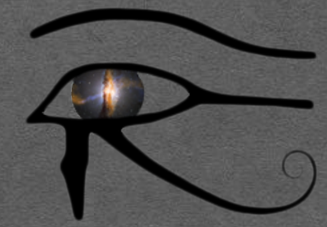
AMON
Astrophysical Multimessenger Observatory Network

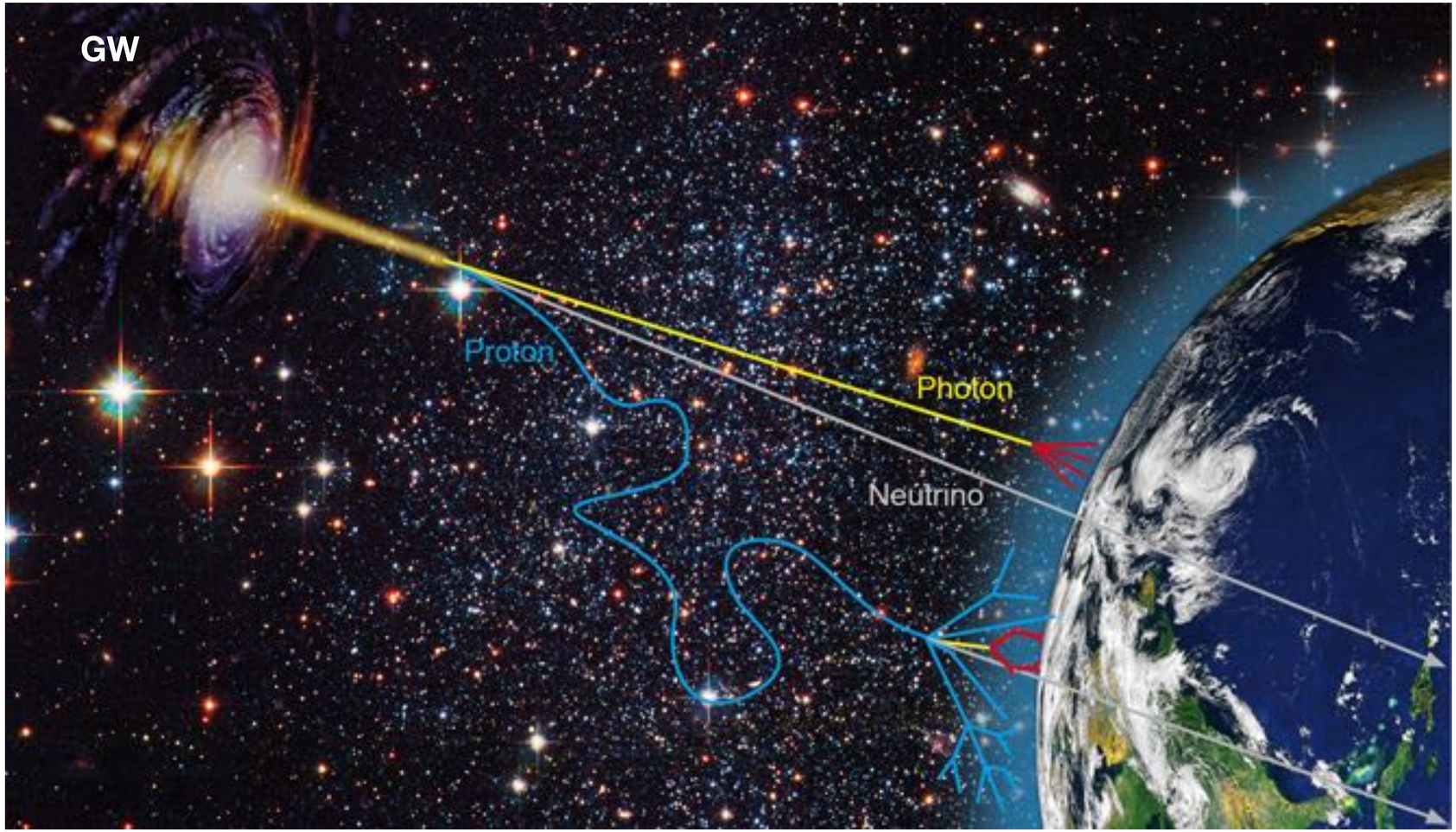



# AMON Multimessenger Alerts: Past and Future

Hugo Ayala

PennState
Eberly College
of Science

# Entering a new era where we can detect the messengers of the four forces of nature.






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

# Entering a new era where we can detect the messengers of the four forces of nature

| Force | Messenger | Messenger Detected | Sources? |
|---|---|---|---|
| **EM** | Photons | 👍 | Several |
| **Weak** | Neutrinos | 👍 | Three (?) (Sun, SN1987A, TXS 0506 ($3\sigma$)) |
| **Strong** | p, nuclei | 👍 | ? |
| **Gravity** | Gravitational Waves | 👍 | Few and increasing |

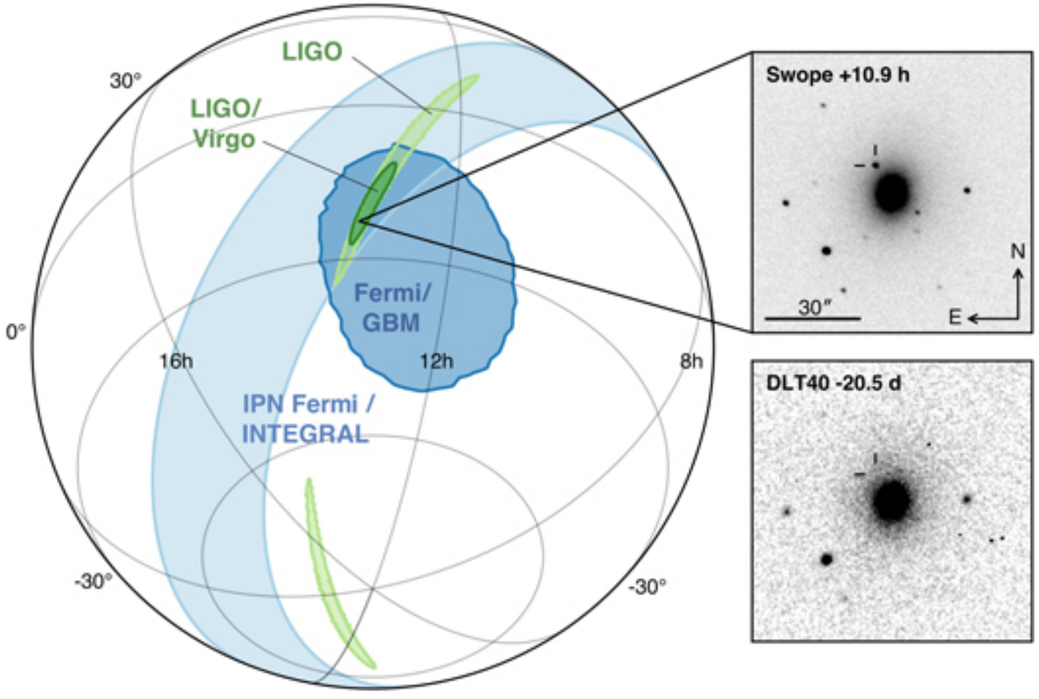


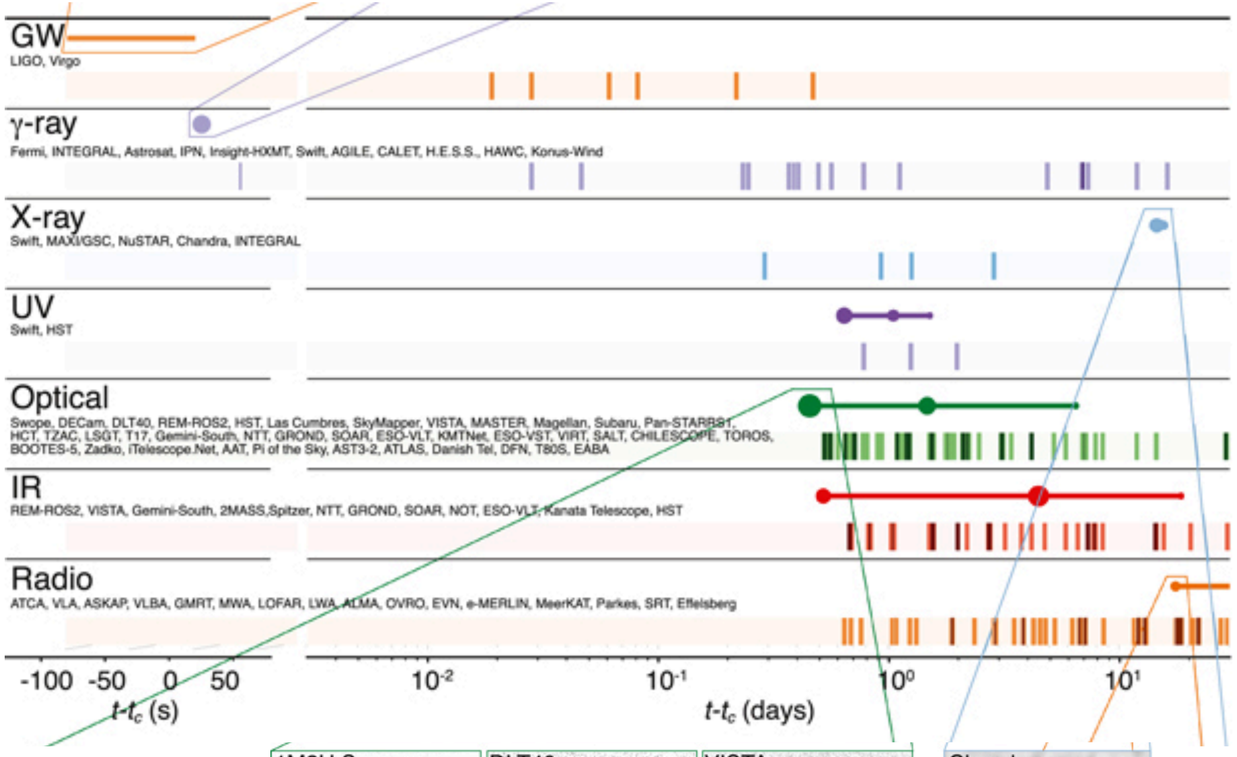
https://astro.desy.de/theory/multi_messenger_astrophysics/index_eng.html

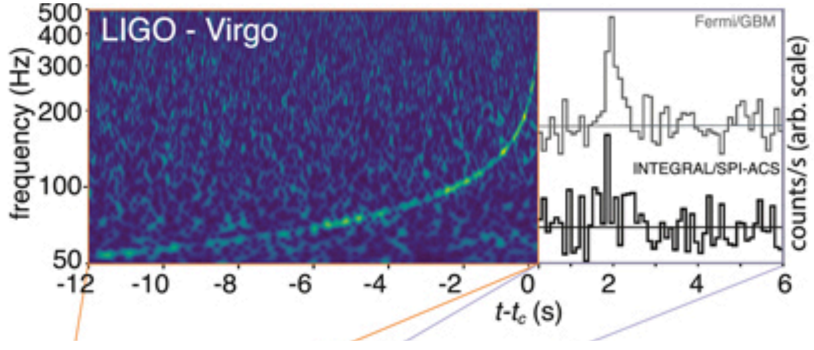
# Each messenger has advantages and disadvantages.

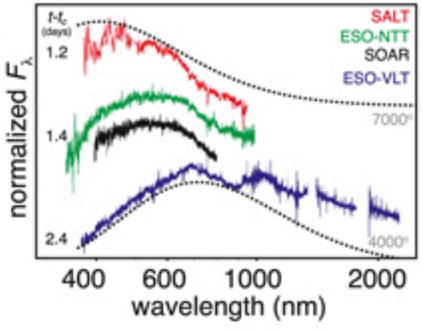
| **Messenger** | **Sample Size** | **Straight Trajectory** | **Pointing Res.** | **Cutoff** |
|---|---|---|---|---|
| $\gamma$ | | | $<<1^{o}$ | $E_{\gamma} < 50$ **TeV**<br>$\gamma\gamma_{IR} \rightarrow e^{-}e^{+}$ |
| $\nu$ | $\sigma_{\nu,matter} < 1$ | | $\sim 1^{o}$ | |
| p, nuclei | | $\overrightarrow{B}$ | - | GZK cutoff<br>$E_p$<30EeV |
| GW | | | 2obs: ~1000 sq.deg.<br>3obs: ~60 sq.deg. | |

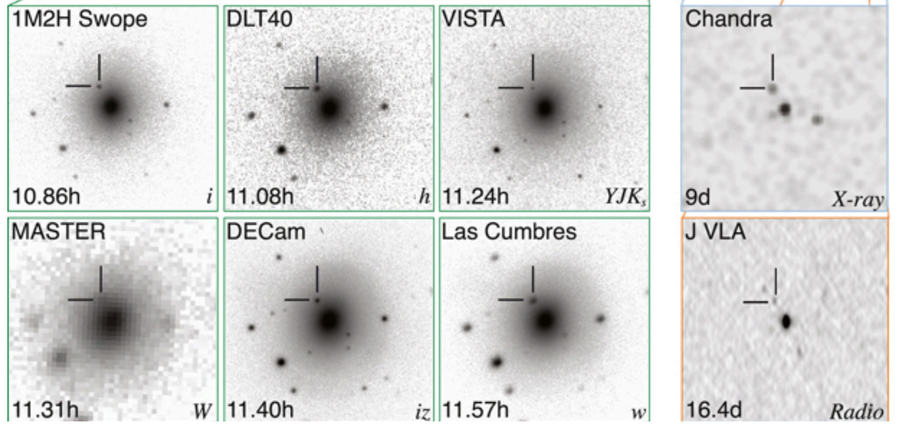
# Example 1: Electromagnetic radiation from a binary neutron star merger confirmed for GW170817.



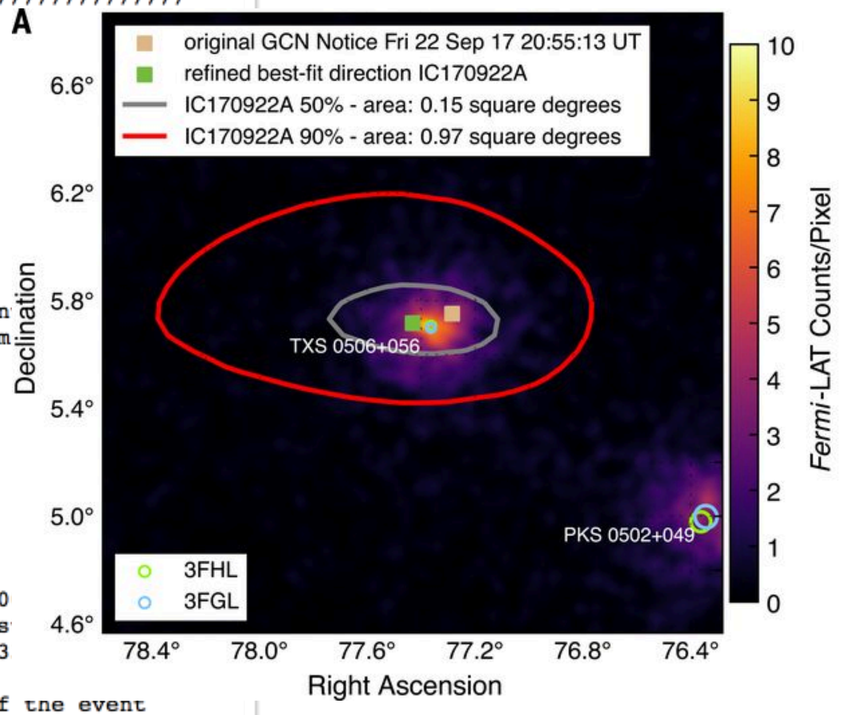



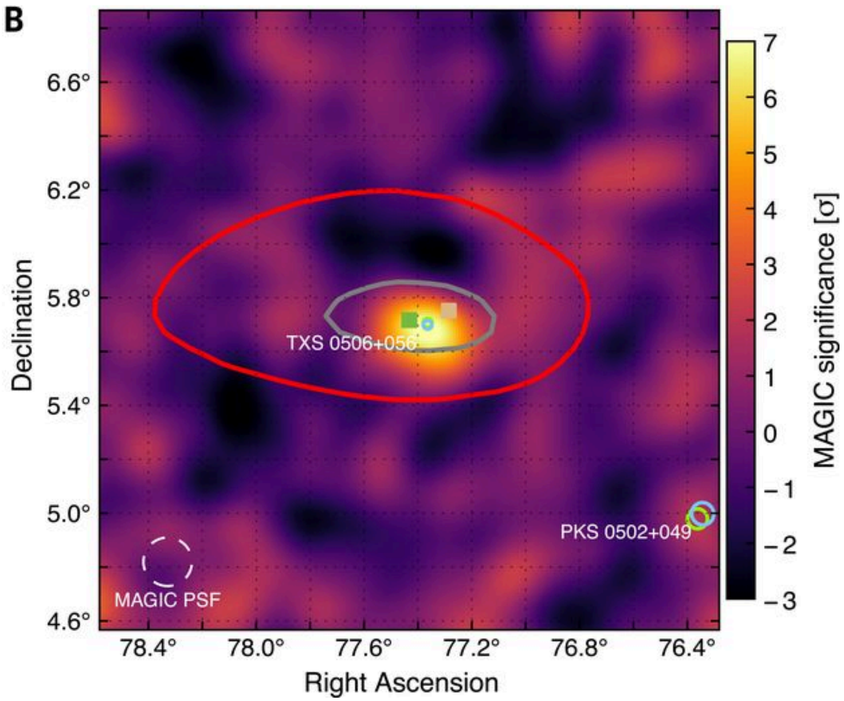



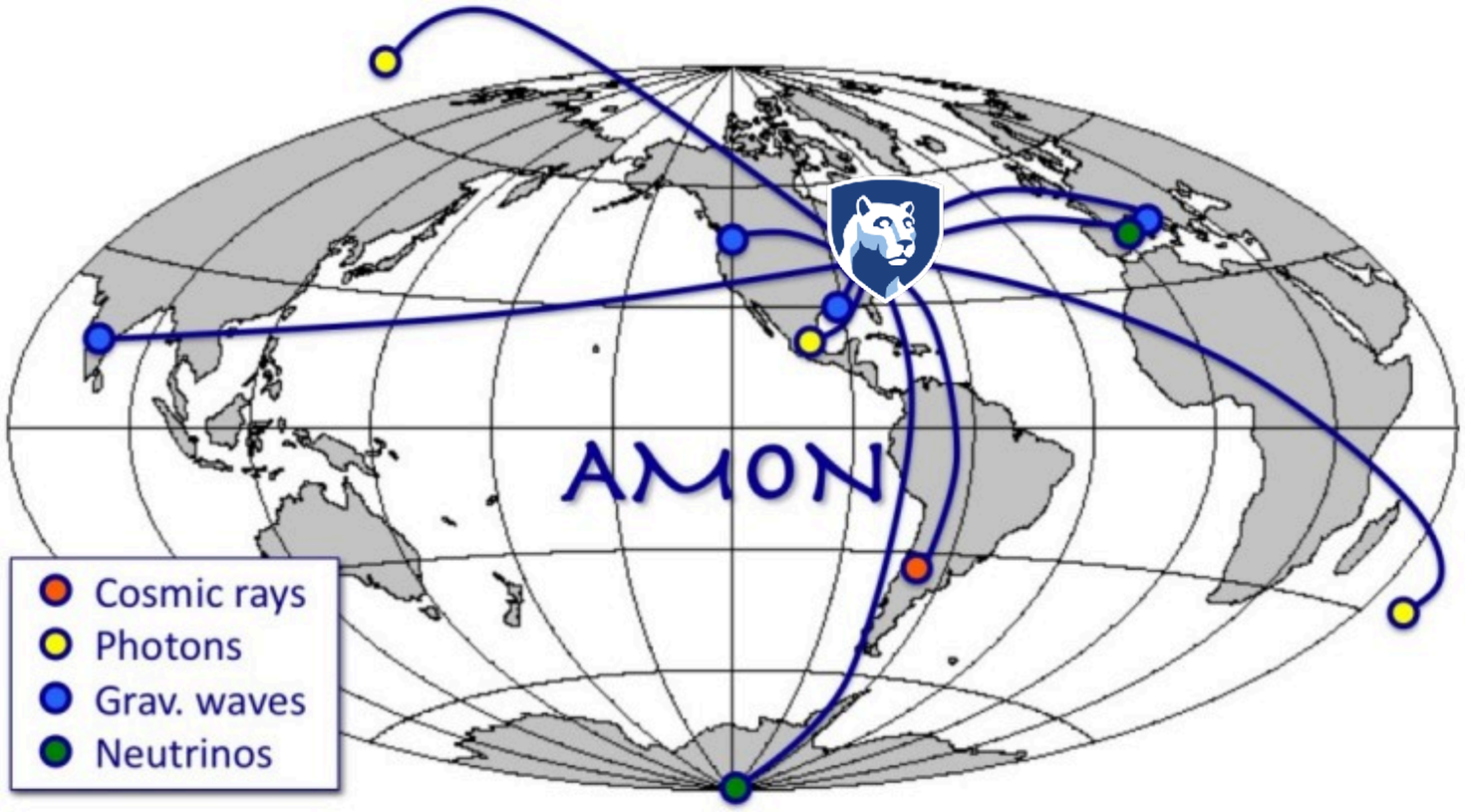
Example 2: Coincidence between high-energy neutrinos and gamma-rays from Blazar TXS 0506+056. First evidence of source of neutrinos ($3.5\sigma$). AMON contributed to the distribution of the event IC170922A.

```
////////////////////////////////////////////////////////////////////////
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.
```



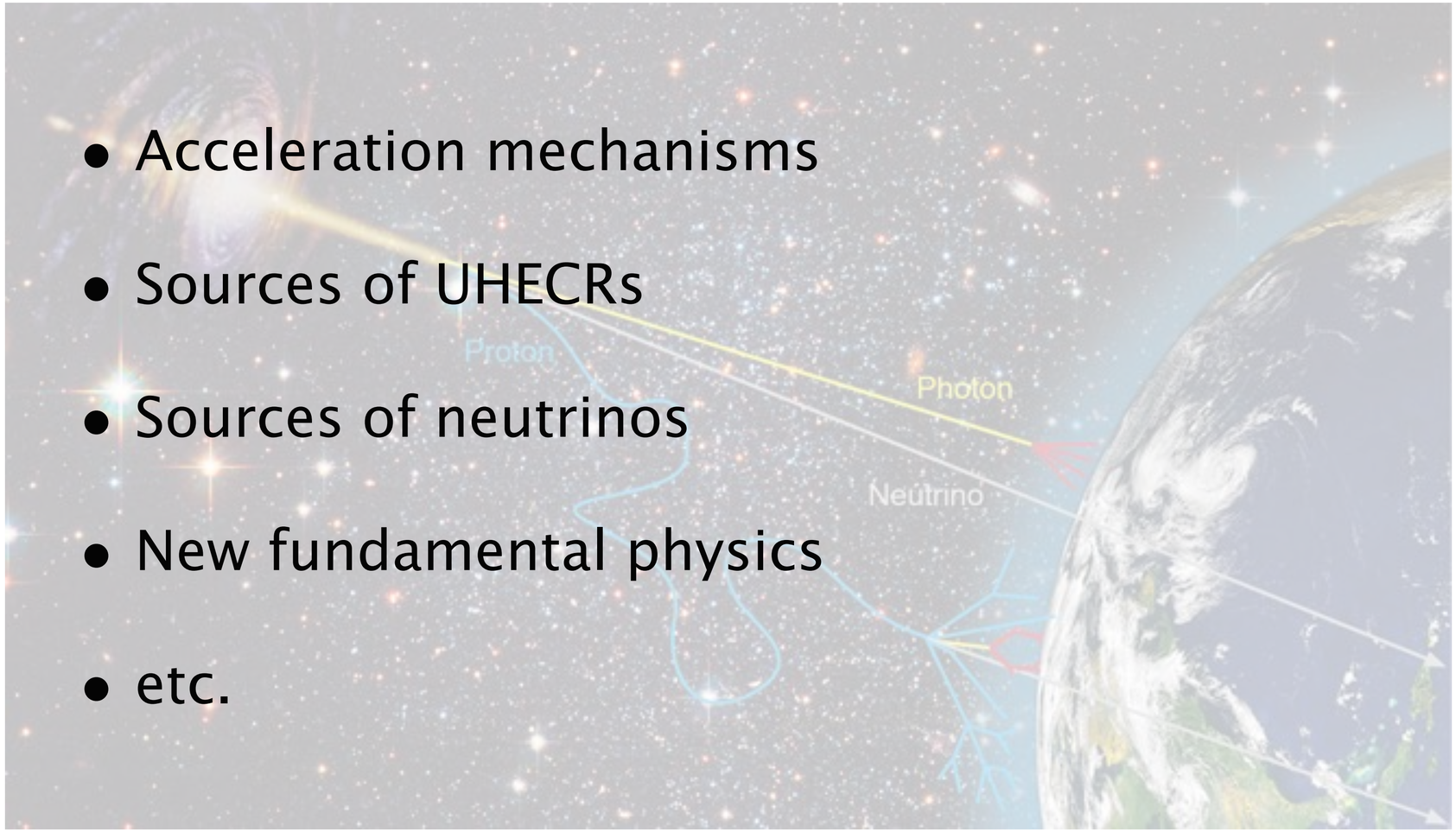



Another approach to multimessenger astrophysics is real-time searches. AMON has been built with this idea and with the use of **sub-threshold data**




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

# Focusing on high-energy astrophysics. We want to solve some of the current questions in the field




- Acceleration mechanisms
- Sources of UHECRs
- Sources of neutrinos
- New fundamental physics
- etc.



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

# Large span of transient events that we can look for:

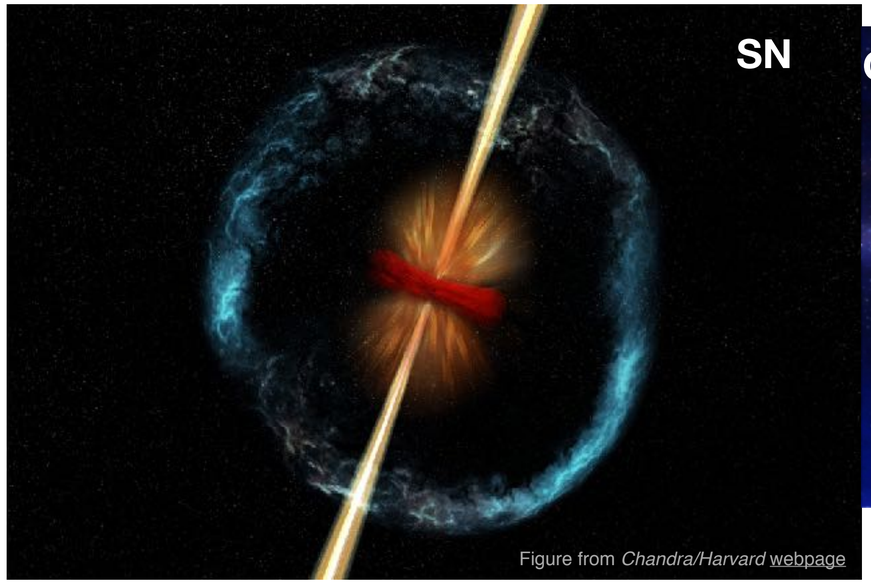
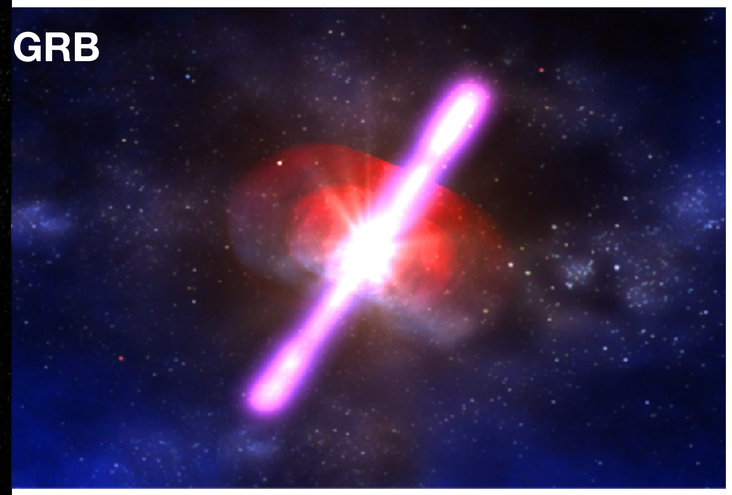
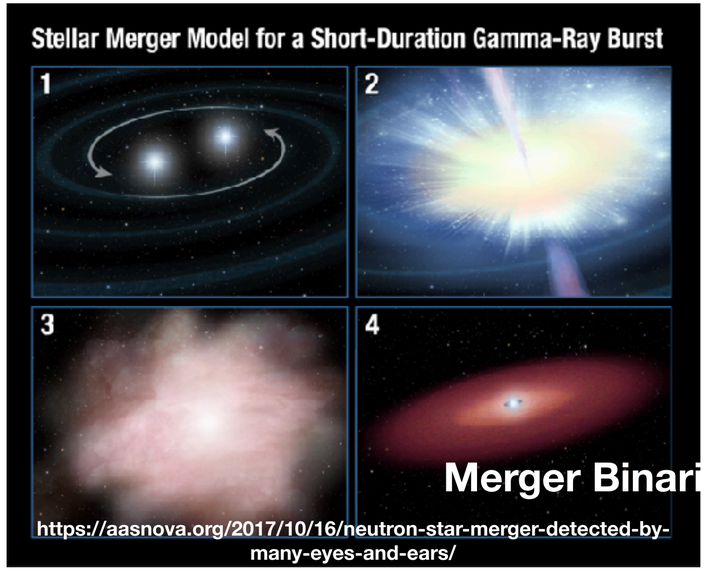


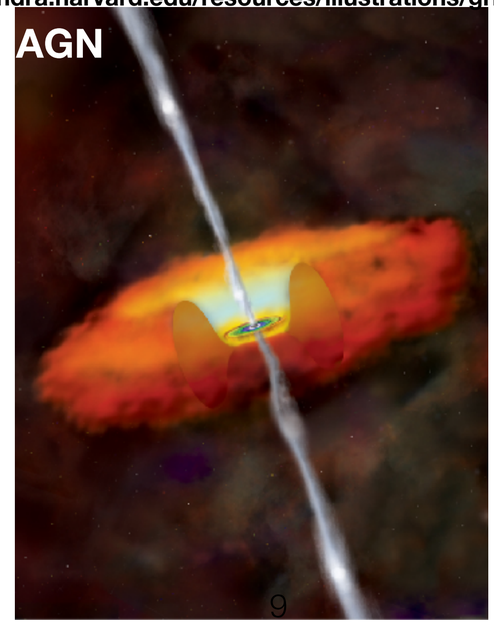
Figure from *Chandra/Harvard* webpage



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



https://aasnova.org/2017/10/16/neutron-star-merger-detected-by-many-eyes-and-ears/



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

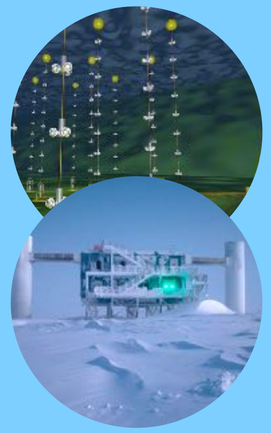
- Long GRBs
- Short GRBs
- SN
- Choked jet supernova
- Blazars
- PBHs
- Binary Mergers
- …

# AMON members and prospective members.

CR

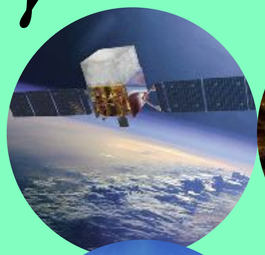
Pierre Auger

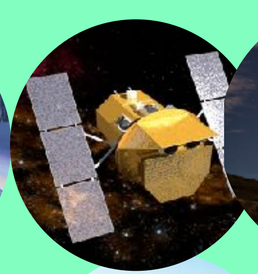
$\nu$



IceCube
ANTARES

$\gamma$

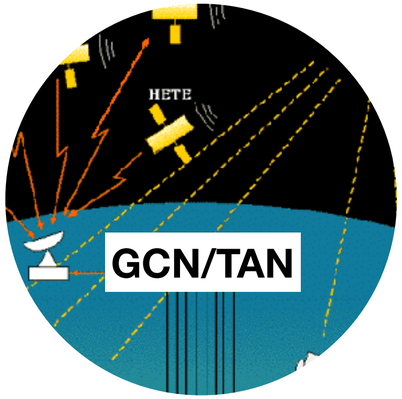




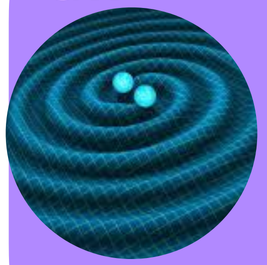
SWIFT
VERITAS
HESS
MAGIC

FACT
Fermi
HAWC

AMON
Astrophysical Multimessenger Observatory Network




GW

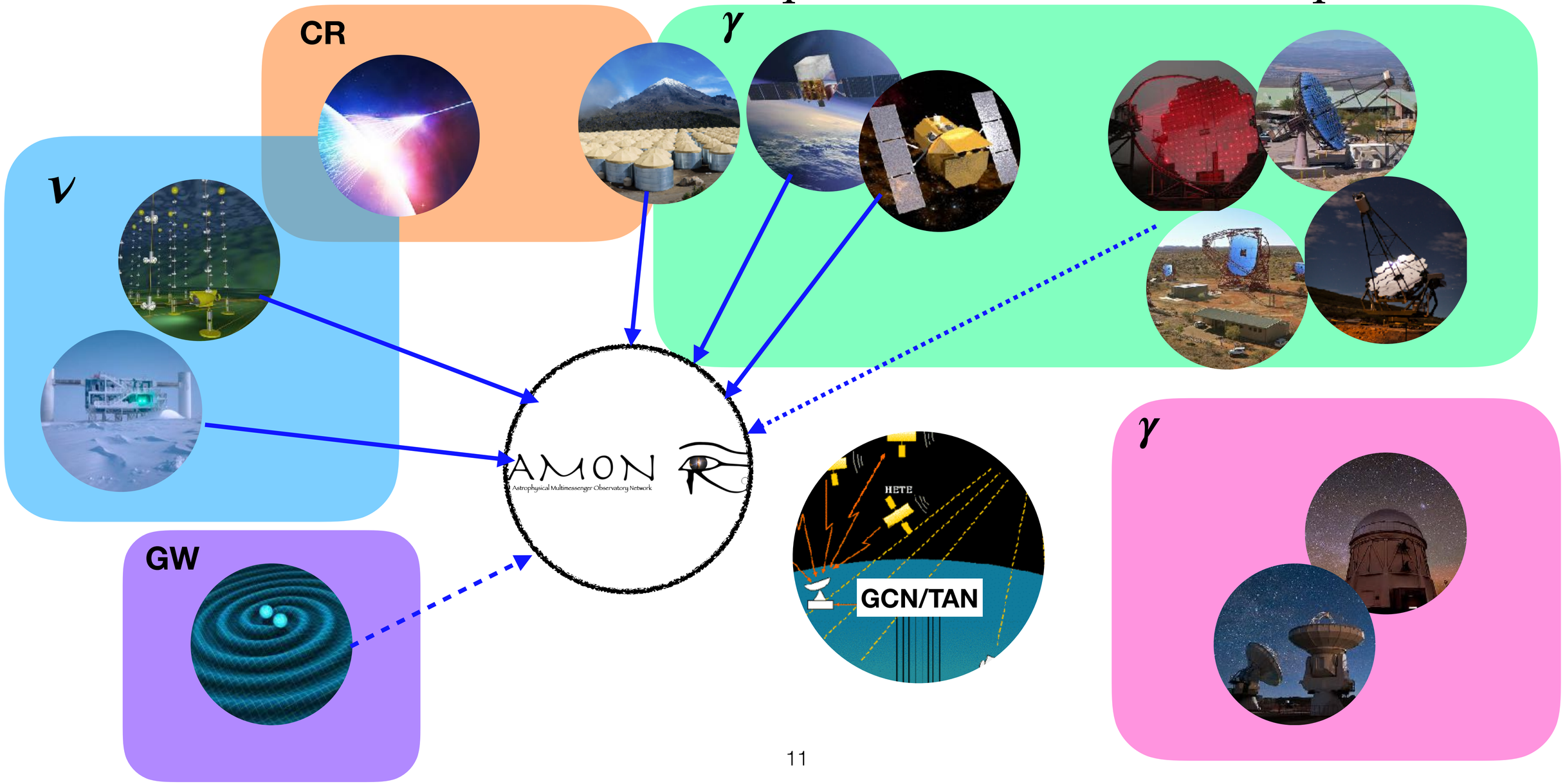


LIGO-
Virgo

$\gamma$

LMT
Palomar Transient Factory
MASTER

# AMON receives sub-threshold data events and send alerts to GCN/TAN which then is distributed to partner observatories/public



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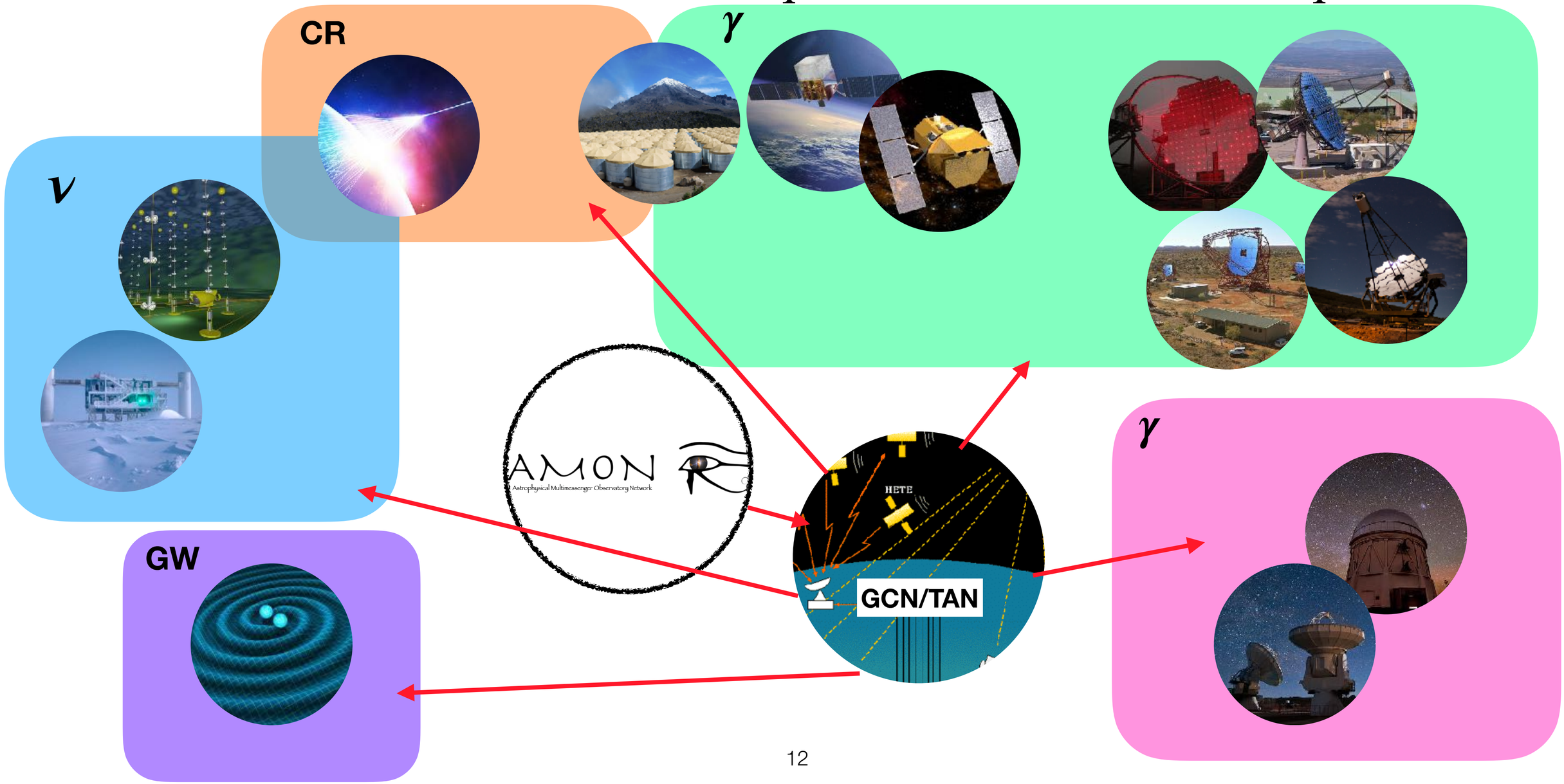

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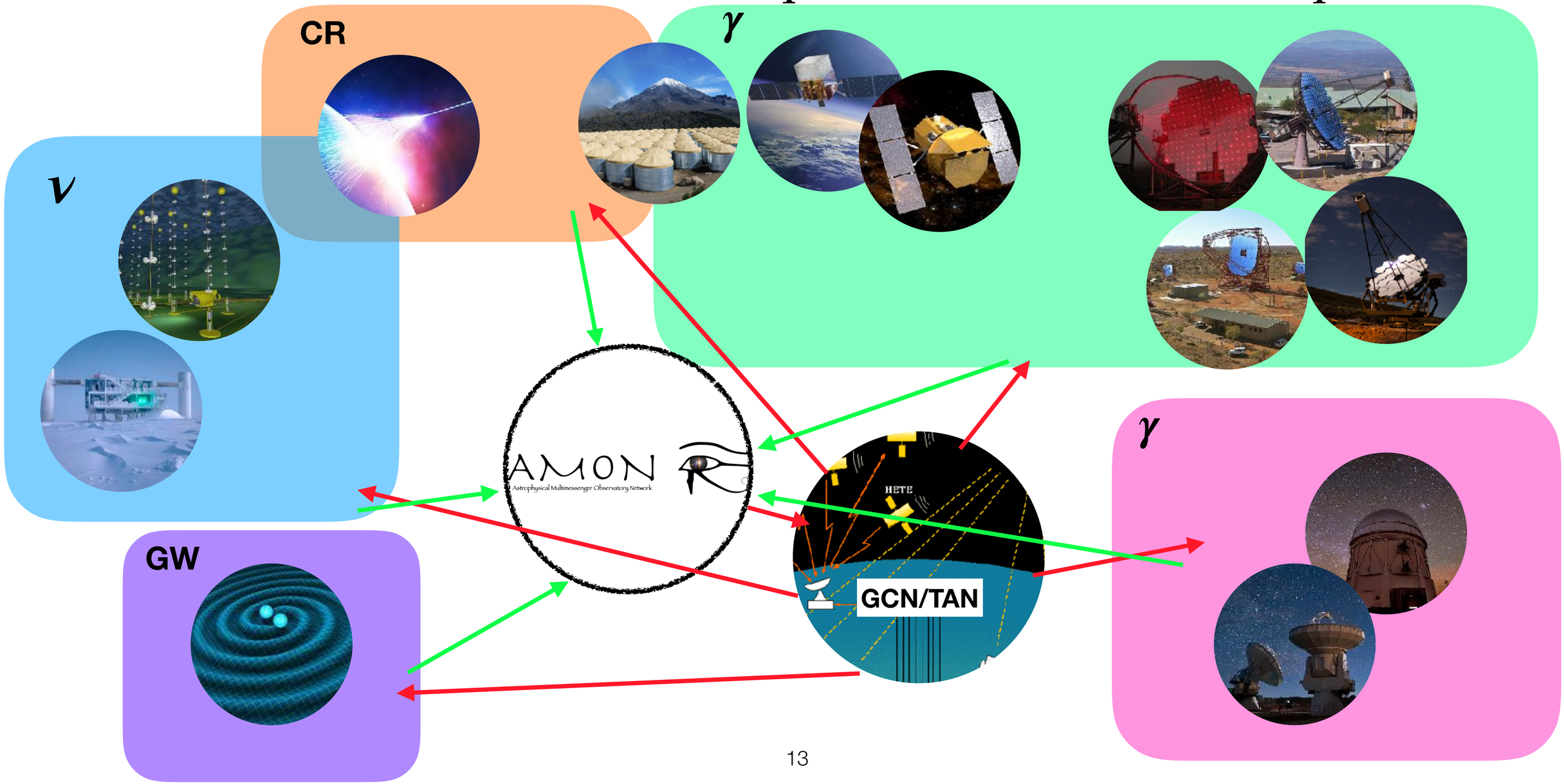
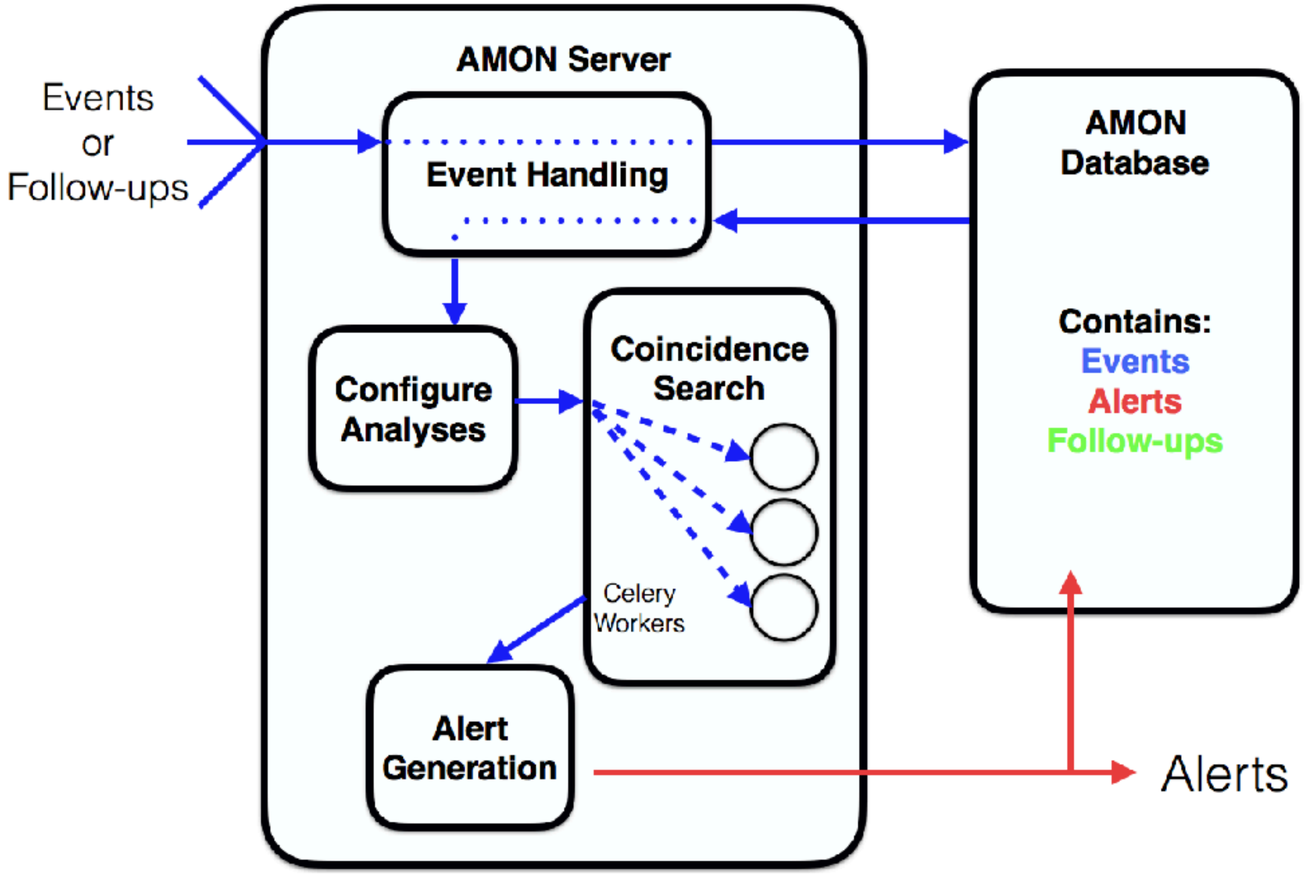


AMON uses an **asynchronous distribution system** to calculate coincidence searches in real-time. Using the **VOEvent protocol**.
Software is written in Python. Uses Celery, Twisted and Comet.



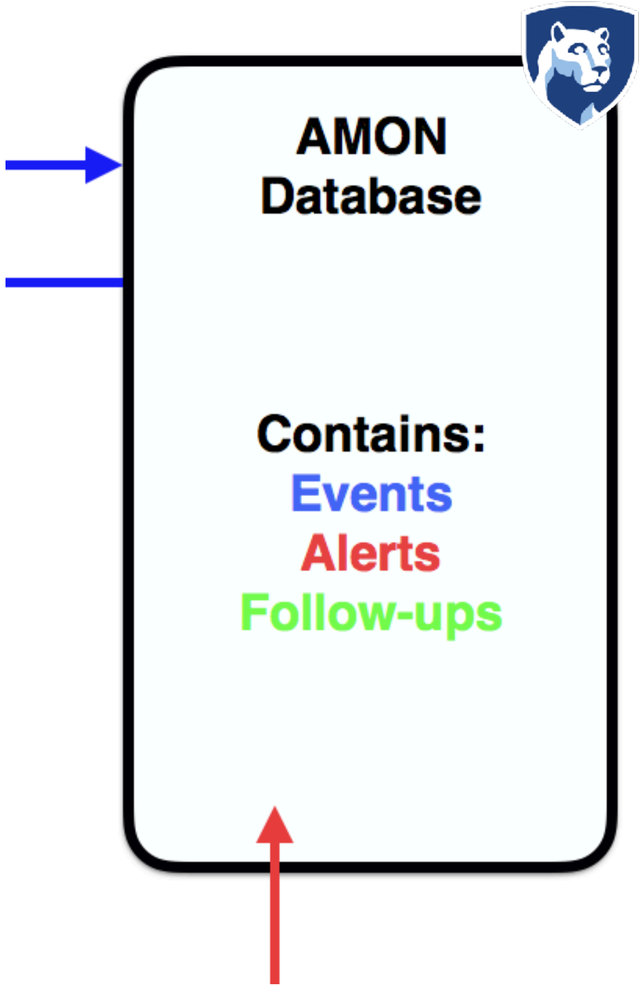

Celery

TWISTED

COMET

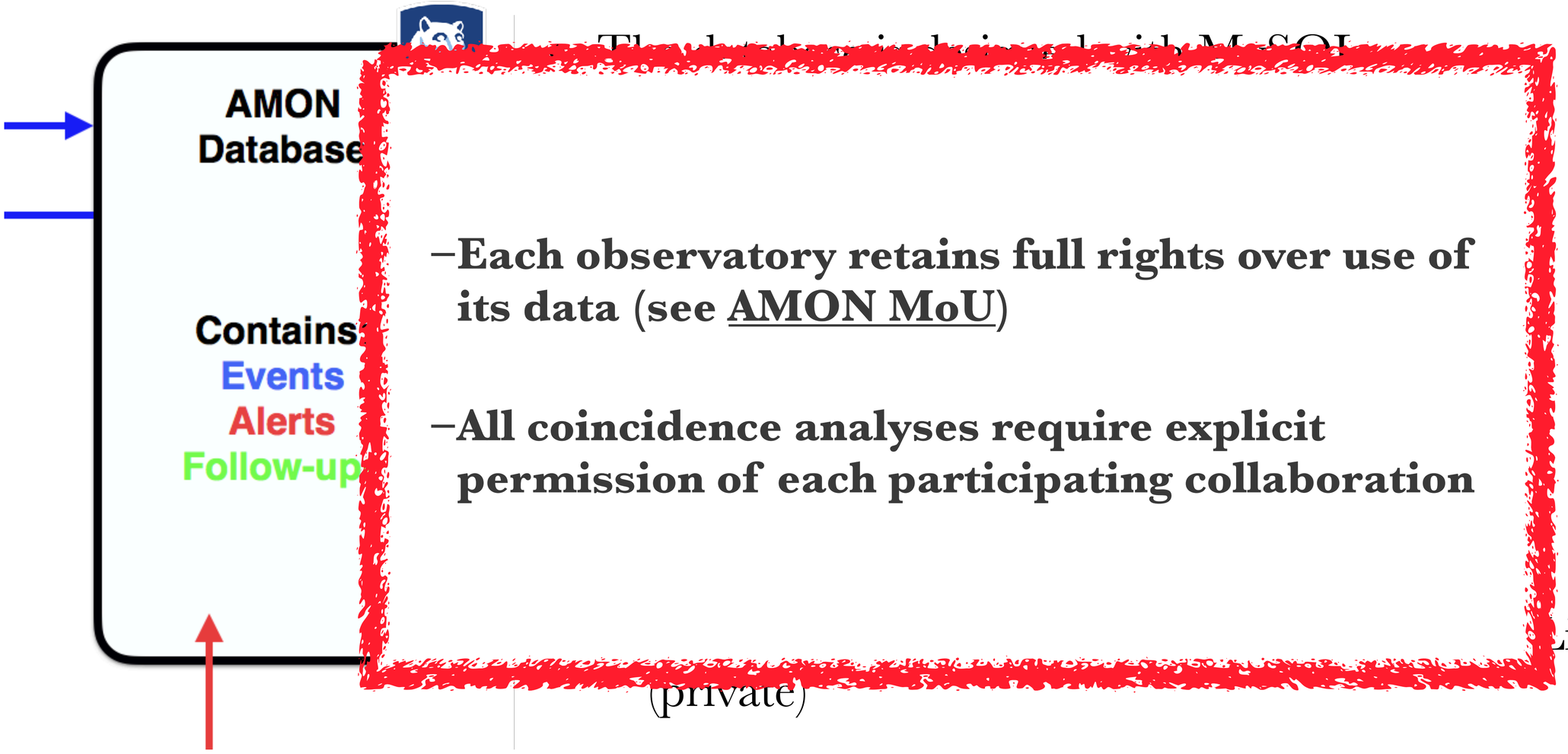
AmonPy software in GitHub:https://github.com/AMONCode/Analysis

# AMON Database resides in two servers at Penn State. Anticipate 1TB/yr of data.



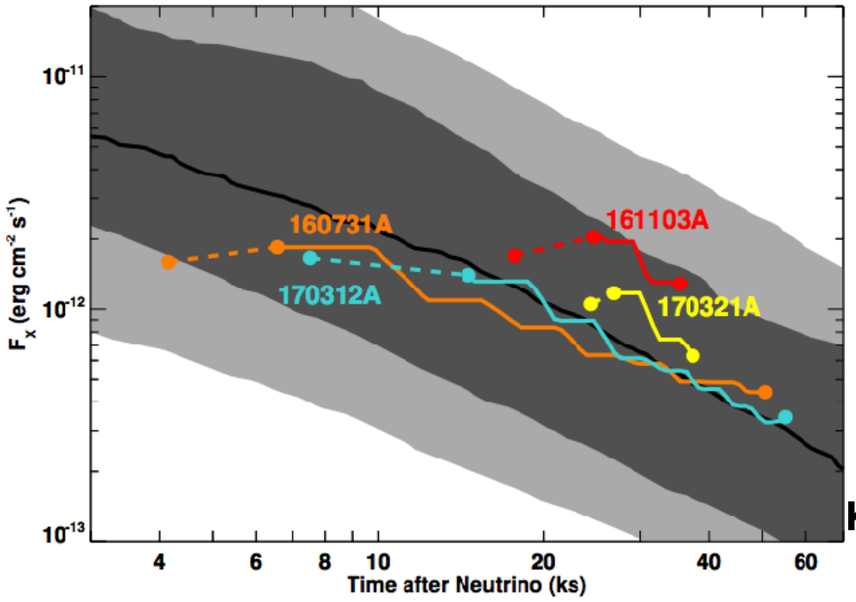

- The database is designed with MySQL
- It currently contains:
  - IC 40/59 and 1 year of IC 86 (public)
  - Realtime IC data (private)
  - SWIFT and Fermi data (public)
  - ANTARES, Auger data (private)
  - HAWC Daily Monitoring and HAWC GRB-Like data (private)
  - FACT data (44 events)

# AMON Database resides in two servers at Penn State. Anticipate 1TB/yr of data.

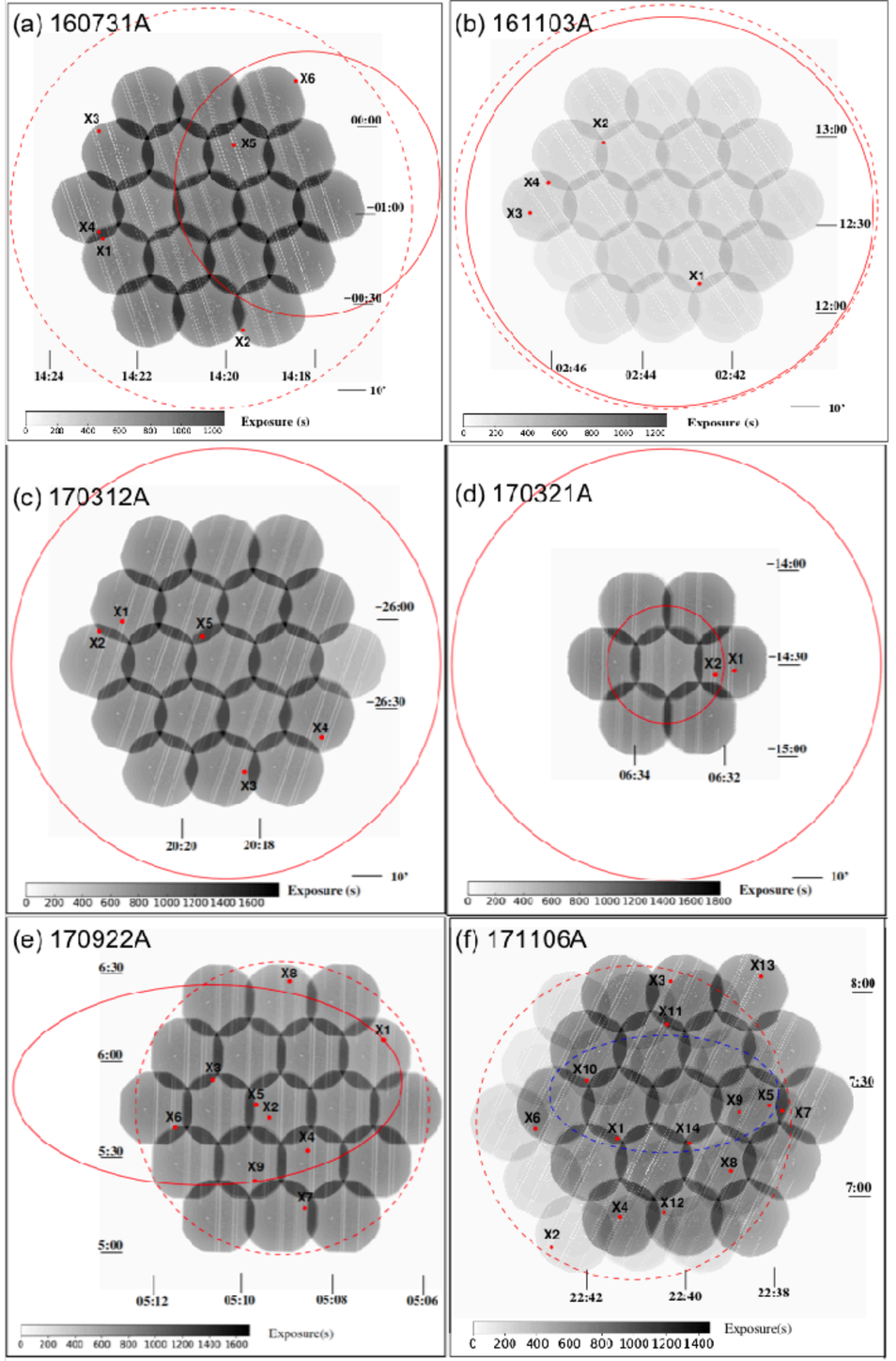


# Results 1A: The Swift Campaigns: follow-up observations

- Observation tiles centered on first IceCube alert (dashed line) HESE/EHE alerts.
- 1st campaign: observations revealed multiple x-ray sources that were previously identified
- No compelling candidate X-ray or UV/optical counterpart for any of the events. Set up flux upper-limits

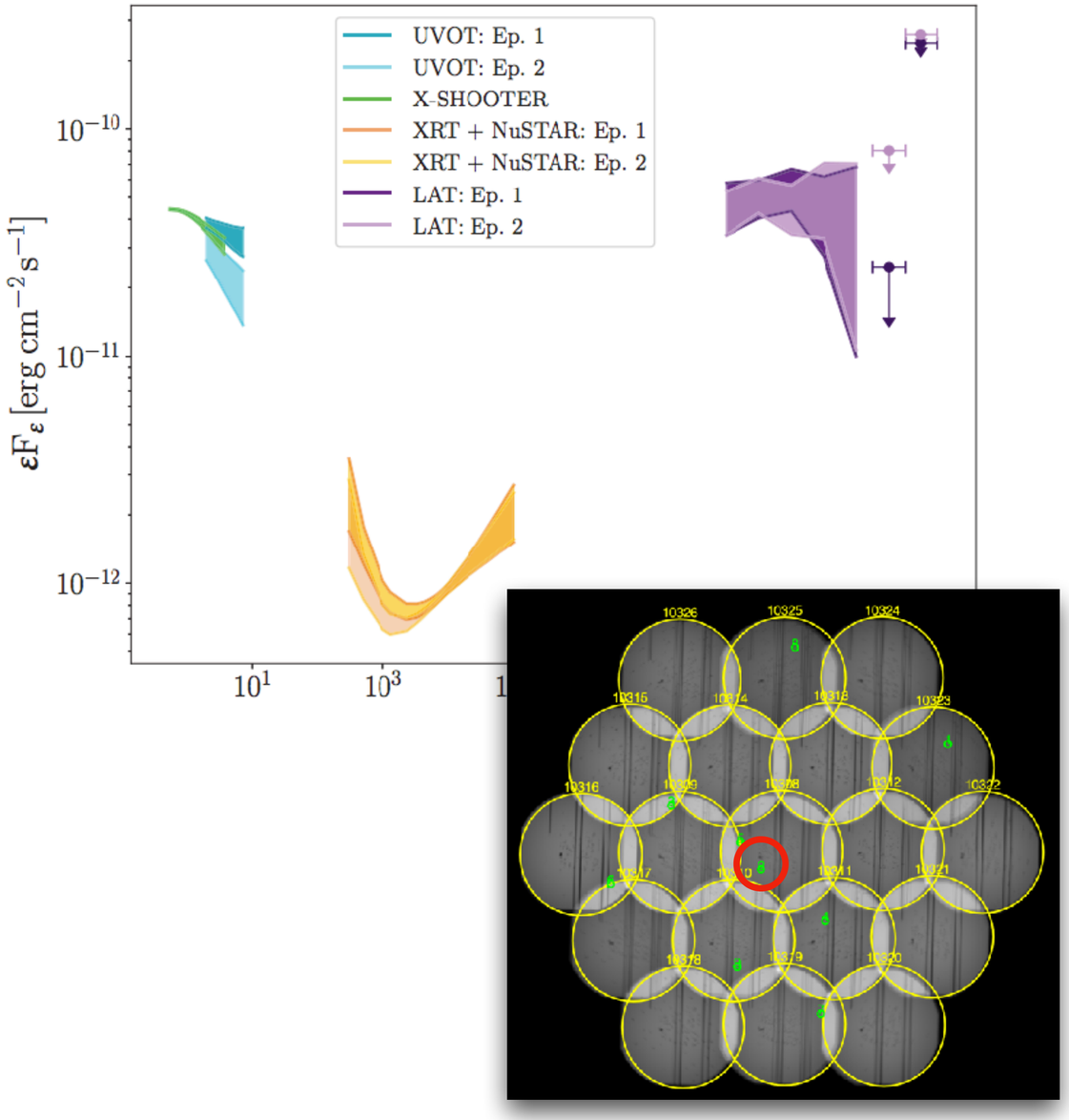



Keivani et al, ICRC 2017



# Results 1B: The Swift Campaigns: 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. (http://iopscience.iop.org/article/10.3847/1538-4357/aad59a/meta)

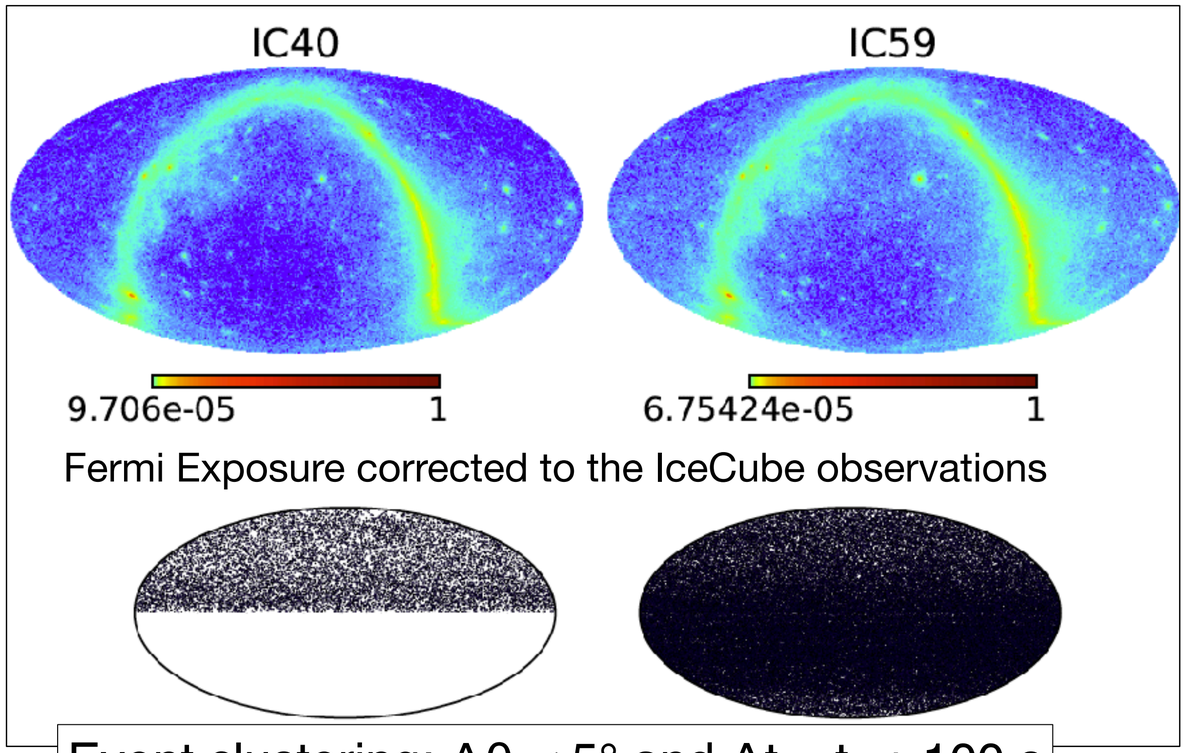


# Other follow ups of AMON-brokered public IceCube Real-time events

AGILE, ANTARES, FACT, Fermi GBM, Fermi LAT, HAWC, H.E.S.S, INTEGRAL, IPN, Konus-Wind, LCOGT, MAGIC, MASTER, Maxi/GSC, Pan-STARRS, PTF, Swift, VERITAS, CALET

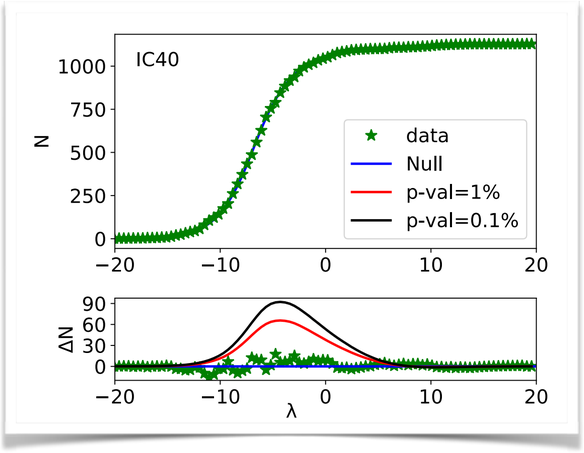
| Event/ Follow-up | $\nu$ | $\gamma$ optical | $\gamma$ high-energy |
|---|---|---|---|
| IC 171106A | | | |
| IC 171025 | | | |
| IC 170922A | | | |
| IC 170321A | | | |
| IC 170312A | | | |
| IC 161210 | | | |
| IC 161103 | | | |
| IC 160814A | | | |
| IC 160806A | | | |
| IC 160731A | | | |

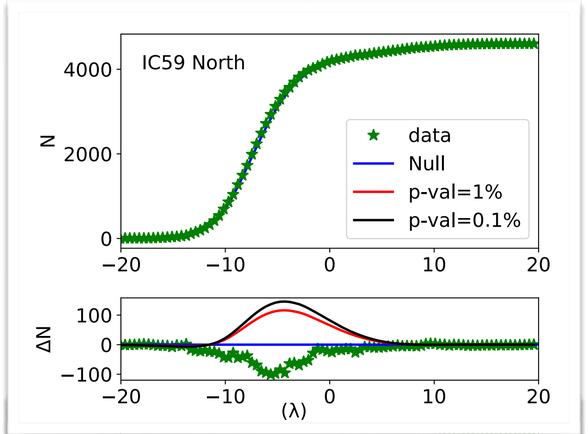
# Results 2: IceCube-*Fermi*LAT archival analysis. No significant deviations from the null hypothesis were found in the unscrambled dataset.

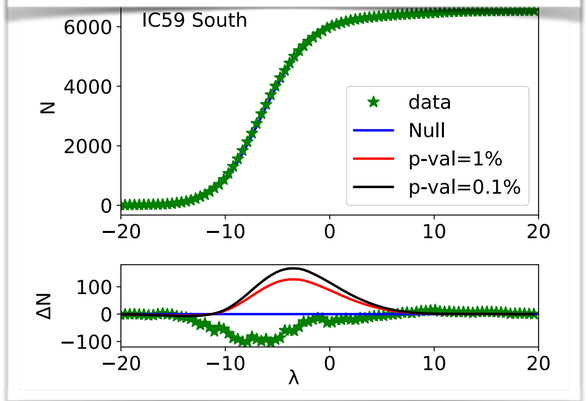



Event clustering: $\Delta\theta < 5°$ and $\Delta t = t_0 \pm 100$ s

| | IC40 | IC59 |
|---|---|---|
| **Num. $\gamma$** | ~15x10$^6$ | ~18x10$^6$ |
| **Num. $\nu$** | ~13x10$^3$ | ~108x10$^3$ |
| **Likelihood** | ~Null | (North+ South) p~5% |




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

**Current Plans:** commission new GCN streams, at least 4 by the end of the year

Using **sub-threshold** data

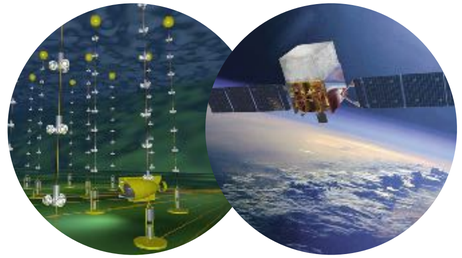
$\gamma$

**HAWC**
**Burst Monitoring**

**FACT**
**Alerts**

$\gamma+\nu$

**IC Singlets +**
**HAWC Daily hotspots**



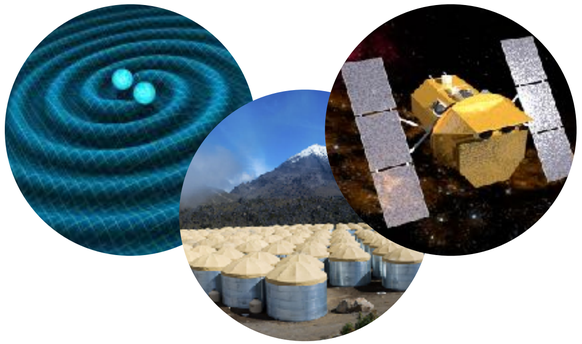
**ANTARES +Fermi LAT**

**IC Singlets +**
**SWIFT-BAT**

**Work On-going**

Using **sub-threshold** data

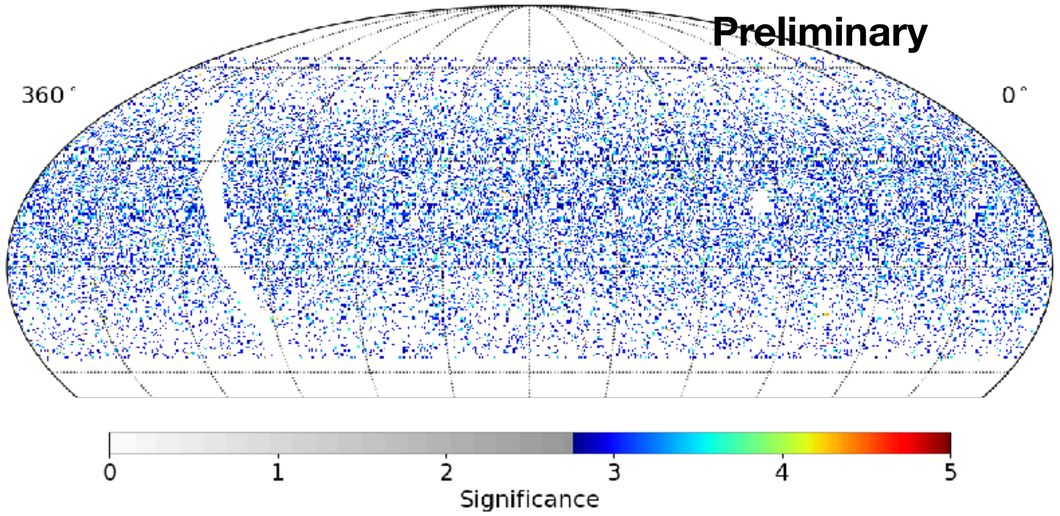
**GW + X**

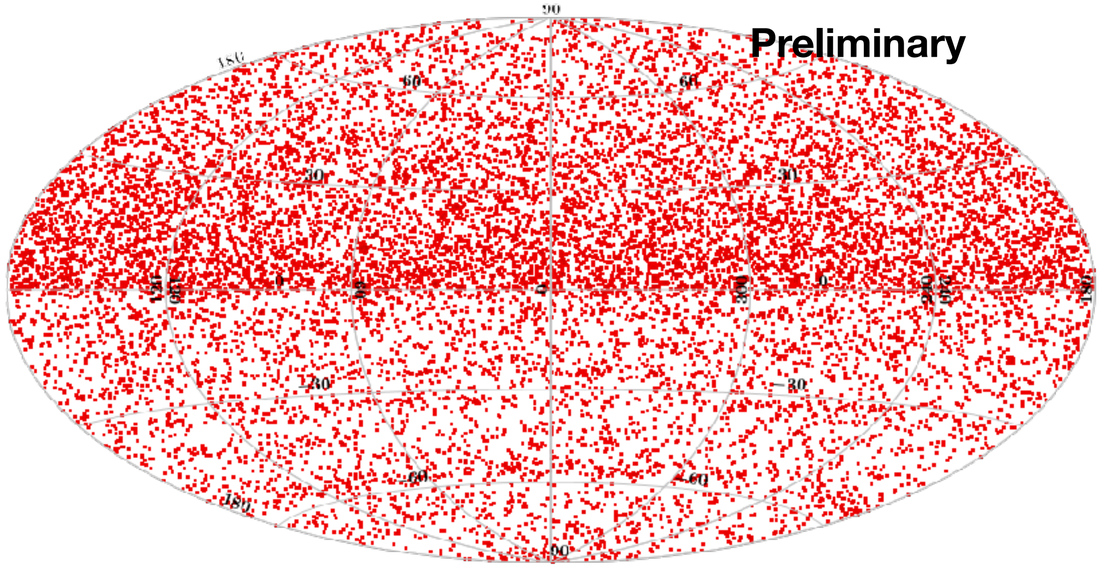


**LIGO-Virgo + HAWC**
**LIGO-Virgo + SWIFT**

**Proposals**

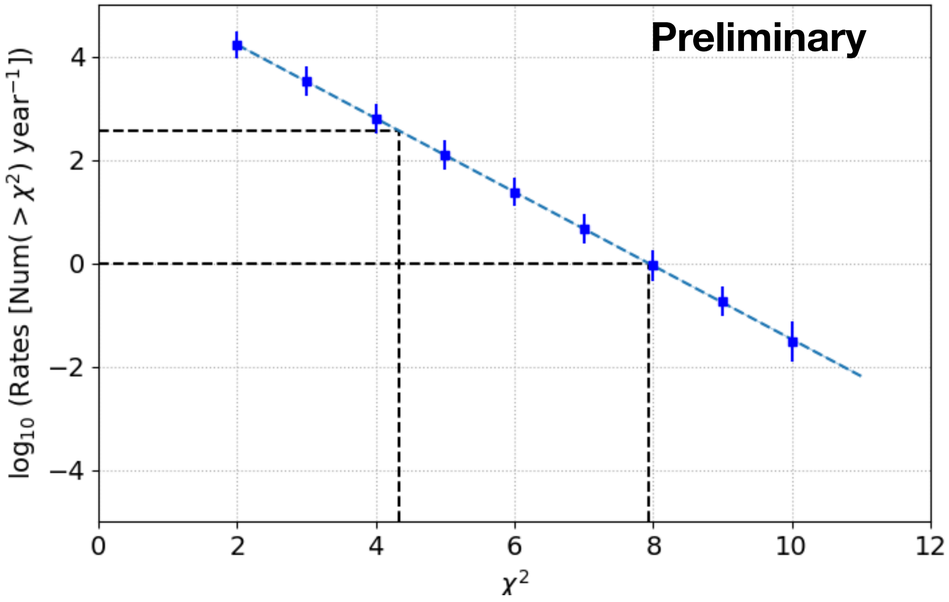
Current plan 1: IC-HAWC analysis has been defined and it is under review.
Tested on 1 month of data from both observatories (scrambled).
Alerts will be sent for specified thresholds that produce a specific FAR.



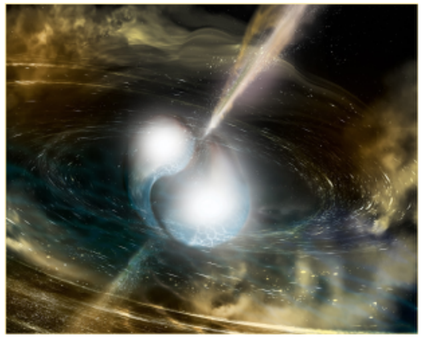




$$\chi^2_{6+2n_\nu} = -2\ln[p_\lambda\, p_{HWC}\, p_{cluster} \prod_i^{n_\nu} p_{i_{IC}}]$$

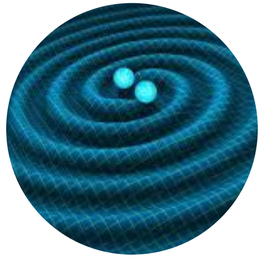
$$\chi^{2\prime} = -\log p_{\chi^2_{6+2n_\nu}}$$

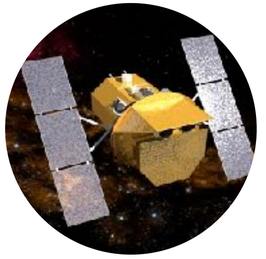


# Current plan 2: LIGO-Virgo/Swift-BAT. We have proposed an defined an analysis with sub threshold data.

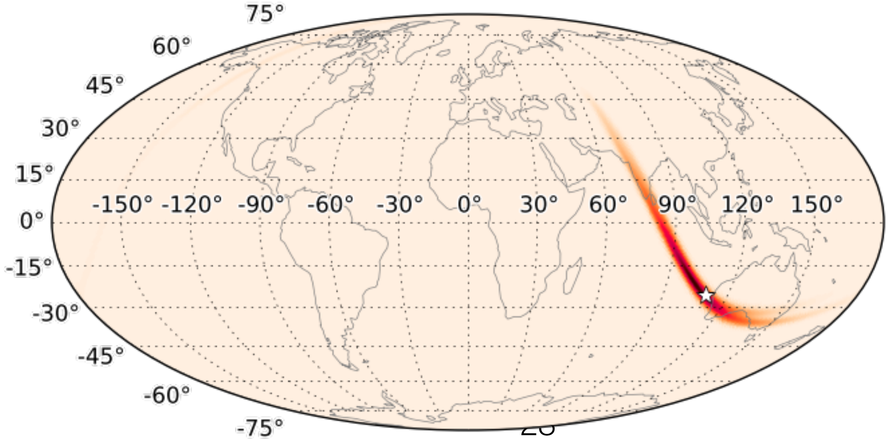


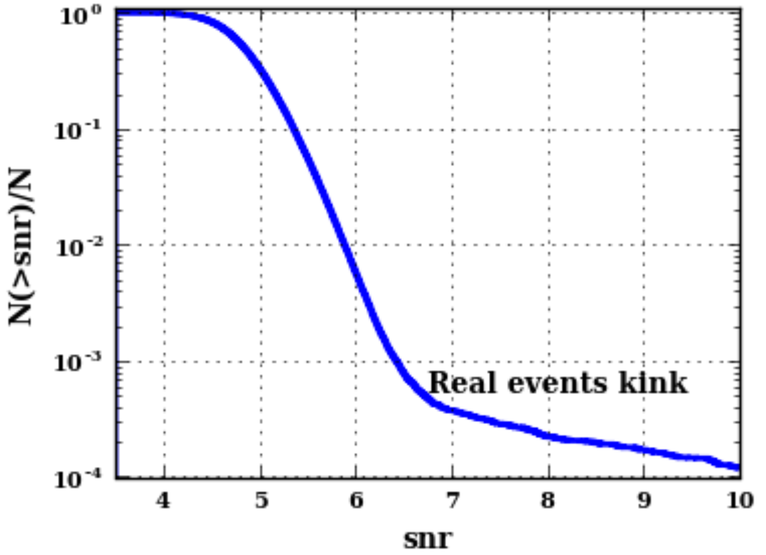
**BNS Mergers**



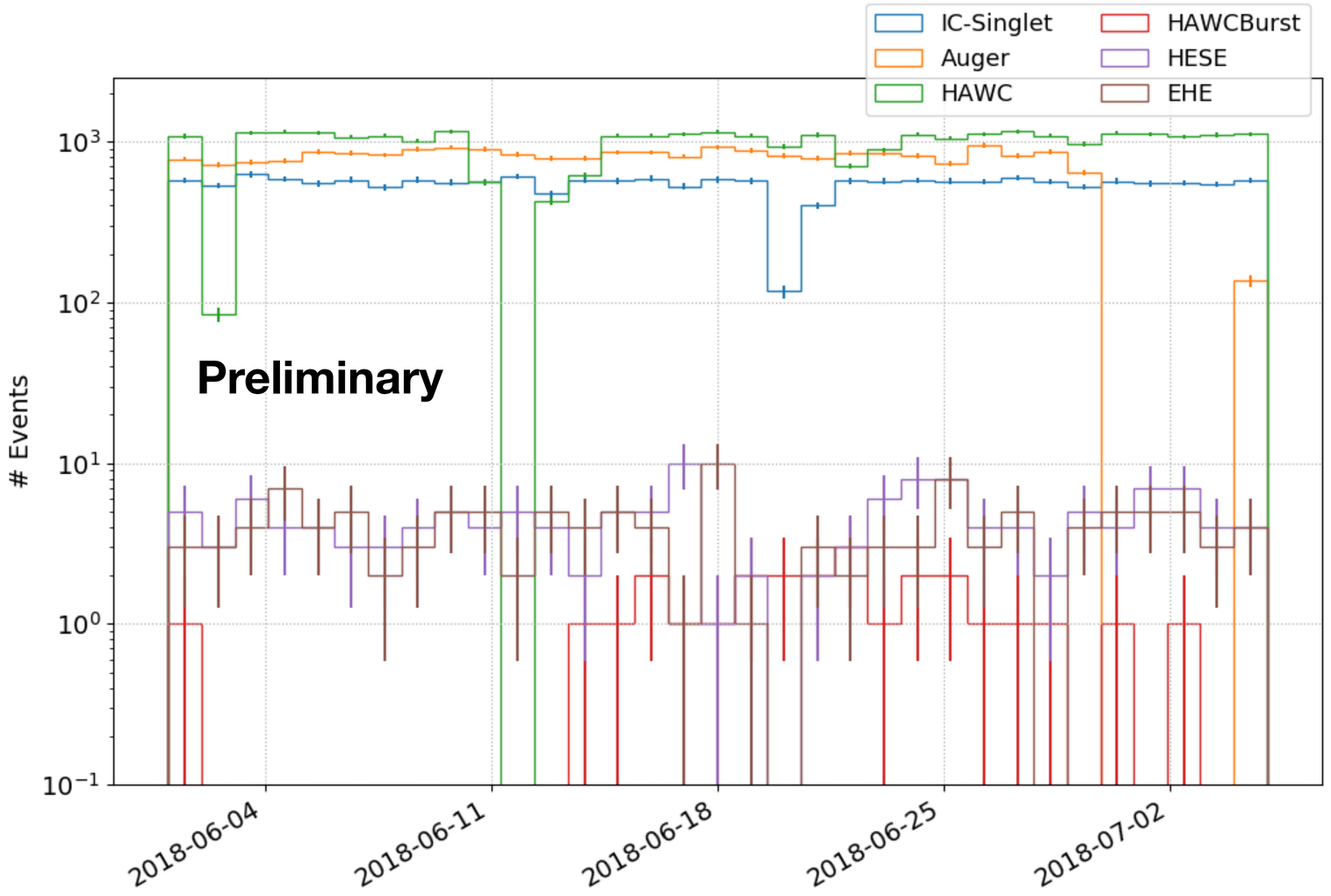


| | | |
|---|---|---|
| **Data** | **Low Latency CBC Detection Pipelines**<br>**• Like GSTLAL**<br>**• FAR, Mass Estimates or NS probability**<br>**BAYESTAR Skymaps**<br>**• 2D or 3D sky map localizations** | **Coded Mask Imager**<br>**• Sub-threshold Image Peaks**<br>**• Few arcmin localization**<br>**•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



# Current Status: AMON is receiving events in real time. Public events can be found in GCN/TAN webpage




- Events in real-time.
- Receiving ~3000 events per day

# AMON server is up and running

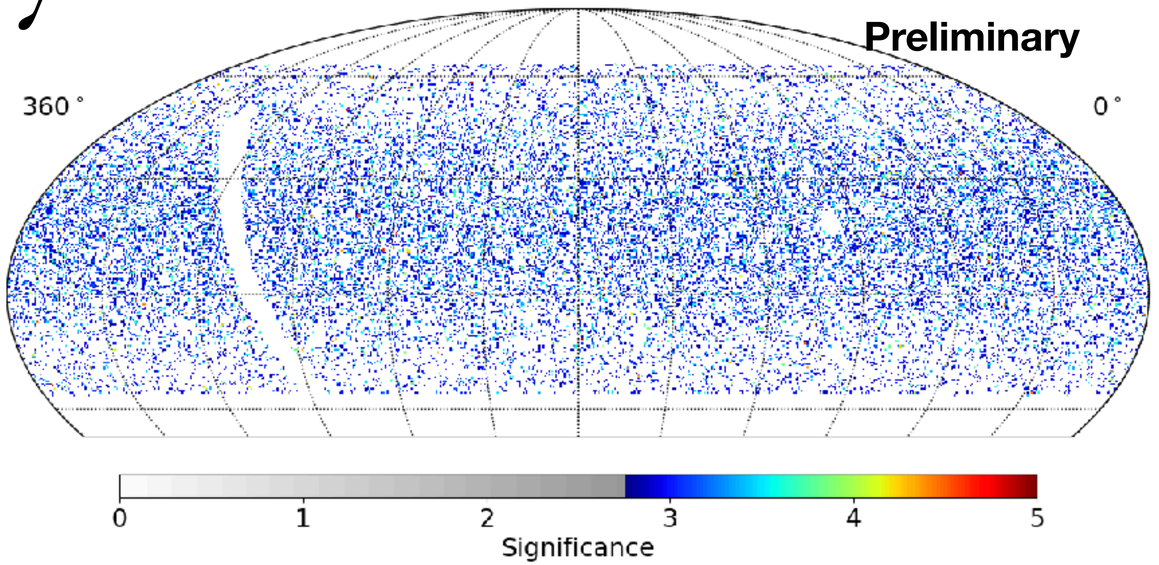
- AMON using **sub-threshold** data for multimessenger searches in **real-time**.
- AMON greatly **simplifies multimessengers searches**:
  - Common data format, transfer protocol, event database, MoUs.
- New participants are always welcome!
- Webpage: http://www.amon.psu.edu/
- MoU: http://www.amon.psu.edu/join-amon/

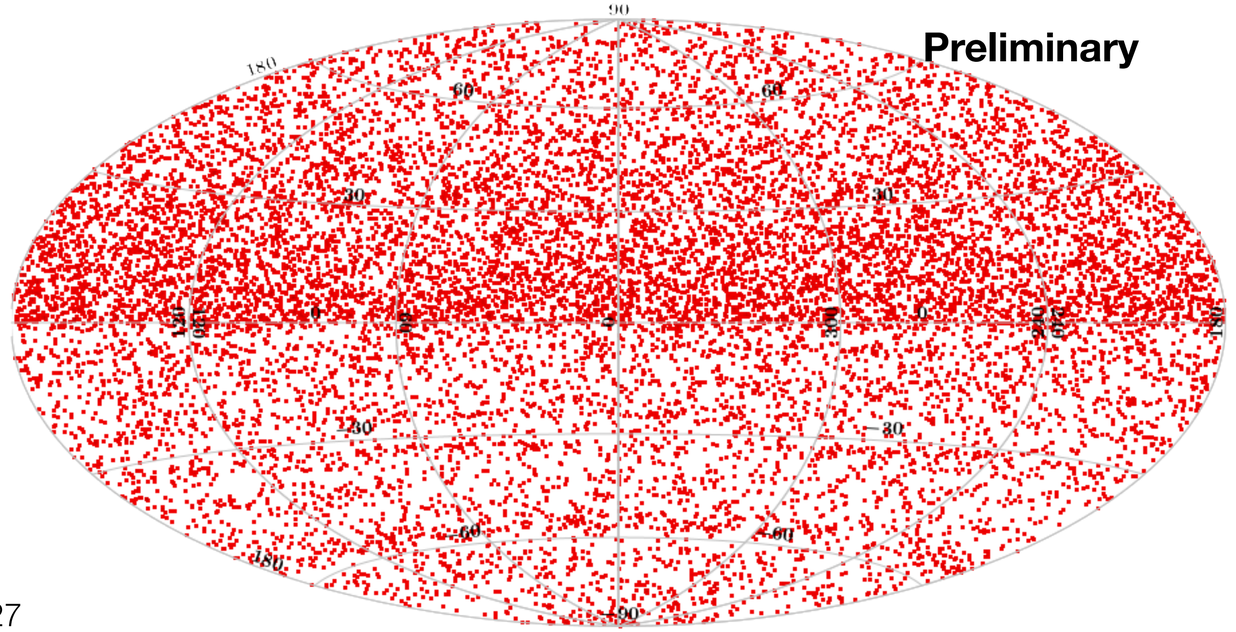
AMON
Astrophysical Multimessenger Observatory Network

# Extra Slides

# HAWC-IC Analysis: The Data

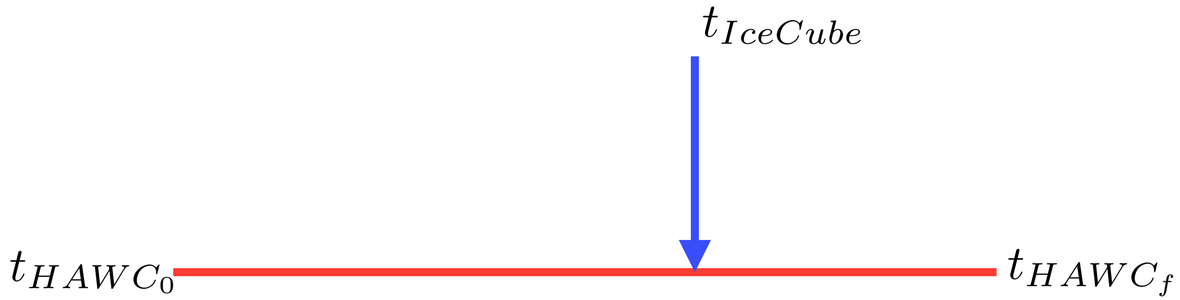
- HAWC **daily hotspots** (span several hours)
  - Parameters: position, error in position, significance (>2.75), start time of transit, end time of transit
- IC **track-like events**:
  - Parameters: position, time of event, false positive rate density (FPRD), signal acceptance, PSF
- **1 month of data**
- **Scramble** these data several times.



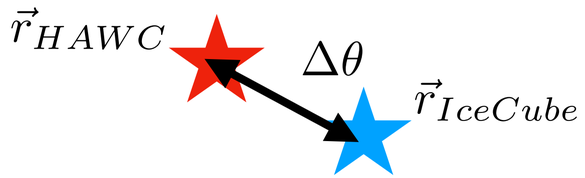



# HAWC-IC Coincidence Analysis

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




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



# Analysis Equations

- Maximize to find the best position of the coincidence

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

- Combine p_values: Fisher's method

$$\chi^2 = -2 \ln[p_\lambda \, p_{HWC} \, p_{cluster} \, p_{IC}]$$