AMON coincidence analysis of sub-threshold events from HAWC and LIGO-Virgo

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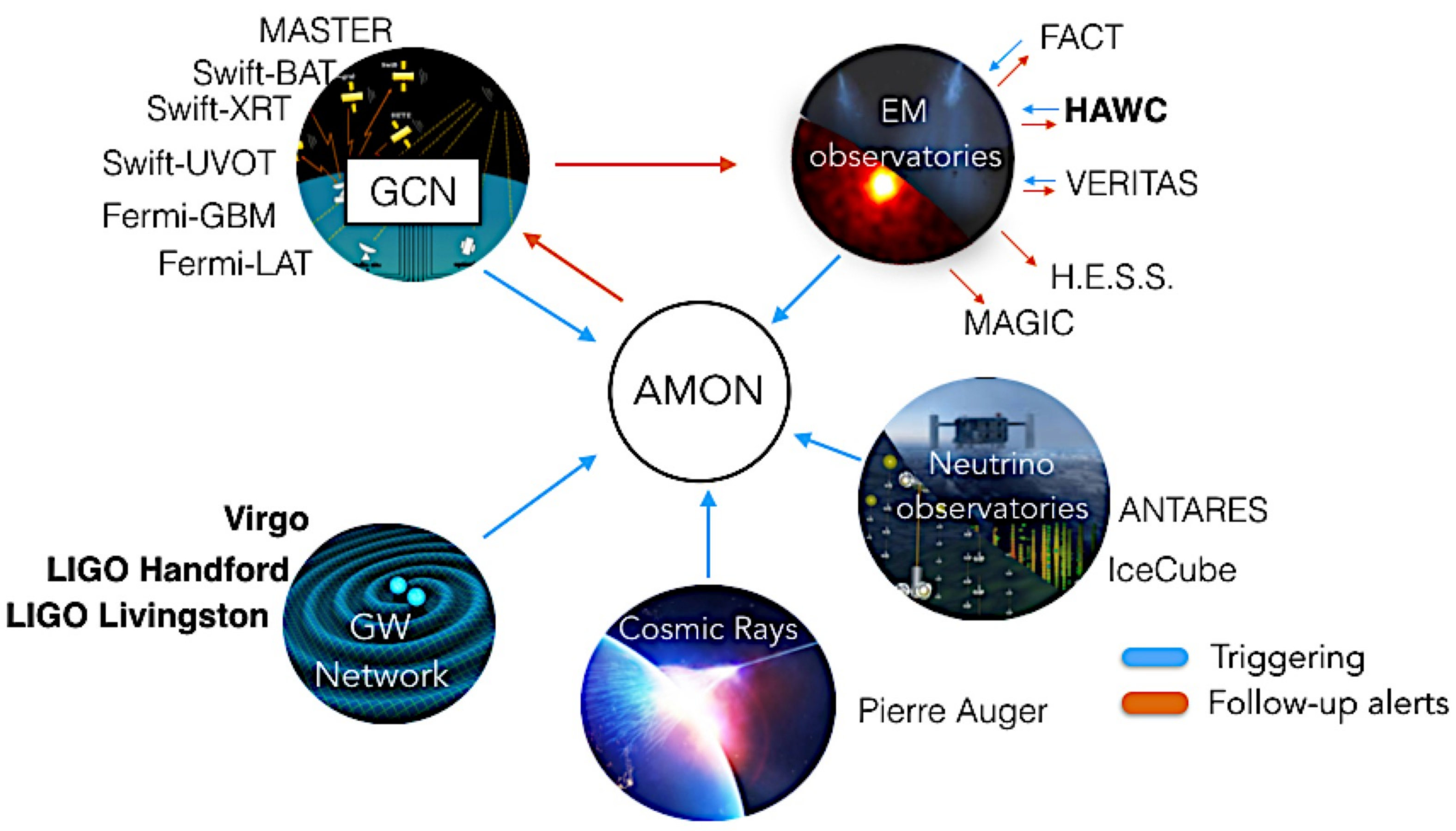
Connecting the four fundamental forces

Multimessenger astrophysics is focused on solving the most enigmatic open questions in astroparticle physics by combining the knowledge from the messengers of the fundamental forces obtianed with different observatories and telescopes.

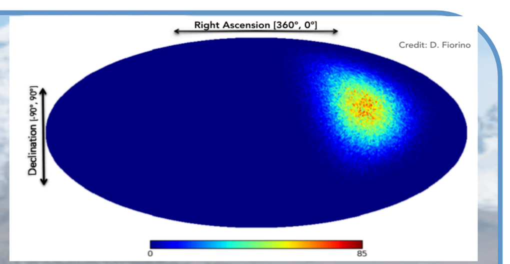
The **Astrophysical Multimessenger Observatory Network (AMON)** [1] enables real-time and archival searches of coincident events of those by using joint correlation analysis techniques, with the goal of finding signal events that are indistinguishable from background events in the detectors due to their sensitivity and promote them to be statistically significant through correlations.



Large FoV observatories monitoring the sky

HAWC – Very High Energy Photons

- Energies: ~ 30 GeV-100 TeV.
- High duty cycle: >95%.
- Large instantaneous FoV: ~2 sr of the sky constantly (2/3 sky in 24h)
- 0.2, 1, 10 and 100 s GRB search running online [2]



LIGO-Virgo (LVC) – Gravitational Waves

- 3 interferometers with different high duty cycles.
- LIGO/Virgo NS range suits HAWC horizon and VHE EBL absorption horizon: during O3, 120/65 Mpc.
- After first NSM detection during O2 [3], estimated BNS detections during O3: 1-50 NSM [4]

Joint coincidence analysis framework

The proposed ranking method checks for coincident events that are *unlikely* coming from background. *A priori* restrictions in sky location and time of the independently reported candidates are applied, in consistency with the science case.

The joint likelihood ratio (JLR) between signal and background hypothesis is found for every direction (E1). The $p_{spatial}$ value is obtained by comparing the JLR distribution of time-scrambled data (TSD). Following Fisher's method in Equation E2, the χ^2 value is computed.

$$\lambda(\vec{x}_S) = \frac{H_1^{GW}(\vec{x}_S)\cdot H_1^{\gamma}(\vec{x}_S)}{H_0^{GW}(\vec{x}_S)\cdot H_0^{\gamma}(\vec{x}_S)} \quad \text{(E1)}$$

$$\chi^2 = -2\cdot ln(p_{sp}\cdot p_{gw}\cdot p_{\gamma}) \quad \text{(E2)}$$

$$p_{GW\gamma} = \int_{\chi^2}^{\infty} f_B(\chi'^2)d\chi'^2 \quad \text{(E3)}$$

HAWC TRIGGER — t_{HAWC},(RA,Dec), p-value
GW TRIGGER — t_{GW},$P(x_s)$,FAR

TEMPORAL COINCIDENCE
$t-t_0 \in [-100, 500]$

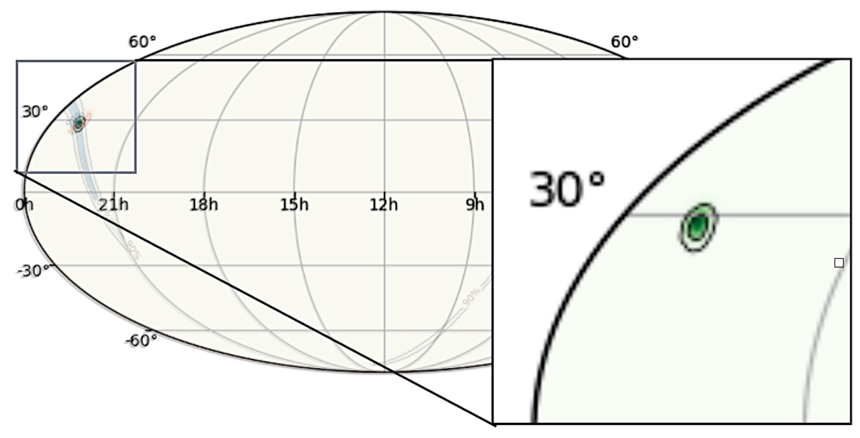
SPATIAL COINCIDENCE
(RA,Dec) $_{HAWC} \in 99\%\ A_{GW}$

$D_{gal} \approx D_{GW}$? YES → Potential galaxy association

LIKELIHOOD RATIO COMPUTATION

P-VALUE OF THE COINCIDENCE

The p-value statistic of the coincident search of gravitational wave and VHE-photons, $p_{GW\gamma}$, is obtained by comparison to TSD using Equation E3.



Subthreshold opportunities

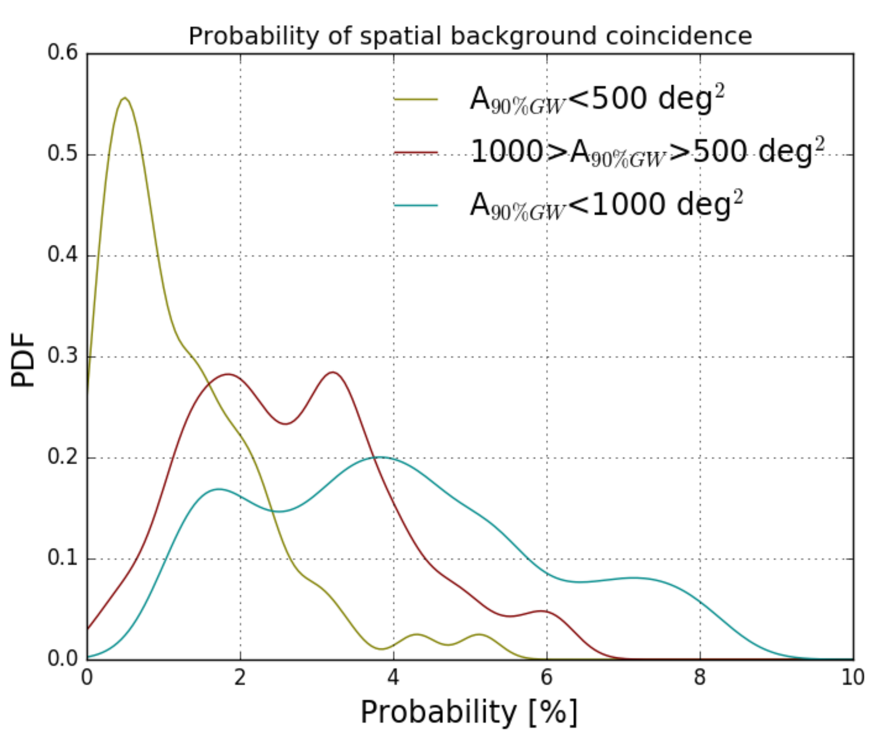
False Alarm Rate (FAR) can be **significantly lowered** by studying coincidences of several sub-threshold data.

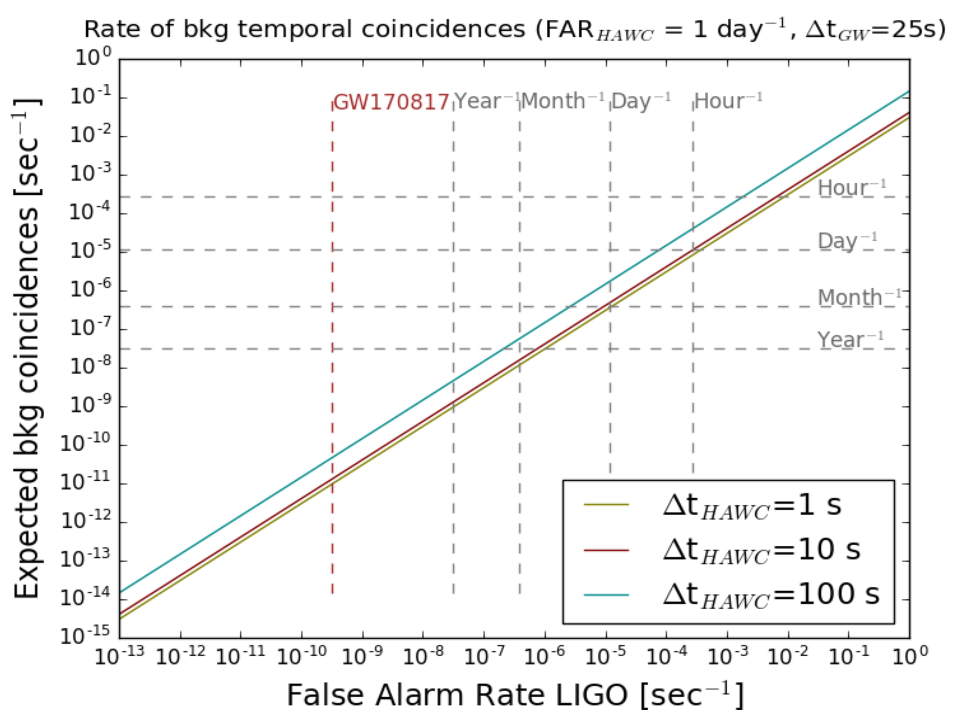
- **HAWC**: The expected number of GRB detections at very high energies suffer of large uncertainties [5]. Estimates of 1.65 yr^{-1} have been derived [6]
- **LVC**: The average probability [%] of GW alerts being actual GW events depency on FAR [7] in shown on the table below.

Epoch\FAR	1/100 years	1/year	1/month	1/week	1/day
P_{GW} O2 BNS	99.4	66.6	15.6	4.4	0.7
P_{GW} O3 BNS	99.8	86.9	38.2	13.2	2.3
P_{GW} design BNS	99.9	96.6	72.6	39.4	9.2

OPAs ↔ P_{astro} < 90%

Background coincidence estimates





- Combined S-T estimate ULs :

Noise-Noise (10^{-4} /10^{-8} sec^{-1} FAR LV)	Noise-Signal (10^{-10} sec^{-1} FAR LV)
~1 per 10 days /1 per 100 years	~1 per 10^4 years

Outlook

The identification GW+ γ transient sources can provide valuable insights into fundamental physics, astrophysics, and cosmology.

Simultaneous detections in VHE would be critical to understand the connection between GRBs showing VHE emission and gravitational waves.
Proposed coincidence analysis:

- Archival analysis of O1&O2 data.
- Real-Time Analysis during O3.

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REFERENCES:
[1] Smith, M.W.E. et al. Astroparticle Physics, 45, 56-70
[2] Wood, J. 2018, arXiv:1801.01550
[3] Abbott, B.P., et al., ApJL, 848(2), L12
[4] LIGO, Virgo and Kagra Collab., Living Reviews in Relativity, 21(1),2.
[5] Taboada, I. & Gilmore, R. C. 2014, Nuclear Instruments and Methods in Physics Research Sec. A, 742, 276
[6] Piron, F. 2016, Comptes Rendus Physique, 17, 617
[7] Lynch,R., Coughlin,M., Vitale, S., Stubbs, C.W.,Katsavounidis,E., arXiv:1803.02880