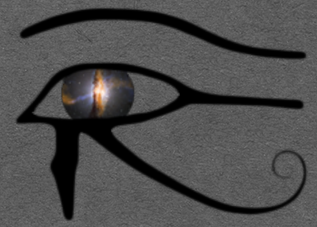
AMON
Astrophysical Multimessenger Observatory Network

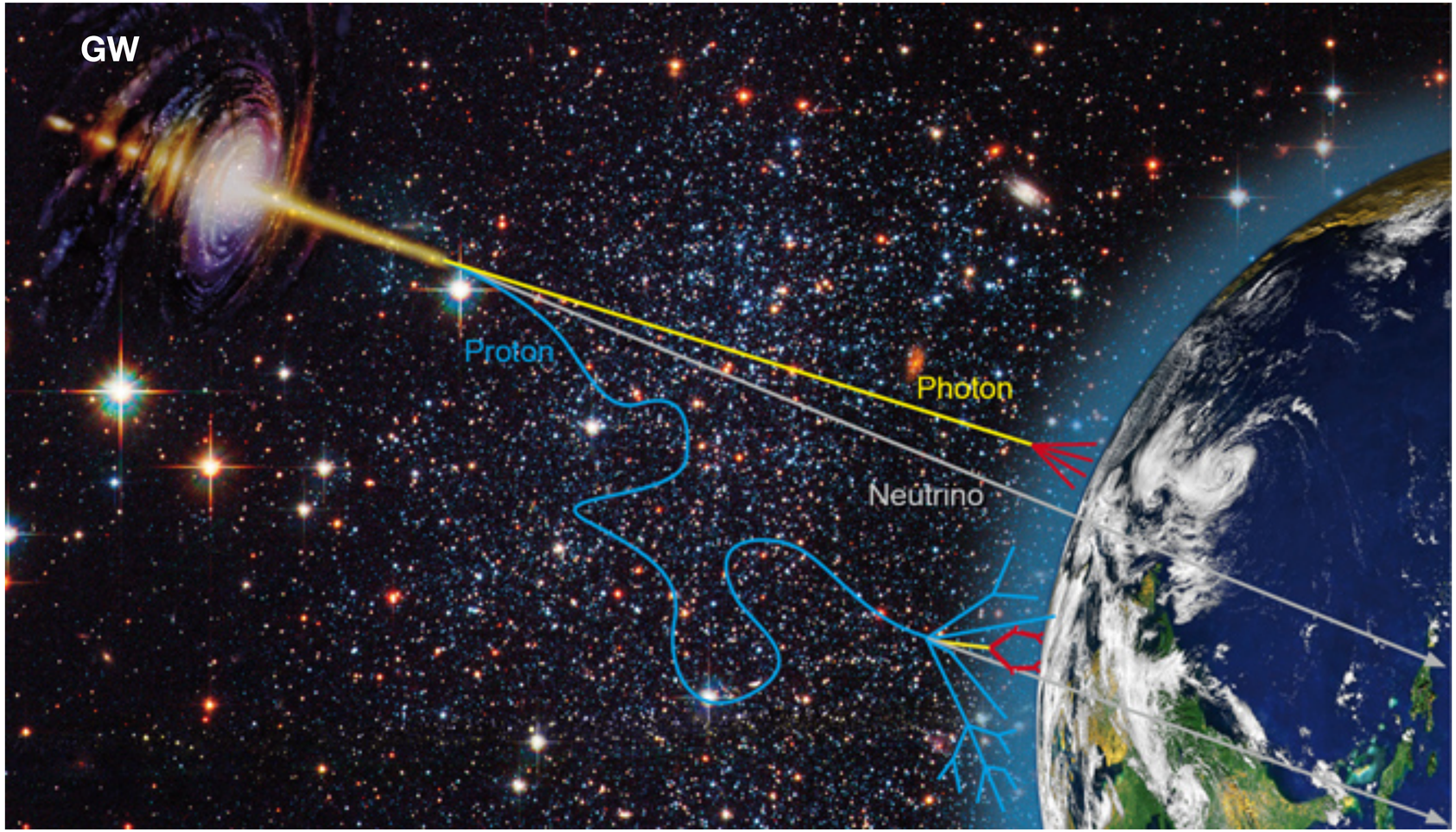


The Astrophysical Multimessenger Observatory Network

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 (3σ))
Strong	p, nuclei	👍	?
Gravity	Gravitational Waves	👍	Few and increasing

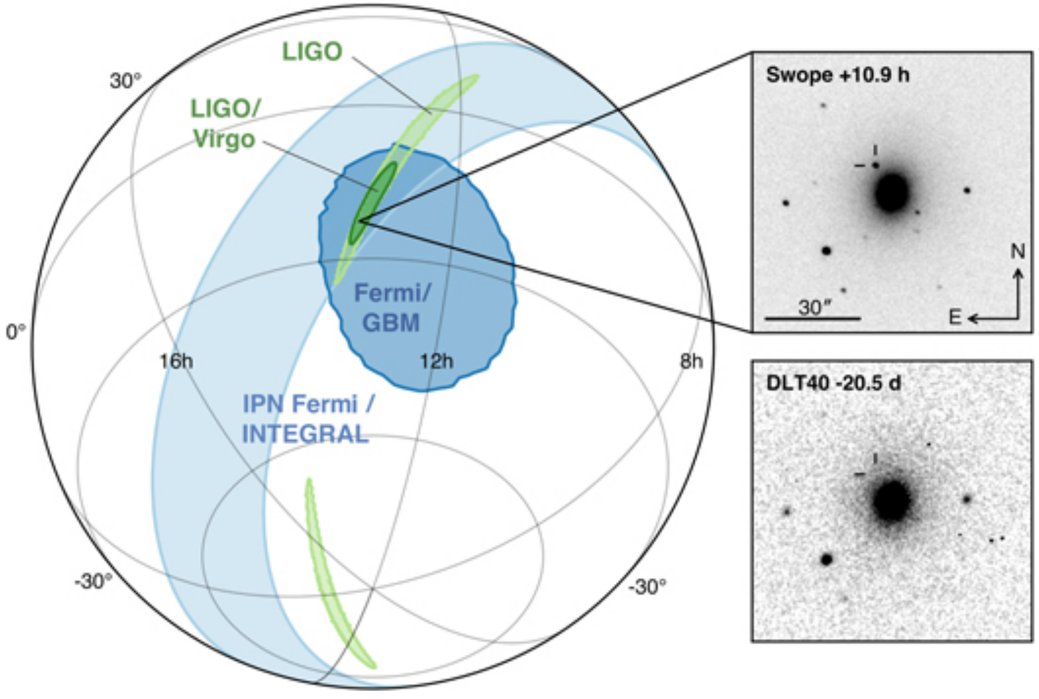
https://astro.desy.de/theory/multi_messenger_astrophysics/index_eng.html

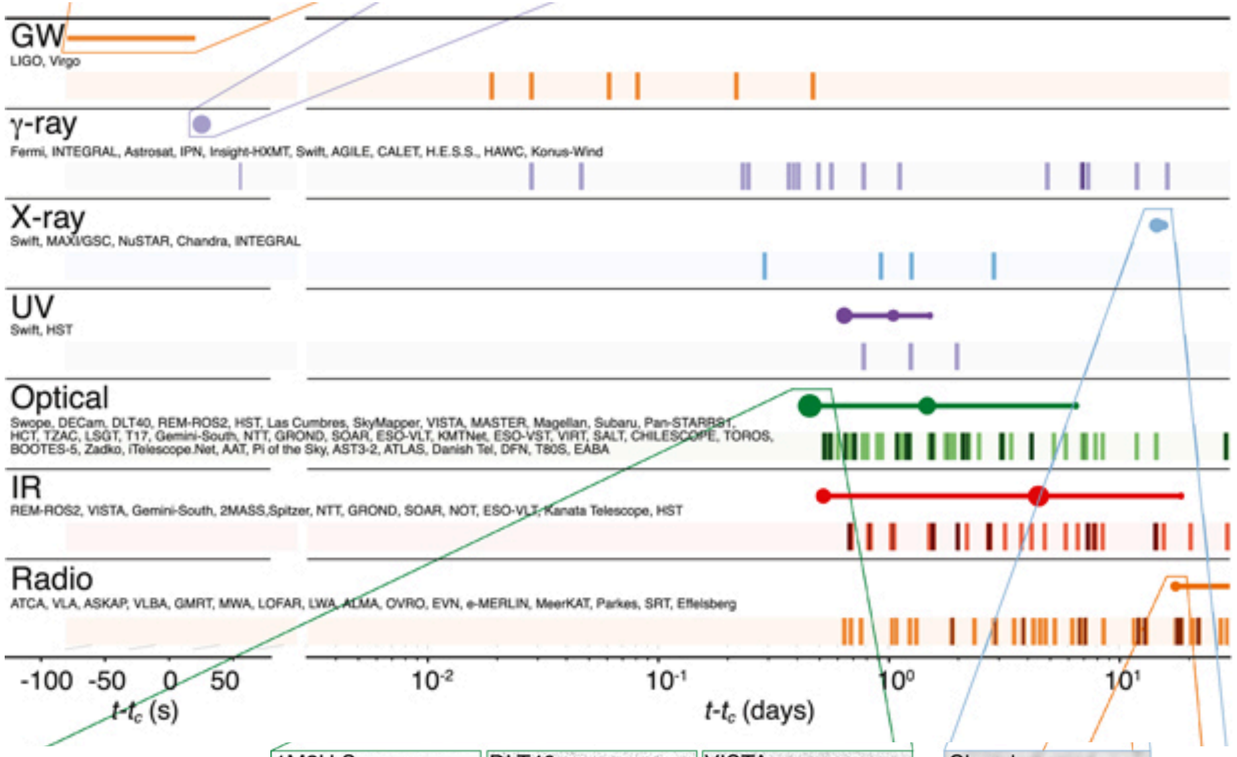
Each messenger has advantages and disadvantages.

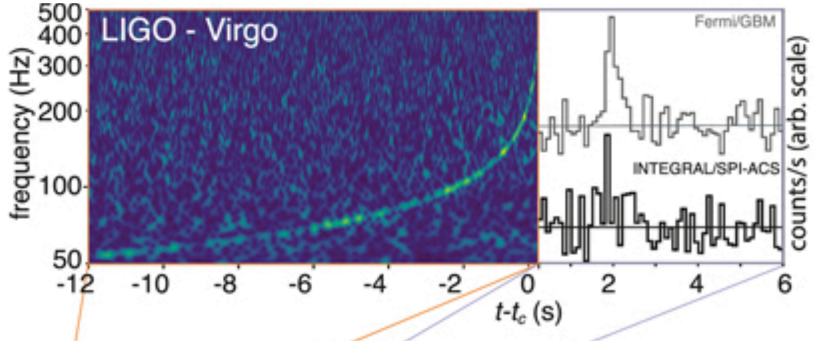
Messenger	Sample Size	Straight Trajectory	Pointing Res.	Cutoff
γ			$<<1^{o}$	$E_{\gamma} < 50$ **TeV** $\gamma\gamma_{IR} \rightarrow e^{-}e^{+}$
ν	$\sigma_{\nu,matter} < 1$		$\sim 1^{o}$	
p, nuclei		$\overrightarrow{B}$	-	GZK cutoff E_p<30EeV
GW			2obs: ~1000 sq.deg.	

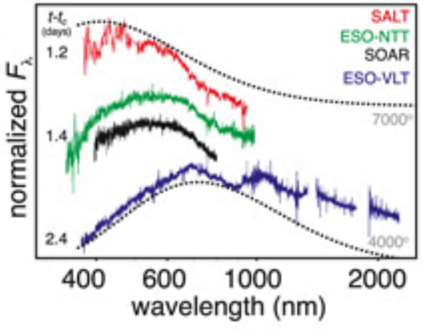
https://astro.desy.de/theory/multi_messenger_astrophysics/index_eng.html

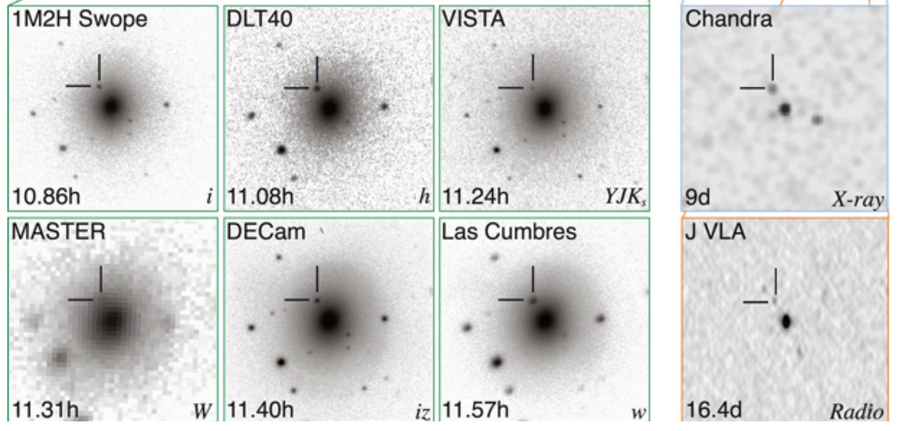
Example 1: Electromagnetic radiation from a binary neutron star merger confirmed for GW170817.





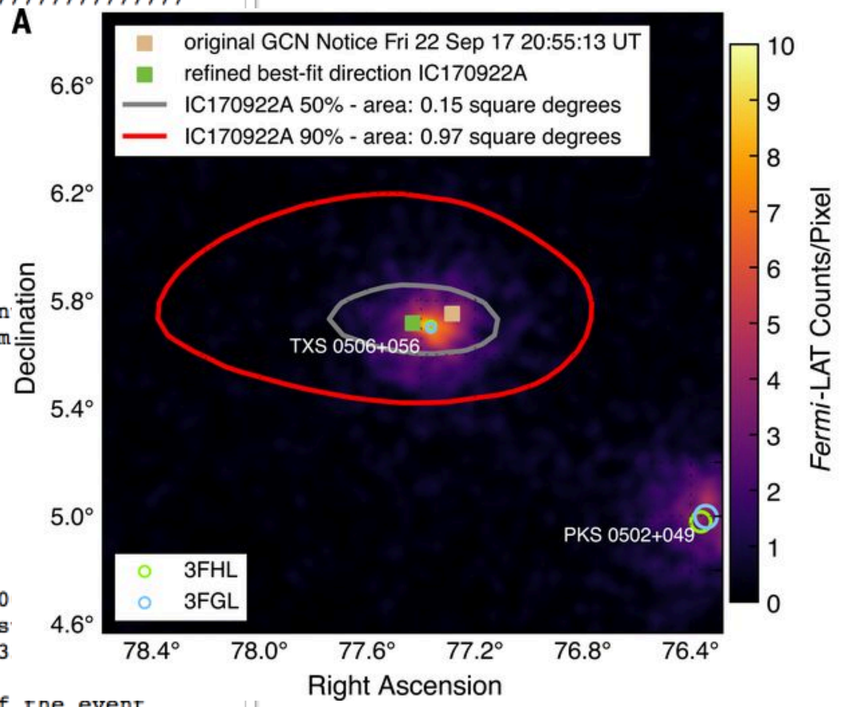


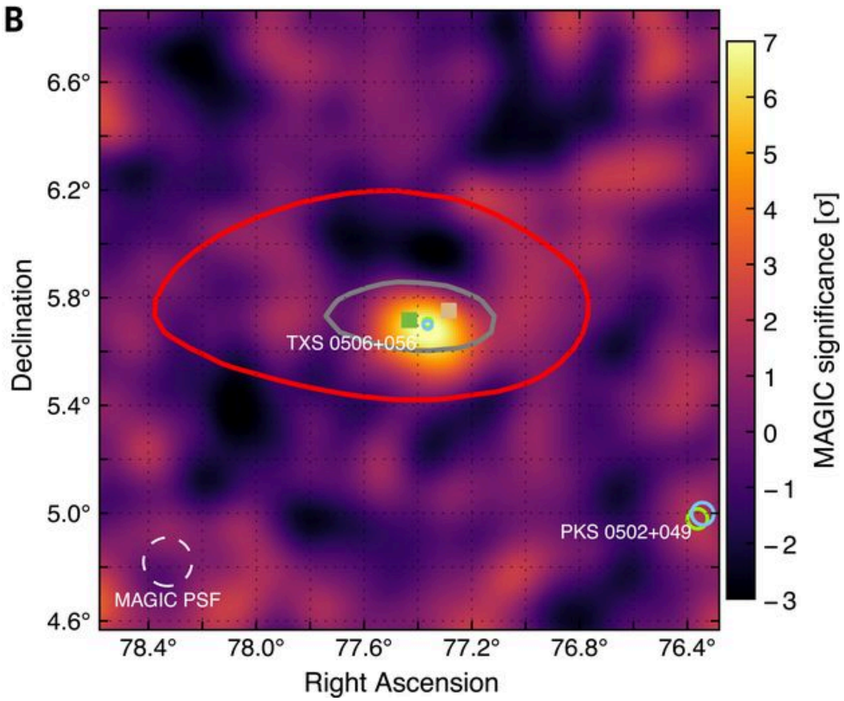




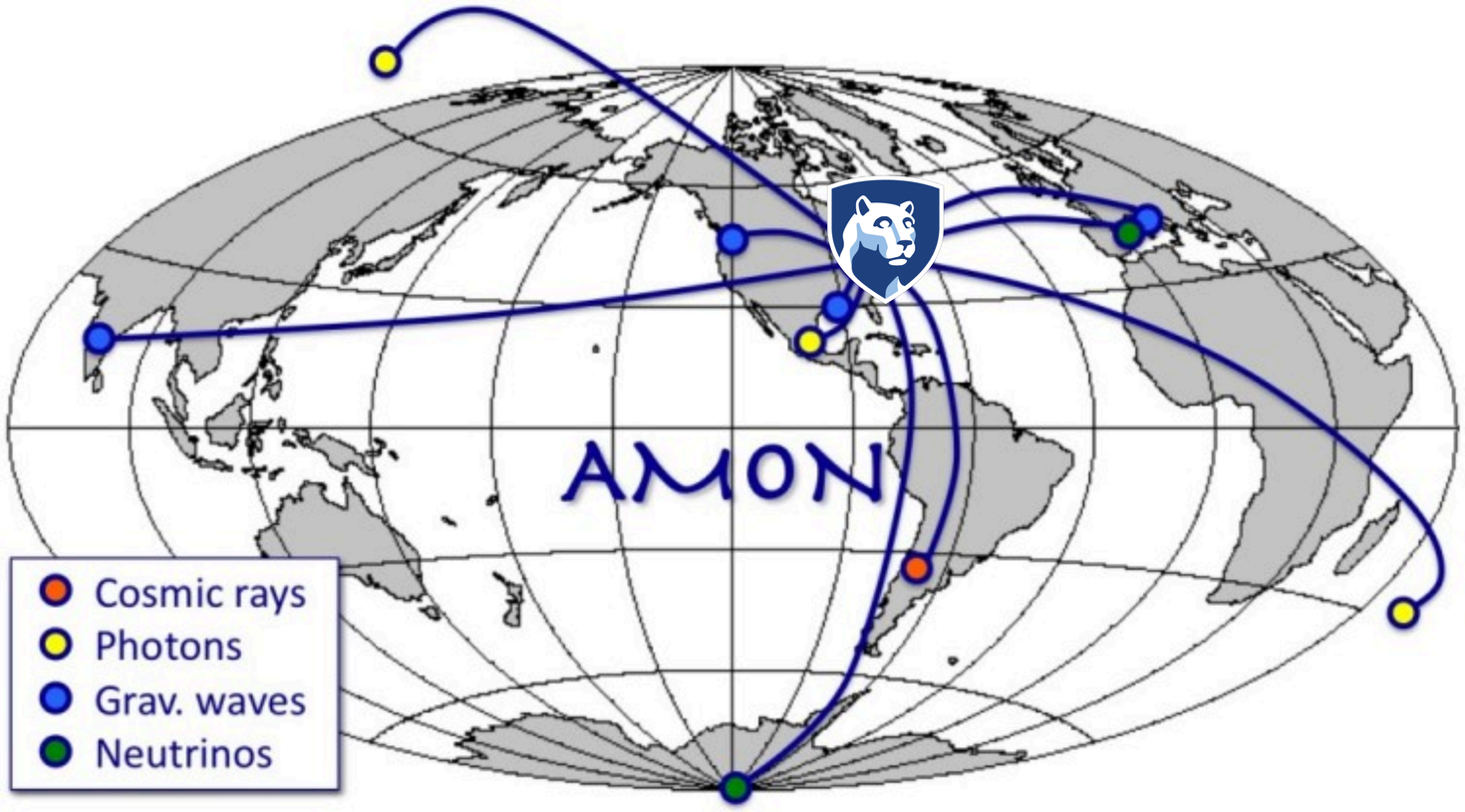
Example 2: Coincidence between high-energy neutrinos and gamma-rays from Blazar TXS 0506+056. First evidence of source of neutrinos (3.5σ). AMON contributed to the distribution of the event IC170922A.

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





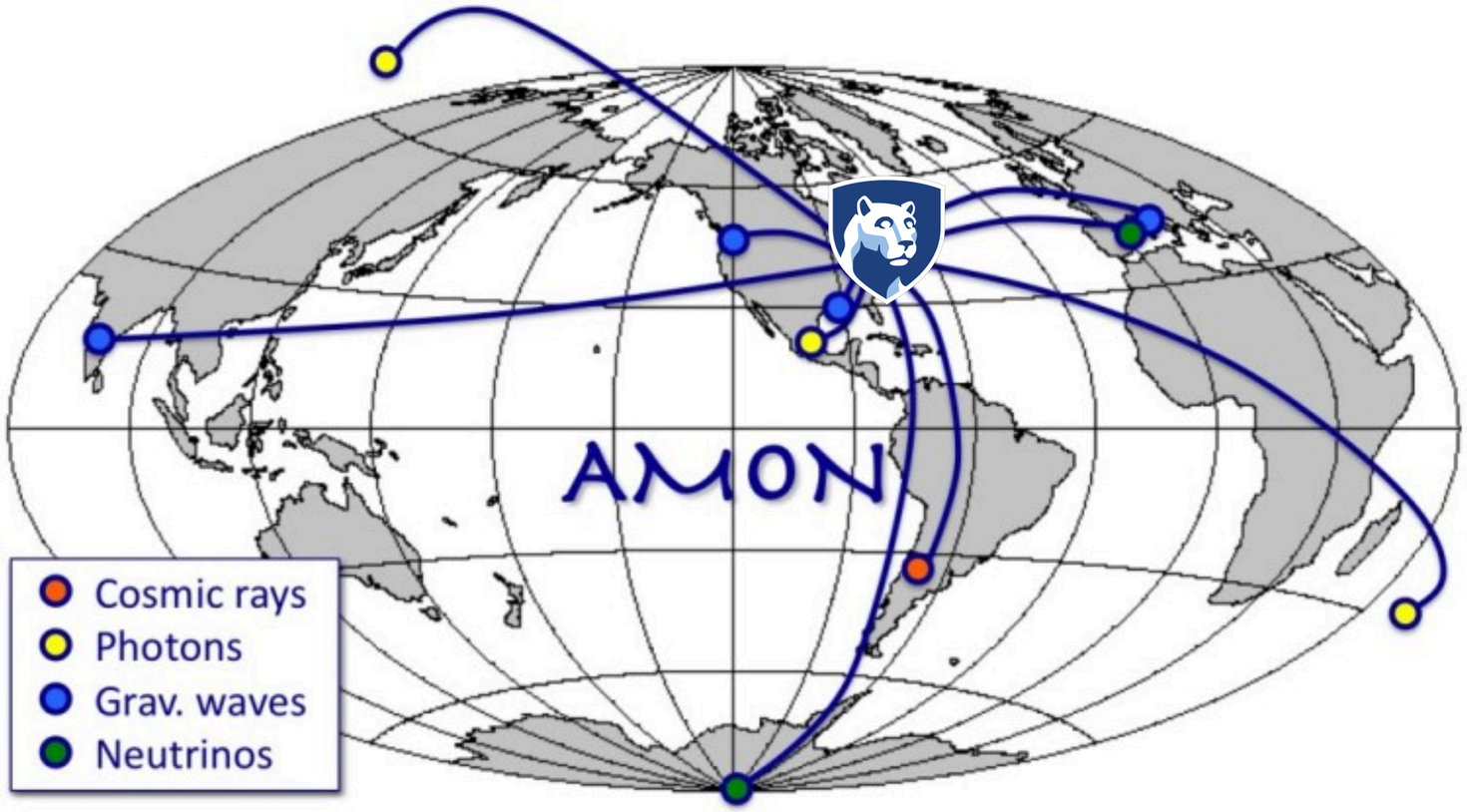
(Near) Real-time searches for transients can continue to advance multimessenger astrophysics. The Astrophysical Multimessenger Observatory Network (AMON) has been built with this idea.



- **Real-time coincidences**
  - Receive the event after it is built in each observatory and do the coincidence analysis right away in the AMON servers.
- **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

https://arxiv.org/abs/1903.08714

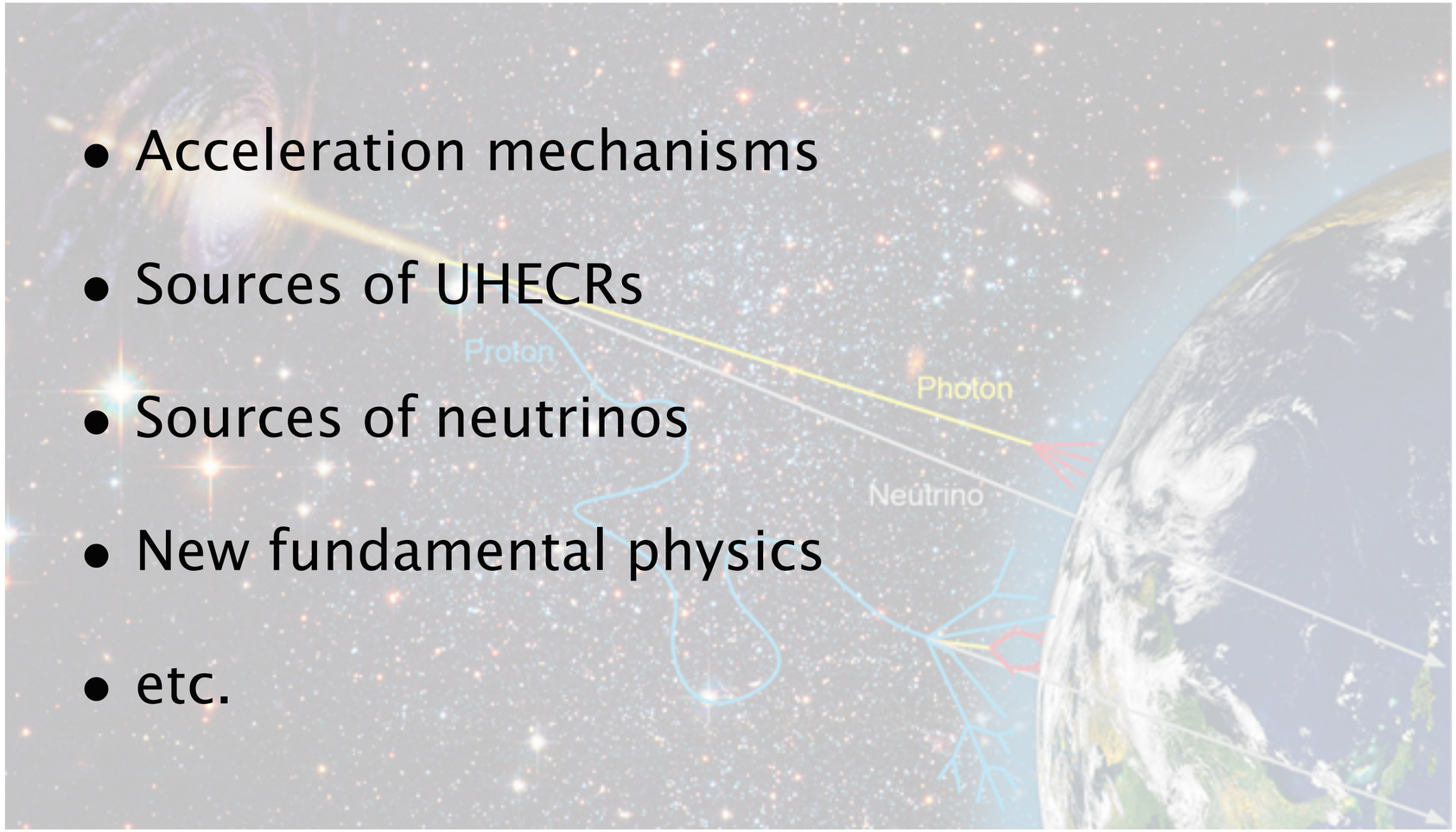
AMON Framework



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

https://arxiv.org/abs/1903.08714

Focusing on high-energy astrophysics. We want to help 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:

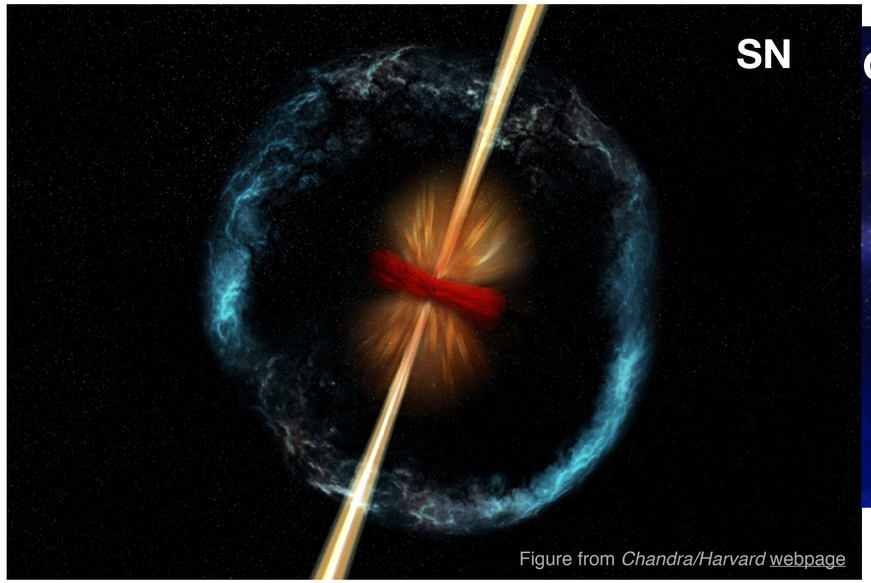
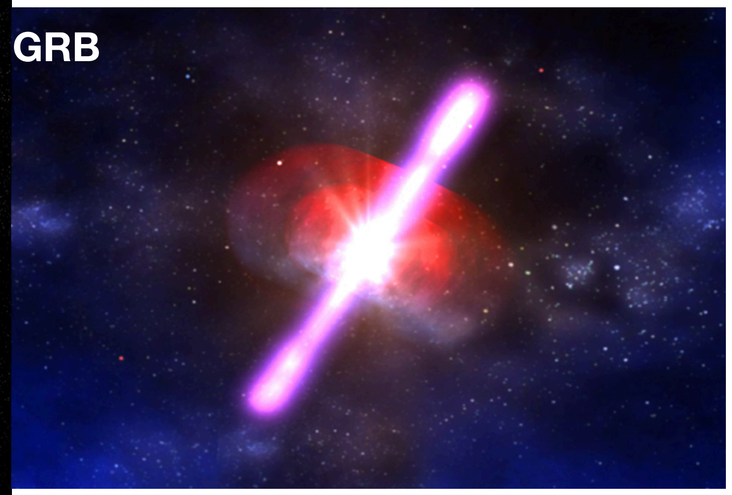
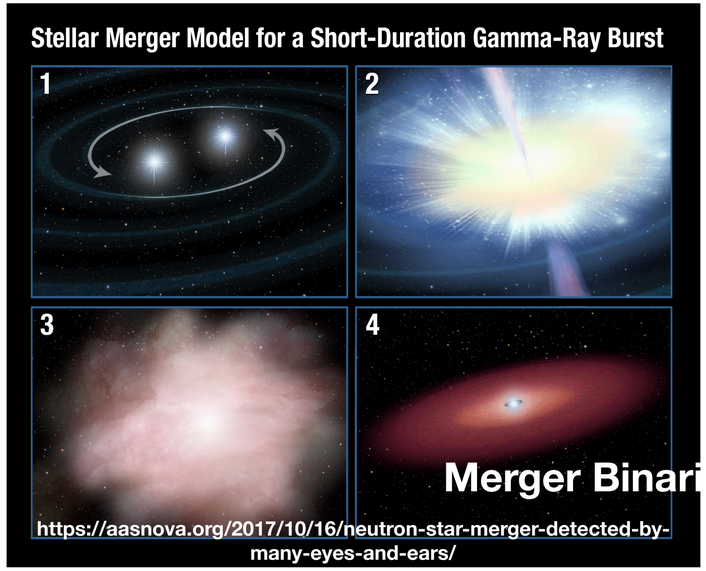


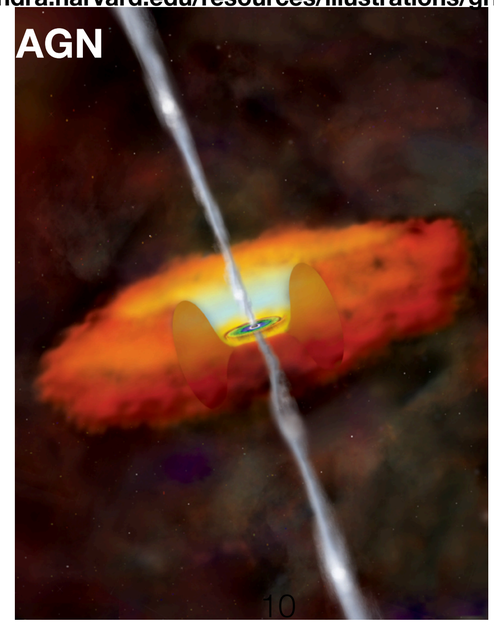
Figure from *Chandra/Harvard* webpage



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/

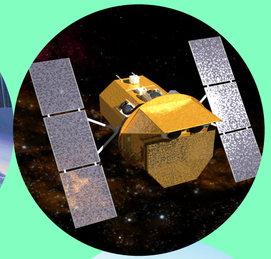
- Long GRBs
- Short GRBs
- SN
- Choked jet supernova
- Blazars
- PBHs
- Binary Mergers
- …

AMON members and prospective* members.

CR

Pierre Auger

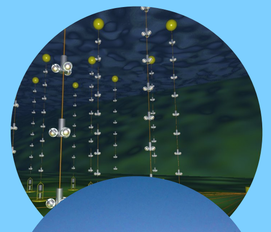
γ



SWIFT
VERITAS
HESS
MAGIC

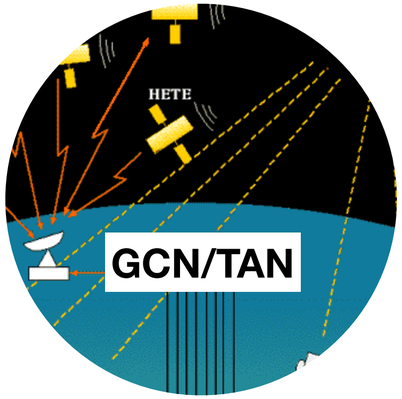
FACT
Fermi
HAWC

ν

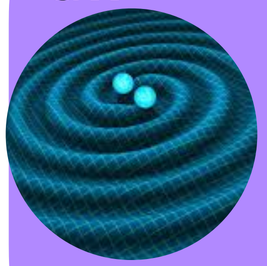


IceCube
ANTARES

AMON
Astrophysical Multimessenger Observatory Network



GW

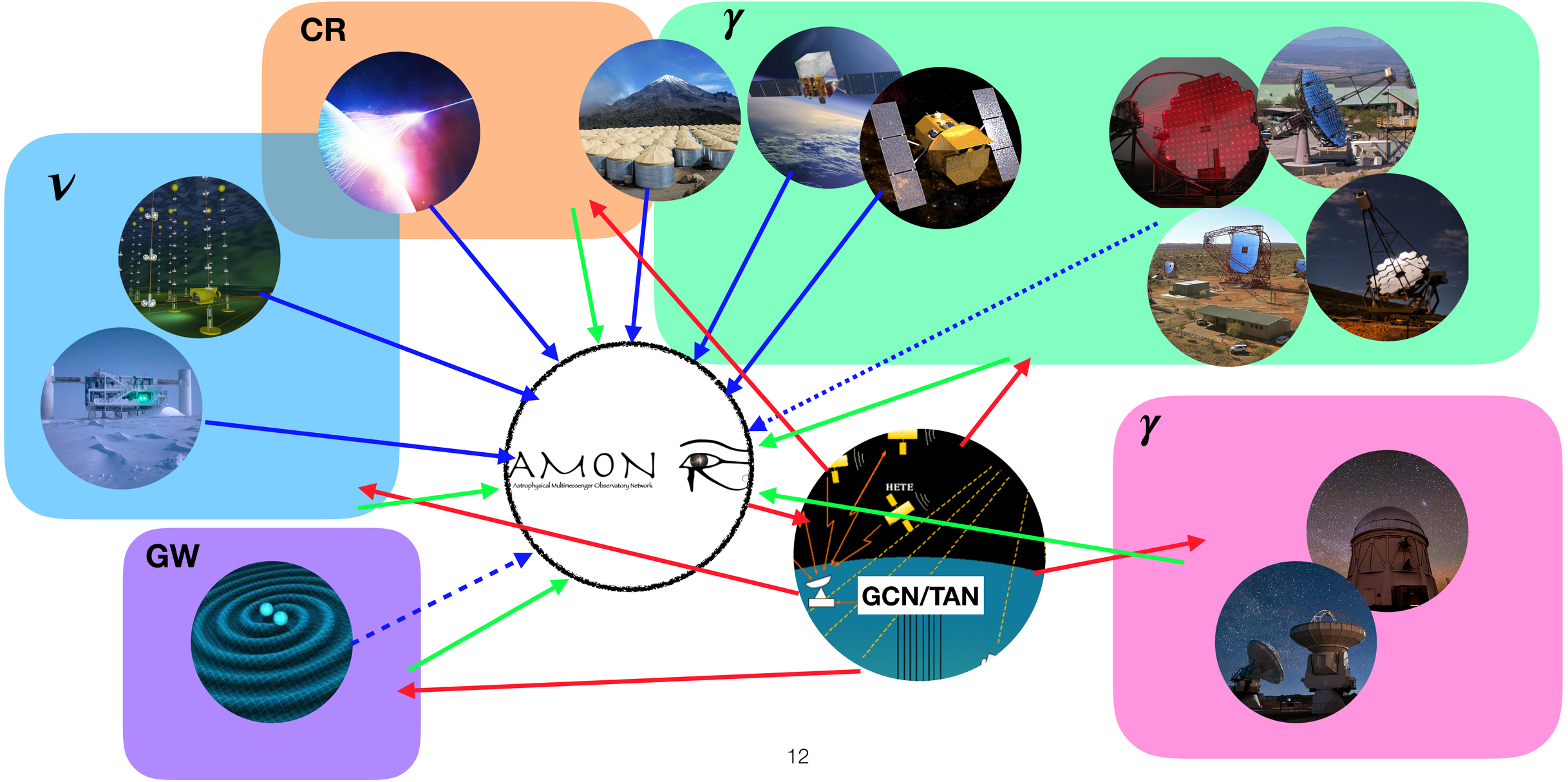


*LIGO-Virgo

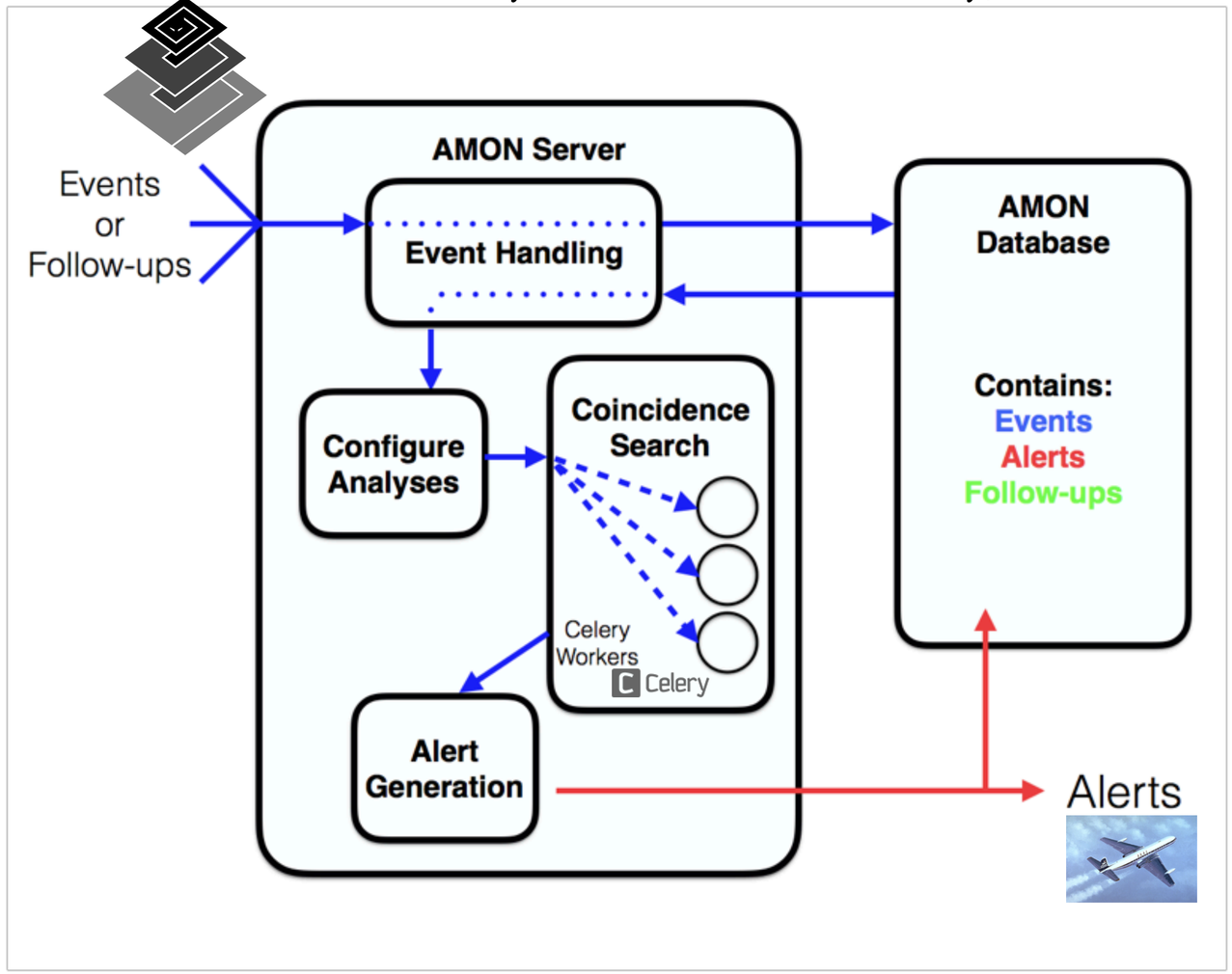
γ

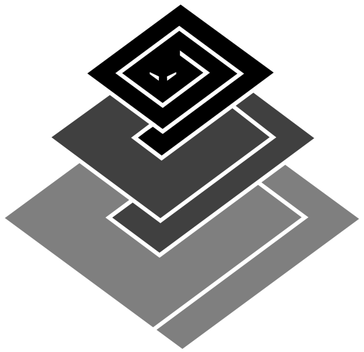
LMT
Palomar Transient Factory
MASTER

AMON receives sub-threshold data events and sends alerts to GCN/TAN which then are distributed to partner observatories/public. Interesting follow-ups are sent back to AMON and AMON then broadcasts alert revisions



Technical Implementation: 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.



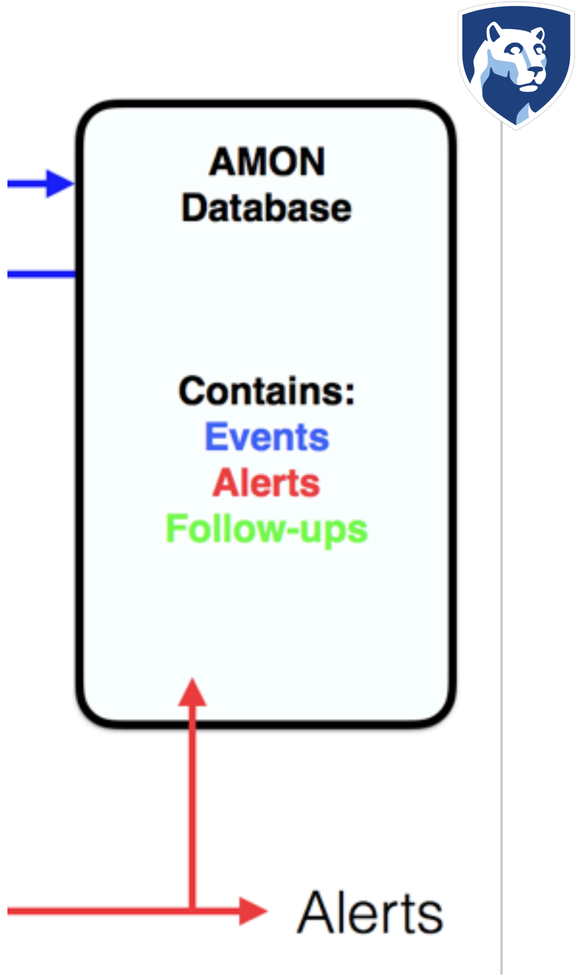


TWISTED

COMET

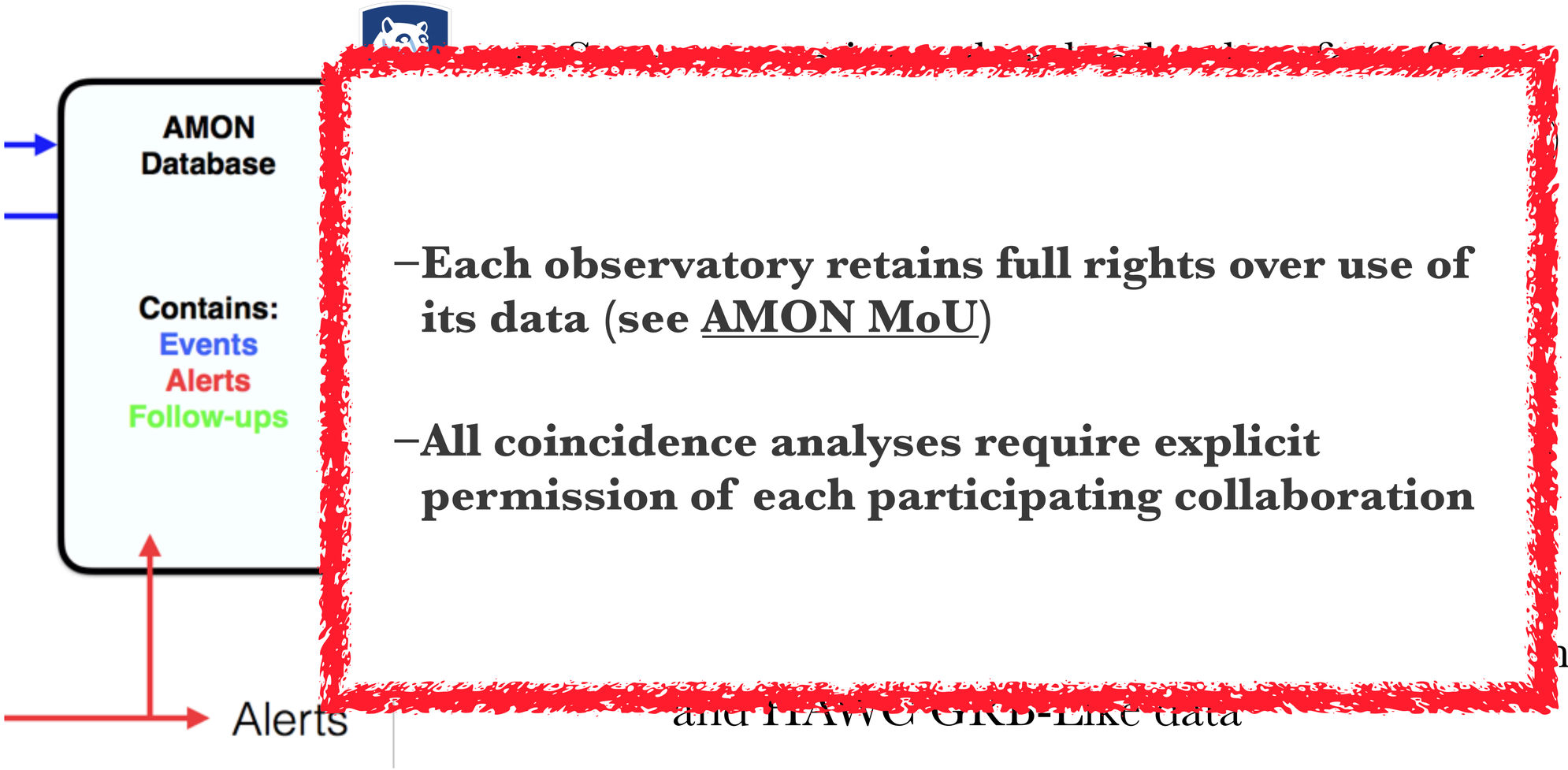
AmonPy software in GitHub:https://github.com/AMONCode/Analysis

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



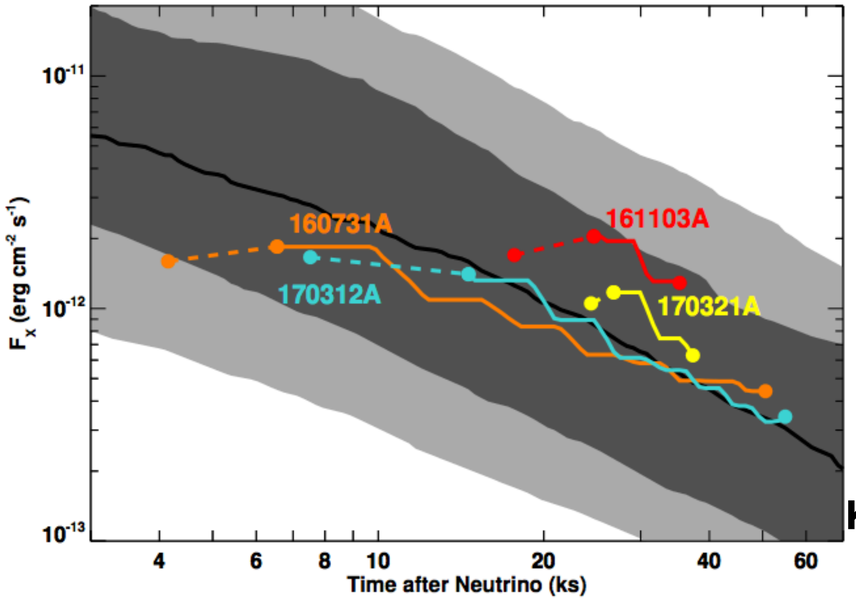
- Servers are mirrored and redundant for safety.
- Uptime of 99.99% (<1 hr of downtime per year)
- The database is designed with MySQL
- It currently contains:
  - Public:
    - IC 40/59 and 1 year of IC 86, SWIFT and Fermi data
  - Private:
    - ANTARES, Auger data, HAWC Daily Monitoring and HAWC GRB-Like data

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

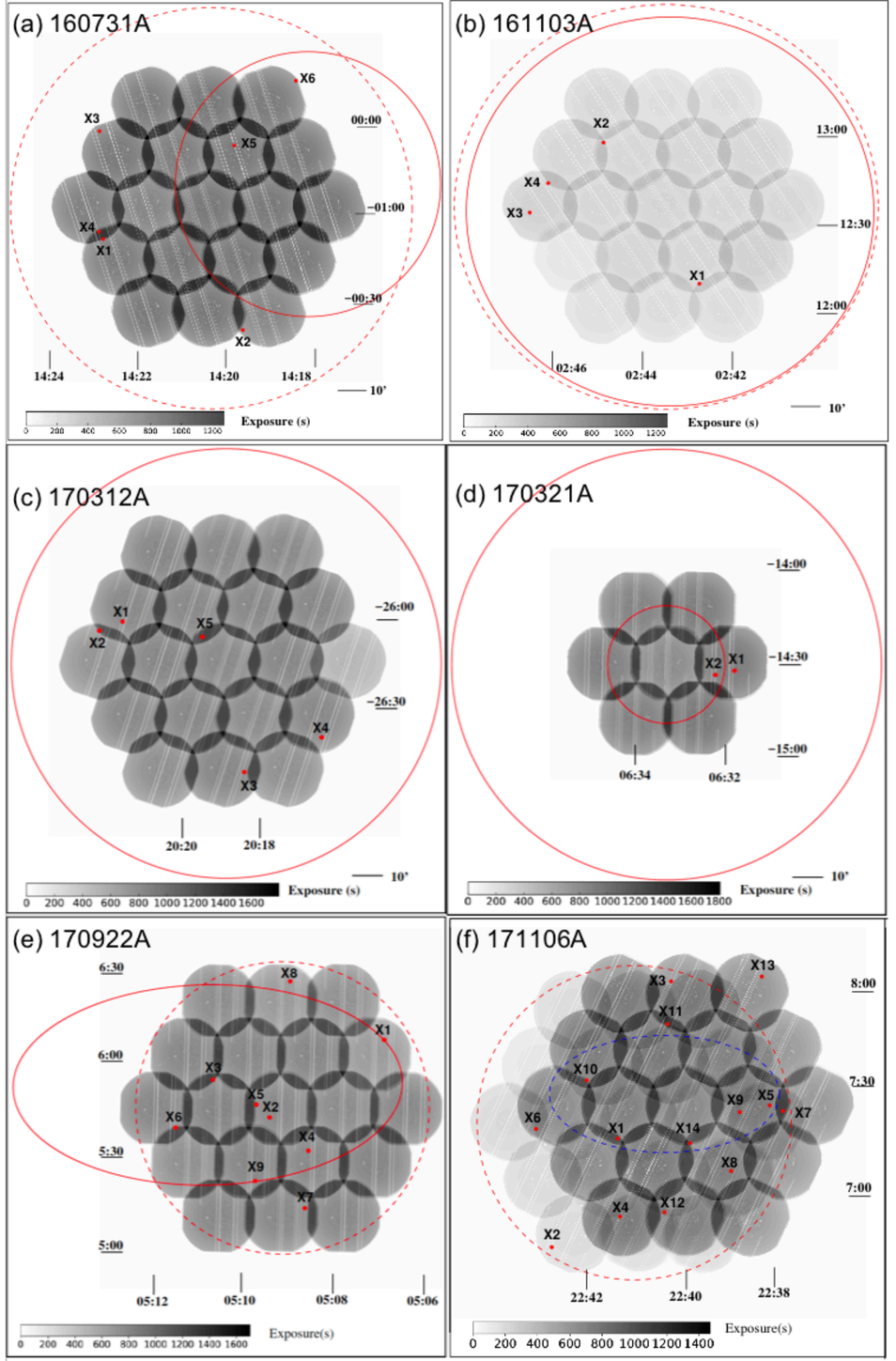


Results 1A: The Swift Campaigns: follow-up observations

- Observation tiles centered on first IceCube alert (dashed line)
- 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



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, Insight-HXMT

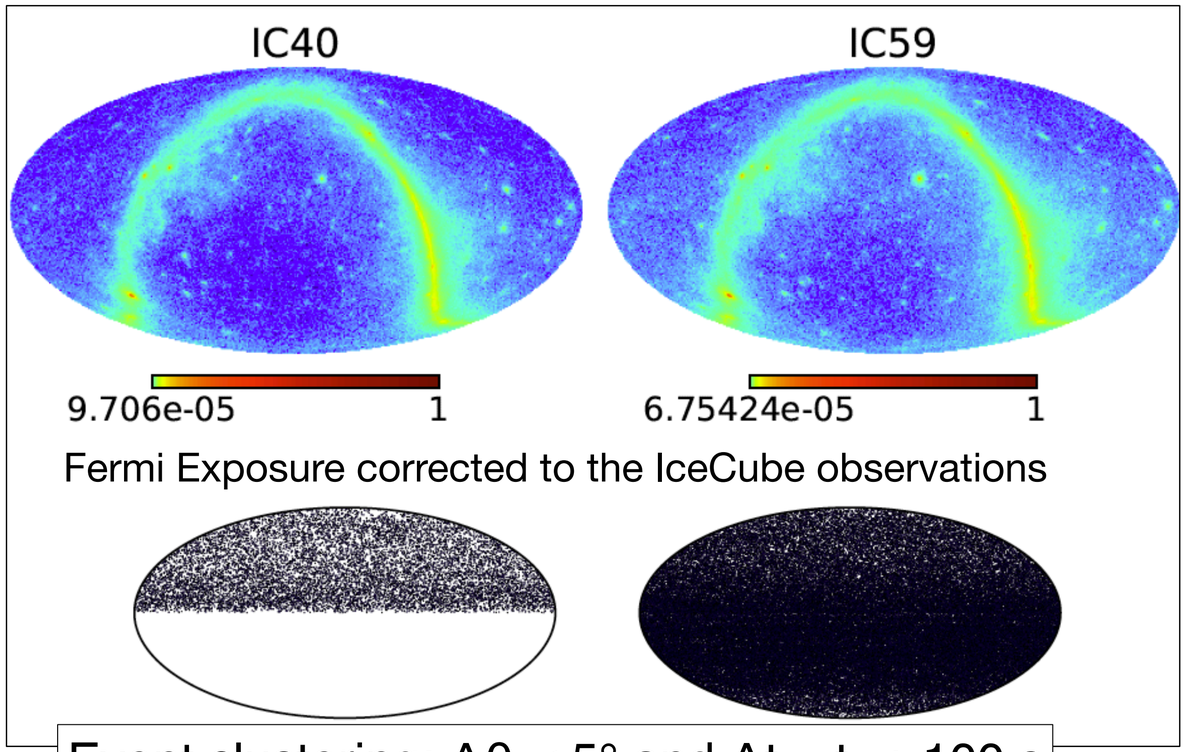
Event/ Follow-up	ν	γ optical	γ high-energy
IC 190504A			
IC 190503A			
IC 190331A			
IC 190221A			
IC 190124A			
IC 190104A			
IC 181023A			
IC 181014A			
IC 180908A			

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

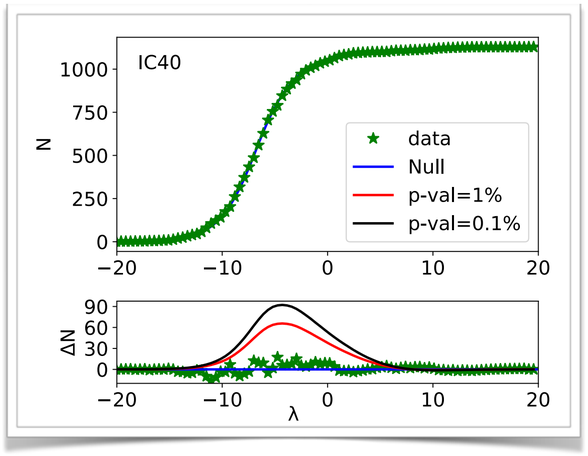
Event/ Follow-up	ν	γ optical	γ high-energy
IC 171106A			
IC 171025			
IC 170922A			
IC 170321A			
IC 170312A			
IC 161210			
IC 161103			
IC 160814A			
IC 160806A			
IC 160731A			

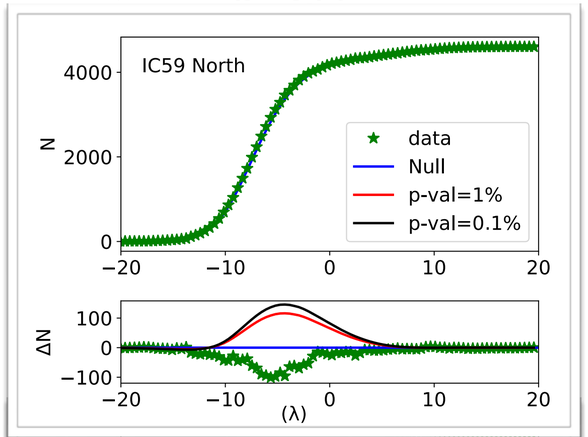
Results 2: IceCube-*Fermi*LAT archival analysis. No significant deviations from the null hypothesis were found in the unscrambled dataset.

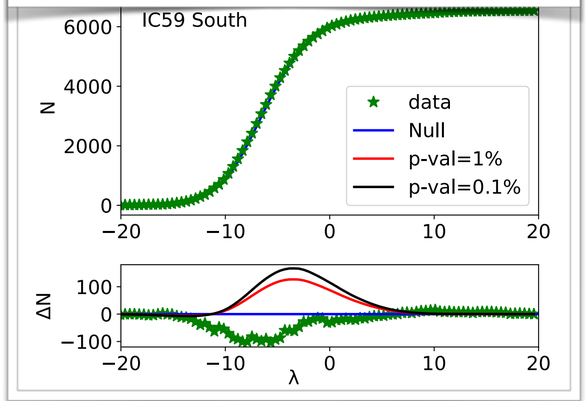


Event clustering: $\Delta\theta < 5°$ and $\Delta t = t_0 \pm 100$ s

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



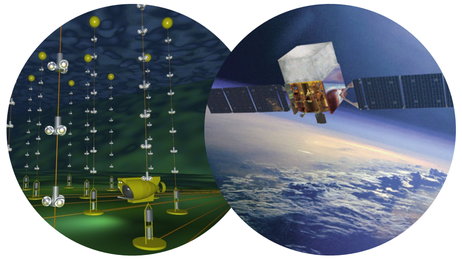




- See ApJ paper

Results 3: started sending realtime alerts of coincidences between ANTARES and Fermi-LAT

$\gamma+\nu$



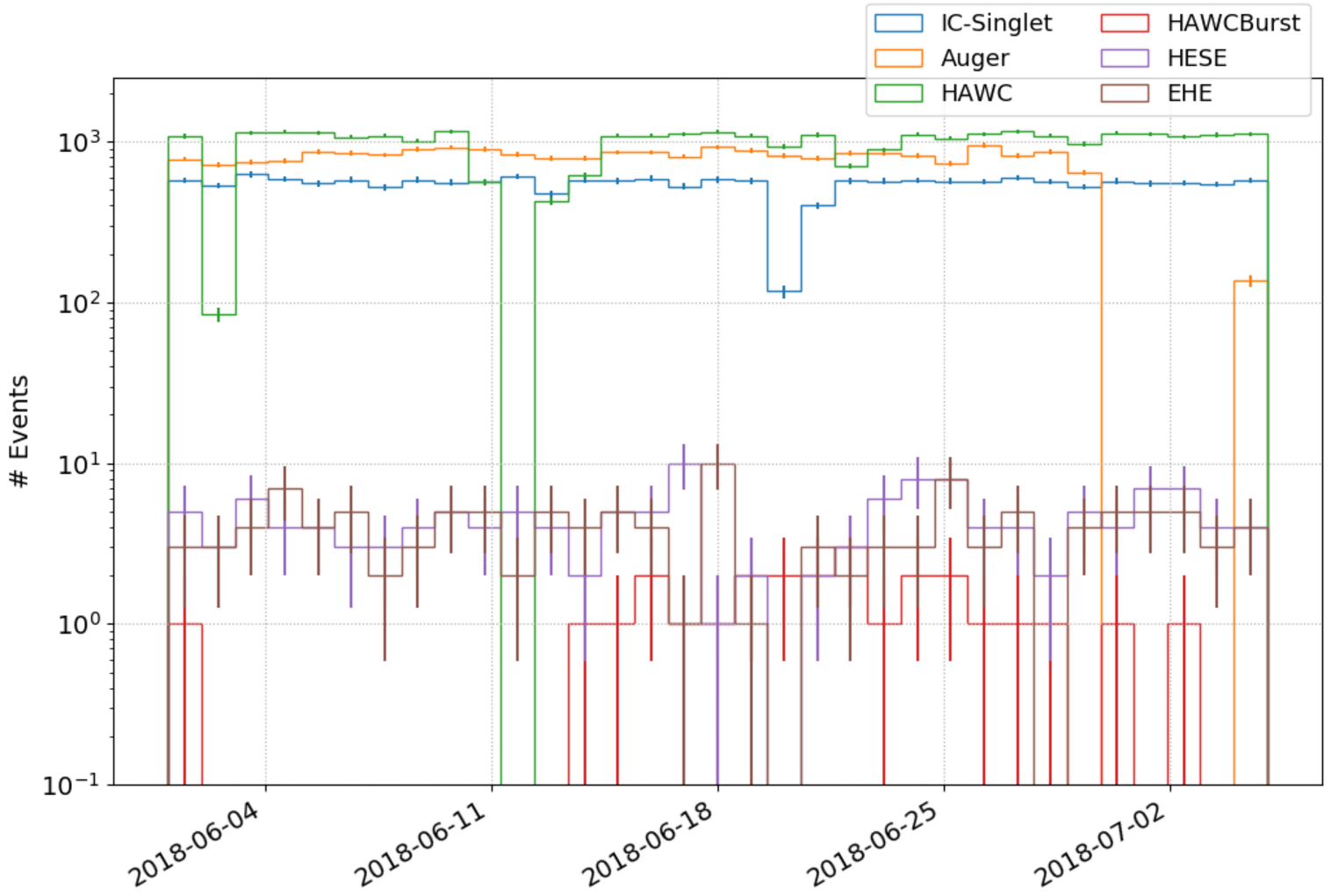
ANTARES +Fermi LAT

- Coincidence defined as follows:
  - Spatial: events are less than 5° from each other
  - Temporal: ±1000s from time of neutrino
- Use of a pseudo-likelihood method for ranking statistic

Coincidence	Day	False Alarm Rate (per year)
1	2019/04/28	2.055
2	2019/05/12	0.063

See https://arxiv.org/abs/1904.06420 for method description

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

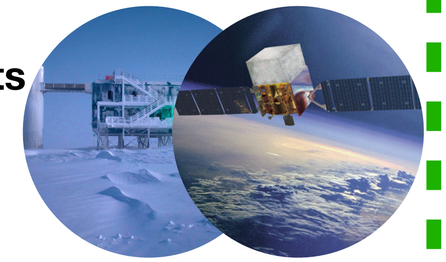


- Events in real-time.
- Receiving ~3000 events per day

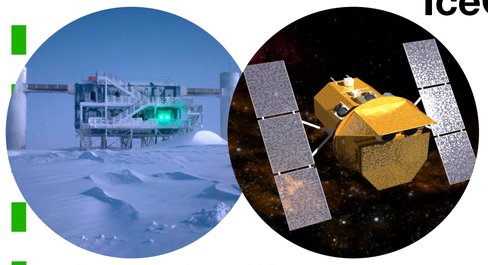
Current Plans: commission new GCN streams. Working towards new IceCube streams, HAWC Burst and ANTARES-FermiLAT

γ+ν

IceCube Singlets +
HAWC Daily hotspots



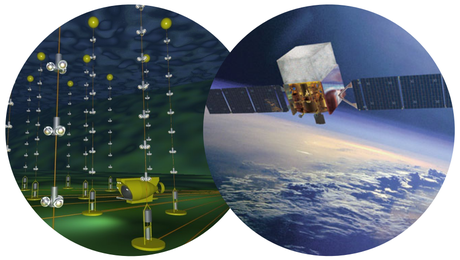
IceCube +Fermi LAT



IceCube Singlets +
SWIFT-BAT

Work On-going

γ+ν



ANTARES +Fermi LAT

γ

HAWC
Burst Monitoring

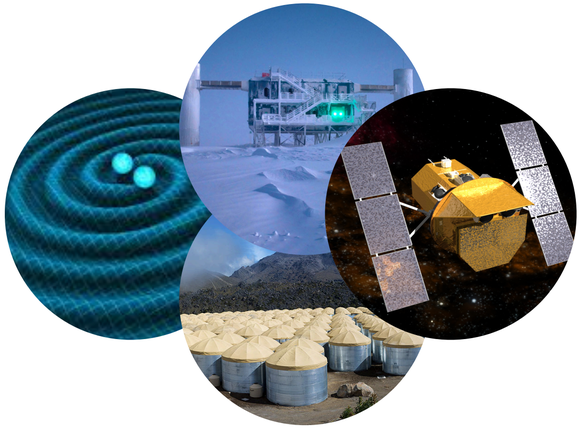
ν

New IceCube
Streams

Close to be in GCN

Using **sub-threshold** data

GW + X



LIGO-Virgo + IC
LIGO-Virgo + HAWC
LIGO-Virgo + SWIFT

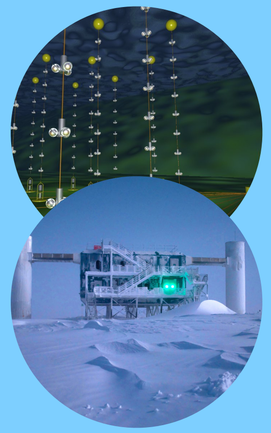
Proposals

AMON members and prospective* members.

CR

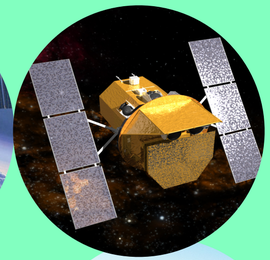
Pierre Auger

ν



IceCube
ANTARES

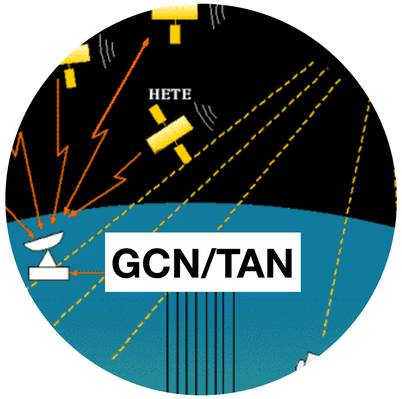
γ



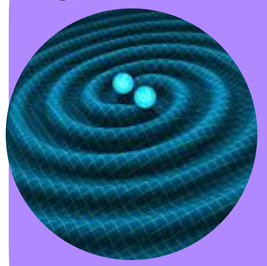
SWIFT
VERITAS
HESS
MAGIC

FACT
Fermi
HAWC

AMON
Astrophysical Multimessenger Observatory Network



GW



*LIGO-
Virgo

γ

LMT
Palomar Transient Factory
MASTER

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

Back-up Slides

Data description:

HAWC events are “hotspots” of significant excesses above background averaged over 1 transit of the event above the detector.

IceCube events are single through-going track events.

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**

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: possible mechanism is hybrid leptonic scenario γ-rays produced by IC and high energy neutrinos by subdominant hadronic component. (https://arxiv.org/pdf/1807.04537.pdf)