Data analysis for Supernova search: A focus on multimessenger approaches

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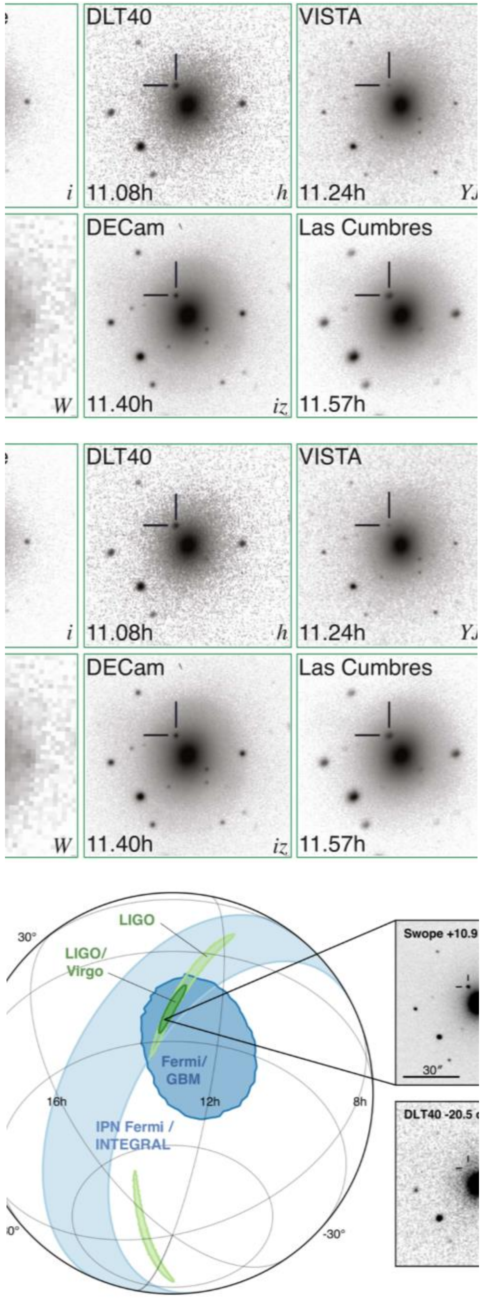
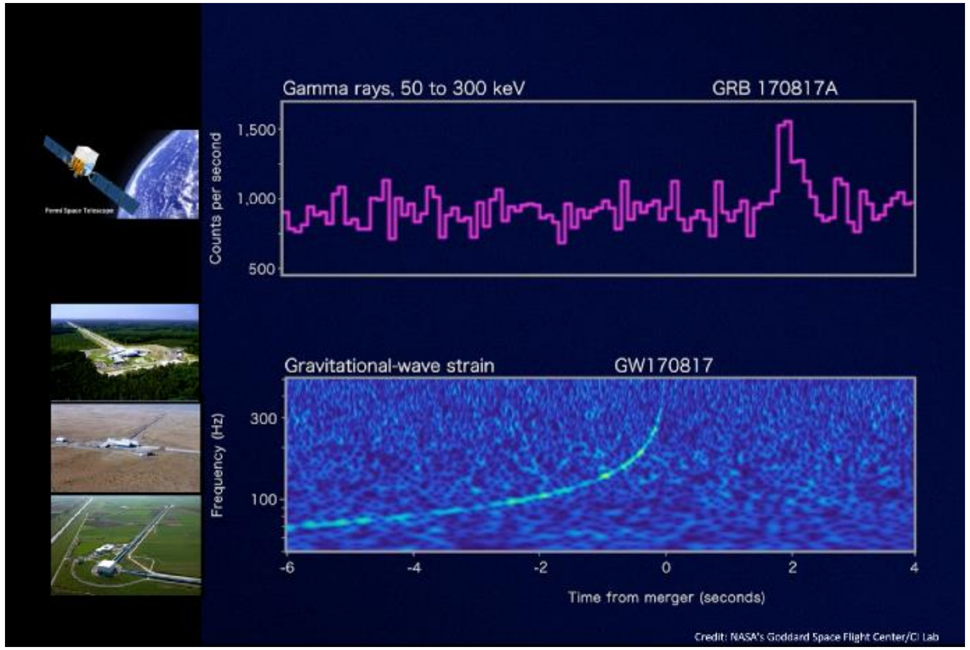
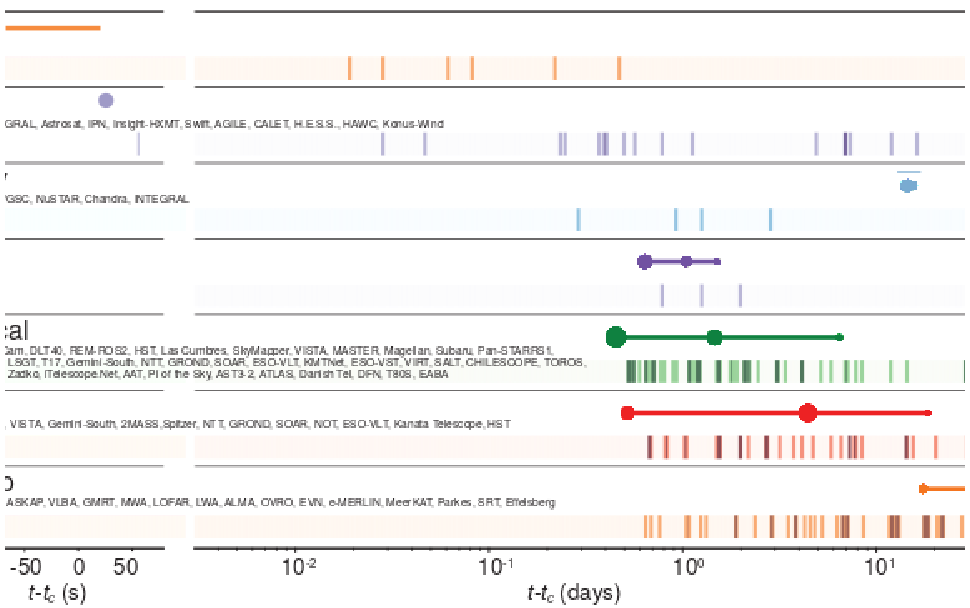
Multi-messenger: WHY?

GW170817 + GRB170817A

- First Multi-messenger GW+EM detection
- Binary Neutron Star Coalescence
  - Triggered by coincident GW and GRB
- *Phys. Rev. Lett.* ***119**, 161101 (2017)*
- *Astrophys. J. Lett.* ***848**, L12 (2017)*

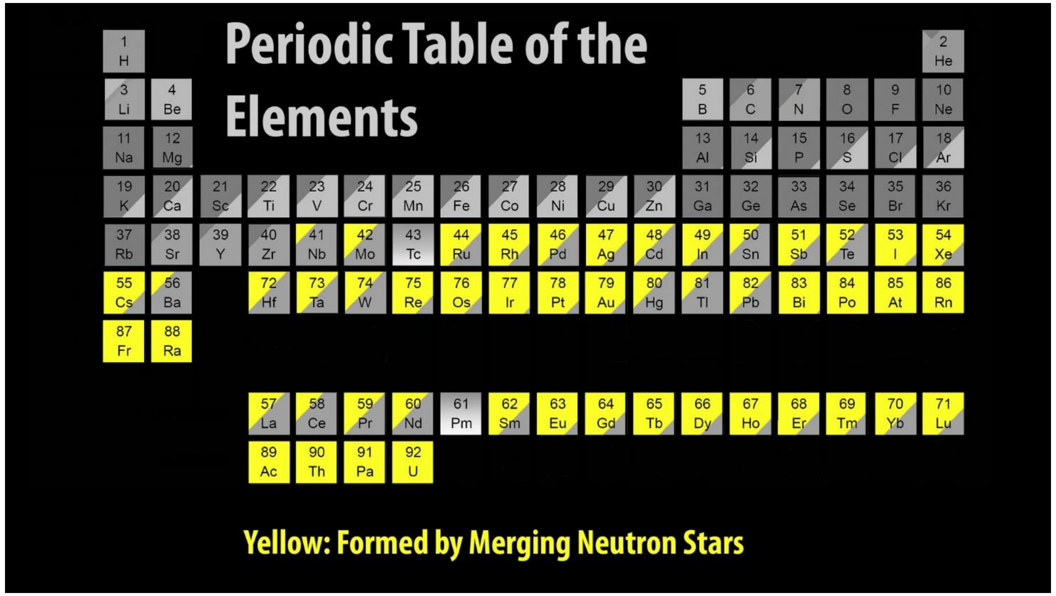




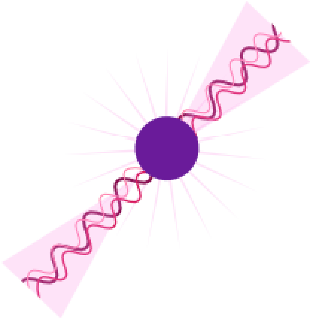


The dawn of multimessenger astronomy

NEW DISCOVERIES WITH ONE EVENT

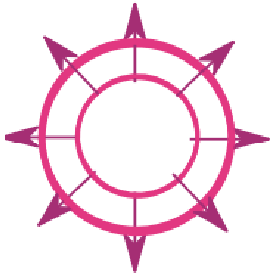


Observing both electromagnetic and gravitational waves from the event provides compelling evidence that gravitational waves travel at the same speed as light.



This multimessenger event provides confirmation that neutron star mergers can produce short gamma ray bursts.

The observation of a kilonova allowed us to show that neutron star mergers could be responsible for the production of most of the heavy elements, like gold, in the universe.

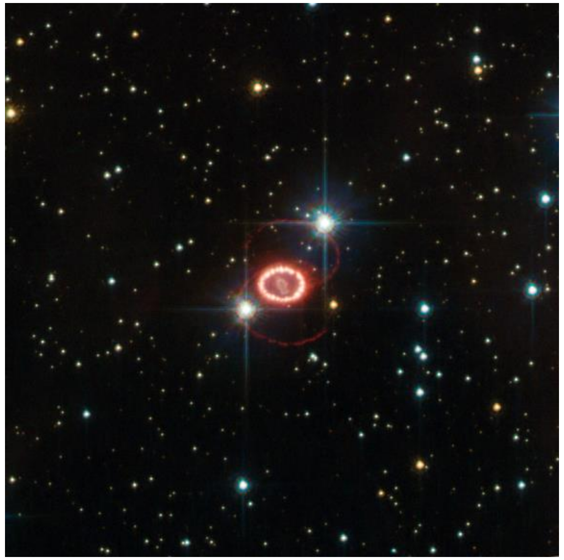


GW170817 allows us to measure the expansion rate of the universe directly using gravitational waves for the first time.

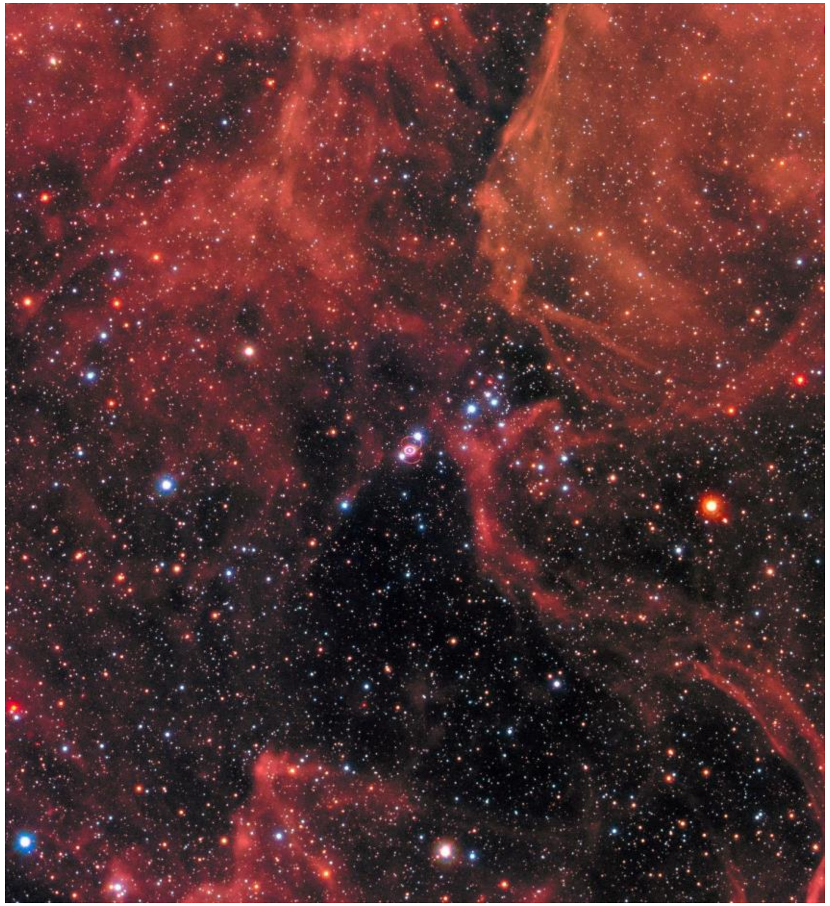
1987 supernova

- The first multi-messenger detection
  - EM spectrum
  - Neutrino

  - No GW observed (Resonant bars)



Credits: By NASA, ESA



Credits: By NASA, ESA, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation) and P. Challis (Harvard-Smithsonian Center for Astrophysics)

Advantages of a Multi-Messenger SN detection

- Increase detection confidence

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- Sky localization
  - Galaxy, object
  - Luminosity vs comoving distance
    - Cosmological estimation (z, H, …)

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- Increase detection confidence
- Sky localization
  - Galaxy, object
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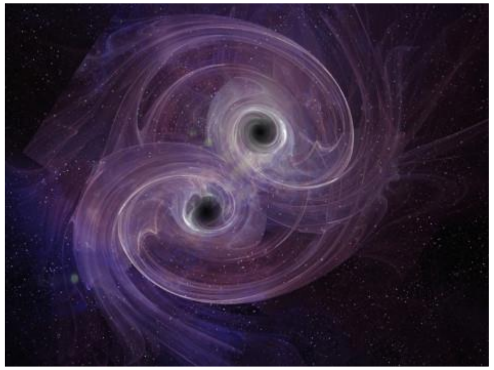
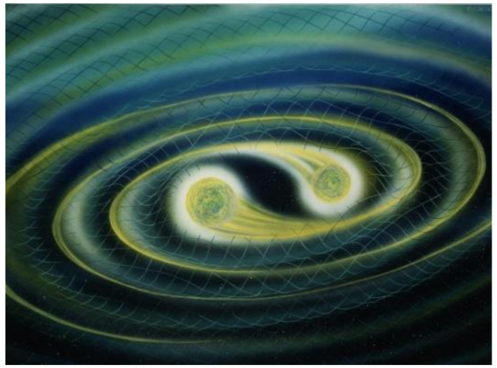
    - Cosmological estimation (z, H, …)
- Source characteristics
  - M/R from GW (*see H. Andresen, A. Torres-Forné*)
  - R from ν (*Astrop. Phys 31, 2009*, see M. Ballelli)
  - More …

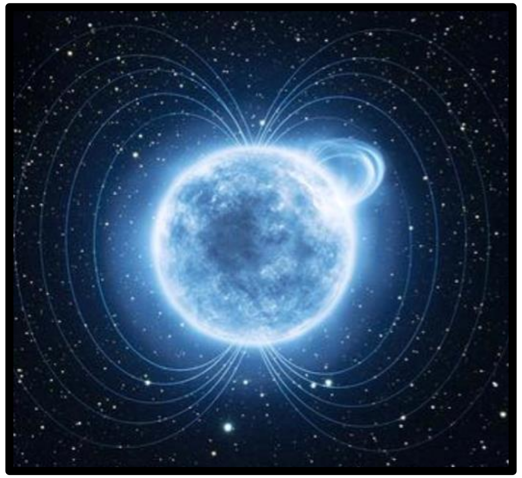
Multi-messenger: WHO?

Multi-messenger sources

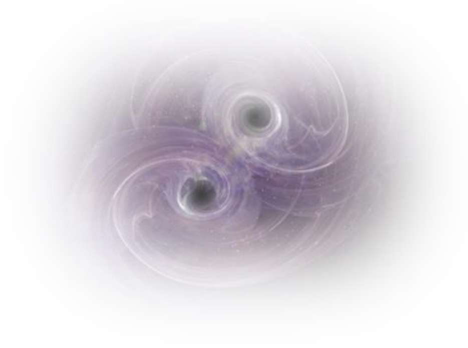
Coalescence of binary system of neutron stars and/or stellar-mass black-hole

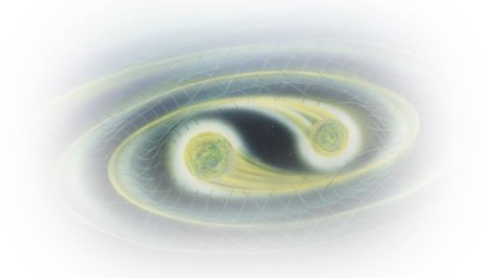
Isolated neutron stars



Core-collapse of massive stars

Multi-messenger sources





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radio C
Intermezzo

Hypothesis test

Signal presence	
Yes	No

- At each time the signal could be present or not

Hypothesis test

		Signal presence	
		Yes	No
Decision rule	Yes		
	No		

- At each time the signal could be present or not
- At each time we can decide that the signal is present or not (decision rule)

Hypothesis test

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Decision rule	Yes	True Alarm	False Alarm
	No	False Dismissal	True Dismissal

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- 4 situations: two right and other wrong

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- At each time the signal could be present or not
- At each time we can decide that the signal is present or not (decision rule)
- 4 situations: two right and other wrong
- Neyman-Pearson criterion: best decision rule gives greater True Alarm Rate at the same False Alarm Rate

True alarm

- Simulated gravitational waves are injected in the data to characterize detection efficiency according to:
  - GW parameters (or source parameters)
  - source distance
  - characteristic frequency
  - …

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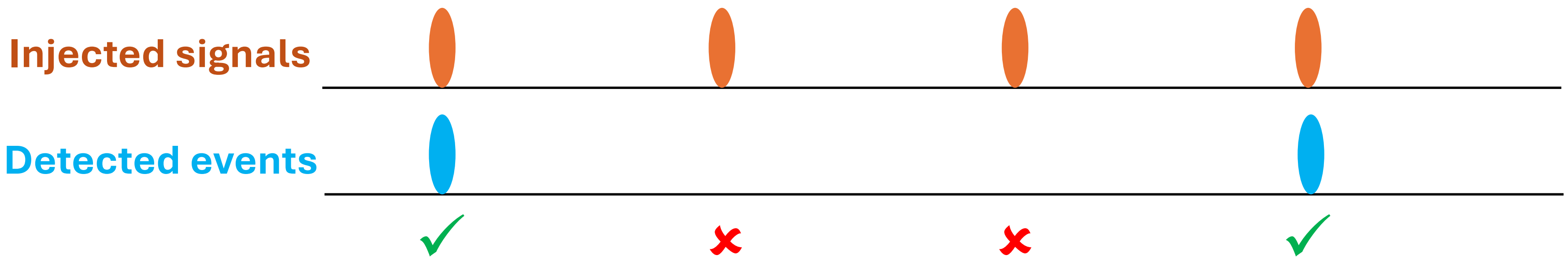
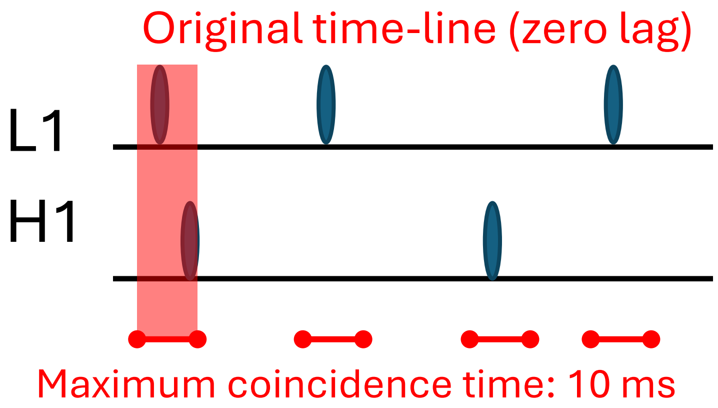


False Alarm

- Noise artefacts in more detectors can by chance produce coincidences



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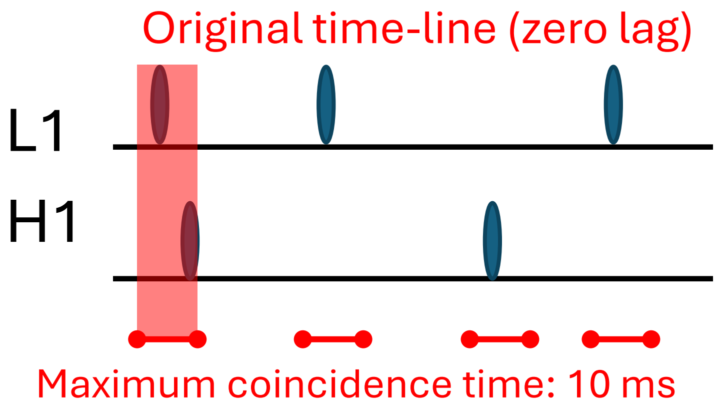
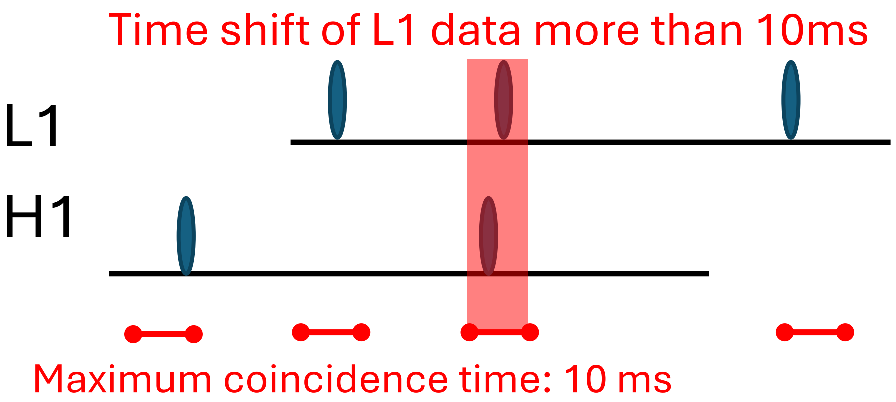
- Time-shift procedure: characterize statistically the rate of this accidental coincidences





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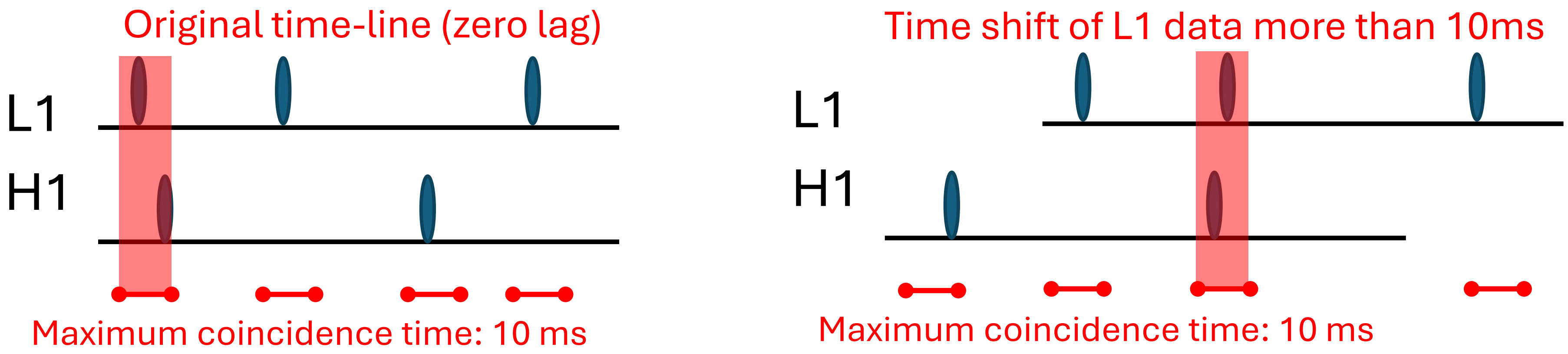


- Re-sampling many times give enough statistics to assess confidence to an event on the zero lag (Background)

GW algorithms

- Given the lack of SN models, GW algorithms open to wide class of signals
  - Coherent WaveBurst, X-Pipeline, BayesWave, ...
- Main limiting factor: SNR
  - Minimum detectable SNR
  - GW from SN has really low energy
- Highly affected by noise excesses

Search for excess power
in time-frequency domain
(Wavelet, Q-transform, ...)

⬇

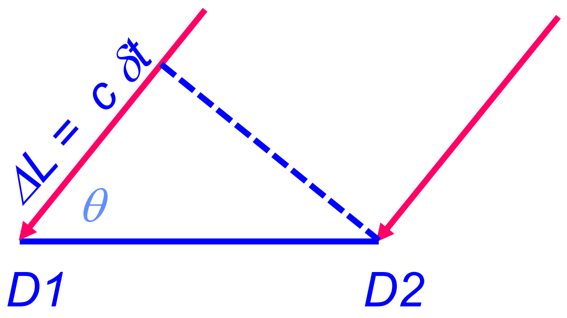
Combine coherently the excess powers of
different detector in a unique data stream
Consider time-delay between detectors
Include antenna pattern factors

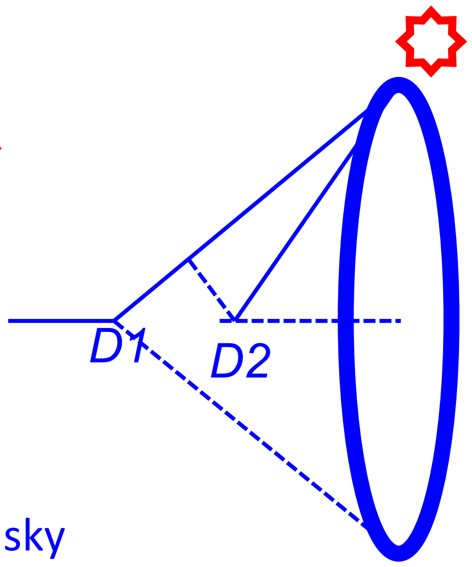
⬇

Calculate a detection statistic and compare
the one of each candidate to the
background distribution

Source localization

- *The **sky position** of a GW source is mainly **evaluated by triangulation**, measuring the differences in signal arrival times at the different detector sites*





2-detectors → annulus in the sky

Source localization

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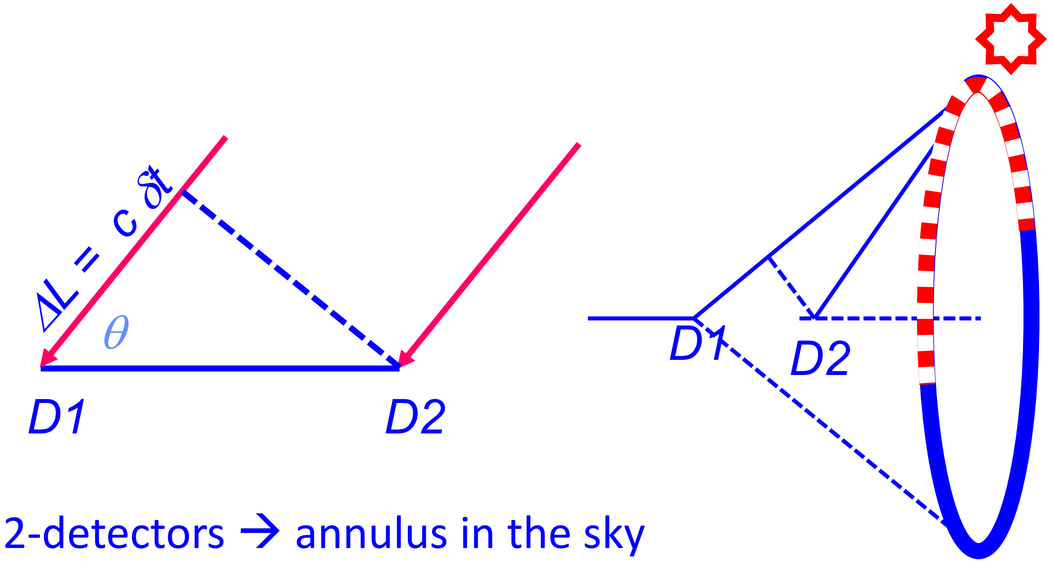
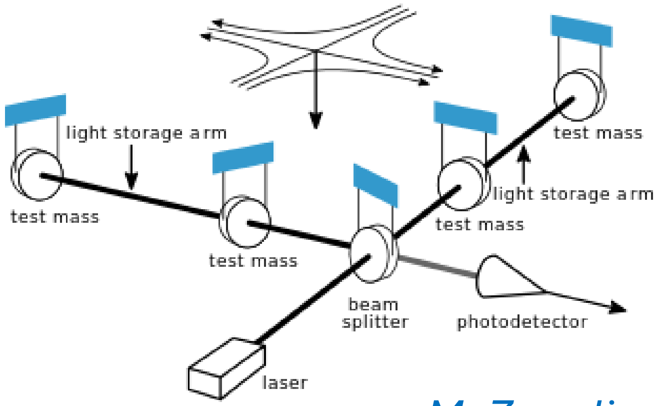
$$\xi(t) = F_{+}(\theta,\varphi,\psi)h_{+}(t) + F_{\times}(\theta,\varphi,\psi)h_{\times}(t)$$



2-detectors → annulus in the sky

MOREOVER: ANTENNA PATTERNS SELECT/DISCARD SKY ZONES

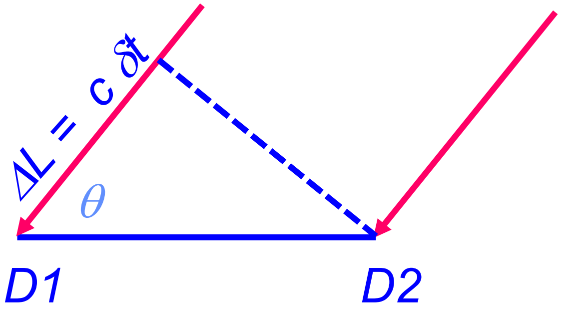


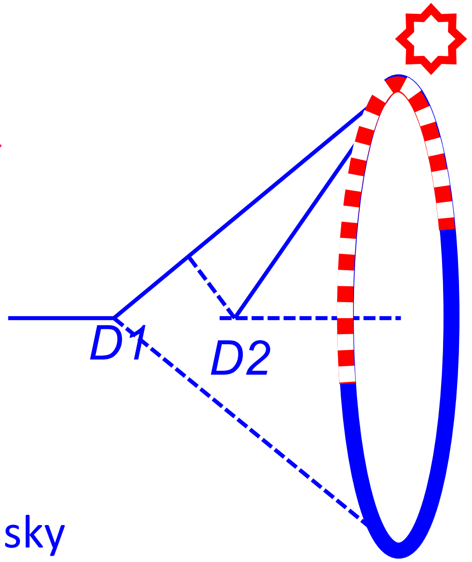
see M. Zanolin

Source localization

- *The* ***sky position*** *of a GW source is mainly* ***evaluated by triangulation,*** *measuring the differences in signal arrival times at the different detector sites*

- ***Localization requires a network of GW detectors***





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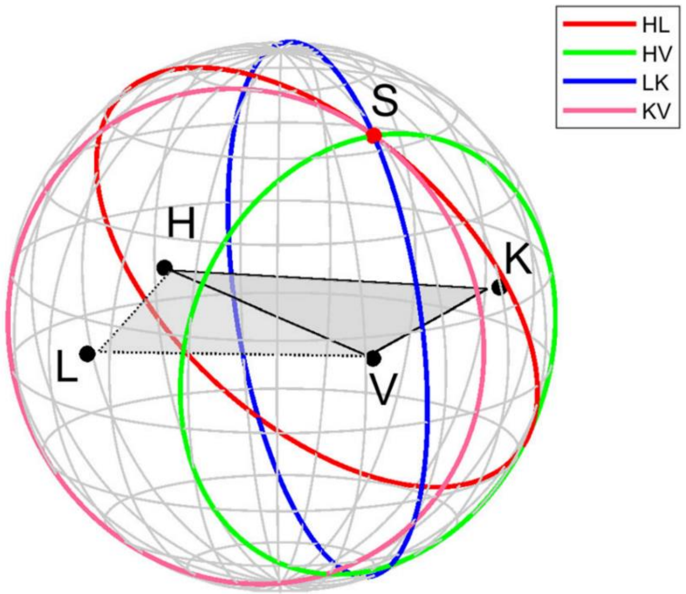
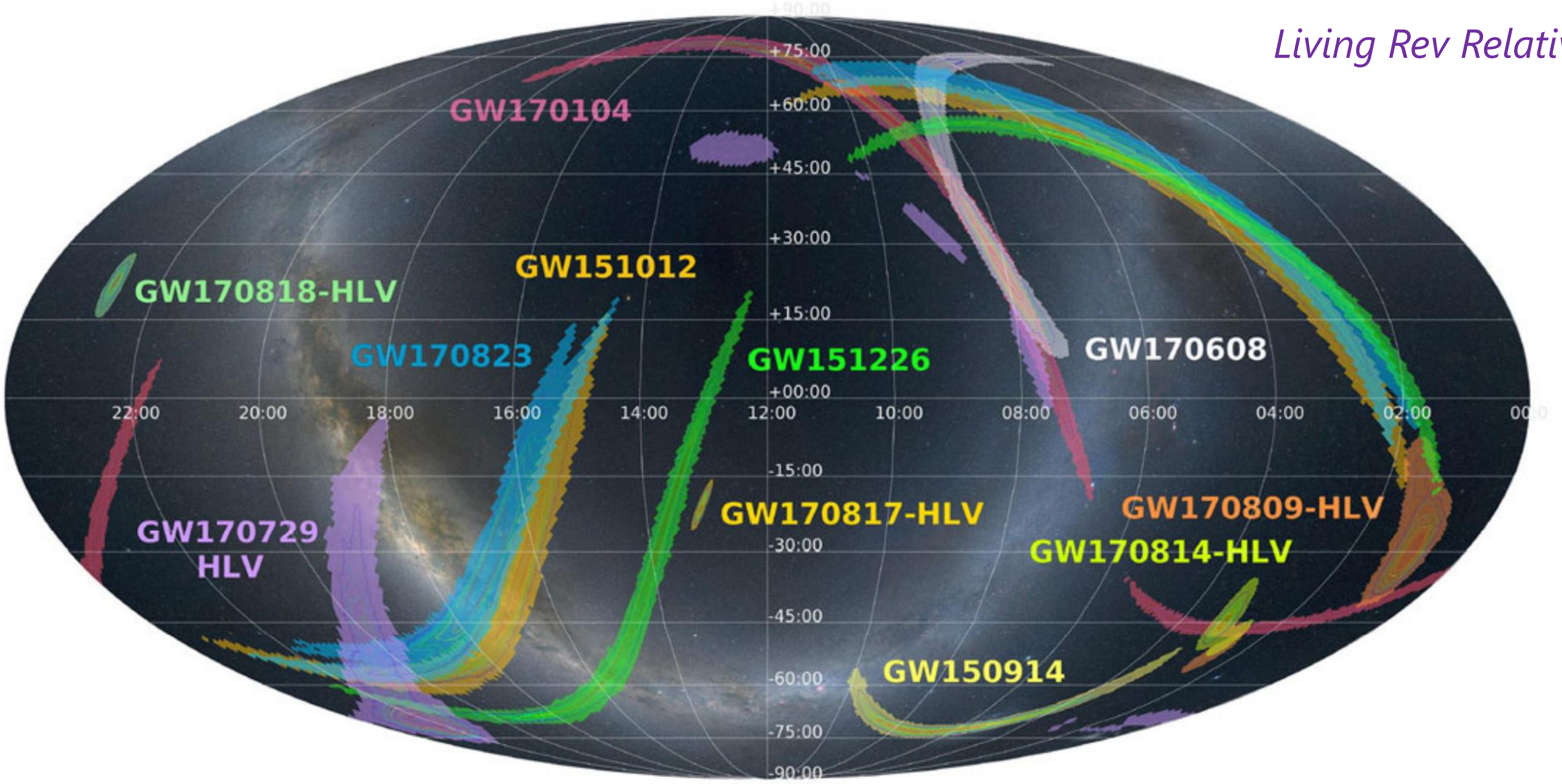


>3-detectors → localize

Various localizations

Living Rev Relativ 23, 3 (2020)



Sky locations of GW events confidently detected in O1 and O2

Multi-messenger: WHERE&WHEN?

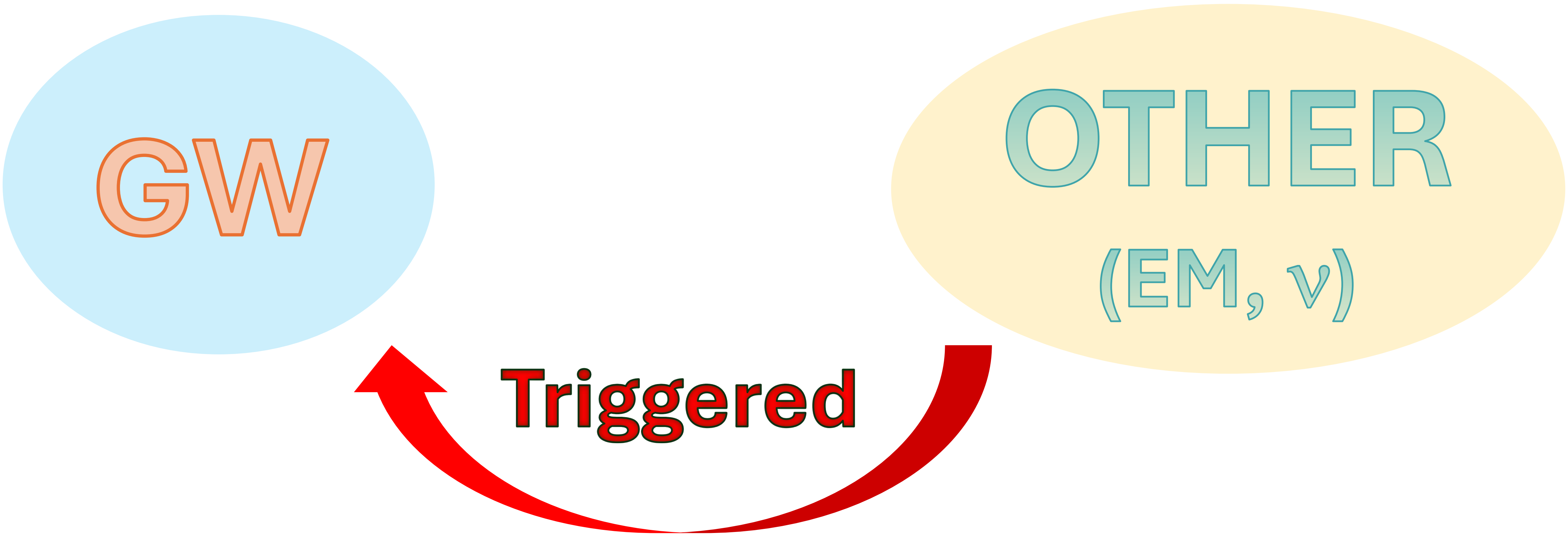
GW point-of-view

GW

OTHER

(EM, ν)

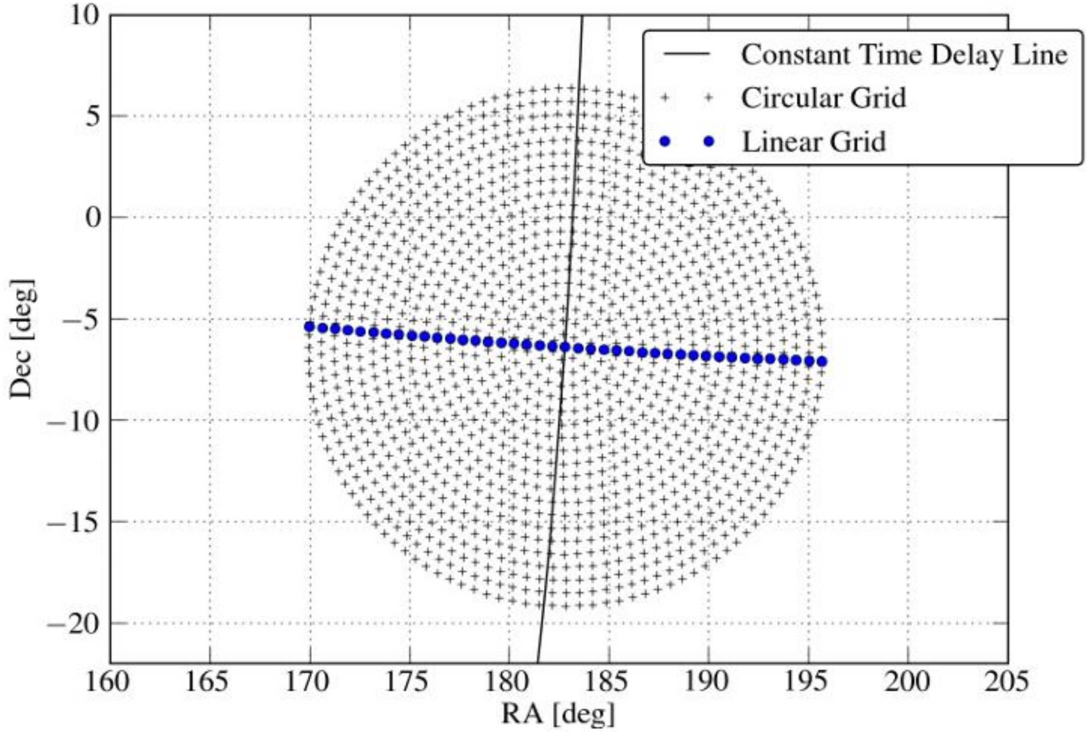
GW point-of-view



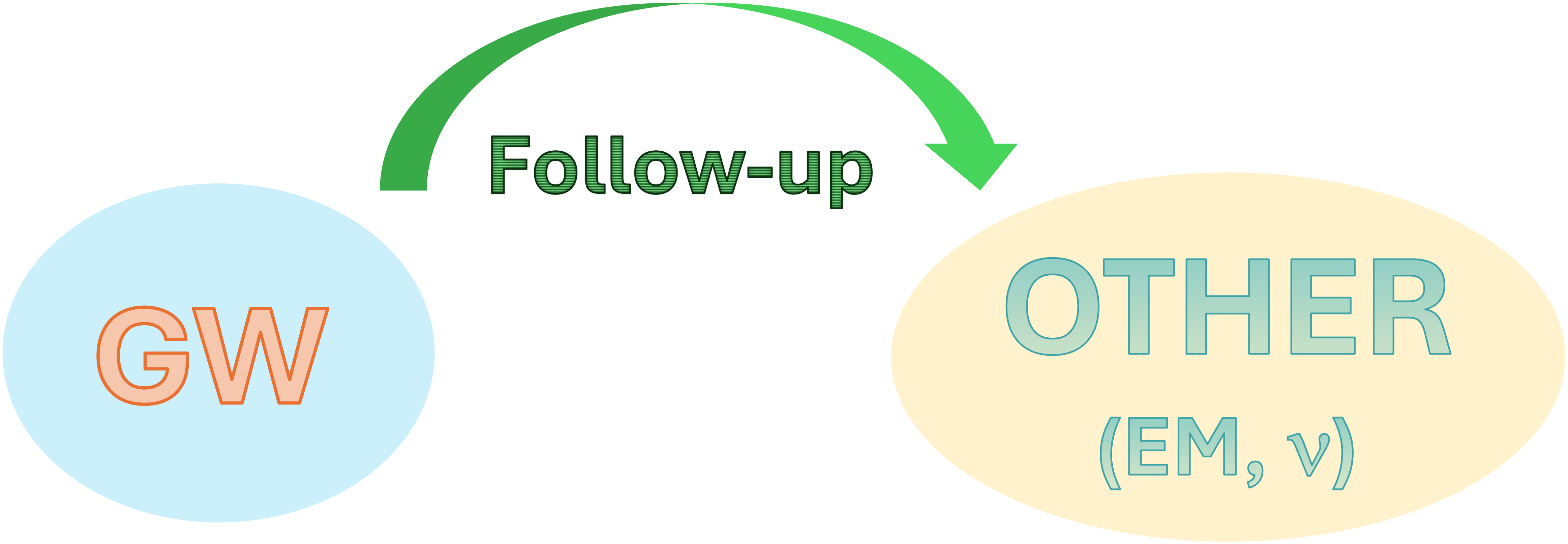
GW+EM Triggered

- GW analysis for Sky directions and timing given by other messengers
  - SN from Optical trigger (*see S. Klimenko, R Poggiani, Y. Zheng*)
  - GRB trigger
- Knowing sky position and time window allows to reduce FAR
  - Increase detection probability

Phys. Rev. D 89 122004



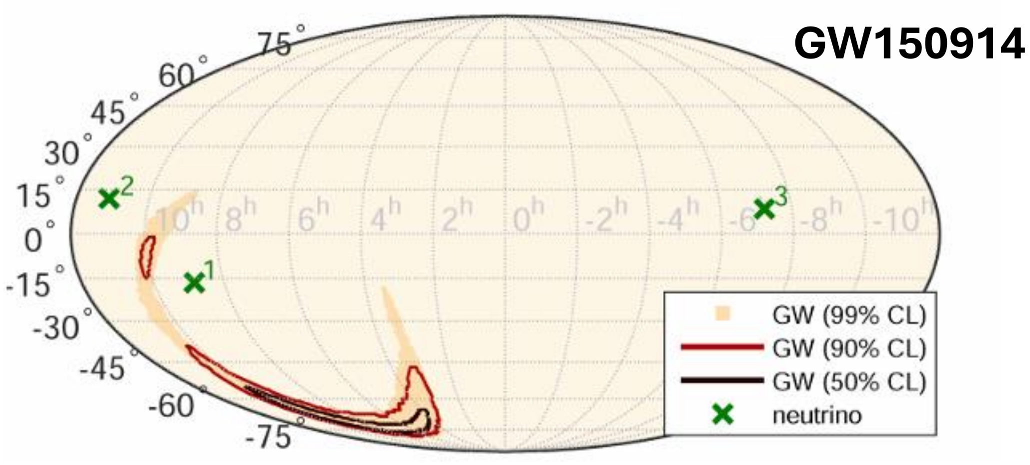
GW point-of-view



GW+ν

Follow-up

- Search for Neutrino at same time of GW Triggers



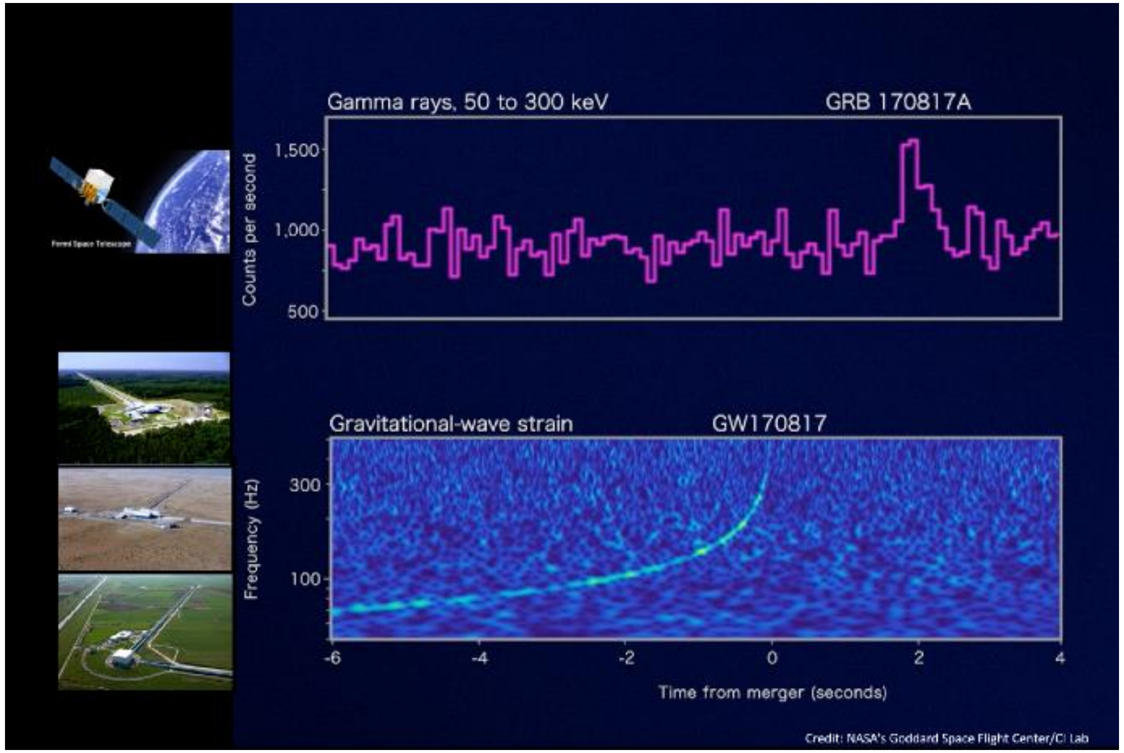
[Phys. Rev. D **93**, 122010 (2016)]

GW+ν

Follow-up

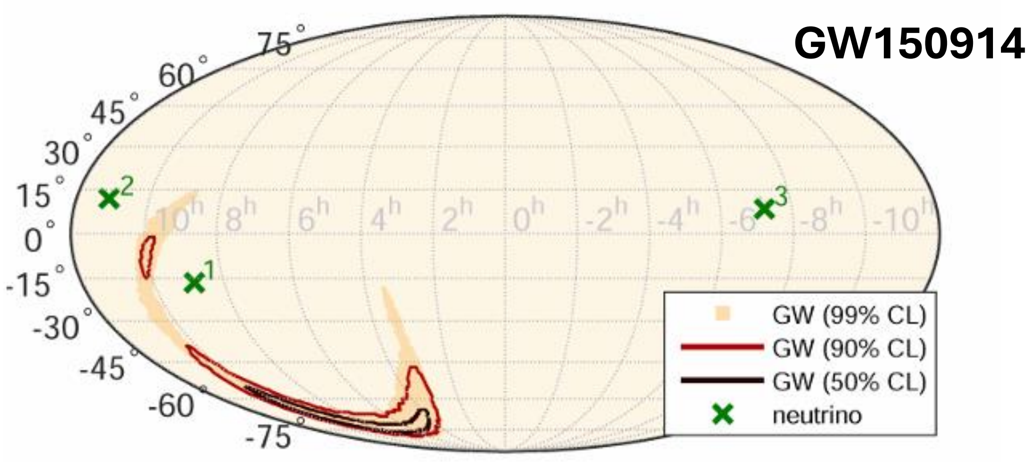
GW+EM

GW170817



- Search for Neutrino at same time of GW Triggers

GW150914



*Phys. Rev. D **93**, 122010 (2016)*

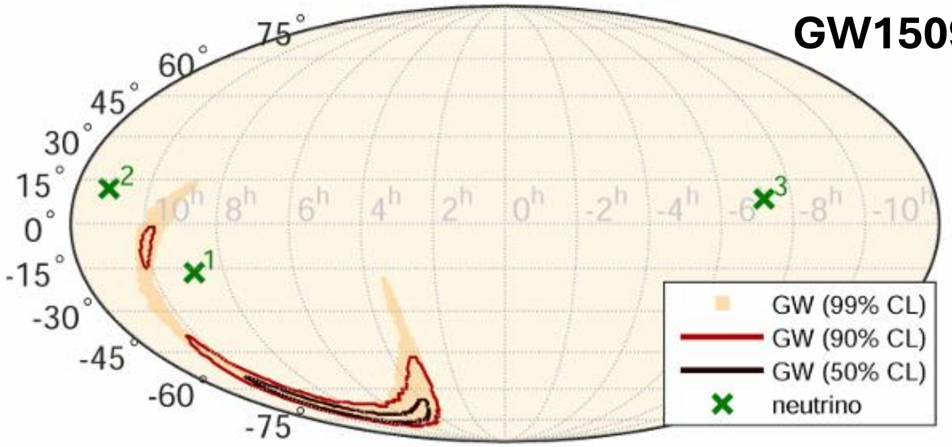
GRB 1.7 after GW
GW won the race!

GW+ν Follow-up

JOINT SEARCH GW+EM

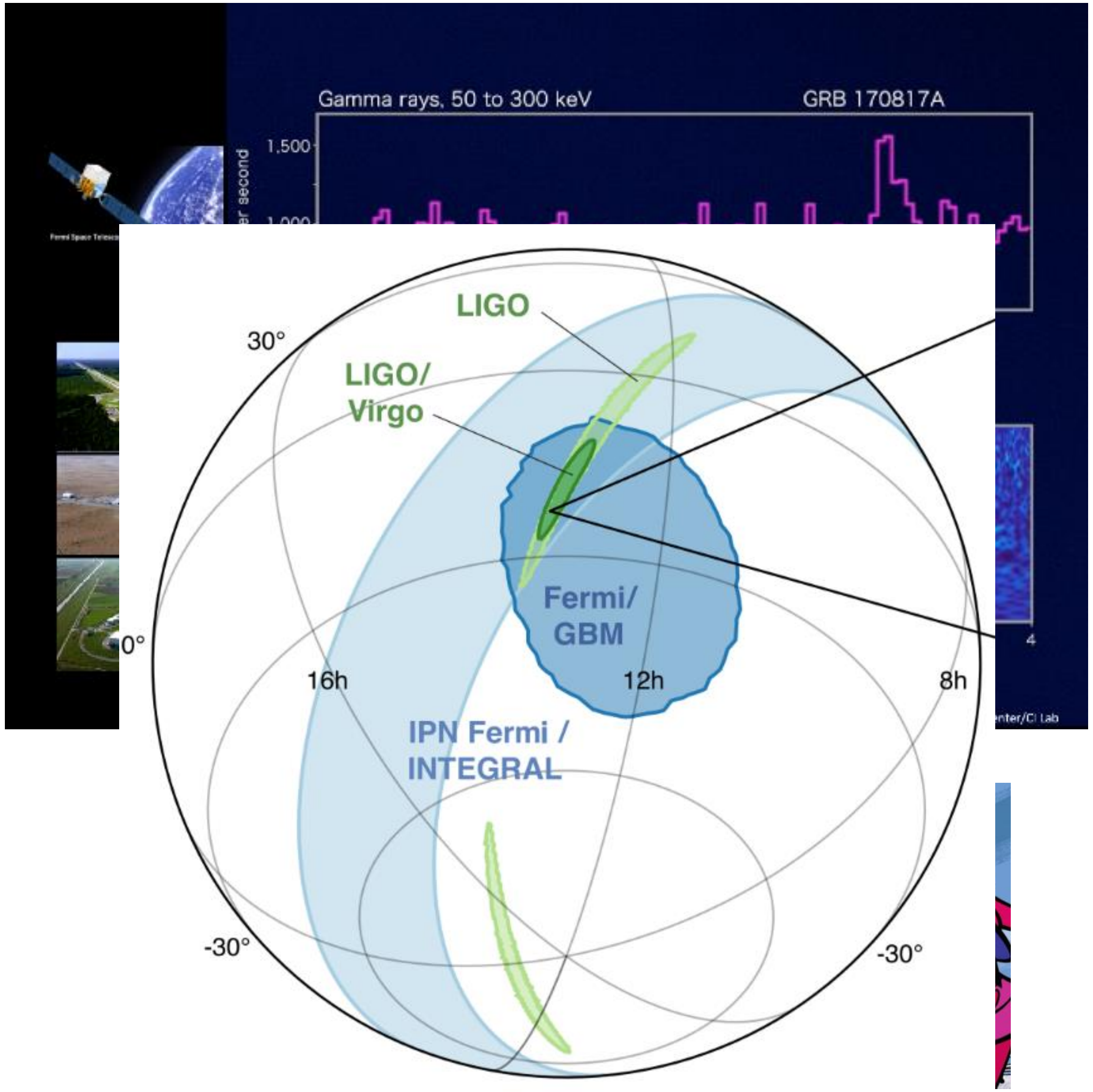
- Search for Neutrino at same time of GW Triggers

GW150914

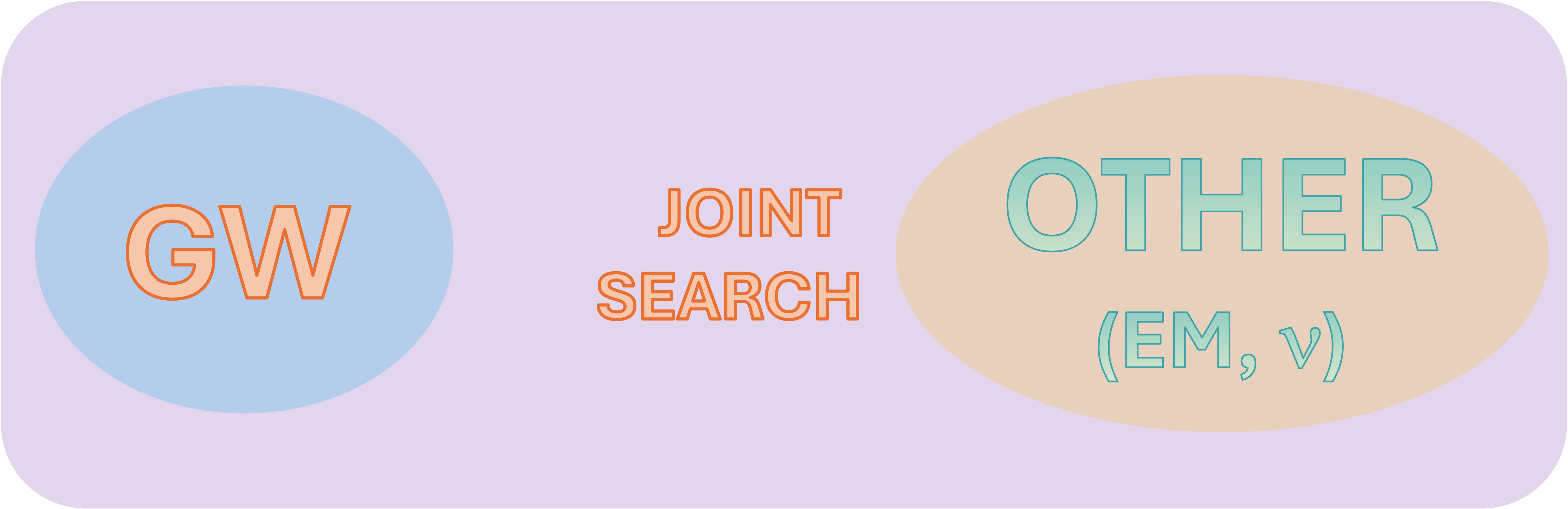


[Phys. Rev. D **93**, 122010 (2016)]

GW170817



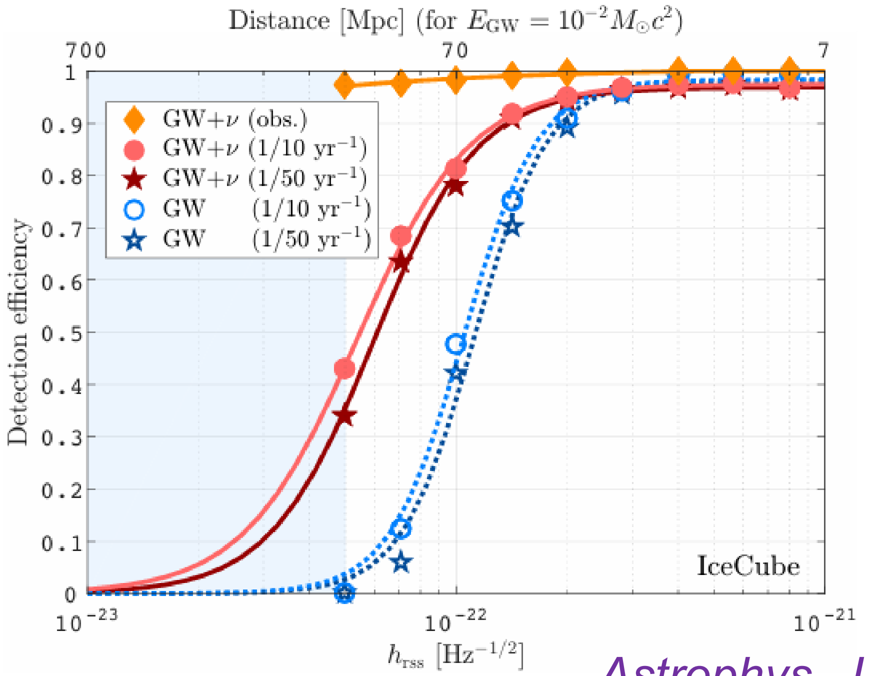
GW point-of-view



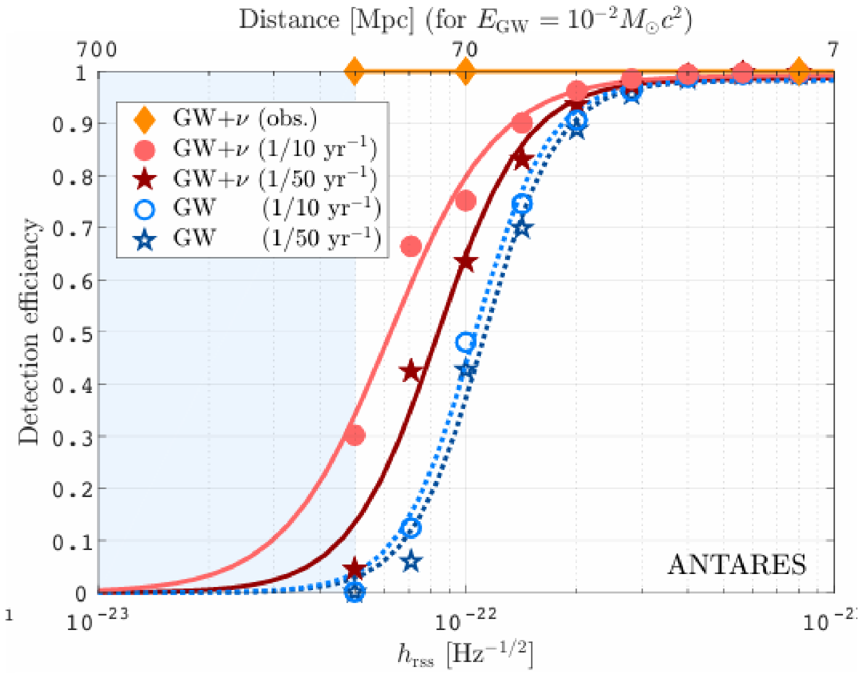
GW+ν

JOINT SEARCH

- Search for Neutrino at same time of GW Triggers
- Search for Neutrino and GW occurring the same time and sky directions
  - Joint sky map probability



[Astrophys. J. **870**, 134 (2019)]



Multi-messenger: WHAT (else)?

Not exhaustive overview on search approaches not already mentioned

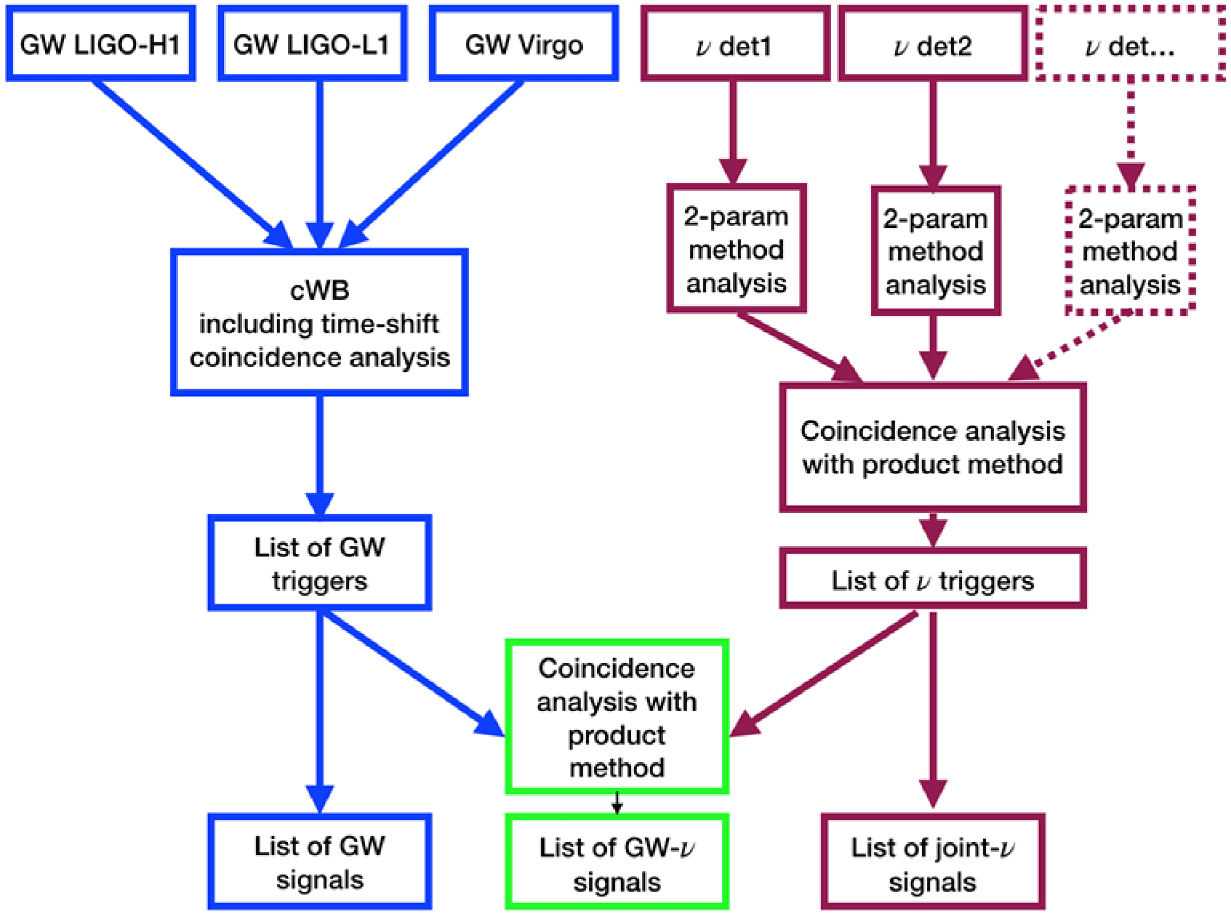
Time coincidence between messengers

JOINT SEARCH

JCAP11(2021)021

- Improve detection of sub-threshold signal combining information from Neutrino and GW triggers

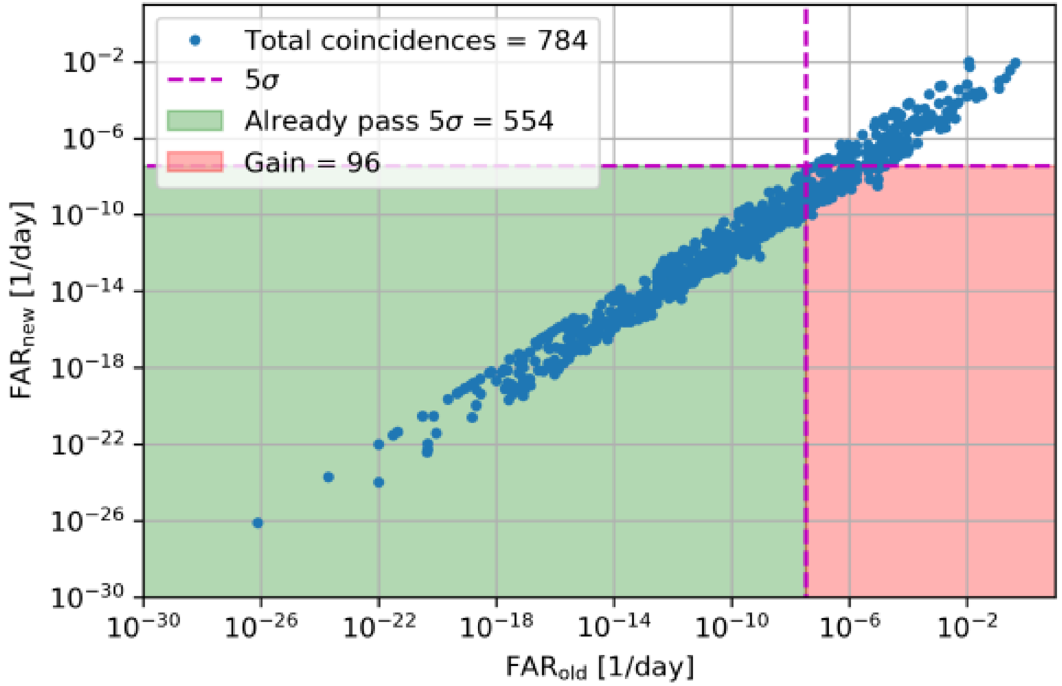
$$\mathrm{FAR_{glob}} = \mathrm{Net} \times w_c^{\mathrm{Net}-1} \prod_{X=1}^{\mathrm{Net}} \mathrm{FAR}_X$$

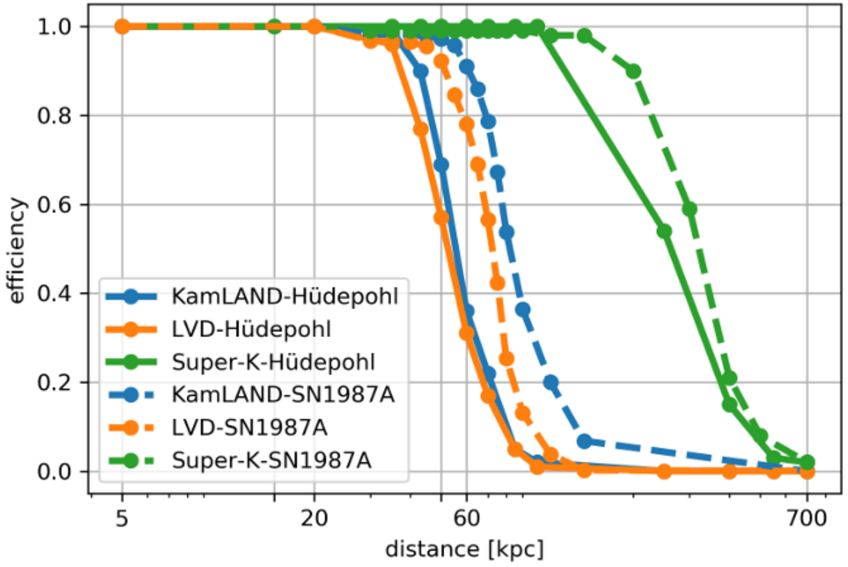


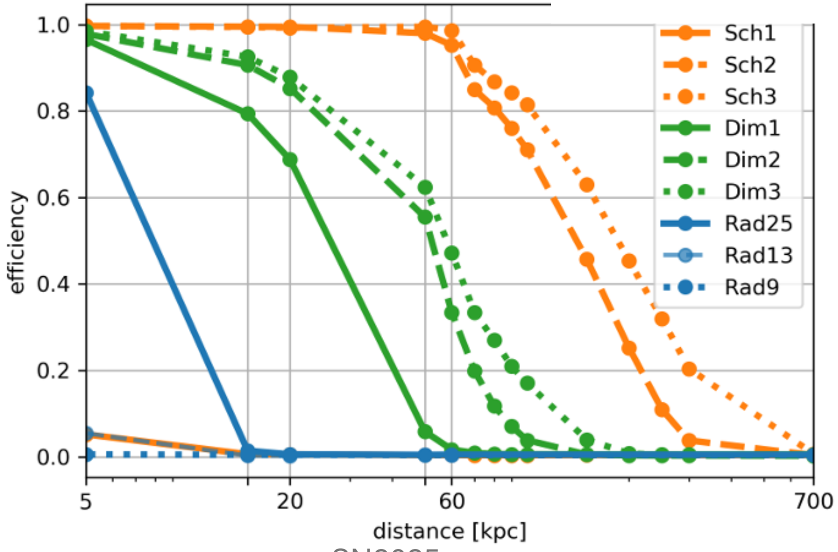
Time coincidence between messengers

JCAP11(2021)021

JOINT SEARCH





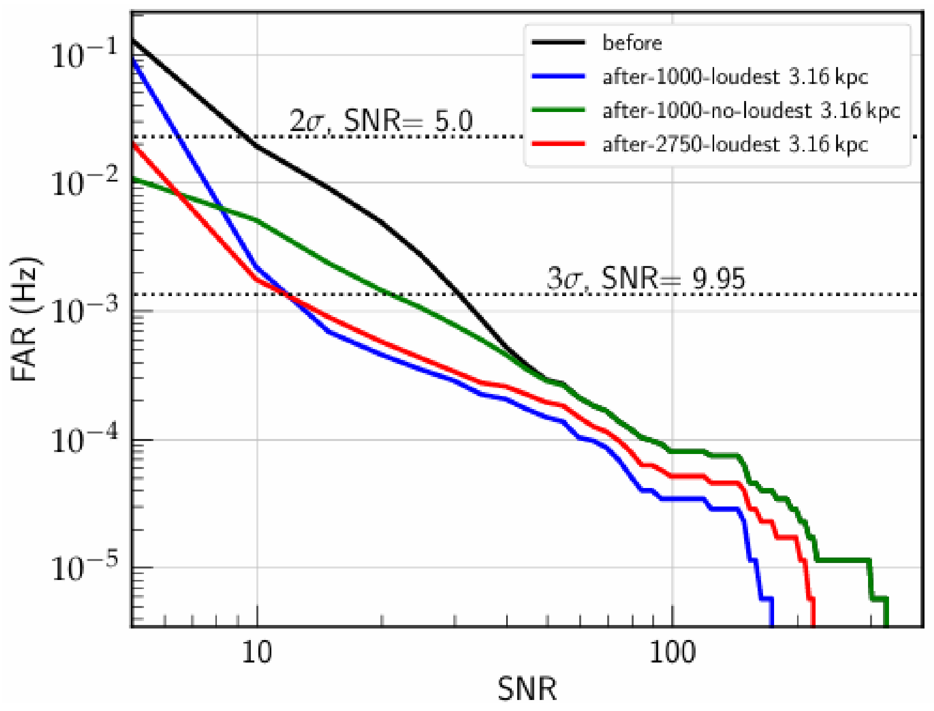


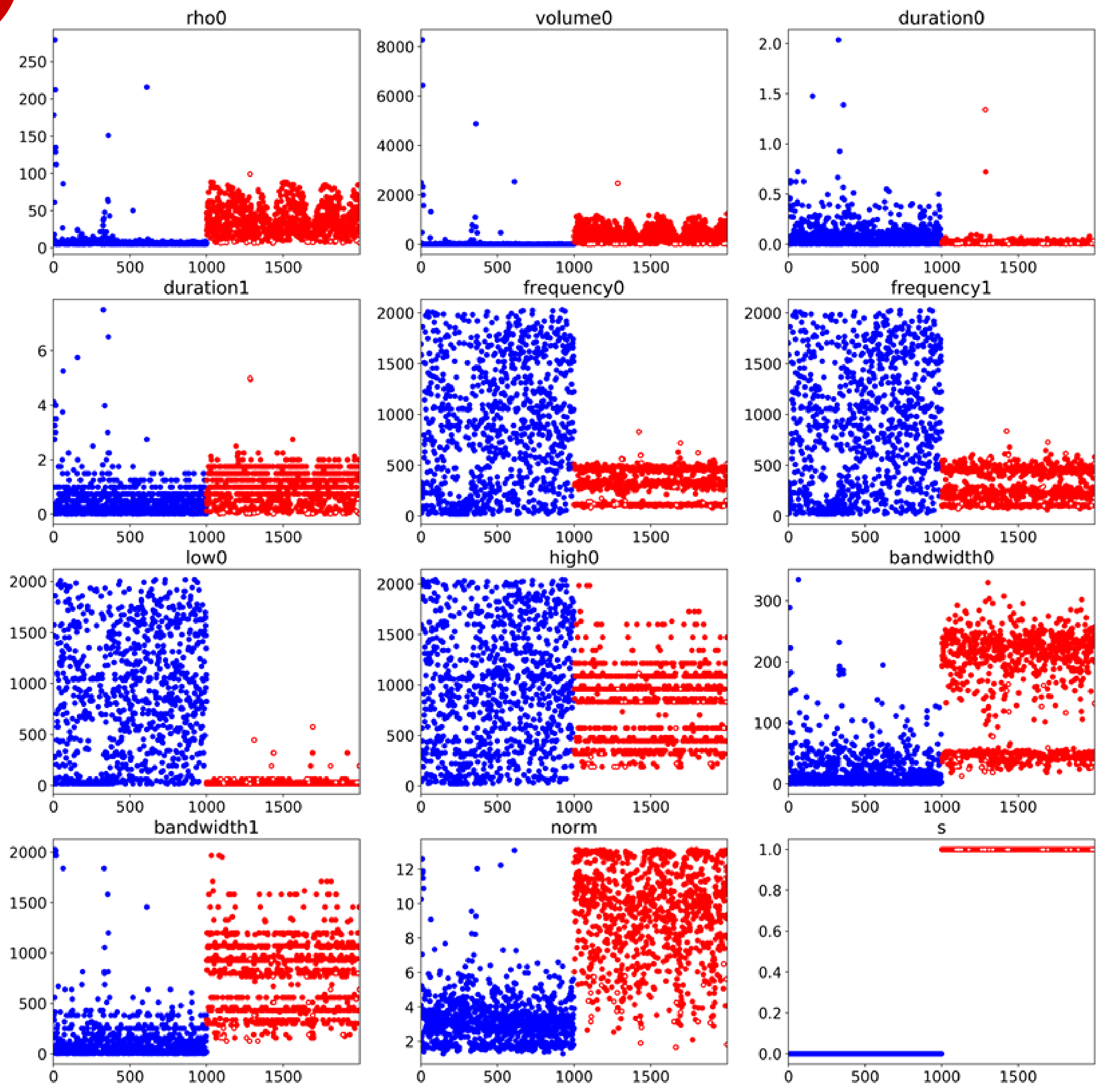
- PRO: low GW combined with high ν: detection
- CONTRA: Difficult to reconstruct low GW

Machine learning

Triggered

- Search for SN when only one GW detector is working
- Train NN on coherent WaveBurst parameters



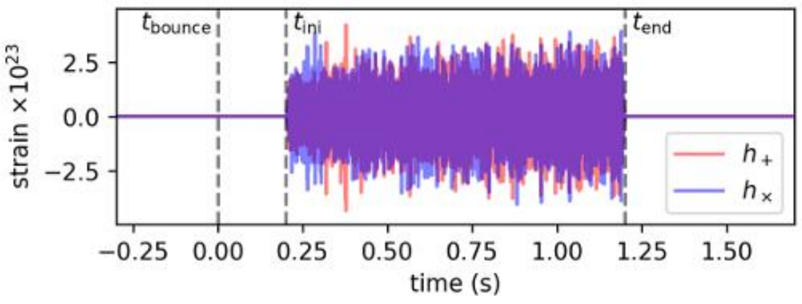


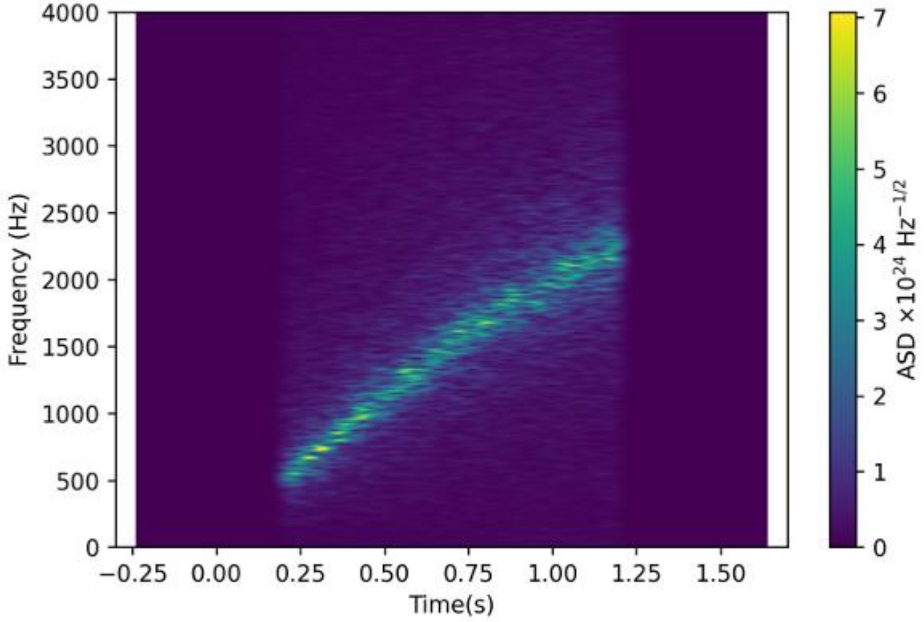
Mach. Learn.: Sci. Technol. 1 015005 (2020)

Neural network

Triggered

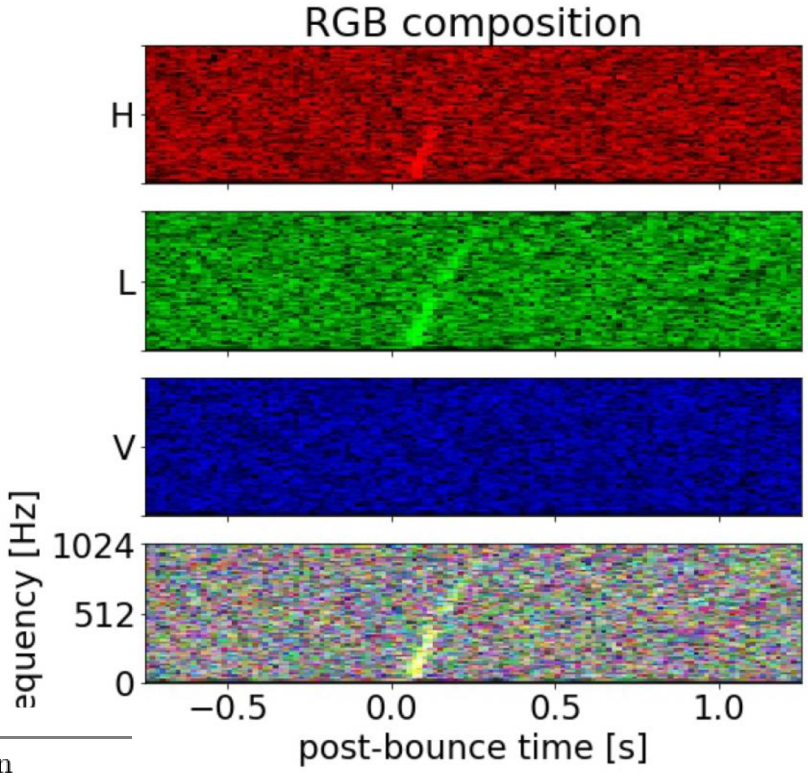
Phys. Rev. D 103, 063011





Phys. Rev. D 111 (2025) 8, 083022

- Common Time-Frequency signature for GW SNe
- Train NN on approximate waveforms to enhance detection



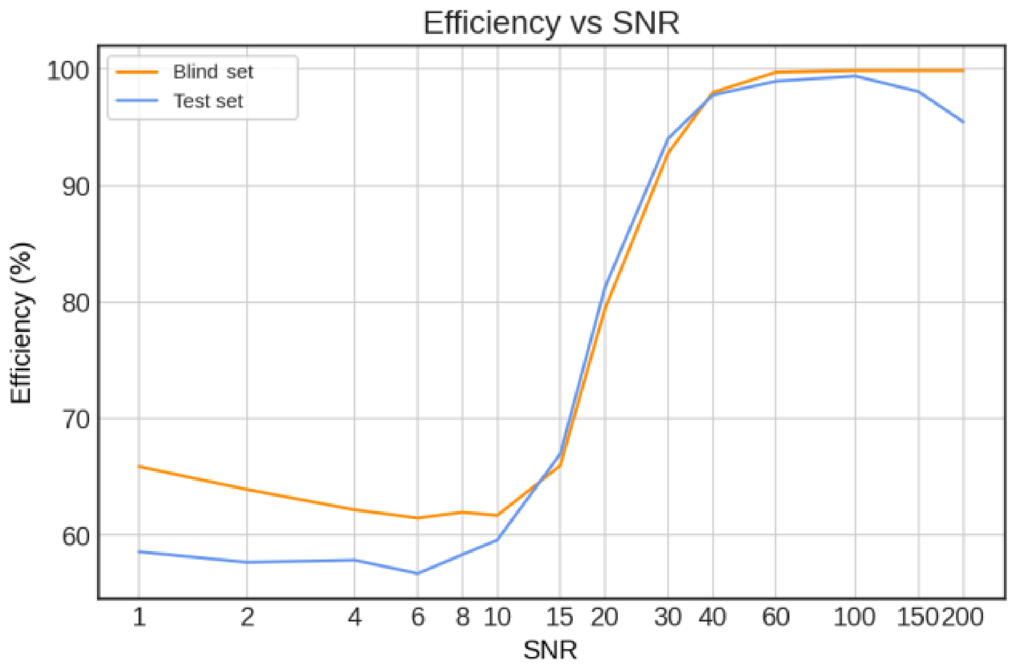
parameter	min.	max.	Δ	description
t_{ini} [s]	0	0.2	0.1	beginning of the waveform
t_{end} [s]	0.2	1.5	0.1	end of the waveform
f_0 [Hz]	50	150	50	frequency at bounce
f_1 [Hz]	1000	2000	500	frequency at 1 s
f_2 [Hz]	1500	4500	1000	frequency at 1.5 s
f_{driver} [Hz]	100	200	100	driver frequency
Q	(1, 5, 10)			quality factor
D [kpc]	(1, 2, 5, 10, 15)			distance to source

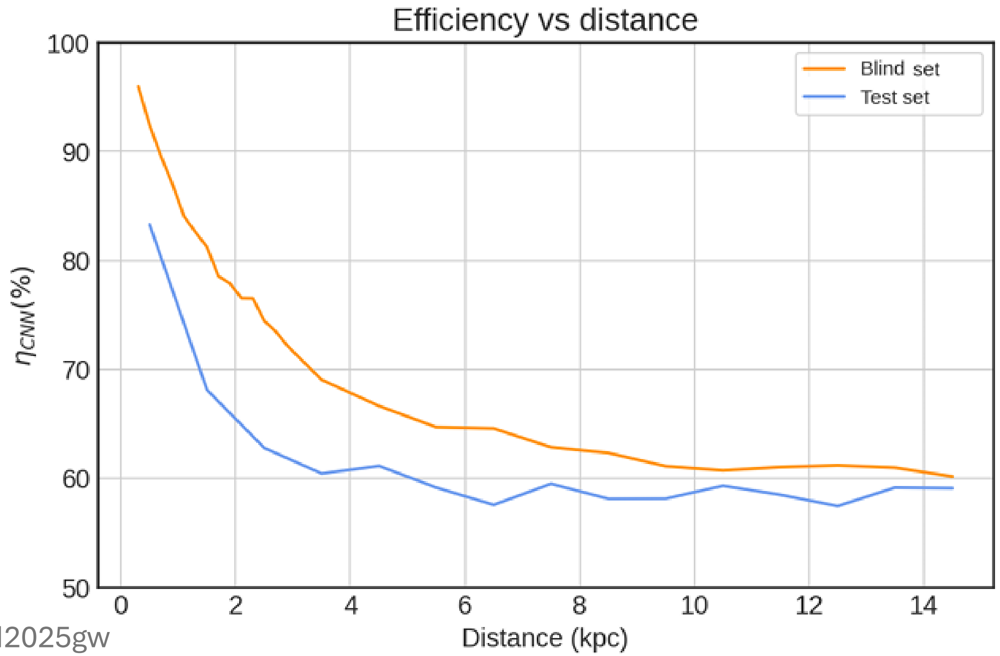
Neural network

Triggered

- Common Time-Frequency signature for GW SNe
- Tested on literature waveforms

Model name	reference	M_{ZAMS}	comments
s9	[43]	$9M_\odot$	Low mass progenitor, low GW amplitude.
s25	[43]	$25M_\odot$	Develops SASI.
s13	[43]	$13M_\odot$	Non-exploding model.
s18	[44]	$18M_\odot$	Higher GW amplitude.
he3.5	[44]	-	Ultra-stripped progenitor ($3.5M_\odot$ He core).
SFHx	[45]	$15M_\odot$	Non-exploding model. Develops SASI.
mesa20	[46]	$20M_\odot$	
mesa20_pert	[46]	$20M_\odot$	Same as mesa20, but including perturbations.
s11.2	[27]	$11.2M_\odot$	
L15	[23]	$15M_\odot$	Simplified neutrino treatment.



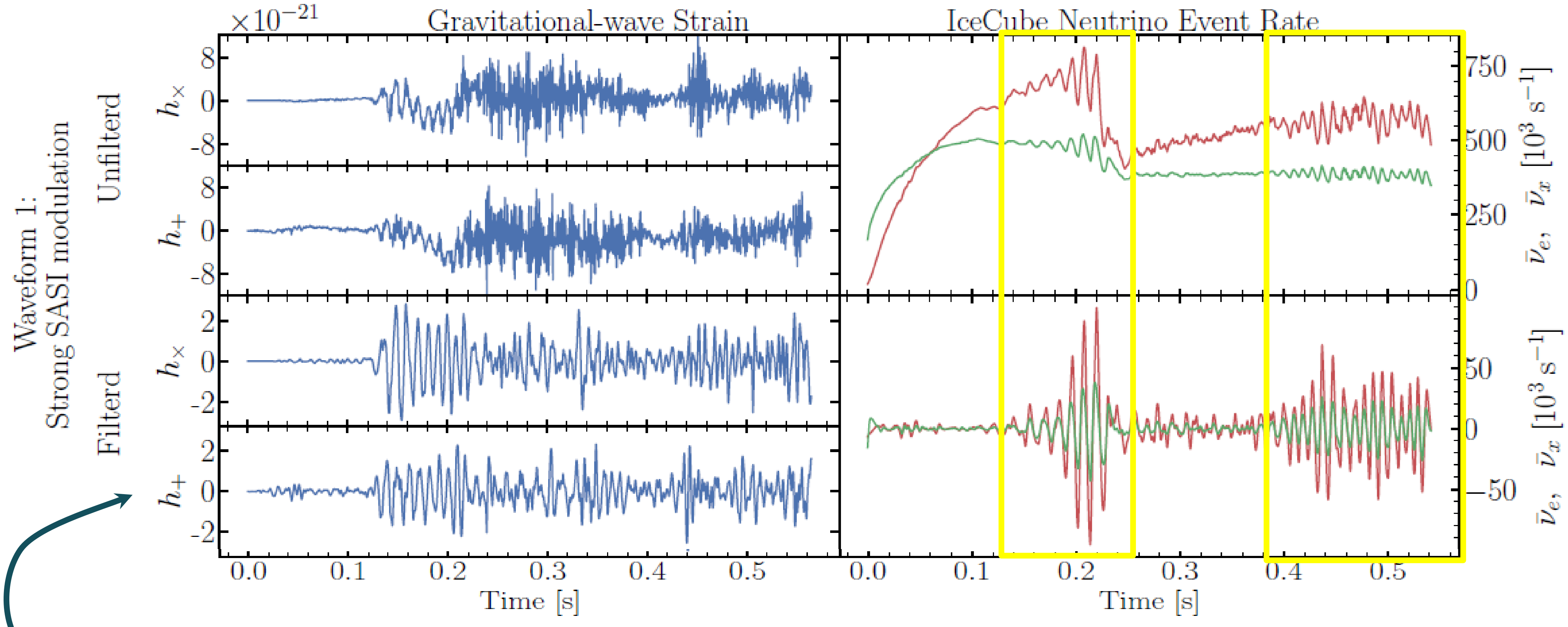


Matching filter

Triggered

Phys. Rev. D **108**, 103036

Progenitor: non-rotating star of solar metallicity with zero-age main sequence mass of 27 M



Band pass filter of 50-300 Hz

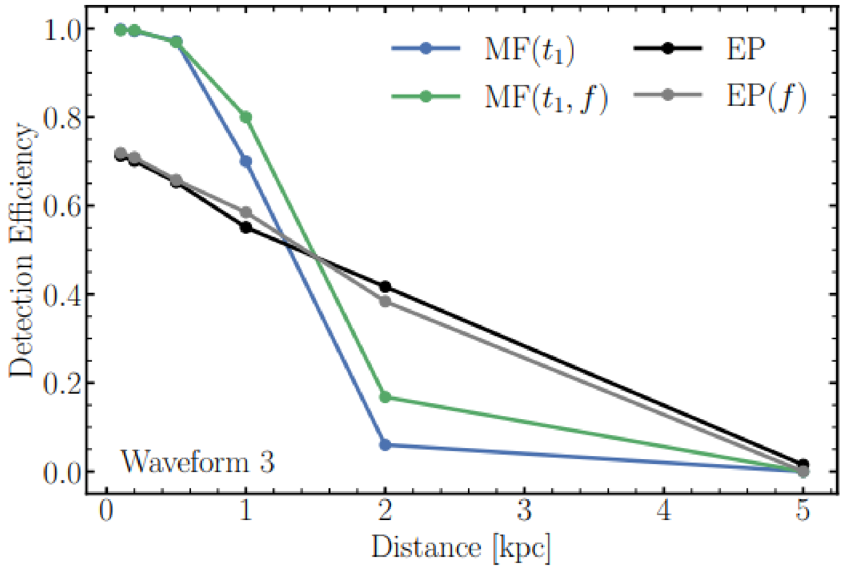
3 cases explored changing observer directionality strong, intermediate and weak SASI modulations

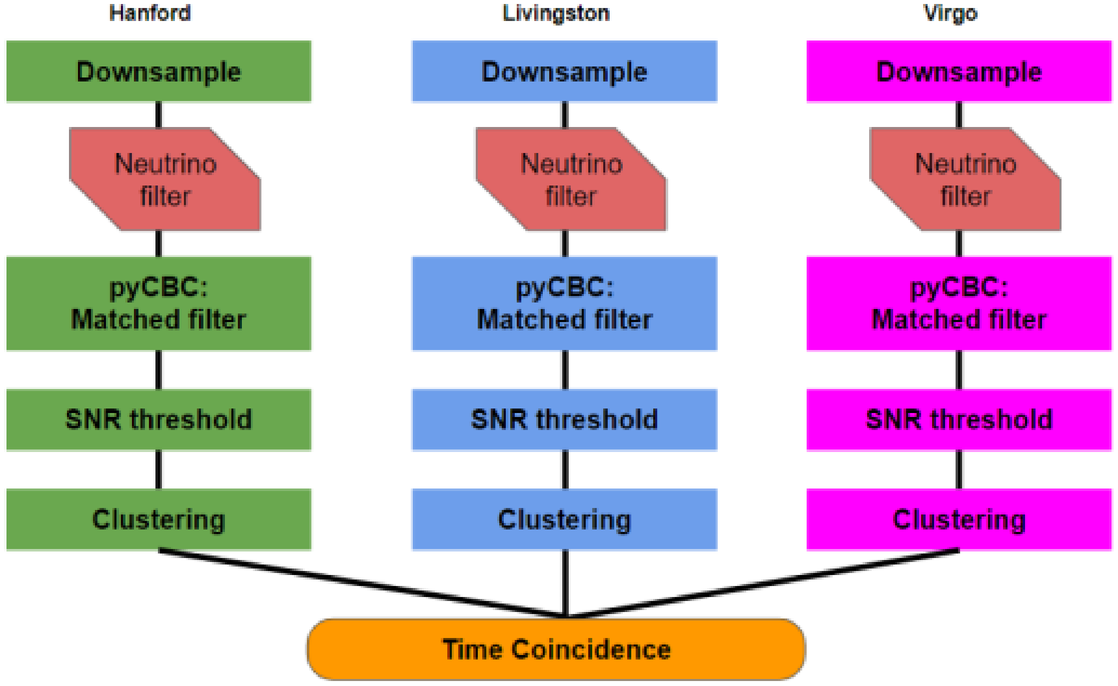
Matching filter

Triggered

[Phys. Rev. D **108**, 103036](#)

- Combine information from the Standing Accretion Shock Instabilities between Neutrino and GW signals
  - Can we do a matched filter even if the signals is not perfectly matching?
- Implementation of a new algorithm to perform this search





Conclusions

- Multi-messenger already shown its potentiality for new physics and discoveries
- Supernovae are one of the best sources for multi-messenger search
- More groups already performed multi-messenger studies
- Waiting for the SN!