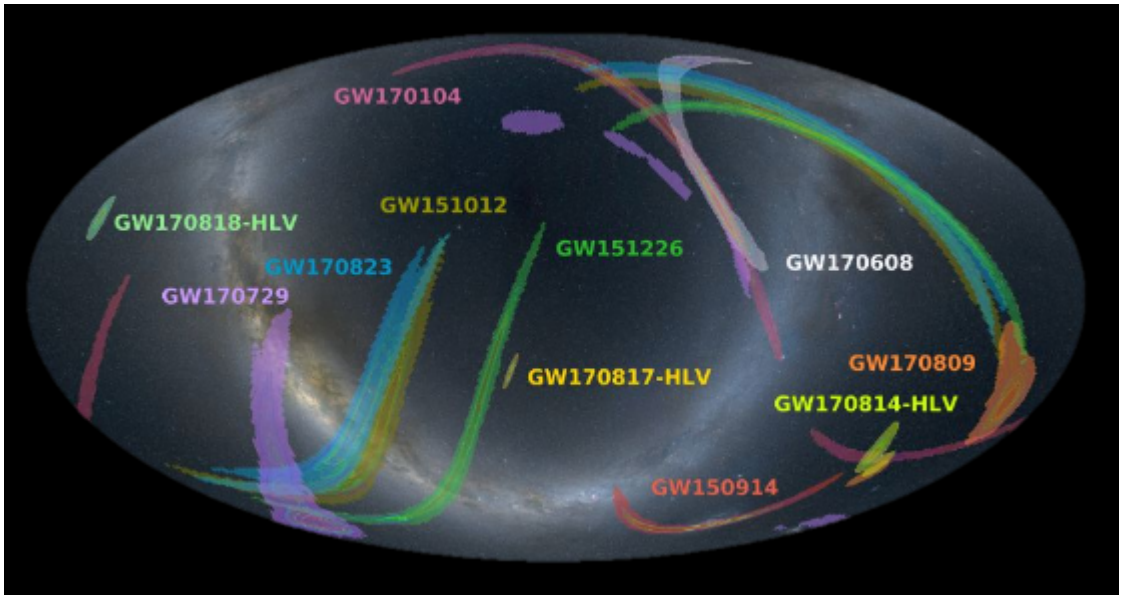
LIGO/Virgo gravitational wave searches in the KM3Net era



Marie Anne Bizouard, ARTEMIS CNRS/Observatoire de la Cote d'Azur
on behalf of the LIGO scientific collaboration and the Virgo collaboration

KM3Net town hall meeting, Marseille, 17-19 december 2019

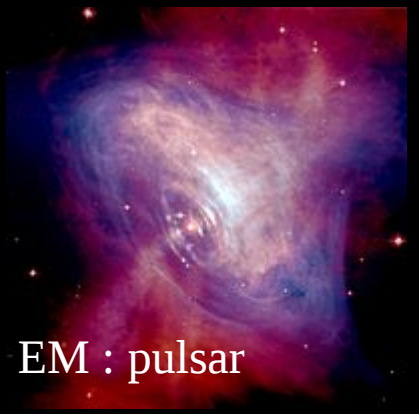
LIGO-Virgo gravitational wave sources

- Sources can be transient or of continuous nature, well modelled or un-modelled
- Many GW sources are EM or neutrinos emitters as well

Coalescence of compact sources (black holes, neutron stars)

EM : short GRB, kilonova
HEN : short GRB

Rapidly rotating neutron star (destorted crust)

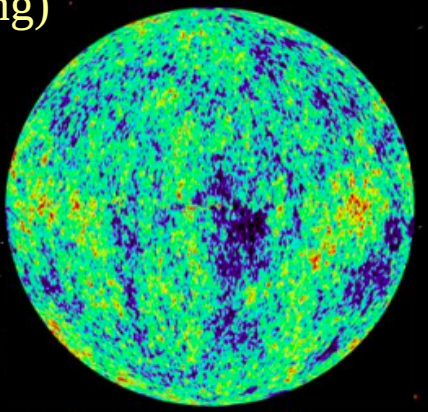


EM : pulsar

Burst (core collapse supernova, fallback back accretion, cosmic strings, ...)

EM : long GRB, supernova
LEN : supernova
HEN : hypernova

Unresolved sources of GW forming a background (astrophysics and/or big bang)



LIGO-Virgo gravitational wave sources

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Coalescence of compact sources
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EM : short GRB, l
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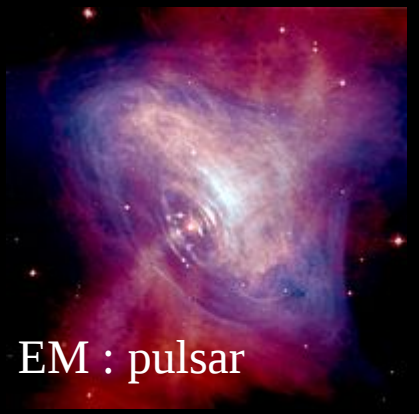

EM : pulsar

Synergy with neutrino detectors :
Multi-messenger searches

Bur supernova,
f cretion, cosmic

EM : long GRB, supernova
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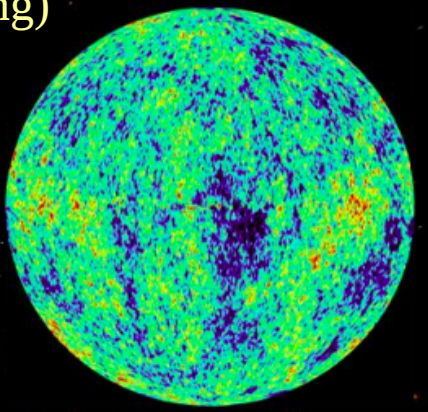
Unresolved sources of GW
forming a background (astrophysics
and/or big bang)



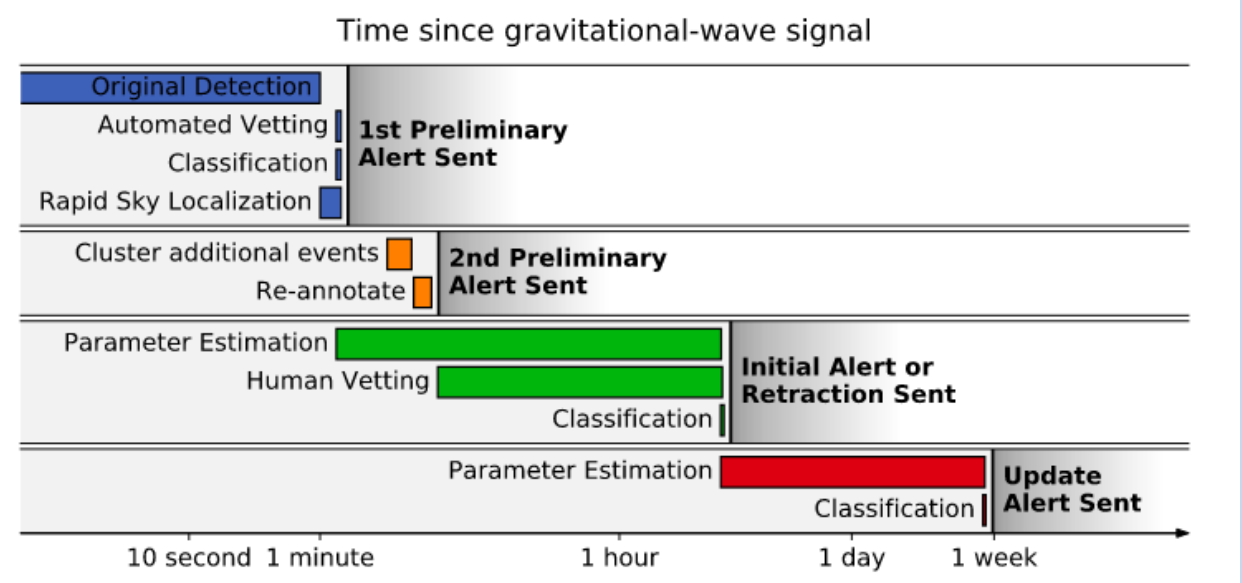
LIGO-Virgo gravitational wave transient searches

All-sky/all-time offline searches. *CBC, burst unmodelled, etc*

Triggered searches : searches that use EM or neutrino observations to drive the detection of GWs (time and direction). *GRB, CCSN, FRB, magnetar giant flares, pulsar glitches, HEN, etc*

Low-latency searches → *GW triggers follow-up : search EM/neutrino counterpart candidates, identify the source, host galaxy.*

LVC alerts timeline

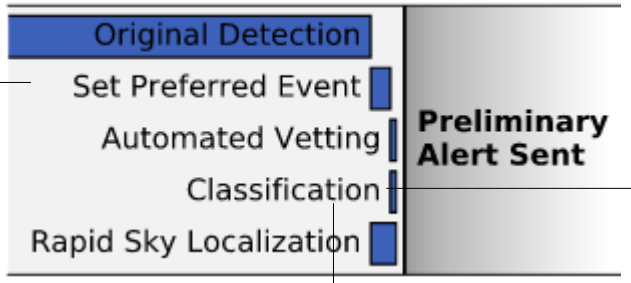


https://emfollow.docs.ligo.org/userguide/index.html

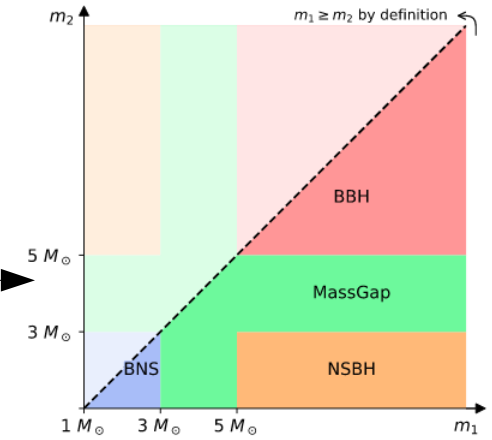
LIGO-Virgo alerts : content

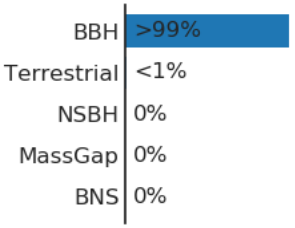
* From output of 5 pipelines
* Based on :
 - FAR
 - SNR
 - CBC/burst pipeline
 - IFOs involved

CBC : 1 event / 2 months
Burst : 1 event / year



- **Nature of the binary :**





arXiv:1903.06881

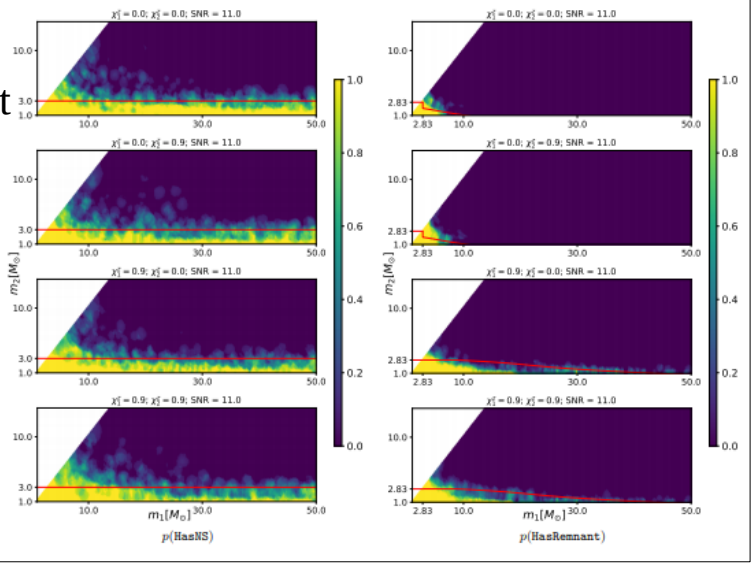
Compute probability that the super-event belongs to each category using Poison occurence rate and astro source events rate.

- **HasNS and HasRemnant :**

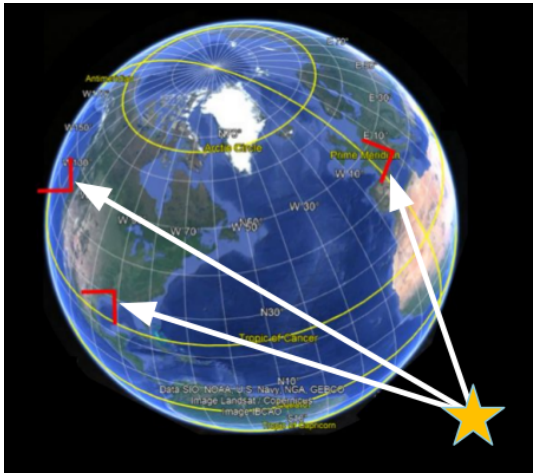
« EM bright » the binary is expected to have at least one neutron star (NS) component and/or form a remnant made of matter.

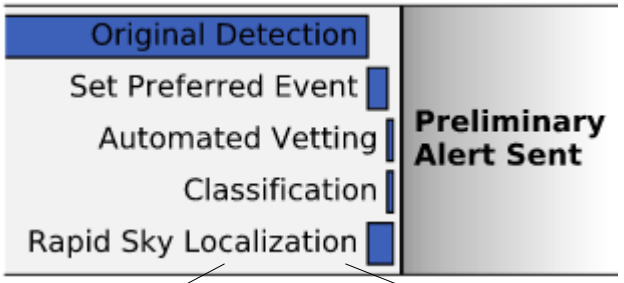
Compute probabilities p(HasNS) and p(HasRemnant) based on distribution of m1, m2, χ1 and χ2 for certain EOS and using a neural network method to be fast.

arXiv:1911.00116



LIGO-Virgo alerts : content

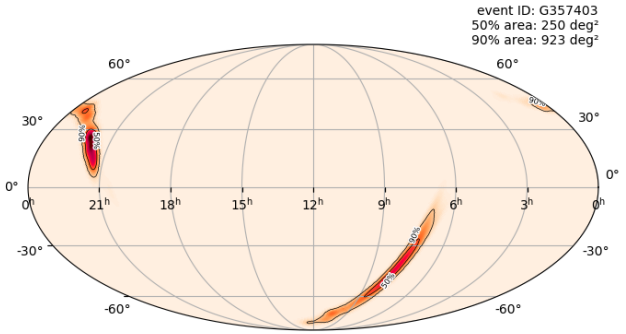




arXiv:1508.03634

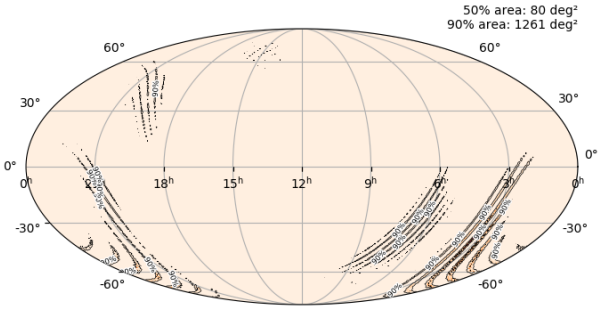
- **Bayestar CBC event localization**

In a few tens of seconds, using the matched-filter time series from the search pipeline it calculates the posterior probability distribution over the sky location and distance of the source by coherently modeling the response of the gravitational-wave detector network.



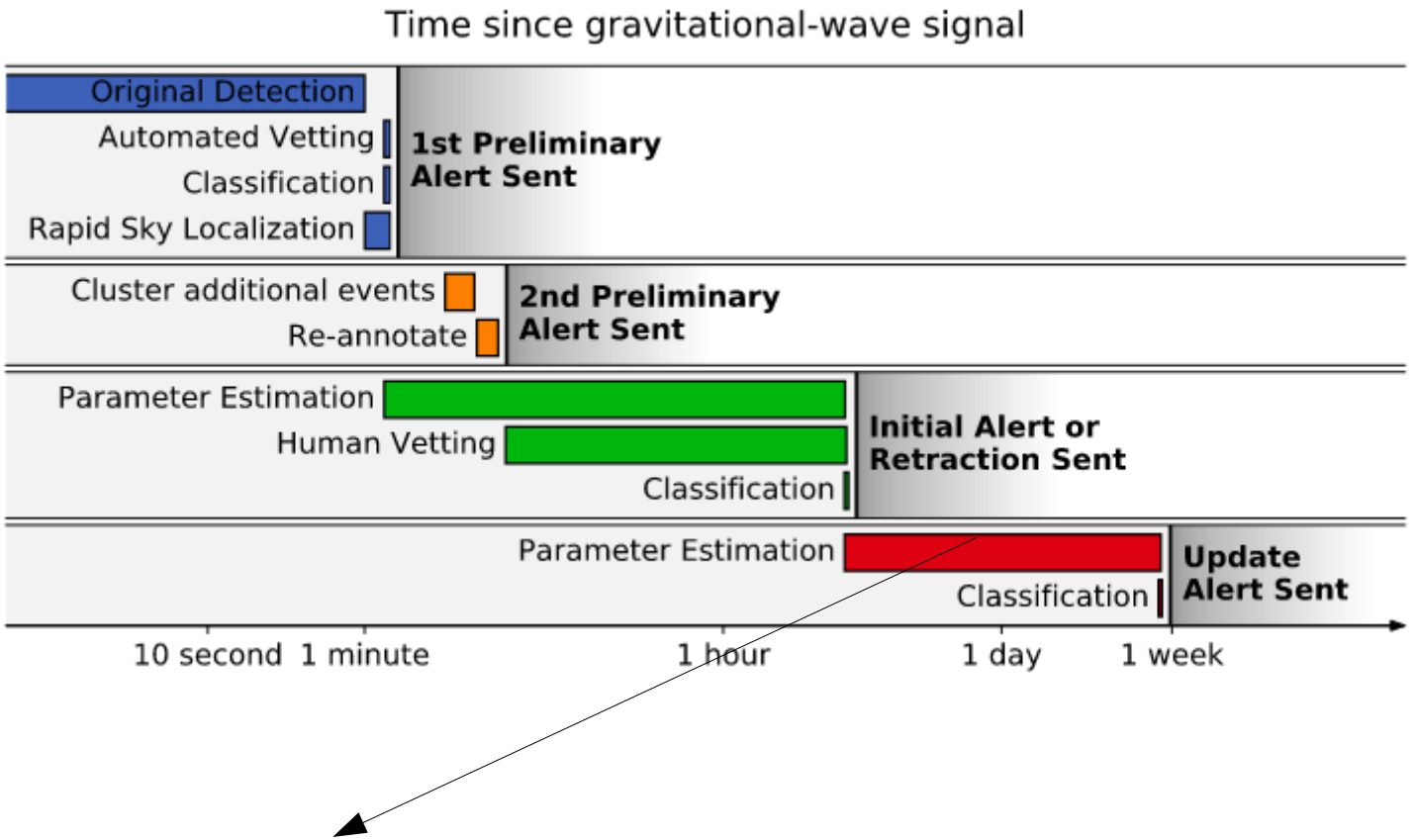
- **CWB unmodelled burst localization**

cWB, the burst search pipeline, performs a rapid sky localization based on its coherent reconstruction of the gravitational-wave signal using a wavelet basis and the response of the gravitational-wave detector network.



LIGO-Virgo alerts : after the first alert

Second automatic alert to gather all triggers information



Final parameter estimation (CBC case) :

- Bayesian parameter estimation Markov Chain Monte Carlo (MCMC) or Nested sampling

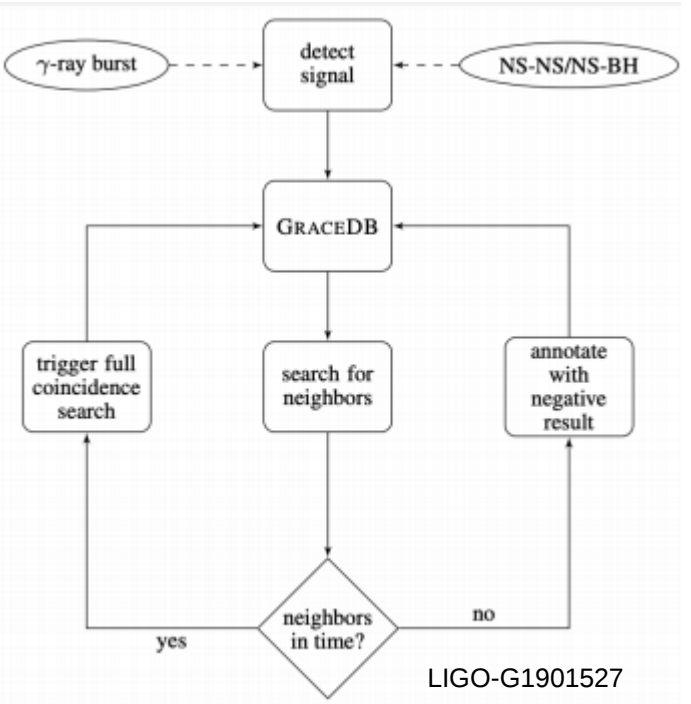
15 parameters (masses, spins, luminosity distance, inclination angle, ...)

- Frequency domain vs time domain with different post-newtonian waveforms and EOS for BNS or NSBH.

LIGO-Virgo alerts : coincidence with external triggers

RAVEN, the Rapid on-source VOEvent Coincidence Monitor

- Low-latency pipeline searching for coincidences between gravitational wave (GW) candidates and astrophysical alerts external to the LIGO-VIRGO collaboration,
- including gamma-ray bursts (GRB) (Fermi, Swift) and neutrino bursts (SNEWS)
- RAVEN will calculate a joint false alarm rate (FAR) using timing and spatial information from coincident events :

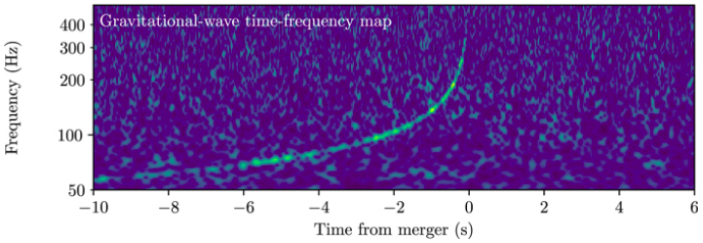


$$FAR_c = FAR_{GW} R_{EM} \Delta t / I_\Omega$$

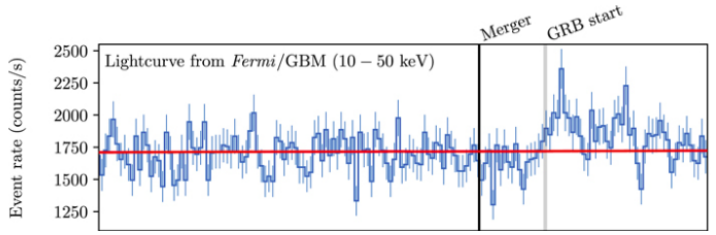
Spatial overlap integral

→ increase the detection rate

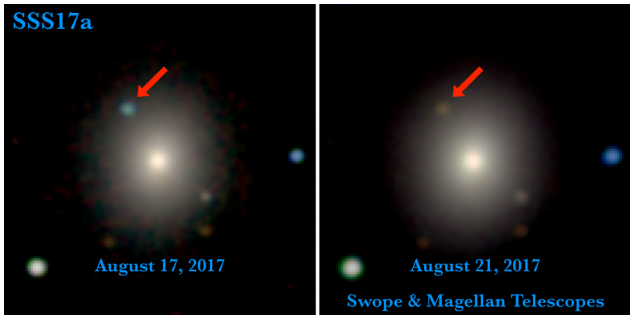
GW170817 multi-messenger physics : combining all information



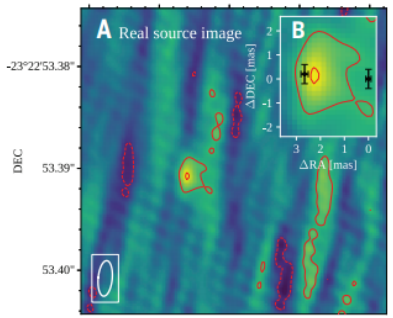
GW



GRB



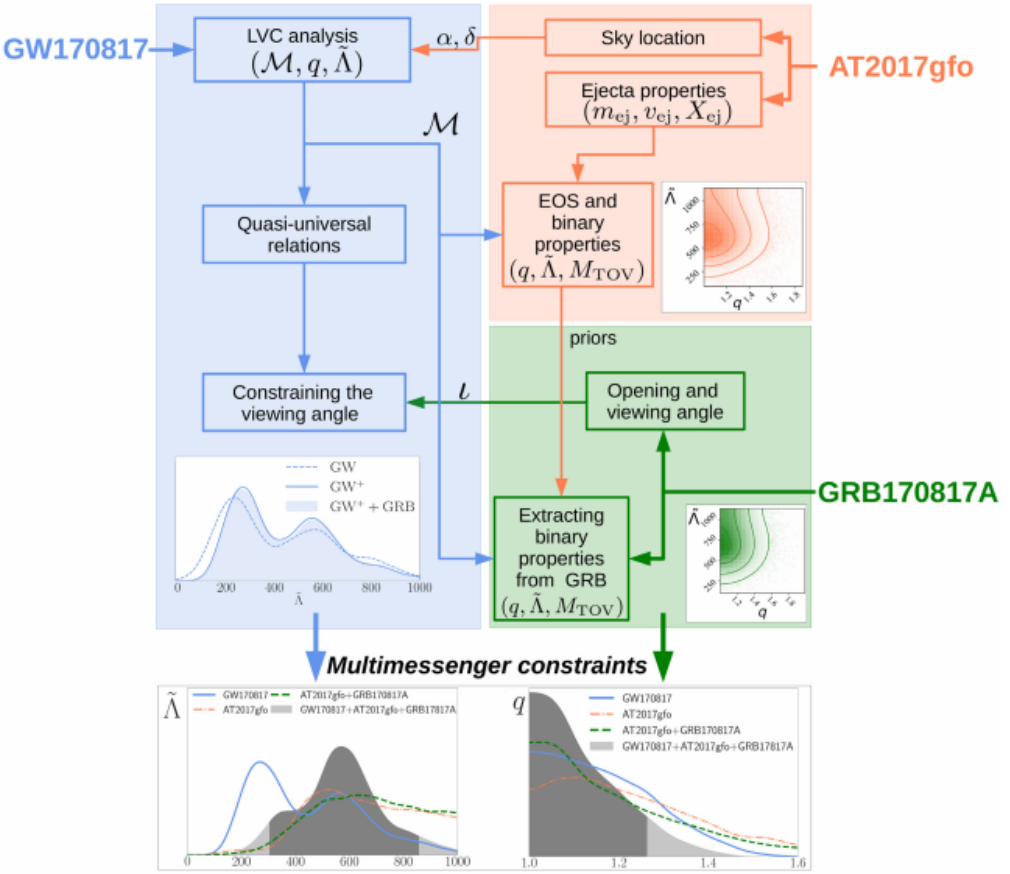
Kilonova

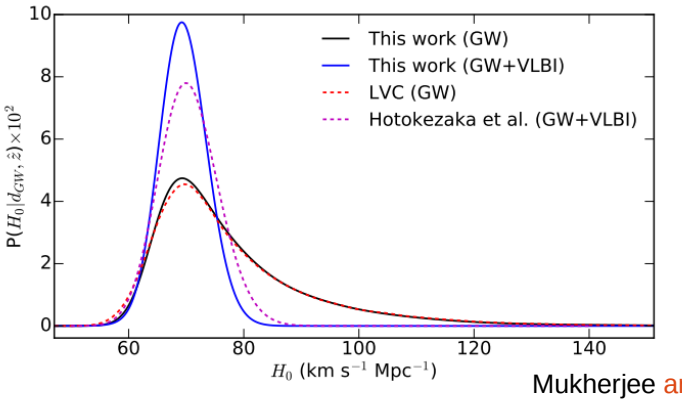


Afterglow

Ghirlanda arXiv:1808.00469

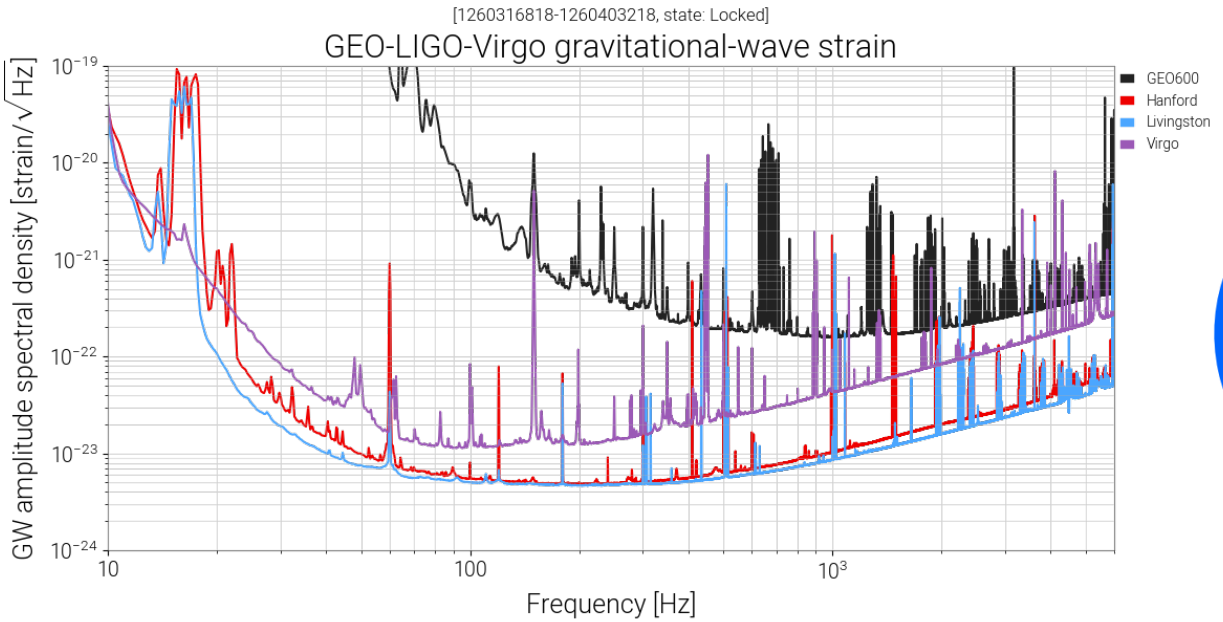
Coughlin arXiv:1812.04803





Mukherjee arXiv:1909.08627

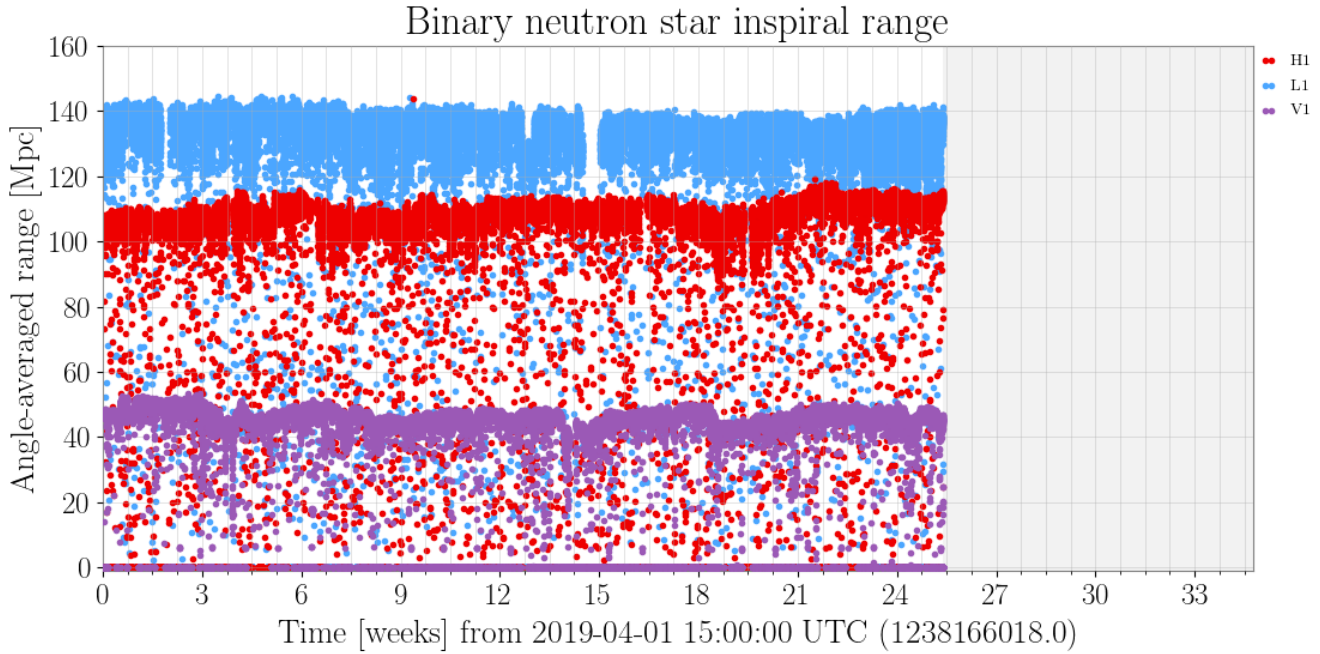
LIGO-Virgo O3 run



Network duty factor

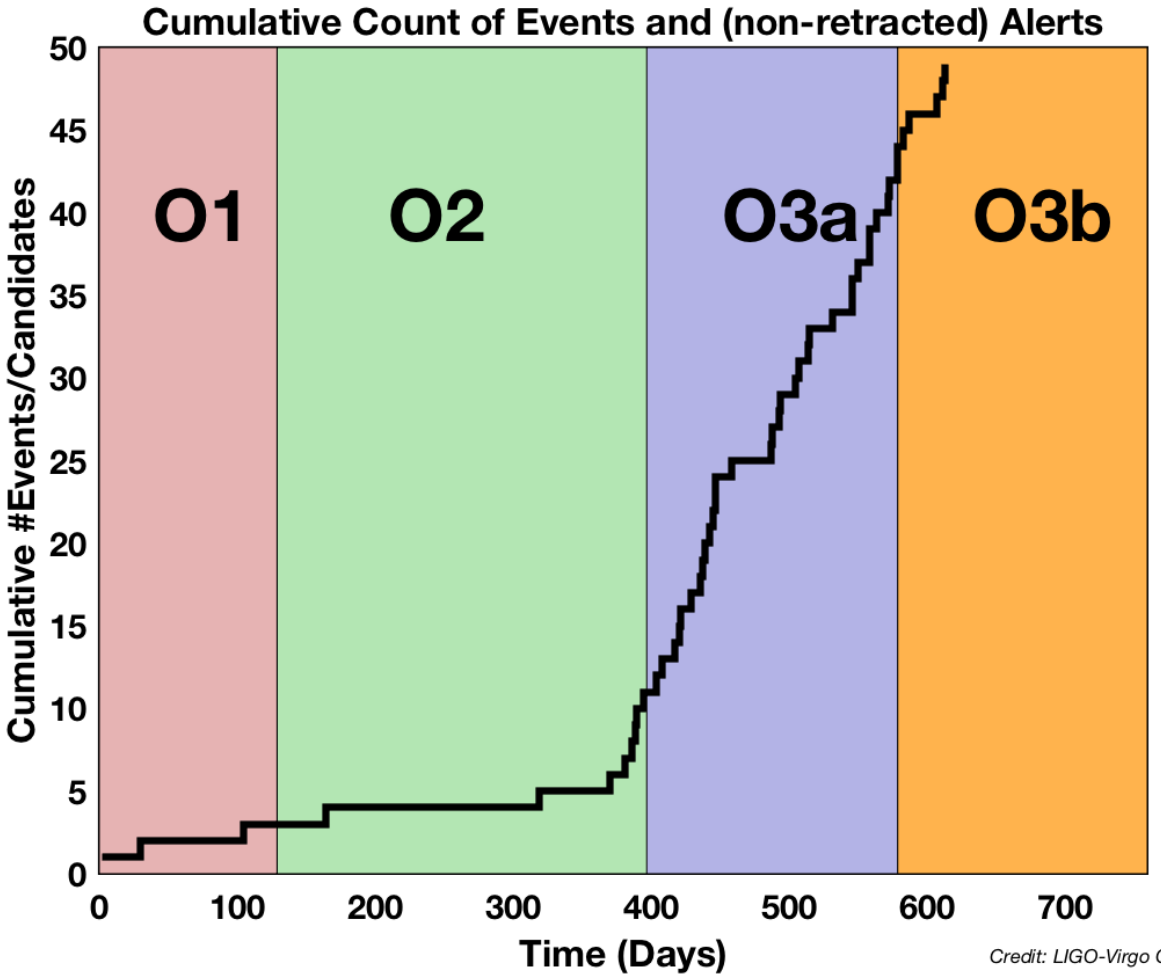
[1238166018-1259193618]

- Triple interferometer [44.0%]
- Double interferometer [37.6%]
- Single interferometer [15.2%]
- No interferometer [3.2%]



KAGRA has joined

O3 GW events so far



Credit: LIGO-Virgo Collaboration

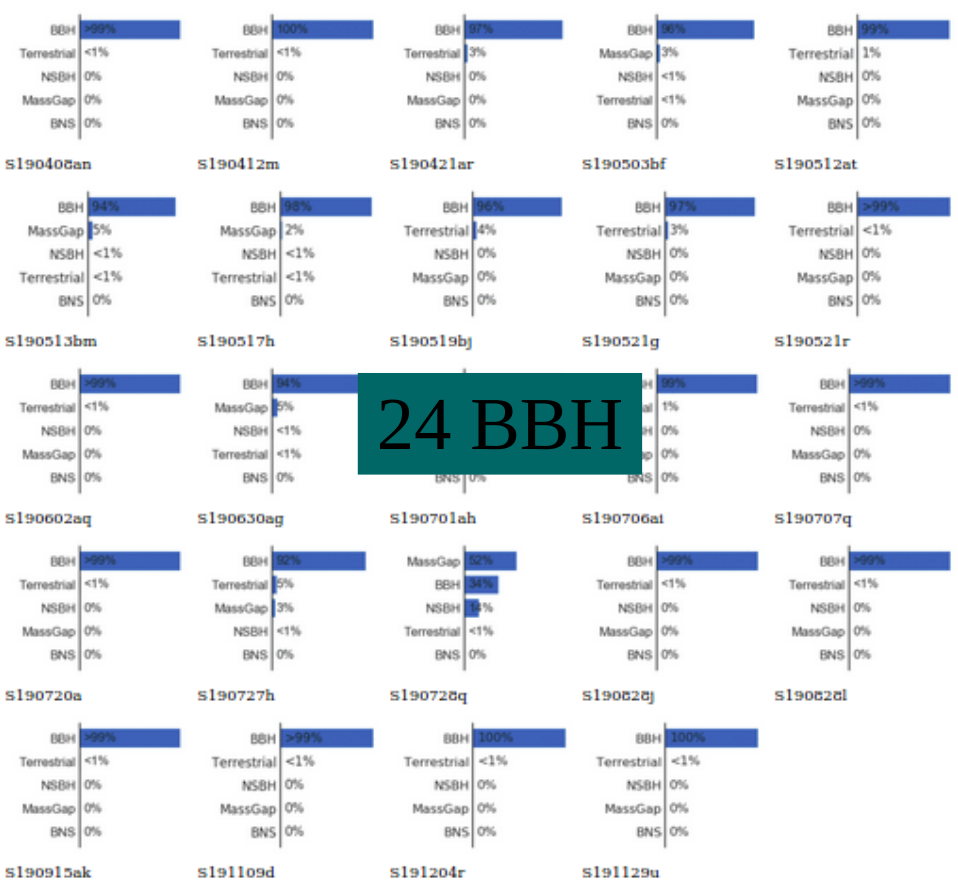
Detection number predictions for each CBC type are given as detection counts including Poisson statistical variations and based on a one-calendar-year observing run.

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
	Events after ~8 months	5	5	24

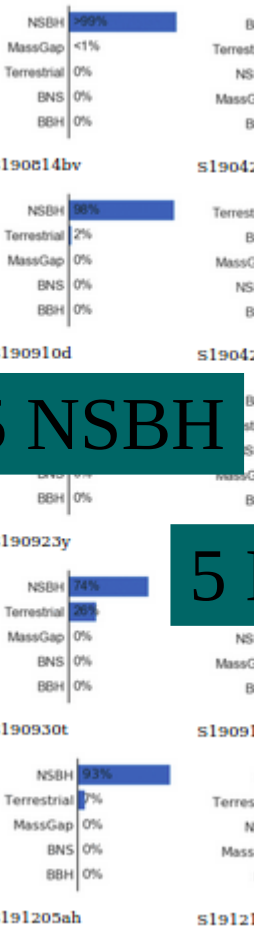
Alerts classification

https://gracedb.ligo.org/superevents/public/O3/

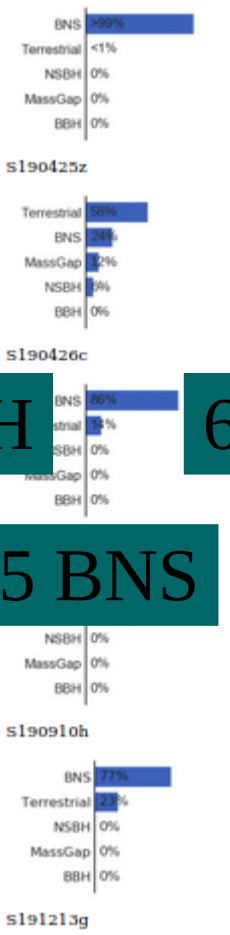
BBH	NSBH	BNS	Mass Gap	Terrestrial



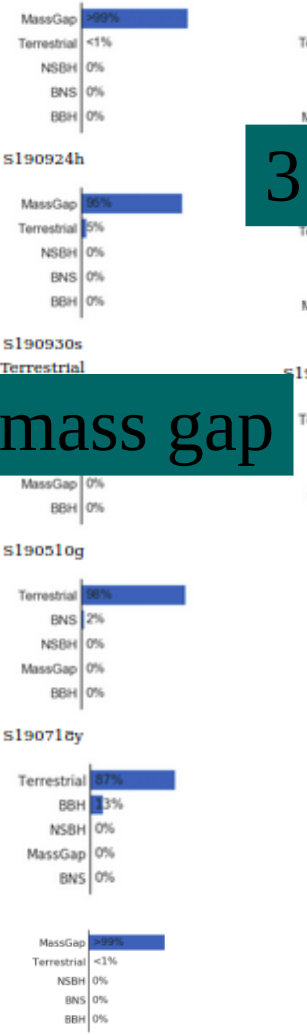
24 BBH



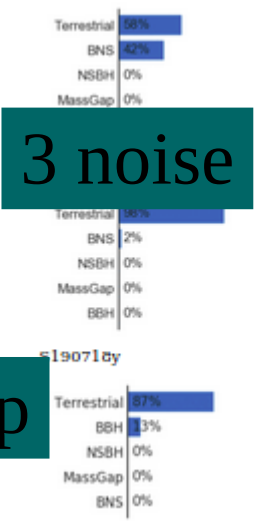
5 NSBH



5 BNS



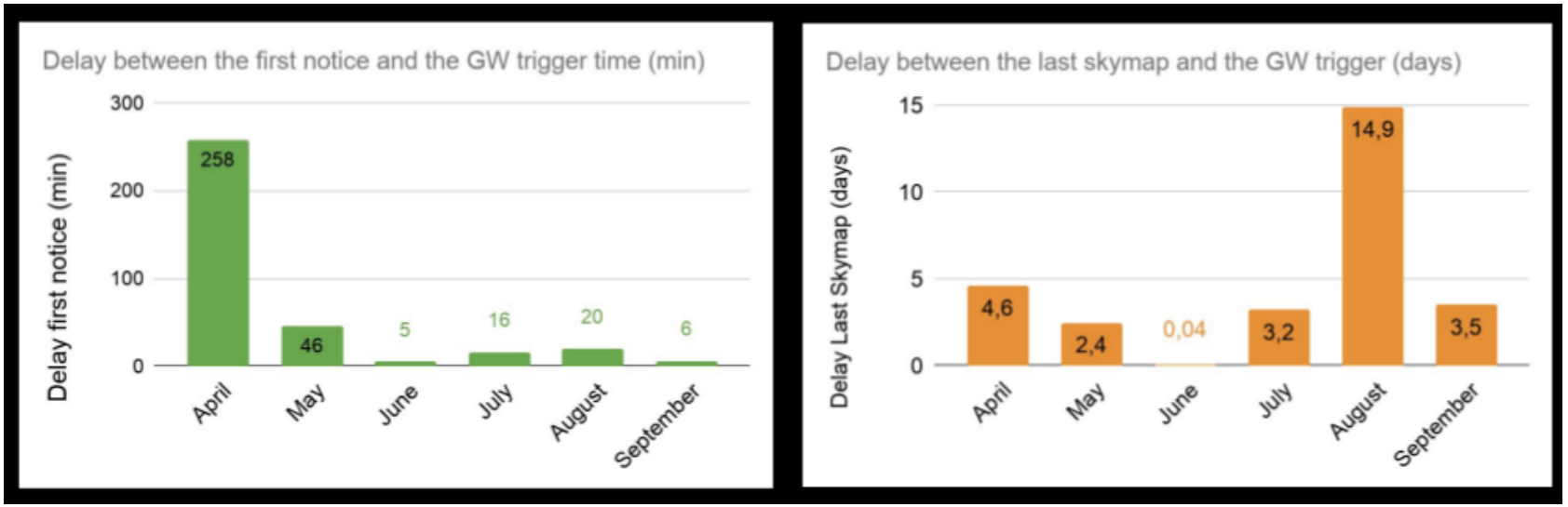
6 mass gap



3 noise

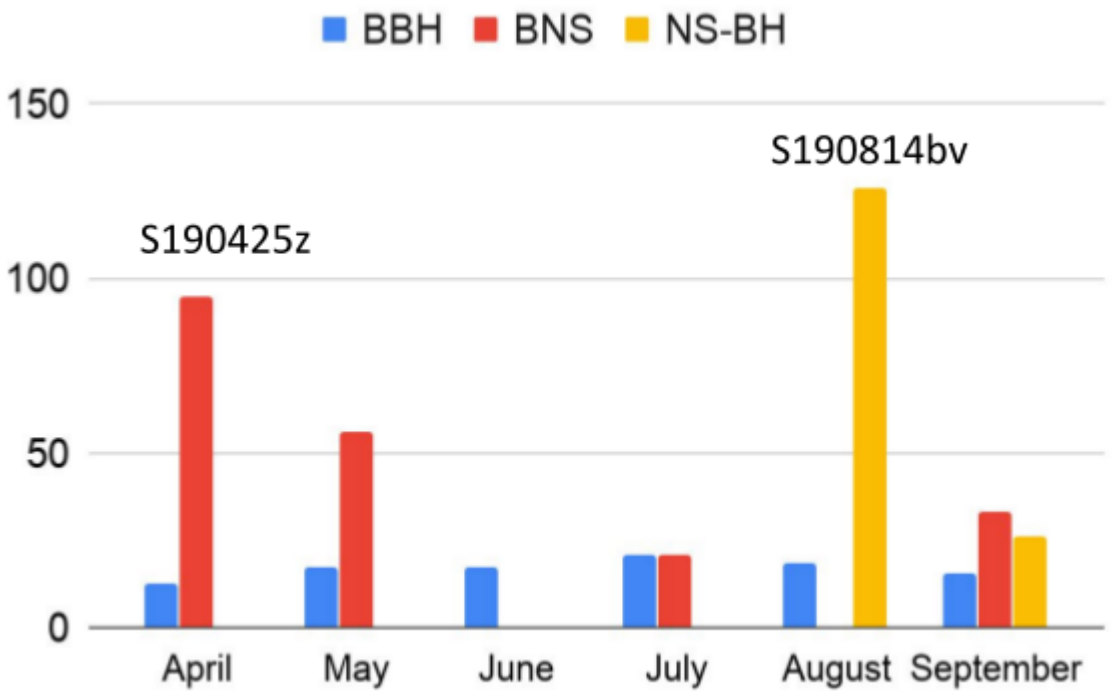
and 16 retractions

Alerts statistic



- Alert updates
  - when we improve the classification and/or the sky map.
  - timing not predictable but source of insatisfaction.

Alerts statistic : GCN traffic



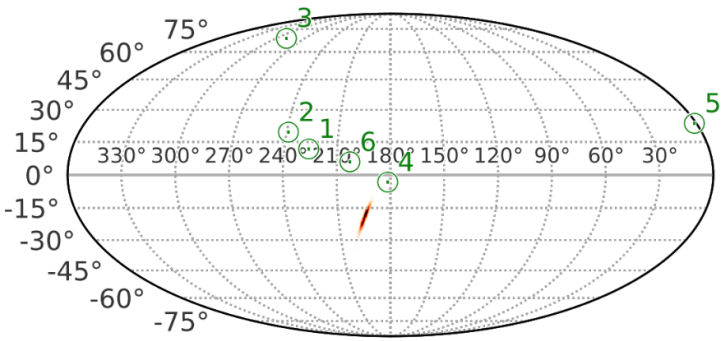
- LIGO-Virgo candidates currently generate ~40-50% of GCN circular trafic
  - S190425z (BNS) and S190814bv (NSBH) generated ~120 circulars
  - S190728q (MassGap then BBH) generated ~40 circulars
  - Fermi GBM-190816 generated ~20 circulars

LIGO-Virgo O3 run : GW and neutrinos

- LVC publication plan includes :
  - a joint High Energy Neutrino / GW search (GWHEN). Possible sources :
    - BH with accretion disk/tidal disruption
    - AGN blazar flare
    - Binary BH merger
    - Long GRB, supernova and choked jet supernova.
  - a search for GW emitted by (galactic) CCSN (low energy neutrino signal providing accurate timing information)

LIGO-Virgo O3 run : GW and neutrinos

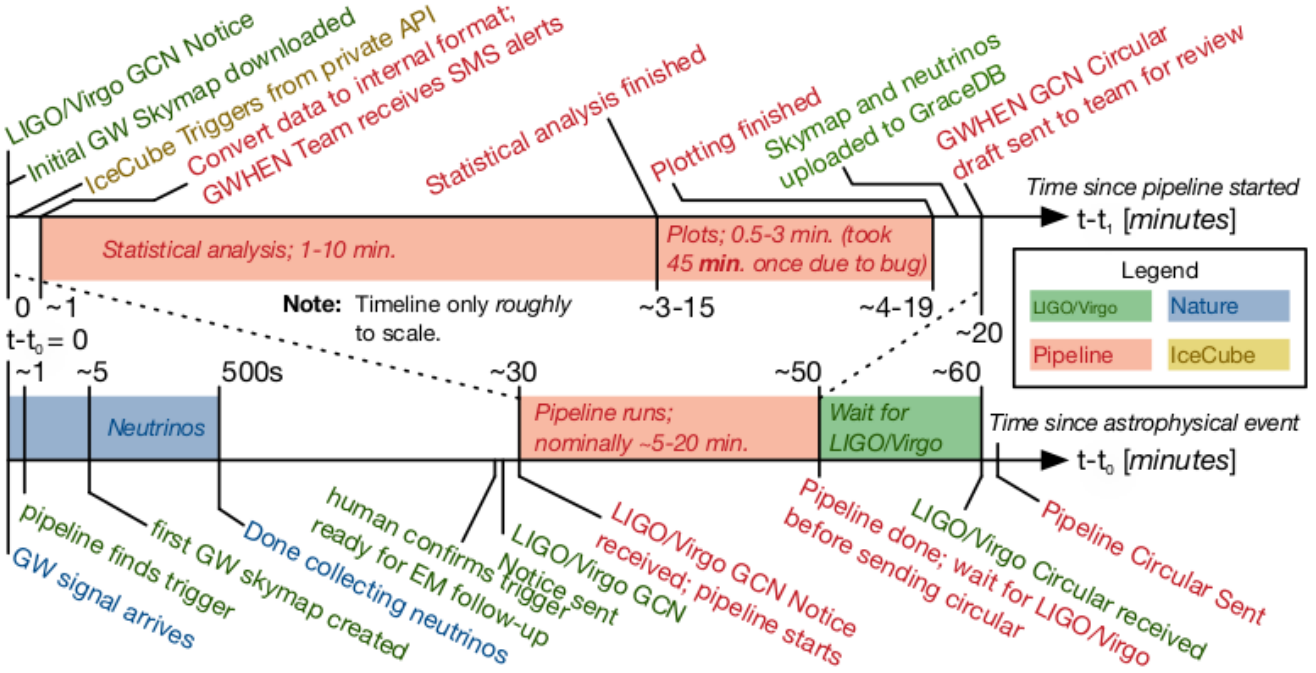
- GWHEN searches with IceCube and ANTARES data through MOUs
  - Many publications, including the follow up of the O1/O2 main CBC sources
  - Since O2 : low latency searches using public LVC alerts



  - Currently under development : sub-threshold LL symetric joint searches
    - LL : rapid identification is needed for timely follow-up observations of transient emission
    - Sub-threshold : searches based on triggers that could not individually be established as discoveries

LIGO-Virgo O3 run : LLAMA pipeline

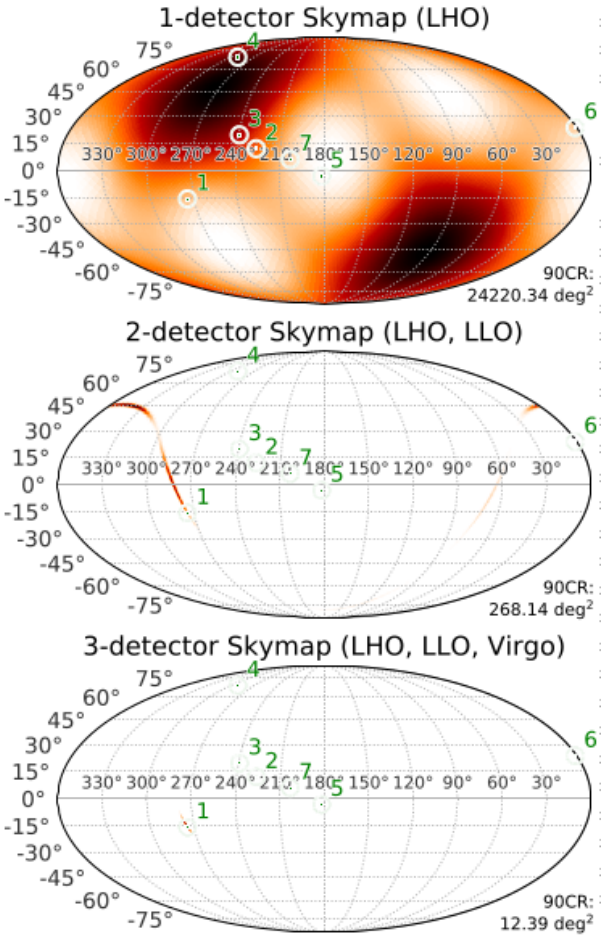
See Imre Bartos talk



Countryman et al, arXiv:1901.05486

Bartos et al. arXiv:1810.11467

Joint sky map



LVC + KM3Net : prospectives

Baret et al, https://www.epj-conferences.org/articles/epjconf/pdf/2019/12/epjconf_vlvnt2018_02009.pdf

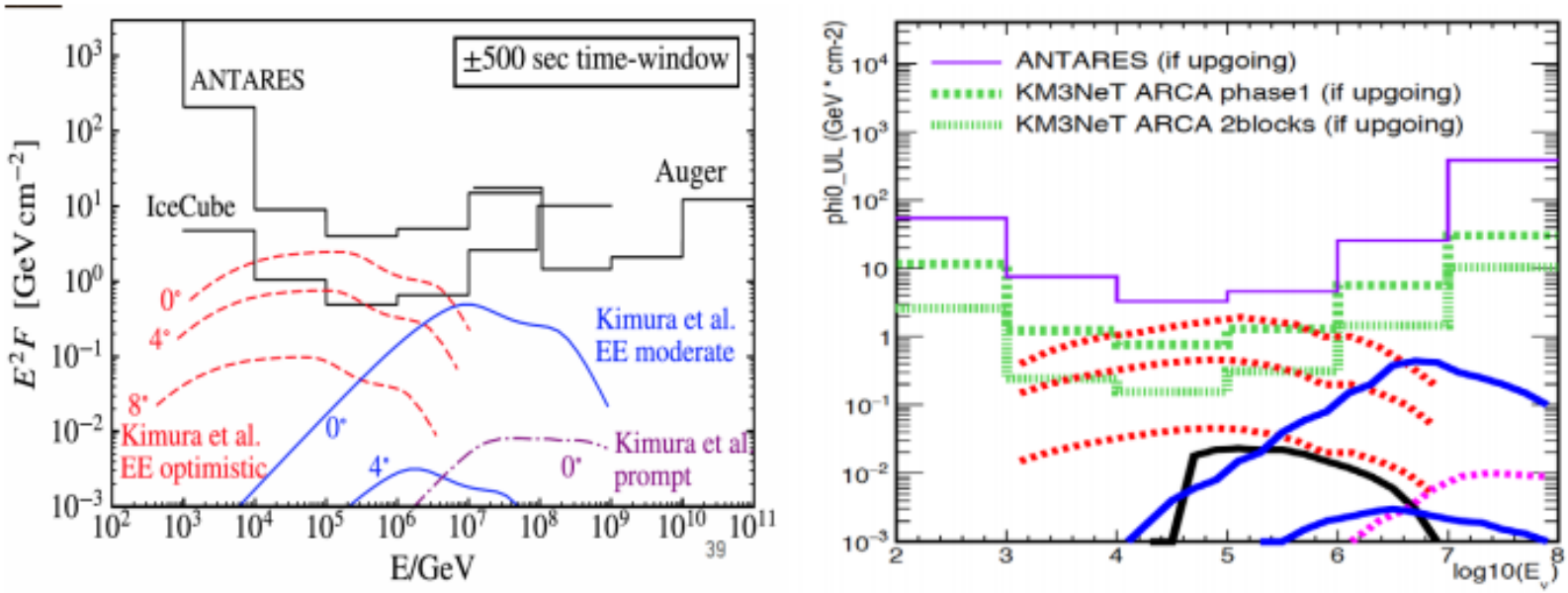
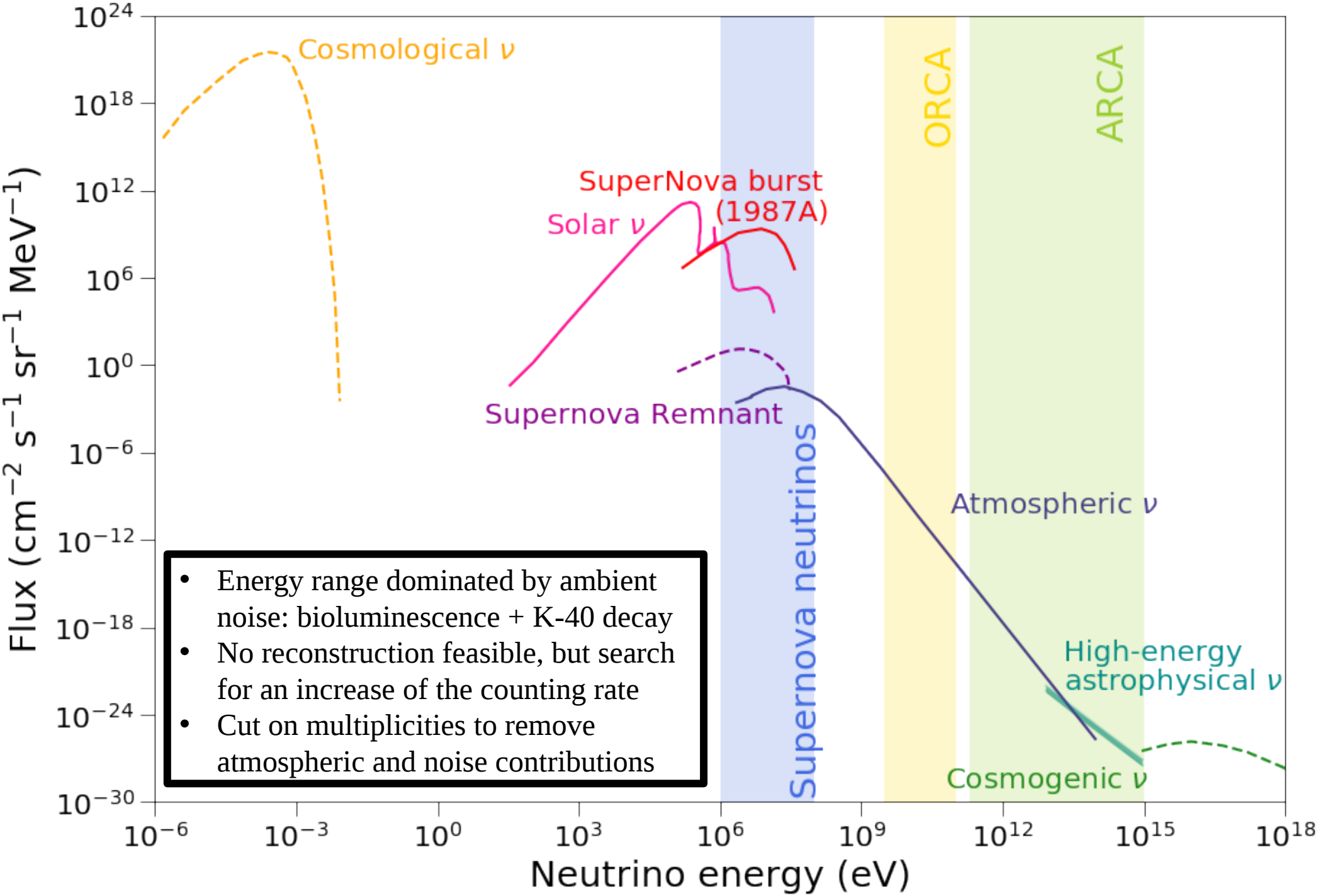


Figure 2. Left: High energy neutrino fluence upper limits for the ANTARES, IceCube and AUGER detectors in the direction of GW170817 together with model predictions [9]. Right: Same as left for ANTARES and KM3NeT for its different construction phases in case the source was in the up-going events field of view. The Baikal GVD experiment has performed a similar analysis, see [8].

KM3NeT for CCSN neutrino searches

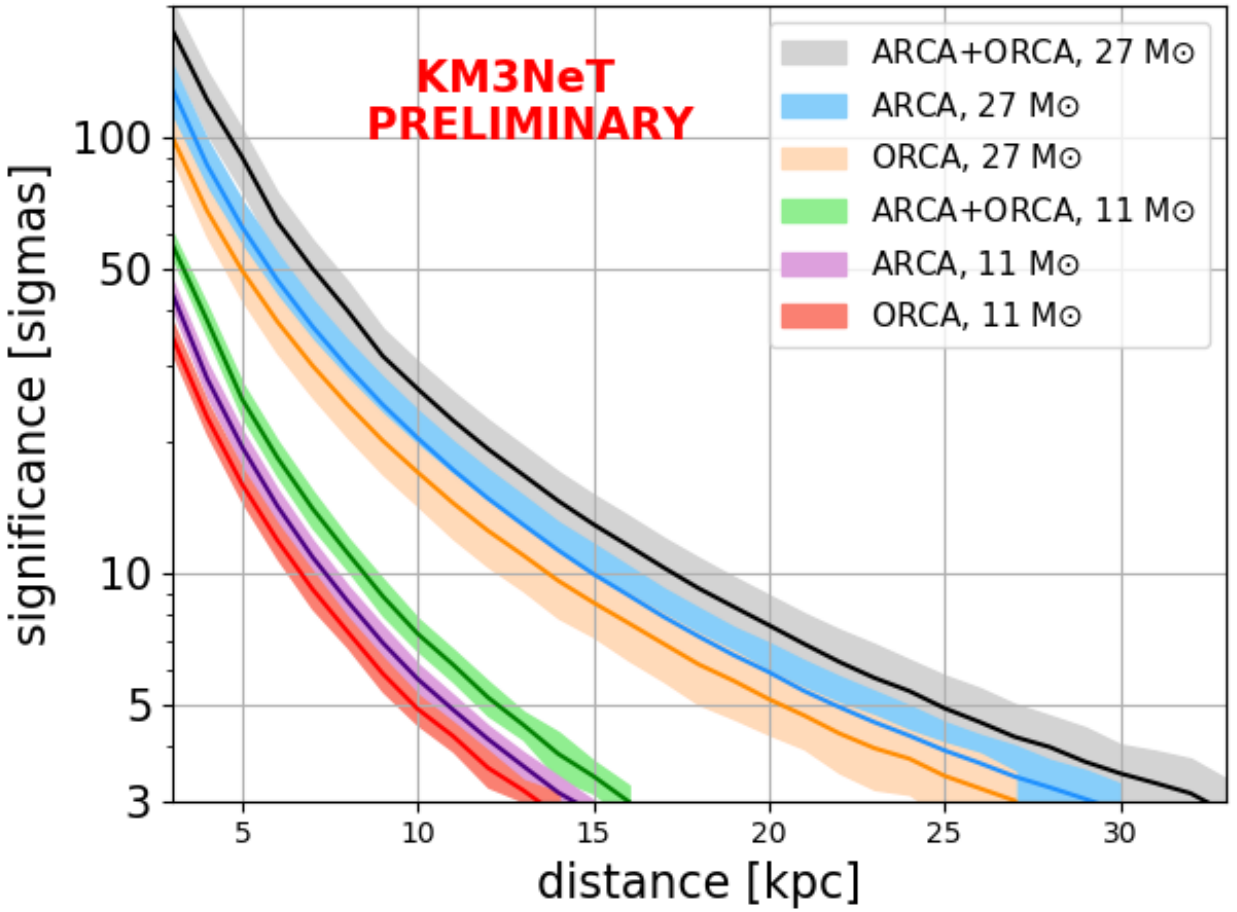
From Gwen de Wasseige



- Energy range dominated by ambient noise: bioluminescence + K-40 decay
- No reconstruction feasible, but search for an increase of the counting rate
- Cut on multiplicities to remove atmospheric and noise contributions

From Gwen de Wasseige

Sensitivity



See Massimiliano Lincetto talk

- KM3NeT is sensitive to electron anti-neutrinos via inverse beta decay
- KM3Net will be part of SNEWS

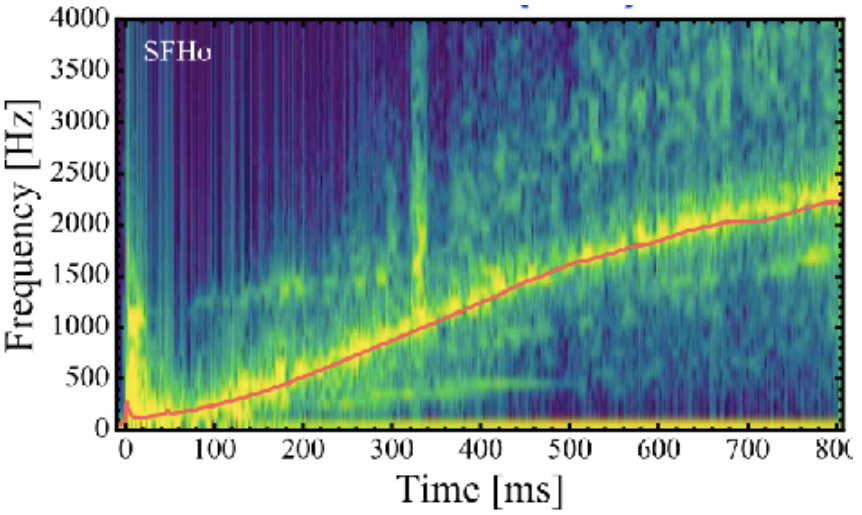
	2025 ORCA115 + ARCA230	
27 M_{sun}	5 σ	25 kpc
11 M_{sun}	5 σ	Galactic center (even with just ORCA)

(conservative estimate)

M. Colomer for the KM3NeT Collaboration, ICRC 2019

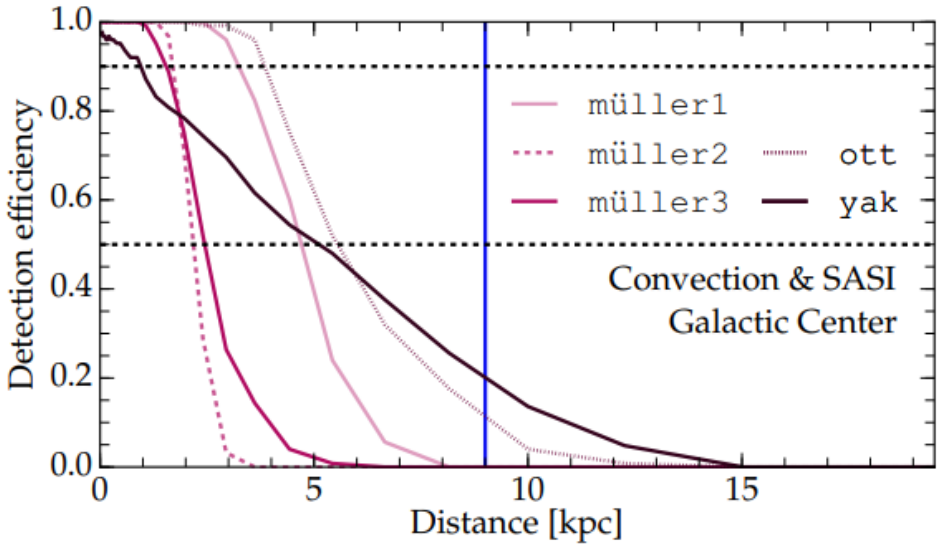
The CCSN GW detection panorama in the next 10 years

- Advanced LIGO / advanced Virgo / KAGRA: 2 types of searches:
  - All-sky/ all-time searches (silent supernova)
  - Targeted searches (neutrino & optical alerts):
    - false alarm rate reduced,
    - a short on source window allows to use signal extraction methods that are computing time limited (Bayesian methods using CCSN waveforms or simplified models).



Sensitivity: limited to the Galaxy

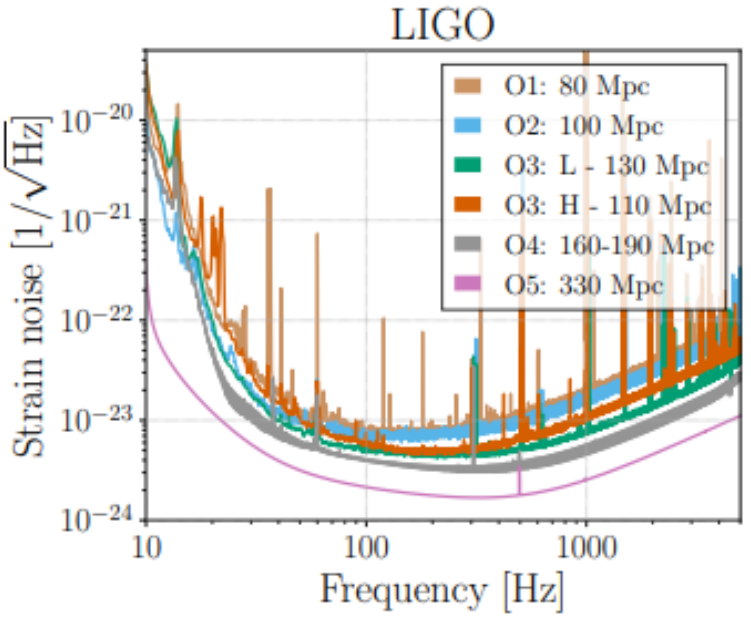
Gossan et al, arXiv: 1511.02836

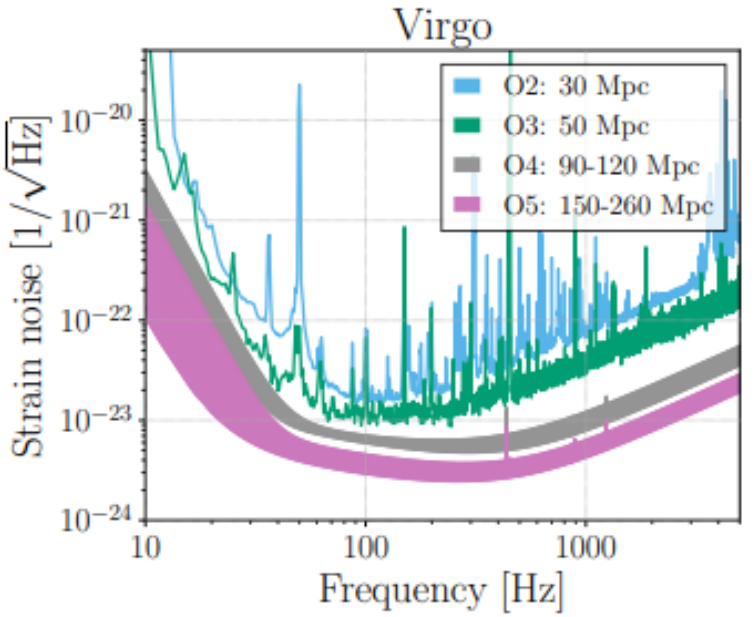


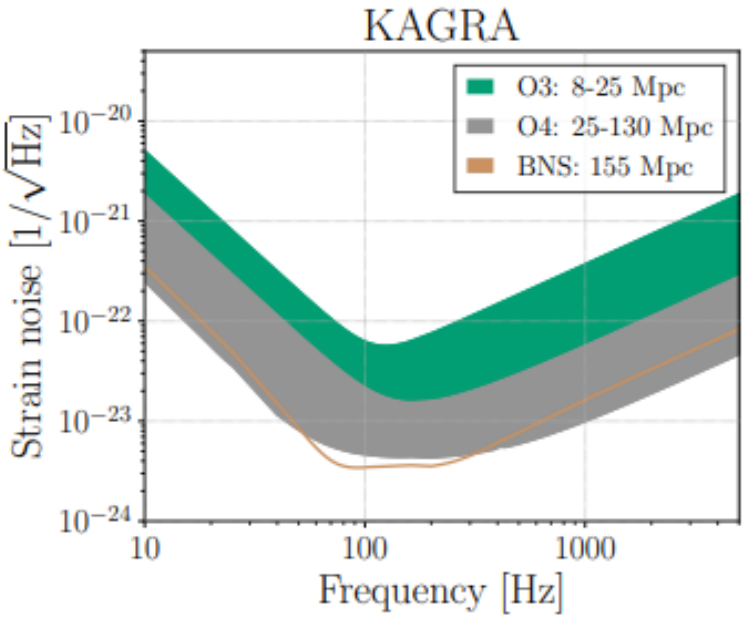
- Source parameter estimation :
  - Agnostic waveform reconstruction using the coherence of the GW polarizations in 2 or more GW detectors data.
  - Identify some of the (loudest) features expected in the different phases : rotation at bounce, quiessence phase, SASI, PNS oscillation modes, …
  - Determine the explosion mechanism : neutrinos or MHD.
  - Constrain EOS, progenitor mass, ..

LIGO-Virgo-KAGRA in the KM3net era

arXiv:1304.0670







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Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	250 – 310	310 – 390	250 – 340
O4	HLVK	29 – 48	48 – 69	33 – 47
		Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.	Comoving Volume (10^3 Mpc^3) 90% c.r.
O3	HLV	90 – 130	590 – 1000	11000 – 19000
O4	HLVK	43 – 71	400 – 560	6400 – 10000

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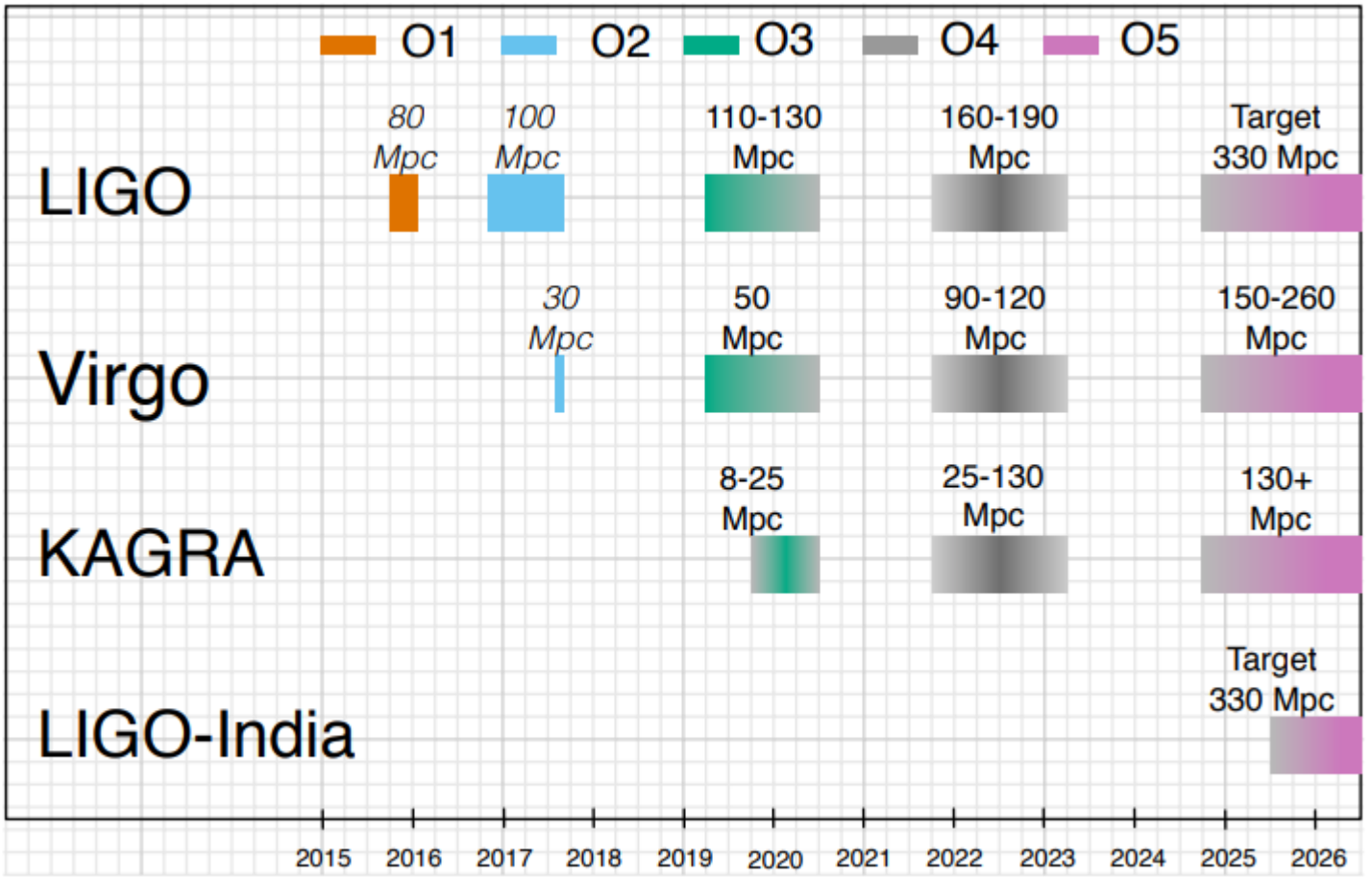
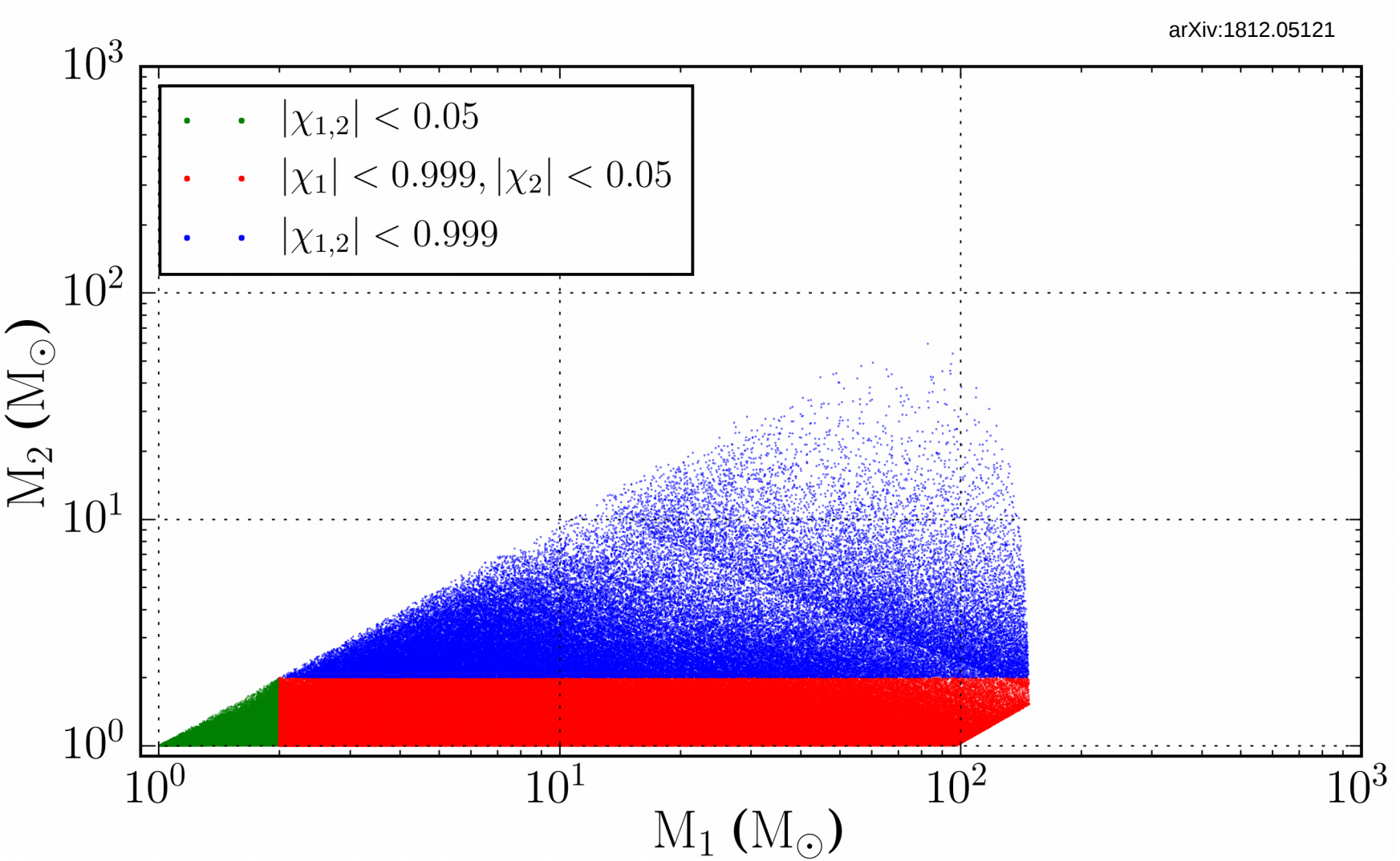


Concluding remarks

- GW and neutrino (+EM) messengers to study the same transient sources : clear synergy between GW detectors and neutrino detectors.
- LVK GW alerts are public (GCN and VOEvent).
- LVK data are public 18 months after the first 6 months of a run.
- LVC event portal : https://www.gw-openscience.org/eventapi

GSTLAL template bank