THE THIRD OBSERVATIONAL RUN (O3) OF ADVANCED LIGO AND ADVANCED VIRGO:

GRAVITATIONAL WAVE SOURCE CANDIDATES, FOLLOW-UP ACTIVITIES AND PRELIMINARY RESULTS

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and

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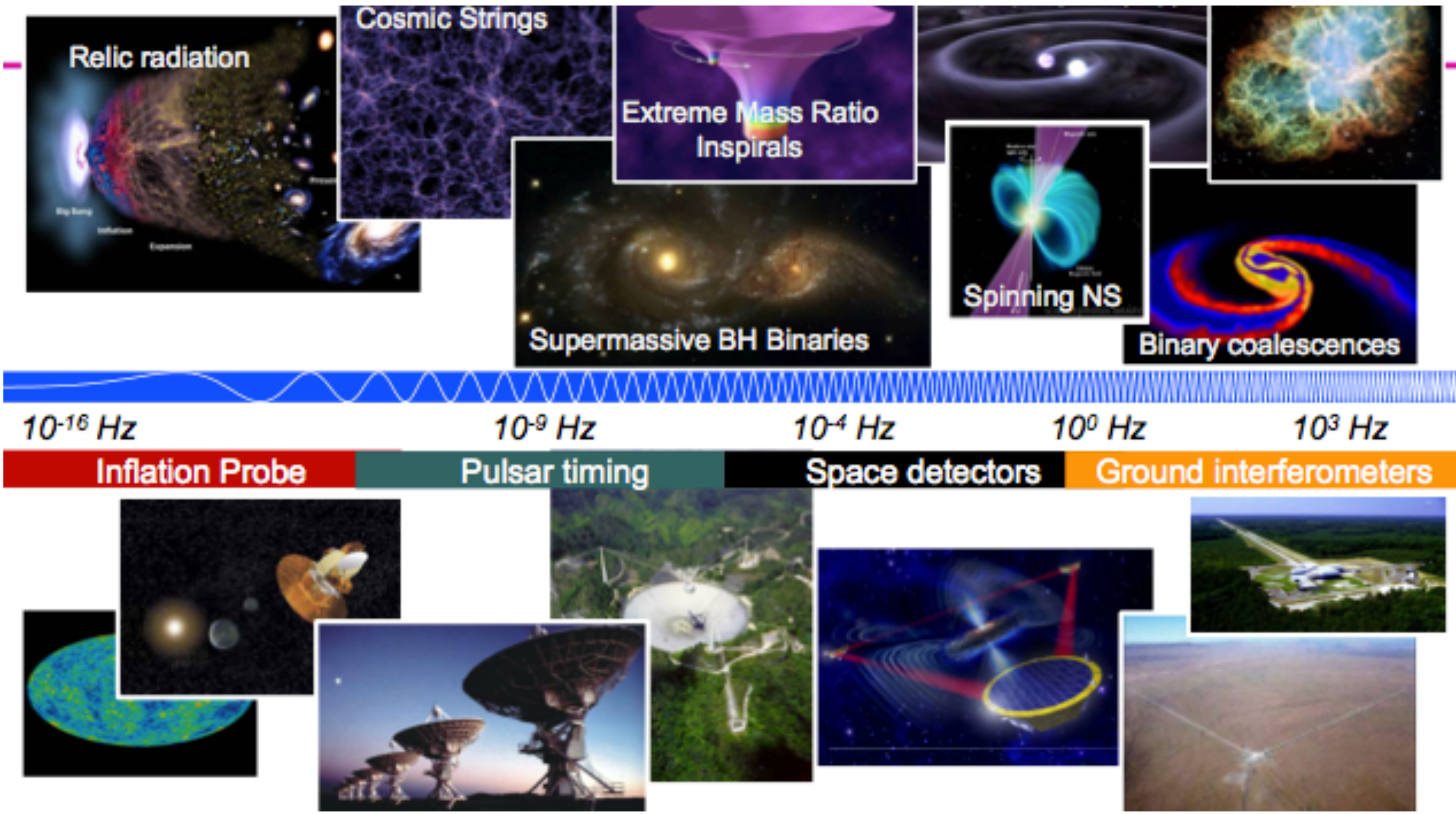
Outline

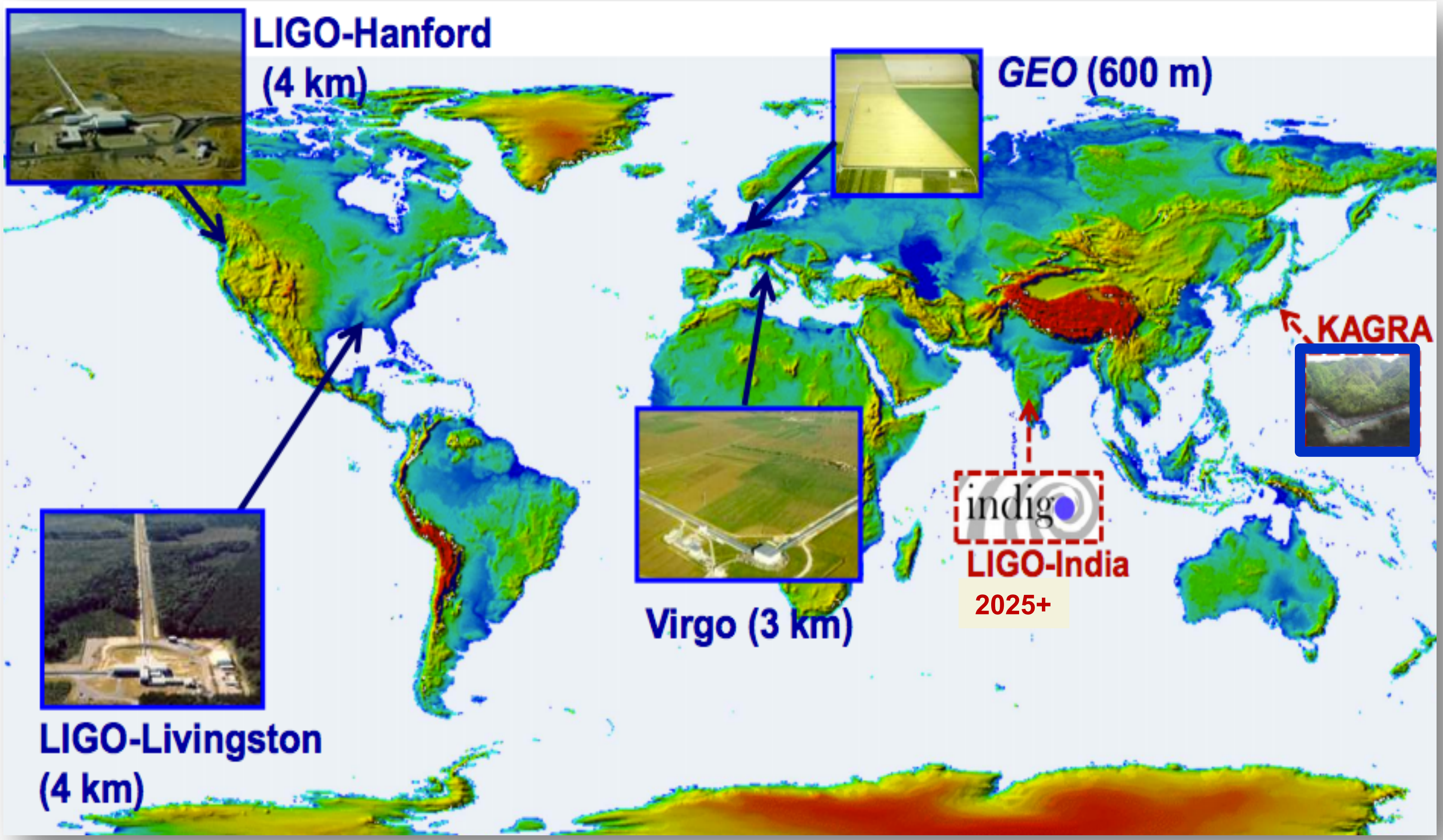
- I part (Giulia)
  - brief introduction on past runs
  - O3: what's news?
  - Future perspectives (1)

- II part (Andrea)
  - Update on GW170817
  - GRAWITA and ENGRAVE
  - Ongoing works
  - Future perspectives (2)

High Frequency (10-1000 Hz) GW sources

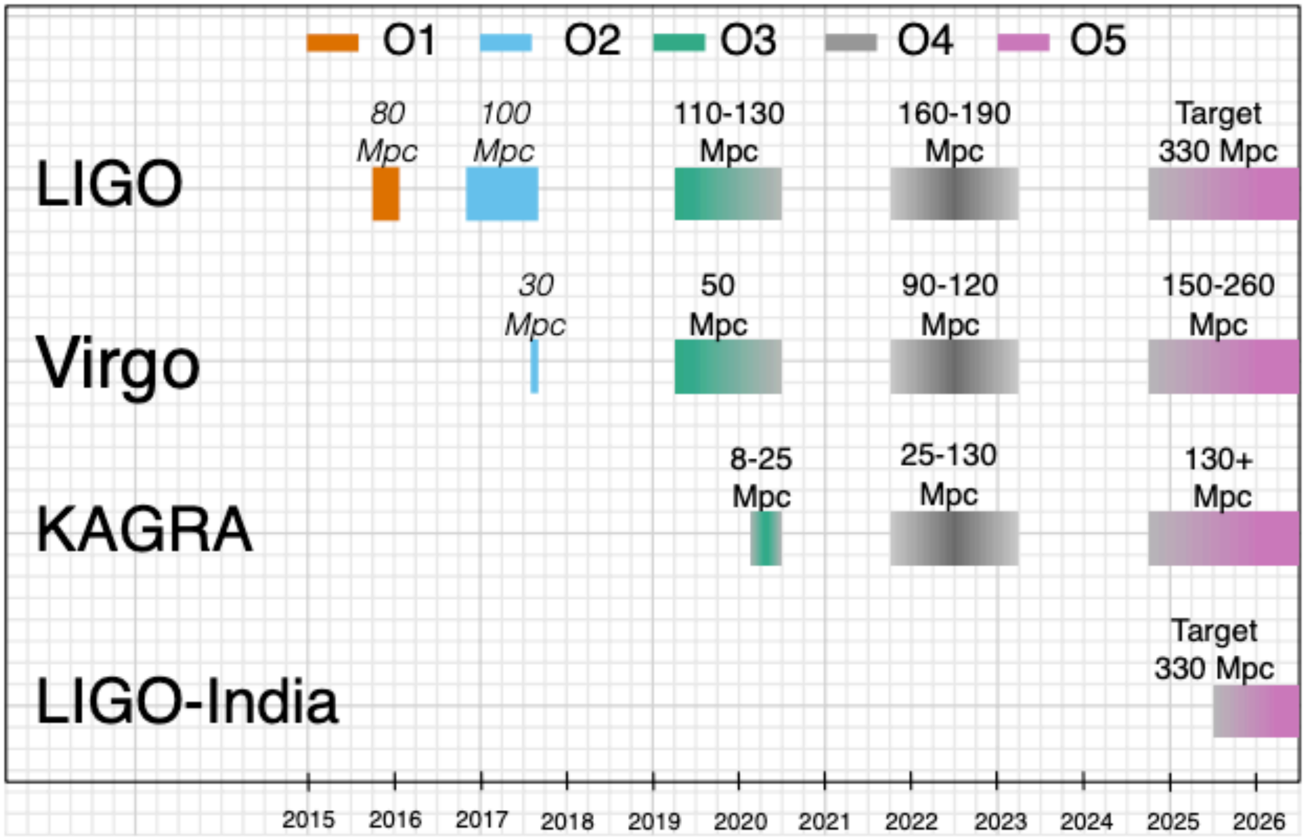


The current (second generation, 2G) GW detector network



Credit:LIGO-Virgo

The 2G detector network timeline



LVC, Living Rev. Relativ., arXiv:1304.0670v10

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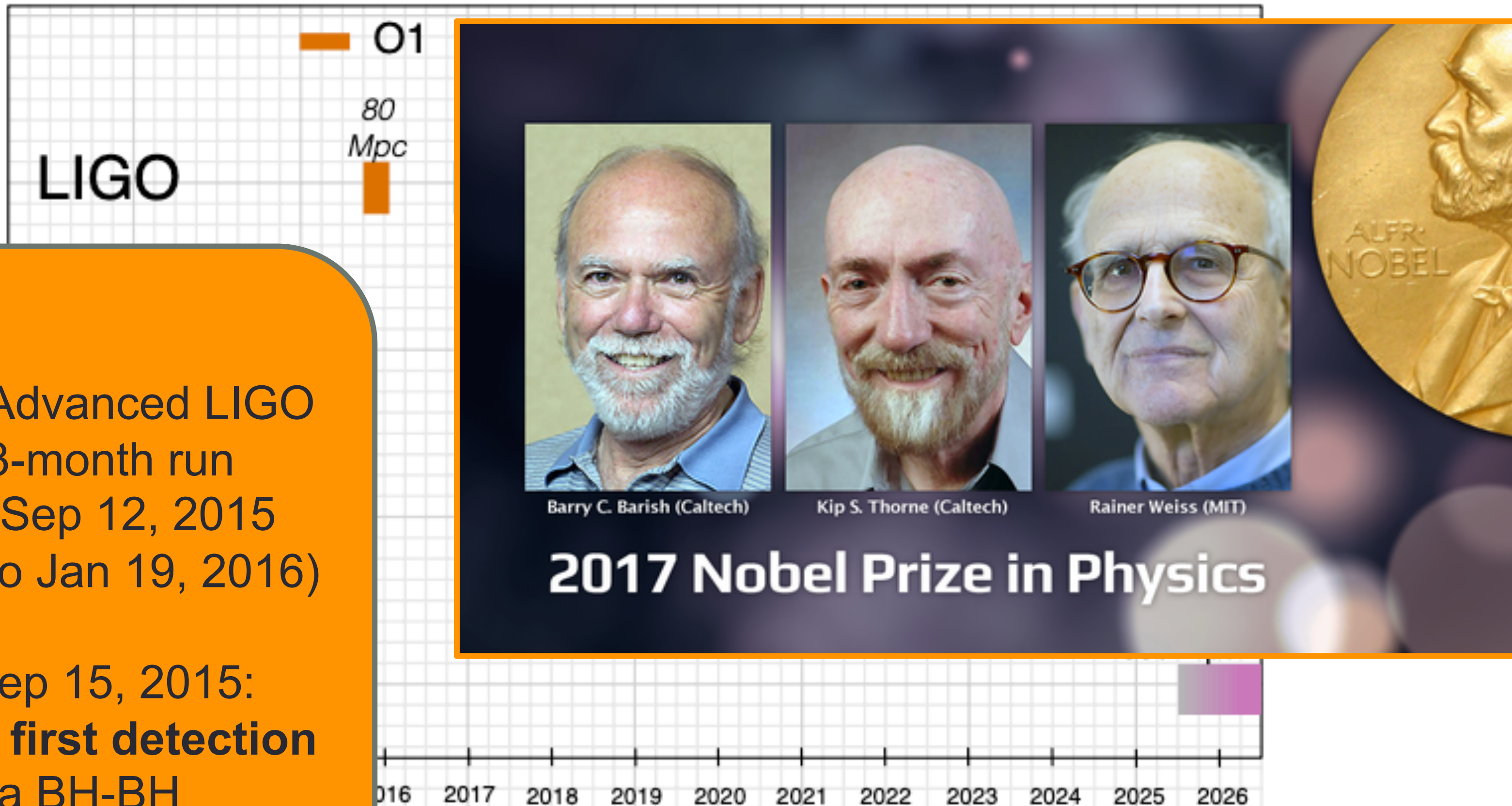
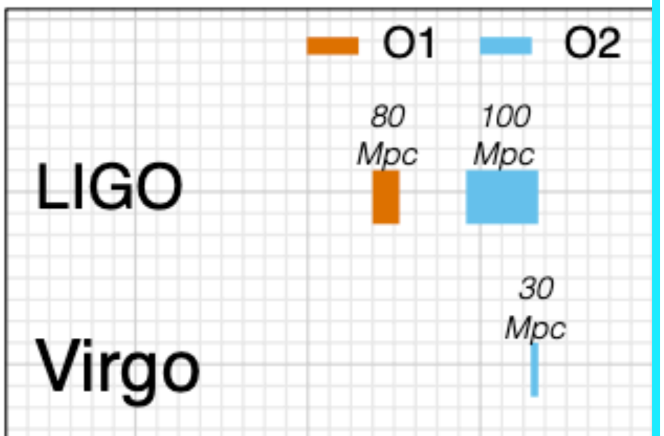


- O1:
  - Advanced LIGO
  - 3-month run (Sep 12, 2015 to Jan 19, 2016)
- On Sep 15, 2015: **GWs first detection** from a BH-BH merger (GW150914)

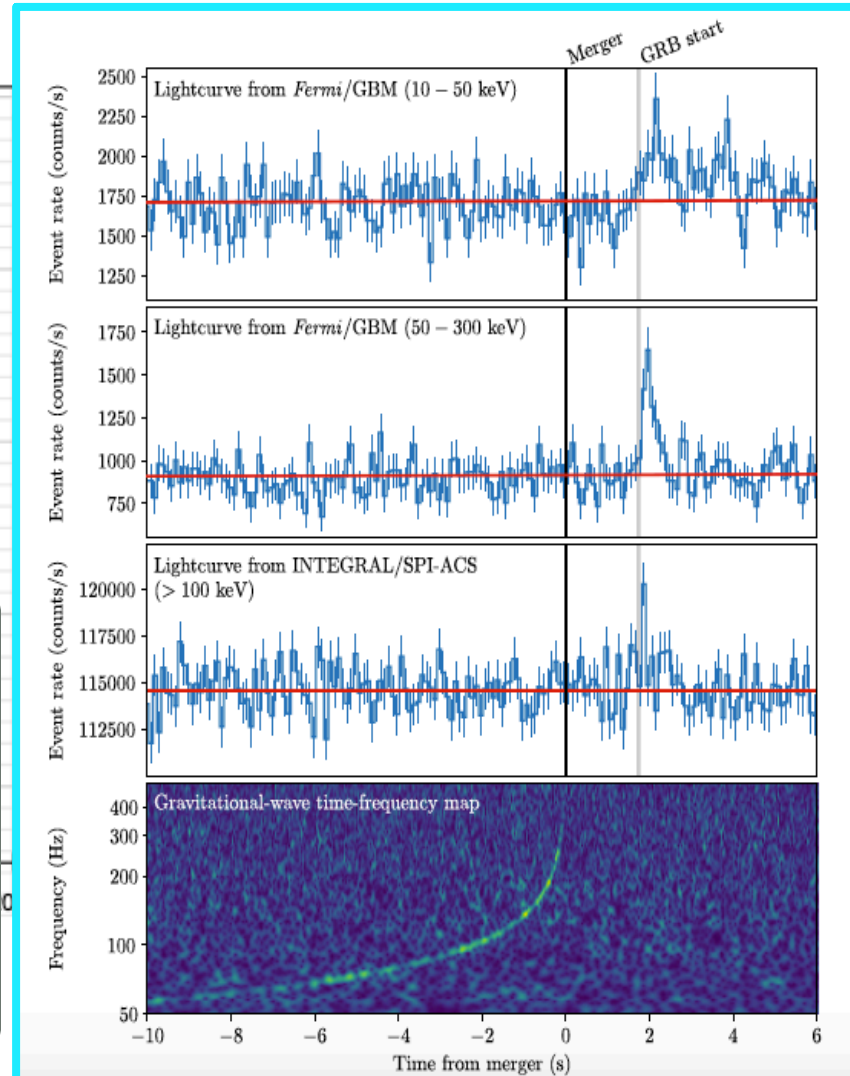
Abbott+2016, PRL, 116, 061102

The 2G detector network timeline



- O2:
  - 9-month second run (Nov 30, 2016 to Aug 25, 2017)
  - Aug 2017: Virgo joined LIGO network

- **First electromagnetic counterpart: a short GRB associated with** a NS-NS merger (GRB 170817)

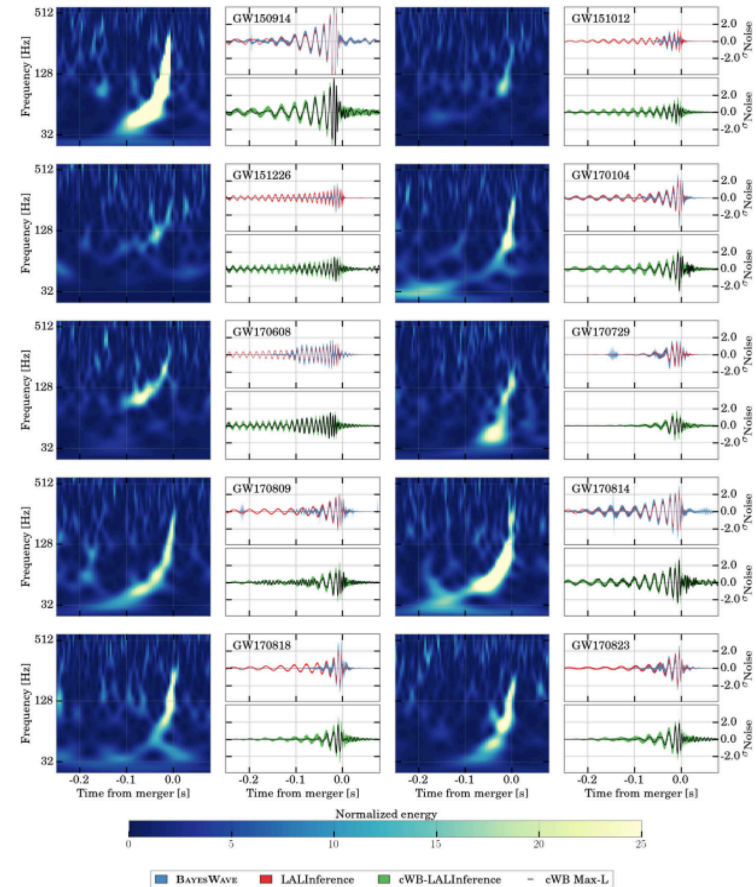


Abbott+2017, ApJL 848,L13

O1+O2: The first GW transient catalog of compact binary mergers (GWTC-1)

B.P. Abbott et al. Physical Review 9,031040 (2019)

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_f/M_\odot$	a_f	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\,s^{-1}})$	d_L/Mpc	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.4}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	440^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	182
GW151012	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	$35.6^{+10.8}_{-3.8}$	$0.67^{+0.13}_{-0.11}$	$1.6^{+0.6}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1080^{+550}_{-490}	$0.21^{+0.09}_{-0.09}$	1523
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	450^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1033
GW170104	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	$48.9^{+5.1}_{-4.0}$	$0.66^{+0.08}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.3^{+0.6}_{-1.0}\times10^{56}$	990^{+440}_{-430}	$0.20^{+0.08}_{-0.08}$	921
GW170608	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	$17.8^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.9^{+0.0}_{-0.1}$	$3.5^{+0.4}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	392
GW170729	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	$79.5^{+14.7}_{-10.2}$	$0.81^{+0.07}_{-0.13}$	$4.8^{+1.7}_{-1.7}$	$4.2^{+0.9}_{-1.5}\times10^{56}$	2840^{+1400}_{-1360}	$0.49^{+0.19}_{-0.21}$	1041
GW170809	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	$56.3^{+5.2}_{-3.8}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	1030^{+320}_{-390}	$0.20^{+0.05}_{-0.07}$	308
GW170814	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	$53.2^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$	$2.7^{+0.4}_{-0.3}$	$3.7^{+0.4}_{-0.5}\times10^{56}$	600^{+150}_{-220}	$0.12^{+0.03}_{-0.04}$	87
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+7}_{-15}	$0.01^{+0.00}_{-0.00}$	16
GW170818	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.4^{+4.9}_{-3.8}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1060^{+420}_{-380}	$0.21^{+0.07}_{-0.07}$	39
GW170823	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	$65.4^{+10.1}_{-7.4}$	$0.72^{+0.09}_{-0.12}$	$3.3^{+1.0}_{-0.9}$	$3.6^{+0.7}_{-1.1}\times10^{56}$	1940^{+970}_{-900}	$0.35^{+0.15}_{-0.15}$	1666

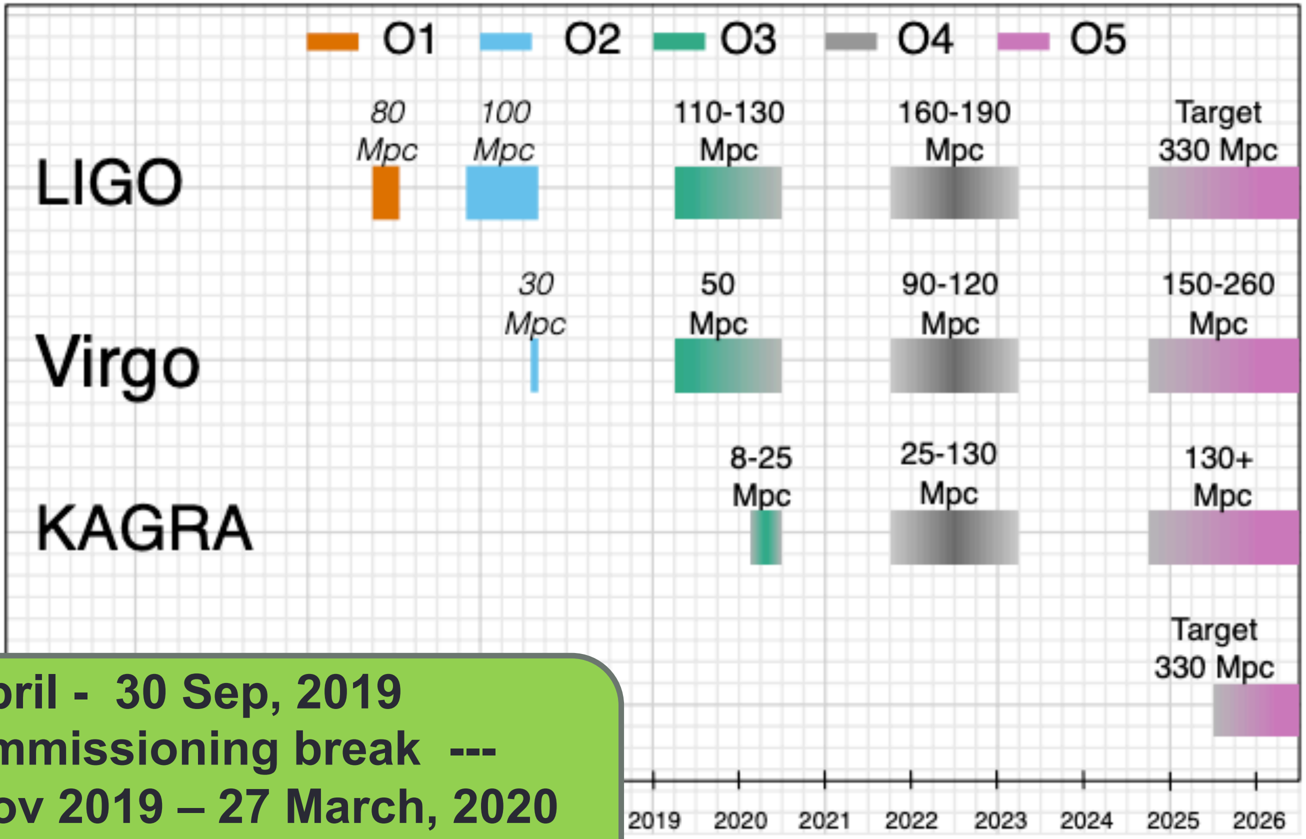


10 BH-BH
$z = 0.07 - 0.49$
$M_{1,2} = 8 - 50\ M_\odot$
$M_{tot} = 18 - 80\ M_\odot$

1 NS-NS
$z = 0.001$
$M_{1,2} = 1.27 – 1.19\ M_\odot$
$M_{tot} < 2.8\ M_\odot$

Data and sw tools available at
https://www.gw-openscience.org/about/

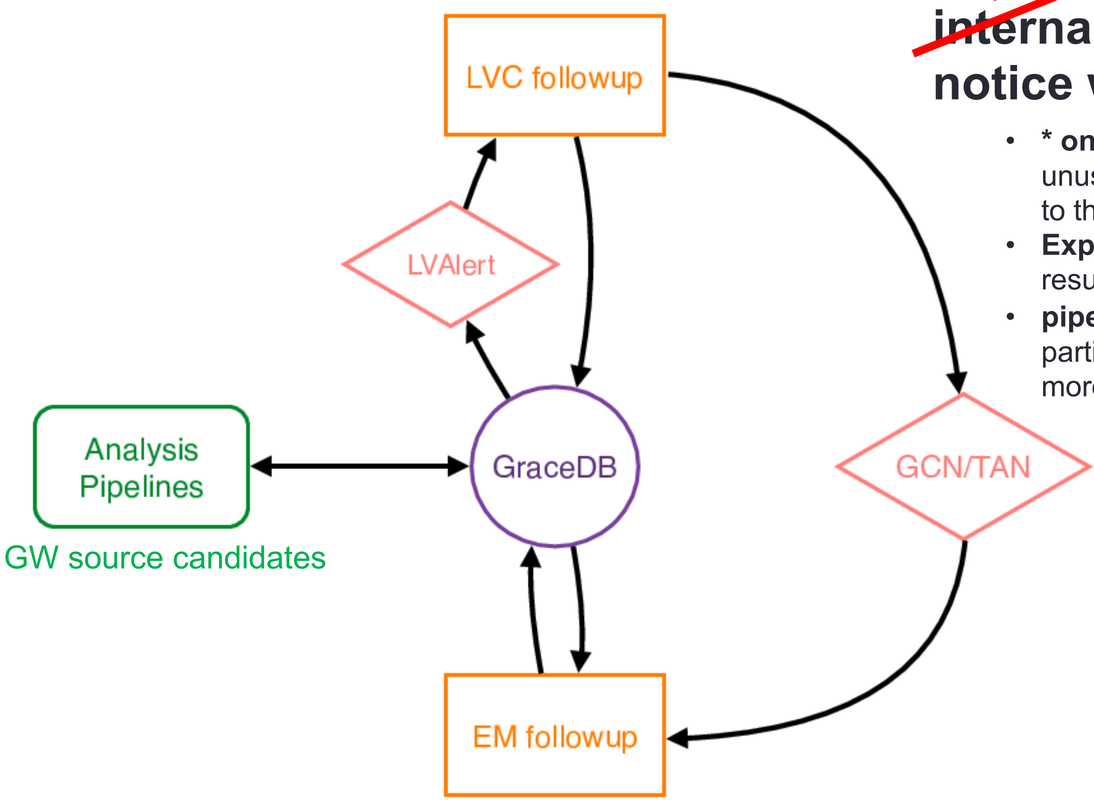
The third observing run O3



O3a: 1 April - 30 Sep, 2019
-- commissioning break ---
O3b: 1 Nov 2019 – 27 March, 2020
-- COVID-19 pandemic --
O3c: ??

O3: automatic and public alerts

https://gracedb.ligo.org/documentation/general.html



~~internal~~ public (LVC) "preliminary" notice without human vetting*

- * **on-site operators** check detector status <1min for unusual events (thunderstorms, trucks driving close to the buildings, etc.)
- **Experts and on-duty advocates** check authomatic results and data quality for validation (<15-30 min)
- **pipeline experts** check pipeline results, in particular the significance of marginal triggers or more candidate events close in time

Alerts to ~~MoU~~ public partners

*

The Astrophysical Journal, 875:161 (20pp), 2019 April 20
https://doi.org/10.3847/1538-4357/ab0e8f
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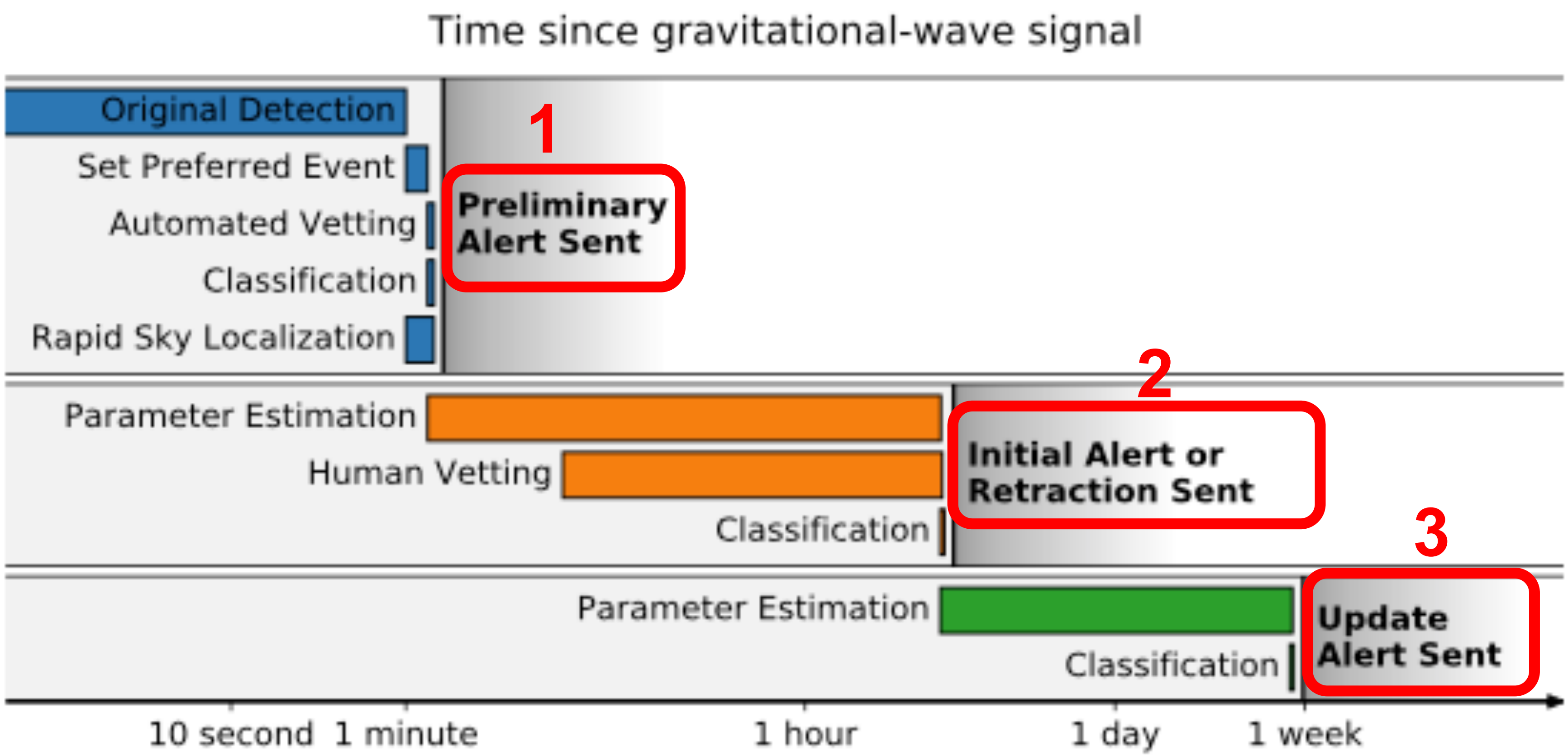
Low-latency Gravitational-wave Alerts for Multimessenger Astronomy during the Second Advanced LIGO and Virgo Observing Run

O3: automatic and public alerts

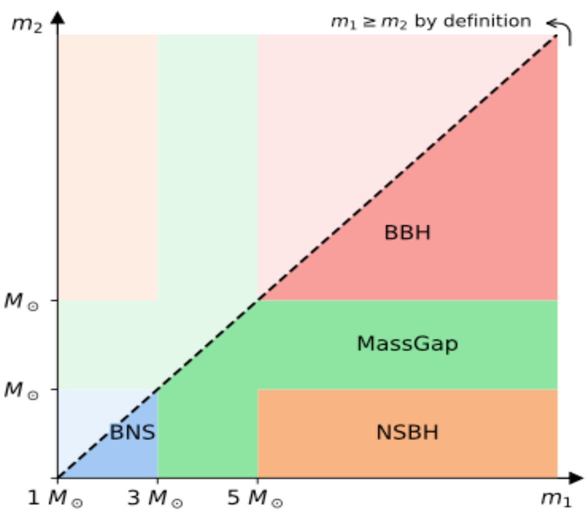
3 types of alerts are sent with different latencies



Abbott+2020, arXiv:1304.0670v10

O3: CBC signal identifier

- The probability that a Compact Binary Coalescence (CBC) is of astrophysical origin (i.e. not noise – "terrestrial") and it belongs to one of 4 astrophysical class

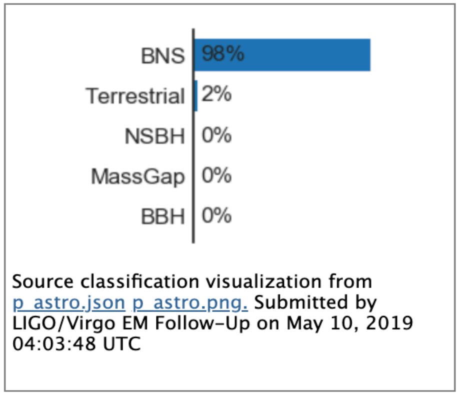


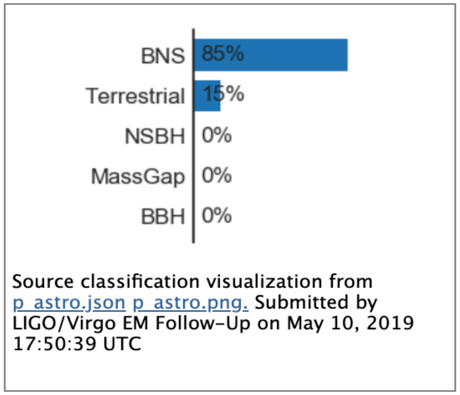
Abbott+2020, arXiv:1304.0670v10

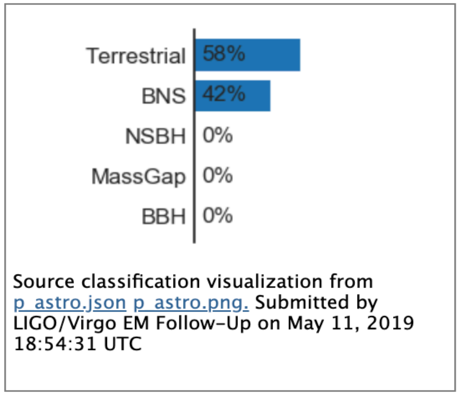
BNS: both component masses <3 $M_\odot$
BBH: both component mass > 5 $M_\odot$
NSBH: one component mass < 3 $M_\odot$ and the other > 5 $M_\odot$
Mass Gap: 3 $M_\odot$ < one component mass < 5 $M_\odot$

classification can change in time as more sophisticated data analysis algorithms are applied

https://gracedb.ligo.org/superevents/S190510g/view/







Example: identifier probability for the BNS candidate s190510g

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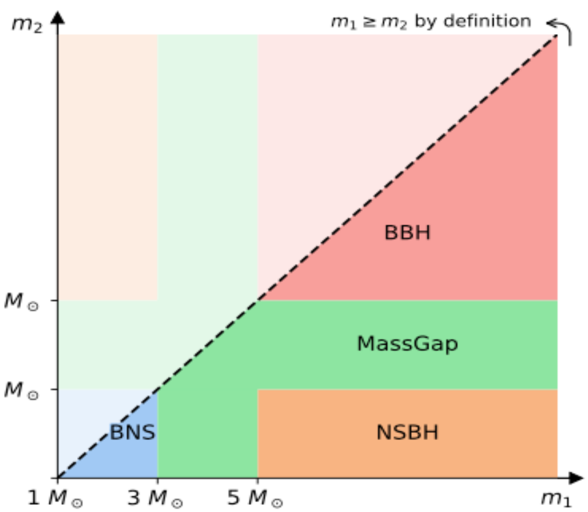
Abbott+2020, arXiv:1304.0670v10



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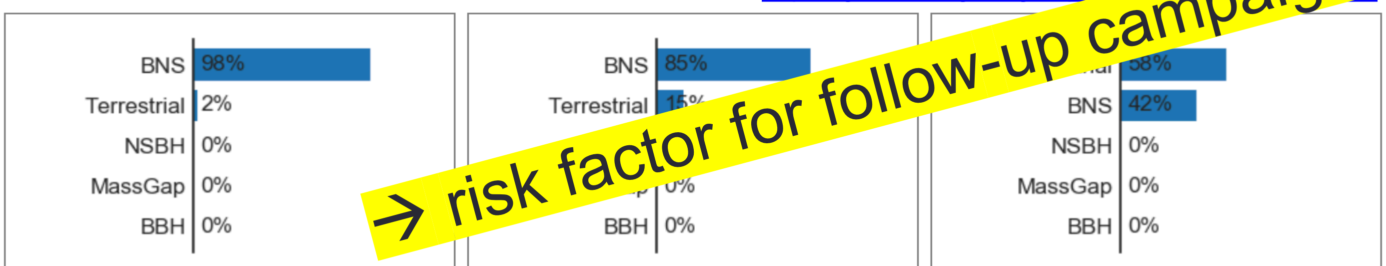
https://gracedb.ligo.org/superev...

→ risk factor for follow-up campaigns!



Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on May 10, 2019 04:03:48 UTC

Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on May 10, 2019 17:50:39 UTC

Source classification visualization from p_astro.json p_astro.png. Submitted by LIGO/Virgo EM Follow-Up on May 11, 2019 18:54:31 UTC

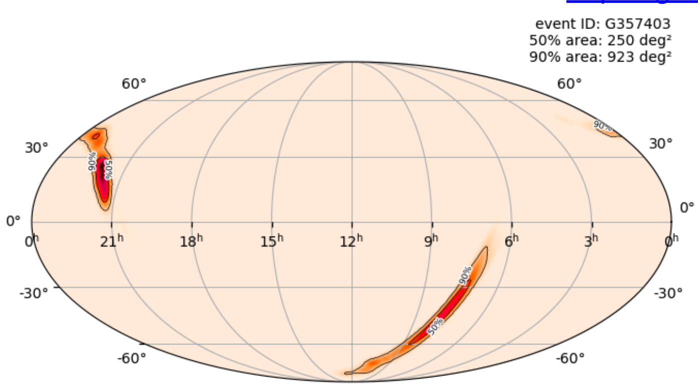
Example: identifier probability for the BNS candidate s190510g

GW source sky localisations

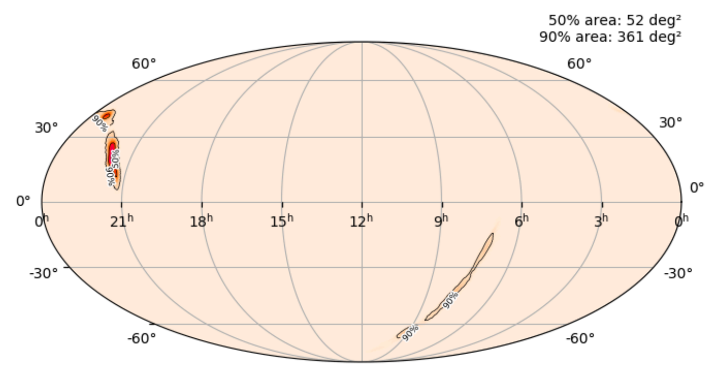
- ~~Sky coordinates~~ → All-sky probability surface density distribution of the source's sky position («Skymap»)

Skymap are generated with different methods that require different computational times

Example of two skymaps for the same event
(BBH candidate S191215w)
https://gracedb.ligo.org/superevents/S191215w/view/



BAYESTAR (923 deg^2 at 90%)
T0+15 min



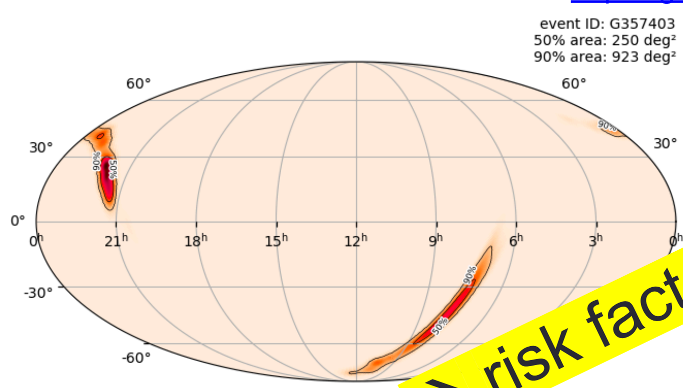
LALINFERENCE (361 deg^2 at 90%)
T0+4.5 days

GW source sky localisations

- ~~Sky coordinates~~ → All-sky probability surface density distribution of the source's sky position («Skymap»)

Skymap are generated with different methods that require different computational times

Example of two skymaps for the same event
(BBH candidate S191215w)
https://gracedb.ligo.org/superevents/S191215w/vi



BAYESTAR (923 deg^2 at 90%)
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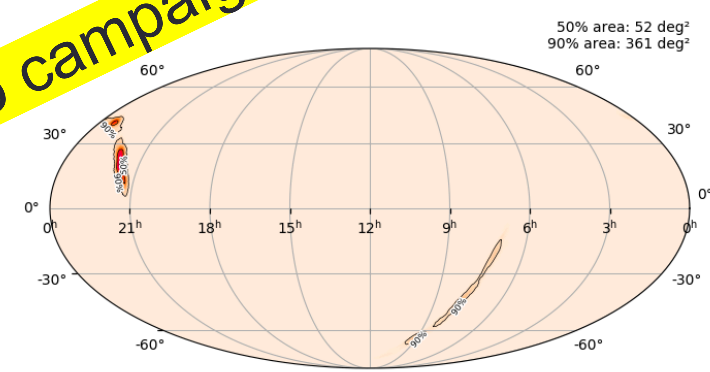
→ risk factor for follow-up campaigns!



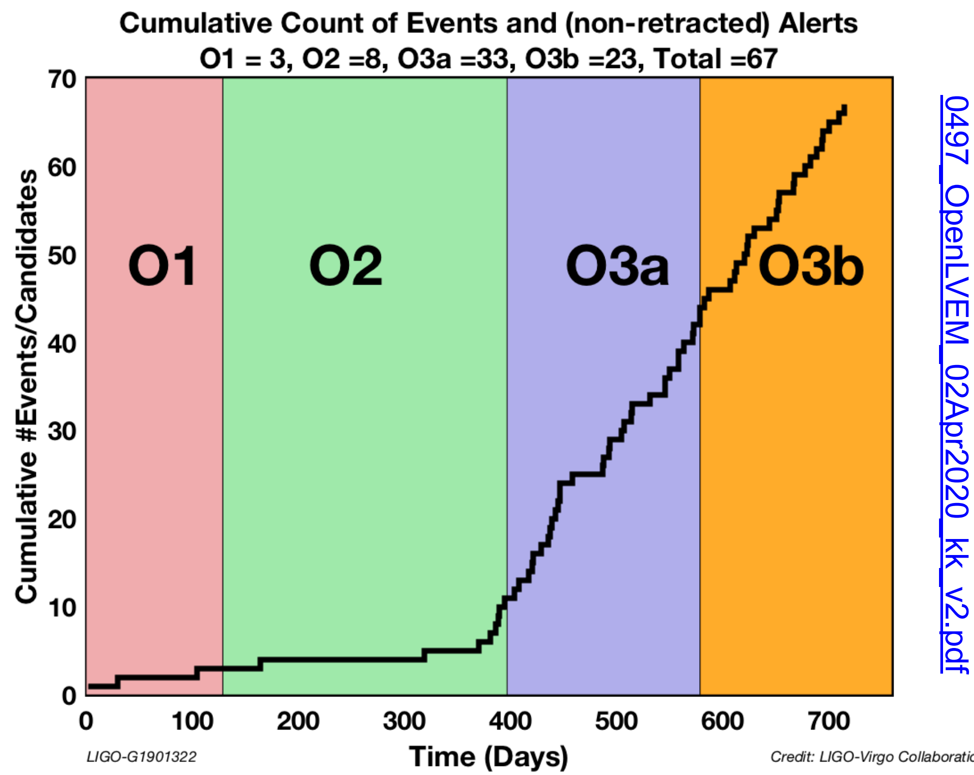
LALINFERENCE (361 deg^2 at 90%)
T0+4.5 days

O3: GW source candidates

O3: GW source candidates

- O3: ~11 months
- **56 GW source candidates** → ~5 times the O1+O2 sources
  - 7 BNS
  - 5 NSBH
  - 37 BBH
  - 4 Mass Gap
- Off-line analysis still on-going to confirm candidates and classification or retract them

PRELIMINAR*



https://dcc.ligo.org/public/0167/G2000497/002/G2000497_OpenLVEM_02Apr2020_kk_v2.pdf

* from: https://gracedb.ligo.org/superevents/public/O3/
based only on:
- FAR threshold 0.5/month
- on-line classification

O3: GW source candidates

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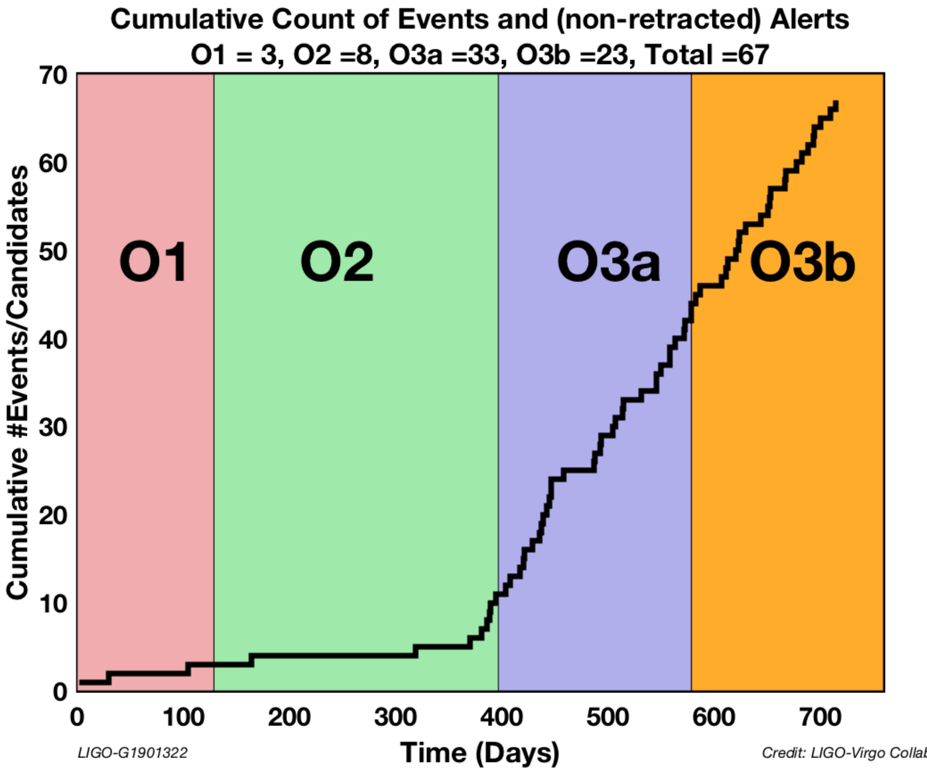

https://dcc.ligo.org/public/0167/G2000497/002/G2000497_OpenLVEM_02Apr2020_kk_v2.pdf

So far only two GW sources have been confirmed (i.e. published): GW190425 (BNS) and GW190412 (BBH) arXiv:2004.08342

GW 190425

The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20 https://doi.org/10.3847/2041-8213/ab75f5
© 2020. The Author(s). Published by the American Astronomical Society.
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GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_{\odot}$

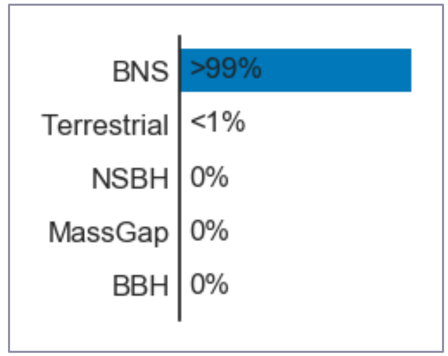
B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], S. Abraham[3], F. Acernese[4,5], K. Ackley[6], C. Adams[7], R. X. Adhikari[1], V. B. Adya[8],

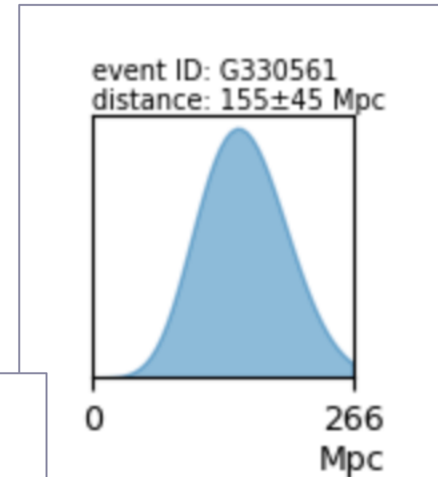
Abbott, B P et al. ApJL 892, L3, 2020

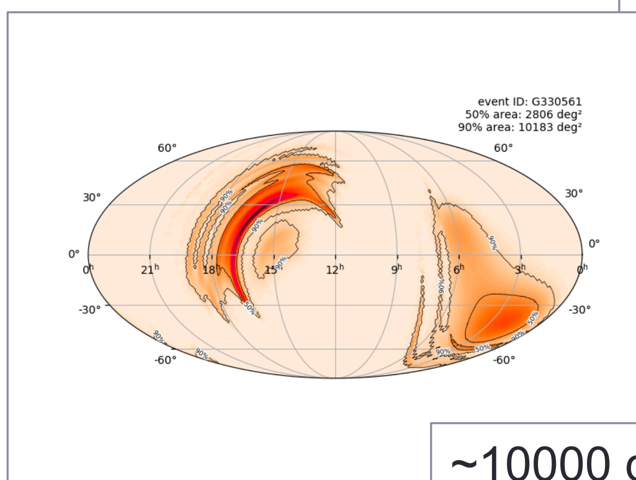
Preliminary online classification of GW190425 is NS-NS merger
→e.m. counterpart is expected!

...But 3 challenging factors:

- DL~160 Mpc → much farther than GW170817 (40 Mpc)
- Discovered with
  - LIGO-L: SNR=12.9
  - LIGO-H: offline
  - Virgo: SNR=2.5
- → very coarse localisation
- no high-energy counterpart was found (i.e. a coincident GRB)







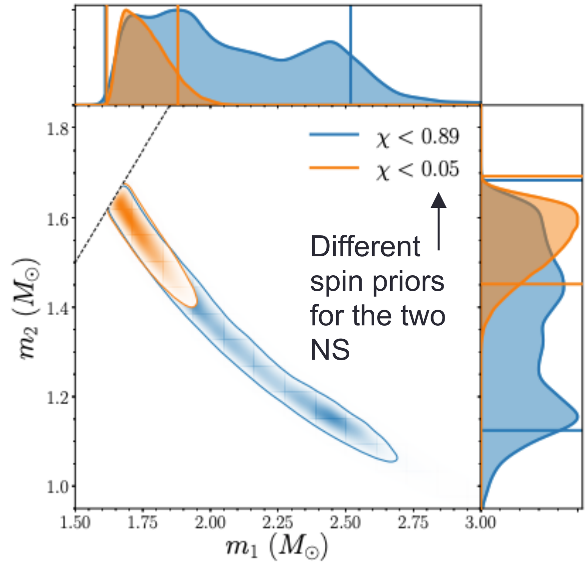
~10000 deg^2 at 90%
~3000 deg^2 at 50%

https://gracedb.ligo.org/superevents/S190425z/view/

GW 190425

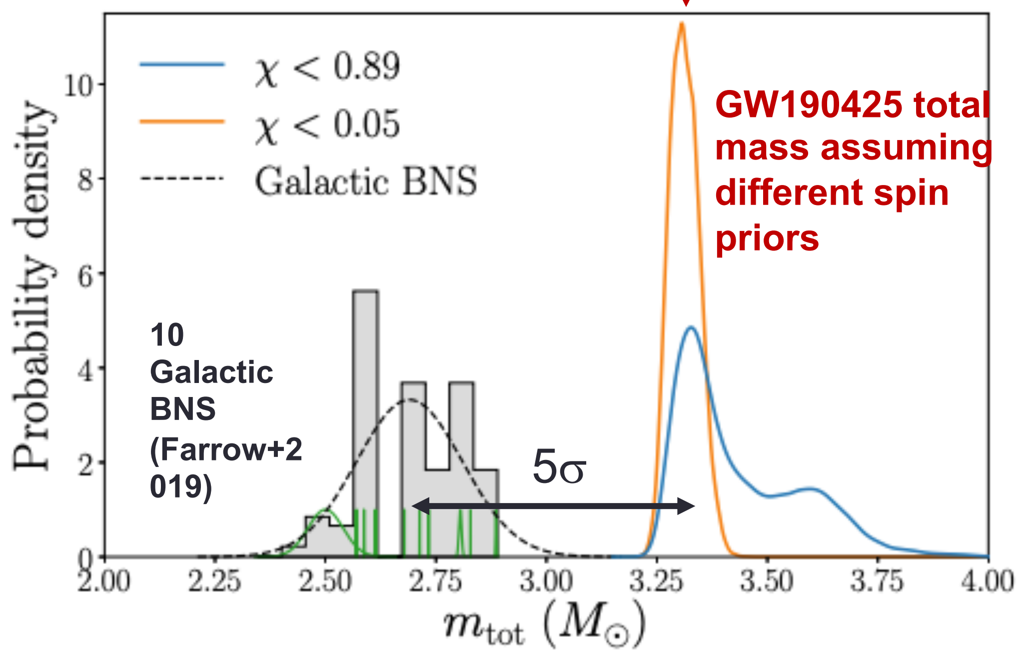
Abbott, B P et al. ApJL 892, L3, 2020

- Binary component masses are consistent with NS
- M_{tot} → inconsistent with respect to the total mass of Galactic BNS expected to merger within a Hubble time
  - Possible bias in Galactic PSR radio surveys against massive BNS
    - expected to merge in <10 Myr
    - massive NS may have weaker magnetic fields?
- Heavy NS-NS systems possible formation origins:
  - Dynamical encounter (can select heavier NS)
  - Low metallicity stars in isolated binaries



$m_1 = 1.61 - 2.52\ M_\odot$
$m_2 = 1.12 – 1.68\ M_\odot$

$M_{tot} = 3.2-3.7\ M_\odot$



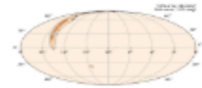
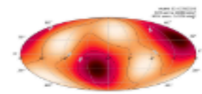
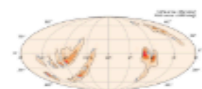
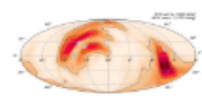
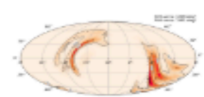
O3 – NS-NS candidates

- 6 additional BNS candidates with lower confidence level

https://gracedb.ligo.org/superevents/public/O3/

- still under analysis...

follow-up campaign (see 2nd part by Andrea)

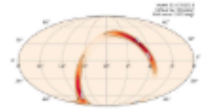
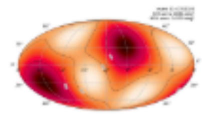
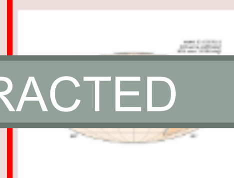
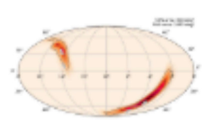
	Event	Classification	Skymap	GW skymap Area at 90%
follow-up	S190426c	BNS (49%), MassGap (24%), Terrestrial (14%), NSBH (13%)		1131 deg^2
	S190910h	BNS (61%), Terrestrial (39%)		>24000 deg^2
	S200213t	BNS (63%), Terrestrial (37%)		2587 deg^2
	RETRACTED	(25%)		
follow-up	S191213g	BNS (77%), Terrestrial (23%)		4480 deg^2
follow-up	S190901ap	BNS (86%), Terrestrial (14%)		14753 deg^2
follow-up	S190425z	BNS (>99%)		7461 deg^2
follow-up	S190510g	Terrestrial (58%), BNS (42%)		1166 deg^2

O3 – NS-BH candidates

- 5 candidates so far

- **S190814bv** largest probability (>99%)
  - DL~240 Mpc
  - S/N=25 (3 detector network)
  - LVC publication in preparation...
  - → very precise localisation

Massive follow-up campaign! (see 2nd part by Andrea)

Event	Classification	Skymap	GW skymap Area at 90%
S190923y	NSBH (68%), Terrestrial (32%)		2107 deg^2
S190930t	NSBH (74%), Terrestrial (26%)		>24000 deg^2
RETRACTED	NSBH (83%), ... (17%)		
RETRACTED	NSBH (85%), ... (15%)		
S191205ah	NSBH (93%), Terrestrial (7%)		6378 deg^2
S190910d	NSBH (98%), Terrestrial (2%)		2482 deg^2
S190814bv	NSBH (>99%)		23 deg^2

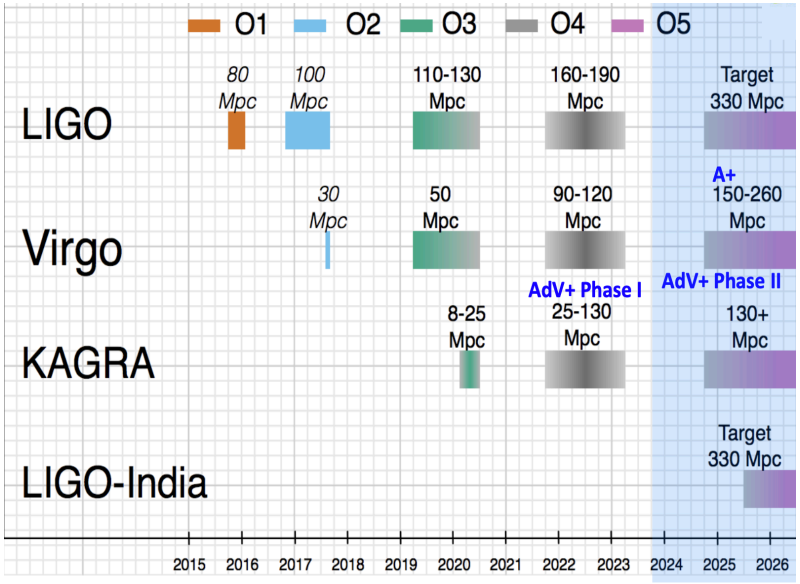
https://gracedb.ligo.org/superevents/public/O3/

Future perspectives: GW detectors

- O4 → fall 2021 ?:
  - Advanced Virgo+ (Phase I)
- O5 → end 2024:
  - Advanced Virgo+ (Phase II)
  - LIGO A+
  - LIGO-India (+2025)

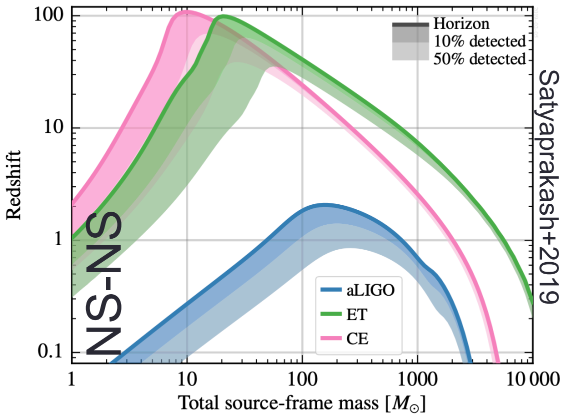
LRR, arXiv:1304.0670v10

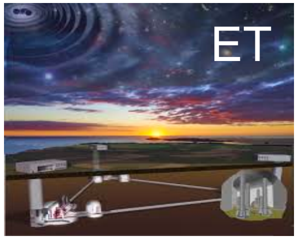
Credit: Branchesi



\>2030 → 3rd generation → ~ O(10^5) NS-NS!

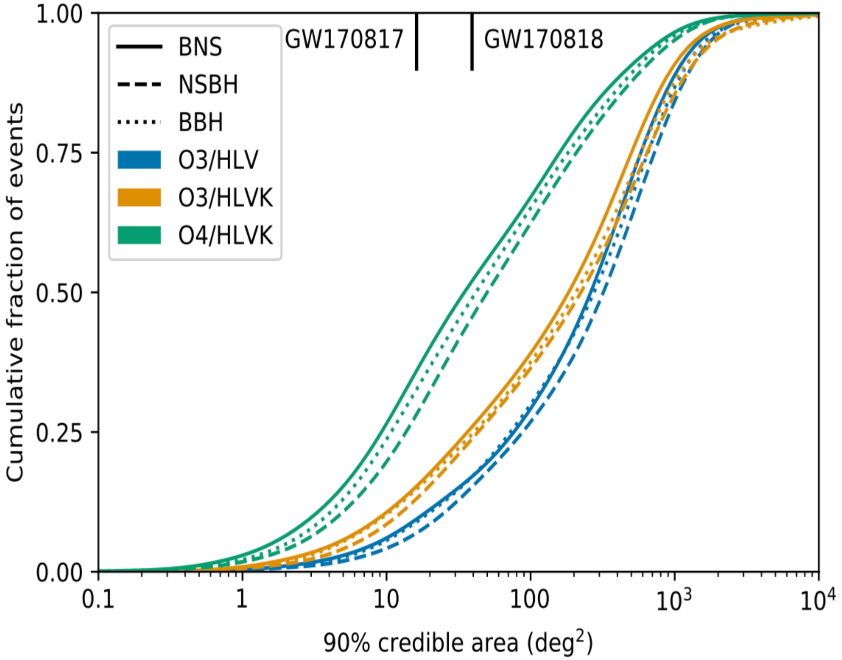
- Two main projects so far:
  - Einstein Telescope (EU)
  - Cosmic Explorer (USA)



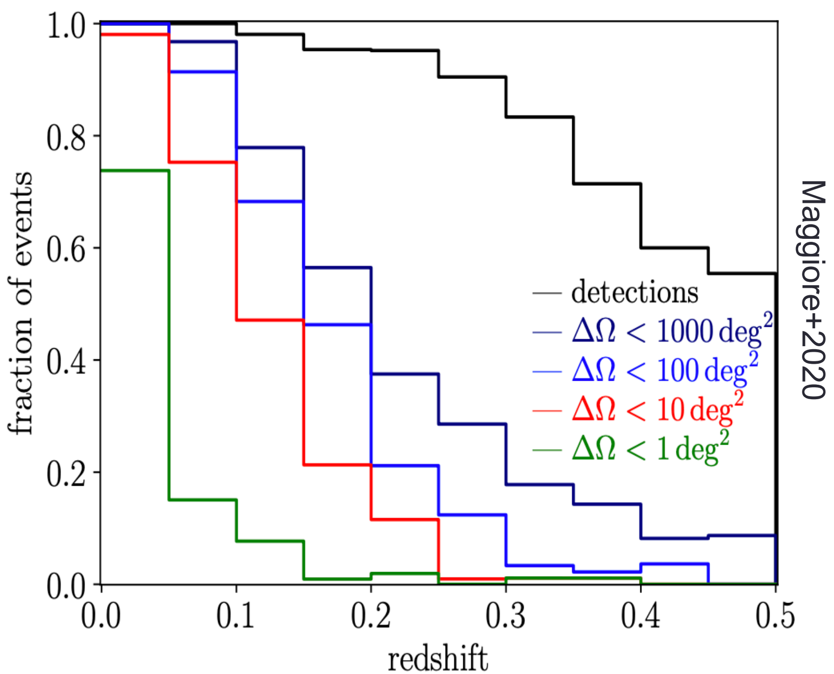


Future perspectives: GW sources sky localization accuracy

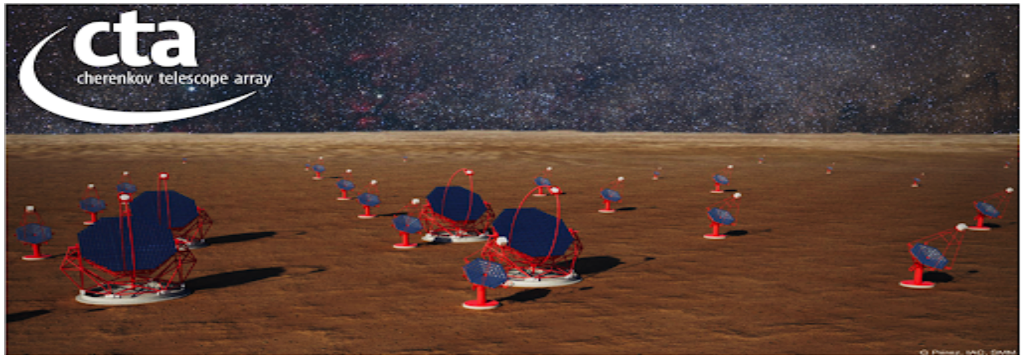
LRR, arXiv:1304.0670v10 2G

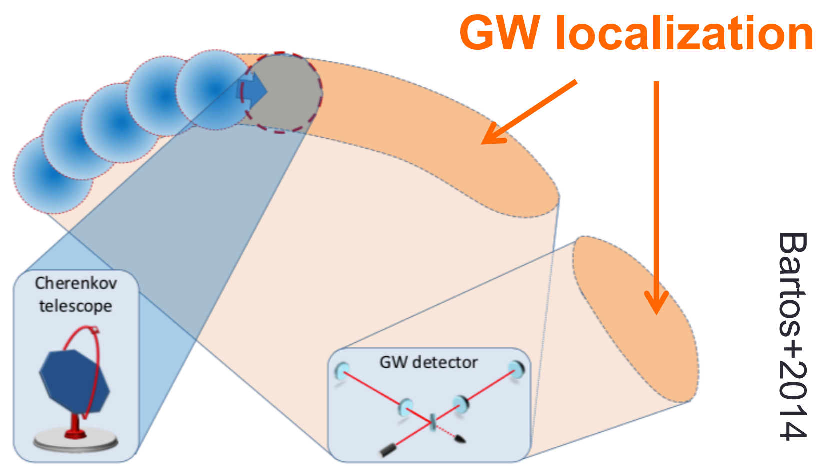


ET+2G



- Both with 2G and 3G, the bulk of GW sources will have localization >> deg^2
- **Electromagnetic counterpart searches → large FoV and fast reacting facilities**





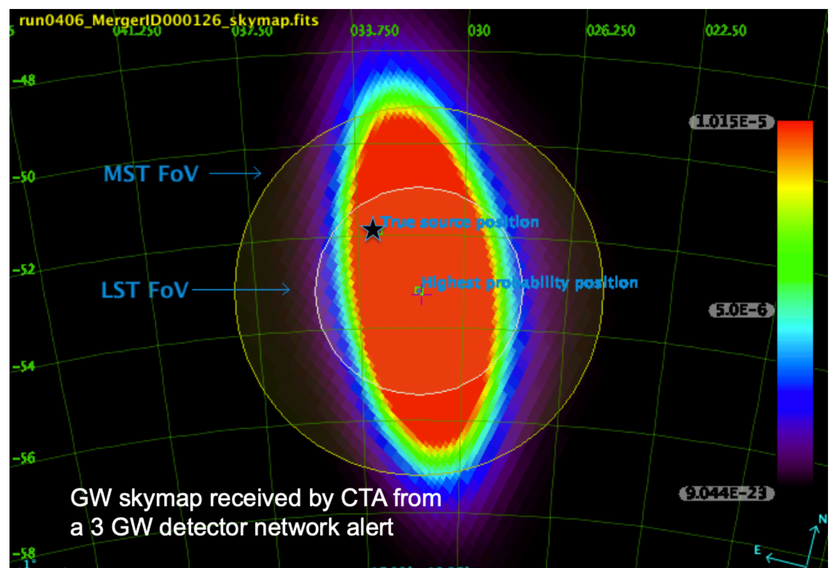
Bartos+2014

- **CTA** is the next gen. of Imaging Atmospheric Cherenkov Telescopes, ~10x more sensitive (20 GeV-300 TeV)→ will be completed by ~2025
  - large FoV (tens of deg^2)
  - arcmin source localization
  - fast pointing capabilities (<30s)

- **CTA will follow-up GW sources and/or localize short GRBs**

CTA activities @ OAS:

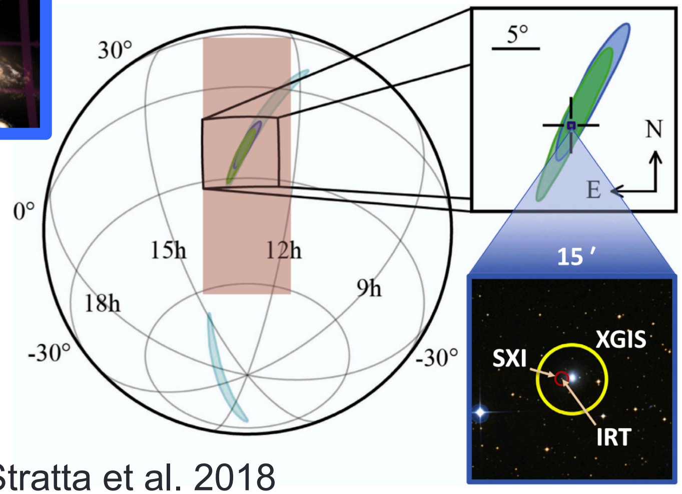
- Simulations of short GRB observations and blind searches in large sky regions
- Development of Real Time Analysis
- CTA sensitivity for transient sources



Stratta+2019, poster presented at CTA Symposium

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

- ESA mission project in competition with 2 others projects (ENVISION and SPICA)
- → if selected for phase B (mid 2021), launch date is 2032
  - huge FoV → T. will detect the e.m. counterparts of GW sources
  - sky localization accuracy of arcmin/arcsec level
  - fast communication of sky coordinates

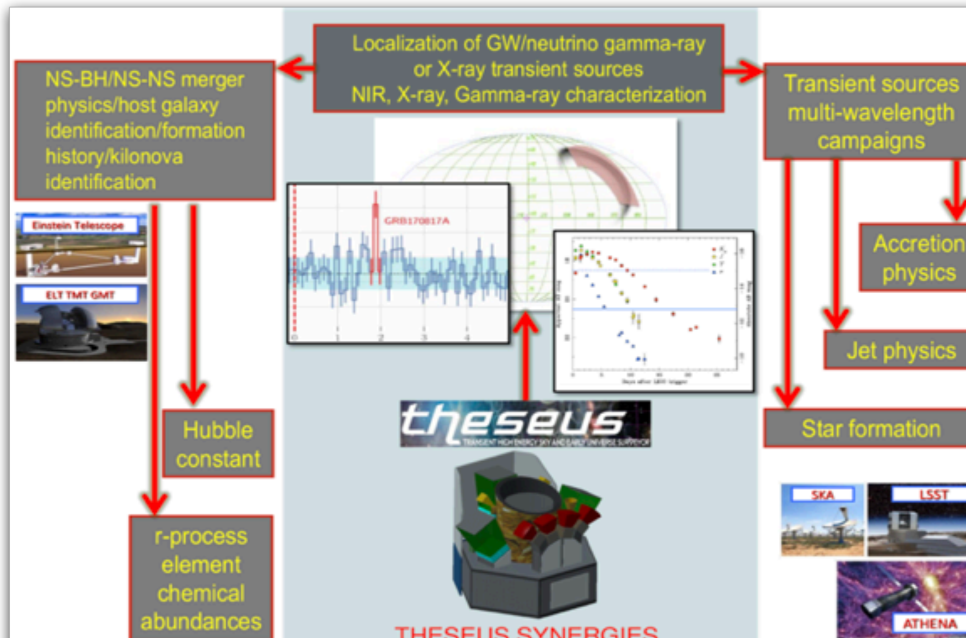


Stratta et al. 2018

- **Theseus will optimize the synergies between GW interferometers and excellent facilities, e.g.**
  - **E-ELT**
  - **Athena**
  - **SKA**

Theseus activities @ OAS

- PI-ship X-ray and Gamma-ray Imager and Spectrometer (XGIS) detector
- Membership to ESA Science Study Team



https://www.isdc.unige.ch/theseus/

Summary (1st part)

- O3: the era of public and fast alerts
- 56 GW source candidates, 2 GW sources have been confirmed →GW data analysis still ongoing and several new publications are in preparation...
- fast reacting + large FoV e.m. facilities will be mandatory even with full 5 detector network and with 3G detectors in order to find the e.m. counterparts

Extra slides

Future perspectives with 2G

LRR, arXiv:1304.0670v10

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}

		Area ($\deg^2$) 90% c.r.	Area ($\deg^2$) 90% c.r.	Area ($\deg^2$) 90% c.r.
O3	HLV	270^{+34}_{-20}	330^{+24}_{-31}	280^{+30}_{-23}
O4	HLVK	33^{+5}_{-5}	50^{+8}_{-8}	41^{+7}_{-6}

Only a small fraction will be detected as short GRBs
→ expected low rate of short GRB + GW (<1/yr)

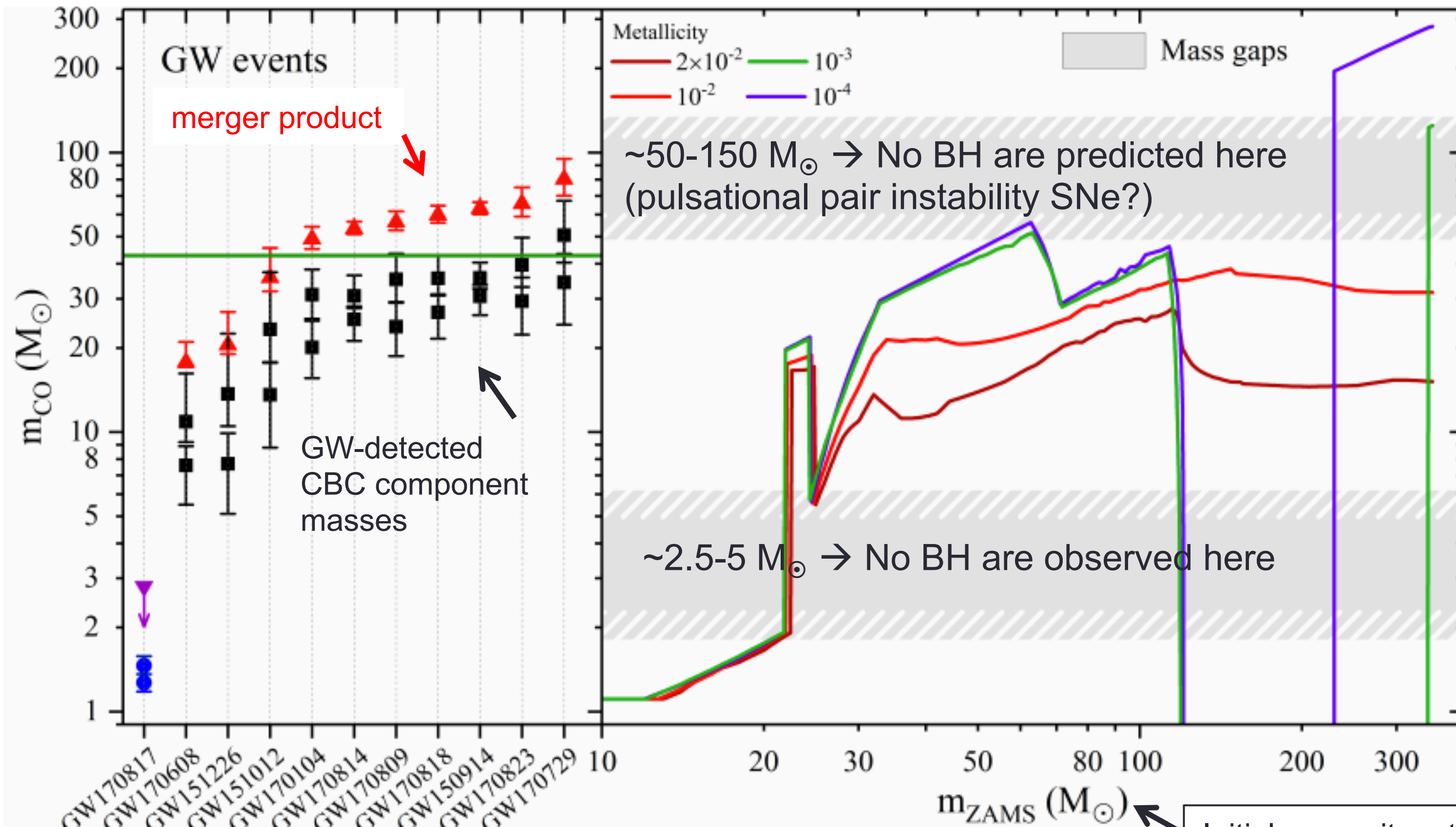
From LVC open call on 15-11-2018

Detection rates in O3

- Binary neutron stars (BNS)
  - 1/month to 1/year
  - Median 90% credible localization 120-180 deg^2; 12-21% localized < 20 deg^2
- Binary black holes (BBH)
  - few/week to few/month
- Neutron-star black-hole binaries (NSBH)
  - Uncertain, estimates include zero
- Other transients
  - Unknown
- **LIGO-Virgo target contamination of public alerts**
  - **Contamination ~10% of public alerts across all categories together**
  - **BNS, NSBH & other transients may individually have higher contamination**

LSC LIGO Scientific Collaboration 3 VIRGO

BH mass from stellar evolution theory



Initial progenitor star mass

Abbott et al. 2018 arxiv:1811.12940

LIGO/Virgo observations are biased towards high BH masses due to larger volumetric sensitivity

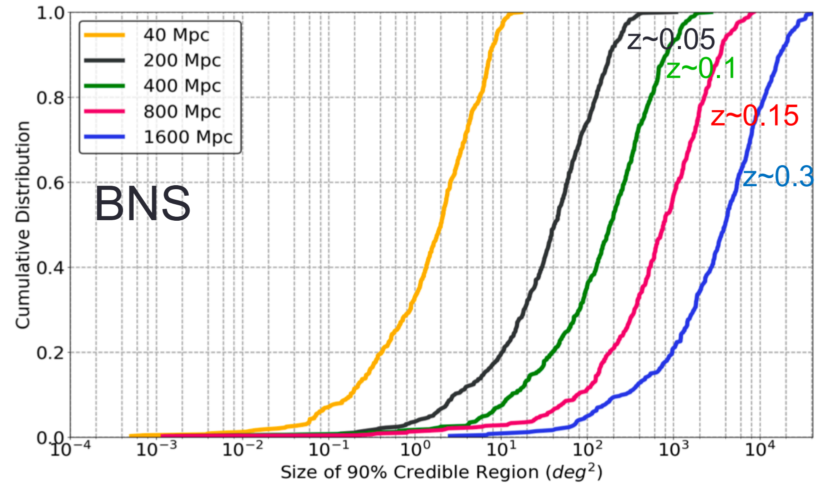
GW source sky localization with 3G

u.l. on the size of error box

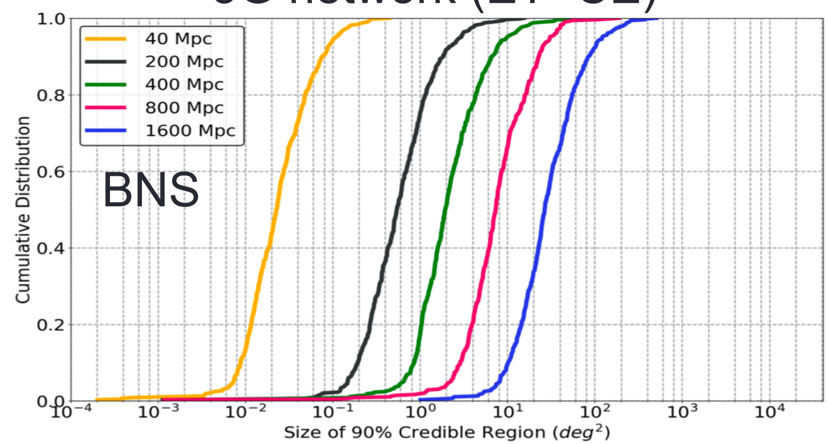
Network	d (Mpc)	n	50% (deg^2)	90% (deg^2)	≤ 100 (deg^2)	≤ 30 (deg^2)
ET	40	500	2	8	100%	100%
	200		42	183	74%	40%
	400		187	837	36%	16%
	800		764	3485	11%	5%
	1600		3994	1.7×10^4	5%	2%
	Uniform [1]	3000	1.7×10^4	> Sky	3%	2%
CE	40	500	252	2212	30%	10%
	200		6118	> Sky	1%	0%
	400		2.6×10^4	> Sky	0%	0%
	800		> Sky	> Sky	0%	0%
	1600		> Sky	> Sky	0%	0%
	Uniform [1]	5000	> Sky	> Sky	0%	0%
ET & CE	40	500	2×10^{-2}	8×10^{-2}	100%	100%
	200		5×10^{-1}	1.8	100%	100%
	400		2	7	100%	99%
	800		7	23	99%	94%
	1600		27	85	92%	55%
	Uniform [1]	5000	128	538	41%	12%

[1] Uniformly distributed in the comoving volume.

3G Einstein Telescope



3G network (ET+CE)



Chan+2018, Phys. Rev. 97, 123014

“Early warning” with 3G

TABLE II: Statistical Summary of Results For Early Warning

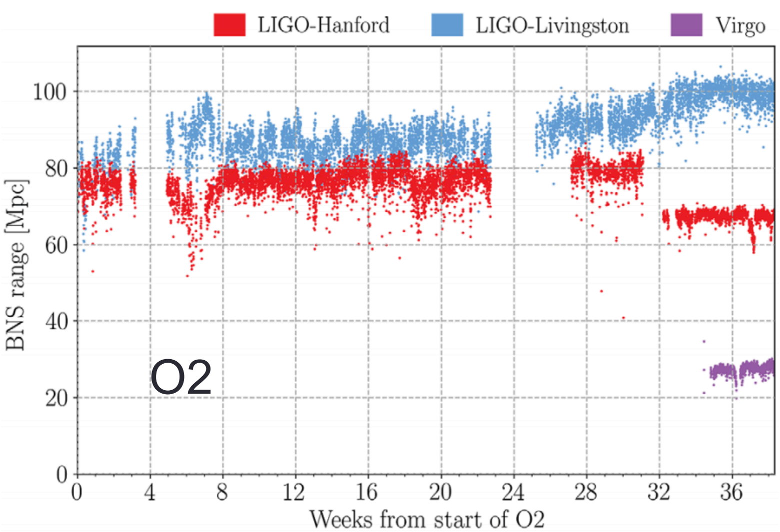
Network	d (Mpc)	n	100 sec	0.5 hrs	2 hrs	5 hrs	10 hrs
ET	40	500	100%	100%	99%	66%	18%
	200		58%	39%	13%	2%	0%
	400		28%	16%	4%	0%	0%
	800		9%	4%	0%	0%	0%
	1600		3%	1%	0%	0%	0%
	Uniform [1]	3000	2%	1%	0%	0%	0%
ET & CE	40	500	100%	100%	99%	66%	18%
	200		100%	74%	13.4%	2%	0%
	400		98%	27%	4%	0%	0%
	800		51%	4%	0%	0%	0%
	1600		5%	1%	0%	0%	0%
	Uniform [1]	5000	4%	1%	0%	0%	0%

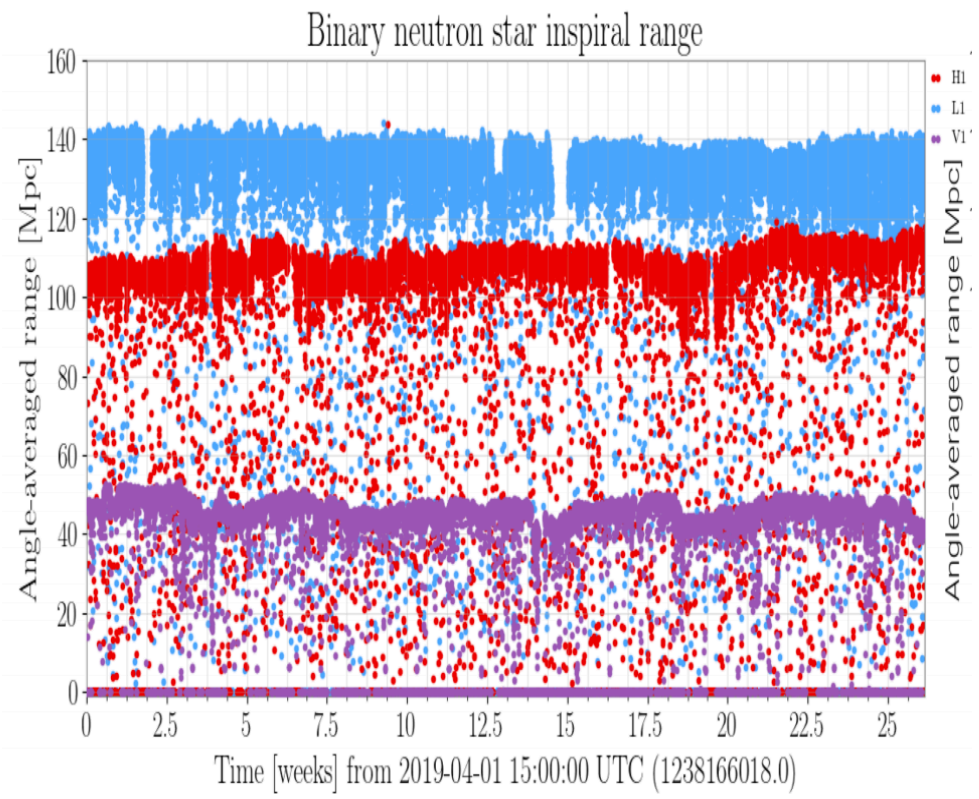
[1] Uniformly distributed in the comoving volume.

A brief statistical summary of the results for early warning. In the first row, we again use d to denote distance and n the number of injections. The third to the seventh columns indicate the fraction of detectable events that meet the early warning criteria within the corresponding times.

Chan+2018, Phys. Rev. 97, 123014

O3: increased sensitivity





B.P. Abbott et al. Physical Review 9,031040 (2019)

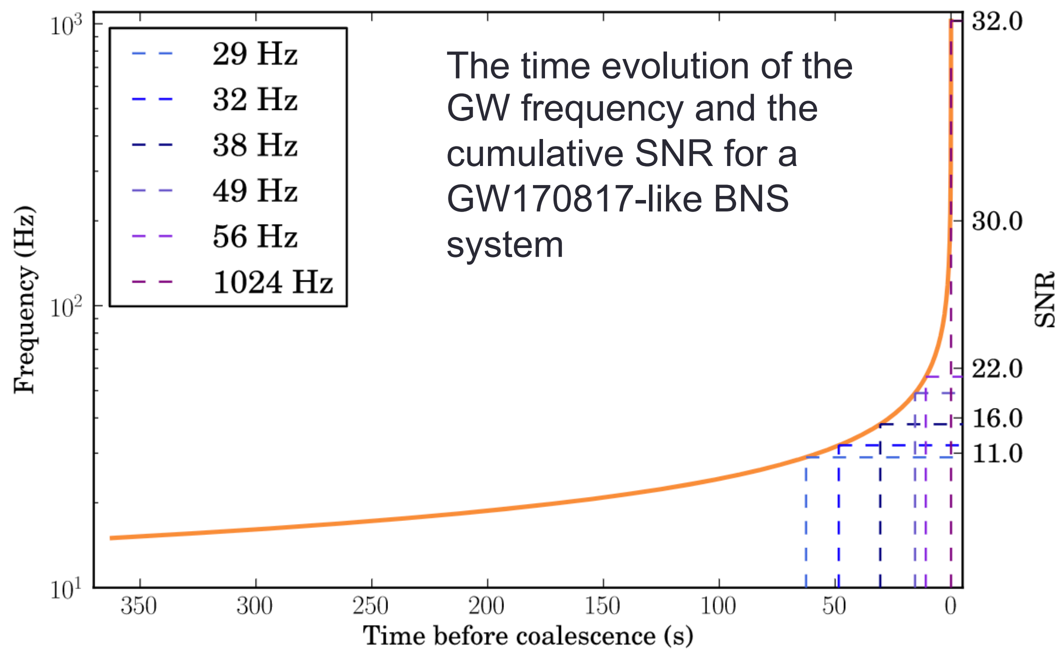
https://dcc.ligo.org/public/0167/G2000497/002/G2000497_OpenLVEM_02Apr2020_kk_v2.pdf

O3: “early warning” tests (June 2020)

- The inspiral signal of some NS-NS (the most nearby) enters in the detector frequency band with SNR>11 up to tens of sec before merger

- 10/6: 1-week test on experimental capability to produce and distribute early warning on replayed data

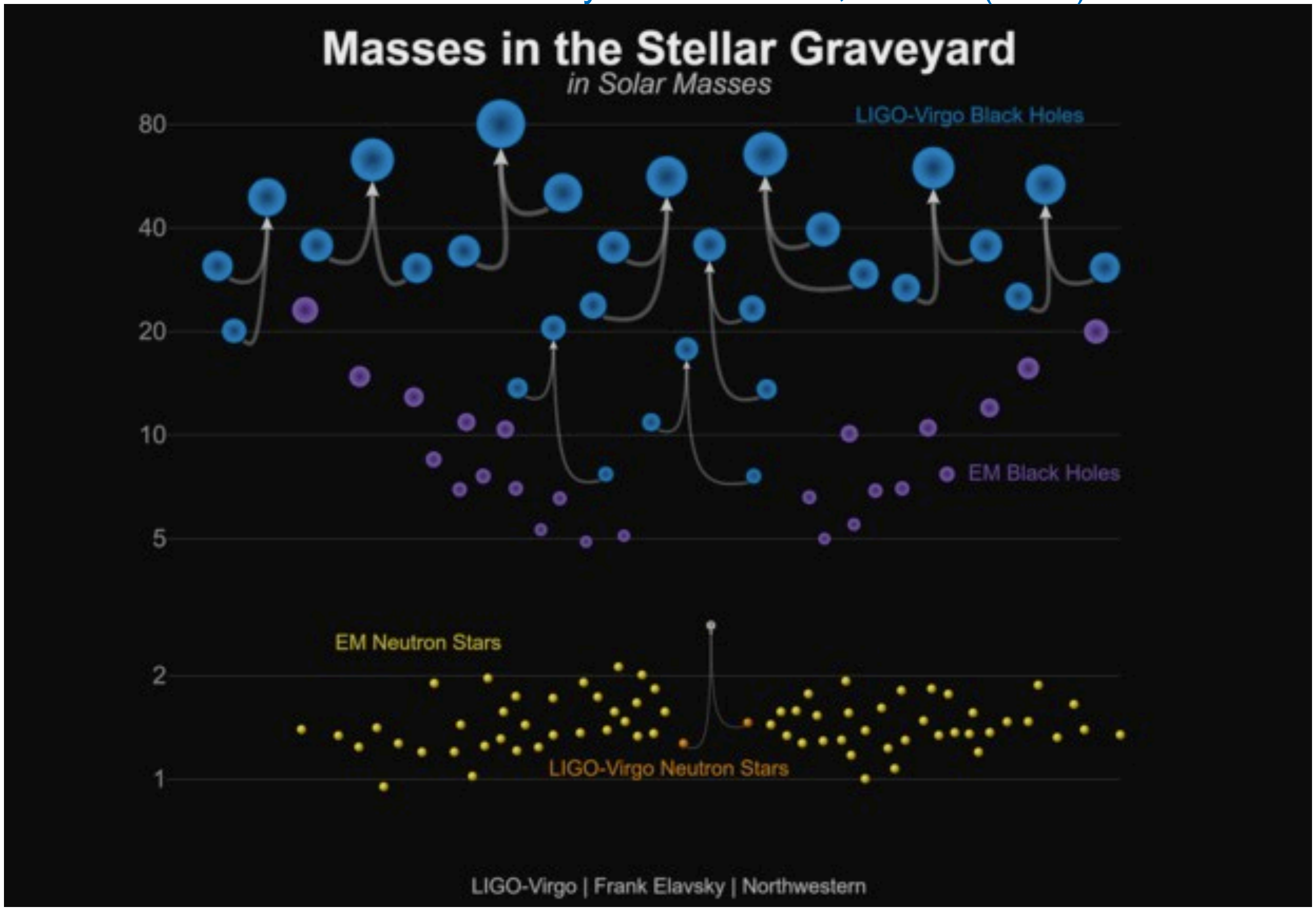
- Results ??



https://emfollow.docs.ligo.org/userguide/early_warning.html

O1+O2: The first GW catalog of compact binary mergers (GWTC-1)

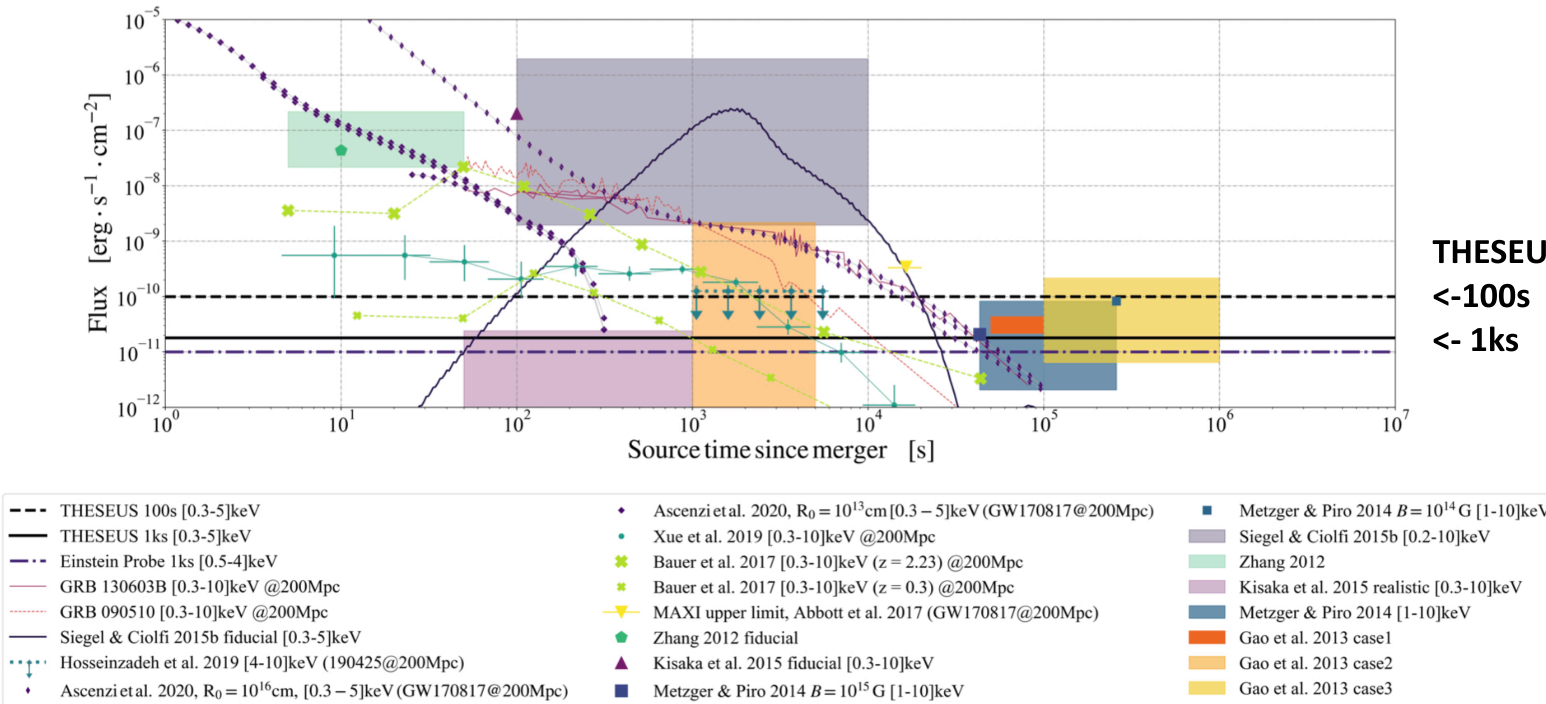
B.P. Abbott et al. Physical Review 9,031040 (2019)



https://www.ligo.caltech.edu/image/ligo20181203a

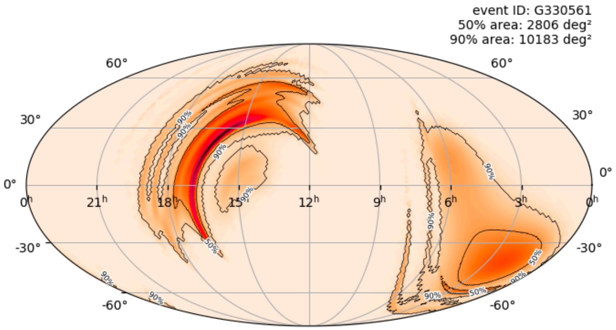
Expected X-ray emission @ 200 Mpc

Figure by S. Vinciguerra



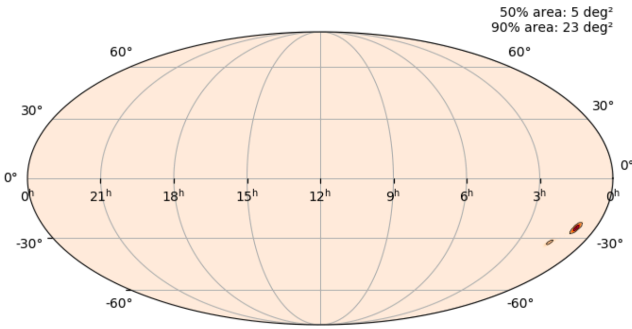
THESEUS/SXI
<-100s
<- 1ks

High energy follow-up of GW 190425 and S190814bv



GW190425 (NS-NS)

- No simultaneous detection from:
  - INTEGRAL (GCN 25323)
  - Fermi (GCN 25326, 25385)
  - AGILE (GCN 25327, 25335)
  - Swift/BAT (GCN 25341)
  - Insight/HXMT (GCN 25365)
  - Konus/Wind (GCN 25369)

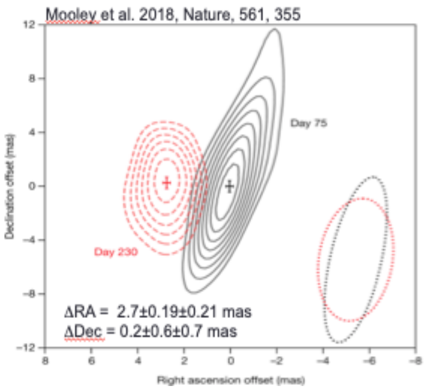


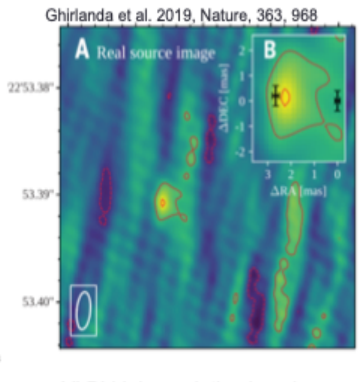
S290814bv (NS-BH)

- INTEGRAL excess?
  - ~100% coverage, SPI-ACS marginal excess at T0+6s with SNR~3.7 (Martin-Carrillo et al. 2019, GCN 24169)
- No simultaneous detection from:
  - Swift/BAT: ~ 7% coverage (GCN 24184)
  - Fermi/GBM: 55.6% coverage (GCN 24185)
  - Fermi/LAT: 37% coverage (GCN 24266)
  - Insight-HXMT/HE: 46% coverage (GCN 24213)

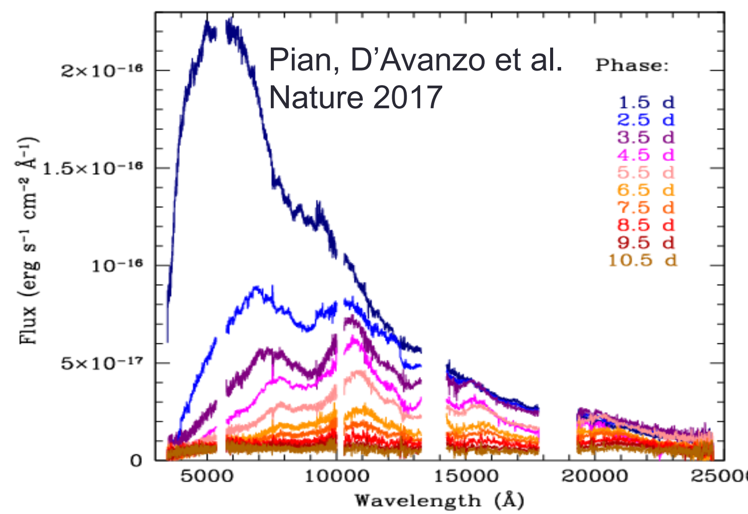
See 2nd part of the talk for the optical follow-up results...

Joint GW+EM observations: lesson learned from GW170817

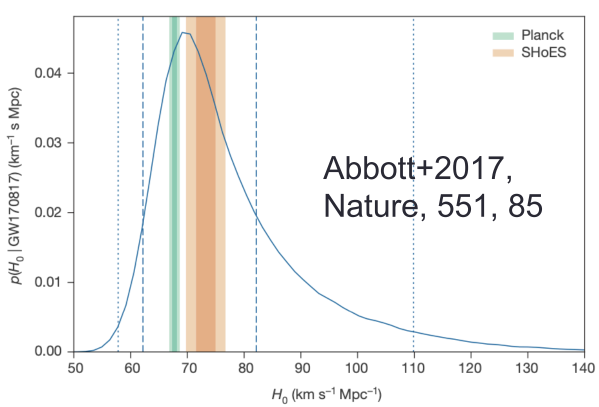




First direct evidence that NS-NS mergers can generate a **relativistic+narrow jet**



Confirmation that BNS have a crucial role for cosmic **r-process nucleosynthesis**

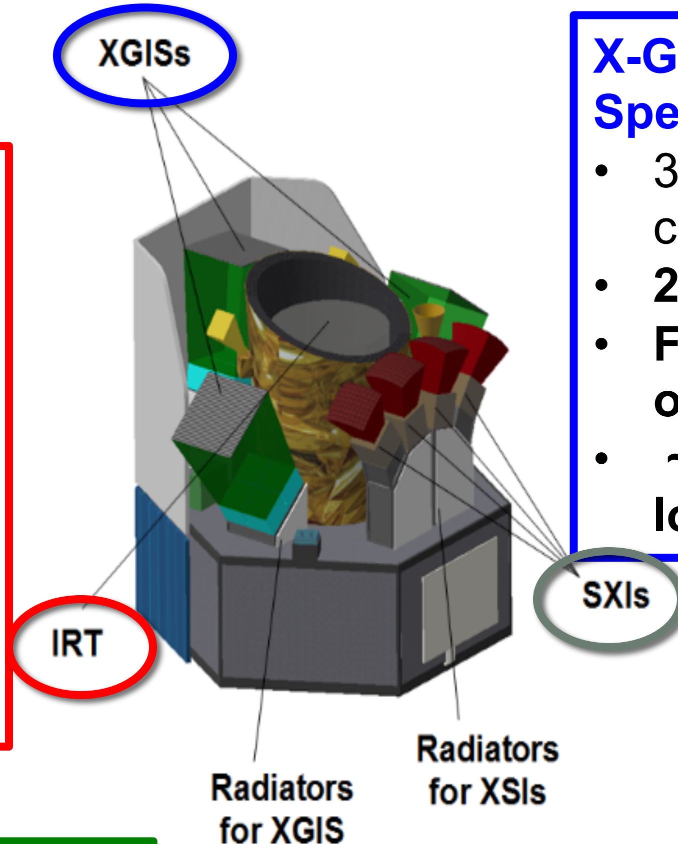


First independent measure of **H0 that can be relevant to solve the current tensions with future observations**

theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

Accepted by ESA for phase A study (planned for 2032+)

InfraRed Telescope (IRT)
- 0.7m class IR telescope
- **0.7 – 1.8 μm band**
- **10'x10' FOV**
- **Imaging + moderate resolution spectroscopy capabilities**

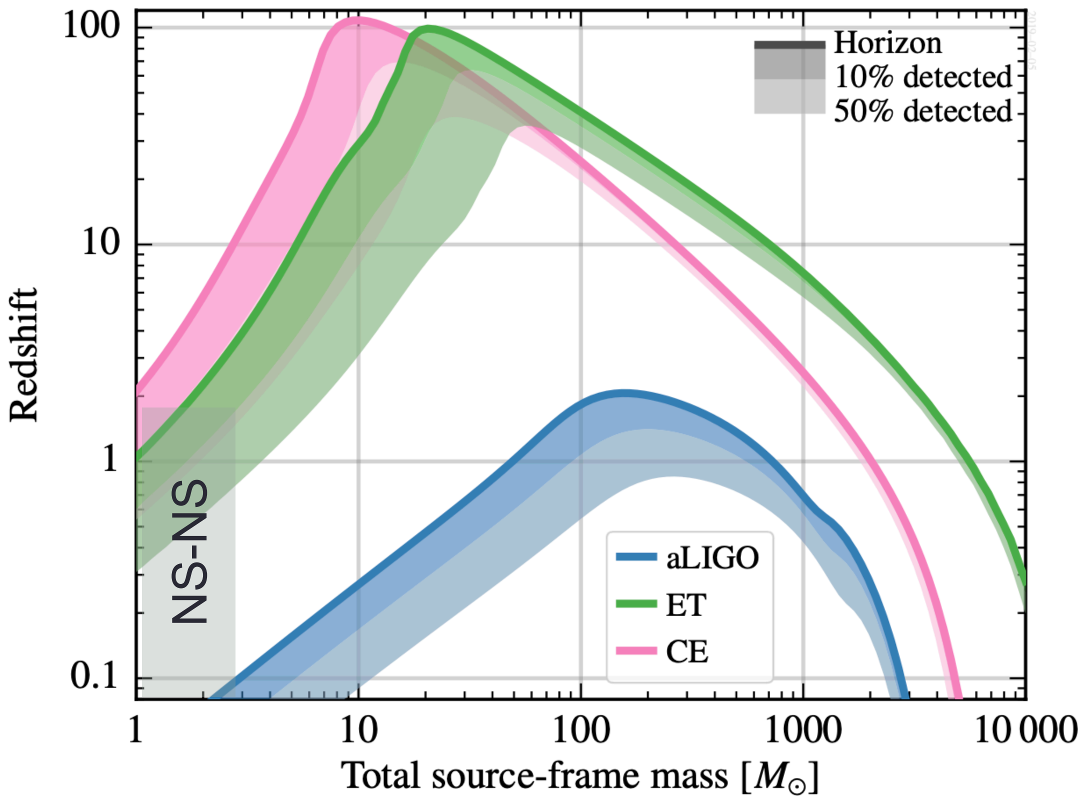


X-Gamma rays Imaging Spectrometer (XGIS)
- 3 coded-mask X-γ ray cameras
- **2 keV – 10 MeV band**
- **FOV of ~2-4 sr, overlapping the SXI,**
- **~5 arcmin source location accuracy**

Soft X-ray Imager (SXI)
- set of 4 sensitive lobster-eye telescopes
- **0.3 - 5 keV band,**
- **FOV of ~1sr**
- **0.5-1 arcmin source location accuracy**

Rapid slewing bus (>10°/min)
Prompt downlink (< 10-20s)
64% sky coverage

Future perspectives



- 2025-2030 → full network of 2G GW interferometers
- >2030 → third generation GW interferometers

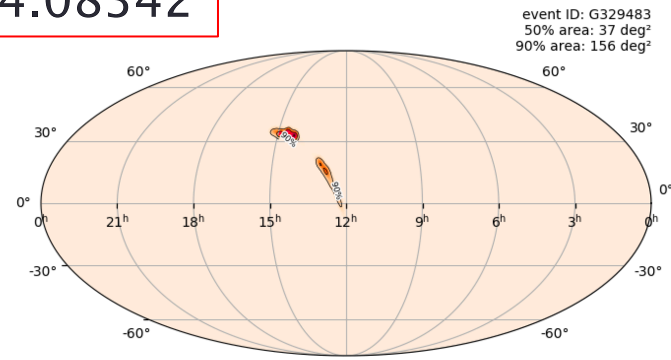
GW 190412

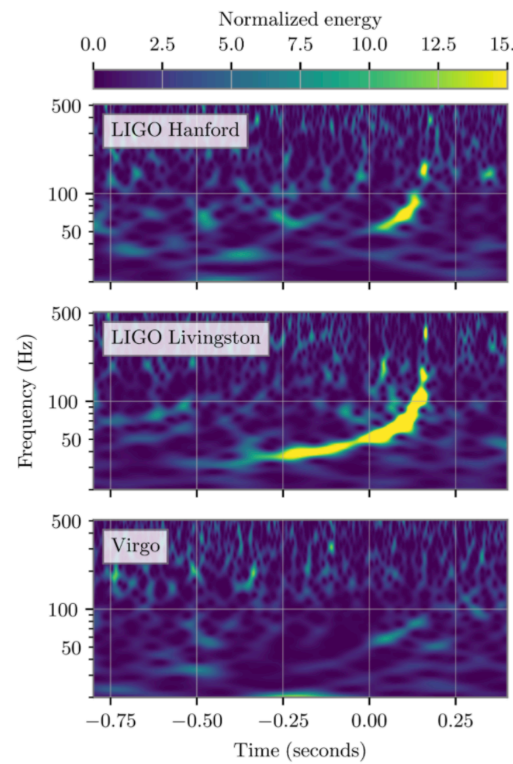
arXiv:2004.08342

- GW 190412 was a BH-BH merger at DL~735 Mpc (z~0.15)
- Discovered with
  - LIGO-L: SNR=15.6
  - LIG-H: SNR=8.6
  - Virgo: SNR=3.7

→ very good localisation (156 deg^2) but no e.m. counterpart detection so far

- **BH-BH components had very different masses far (m_1 ~ 8 $M_\odot$ m_2 ~ 30 $M_\odot$) and the most extreme mass ratio measured so**
- This asymmetry in masses modifies the GW signal and enable to better:
  - Disentangle the distance and inclination degeneracy
  - the spin of the heavier black hole
  - the system precession
  - GR prediction of higher multipoles

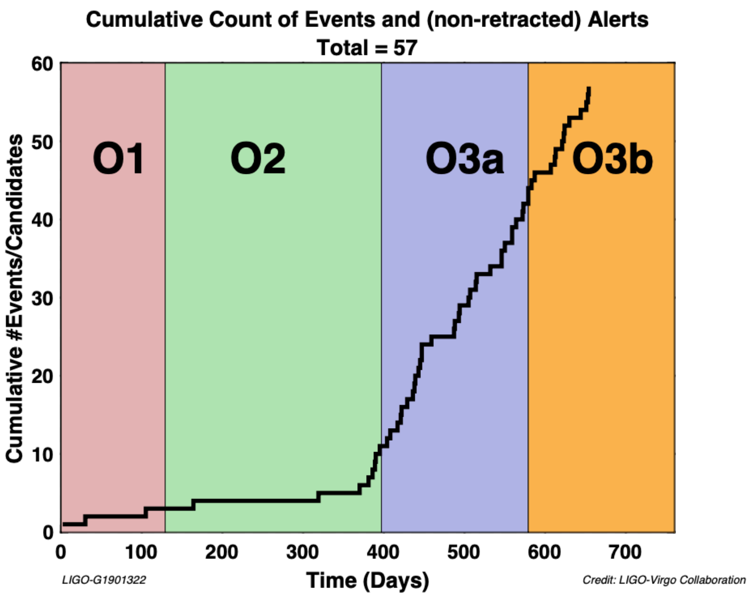


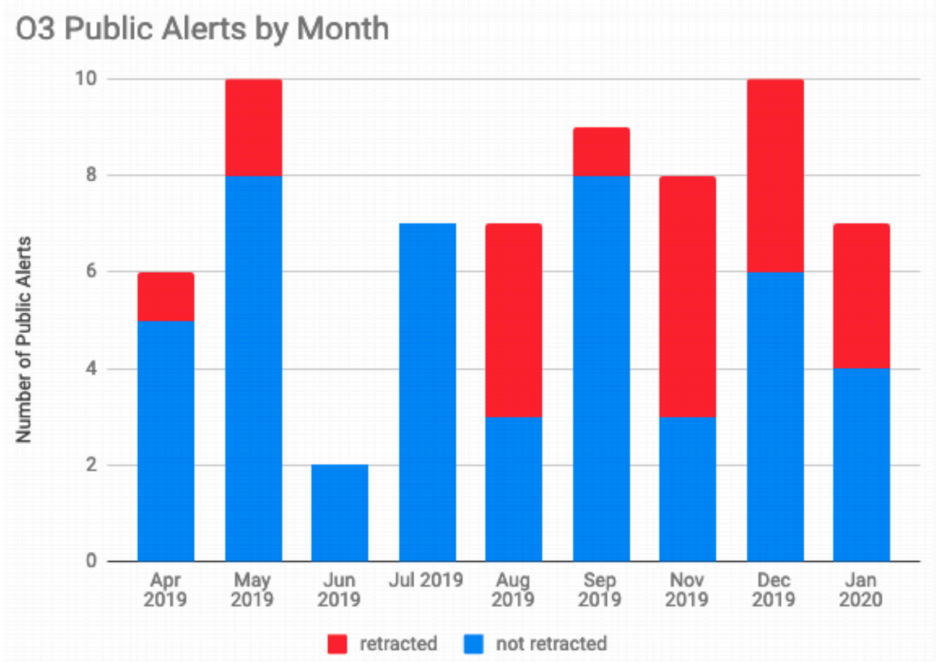


https://gracedb.ligo.org/superevents/public/O3/

https://www.ligo.org/science/Publication-GW190412/index.php

Some stats. 19 alerts including 8 retractions since the last OpenLVEM telecon on Nov/21/2019.





https://dcc.ligo.org/LIGO-G1901322/public

https://dcc.ligo.org/public/0165/G2000062/005/G2000062_OpenLVEM_16Jan2000_kk_v5.pdf

THE THIRD OBSERVATIONAL RUN (O3) OF ADVANCED LIGO AND ADVANCED VIRGO

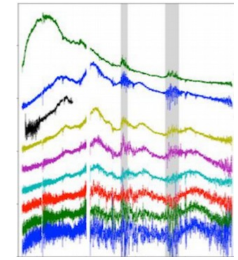
SEARCH AND FOLLOW-UP OF OPTICAL/NIR COUNTERPARTS

Giulia Stratta

Andrea Rossi

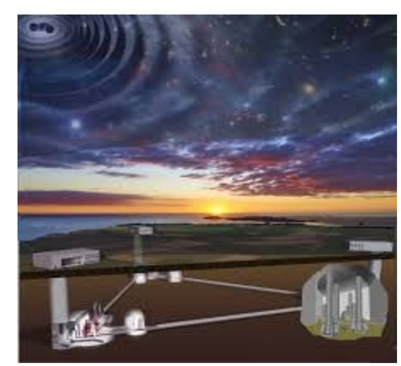
Istituto Nazionale di Astrofisica (INAF), Osservatorio di Astronomia e Scienze dello spazio (OAS) – Bologna (Italy)

Outline



- More about GW 170817
- GRAWITA
- ENGRAVE

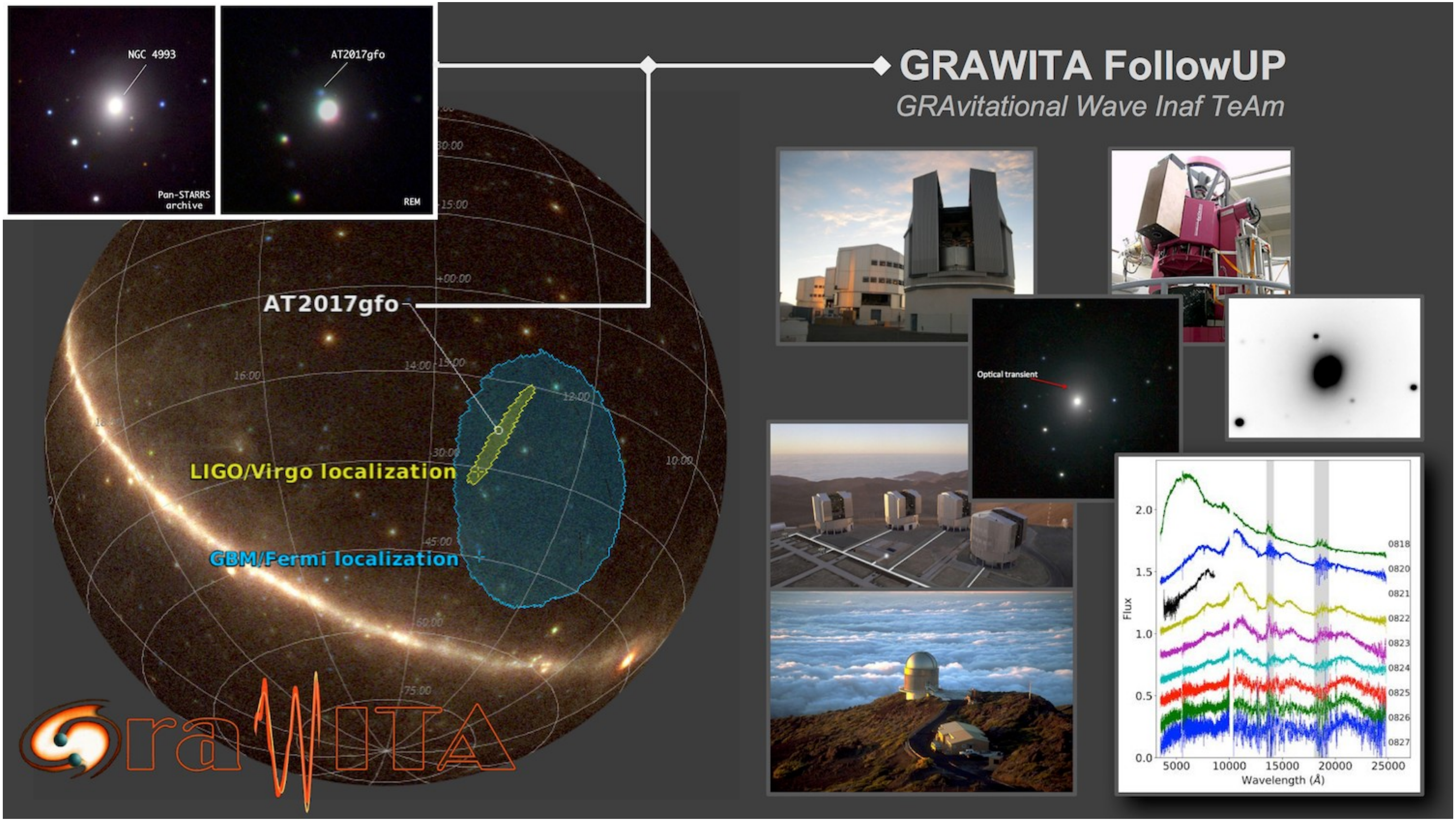
- Ongoing works



- Future perspectives (2)

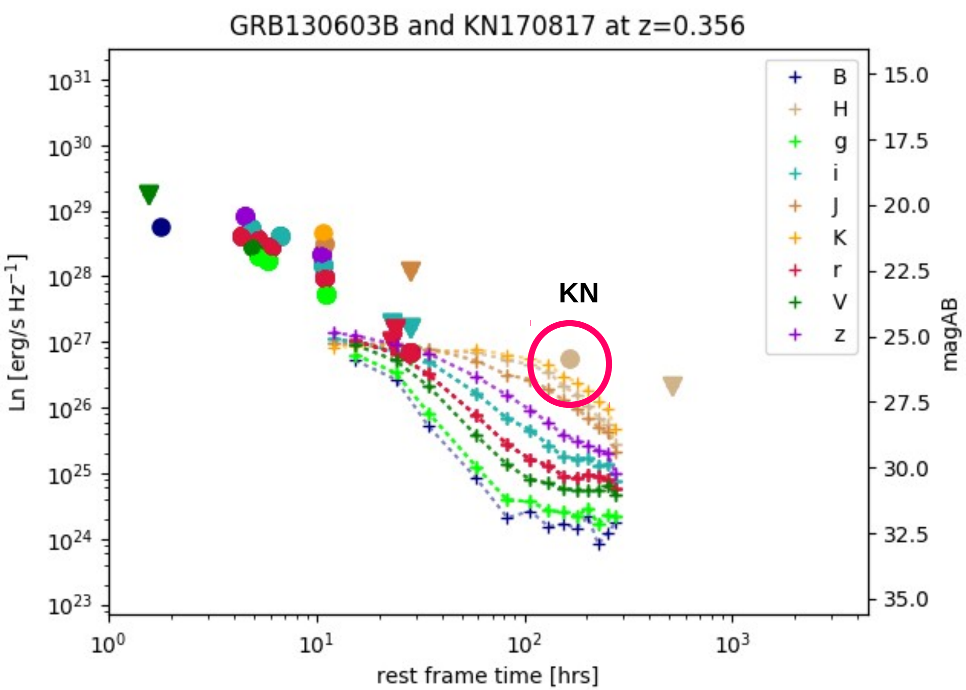
GW170817

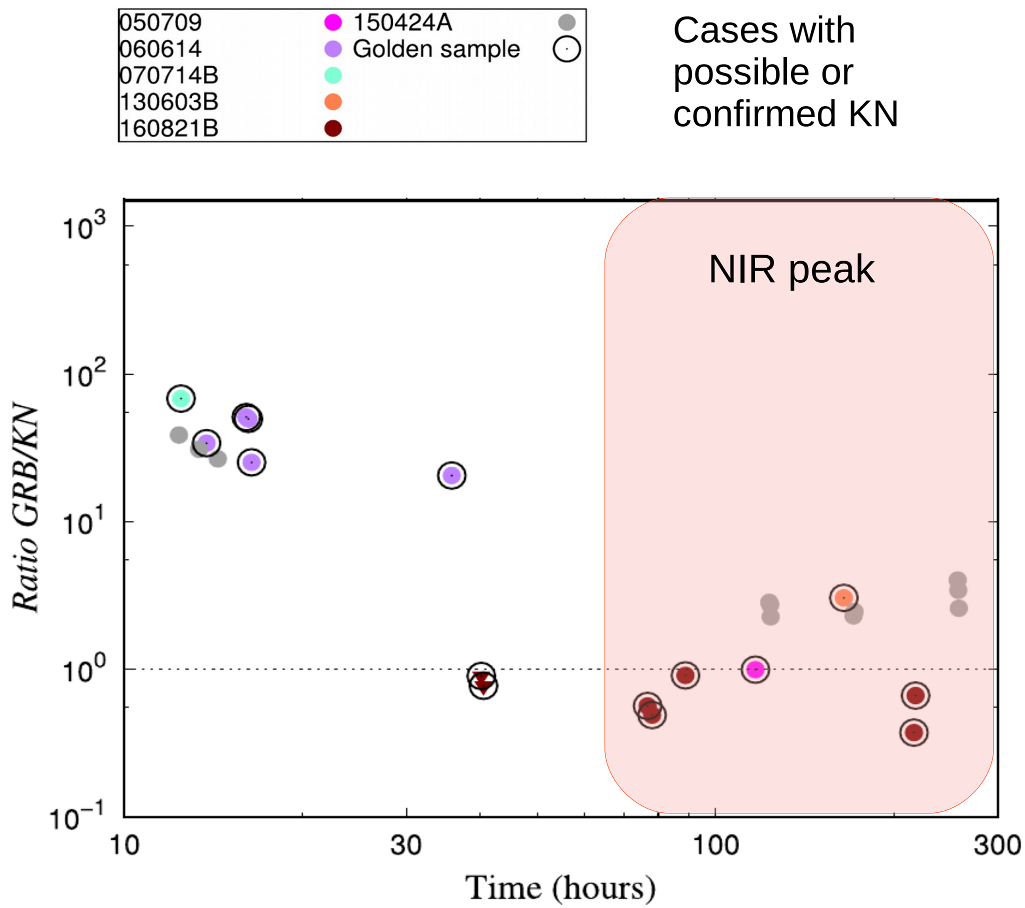
Three-In-One Event: GW signal, short GRB, and a kilonova



GW170817 - AT2017gfo

KN AT2017gfo and short GRBs





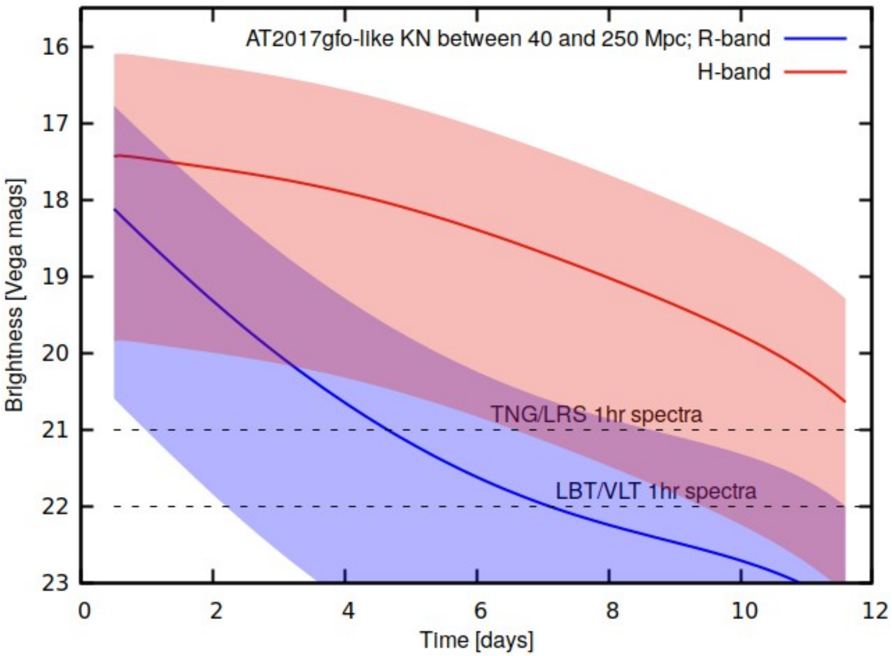
Cases with possible or confirmed KN

Rossi, Stratta et al., 2020, MNRAS 493, 3379
See also Ascenzi et al., 2019

- Constraints on the luminosity of the kilonova
- NIR component similar to AT2017gfo

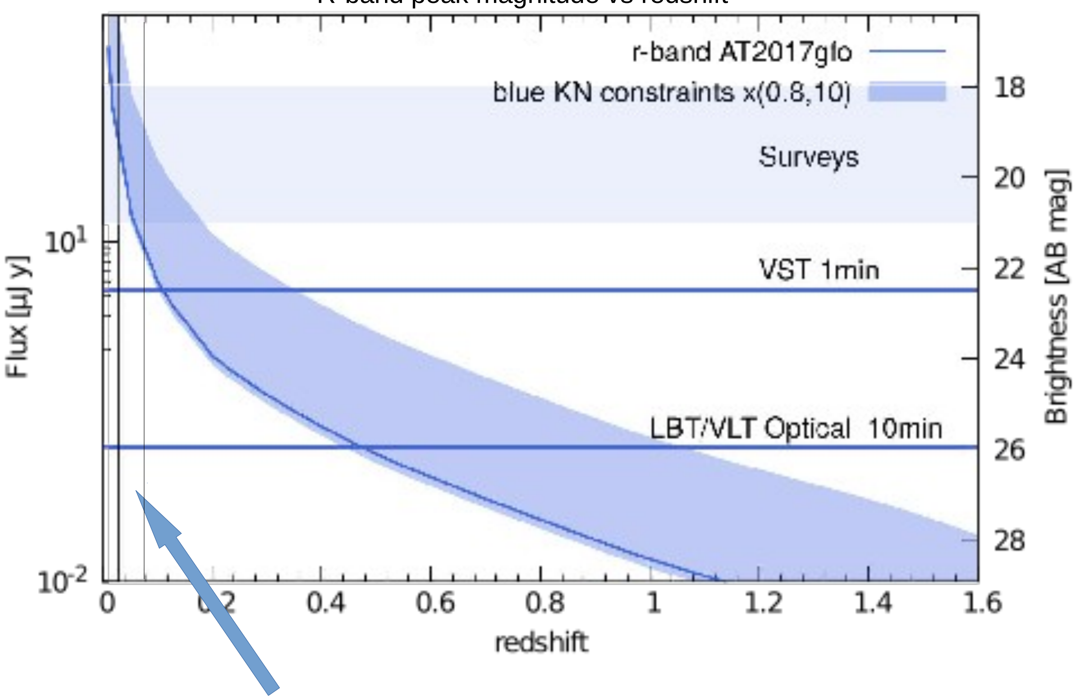
GW170817 - AT2017gfo

KN AT2017gfo at larger distances
0.01<z<0.05
- Optical evolution faster than NIR!



The problem is to localize EM counterparts, not their follow-up

R-band peak magnitude vs redshift



~130Mpc O3 Ligo BNS range
~330Mpc O5 Ligo BNS range

Moving on from
Rossi, Stratta et al., 2020, MNRAS 493, 3379

Gravitational waves @ INAF

GRAWITA: GRAvitational Wave Inaf TeAm

GRAWITA Working Groups

Large INAF community ~100 members (P.I. Brocato)
Community with great experience studying transients (SN, GRBs) , large FOV survey

Group mails:

- WG1 24H/7d OPERATION TEAM (subscribers), Leader: P. D'Avanzo
- WG2 WIDE FIELD SEARCH (subscribers), Leader: F. Getman
- WG3 CHARACTERIZATION & FOLLOW-UP in Optical NearIR bands (subscribers), Leader: A. Melandri
- WG4 RADIO Follow-up (subscribers), Leader: M. Orienti
- WG5 HIGH ENERGY Prompt and Follow-up (subscribers), Leader: A. Bulgarelli
- WG6 THEORETICAL MODELS (subscribers), Leader: R. Ciolfi
- WG7 ARCHIVING & WEB ACTIVITIES (subscribers), Leader: L. Nicastro

GOALS:

- Search
- Follow-up
- Characterization

of EM counterparts of GW events

www.grawita.inaf.it

GraWITA

Gravitational waves @ INAF

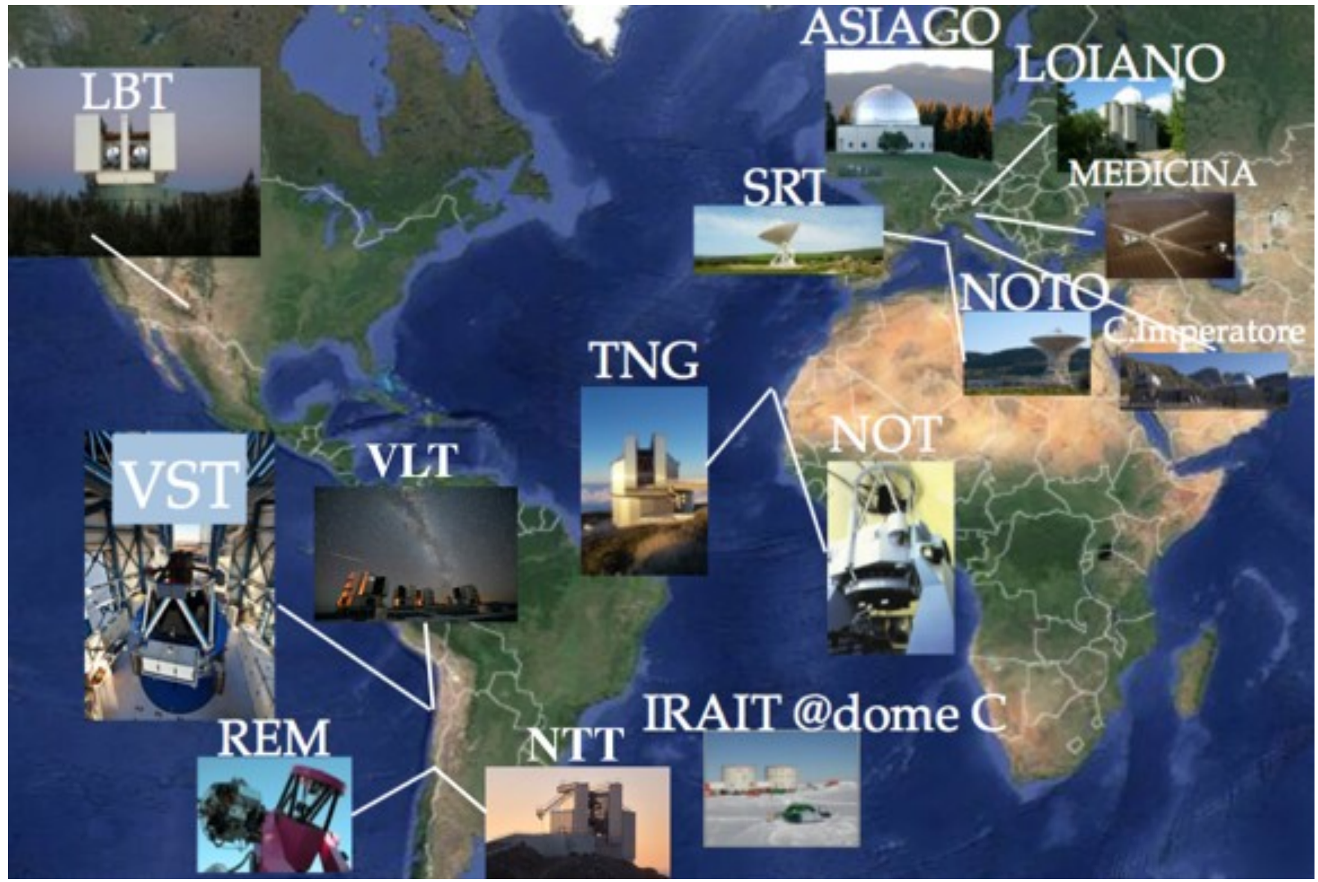
Multi-wavelength Observing Facilities:

Visible: VST, LBT, TNG, NOT + small telescopes [REM, 1.82m (Asiago, IT), 1.52m (Loiano, IT), 0.9m C. Imperatore, IT)]

Near-mid IR: 1.1m AZT-24 (C. Imperatore,IT), IRAIT (Antarctica)

Radio: 64m SRT (Cagliari, IT), 2x 32m (Medicina and Noto, IT)

Collaboration: ENGRAVE, ePESSTO, VISTA (Vinrouge), MAGIC, SWIFT, INTEGRAL, AGILE
SUPERGRAWITA

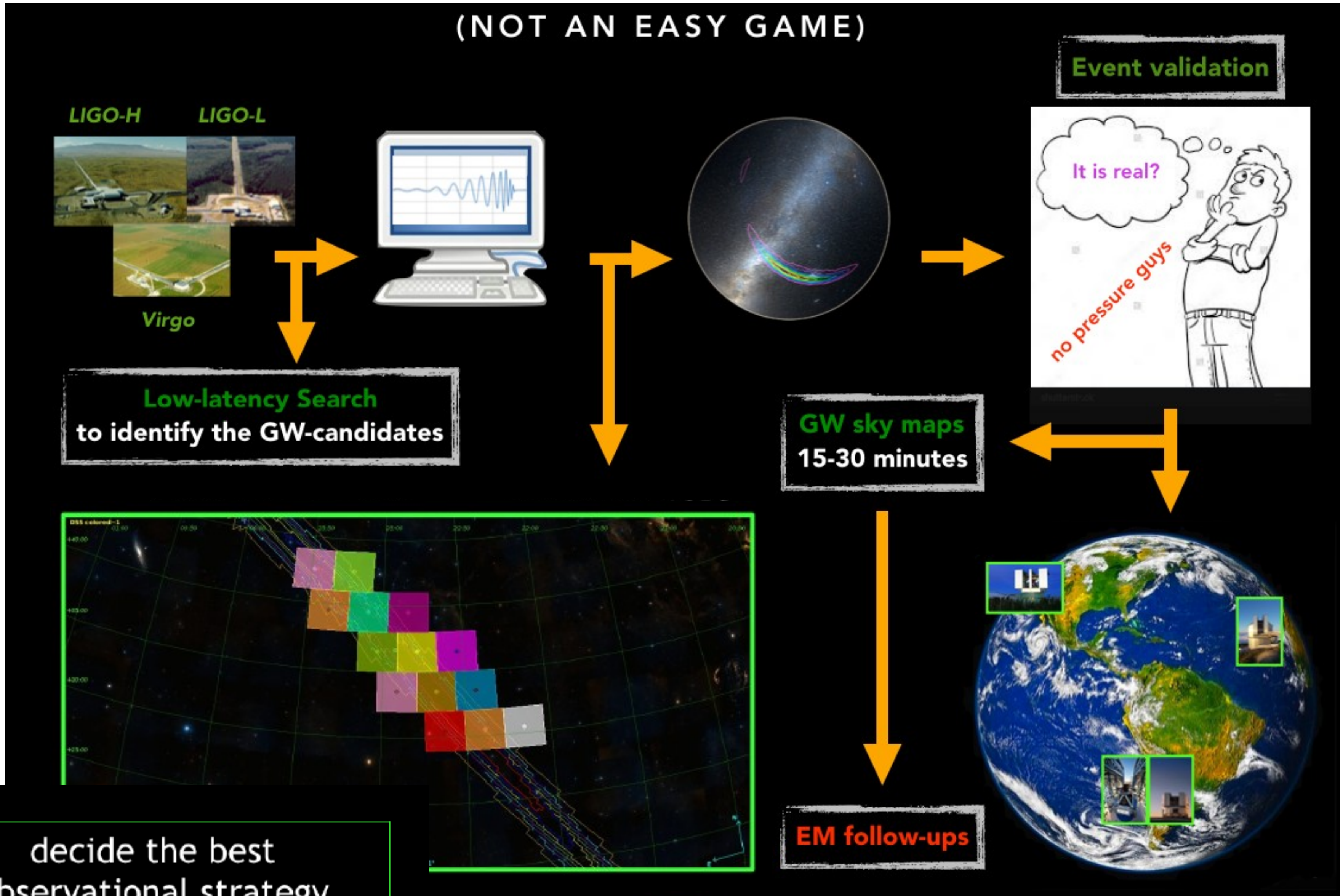


GRAWITA publications during O1, O2 and O3: 18 refereed papers, 57 GCNs

https://www.grawita.inaf.it/publications/

GraWITA
Gravitational waves @ INAF

Follow-up strategy

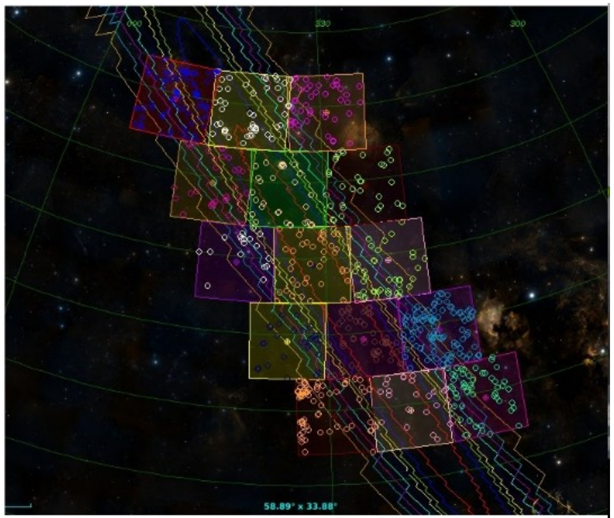


decide the best
observational strategy

Credit S. Covino

TOOLS

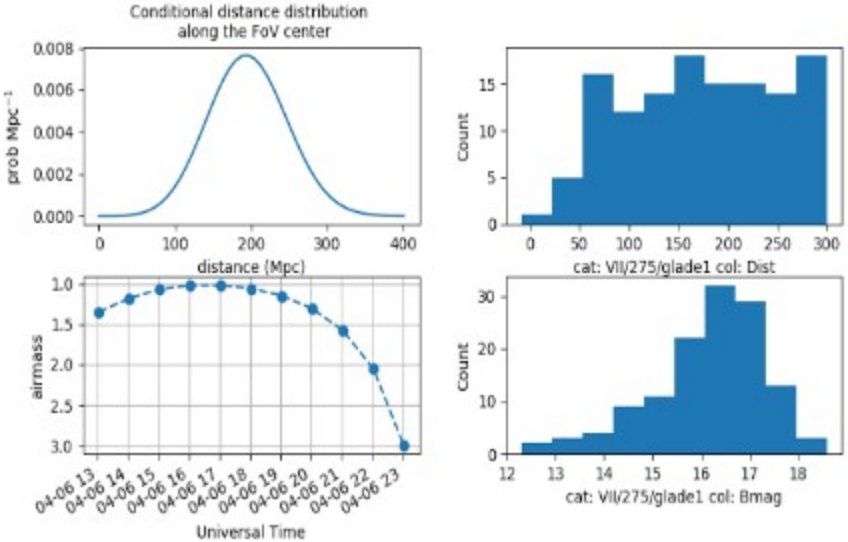
GWsky: used to generate a sequence of pointings given a specific Field of View
https://github.com/ggreco77/GWsky
(G. Greco, Urbino Univ.)



Each Field of View is accompanied by descriptive statistics to manage the sequence of pointings.

Pipelines:

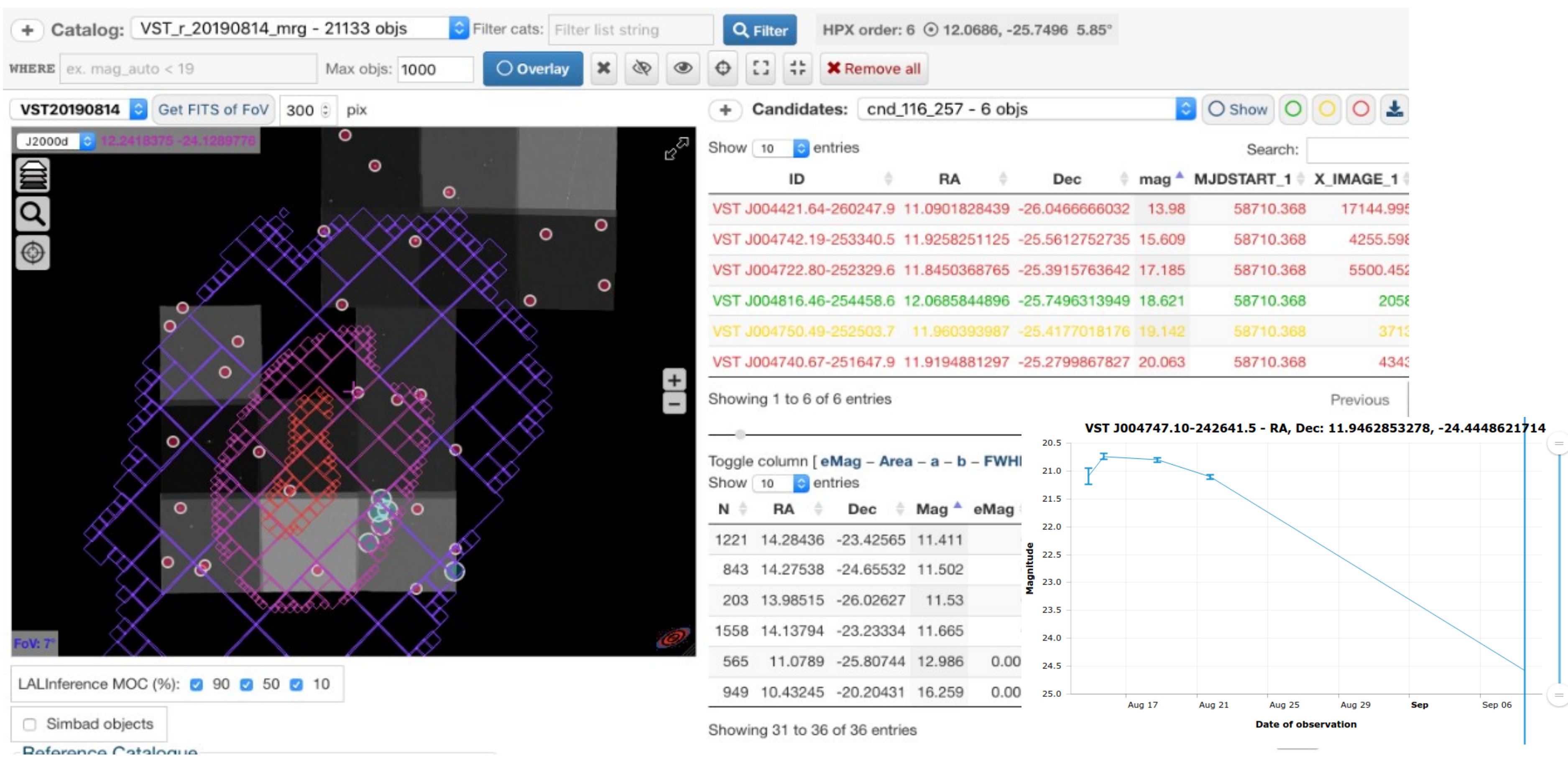
- Image subtraction
(E. Cappellaro INAF/OA-Pd)
- Photometry
(S. Covino INAF/OA-Brera)



Gravitational waves @ INAF

TOOLS

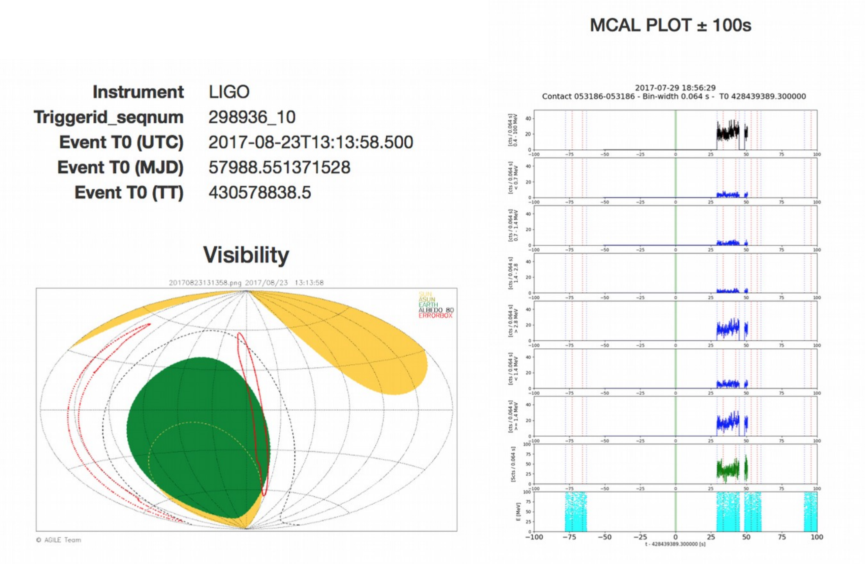
VST Browse: Skymap covered, everything about VST candidates, light curves, online catalogs, image download
www.grawita.inaf.it/VSTbrowse (L. Nicastro, INAF/OAS)

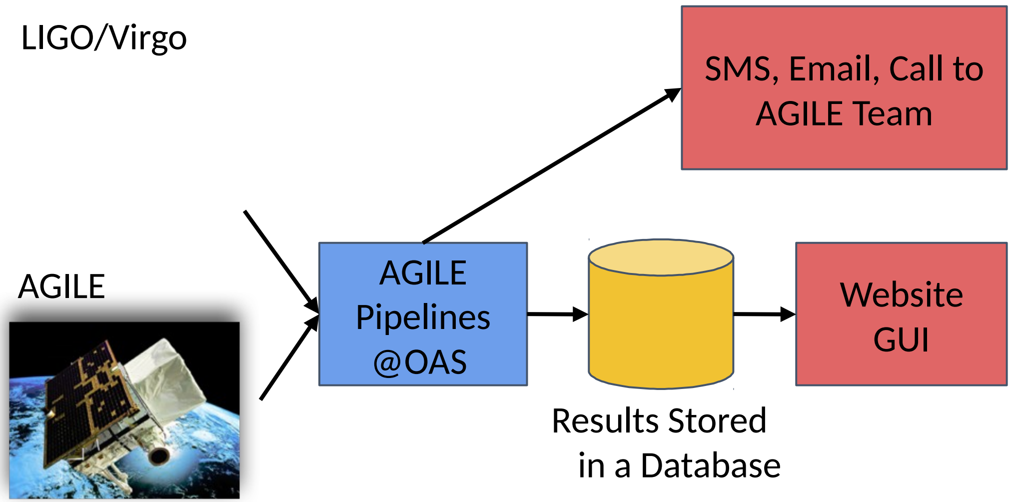


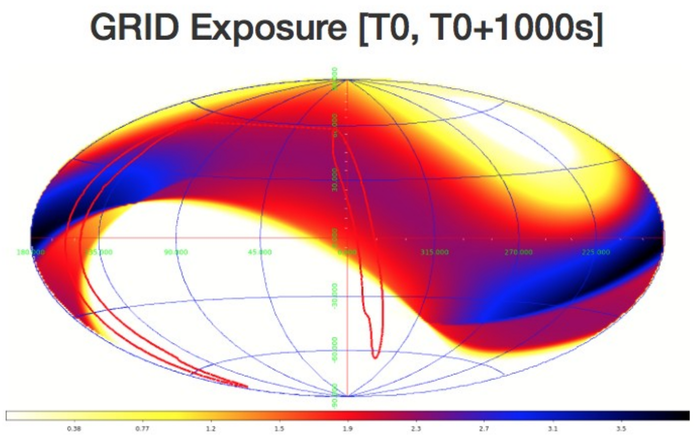
AGILE Real Time Analysis for GW Alerts

AGILE system reacts to LIGO/VIRGO GW Alerts:

- sending **notifications to the AGILE Team**
- performing **a real-time analysis of AGILE data** to detect possible EM counterparts.
- The same system is used also for GRB and neutrino events.
- Developed and is running @**OAS Bologna**
- **OAS Bologna responsible for the follow-up operations**
- Results also accessible through a **mobile App** (AGILEScience)
- People: A. Bulgarelli, N. Parmiggiani, V. Fioretti, L. Baroncelli, M. Trifoglio, F. Gianotti, A. Addis







Electromagnetic counterparts of gravitational wave sources at the Very Large Telescope

- To use the ESO facilities to research gravitational wave events (since April 2019)
- Over 250 researchers, with both theoretical and observational expertise.
- www.engrave-eso.org

Operations

On-call schedule

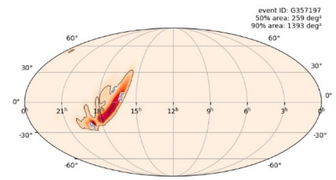
Writing team schedule

- **Follow-up strategy**
- Devoted to characterize the candidates
- When to keep a look-out: everything, but especially NS+*, or close BBH
- **When to trigger:**
- We follow-up counterparts reported elsewhere (via GCNs https://gcn.gsfc.nasa.gov)
- What it is? Spectroscopy (X-Shooter/FORS2) is the answer

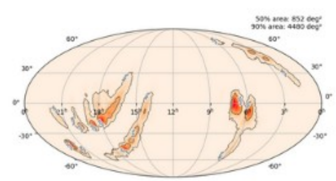
Working Groups

WG-IMG
WG-SPEC
WG-POL
WG-RADMM
WG-INFRAST
WG-THEORY
WG-EPO
WG-EXT
WG-KN-SEARCH

Where to look for candidates? And which candidates? … not so easy

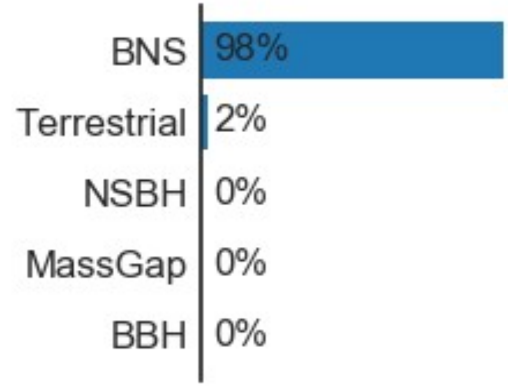


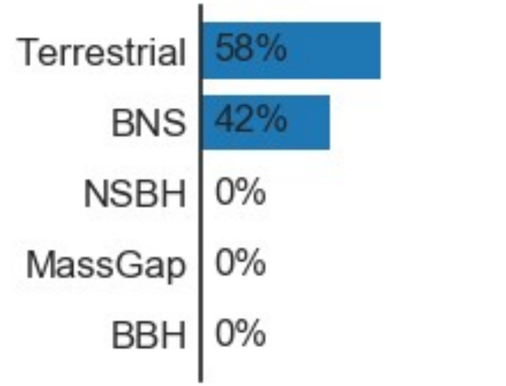
Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Dec 13, 2019 04:38:30 UTC



Mollweide projection of LALInference.fits.gz LALInference.png. Submitted by LIGO/Virgo EM Follow-Up on Dec 14, 2019 00:59:56 UTC

Sky localization can change (S191213g)





GW classification can change (S190510g)

RESULTS GW190425

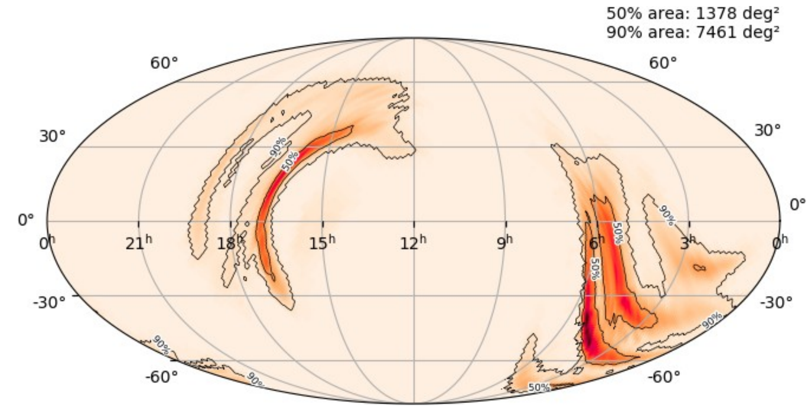
- **GW190425: second GW signal from a BNS at 156+-41 Mpc**

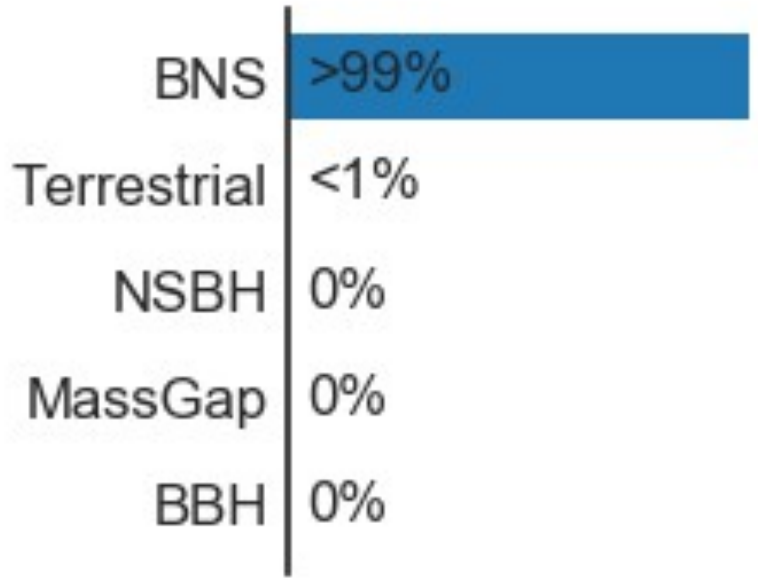
  Unfortunately only Livingston(L1) and VIRGO were observing

  Localization >7000 deg^2 only surveys

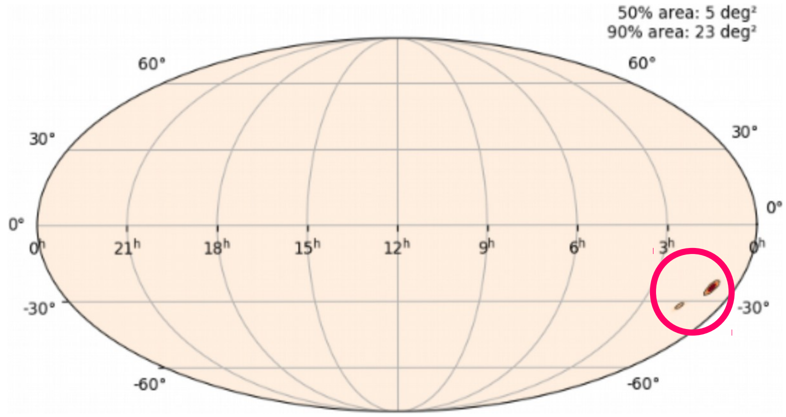
- Wide search difficult: e.g. ZTF, Pan-STARRS <~25% final skymap(~50 candidates)
- GRAWITA: **LBT and TNG** could exclude 2 candidates (both SN) from ZTF and Pan-STARRS

  Carini et al., GCN 24252; Izzo et al., GCN 24208





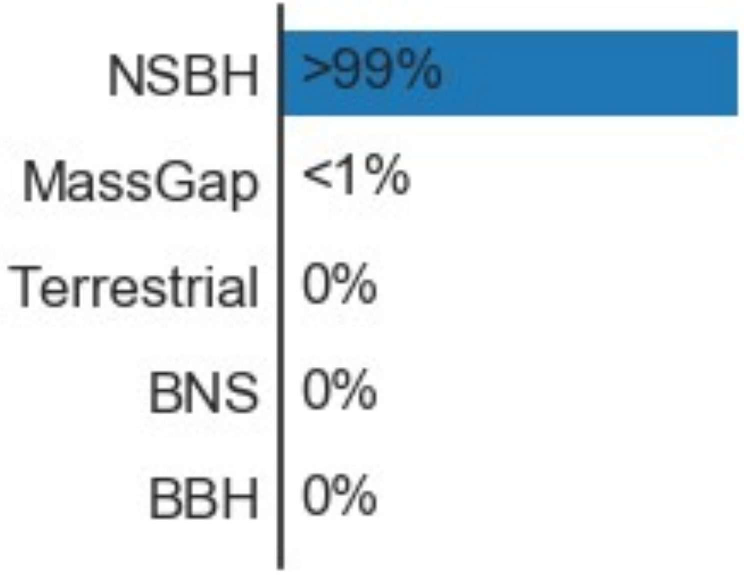
RESULTS S190814bv



S190814bv:

- first BHNS
- large distance 267±52 Mpc

  (40 Mpc for GW 170817)



Importance of a EM counterpart:

- To give a precise sky localisation
- Can a BHNS merger produce heavy elements like a BNS merger? (see GW170817)

RESULTS S190814bv

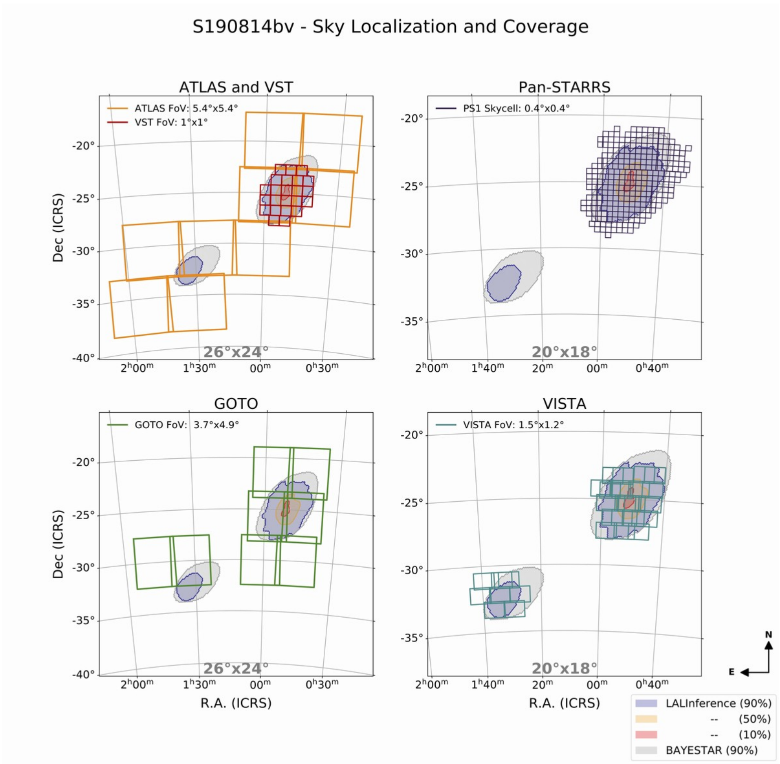
1st ENGRAVE paper

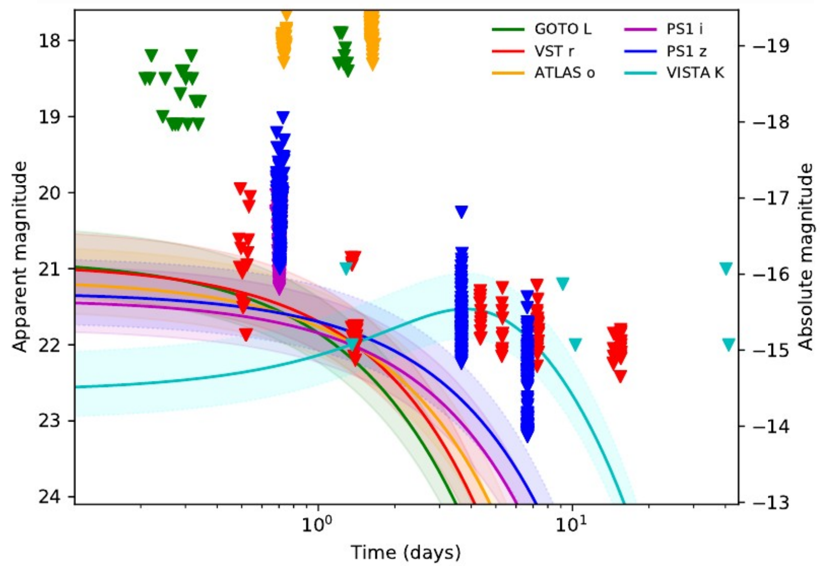
Ackley et al. 2020 arXiv:2002.01950v1

Wide-field survey observations and results

- **~80 candidates but no convincing electromagnetic counterpart in 33%-99.8% of the sky localization**
- **GRAWITA: VST provided deep optical limits with coverage to ~90% (~60%) within 4 days (1 day)**

Exclude a KN with large ejecta mass M>0.1 Msun
(no AT2017gfo but some brighter GRB/KN**)**





AT2017gfo light curves and upper limits from wide filed campaign

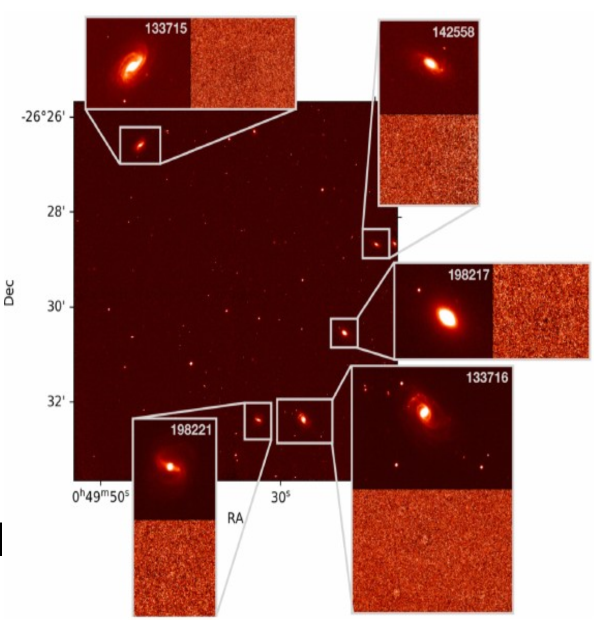
RESULTS S190814bv

1st ENGRAVE paper

Ackley et al. 2020 arXiv:2002.01950v1

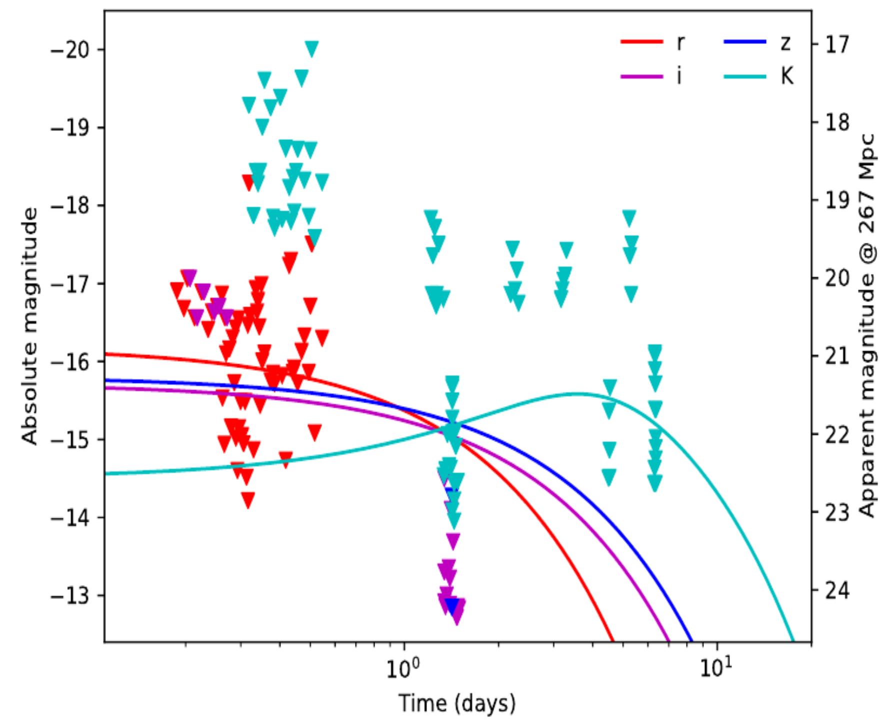
Targeted search of galaxies

- **Selected via probability to host the GW**
- **Can reach necessary depth**
- **We estimate that ~50% of galaxies could be covered**



VLT/HAWK-I
(TNG/NICS)

AT2017gfo light curves and upper limits from targeted search



Future events at ~100 Mpc detected only by large facilities with both high sensitivity and large field of view.

RESULTS S190814bv

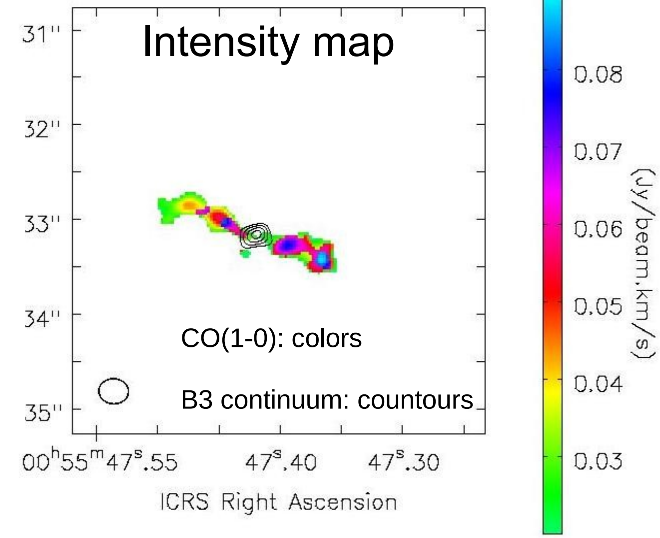
AT 2019osy:
ASKAP unusual radio transient
2d post-merger
(e.g., Bhattacharya et al., 2019)

ALMA observations:
Sep 5 and Sep 19

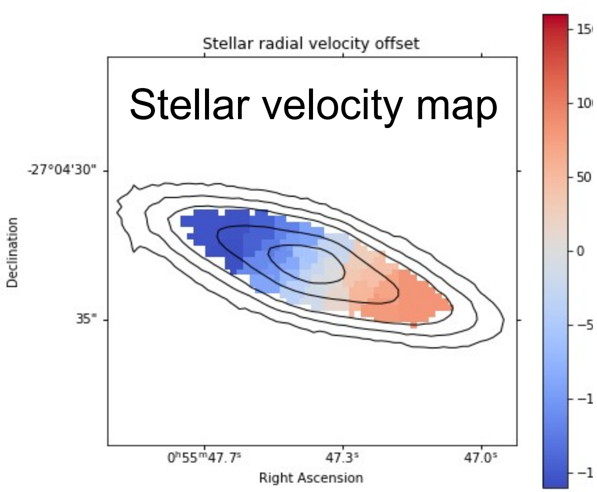
Detection only in B3 (from AGN)
(100 GHz)

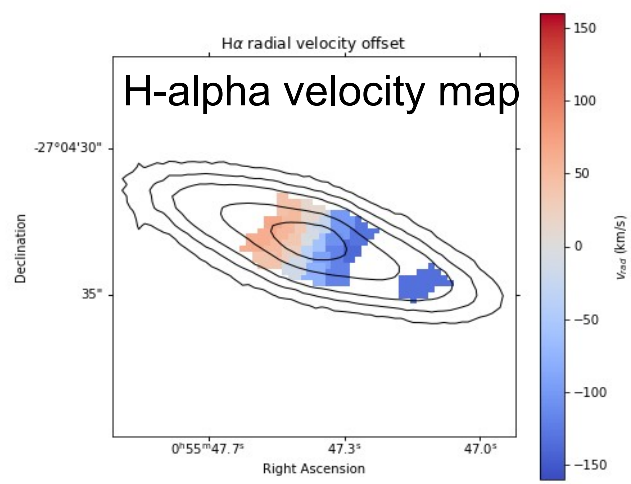
Most likely aLLAGN in a SF galaxy
(in agreement with radio Dobie et al., 2019)

Paper in prep.



© Rosita Palladino (INAF/IRA)





MUSE

gas-versus-stars counter-rotation

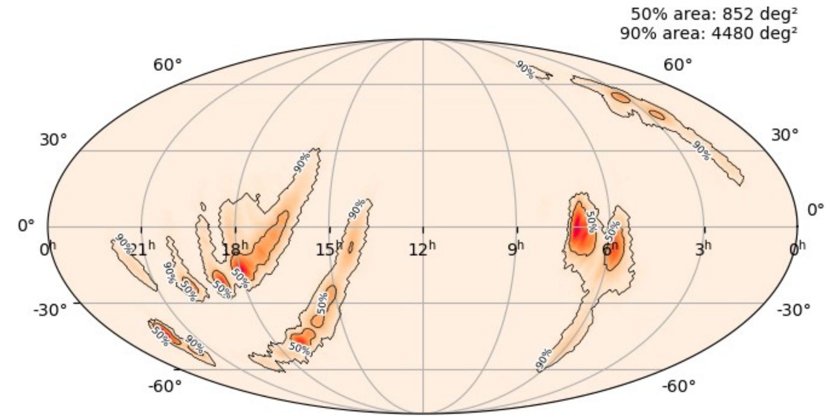
©Luca Izzo (DARK)

RESULTS S191213g

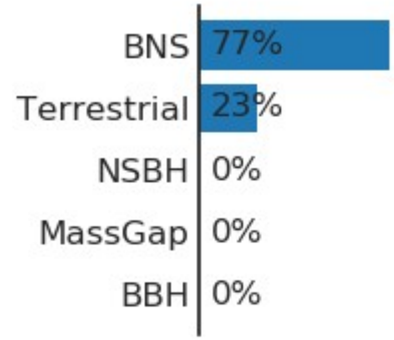
- **S191213g:** BNS event at ~200 Mpc
- **AT2019wxt:** Candidate with rapid evolution similar to blue KN discovered by Pan-STARRS1
- **GRAWITA:**
  1 TNG epoch (J band)
- **ENGRAVE:**

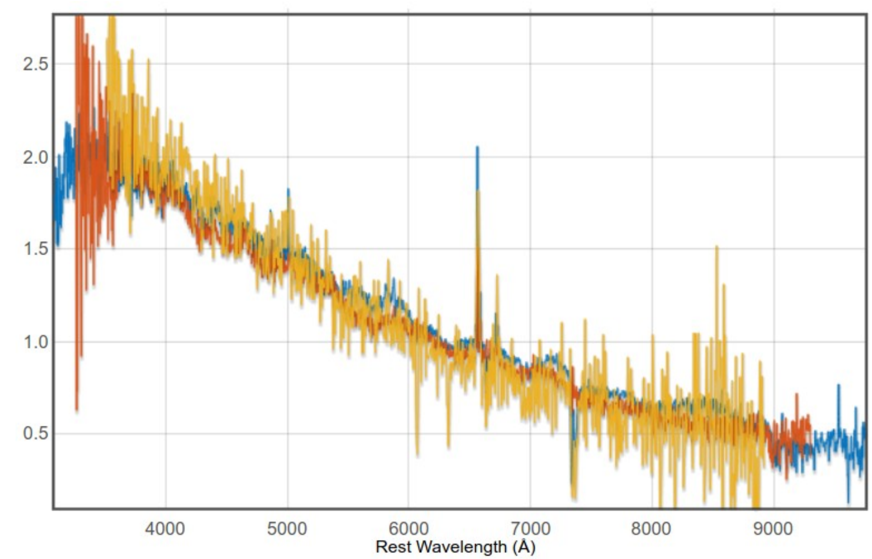
  X-Shooter spectra:
  possible SN with
  unusual rapid decay

  Paper in prep.



201+-80 Mpc





SN_2019wxt - 2019-12-19 05:10:39 LBT / MODS2 (None)
SN_2019wxt - 2019-12-19 01:24:45 VLT-UT1 / FORS2 (adH0cc)
SN_2019wxt - 2019-12-19 00:50:08 ESO-NTT / EFOSC2-NTT (ePESSTO+)

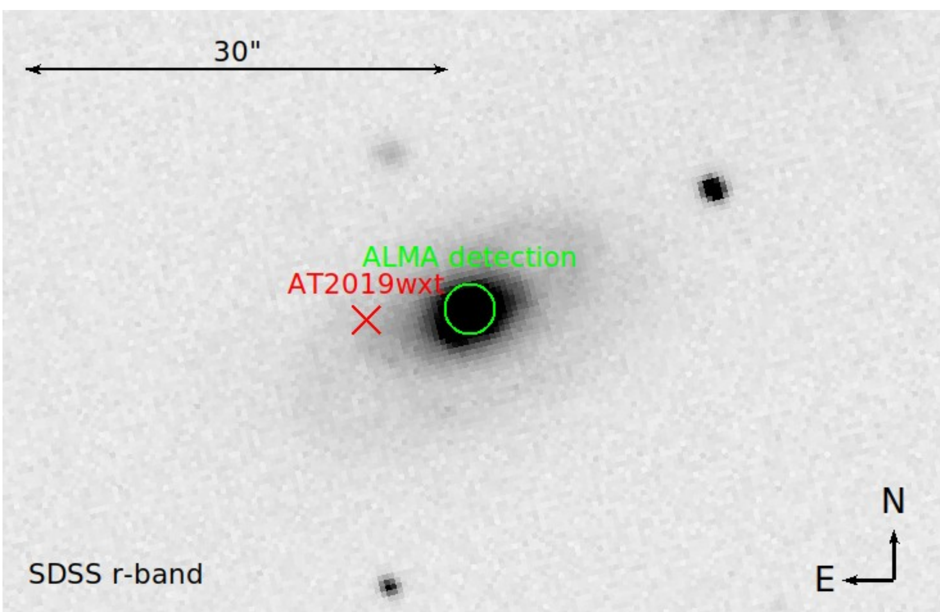
RESULTS S191213g

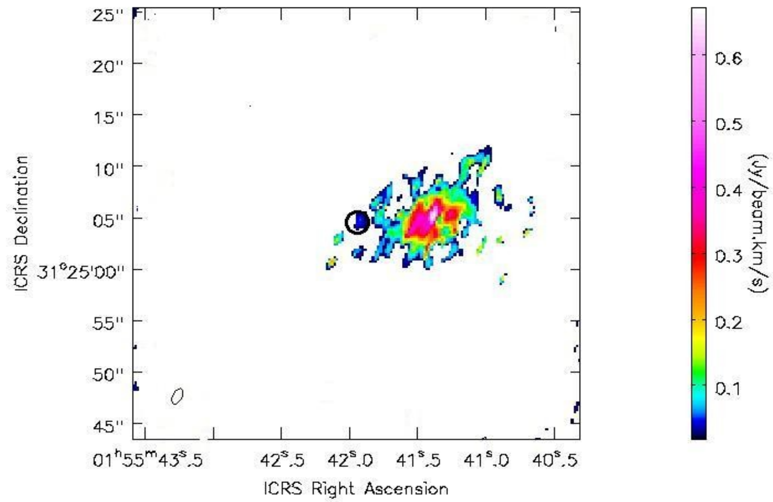
AT 2019wxt:
PS1 candidate with rapid evolution similar to blue KN

ENGRAVE/ALMA observations of AT2019-wxt
1 epoch on March 5 2020 (> 3 months)
Band 3 (100 GHz)

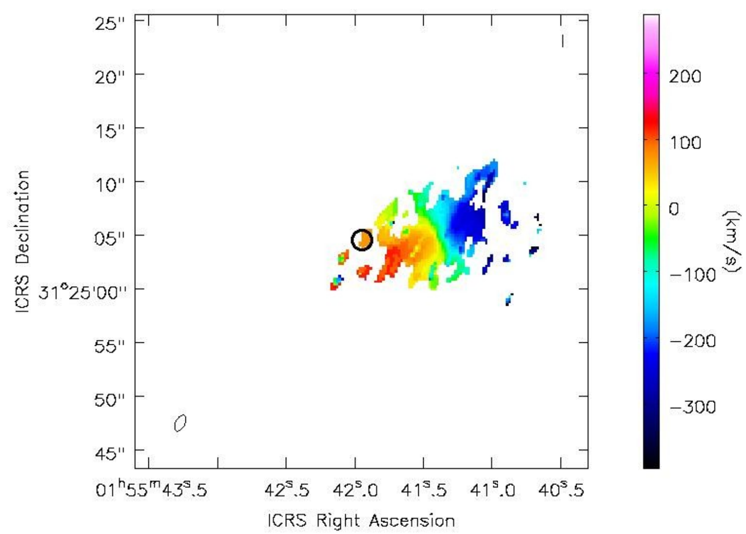
Continuum peak 5.54e-4 Jy/beam S/N = 46

- We do not see the transient …
- … but host galaxy's emission due to star formation
- CO emission at transient location





CO(1-0) line at 111.265 GHz (z=0.03)



VST
S190701ah (BBH)
S190728q (BBH)
S191204r (BBH)
S190510g (BNS)

Asiago
S190426c (BNS)
S190901ap (BNS)

TNG
S191213 (BNS)
GW190425z (BNS)
S190814bv (NSBH)

Gravitational waves @ INAF

Follow-up
(in the literature)

REM
GW190510g (BNS)

LBT
GW190425z (BNS)

Loiano
S190510g (BNS)
S191216ap (BHBH)

Savelli
S190408an (BBH)
S200115j (Mass Gap)

Waiting for O4

follow-up of non-GW kilonovae (blind searches)

GRAWITA:

Loiano TBD

TNG submitted

REM submitted

SRT accepted

NOT submitted

VST beyond 2021 call for ideas

LBT waiting for call

ENGRAVE:

VLT submitted

HST accepted

ALMA: valid until the end of September 2021 with carry-over until September 2022(!).

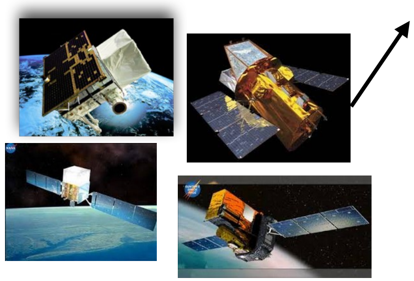
GraWITA
Gravitational waves @ INAF

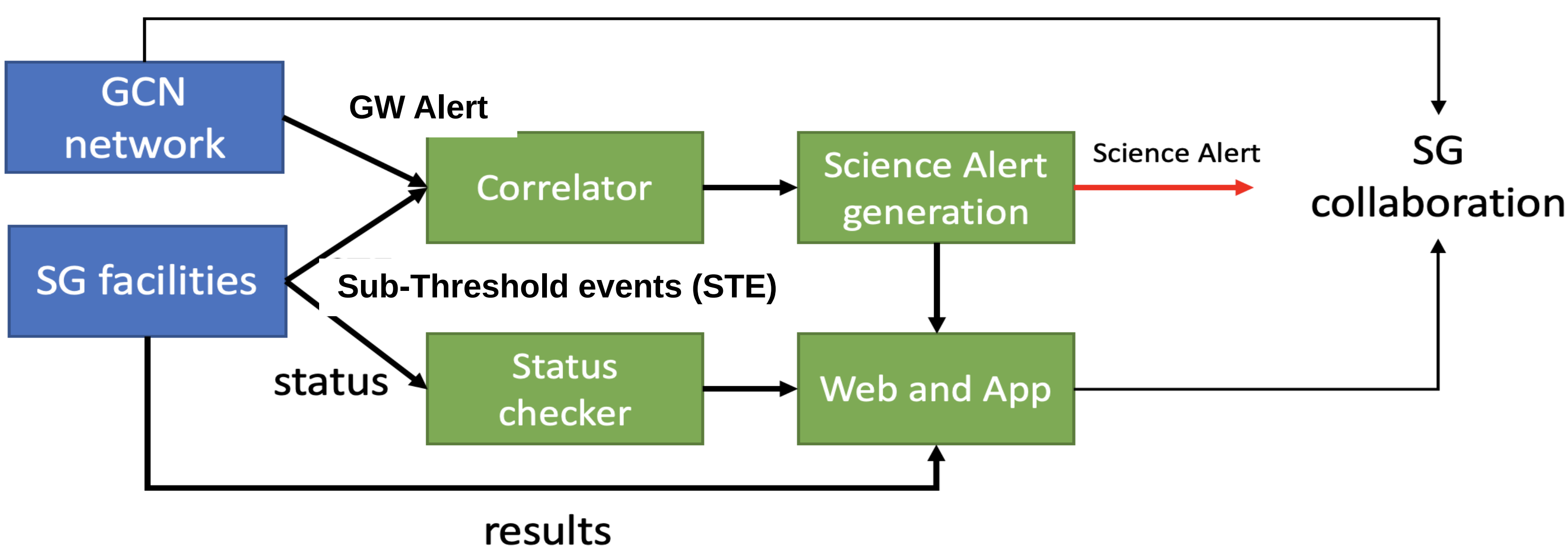
Super GRAWITA

- Proposed as **PRIN-INAF project** (coordination: A. Bulgarelli).
- Aimed at **providing information from satellite** data on the prompt electromagnetic emission associated with GW sources. The main purpose is to provide the satellite status and results available to the GRAWITA community in the shortest possible time.
- **To develop a collaborative platform**, the Super-GRAWITA platform, to enable a joint collaboration between GRAWITA facilities and high-energy (HE) satellites (AGILE, INTEGRAL, Swift, Fermi) with INAF participation, for prompt e.m. GW counterpart searches.
- **A first prototype is under development** within the AHEAD2 project, WP12.2 (OAS people: A. Bulgarelli, N. Parmiggiani, A. Addis)

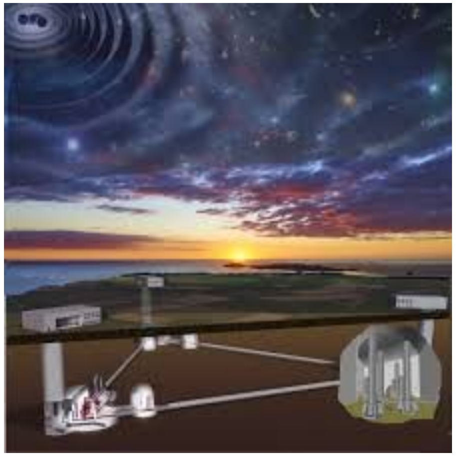
LIGO/Virgo

AGILE, SWIFT , FERMI, INTEGRAL

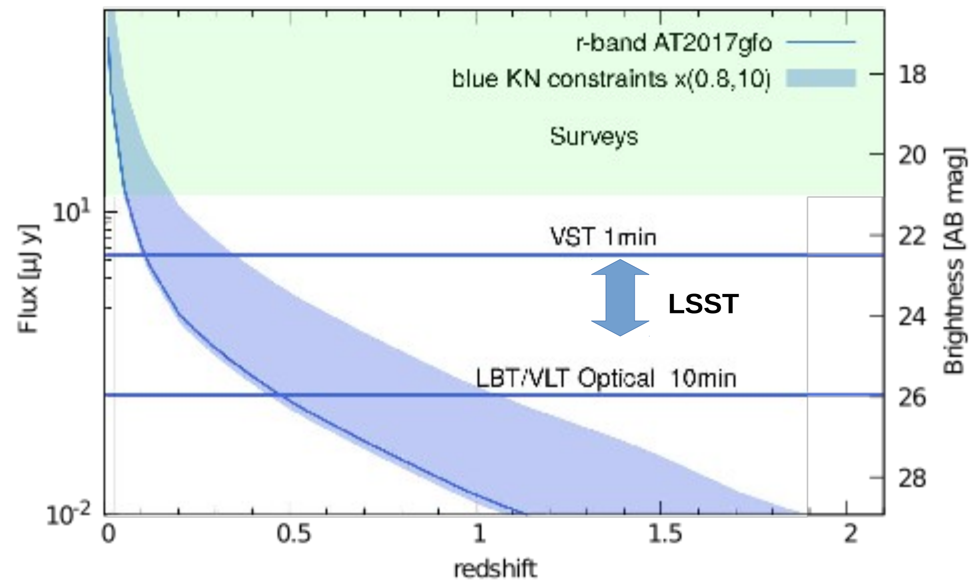




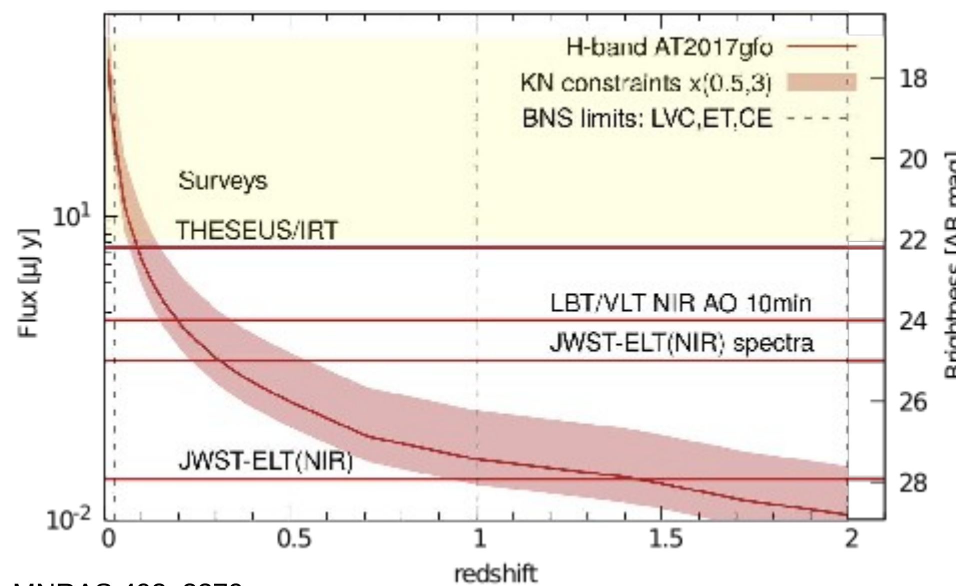
FUTURE PERSPECTIVE
in the 30s during 3G interferometers and ELT/JWST



3G GW observatories like Einstein Telescope, Cosmic Explorer will increase the BNS range beyond z=1 (2 for CV)



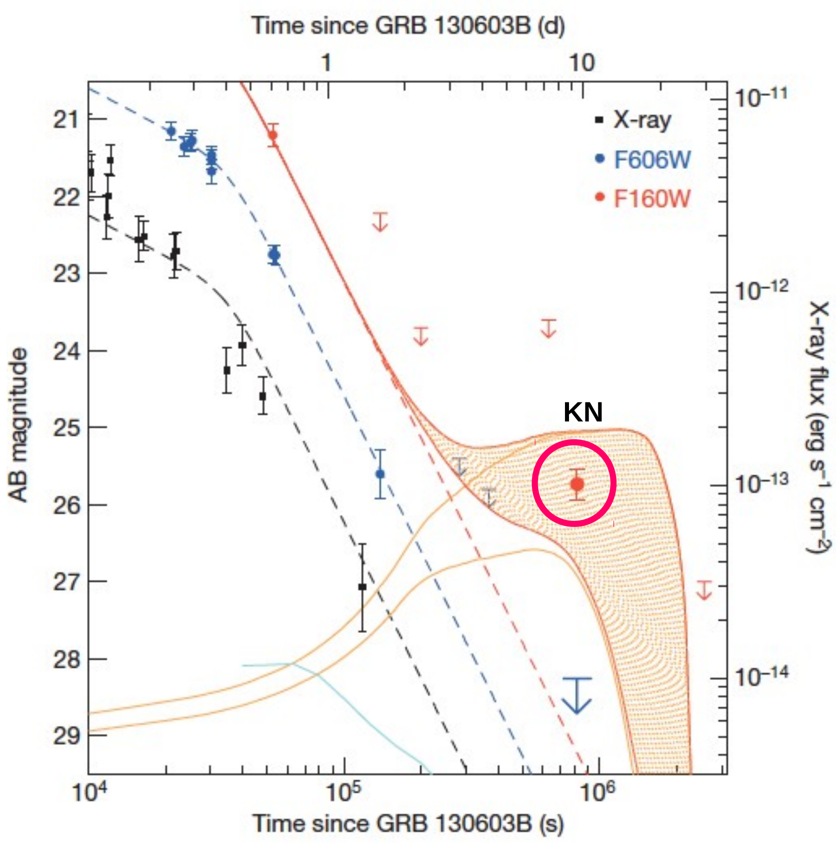
INAF is deeply involved in ELT and in particular INAF/OAS in MAORY, the multi-conjucate AO system for MICADO which first light is expected around 2027-2028



Rossi, Stratta et al., 2020, MNRAS 493, 3379

FUTURE PERSPECTIVE

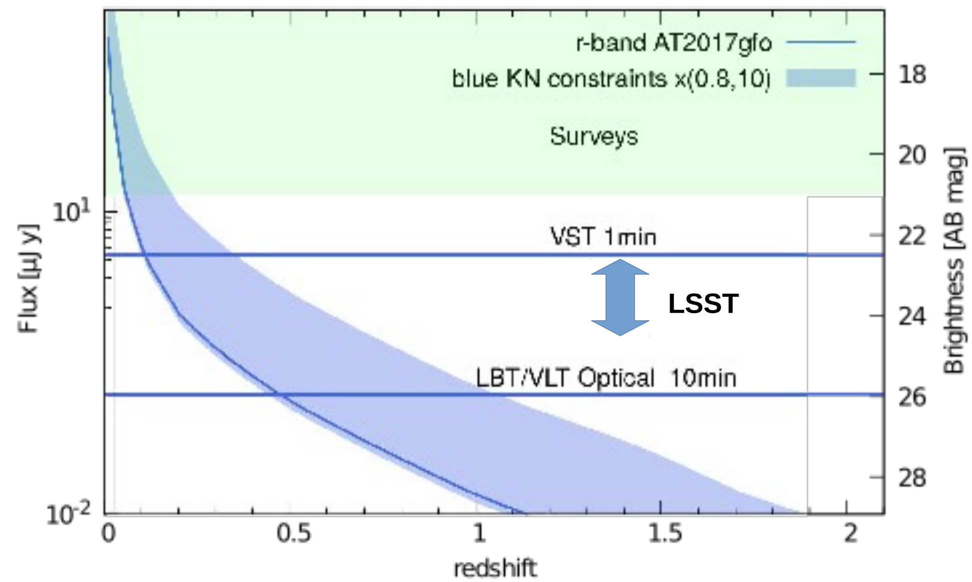
Short GRBs localized by THESEUS/IRT may help

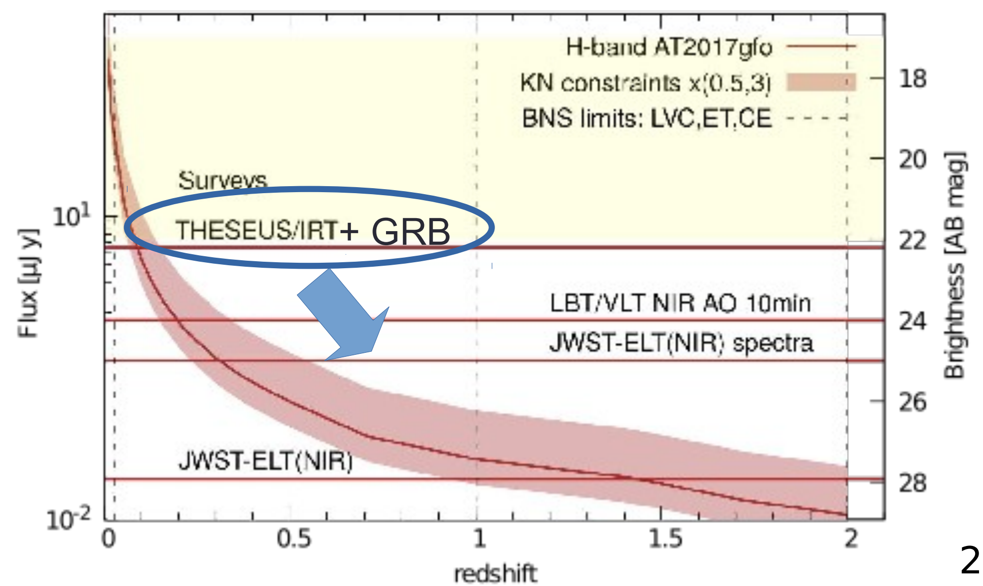


Kilonova in short GRB 130603B:

- Fainter than afterglow,
- but dominating NIR at late time!

(Tanvir+2013)





Summary (2nd part)

- Constraints on Kilonova luminosity and perspectives on the search for the KN counterpart
- GRAWITA followed-up all the most important events
  including the first BHNS event
- ENGRAVE started operations

  first paper: EM follow-up of the first BHNS event
- >1 year before O4 but …

  …we keep our eyes open for non-GW KNe
- Future perspective:

  we need optical/NIR facilities with both high sensitivity and large field of view

GRAZIE