Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA) search for common sources of gravitational waves and high-energy neutrinos

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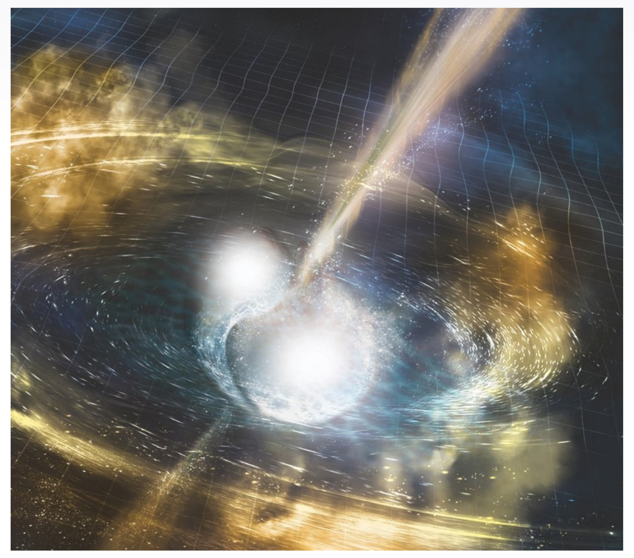
We want to discover common sources of gravitational waves (GW) and high energy neutrinos. Potential sources are:



⇒Binary neutron star mergers (a potential kilonova)

⇒Neutron star-black hole mergers

⇒Binary black hole mergers with an accretion disc

⇒Core collapse supernova

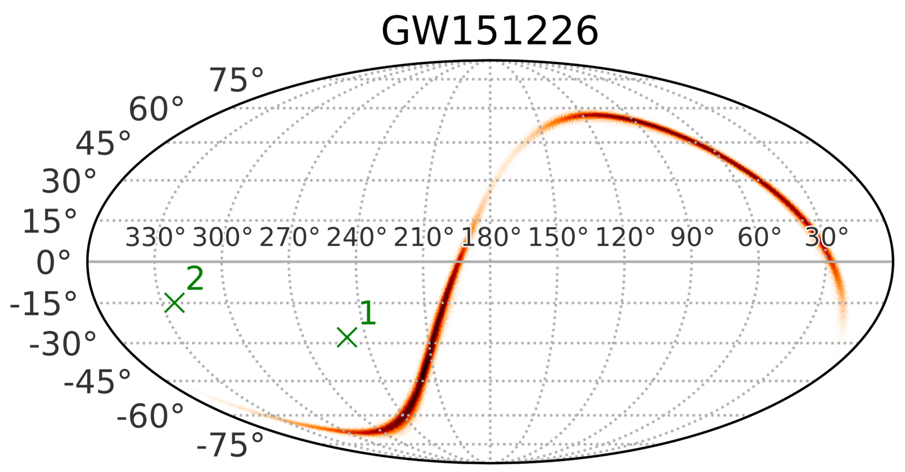
⇒…

Finding high-energy neutrino counterparts to GWs provides much better sky localization for further astronomical follow-ups

⇒GW skymap sizes for 2 and 3 detectors can range in ~10-10^4 deg^2

⇒High energy neutrino localization can range in ~0.1-10 deg^2

⇒Even smaller overlap of GW and high-energy neutrino localization



⇒Subthreshold GW or high-energy neutrino detections' significance can be increased by additional counterparts

Improved significance calculation by using the GW distance information, in addition to the previous searches

GW inputs

- -Detector sensitivity and background characteristics
- -Sky localization
- -Detection time
- -p_{astro} for subthreshold GWs
- -<u>Mean distance (with astrophysical priors)</u>

Neutrino inputs

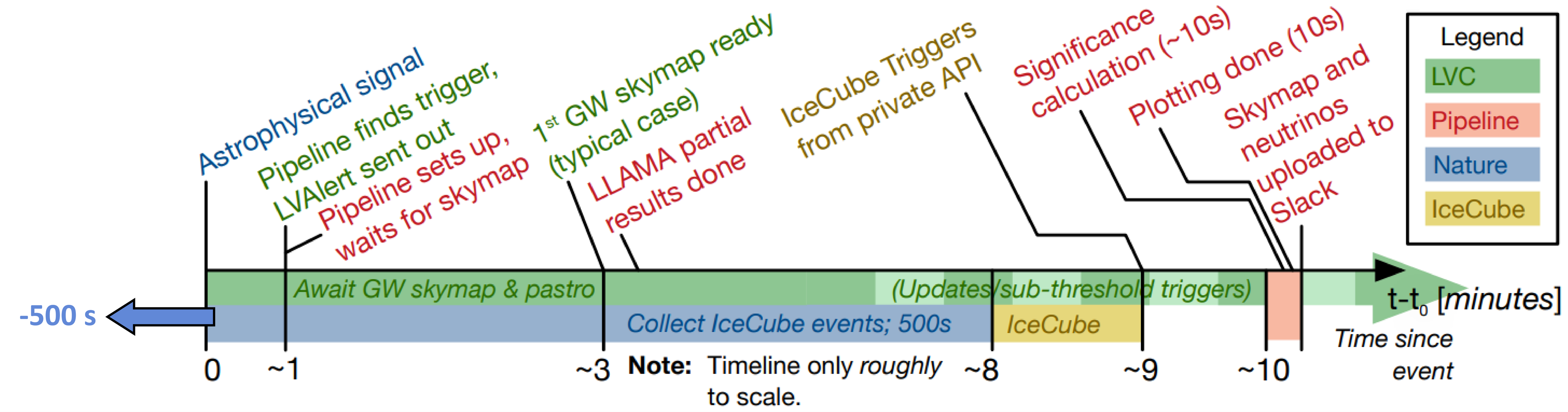
- -Detector sensitivity and background characteristics
- -Sky localizations
- -Localization uncertainties
- -Detection times
- -Energies

⇒Test statistic is the odds ratio of a joint detection (H_s) vs background (H_0) or unrelated detections (H_c)

$$\mathcal{O}_{\mathrm{gw}+\nu} = \frac{P(H_s|\mathbf{x}_{\mathrm{gw}}, \mathbf{X}_\nu)}{P(H_0|\mathbf{x}_{\mathrm{gw}}, \mathbf{X}_\nu) + P(H_c|\mathbf{x}_{\mathrm{gw}}, \mathbf{X}_\nu)}$$

Realtime search during LIGO-Virgo's 3rd observing run with IceCube (April '19-April '20)

- Followed-up 56 GW candidates announced by LIGO-Virgo Collaborations in low latency
- Notification of the astronomical society by GCN circulars - from the IceCube Collab.
- Follow-up is completed in minutes

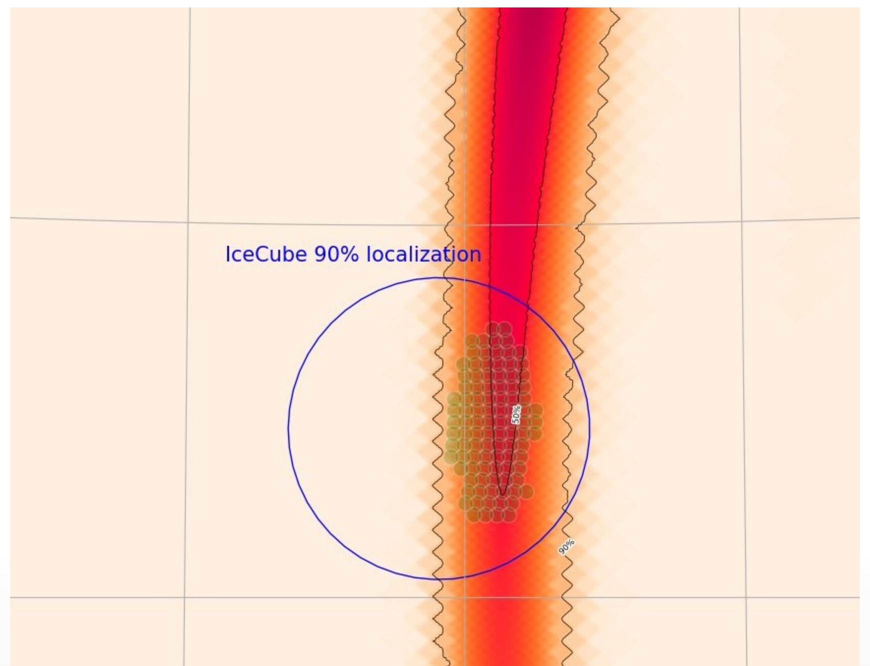


A special follow-up of a significant event sent out by GCN: S191216ap

- One coincident subthreshold gamma-ray detection by HAWC observatory for the event S191216ap
- Binary black hole merger at ~376 Mpc, LLAMA p-value of 0.6%

  ⇒=More significant than 99.4% of unrelated coincidences

  ⇒Close binary black hole merger!



Swift follow-up of S191216ap and the coincident neutrino
Triggered by A. Keivani's Swift GI program, Cycle 15
—image from A. Tohuvavohu's Twitter

No decisive electromagnetic counterparts for any of the sent out GW-neutrino coincidences

References

- LLAMA documentation: https://multimessenger.science
- LLAMA significance calculation: Bartos, I. et al, *Bayesian multimessenger search method for common sources of gravitational waves and high-energy neutrinos*, Phys. Rev. D **100**, 083017
- LLAMA pipeline description: Countryman, S. et al, *Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA) with Gravitational-Wave and High-Energy Neutrino Candidates,* arXiv:1901.05486

GECo | Columbia University in the City of New York | UF University of Florida | University of Maryland | Stockholms Universitet | Neutrino 2020