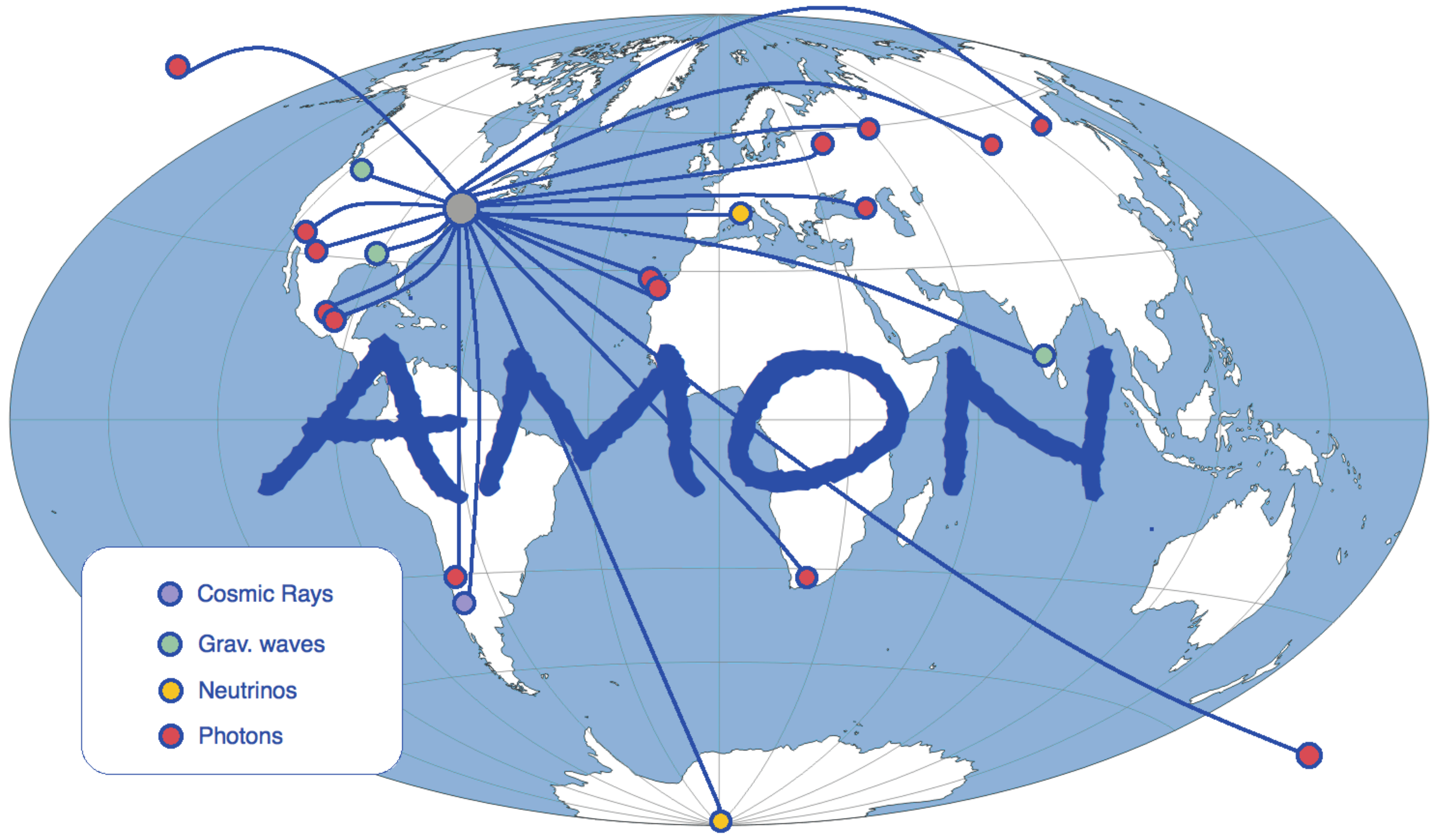
A new era of discoveries from astrophysical multimessengers

Sub-threshold multimessenger analyses with



Miguel Mostafá

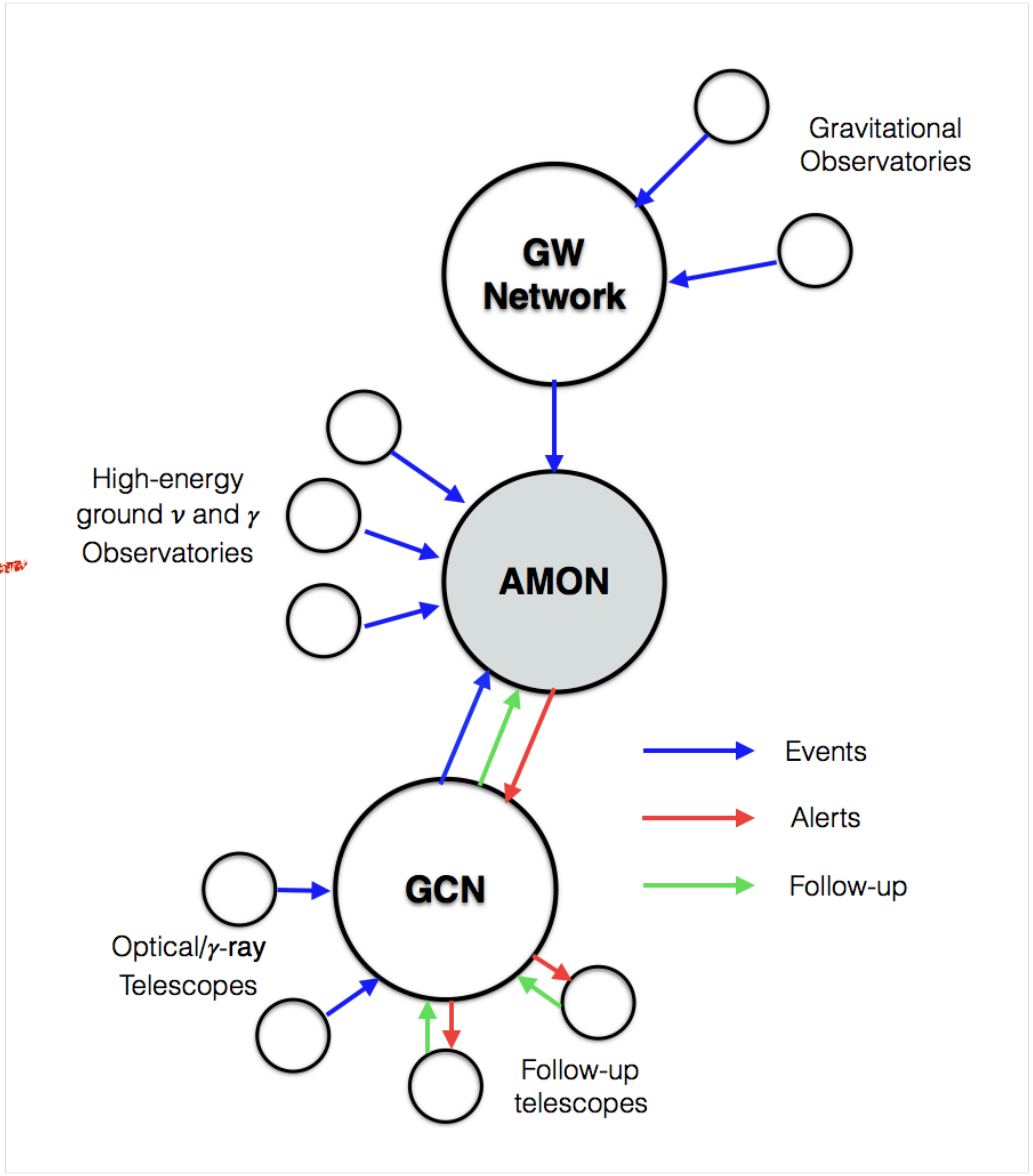
PennState
Eberly College of Science

Town Hall KM3NeT Meeting — September 20-22, 2022

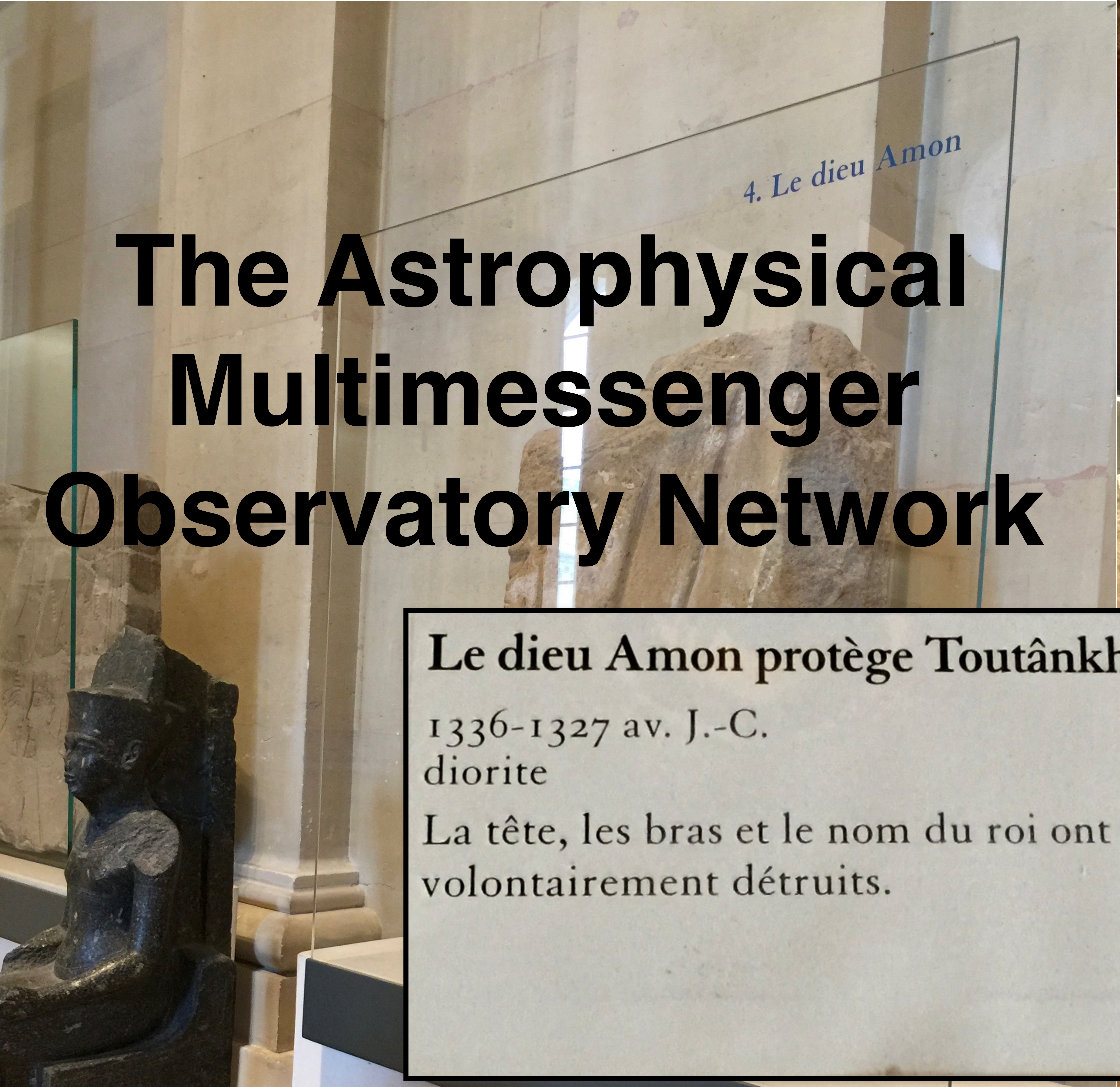
Outline today

Not today

- The Messengers
  - Current status
  - Next generation
  - First multimessenger results?
- AMON
  - Introduction
  - Archival analyses
  - Real-time coincidences
  - Prospects



The Astrophysical Multimessenger Observatory Network



Le dieu Amon protège Toutânkhamon

1336-1327 av. J.-C.
diorite

La tête, les bras et le nom du roi ont été volontairement détruits.

E 11609

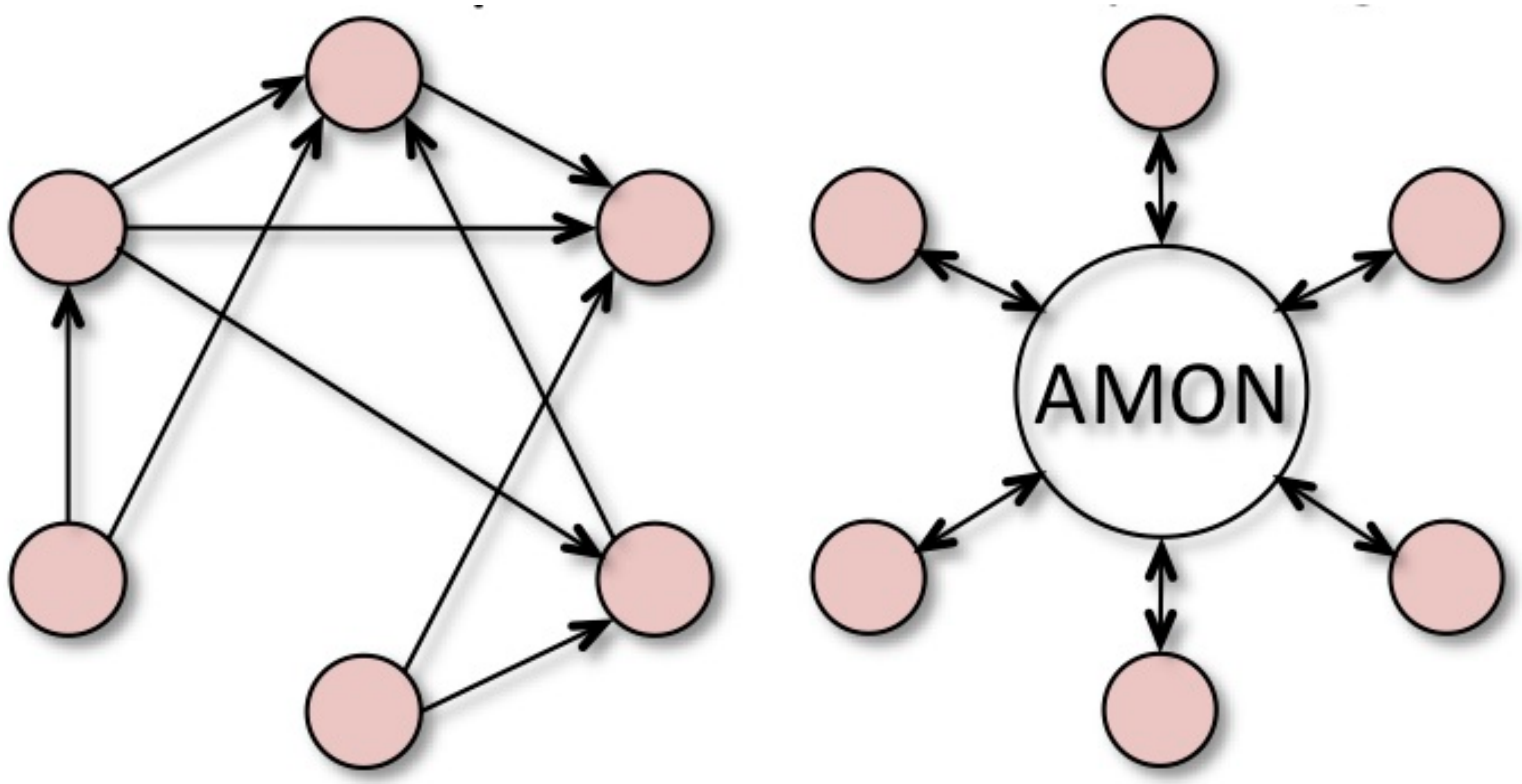
The AMON concept

AMON provides the **framework** for:

- **Real-time** and near real-time sharing of *subthreshold* data among *multimessenger* observatories
- Real-time and archival searches for any **coincident** (in time and space) signals.
- Prompt distribution of **alerts** for follow-up observations

https://www.amon.psu.edu/

AMON unifies and simplifies existing *multimessenger* efforts:



Astrop. Phys. Vol. 45, 56–70, 2013

Astrop. Phys. Vol. 114, 68–76, 2020

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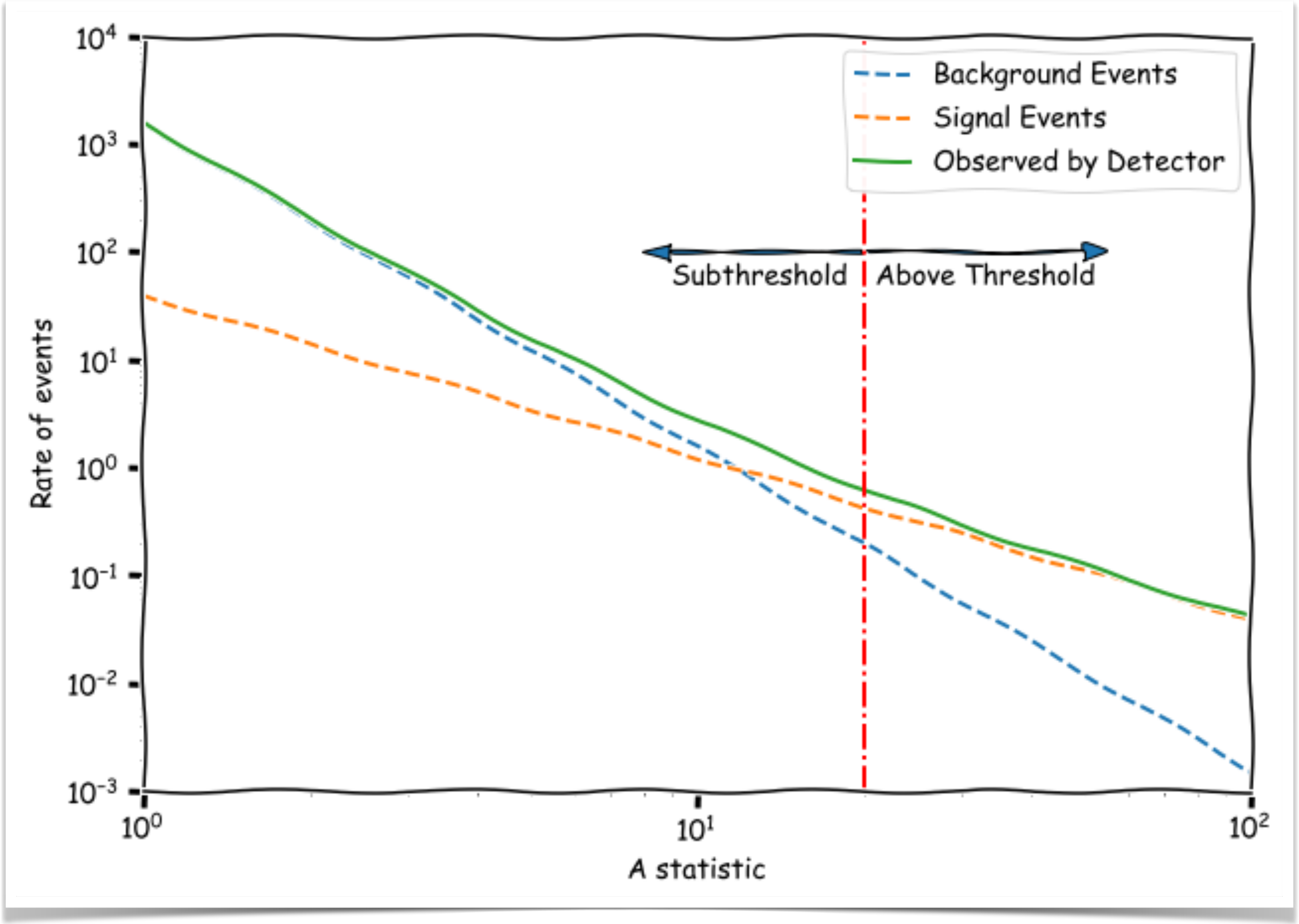
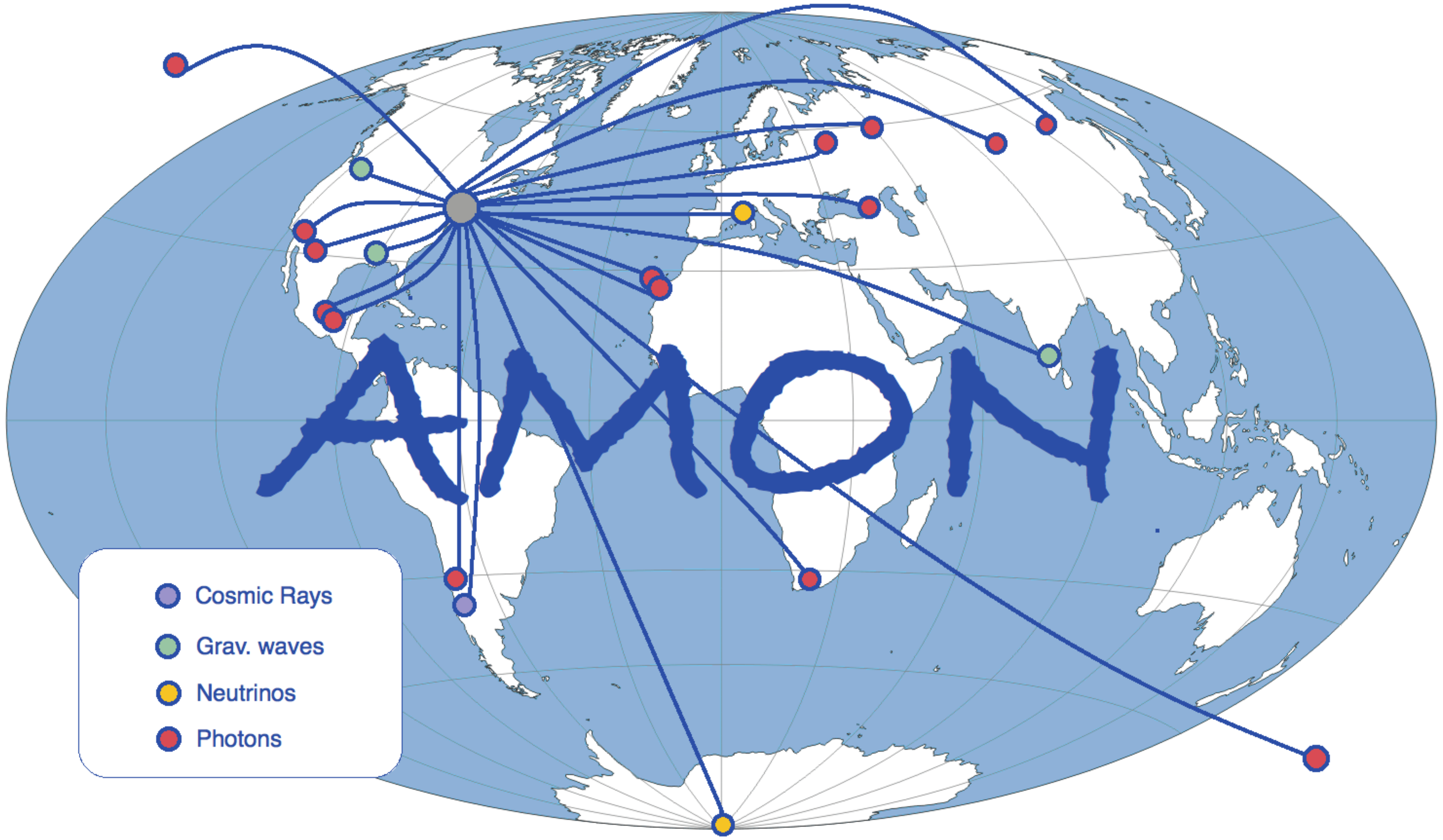


https://www.amon.psu.edu/

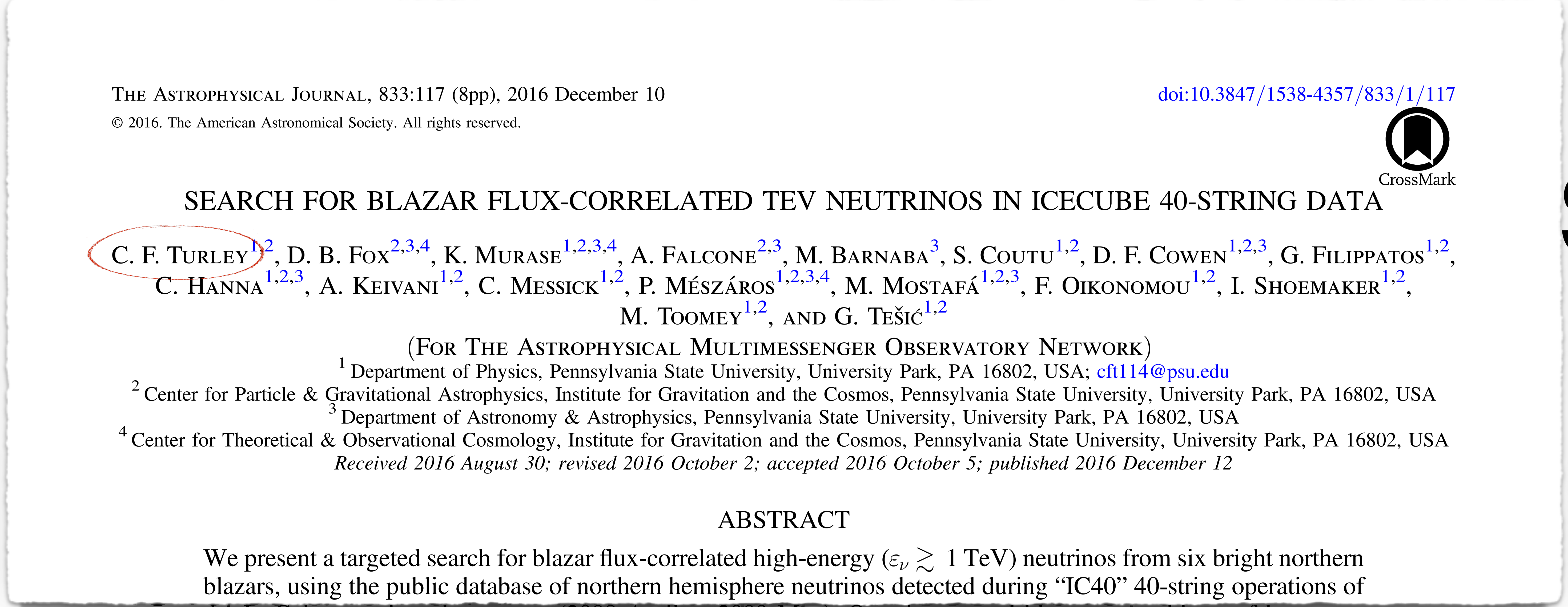
The Network

- **Triggering:** IceCube, ANTARES, Auger, HAWC, VERITAS, FACT, Swift-BAT, MAGIC, HESS
- **Follow-up:** Swift-XRT & UVOT, VERITAS, FACT, MASTER, LCOGT, MAGIC, HESS
- **Pending:** LIGO, PTF, TA, LHAASO, …



https://www.amon.psu.edu/join/

sis examples


THE ASTROPHYSICAL JOURNAL, 833:117 (8pp), 2016 December 10 doi:10.3847/1538-4357/833/1/117

CrossMark

SEARCH FOR BLAZAR FLUX-CORRELATED TEV NEUTRINOS IN ICECUBE 40-STRING DATA

C. F. TURLEY[1,2], D. B. FOX[2,3,4], K. MURASE[1,2,3,4], A. FALCONE[2,3], M. BARNABA[3], S. COUTU[1,2], D. F. COWEN[1,2,3], G. FILIPPATOS[1,2], C. HANNA[1,2,3], A. KEIVANI[1,2], C. MESSICK[1,2], P. MÉSZÁROS[1,2,3,4], M. MOSTAFÁ[1,2,3], F. OIKONOMOU[1,2], I. SHOEMAKER[1,2], M. TOOMEY[1,2], AND G. TEŠIĆ[1,2]
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[2] Center for Particle & Gravitational Astrophysics, Institute for Gravitation and the Cosmos, Pennsylvania State University, University Park, PA 16802, USA
[3] Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802, USA
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Received 2016 August 30; revised 2016 October 2; accepted 2016 October 5; published 2016 December 12

ABSTRACT

We present a targeted search for blazar flux-correlated high-energy ($\varepsilon_\nu \gtrsim$ 1 TeV) neutrinos from six bright northern blazars, using the public database of northern hemisphere neutrinos detected during "IC40" 40-string operations of

- IC40/59 and Swift-BAT sub-threshold (in progress)
- IC40 and VERITAS blazar TeV flares: Astrophys. J. **833** (2016) 117

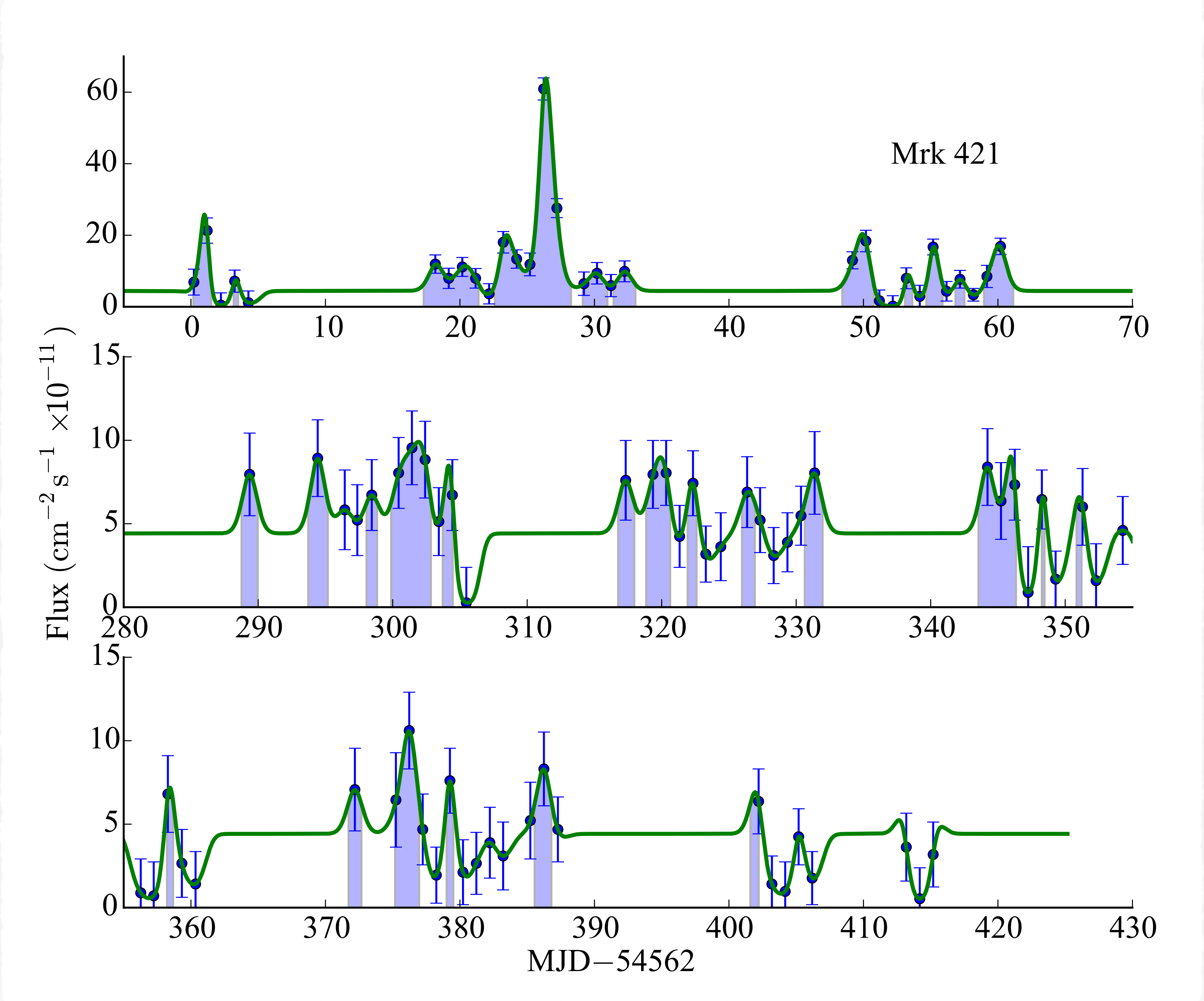

Fig. 2.— Times of interest for Markarian 421. These times were selected in our initial optimization as the most sensitive search for associated neutrinos (Sec 2.3). The selection includes 45.6 days with a total γ-ray fluence of $4.1 \times 10^{-4}\,\mathrm{cm}^{-2}$ and yields an expected background of 1.03 neutrinos.

- γ rays + gravitational waves
  - Swift and LIGO S5 (in progress)
- ν's + γ rays + cosmic rays
  - PBH evaporation searches, G. Tešić, PoS (ICRC'15) 328 (2015)
- others… FRB + Swift: ApJL **832** (2016) L1

Early archival analysis examples

- ν's + γ rays
  - IC40 and Fermi-LAT, A. Keivani et al., PoS (ICRC'15) 786 (2015)
  - IC40/59 and Fermi-LAT: Astrophys. J. **863** (2018) 64
  - IC40/59 and Swift-BAT sub-threshold (in progress)

The Astrophysical Journal Letters, 832:L1 (9pp), 2016 November 20
doi:10.3847/2041-8205/832/1/L1

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DISCOVERY OF A TRANSIENT GAMMA-RAY COUNTERPART TO FRB 131104

J. J. DeLaunay[1,3], D. B. Fox[2,3,4], K. Murase[1,2,3,4], P. Mészáros[1,2,3,4], A. Keivani[1,3], C. Messick[1,3], M. A. Mostafá[1,3], F. Oikonomou[1,3], G. Tešić[1,3], and C. F. Turley[1,3]
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Received 2016 September 26; accepted 2016 September 29; published 2016 November 11

ABSTRACT

We report our discovery in *Swift* satellite data of a transient gamma-ray counterpart (3.2σ confidence) to the fast radio burst (FRB) FRB 131104, the first such counterpart to any FRB. The transient has a duration $T_{90} \gtrsim 100$ s and a fluence $S_\gamma \approx 4 \times 10^{-6}$ erg cm^{-2}, increasing the energy budget for this event by more than a billion times; at the nominal $z \approx 0.55$ redshift implied by its dispersion measure, the burst's gamma-ray energy output is $E_\gamma \approx 5 \times 10^{51}$ erg. The observed radio to gamma-ray fluence ratio for FRB 131104 is consistent with a lower

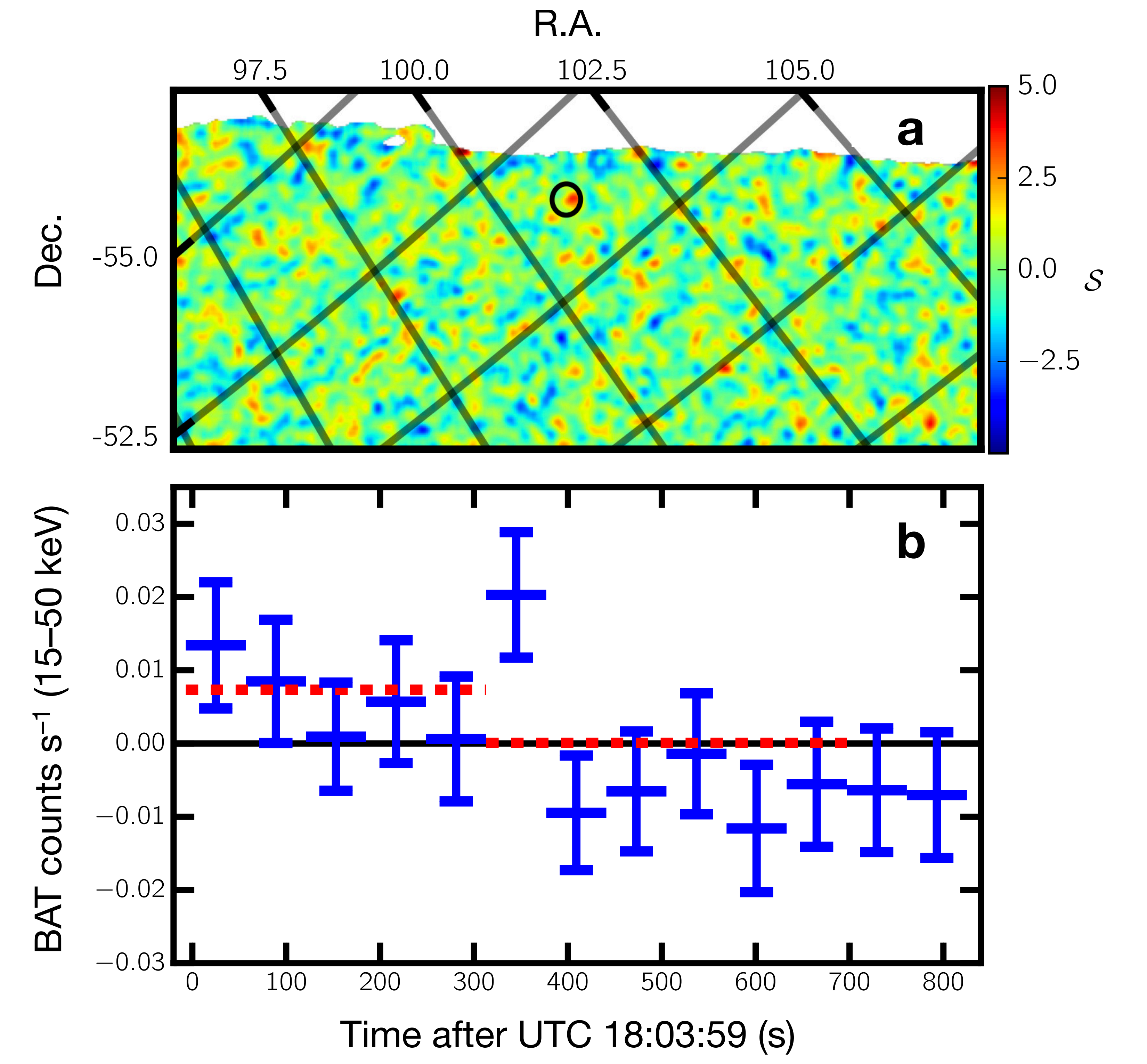

Figure 1. Swift BAT discovery image and light curve for the transient gamma-ray counterpart to FRB 131104, Swift J0644.5−5111. (a) Swift J0644.5−5111 discovery image (15–150 keV; UTC 18:03:52 start; 300 s exposure), showing a small portion of the BAT field of view in tangent plane projection. The search region for FRB 131104 (black circle) is shown; regions with <1% coding are masked. The point-like excess associated with the gamma-ray transient peaks at signal-to-noise $\mathcal{S} = 4.2\sigma$. (b) Soft-band (15–50 keV) light curve for Swift J0644.5−5111. Time is measured from the FRB detection, UTC 18:03:59. Both 64 s (blue) and 320 s (red dashed) flux measurements are shown; error bars are $\pm 1\sigma$.

- others… FRB + Swift: ApJL **832** (2016) L1

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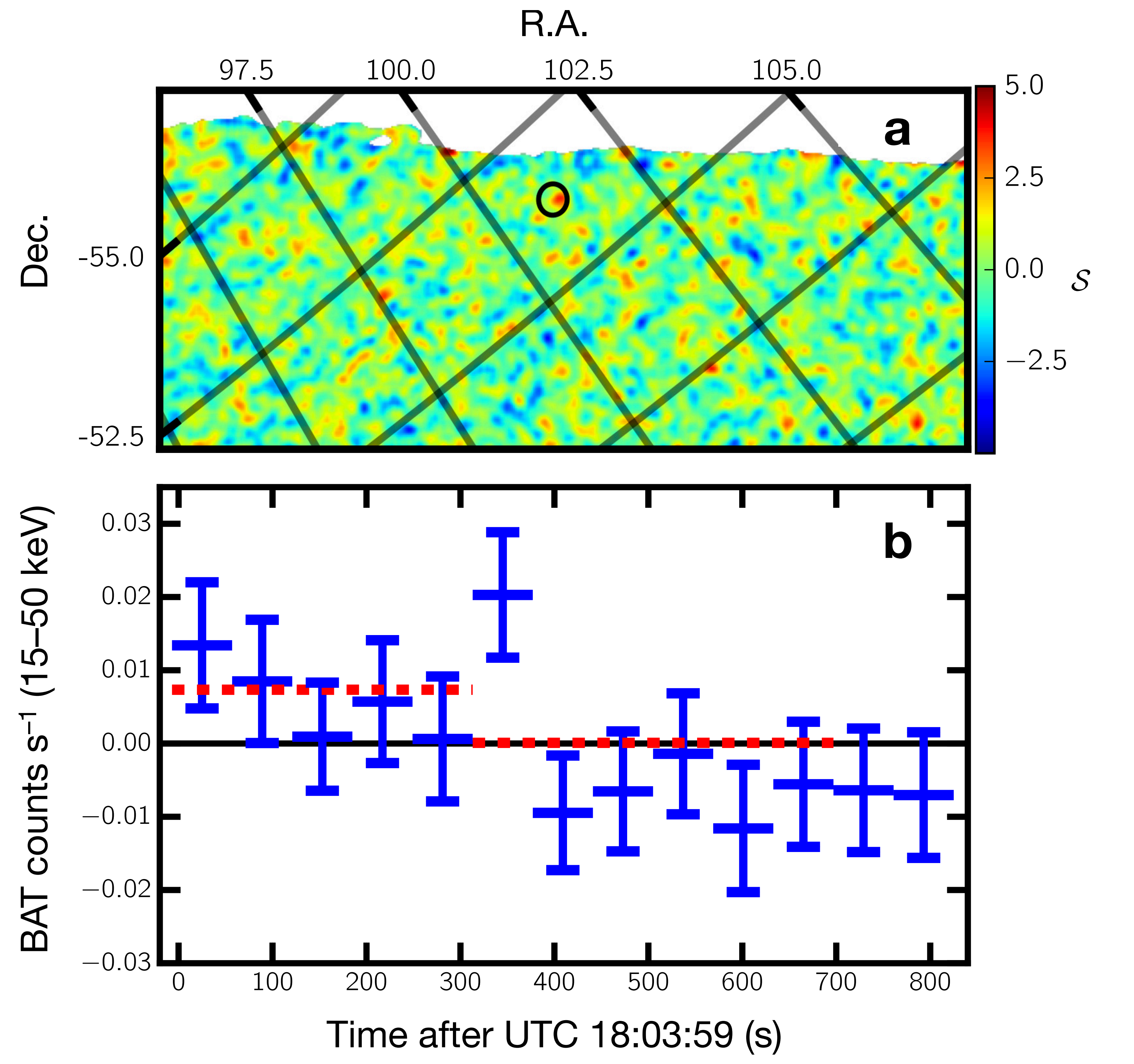

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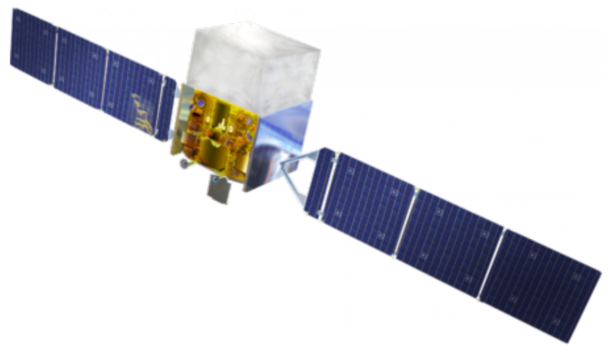
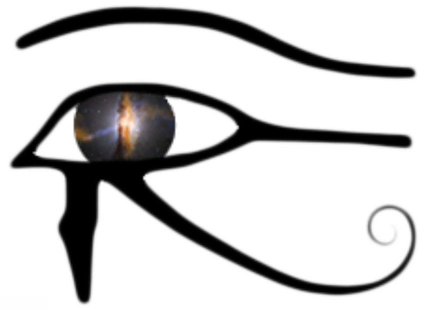
Archival analysis: IC+Fermi

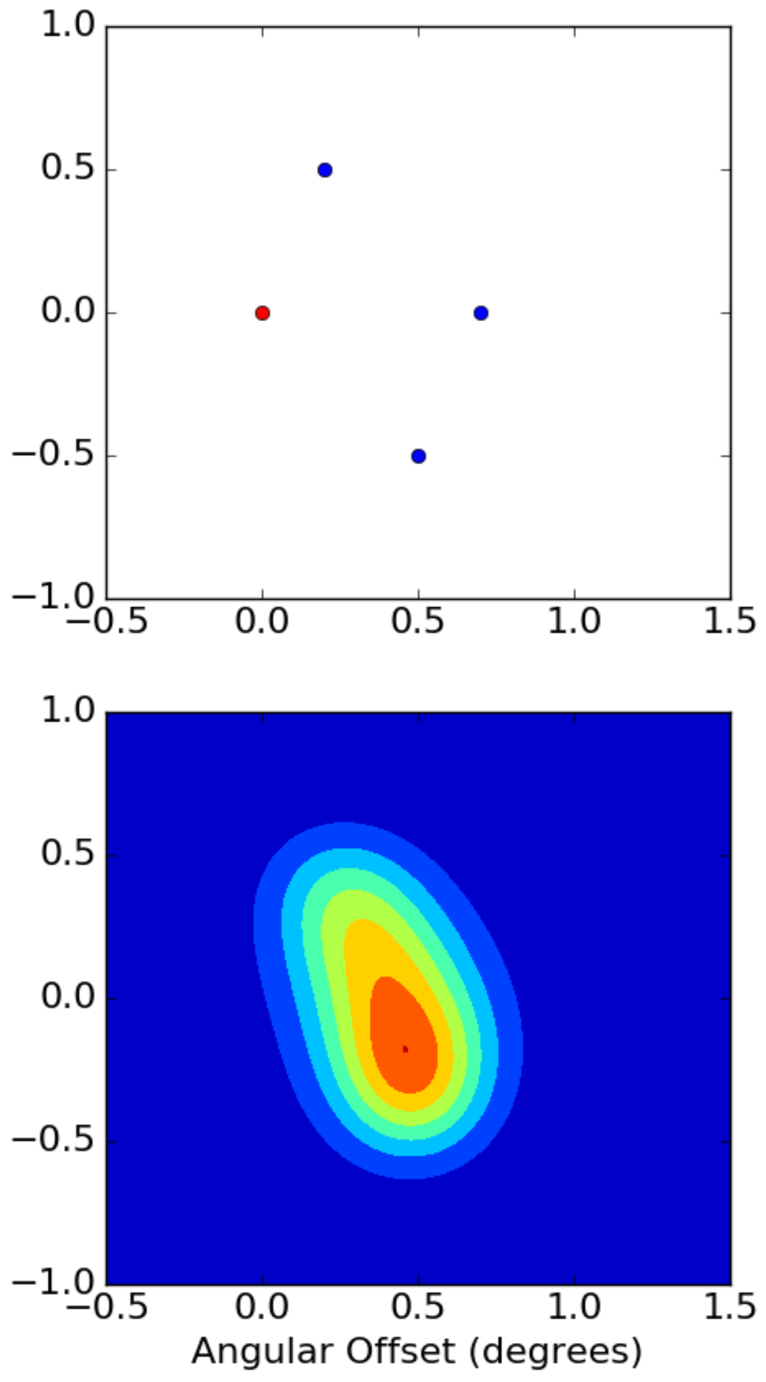


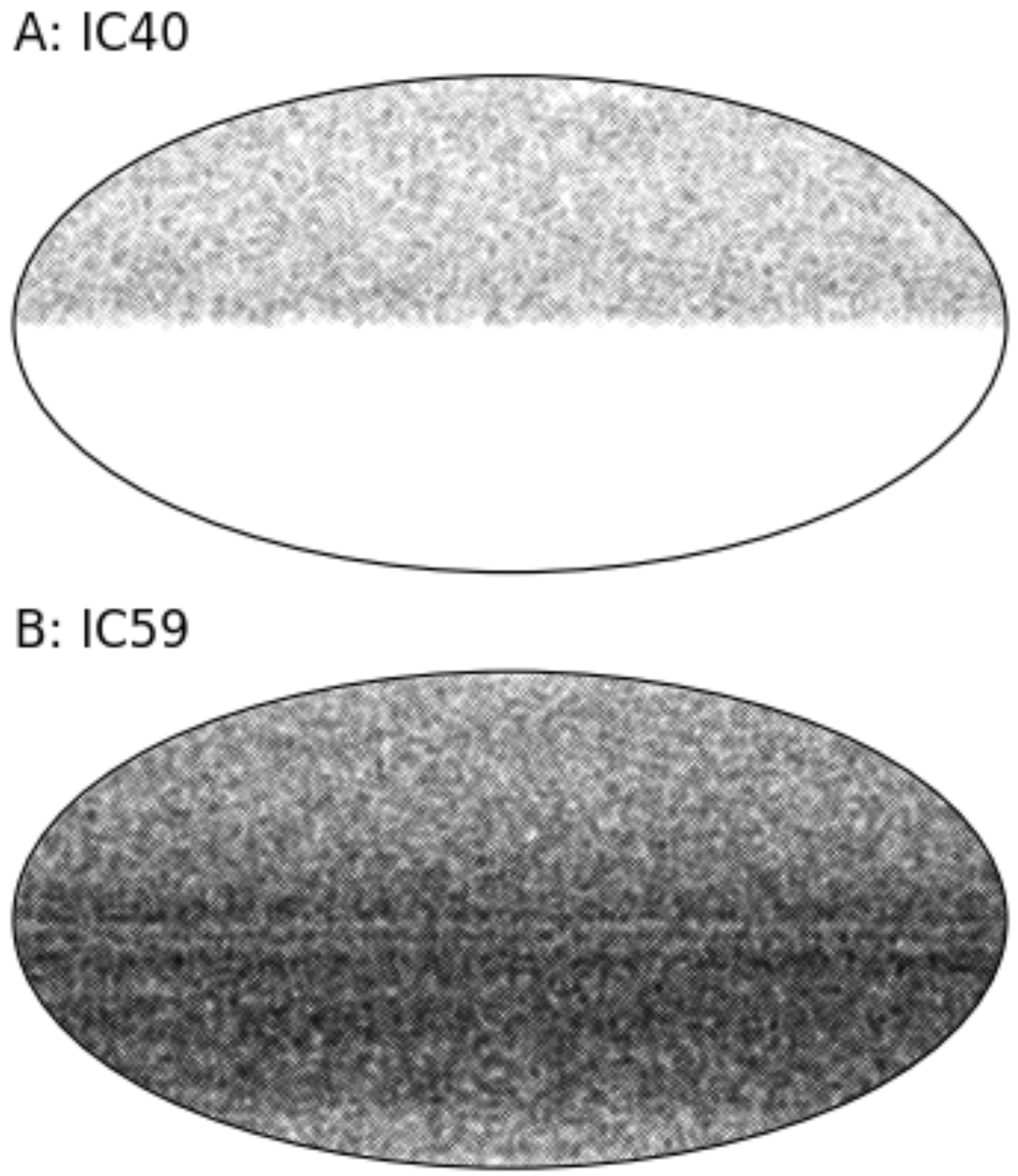


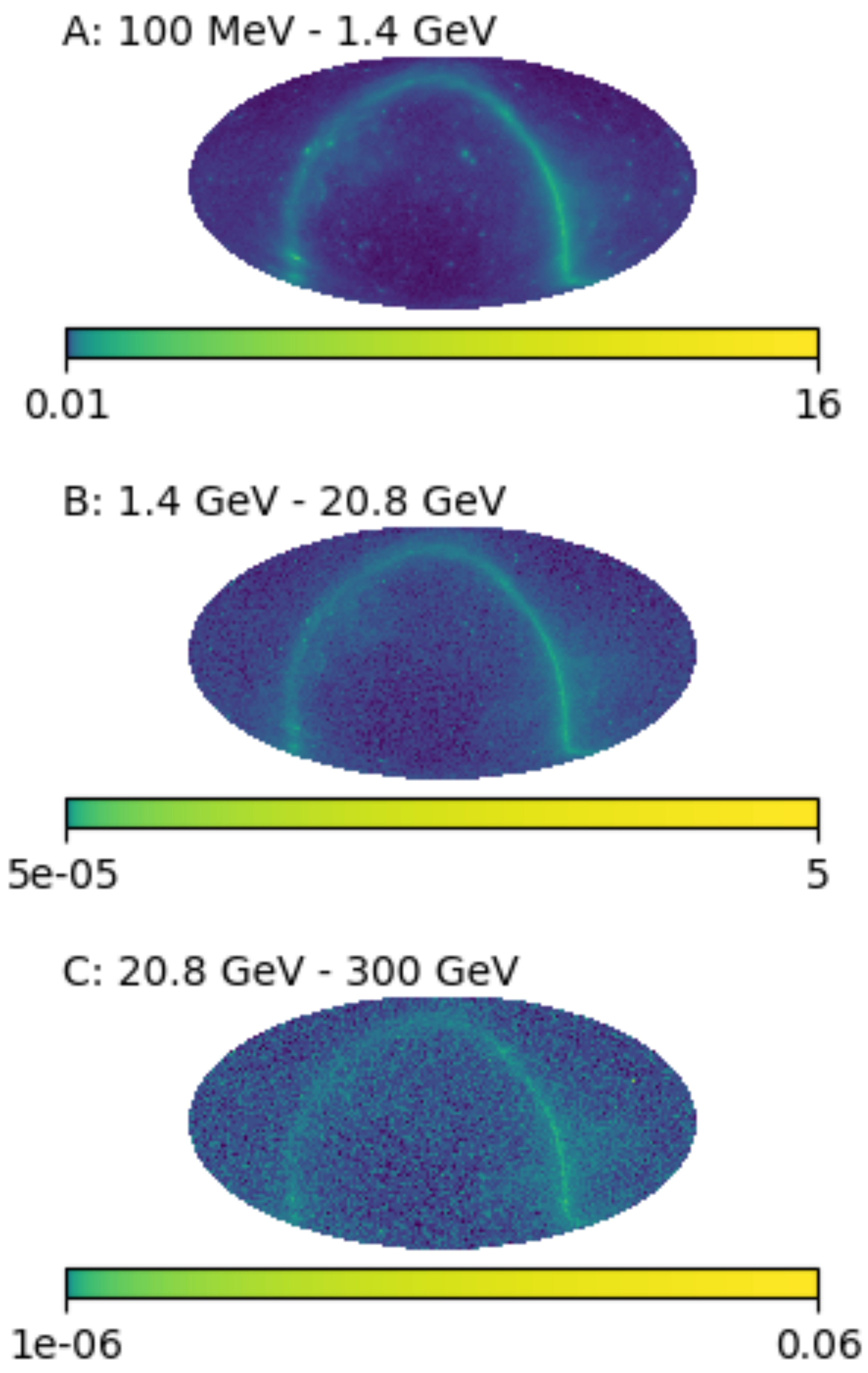
Coincidence parameters

$$\Delta t = \pm 100 \text{ s}$$

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



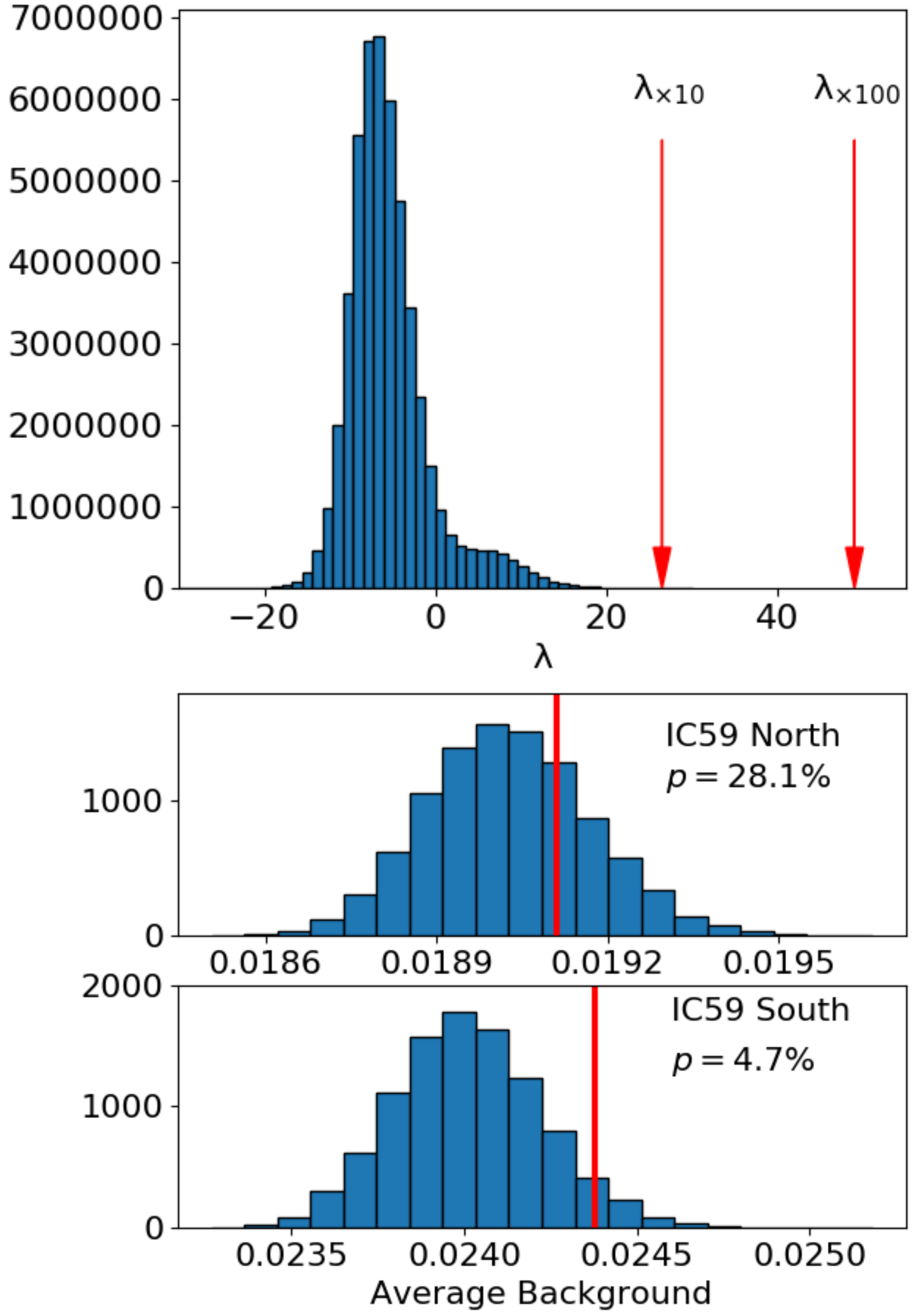




- Localize coincidence by max overlap of PSFs
- Rank coincidences by a log-likelihood statistic

Archival analysis: IC+Fermi

- Two ways to identify a coincidence signal:
  - Look for excess of events with high log-likelihood values (real time search)
  - Comparison of real and null distributions with the Anderson-Darling test



Archival analysis: IC+Fermi

- Developed a **time sensitive** coincident analysis for IceCube and Fermi data
- Methods sensitive to
  - rare high-multiplicity events; e.g., GRBs
  - a population of cosmic signals

Details at arXiv:1802.08165
Turley *et al.*, Astrophys. J. **863** (2018) 64

- Found a potentially interesting ($p = 4.7\%$) correlation between photon and neutrino populations
- Analysis was then extended to
  - cover all archival Fermi and IceCube data, and
  - also to include ANTARES data!

Details at arXiv:1904.06420
Ayala Solares *et al.*, Astrophys. J. **886** (2019) 98

- Code for **real-time analysis** on the AMON servers started running in 2020

First online analyses & follow-ups

- Real-time ν notices
    - **HESE** GCN notices went live in **April 2016**
    - **EHE** notices followed in **July 2016**
    - HE ν from flaring blazar
- Swift proposals
    - X-ray and UV/optical counterparts to HE ν's
    - X-ray and UV/optical counterparts to ν's + X- and γ-ray coincidences

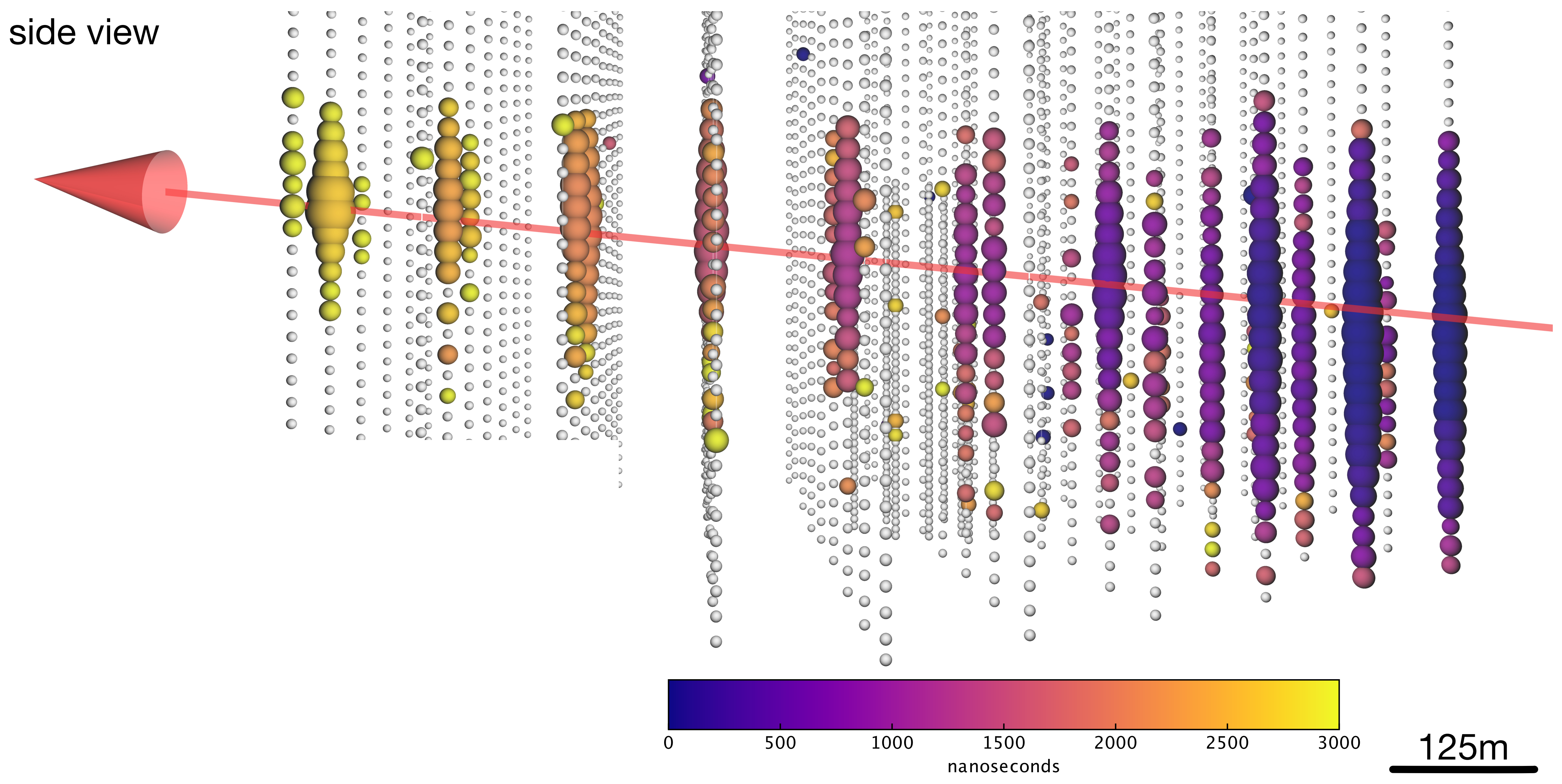
First Notice example

To take advantage of multi-messenger opportunities, the IceCube neutrino observatory (13) has established a system of real-time alerts that rapidly notify the astronomical community of the direction of astrophysical neutrino candidates (14). From the start of the program in April 2016 through October 2017, 10 public alerts have been issued for high-energy neutrino candidate events with well-reconstructed directions (15).

…

The neutrino alert

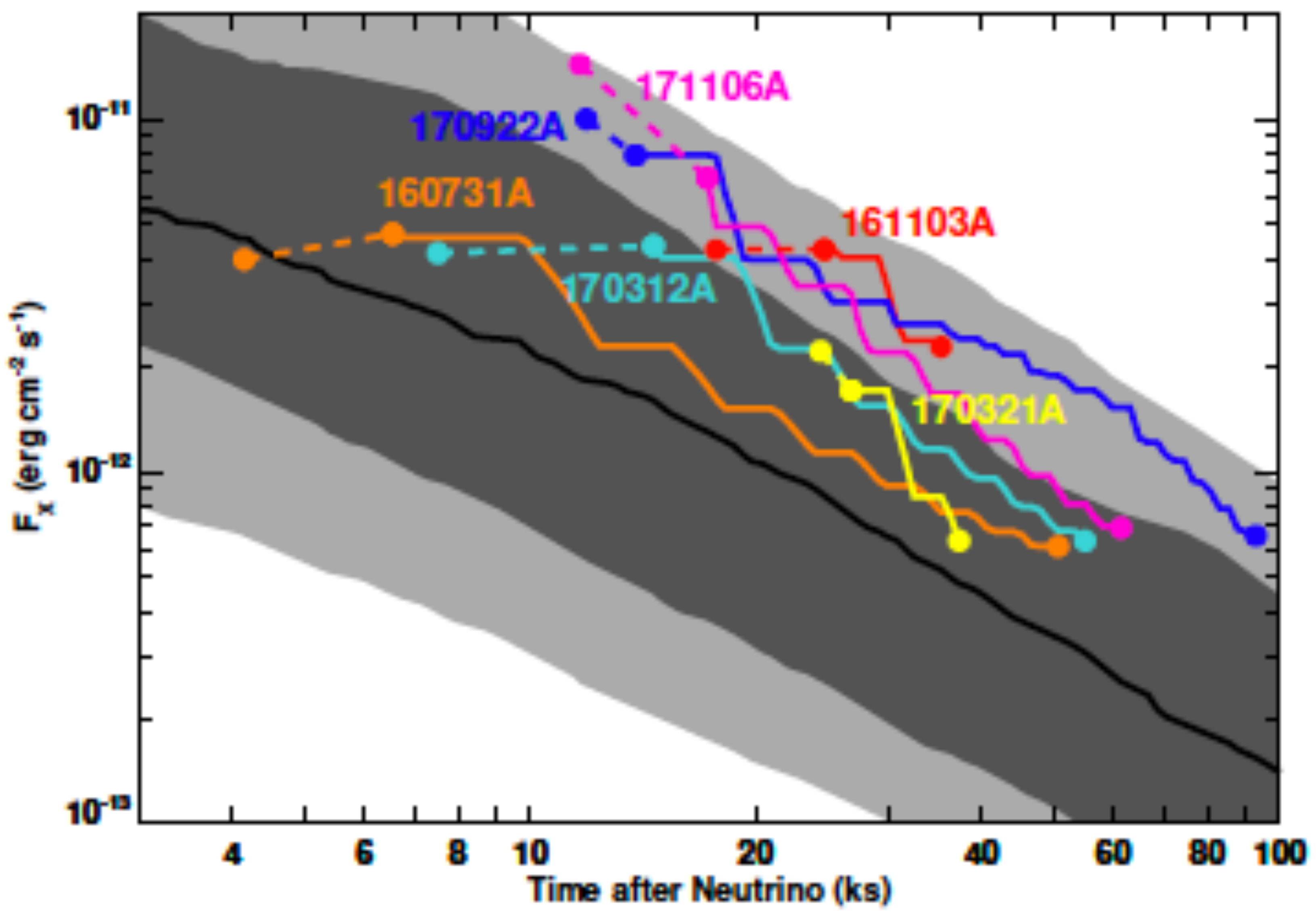
IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 m and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detector array, a muon is produced mov- ing through the ice at superluminal speed and creating Cherenkov radiation detected by the DOMs. On 22 September 2017 at 20:54:30.43 Coordinated Universal Time (UTC), a high-energy neutrino-induced muon track event was detected in an automated analysis that is part of IceCube's real-time alert system. An automated alert was distributed (*17*) to observers 43 seconds later, providing an initial estimate of the direction and energy of the event. A sequence of refined reconstruction algorithms was automatically started at the same time, using the full event information. A representation of this neutrino event with the best-fitting reconstructed direction is shown in Figure 1. Monitoring data from IceCube indicate that the observatory was functioning normally at the time of the event.

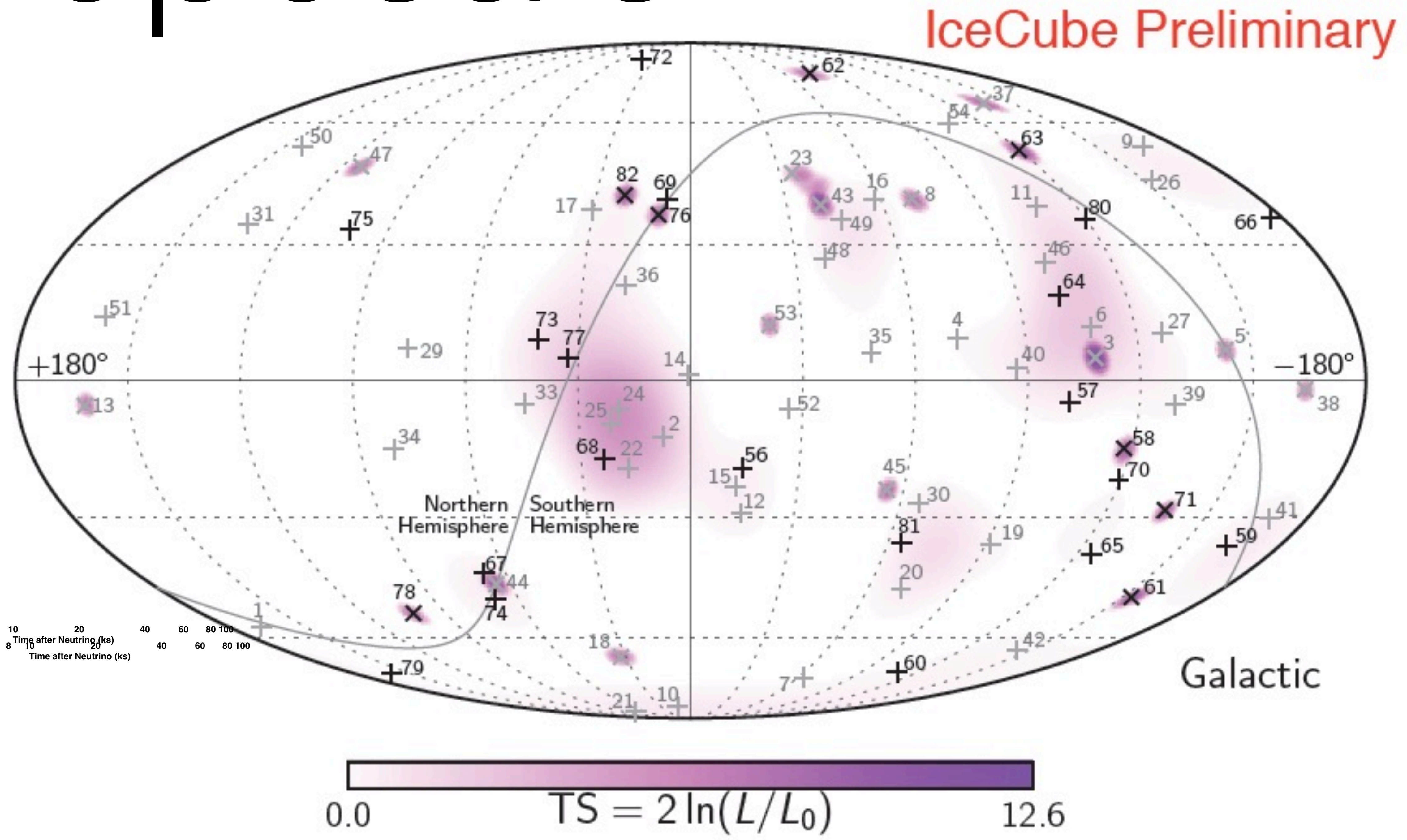


17. IceCube Collaboration, *GRB Coordinates Network/AMON Notices* **50579430_130033** (2017).

Swift proposals

1



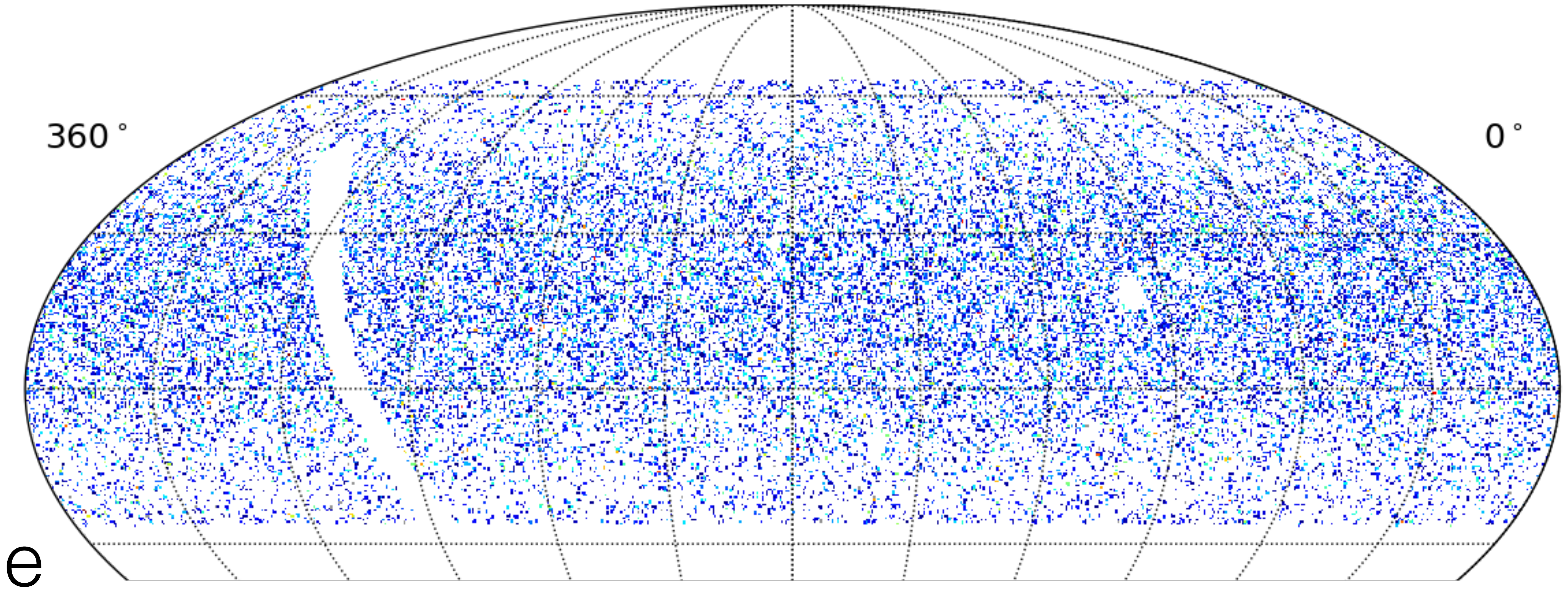


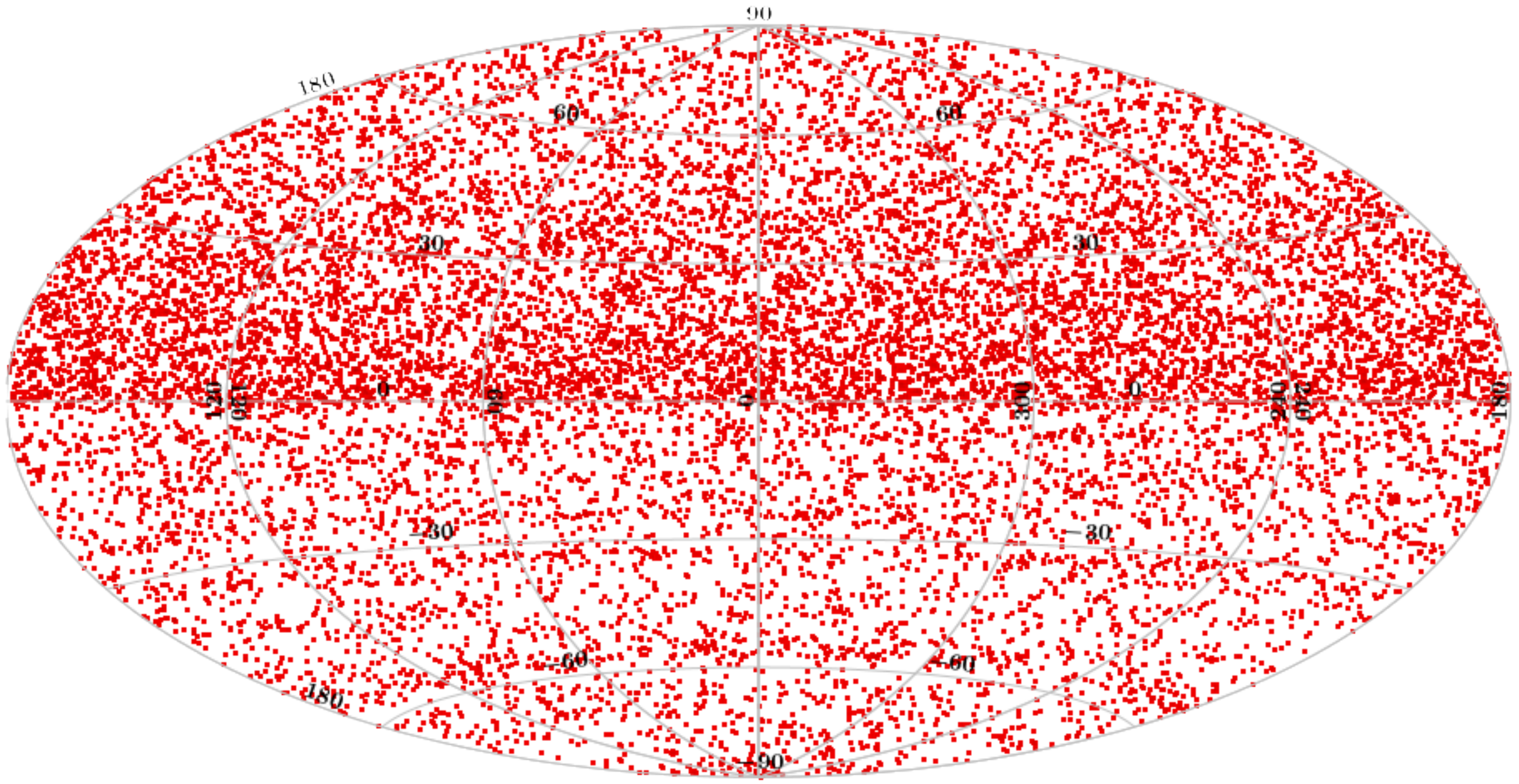
2

ν	γ	r_{90}	Average Latency	Potential Sources
ANTARES	*Fermi*-LAT	~0.3°	~5 hrs	
IceCube	HAWC	~0.1°	~7 hrs	AGNs, GRBs
IceCube	*Fermi*-LAT	~0.3°	~5 hrs	
IceCube	*Swift* BAT	~4'	~8 hrs	

Coincidence alert: IC+HAWC

- Proof-of-concept dataset (**1 month**)
  - HAWC daily *sub-threshold* **hotspots**
    Parameters: position, error in position, significance (>2.75), start time of transit, end time of transit
  - IC **track-like** events
    Parameters: position, time of event, false positive rate density (FPRD), signal acceptance, PSF





Coincidence alert: IC+HAWC

- Temporal and spatial coincidence

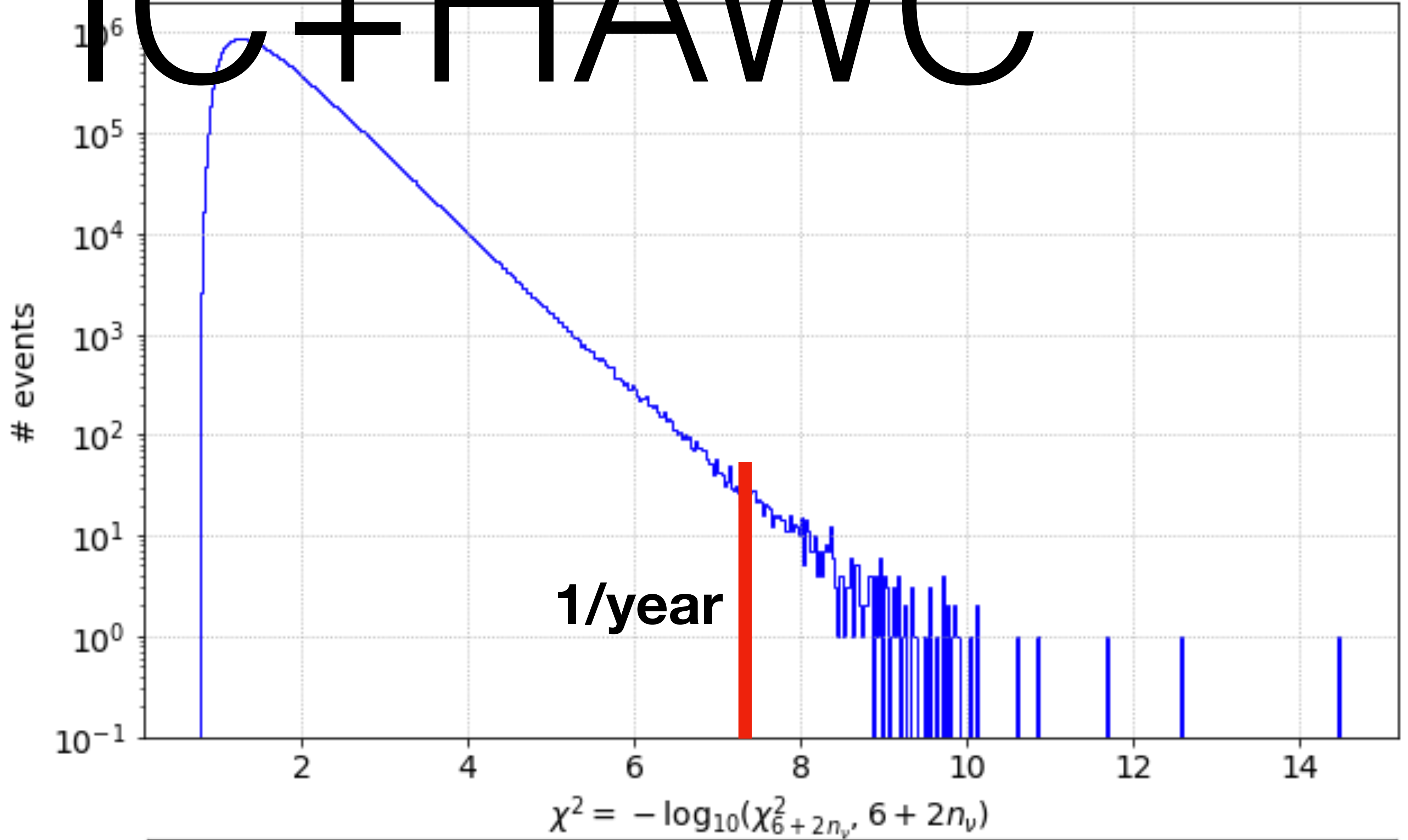
- Best position of the coincidence

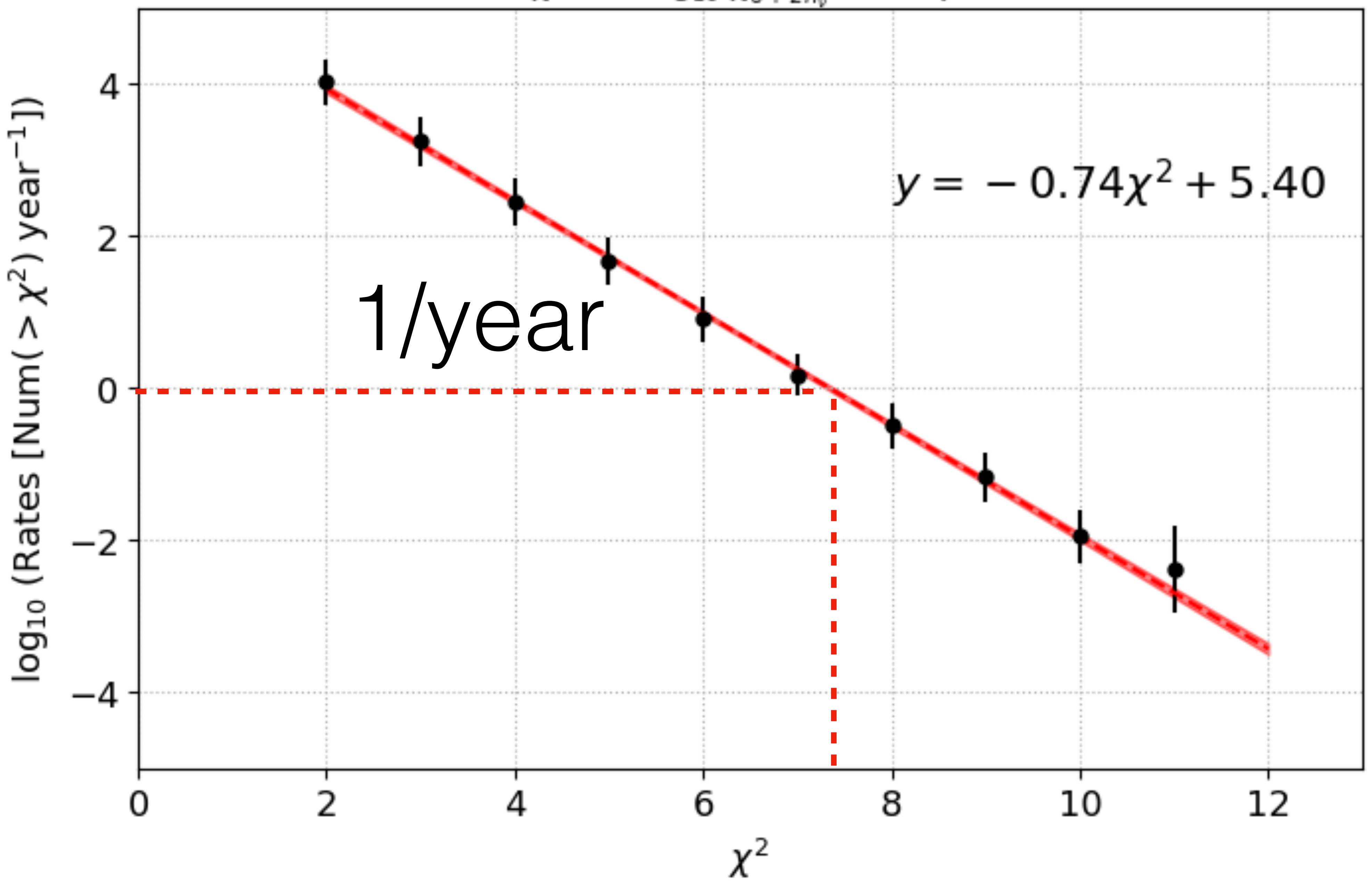
$$\lambda(\vec{x}) = \begin{cases} \sum_{i=1}^{2}(\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) & 1\gamma, 1\nu \\ \sum_{i=1}^{N}(\ln(\mathcal{S}_i(\vec{x})) - \ln(\mathcal{B}_i)) + \sum_{i=2}^{N-1}\sum_{j=i+1}^{N} \ln T_{HWC} - \ln|\Delta T_{ij}| & 1\gamma, > 1\nu. \end{cases}$$

- Combine p values using Fisher's method

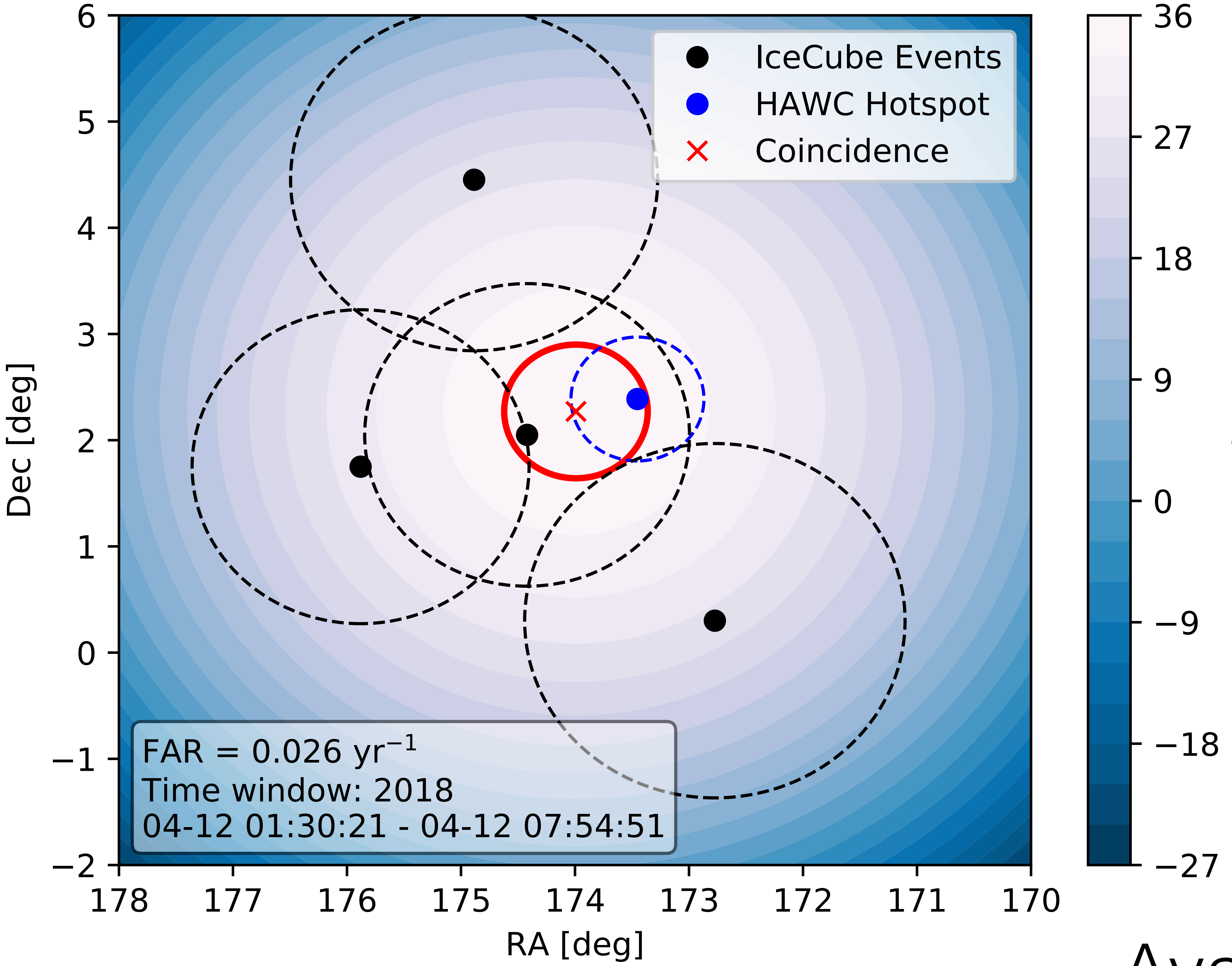
$$\chi^2 = -2\ln[p_\lambda\, p_{HWC}\, p_{cluster} \prod_{i}^{n_\nu} p_{i_{IC}}]$$

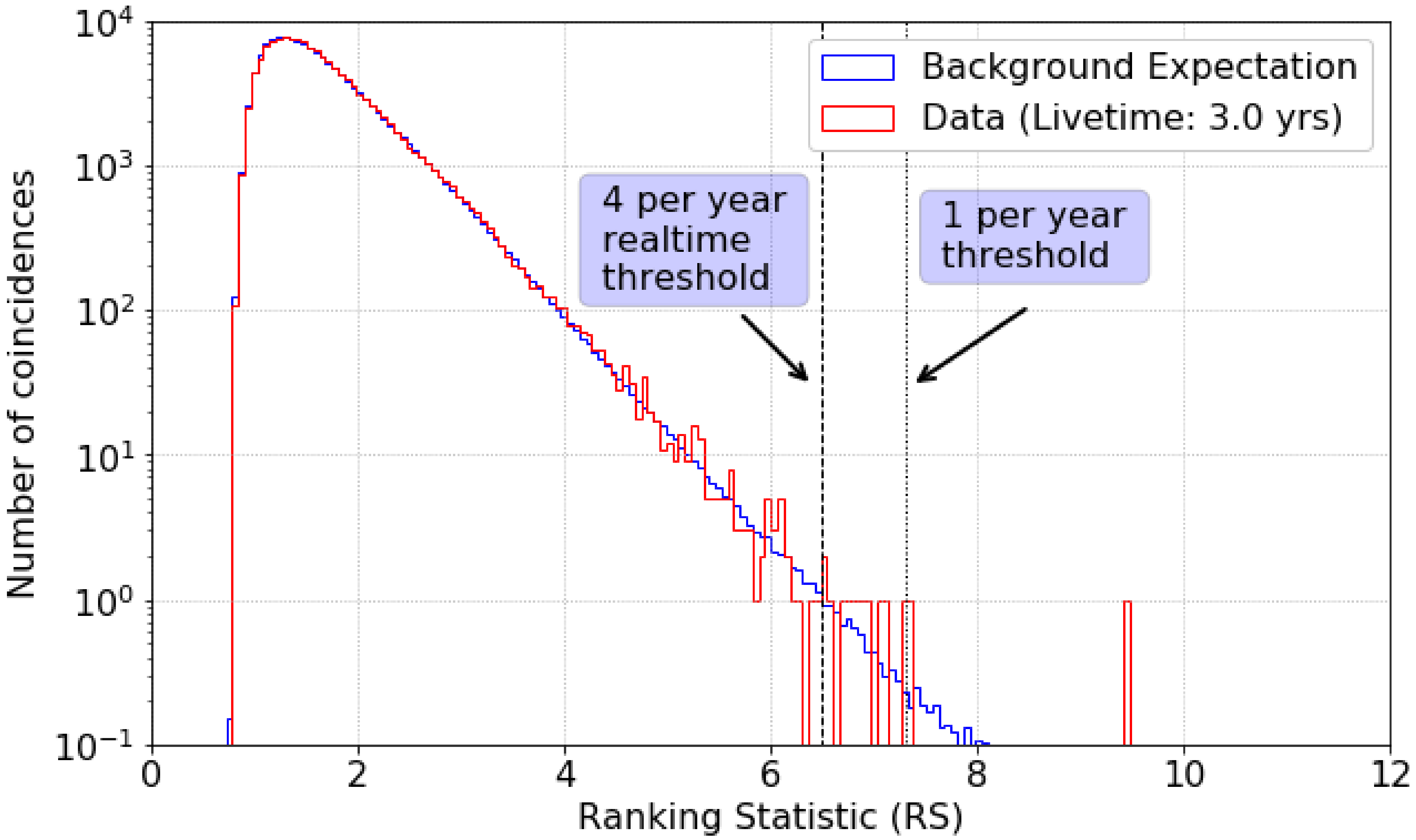
- Account for different DoF for different multiplicities, and use $-\log[p(\chi^2 > \chi^2_{obs})]$ to rank coincidences





Coincidence alert: IC+HAWC



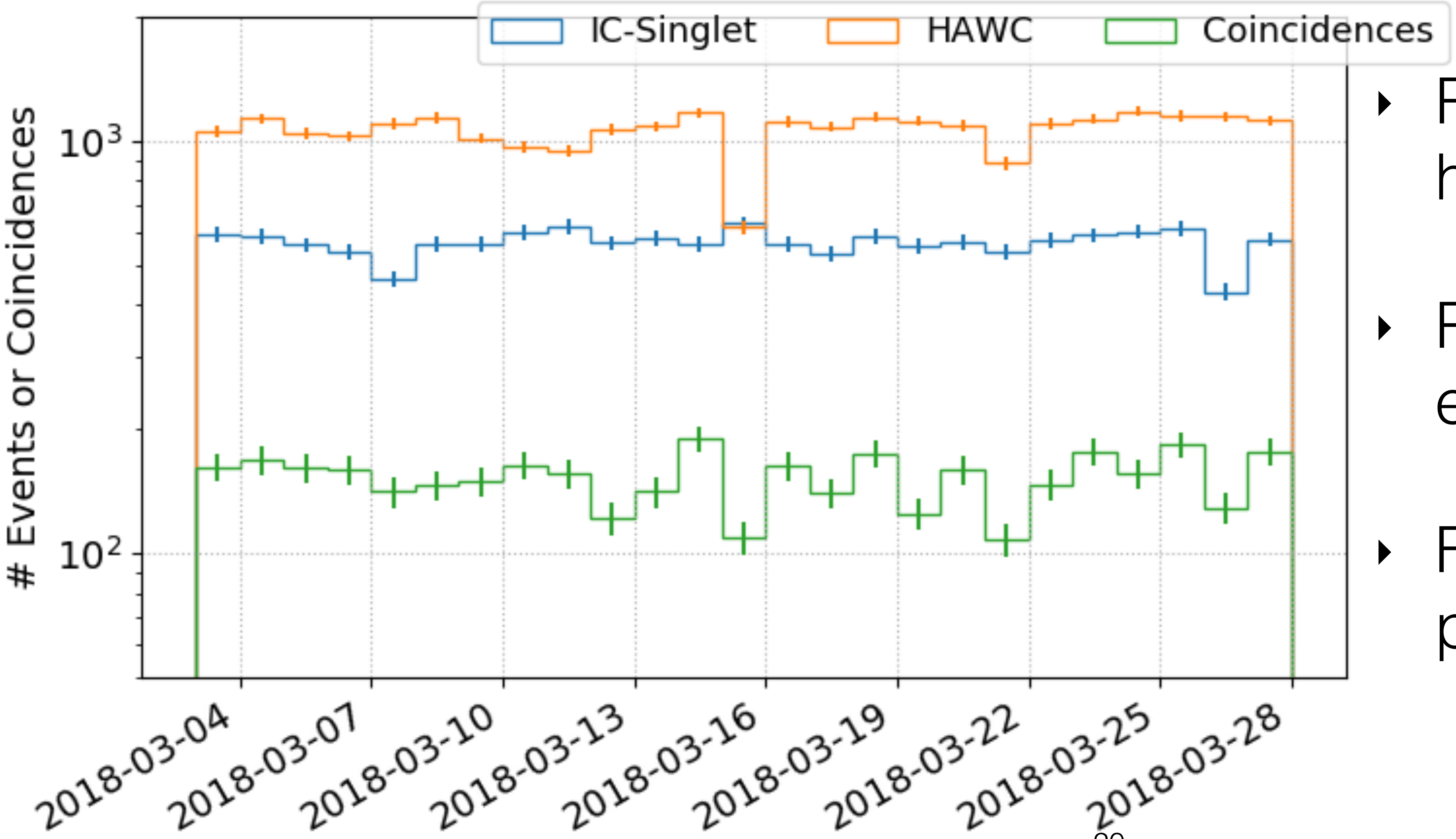


Archival analysis at arXiv:2008.1061

Ayala Solares *et al.*, Astrophys. J. **906** (2021) 63

Coincidence alert: IC+HAWC

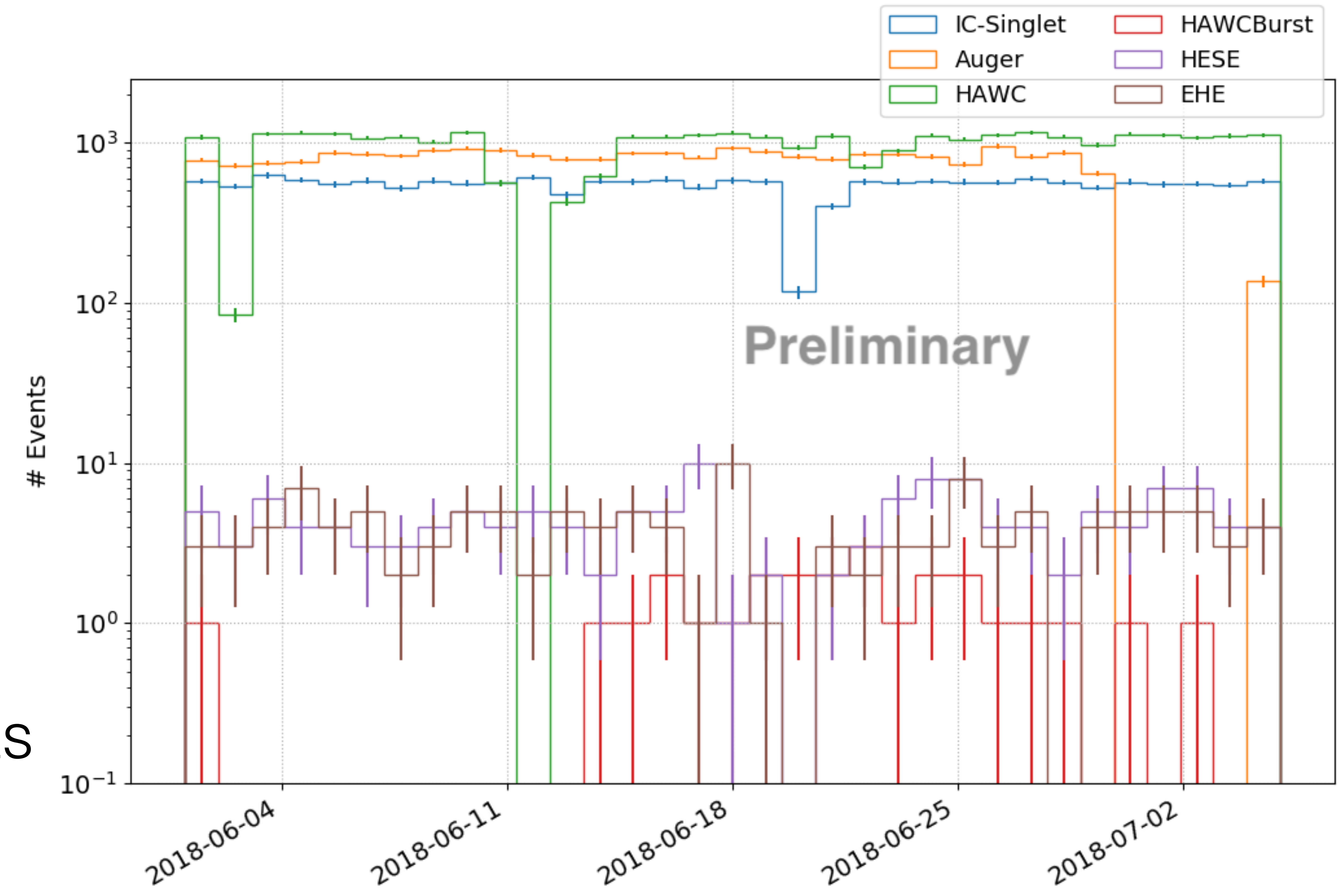
- Moving to **real-time** analysis!



- Receiving ~1000 HAWC daily hotspot per day
- Receiving ~600 IC track-like events per day
- Finding ~150 coincidences per day

VHE γ Notices

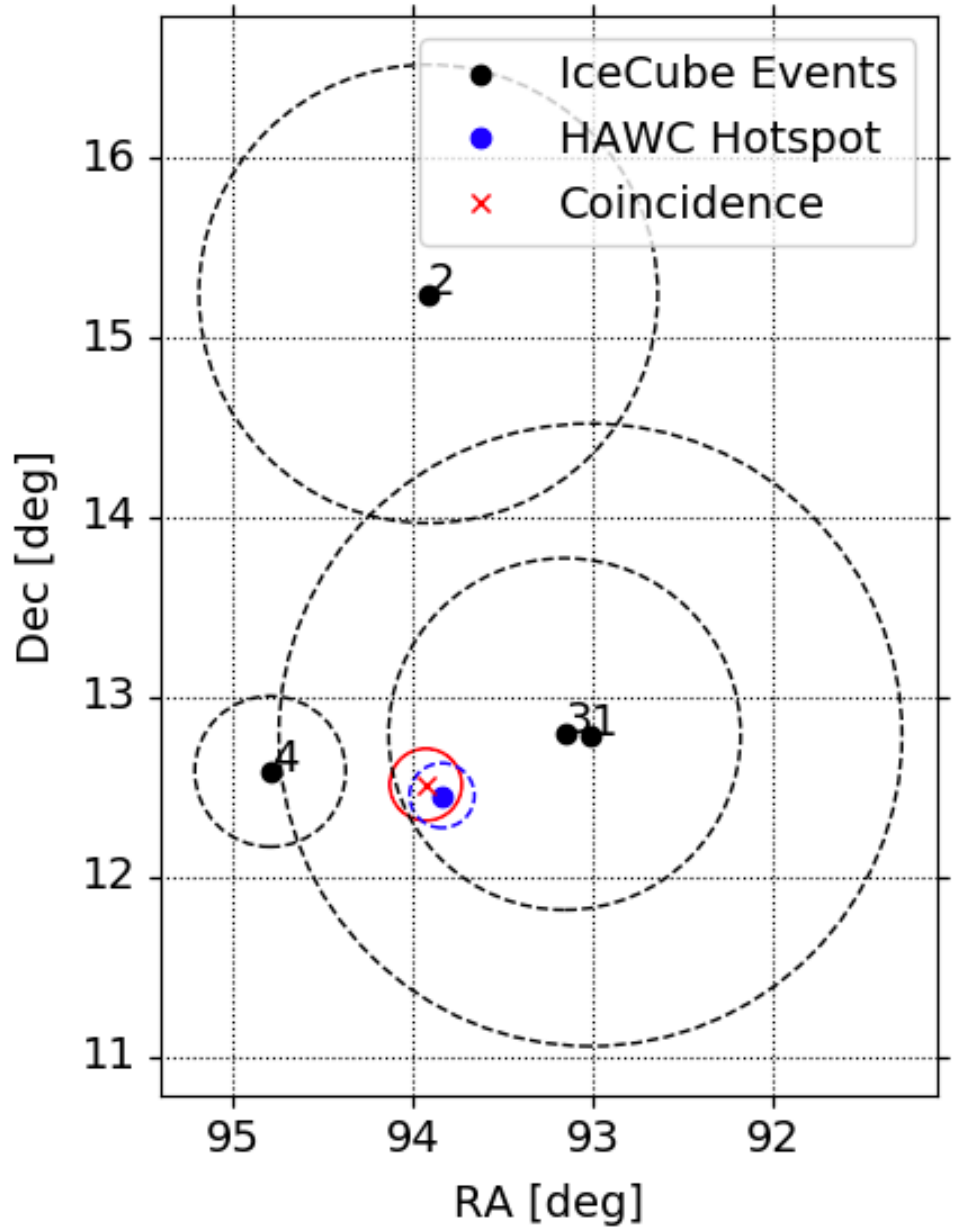
- Started receiving HAWC's own GRB *sub-threshold* triggers
- Studied FARs
  - internal a few/day
  - send to GCN the 1/year events



New alerts

- New GCN channel for **IceCube-HAWC alerts**

- New (separate) GCN channel for **HAWC GRB-like notices** (similar to the HESE or EHE IceCube notices)



Alert from May 14, 2021

Coincidence alerts in the $\boldsymbol{\nu}$-γ channel

- Real-time alerts have a threshold of 4/year
    - 14 alerts sent to GCN
- Archival FAR threshold is 1/year
    - 7 coincidences found

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

AMON status

- First Multimessenger Alerts!
  - IC+HAWC
  - ANTARES+Fermi-*LAT*
- Pass-through Notices:
  - Gold & Bronze IC events
  - HAWC GRB-like events

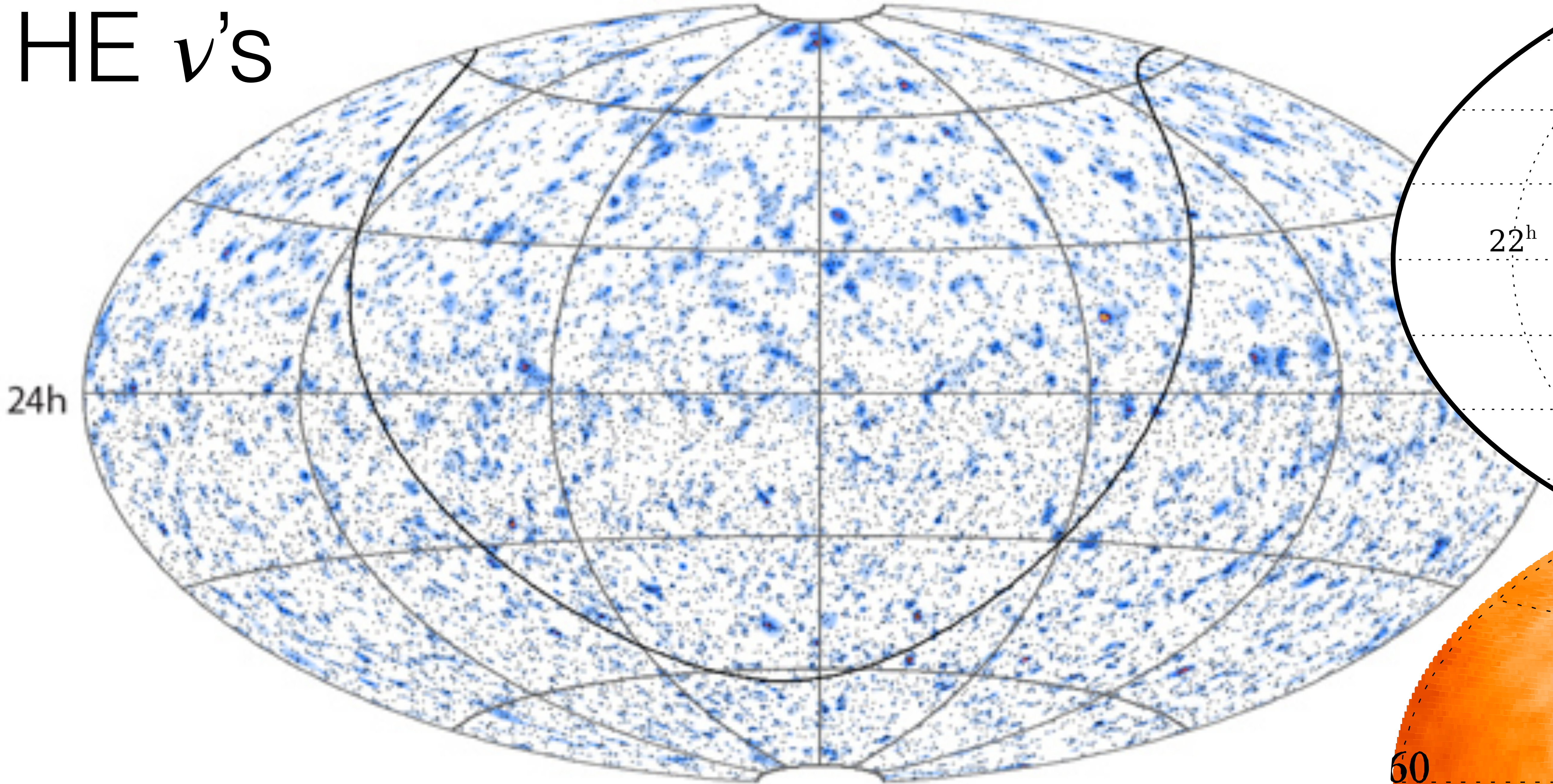
In development

Channel	Facilities	δr	ΔT_{search}	Latency (hours)	Potential Sources
$\gamma - \nu$	ANTARES-*Fermi*-LAT	$\sim 0.3^\circ$	2000 sec	1–12	GRBs
	IceCube-HAWC	$\sim 0.1^\circ$	~ 6 hours	3–8	AGNs, GRBs
	IceCube-*Fermi*-LAT	$\sim 0.3^\circ$	2000 sec	1–12	GRBs
	IceCube-*Swift*-BAT	$< 0.1^\circ$	300 sec	1-8	AGNs, GRBs TDEs, SGRs
γ-GW	LIGO/Virgo- HAWC	$\leq 0.8^\circ$	~ 6 hours	3–8	GRBs
	LIGO/Virgo-*Fermi*-LAT	$\sim 0.3^\circ$	2000 sec	1–12	GRBs
	LIGO/Virgo-*Swift*-BAT	$< 0.1^\circ$	300 sec	1-8	GRBs TDEs, SGRs
$\gamma - \nu$-CR	IceCube-HAWC-Pierre Auger	$\leq 0.8^\circ$	2000 sec	1–12	PBHs
Pass-through	HESE-EHE IceCube	$< 0.75^\circ$ (90%)	–	< 1 min	AGNs, GRBs
	Gold-Bronze IceCube	$< 0.4^\circ$ (90%)	–	< 1 min	AGNs, GRBs
	HAWC Burst	$\leq 0.8^\circ$ (68%)	0.2,1,10,100 sec	< 1 min	GRBs
	FACT	$< 0.1^\circ$	–	< 1 min	AGNs, GRBs TDEs, SGRs
	Auger Doublets	$\sim 1^\circ$	–	$\lesssim$ 10min	AGNs, GRBs TDEs, SGRs

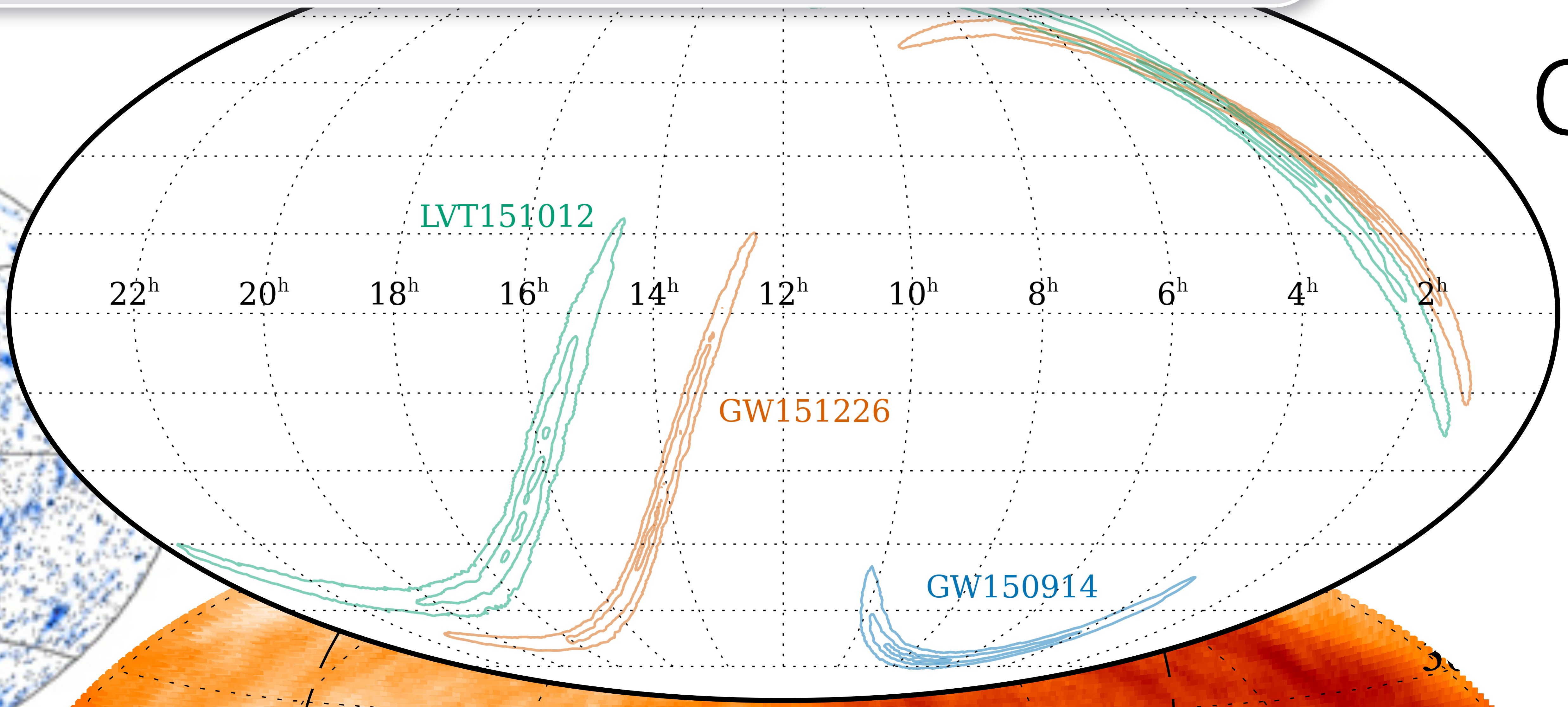
Prospects

Sub-threshold cosmic rays, ν's, γ rays, and GWs in **real time!**

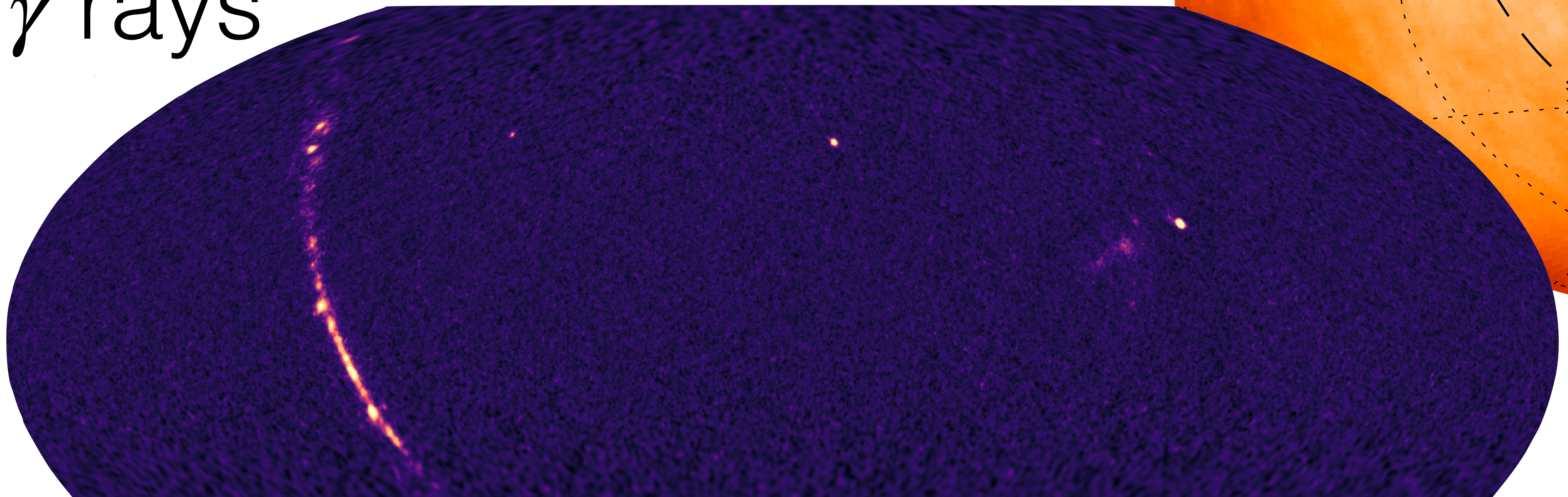
HE ν's

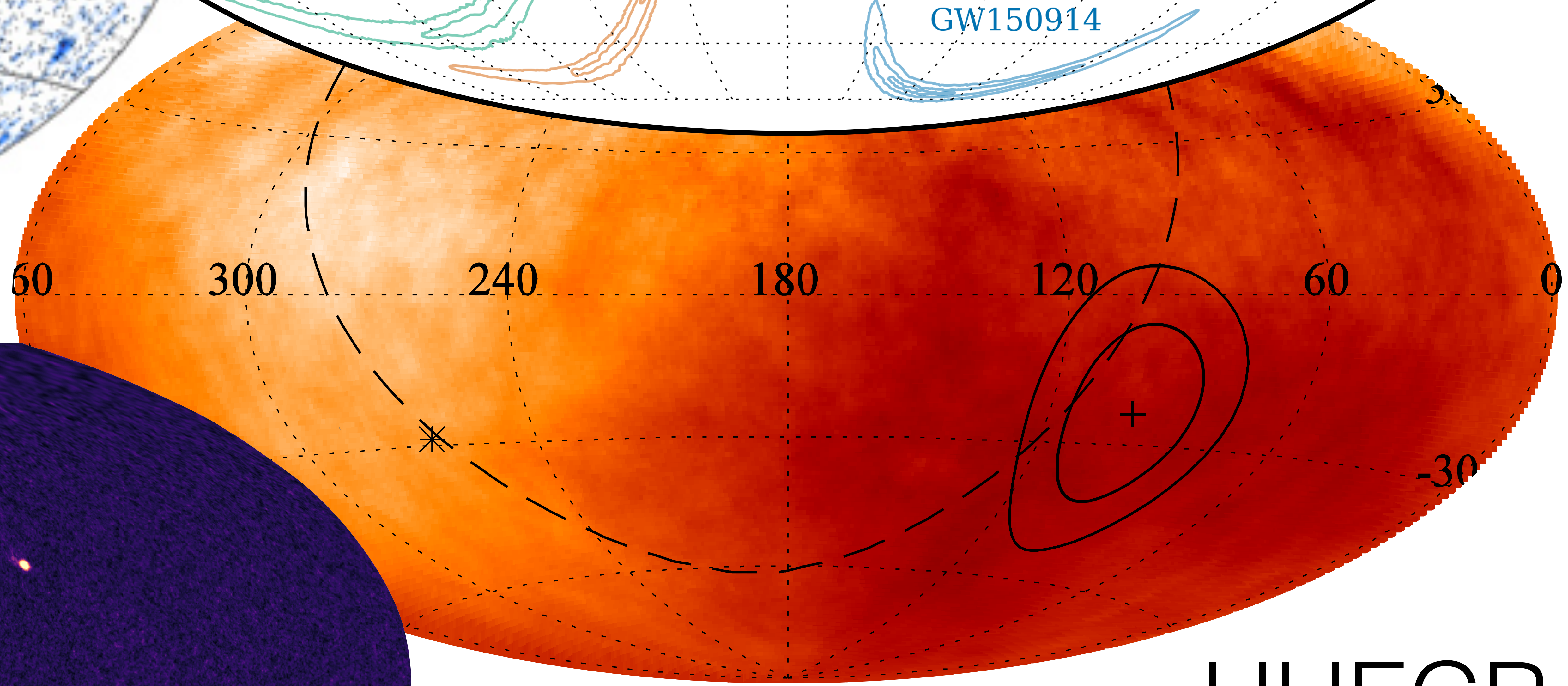


GW



VHE γ rays





UHECR

AMON progress

- AMON has made a significant progress toward **real-time** and archival analyses
- AMON high-uptime servers are online and **fully operational**
- Fast distribution of **IceCube alerts** of likely cosmic neutrinos to GCN/TAN since 2016
- Started issuing γ-ν coincidence alerts (HAWC—IceCube and Fermi-LAT—ANTARES), as well as new pass-through channels (e.g., HAWC and ANTARES)

Conclusions

- Current generation detectors are fantastic!
- Next generation detectors will be yuuge!
- **Multimessenger** is the best way to make progress toward understanding the messages!

Thank you!

Credit: Fabian Schüssler

Pre-covid Mostafa's group at Penn State