Multi-messenger astronomy : from the analysis of transient sources of gravitational waves to electromagnetic counterparts searches

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Overview

Introduction

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My work:

LIGO-Virgo

- Detector characterisation
- Production/validation of GW alerts
- Search for GW associated to GRB

GW follow-up

- Optimisation of the observations
- GRANDMA/SVOM O3 campaign
- short GRB host population study

Gravitational waves analysis

Channel safety

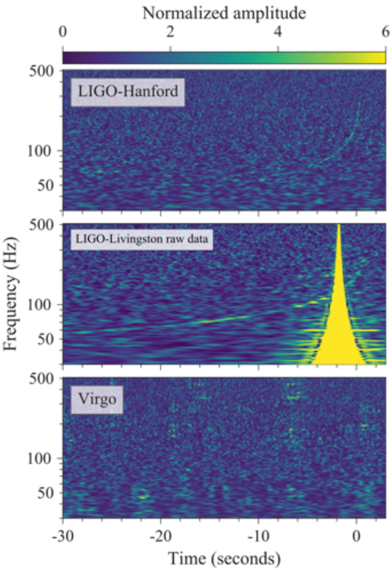
O3a (1 April 2019 to 1 October 2019)
O3b (1 November 2019 to 27 March 2020)

Virgo data quality analysis: aim to ensure that GW candidates are astrophysical.

GW170817

Detection pipelines point to an interesting candidate

$\rightarrow$ visible contamination by transient noise in LIGO-Livingston data

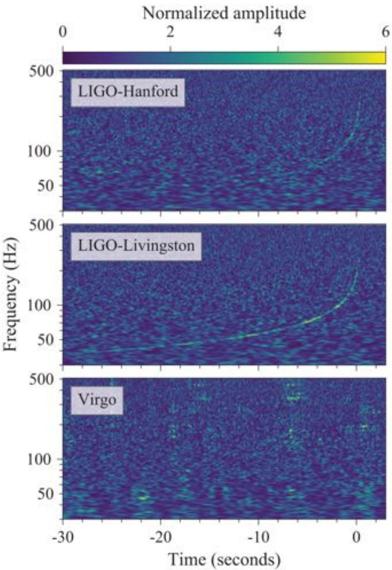


GW170817

Detection pipelines point to an interesting candidate

→ visible contamination by transient noise in LIGO-Livingston data (removed)

Compact binary coalescence signal



Channel safety

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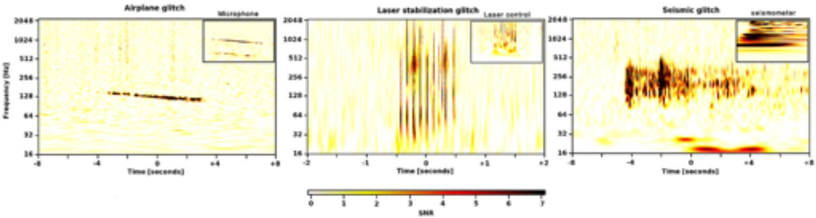
Search for correlations between auxiliary channels, investigating the detector environment and operation, and the h(t) to produce vetoes



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Are channels (in)sensitivity to gravitational waves?

- Transfer functions between the h(t) and most auxiliary channels are not well known or understood $\rightarrow$ Hardware injections
- Infer the coupling between auxiliary channels and h(t)

Method : General principle (from LIGO)

(Essick et al. 2021)

Quantify the significance of any coincidence between auxiliary channels and h(t), the probability being based on the proximity of the coincidence and the rarity of the events involved (SNR ρ and rate λ).

Assume:

- Triggers in each channel are independent of events in other channels
- Each set of triggers are distributed according to a Poisson process with a constant rate

Method : General principle

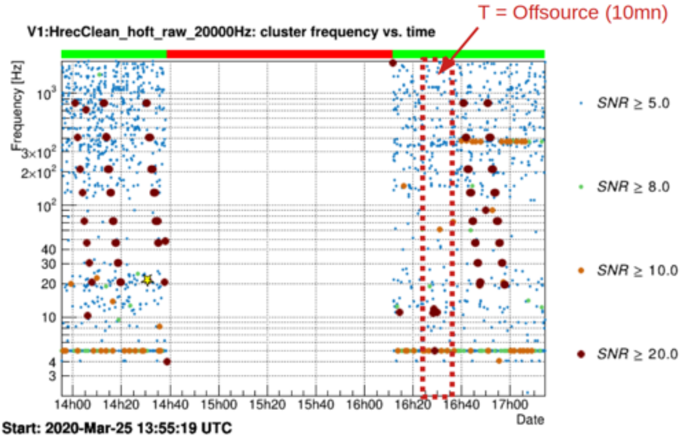
The probability of observing an event as close or closer to an uncorrelated time-of-interest

$$\Rightarrow \; P_{min}(\Delta t \leq \tau) = \min_{\rho_{thr}} \{P(\Delta t \leq \tau | N(\rho \geq \rho_{thr}), T)\}$$

Considering multiple subsets (in ρ), where T is a time duration and N is the number of trigger within this period.

Setup for Virgo

- N, T ? $\Rightarrow$ $T \sim 10$ mn



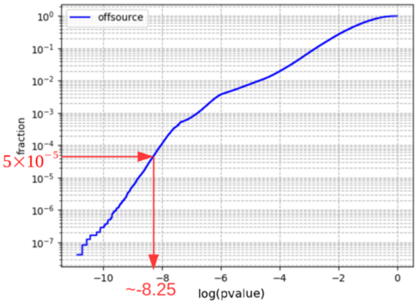
Setup for Virgo

- N, T ? $\Rightarrow$ $T \sim$ 10 mn
- 2443 channels analysed
- Adapt the analysis to the Virgo data
  - Different triggers used
  - Virgo environment
- 3 sets of hardware injections

all combination of frequency-SNR pair signal:
frequency in [19, 31, 47, 73, 129, 211, 409, 811] Hz
SNR in [20, 50, 100, 500]
$\Rightarrow$ 32 injected signal by set

Classification

Classification threshold using the offsource cumulative distribution of pvalue



With $\sim$ 2500 channels and 8 different frequencies injected, we expect less than one wrong classification if we take a threshold according the a fraction equal to $\frac{1}{2500\times8} = 5 \times 10^{-5}$

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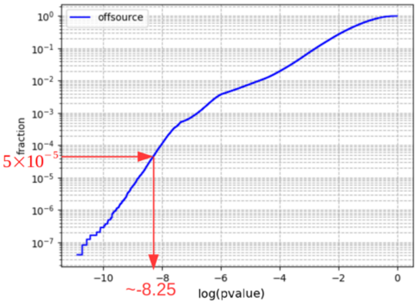

Classify computing at the time of the injections

- log(pvalue) $<$ -8.25
  $\Rightarrow$ danger
- -8.25 $<$ log(pvalue) $<$ -7.25
  $\Rightarrow$ warning
- -7.25 $<$ log(pvalue)
  $\Rightarrow$ ok

With $\sim$ 2500 channels and 8 different frequencies injected, we expect less than one wrong classification if we take a threshold according the a fraction equal to $\frac{1}{2500\times 8} = 5 \times 10^{-5}$

Results

Over $\sim$2500 channels: 53 classified as "Danger", 16 classified as "warning" and all the others as "ok".

Compatible with the most obvious expectations (channels undoubtedly expected to be safe/unsafe)

Compatible with previous (O3a) channel safety analysis, "hand-made" method with visual inspection of spectrograms.

The analysis was improved to be more "user friendly" + user guide for further analysis (O4)

Search for gravitational waves associated to GRB

Divided in two different analyses:

- Modelled search dedicated to compact binary mergers
- Unmodelled search for generic transients

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Unmodelled search for generic transients

Carried out with `X-Pipeline` software package.

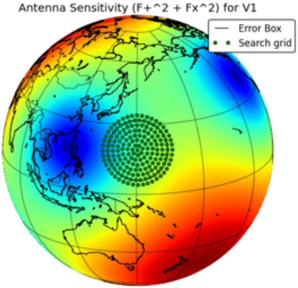
Looks for consistent excess power that is coherent across the network of gravitational waves detectors

Onsource search window of [-10, 1] min around the GRB trigger $\rightarrow$ expected to encapsulate the time delay between GW emission and any GRB prompt emission (long or short)

105 GRBs analysed in O3a (12 by myself)

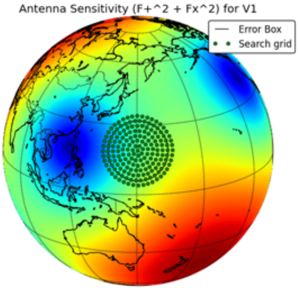
Unmodelled search for generic transients

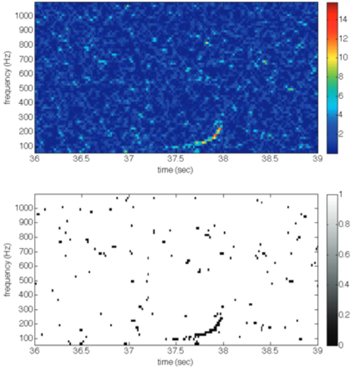
For each sky position $\rightarrow$ time shift the data to respect the time delay between detectors



Unmodelled search for generic transients

For each sky position → time shift the data to respect the time delay between detectors → time frequency map of coherent energy





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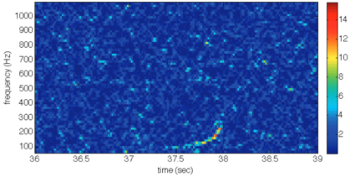
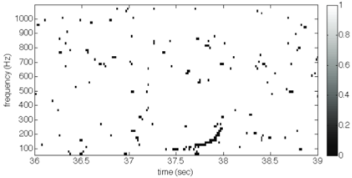


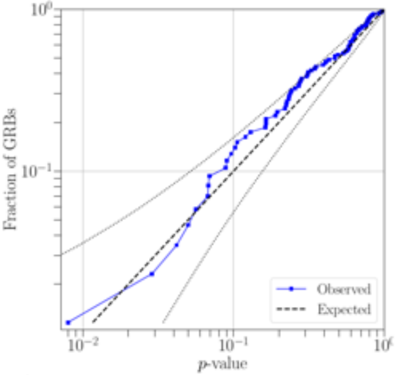
pvalue → Probability of background noise producing a cluster in the onsource interval with the significance of the loudest surviving cluster

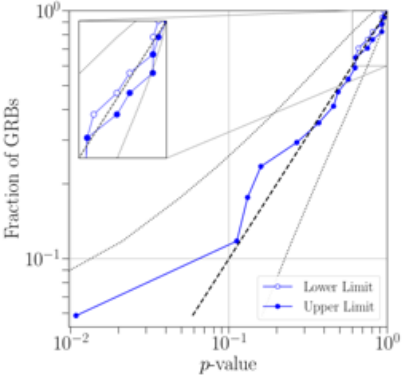


Results for O3a

Unmodelled
105 GRBs

Modelled
33 GRBs





Cumulative distribution of pvalues for the loudest onsource events for the unmodelled (left) and modelled (right) search in O3a. Dashed line indicates expected distribution for a no-signal hypothesis, dotted lines: 90% band.

Results for O3a - exclusion distances

Modelled search (Short GRBs)	BNS	NSBH Generic Spins	NSBH Aligned Spins
D_{90} [Mpc]			
O2	80	105	144
O3a	119	160	231

Unmodelled search (All GRBs)	CSG 70 Hz	CSG 100 Hz	CSG 150 Hz	CSG 300 Hz
D_{90} [Mpc]				
O2	112	113	81	38
O3a	146	104	73	28

Unmodelled search (All GRBs)	ADI A	ADI B	ADI C	ADI D	ADI E
D_{90} [Mpc]					
O2	32	104	40	15	36
O3a	23	123	28	11	33

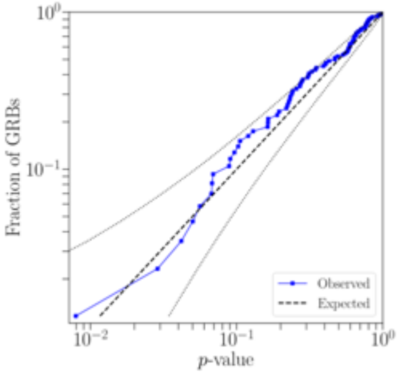
Circular Sine-Gaussian (CSG)

Disk instability models (ADI)

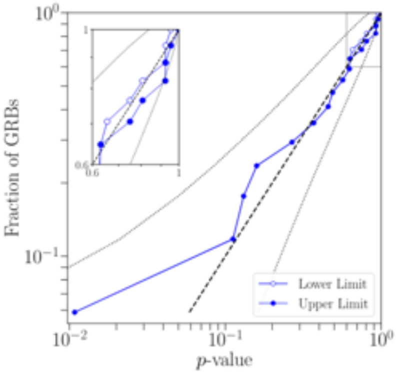
Unmodelled search limited by transient noise during O3a
$\rightarrow$ Autogating for O3b

Results for O3b

Unmodelled
86 GRBs



Modelled
17 GRBs



Cumulative distribution of pvalues for the loudest onsource events for the unmodelled (left) and modelled (right) search in O3a. Dashed line indicates expected distribution for a no-signal hypothesis, dotted lines: 90% band.

Results for O3b - exclusion distances

Modeled search (Short GRBs)	BNS	NSBH Generic Spins	NSBH Aligned Spins
D_{90} [Mpc]	149	207	257

Generic transient search (All GRBs)	CSG 70 Hz	CSG 100 Hz	CSG 150 Hz	CSG 300 Hz
D_{90} [Mpc]	166	126	92	42

Generic transient search (All GRBs)	ADI A	ADI B	ADI C	ADI D	ADI E
D_{90} [Mpc]	34	140	54	22	52

Circular Sine-Gaussian (CSG)

Disk instability models (ADI)

Unmodelled search less limited by glitches
$\rightarrow$ Autogating working well

Key points of the gravitational waves follow-up challenge

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General objectives: multi-wavelength detection, highly sampled light curve, measure the redshift and spectral feature

Several difficulties:

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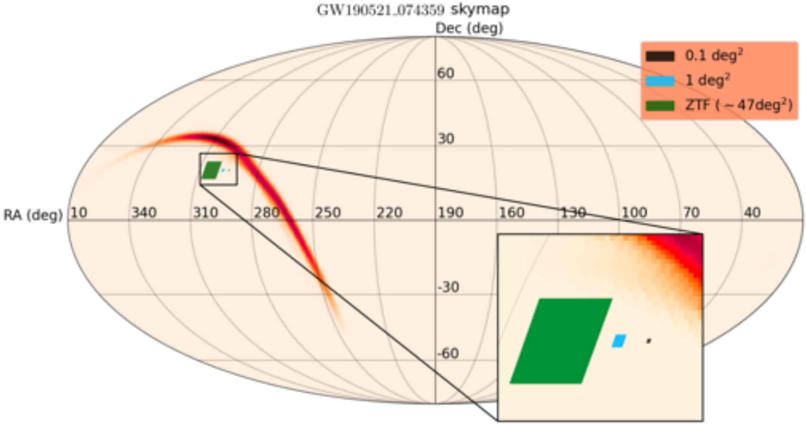
Several difficulties:

- Large uncertainty on localisation

Large uncertainty on localisation

GW localisation from a few tens to more than 1000 square degrees $\sim 500\ \text{deg}^2$



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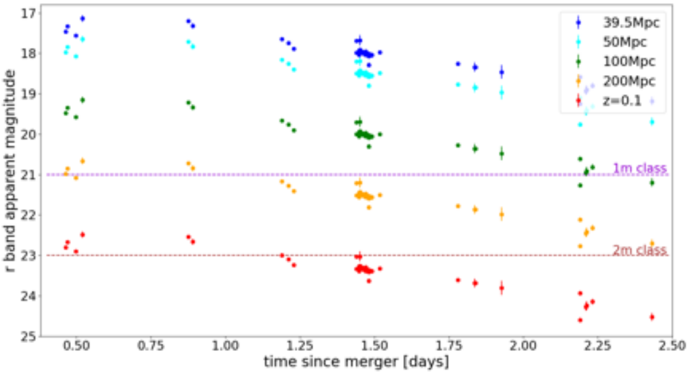
General objectives: multi-wavelength detection, highly sampled light curve, measure the redshift and spectral feature

Several difficulties:

- Large uncertainty on localisation $\Rightarrow$ Largest FoV possible
- Faint and fast decaying transient

Faint and fast decaying transient

kilonova emission: example of GW170817 kilonova, apparent magnitude peaked at $\sim$17 mag in r band



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Several difficulties:

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Key points of the gravitational waves follow-up challenge

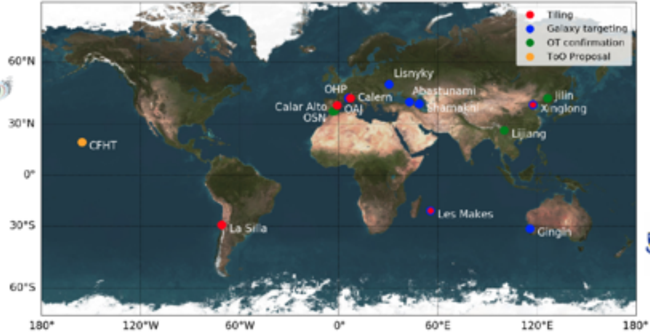
General objectives: multi-wavelength detection, highly sampled light curve, measure the redshift and spectral feature

Several difficulties:

- Large uncertainty on localisation $\Rightarrow$ Largest FoV possible
- Faint and fast decaying transient $\Rightarrow$ Fast/deep observations
- Identification of candidates $\Rightarrow$ Develop dedicated tools

GRANDMA

- ~ 25 telescopes in 20 observatories
  both hemispheres + very good longitude coverage
- ~ 70 persons involved



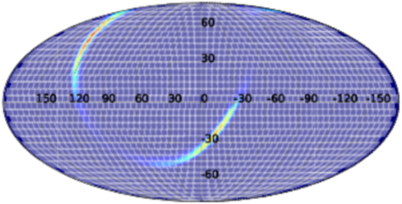
Gravitational waves follow-up optimisation

Tiling strategy

Used for large FoV telescopes. Precomputed tiling of the sky optimized to limit the overlap between the tiles.

GW skymaps are provided in the HEALPix format.
$\rightarrow$ 2D probability in each tile

Schedule the tiles observations according to the 2D probability they contain, after observability check

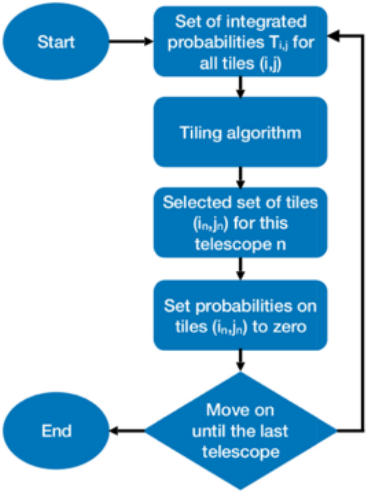


Tiling strategy development

Telescopes are not considered independently

→share the sky coverage and limit the network overlap

Implementation of "golden" regions:
regions of the sky that are not decremented at each step
→most interesting regions of the skymap are imaged several times by the network



Galaxies targeting - Standard approach, moving to 3D

Hypothesis: the source is located within a galaxy

- Choice of the catalog, what we need:
  - all sky
  - provide distance
  - completeness compatible with LIGO-Virgo-KAGRA range

$\Rightarrow$ GLADE (Dálya et al. 2018)

Constructed (combined and matched) from four existing galaxy catalogs: GWGC, 2MPZ, 2MASS XSC and HyperLEDA. GLADE contains $\sim$3,000,000 objects.

- Selection in the catalog of compatible galaxies for a certain 3D volume: RA, Dec, distance

Galaxies targeting - Standard approach

How do we use the galaxies?

We need to define a grade (weight) to put on each galaxy

Standard definition of the grade

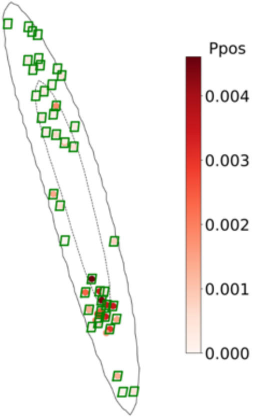
We use the 3D probability:

$$P_{pos} = P_{dV} = \frac{P_{pixel}}{Pixel\ area} N_{pixel}\, e^{-\frac{1}{2}\left(\frac{D_{galaxy} - \mu_{pixel}}{\sigma_{pixel}}\right)^2}$$

Where μ_{pixel} , σ_{pixel} and N_{pixel} are respectively the mean distance, the standard deviation and the normalization factor of the Gaussian distribution at the given pixel. D_{galaxy} is the galaxy distance fetch from the catalog.

Results

GW170817 : tiles for a typical telescope FOV = $20' \times 20'$

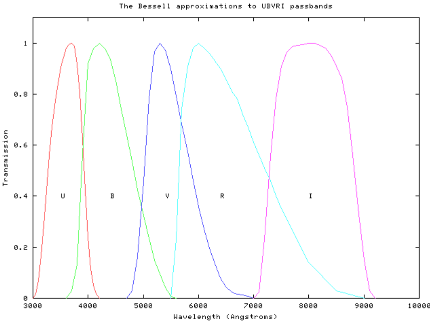


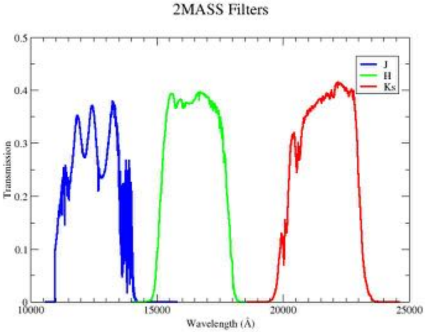
Upgrading the grade : available information

Adding galaxy properties to the grade

Only information available on GLADE

- B,J,H,K Luminosity (not for all galaxies)
  $\Rightarrow$ sufficient to deduce interesting properties from it?



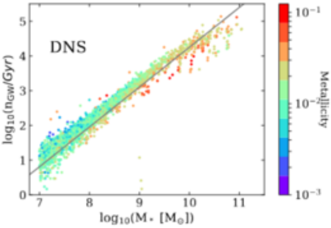


Upgrading the grade : focus on stellar mass

Why the stellar mass?

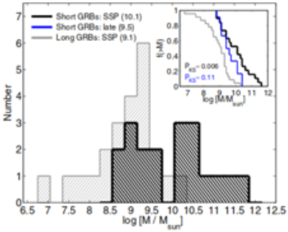
Both BNS merger population simulations and short GRB host population point out the stellar mass as an important indicator.

BNS population simulations



(Artale et al. 2019)

Short GRB host population



(Leibler & Berger 2010)

Use the B luminosity (from GLADE) as an "indicator of mass" (Arcavi et al. 2017)

The B band is highly sensitive to the galaxy dust attenuation

$\Rightarrow$ We should use near infrared band

$\Rightarrow$ K (2.2 μm) band is provided by GLADE but:

- K band is still a bit affected by the dust attenuation
- only $\sim$67% of the galaxies in the catalog (up to 400Mpc) have K band information

$\Longrightarrow$ Utilization of the WISE1 band (3.4 μm)

A new catalog dedicated to the follow-up of GW event!

(Ducoin et al. 2020, MNRAS, 492, 4768. doi:10.1093/mnras/staa114)

MANGROVE: Mass AssociatioN for GRavitational waves ObserVations Efficiency

Cross-match AllWISE and GLADE (400Mpc):

After all treatment we have $\sim$93% of the galaxies with WISE1 band

Determination of the stellar mass

From WISE1 band we can determine the stellar mass using a constant mass to light ratio (Kettlety et al. 2017)

$$\Upsilon_*^{3.4\mu m} \sim 0.60 M_\odot / L_{\odot,3.4\mu m}$$

In good agreement with more robust stellar mass estimation.

Reformulation

Adding a factor to the grade

We can now change the grade adding a mass factor:

$$G_{mass} = \frac{M_{*,galaxy}}{\sum M_{*,galaxy}}$$

Huge drawback of the product expression

Can't define G_{mass} when you don't have the stellar mass info (= W1 mag)

$\Rightarrow$ forced to throw away $\sim 7\%$ of the catalog

We chose to reformulate the grade:

$$G_{tot} = P_{pos} \times P_{mass} \qquad \Rightarrow \qquad G_{tot} = P_{pos}\left(1 + \alpha\beta G_{mass}\right)$$

Reformulation

$$G_{tot} = P_{pos}\left(1 + \alpha\beta G_{mass}\right)$$

whit α ensuring that the two factors in the addition are, in mean, contributing as much:

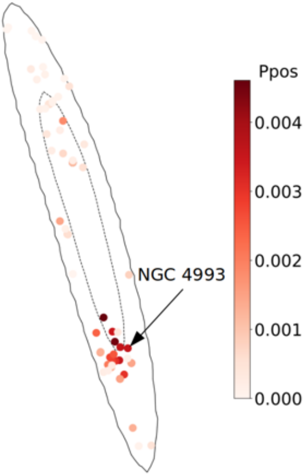
$$\frac{\sum P_{pos}}{N} = \frac{\sum P_{pos}\,\alpha\,G_{mass}}{N}$$

$$\Rightarrow \alpha = \frac{\sum P_{pos}}{\sum P_{pos}\,G_{mass}}$$

The parameter β is used to weight the importance of G_{mass} in the total grade $\Rightarrow$ Set $G_{mass} = 0$ to fall back on P_{pos}

Results

GW170817



Only EM counterpart detected for a GW so far

$\Rightarrow$ Mandatory to test our grade on it

- 90% skymap $\sim 30 deg^2$
- distance 40 ± 8 Mpc
- 65 galaxies compatibles

Results

Galaxies with high stellar mass are prioritized compared to galaxies with small stellar mass

Without stellar mass ⇒ NGC 4993 ranked 5
With the stellar mass addition ⇒ NGC 4993 ranked 1

Keep candidates without stellar mass estimation (first at 9th position)

(Ducoin et al. 2020, MNRAS, 492, 4768. doi:10.1093/mnras/staa114)

Dedicated website : https ://mangrove.lal.in2p3.fr/

GRANDMA and SVOM observations during O3 run

During O3:

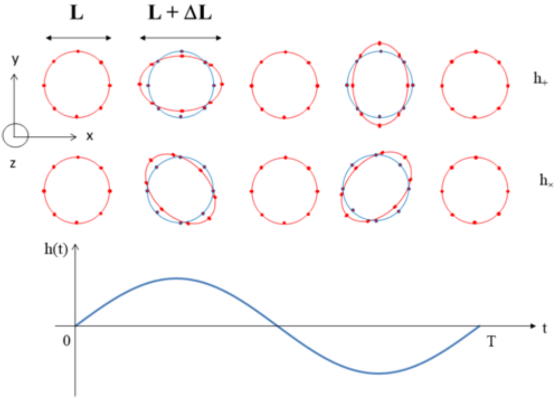
GRANDMA followed-up 49 out of 56 alerts, reported via GCN
Minimal time delay ~ 15mn
Total coverage of over 9000 deg^2

No interesting transient candidates, weak constraint on the ejecta mass (BNS candidate S200213t)

MERCI!

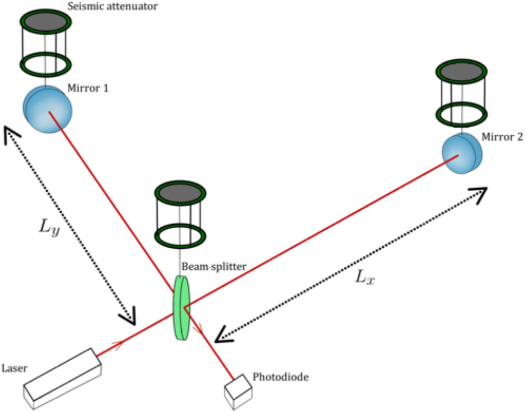
Gravitational waves

Disturbances in the curvature of spacetime produced by accelerating objects.



Relative change in distance $\Delta L/L$ proportional to the amplitude of the gravitational wave h, also called *strain amplitude*.

Ground based interferometric detectors



GW along z axis, only h_+ along the interferometer arm

$$L_x \sim L_0 + \frac{1}{2} L_0 h_+(t)$$

$$L_y \sim L_0 - \frac{1}{2} L_0 h_+(t)$$

$$\frac{\Delta L}{L} \propto h_+(t)$$

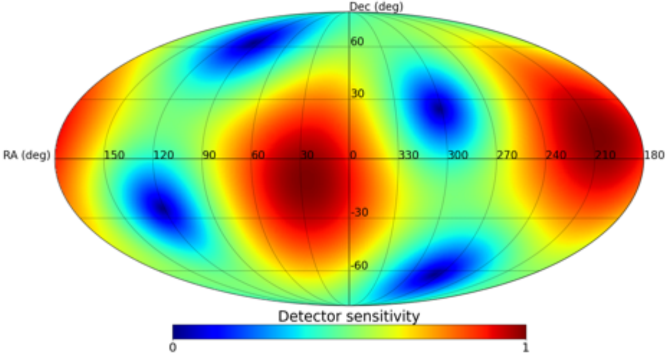
$$P_{out} \sim \tfrac{1}{2} P_{in} [1 - \cos(\alpha + \tfrac{2\pi}{\lambda} \Delta L)]$$

α: phase difference at the beam-splitter
λ: laser wavelength

Power change in the photon detector signal over time proportional to ΔL $\rightarrow$ direct measure of $h(t)$

Detectors angular response

General response of the detector



Mollview projection for Virgo interferometer computed for the 04/10/2021 at 10:00

Poor localisation of transient sources
$\rightarrow$ needs for a network of detectors + triangulation

Multi-messenger astronomy with gravitational waves: GW170817 GRB170817A AT2017gfo

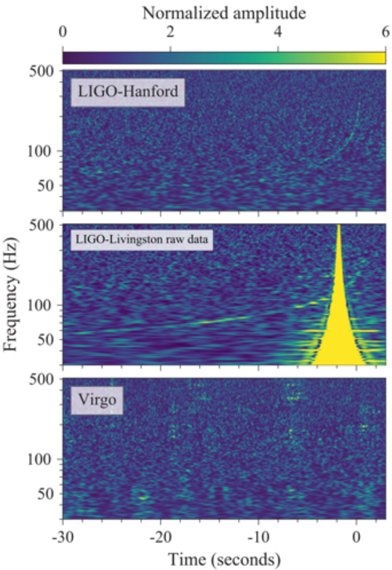
GW170817

17th August 2017, the LIGO-Virgo network is observing

GW170817

Detection pipelines point to an interesting candidate

$\rightarrow$ visible contamination by transient noise in LIGO-Livingston data



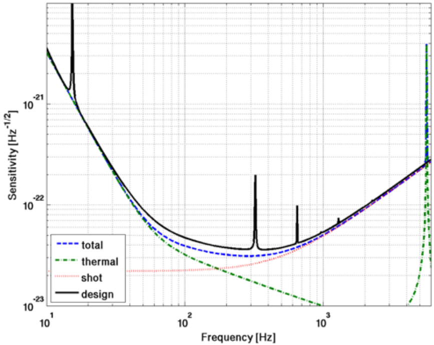
Detectors noises

Fundamental noises

Contributions to the amplitude spectral density

- Seismic noise
- Thermal noise
- Quantum noise

+ technical noise

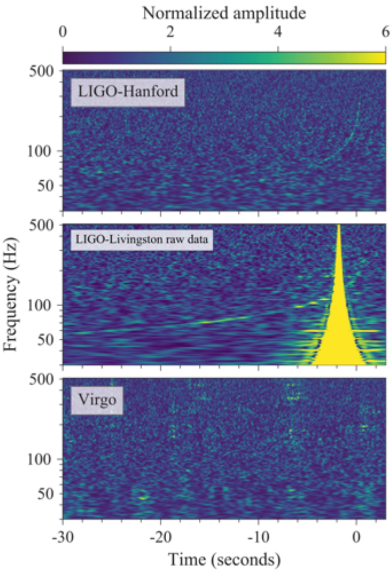


GW data largely contaminated by transient noise ("glitches").
$\rightarrow$ Need for data quality monitoring and Vetoes

GW170817

Detection pipelines point to an interesting candidate

→ visible contamination by transient noise in LIGO-Livingston data

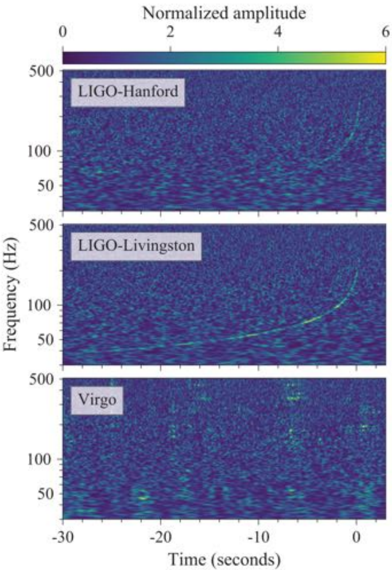


GW170817

Detection pipelines point to an interesting candidate

→ visible contamination by transient noise in LIGO-Livingston data (removed)

Compact binary coalescence signal



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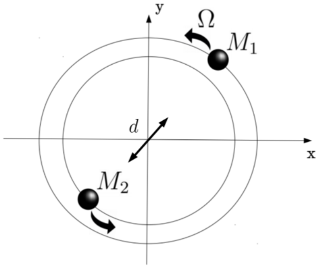
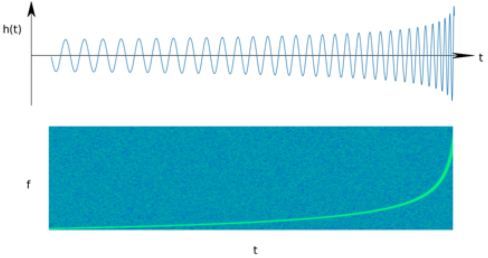




$$h \sim \frac{(GM)^2}{rd}$$

$$h_{GW170817} \sim 10^{-22} \quad \text{near merger time}$$

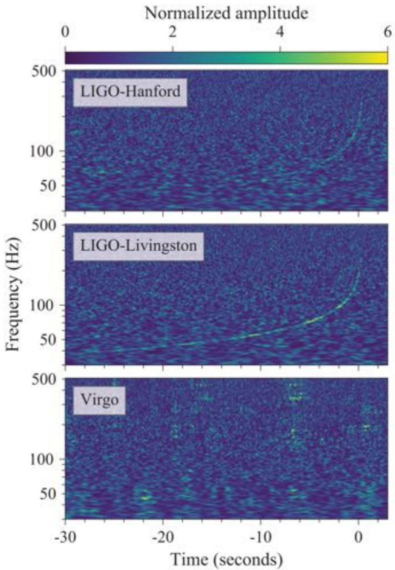
GW170817

Detection pipelines point to an interesting candidate

$\rightarrow$ visible contamination by transient noise in LIGO-Livingston data (removed)

Compact binary coalescence signal

$\rightarrow$ BNS



GW170817

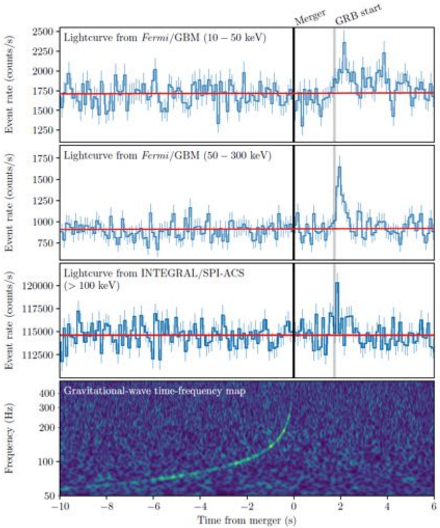
Detection pipelines point to an interesting candidate

→ visible contamination by transient noise in LIGO-Livingston data (removed)

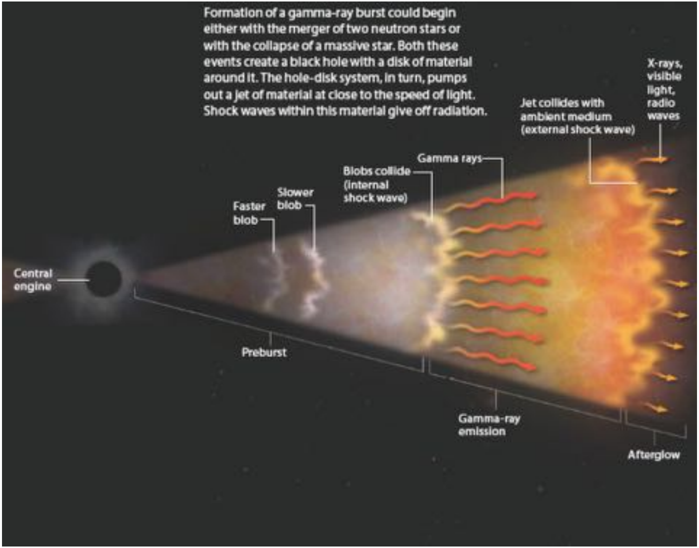
Compact binary coalescence signal

→ BNS

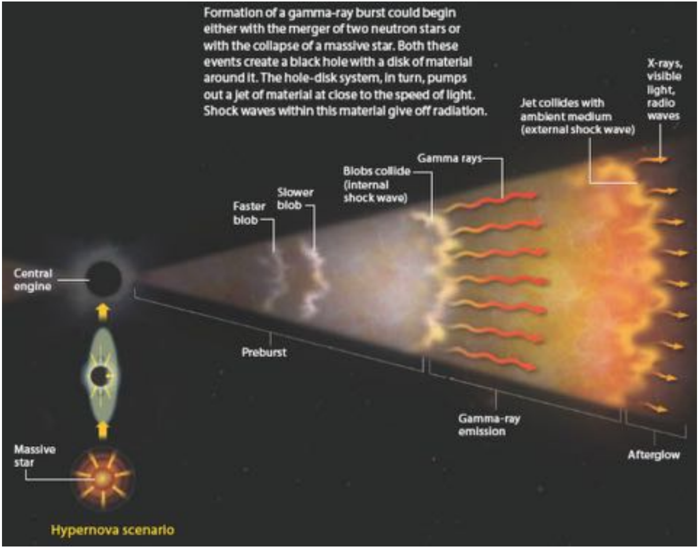
GRB170817A, weak short GRB



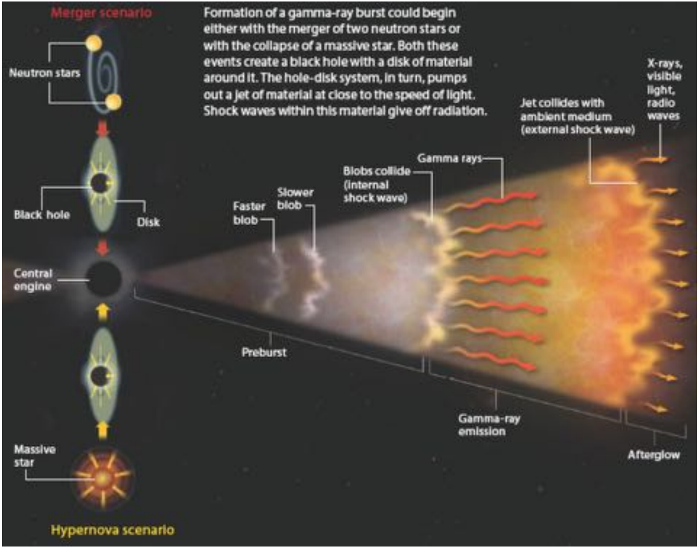
GRB emission



GRB emission



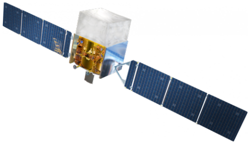
GRB emission



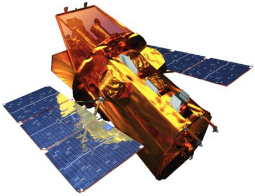
GRB detectors

Fermi GBM

- Since 2008: observed ~ 2500 GRBs (8-30 Mev)
- Field of view of 9 steradians
- Poor localisation of the source (~ 17 deg error radius)



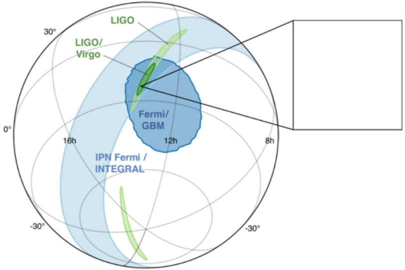
Neil Gehrels Swift Observatory



- BAT field of view of 1.4 steradian (15-150 keV)
- Since 2004: more than 1000 GRBs detected
- X-ray Telescope (XRT) and Ultraviolet/Optical Telescope (UVOT)

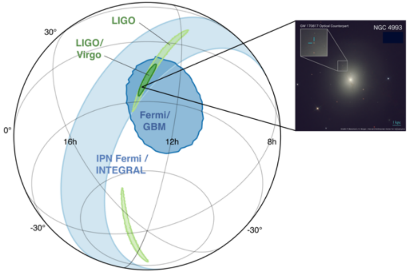
GW170817 follow-up

- Combine GW-GRB localisation



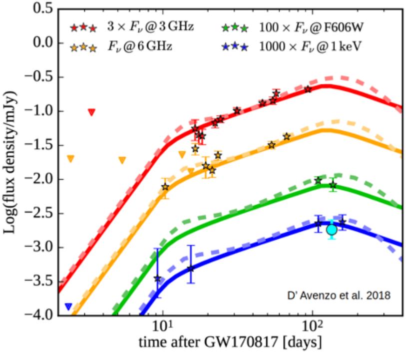
GW170817 follow-up

- Combine GW-GRB localisation
- kilonova transient: AT2017gfo



GW170817 follow-up

- Combine GW-GRB localisation
- kilonova transient: AT2017gfo
- Multi-wavelength Afterglow



GW170817 follow-up

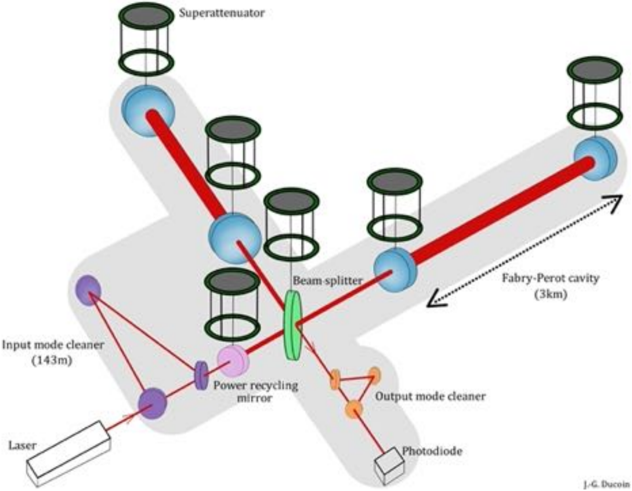
- Combine GW-GRB localisation
- kilonova transient: AT2017gfo
- Multi-wavelength Afterglow
- Unprecedented fruitful

scientific outcome

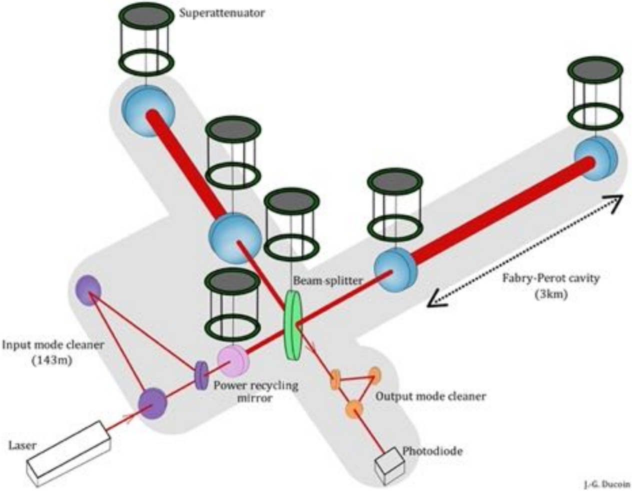
First electromagnetic counterpart to GW
First unambiguous kilonova observation
Physics of strong-gravity
speed of GW
Merger and post-merger phase
Neutron star equation of state
Energy/geometry of the ejecta
Merger remnant
Ambient medium
R-process and heavy elements factory
Derivation of the Hubble Constant
Short GRBs link with BNS merger

⋮

Ground based interferometric detectors



Ground based interferometric detectors



The O3 run of Advanced Virgo and LIGO

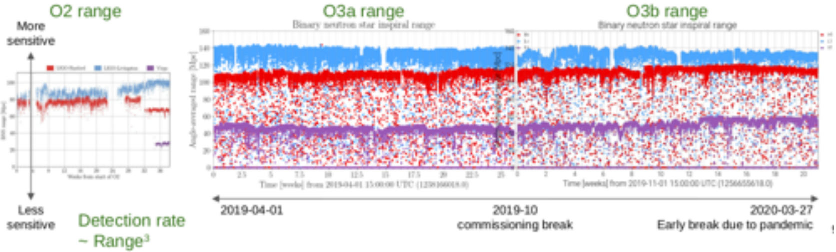
LIGO improvements

Phys. Rev. D 102, 062003 (2020)

- Increased laser power
- Squeezed light
- Reduction of technical noise

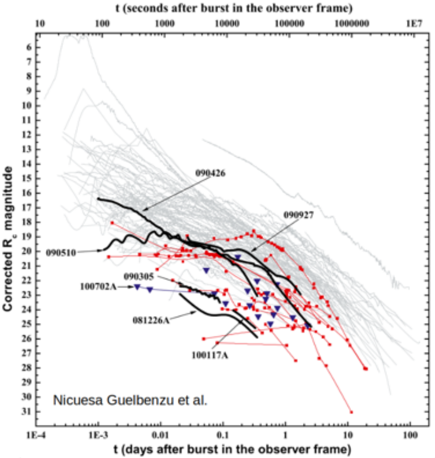
Virgo improvements

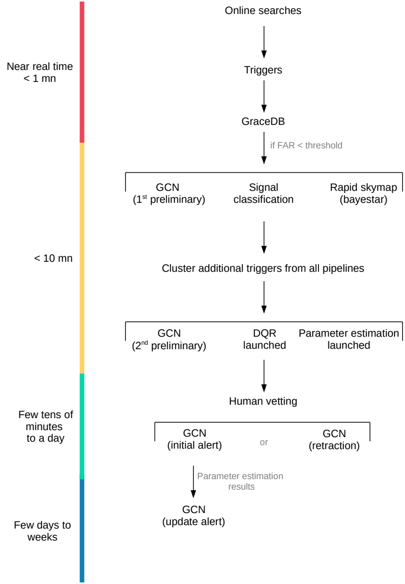
- Increased laser power
- Squeezed light
- Reduction of technical noise
- Restored fused silica suspensions



Faint and fast decaying transient

Short GRB afterglow





Gravitational waves alerts

My contributions

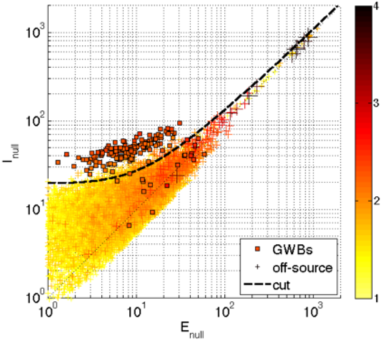
- RAVEN
- DQR : UPV 24h
- Candidates validation and release
- Safety channel analysis

Unmodelled search for generic transients

`X-Pipeline` vetoes clusters that have properties similar to the noise background, example of the Median-tracking veto:

E: coherent energie
I: incoherent energie

for glitch a $E \sim I$.



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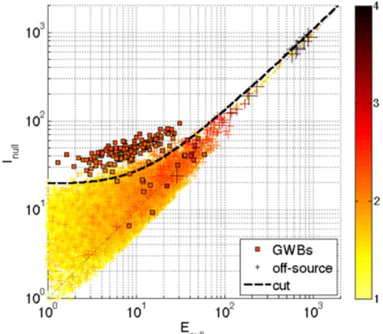
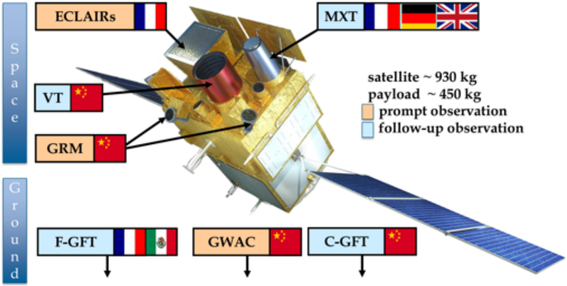


pvalue $\rightarrow$ Probability of background noise producing a cluster in the onsource interval with the significance of the loudest cluster

SVOM



On board

	FoV	band
ECLAIRs	2 steradian	4 – 150 keV
GRM	5.6 steradian	15 – 5000 keV
MXT	64^2 arcmin^2	0.2 – 10 keV
VT	26^2 arcmin^2	B, R

On ground

	FoV	band
GWAC	5400 deg^2	R
F-GFT	$(26 - 21.7)^2$ arcmin^2	$g\ r\ i\ z\ y\ J\ H$
C-GFT	21^2 arcmin^2	$g\ r\ i$
F30	4 deg^2	$U\ B\ V\ R\ I$
F60	19^2 arcmin^2	$U\ B\ V\ R\ I$

List of GRANDMA telescopes

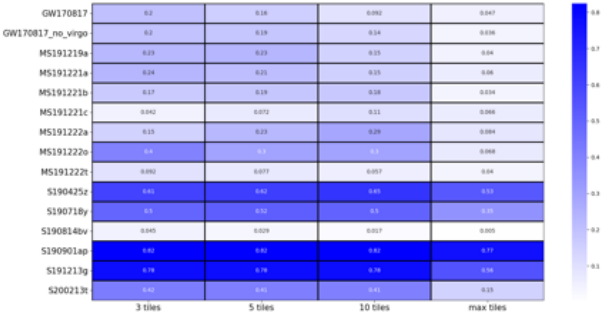
Telescope Name	Location	Aperture (m)	FOV (deg)	Filters	Typical lim mag (AB mag)	Maximum Night slot (UTC)
TAROT/TCH	La Silla Obs.	0.25	1.85×1.85	Clear, $g'r'i'$	18.0 in 60s (Clear)	00h-10h
FRAM-Auger	Pierre Auger Obs.	0.30	1.0×1.0	BVR_CI_C, Clear	17.0 in 120s (R_C)	00h-10h
CFHT/WIRCAM	CFH Obs.	3.6	0.35×0.35	JH	22.0 in 200s (J)	10h-16h
CFHT/MEGACAM	CFH Obs.	3.6	1.0×1.0	$g'r'i'z'$	23.0 in 200s (r')	10h-16h
Thai National Telescope	Thai National Obs.	2.40	0.13×0.13	Clear, $u'g'r'i'z'$	22.3 in 3s (g')	11h-23h
Zadko	Gingin Obs.	1.00	0.17×0.12	Clear, $g'r'i'I_C$	20.5 in 40s (Clear)	12h-22h
TNT	Xinglong Obs.	0.80	0.19×0.19	$BVg'r'i'$	19.0 in 300s (R_C)	12h-22h
Xinglong-2.16	Xinglong Obs.	2.16	0.15×0.15	$BVRI$	21.0 in 100s (R_C)	12h-22h
GMG-2.4	Lijiang Obs.	2.4	0.17×0.17	$BVRI$	22.0 in 100s (R_C)	12h-22h
UBAI/NT-60	Maidanak Obs.	0.60	0.18×0.18	BVR_CI_C	18.0 in 180s (R_C)	14h-00h
UBAI/ST-60	Maidanak Obs.	0.60	0.11×0.11	BVR_CI_C	18.0 in 180s (R_C)	14h-00h
TAROT/TRE	La Reunion	0.18	4.2×4.2	Clear	16.0 in 60s (Clear)	15h-01h
Les Makes/T60	La Reunion.	0.60	0.3×0.3	Clear, BVR_C	19.0 in 180s (R_C)	15h-01h
Abastumani/T70	Abastumani Obs.	0.70	0.5×0.5	BVR_CI_C	18.2 in 60s (R_C)	17h-03h
ShAO/T60	Shamakhy Obs.	0.60	0.28×0.28	BVR_CI_C	19.0 in 300s (R_C)	17h-03h
Lisnyky/AZT-8	Kyiv Obs.	0.70	0.38×0.38	$UBVR_CI_C$	20.0 in 300s(R_C)	17h-03h
TAROT/TCA	Calern Obs.	0.25	1.85×1.85	Clear, $g'r'i'$	18.0 in 60s (Clear)	20h-06h
FRAM-CTA	ORM	0.25	0.43×0.43	Clear, BVR_Cz',	16.5 in 120s (R_C)	20h-06h
IRIS	OHP	0.50	0.4×0.4	Clear, $u'g'r'i'z'$	18.5 in 60s (r')	20h-06h
T120	OHP	1.20	0.3×0.3	$BVRI$	20.0 in 60s (R)	20h-06h
OAJ/T80	Javalambre Obs.	0.80	1.4×1.4	r'	21.0 in 180s (r')	20h-06h
OSN/T150	Sierra Nevada Obs.	1.50	0.30×0.22	BVR_CI_C	21.5 in 180s (R_C)	20h-06h
CAHA/2.2m	Calar Alto Obs.	2.20	0.27	$u'g'r'i'z'$	23.7 in 100s (r')	20h-06h
VIRT	Etelman Obs.	0.50	0.27×0.27	$UBVRI, Clear$	19.0 in 120s (Clear)	22h-04h

SVOM satellite follow-up optimisation

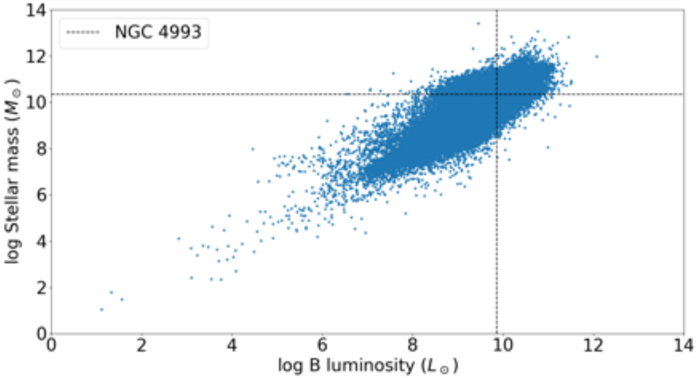
Difference between the mean number of galaxy observed with galaxy targeting strategy and the mean number of galaxy observed with the tilling strategy, normalised by the maximum of observed galaxy

SVOM satellite follow-up optimisation

Difference between the mean quantity of grade observed with galaxy targeting strategy and the mean quantity of grade observed with the tilling strategy, normalised by the maximum of observed quantity of grade

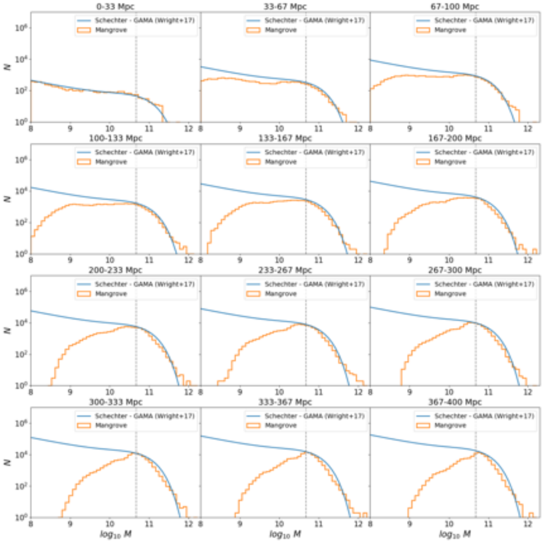


B band / stellar mass



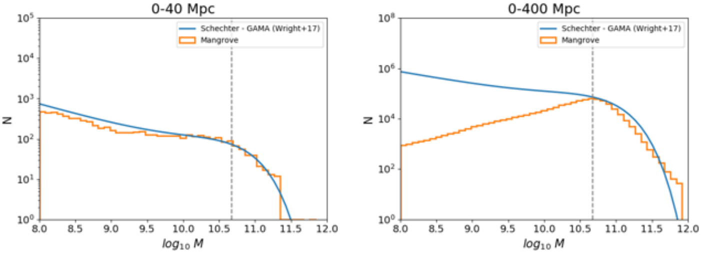
GLADE B band luminosity / stellar mass (using the W1 band).
Crossing of the dashed lines : NGC4993 (host of GW170817)

Completeness



Completeness

Completeness in terms of mass: ~100% up to 40Mpc, ~50% up to 400Mpc



AGN flag

Identification of AGN from mid-infrared color criterion:
$W1 - W2 \geq 0.8$ mag

Short Gamma-ray Burst host galaxies population study

Aim to update the previous results available in the literature (~ 10 years old)

Determine the properties of the galaxies, such as stellar mass and SFR

Use these properties to optimise the gravitational wave follow-up

Short GRB sample

Short GRBs sample from the BAT catalog
selecting GRBs with 0 $\leq$ T_{90} - $T_{90\ err}$ $\leq$ 2s

+ flagged as (possible) short GRBs with extended emission

Few additional GRBs from HETE-2, INTEGRAL, Fermi GBM

$\Rightarrow$ A total of 181 GRBs.

Association with host

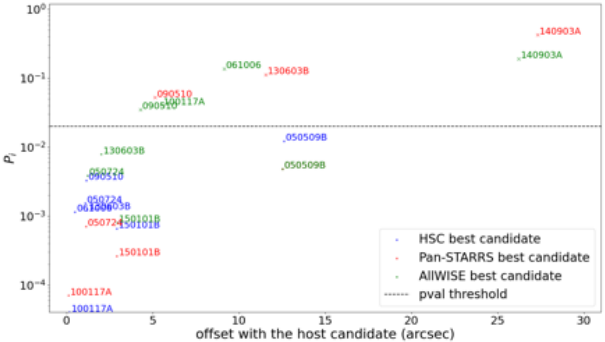
Association is made by estimating the chance alignment between a given GRB localisation and nearby galaxies.
Probability of chance alignment for a given GRB and a given galaxy i is expressed as:

$$P_i = 1 - e^{\pi r_i^2 \sigma(\leq m_i)} \quad (1)$$

Where r_i is the angular distance between the GRB localisation and the galaxy center, $\sigma(\leq m_i)$ is the number of galaxies per arcsecond square having a magnitude below m_i (magnitude of the galaxy i).
Galaxies are taken from several survey catalogs: Pan-STARRS, HSC, AllWISE

Chance alignment threshold

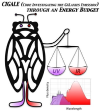
To identify good host galaxy candidate: need to define a threshold in $P_i \rightarrow$ golden sample



A threshold of of 0.02 allows to separate interesting and uninteresting host galaxy candidates. We find 46 Associations.

SED fitting procedure

Determine the galaxies properties → SED fitting is performed with the `CIGALE` code (Code Investigating GALaxy Emission).



Cigale use an energy balance principle where the energy emitted by dust in the mid- and far-infrared exactly corresponds to the energy absorbed by dust in the ultraviolet-optical range.

→ robust for the estimation of the attenuation properties of the galaxies, the SFR, stellar mass and the separation of the emission of active galactic nuclei.

But require (near-)infrared data to provide reliable results

GRBs host photometry

CIGALE $\rightarrow$ 5 photometric measurements covering from the UV to NIR rest-frame + one detection above 1500 nm rest-frame.

compilation of the GRB host photometry,
a very time consuming work:

- Collected the data from the various catalogs
- check the photometric error and data quality flags
- compile the available data in the literature, papers and GCNs
- compiled date are converted in the standard calibration system, check for Galactic extinction...

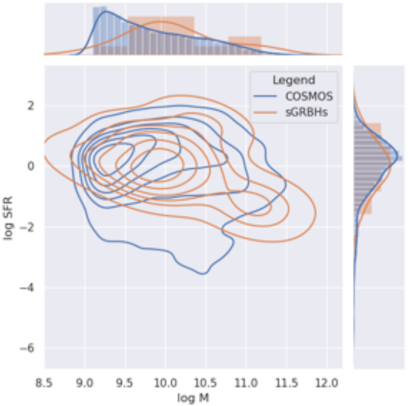
Among the 46 galaxies that are associated: 37 galaxies fulfil the photometric requirement.

Results of the fits

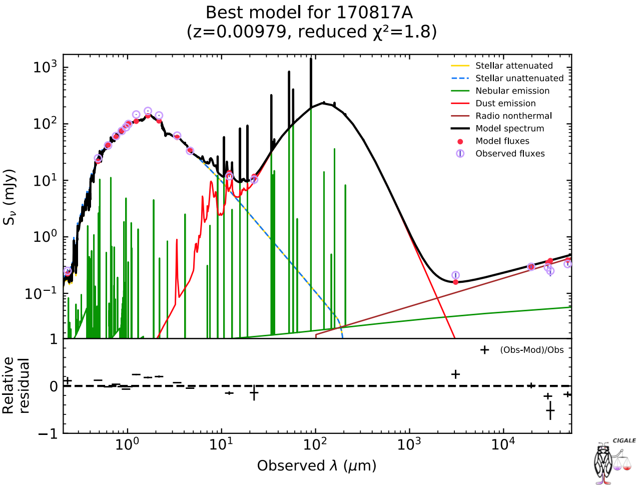
Similar trend than previous works → significantly extend the statistic

Hosts appear to be more massive and less active than the field galaxies

Gravitational wave follow-up:



SED fitting


Best model for 170817A
(z=0.00979, reduced χ²=1.8)
Stellar attenuated
Stellar unattenuated
Nebular emission
Dust emission
Radio nonthermal
Model spectrum
Model fluxes
Observed fluxes
(Obs-Mod)/Obs
Sν (mJy)
Relative residual
Observed λ (μm)
CIGALE