How to search for multiple messengers - a general framework beyond two messengers arXiv:2010.04162

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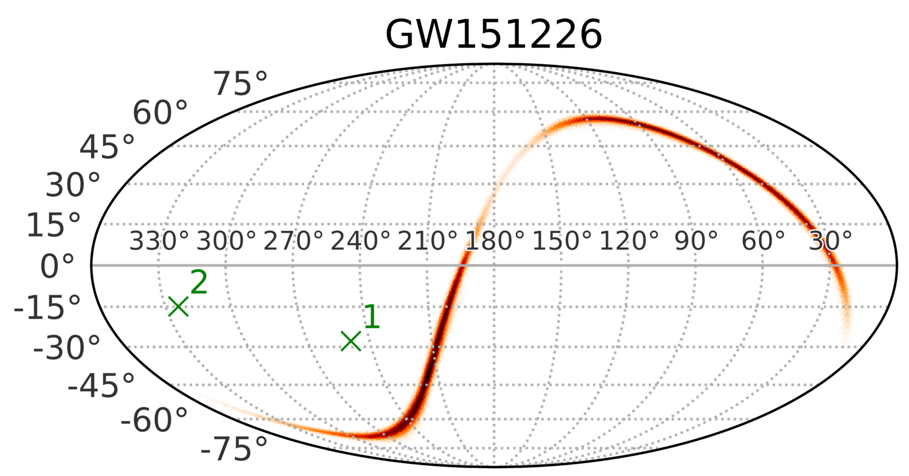
All multi messenger searches are currently looking for two messenger coincidences, i.e.

⇒Gravitational waves (GW) - neutrinos

⇒Neutrinos-gamma ray bursts

⇒...



Multi messenger detections enable

⇒Better understanding of physical processes

⇒Elevated significance of subthreshold detections with correlations

⇒Guidance to astronomers with real-time follow-ups

◊i.e. IceCube's real-time follow-up of GW candidates in O3

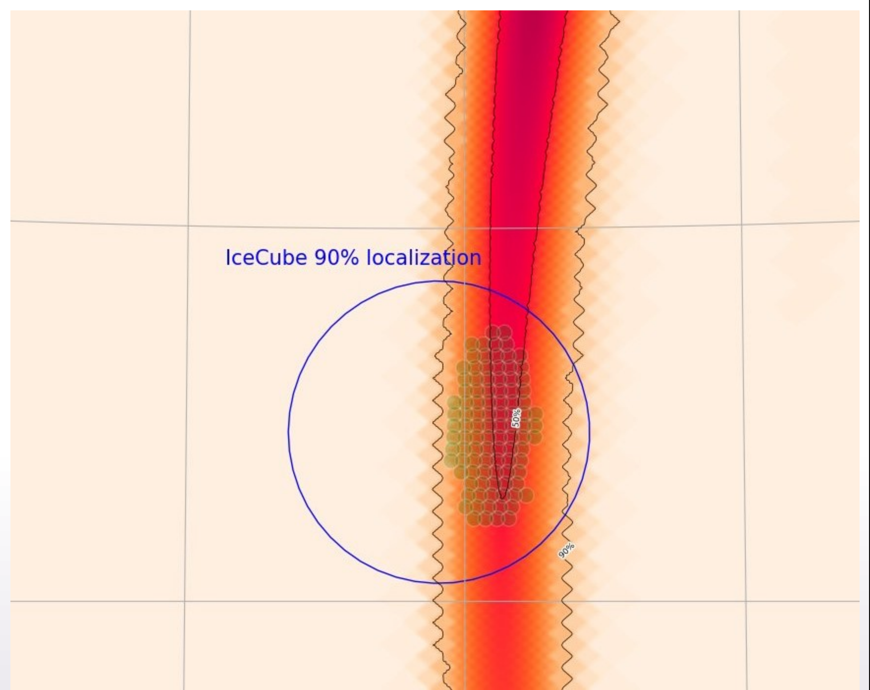
⇒No need of a detector upgrade!

A triple coincidence from the real-time follow-up? (Dec '19)

⇒GW candidate S191216ap by LIGO/Virgo

⇒Potential neutrino counterpart from IceCube's real-time follow-up

⇒HAWC subthreshold gamma ray coinciding with the GW and the neutrino on the sky



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

Need a statistical treatment for multiple messengers for such multiple coincidences!

Many messengers many hypotheses...

⇒Astrophysical or noise

⇒Related or unrelated

For *n* messengers, there are *f(n+1)* hypotheses

$$f(n) = \sum_{i=0}^{n-1} \binom{n-1}{i} f(i), \;\; f(0) = 1$$

What is the optimal test statistic for this case?

For two hypotheses, likelihood ratio is the optimal test statistic.

⇒Model independent optimal multi messenger search doesn't exist!

Model dependent optimal test statistic with Bayesian statistics:

$$\mathrm{TS}(\mathbf{x}) = \frac{P(\mathbf{x}|H_s)}{P(\mathbf{x}|H_n)} = \frac{\sum_i P(\mathbf{x}|H_s^i)P(H_s^i)}{\sum_j P(\mathbf{x}|H_n^j)P(H_n^j)} \times \frac{\sum_j P(H_n^j)}{\sum_i P(H_s^i)}$$

Combined signal hypothesis; Model dependent prior probability; Independent of **x**; Detection outcomes; Combined null hypothesis; Sub-hypothesis likelihoods

Common source relation through a source parameter: $P(\mathbf{x}|H_a^b) = \int P(\mathbf{x}|\boldsymbol{\theta}, H_a^b)P(\boldsymbol{\theta}|H_a^b)d\boldsymbol{\theta}$

Future outlook: Increasing sensitivities and new detectors (i.e. upgrades in LIGO/Virgo/KAGRA, IceCube Gen2, KM3NeT, Vera Rubin Observatory, Ultrasat...) will provide greater amount of data, eventually creating multiple coincidences, requiring analysis of the coinciding multiple messengers! The treatment here is was designed to be adoptable by the LLAMA pipeline infrastructure, which is used for GW+neutrino searches [1,2] in the advanced gravitational-wave detectors era.

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