The Astrophysical Multimessenger Observatory Network

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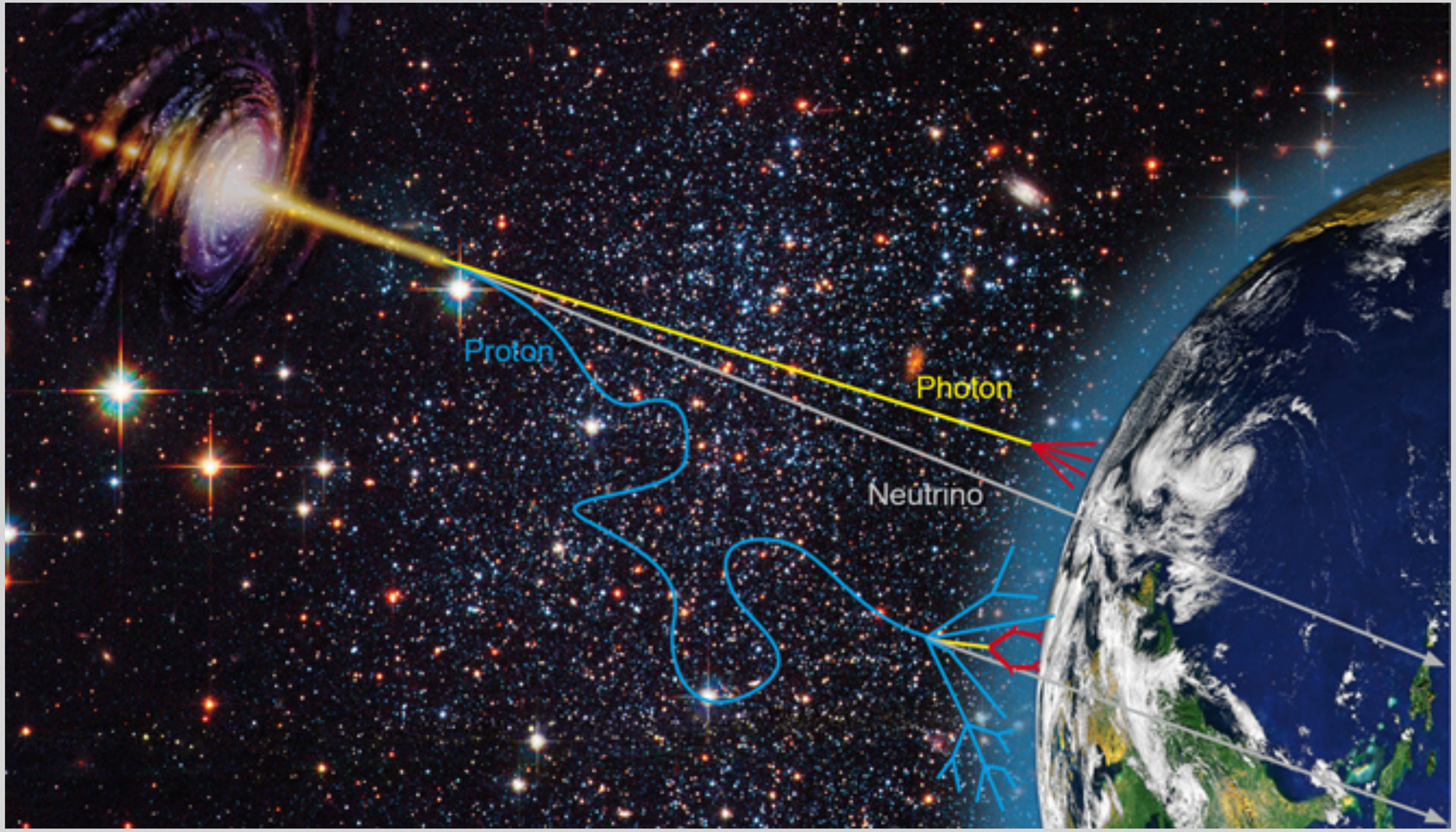
Studying the universe with multi-messenger astrophysics



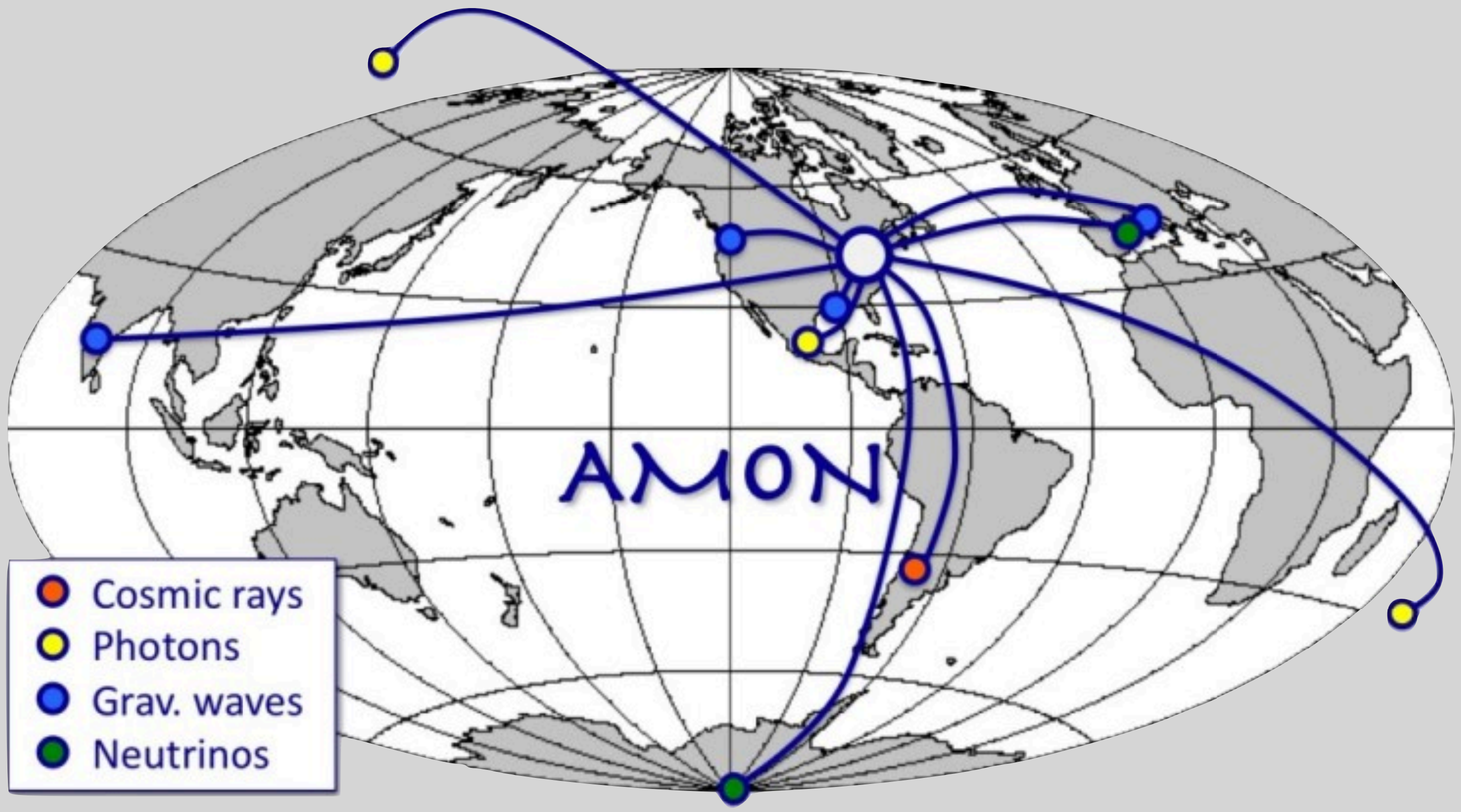
https://astro.desy.de/theory/multi_messenger_astrophysics/index_eng.html

Studying the universe with multi-messenger astrophysics

Force	Messenger	Messenger Detected	Sources?
EM	Photons	👍🏽	Myriads
Weak	Neutrinos	👍🏽	Sun, SN1987A, TXS 0506, TDE and NGC 1068 (3σ)
Strong	p, nuclei	👍🏽	Hotspots?
Gravity	Gravitational Waves	👍🏽	> 100 (a few with EM rad.)

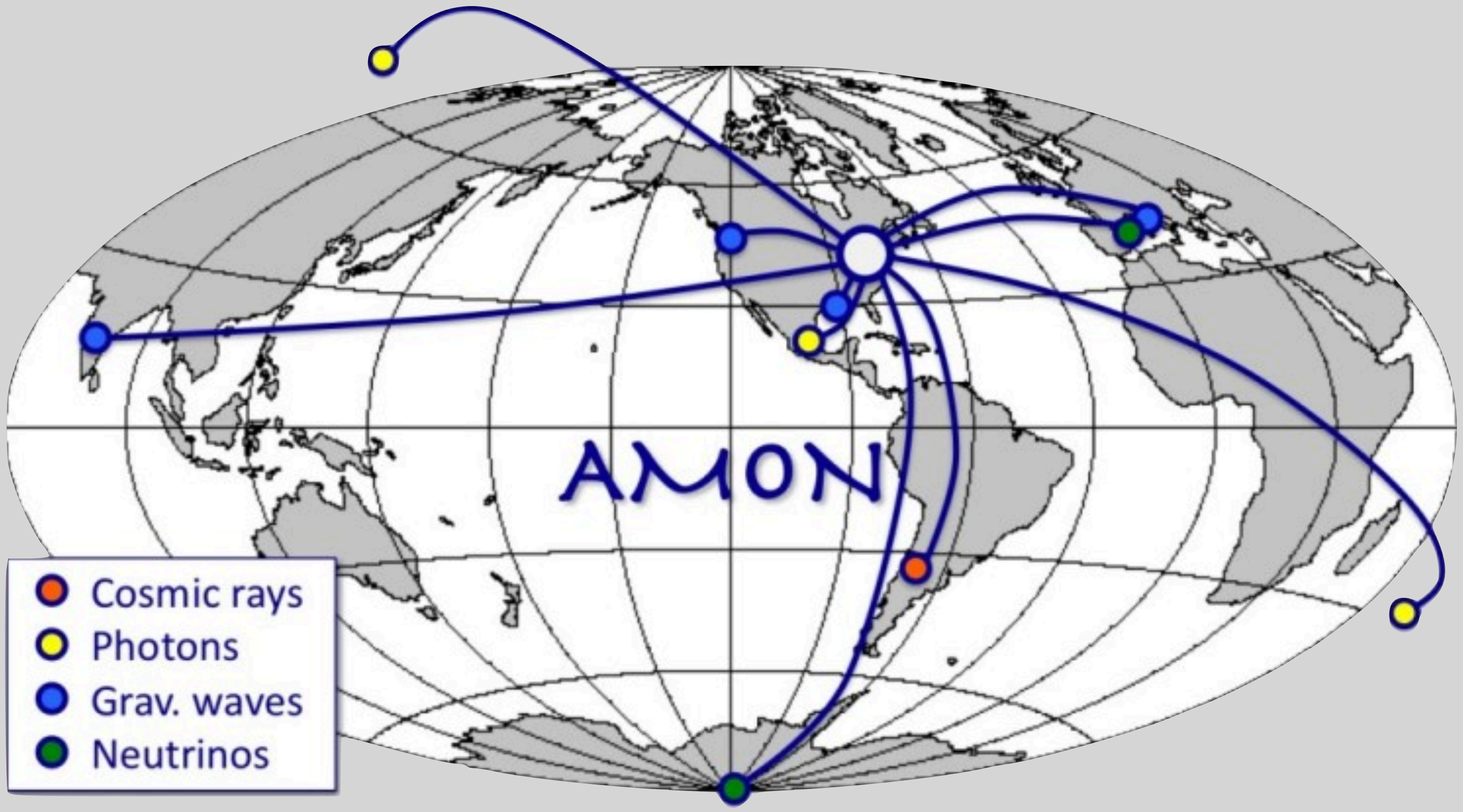
https://astro.desy.de/theory/multi_messenger_astrophysics/index_eng.html

The AMON Idea



- *Discovery of transient multi-messenger sources*
- *Trigger follow-up observations to identify and study counterparts*
- *Archival Analyses in search of multi-messenger activity*

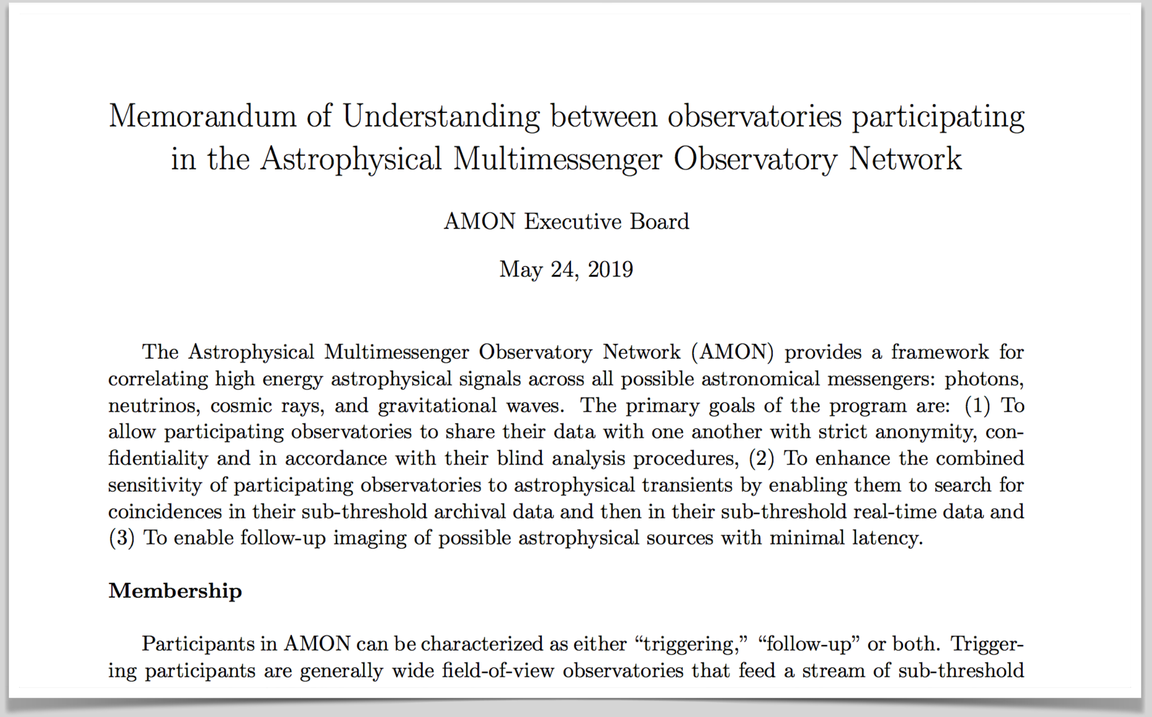
AMON: a framework to perform multi-messenger searchers



- **Real-time coincidences**
  - Use of **sub-threshold data**
- Archival Studies
  - Store events
  - Coincidence analyses
- Partners:
  - Triggering Observatories
  - Follow-up Observatories
- Pass-Through
  - Broadcast directly to GCN/TAN and SCIMMA

Joining AMON

- MoU: amon.psu.edu/join-amon/
- “As simple as possible, but no simpler”
- Follow-up as you will and report results internally (if private)
- Don’t publish on someone else’s private alert without their participation or permission
- Ultimately: Joint or separate (but coordinated) publication



Memorandum of Understanding between observatories participating in the Astrophysical Multimessenger Observatory Network

AMON Executive Board

May 24, 2019

The Astrophysical Multimessenger Observatory Network (AMON) provides a framework for correlating high energy astrophysical signals across all possible astronomical messengers: photons, neutrinos, cosmic rays, and gravitational waves. The primary goals of the program are: (1) To allow participating observatories to share their data with one another with strict anonymity, confidentiality and in accordance with their blind analysis procedures, (2) To enhance the combined sensitivity of participating observatories to astrophysical transients by enabling them to search for coincidences in their sub-threshold archival data and then in their sub-threshold real-time data and (3) To enable follow-up imaging of possible astrophysical sources with minimal latency.

Membership

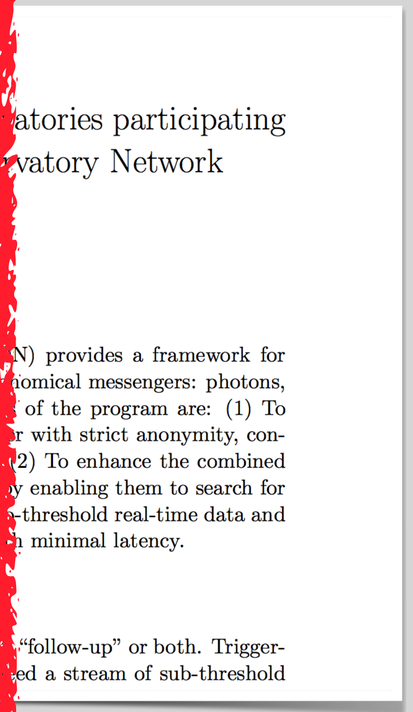
Participants in AMON can be characterized as either “triggering,” “follow-up” or both. Triggering participants are generally wide field-of-view observatories that feed a stream of sub-threshold

Joining AMON

- MoU: amon.psu.edu/join-amon/
- "As simple
- Follow-up a
  internally (i
- Don't publi
  alert withou
  permission
- Ultimately:
  coordinated) publication

– **Each observatory retains full rights over use of its data (see AMON MoU)**

– **All coincidence analyses require explicit permission of each participating collaboration**


atories participating
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N) provides a framework for
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2) To enhance the combined
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minimal latency.

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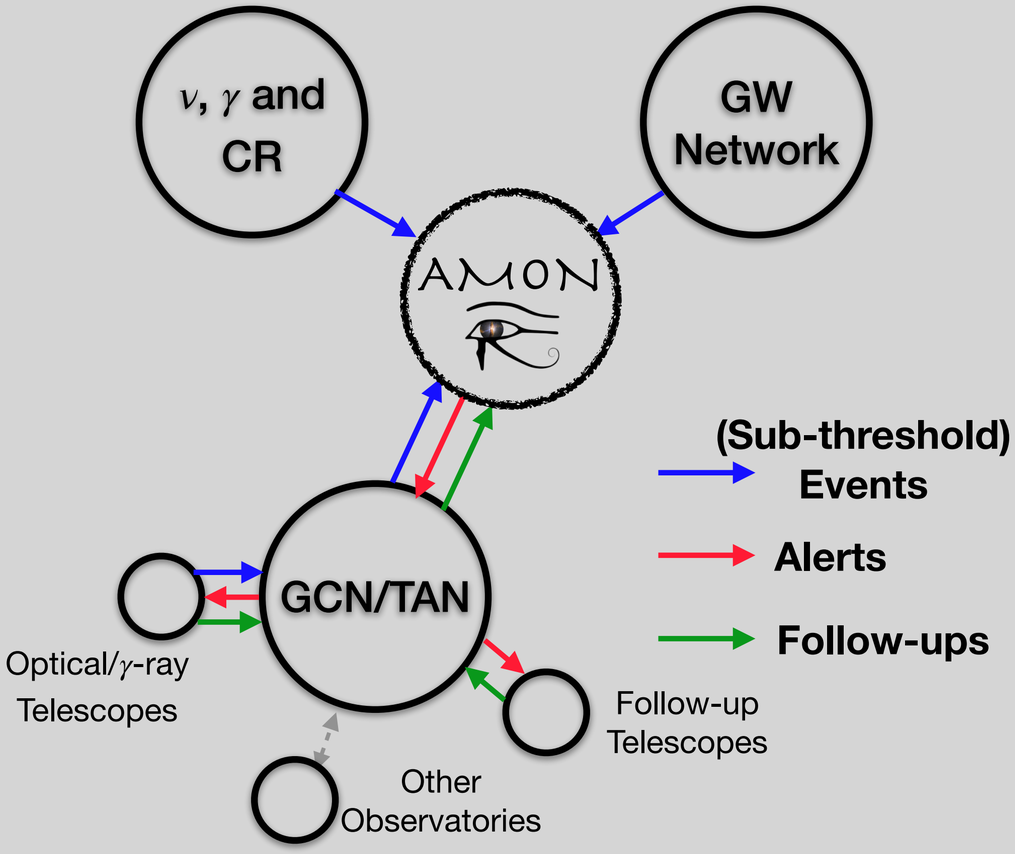
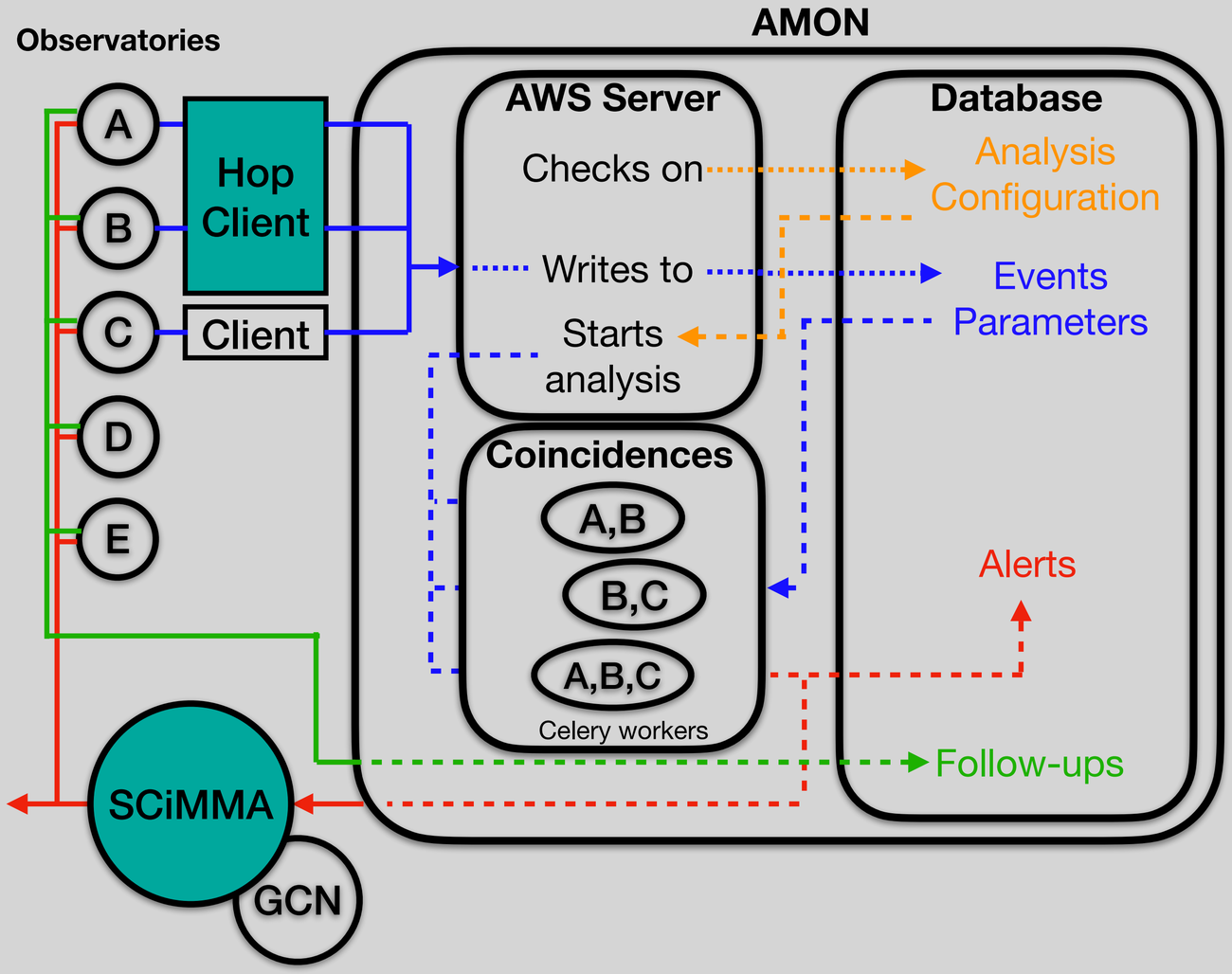
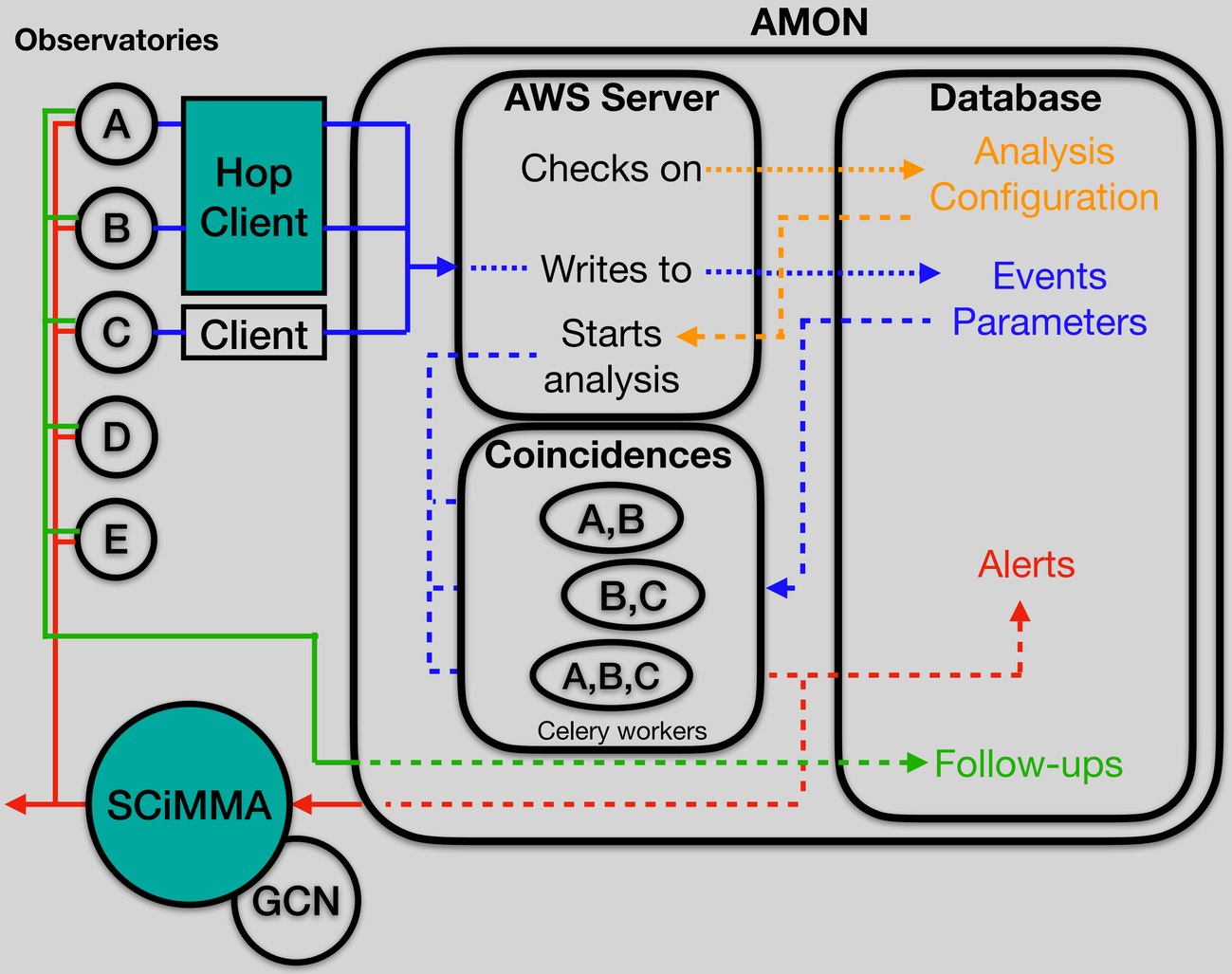
AMON Network and Hardware





Technical Implementation: AMON uses an asynchronous distribution system to calculate coincidence searches in real-time.



Powered by MySQL

Celery

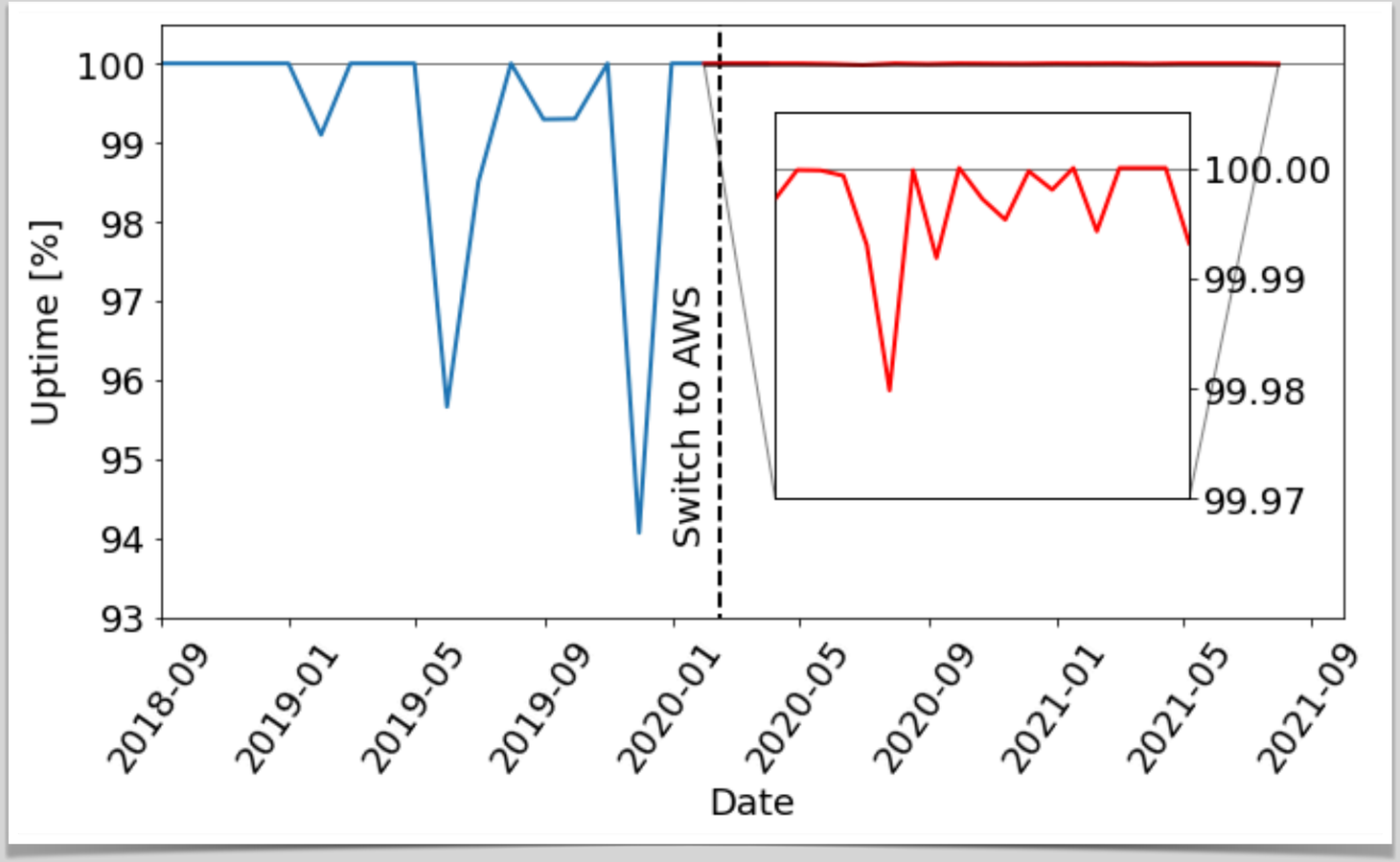
TWISTED

COMET

AmonPy software in GitHub:https://github.com/AMONCode/Analysis

AMON Server

- Recently transitioned from PSU servers to AWS servers

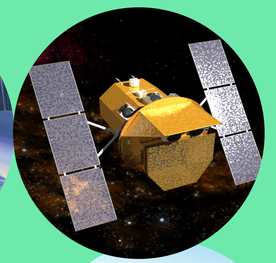


AMON Members (and per-project* members)

CR

Pierre Auger

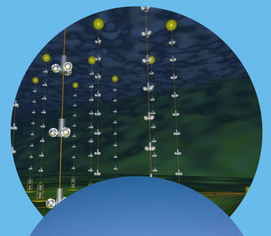
γ



SWIFT
VERITAS
HESS
MAGIC

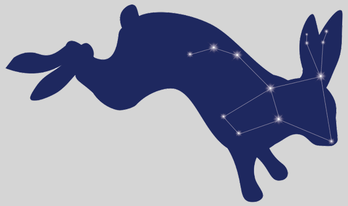
FACT
Fermi
HAWC

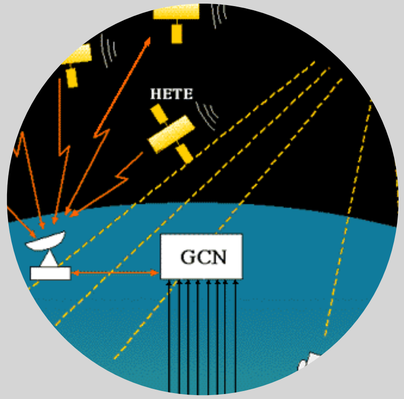
ν



IceCube
ANTARES

AMON
Astrophysical Multimessenger Observatory Network

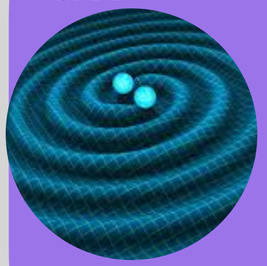




γ

LMT
Palomar Transient Factory
MASTER

GW

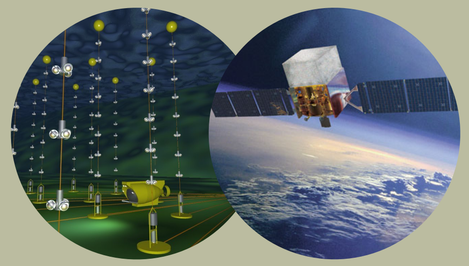


***LIGO-Virgo**

The NuEM channel: analyses

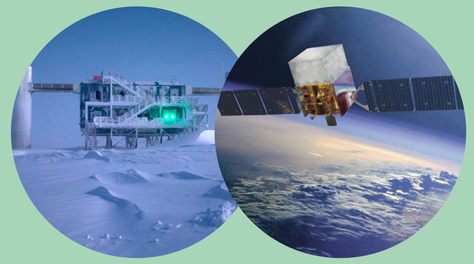
Archival Analysis

Real-time analysis

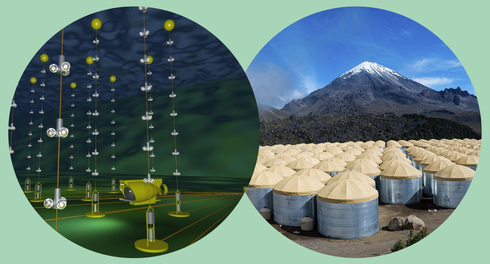


ANTARES +Fermi LAT

IceCube + HAWC



IceCube +Fermi LAT



ANTARES + HAWC*

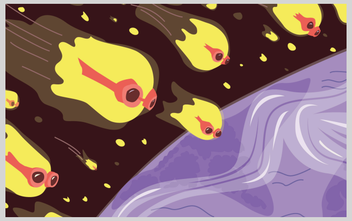
*Preliminary results in this presentation

Coincidences in the NuEM Channel

- FAR threshold is < 4 per year for real-time alerts.
- For archival coincidences we looked at the ones with <1 per year

Name	R.A. [°]	Decl. [°]	$\delta\theta$ [°]	FAR [yr^{-1}]	Time UTC
Real-time alerts					
NuEM-211020A	99.76	9.07	0.17	0.86	2021-10-20 14:13:38
NuEM-210515A	93.64	14.66	0.15	3.93	2021-05-15 00:20:43
NuEM-210515B	93.93	12.51	0.20	1.90	2021-05-15 00:19:27
NuEM-210111A	162.34	19.46	0.37	3.85	2021-01-11 13:06:41
NuEM-201124A	134.99	7.74	0.23	2.96	2020-11-24 14:13:37
NuEM-201107A	140.20	29.76	0.15	3.49	2020-11-07 15:55:31
ANTARES-Fermi 200704A	255.42	-34.48	0.43	0.98	2020-07-04 15:53:48
NuEM-200202A	200.30	12.71	0.17	1.39	2020-02-02 14:07:52
ANTARES-Fermi 191011A	49.96	18.80	0.40	1.21	2019-10-11 15:54:32
Archival Coincidences					
ANTARES-Fermi	248.00	-7.7	0.07	0.09	2012-11-21 20:19:52
ANTARES-Fermi	279.68	-5.05	0.10	0.09	2014-08-05 11:13:33
HAWC-IceCube	4.93	2.96	0.16	0.99	2016-12-12 04:38:41
HAWC-IceCube	173.99	2.27	0.53	0.026	2018-04-12 07:54:51
HAWC-ANTARES	25.6	25.0	0.2	0.7	2016-01-08 04:39:38
HAWC-ANTARES	222.8	-0.8	0.2	0.87	2017-09-07 01:21:22
HAWC-ANTARES	85.4	3.4	0.2	0.41	2019-03-29 03:01:18

More Comments on NuEM Channel

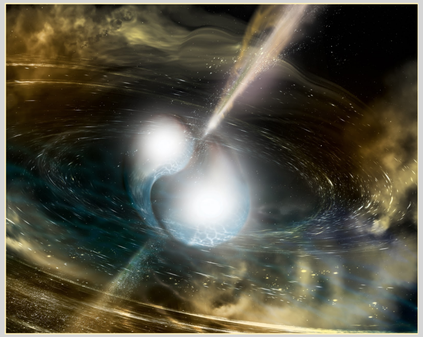


- AMON NuEM channel is active
  - Searching for high-energy gamma-ray and neutrino coincidences
  - Using sub-threshold data
- We encourage follow-up observations of these coincidences

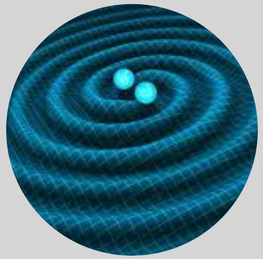
Name	Followed by
NuEM-211020A	ANTARES,Swift-XRT
NuEM-210515A/B	ANTARES
NuEM-210111A	ANTARES, INTEGRAL,MAXI
NuEM-201124A	ANTARES
NuEM-201107A	*Fermi*-LAT
NuEM-200202A	MASTER, ANTARES
FERMI-ANTARES-191011A	MASTER

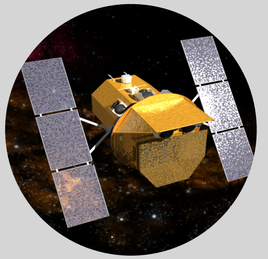
- Visit the https://amontom.science.psu.edu/ to query alerts

A glimpse of a GW+EM with AMON: Swift + LVC O3 analysis

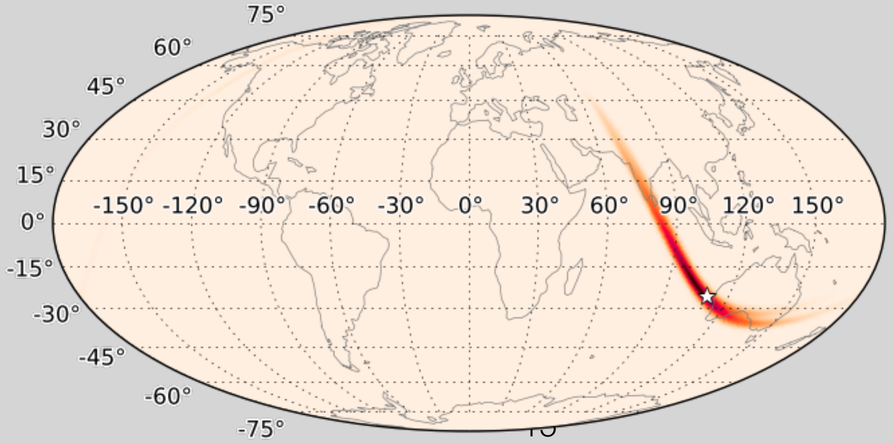


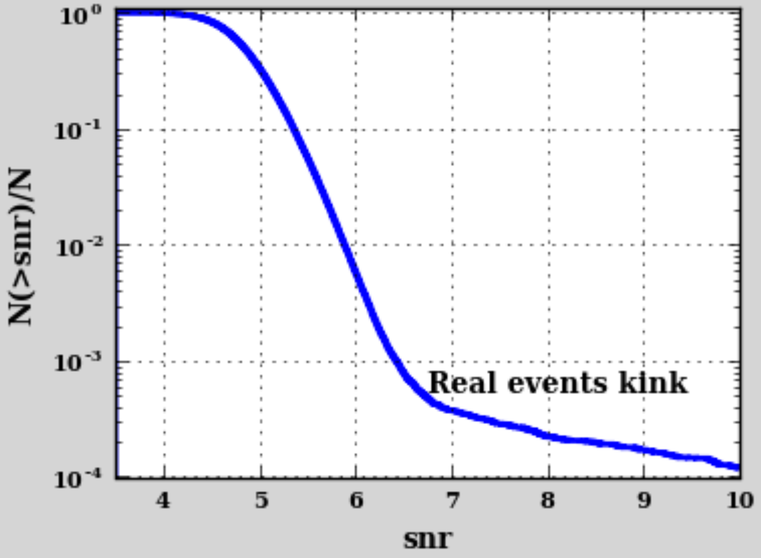
BNS Mergers





	Low Latency CBC Detection Pipelines	Coded Mask Imager
Data	• Like GSTLAL • FAR, Mass Estimates or NS probability **BAYESTAR Skymaps** • 2D or 3D sky map localizations	• Sub-threshold Image Peaks • Few arcmin localization • Exposure from milliseconds-minutes • 15-150 KeV
Background	**Detector noise** **Non-astrophysical transients;** • Trucks driving by, etc.	**Detector Noise Fluctuations**





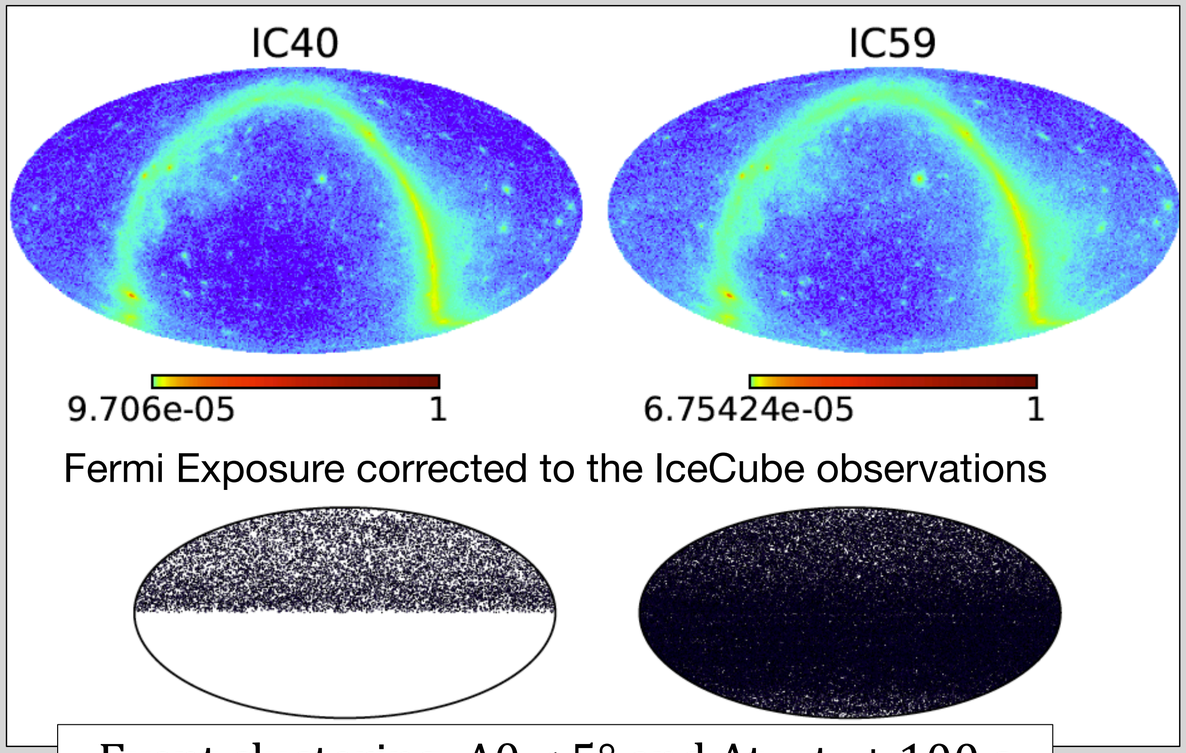
DeLauny, Tohuvavohu 2021
https://arxiv.org/abs/2111.01769

AMON server is up and running

- AMON greatly **simplifies multimessengers searches**:
  - Common data format, transfer protocol, event database, MoUs.
- Past:
  - Archival analyses, help in the discovery of TXS 0506+056.
- Present:
  - AMON is issuing alerts from sub-threshold data for multimessenger searches in real-time.
  - Pass-through alerts
- Future:
  - Updating to SCIMMA cyber-infrastructure
- New participants are always welcome!

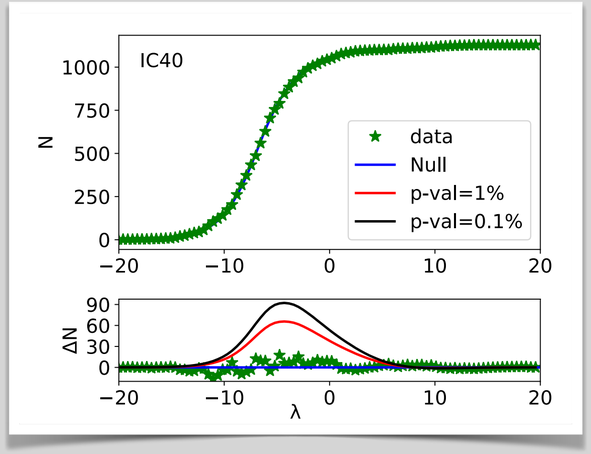
Back-up

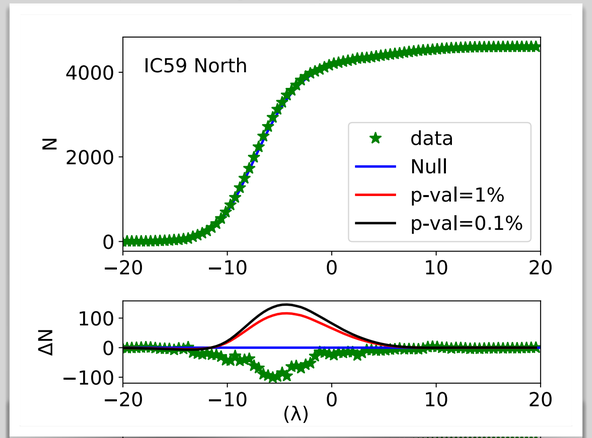
IceCube-*Fermi*LAT

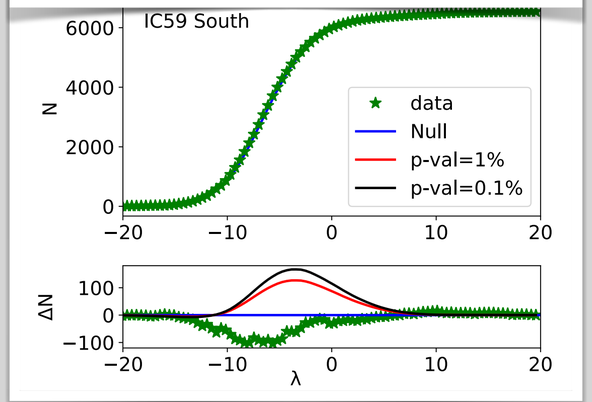


Event clustering: $\Delta\theta < 5°$ and $\Delta t = t_0 \pm 100$ s

	IC40	IC59
Num. γ	~15x10^6	~18x10^6
Num. ν	~13x10^3	~108x10^3
Likelihood	~Null	(North+ South) p~5%

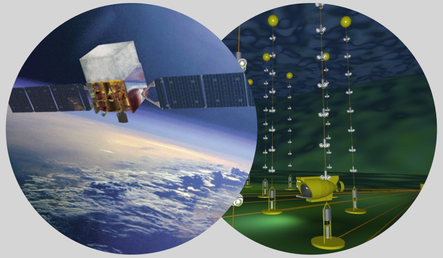






- ApJ Link: http://iopscience.iop.org/article/10.3847/1538-4357/aad195/meta

ANTARES - Fermi LAT



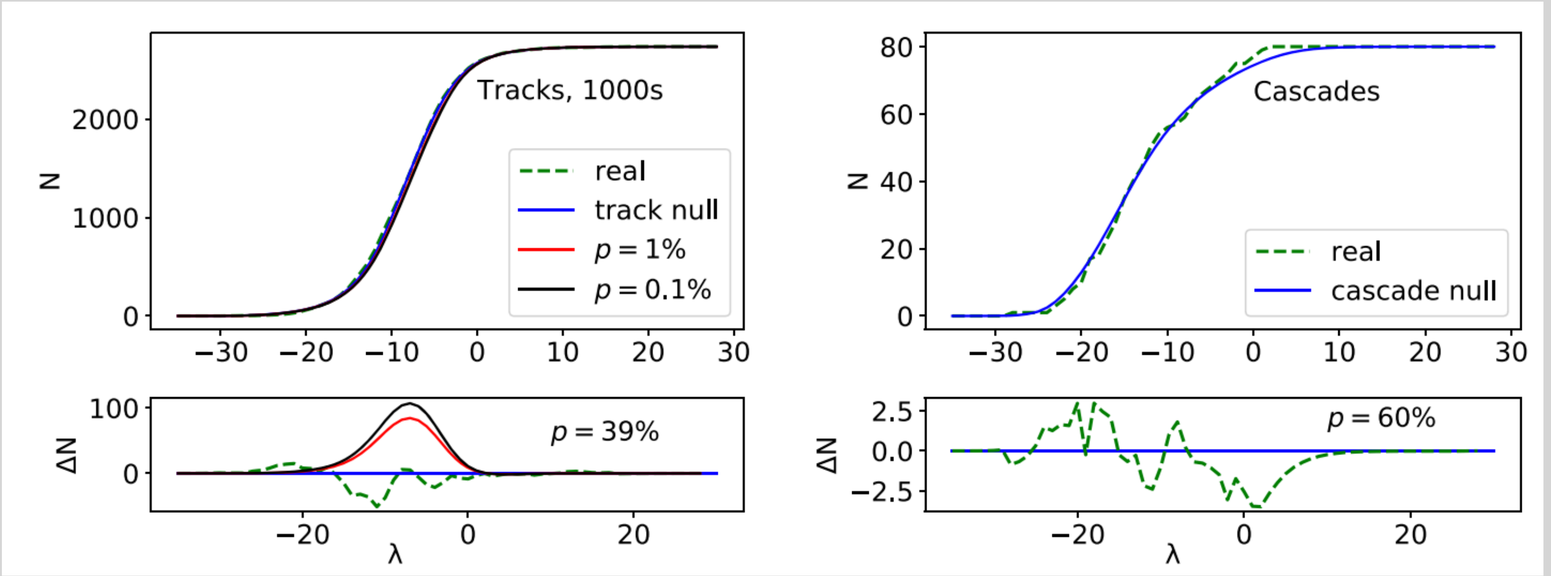


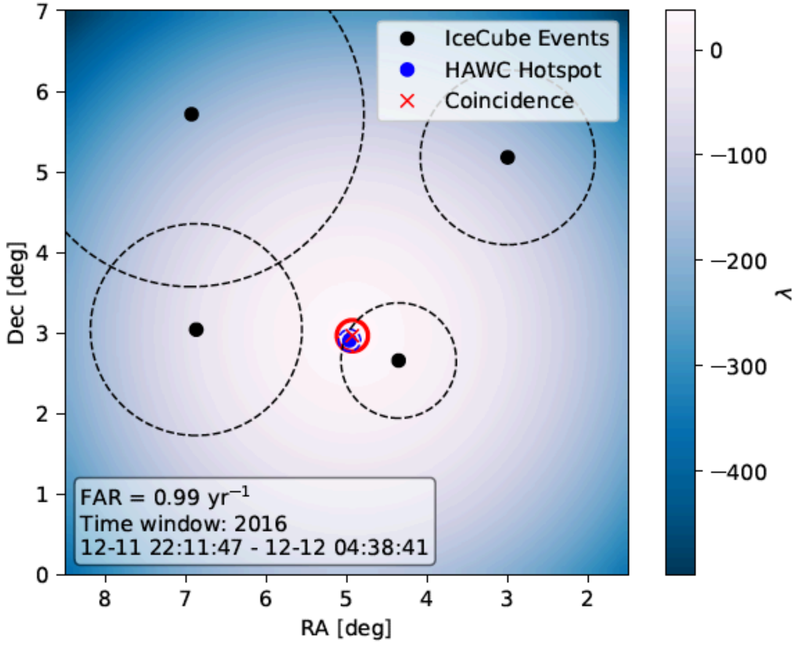
Table 2
High-λ Events

Date	Time (UTC)	MJD	Δt (s)	Position (J2000)	$r_{1\sigma}$	$N_{\rm ph}$	λ	FAR ($\rm yr^{-1}$)
2012 Nov 21	20:19:52	56252.8471	307	$248.^{\circ}00, -7.^{\circ}70$	$2'$	1	18.9	0.09
2014 Aug 5	11:13:33	56874.4677	750	$279.^{\circ}68, -5.^{\circ}05$	$3'$	2	18.8	0.09

Note: Date, Time, and MJD show the central time of the coincidence, while Δt measures the separation between the earliest and latest particles in the coincidence in seconds. Position gives the R.A. and decl. (in degrees) of the best-fit position, while $r_{1\sigma}$ gives the approximate 1σ error on the angular uncertainty in arcminutes (39% containment, assuming a Gaussian form). $N_{\rm ph}$ is the number of photons in the coincidence. The false alarm rate (FAR) is calculated as the number of events of that λ or higher expected per year.

Turley, et al 2019

IceCube - HAWC



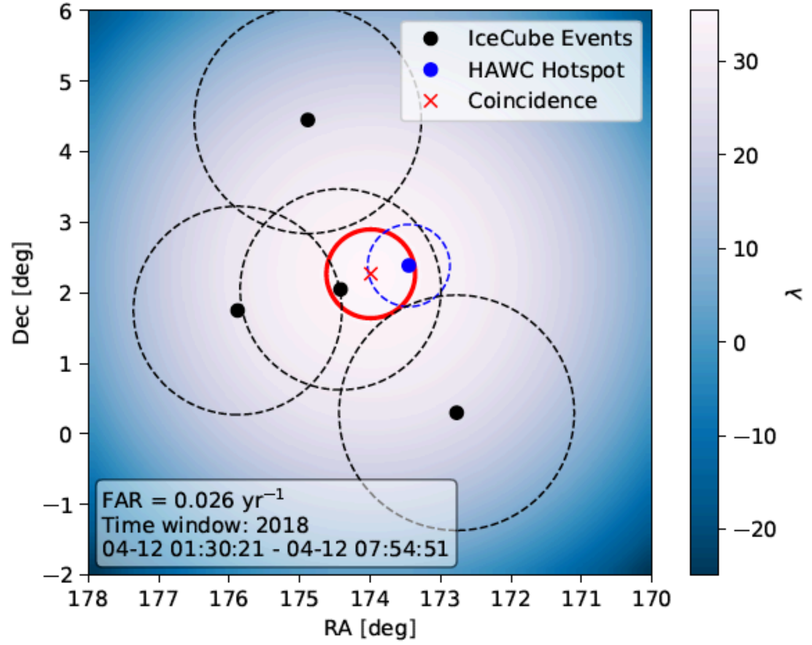
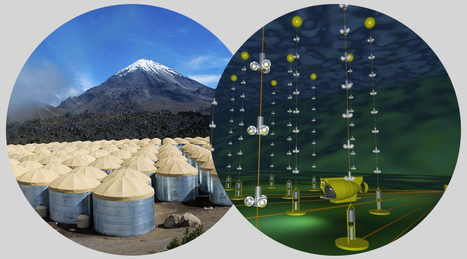
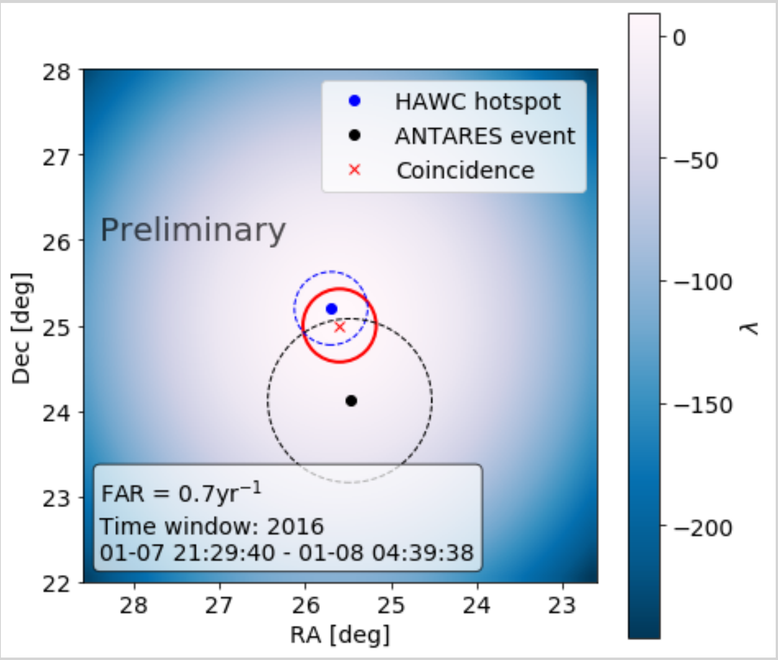


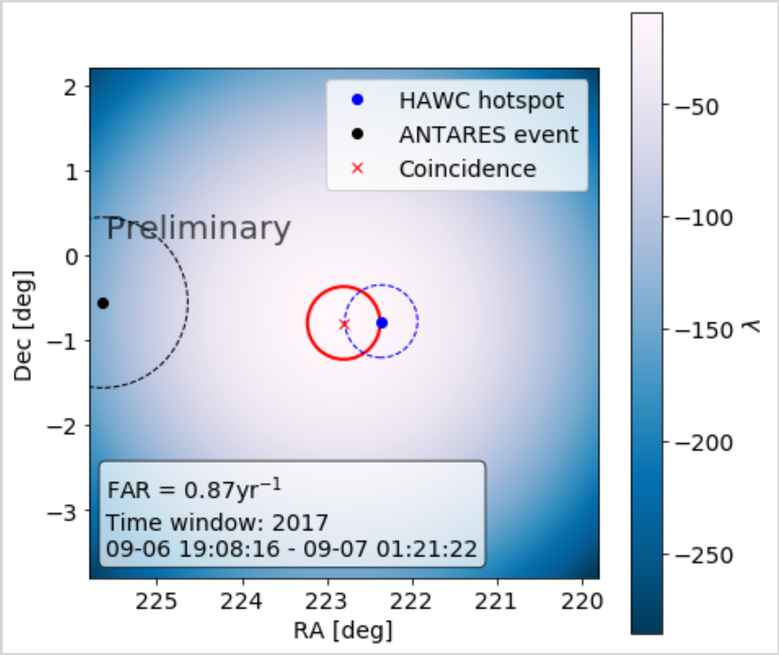
Figure 5. Skymaps of the coincidences with the lowest FAR found in the 3 years of archival data. Position of the individual events are marked with the dots. The best-fit combined positions $\boldsymbol{x}_{\text{coinc}}$, found after optimizing Eq. 3, are marked with a cross. Circles are the 50% containment region.

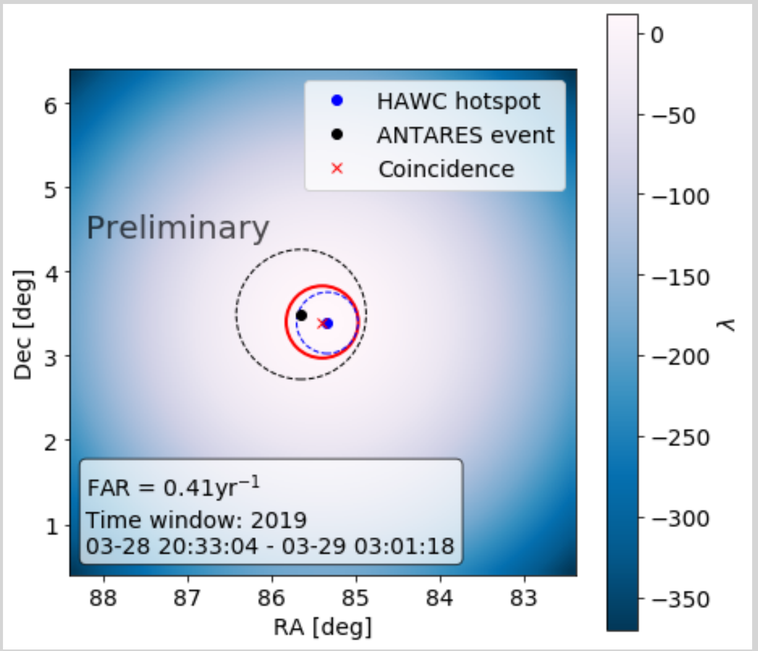
H. A. Ayala Solares *et al* 2021 *ApJ* **906** 63

HAWC-ANTARES









Ayala et al. 2021 ICRC
https://arxiv.org/abs/2108.04920