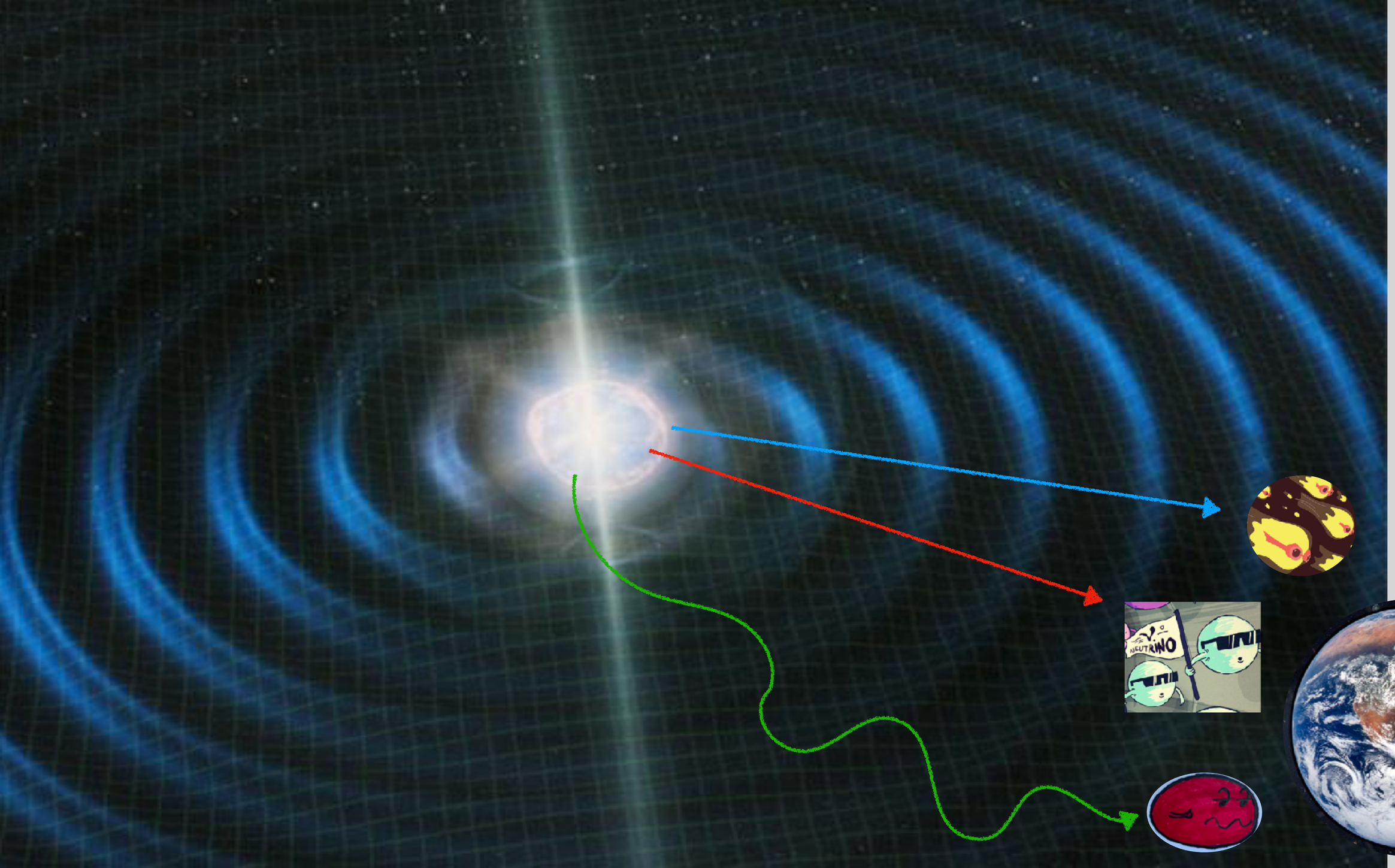
AMON
Astrophysical Multimessenger Observatory Network

The Astrophysical Multimessenger Observatory Network and the Neutrino-Electromagnetic channel

Hugo Ayala

PennState
Eberly College of Science


?
NEUTRINO

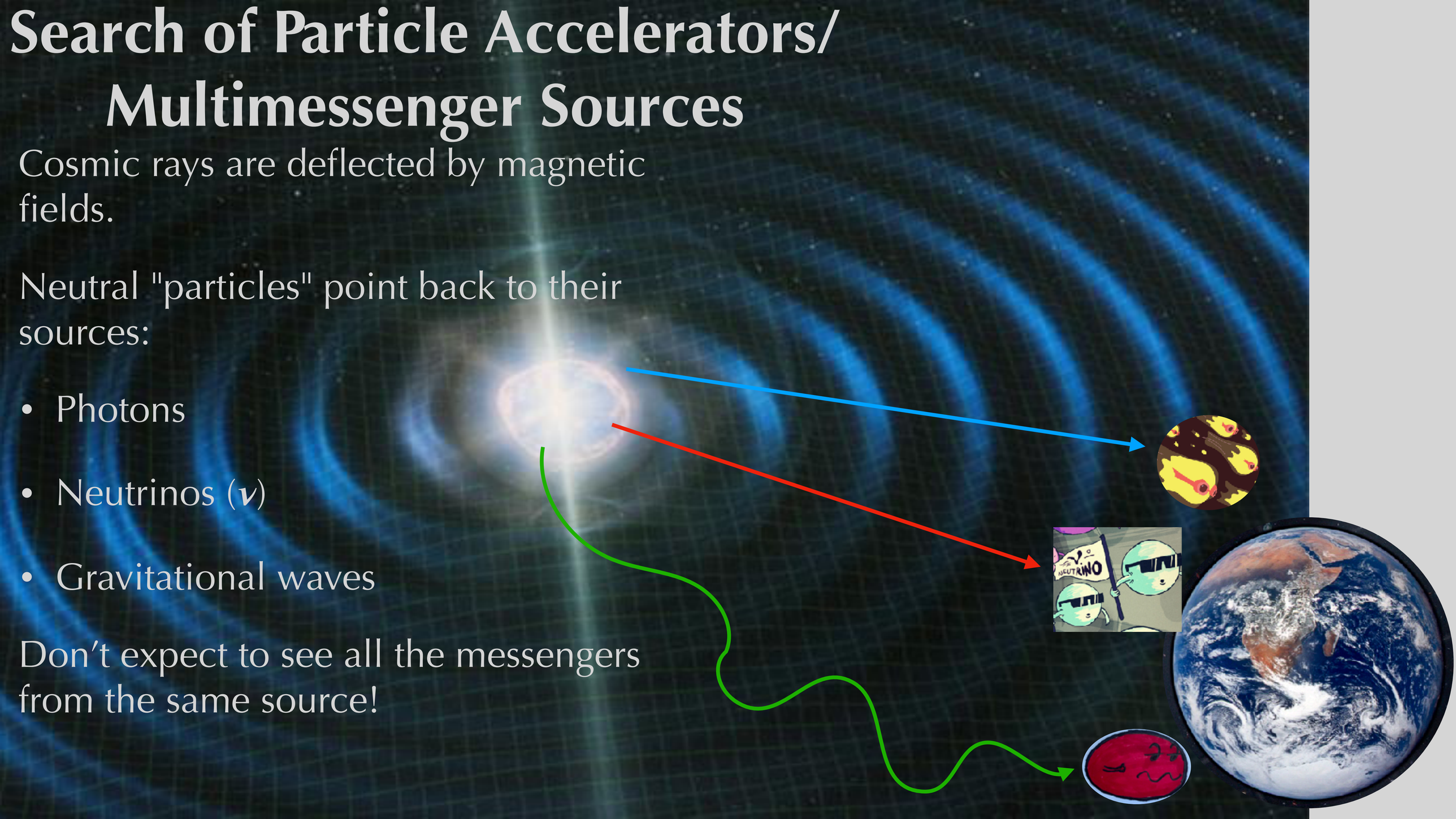
Search of Particle Accelerators/ Multimessenger Sources

Cosmic rays are deflected by magnetic fields.

Neutral "particles" point back to their sources:

- Photons
- Neutrinos (ν)
- Gravitational waves

Don't expect to see all the messengers from the same source!

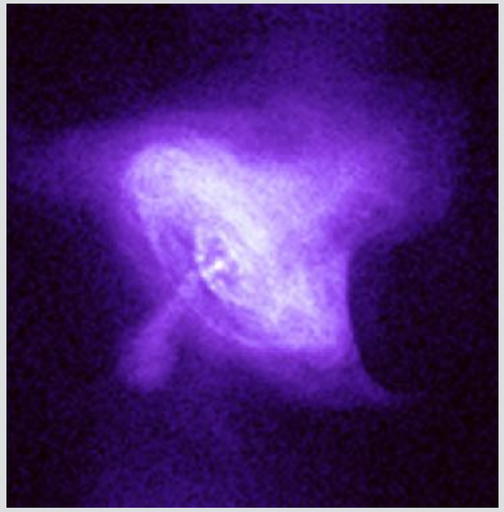


Particle Accelerators in Nature

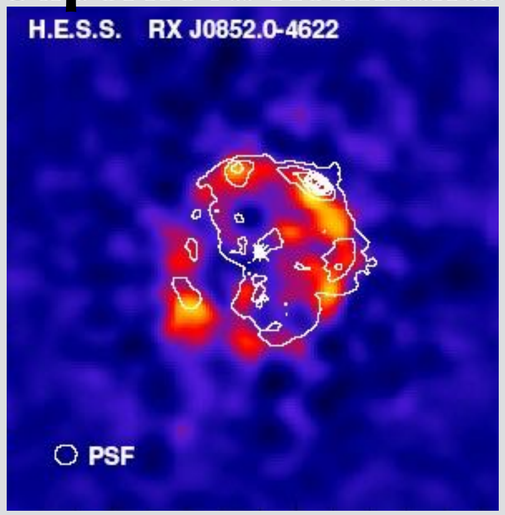
Galactic

Extragalactic

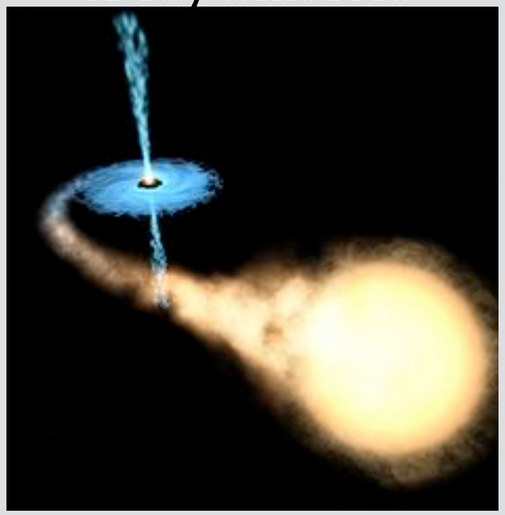
Pulsar Wind Nebulae



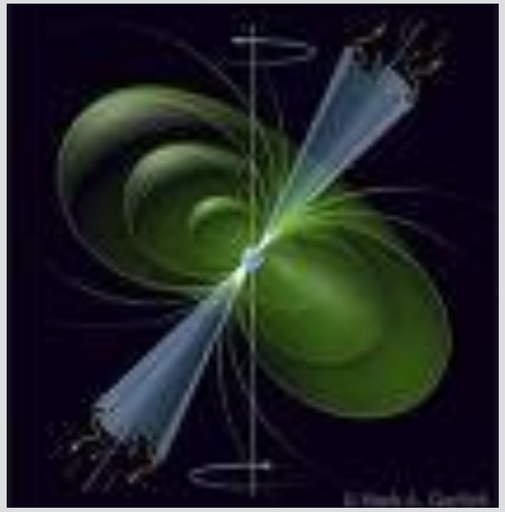
Supernova Remnants

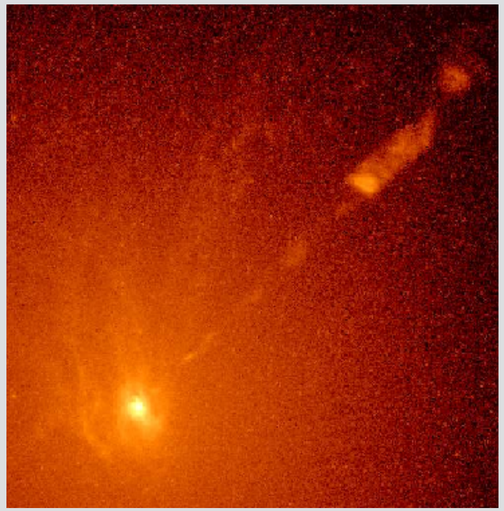


X-ray binaries

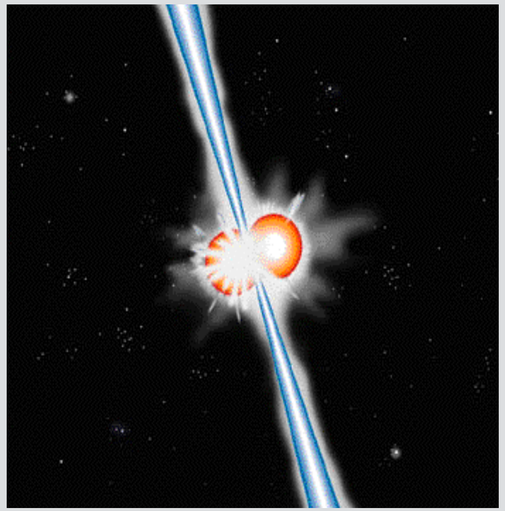


Pulsars

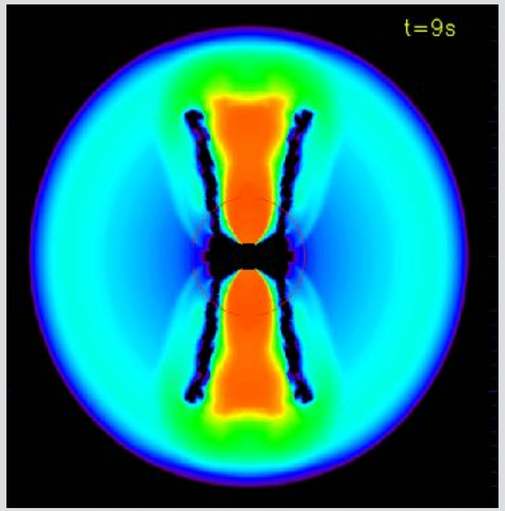




Active Galaxies



Short γ-ray Bursts



Long γ-ray Bursts

Starburst Galaxies

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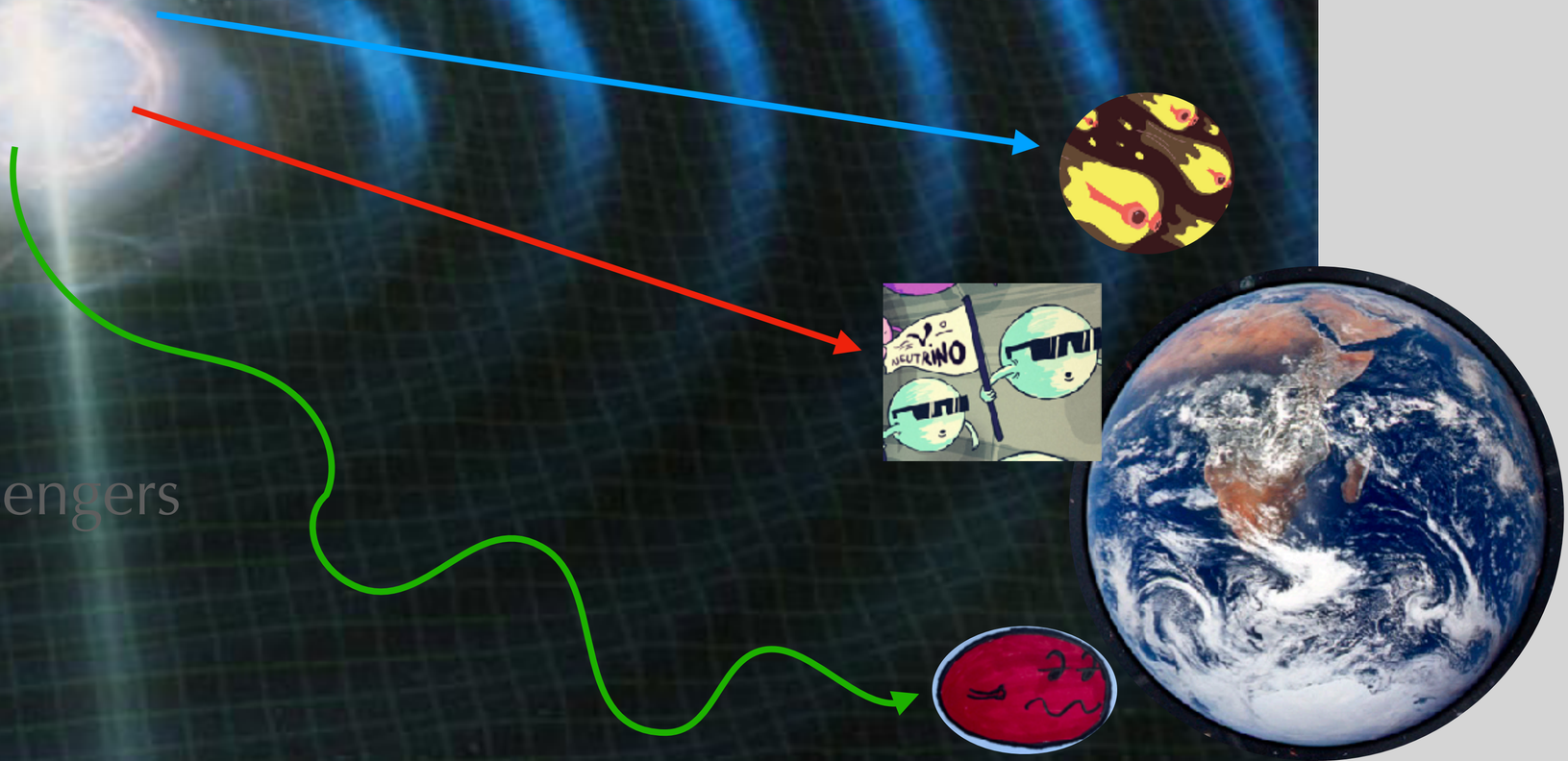
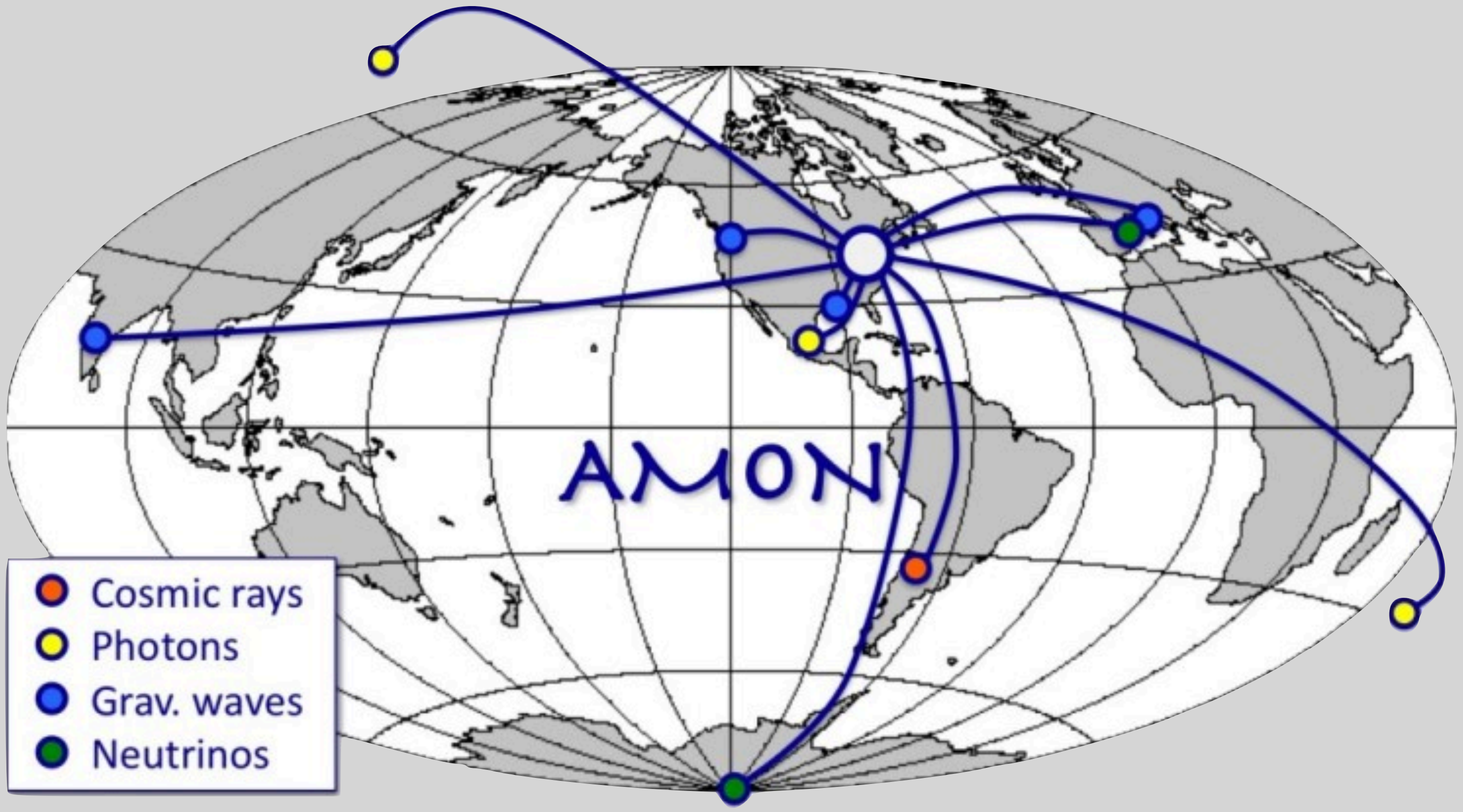
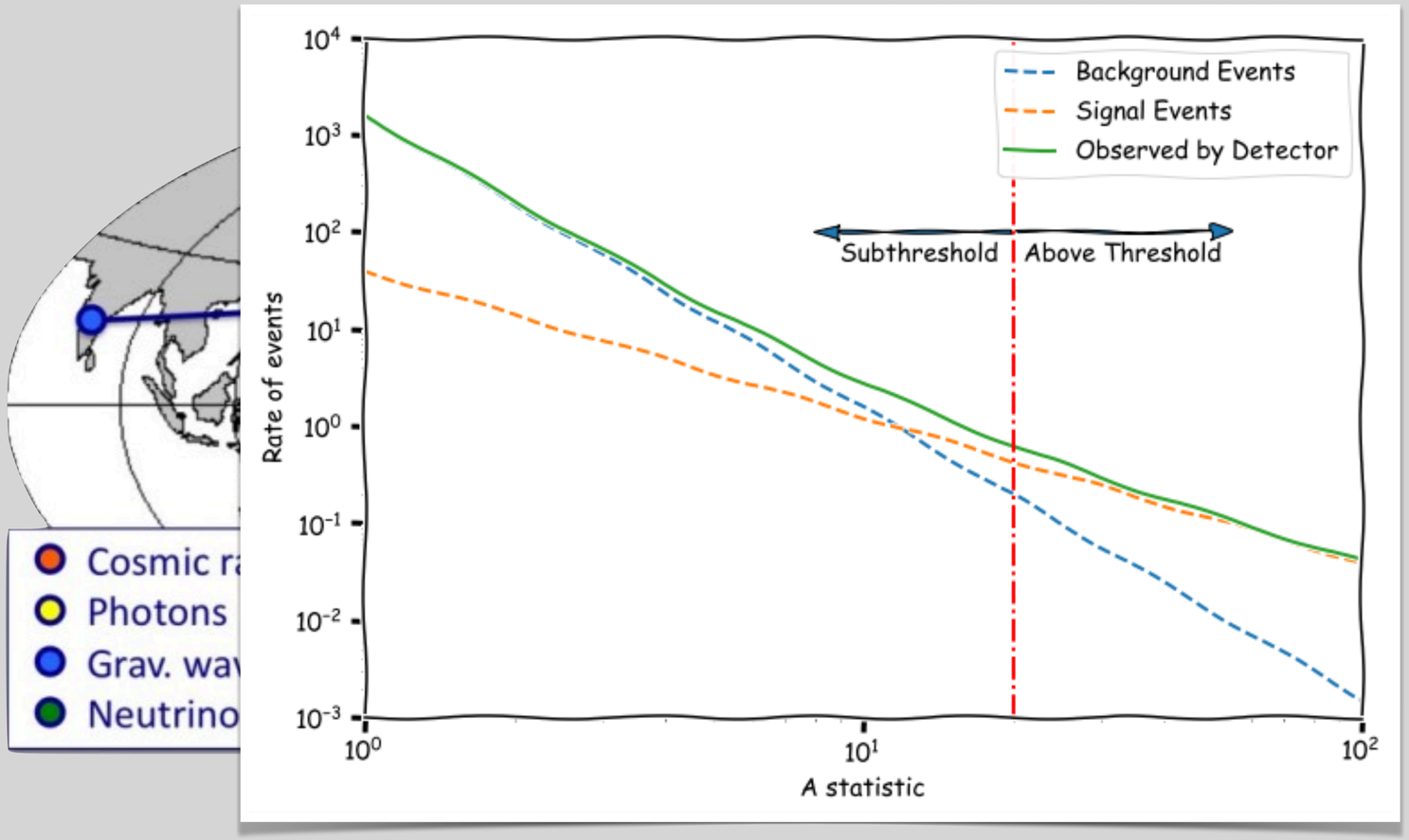


Astrophysical Multimessenger Observatory Network: a Multimessenger approach



- *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



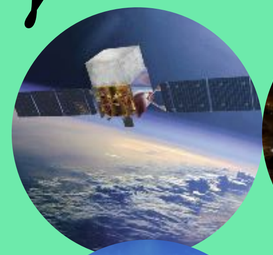
- **Real-time coincidences**
  - Use of **sub-threshold data**
- Archival Studies
  - Store events
  - Coincidence analyses
- Partners
  - Triggering Observatories
  - Follow-up Observatories
- Pass-Through
  - Broadcast directly to GCN/TAN and SCIMMA

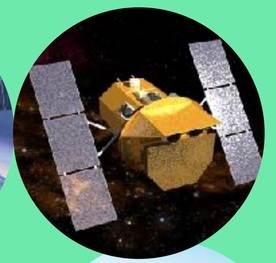
AMON Members (and per-project* members)

CR

Pierre Auger

γ





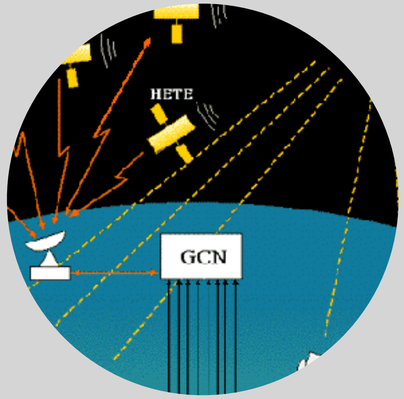
SWIFT
VERITAS
HESS
MAGIC

FACT
Fermi
HAWC

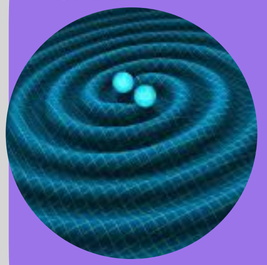
ν

IceCube
ANTARES

AMON
Astrophysical Multimessenger Observatory Network



GW



*LIGO-Virgo

γ

LMT
Palomar Transient Factory
MASTER

AMON Team

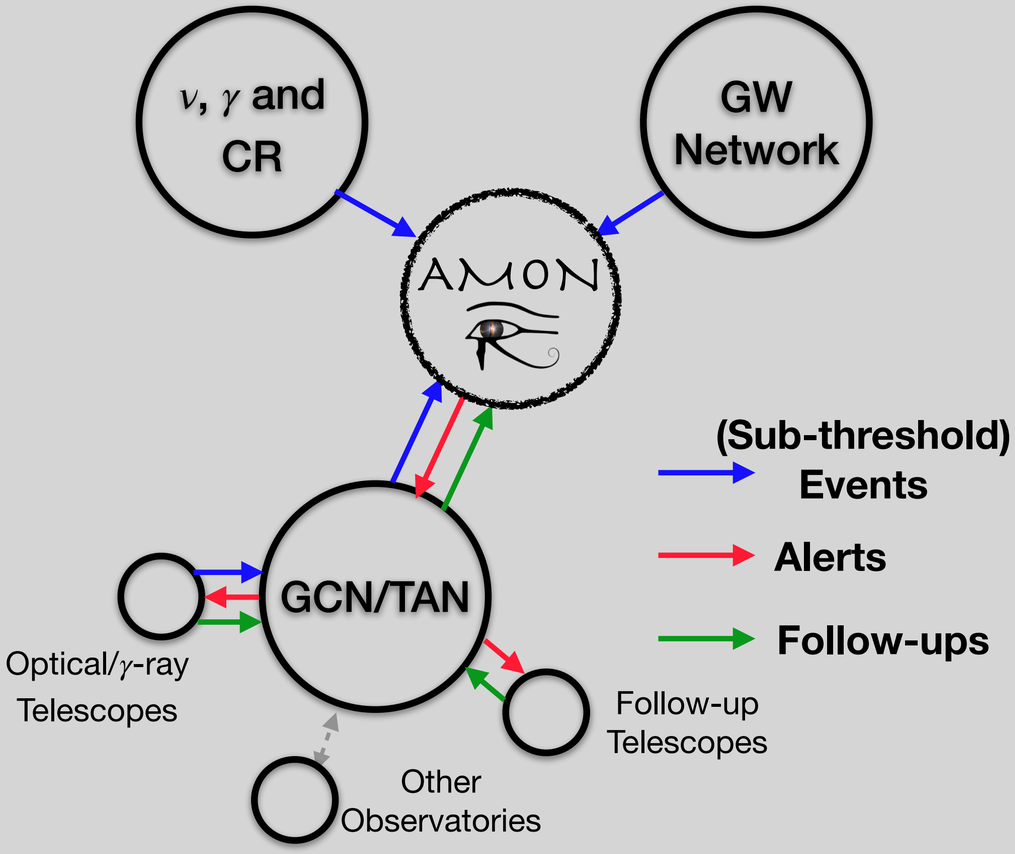


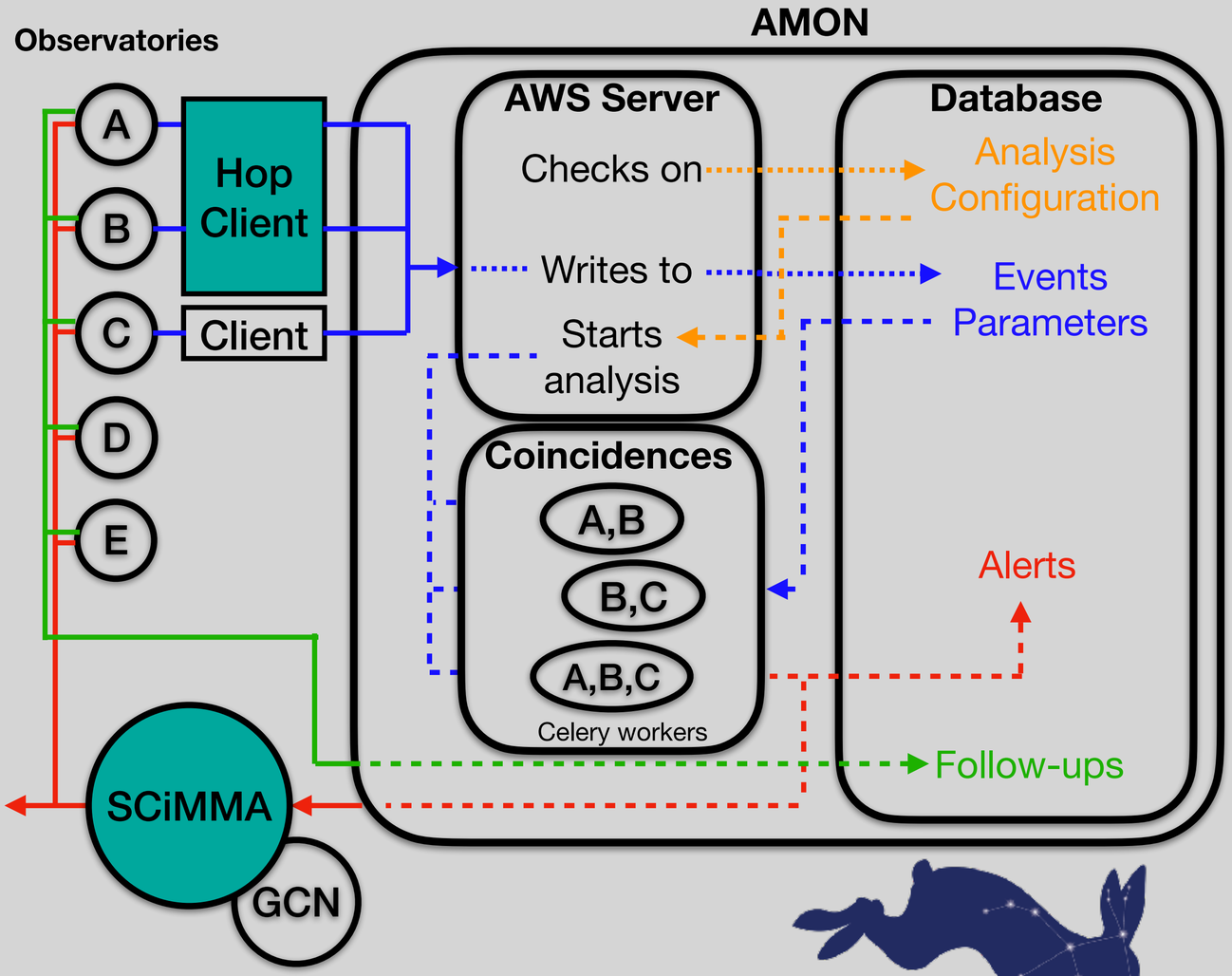






AMON Network and Hardware





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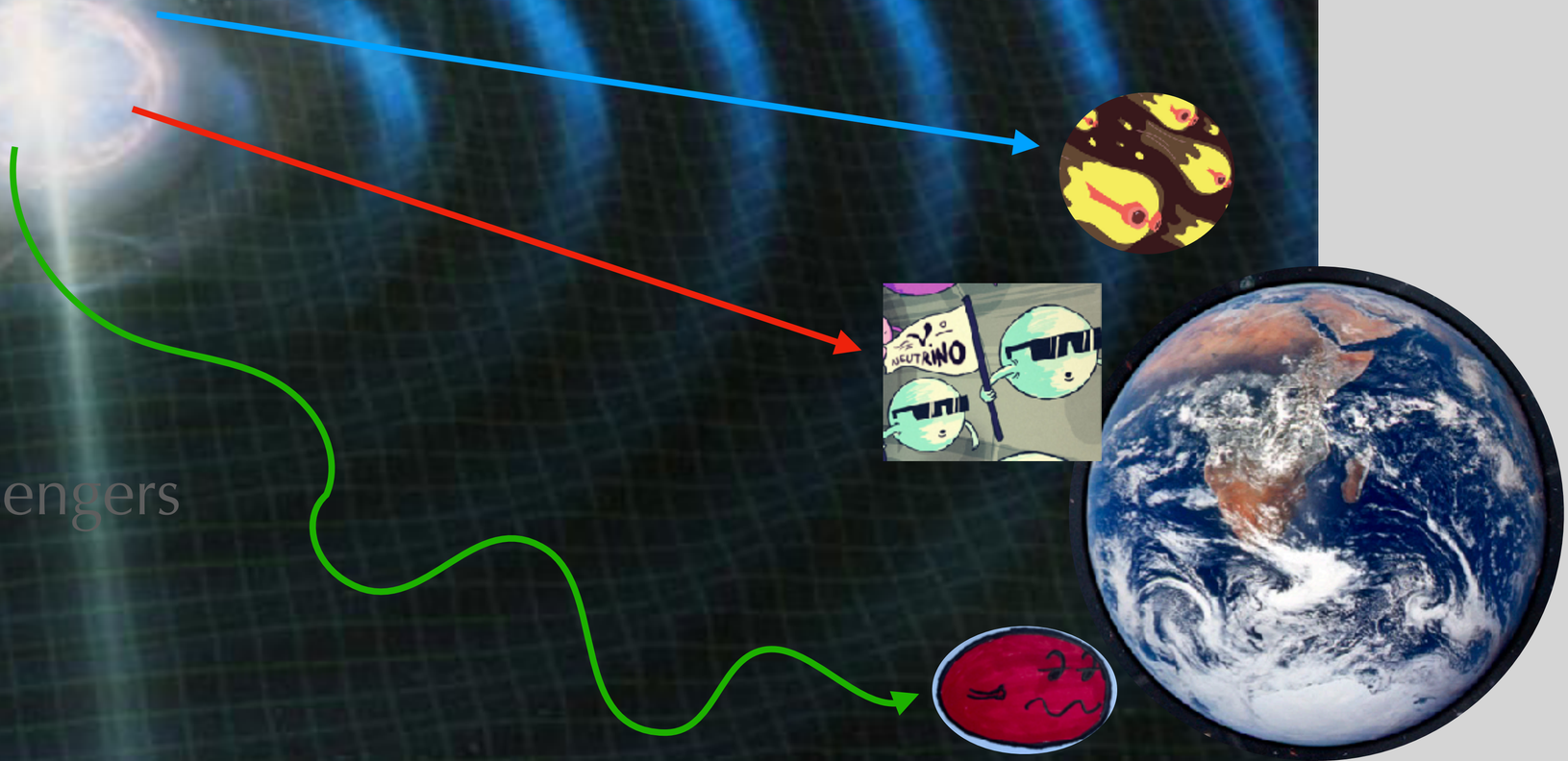
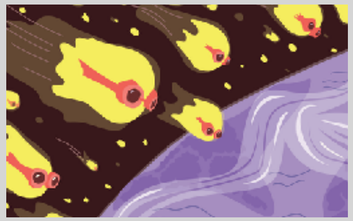
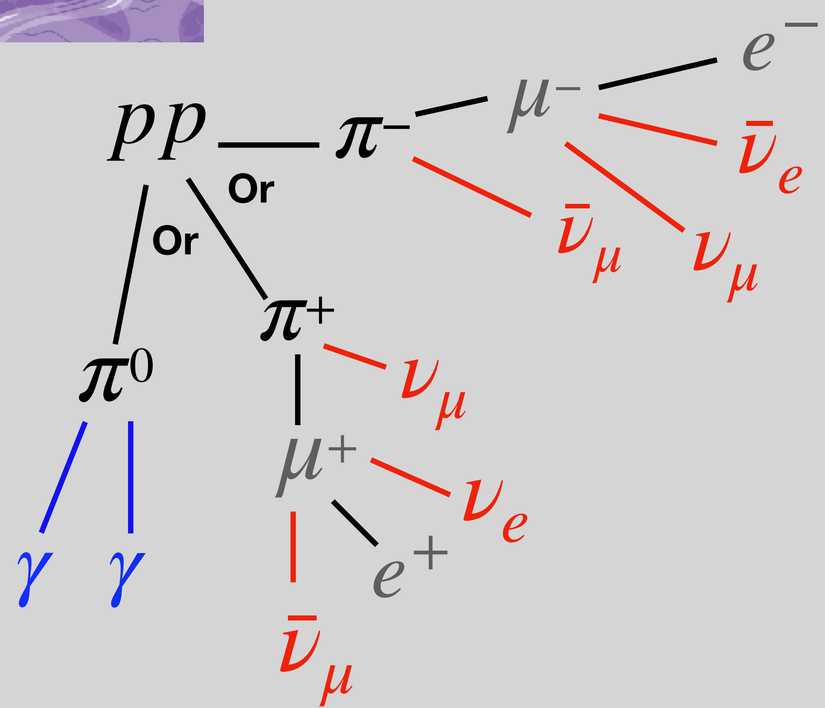


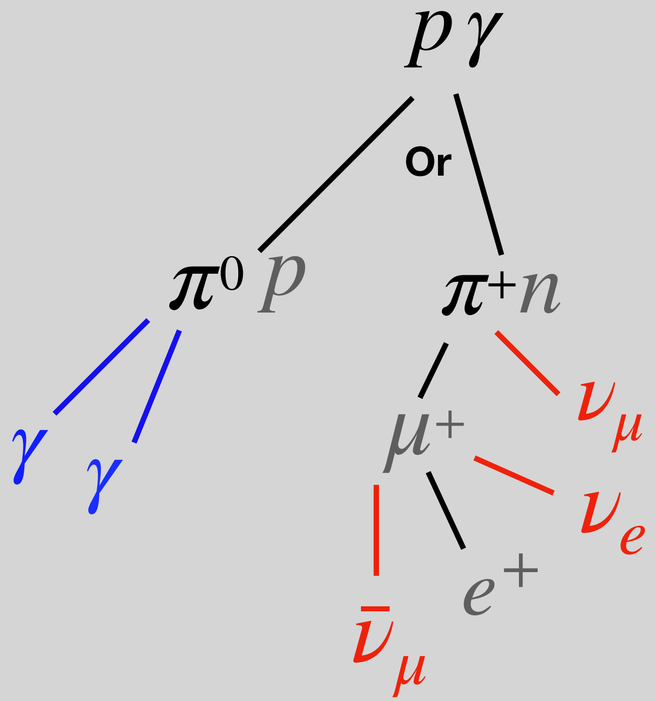
The Neutrino-Electromagnetic channel

- 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)

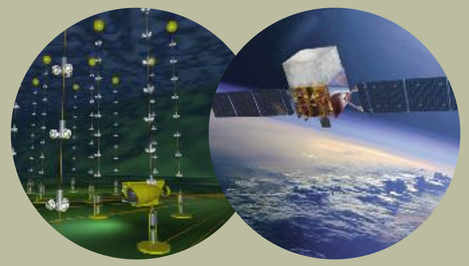




The NuEM channel: analyses

Archival Analysis

Real-time analysis



ANTARES +Fermi LAT

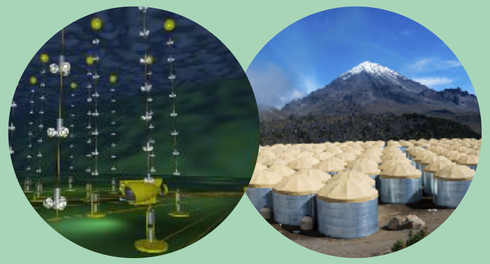
Ayala, et al 2021

IceCube + HAWC

Ayala, et al 2021

IceCube +Fermi LAT

Turley, et al 2018



ANTARES + HAWC

Paper submitted to ApJ

The NuEM channel: analyses

Archival Analysis

Real-time analysis

ANTARES +Fermi LAT

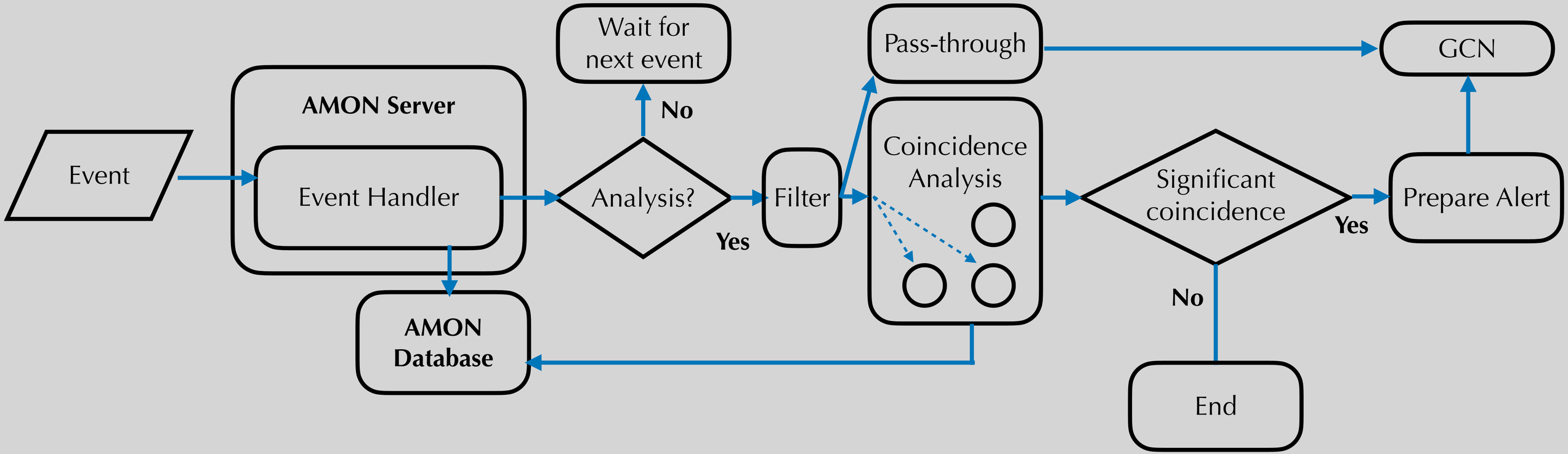
IceCube + HAWC

ANTARES has ceased operations

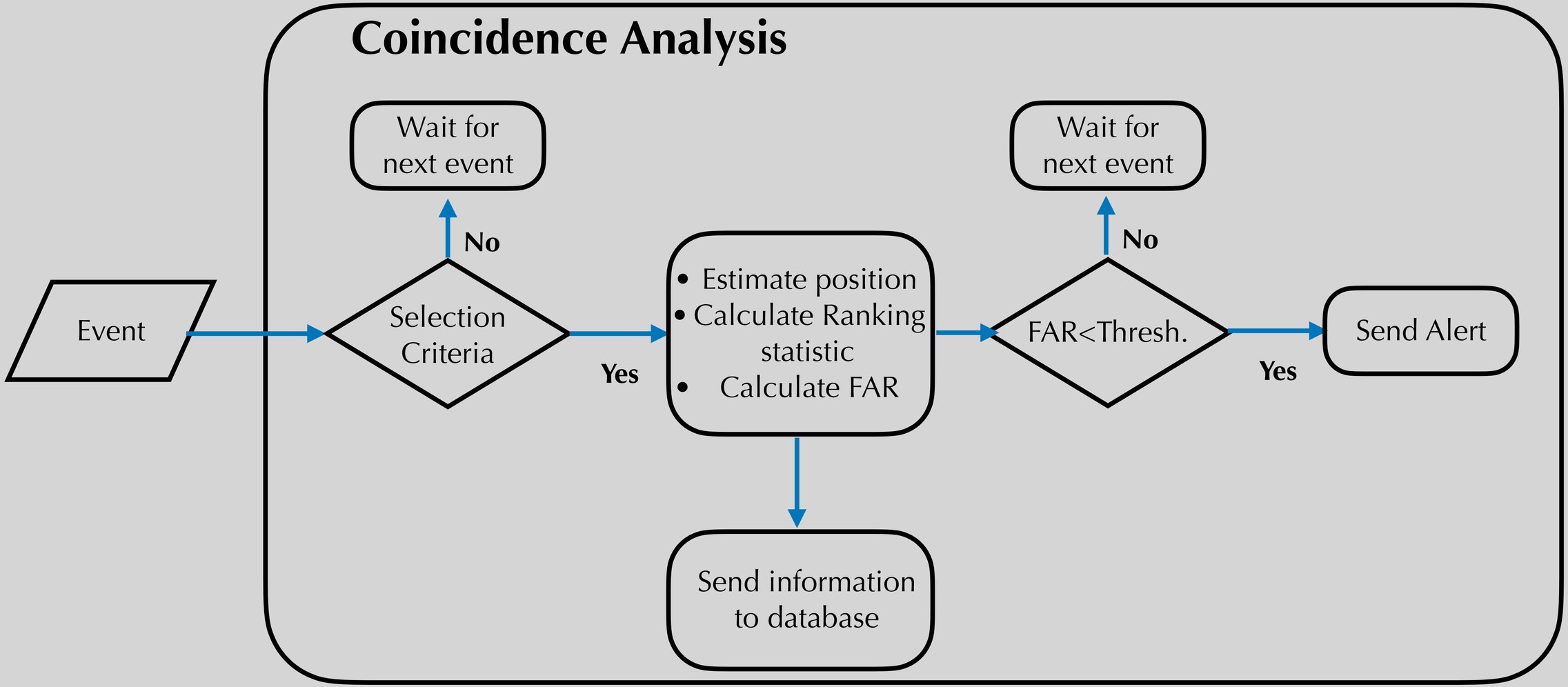
IceCube +Fermi LAT

ANTARES + HAWC*

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

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

$\Delta t \pm 100s$

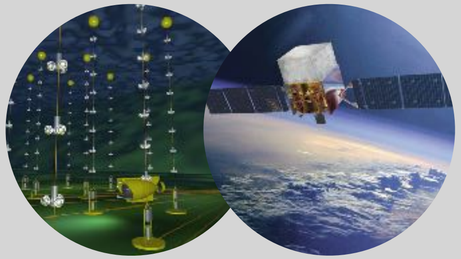
IceCube + HAWC

Ayala, et al 2021

A HAWC event and
Neutrino events

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

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



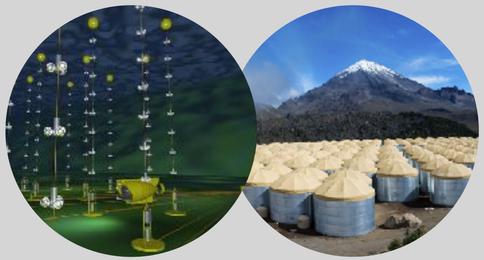
ANTARES +Fermi LAT

Ayala, et al 2021

Neutrino event
tracks (cascades)
And photons

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

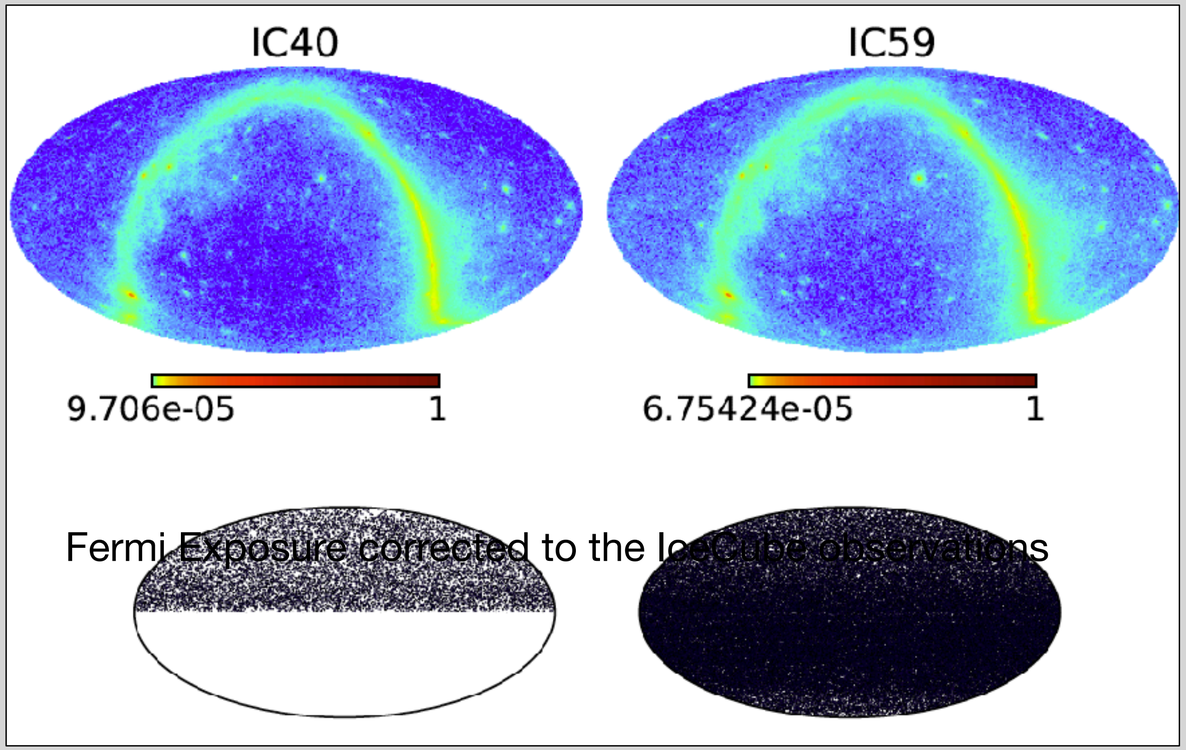
$\Delta t \pm 1000s$



ANTARES + HAWC

Paper in preparation

IceCube - Fermi LAT



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

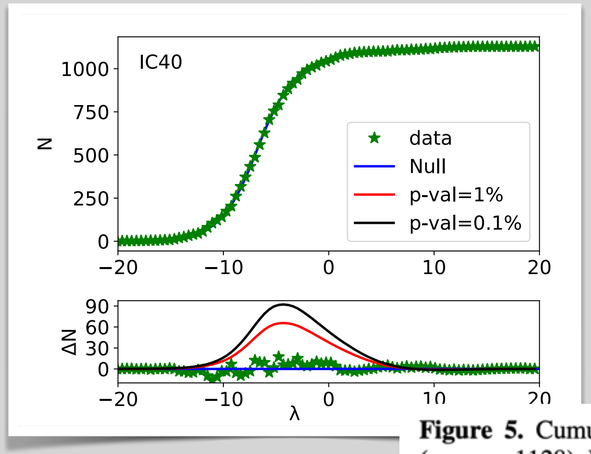
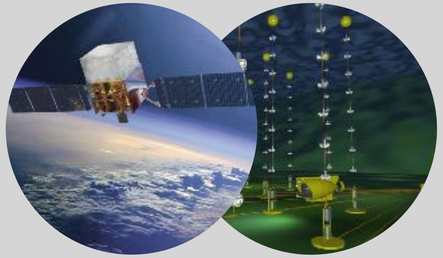


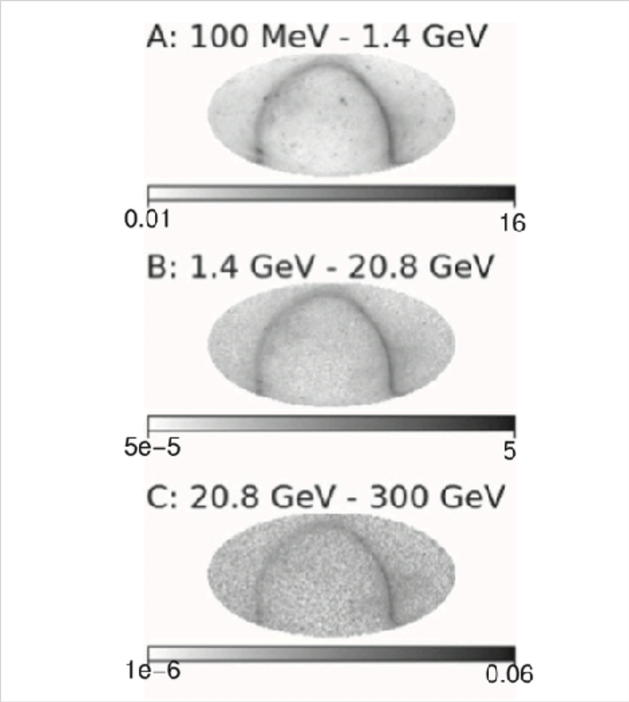
Figure 5. Cumulative and residual test statistic (λ) distributions for IC 40 ($n_{\nu+\gamma} = 1128$). Upper panel: cumulative IC 40 λ distributions for unscrambled data (green stars), scrambled data/null distribution (blue line), and signal injections yielding $p = 1\%$ (red line) and $p = 0.1\%$ (black line). Lower panel: residuals, plotted as null minus alternative, for IC 40 data (green stars) and the two signal-injection distributions (red and black lines).

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

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

ANTARES - Fermi LAT





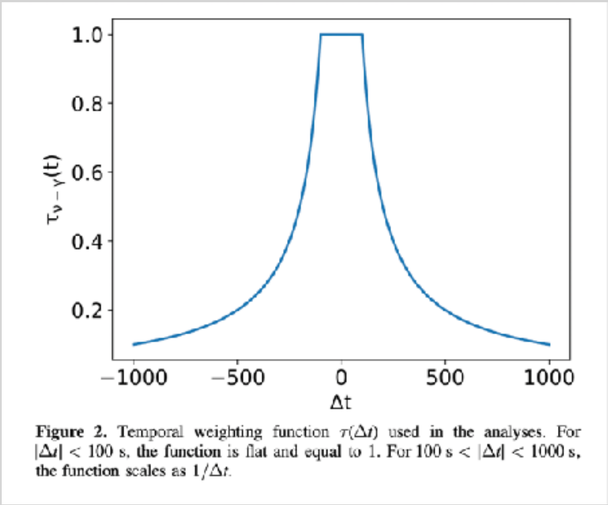
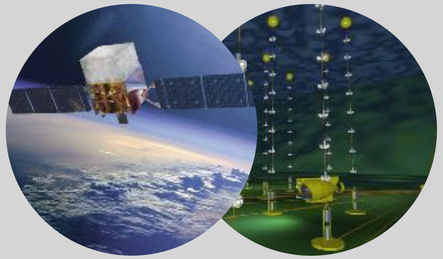


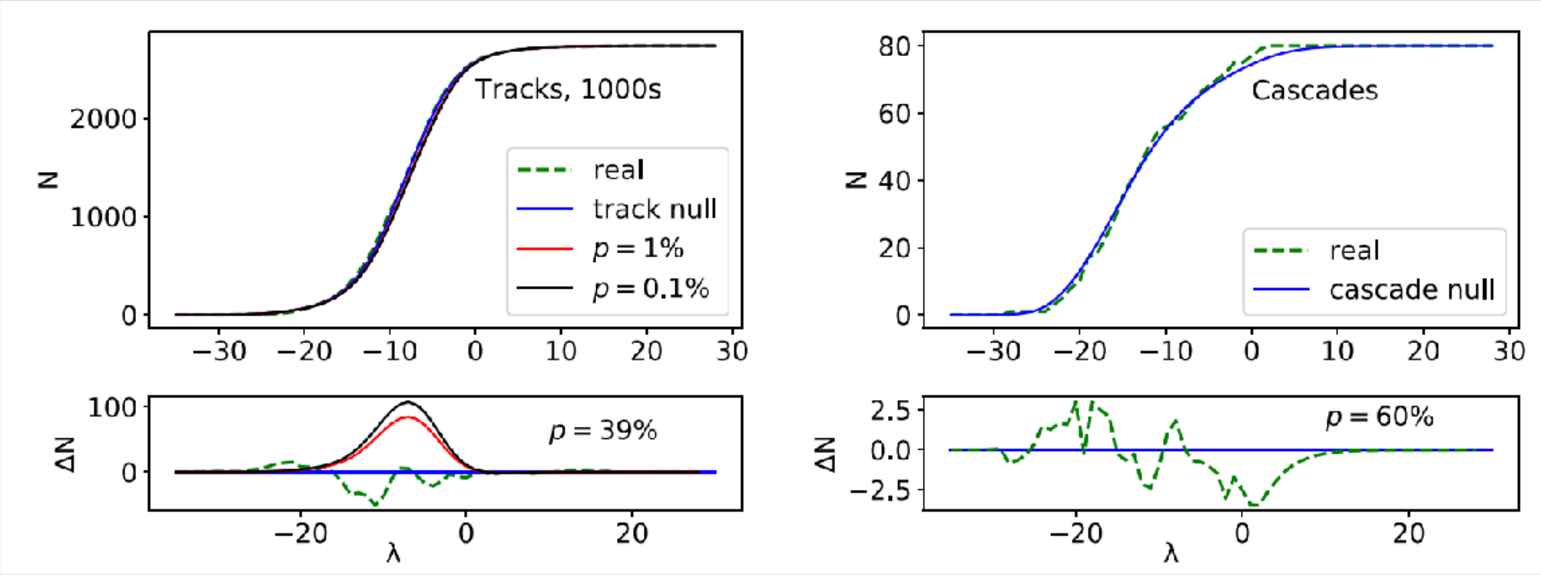
Figure 2. Temporal weighting function $\tau(\Delta t)$ used in the analyses. For $|\Delta t| < 100$ s, the function is flat and equal to 1. For $100\,\text{s} < |\Delta t| < 1000$ s, the function scales as $1/\Delta t$.

- Use of track and cascade events from Antares
- Spatial selection: $\Delta\theta < 5^{\circ}(10^{\circ})$
- Temporal selection: $\Delta t \pm 1000s$
- Neutrino multiplets are constrained to have each neutrino within both the angular and temporal separation of each other neutrino.
- Photons fall within the angular and temporal window as measure from the average neutrino position and time.

Turley, et al 2019

ANTARES - Fermi LAT





- Coincidences are still consistent with background expectations
- Interestingly, second coincidence comes from a busy region.

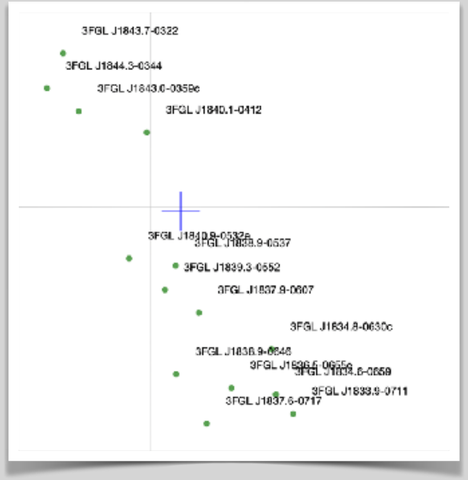


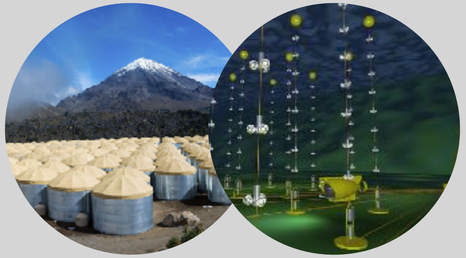
Table 2
High-λ Events

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°.00, −7°.70	2′	1	18.9	0.09
2014 Aug 5	11:13:33	56874.4677	750	279°.68, −5°.05	3′	2	18.8	0.09

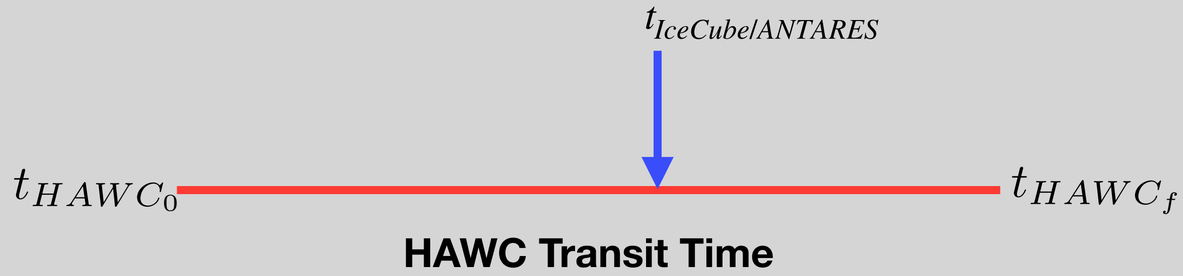
Note: Date, Time, and MJD show the central time of the coincidence, while Δt measures the separation between the earliest and latest particles in the coincidence in seconds. Position gives the R.A. and decl. (in degrees) of the best-fit position, while $r_{1\sigma}$ gives the approximate 1σ error on 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

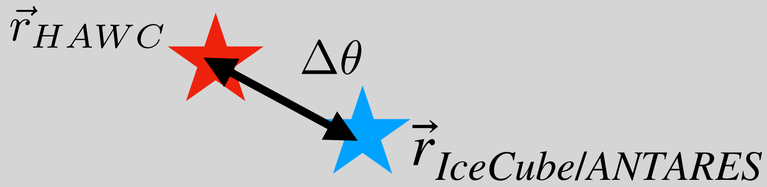
HAWC-IceCube/ANTARES



- **Temporal selection**: Time of IceCube/ANTARES event inside of HAWC monitoring transit time

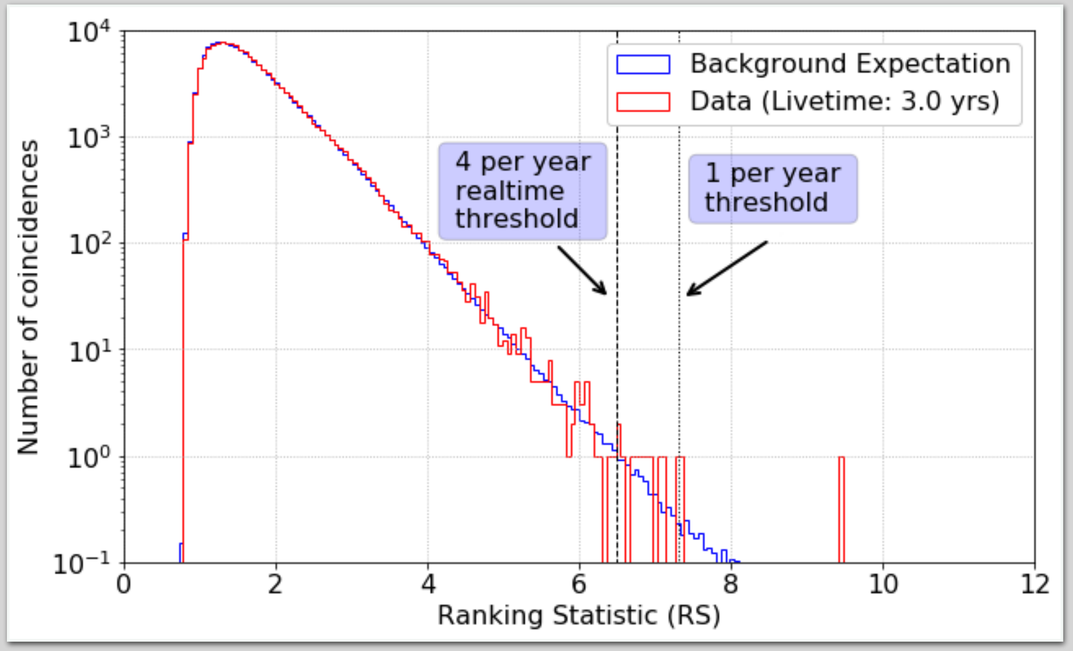


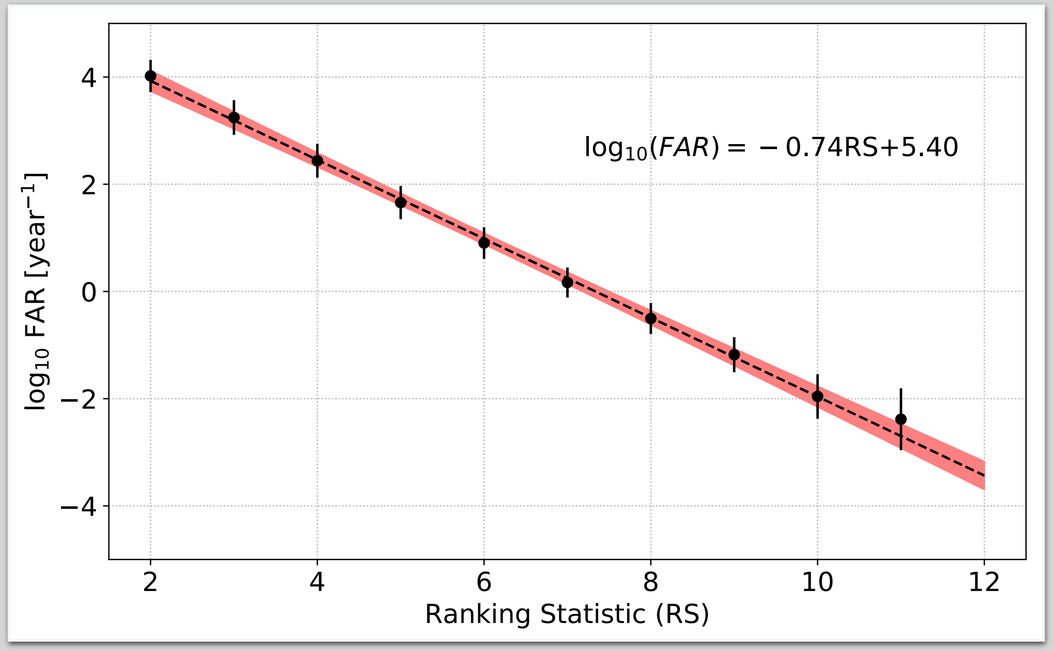
- **Spatial selection**: Angular distance between IceCube/ANTARES event and HAWC hotspot less than 3.5°



The NuEM channel: how to obtain the FAR

- We perform simulations by scrambling the datasets several times.
- Build the ranking statistic distribution
- Calculate the false alarm rate





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Archival coincidences: HAWC-IceCube

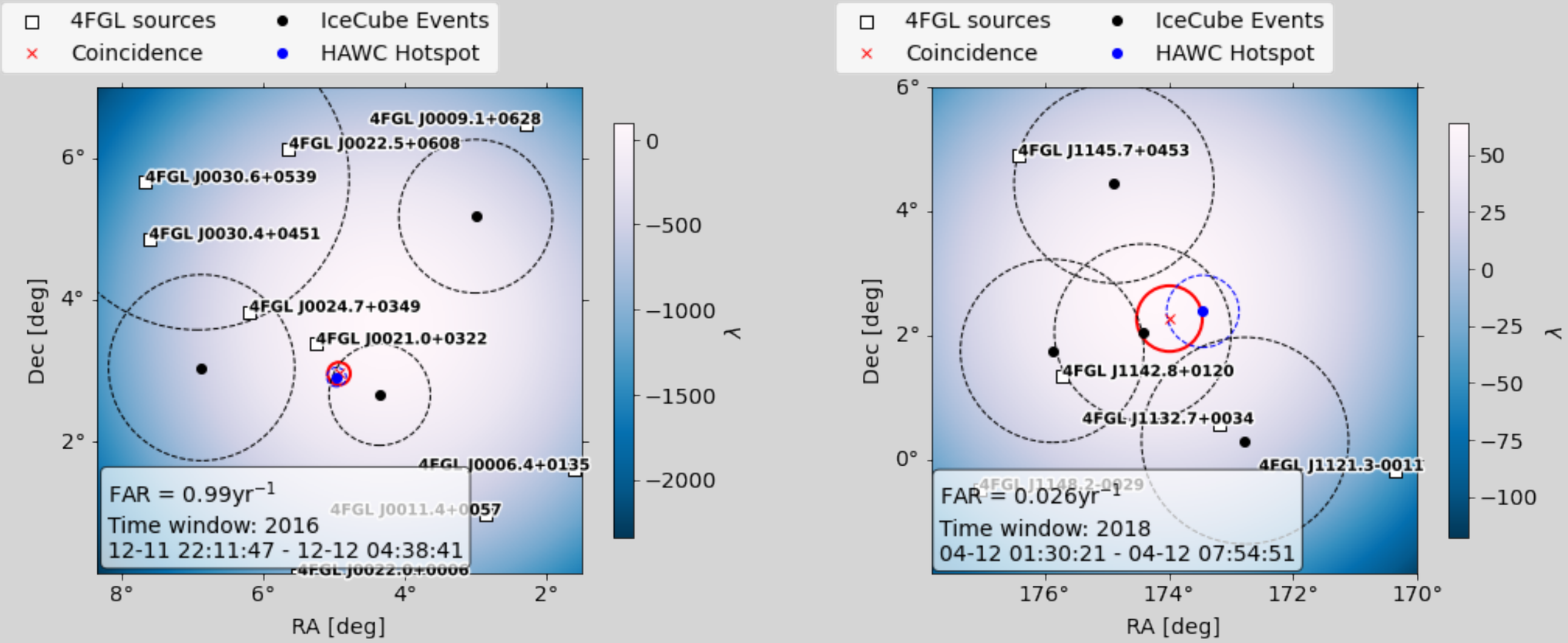

Figure 5. Skymaps of the coincidences with the lowest FAR found in the 3 years of archival data. Position of the individual events are marked with the dots. The best-fit combined positions x_{coinc}, found after optimizing Eq. 3, are marked with a cross. Circles are the 50% containment region.

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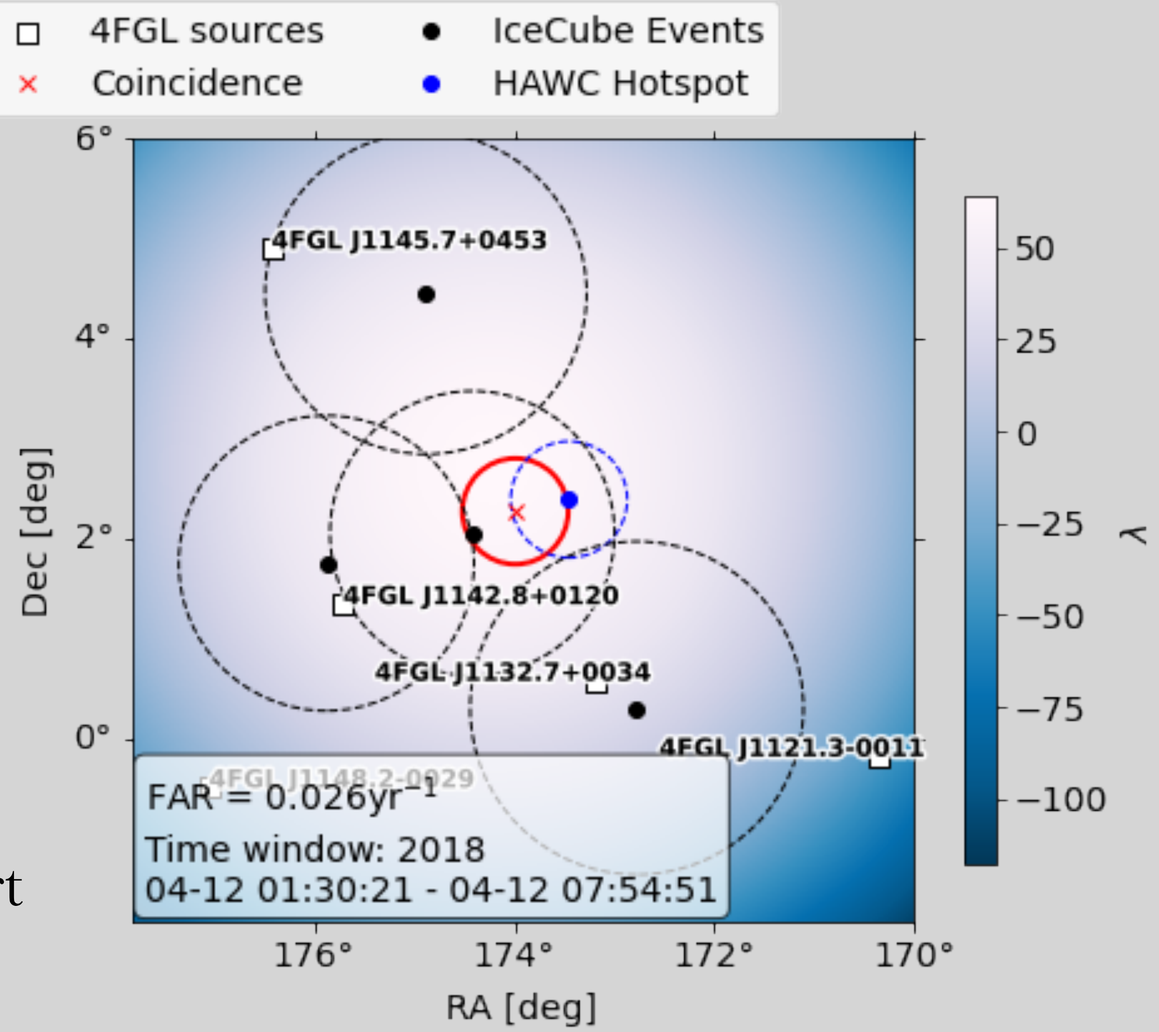
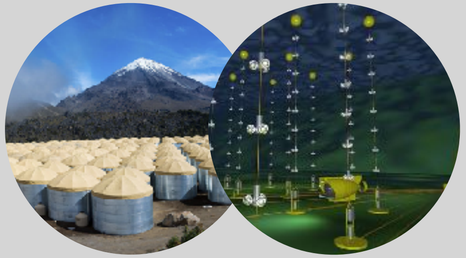
- SIMBAD: Several radio galaxies

116	NVSS J113719+022200	*1284.06*	rG	11 37 20.0731136923	+02 21 59.722380130
1	NVSS J113605+021717	*140.36*	Rad	11 36 05.90	+02 17 17.0
23	NVSS J113520+021930	*584.95*	Rad	11 35 20.90	+02 19 31.0
46	NVSS J113645+021112	*774.36*	Rad	11 36 45.20	+02 11 11.0
72	Zel 1134+027	*1034.93*	Rad	11 36 35	+02 30.7
145	NVSS J113454+015950	*1368.07*	Rad	11 34 54.40	+01 59 45.0
160	NVSS J113451+023301	*1424.63*	Rad	11 34 51.10	+02 33 10.0
175	NVSS J113449+023429	*1492.22*	Rad	11 34 50.10	+02 34 29.0
246	NVSS J113651+024305	*1810.23*	Rad	11 36 52.30	+02 43 06.0
263	NVSS J113756+022327	*1845.76*	Rad	11 37 57.30	+02 23 26.0

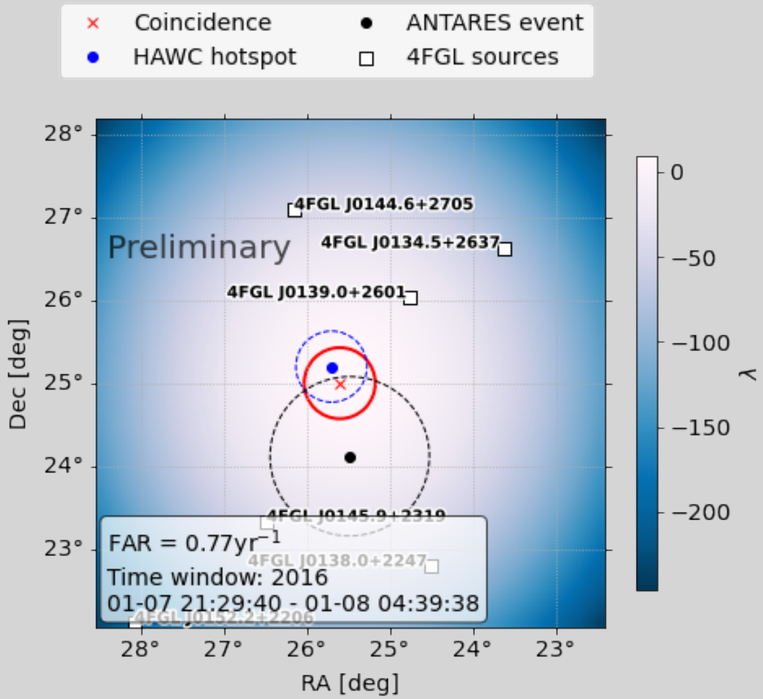
- FAVA: closest sources are 1.87° and 1.97° apart from coincidence.

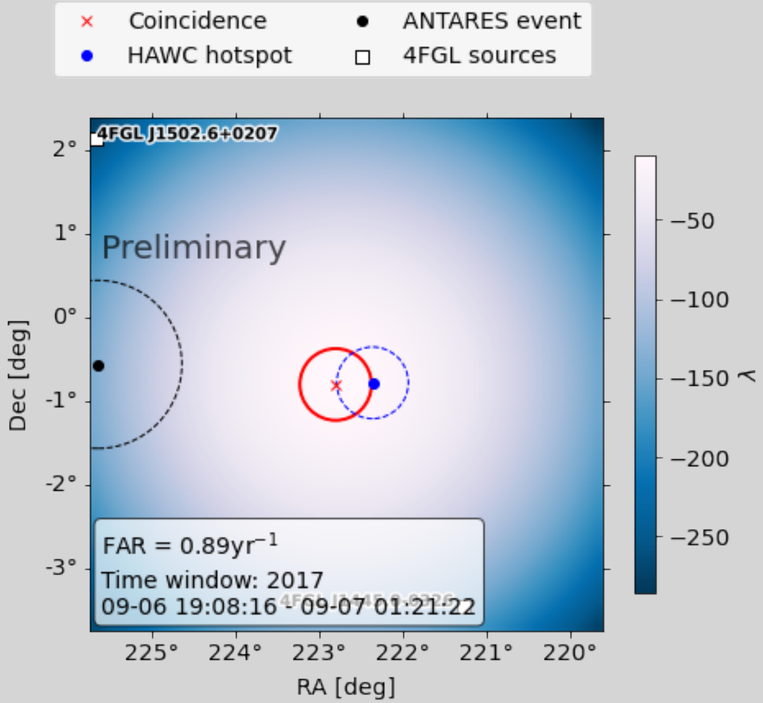


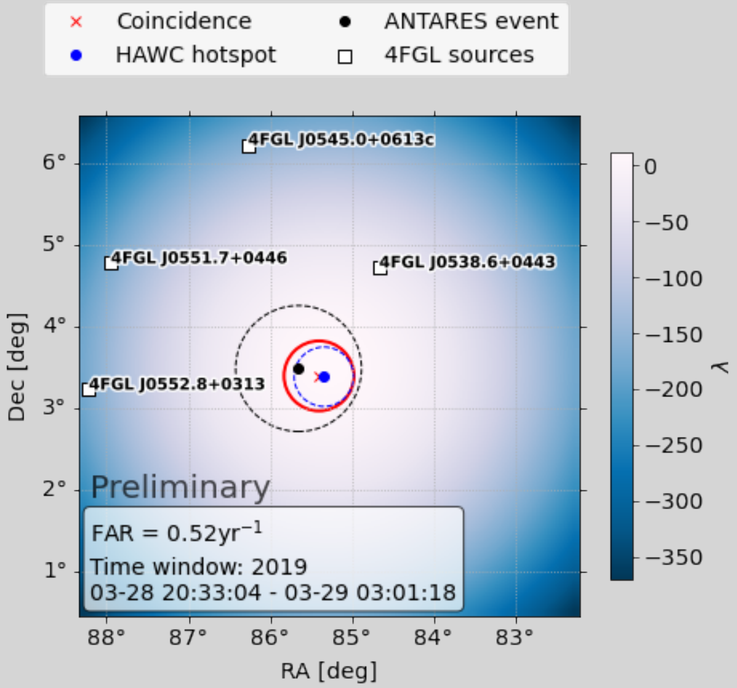
Archival coincidences: HAWC-ANTARES



- No counterpart found in the SIMBAD catalog and the Fermi All-sky Variability Analysis (FAVA) monitoring



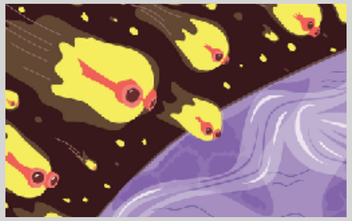




- Publication submitted to journal.

More on NuEM Channel

- 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

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

Future of the NuEM Channel

- Light curves of the order of ~weeks and ~months -> Increase time window search

TDE AT2019dsg
https://arxiv.org/abs/2202.03788

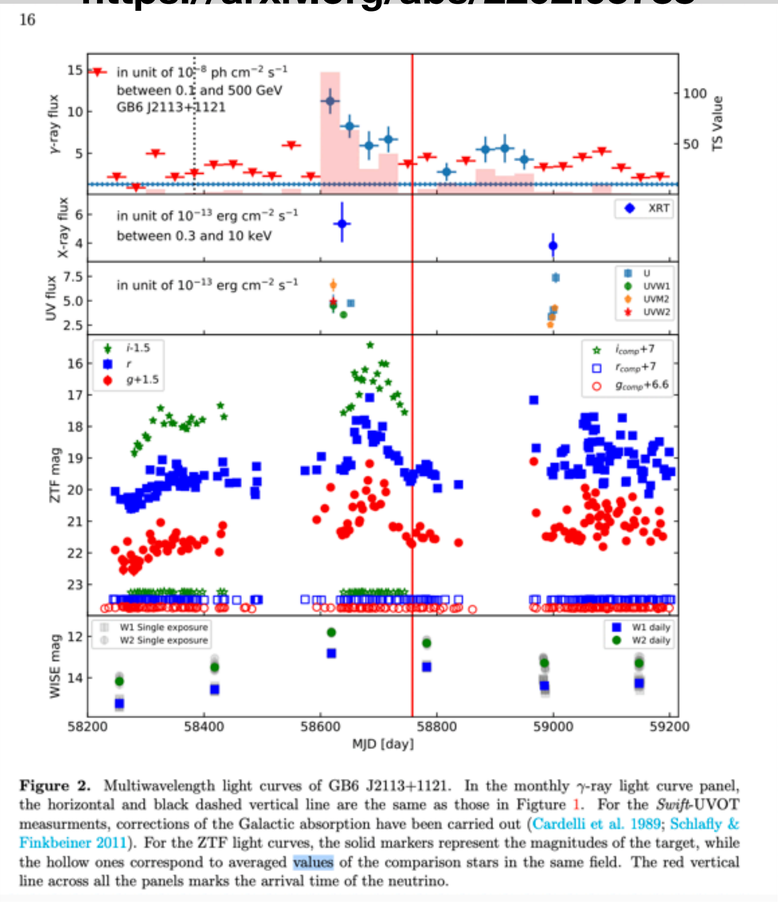
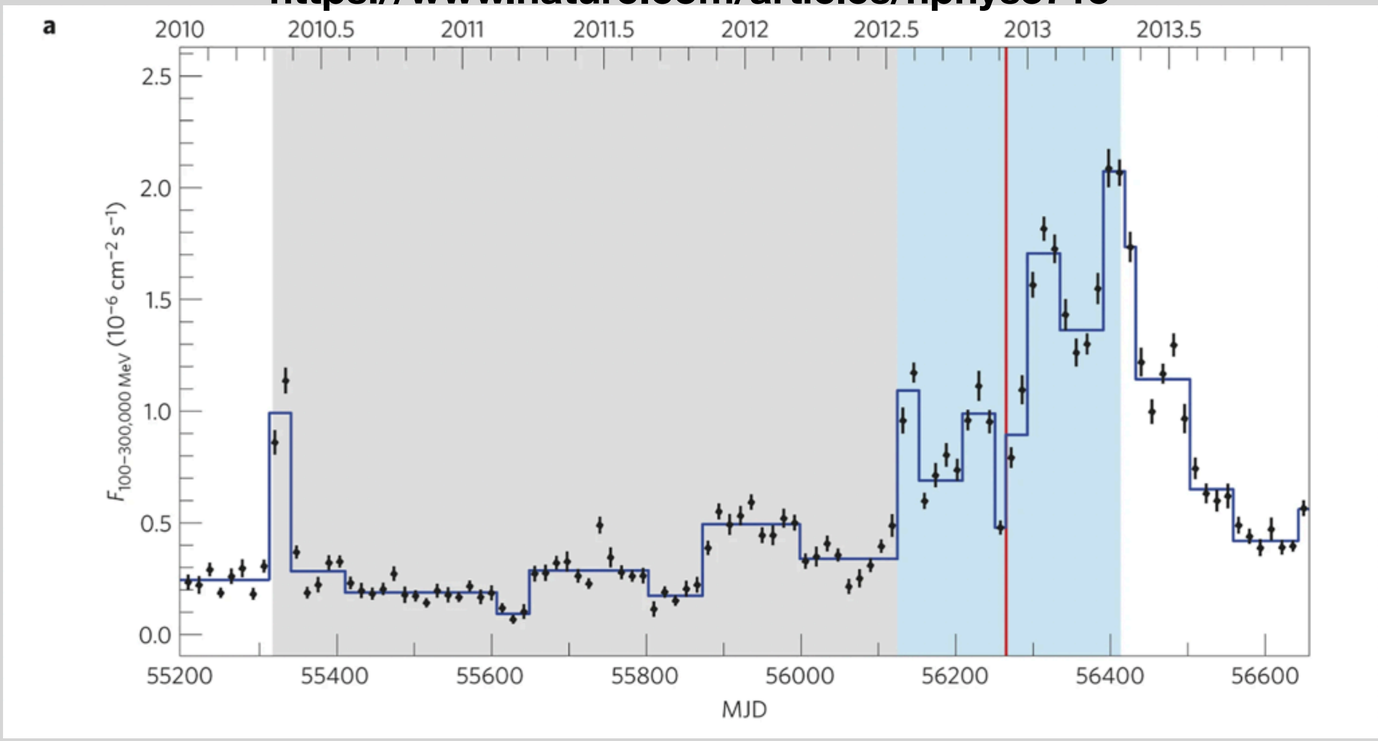


Figure 2. Multiwavelength light curves of GB6 J2113+1121. In the monthly γ-ray light curve panel, the horizontal and black dashed vertical line are the same as those in Figure 1. For the *Swift*-UVOT measurments, corrections of the Galactic absorption have been carried out (Cardelli et al. 1989; Schlafly & Finkbeiner 2011). For the ZTF light curves, the solid markers represent the magnitudes of the target, while the hollow ones correspond to averaged values of the comparison stars in the same field. The red vertical line across all the panels marks the arrival time of the neutrino.

Outburst of blazer PKS B1424-418
https://www.nature.com/articles/nphys3715



Connect to AMON

- Use GCN to listen to alerts

3) **ICECUBE_ASTROTRACK_GOLD Notice:** a single high-energy IceCube track neutrino event.

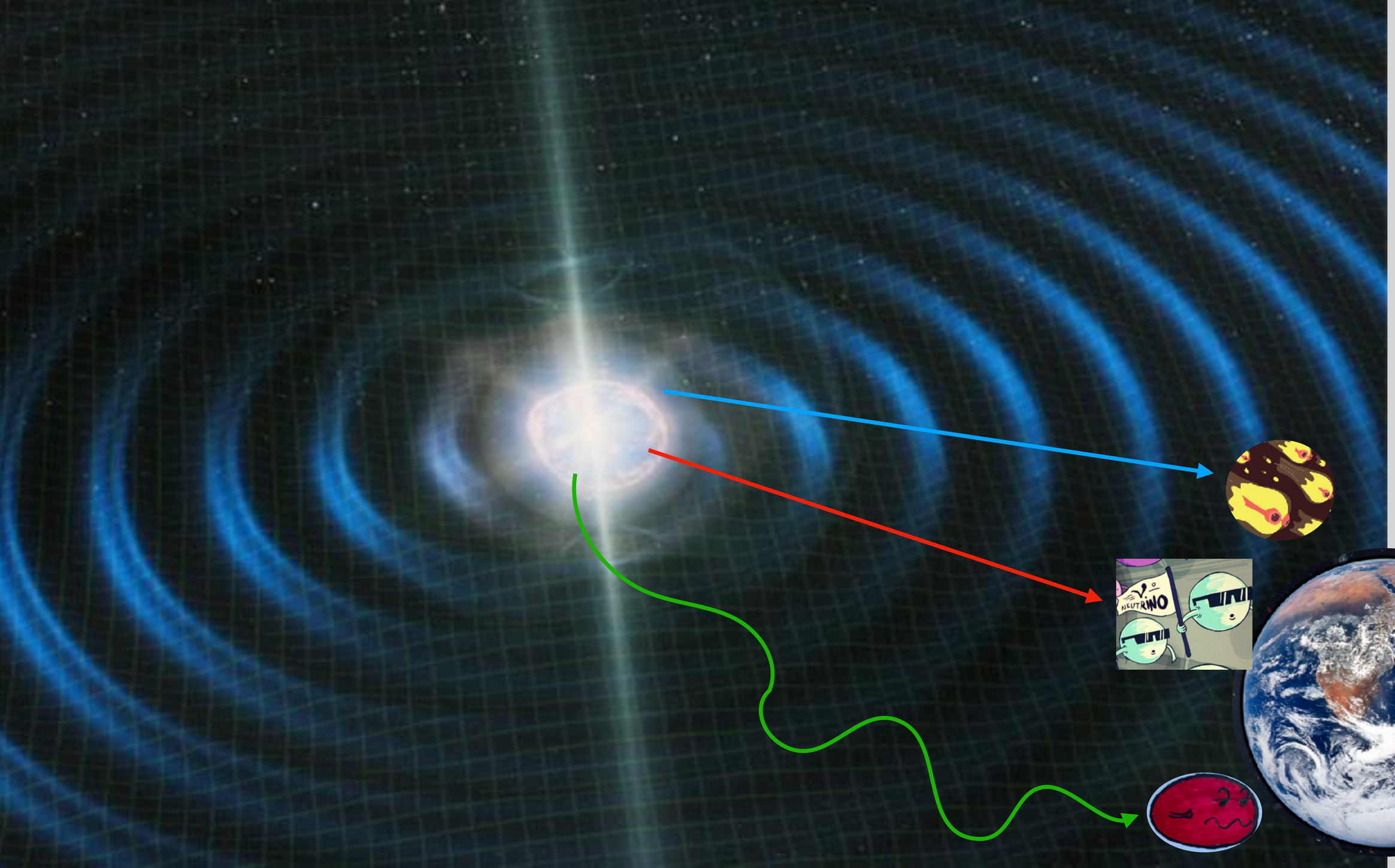
4) **ICECUBE_ASTROTRACK_BRONZE Notice:** a single high-energy IceCube track neutrino event.

5) **HAWC_BURST_MONITOR Notice:** HAWC alerts from short time-scale searches looking for GRBs.

6) **AMON_NU_EM_COINC Notice:** a coincidence between an X-/gammaray instrument and a neutrino instrument (IceCube or ANTARES).

7) **AMON_ICECUBE_CASCADE Notice:** a low-latency single high energy IceCube cascade neutrino event direction.

- Use SCiMMA for NuEM alerts https://hop.scimma.org
- Beta version: Visit the https://amontom.science.psu.edu/ to query alerts
- Contact: hgayala@psu.edu


NEUTRINO

Back-up Slides

Ranking Statistic for the analyses with Fermi

Fermi+IceCube

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

Fermi+ANTARES

$$\lambda = 2 \ln \frac{P_{\nu\gamma}(\boldsymbol{x})\, n_\nu!\, n_\gamma!\, \Pi_{\nu,\gamma}\, \tau(\Delta t_i)}{\Pi_\gamma\, B_{\gamma,i}(\boldsymbol{x})} + \sum_\nu \ln \frac{1 - p_{c,i}}{p_{c,i}},$$

Ranking statistic is based on Fisher's method.

For the HAWC+IceCube and HAWC+ANTARES

$$\chi^2_{6+2n_\nu} = -2\ln[p_\lambda p_{HAWC} p_{cluster} \prod_i^{n_\nu} p_{IC,i}]$$

P-value from Maximum likelihood, Spatial Selection

HAWC hotspot significance

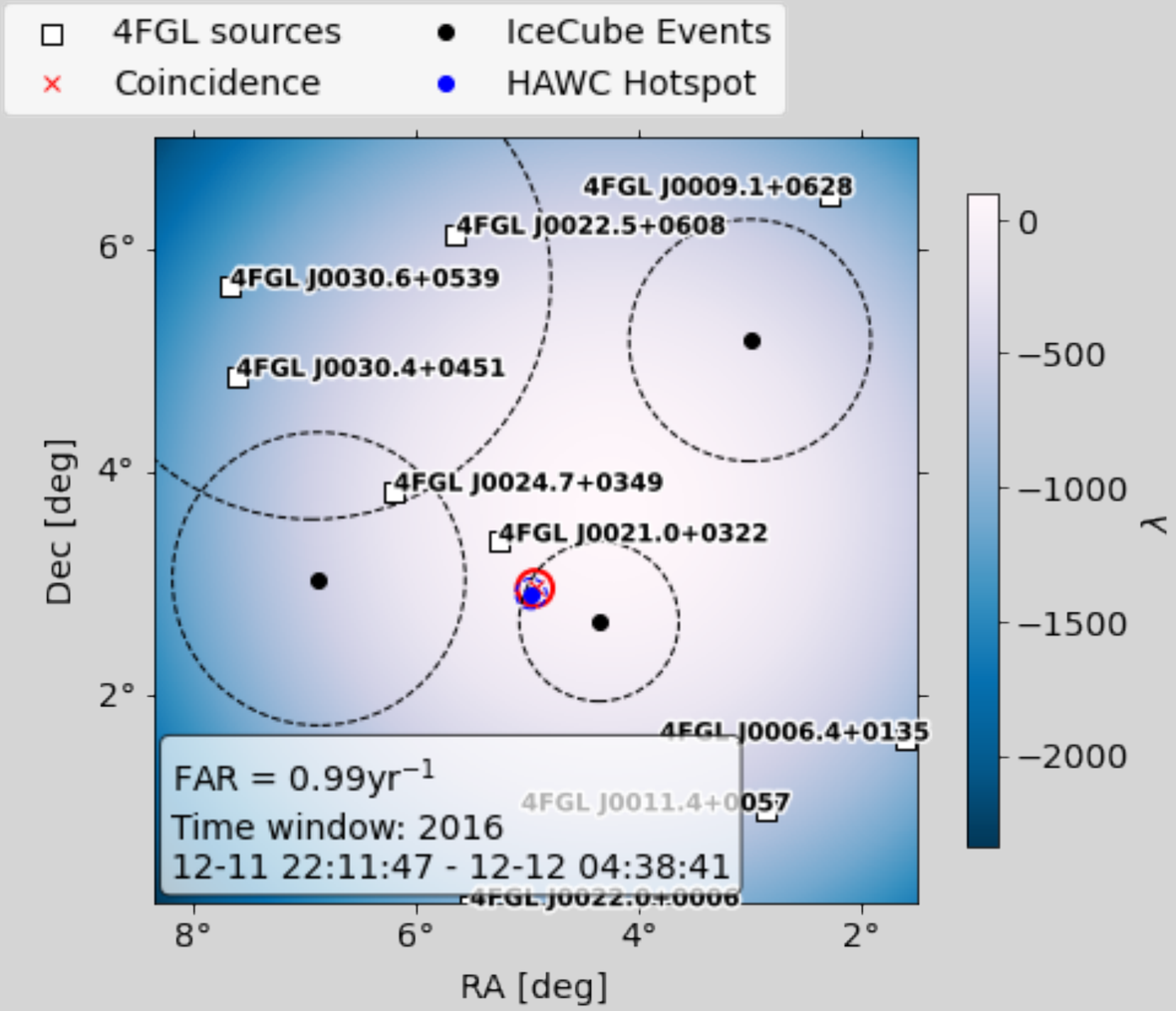
Probability of more Than one neutrino In the transit time

$p_{Cluster} = 1 - \sum_{i=0}^{N-2} Pois(i;\lambda)$

P-value of the IceCube Neutrino based on energy

$$R.S. = -\log p(>\chi^2_{6+2n_\nu})$$

Ranking statistic (R.S.) value. It takes into account the number Of DoF



- SIMBAD: TXS 0017+026 (PKS 0017+026): radio galaxy (radio source). It is 58.25 arcsec (132.7 arcsec) from coincidence.