AMON
Astrophysical Multimessenger Observatory Network

The Astrophysical Multimessenger Observatory Network

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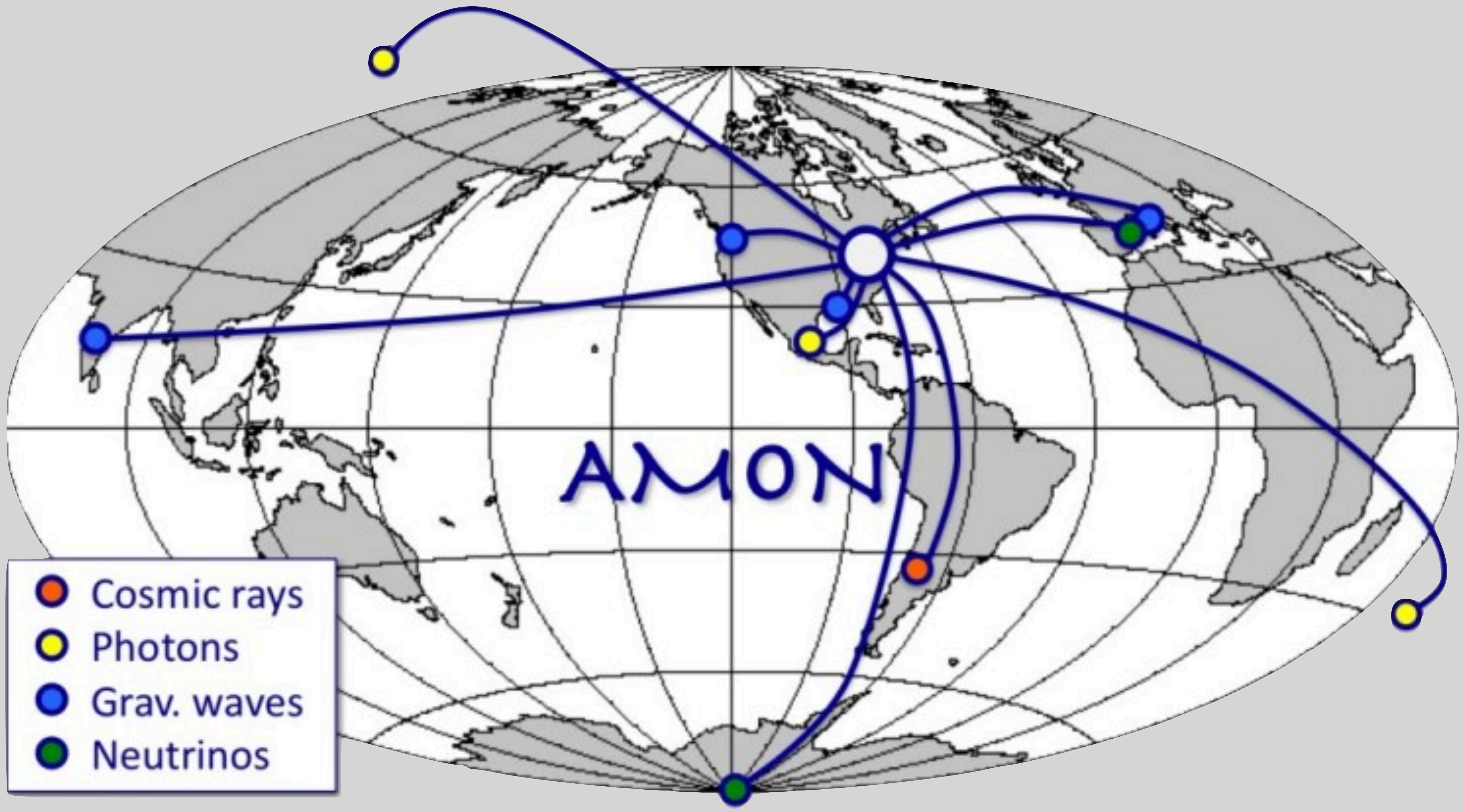
PennState
Eberly College of Science

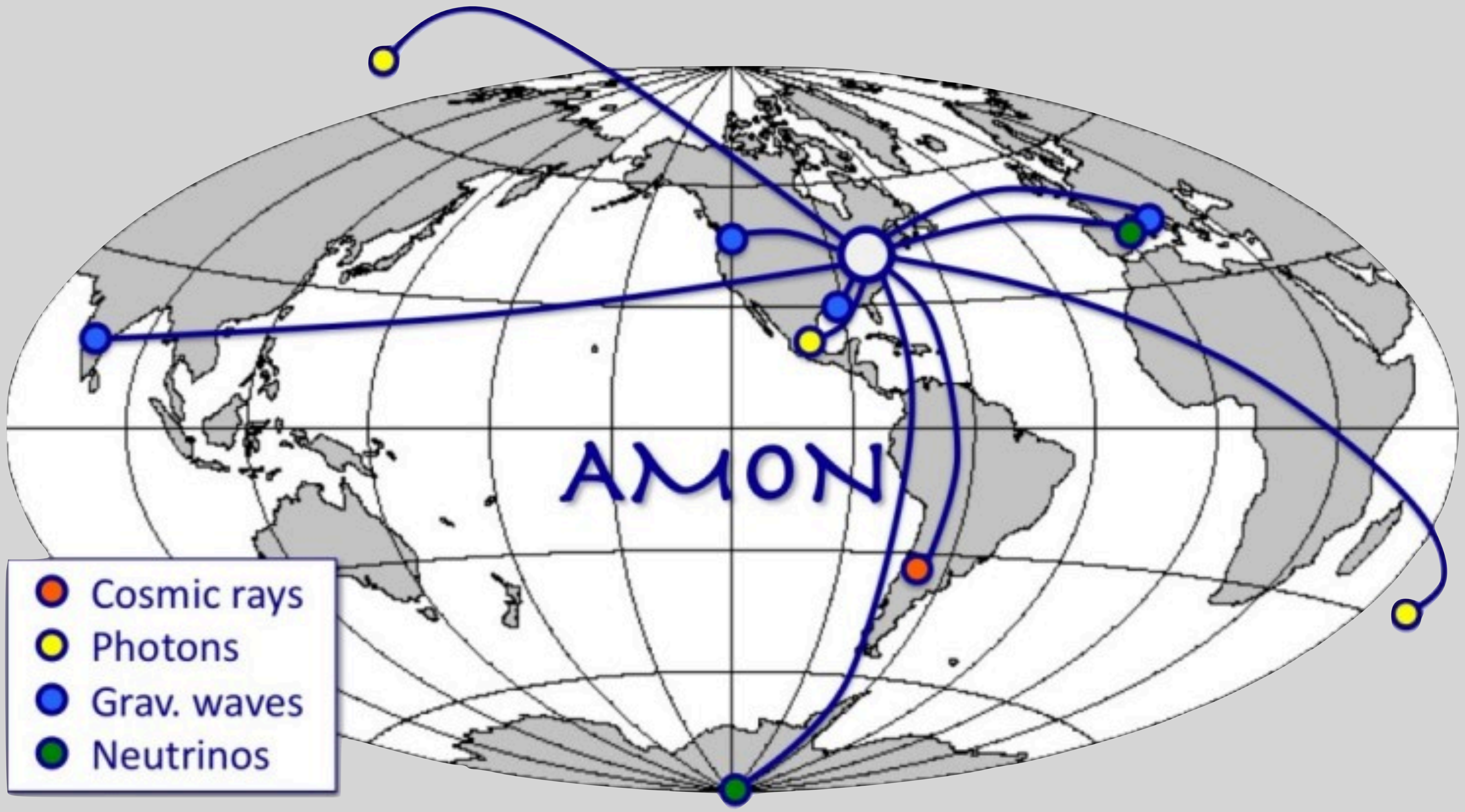

NEUTRINO

Astrophysical Multimessenger Observatory Network: a Multimessenger approach



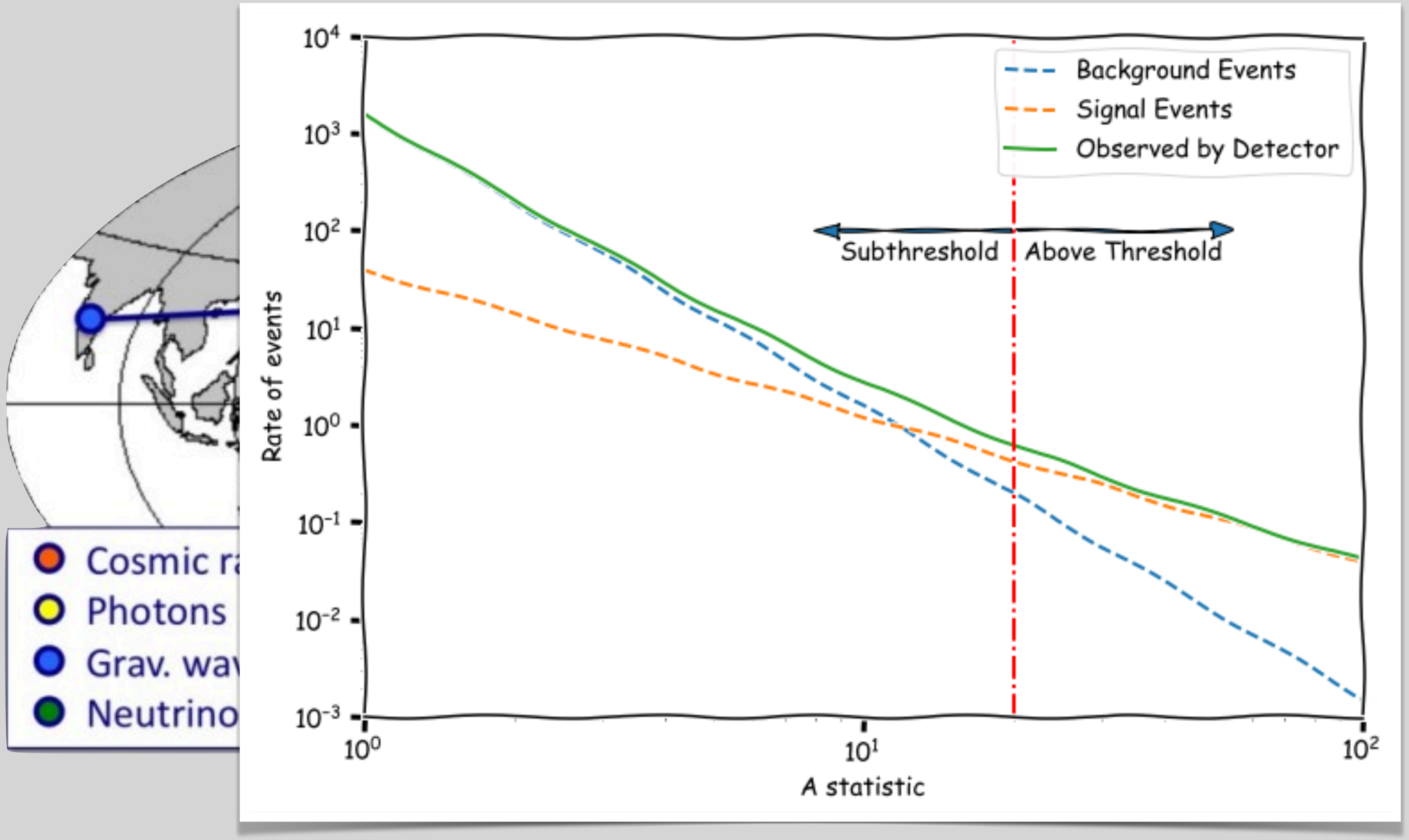
- *Discover transient multi-messenger sources*
- *Trigger follow-up observations to identify and study counterparts*
- *Analyze archival data in search of multi-messenger activity*

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

AMON: a framework to perform multi-messenger searchers



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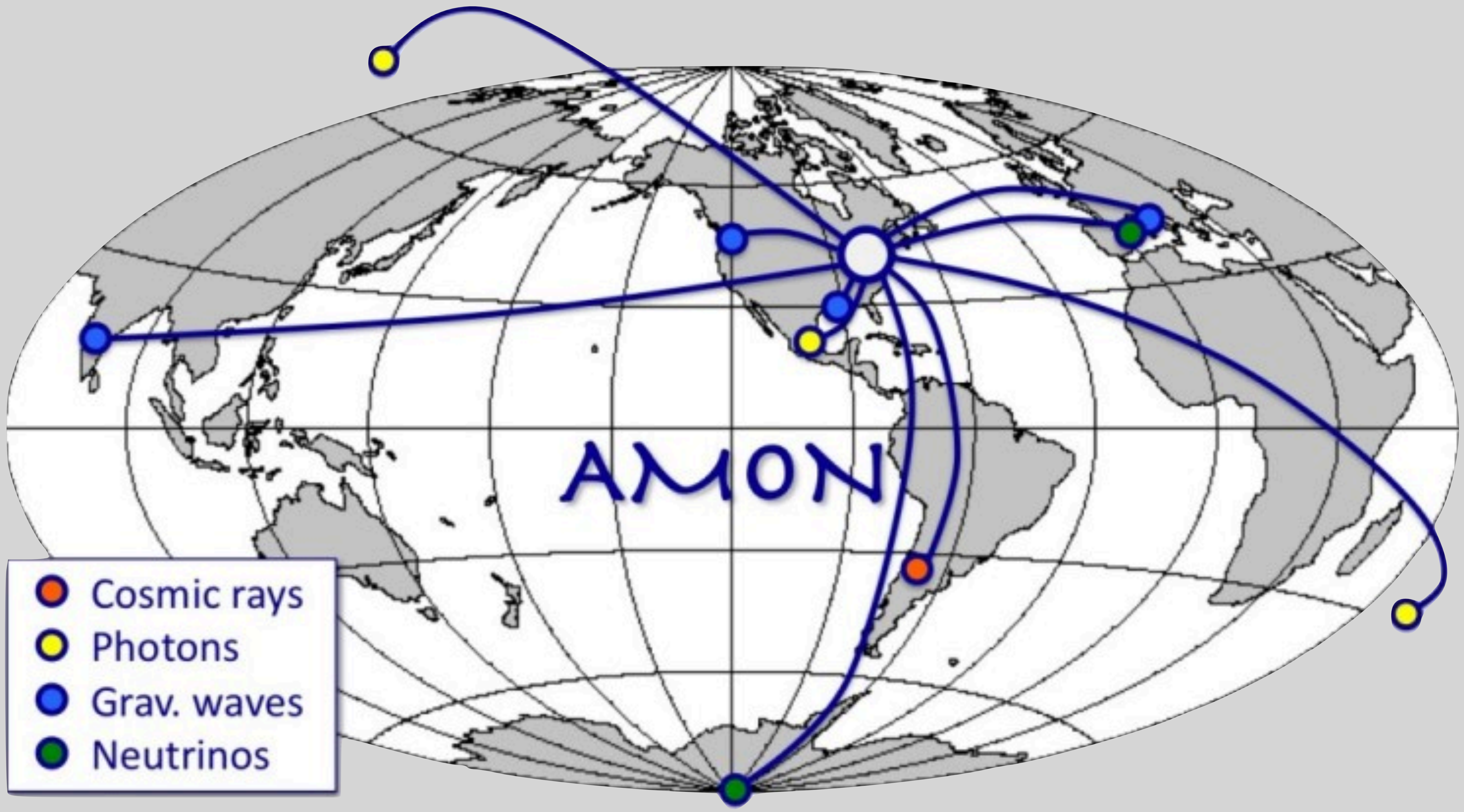

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AMON Members (and per-project* members)

CR

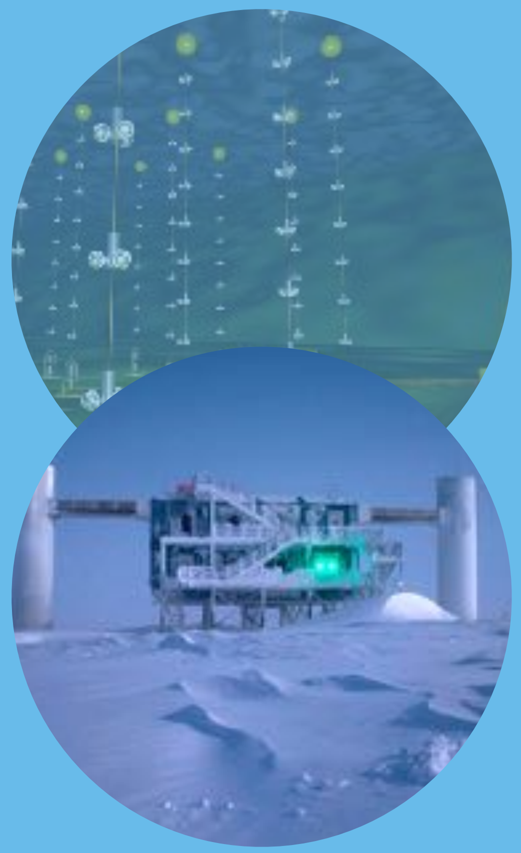
Pierre Auger

γ

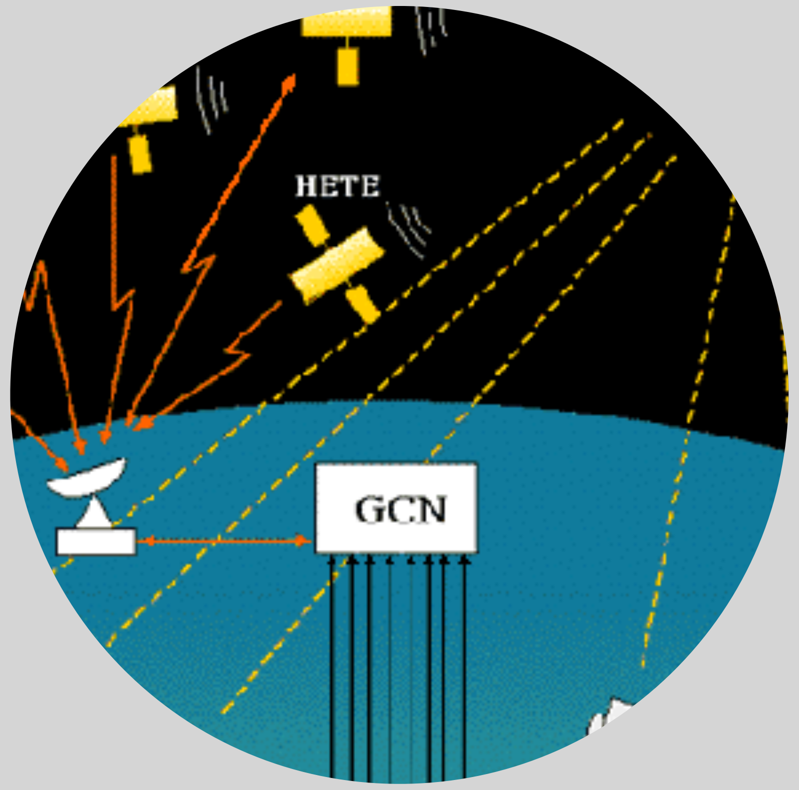
SWIFT
VERITAS
HESS
MAGIC

FACT
Fermi
HAWC

ν



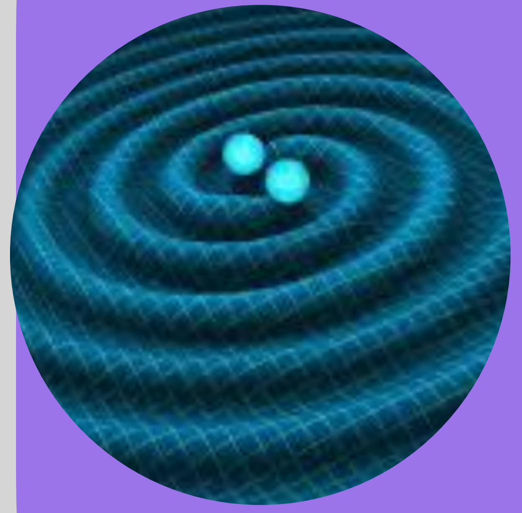
IceCube
ANTARES



γ

LMT
Palomar Transient Factory
MASTER

GW

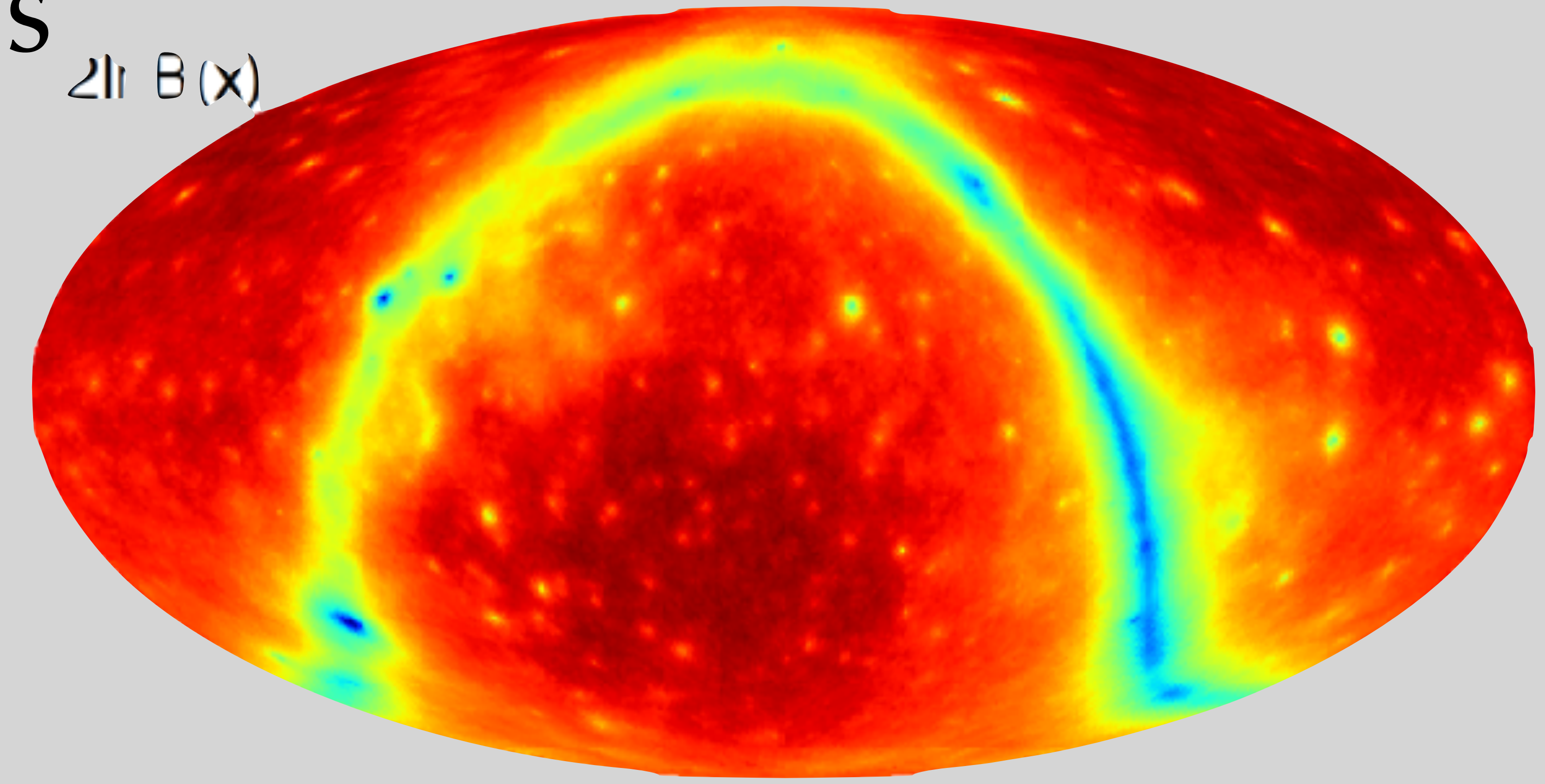


*LIGO-Virgo

AMON: a brief history

$$\lambda = 2 \ln \frac{(P_{\gamma 1}(\vec{x}) P_{\gamma 2}(\vec{x}) \ldots P_{\gamma n}(\vec{x})) n! (P_\nu(\vec{x}))}{B_1(\vec{x}, E_1, \theta_1) B_2(\vec{x}, E_2, \theta_2) \ldots B_n(\vec{x}, E_n, \theta_n)}$$

- Prehistory: Archival multimessenger analyses + partner negotiations
  - IceCube and Fermi



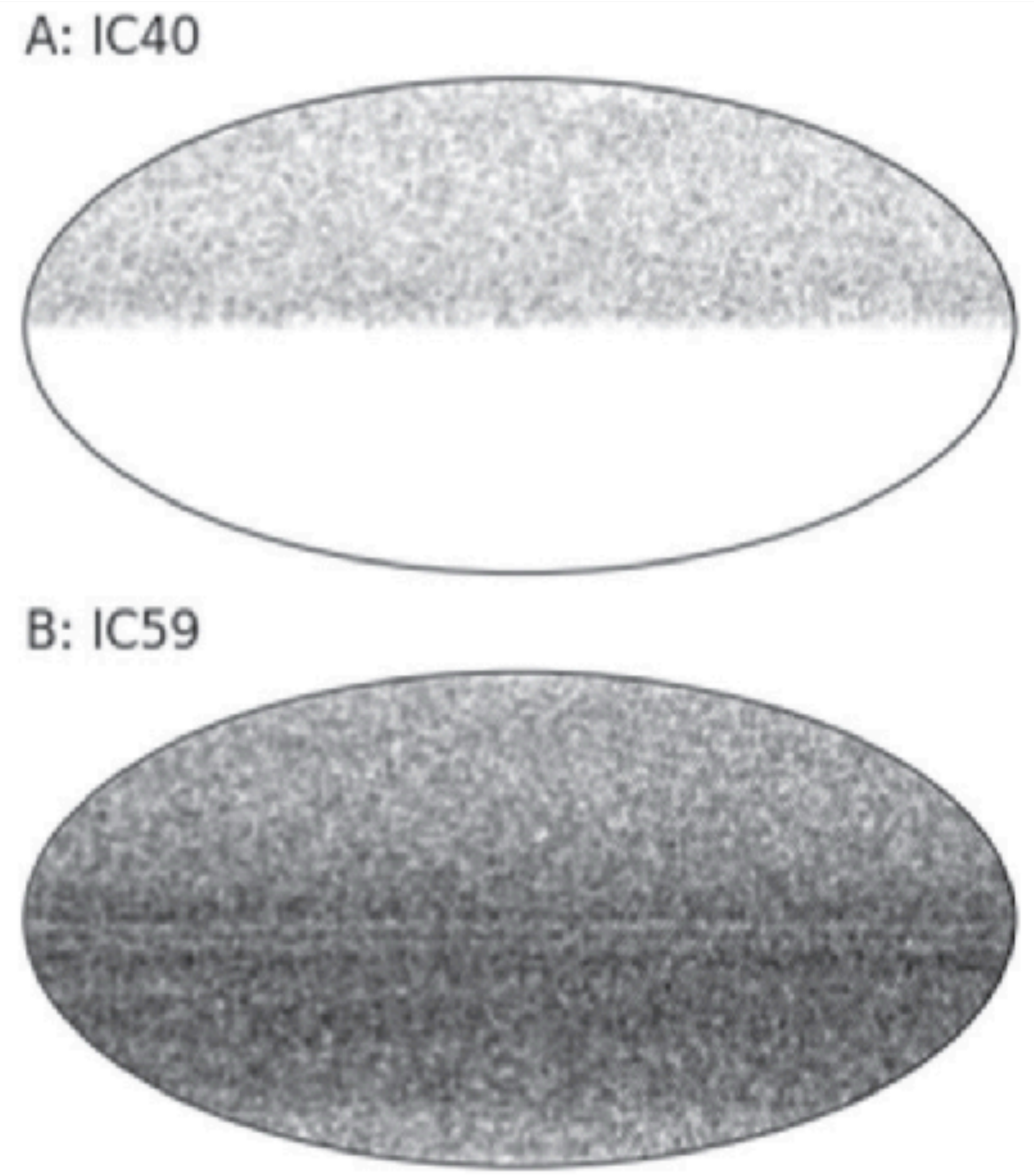


Figure 1. Neutrino sky positions from IC 40 and IC 59. No cosmic structure nor significant point-source detections have been reported from these data (Abbasi et al. 2011; Aartsen et al. 2013c).

Keivani+15, Turley+18

AMON: a brief history

- Prehistory: Archival multimessenger analyses + partner negotiations
- First Alerts: IceCube likely-cosmic neutrino pass-through alerts, April 2016

Bacodine April 8, 2016 at 10:28 PM
To: Derek Fox
Reply-To: Scott Barthelmy
AMON IceCube HESE Notice type added to GCN

TO: All GCN Notice recipients
RE: AMON IceCube HESE Notice type is available
DT: 08 April 2016

INTRODUCTION:

The GCN system has been modified to incorporate the distribution of candidate coincidence events produced within a single instrument and/or between multiple instruments within the AMON project.
Currently, only HESE (High Energy Starting Event) notices within the IceCube instrument are being produced.
This will expand to include the AMON_ICECUBE_COINC type and others in the future.
Like all the other sources of transient information within the GCN system,
users can elect to receive this AMON_ICECUBE_HESE Notice type.

OCCURRENCE RATE:
There will be about 4 AMON_ICECUBE_HESE Notices per year.

TIME DELAY:
The time delays for this notice type will range from 0.5 to 3 minutes
after the neutrino interacts in the IceCube detector.

LOCATION ERROR:
The location uncertainties are in the 2-9 deg range (radius, stat+sys, 90% containment).
The uncertainty in the location will depend on:
(a) the energy of the neutrino, and
(b) the track-vs-cascade nature of the energy deposited in IceCube.

AMON: a brief history

- Prehistory: Archival multimessenger analyses + partner negotiations
- First Alerts: IceCube likely-cosmic neutrino pass-through alerts, April 2016
- IceCube 170922A neutrino & TXS 0506+056 (IceCube et al. 2018) + Swift/NuSTAR obs. (Keivani+18), Sep 2017+

AMON: a brief history

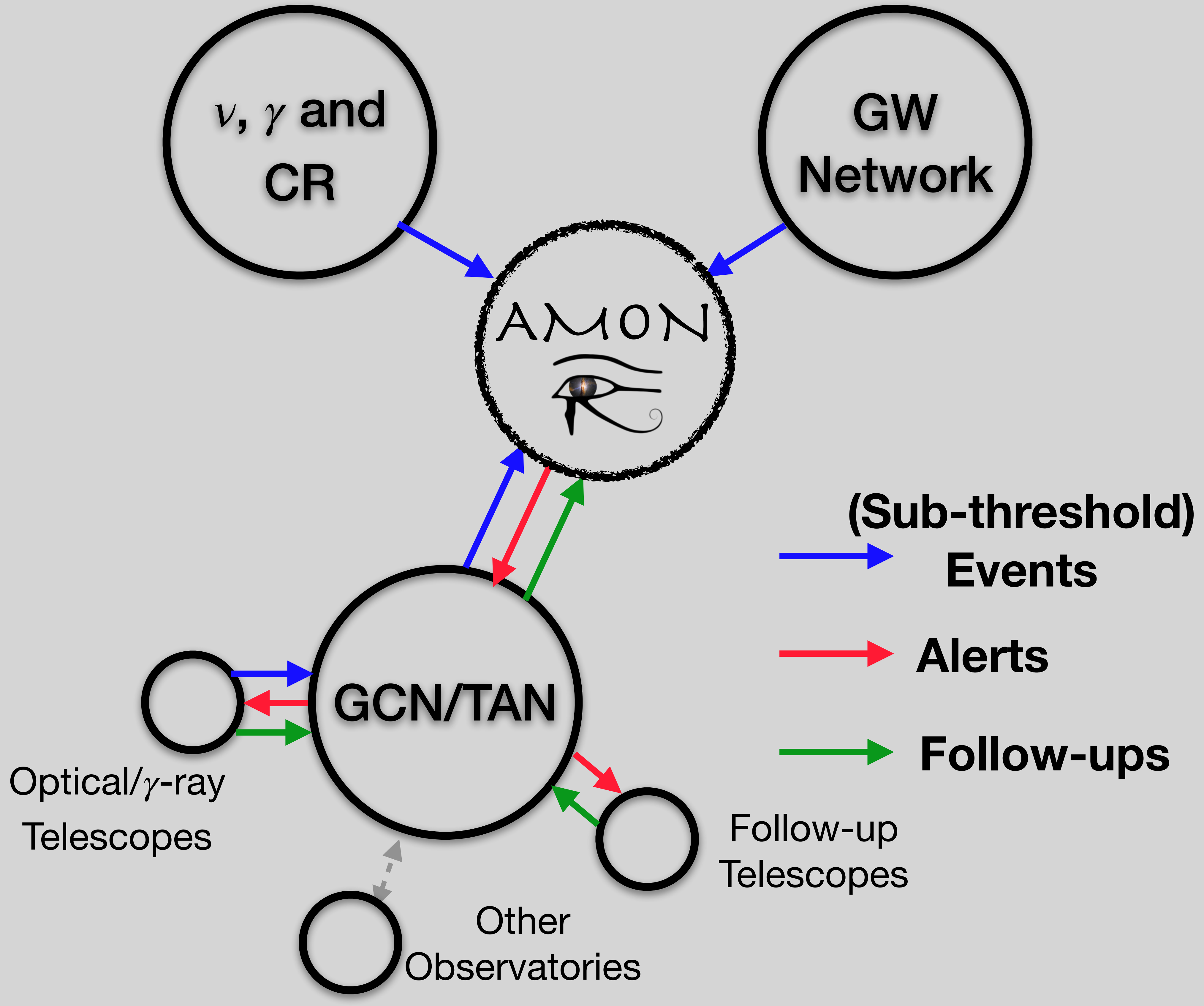
- Prehistory: Archival multimessenger analyses + partner negotiations
- First Alerts neutrino p
- First MM D neutrino & 2018) + Sv Sep 2017+
- First MM AMON Alert sent: Fermi + ANTARES private alert stream (see Turley+19), July 2019

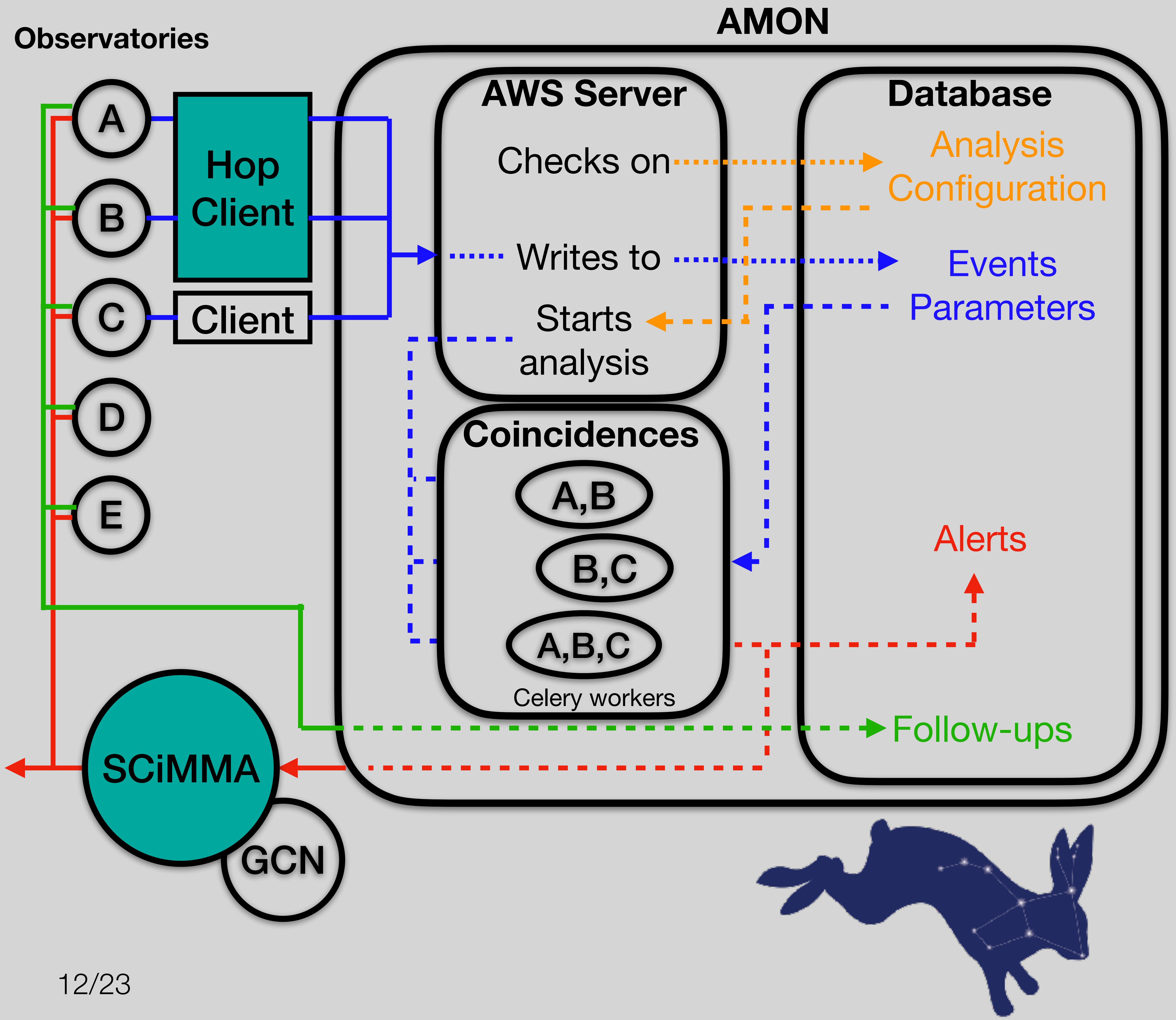
From: **amon amon** <amon.psu@gmail.com>
Date: Tue, Apr 30, 2019 at 3:49 PM

All,
We've had our first Fermi-ANTARES coincidence, detected on 2019/04/28 at 18:49:34 UT. The coincidence was at the sky location of (RA, Dec) = (308.0976, +13.9467)° with a 90% containment radius of 0.868° and had a false alarm rate of 2.055 per year. Normally, this alert would have been sent out via GCN, but as that stream not currently active, we are sending the alert to AMON followup partners by email. The XML file containing the event information has been attached to this message.

Turley+19

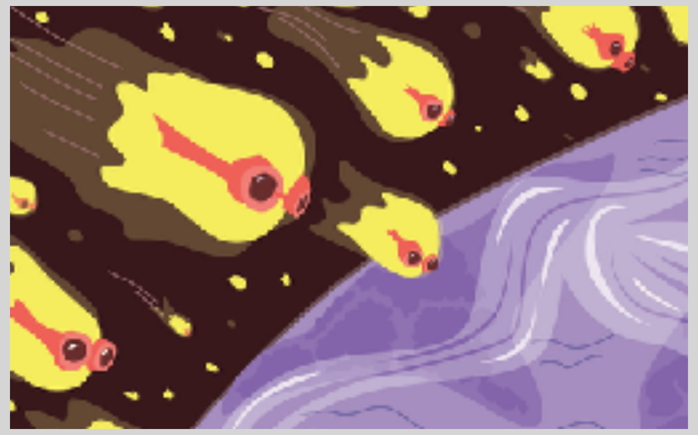
AMON Network and Hardware



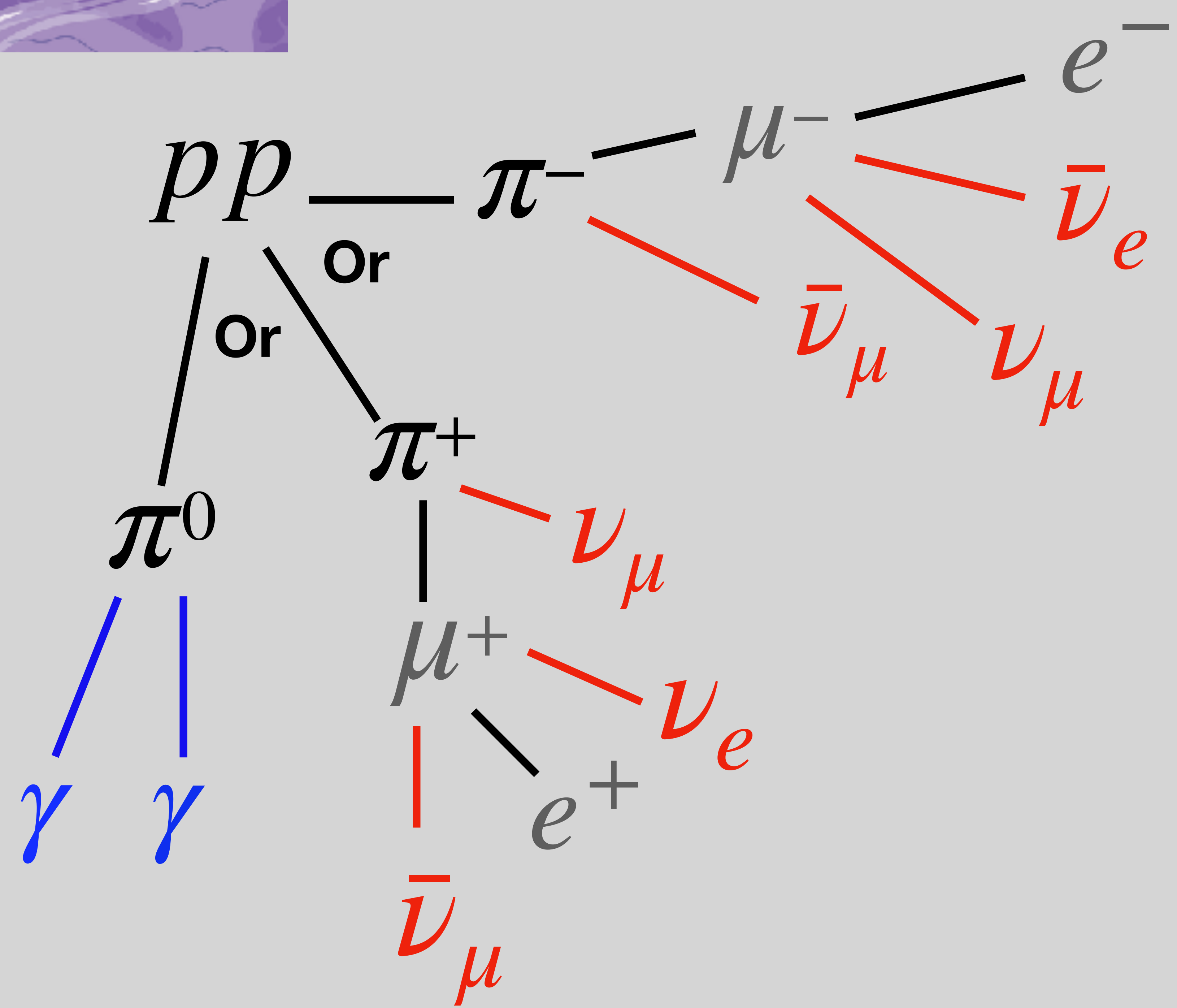


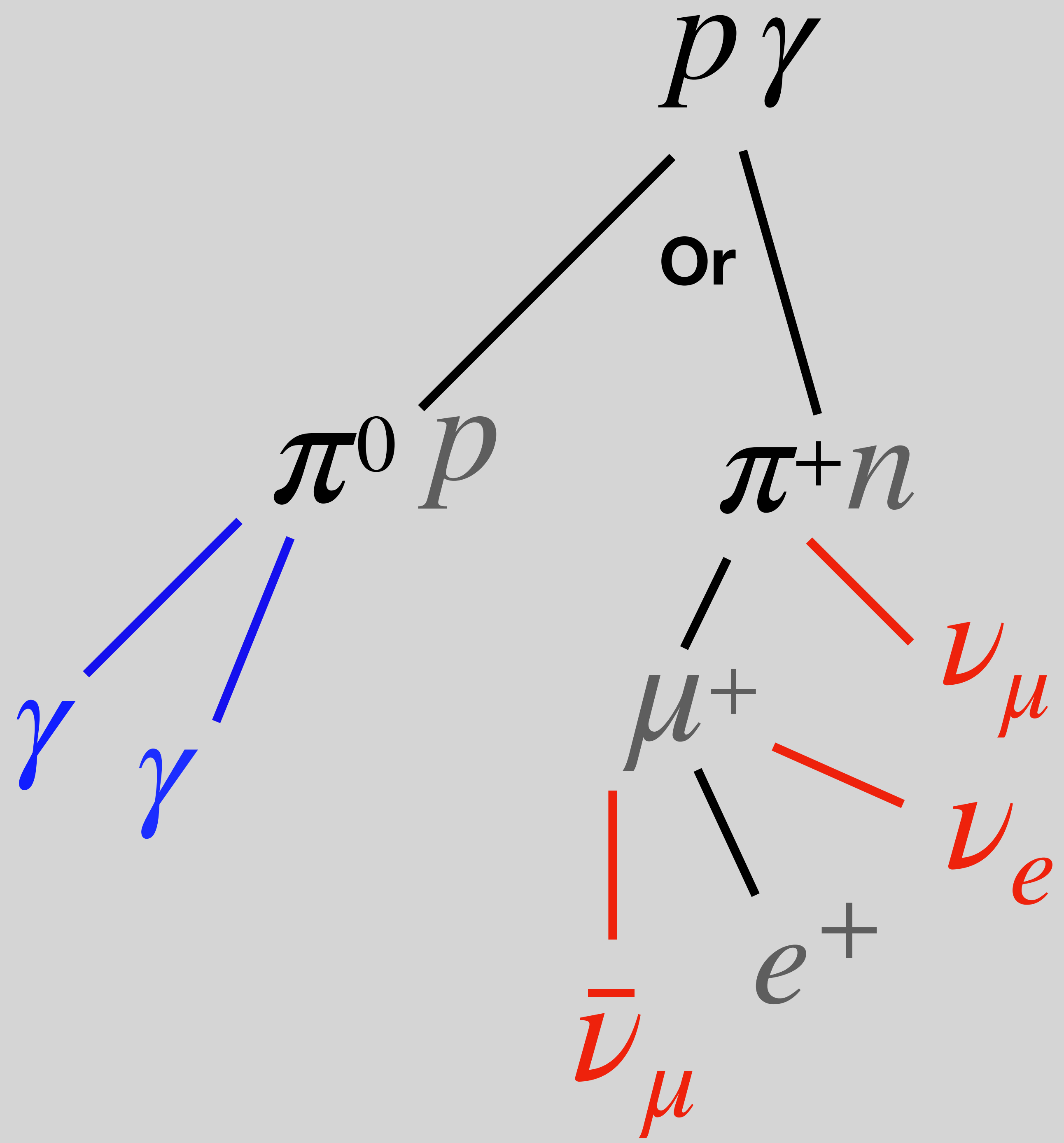
The Neutrino-Electromagnetic channel

- Coincidence analyses between very-high-energy gamma-ray data and high-energy neutrino data



- Objective: Search for sources of high-energy neutrinos (i.e. hadronic accelerators)

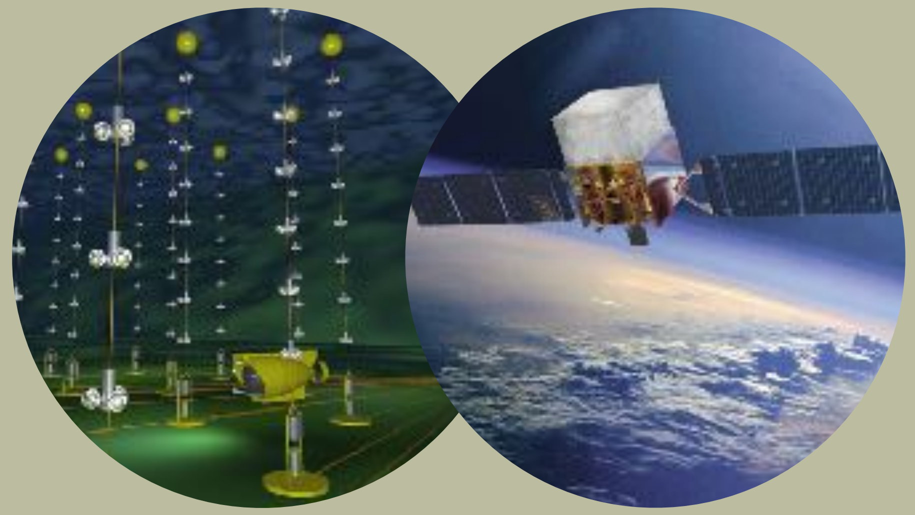




The NuEM channel: analyses

Archival Analysis

Real-time analysis



ANTARES +Fermi LAT

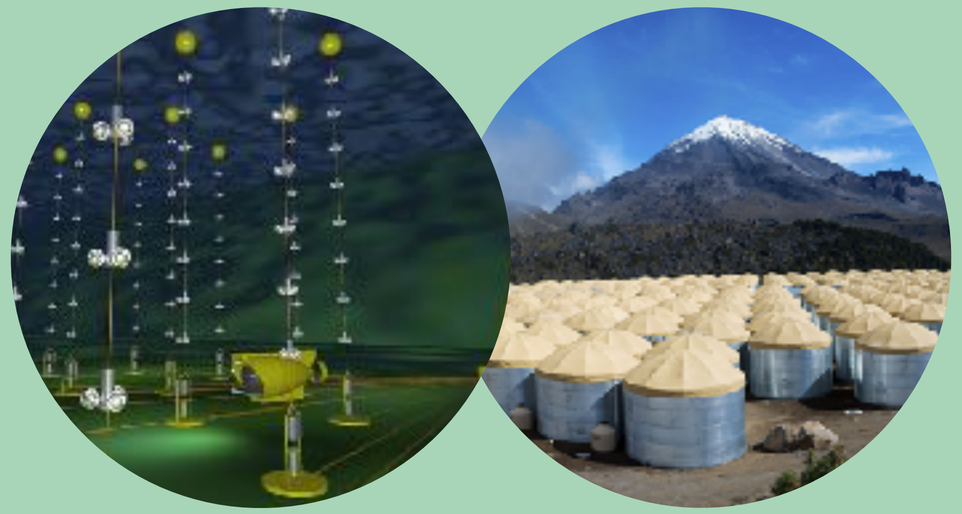
Ayala, et al 2021

IceCube + HAWC

Ayala, et al 2021

IceCube +Fermi LAT

Turley, et al 2018

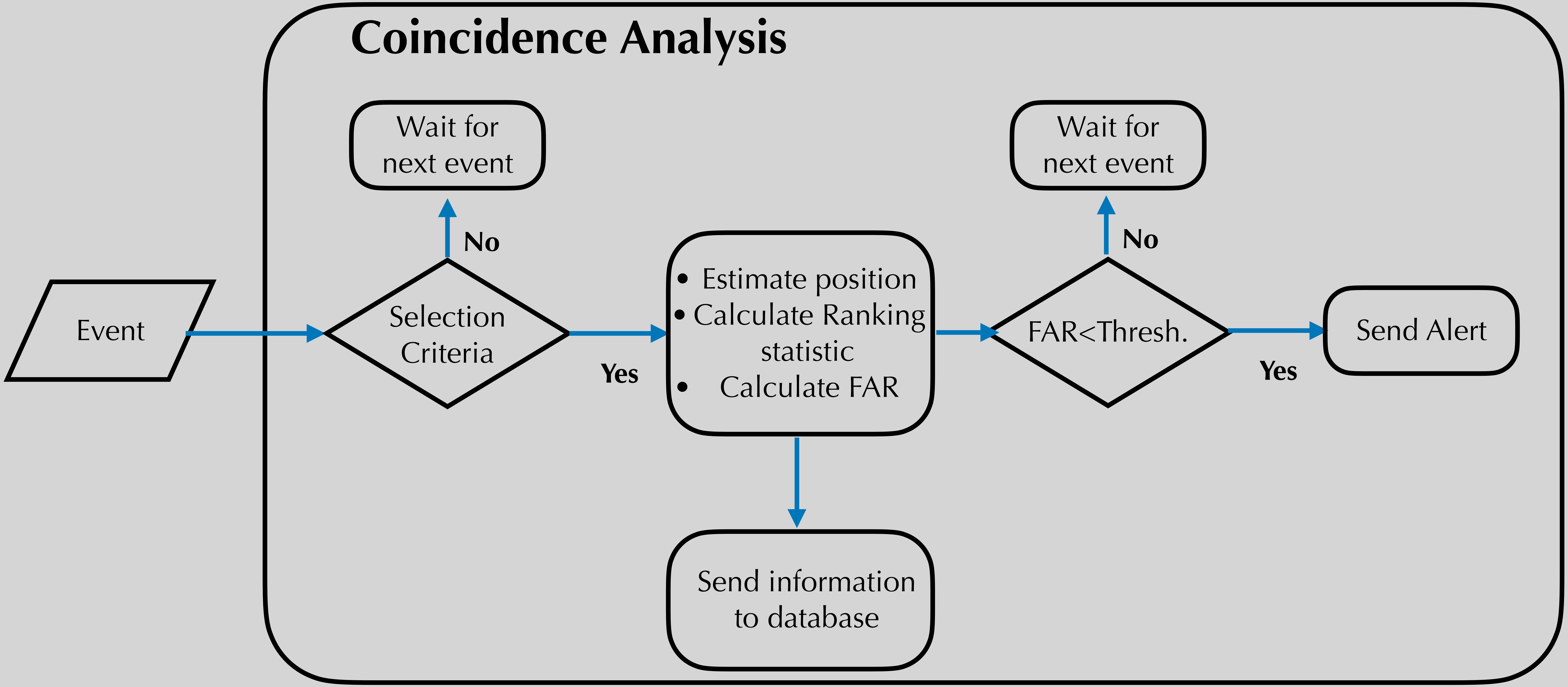


ANTARES + HAWC

Paper in preparation

The NuEM channel: pipeline

The NuEM Channel: algorithm



The NuEM Channel: selection criteria

IceCube +Fermi LAT
Turley, et al 2018

A neutrino event
and all photons

$\Delta\theta < 5^{\circ}$

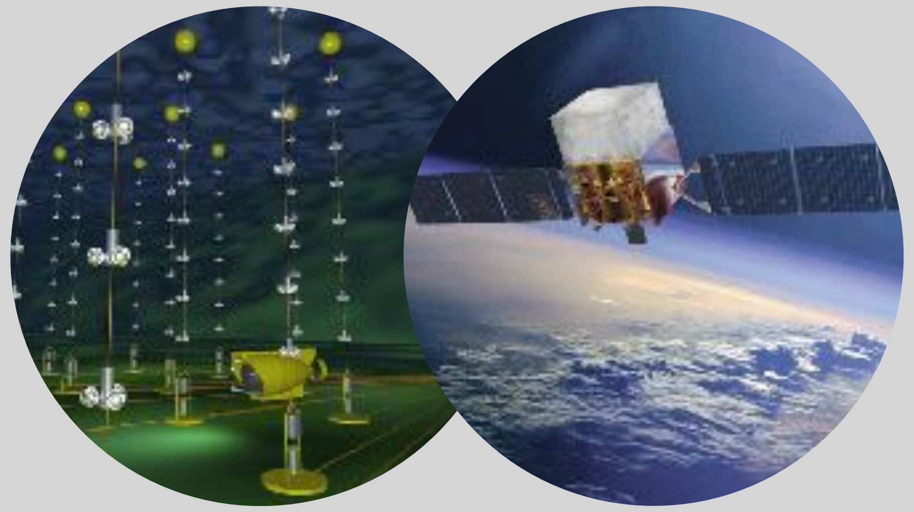
$\Delta t \pm 100s$

IceCube + HAWC
Ayala, et al 2021

A HAWC event and
Neutrino events

$\Delta\theta < 3.5^{\circ}$

$\Delta t \sim HAWC_{\text{transit}}$

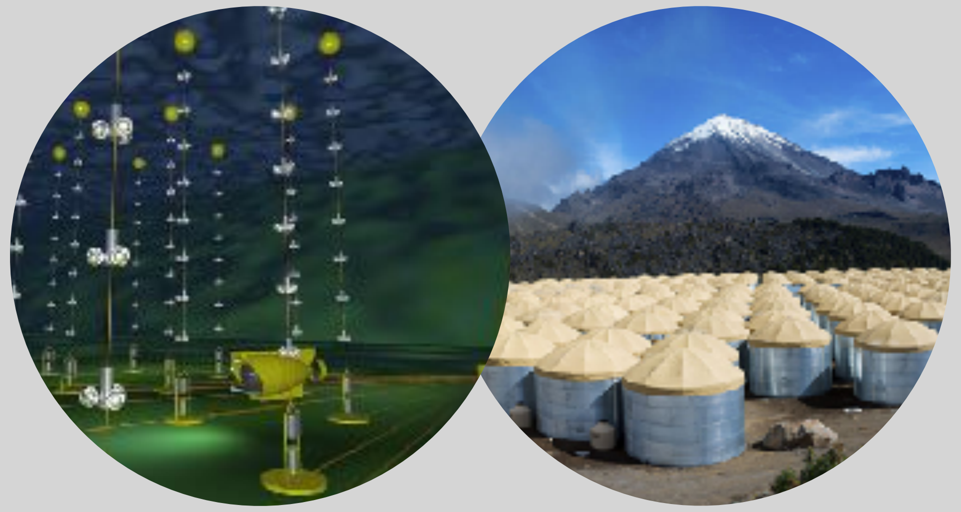


ANTARES +Fermi LAT
Ayala, et al 2021

Neutrino event
tracks (cascades)
And photons

$\Delta\theta < 5^{\circ}(10^{\circ})$

$\Delta t \pm 1000s$



ANTARES + HAWC
Paper in preparation

Archival coincidences: HAWC-IceCube

A HAWC event and Neutrino events

$\Delta\theta < 3.5^{\circ}$

$\Delta t \sim HAWC_{\text{transit}}$

- No counterpart found in the SIMBAD catalog and the Fermi All-sky Variability Analysis (FAVA) monitoring, but several sources in the region.

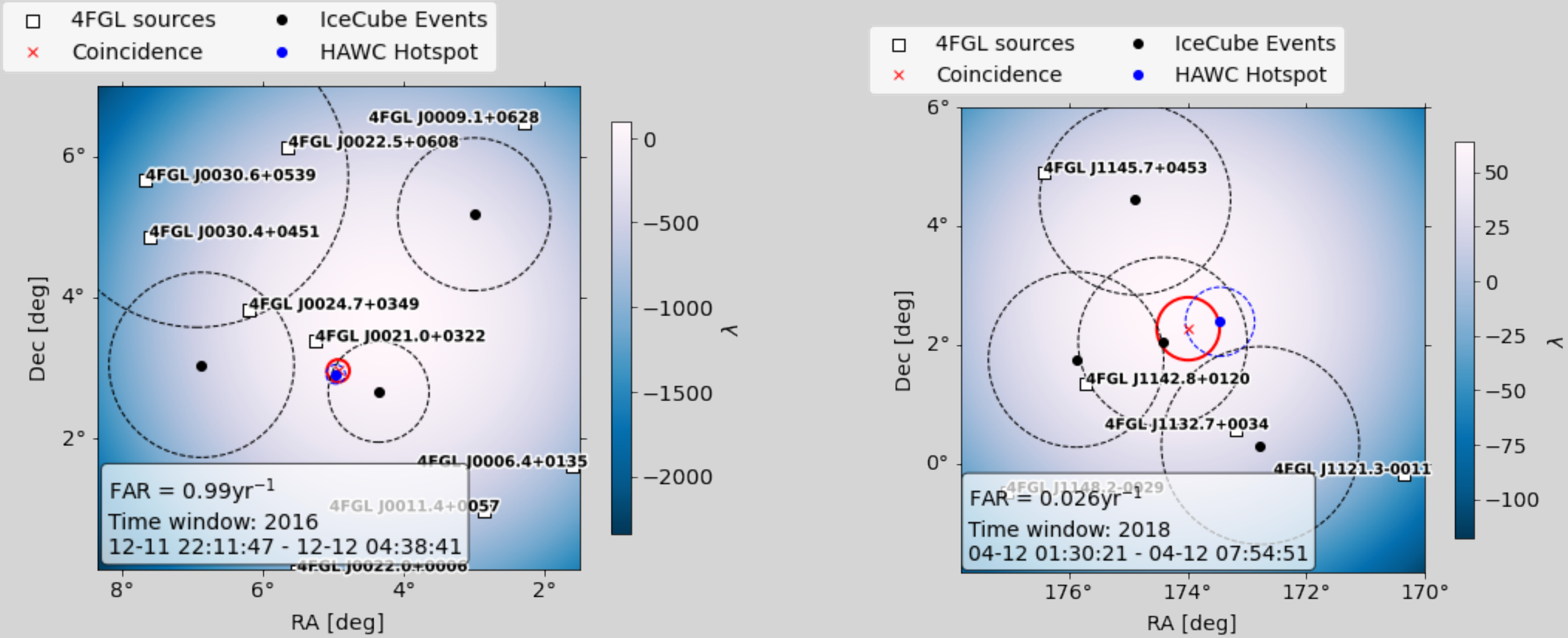
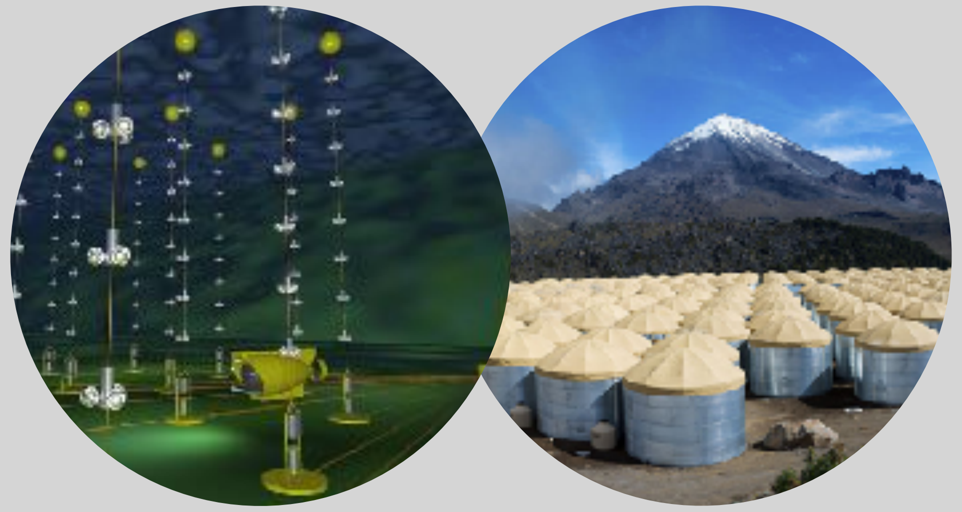


Figure 5. Skymaps of the coincidences with the lowest FAR found in the 3 years of archival data. Position of the individual events are marked with the dots. The best-fit combined positions x_{coinc}, found after optimizing Eq. 3, are marked with a cross. Circles are the 50% containment region.

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

Archival coincidences: HAWC-ANTARES



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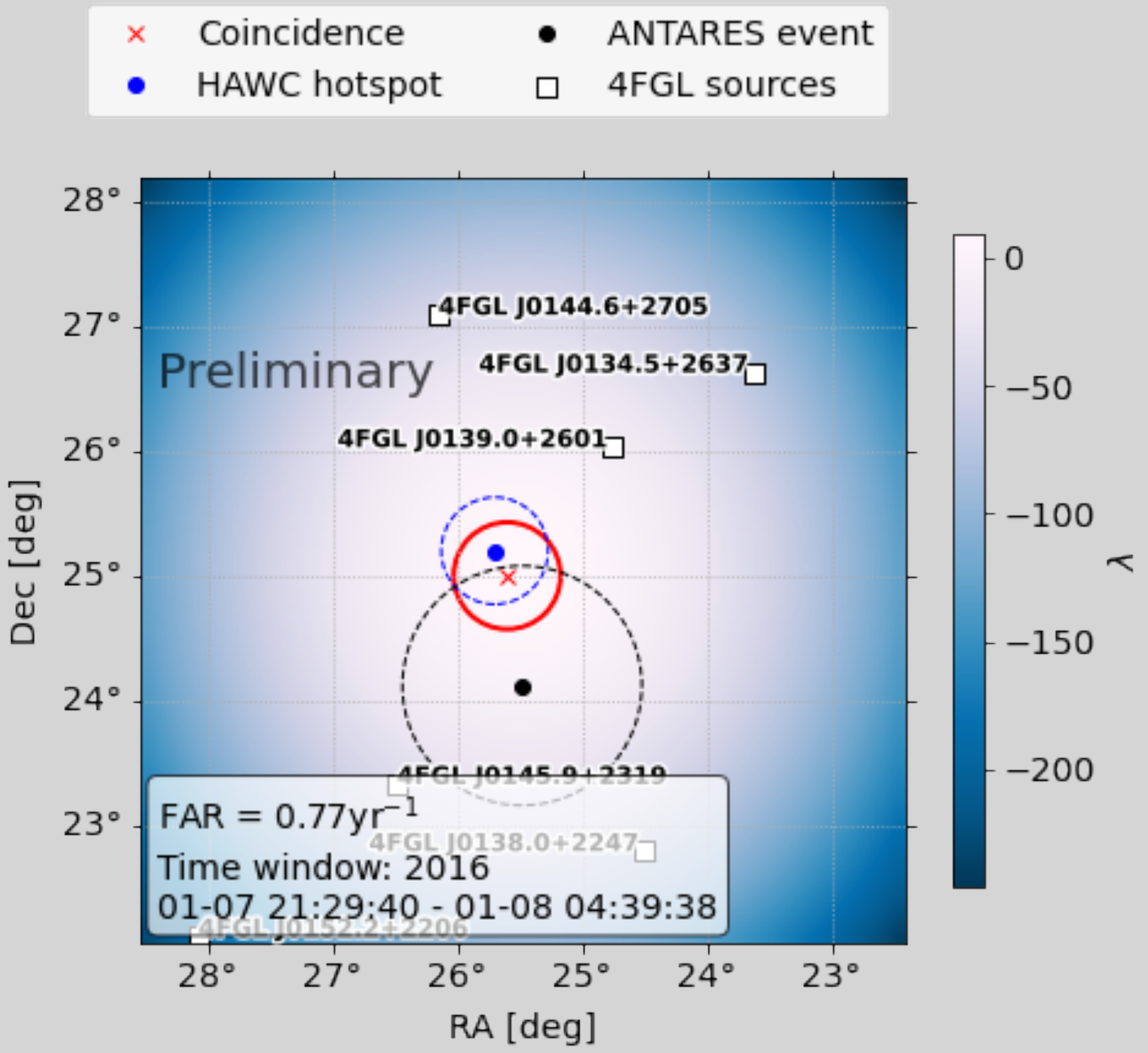
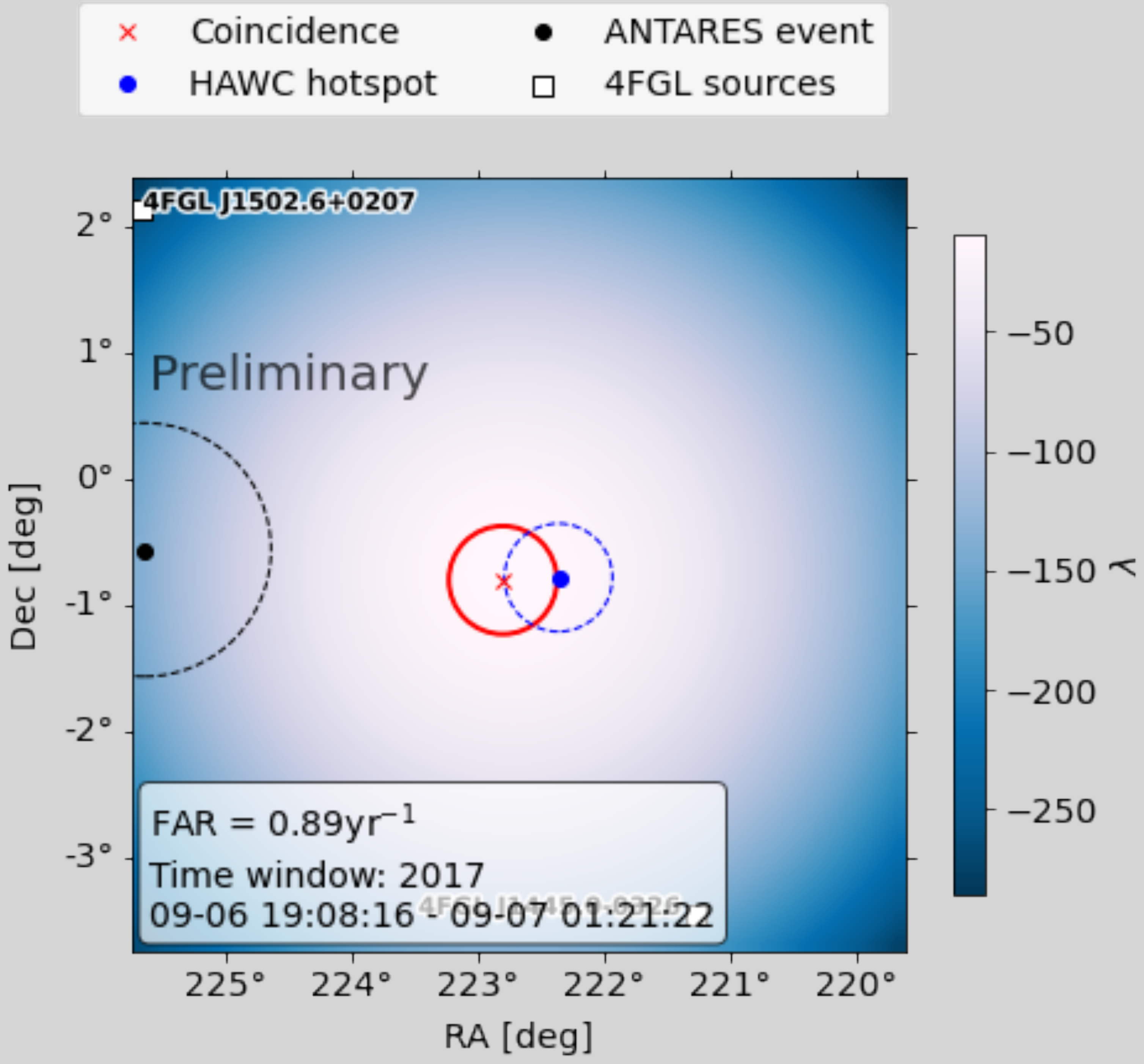
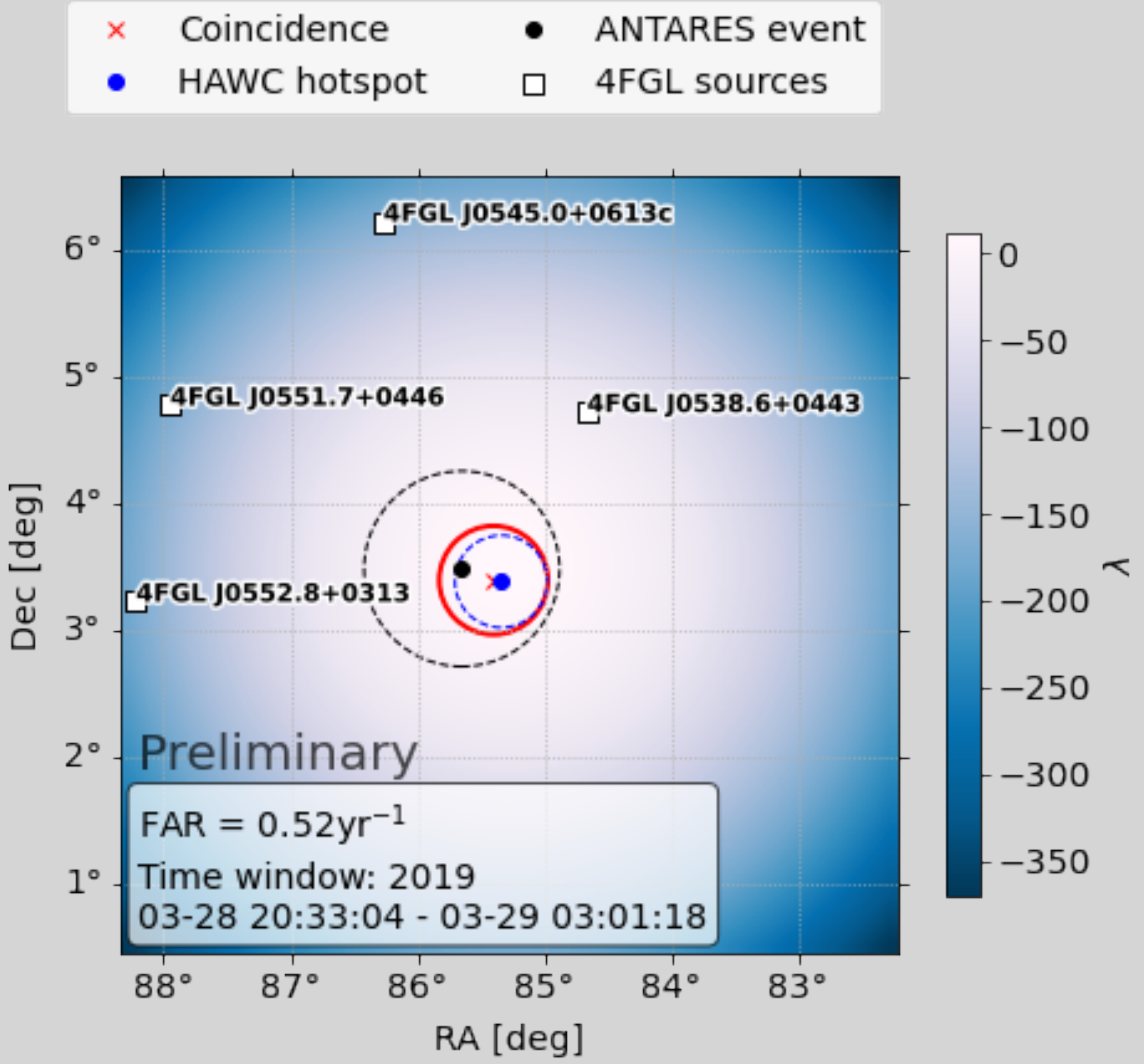






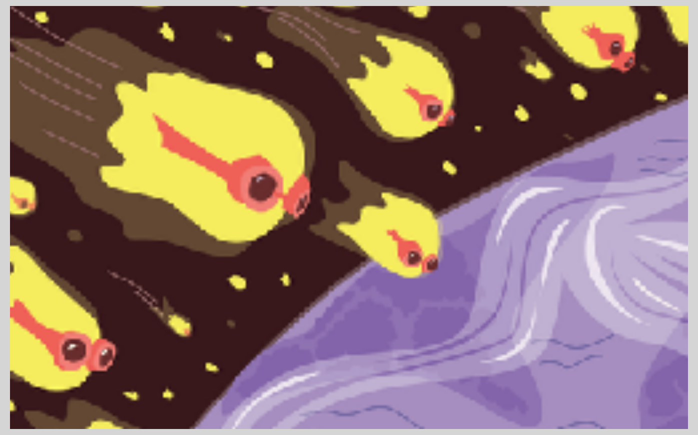
Coincidences in the NuEM Channel

Name	R.A. [°]	Decl. [°]	$\delta\theta$ [°]	FAR [yr^{-1}]	Time UTC
Real-time alerts					
NuEM-220728A	108.9	40.9	0.27	1.14	2022-07-28 20:25:53
NuEM-220220A	221.35	13.23	0.17	1.25	2022-02-20 14:19:37
NuEM-220212A	307.57	1.60	0.31	2.87	2022-02-12 20:19:02
NuEM-220116A	322.13	27.26	0.14	0.57	2022-01-16 23:26:40
NuEM-211209A	12.03	-5.75	0.18	2.06	2021-12-09 04:38:48
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

- FAR threshold is < 4 per year for real-time alerts.
  - 14 alerts sent to GCN
- For archival coincidences we looked at the ones with FAR <1 per year
  - 9 coincidences found

More Comments on NuEM Channel

- AMON NuEM channel is active
  - Using sub-threshold data

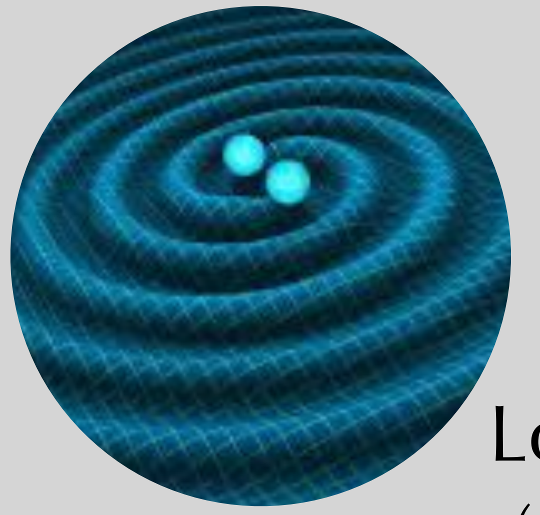


- We encourage follow-up observations of these coincidences

Name	Followed by
NuEM220220A	MASTER
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

Swift + LVC O3 analysis

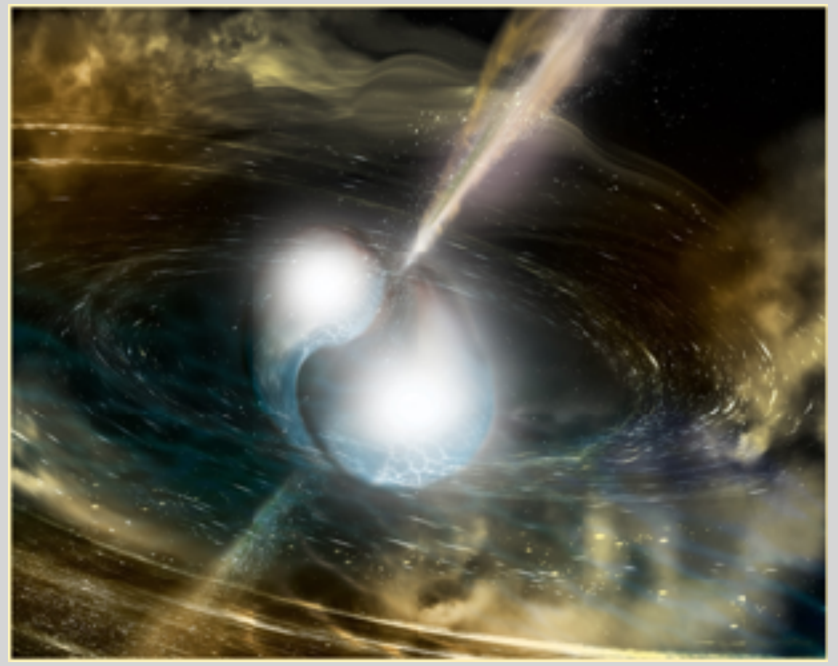


LVC

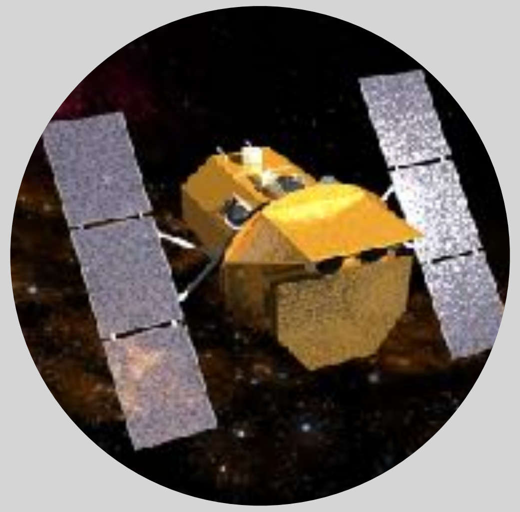
Data

Low Latency compact binary coalescence.
(CBC) Detection Pipelines
•FAR, Mass Estimates or NS probability
BAYESTAR Skymaps
•2D or 3D sky map localizations

BNS
Mergers



SWIFT



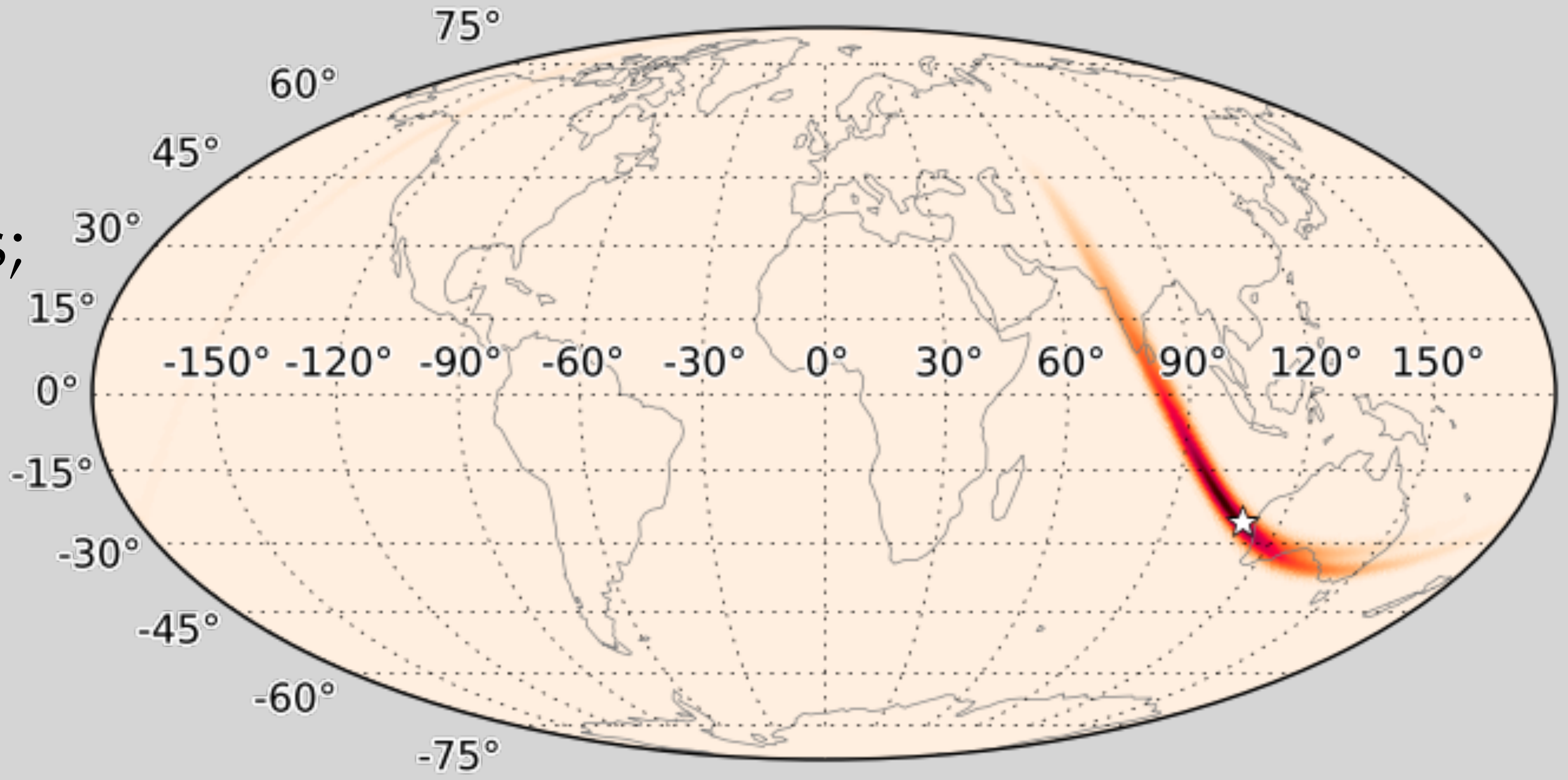
Data

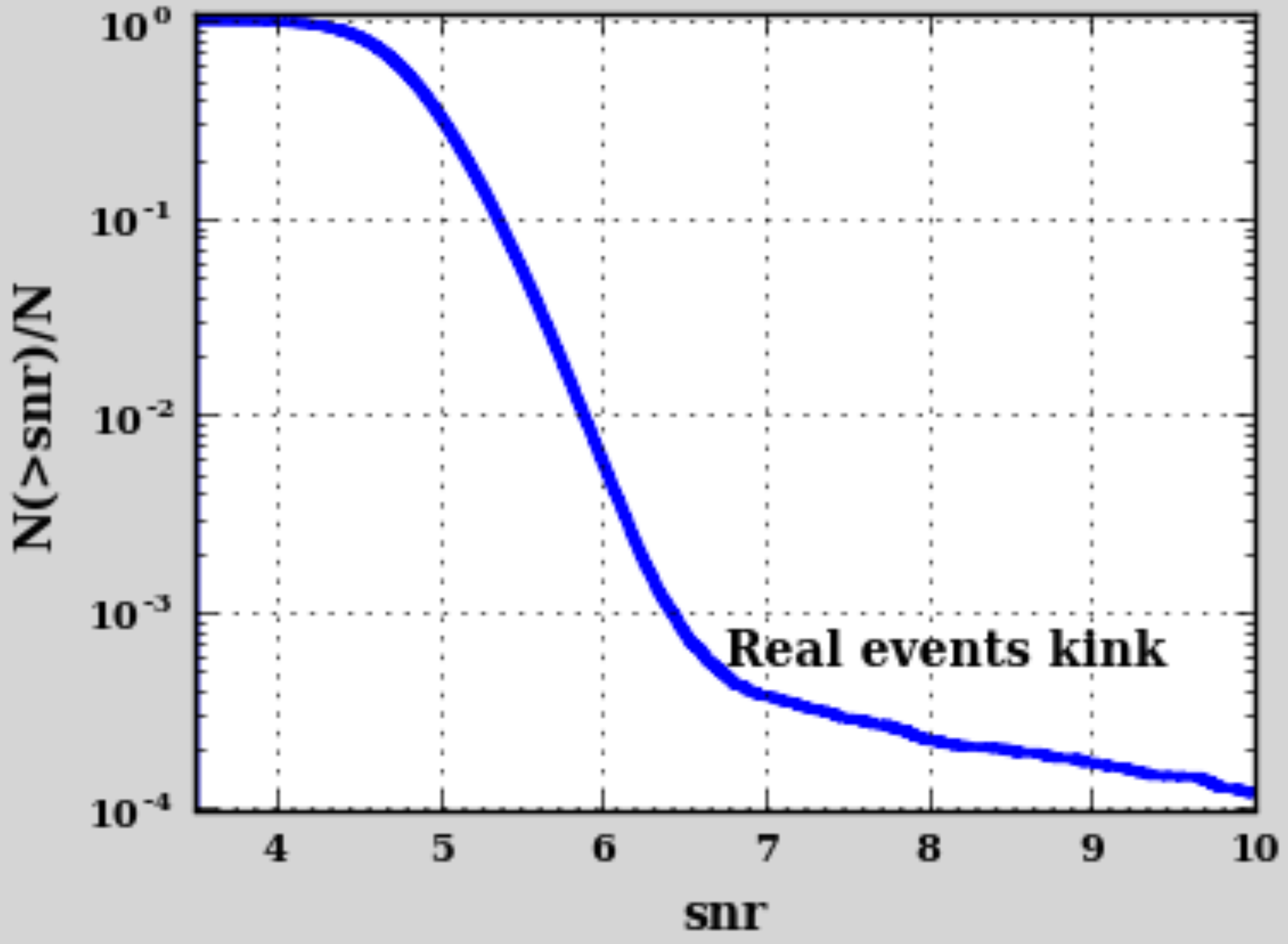
GUANO-NITRATES
Coded Aperture Imager
•Sub-threshold Image Peaks
•Exposure from milliseconds-minutes

Detector Noise Fluctuations

Background

Detector noise
Non-astrophysical transients;
•Trucks driving by, etc.





- Preparing for O4:
  - Low FAR coincidences will be distributed publicly

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

AMON server is up and running

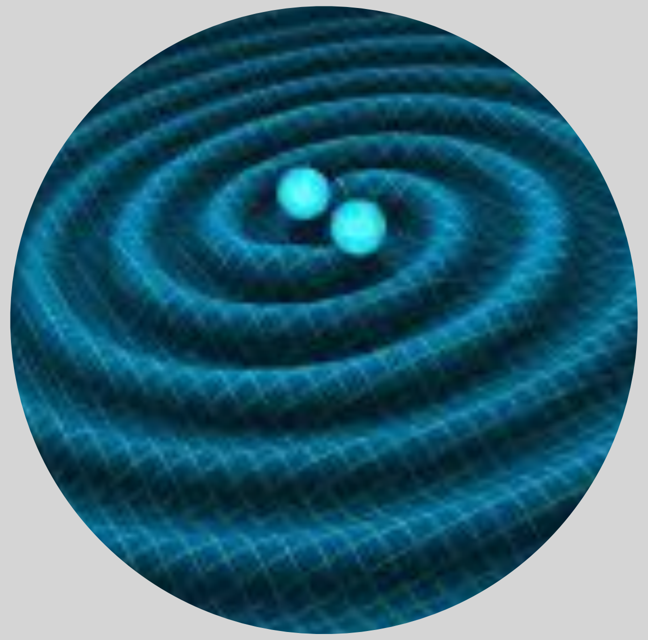
- AMON greatly **simplifies multimessengers searches**:
  - Common data format, transfer protocol, event database, MoUs.
- Past:
  - Archival analyses, help in the discovery of TXS 0506+056.
- Present:
  - AMON is issuing **alerts from sub-threshold data** for multimessenger searches in real-time.
  - **Pass-through alerts**
- Future:
  - Updating to SCIMMA cyber-infrastructure. We will look to send alerts to new GCNl
  - MMA with gravitational waves.
- **New participants are always welcome!**
- **Website: amon.psu.edu**

Thank you

NSF

AMON
Astrophysical Multimessenger Observatory Network

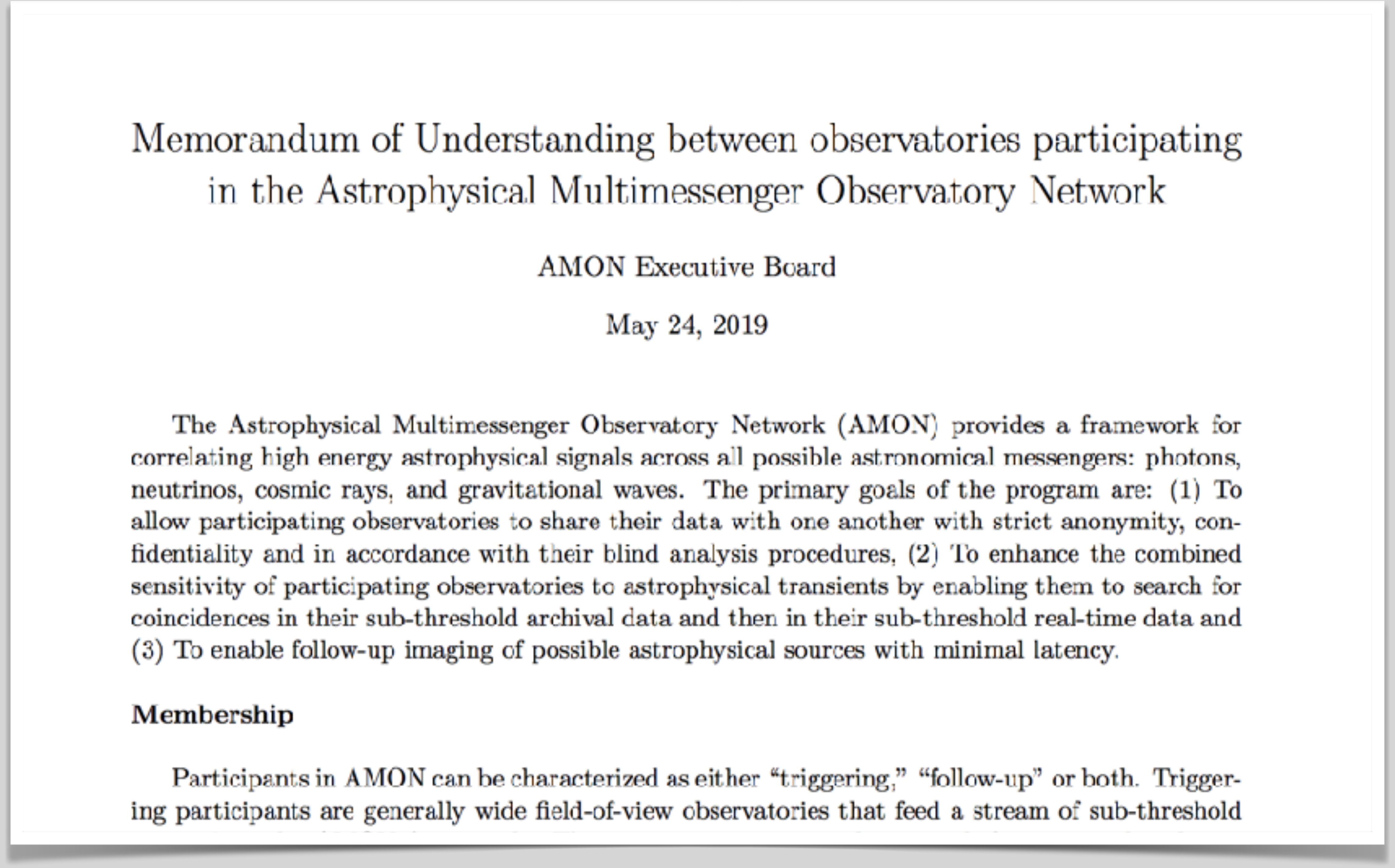
PennState
Eberly College
of Science



Back-up

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

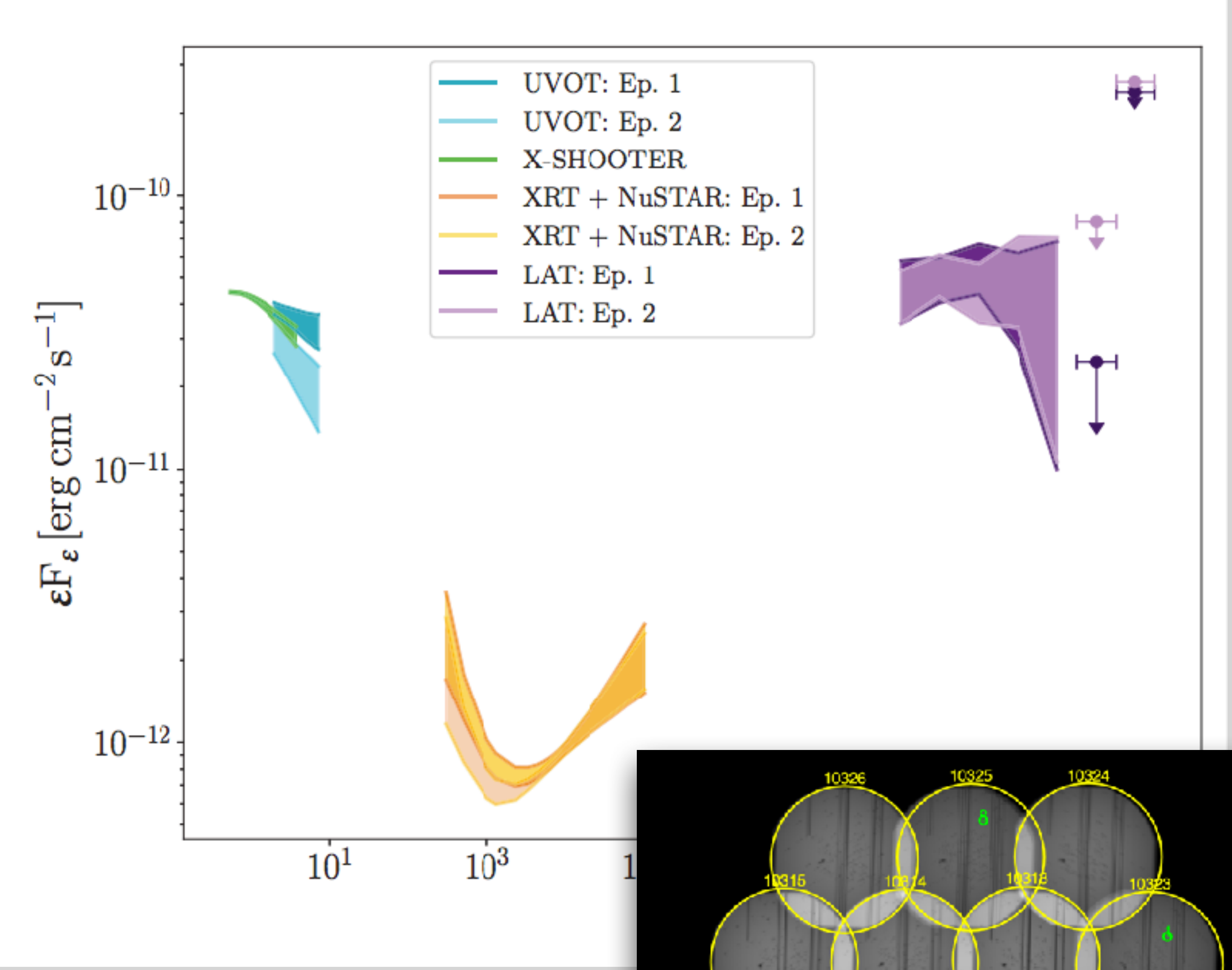
The Astrophysical Multimessenger Observatory Network (AMON) provides a framework for correlating high energy astrophysical signals across all possible astronomical messengers: photons, neutrinos, cosmic rays, and gravitational waves. The primary goals of the program are: (1) To allow participating observatories 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.

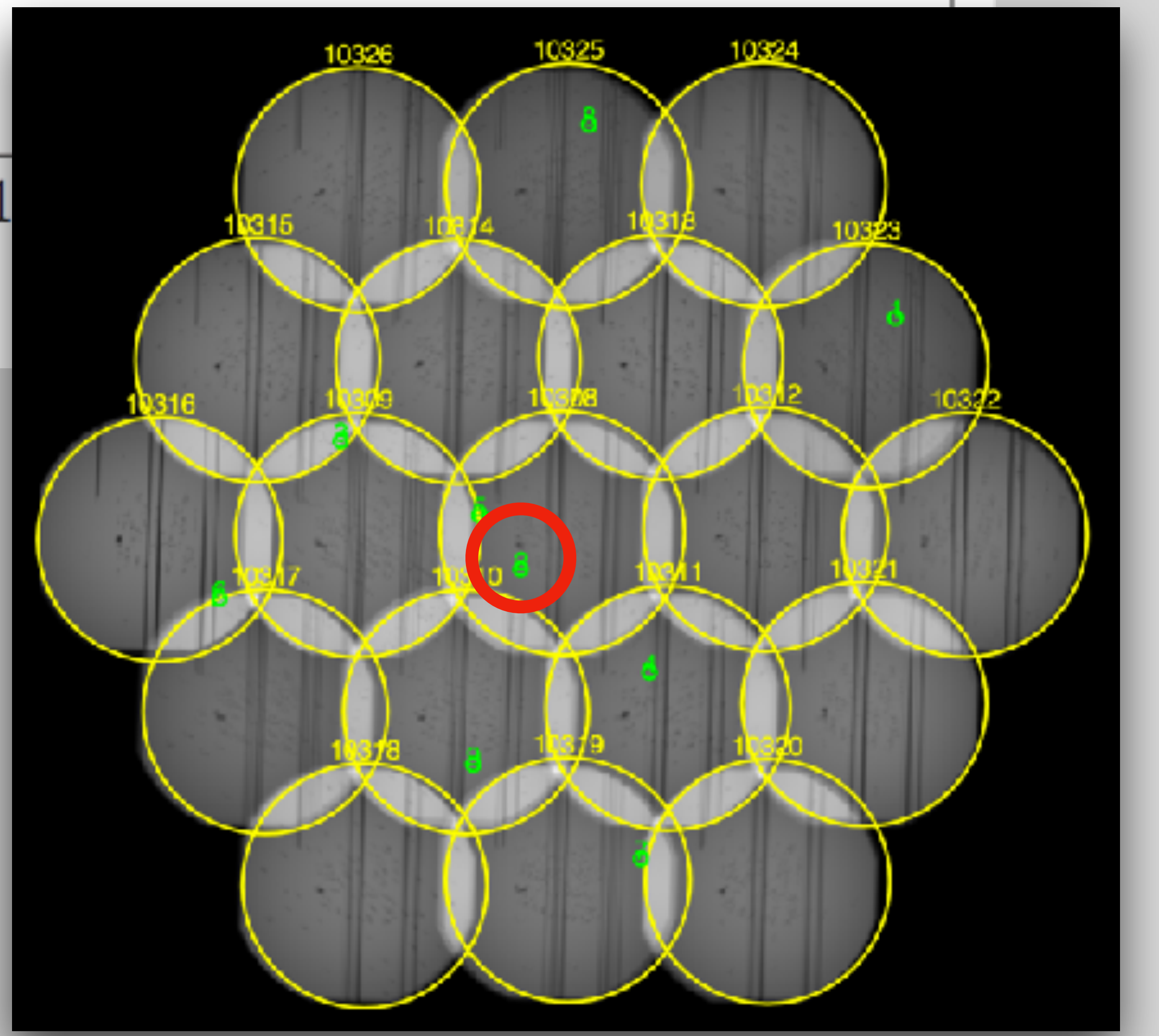
Membership

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

Swift-IceCube: IC170922A

- Tiles around IC170922A
  - Nine sources revealed in the field of view
  - TXS 0506+056 or J0509+0541 is circled in Red
- Keivani et al. 2018: combined data from Swift, NuSTAR, and X-shooter data with Fermi observations. Lepton-hadronic model to explain emission.
- Other work: Ansoldi 2018, Cerruti 2018, Cao 2019





Studying the universe with multi-messenger astrophysics

Force	Messenger	Messenger Detected	Sources?
EM	Photons		Myriads
Weak	Neutrinos		Sun, SN1987A, TXS 0506, TDE(AT2019dsg) and NGC 1068 (~3σ)
Strong	p, nuclei		Hotspots?
Gravity	Gravitational Waves		~100 (BBH, BNS, BBHNS,…)

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

- The Astrophysical Multimessenger Observatory Network (AMON) aims to connect the world's leading high-energy and multimessenger observatories. AMON's objective are to evoke the discovery of new multimessenger phenomena, exploit these phenomena as tools for fundamental physics and astrophysics, and explore archival datasets in search of multimessenger activity. Present projects include distributing low-latency multimessenger alerts from the Neutrino-Electromagnetic (NuEM) channel, and triggering real-time preservation and analysis of data from NASA's Swift satellite based on LIGO+Virgo+Kagra gravitational-wave alerts. Looking ahead, AMON will continue providing useful real-time analyses of a wide variety of high-energy and multimessenger data streams, while upgrading its systems to cloud-based and SCiMMA-standard cyberinfrastructure, and strengthening its ties with the theoretical and time domain astrophysics communities.