Kilonovae in the multi-messenger era

Dr. Sarah Antier
CNES Fellowship,
APC, Paris

What is multi-messenger astronomy ?

Transient phenomena: shortest times scales (milliseconds to several years)

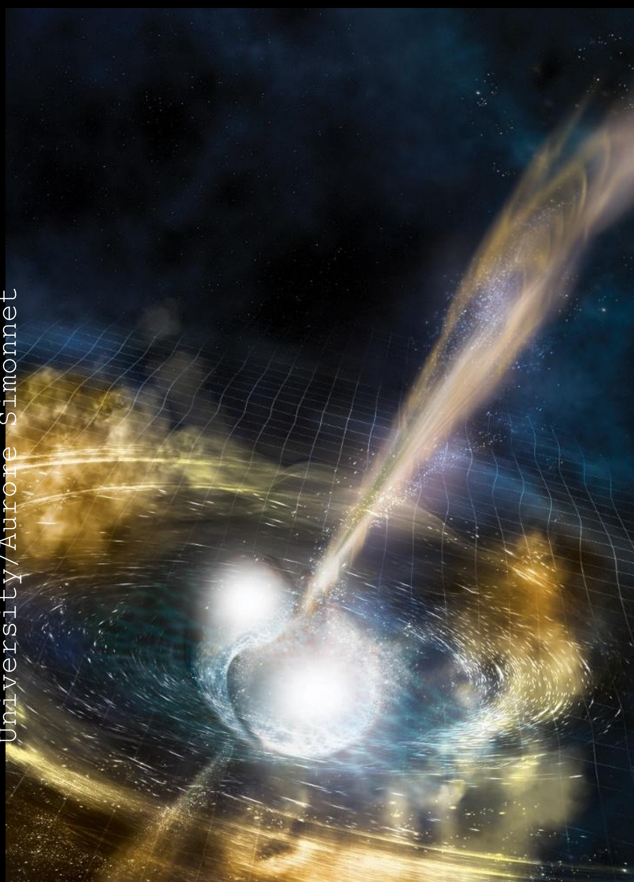


Image Credit: LSC/Sonoma State University/Aurore Simonnet

To emit GWs, a source must be compact, relativistic and asymmetric

Merger (NS-NS; NS-BH; BH-BH)

- Short GRBs, Kilonova
- Other cases ? FRB ?

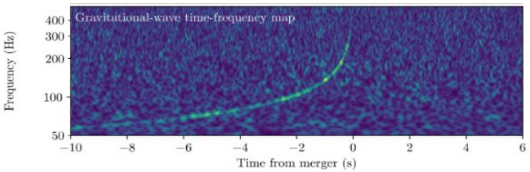
Collapse of a single star

- Type Ib, Ic, II supernovae
- Long GRBs
- Intermediate cases

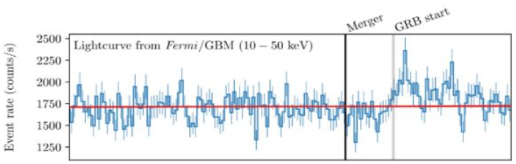
Neutron star instabilities

- Soft Gamma-ray repeaters
- Radio/ Gamma-ray pulsar glitches

GW170817- First multi-messenger event

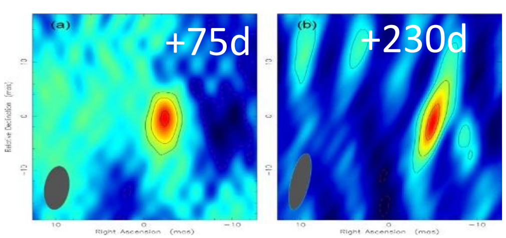


Ondes gravitationnelles
Système Initial

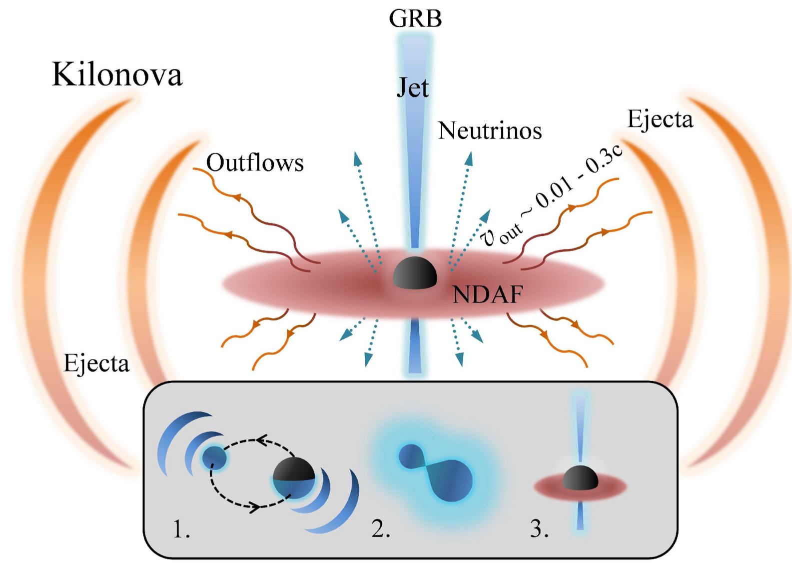


GRB
Jet
Mécanismes d'accélération

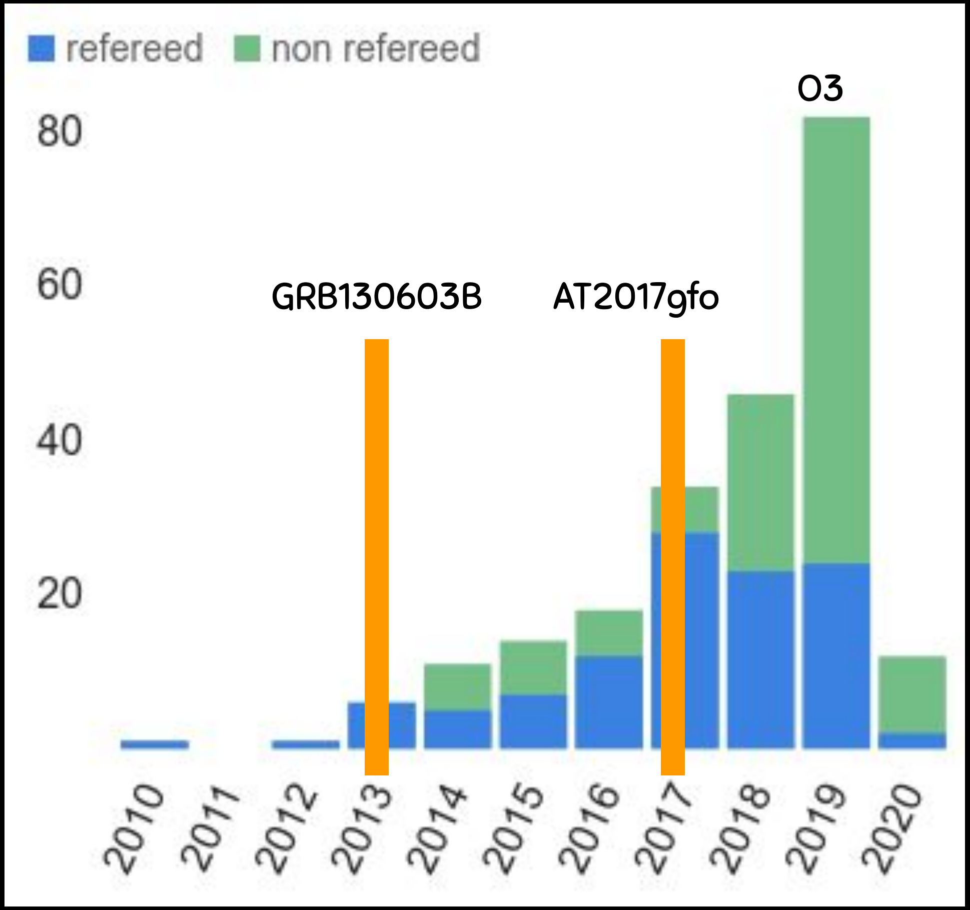
Kilonova
Localisation (arcsec)
Galaxie hôte
Décalage vers le rouge



Rémanence
Géométrie de l'émission



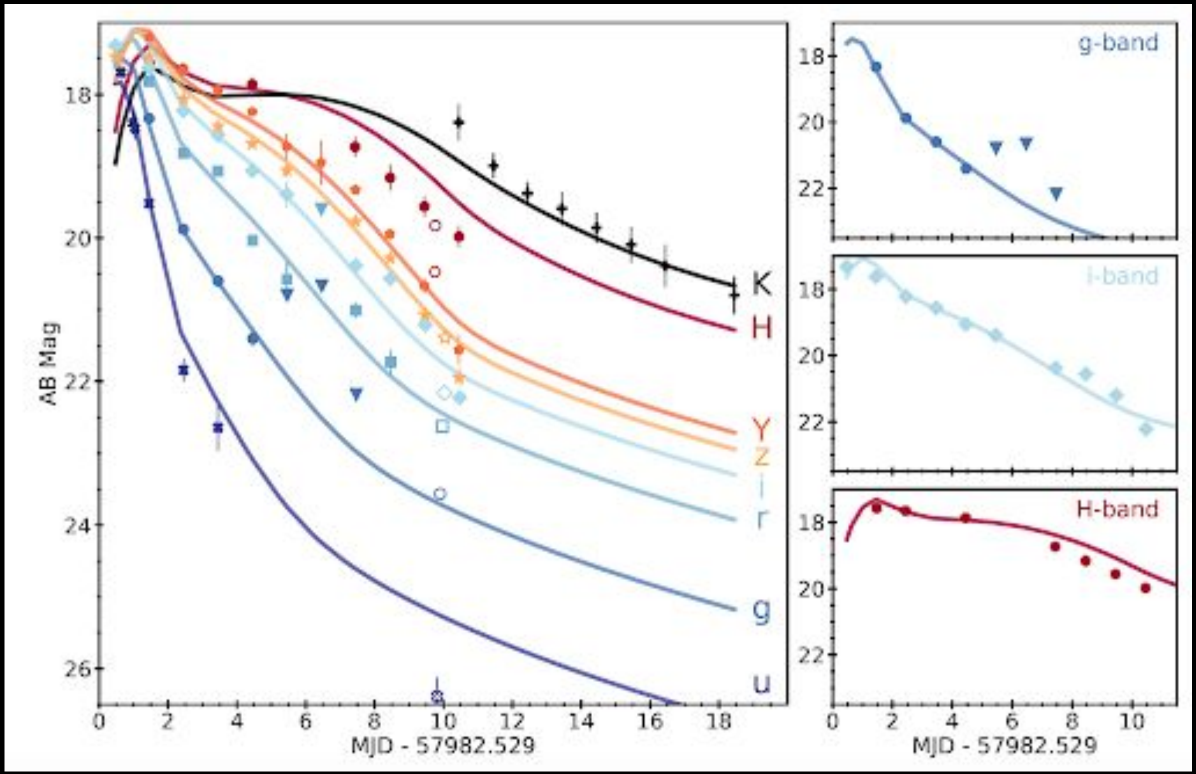
“Kilonovae” a very short story in astronomy



(Lattimer & Schramm) 1974

Kilonovae

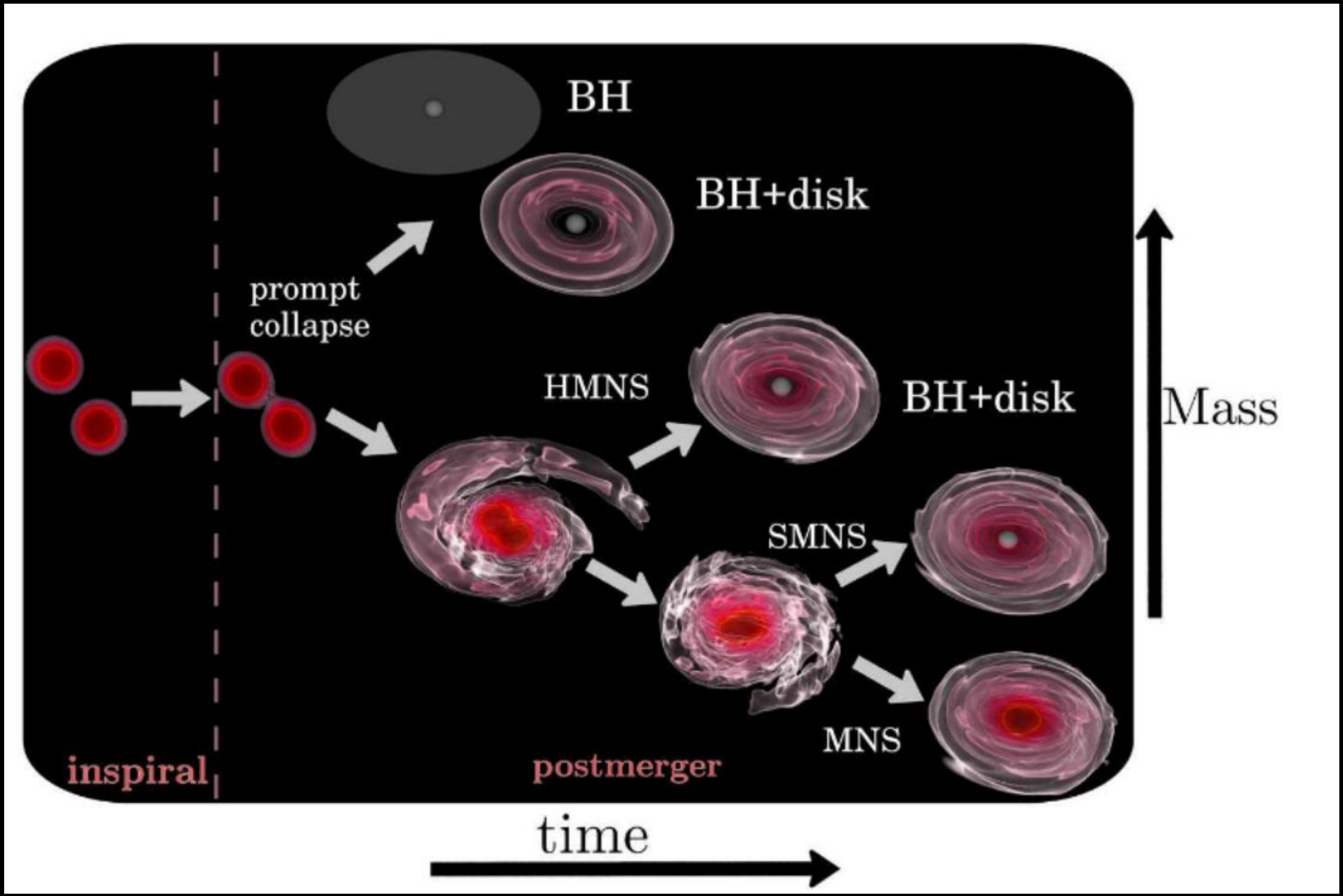
Villar et al., 2017



- Connected to compact binary coalescence
- Thermal emission due to the radioactive decay of freshly synthesized elements in neutron-rich ejecta

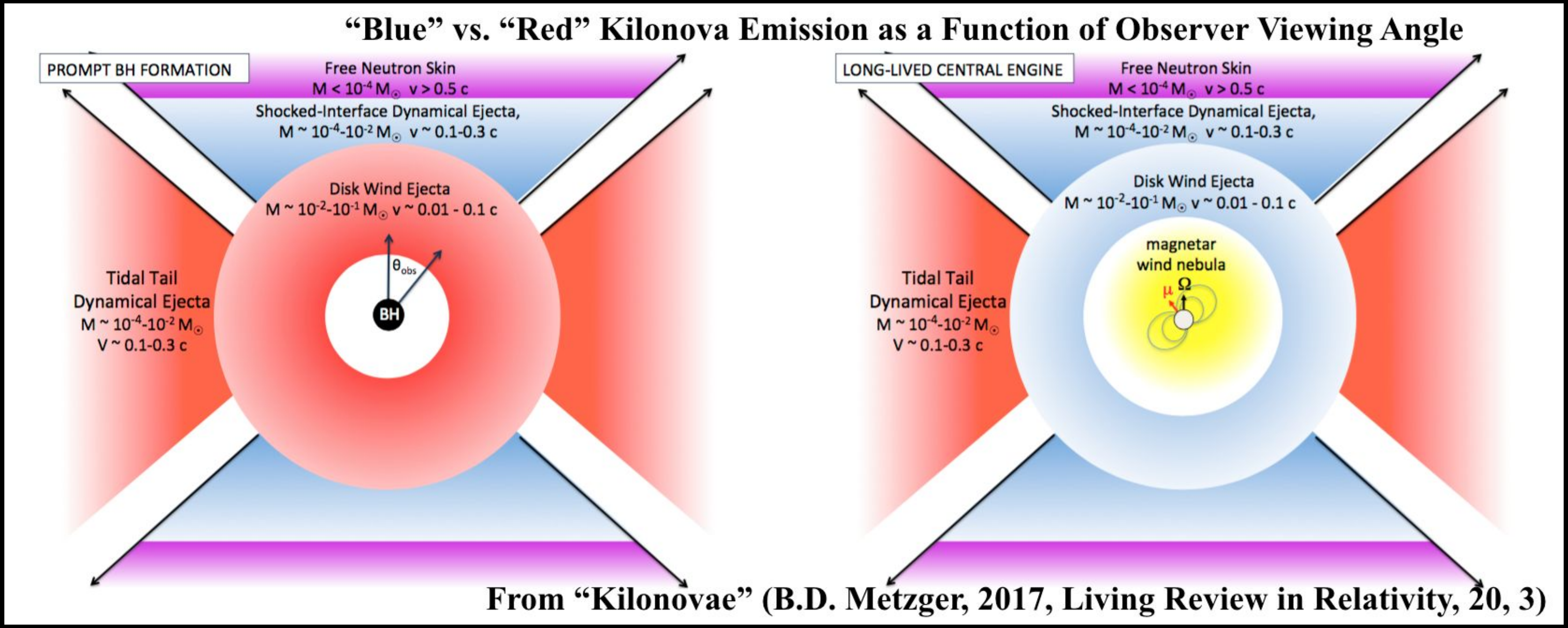
Neutron stars or neutron star – black hole coalescence

NS Mass : [1.0 , 2.2] solar mass and NS Radius: [10 15] km



Kilonovae depends on various parameters as EOS of NS and mass ratio of the compact objects

Kilonovae



- Dynamical ejecta
  - Equatorial (Neutron rich) : High fraction of Lanthanide : Red kilonova
  - Polar (Neutron poor): Blue kilonova
- Contribution from the accretion disk (blue and red)

one
and
only.

Kilonovae discoveries

P1: GRB observations

Less than 1 kilonova-GRB per year

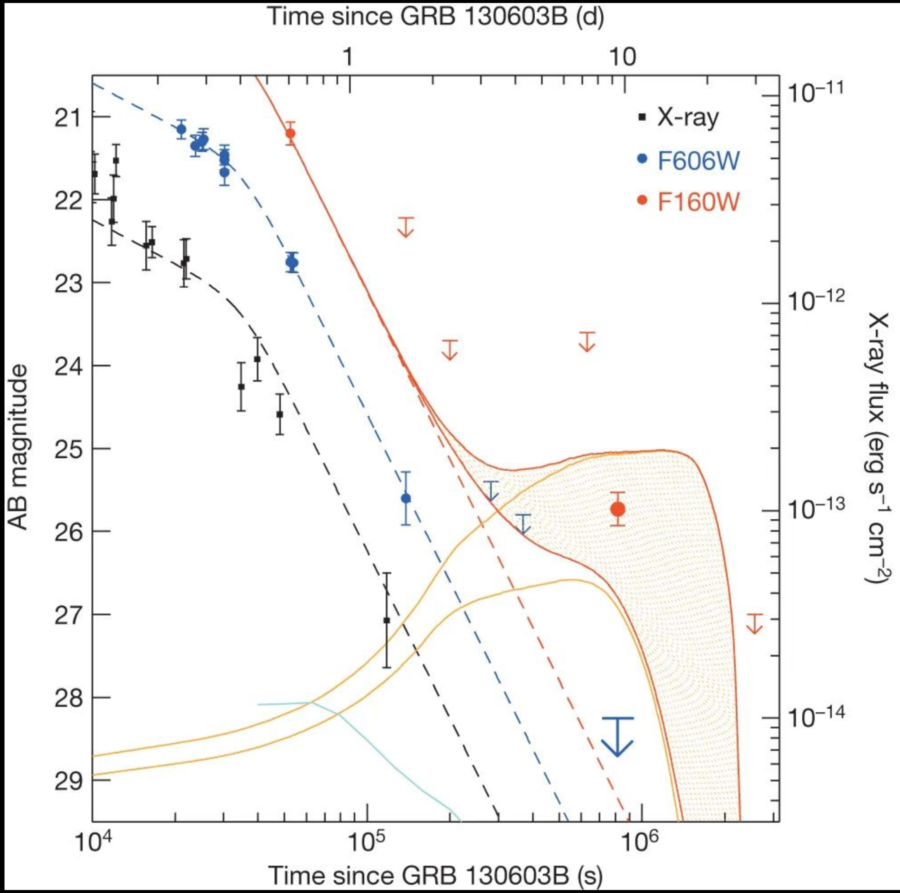
P2: GW observations

1 – 8 kilonovae at 160 Mpc (O3)
GW BNS range 330 Mpc (2025)

P3: Optical surveys

up to 26 mag, 600 Mpc

Proposition 1: Observations with GRB alerts



GRB130603B, Tanvir et al., 2013
z ~ 0.356

and other cases in GRB 060614, GRB 050709, GRB 150101B, GRB 070809, GRB160821B

Proposition 1: Observations with GRB alerts
Gamma-ray bursts searches

Fermi/ GBM:

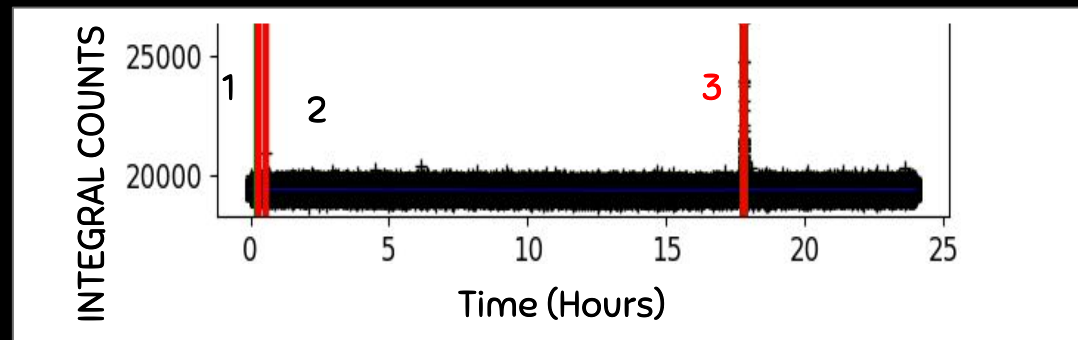
- ✘ 12 NaI detectors, 2 BGO detectors
- ✘ 4.4 keV – 2 MeV (NaI)
- ✘ Semi-major axis 6 900 km, period 95 min.
- ✘ Daily photons data

INTEGRAL / SPI-ACS:

- ✘ 19 HPGe detectors
- ✘ 75 keV – 2 MeV
- ✘ Semi-major axis 88 000 km, period 72 hours
- ✘ Already binned data in single energy bond

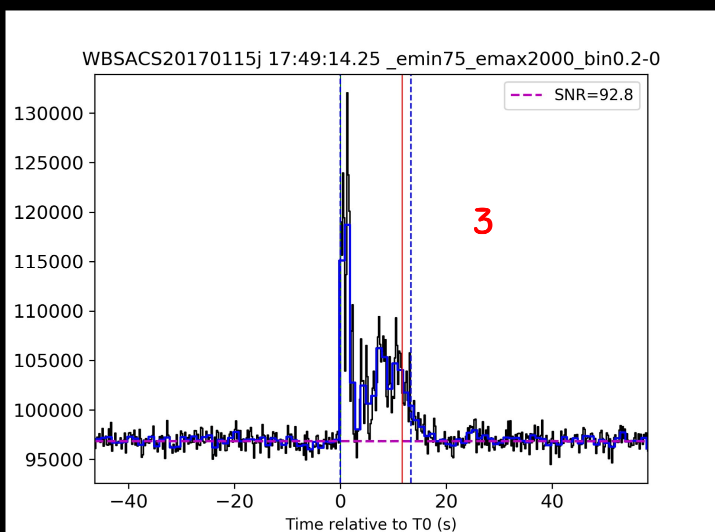
Proposition 1: Observations with GRB alerts
Gamma-ray bursts searches : FWBS pipeline

Science data → Background removal → Change points detections



GRB candidates

Multi-energy band search / detector



Validation

Proposition 2: Observations with GRB alerts
Gamma-ray bursts searches : FWBS pipeline

Fermi/ GBM

INTEGRAL / SPI-ACS

Proof of concept

60 days (in 2017, 2018)

- ✘ 42/44 GRBs in coincidence with Fermi/GBM standard method
- ✘ 1.2 event/day in E > 50 KeV
- ✘ 19 events / day in E < 50 KeV

Full 2017, 2018, 2019 analysis

- ✘ 3 events per day
- ✘ 130 GRBs in coincidence with Fermi/GBM
- ✘ 60% of GRB supplement detection than classical INTEGRAL methods

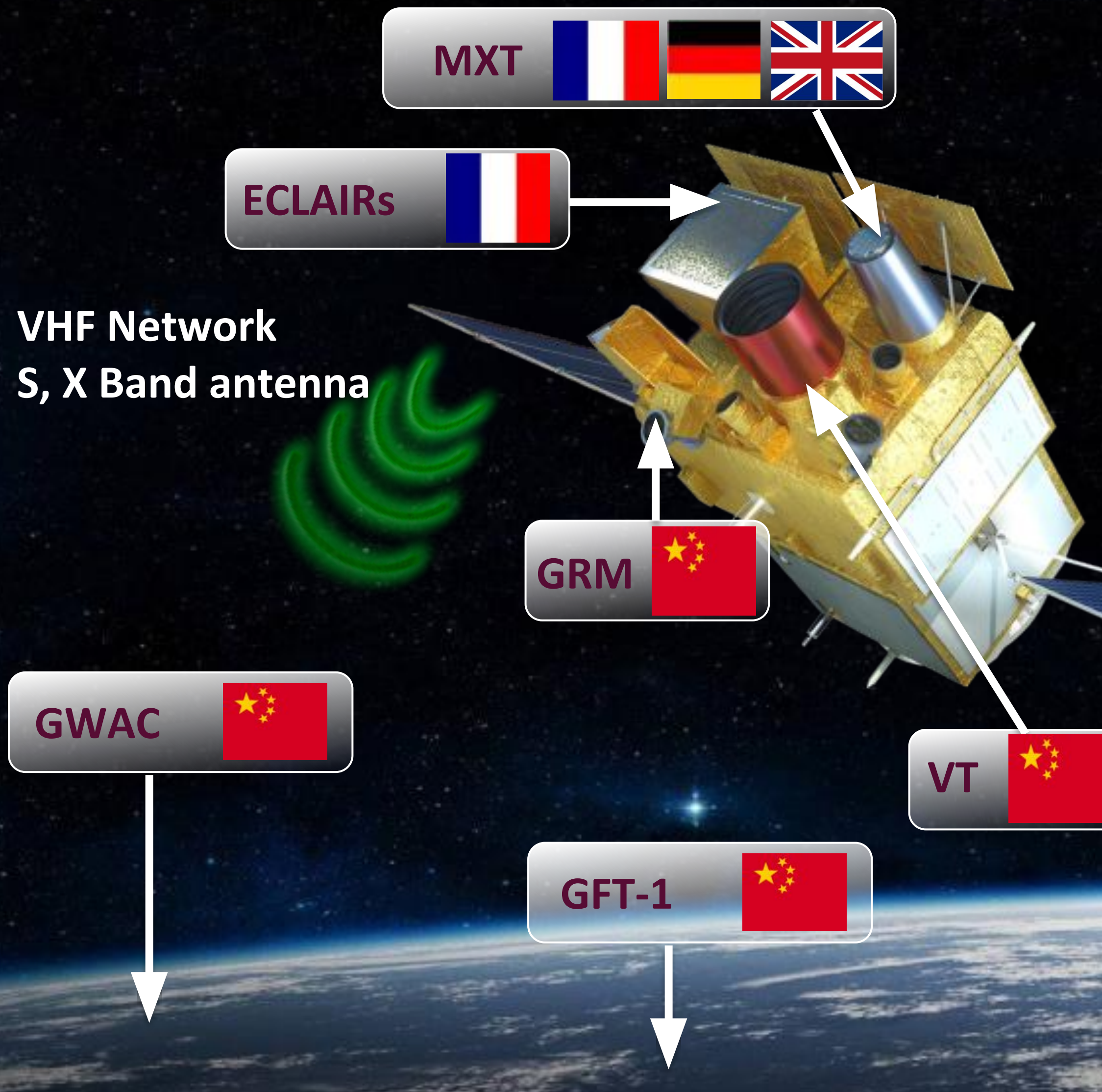
Detection of gamma-ray transients with wild binary segmentation

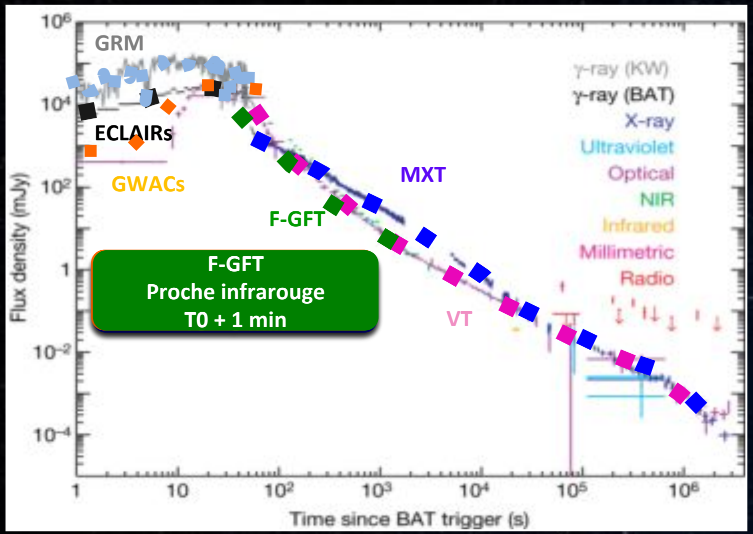
https://arxiv.org/abs/1909.10002

S. Antier[1,2], K. Barynova[2,3], P. Fryzlewicz[4], C. Lachaud[1], G. Marchal-Duval[2]

SVOM: Space-based multiband astronomical Variable Objects Monitor

Satellite to be launched in 2021



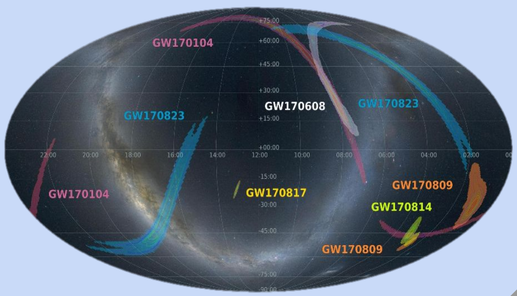


Cordier et al., PoS, *Swift:10* (2015)

14

Proposition 2: Observations with GW alerts
Multi-messenger astronomy with LVC

ELECTROMAGNETIC



Kilonovae

Gamma-ray bursts

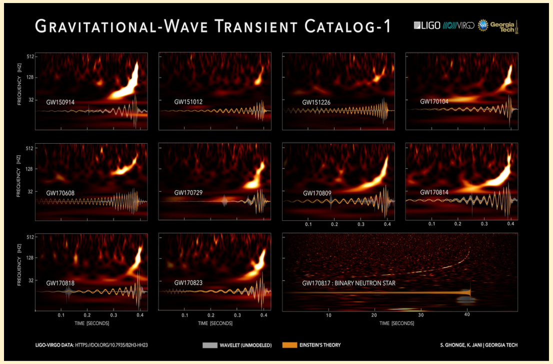
GRAVITATIONAL WAVES
From coalescence of compact sources

ONLINE

Trigger time, nature of the event, rough localization

ALL SKY BLIND SEARCHES

ONLINE



Precised localization, Trigger time, inclination

TARGETED SEARCHES

OFFLINE

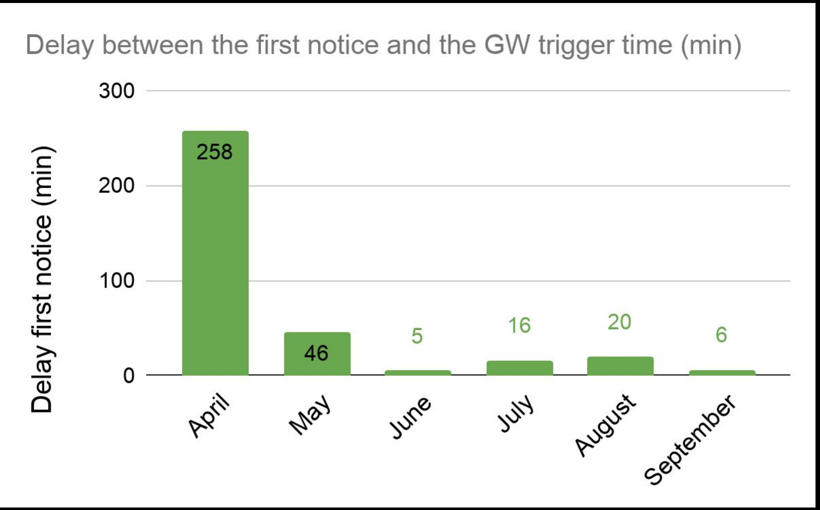
Proposition 2: O3ab summary

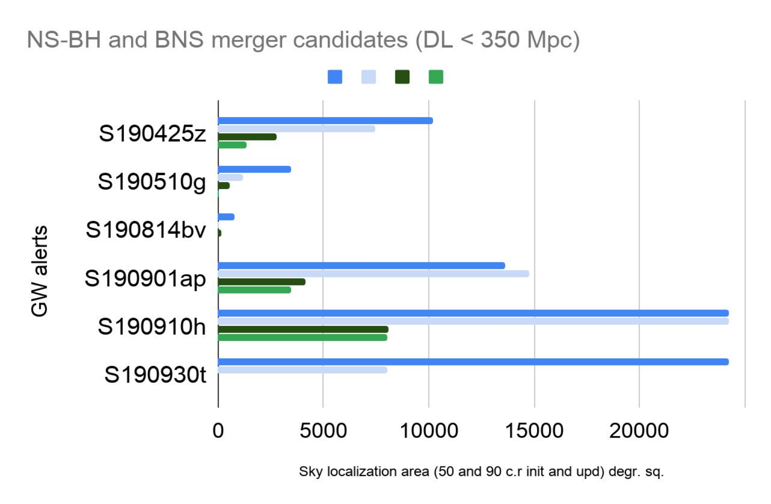
48 public GW alerts, 1 burst alert

7 BNS 7 NS-BH 33 BBH mergers candidates

22 retractions

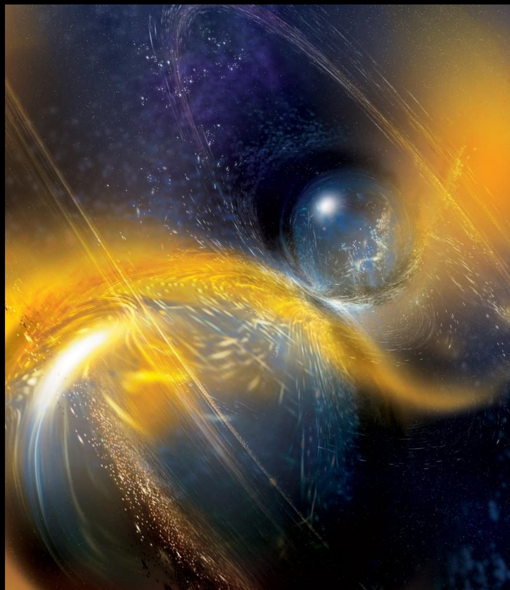
FINAL CONTENT MAY DIFFER !

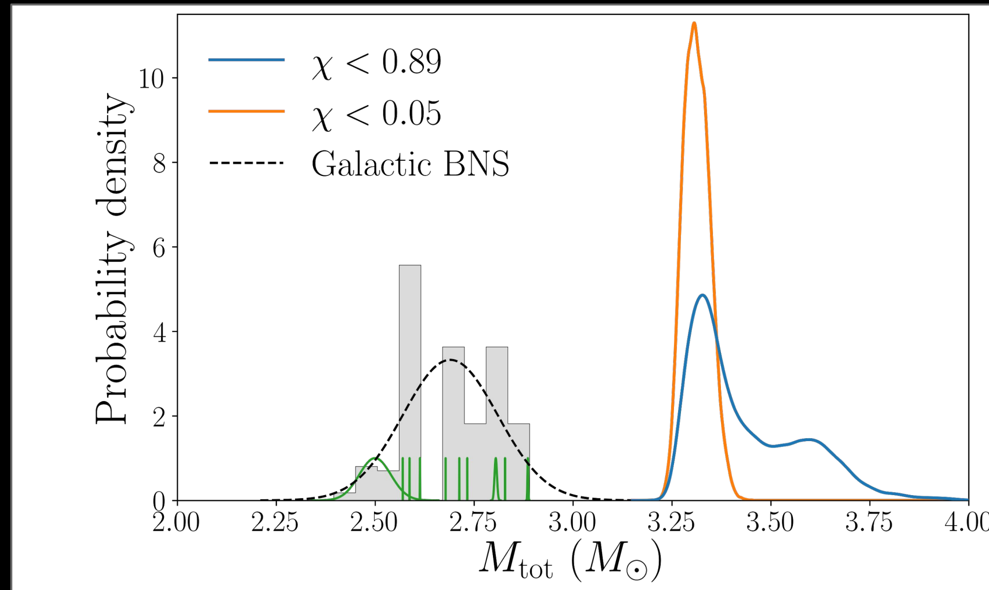




GW190425

LSC LIGO Scientific Collaboration VIRGO



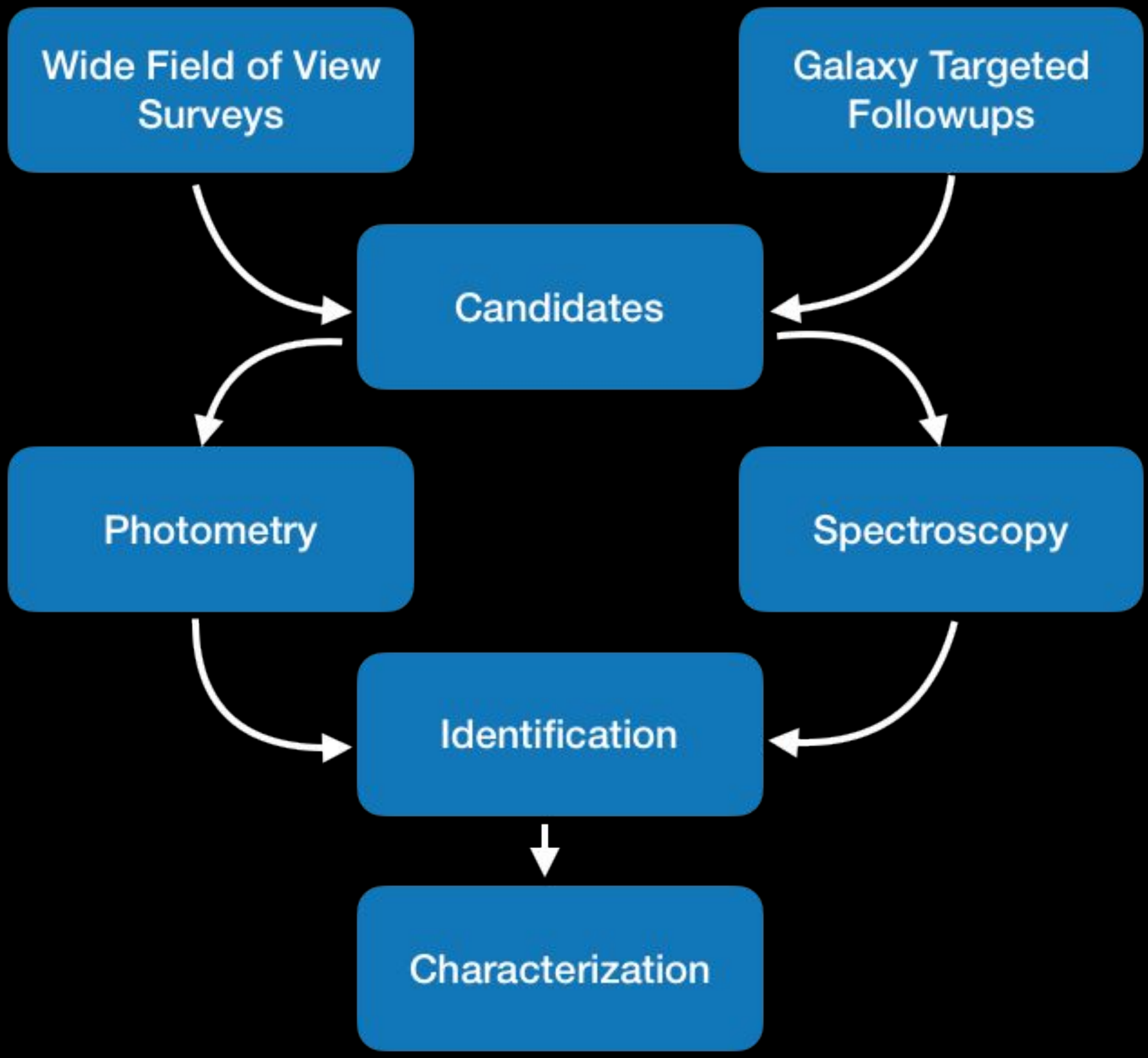


On 08:18:05 UTC, L1 single detection, 8000 deg2 for 90% sky area localization, 156 Mpc +/− 41 Mpc
FAR: one chance event in 69,000 years
initial m1: 1.61 and 2.52 solar mass and initial m2: 1.12 and 1.68 solar masses
total mass: 3.0 – 3.7 solar masses

GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_\odot$

The LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, G. Allen, A. Allocca, M. A. Aloy, P. A. Altin, A. Amato, S. Anand, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Arène, N. Arnaud, S. M. Aronson, K. G. Arun, S. Ascenzi, G. Ashton, S. M. Aston, P. Astone, F. Aubin, P.

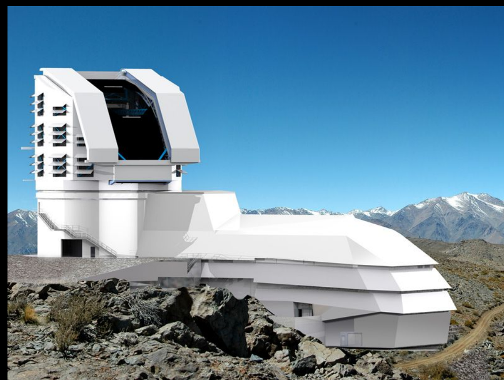
Proposition 2: Observations with GW alerts



GRANDMA

Global Rapid Advanced Network Devoted to Multimessenger Addicts

1.



3.

Local team – scientists – Infrastructure

2.

Connecting existing facilities that are not supposed to be connected within a year

Created in April, 2018

by LAL – Obs Nice

More than 70 scientists

PI. S.Antier

Present in

13 countries

18 observatories

26 institutes / groups

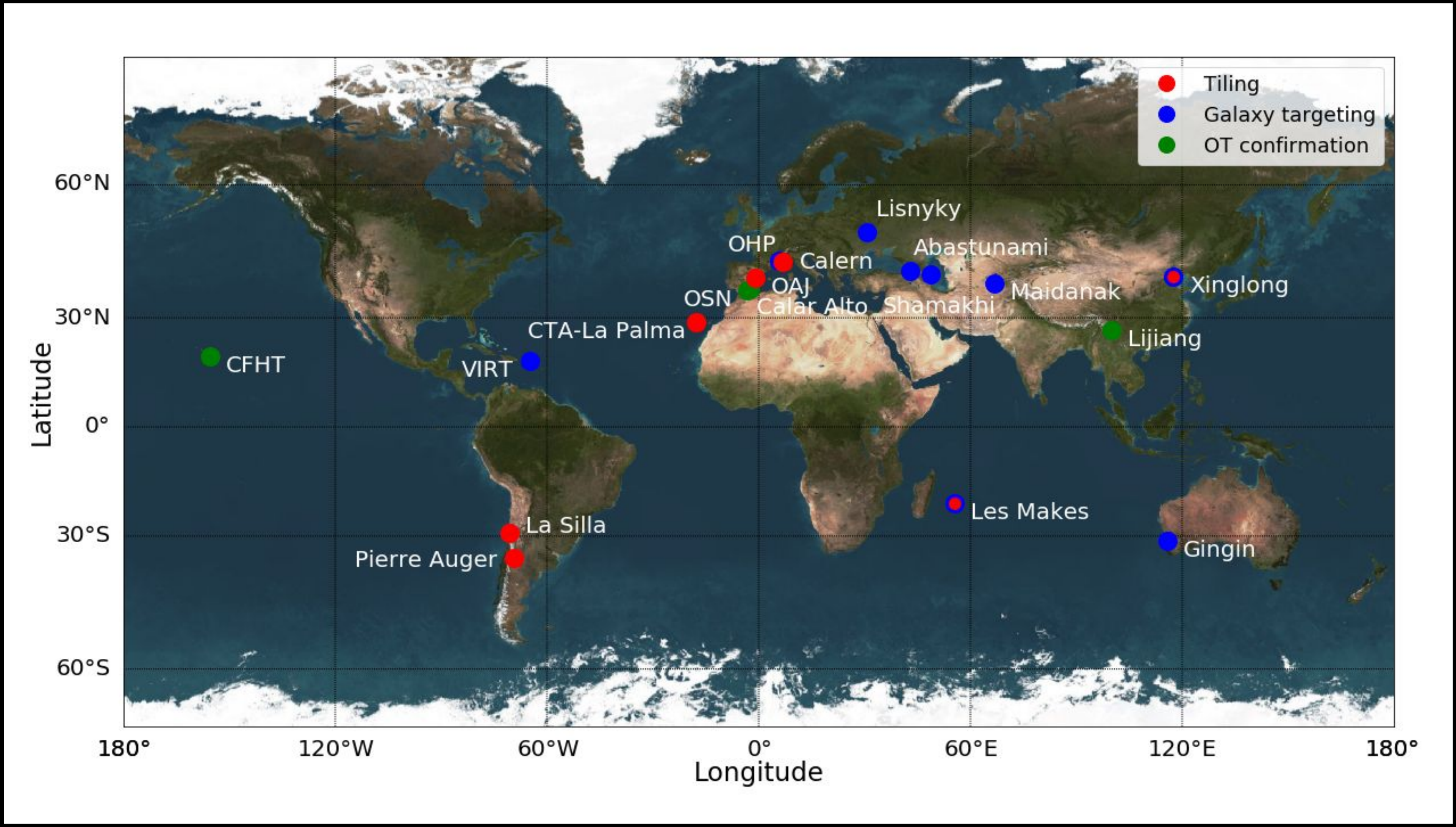
CNRS/– APC – IAP – LAL – Obs Nice – IRAP – LAM

The first six months of the Advanced LIGO's and Advanced Virgo's third observing run with GRANDMA

S Antier, S Agayeva, V Aivazyan, S Alishov, E Arbouch, A Baransky, K Barynova, J M Bai, S Basa, S Beradze ... Show more

Monthly Notices of the Royal Astronomical Society, Volume 492, Issue 3, March 2020, Pages 3904–3927, https://doi.org/10.1093/mnras/stz3142

GRANDMA : An Empire when the sun never rises



Accepted ToO Proposal 2020A
CFHT (PI. Coleiro) – GTC (PI. Kann) – TNT/TRT (PI. Noysena)

Joint Scheduler

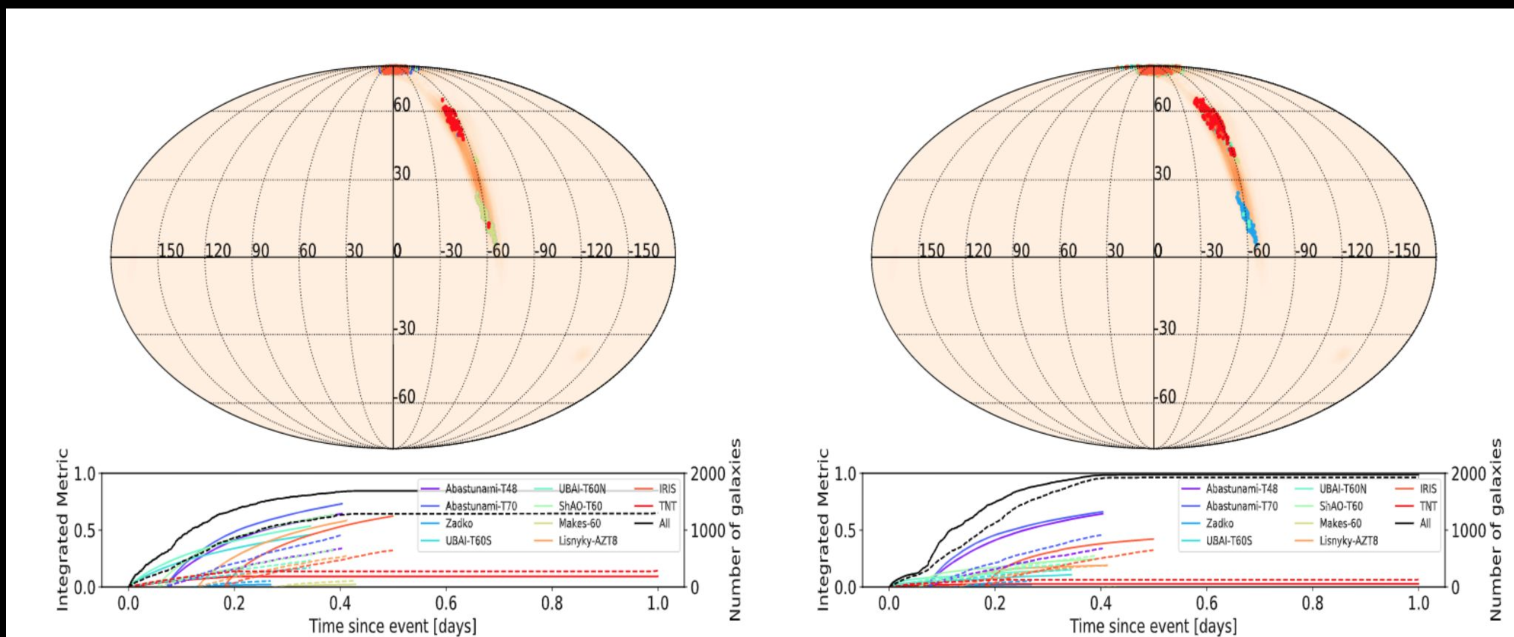
✘ Spatial coverage

Distribution of the tiles over the network

✘ Temporal resolution

Best portion of the credible region observed several times with 1h delay minimum

Designed for each telescope

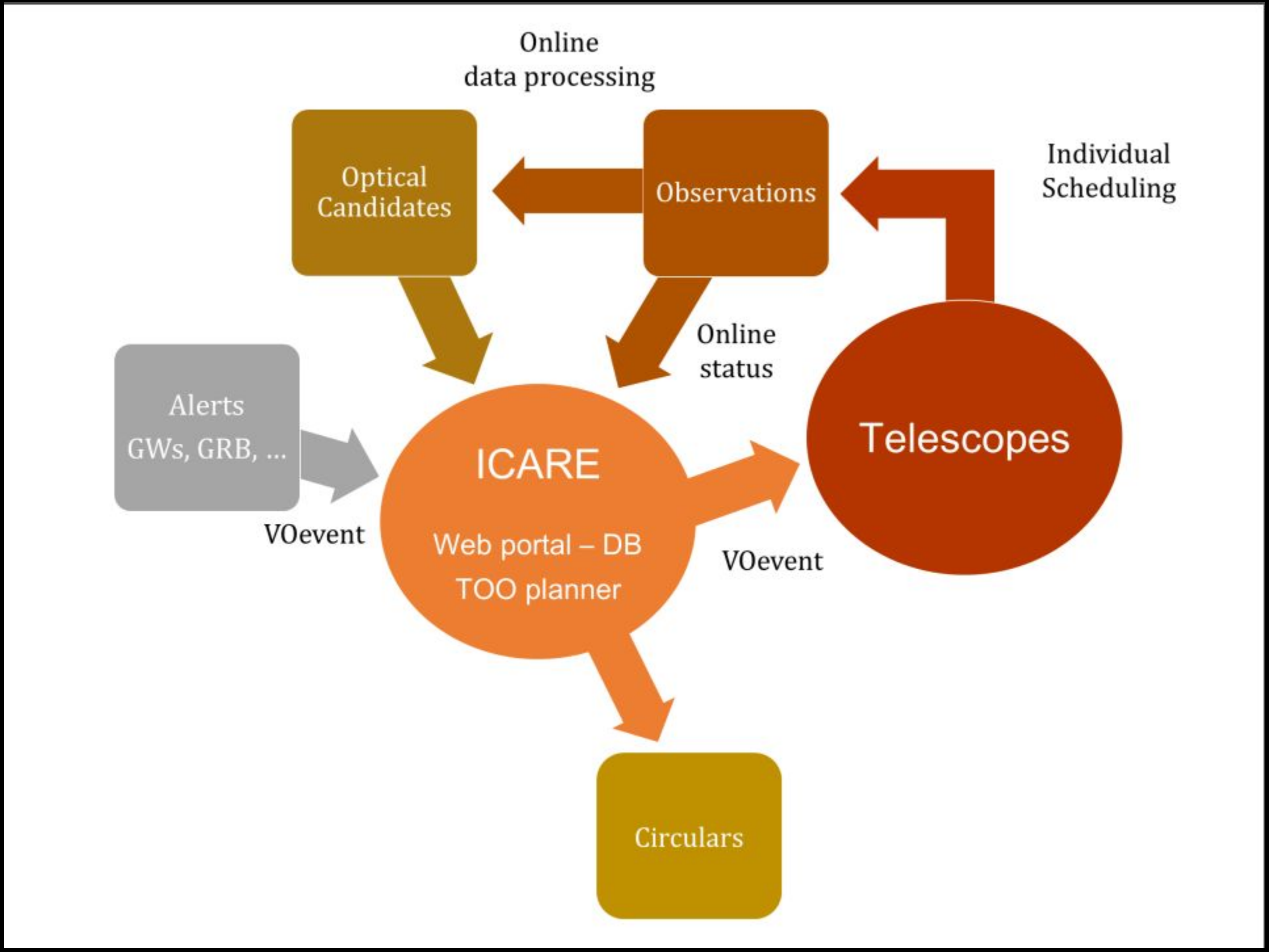


Optimizing multitelescope observations of gravitational-wave counterparts

Michael W Coughlin, Sarah Antier, David Corre, Khalid Alqassimi, Shreya Anand, Nelson Christensen, David A Coulter, Ryan J Foley, Nidhal Guessoum, Timothy M Mikulski ... Show more

Monthly Notices of the Royal Astronomical Society, Volume 489, Issue 4, November 2019, Pages 5775–5783, https://doi.org/10.1093/mnras/stz2485

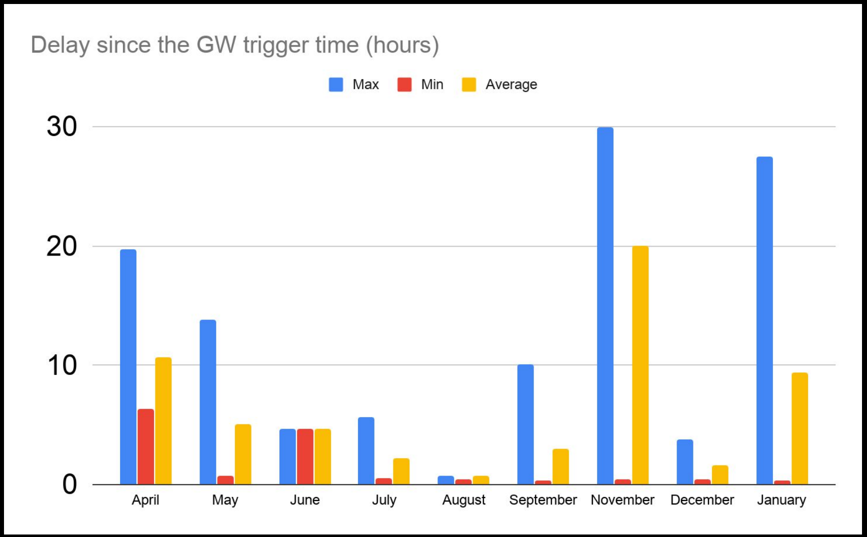
ICARE
Interface and Communication for Addicts of the Rapid follow-up in multi-messenger Era

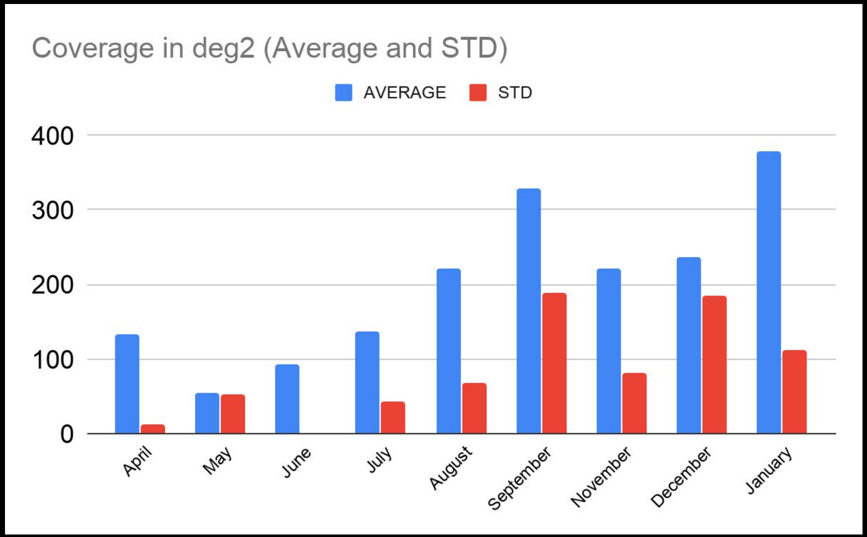


GRANDMDA O3 observational report

43/48 follow-up of GW alerts

7 BNS 6 NS-BH 30 BBH MERGERS





Global effort : No discovery yet, O3A summary

	GW alert rate	Telescopes involved	Time available	Delay	Nom. sensitivity GW Follow-up	Nom. sensitivity counterpart Follow-up	Spectroscopy	Other-wavelength
GRANDMA	27	23 in 17 sites	unlimited	~30 min	17 – 21 (c,r)	~23	~ 19 mag	gamma, smm (?)
GROWTH	8	~60 in 19 sites	few hours per alerts	~ hours	20.5 (g, r) ~22 (r, z)	~23	~ 22 mag	gamma radio
MASTER	31	14 in 7 sites	unlimited	~ minutes	~ 19 (c)	~20	no	–
GRAWITA	~8	~10 in 3 sites	few hours per alert Asiago unlimited	~ hours	16 – 22 (r)	~23	~ 22 mag collab. ENGRAVE	radio
GOTO	~5	2 in 2 sites	few hours per alerts	~ dozen of minutes	~20 (l)	~21	–	–
SVOM	11	7 in 3 sites	unlimited	~ hours	16 – 18 (c,r)	~21	~ 19 mag	Future
PS1 – Atlas	~7	2 in 1 site	few hours per alerts	~ hours	~19.5 (o) ~ 21 mag (i)	~22	collab. ENGRAVE	–

90% of GW alerts followed

Kilonova-Cactcher
Citizen science program

Université de Paris

45 000 euros

Multi-wavelength project
Including Physicist and astronomers

76% of first NS-BH loca.
covered in 1h at 17 mag

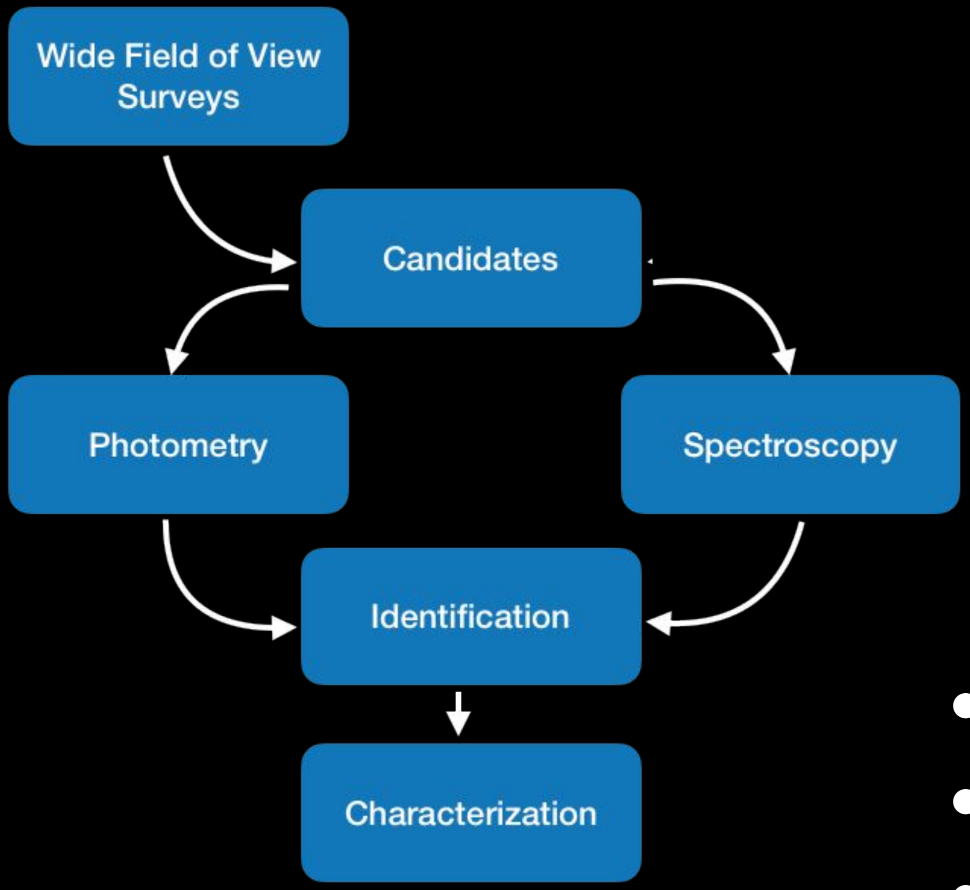
GRANDMA

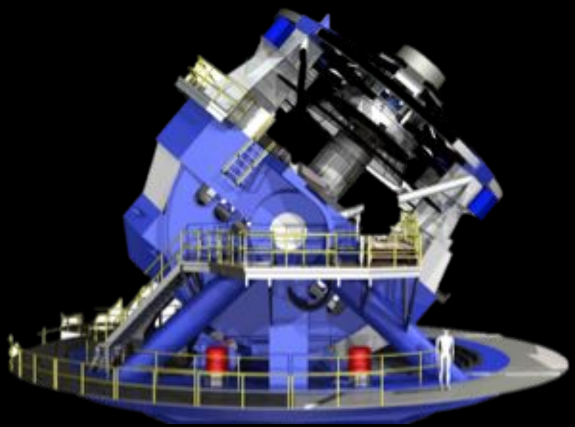
Multimessenger
Universal
Plateform ICARE

16 min between GW TO
and GRANDMA min obs

Geographic diversity
25 telescopes

P3: Observations with Optical surveys





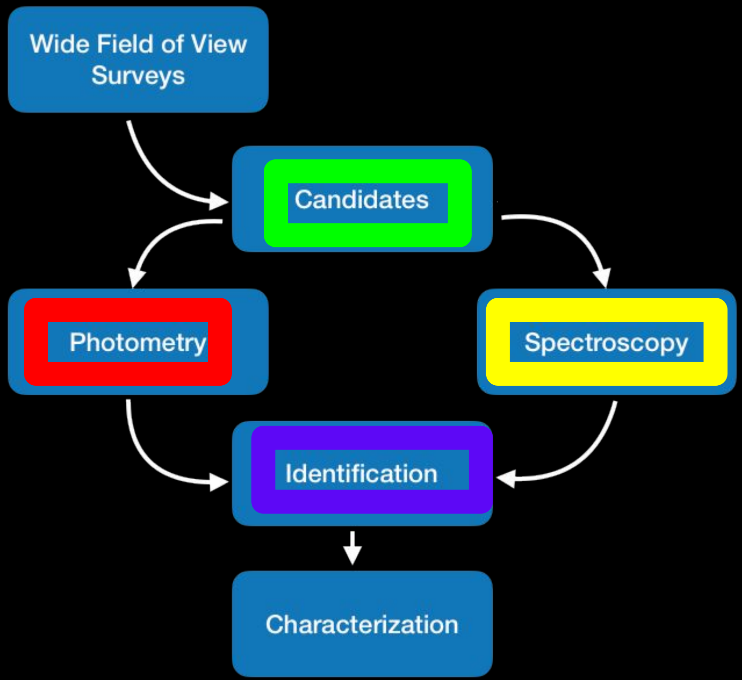
LSST

- Ten year sky survey from 2022
- Coverage of 9.2 sq deg FOV
- Raw alert flow > 1 million

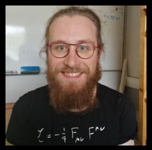
in compa. ZTF ~ 200 000 per day

Où est la kilonova Charlie ?

P3: Grandma initiative to Face Alert deluge



Detection pipeline for candidates
with D. Corre, E. Bertin



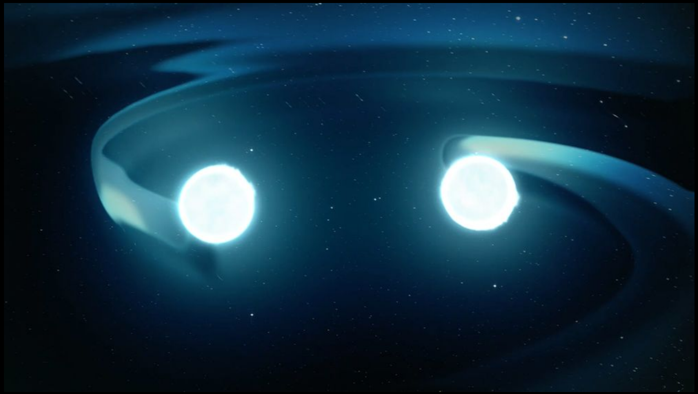
Standardized photometric calibration
with P. A. Duverne, P. Hello

Standardized spectrocopy
with A. Coleiro

Classification of the candidates (supernova, ...)
with C. Stachie, M. Coughlin

Astrophysics on Compact binary coalescence

M. Coughlin (Uni Minnesota)



S. Antier (APC)

Nuclear physics

Equation of state of nuclear matter

T. Dietrich (Uni Postdam)

Cosmology

Measuring the Hubble constant

None Kilonova : something for nothing

research highlights

GRAVITATIONAL WAVES

Something for nothing

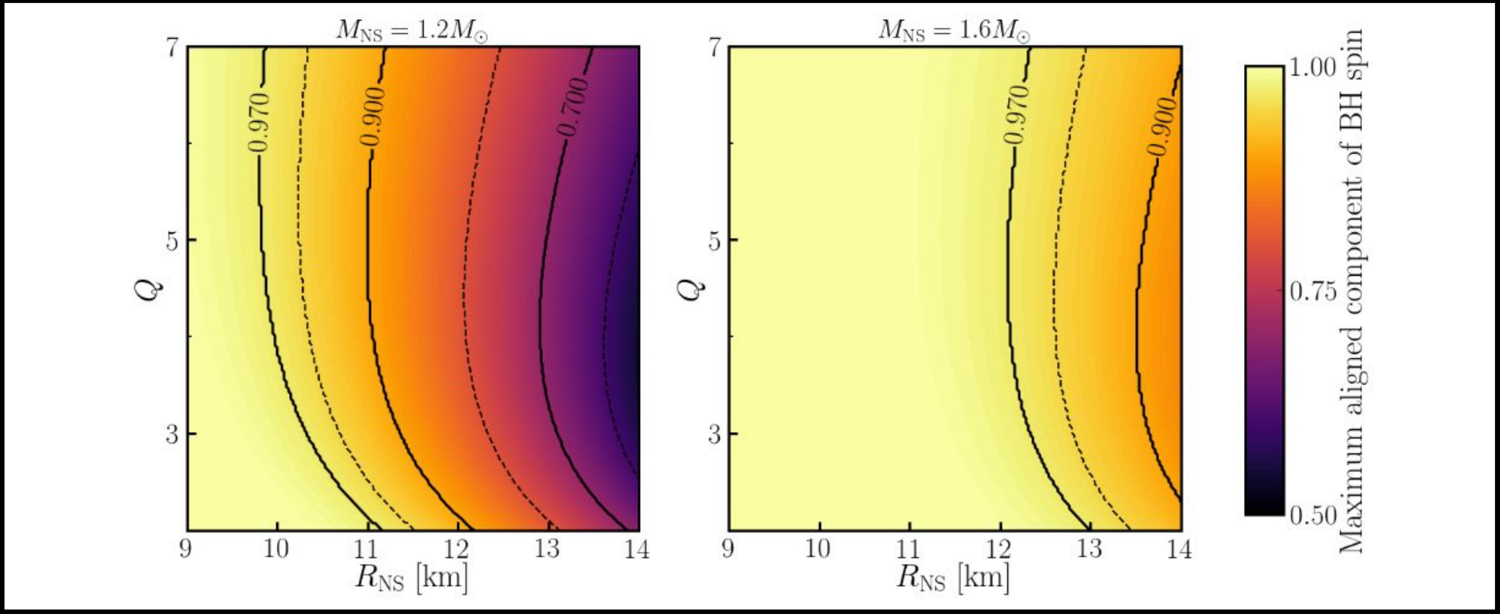
Mon. Not. R. Astron. Soc. https://doi.org/10.1093/

Implications of the search for optical counterparts during the first six months of the Advanced LIGO's and Advanced Virgo's third observing run: possible limits on the ejecta mass and binary properties

Michael W Coughlin, Tim Dietrich, Sarah Antier, Mattia Bulla, Francois Foucart, Kenta Hotokezaka, Geert Raaijmakers, Tanja Hinderer, Samaya Nissanke

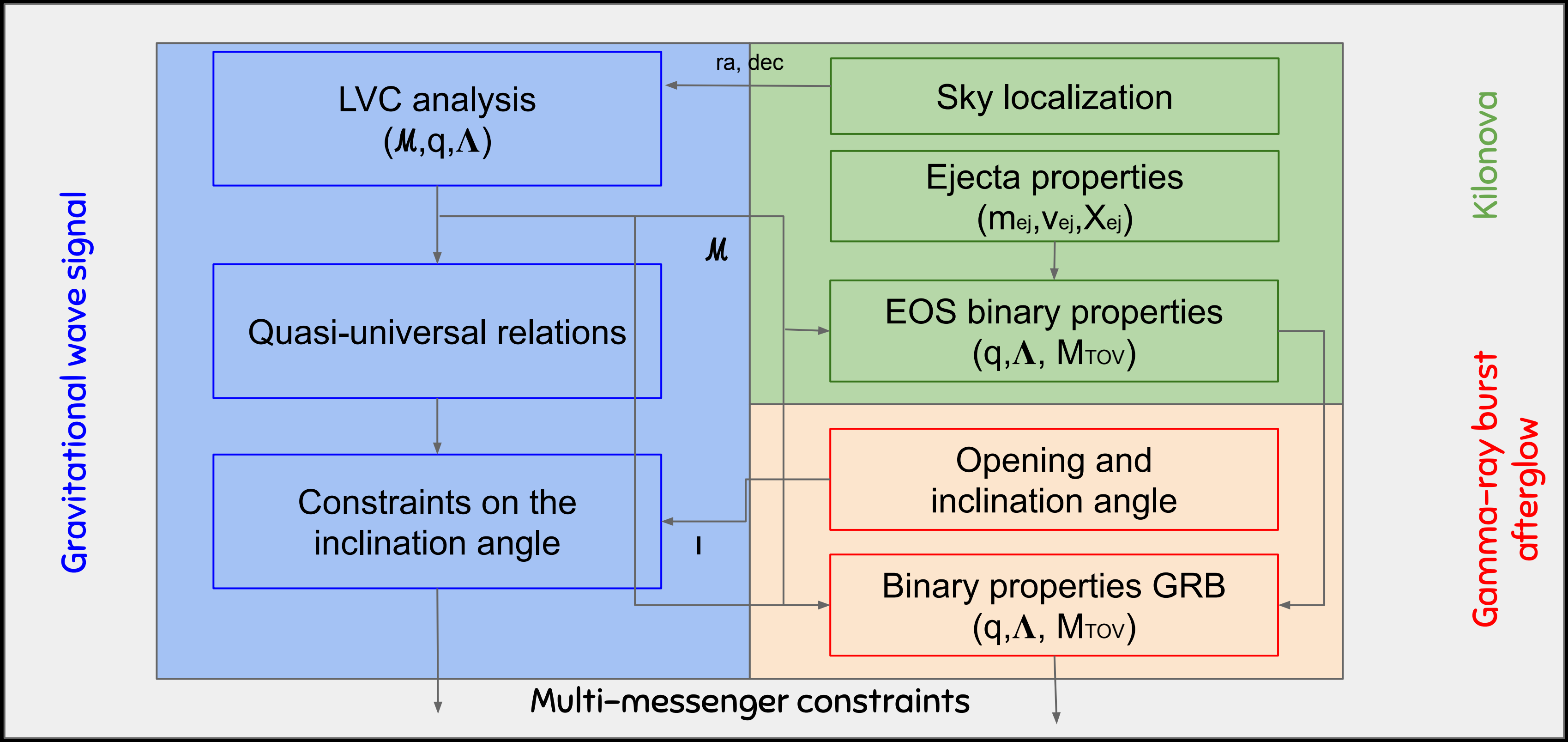
Monthly Notices of the Royal Astronomical Society, Volume 492, Issue 1, February 2020, Pages 863–876, https://doi.org/10.1093/mnras/stz3457

Published: 10 December 2019 **Article history** ▾

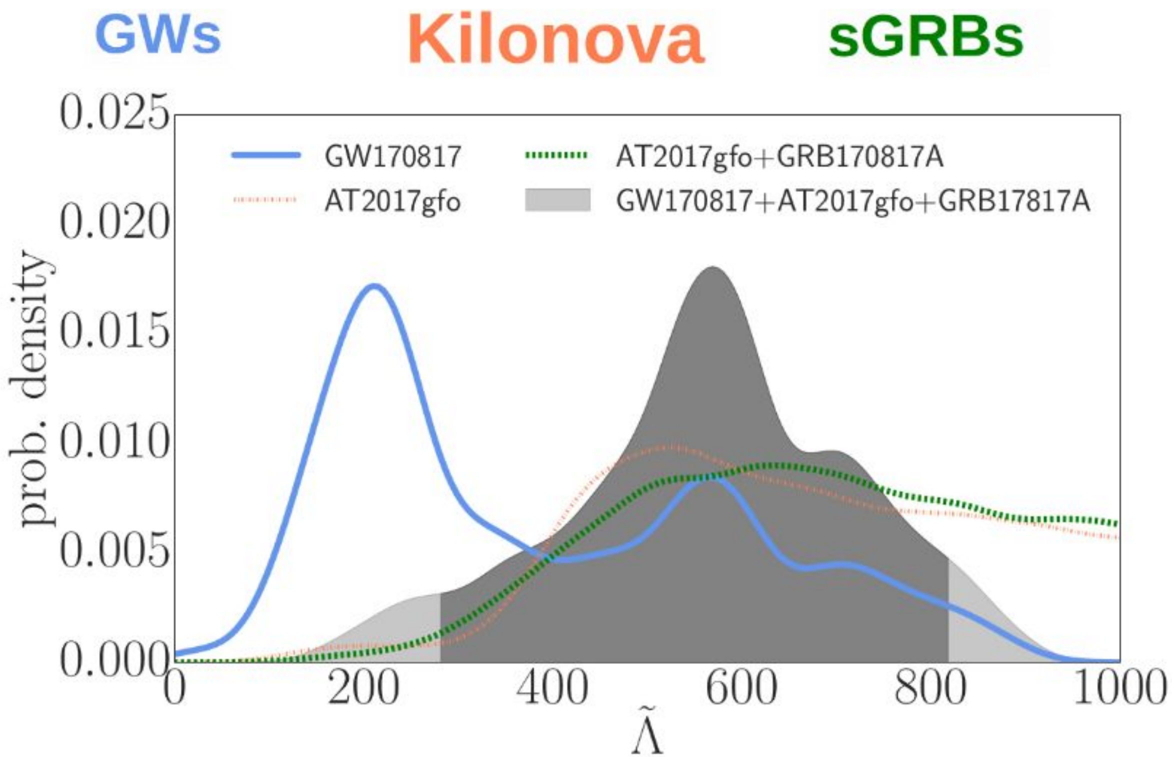


Thanks to the observations done by the astronomical community, if 190426c originated from a BHNS merger, we find that the non-observation of a kilonova rules out the event being from a black hole with a large, aligned spin combined with low-mass star.

Multi-messenger astronomy
A bridge between Physics and Astrophysics



Multi-messenger astronomy
A bridge between Physics and Astrophysics



Multimessenger Bayesian parameter inference of a binary neutron star merger

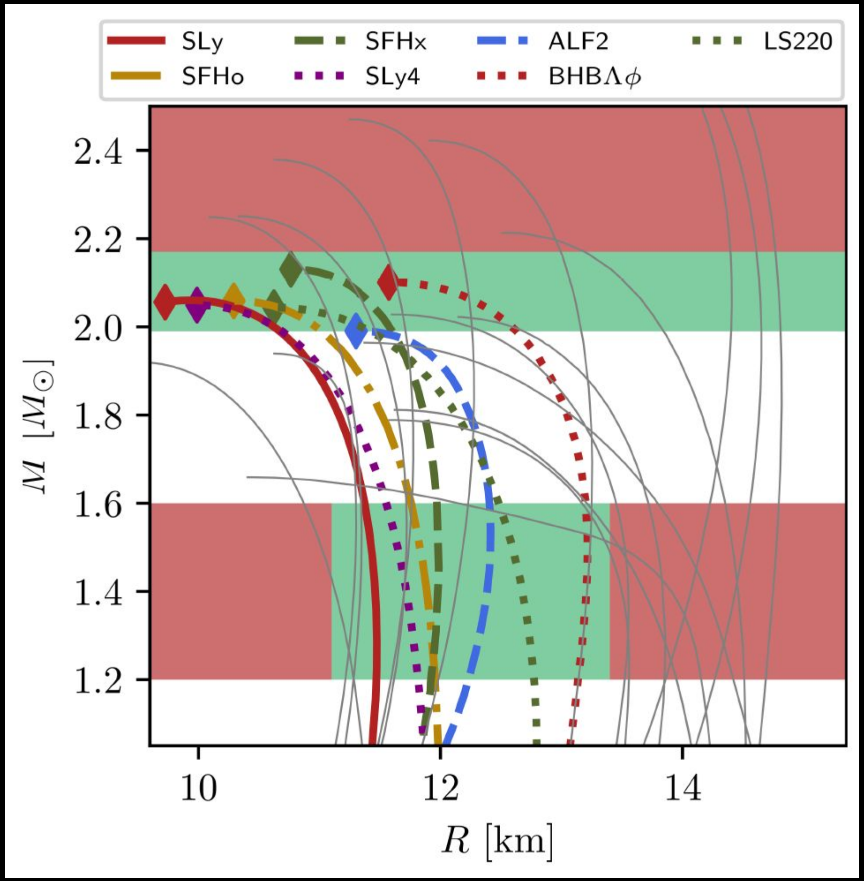
Michael W Coughlin ✉, Tim Dietrich, Ben Margalit, Brian D Metzger Author Notes

Monthly Notices of the Royal Astronomical Society: Letters, Volume 489, Issue 1, October 2019, Pages L91–L96, https://doi.org/10.1093/mnrasl/slz133

Published: 29 August 2019 **Article history ▾**

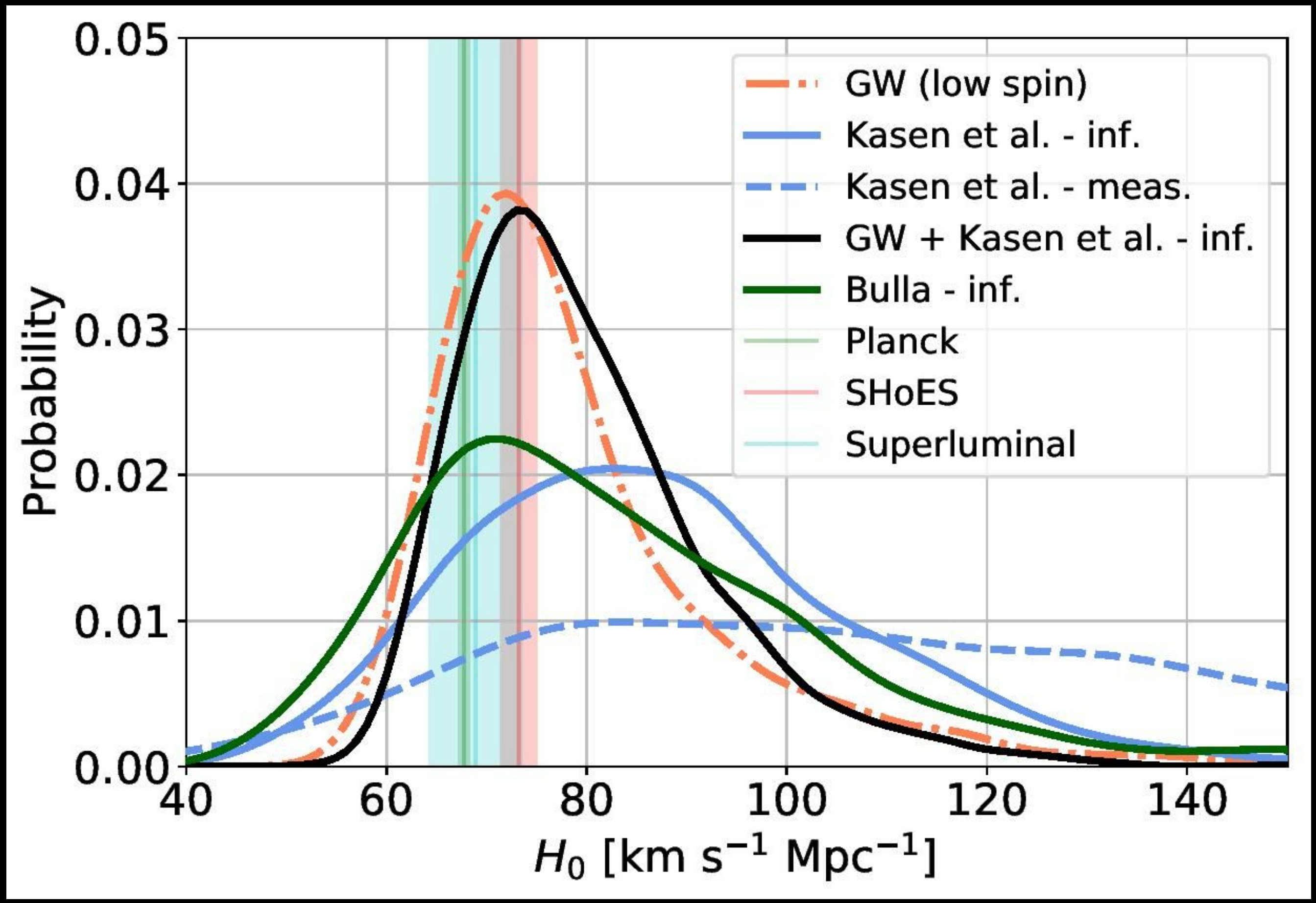
Parameter	90% confidence interval
M	$[2.722, 2.755] M_\odot$
q	$[1.00, 1.29]$
$\tilde{\Lambda}$	$[279, 822]$
R	$[11.1, 13.4]$ km

Multi-messenger astronomy
A bridge between Physics and Astrophysics



The constraints on tidal deformability yields constraints on possible NS EOS

Kilonovae as standard candles ?



Using kilonovae as standard candles to measure the Hubble Constant

Michael W. Coughlin, Tim Dietrich, Jack Heinzel, Nandita Khetan, Sarah Antier, Nelson Christensen, David A. Coulter, Ryan J. Foley

(Submitted on 2 Aug 2019 (v1), last revised 13 Aug 2019 (this version, v2))

The future for multi-messengers area is bright !

In the PAST

O1/O2 campaign

BH-BH mergers
NS-NS merger

In the future: O3 and beyond

Mergers: BNS rate (4-80) in 2020, up to 19
Collapse of massive star
Isolated neutrons star instabilities

Populations studies
Remanent studies

Electromagnetic emissions
On different angles

→ Global picture of the Violent Universe