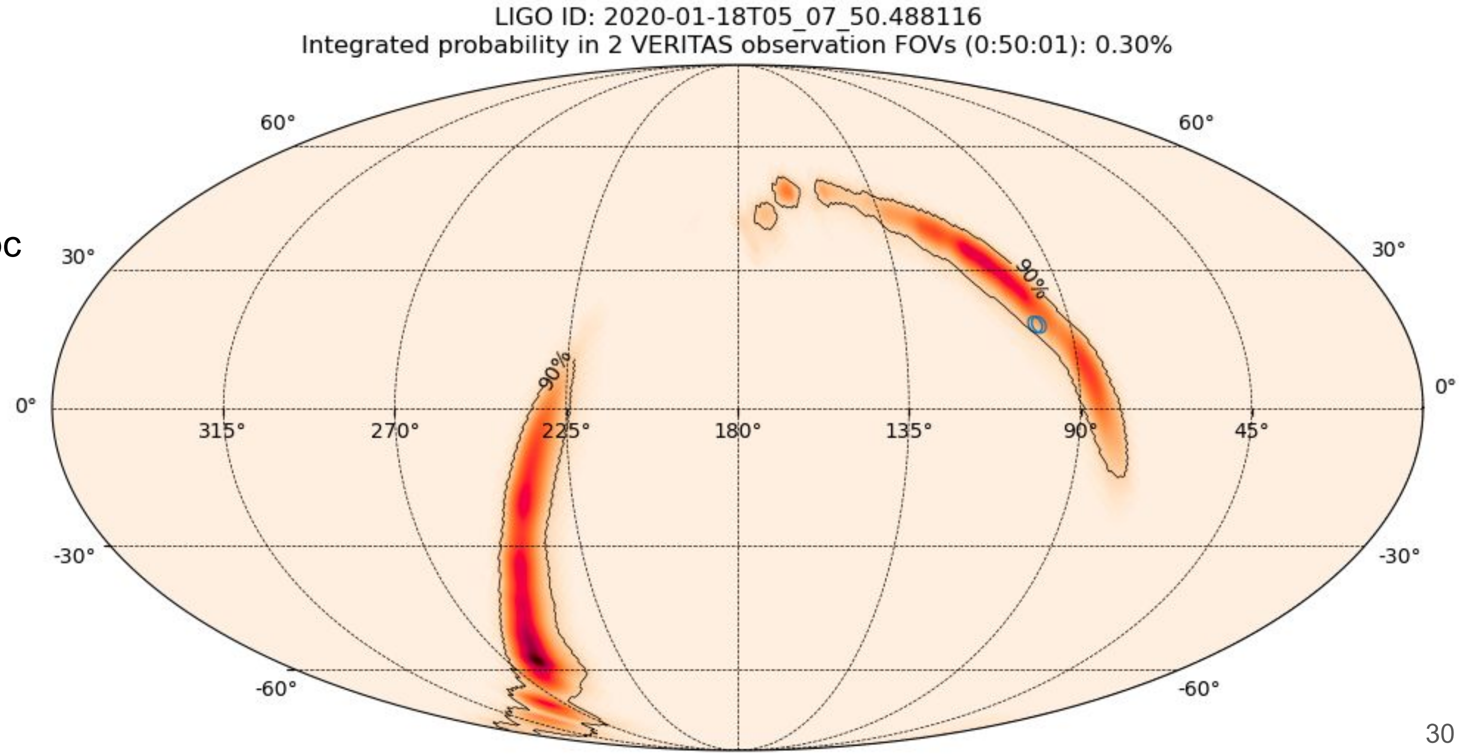
Distance = 258+/-77 Mpc

Mass Ratio = 1.198

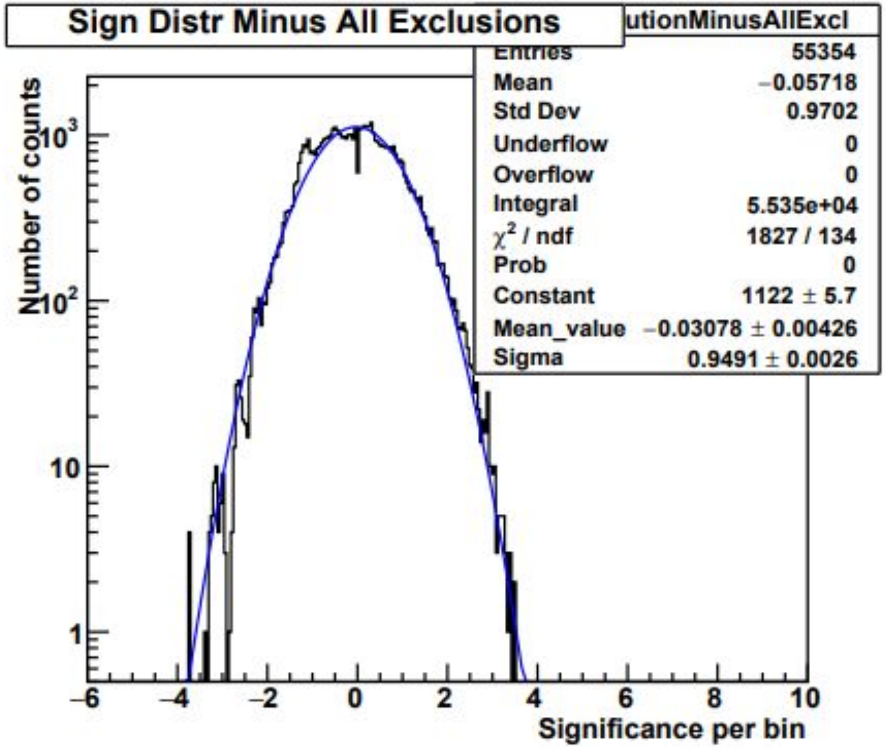
Chirp Mass = 0.9638

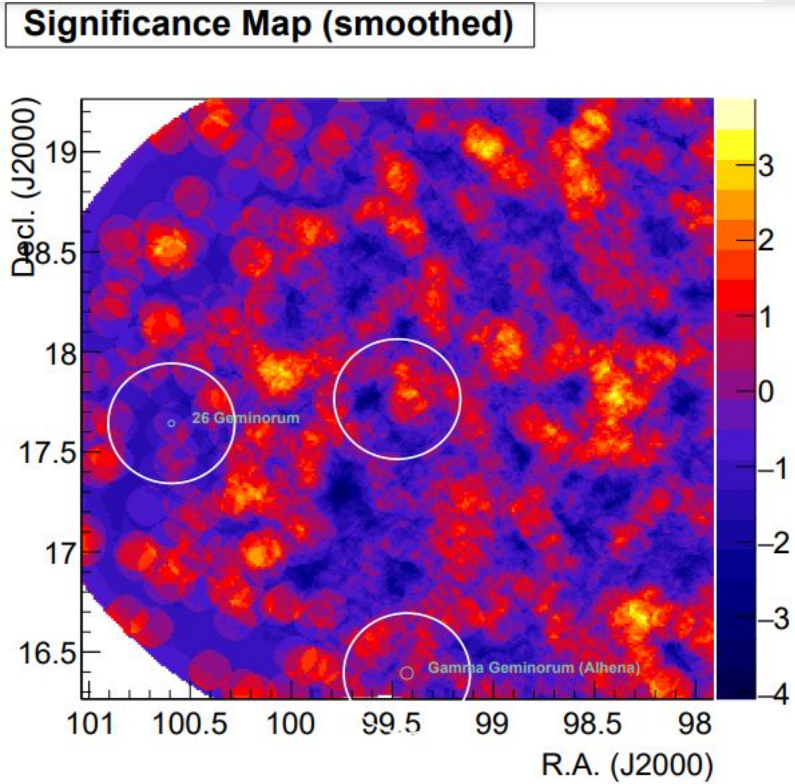
Total Mass = 2.225

Lower Mass = 1.012



Analysis Results





This preliminary analysis found no significant signal.

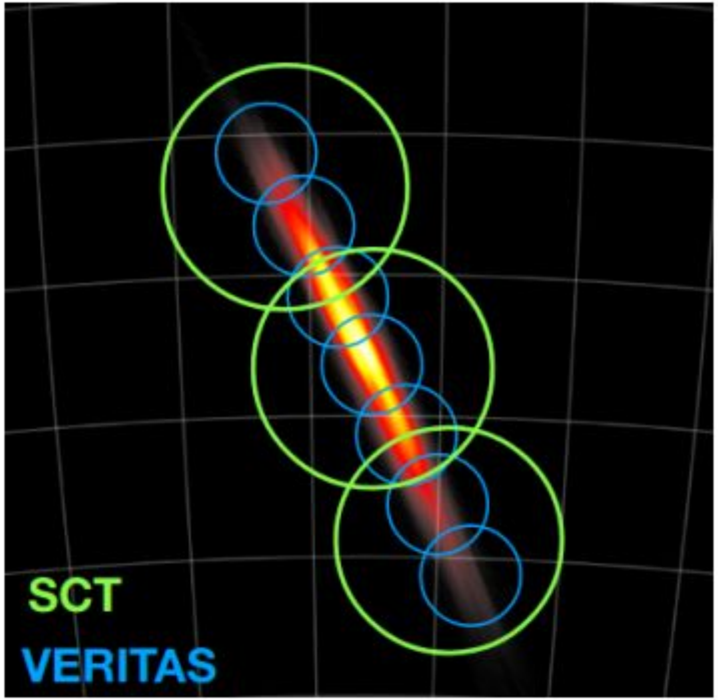
Discussion

No significant signal was detected from our candidate.

Some important considerations:

- ➢ VERITAS has a limited field of view (~3.5 degrees)
- ➢ VERITAS hasn’t gotten lucky with detecting a long or short GRB as of yet
    - ○ MAGIC has detected a long GRB and a 3σ hint of a short GRB in VHE

Future Plans: pSCT



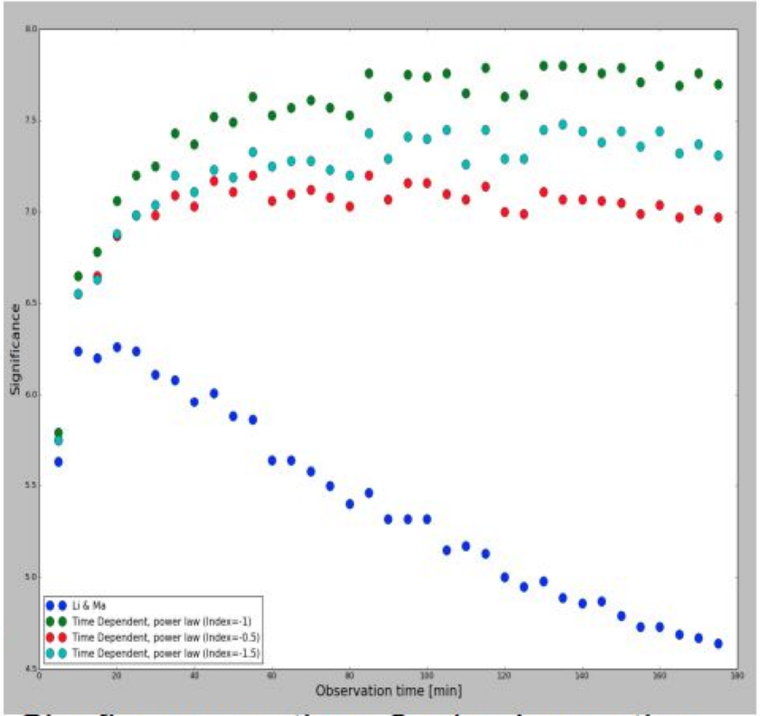
- How SCT and VERITAS could be used to follow-up on a Gravitational-wave event.
- During LIGO O4 Run, pSCT plans to follow-up on GW alerts with VERITAS.

[VERITAS Highlights 2022]

Future Directives: Time-dependent Analysis

Less concerns about the time window of the analysis because time-dependent would prioritize and the signals that come closer to some time t_0.

- Li and Ma peaks at some time before falling off



Signficance vs. time. 2 min observation delay, bgRate=1/min. Decay index of -1

Credit: Ori Weiner

Acknowledgements

VERITAS/CTA Group at Columbia University

Thank you my mentors in the VERITAS/CTA group, Dr. Reshmi Mukherjee and Colin Adams and my mentor in the GECo group, Dr. Zsuzsanna Marka.

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NEVIS LABORATORIES
COLUMBIA UNIVERSITY

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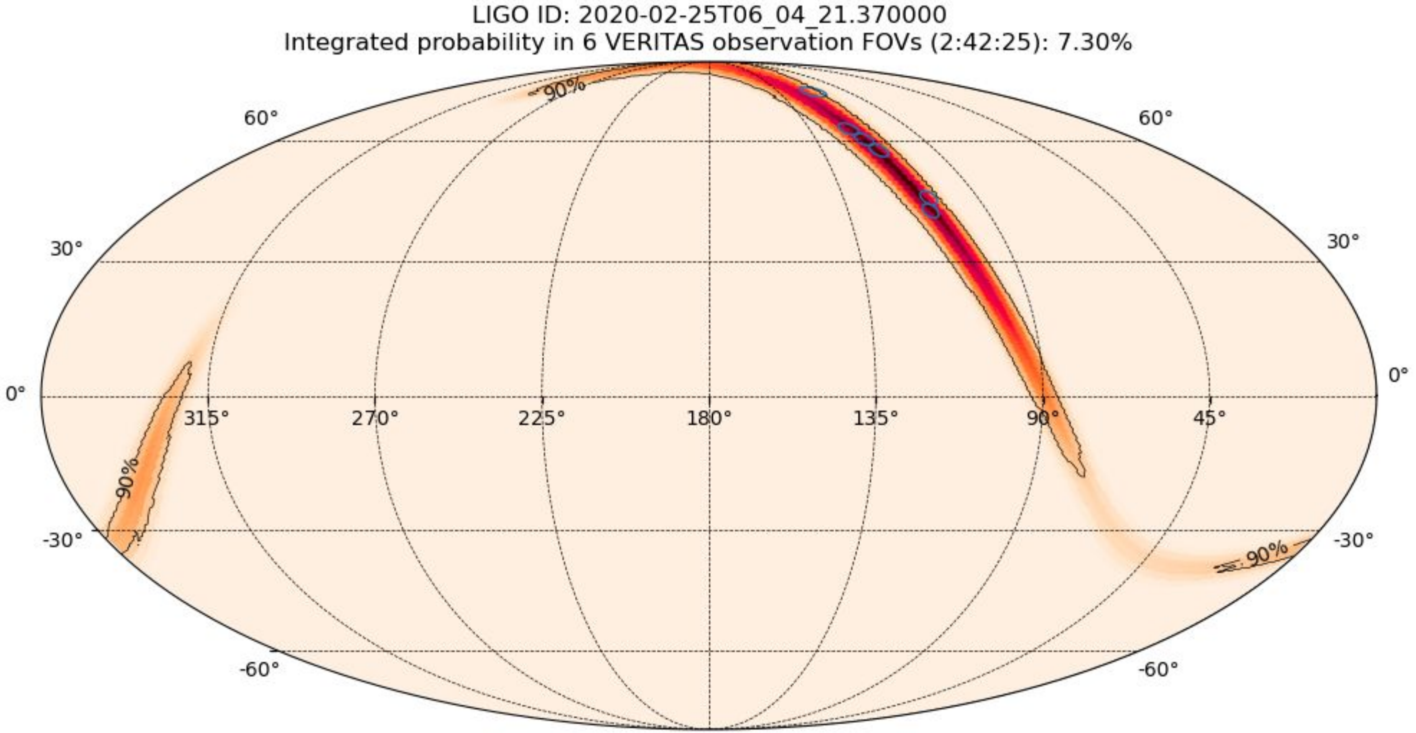
Thank you!

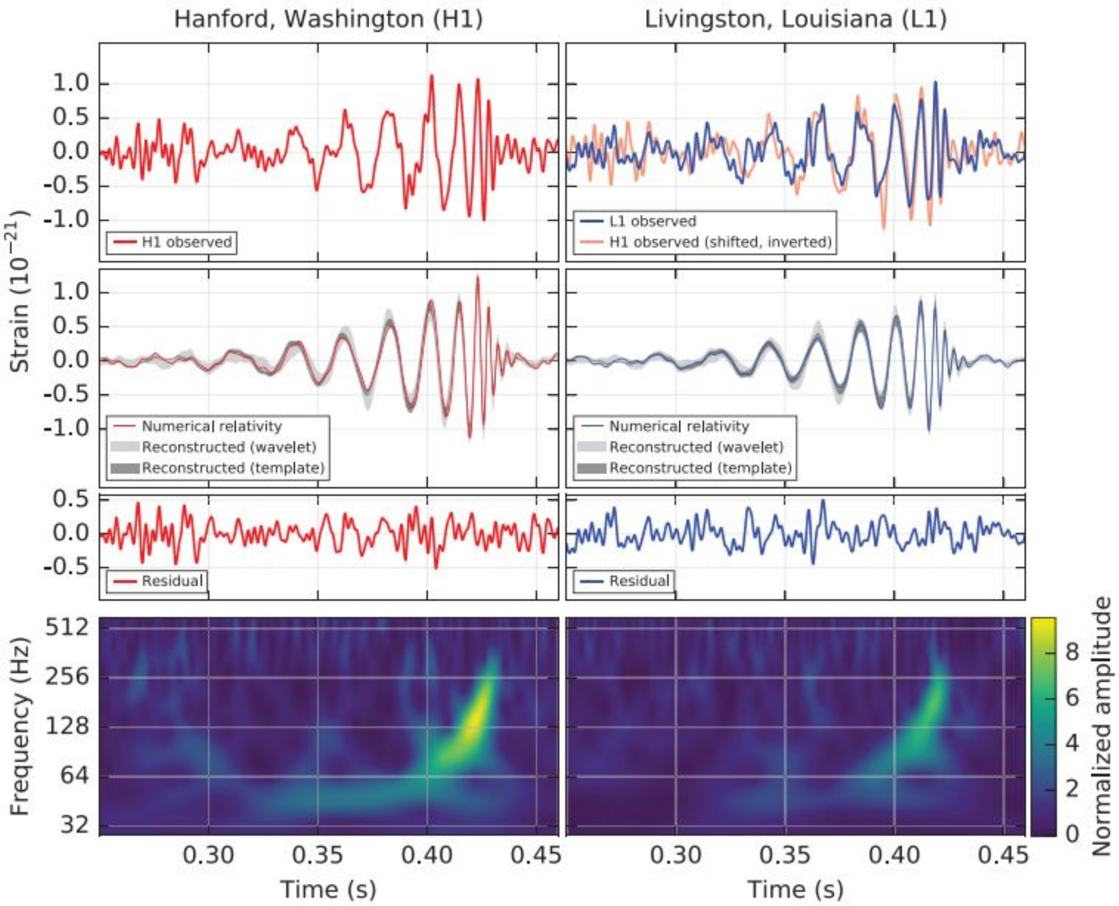
Appendix A:
Extra Materials

Discussion: VERITAS Follow-up of LIGO Event

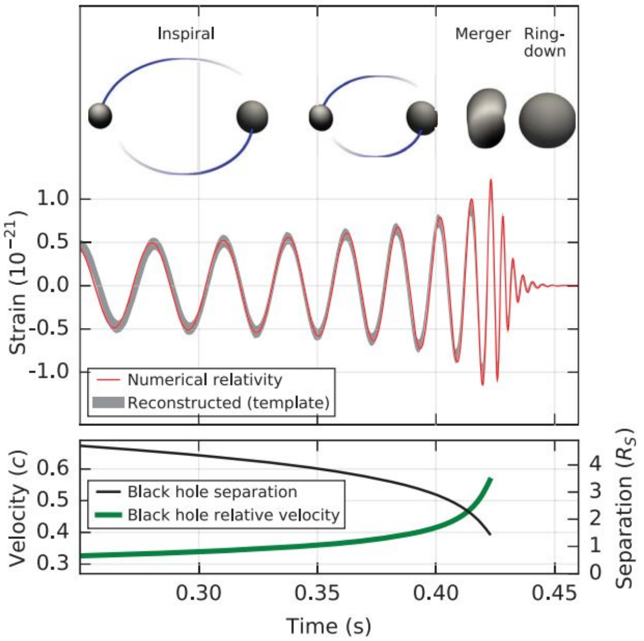
- LIGO Event Time: 2/25/2020 6:04 UTC
- VERITAS Observation start time: 2/25/2020 6:13 UTC, **~9 minute delay in observation.**



First detection of a GW event: BBH merger

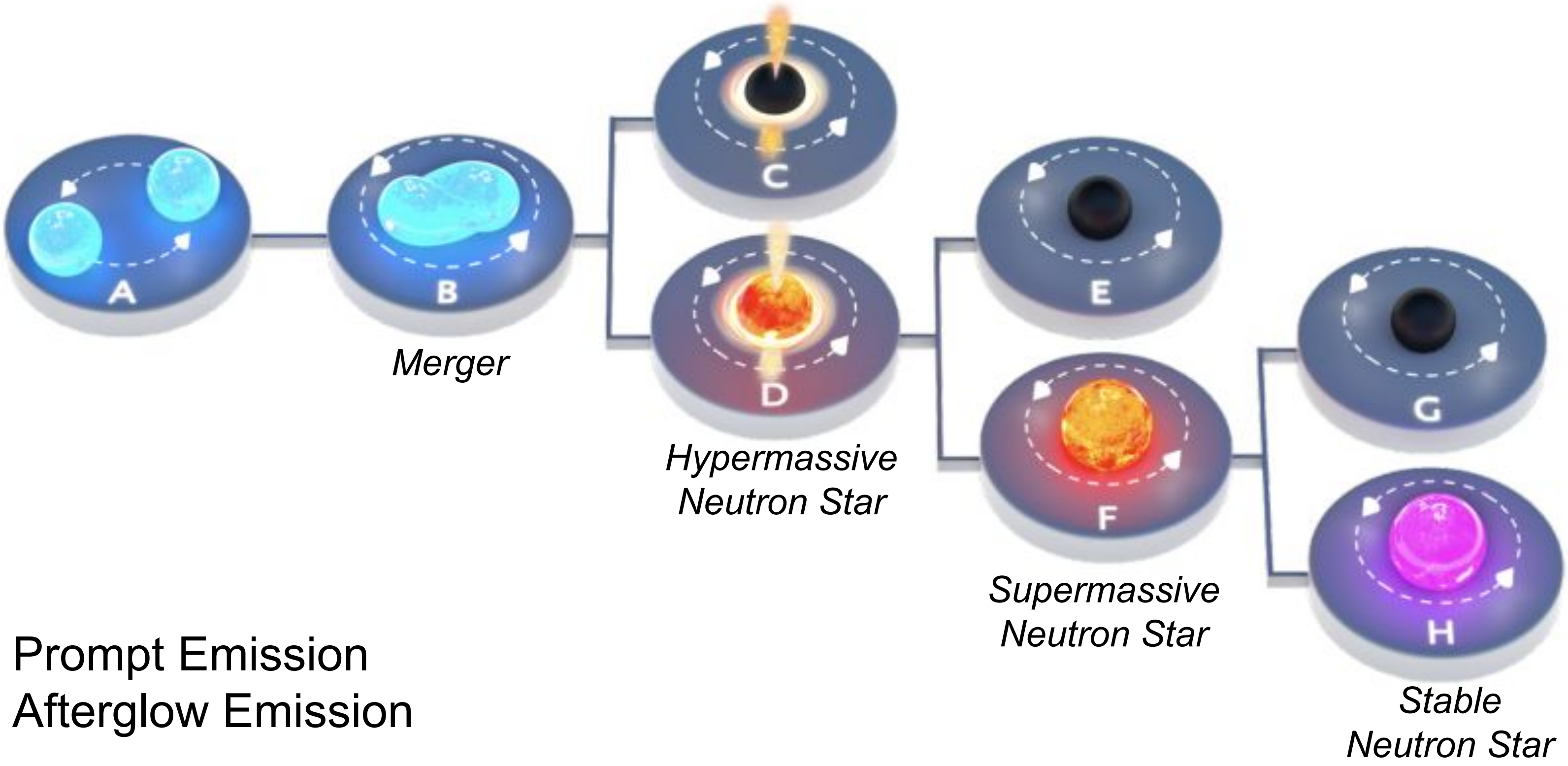


September 14, 2015
09:50:45 UTC



Adapted from [Abbott 2016](#)

The fate of Binary Neutron Star mergers



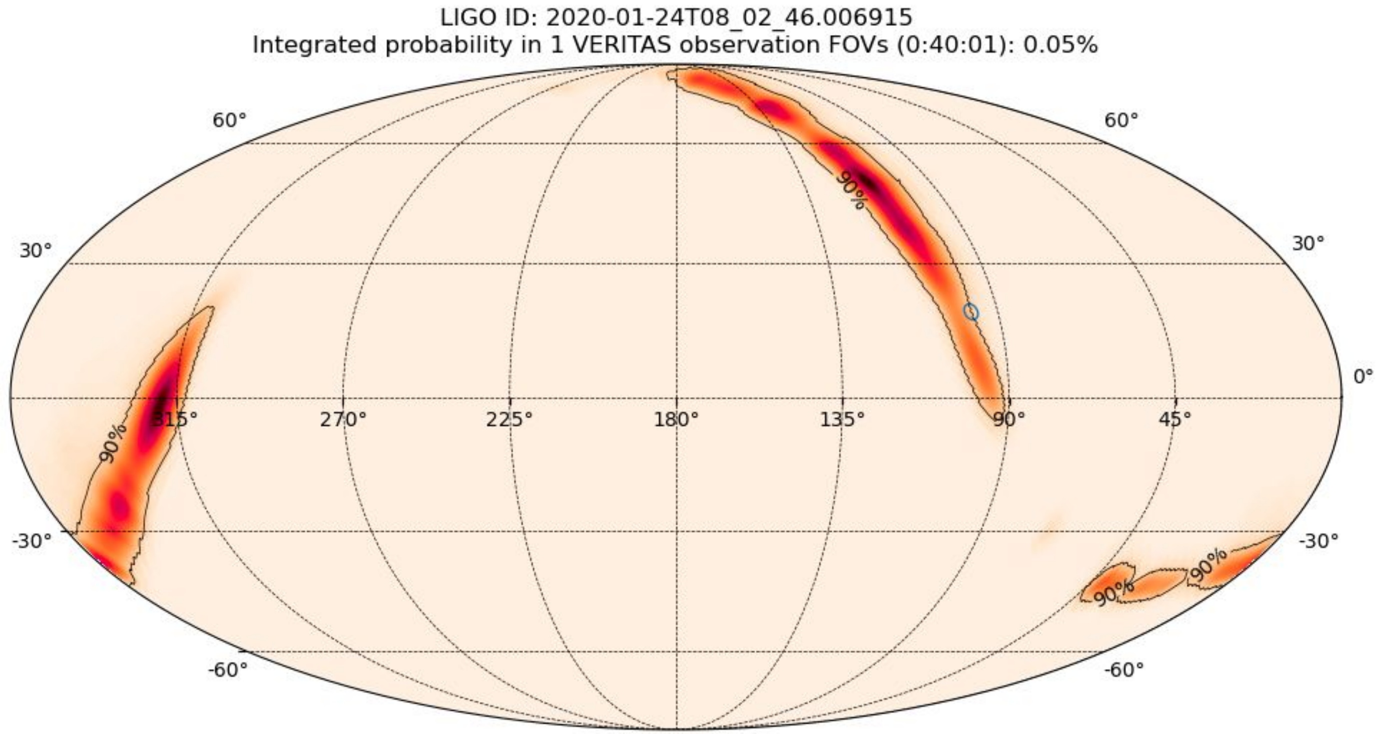
- Prompt Emission
- Afterglow Emission

Adapted from [N. Sarin 2021]

Appendix B:
Candidate FOVs on LIGO Skymap

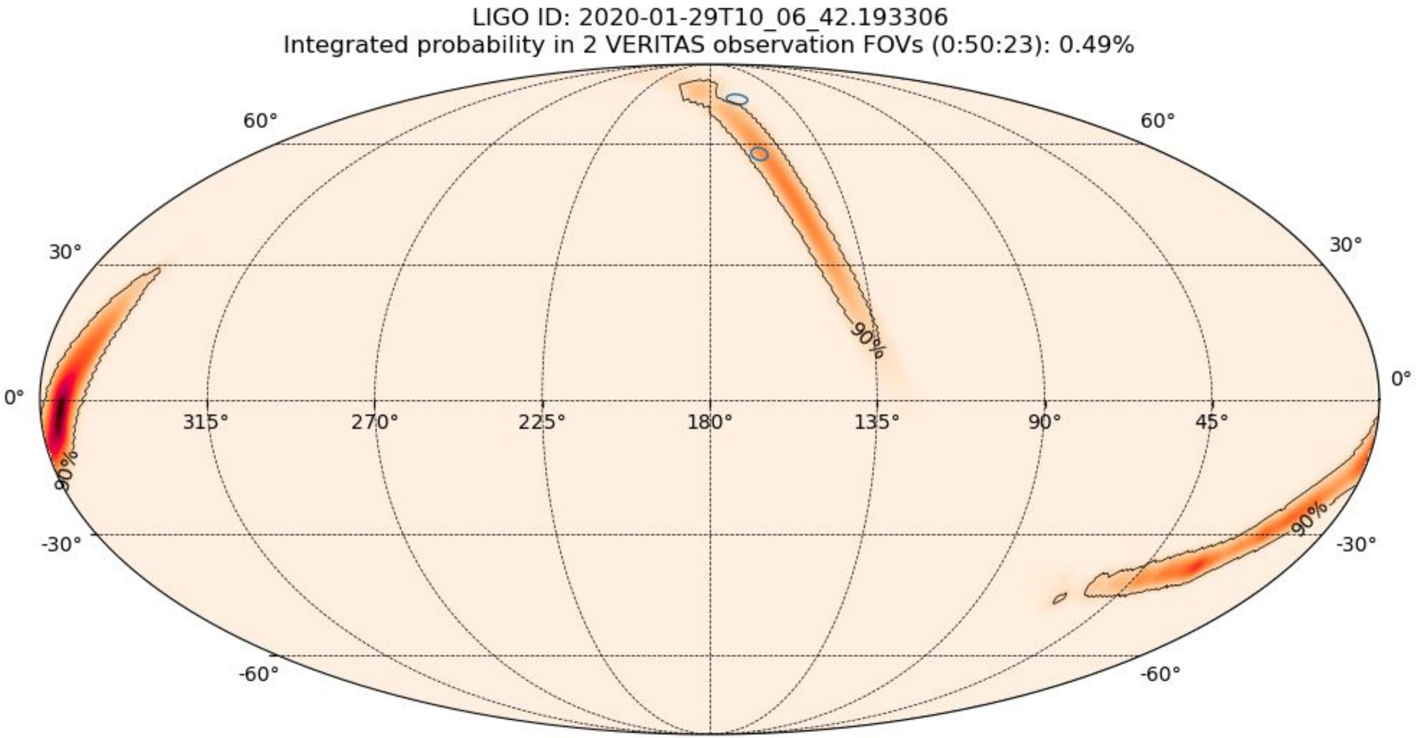
Run #: 95396, LIGO Event ID: 1263888184

- ➢ VERITAS Observing Time: 1/24/2020 7:22 UTC to 1/24/2020 8:02 UTC
- ➢ LIGO Event Time: 1/24/2020 8:02 UTC



Run #: 95528, LIGO Event ID: 1264327620

- VERITAS Observing Time: 1/29/2020 9:32 UTC to 1/29/2020 10:07 UTC
- LIGO Event Time: 1/24/2020 8:02 UTC



Run #: 95667, LIGO Event ID: 1264747176

- VERITAS Observing Time: 2/3/2020 UTC 6:14 to 2/3/2020 6:44 UTC
- LIGO Event Time: 2/3/2020 6:39 UTC