Image Credit: NASA Goddard Space Fight Center / CI Lab

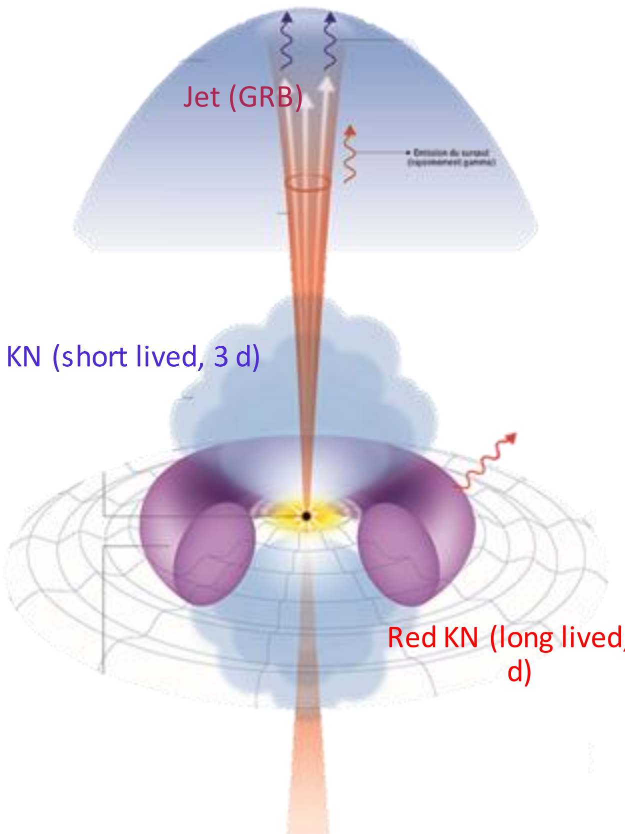
Multi-messenger observations of O4 gravitational wave events: a study case with GRANDMA

Sarah Antier

Astronome Adjoint, Artémis - OCA – UCA

Thanks for R. DePietri, P.A Duverne, D. A. Kann, D. Estebez, M. Coughlin for their material, I. Tosta e Melo

Multi-messenger observations of neutron star coalescences



EM counterpart to GW **<u>needs matter</u>**

Binary neutron stars are the most promising MMA source

GRB : Powered by on-axis jet

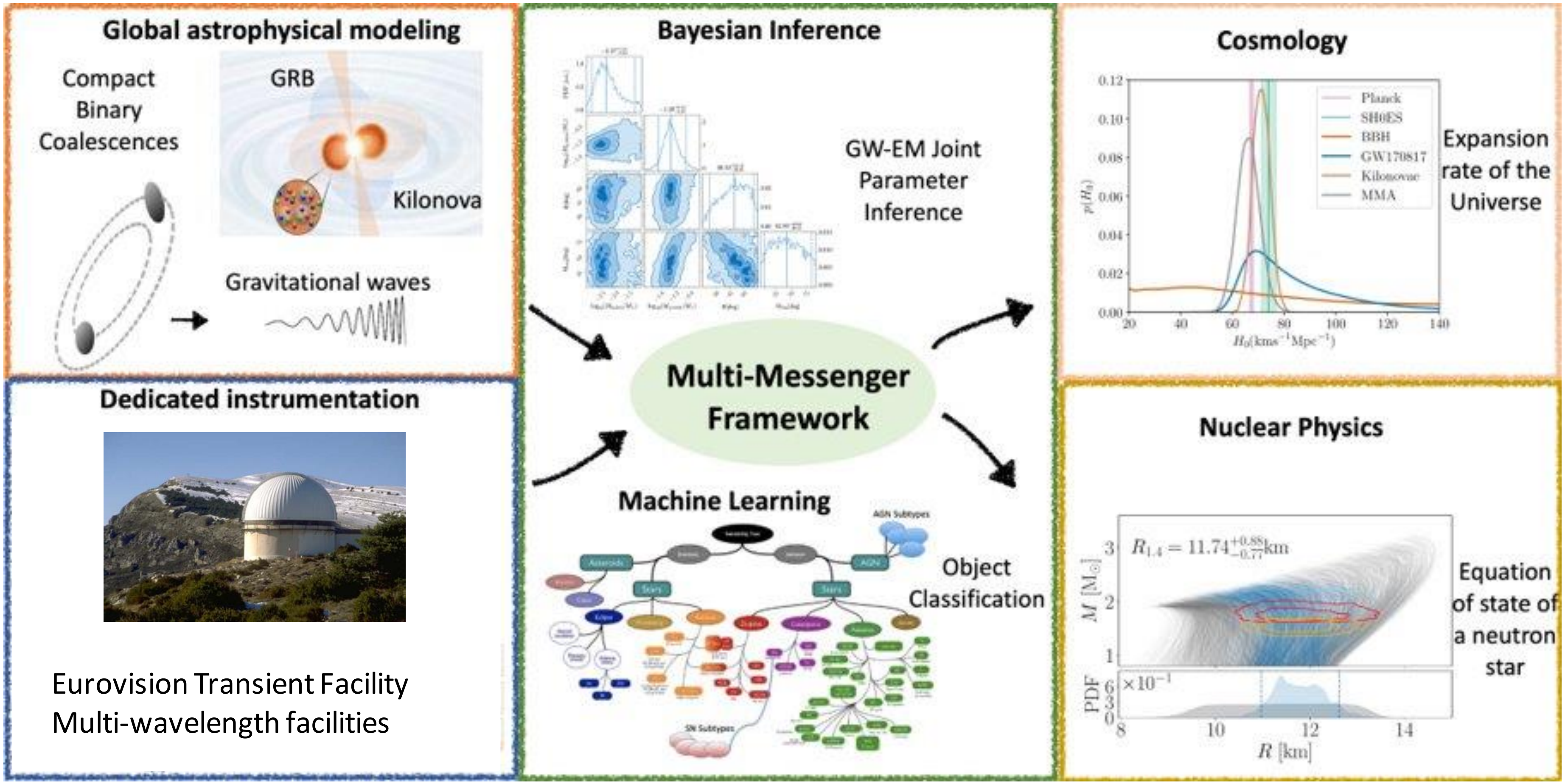
Kilonova (KN): **Optical** and **NIR** transient **powered by r-process** in **neutron rich** environment. Only **one** clear confirmed event (**AT2017gfo**)

AT2017gfo/GW170817 properties

- 40 Mpc
- Localized in NGC4993
- Identified by LVK in 39 deg2
- *~10 galaxies compatible*
- *Absolute K-band magnitude M_K = -16 mag*
- Fading at 0.5 mag per day

*There are some predictions, and even claims of EM counterparts (see LVC – <u>190521g</u>)

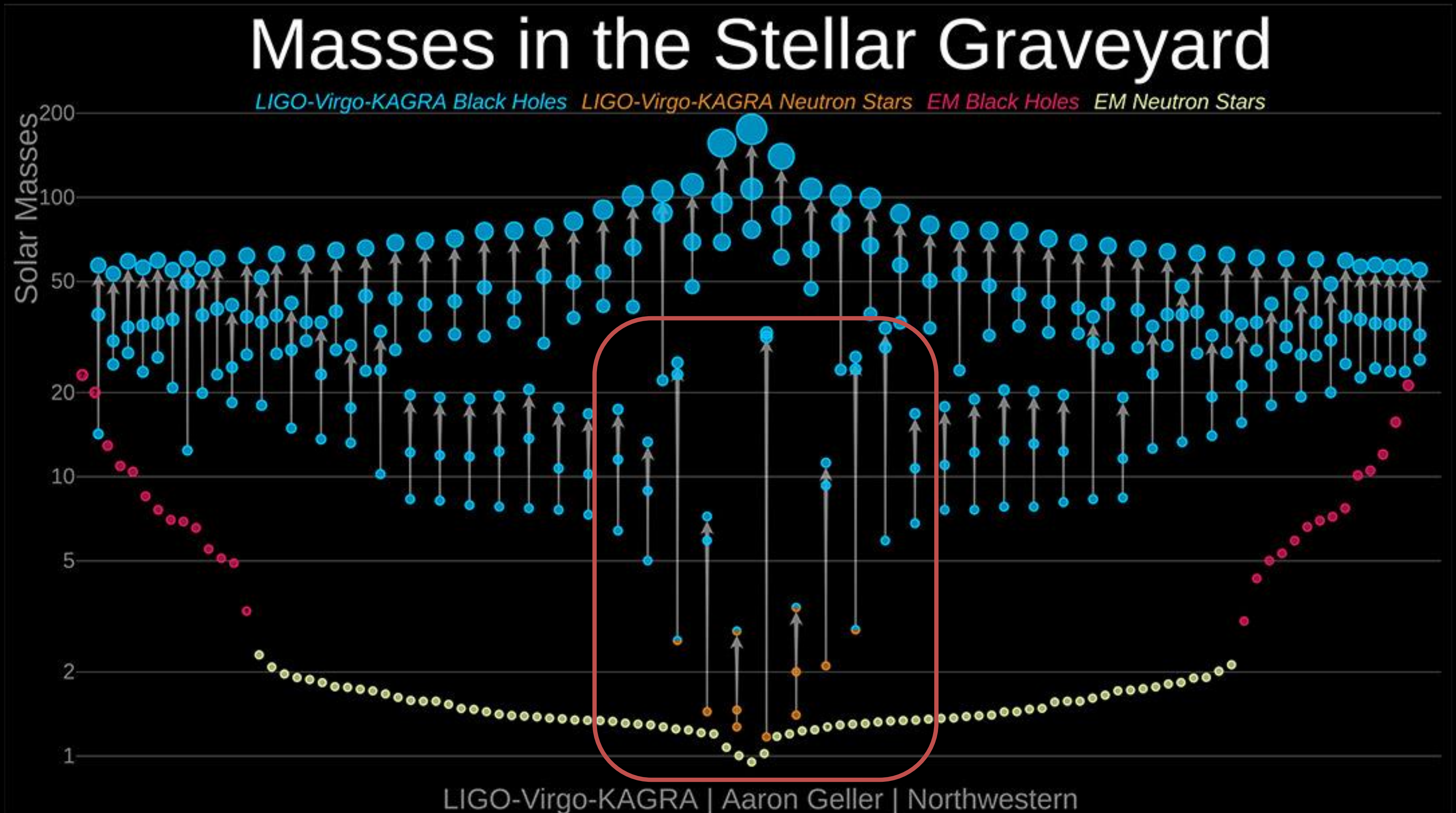
Multi-Messenger Ecosystem



Open data
Sharing of results

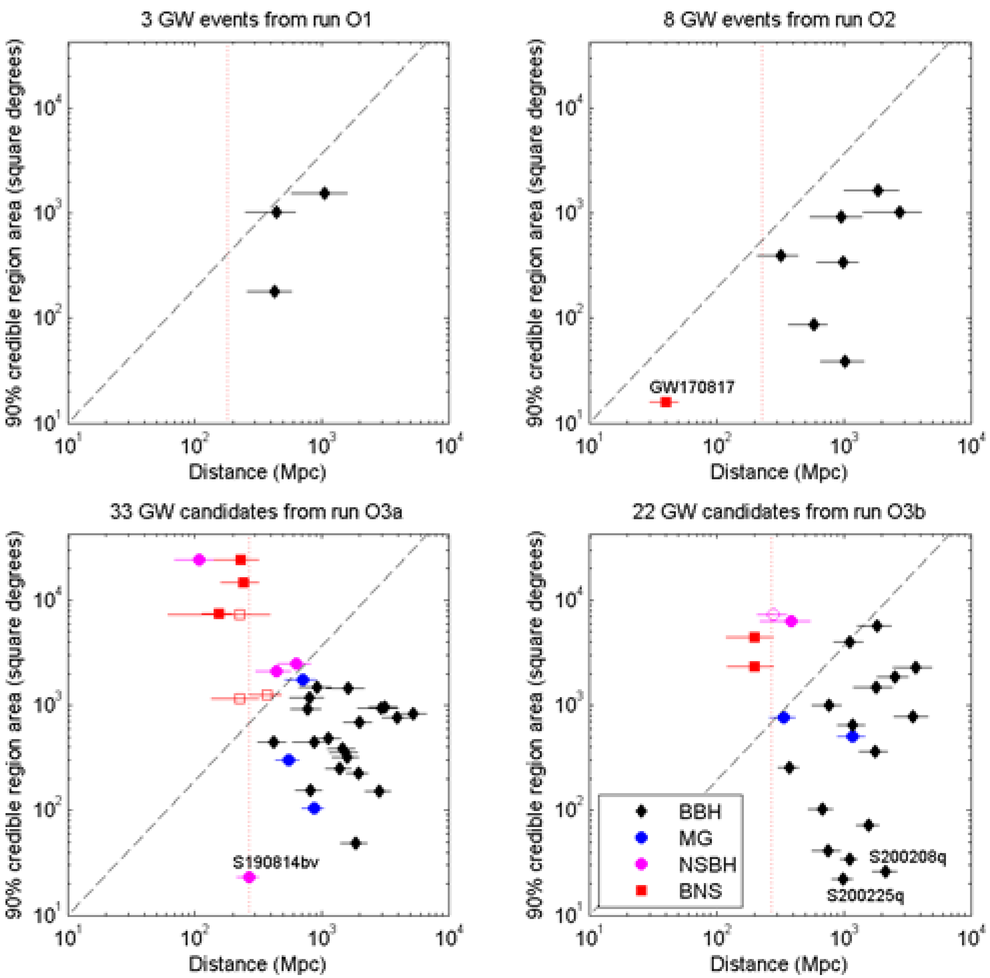
Rapid analysis tools with ML

Multi-physics expertise



Multi-messenger
opportunies ?

Alert statistics O1, O2 and O3



Antier et al., GRANDMA O3, 2020

From April 2019 to March 2020
~ 330 days

80 +1 alerts with 56+1 “still alive”
24 retractations (30 % retracted)

A traffic of alerts 4 times bigger than O2

41 alerts with updated sky localization areas
(73% of the total of the alerts)

52 of the alerts with P (Terres) < 50 %

8 BNS candidates
6 NS-BH candidates
5 Mass-Gap candidates
36 BBH candidates
1 burst candidate
1 LIGO/Virgo - GBM-190816

~7 min delay for delivering the alert post-merger (see O3b catalog article)

Overview of the O3 follow-up

~100 groups/instruments/missions → similar to O2

5 neutrinos observatories: Pierre-Auger, **IceCube**, Antares, KM3Net, Baksan

3 VHE observatories: HAWC, Fermi-LAT, HESS

9 Gamma-ray observatories: **AGILE**, **Fermi-GBM**, **INTEGRAL**, CALET, **Swift-BAT**, INSIGHT, Astrosat, Konus-Wind, IPN

4 X-ray telescopes: MAXI, Swift-XRT, Chandra, NICER

~ 60 UVOIR telescopes/groups/networks: J-GEM, MASTER KMTNet, VINROUGE, SAGUARO, DDOTI, LBT, INT, TMTS, GMG, GROWTH, GRAWITA, Pan-STARRs, GROND, CNEOST, Gaia, ATLAS, RATIR, Liverpool, GOTO, Wendelstein, SVOM, Skymapper, GRANDMA ,HST, KAIT, HB, DESGW/DECAM-SOAR, Swift/UVOT, TOROS, GTC, WHT, LCO, CHES, NOFS, GWFUNC, CrAO, SALT, Iki-Fun, Magellan/IMACS, NOT, MeerLicht, 1M2H, SWOPE, UKIRT/WFCAM, DCT, ENGRAVE/ESO, CFHT, DOAO, SNIFS, SAO, MITSuME, ASAS-SN, COALTI, SQUEAN, LOAO, YAHPT, BOOTES, LT, MMT, NTT, GECKO

8 smm-radio telescopes: VLA, ASKAP, ALMA, ATCA, AMI-LA, STARE2, LWA

Follow-up activity during O3

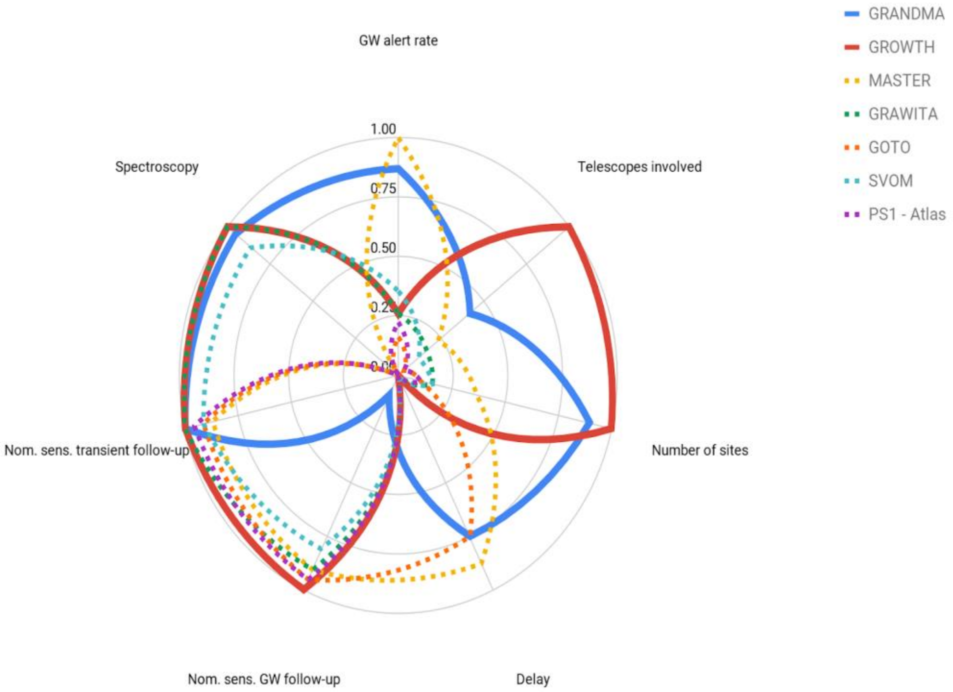
Most active follow-up teams (with GCN participation counts)

- Antares, IceCube followed-up close to 100 % of our alerts
- HAWC, Fermi-LAT followed-up close to 100 % of our alerts
- AGILE, Fermi, INTEGRAL, Calet, Swift-BAT followed-up close to 100 % of our alerts. Less than 60 % for HXMT, Astro-SAT, and Konus-Wind
- MAXI followed-up up close to 100%, Swift-XRT (25%)

UVOIR groups/telescopes/networks

All (above 30 % participation)
MASTER (95%), GRANDMA (90%), KAIT (41%), GROWTH (30%),

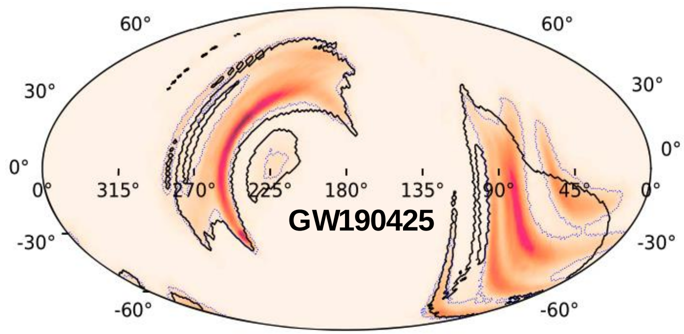
NS-BH/BNS/Mass-Gap Event (above 30%)
MASTER (100%), GRANDMA (90%), GROWTH (80%), GTC (60%), KAIT (50%), WHT, Gaia, Swift-UVOT (45%), GRAWITA, Pan-STARRS (40%), LCO, GWFUNC, DDOTI (30%)

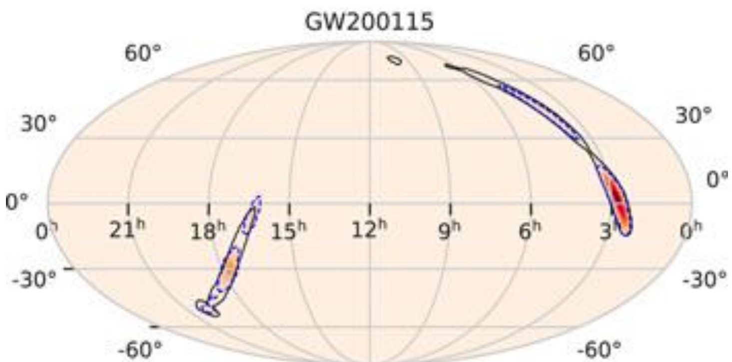


Follow-up teams characteristics

Sky localization of GW events

https://www.gw-openscience.org/eventapi/html/GWTC-3-confident





Optical follow-up of the neutron star-black hole mergers S200105ae and S200115j, Arnand et al.

- **GW190814** (126 GCNs): Gravitational Waves from the Coalescence of a 23 Solar Mass Black - BBH candidate - 267 ± 52 Mpc - 23 deg 2 for the 90 c.r
- **GW190425** (118 GCNs) - BNS - 159 ± 70 Mpc, Observation of a compact binary coalescence with total mass ~3.4 Msun - ~7000 deg2 for the 90 c.r
- S190426c (71 GCNs) - NS-BH candidate (PNS-BH=0.14) - 377 ± 100 Mpc - 1131 deg2 for the 90 c.r - not classified as a confirmed event
- S190510g (56 GCNs) - BNS candidate (42%) - 227 ± 92 Mpc - 1166 deg2 for the 90 c.r --> Rejected
- S191213g (53 GCNs) - BNS candidate (77 %) - 201 ± 81 Mpc - 4480 deg2 for the 90 c.r Rejected

Some References

Limits on the electromagnetic counterpart to S190814bv, DDOTI, Watson et al., 2020

Searching for electromagnetic counterparts to gravitational-wave merger events with the prototype Gravitational-Wave Optical Transient Observer (GOTO-4), Gompertz et al., 2020

Observational constraints on the optical and near-infrared emission from the neutron star-black hole binary merger candidate S190814bv, ESO, ENGRAVE, Ackley et al. 2020

Swift-XRT follow-up of gravitational wave triggers during the third aLIGO/Virgo observing run, Swift, Page et al., 2020

The H.E.S.S. gravitational wave rapid follow-up program, HESS, Ashkar et al, 2021

J-GEM optical and near-infrared follow-up of gravitational wave events during LIGO's and Virgo's third observing run, J-GEM, Sasada et al, 2021

Searches after Gravitational Waves Using ARizona Observatories (SAGUARO): Observations and Analysis from Advanced LIGO/Virgo's Third Observing Run, SAGUARO, Paterson et al., 2021

DECam-GROWTH Search for the Faint and Distant Binary Neutron Star and Neutron Star-Black Hole Mergers in O3a, GROWTH, Arnand, 2021

O4 expectations

LIGO, VIRGO, AND KAGRA OBSERVING RUN PLANS as of 17 June 2021 update;

Observing Run in March 2023

Target sensitivity: LIGO: 160-190 Mpc, Virgo: 80-115 Mpc, Kagra: 1 Mpc with a plan to improve to 3-25 Mpc during O4

Ligo O3 sensitivity ~115 Mpc Hanford and ~133 Mpc Livingston => (160/115)**3 ~ 2.7 in Volume
Virgo O3 sensitivity~50 Mpc => ~4 in Volume

We do expect a factor 3 in the number of events:

We should reasonably expect (since we had reported 79 confident GW events and 81 OPA) to have:

~ 240 OPA , ~ 240 GW events.

That is almost 1 detection per day.

The detection rate, localization does not evolve as fast as expected

Epoch			2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration			4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	200	200
		Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections			0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR	% within	5 deg^2	< 1	2	> *1 – 2*	> *3 – 8*	> *20*
		20 deg^2	< 1	14	> *10*	> *8 – 30*	> *50*
		median/deg^2	480	230	—	—	—
searched area	% within	5 deg^2	6	20	—	—	—
		20 deg^2	16	44	—	—	—
		median/deg^2	88	29	—	—	—

2015

Predictions 04

34 (+78 – 25) BNS and 72 (+75 – 38) NS-BH

Median Luminosity distance : 350 (+/- 10) Mpc for BNS and 620 (+/- 15 Mpc)

90 % c.r region : 1800 (+/-200) deg2 for BNS

Predictions 05

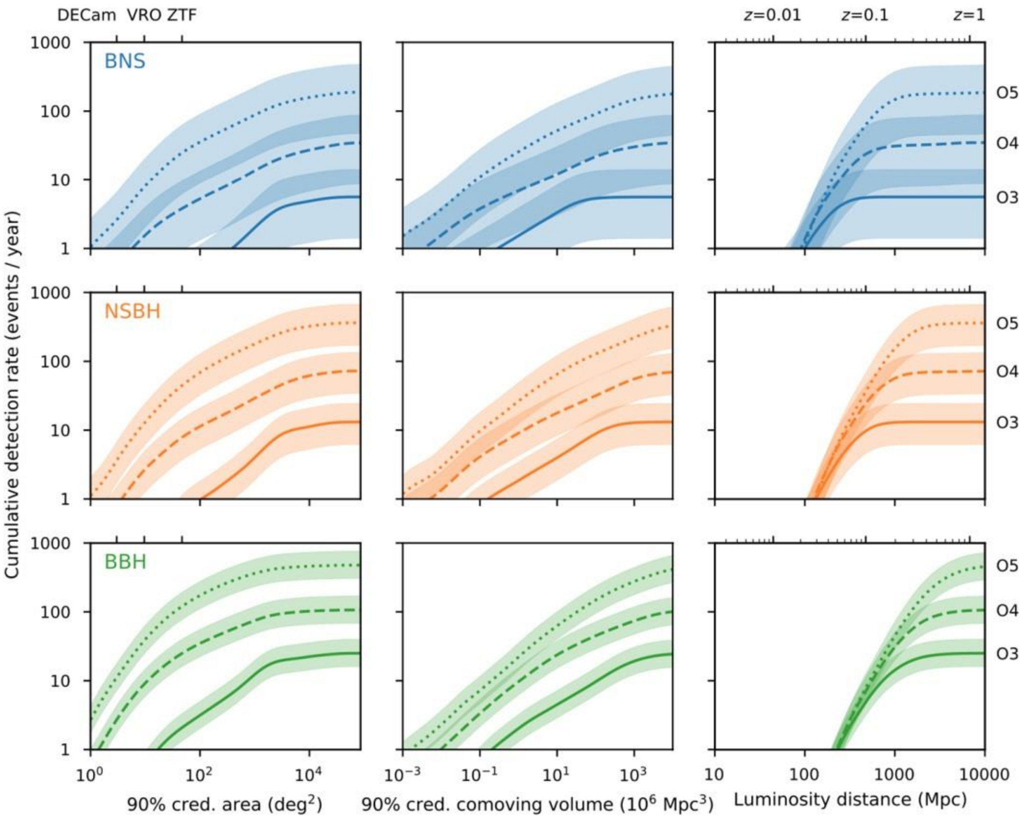
190 (+410 – 130) BNS and 360 (+360 – 180) NS-BHs

Median Luminosity distance : 620 (+/- 16) Mpc for BNS and 1130 (+/- 20 Mpc)

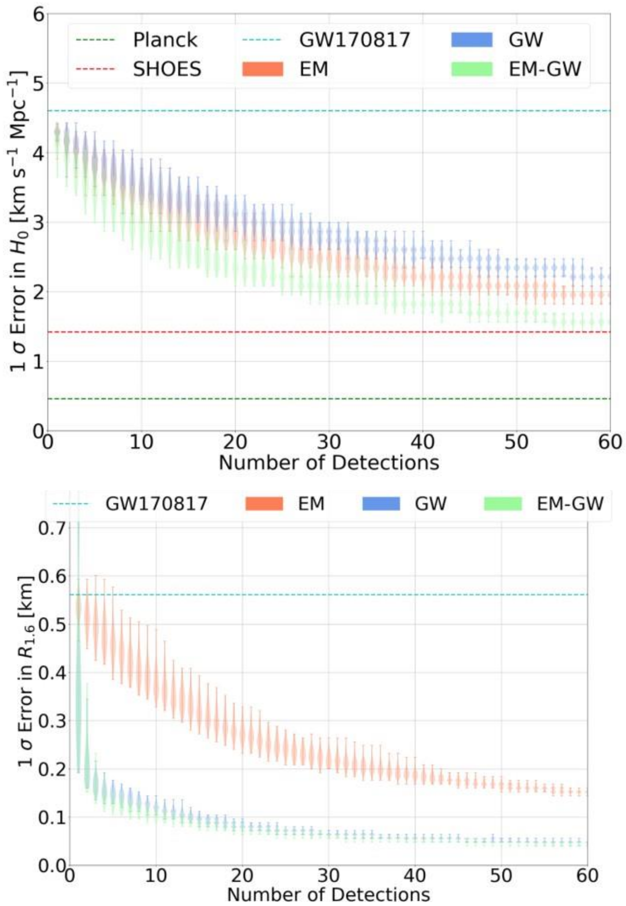
90 % c.r region : 1300 (+/120) deg2 for BNS

Data-driven expectations for electromagnetic counterpart searches based on LIGO/Virgo public alerts, Petrov 2021

Prospects for multi-messenger detections



[Data-driven expectations for electromagnetic counterpart searches based on LIGO/Virgo public alerts](), Petrov 2021



Coughlin, SA et al., in preparation:
Prospects for H0 and EOS based on updates

New Instrumental ressources
Some dedicated Projects

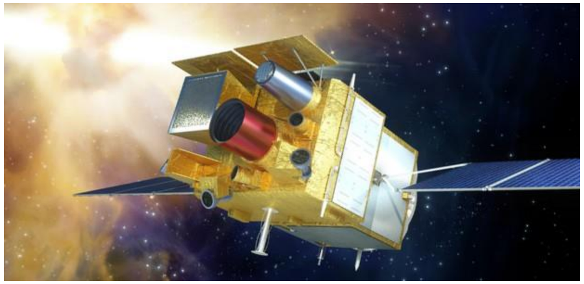
Wide-field Imagers (Optical)

GOTO, network of 42 telescopes
Limiting mag around 19.8 with no filter
Coverage of 800 deg2 per event in O3a
Cadence of 2 – 3 days per point of the sky

--> Similar ZTF, TURBO, BLACKGEM, etc ...

X-ray, Gamma-ray instrumentations

SVOM, at least 1 GRB in coinc per GW during 5 year



Similarly Einstein Probe,

Wide-field UV and IR

WINTER, prediction < 5 KNe during O4
Similarly JFIRST, Dorado

Multi-band photometry / Spectroscopy

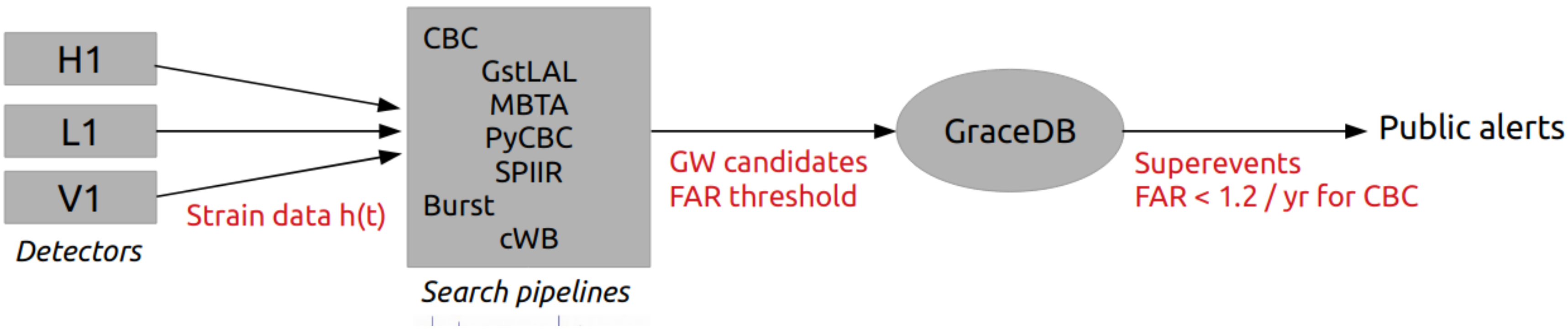
Spectral Energy Distribution v2
~ 10 per night for BNS dist < 150 Mpc
Liverpool,

GW170817

Objective

EM counterpart of GW and neutrino events
Kilonovae

Key elements of the LIGO-Virgo infrastructure

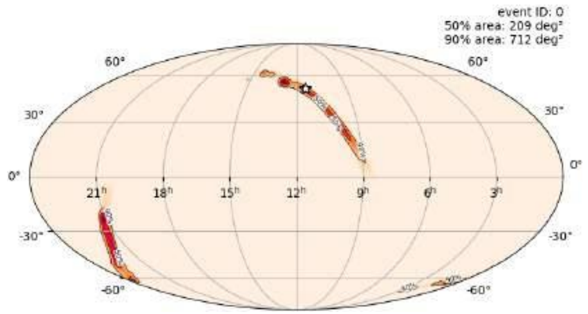


We will provide open public alerts (OPA) for:
Pos-merger alerts and CWB alerts (within minutes or better, final details in sept. 2022)
pre-merger (negative time) early warning alerts.
alerts based on a coincident external public trigger.

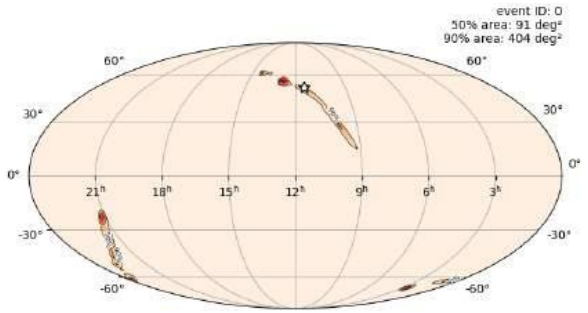
LVK plans to provide (Open) alerts not only in the GCN/TACH infrastructure
You should expect one OPA per day.

The Mass-Gap class compared to O3 will be removed

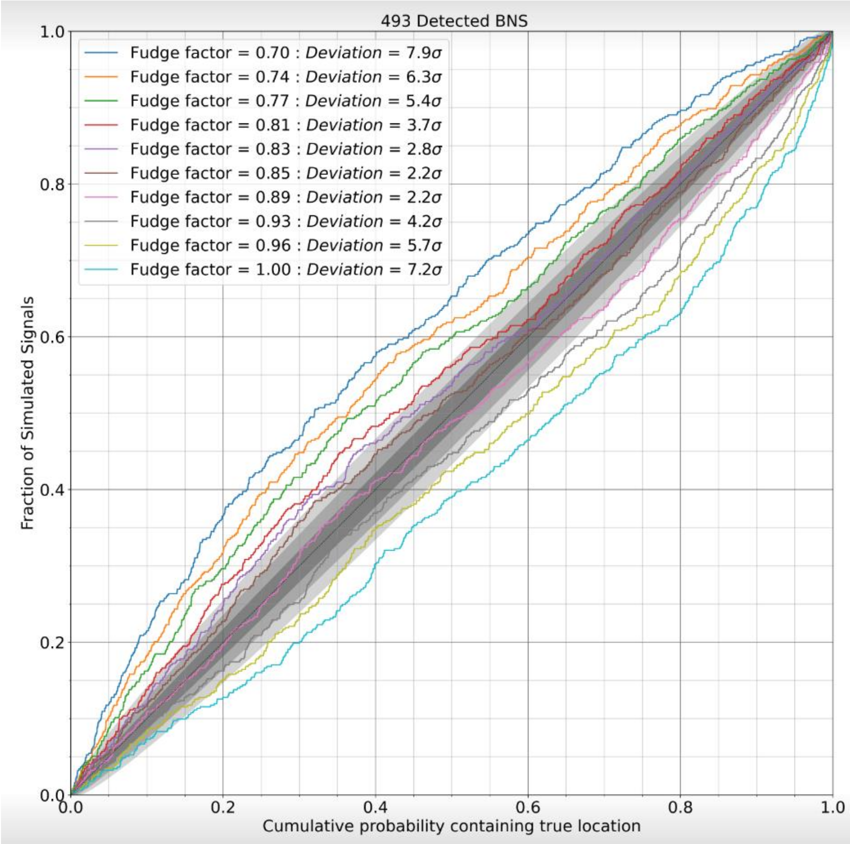
Tuning Rapid sky localization algorithm : Bayestar
A work conducted by PA. Duverne (IJCLAB)



Fudge-factor= 0.75



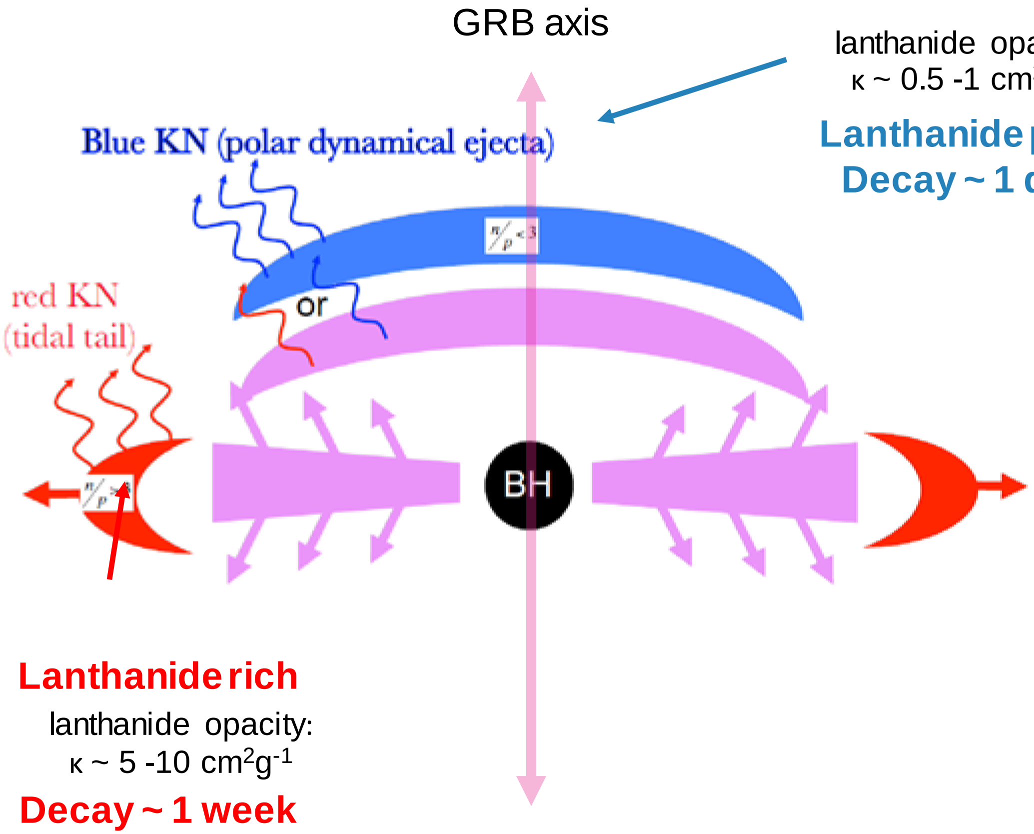
Fudge-factor= 1.0



Optimisation of the pp-plot with BNS signals injected in Gaussian and stationnary noise. The signals were detected using an O3 PyCBC Live instance, and localised with Bayestar

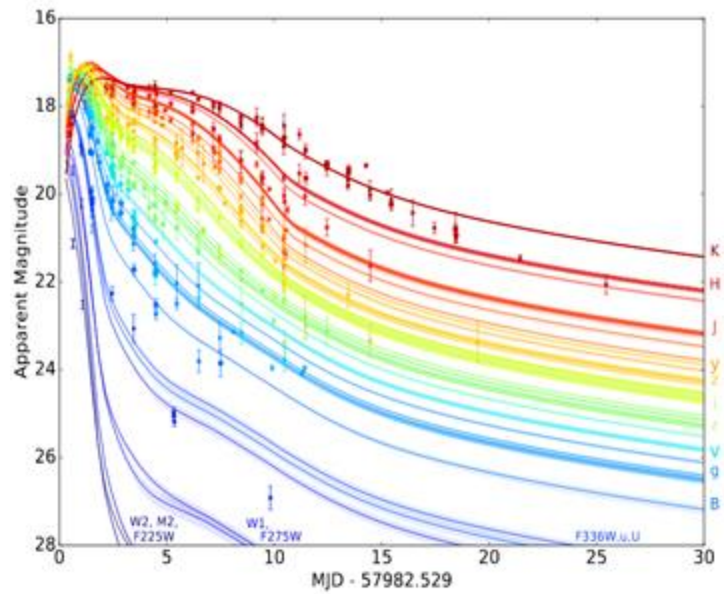
Fudge-factor is a hard coded factor that has been implemented to pass the PP-plot test, prior localizing the signal

Hunting Kilonovae



Observed properties change with:

- mass ratio
- equation of state of NS
- Lanthanide fraction
- nature of the post-merger



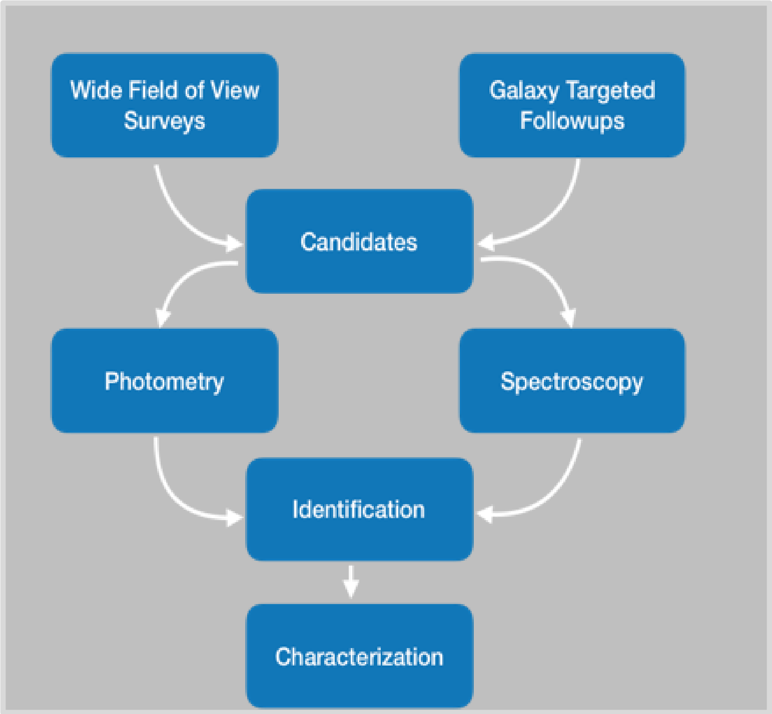
Villar et al. 2017

Science topics with GWs

- **Cosmology**
  - **Independent measure of H_0** (LVK et al. 2017, *Dietrich et al. 2020, Coughlin et al. 2020)*
- **Nuclear Astrophysics**
  - **r-Process** : lanthanide and actinide synthesis (*Barnes et al., Dvorkin et al.)*
  - **Dense matter EOS of NS** : MM sample + numerical simulation (*Essick et al.)*
- **High Energy Astrophysics**
  - **GRB population associated with GW** : GW observation favors on-axis jet
  - **Host galaxy information** : Which type of galaxy for short GRBs
- **GW Sources**
  - **GW progenitor** : KN color evolution to discriminate NS-BH
  - **Post-merger object** : Discriminate between NS & BH remnant

Observing GW events

What are the properties of cold ultra-dense matter ?
What are the properties of ejecta of GW events ?
Properties of kilonovae ? How are heavy metals produced ?
Can we use these mergers for precision cosmology?



Identify and characterize GRB afterglows /KNe associated to GW events

Kilonova Challenge	Solution
Short lived	Speed
Faint - Peak at 20.5 mag at 200 Mpc	Deep Observations
Rapid Color Evolution	Observation in g and r (adding i if possible)
Large localisation uncertainties + Many alerts to follow + Well sampled lightcurves	No duplication Coordination of Observations Choosing alerts

Requires a network of telescopes + data reduction tools (spectro + photometry)
+ expertise on transient follow-up (Postigo, Klotz, Stargate, TAROT) and in collaboration with FINK
+ expertise on GW physics (Virgo members)
+ expertise on ejecta (GRB with SVOM France Daigne, Basa, Kilonovae with GRANDMA)
+ expertise on nuclear physics (Tews, Khan)
+ GW pipelines (GstLAL, Caudill) + LVK low latency (Antier)

Created in April, 2018

by IJCLAB – Observatoire de la côte d'azur

More than 90 scientists

PI. S.Antier (Artémis)
Co-PI. A. Klotz (IRAP)

Work Packages leaders:

- Consortium (Antier)
- Data Base (Perus)
- Follow-up (Tosta e Melo)
- Data reduction (Karpov)
- Online Infrastructure (Leroy)
- Observation plan (Coughlin)
- Citizen science (Turpin)

GRANDMA

+30 institutes / groups

Including in Europe CNRS – Univ. Amsterdam – Univ. Louvain – Univ. Postdam – FZU – INFN - IAA

Present in

18 countries

23 observatories

When the sun never rises

O3b and global summary of O3: **GRANDMA Observations of Advanced LIGO's and Advanced Virgo's Third Observational Campaign**

O3a and presentation of the collaboration: **The first six months of the Advanced LIGO's and Advanced Virgo's third observing run with GRANDMA,** 2020, MNRAS, 492, 3904

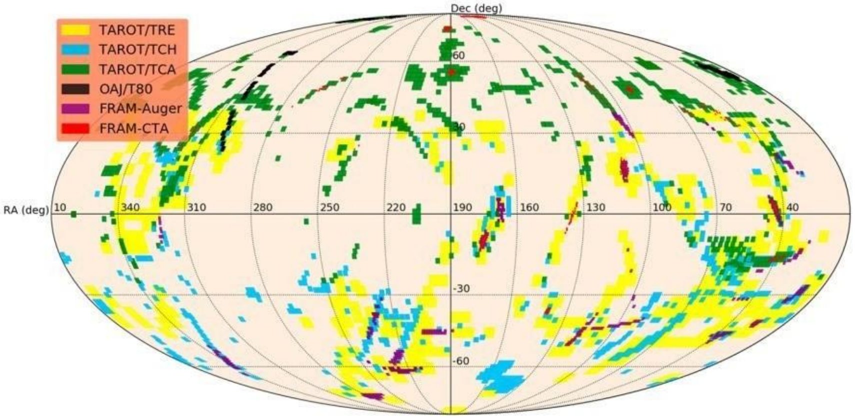
Embrace workforce of gender, geographic, and career diversity

The path to diversity begins with supporting, mentoring, and sponsoring diverse women and men to become leaders – Denise Morrison

- Higher Innovation
- Variety of Different Perspectives
- Increased Creativity
- Faster Problem Solving
- Better Decision Making
- Higher Employee Engagement
- Reduced Collaboration Turnover

GRANDMA GW O3 observations

All O3 observations done by GRANDMA wide field of view teles.



87% of O3 alerts follow-up by GRANDMA

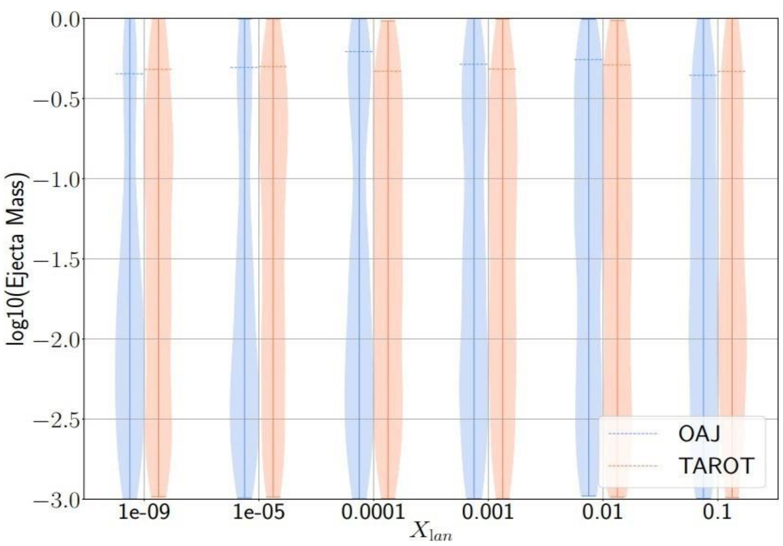
49/56 alerts for O3a

90 minutes delay between first Obs and GW trigger for 50% of the alerts

Minimal delay 15 min (5 min for LVC, 5 min GWEMOPT, 5 min telescope operation)

Coverage in average per alert 200 deg2 at 18 mag

In case of interesting candidates, we can trigger OAJ and CFHT for 100 deg2 with upper limit 22 mag



Constraints on the ejecta mass in terms of lanthanide fractions Xlan for the BNS candidate S200213t based on the OAJ and TAROT observations.

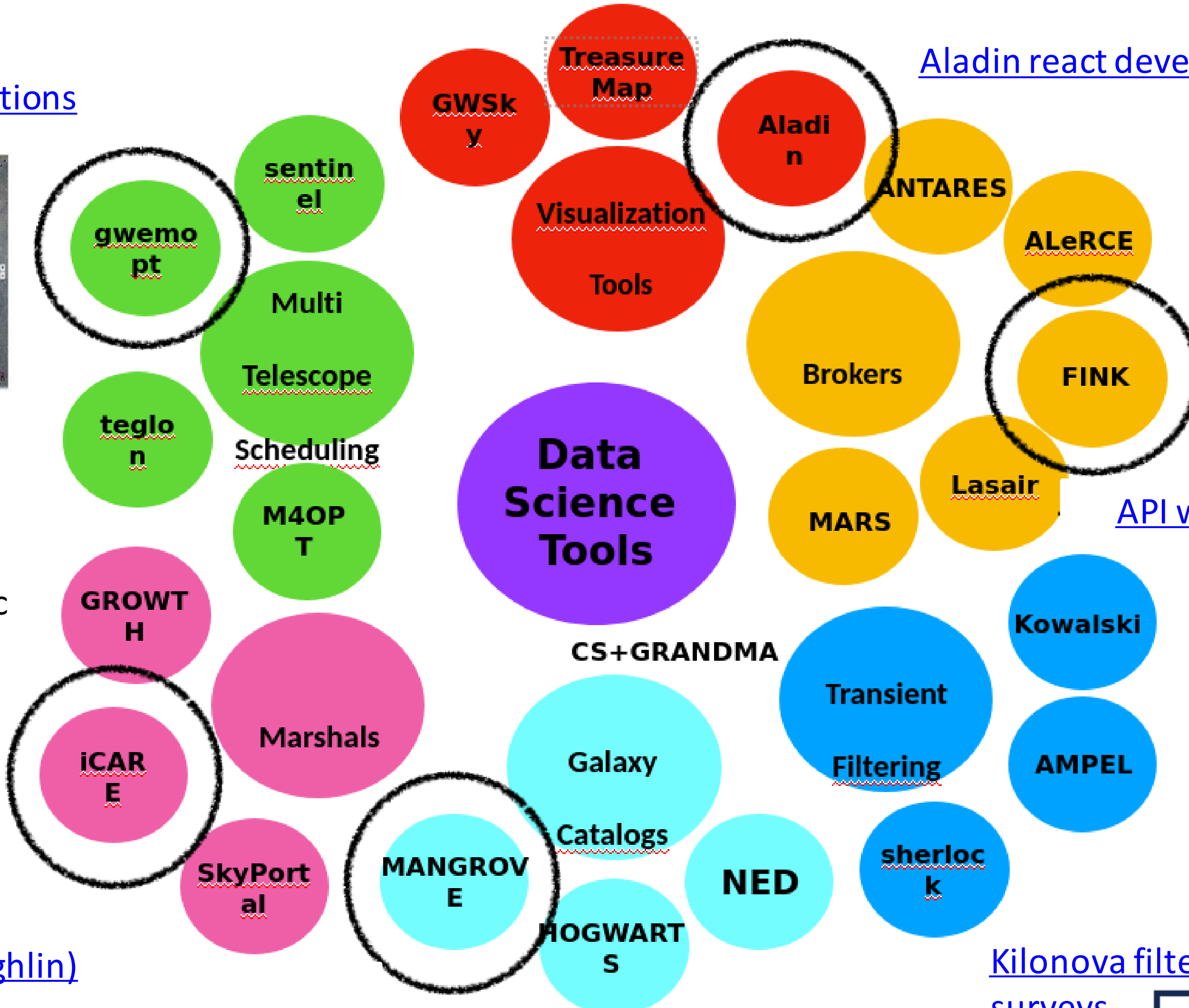
Analysis tools for the MM community
Initiated / Supported by GRANDMA

Multi-plan observations

Ingest Vo – Kafka streams

Generic photometric data reduction
- MUPHOTEN
- STDPIPE

MM Web platform
- ICARE
- Skyportal (see Coughlin)



Aladin react develop.

API with LSST brokers

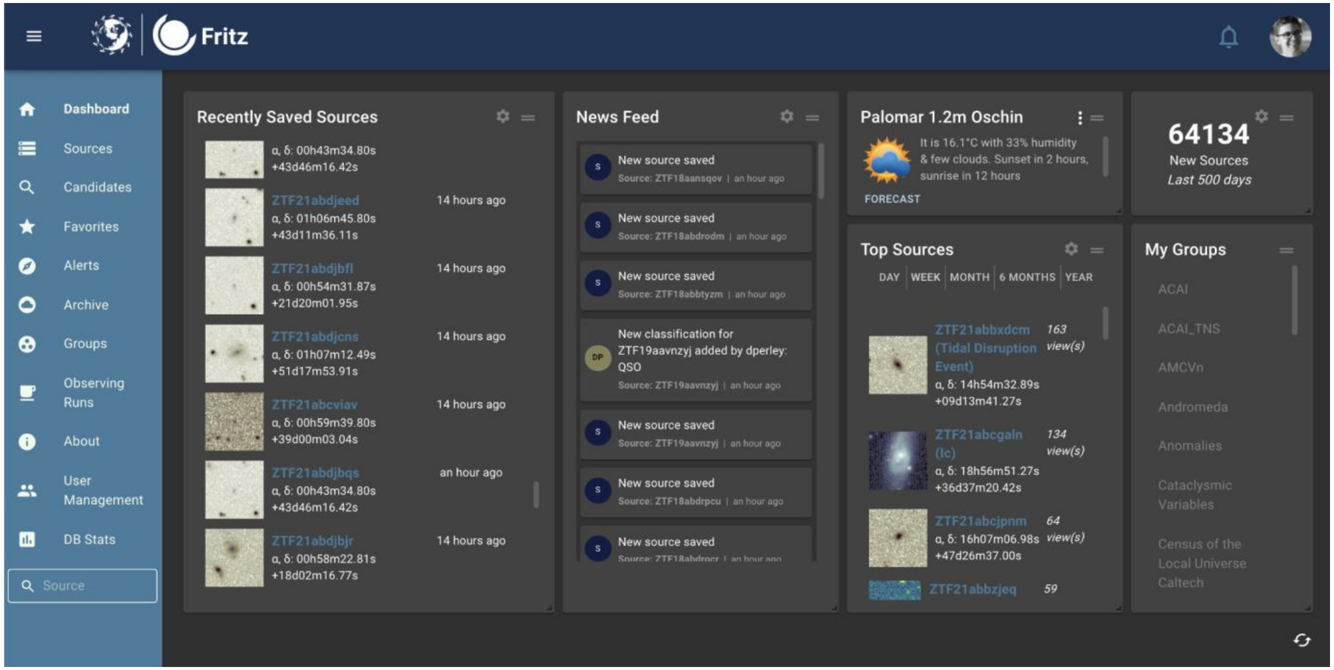
Kilonova filtering for optical surveys

Galaxy catalogs

Funded by individual initiatives but no funding from European programs

All our tools are public used by GRANDMA and other collaborations

SkyPortal: a data science platform to enable time-domain astronomy
PI. Josh Bloom with GRANDMA and GROWTH, M. Coughlin leader of MM

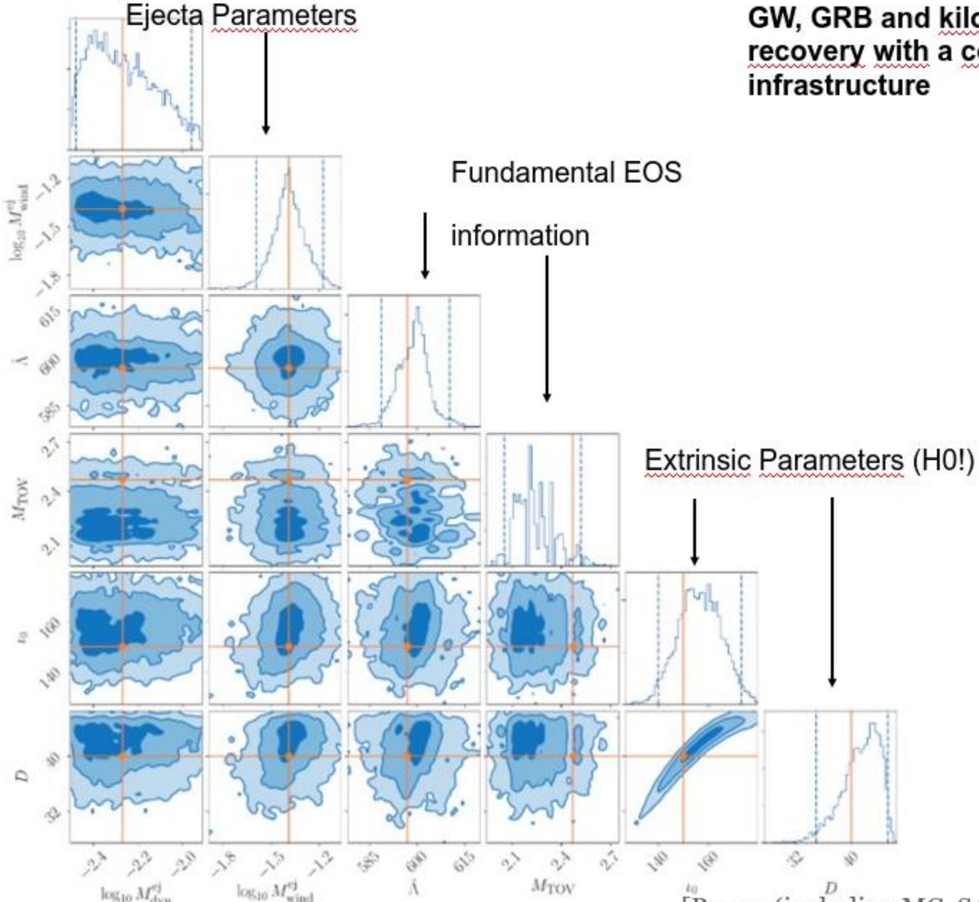


All the capabilities of an effective Marshal:
Multi-survey data archive and alert broker, ML applications, classification and labeling at scale, follow-up observation management: robotic and classical facilities, well-tested, extensive docs, CI/CD

Many MMA capabilities not available elsewhere:
Light curve fitting, multiple telescope scheduling, follow-up prioritization, upper limits / efficiency calculations, notification framework

NMMA: Fully Bayesian Joint-Inference Pipeline GW events

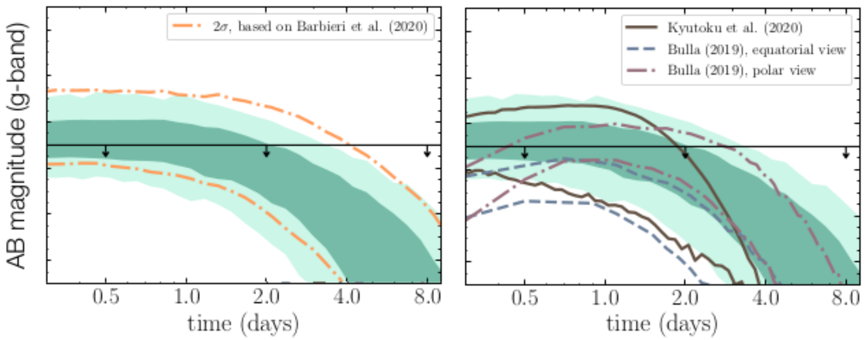
Resp. T. Dietrich (Uni.Postdam) with P. Pang, G. Raajimakers (Uni. Amsterdam, Nikhef)



[Pang+ (including MC, SA), 2021

GW, GRB and kilonova recovery with a combined infrastructure

Raajimakers et al. (2021b): 2102.11569



GRANDMA Citizen science: Kilonova-catcher

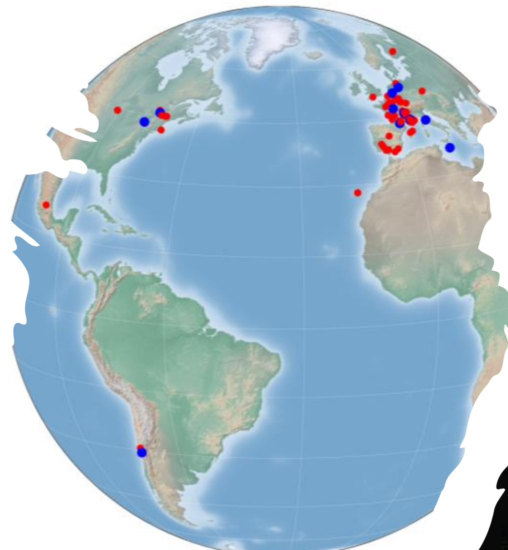
http://kilonovacatcher.in2p3.fr/

Resp. D. Turpin (CEA)

- More than 130 participating telescopes from 15 cm - 60 cm

- Observations made for NS-BH and BNS candidates 100 galaxies observed

- Observations on 12 Fink-KN-SN candidates --> 30 amateurs participated in the ReadyforO4 campaign (April – September 2021) - 1000 obs.

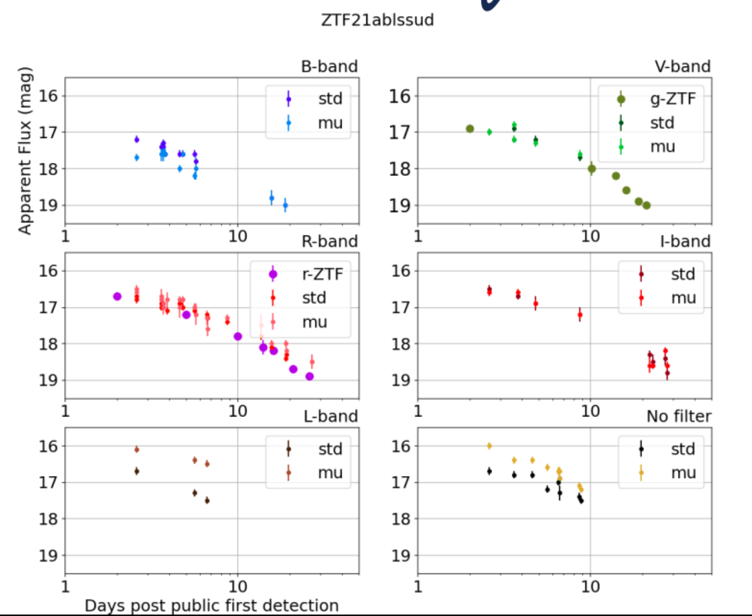


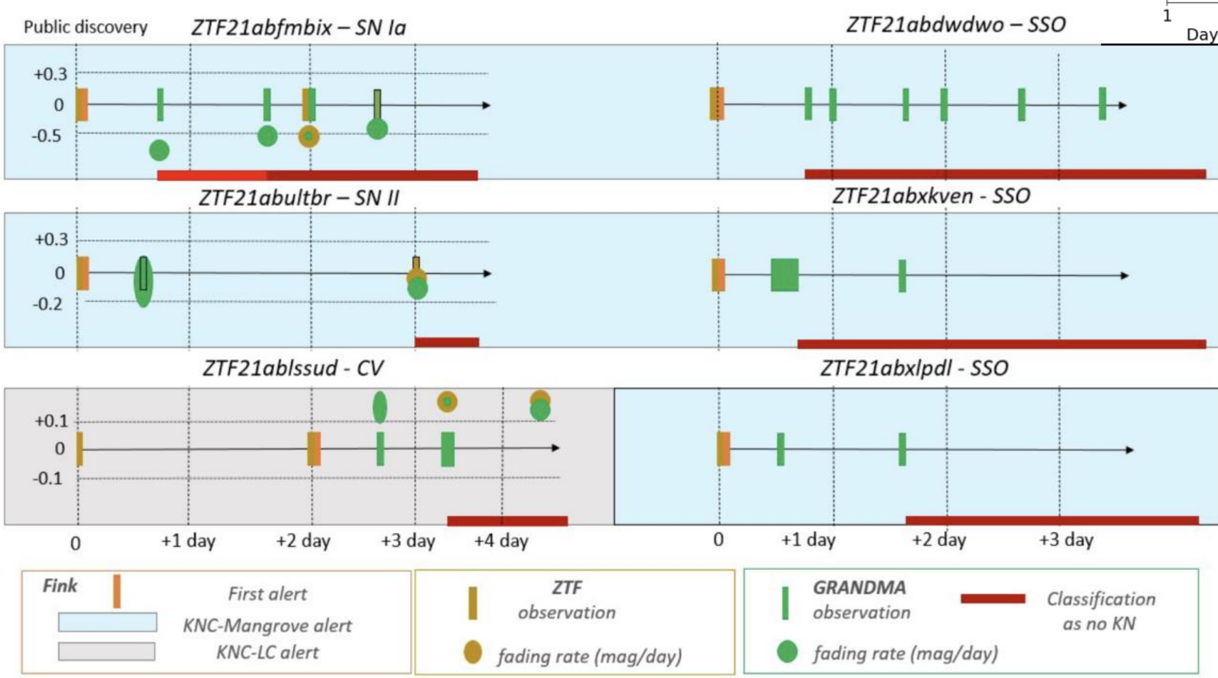
Participation to ZTF/LSST - LIGO-Virgo – SNEWs – KM3NET – IceCube and SVOM alerts

Follow-up of Kilonova candidates with FINK

[GRANDMA Observations of ZTF/Fink Transients during Summer 2021](#), [Aivazyan](#), MNRAS

GRANDMA Observations of ZTF/Fink Transients during Summer 2021:
4 months of observations in 2021
37 telescopes involved + 26 amateur astronomers





A broker to filter LSST triggers based on probable nature
https://fink-broker.org/

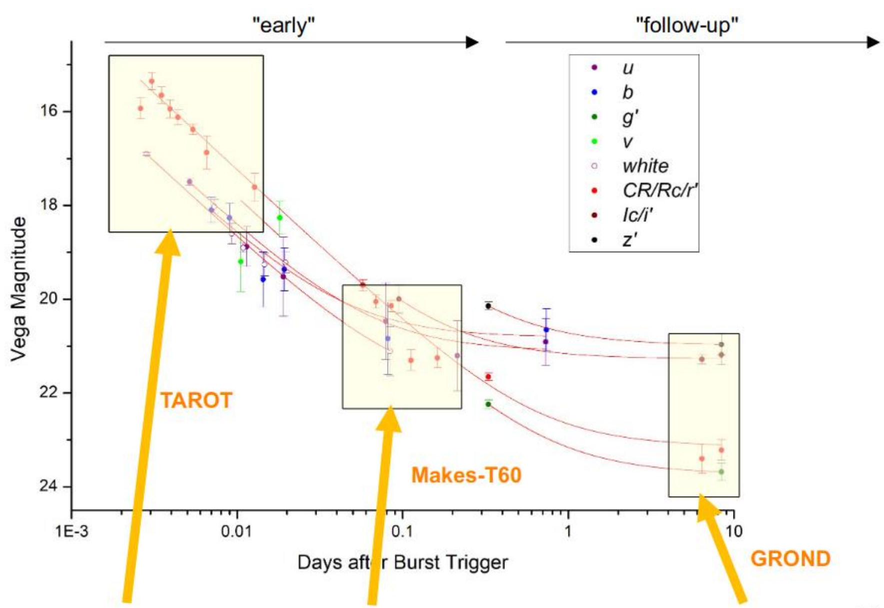
KNe Hunting with GRB follow-up
20.03.2022 to 15.05.2022

20 telescopes involved to follow-up GRBs from SWIFT-BAT
→ Goal : find optical transients and perform follow-up
→ Preparing the O4 campaign (shifts rota, online analysis)

10 + 1 (INTEGRAL) GRBs detected in 9 weeks by Swift-BAT

FROM 11 SWIFT-BAT GRBs, 3 afterglows detected
--> 2 AFTERGLOWS with min PROMPT DATA

Article in preparation



GW 220427A

Field of view 1 to 10°
Filter clear
photometry at 0.5 mag

Field of view 10' to 30'
Filter clear
photometry at 0.5 mag

Field of view 1' to 15'
Filter clear or grJHK
Photometry at 0.2 mag
Spectro mag 19-22

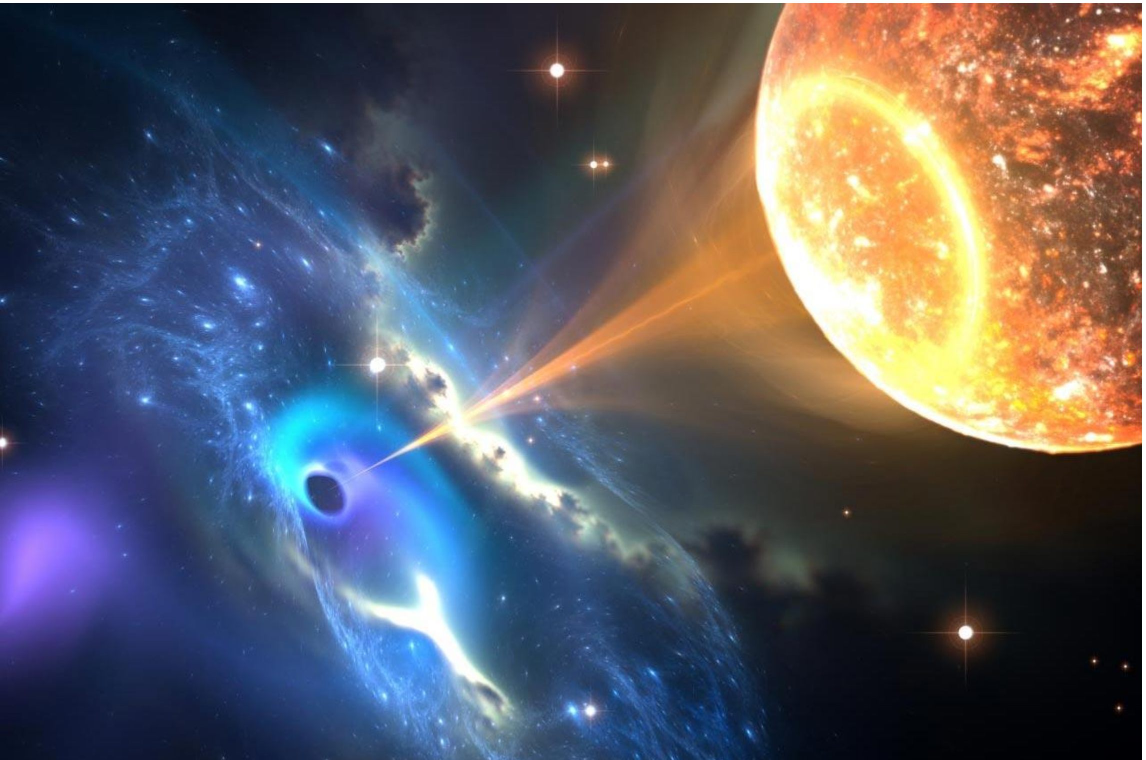
Field of view 1' to 15'
griJHK
photometry at 0.05 mag
Spectro mag 19-22

Conclusion

Alert Providers

LVK - Public LIGO-Virgo alerts during O4
Pre and post mergers alerts
Three times more detections but
Median 90 % c.r Sky localization area does not increase compared to O3

GRBs triggers with Swift and Fermi
Proliferation of online investigation of orphan Kilonovae with optical surveys



Follow-up

Start of the golden age of farms of telescopes (with machine learning): GOTO, BlackGem, ZTF, LSST

Rise of wide-field NIR imagers and low resolution spectroscopy for time-domain

Initiative in X-ray and UV instrumentation

Proliferation of tools financed by projects but hardly be directly useful for others

The standardisation and int-operability is hard and takes time

Hard to keep manpower ressources in multi-messenger because of the rare event aspect

But I believe that the solution of MMA science is a network of <u>Telescopes (with private and public data)</u> and a network of <u>People</u> (EM & GW)

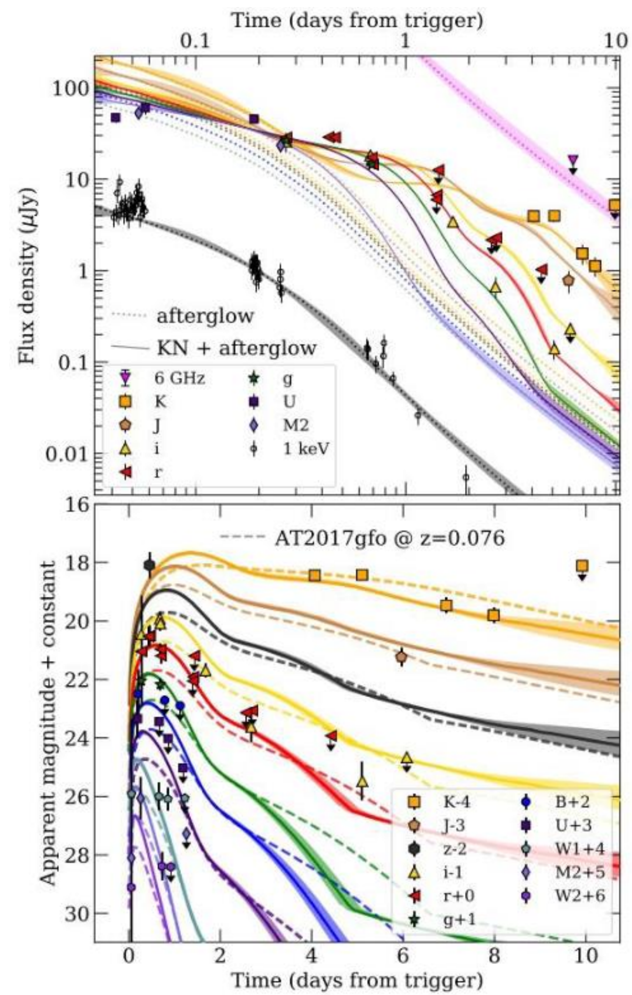
Intro - Kilonova without GWs ?

< 10 candidates in the literature

GRB 211211A
2204.10864: J. Rastinejad et al: [A Kilonova Following a Long-Duration Gamma-Ray Burst at 350 Mpc]

An event combining multiple aspects that had been thought to be well-understood, in a way that raises far more questions than it (initially) provides answers, dissolving accepted norms.

NIR follow-up reveals very strong color evolution to the red combined with deep upper limits on a classical SN, and it was indicated with MOTSFITS that the best fit comes from KN + afterglow



Optical survey
[A strategy for LSST to unveil a population of kilonovae without gravitational-wave triggers], Andreoni 2019
Only 7 KNe / year with baseline2018a LSST cadence
More than 3 times more with a daily night strategy with two bands

Survey to EM partners
Organized by the LVK

EM Lessons

World-wide collaborations — Follow-up is difficult without it, saves those sleepless nights

Search and Follow-up — More, more, more!
Candidates->Identification
Especially spectra!

Data Science Tools — Resolving the same problems. Needs more coordination, in particular schedulers/TOMs

Future Observatories — Fast-slewing telescopes, with deeper sensitivity and redder filters (LSST?)

Ways LVC May help

Public Alerts — Complete Success! Very broad participation (with amateurs !)

Observing Scenarios — Need Realistic
FARs/skymaps - Difficult
For proposals without it

Run Timescales — Could be 5 years between counterparts if does not reopen until 2022

Extra Communication — Rapid (automated?) LALInference skymaps, updated event properties, FAR/DQ information like scattered light event, etc. Chirp mass?