Image Credit: NASA Goddard Space Flight Center / CI Lab

# Kilonovae and coalescence of neutron stars

*Dr. Sarah Antier*
CNES Fellowship,
APC, Paris

# What is multi-messenger astronomy ?

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

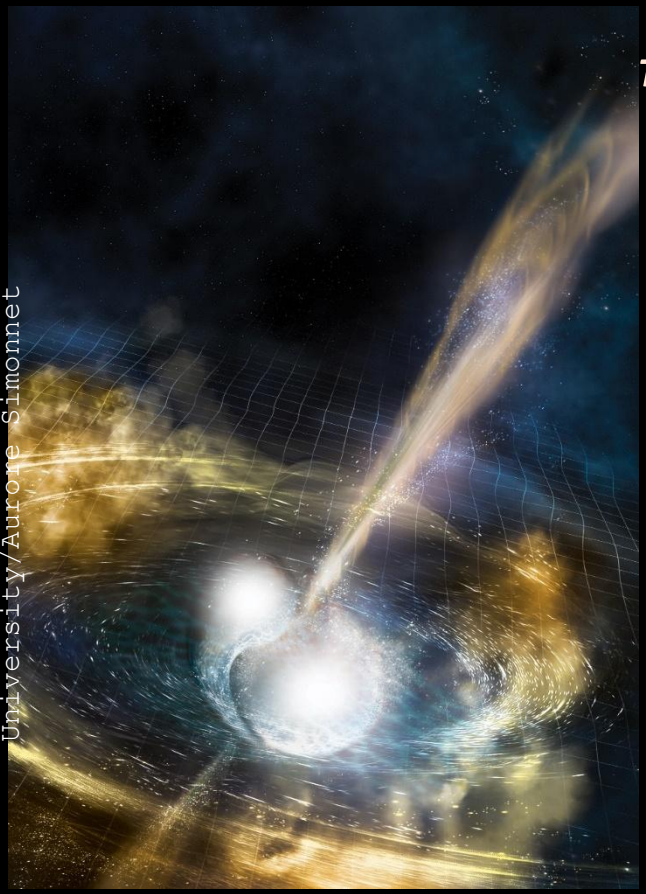


Image Credit: LSC/Sonoma State University/Aurore Simonnet

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

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

- Short GRBs, Kilonova
- Other cases ? FRB ?

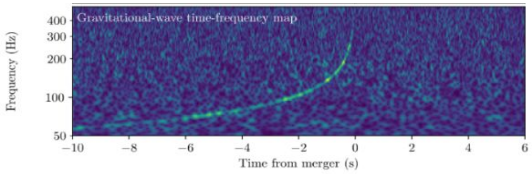
**Collapse of a single star**

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

**Neutron star instabilities**

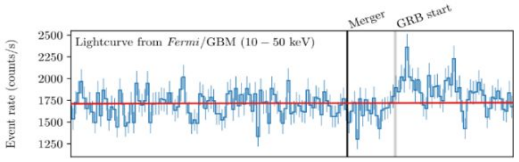
- Soft Gamma-ray repeaters
- Radio/ Gamma-ray pulsar glitches

# GW170817- First multi-messenger event




**Ondes gravitationnelles**

Système Initial




**GRB**

Jet

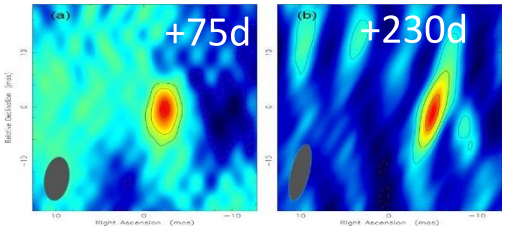
Mécanismes d'accélération


**Kilonova**

Localisation (arcsec)

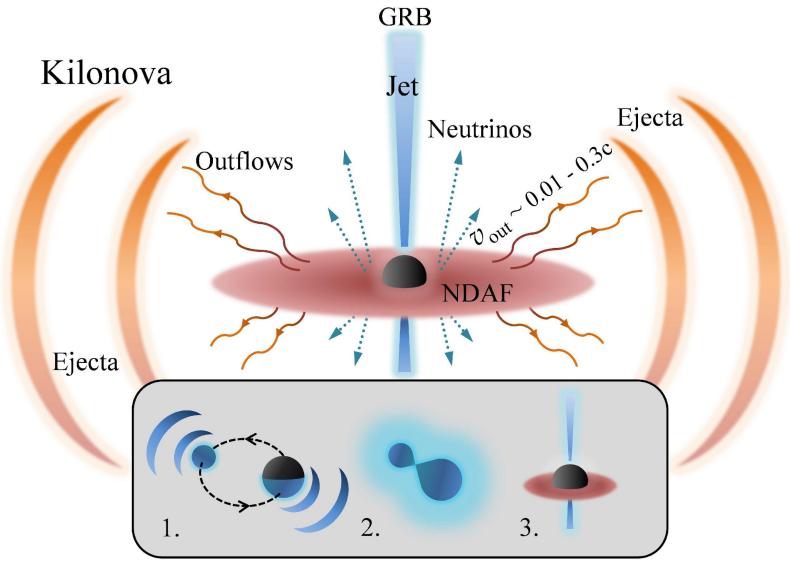
Galaxie hôte

Décalage vers le rouge

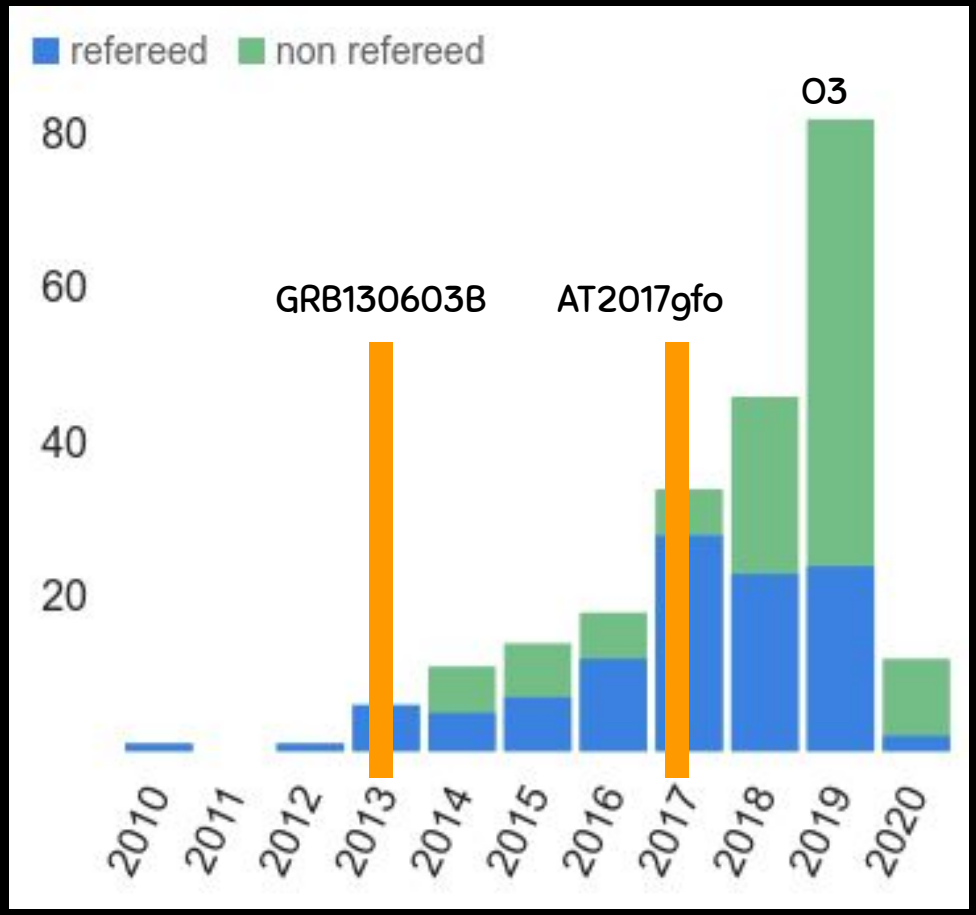



**Rémanence**

Géométrie de l'émission



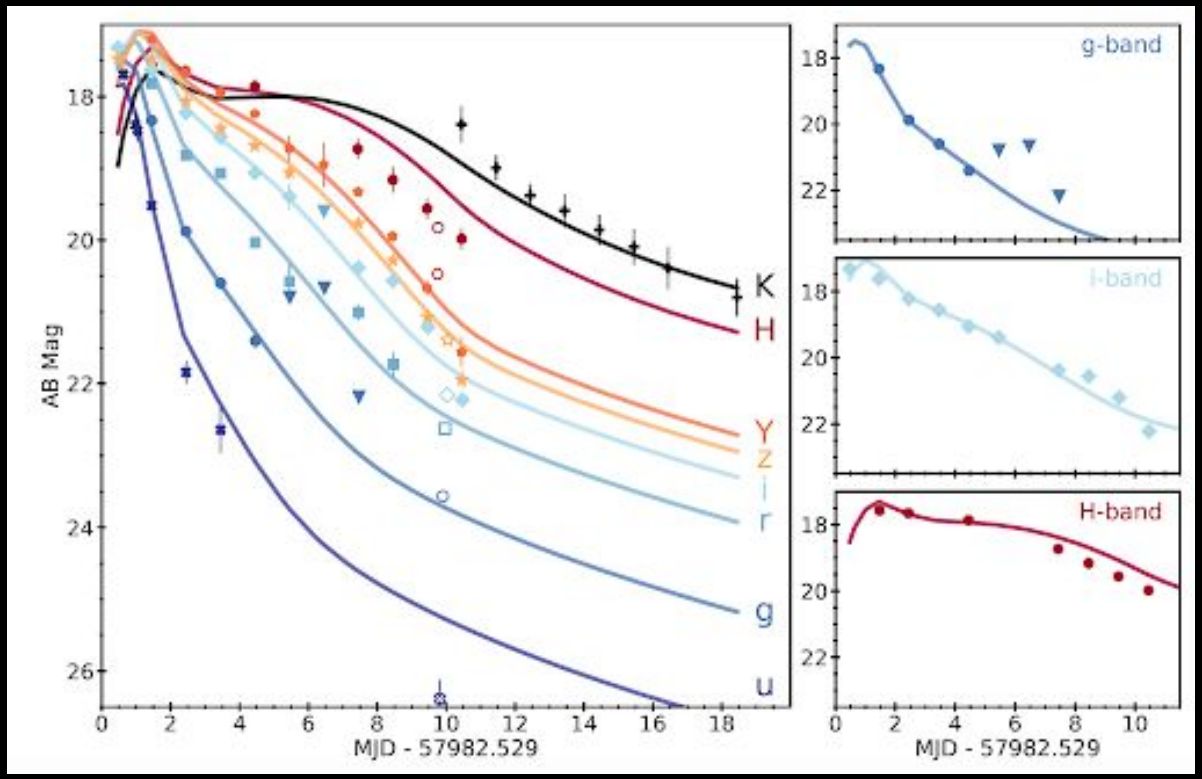
# "Kilonovae" a very short story in astronomy




(Lattimer & Schramm) 1974

# Kilonovae

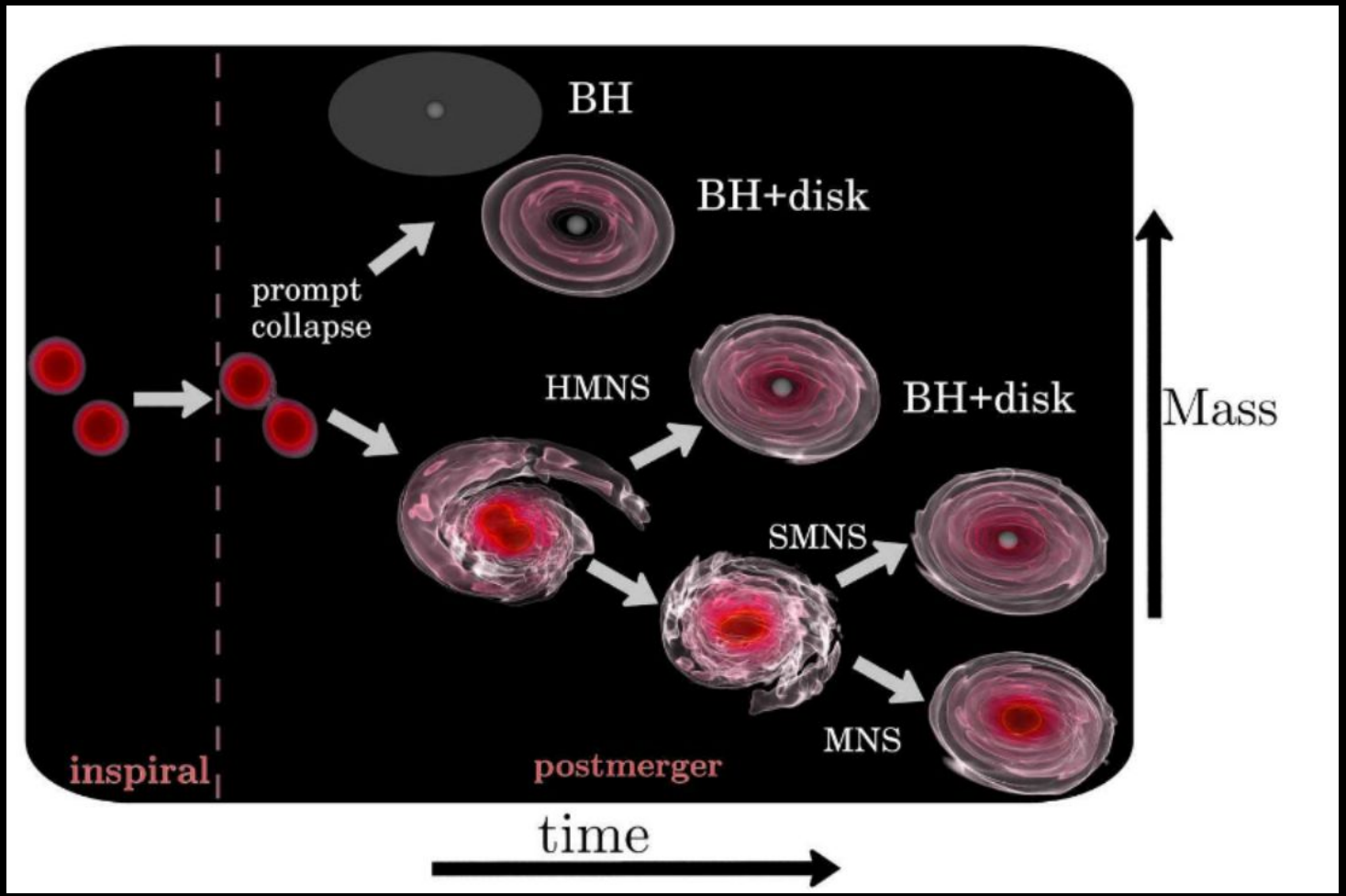
Villar et al., 2017




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

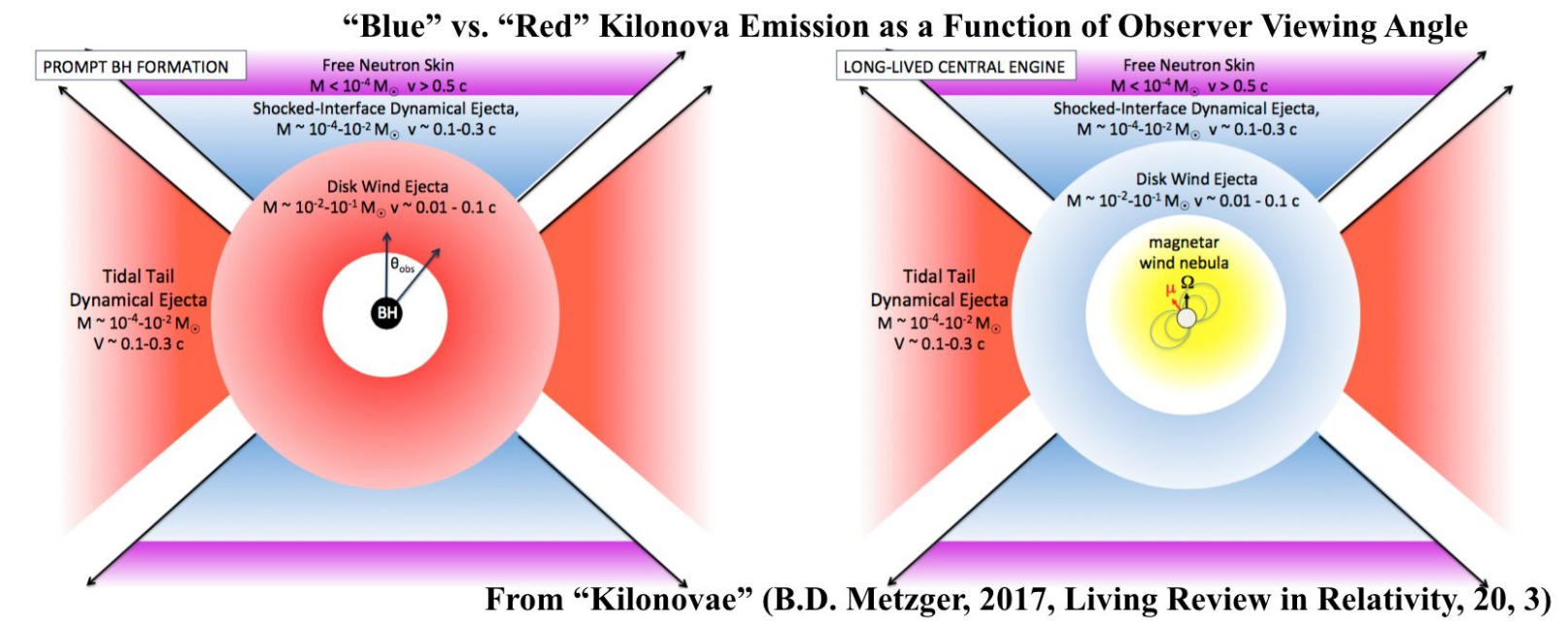
# Neutron stars or neutron star – black hole coalescence

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 tw compact objects

# Kilonovae




- Dynamical ejecta
  - Equatorial (Neutron rich) : High fraction of Lanthanide
  - 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

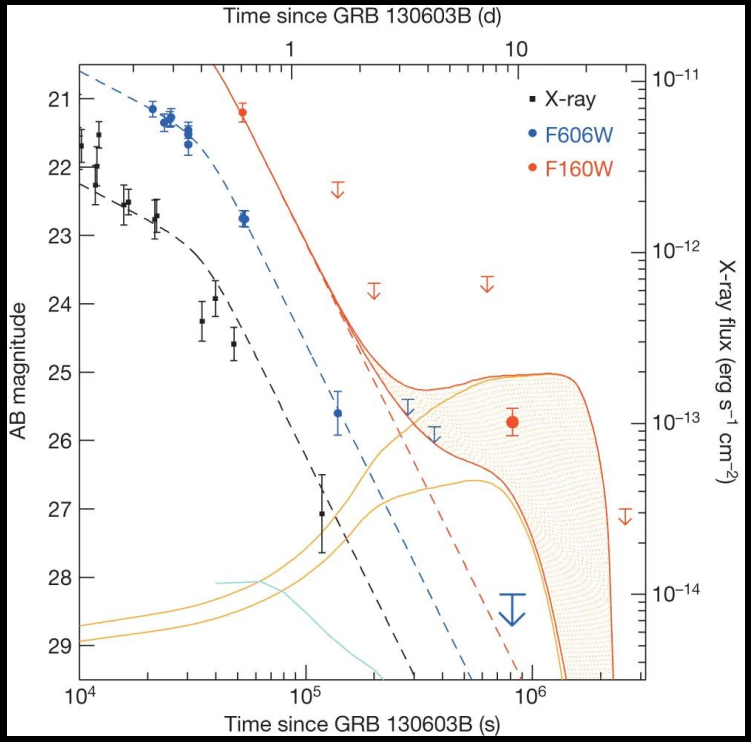
## P2: GW observations

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

## P3: Optical surveys

up to 26 mag, 600 Mpc

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

**Fermi/ GBM:**

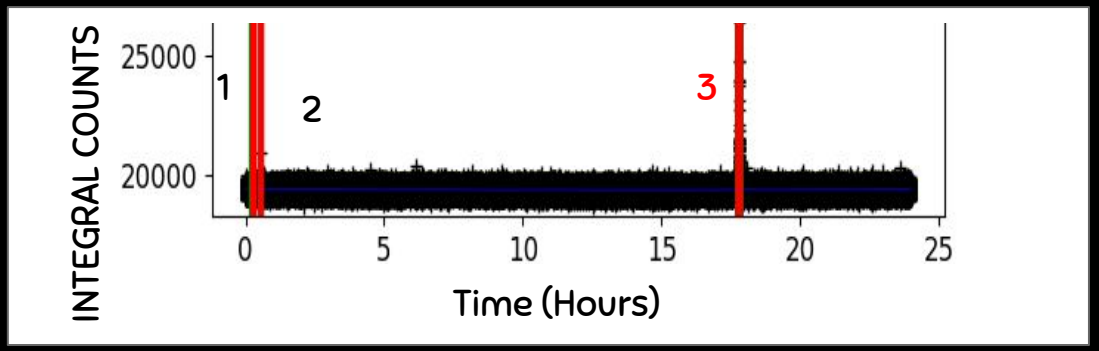
- ✘ 12 NaI detectors, 2 BGO detectors
- ✘ 4.4 keV – 2 MeV (NaI)
- ✘ Semi-major axis 6 900 km, period 95 min.
- ✘ Daily photons data

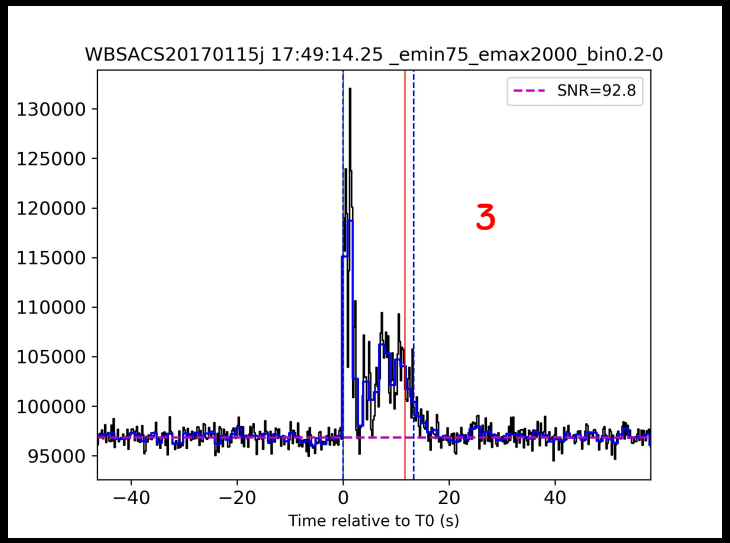
**INTEGRAL / SPI-ACS:**

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

# Proposition 2: 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 / h 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**

MXT

ECLAIRs

**VHF Network**
**S, X Band antenna**

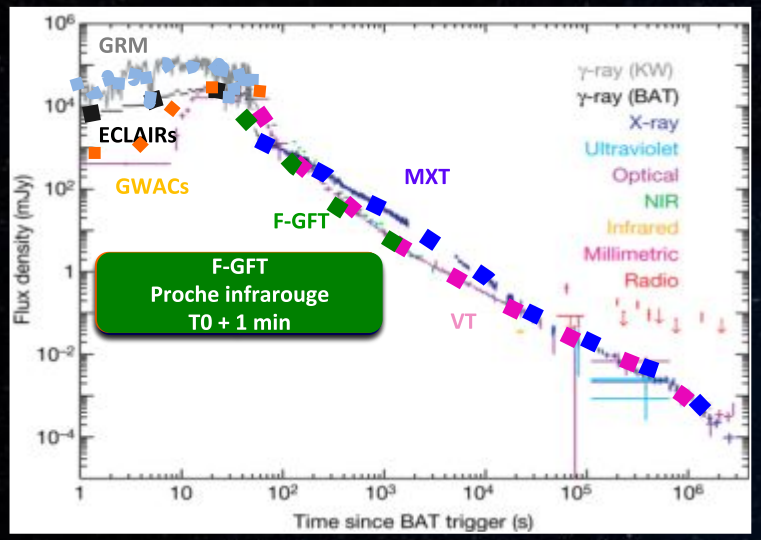
GRM

GWAC

VT

GFT-1

GFT-2



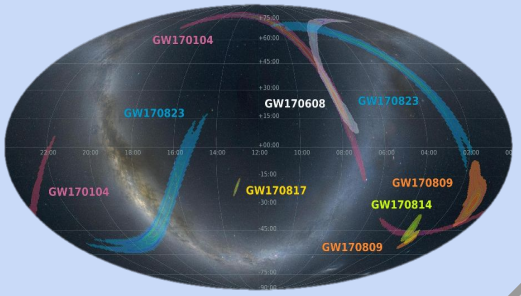

Cordier et al., PoS, *Swift:10* (2015)



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

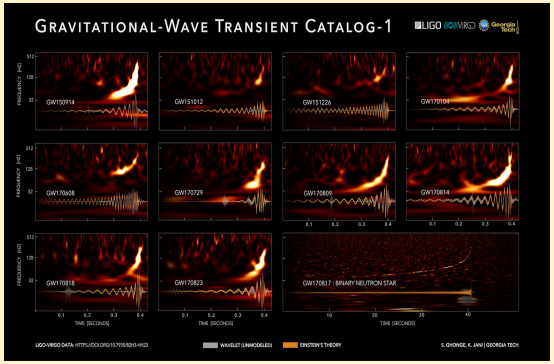
Trigger time, nature of the event, rough localization

ONLINE

Precised localization, Trigger time, inclination

OFFLINE

ALL SKY BLIND SEARCHES




TARGETED SEARCHES



LSC LIGO Scientific Collaboration VIRGO

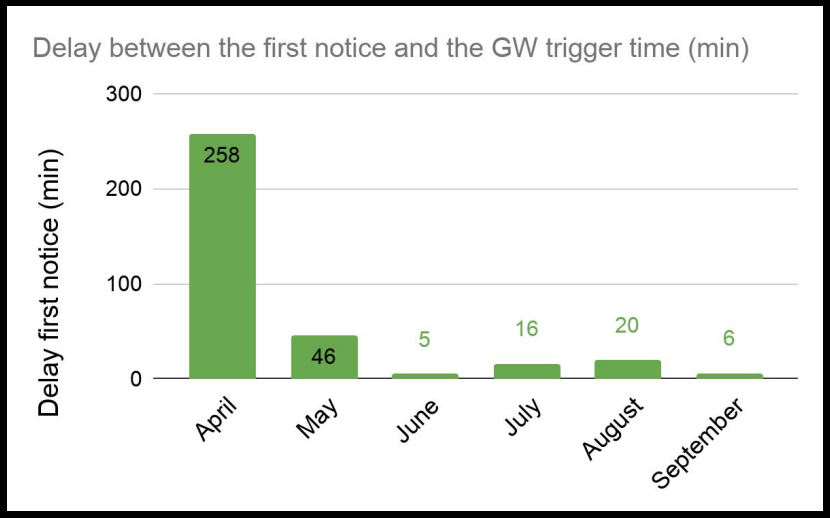
# Proposition 2: O3ab summary

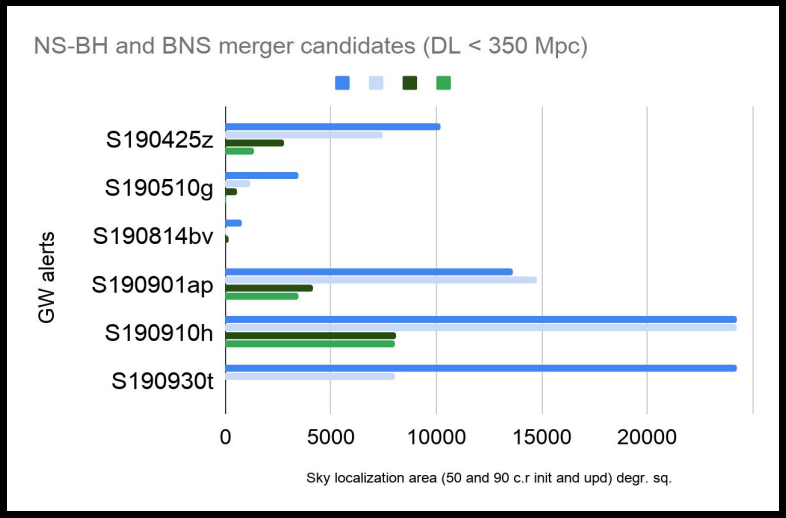
47 public GW alerts, 1 burst alert

7 BNS 7 NS-BH 32 BBH mergers candidates

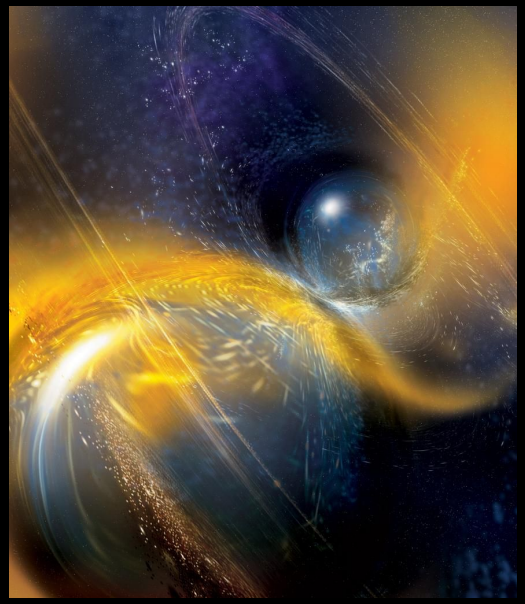
22 retractations

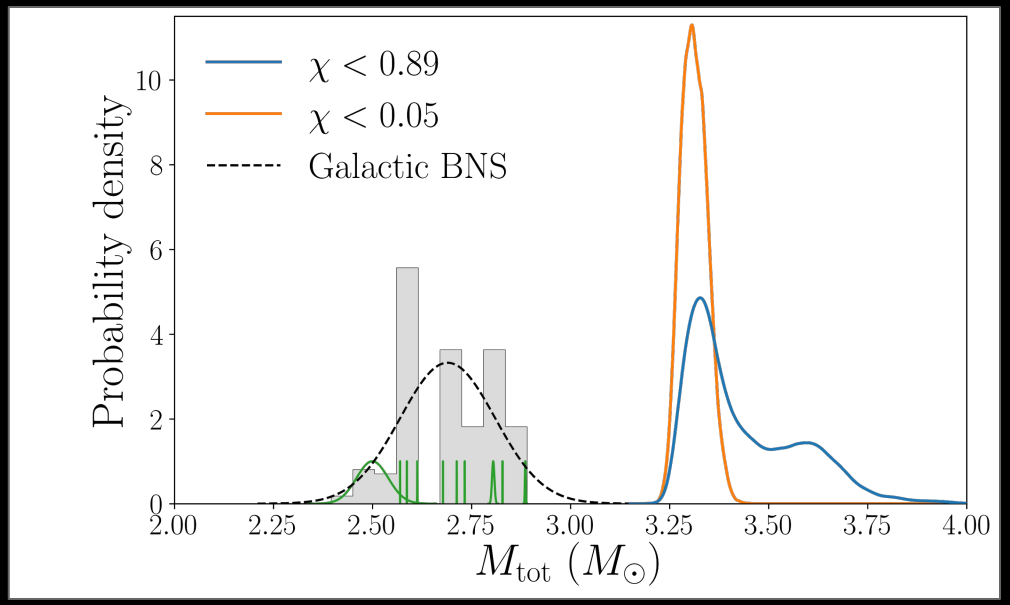
Final content may differ !



# GW190425



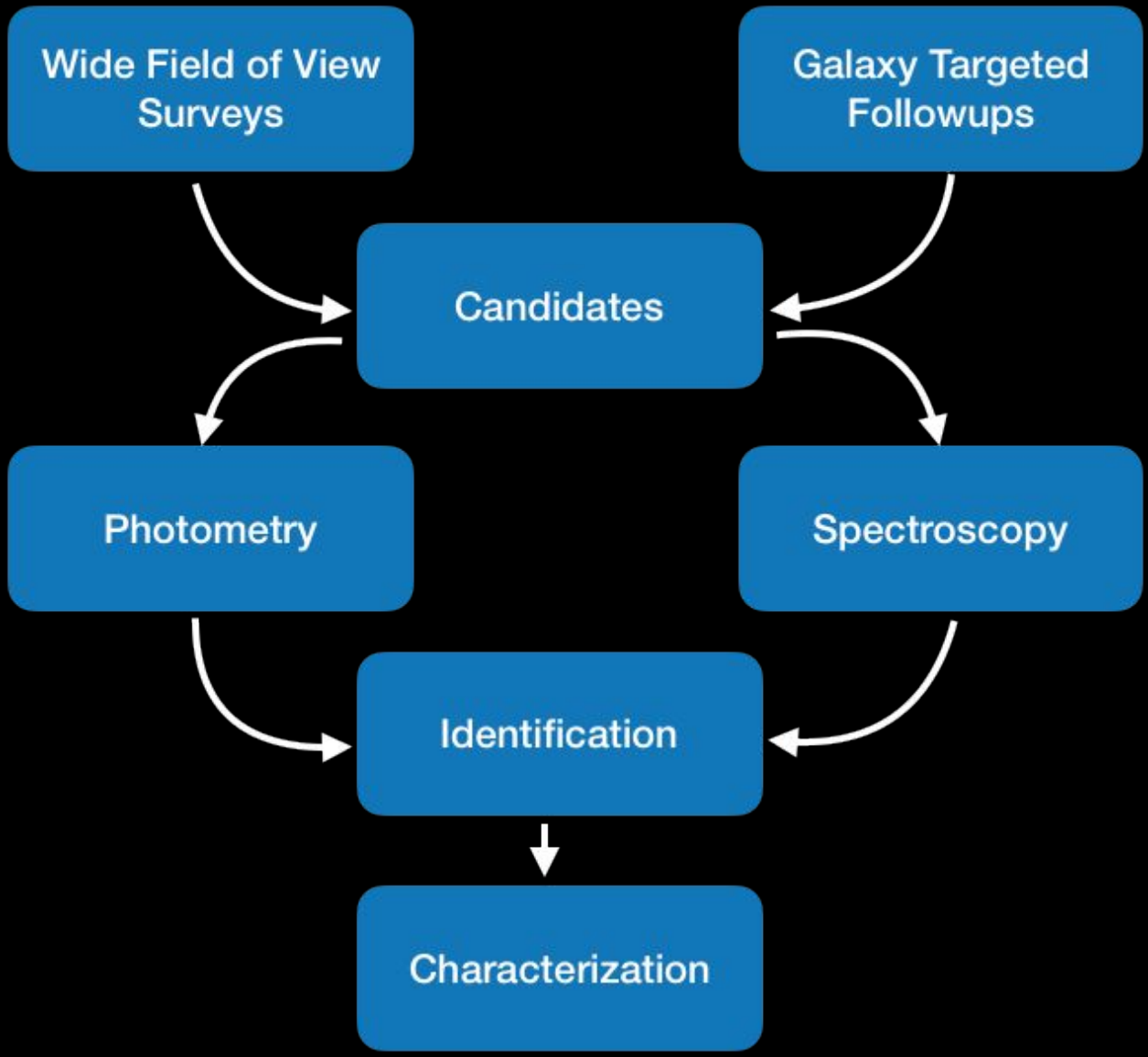



On 08:18:05 UTC, L1 single detection, 8000 deg2 for 90% sky area localization, 156 Mpc +/- 41 Mpc
FAR: one chance event in 69,000 years
initial m1: 1.61 and 2.52 solar mass and initial m2: 1.12 and 1.68 solar masses
total mass: 3.0 – 3.7 solar masses

**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.

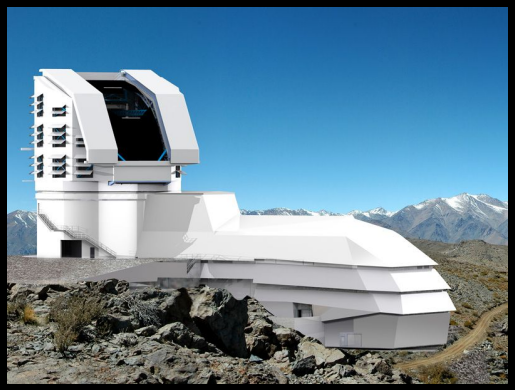
# Proposition 2: Observations with GW alerts



# GRANDMA

## Global Rapid Advanced Network Devoted to Multimessenger Addicts

1.



2.

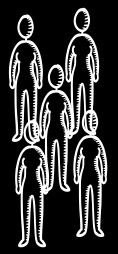
3.

Local team – scientists – Infrastructure

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

26 institutes / groups

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

Present in

13 countries

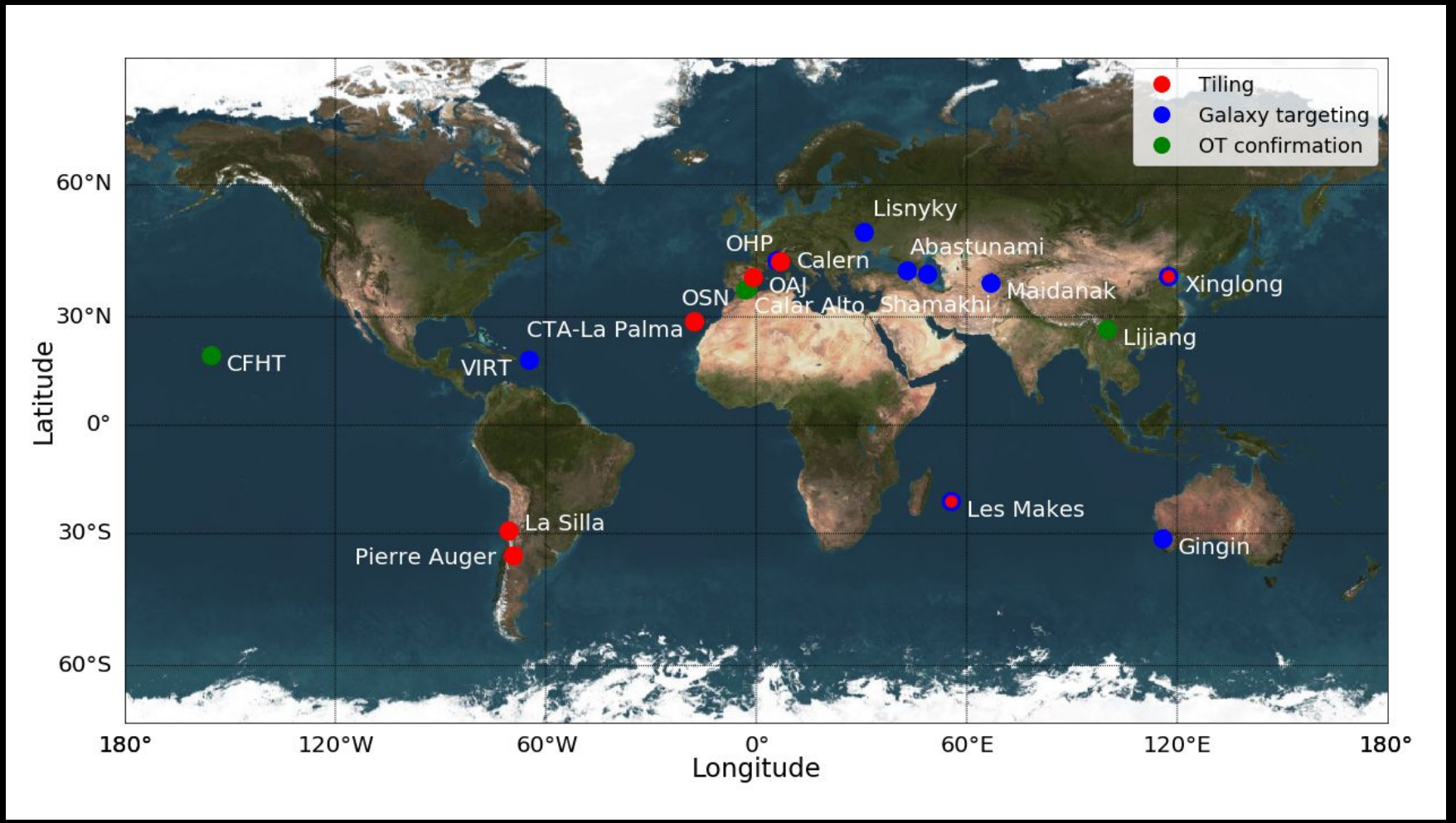
18 observatories

**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

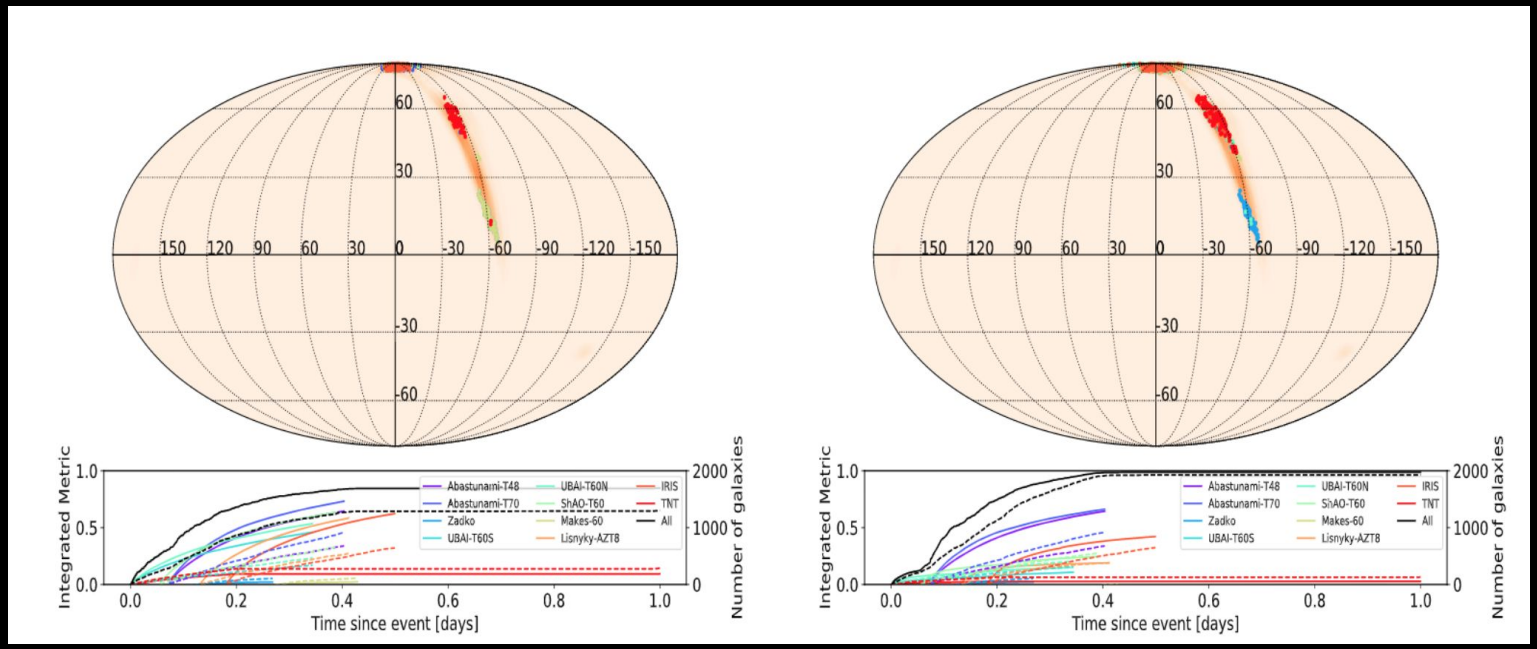
- ✘ Spatial coverage

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



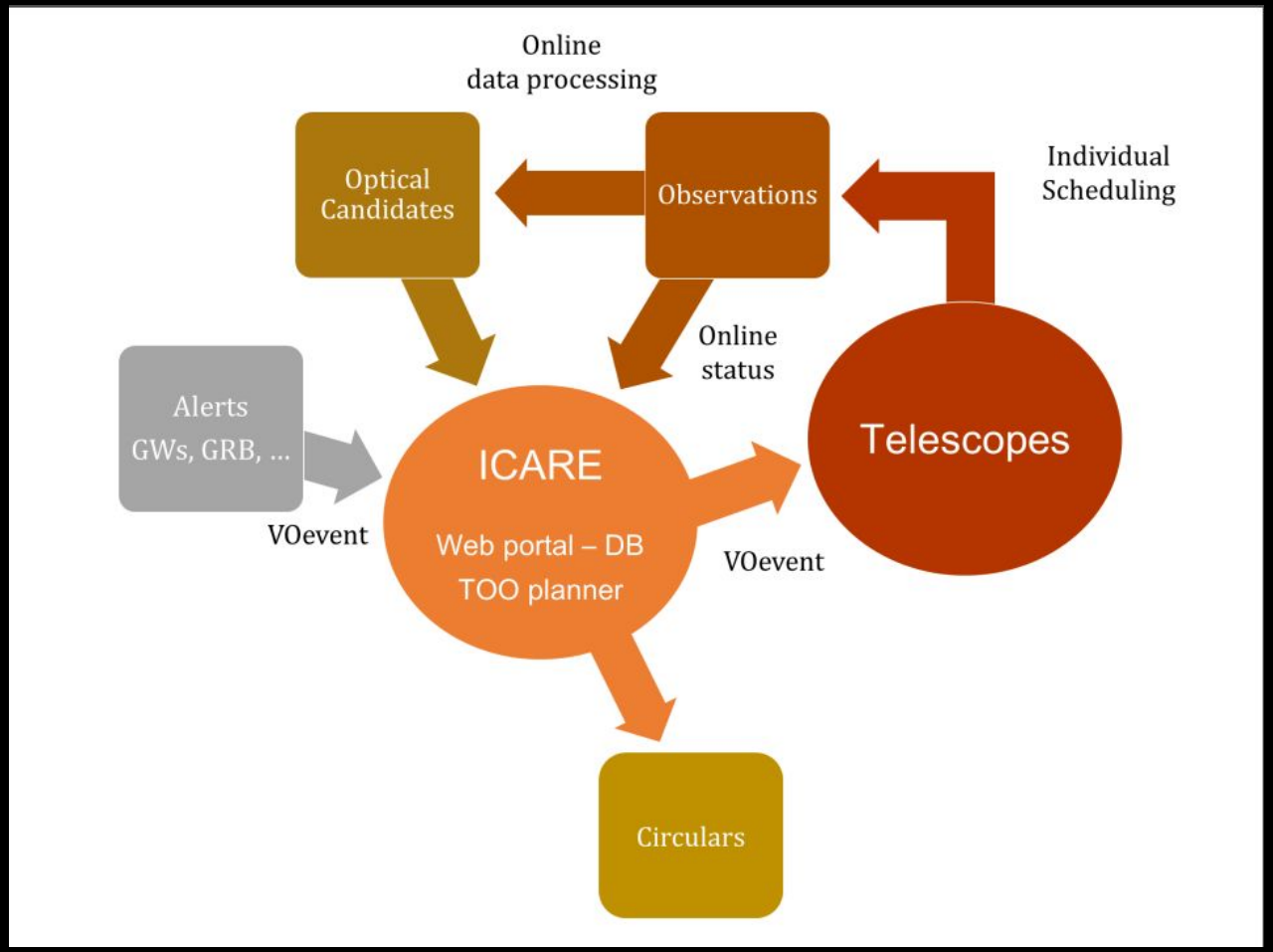

**Optimizing multitelescope observations of gravitational-wave counterparts**

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

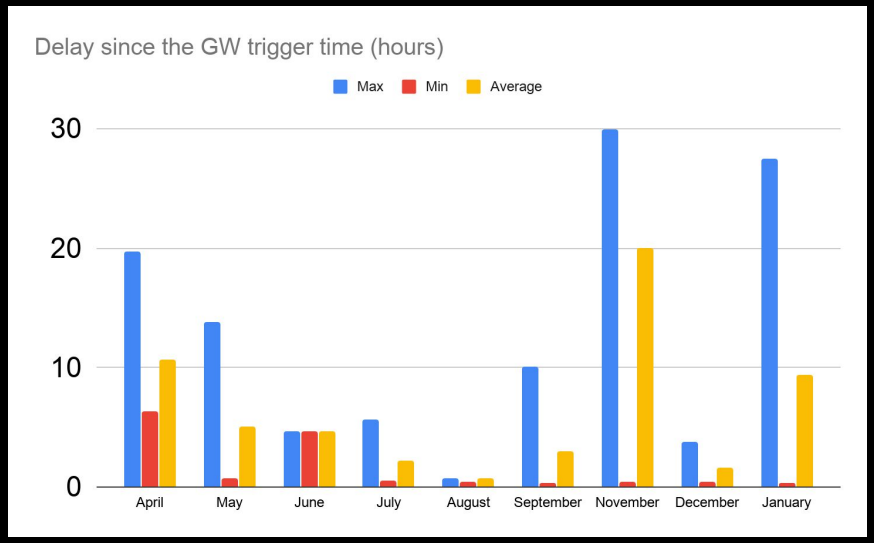
## 42/47 FOLLOW-UP OF GW ALERTS

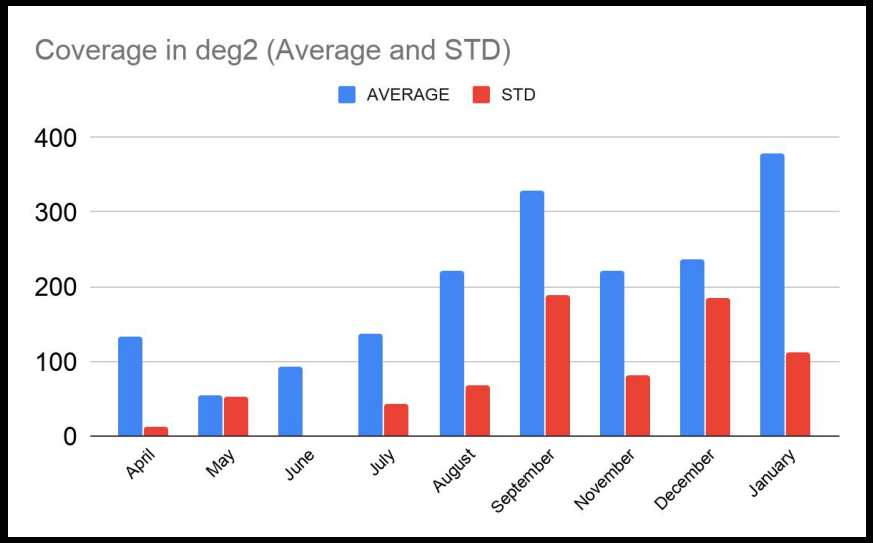
7 BNS

6 NS-BH

29 BBH

MERGERS



90% of GW alerts followed

Kilonova-Catcher
Citizen science program

Université de Paris

4'5 000 euros

Multi-wavelength project
Including Physicist and astronomers

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

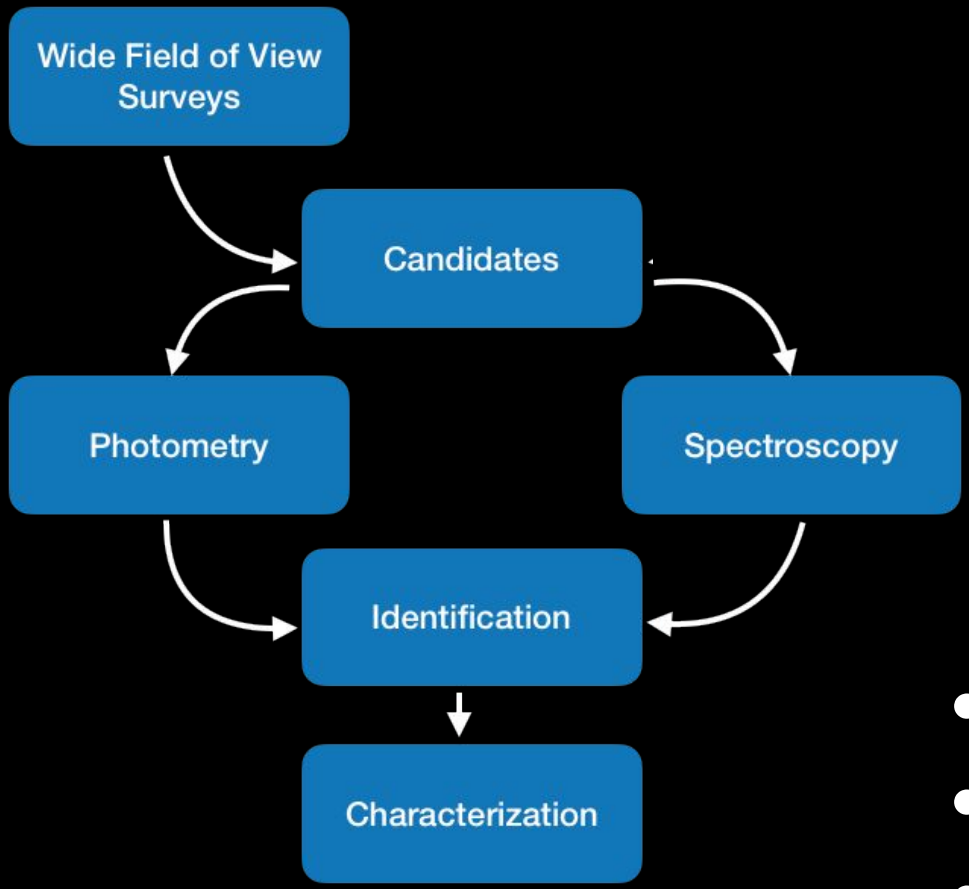
GRANDMA

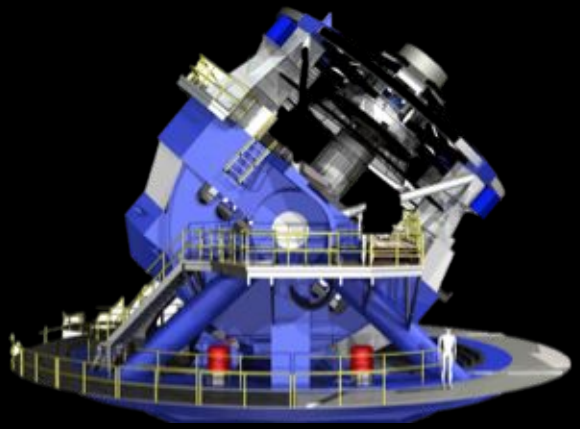
Multimessenger
Universal
Plateform ICARE

16 min between GW TO
and GRANDMA min obs

Geographic diversity
25 telescopes

# P3: Observations with Optical surveys



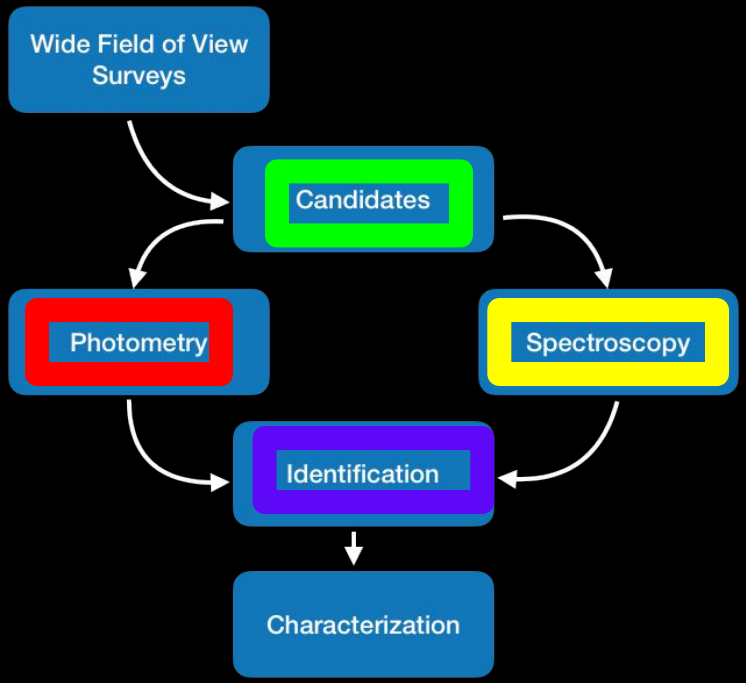
LSST

- 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

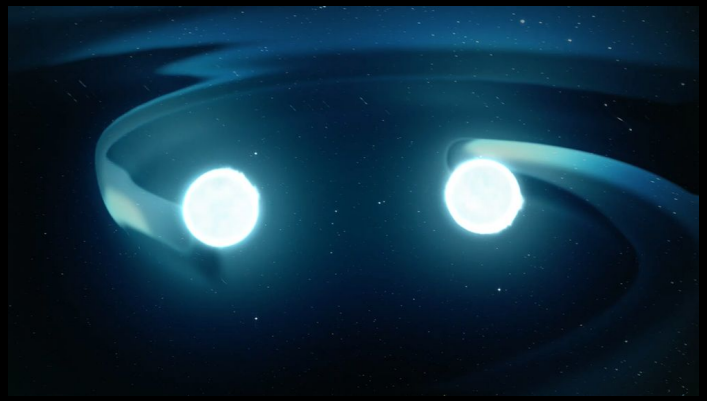
Standardized photometric calibration
with A. Duverne

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**

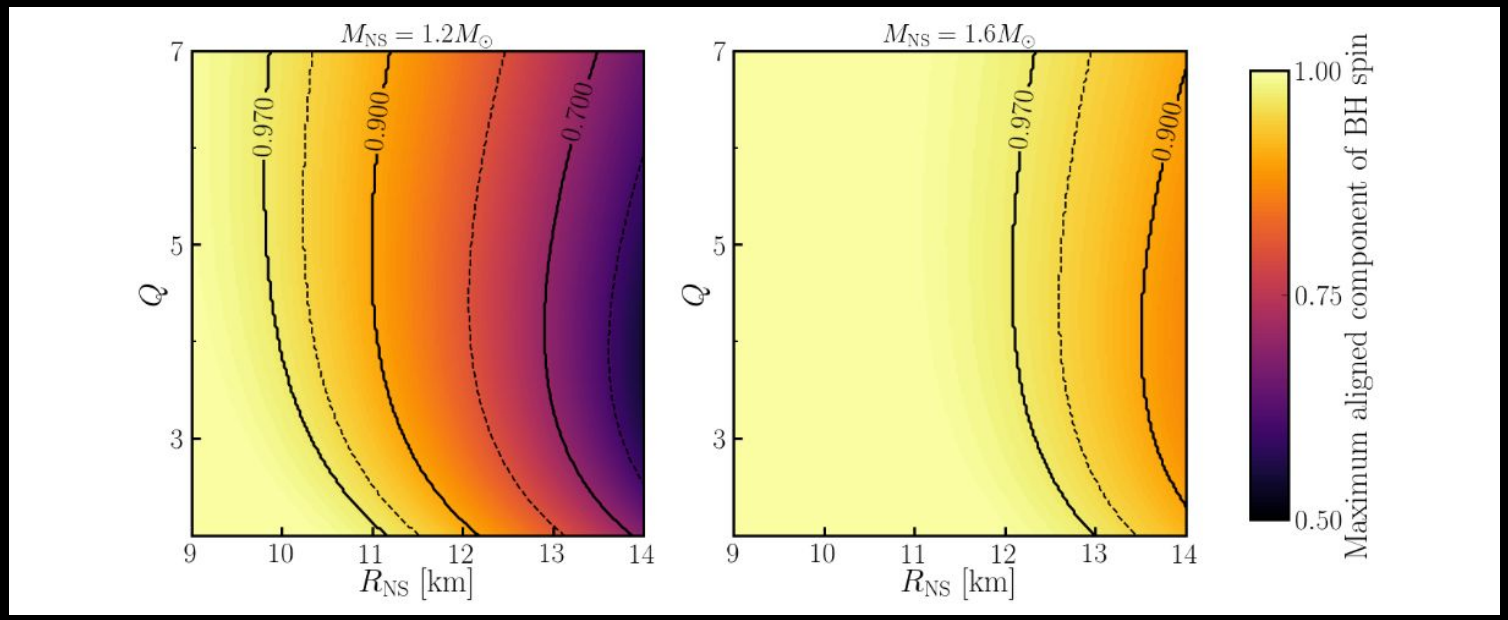
*Mon. Not. R. Astron. Soc.* https://doi.org/10.1093/

**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

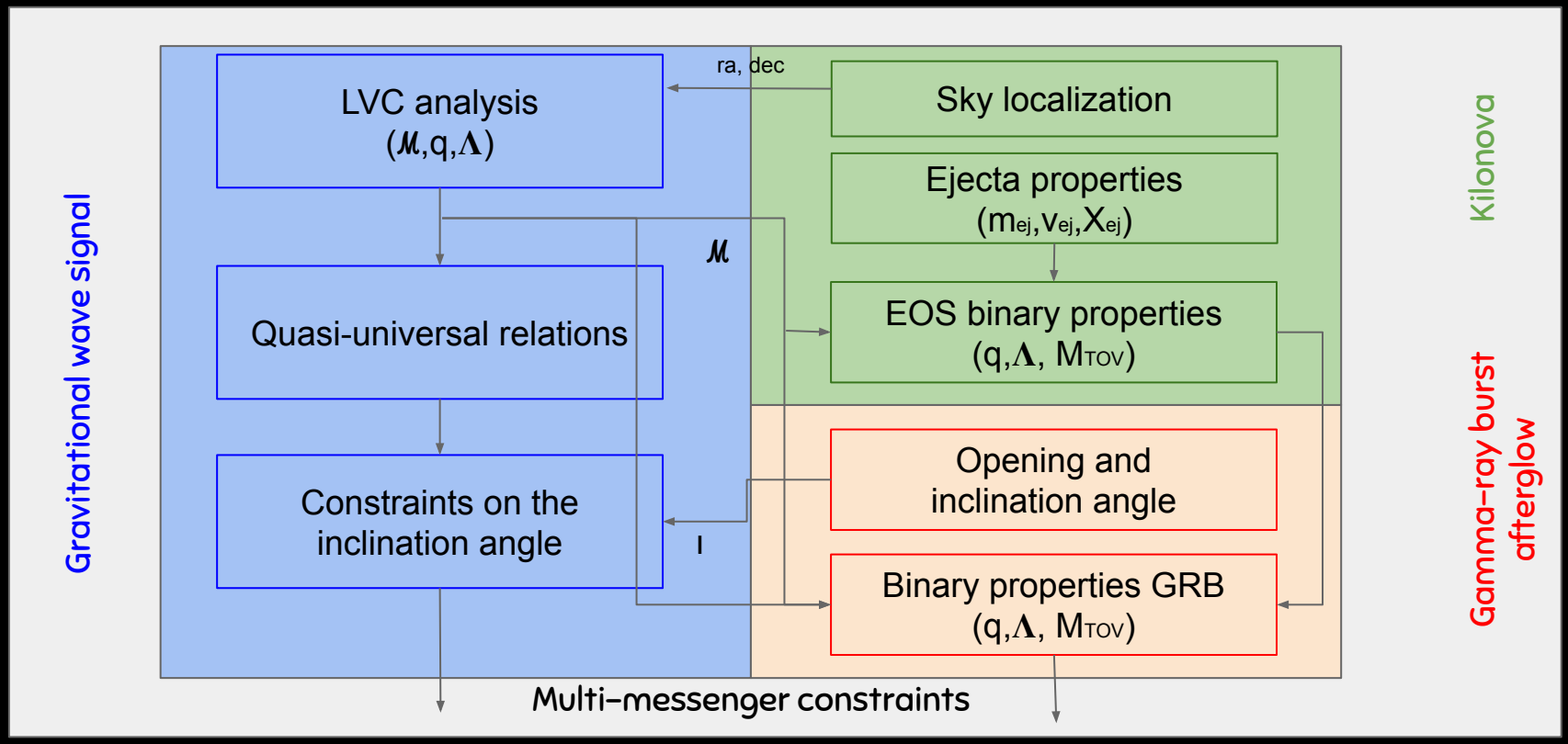
*Monthly Notices of the Royal Astronomical Society*, Volume 492, Issue 1, February 2020, Pages 863–876, https://doi.org/10.1093/mnras/stz3457

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



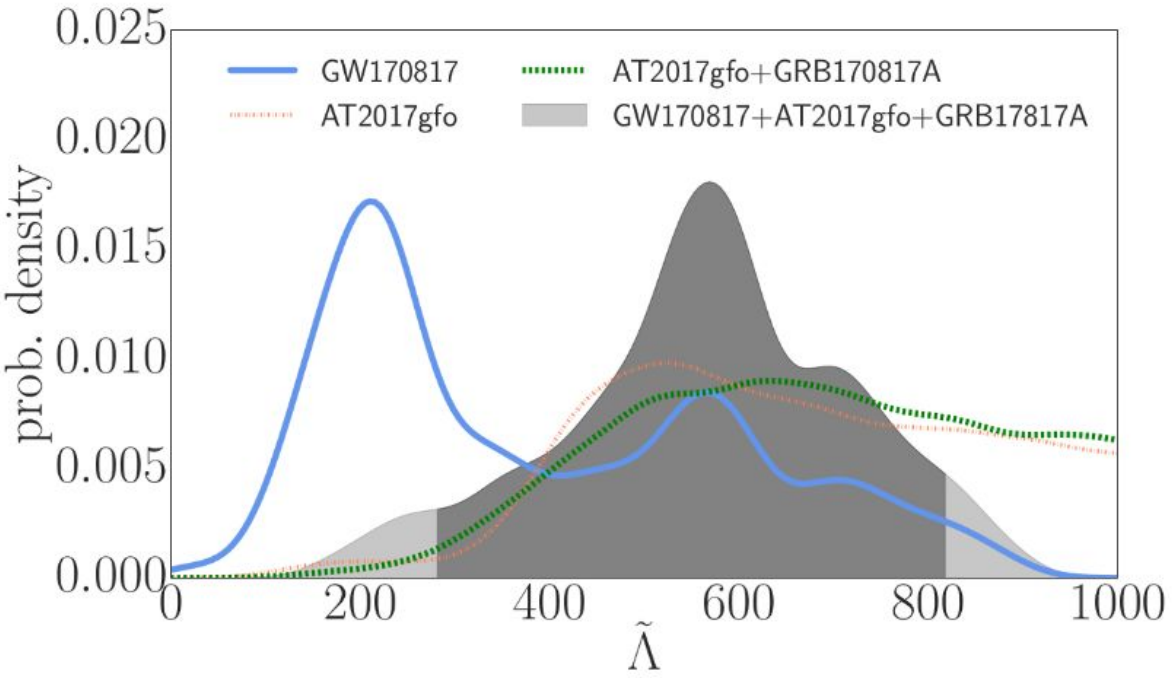

Thanks to the observations done by the astronomical community, if 190426c originated from a BHNS merger, we find that the non-observation of a kilonova rules out the event being from a black hole with a large, aligned spin combined with low-mass star.

# Multi-messenger astronomy
# A bridge between Physics and Astrophysics



# Multi-messenger astronomy
# A bridge between Physics and Astrophysics

**GWs** **Kilonova** **sGRBs**



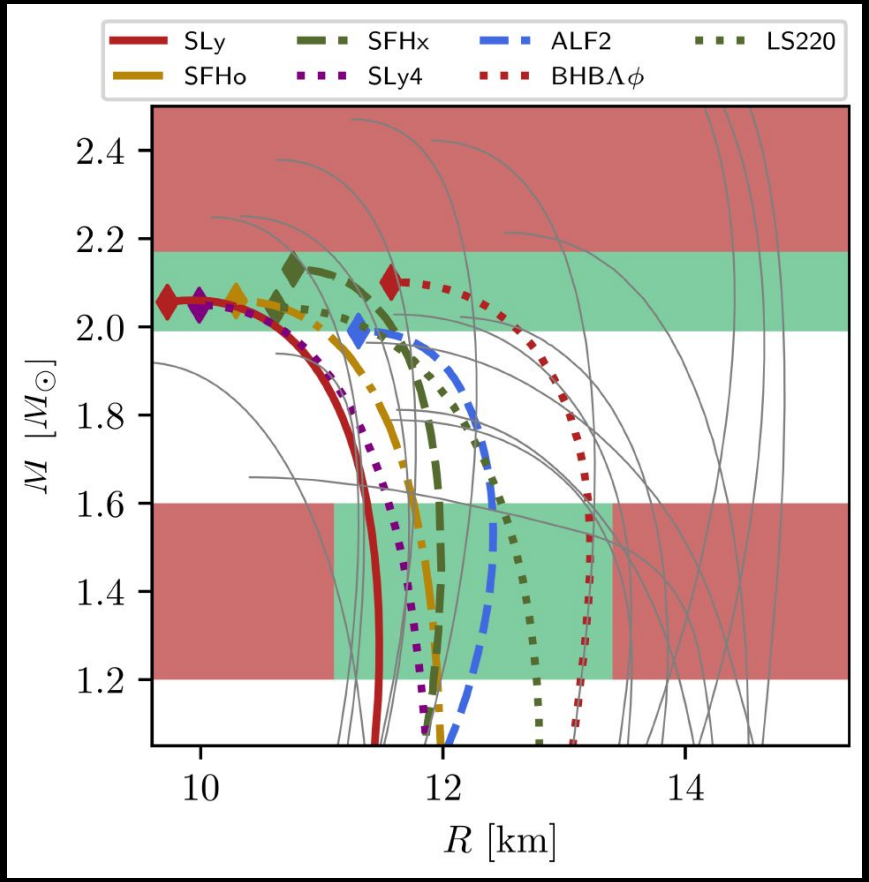

**Multimessenger Bayesian parameter inference of a binary neutron star merger**

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 |

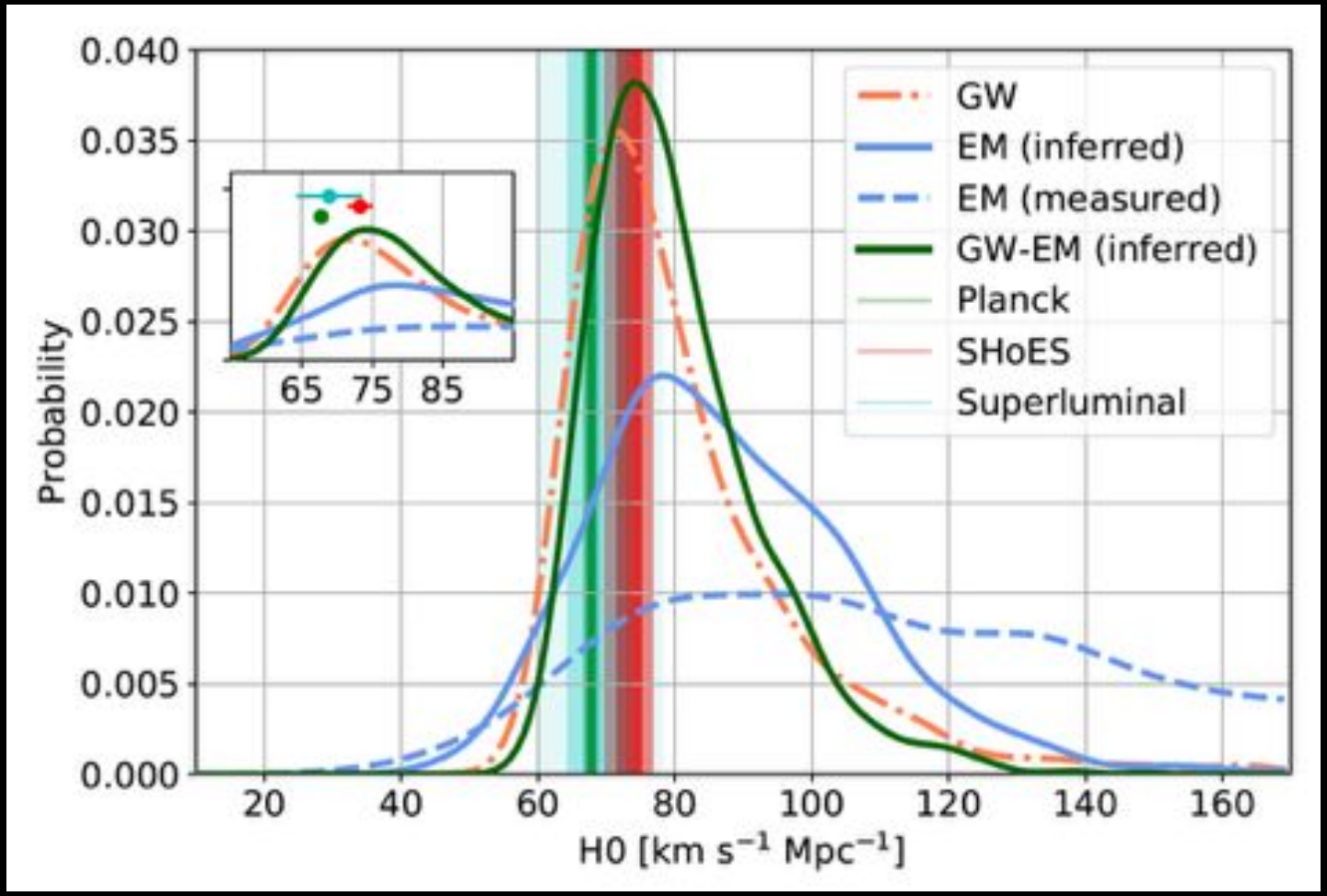
# Multi-messenger astronomy
# A bridge between Physics and Astrophysics




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