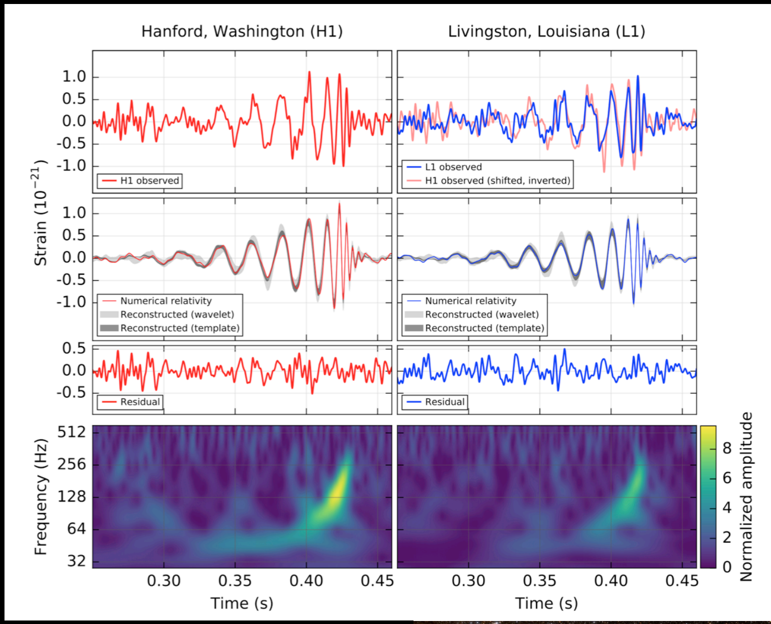


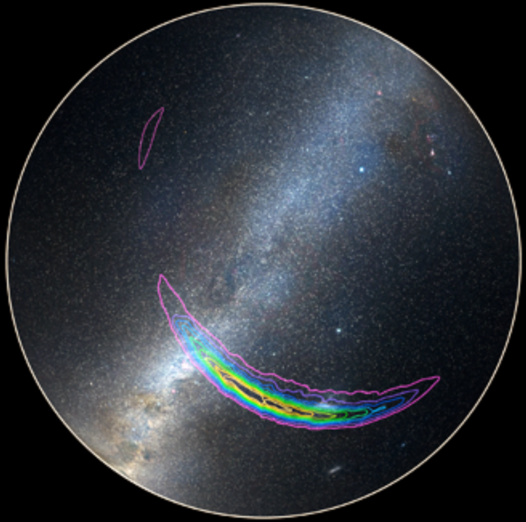



Overview of the LIGO -Virgo EM follow-up program

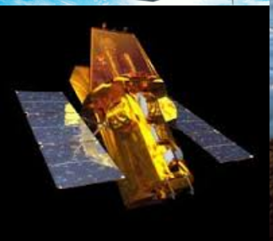
M.Branchesi

Università di Urbino

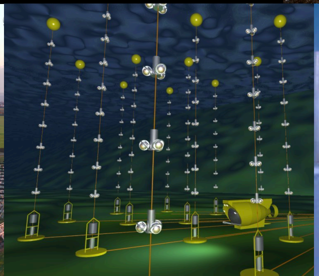
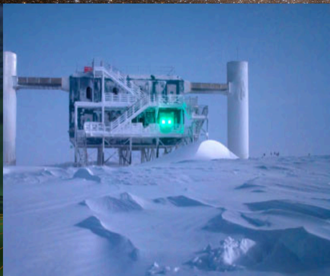
INFN Sezione di Firenze





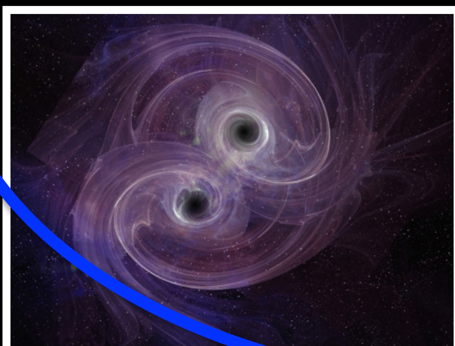


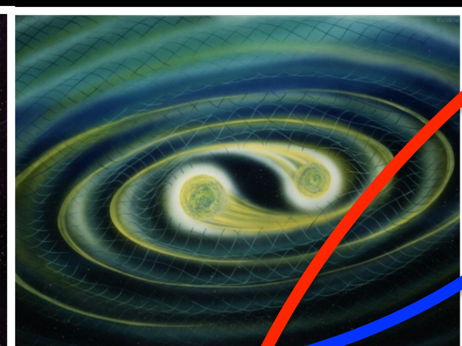


ASTROPHYSICAL SOURCES emitting transient GW signals detectable by LIGO and Virgo (10-1000 Hz)

Coalescence of binary system of neutron stars and/or stellar-mass black-hole

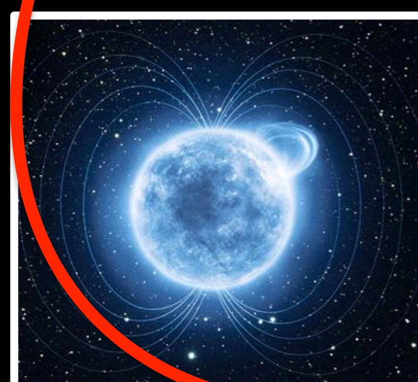




→ MATCHED-FILTER MODEL SEARCHES

Core-collapse of massive stars

Isolated neutron-star



UNMODELED SEARCHES

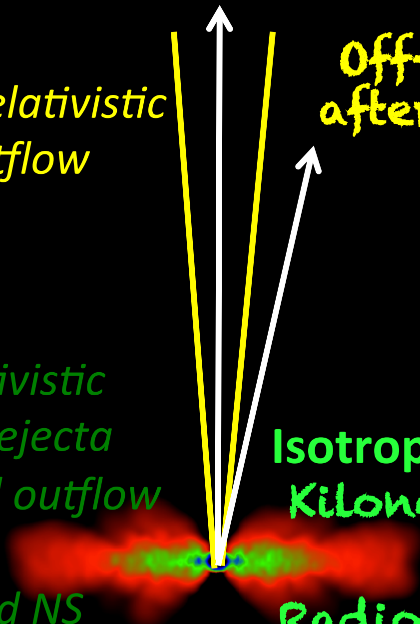
EM emissions

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)
→ Afterglows X-ray, optical, radio
(minutes, hours, days, months)

Ultra-relativistic outflow

Off-axis afterglow



Sub-relativistic dynamic ejecta disk wind outflow

Isotropic emission
Kilonovae (days)

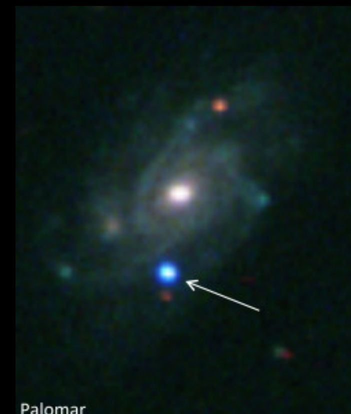
Long-lived NS spindown

.....

Radio remnants
(months, years)
X-ray (min, hrs)

BH-BH mergers ?

Core-collapse of massive stars

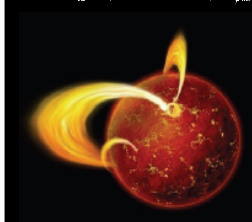


SBO X-ray/UV
(minutes,days)

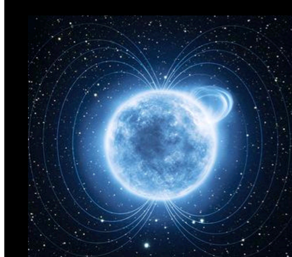
Optical
(weeks, months)

Radio
(years)

Isolated NS instabilities



Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

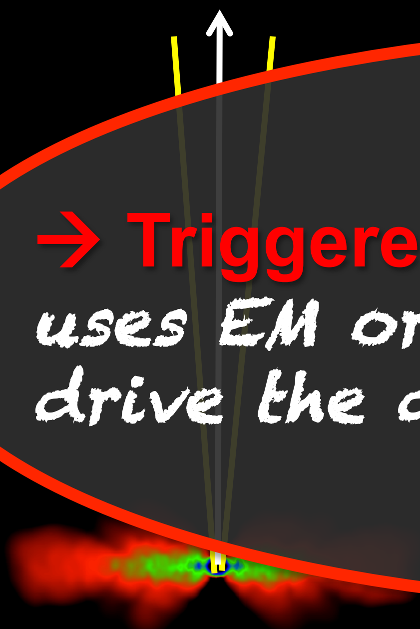


Radio/gamma-ray Pulsar glitches

EM emissions

NS-NS and NS-BH mergers

GRB → *prompt gamma* **(sec)**



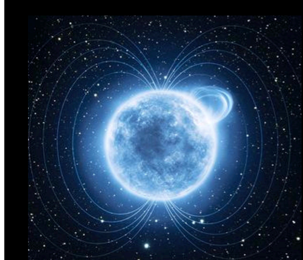
Core-collapse of massive stars

SBO X-ray/UV
(minutes,days)

Optical
(weeks, months)

Isolated NS instabilities

Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars



Radio/gamma-ray Pulsar glitches

→ **Triggered Analysis:** *search that uses EM or neutrino observations to drive the detection of GWs*

EM emissions

NS-NS and NS-BH mergers

GRB → prompt gamma (sec)
→ Afterglows X-ray, optical, radio
(minutes, hours, days, months)

Off-axis afterglow

Isotropic emission
Kilonovae (days)

Radio remnants
(months, years)
X-ray (min, hrs)

Core-collapse of massive stars

SBO X-ray/UV
(minutes,days)

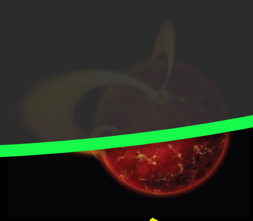
Optical
(weeks, months)

Radio
(years)

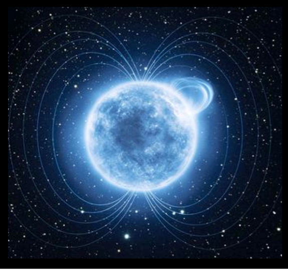
→ EM follow-up: *low-latency GW candidate events to trigger prompt EM observations and archival searches*

BH-BH mergers ?

Isolated NS instabilities

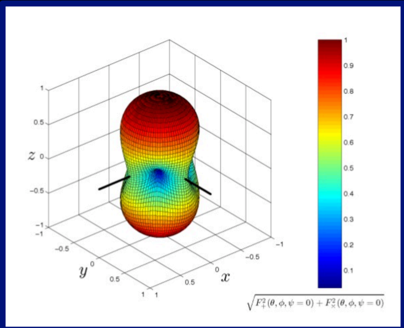


Soft Gamma Ray Repeaters and Anomalous X-ray Pulsars

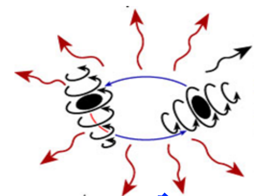


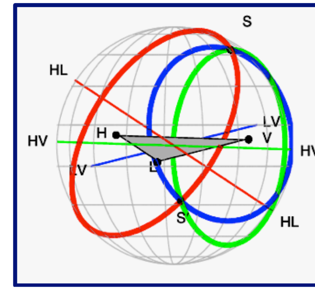
Radio/gamma-ray Pulsar glitches

Sky Localization of GW transients

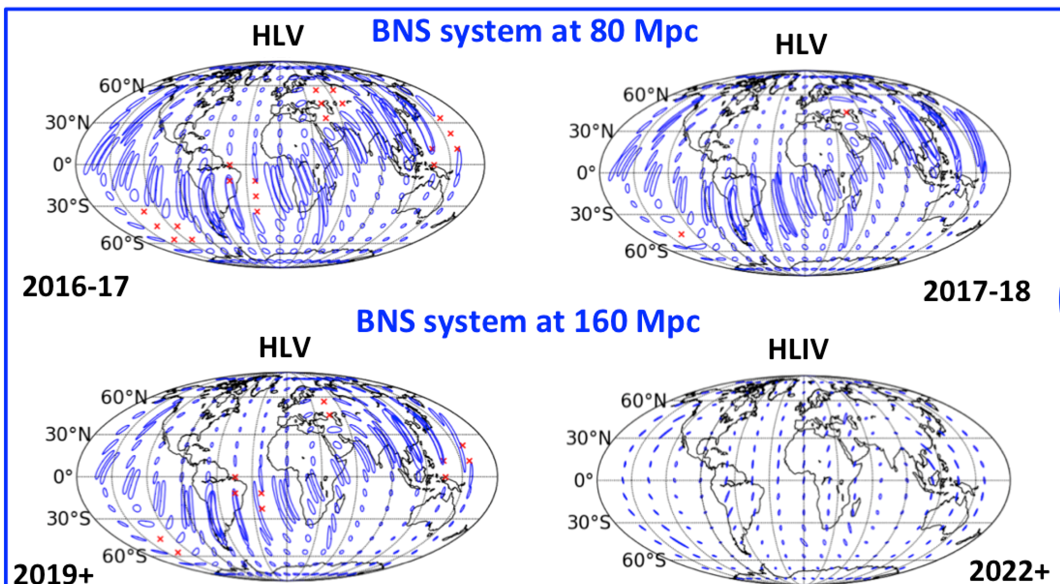


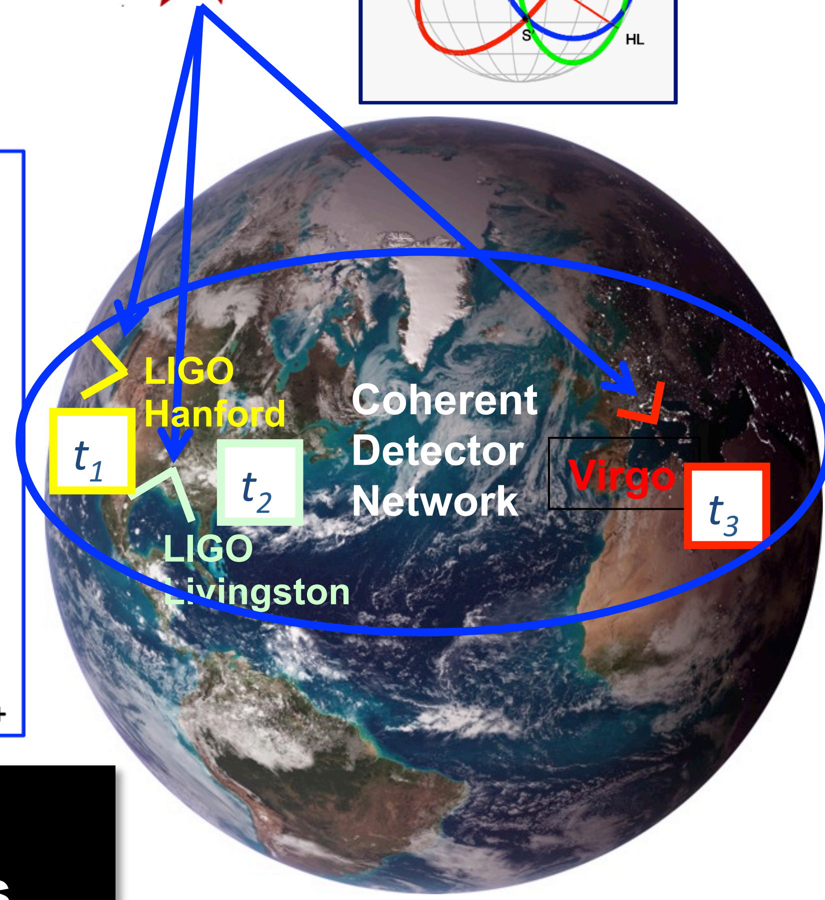
Single GW detector → **good all-sky monitor**, nearly omni-directional
But does not have good directional sensitivity, **not a pointing instrument!**





The **sky position of a GW source** is mainly evaluated by **"triangulation"** based on **arrival time delay between detector sites**





Localization uncertainties of
tens to hundreds of sq. degrees

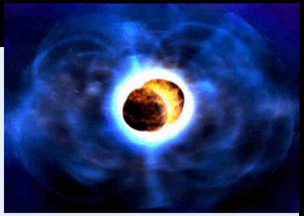
- The EM emission is expected from the high-energy to the radio with different timescales (seconds to years)
- The GW localization cover wide region of the sky

REQUIRE

- Low latency GW data analysis to detect GW candidates
- To send alert in "real-time"
- To engage worldwide EM observatories in the EM follow-up

VIRGO

LSC



In 2012, **LVC agreed policy on releasing GW alerts**

*"Initially, **triggers** (partially-validated event candidates) will be **shared promptly only with astronomy partners who have signed a Memorandum of Understanding** (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting.*

***After four GW events have been published**, further event candidates with high confidence will be **shared immediately with the entire astronomy community**, while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU."*

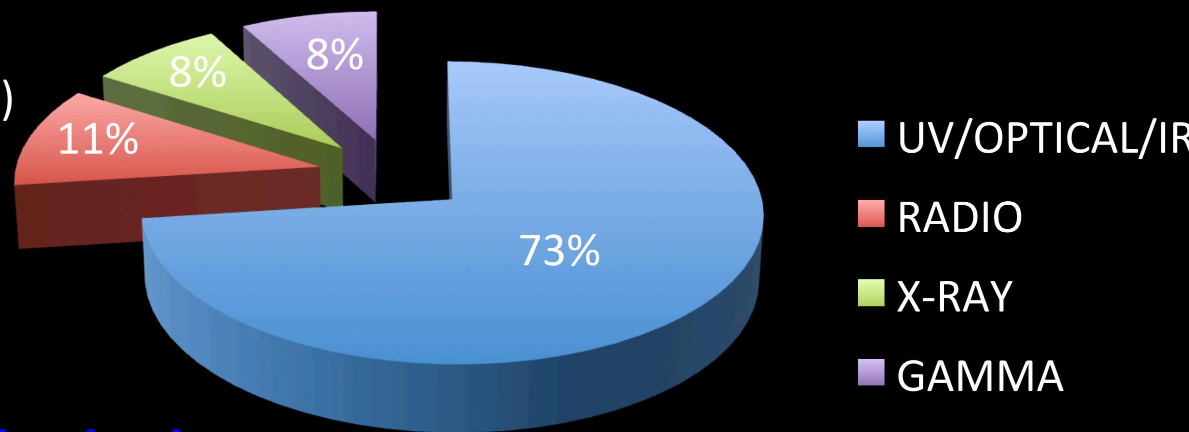
LVC GW-EM follow-up program

Seventy-four MoUs involving

- **160 instruments**

(satellites/ground-based telescopes)

covering the full spectrum from radio to very high-energy gamma-rays!



- *Worldwide astronomical institutions, agencies and large/small teams of astronomers*

63 teams of astronomers were ready to observe during O1 (September 2015 – January 2016)!

Low-latency GW data analysis pipelines to promptly identify GW candidates and send GW alert to obtain EM observations

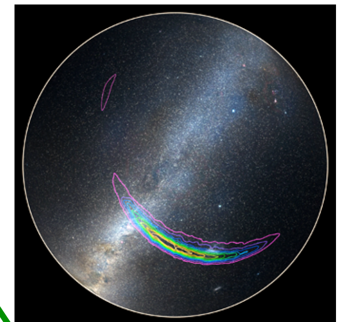
GW candidates

Sky Localization

EM facilities

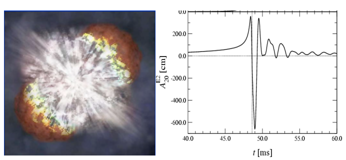
LIGO-H LIGO-L

Virgo

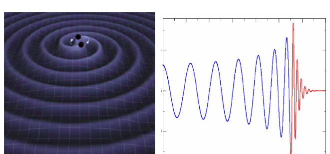


Event validation

Low-latency Search
to identify the GW-candidates

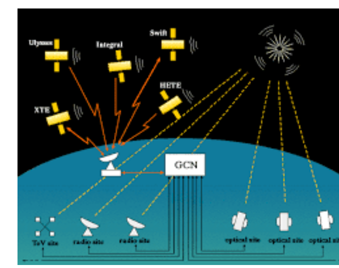


Unmodeled GW burst search



Matched filter with waveforms of compact binary coalescence

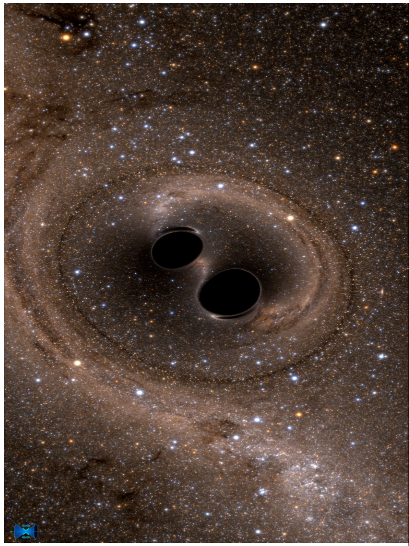
Software to
- select statistically significant triggers wrt background
- Check detector sanity and data quality
- determine source localization

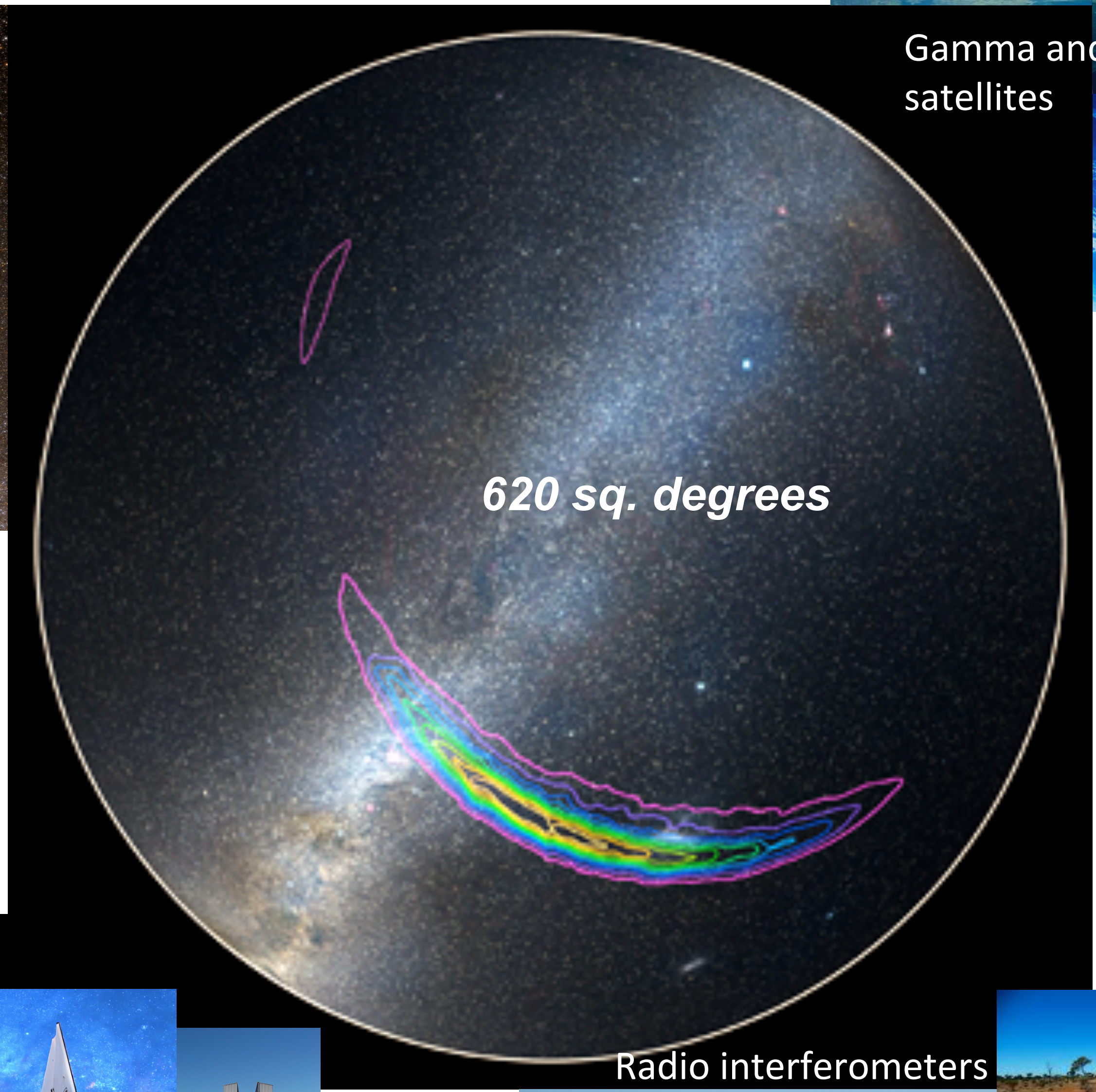


→ a few min → 15/30 min

Parameter estimation codes → Hours,days → GW candidate updates

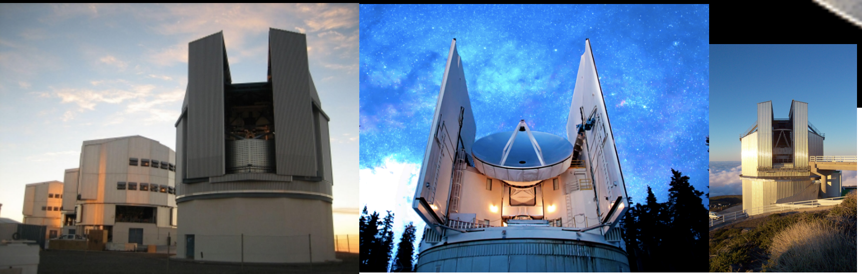
GW150914, hunting the EM signals…





Gamma and X-ray satellites

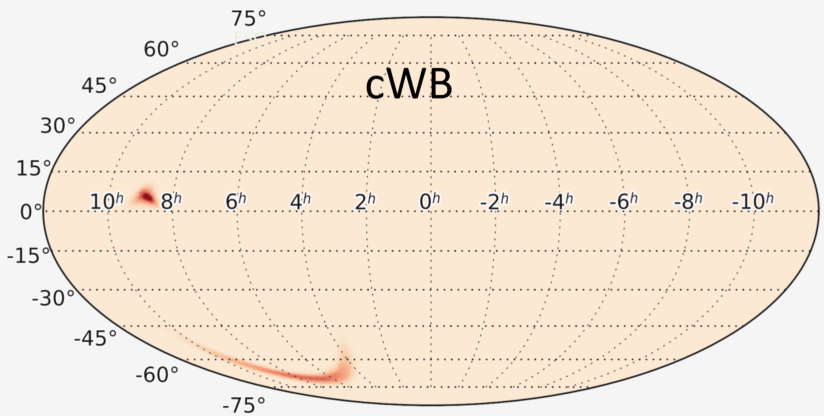
Optical telescopes

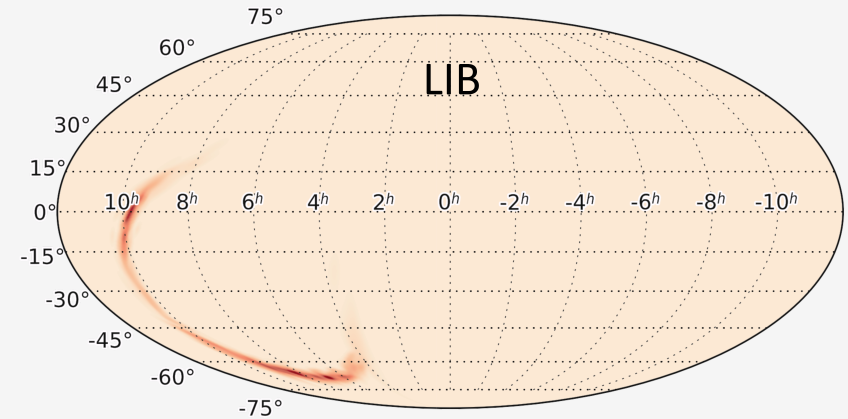


Radio interferometers

- **16 Sept 05:39 *UTC*** *notification about the trigger identified by the online Burst analysis during ER8 (GCN 18330)*

Burst sky maps

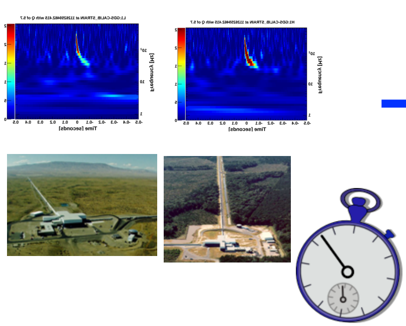




Event time *2015-09-14 09:50:45 UTC* ***FAR*** *1.178e-08 1/3 yr*

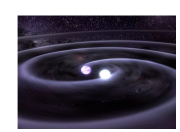
The 50% credible region spans about 200 deg^2 and the 90% region about 750 deg^2

- **03 Oct 23:41 *UTC*** *update → waveform reconstruction appears consistent with expectations for a* ***binary black hole coalescence*** *(GCN 18388)*

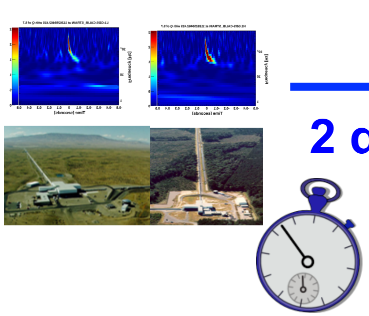


~ 2 days

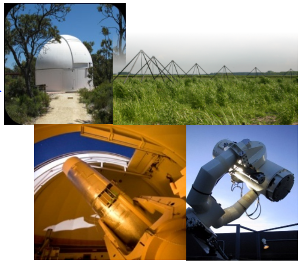
19 days



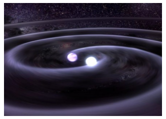
- **12 Jan 2016** *update* → offline calibration and re-analysis ***FAR < 1/100 yr*** *(GCN 18851)*
- **13 Jan** *update* → **Refined localizations** from CBC parameter estimation *(GCN 18858)*



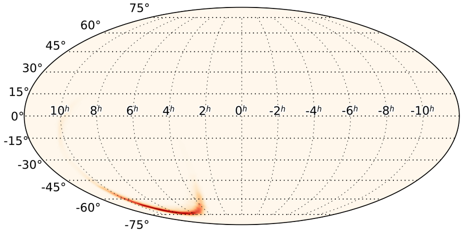
2 days



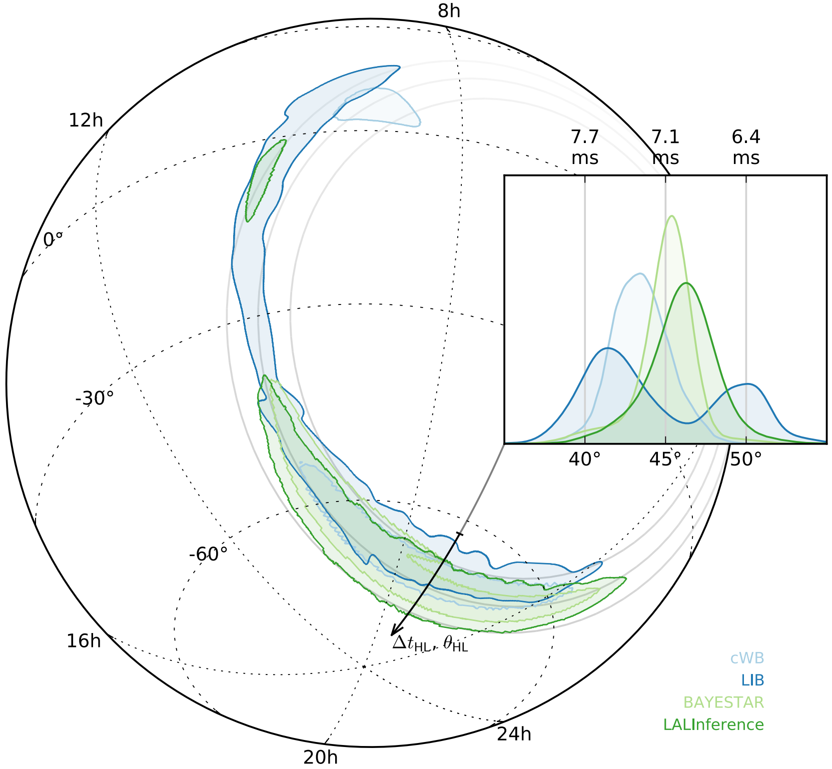
19 days



4 months



LALInference

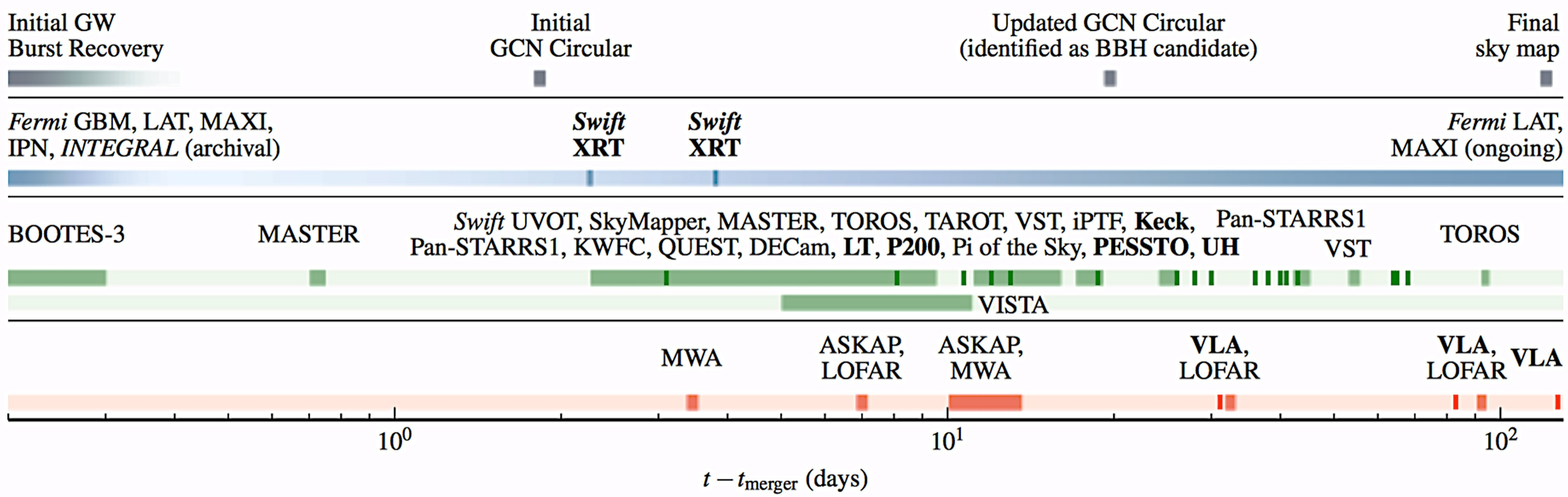


	Area[a]		
	10%	50%	90%
cWB	10	100	310
LIB	30	210	750
BSTR	10	90	400
LALInf	20	150	620

EM follow up observations and archival searches

- ***Twenty-five teams*** *of observers responded to the GW alert*

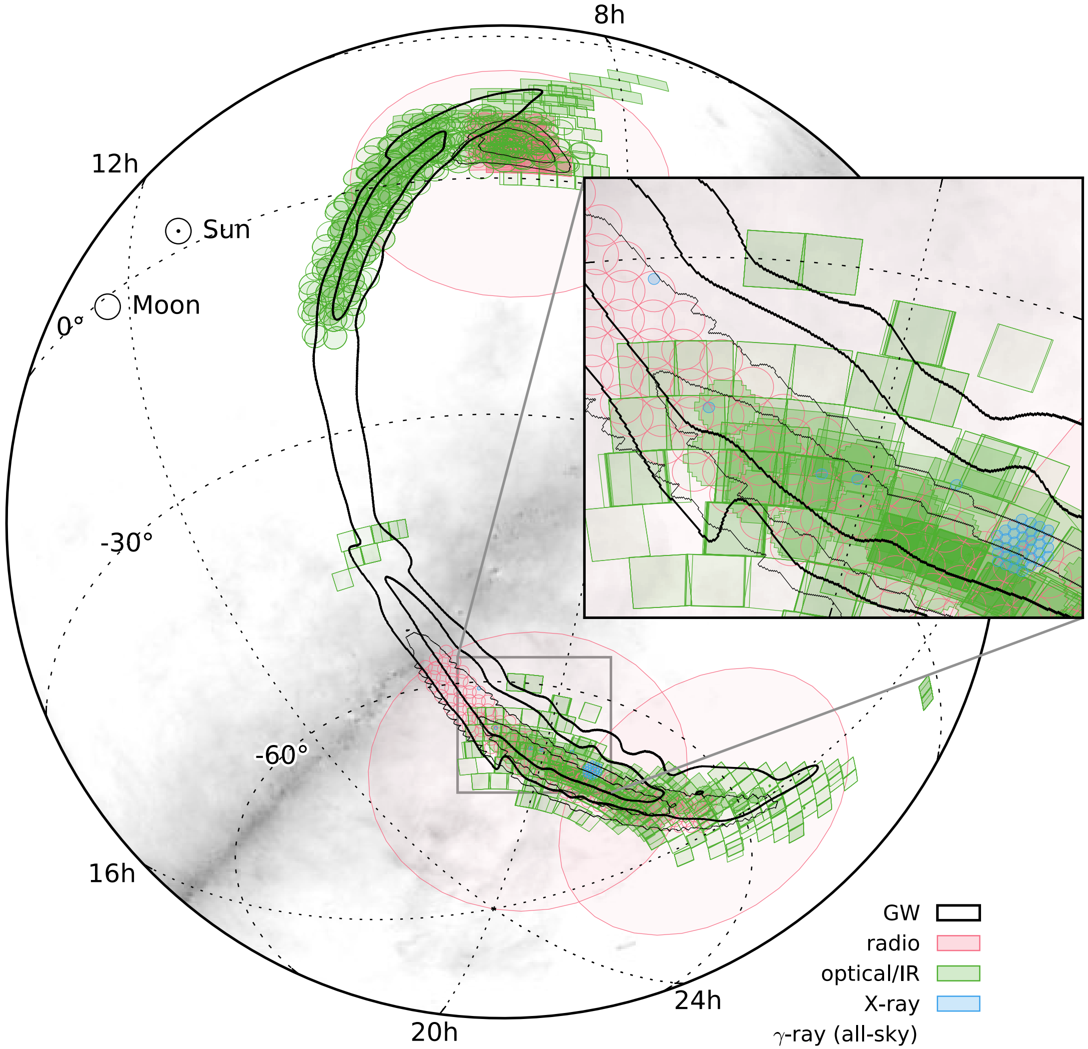
- *The EM observations involved* ***satellites and ground-based telescopes*** *around the globe spanning 19 orders of magnitude in frequency across the EM spectrum*



Paper submitted to ApJL
arXiv:1602.08492

ASKAP, LOFAR, MWA, Fermi/GBM, Fermi/LAT, **INTEGRAL**, IPN, **Swift**, MAXI, BOOTES, MASTER, Pi of the Sky, DES/DECam, **INAF/GRAWITA**, iPTF, J-GEM/KWFC, La Silla–QUEST, Liverpool Telescope, **PESSTO**, Pan-STARRS, SkyMapper, TAROT, Zadko, TOROS, VISTA

Sky map coverage



The astronomer teams tiled portions of the GW sky maps. Some groups, considering the possibility of a NS merger or core-collapse SN, selected fields based on nearby galaxies or pointed at the Large Magellanic Cloud

Skymap coverage/Depth and Results Summary

Most complete coverage in the **gamma-ray down to 10^{-7} erg cm^{-2} s^{-1}**

X-rays coverage complete down to 10^{-9} erg cm^{-2} s^{-1} (MAXI), relatively **sparse at fainter flux** with the Swift XRT

Fermi-GBM sub-threshold search → **weak signal** of 1 sec 0.4 s after the event

fluence (1 keV - 10 MeV) = 2.4×10^{-7} erg cm^{-2}

FAR 4.79×10^{-4} Hz, FAP 0.0022

(**Connaughton et al. arXiv:1602.03920**)

INTEGRAL → no signal but **stringent upper limit**

(**Savchenko et al. 2016 ApJL, 820**)

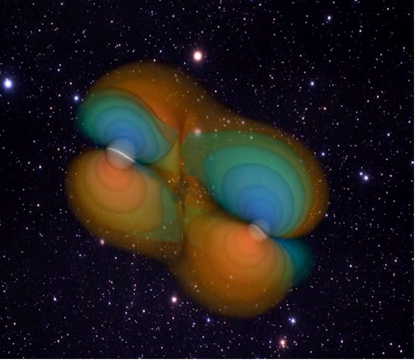
No signal detected by **AGILE** (Tavani et al. arXiv:1604.00955) and **MAXI**

Optical facilities together tiled about **870 deg^2** with a **contained probability of 57% of the initial sky map** and only **36% of the refined sky map**.

The **depth varies widely** among these facilities

Deep photometry, broadband observations and spectroscopy → candidates to be normal population type Ia and type II SNe, dwarf novae and active galactic nuclei, all very likely unrelated to GW150914

The **radio coverage is also extensive**, with the contained probability of 86%, dominated by **MWA** down to **200 mJy**



*EM follow-up of GW150914 demonstrates the **capability to cover large area**, to **identify candidates**, and to rapidly **activate larger telescopes***

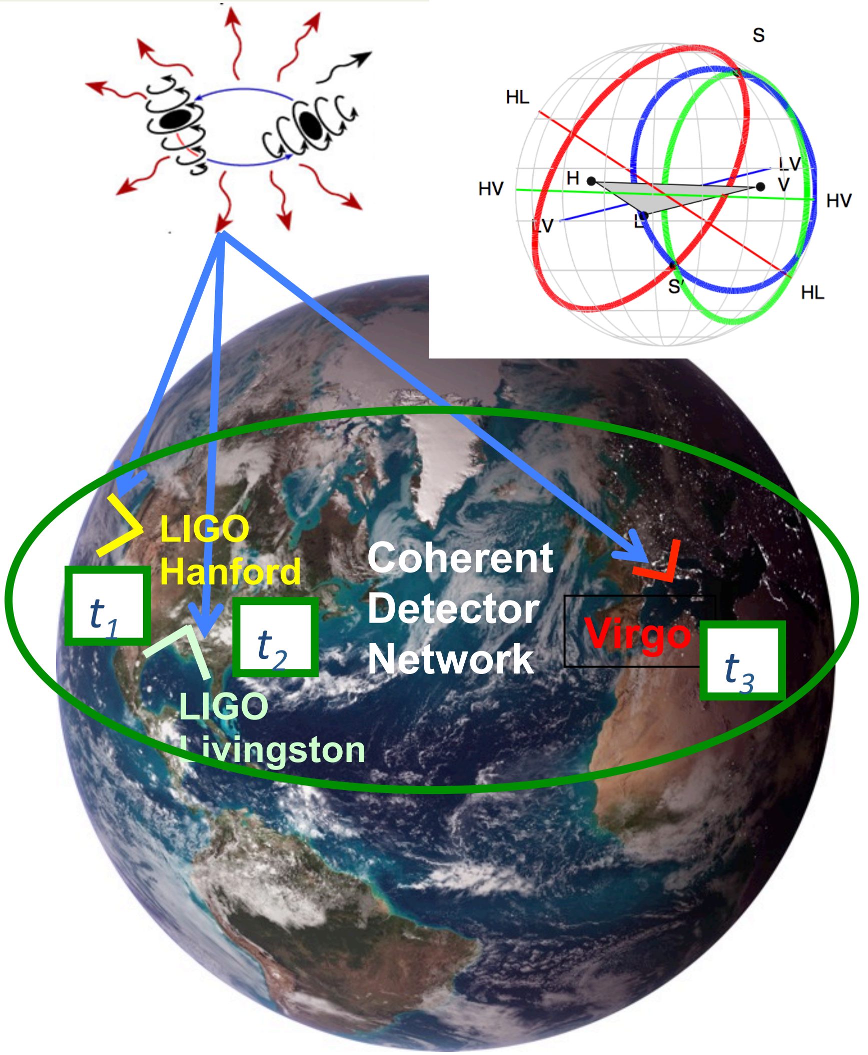
The follow-up campaign sensitive to emission expected from BNS mergers at 70 Mpc range
The widely variable sensitivity across the sky localization is a challenge for the EM counterpart search

Future EM follow-ups of GW will shed light on the presence or absence of firm EM counterparts for BBH

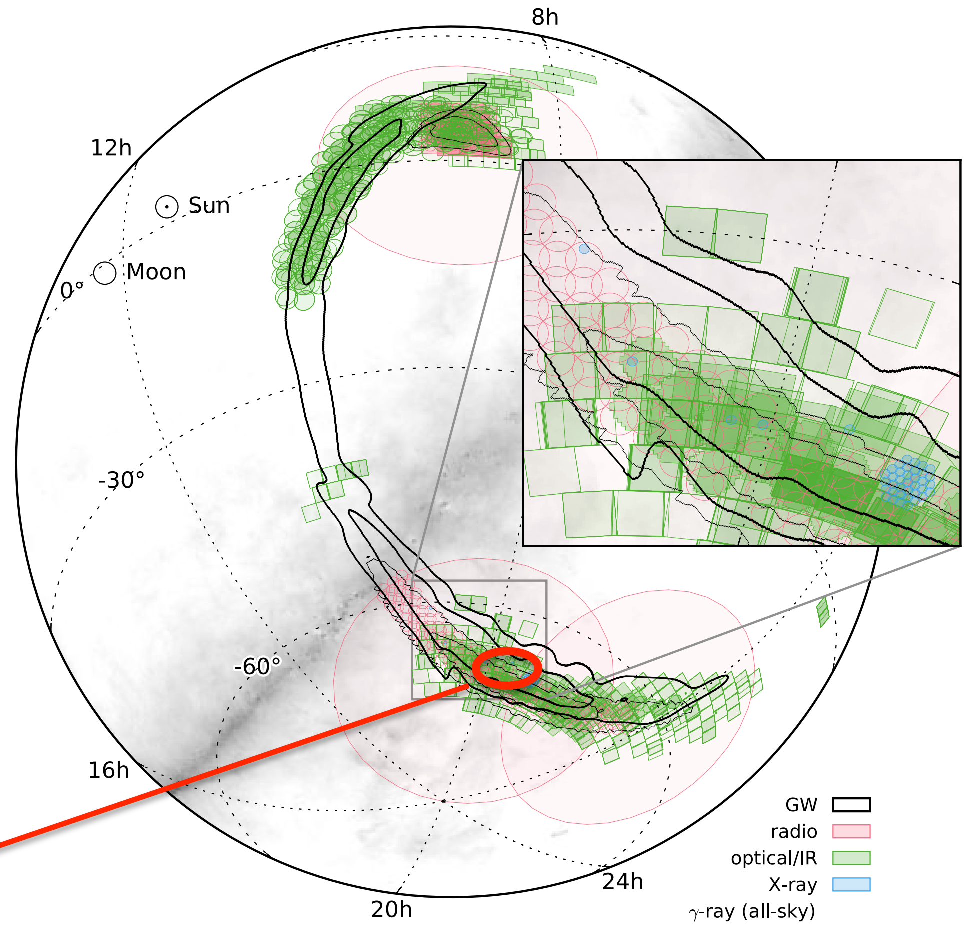
Number of galaxies *within the GW150914 comoving volume of 10^{-2} Gpc^3*

10^5 galaxies *→ impossible to identify the host galaxy in the absence of EM counterpart detection*

Perspectives with Virgo on-line for GW150914 event-like

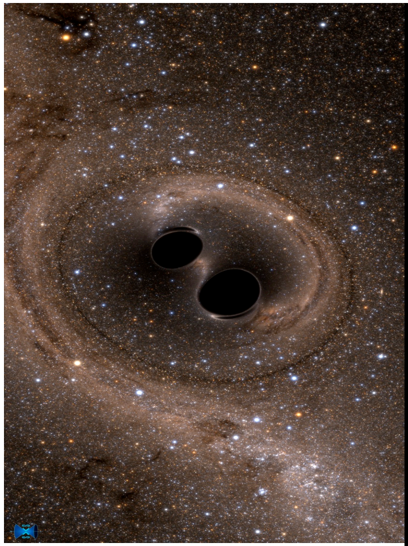


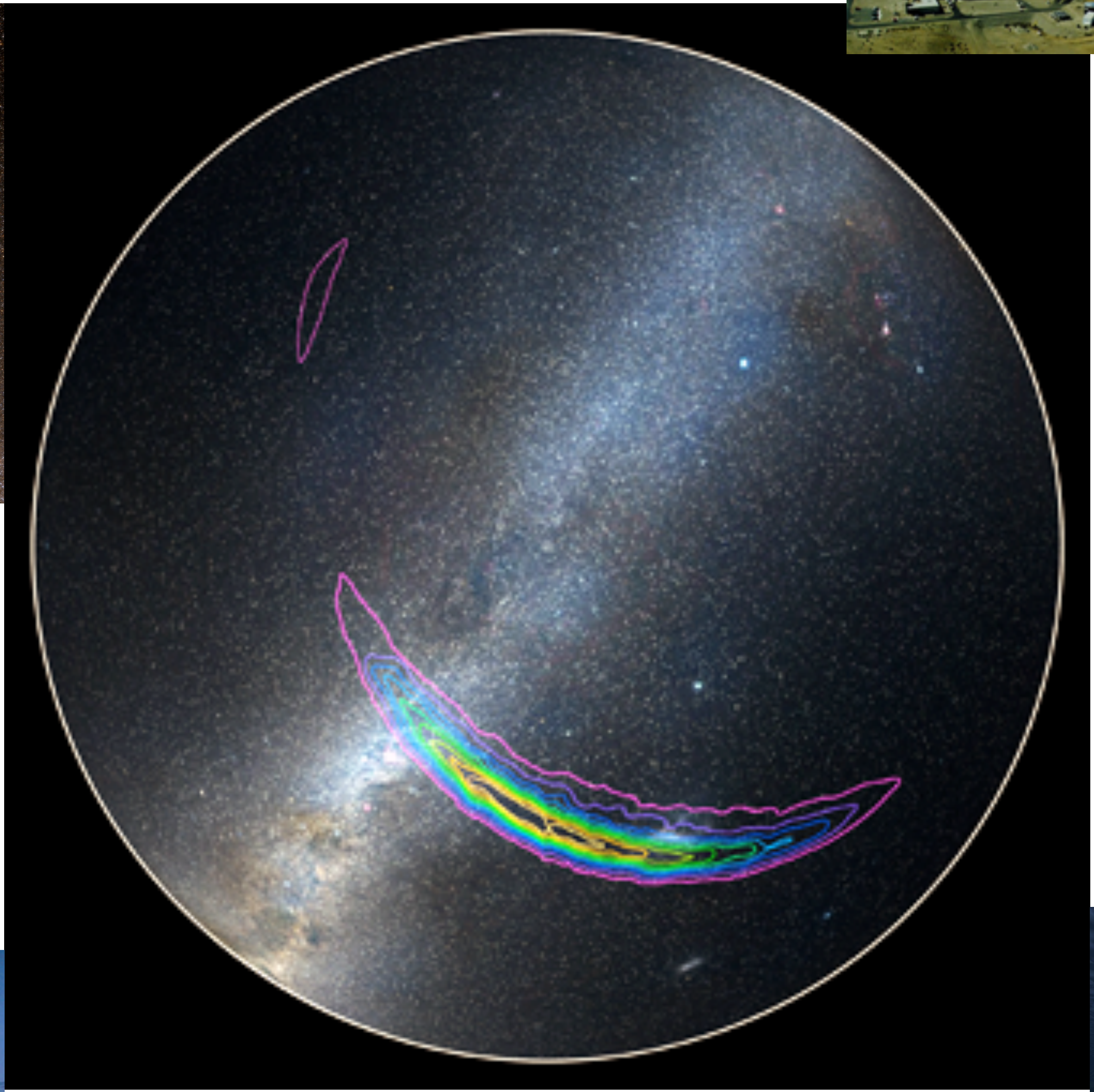
Enabling multi-messenger astronomy with gravitational waves



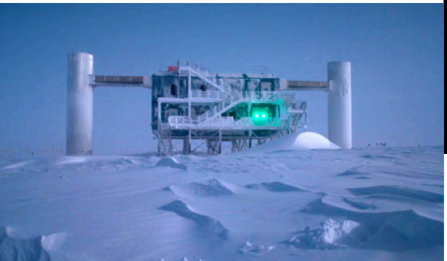
The sky localization of GW150914
*with Virgo **few tens of deg2***
Virgo will significantly improve the
efficiency of the EM searches!

GW150914 neutrino search…

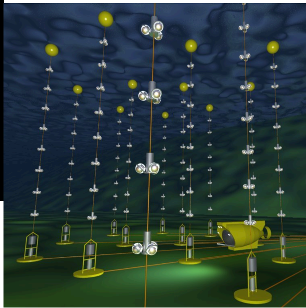




IceCube



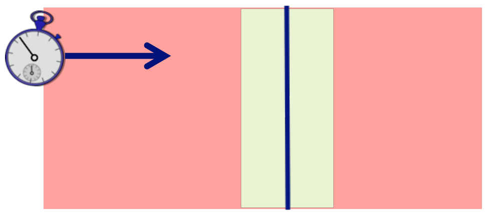
ANTARES



High-Energy Neutrino Follow-up of GW150914

Search for coincident neutrino candidates within data of **IceCube** and **Antares**

Δt ~ 1000 s

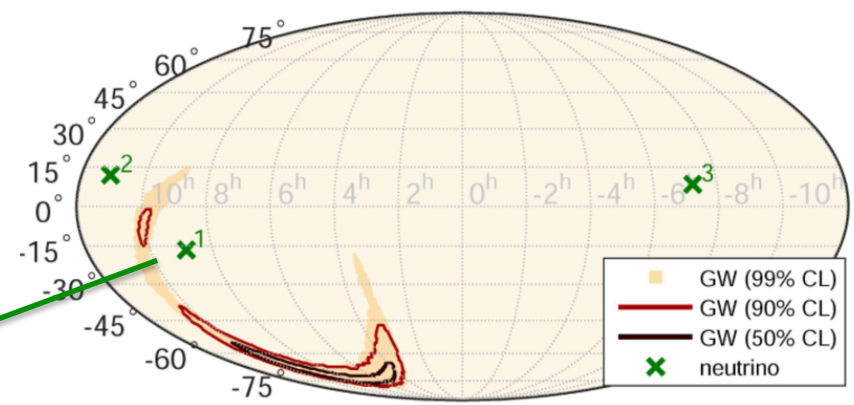


GW150914

Within ±500 s of GW150914:
IceCube neutrino candidates **3**
ANTARES neutrino candidate **0**

- Consistent with the expected atmospheric background
- No neutrino candidate directionally coincident with GW150914

#	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]	fraction
1	+37.2	8.84	−16.6	0.35	175	12.5%
2	+163.2	11.13	12.0	1.95	1.22	26.5%
3	+311.4	−7.23	8.4	0.47	0.33	98.4%

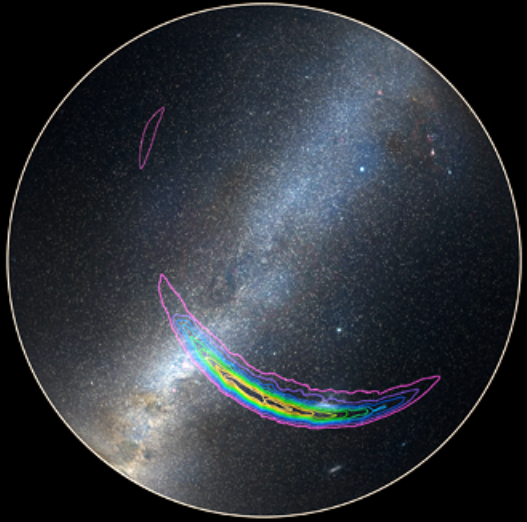


Small angular uncertainties

No-detection is consistent with our expectation from a binary black hole merger

A rapid GW/neutrino detection could be used in targeted EM follow-up

Adrián-Martínez arXiv:1602.05411

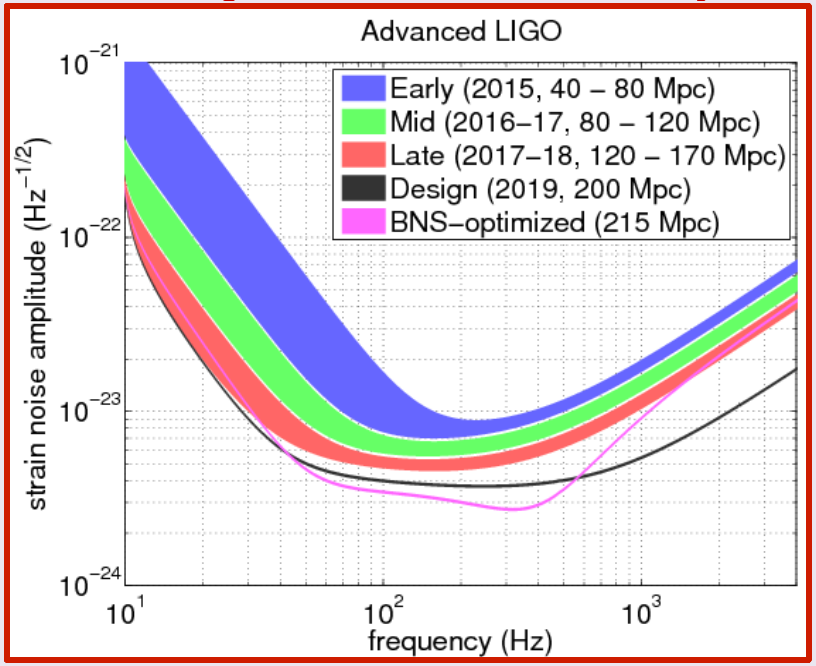


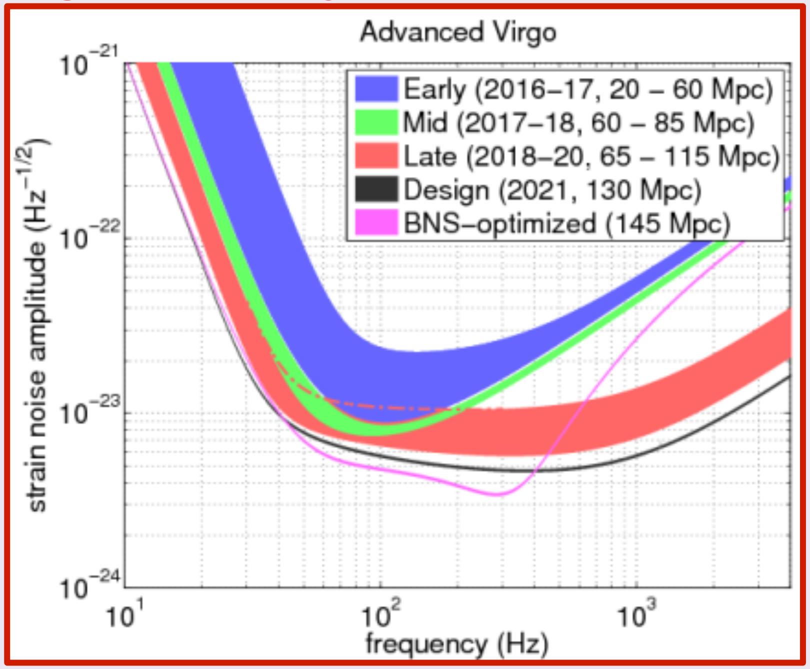
The Advanced LIGO and Virgo project schedules, the detectors sensitivity, sky localization accuracy, and prospects for detection rates

Prospects of Observing and Localizing GWs

LVC 2016, Living Reviews in Relativity, 19

Progression of sensitivity and range for Binary Neutron Stars

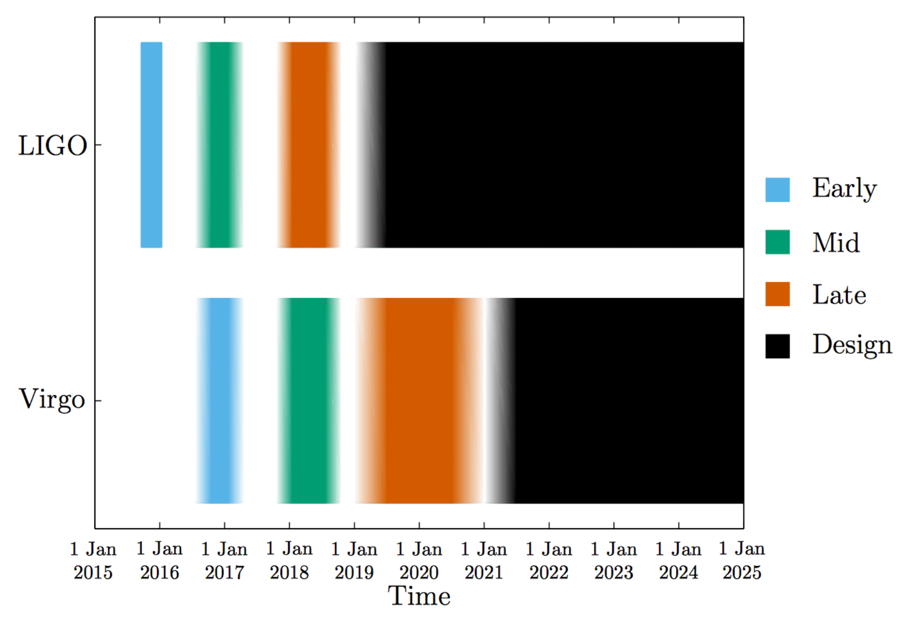




Larger GW-detectable Universe

Prospects of Observing and Localizing GWs

Sensitivity evolution and observing runs



Observing schedule, sensitivities, and source localization

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	—	—	—

Advanced detectors Rate and Range (design sensitivity)

Compact binary coalescence

	Source	Low yr^{-1}	Real yr^{-1}	High yr^{-1}	Max yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

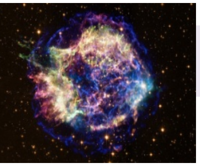
(Abadie et al. 2010, CQG 27)

Mass: NS = 1.4 Mo
BH = 10 Mo

Advanced era

Sky location and orientation averaged range

197 Mpc for NS-NS
410 Mpc for NS-BH
968 Mpc for BH-BH



Core-Collapse Supernovae

About **2 per century** in a Milky way equivalent galaxy **(Li 2011, Cappellaro 1999)**
2 per year within **20 Mpc** **(Li 2011)**

Rate of GW-detectable events unknown

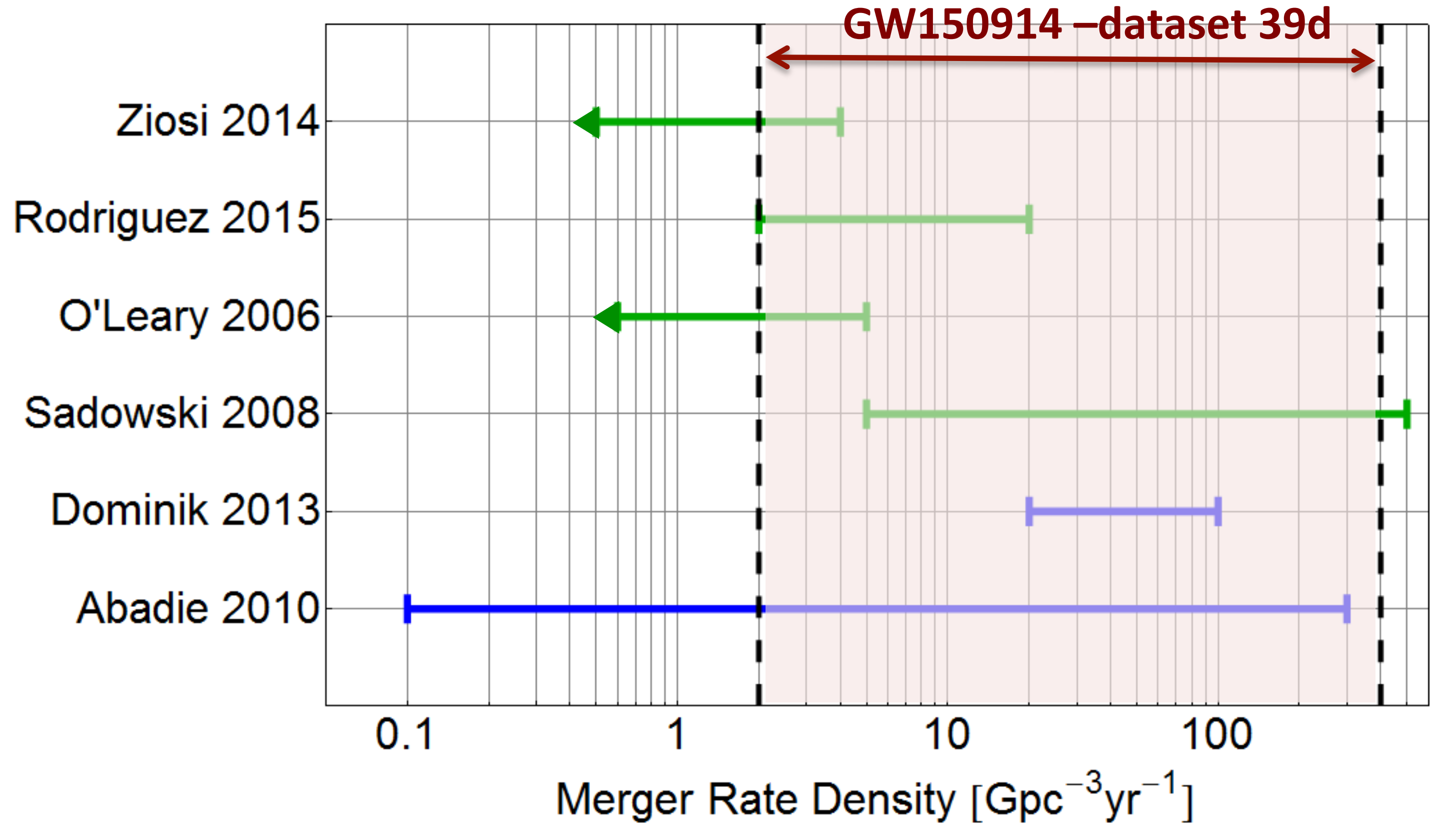
GW-signal detectable **Milky Way** **(Ott et al. 2012)**

Optimistic models **Tens of Mpc** **(Fryer & New 2011)**

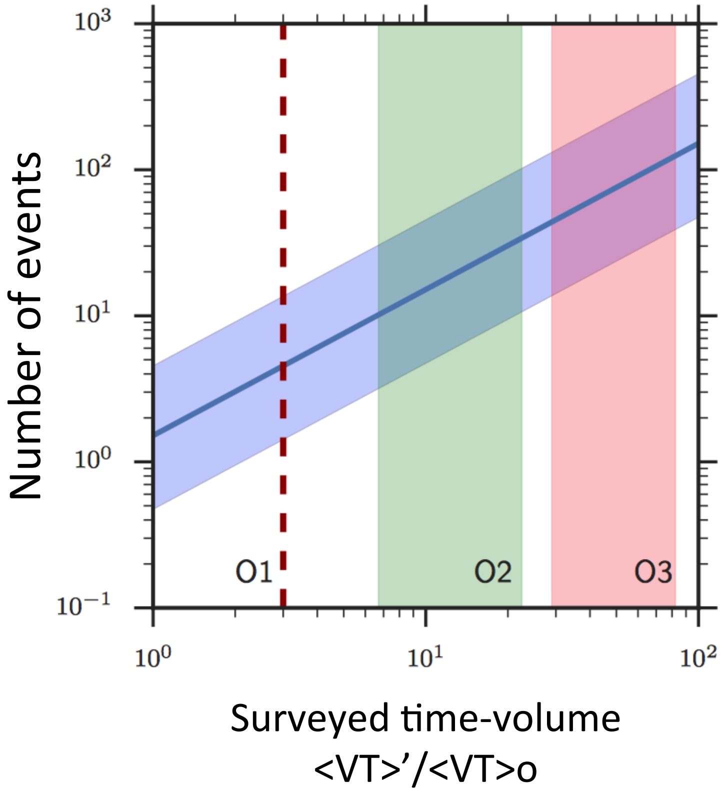
Binary Black-Hole merger rates

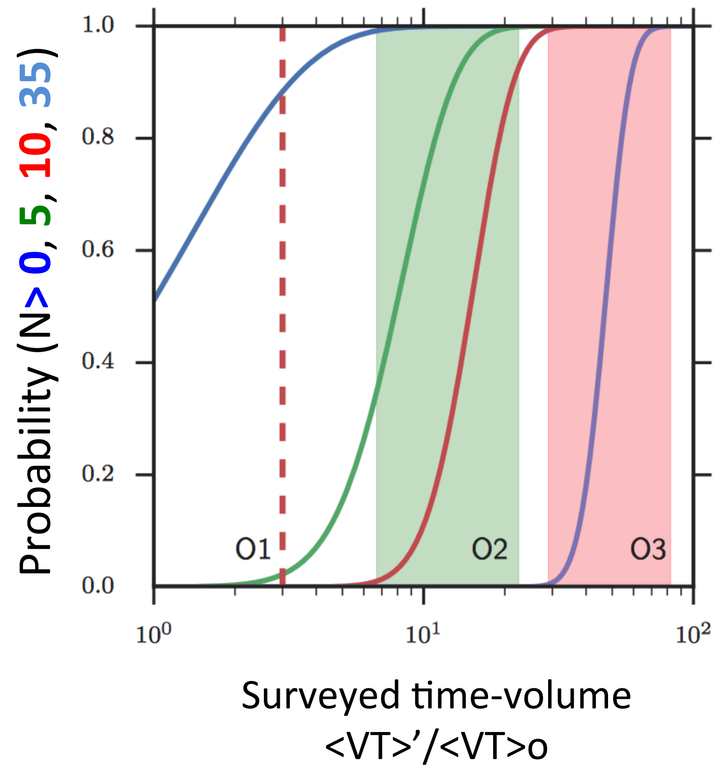
BBH merger rate 2 - 400 Gpc^{-3} yr^{-1} **(LVC 2016 arXiv:1602.03842)**

The rate is consistent with most BBH rate predictions. Only the lowest can be excluded.



Expected number of highly significant BBH events (FARs <1/century)



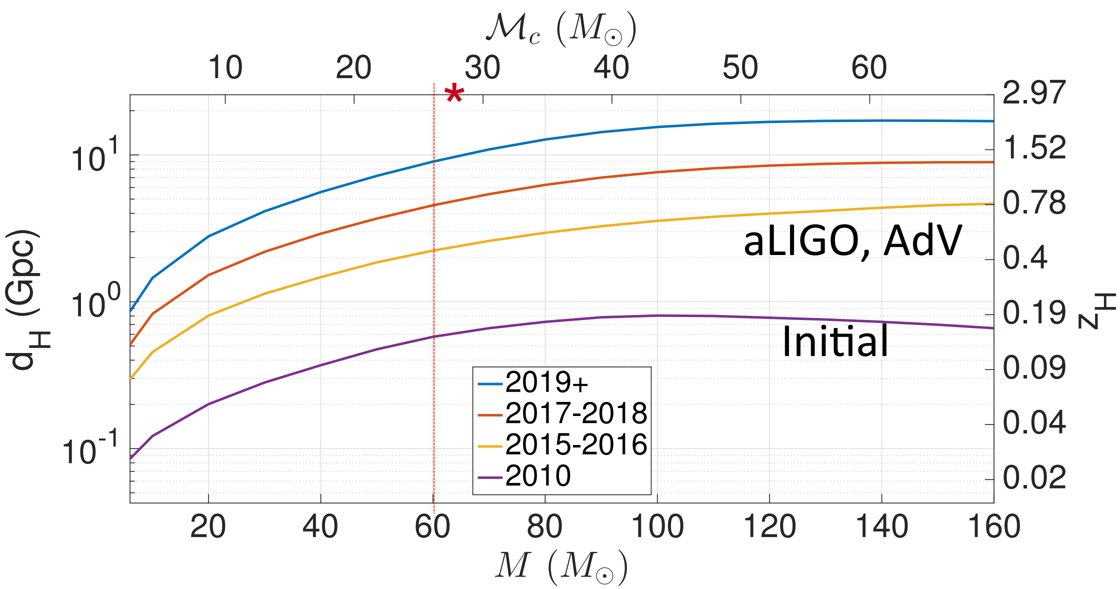


Volume for an equal-mass binary with non-spinning components and total mass 60 Mo, assuming 6 months for O2 and 9 months for O3

Median value for **O2 → 10-30 events** for **O3 → 40-120 events**

The expected number of highly significant events is > 1 at 90% confidence for any experiment surveying about twice <VT>o

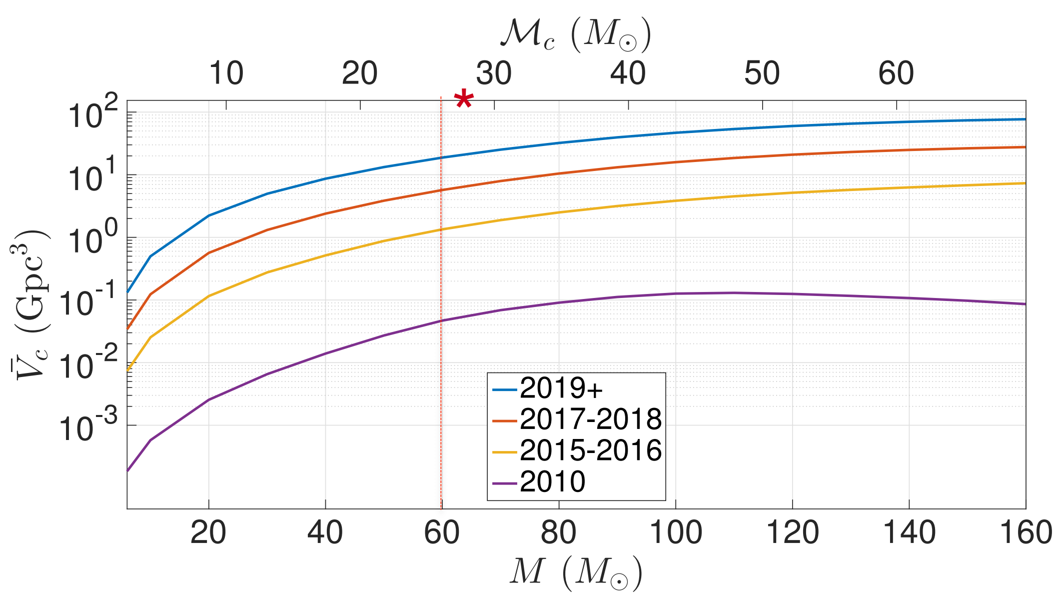
Binary Black-Hole horizon and surveyed volume

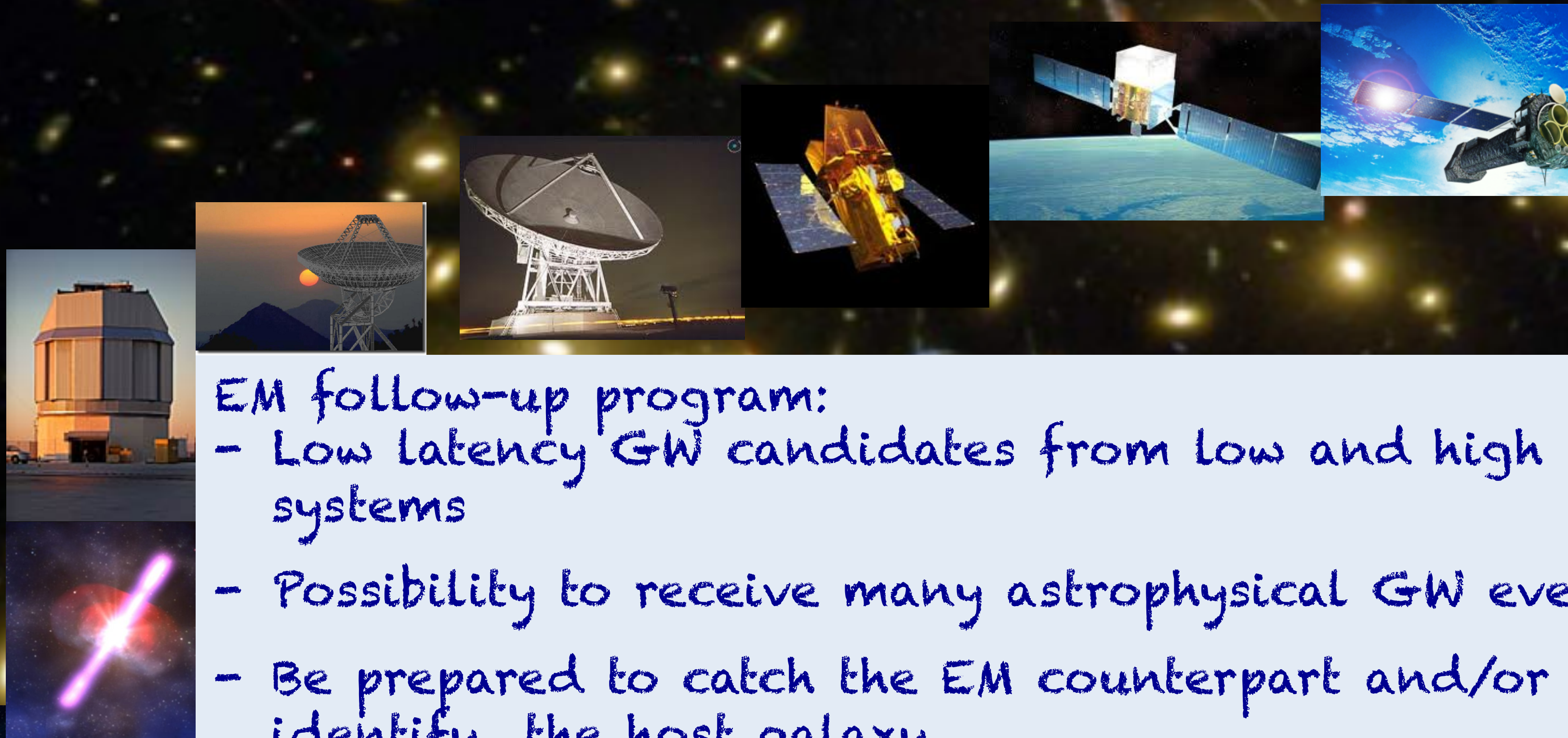


Horizon distance *as function of chirp mass/total mass for a 8 SNR detection of equal mass, non spinning BBH mergers*

Surveyed comoving volume

R = constant merger rate → **expected number of detections** during an observing run of duration *T* is given by ***(R*V*T)***





EM follow-up program:

- Low latency GW candidates from low and high mass systems
- Possibility to receive many astrophysical GW events
- Be prepared to catch the EM counterpart and/or identify the host galaxy