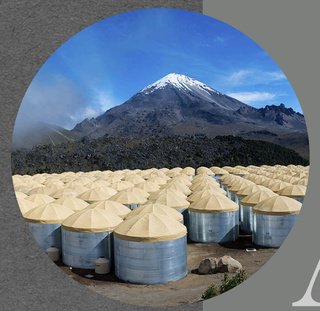
ICRC2019

Madison, WI, USA



HAWC-IceCube Coincidence Analysis with Sub-threshold data

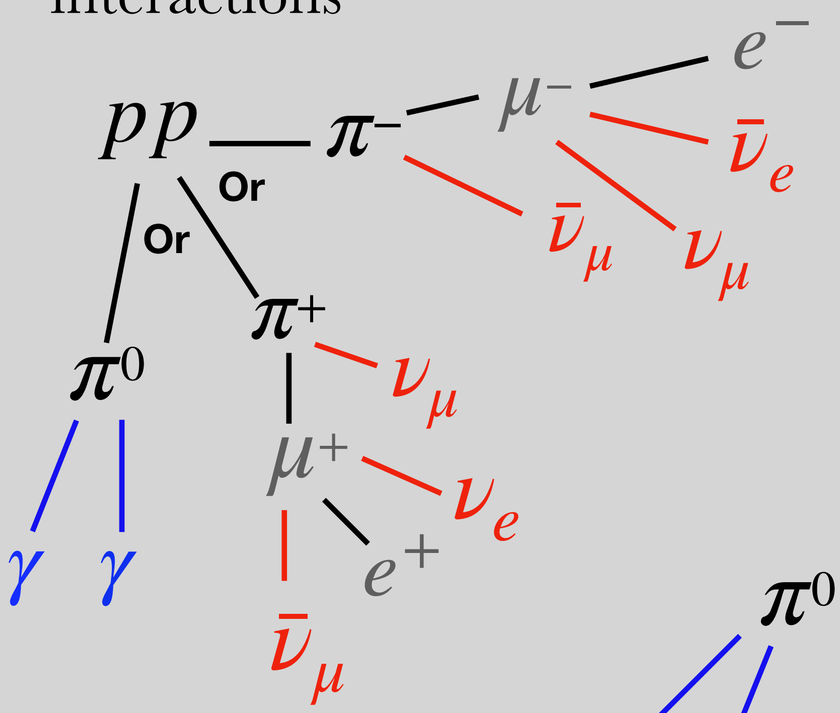
Hugo Ayala
for the HAWC & IceCube Collaborations

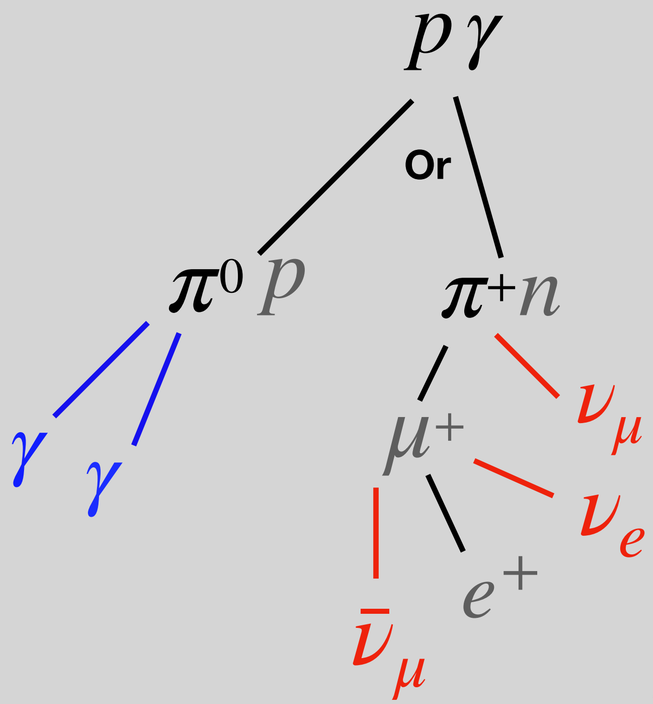
AMON
Astrophysical Multimessenger Observatory Network

PennState
Eberly College of Science

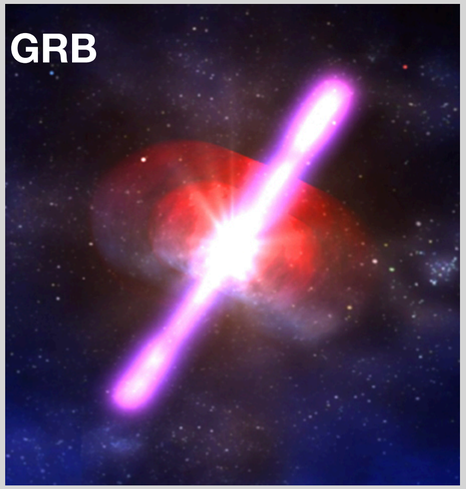
Motivation: search for sources of neutrinos with the help of gamma-ray data

- Physics: photo-hadronic interactions or hadronic interactions

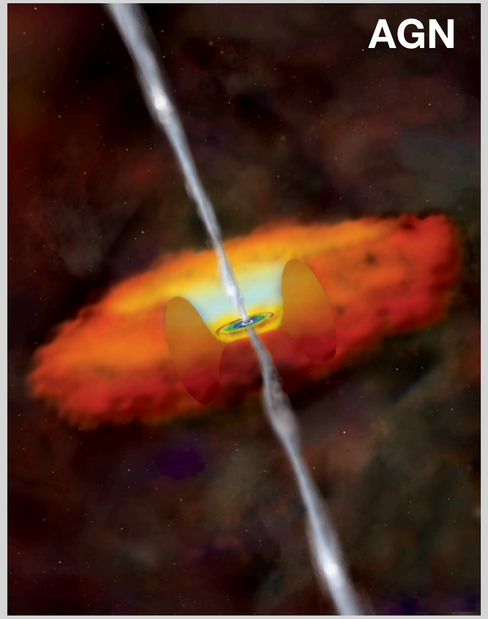




- Possible sources:
  - GRBs
  - Active Galactic Nuclei:
    - Blazars
    - Radio Galaxies
    - Something else?



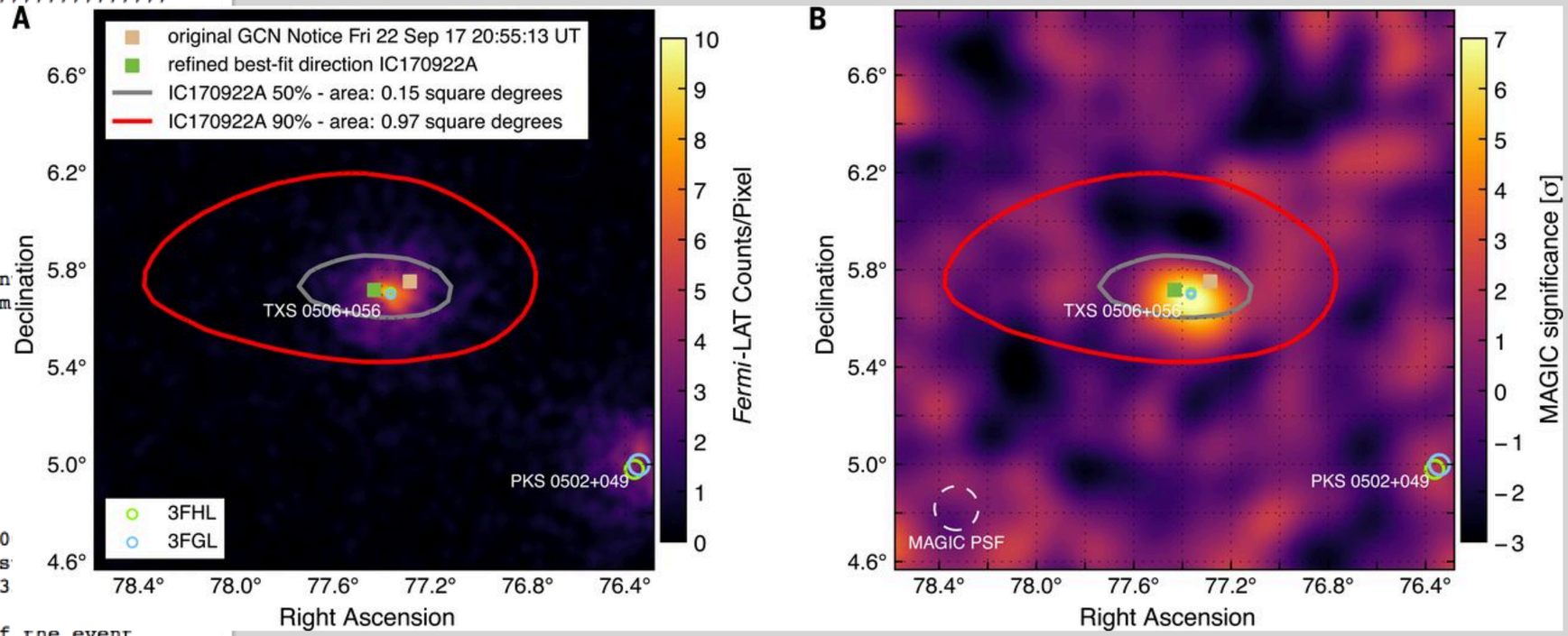
http://chandra.harvard.edu/resources/illustrations/grb.html



http://chandra.harvard.edu/photo/2007/agns/

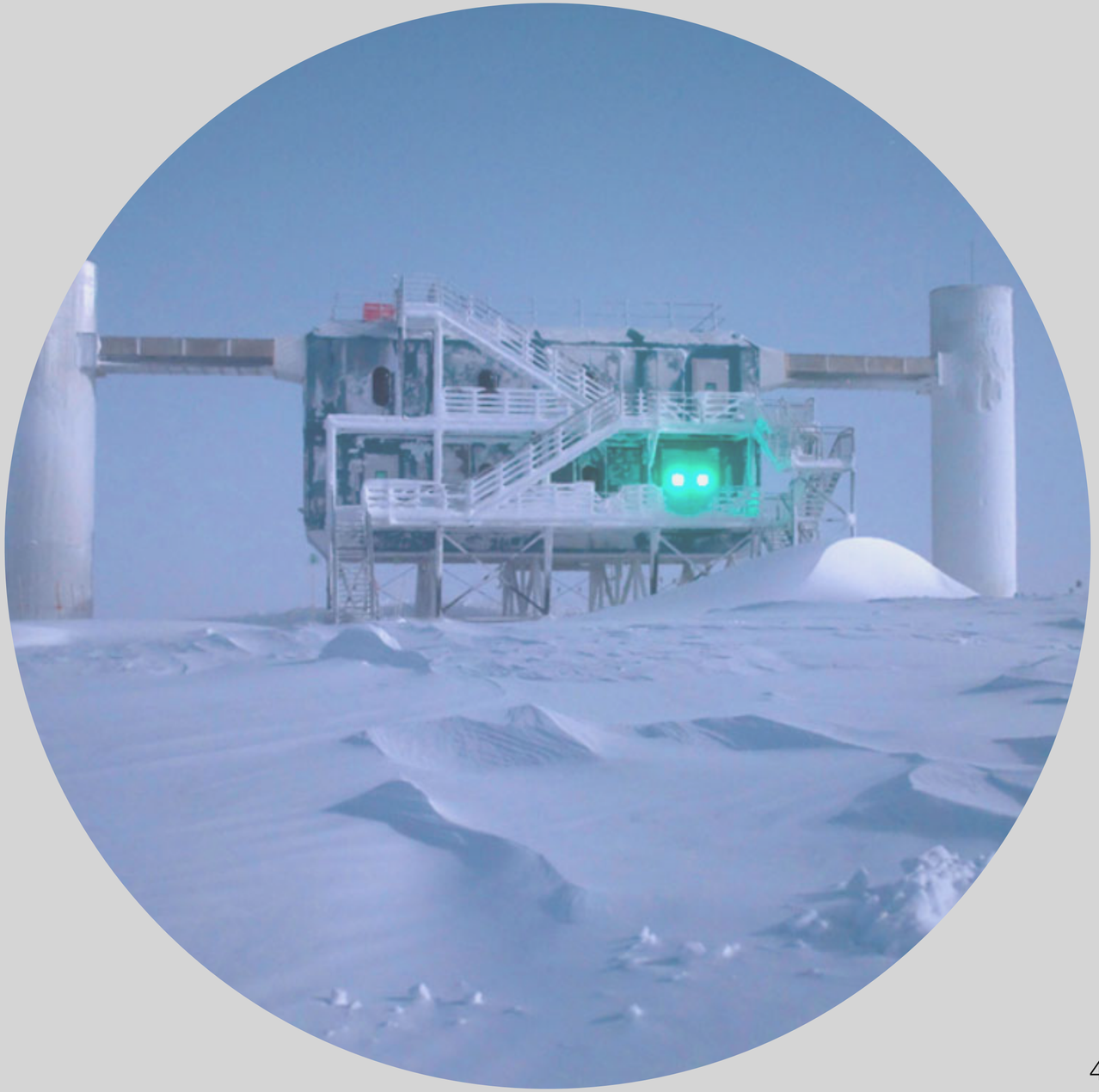
Motivation: search for sources of neutrinos with the help of gamma-ray data.

```
//////////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% con
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 0
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (Wes
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 3
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```



Coincidence between high-energy neutrino and gamma-rays from Blazar TXS 0506+056. First evidence of source of neutrinos (>3σ). AMON contributed to the distribution of the event IC170922A.

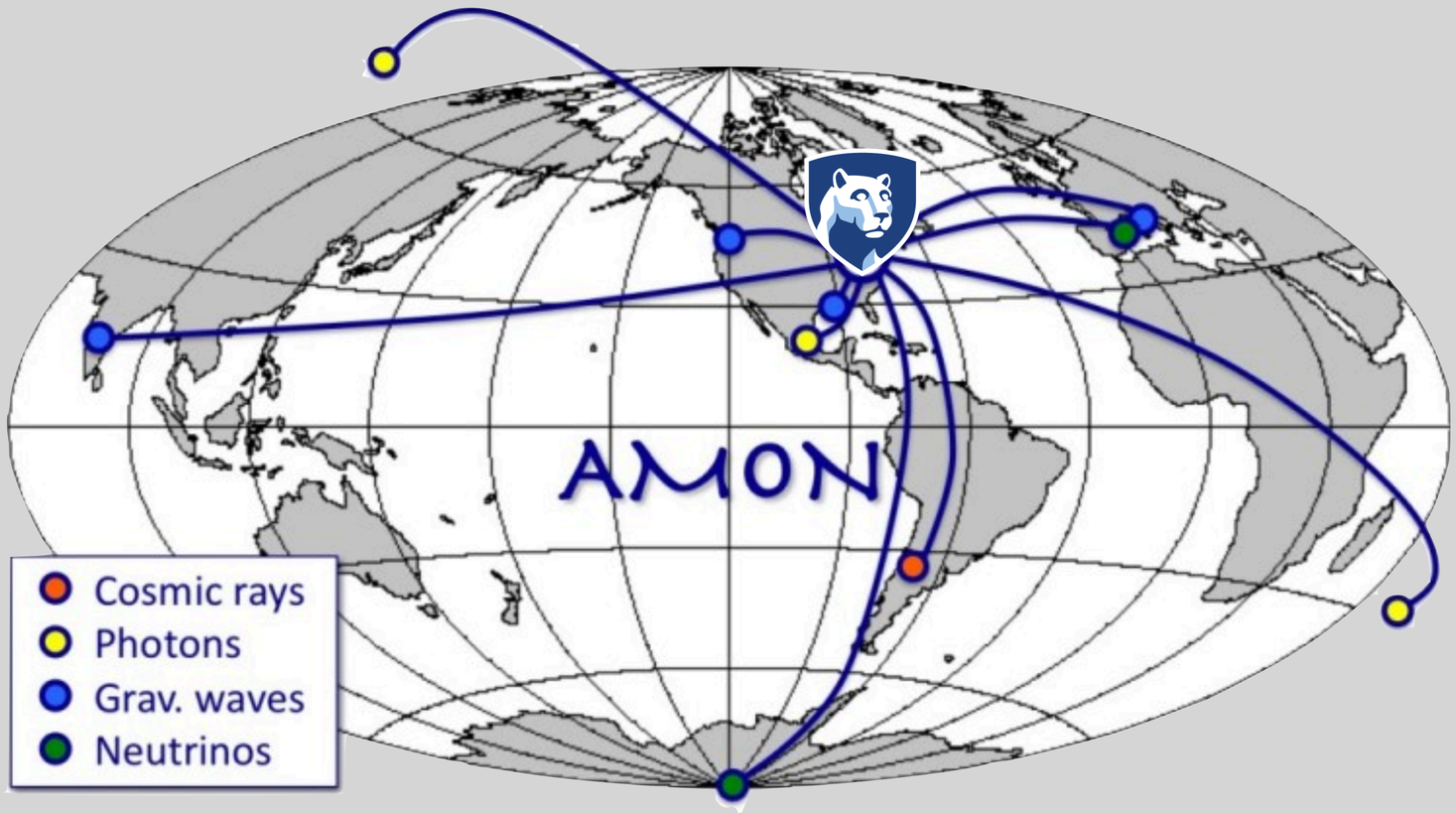
Use the AMON Framework to do coincidence analysis



AMON

Astrophysical Multimessenger Observatory Network

Real-time searches for transients help advance the field of multimessenger astrophysics. The Astrophysical Multimessenger Observatory Network (AMON) has been built for this purpose.



- **Real-time coincidences**
- **Sub-threshold data**
  - Data that is below the detection threshold from each observatory.
  - Careful coincident analysis can bring a sub-threshold event into a possible detection
- Streams:
  - IceCube Gold/Bronze.
  - HAWC GRB-like alerts.
  - ANTARES-Fermi alerts

Ayala Solares et al., Astro. Part., 114, (2020), 68-76

Data description:

HAWC events are "hotspots" of significant excesses above background identified during one full transit of that sky location above the detector.

IceCube events are single through-going track events from muons/muon-neutrinos.

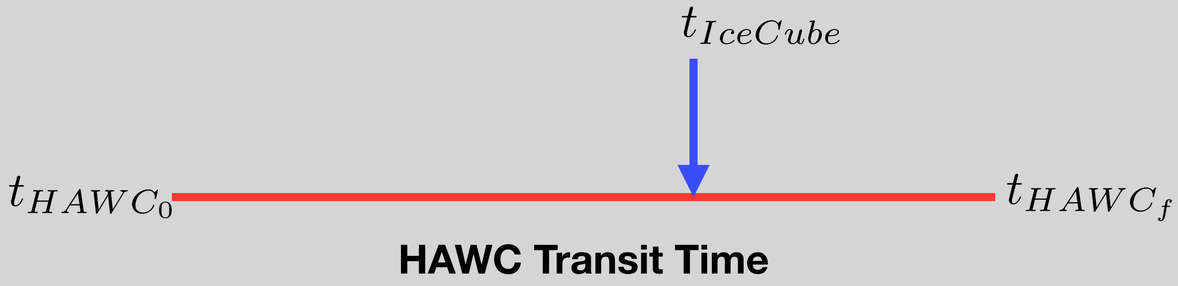
Information sent to AMON from both observatories:

- **Position**
- **Uncertainty in position**
- **Significance (>2.75)**
- **Start time of transit**
- **End time of transit**

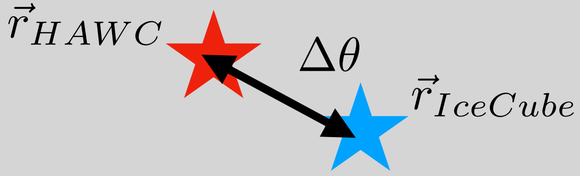
- **Position**
- **Uncertainty in position**
- **Time of event**
- **False positive rate density (FPRD)**
- **Signalness**

Coincidence criteria of the analysis

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



- **Spatial selection**: Distance from IceCube event and HAWC hotspot is less than 3.5°



Ranking the coincidences is based on Fisher's method.
Due to the fact that the DoF are different depending on the number of neutrinos we add an extra step to get the ranking value

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

P-value from Maximum likelihood, Spatial Selection

HAWC hotspot significance

Probability of more Than one neutrino In the transit time

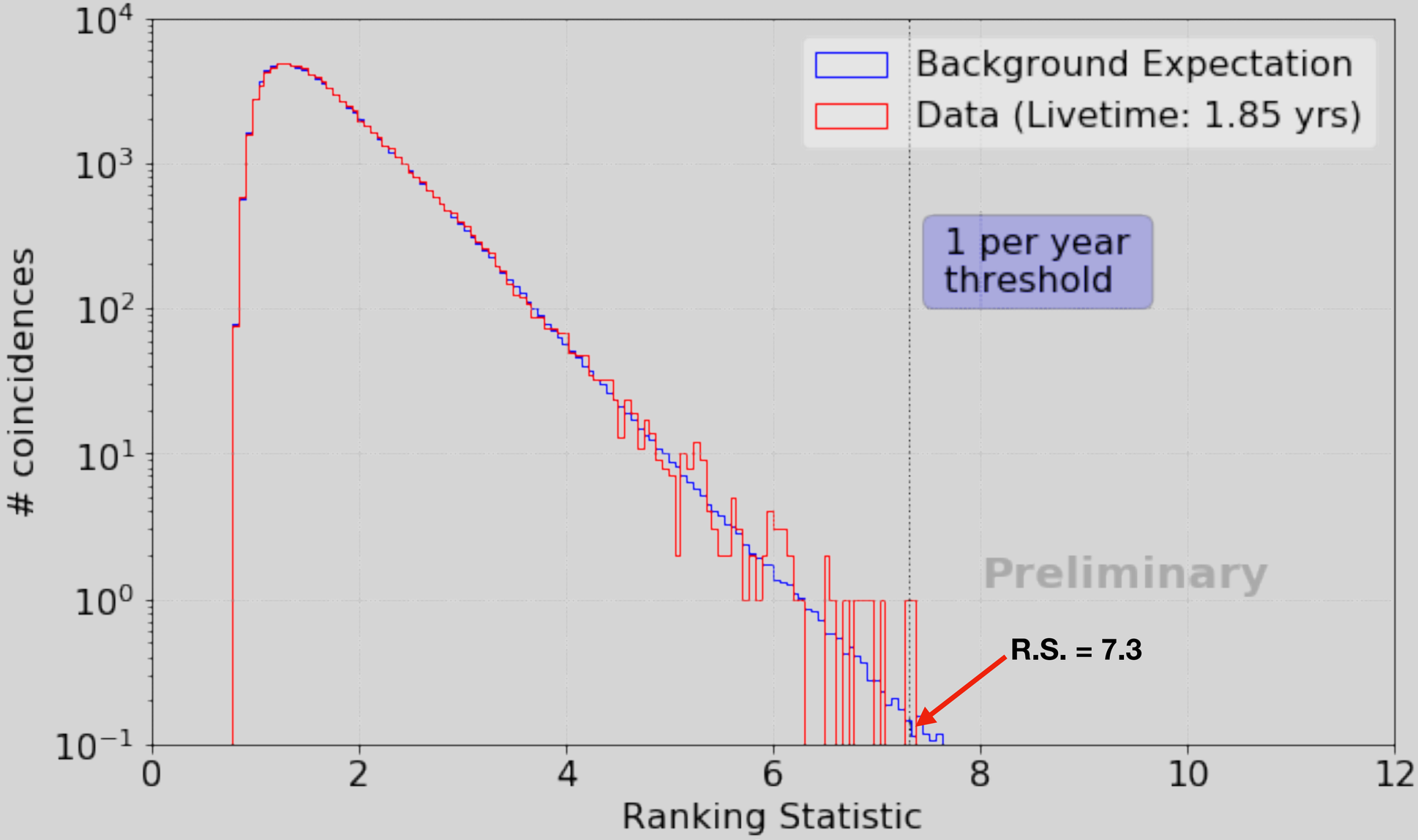
$$p_{Cluster} = 1 - \sum_{i=0}^{N-2} Pois(i;\lambda)$$

P-value of the IceCube Neutrino based on energy

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

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

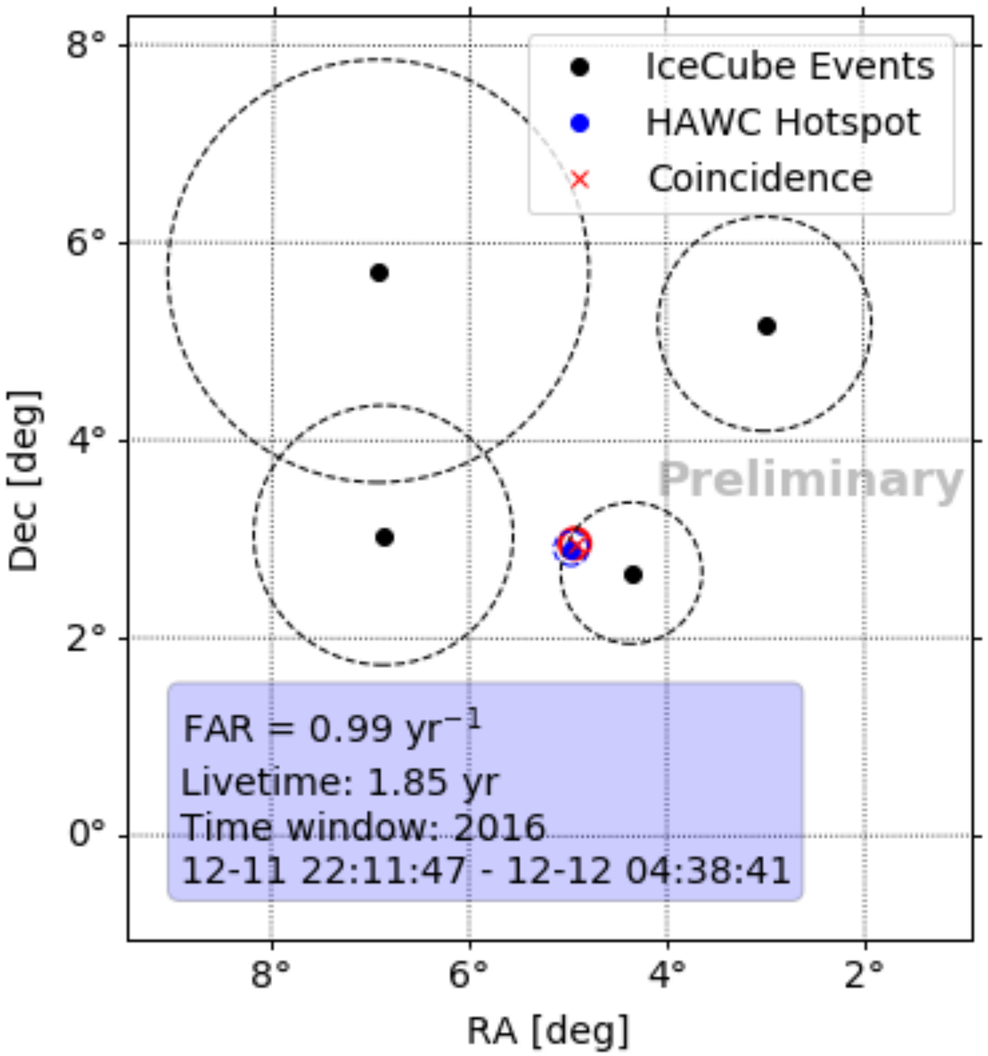
Ranking statistic distribution. Comparison between expected distribution from scrambling the data and actual result from data taken during 2016 and 2017.



Coincidences with the highest ranking statistic values.

Dec [deg]	RA [deg]	Time (End of HAWC transit)	Angular Uncertainty [deg]	Num. Neutrinos	Ranking Statistic	FAR [per year]
2.96	4.93	2016-12-12 04:38:41	0.16	4	7.34	0.99
24.97	339.52	2017-06-07 15:38:15	0.15	3	7.27	1.1

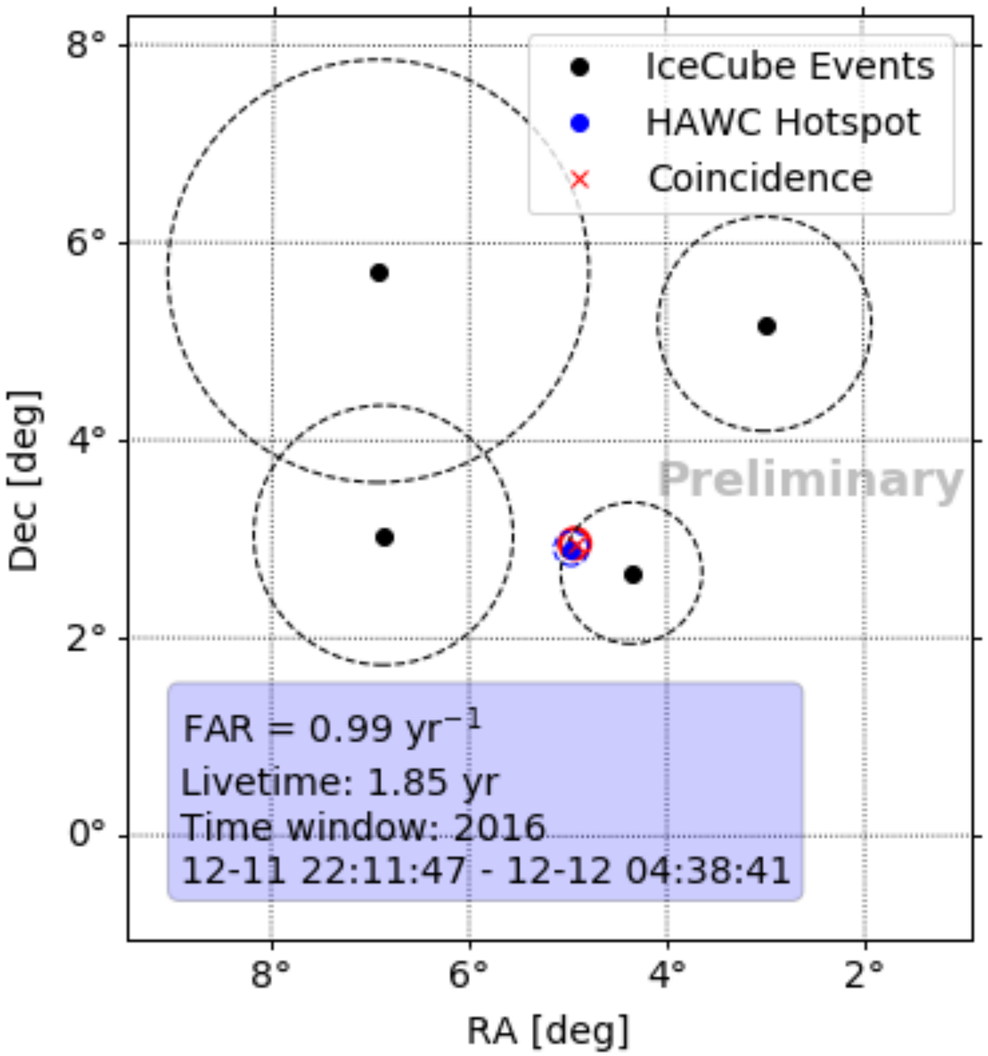
Coincidence with the highest ranking statistic



#	dist(asec)	Identifier	Type	Coordinates
1	49.01	PKS 0017+026	rG	4.94350 +02.96894
2	82.21	LEDA 1242471	G	4.9138 +02.9842
3	140.66	TXS 0017+026	Rad	4.8937 +02.9531
4	169.48	SDSS J001954.03+025717.0	QSO	4.9751279227698 +02.9547283034120
5	209.36	SDSS J001937.93+030118.8	QSO	4.908050 +03.021906
6	236.41	LEDA 1278	G	4.97642 +03.01442
7	238.71	LEDA 1241595	G	4.8667 +02.9478
8	322.81	PB 5870	*	4.9542 +02.8817
9	385.80	SDSS J002004.88+025437.2	BiC	5.020353 +02.910343
10	460.03	V* BZ Psc	LP*	5.0397432211714 +03.0335505306947
11	522.19	BD+02 36	*	4.8312133864148 +03.0744335231459
12	561.84	SDSS J002020.40+025913.8	QSO	5.0849897090915 +02.9871982103513
13	573.72	SDSS J002010.41+025121.5	QSO	5.043409 +02.855988

Sources found in the Simbad catalog inside the coincidence region

Coincidence with the highest ranking statistic

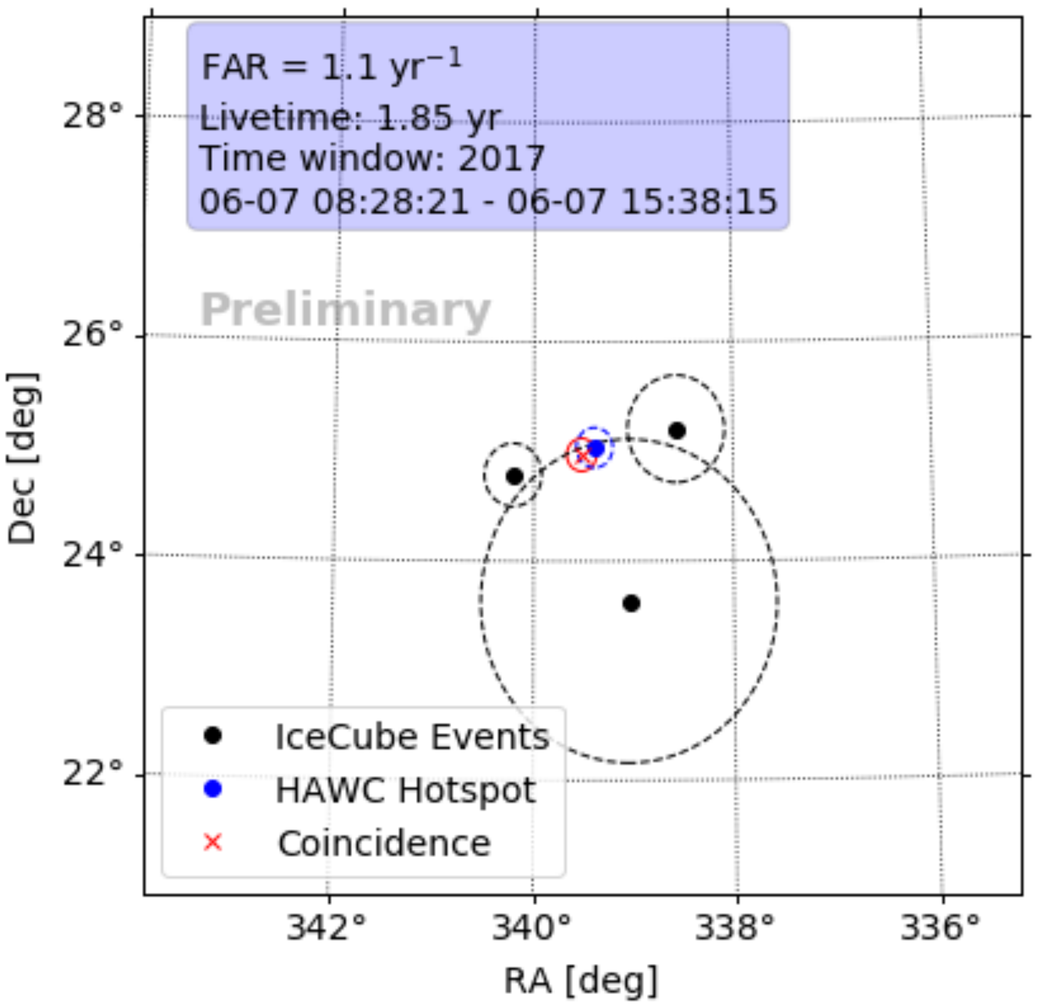


#	dist(asec)	Identifier	Type	Coordinates
1	49.01	PKS 0017+026	rG	4.94350 +02.96894
3	140.66	TXS 0017+026	Rad	4.8937 +02.9531

Interesting radio galaxies found in this coincidence.

But the coincidence's FAR agrees with the background expectation (~1 per year)

Coincidence with the second highest ranking statistics



#	dist(asec)	identifier	typ	coord1 (ICRS,J2000/2000)
1	33.49	2MASX J22380462+2457385	G	339.519258 +24.960722
2	173.32	LP 400-32	PM*	339.4923957509643 +25.0111326397330
3	229.57	LEDA 1723382	G	339.5379 +25.0317
4	252.29	CRTS J223805.3+245359	WU*	339.5222279937096 +24.8999480757153
5	300.05	SDSS J223826.83+245826.6	QSO	339.6118311419671 +24.9740782721494
6	323.64	BD+24 4623	*	339.5423549377214 +25.0575876400103
7	340.05	SDSS J223808.26+245235.2	QSO	339.5344404535175 +24.8764550689214
8	358.93	TYC 2224-1317-1	*	339.4409044043807 +25.0392973572113
9	430.12	TYC 2224-1186-1	*	339.6248746393117 +24.8976757850332
10	510.55	AGES J223823+245207	rG	339.60996 +24.85400

Sources found in the Simbad catalog inside the coincidence region

Conclusion and Future plans

- We presented a coincidence analysis between a gamma-ray detector (HAWC) and neutrino detector (IceCube).
  - Search for sources of neutrinos: GRBs, AGNs (Blazars, Radio galaxies), etc.
  - Show archival results of 2 years of data from HAWC and IceCube.
  - In a lifetime of 1.85 years we found one coincidence event with a FAR of 0.99 per year.
- Aim: run analysis in realtime.
  - Proposal currently under consideration in the collaborations
  - Plan is to send alerts with a false alarm rate of ≤ 1 per year.

Back-up Slides

Calibration of false alarm rate: scrambled 2 years of data from both detectors to construct the false alarm rate of the analysis

FAR (yr^{-1})	R.S.
10	6.0
1	7.3
0.5	7.7
0.1	8.7