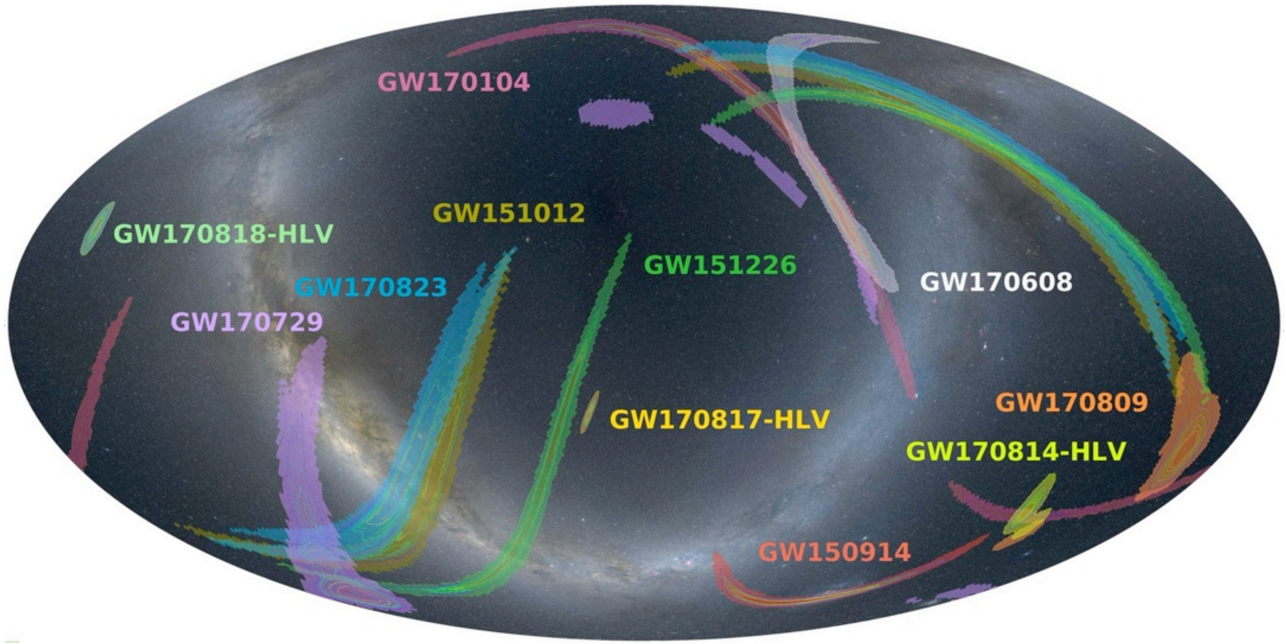
Recent gravitational-wave results from Advanced LIGO and Virgo

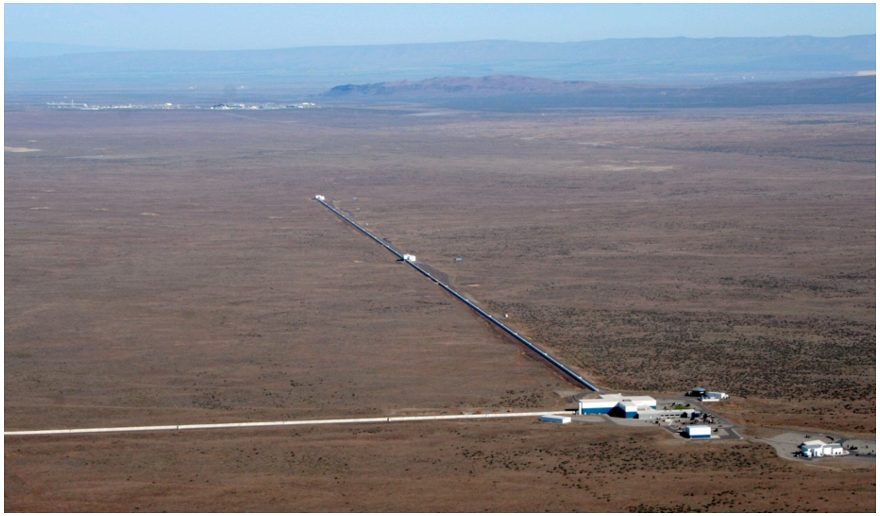


VIRGO

José Antonio Font
Universitat de València
www.uv.es/virgogroup

Our current GW detector network

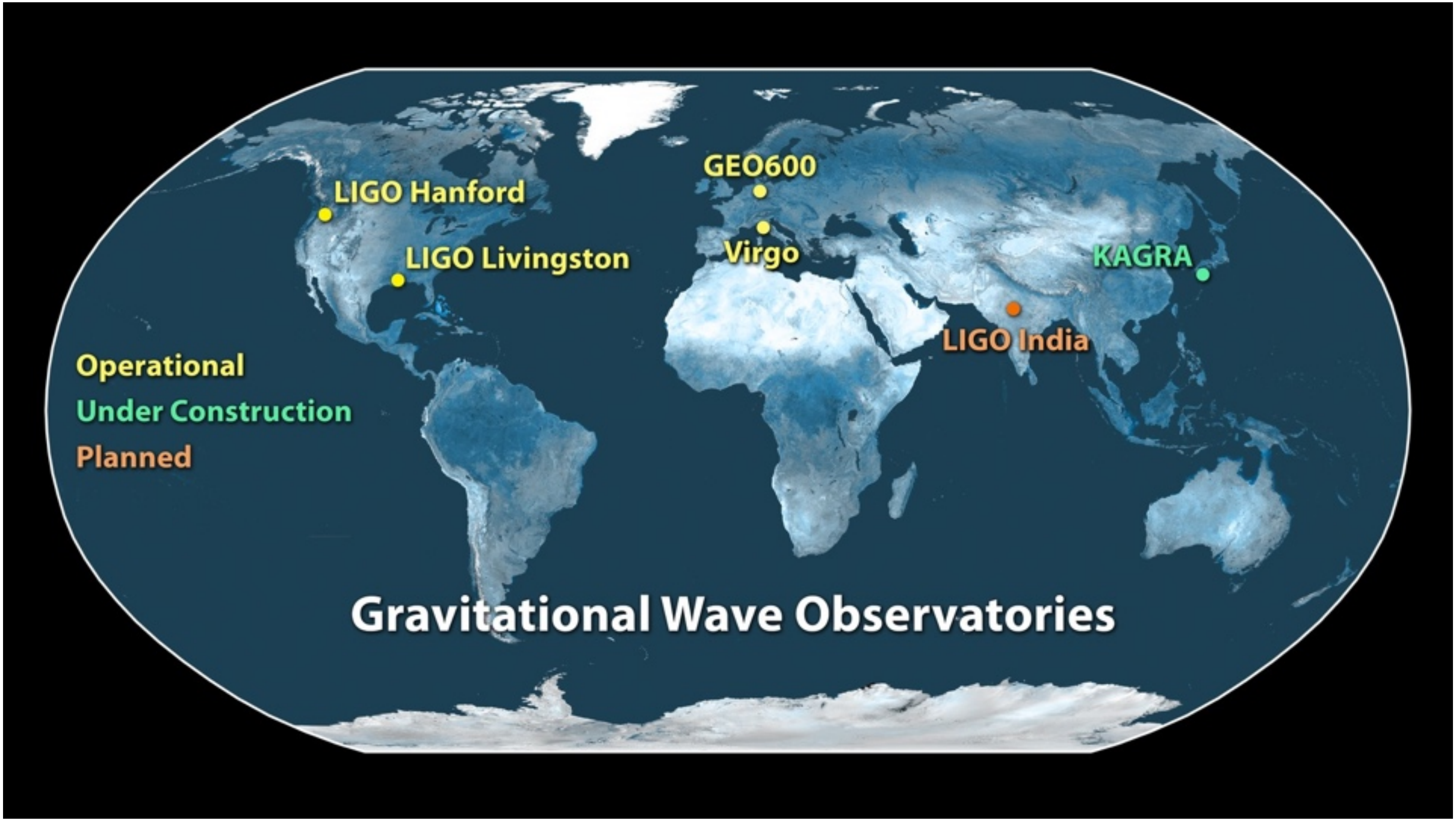
LIGO Hanford Observatory



LIGO Livingston Observatory

Virgo Observatory

Towards a global infrastructure



KAGRA inaugurated on October 4, 2019

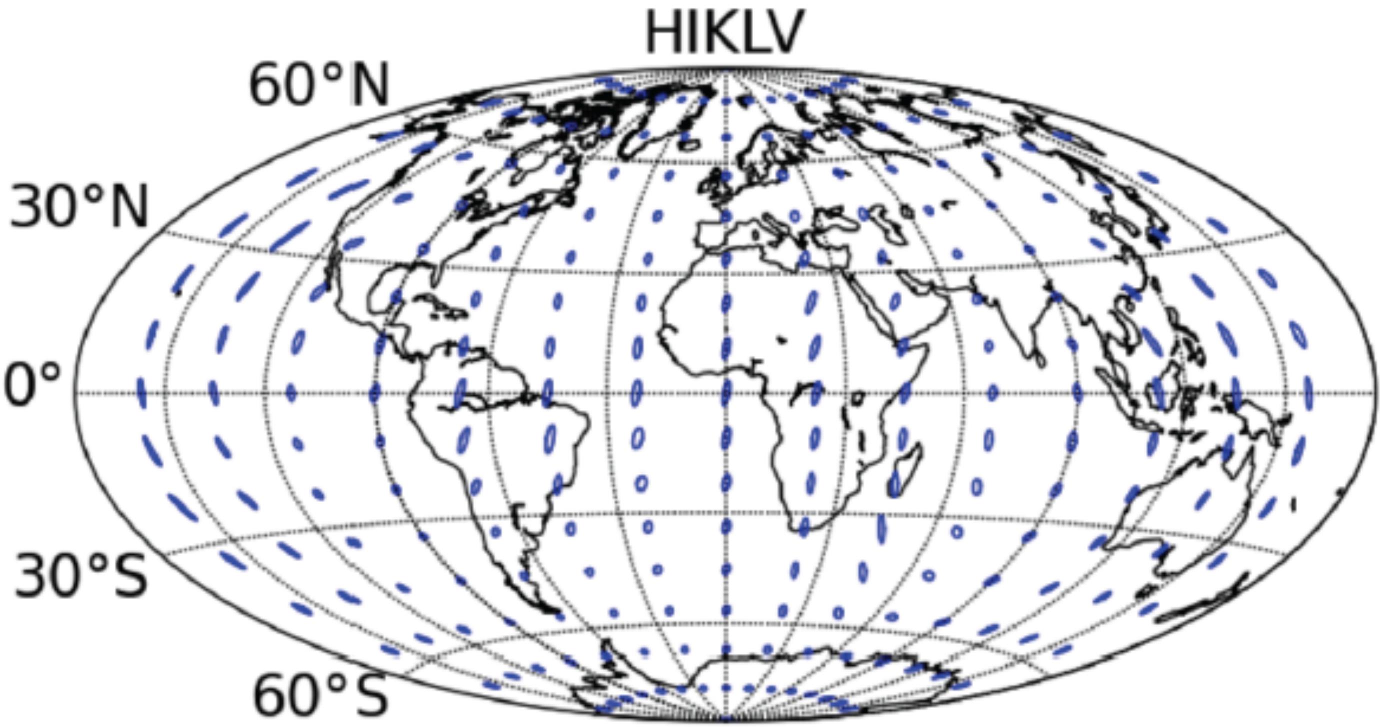
MoA signed with LIGO and Virgo

LIGO-India: construction has started

4 km IFO at Hingoli in Maharashtra, about 450 km from Pune

LIGO-India: online 2024?

Mid-term goal



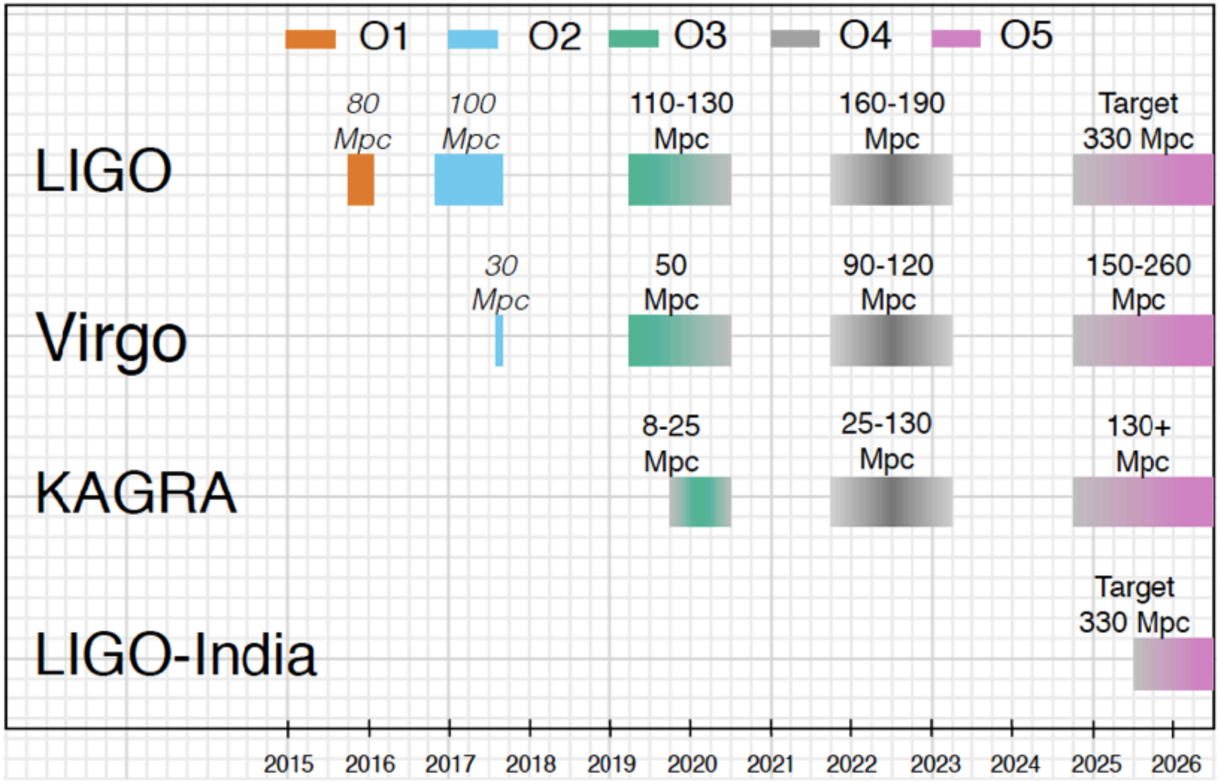
S Fairhurst, CQG 28, 2001

Sky localization capability of advanced detectors by mid 2020s. 5 detector network.

More than 60% of sources could be localized with an accuracy better than **10 deg²** (GW170817 had an uncertainty of 28 deg²).

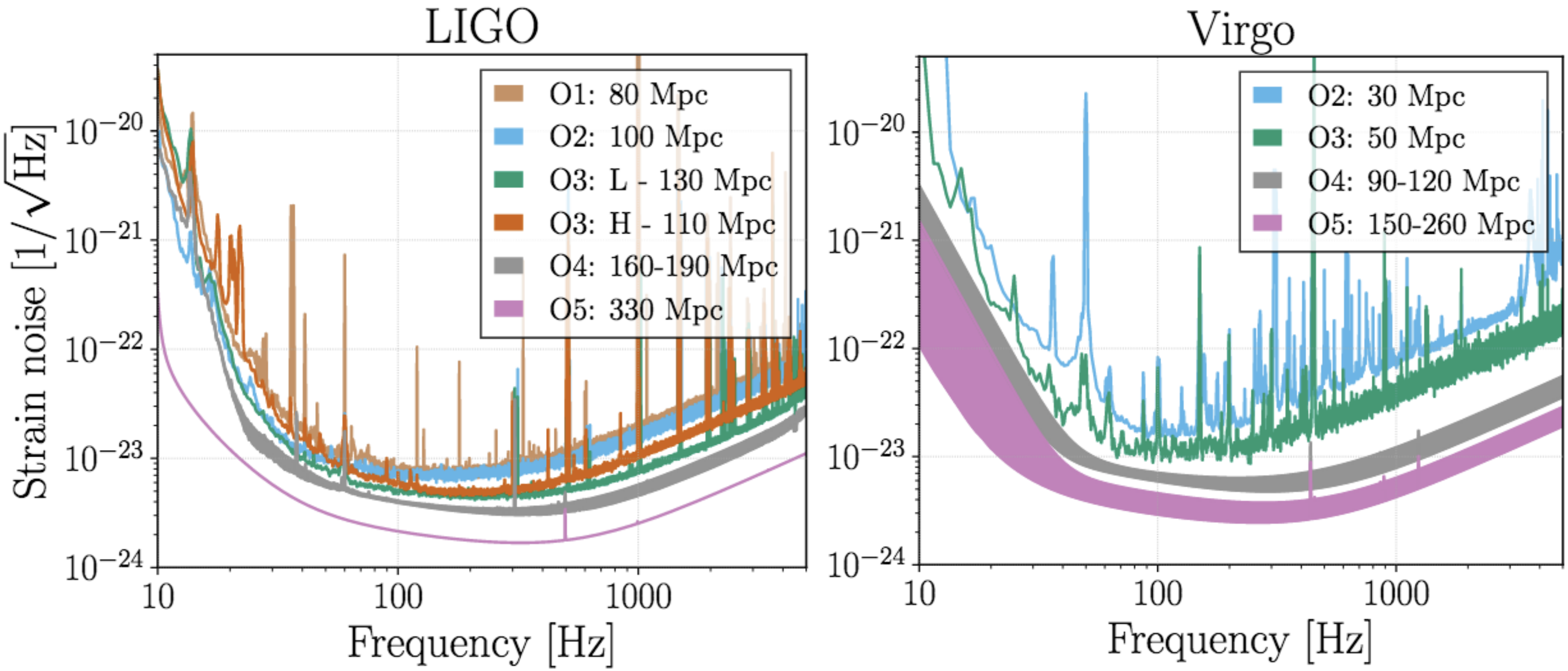
LIGO/Virgo observing runs & BNS range

O1: Sep 12 2015 - Jan 19 2016.
O2: Nov 30 2016 - Aug 25 2017. [Virgo joined on Aug 1]
O3: Apr 1 2019 - Apr 30 2020. [KAGRA to join towards the end]



See Abbott et al, arXiv:1304.0670 (updated Sep 2019)

LIGO/Virgo strain sensitivities



See Abbott et al, arXiv:1304.0670 (updated Sep 2019)

Scientific impact of science with GWs

Multi-Messenger Astrophysics has started: a large community of scientists interested in new gravitational-wave detections.

Fundamental physics

Access to the strong-gravity regime. New tests of General Relativity.
Black hole physics: inspiral, merger, ringdown, quasi-normal modes, echoes.
Lorentz invariance, equivalence principle, polarization, parity violation, axions.

Astrophysics

Observations of BNS mergers. BNS/sGRB association.
Support for the kilonova model, explanation for heavy element nucleosynthesis.

Astronomy

Birth of Gravitational-Wave Astronomy. Studies of populations, progenitors formation, remnants.

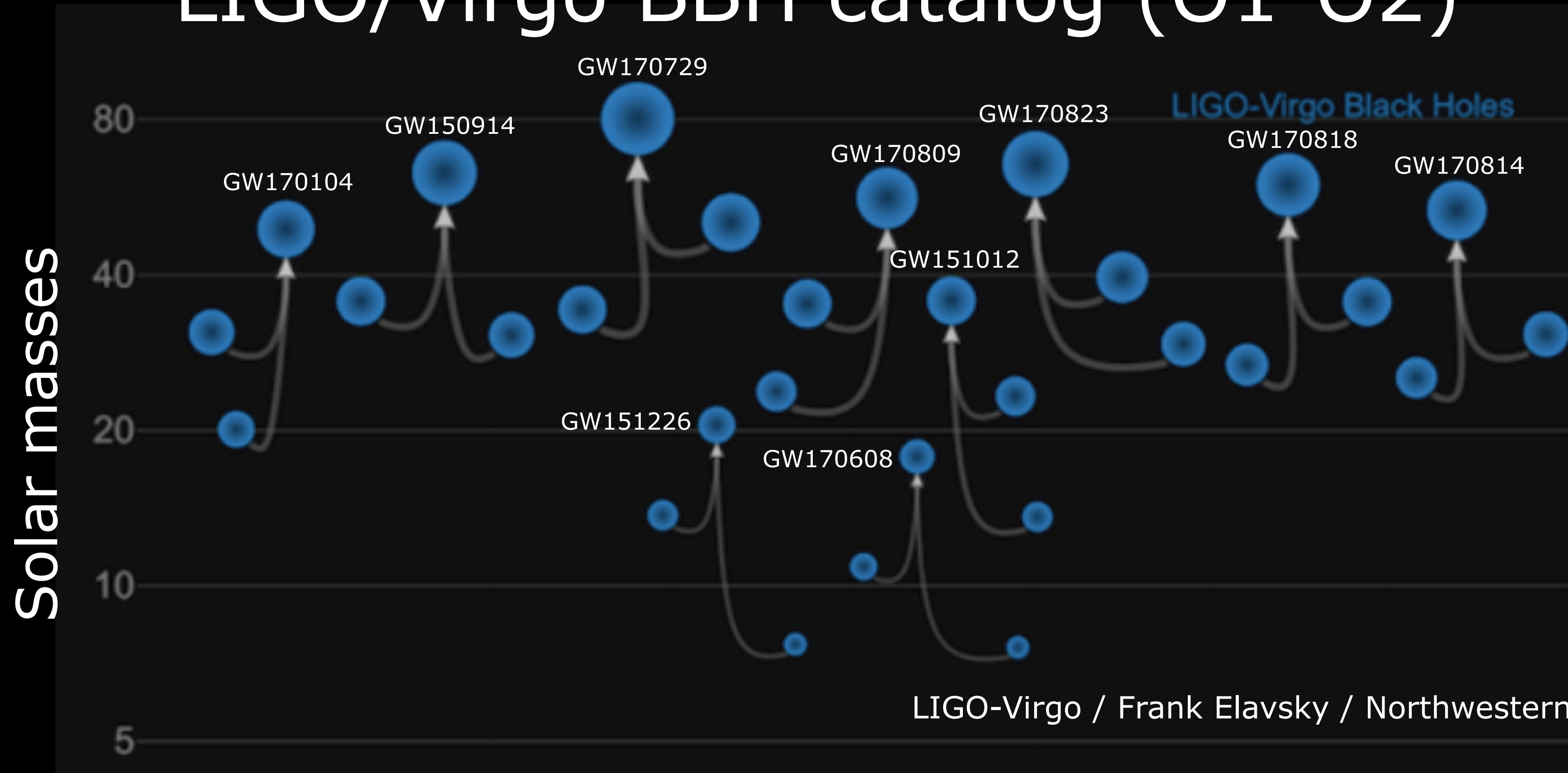
Cosmology

BNS used as standard sirens. Dark matter and dark energy.

Nuclear physics

Tidal deformability information imprinted on the inspiral BNS merger signal. Access to the equation of state of high-density matter.

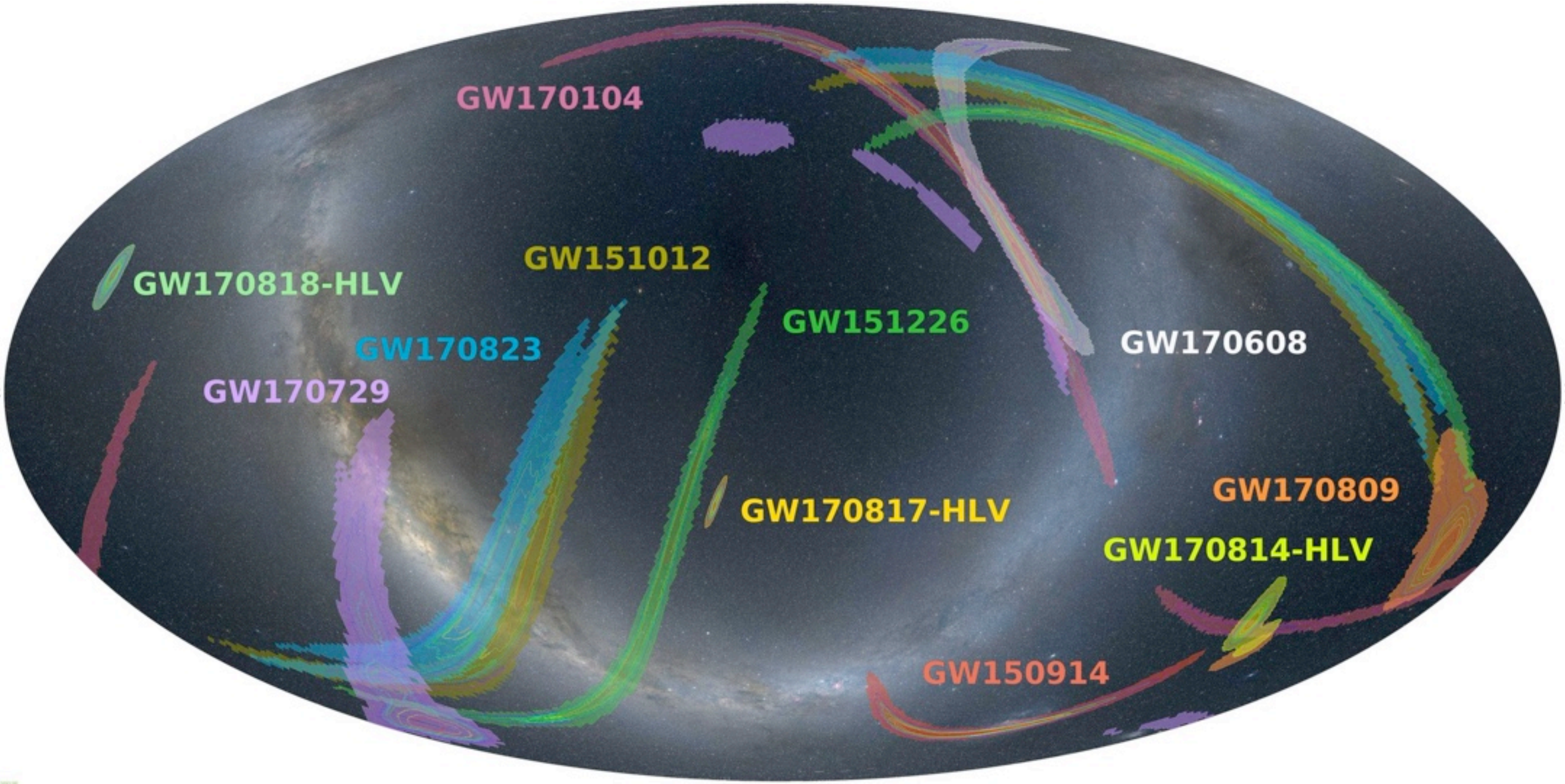
LIGO/Virgo BBH catalog (O1-O2)



GW150914
GW151012 (a.k.a. LVT151012)
GW151226
GW170104
GW170608 (the lightest)

GW170814 (1st triple detection)
GW170729 (the most massive)
GW170809
GW170818
GW170823

O1-O2 CBC detections: sky localisation



See Abbott et al, arXiv:1304.0670 (updated Sep 2019)

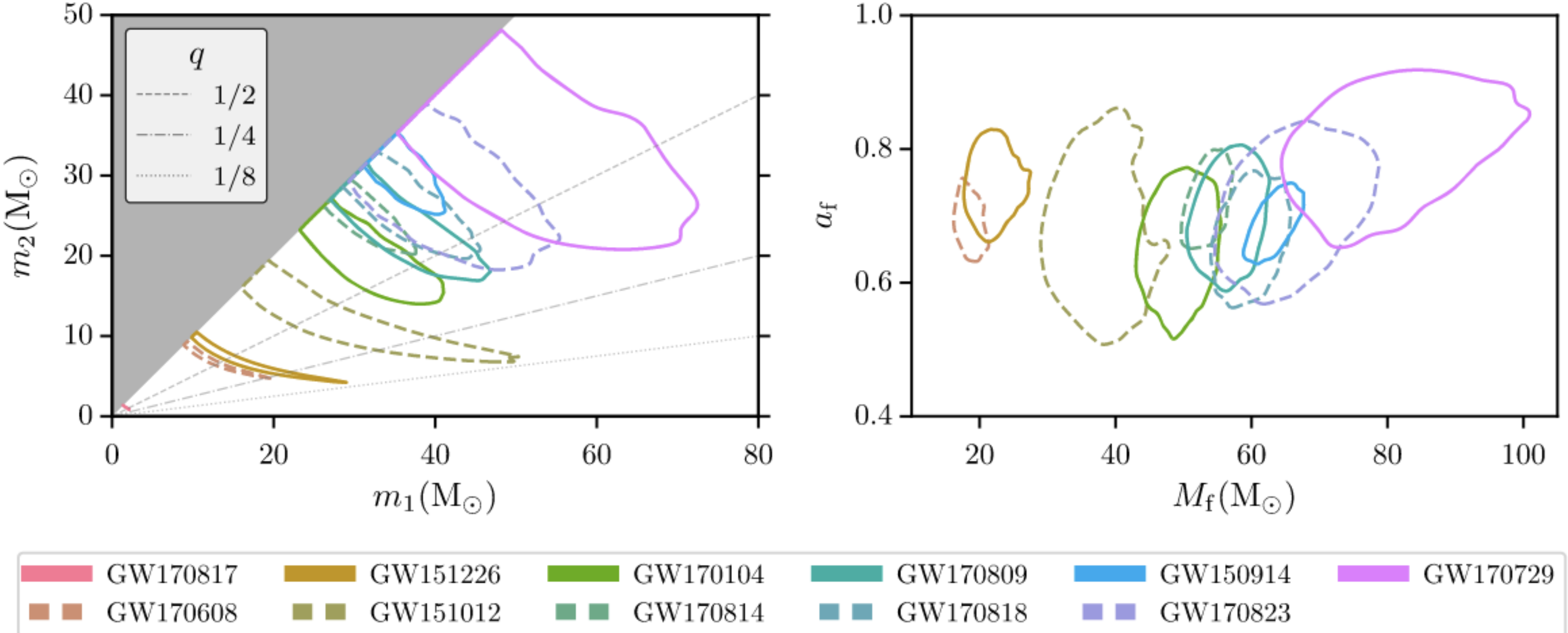
O1-O2 luminosity distance & sky localisation

	Low-latency analyisis			Refined analysis		
Event	d_L (Mpc)	$\Delta\Omega$ (deg^2)	IFOs	d_L (Mpc)	$\Delta\Omega$ (deg^2)	IFOs
GW150914	—	307	HL	440^{+150}_{-170}	182	HL
GW151012	—	—	—	1080^{+550}_{-490}	1523	HL
GW151226	—	1337	HL	490^{+180}_{-190}	1033	HL
GW170104	730^{+340}_{-320}	1632	HL	990^{+440}_{-430}	921	HL
GW170608	310^{+200}_{-120}	864	HL	320^{+120}_{-110}	392	HL
GW170729	—	—	—	2840^{+1400}_{-1360}	1041	HLV
GW170809	1080^{+520}_{-470}	1155	HL	1030^{+320}_{-390}	308	HLV
GW170814	480^{+190}_{-170}	97	HLV	600^{+150}_{-220}	87	HLV
GW170817	40^{+10}_{-10}	31	HLV	40^{+7}_{-15}	16	HLV
GW170818	—	—	—	1060^{+420}_{-380}	39	HLV
GW170823	1380^{+700}_{-670}	2145	HL	1940^{+970}_{-900}	1666	HL

See Abbott et al, arXiv:1304.0670 (updated Sep 2019)

O1-O2 BBH masses

Total mass range: $18.6^{+3.2}_{-0.7}M_\odot - 84.4^{+15.8}_{-11.1}M_\odot$



Dimensionless spin parameter range: $0.66^{+0.08}_{-0.11} - 0.81^{+0.07}_{-0.13}$

Abbott et al, 1811.12907 (GWTC-1 Catalog paper)

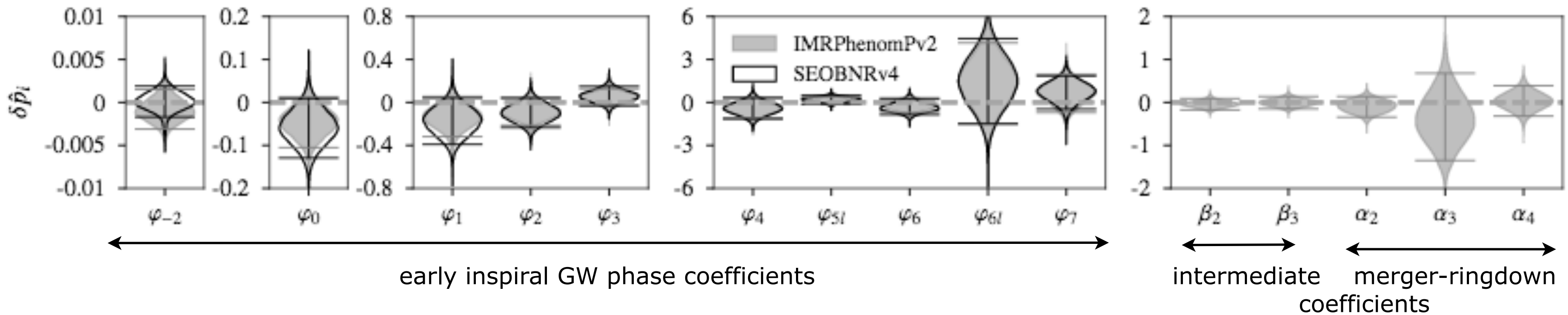
Tests of GR with the BBH signals from GWTC-1

arXiv:1903.04467: Paper presents **four tests** of the consistency of the data with BBH gravitational waveforms predicted by GR:

1. subtract best-fit waveform from data and check the consistency of the residual with detector noise.

2. check consistency of low- and high-frequency parts of observed signals.

3. check phenomenological deviations introduced in the waveform model (including in the post-Newtonian coefficients) are consistent with zero.

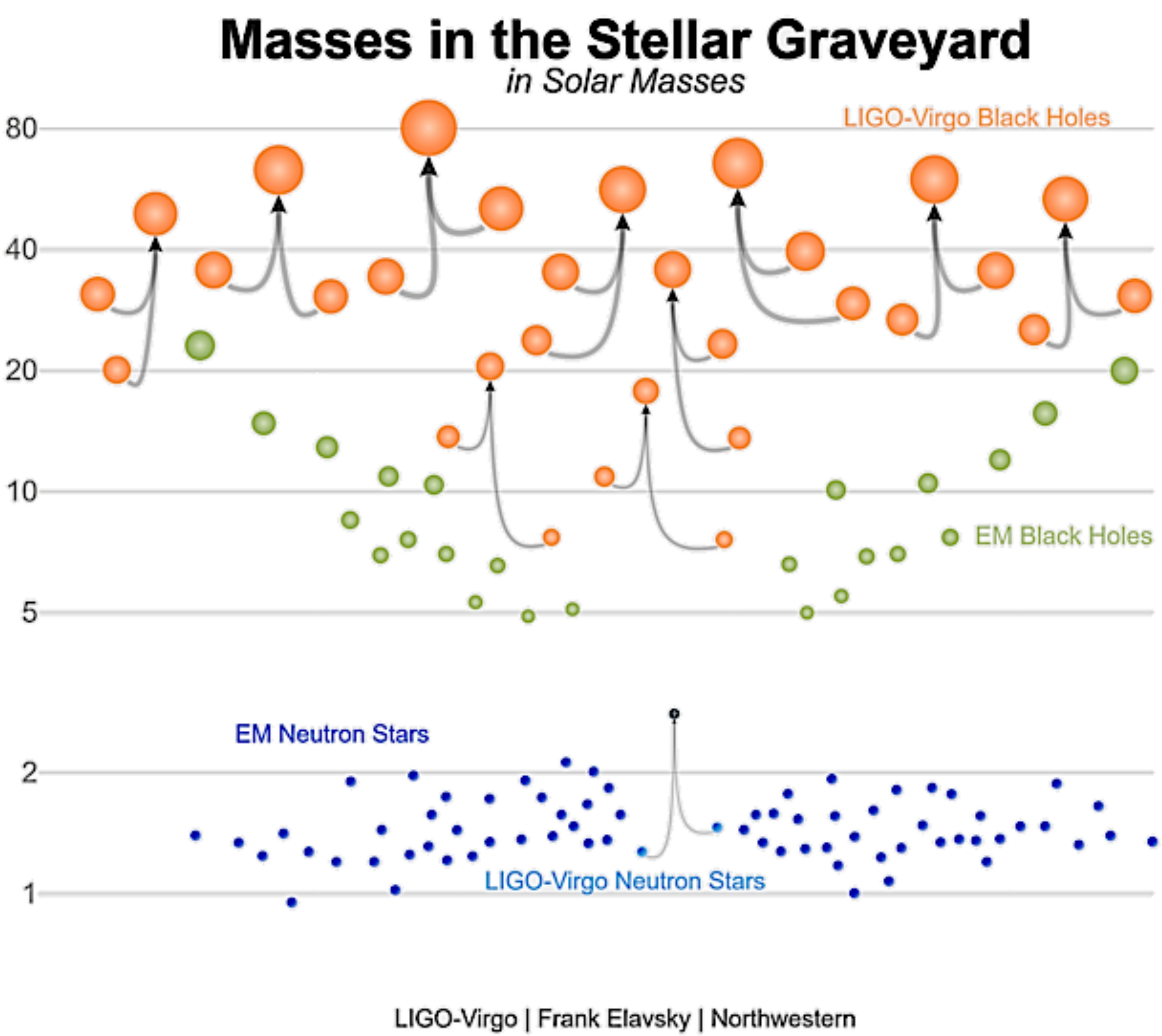


4. constrain modifications to the propagation of GWs due to a modified dispersion relation, including that from a massive graviton.

Best bound for the graviton mass: $m_g \leq 4.7 \times 10^{-23}\,\mathrm{eV}/c^2$

No inconsistency of the data with the predictions of GR is found.

GWTC-1 catalog: two possible mass gaps



$> 50 M_\odot$

PISN explosion

prevents formation of massive BH remnant

$< 5 M_\odot$

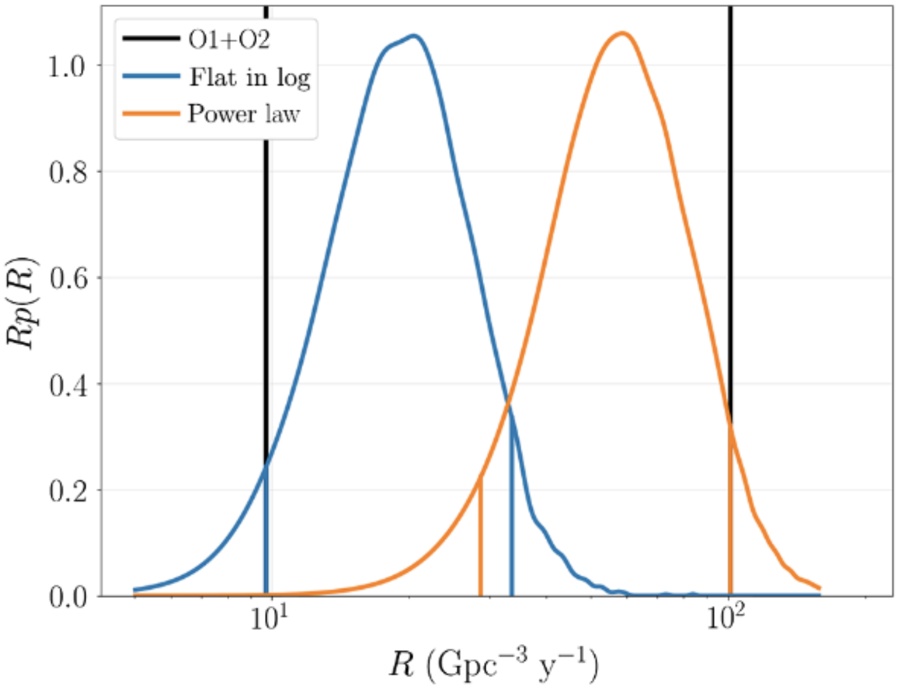
binary evolution

$> 3 M_\odot$

nuclear EOS

GWTC-1 catalog: population rates

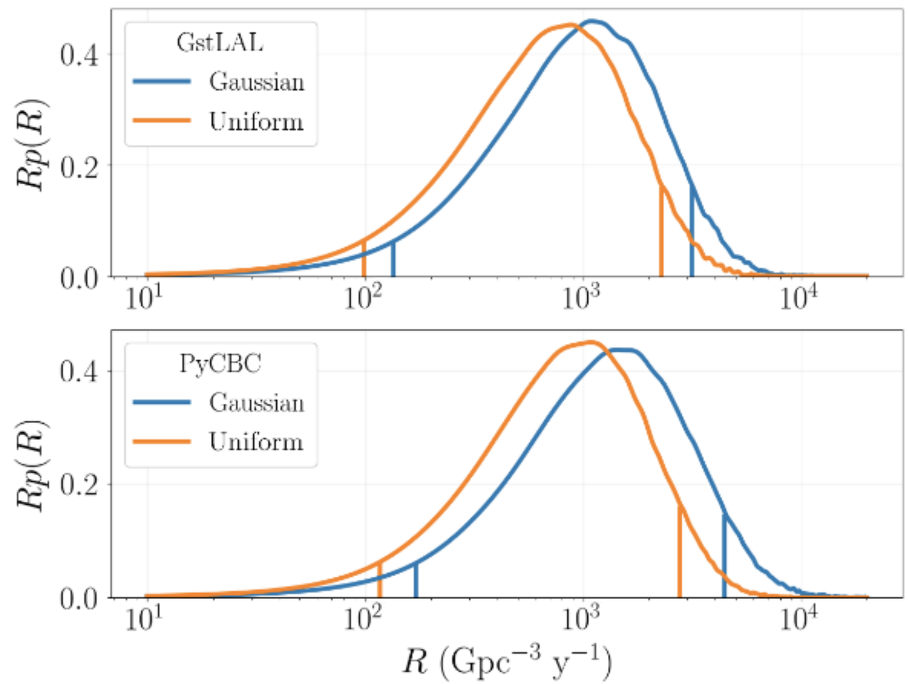
BBH



Posterior distribution — combined PyCBC and GstLAL results — on the BBH event rate for the flat in log (blue) and power-law (orange) mass distributions.

$9.7 - 101\ Gpc^{-3}\, yr^{-1}$

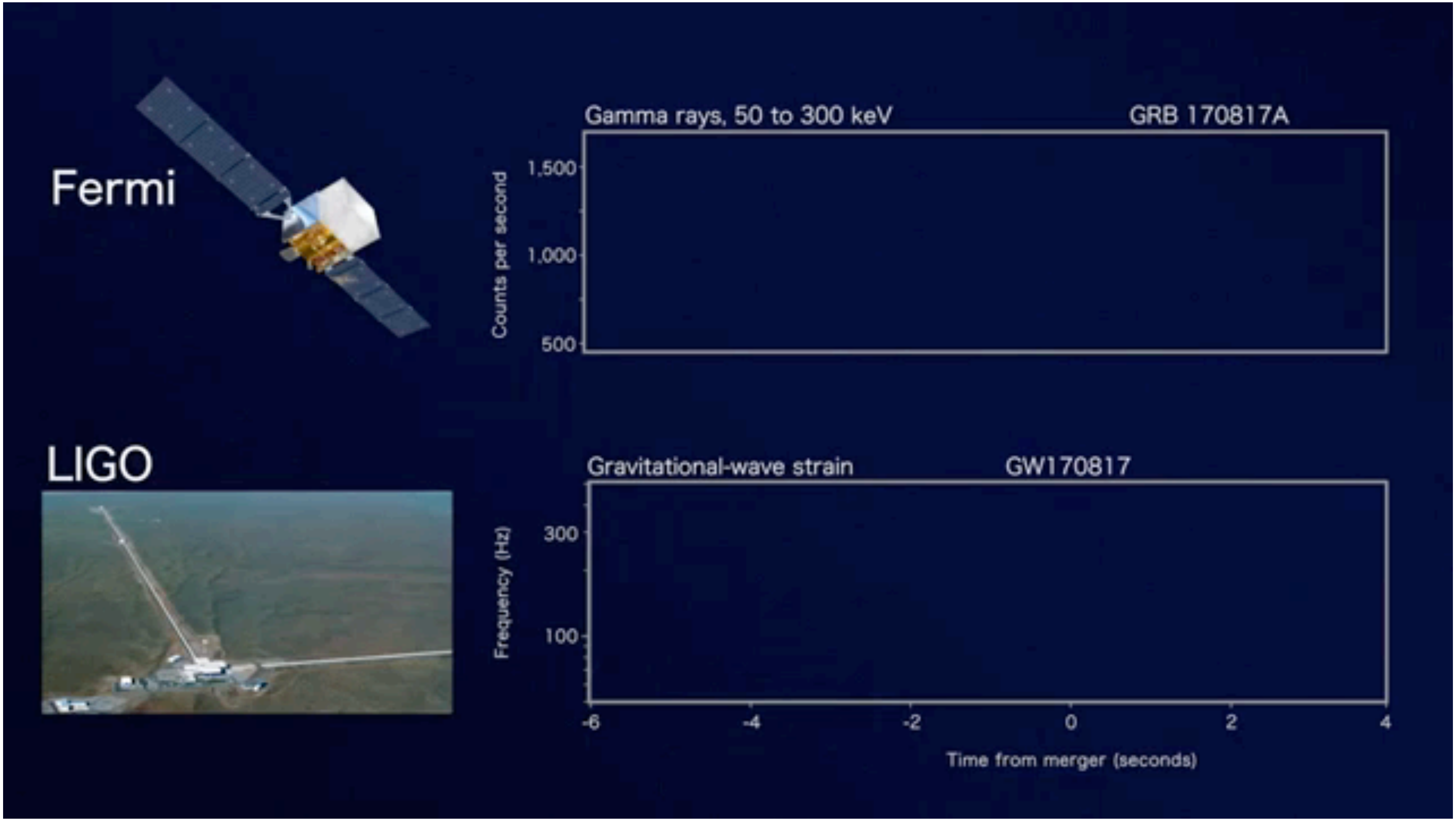
BNS



Posterior distributions of the BNS event rate for the GstLAL and PyCBC searches.

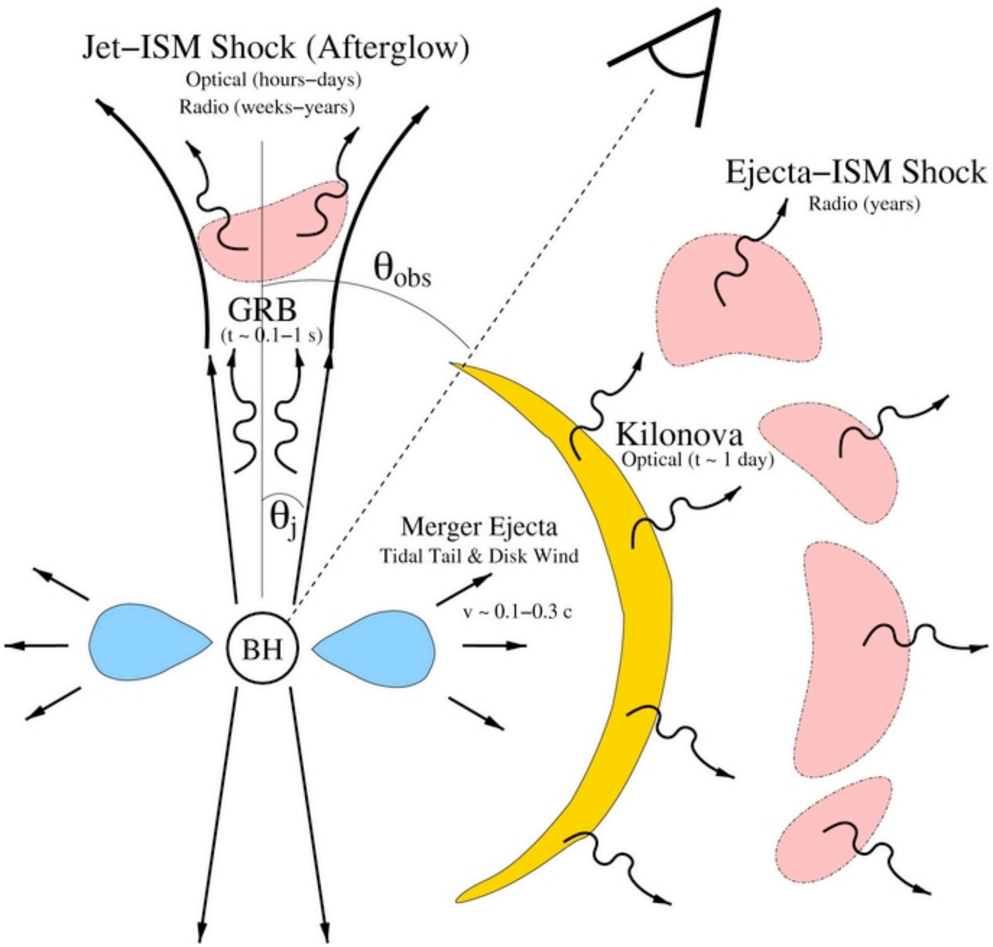
$110 - 3840\ Gpc^{-3}\, yr^{-1}$

On Aug 17, 2017, at 13:41 CET ...



GW170817 and GRB 170817A

Expected EM counterparts of a BNS merger



Metzger & Berger, ApJ, **746**, 48 (2012)

Short GRBs:

prompt γ-ray emission (< 2 s)

afterglow X-ray, optical, radio emission (minutes, hours, days, months)

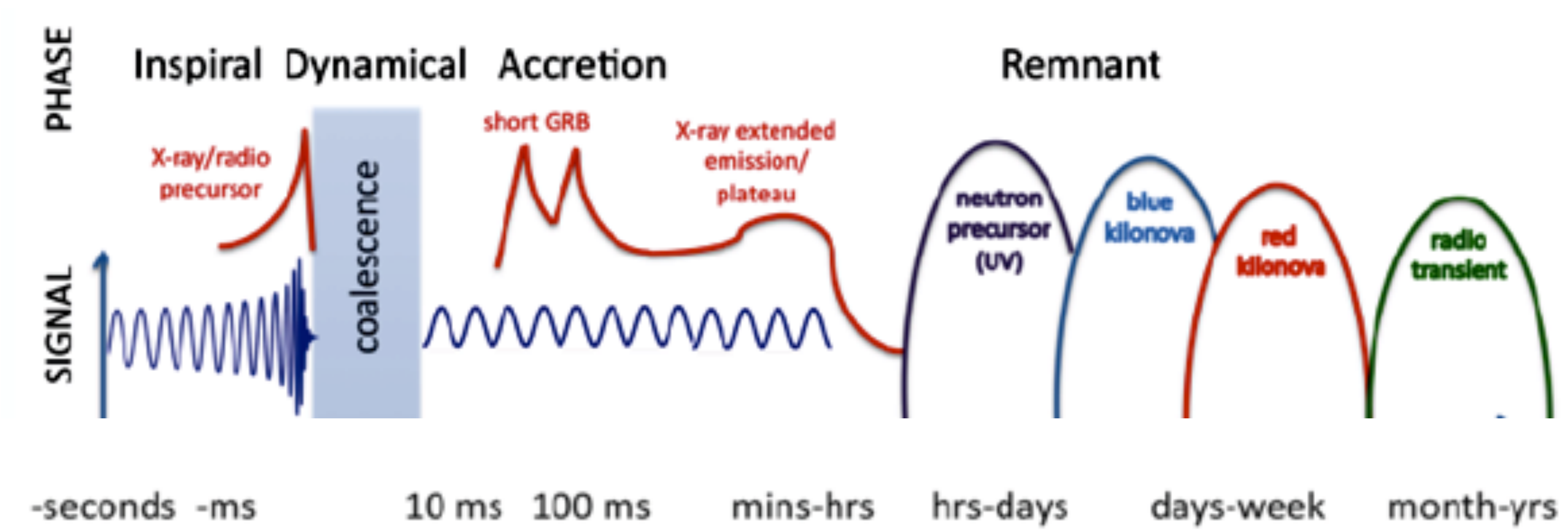
Kilonova:

optical and near IR (days, weeks)

Late blast-wave emission:

radio (months, years)

GW170817's expected chronology



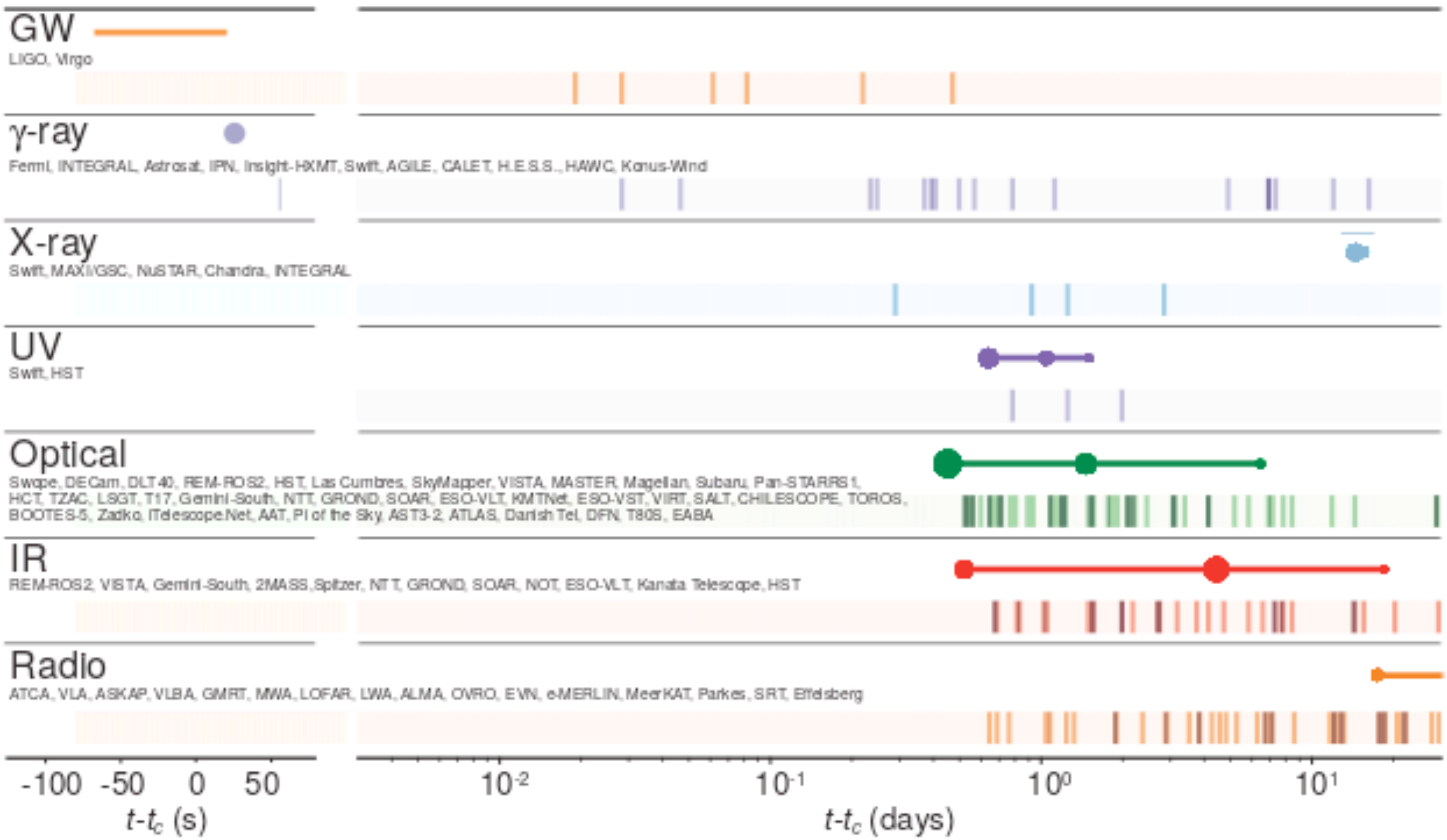
Only the **observation** of a binary neutron star merger (or the merger of a neutron star and a black hole) can prove/discard:

- the association of GRBs with BNS (BH-NS) mergers (Eichler et al 1989).
- the theoretical model of r-process nucleosynthesis of heavy elements (kilonova model; Metzger et al 2010).

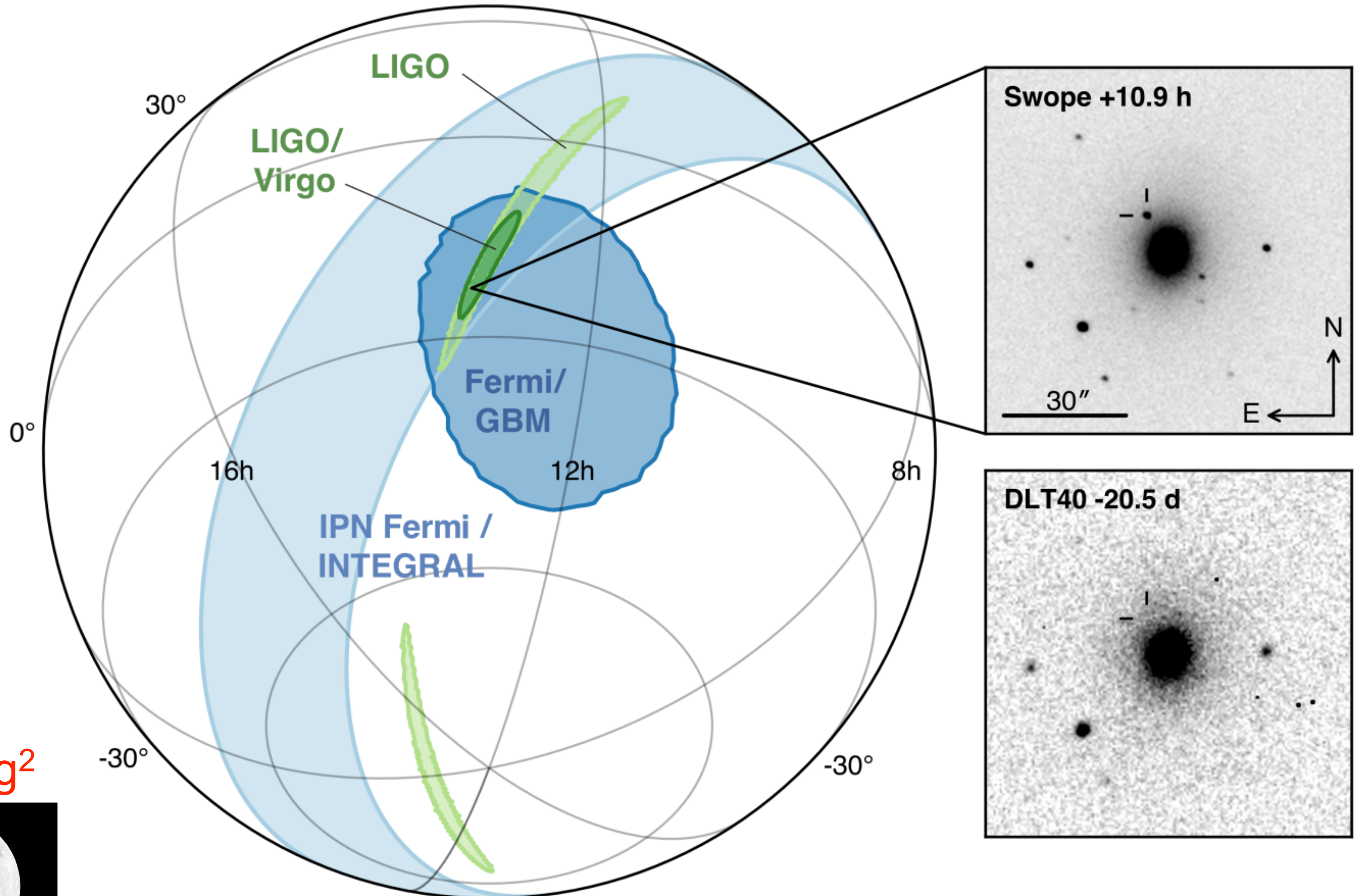
The EM follow-up campaign

A wide-range EM follow-up campaign started in the hours immediately after the observation of GW170817 and GRB 170817A

Abbott et al., ApJ, 848, L12 (2017)



GW170817: the role of Virgo



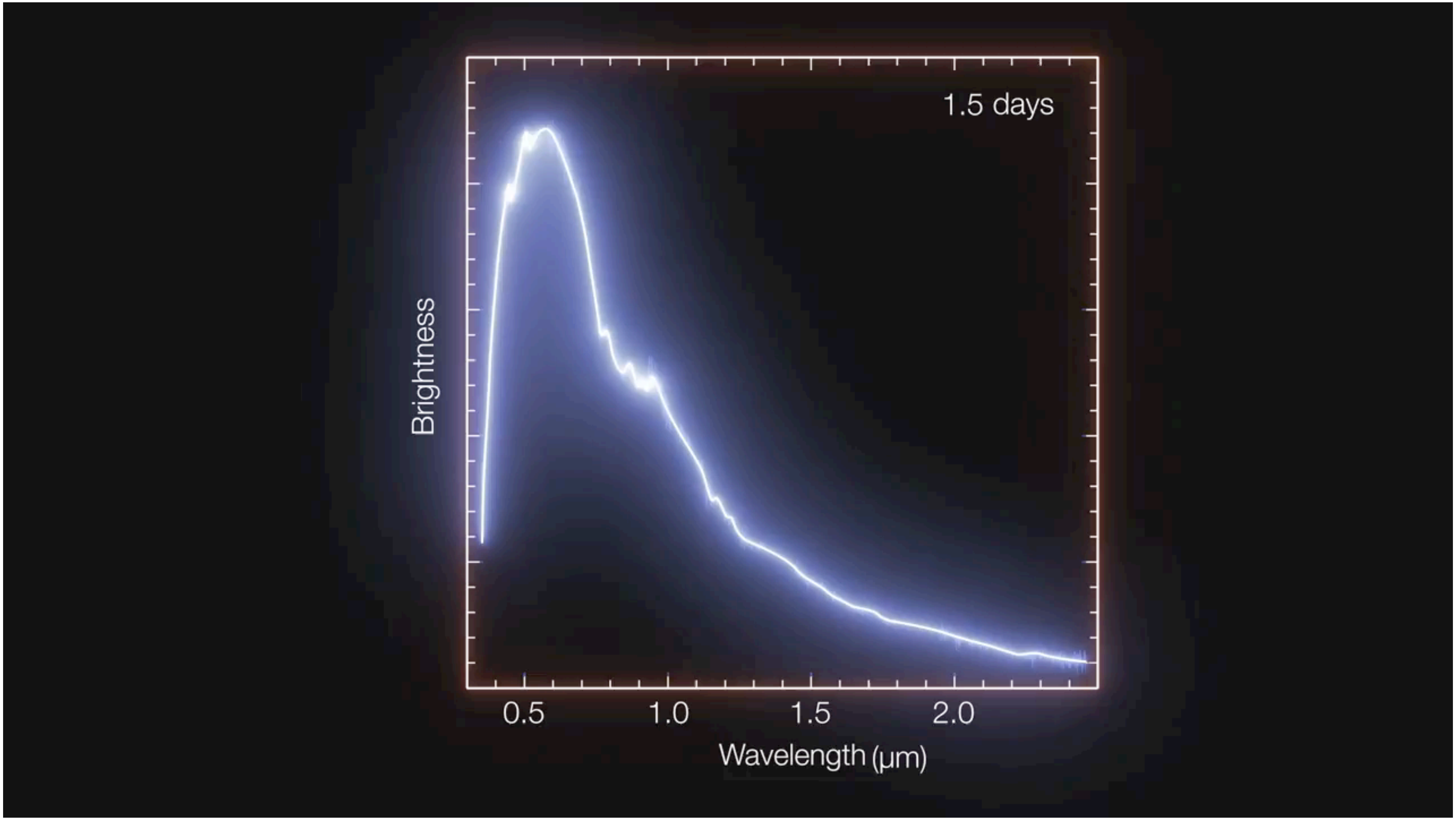
0.2 deg²

28 deg²

GW170817: zooming in on the source

Credit: LIGO/Virgo

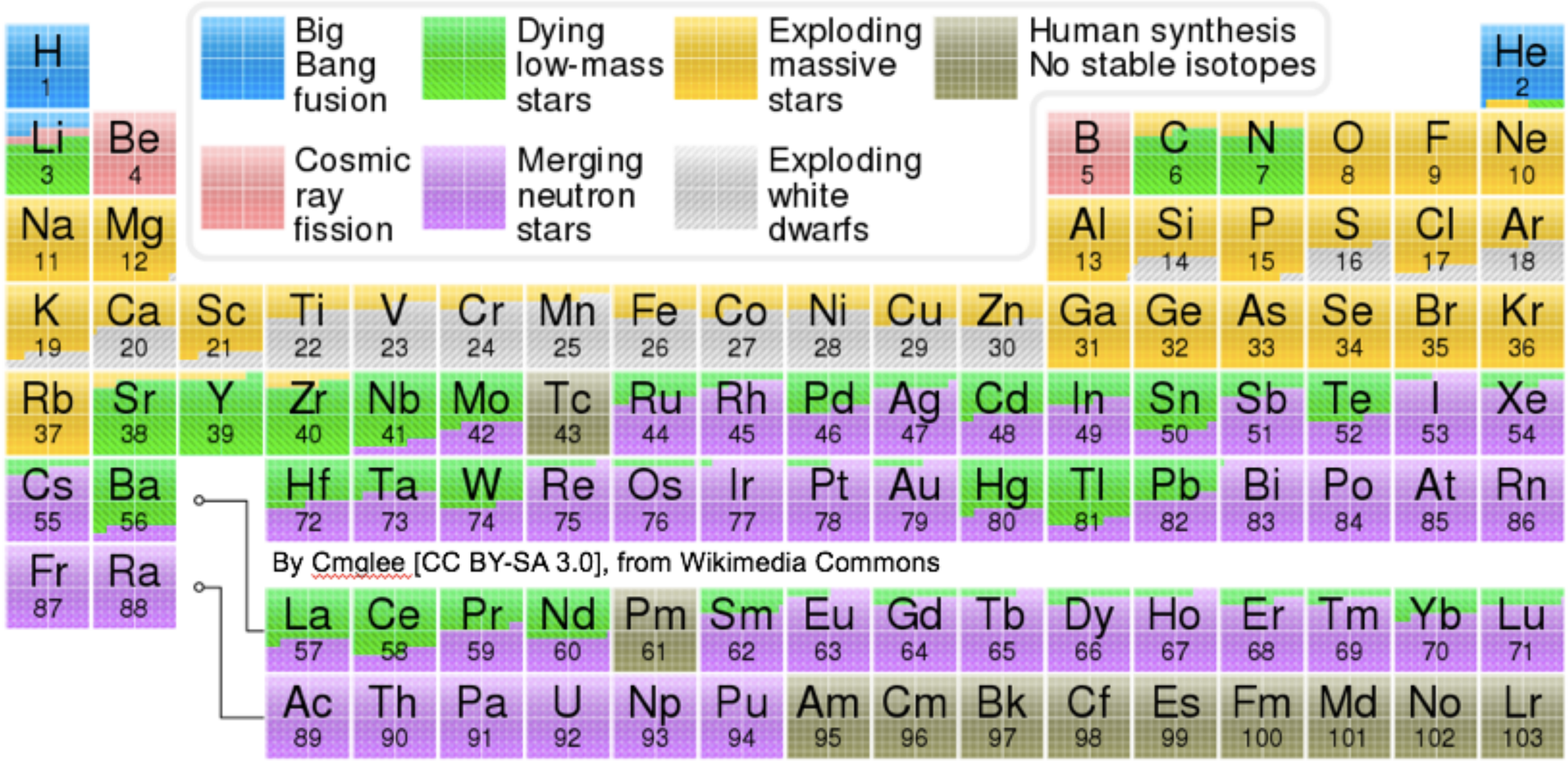
Spectroscopic identification of the kilonova



Credit: ESO/E. Pian et al./S. Smartt & ePESSTO

Zooming in on the kilonova in NGC 4993

Origin of elements

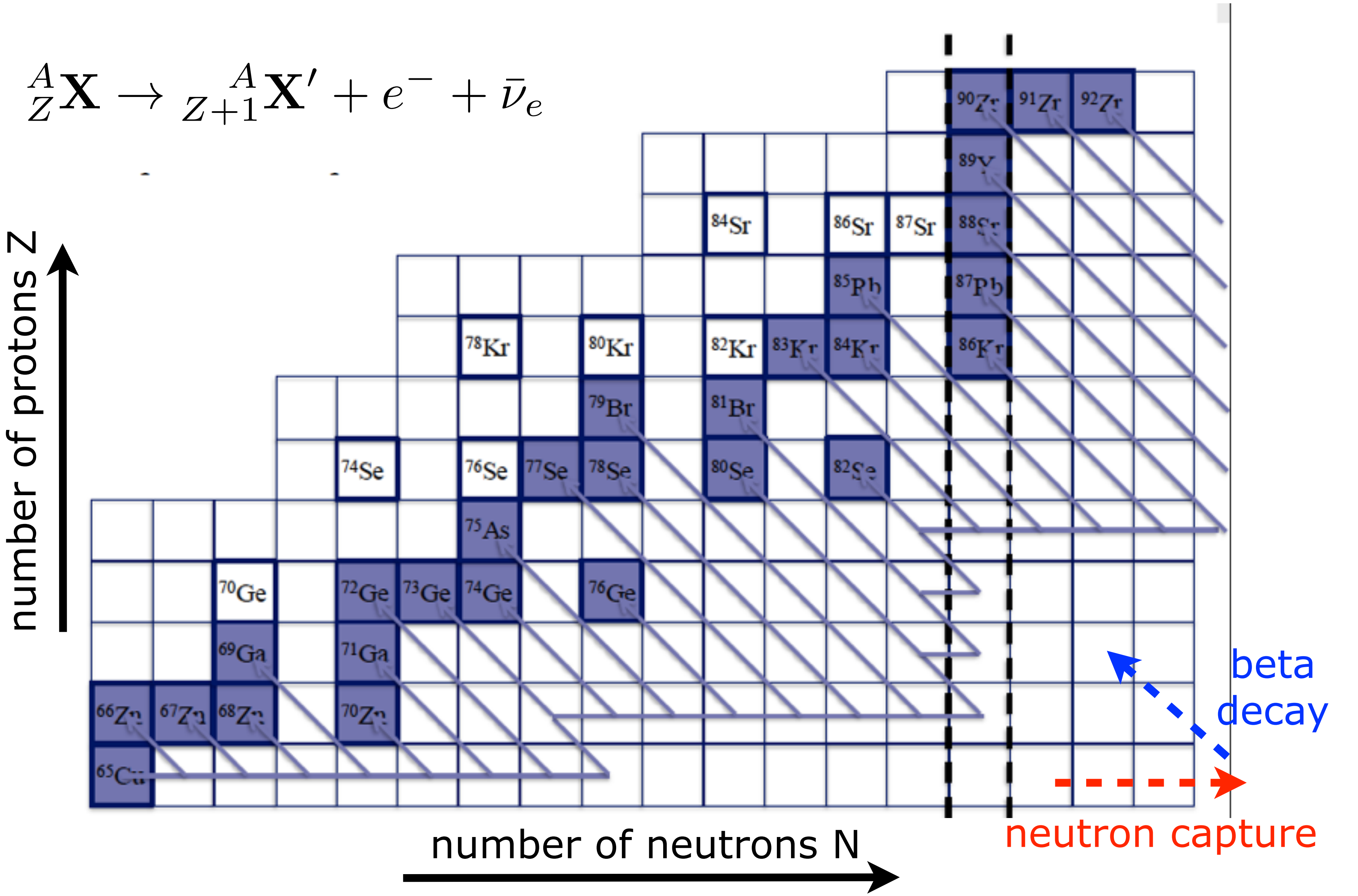


For massive-enough stars, fusion reactions during stellar evolution produce elements up to **Fe**.

Beyond Fe, elements are synthesized in large stars due to neutron capture, both slow (**s-process**, every 10-100 years) and rapid (**r-process**, 100 captures per second).

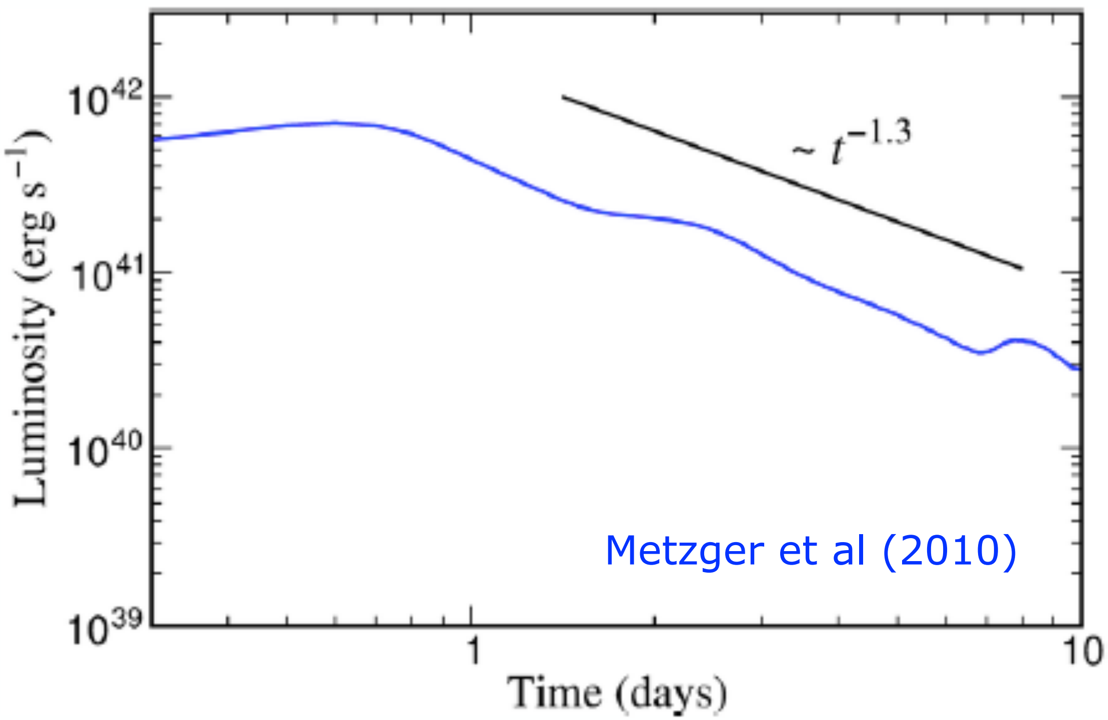
r-process: rapid neutron capture

$$^{A}_{Z}\mathbf{X} \rightarrow {}^{A}_{Z+1}\mathbf{X}' + e^- + \bar{\nu}_e$$



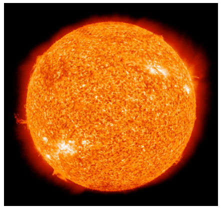
Energy production by r-process

The decay of r-processed elements produces **energy**. Many nuclei decaying at the same time.



Comparison:

100 W
10^9 erg s^{-1}

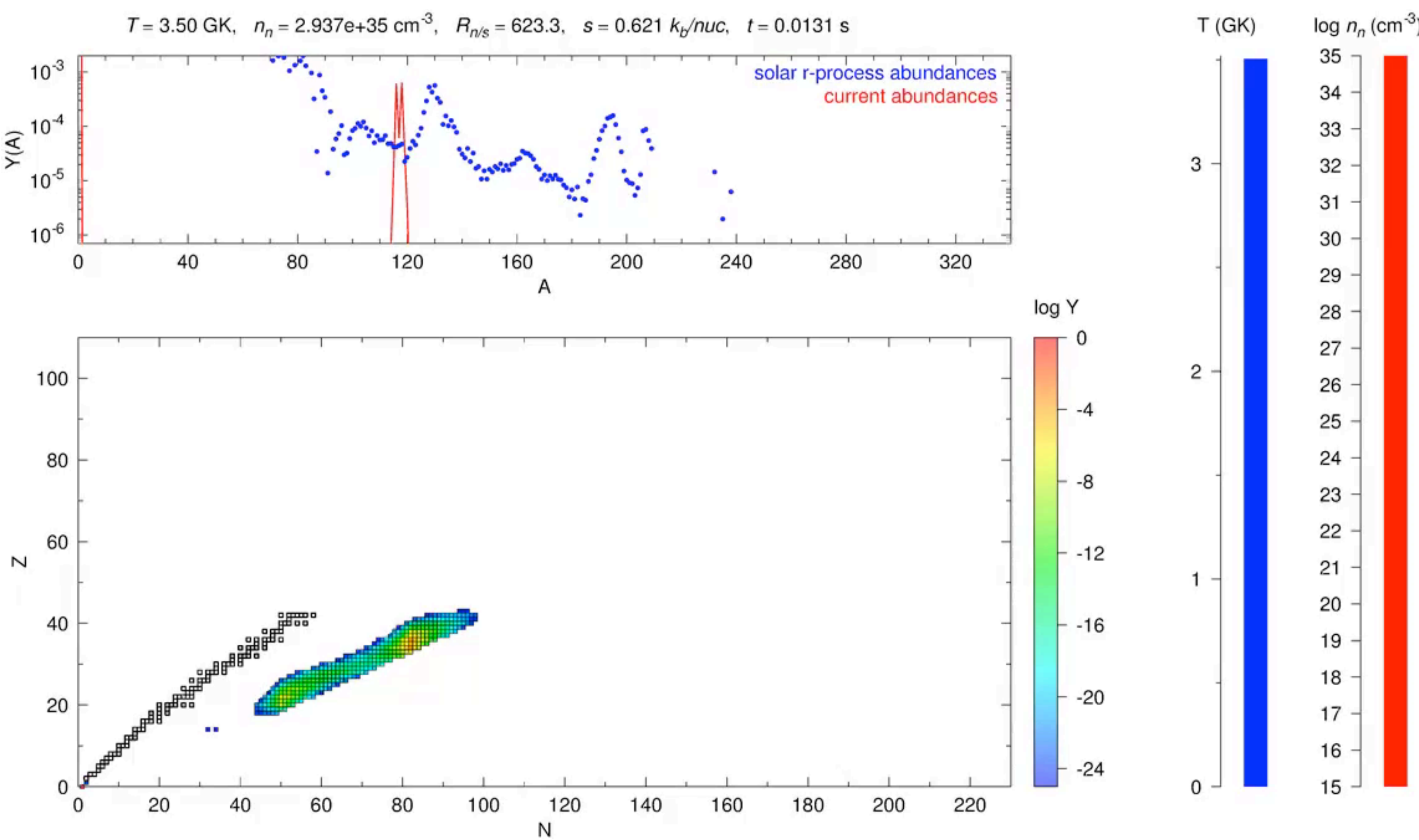


$\sim 10^{33}$ erg s^{-1}

Luminosity equivalent to that produced by 1000 novae (**kilonova**) and decreases on a timescale of a few days.

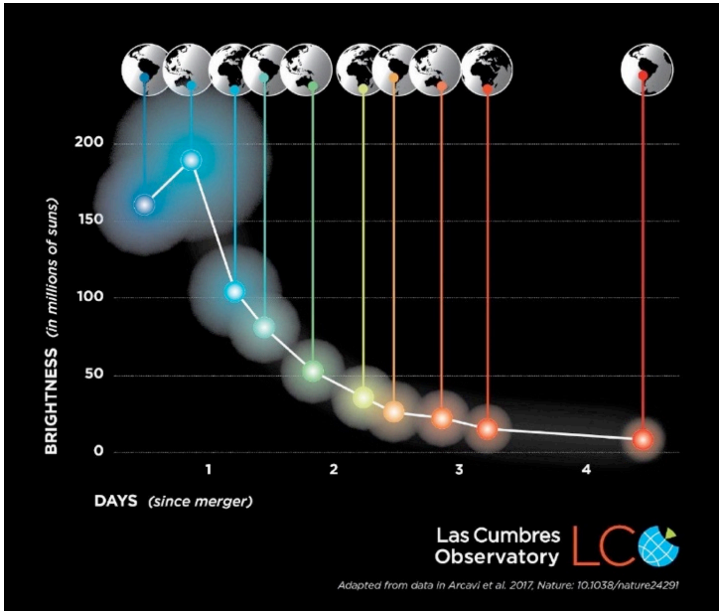
r-process in BNS mergers

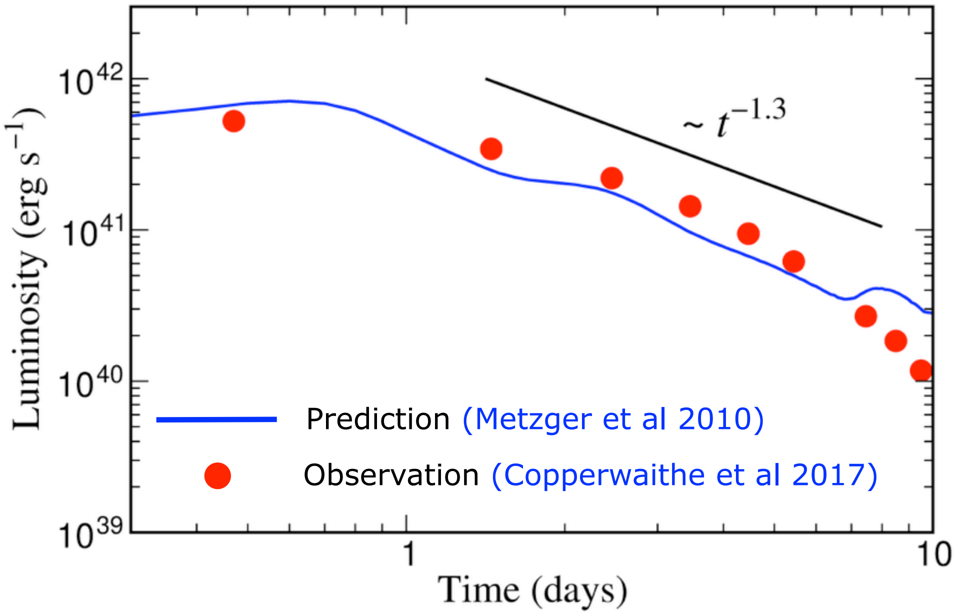
Theoretical models promising. Comparison with solar abundances.



A. Bauswein & G. Martínez-Pinedo (TU-Darmstadt)

Does the kilonova model work for GW170817?





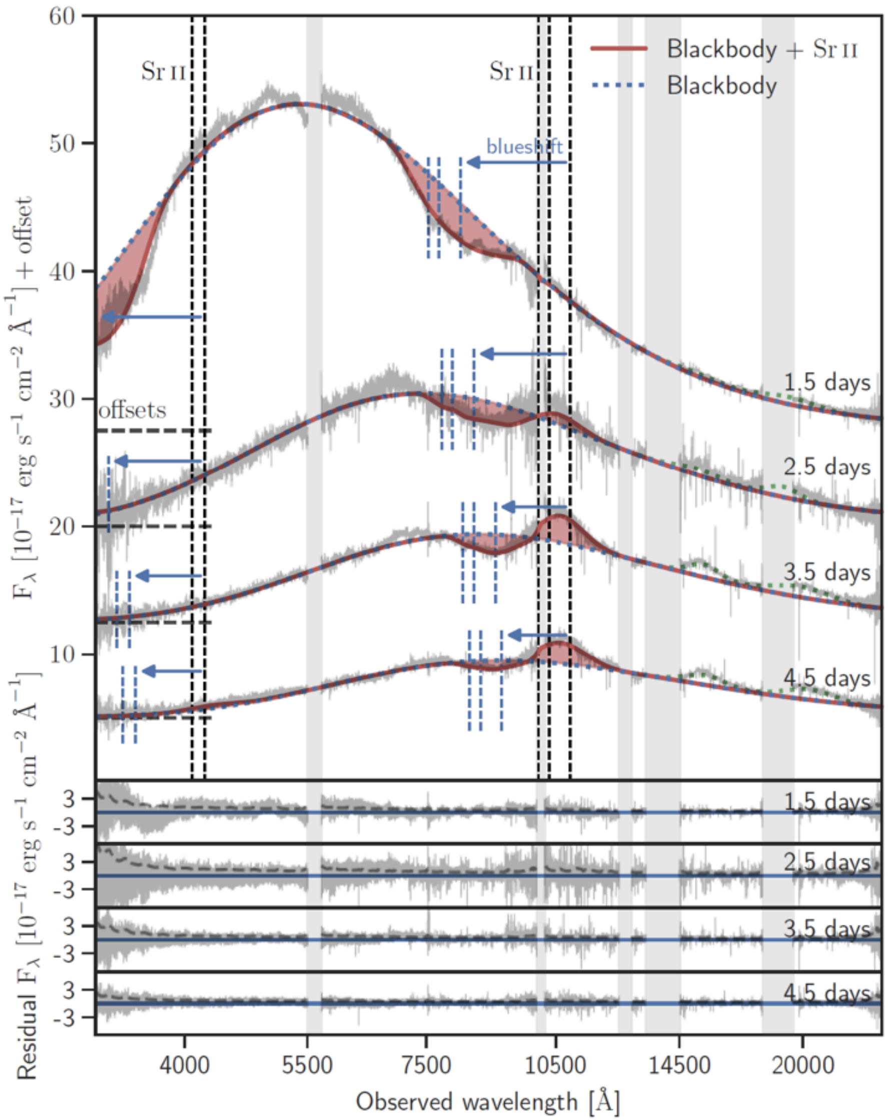
Temporal evolution of the kilonova determined by radiactive decay of nuclei. Two components:

Blue: dominated by light elements (Z < 50)

Red: presence of de lanthanides (Z = 57-71) and/or actinides (Z = 89-103)

GW170817
0.06 solar masses ejected → 10x Earth mass of gold
50x Earth mass of platinum
5x Earth mass of uranium

Identification of strontium in GW170817



Watson et al, arXiv:1910.10510v1

Identification of Sr in GW170817, an element that could only have been synthesized so quickly under an extreme neutron flux, provides the first direct spectroscopic evidence that NS comprise neutron-rich matter.

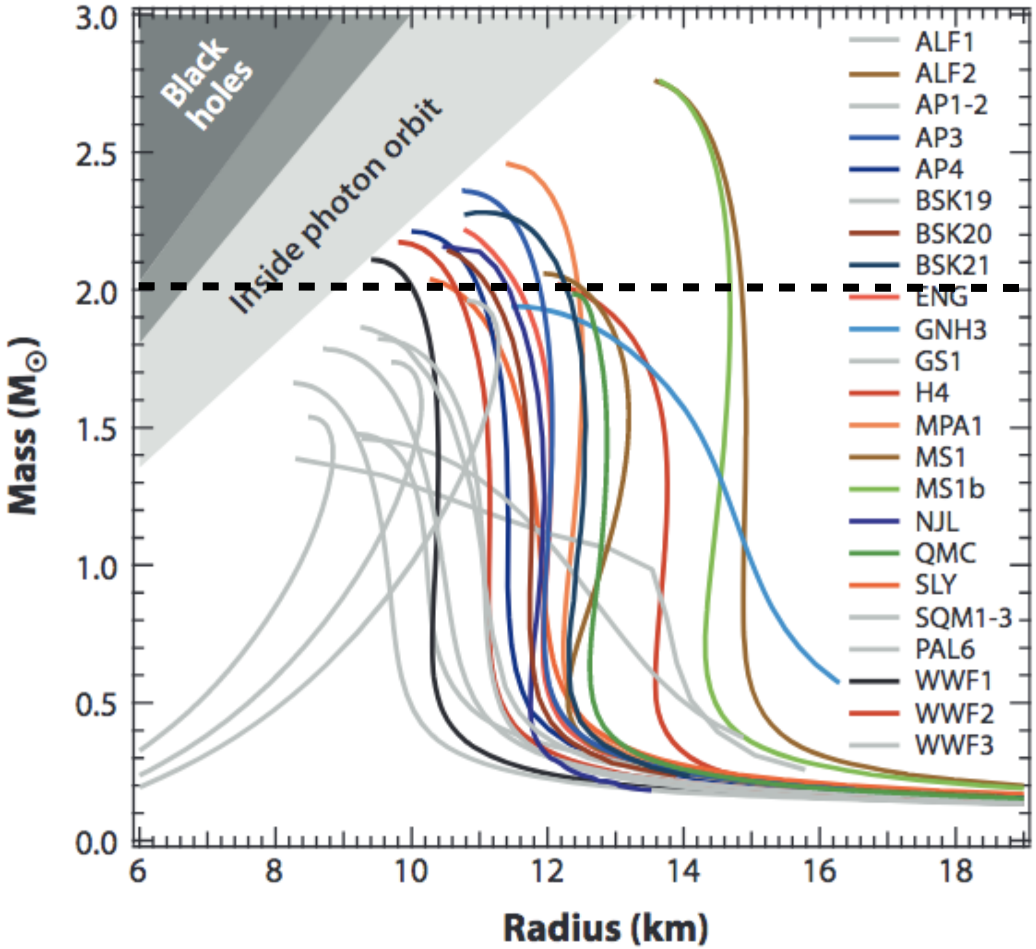
The kilonova has blackbody spectrum (blue dotted lines) with a temperature of 3,700 K.

P Cygni profiles (red transparent fill) increasingly develop in time for the Sr lines.

Lines Doppler broadened by 0.2 c due to the high speed of the ejected material and blue-shifted by 0.23 c.

GWs and extreme matter

First neutron star detected about 50 years ago. Still, the fundamental properties of matter in the core of neutron stars remain largely uncertain. No accurate radius determination.



J0348+0432 (MSP-WD)

$$2.01 \pm 0.04 M_\odot$$

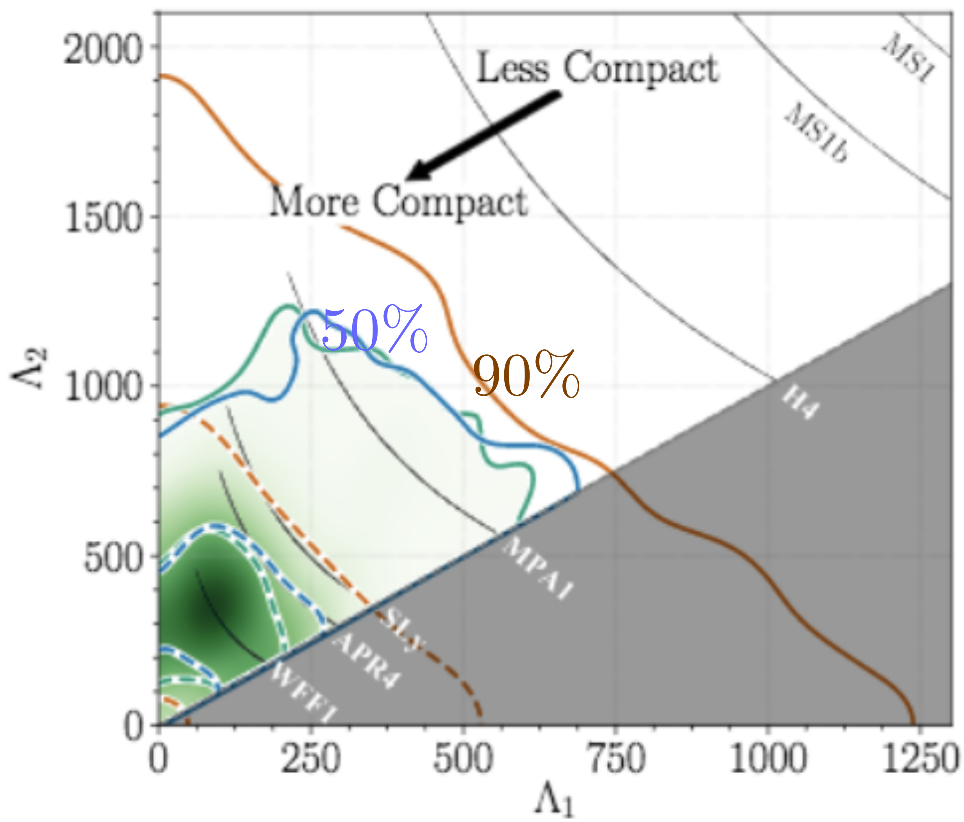
Özel & Freire (2019)

GW170817: constraints on the NS EOS

Gravitational waves contain information about NS tidal deformations

- allows to constraint NS equation of state (EOS)
- becomes significant above $f_{\rm GW} \approx 600\,\mathrm{Hz}$

Probability density for Λ_1, Λ_2



$$\Lambda = \frac{2}{3} k_2 \left(\frac{R}{M}\right)^5$$

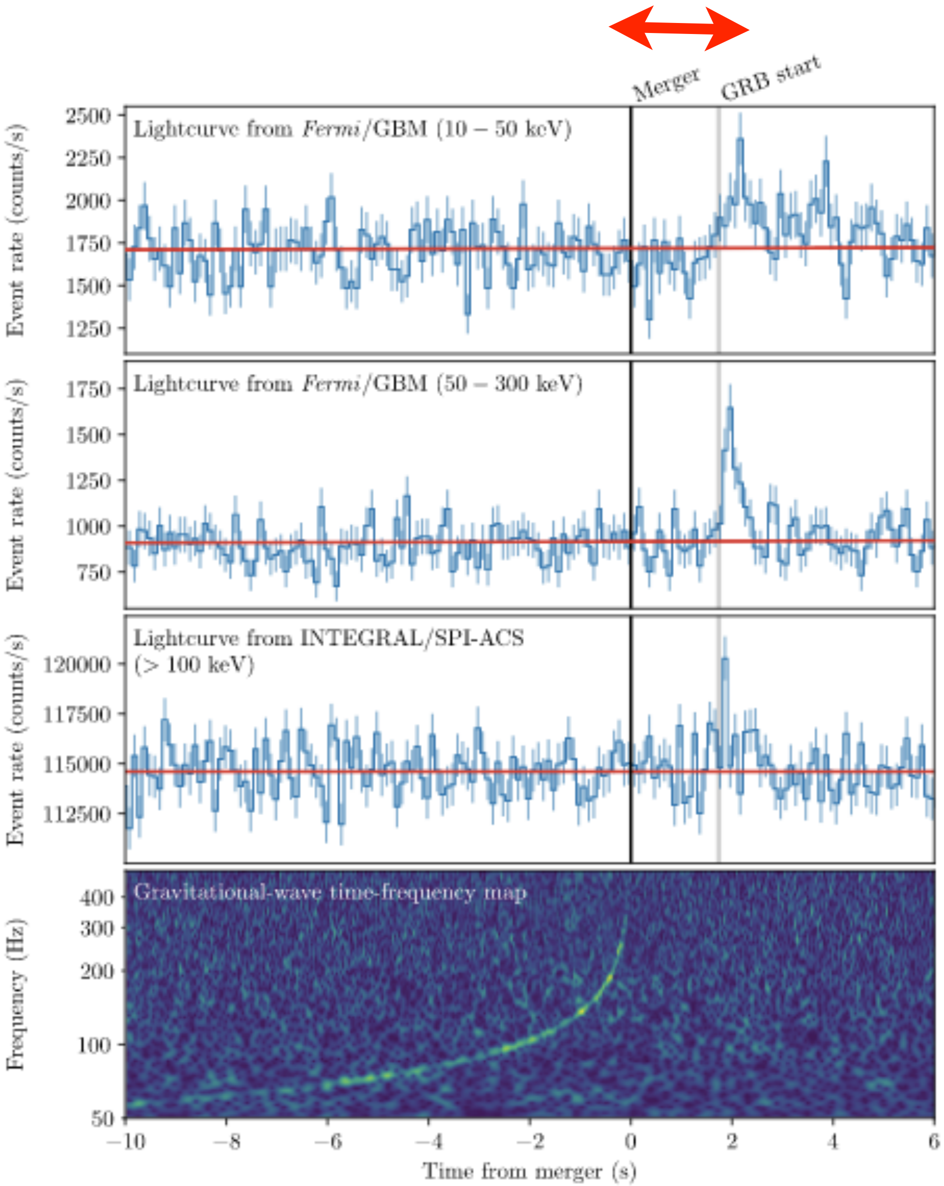
k_2 quadrupole Love number

LVC 1805.11581

"Soft" EOS (more compact NS), such as APR4 or SLy, favored over "stiff" EOS (less compact NS), such as H4 or MS1, which lie outside the 90% credible region.

GW170817 data consistent with **soft EOS and more compact NS**.

GW170817: Implications for fundamental physics



Mind the gap!

Abbott et al, ApJ, **848**, L13 (2017)

GW170817: Implications for fundamental physics

Time delay between GW and GRB detections over 1.3x10[8] light years was

$$\Delta t = (1.74 \pm 0.05)\,\mathrm{s}$$

Define fractional difference between speed of light and GWs as $\dfrac{c_g - c}{c} \approx c\dfrac{\Delta t}{D_L}$

Leads to the following constraint: $-3 \times 10^{-15} \leq \dfrac{\Delta c}{c} \leq 7 \times 10^{-16}$

Large consequences for cosmological theories.

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

Ezquiaga & Zumalacárregui (2017)

with extension to: Einstein-Aether, Horava gravity, Generalised Proca, TeVeS, massive gravity, bigravity, multi-gravity, MOND-like theories.

arXiv:1710.05901, 1710.06394, 1710.05893, 1710.05877….

GW170817: Implications for fundamental physics

Probing whether EM radiation and GWs are affected by background gravitational potentials in the same way is a test of the WEP. The Shapiro effect (Shapiro 1964) predicts that the propagation time of massless particles in curved spacetime is slightly increased w.r.t. the flat spacetime case.

The Shapiro delay is defined as $\Delta t_s = -\frac{1+\gamma}{c^3}\int_{r_e}^{r_0} U(r(l))\,dl$

γ is the PPN parameter parameterising a deviation from Einstein-Maxwell theory.

A conservative bound on $\Delta\gamma = |\gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}}| \leq 2\frac{\Delta t}{\Delta t_s}$

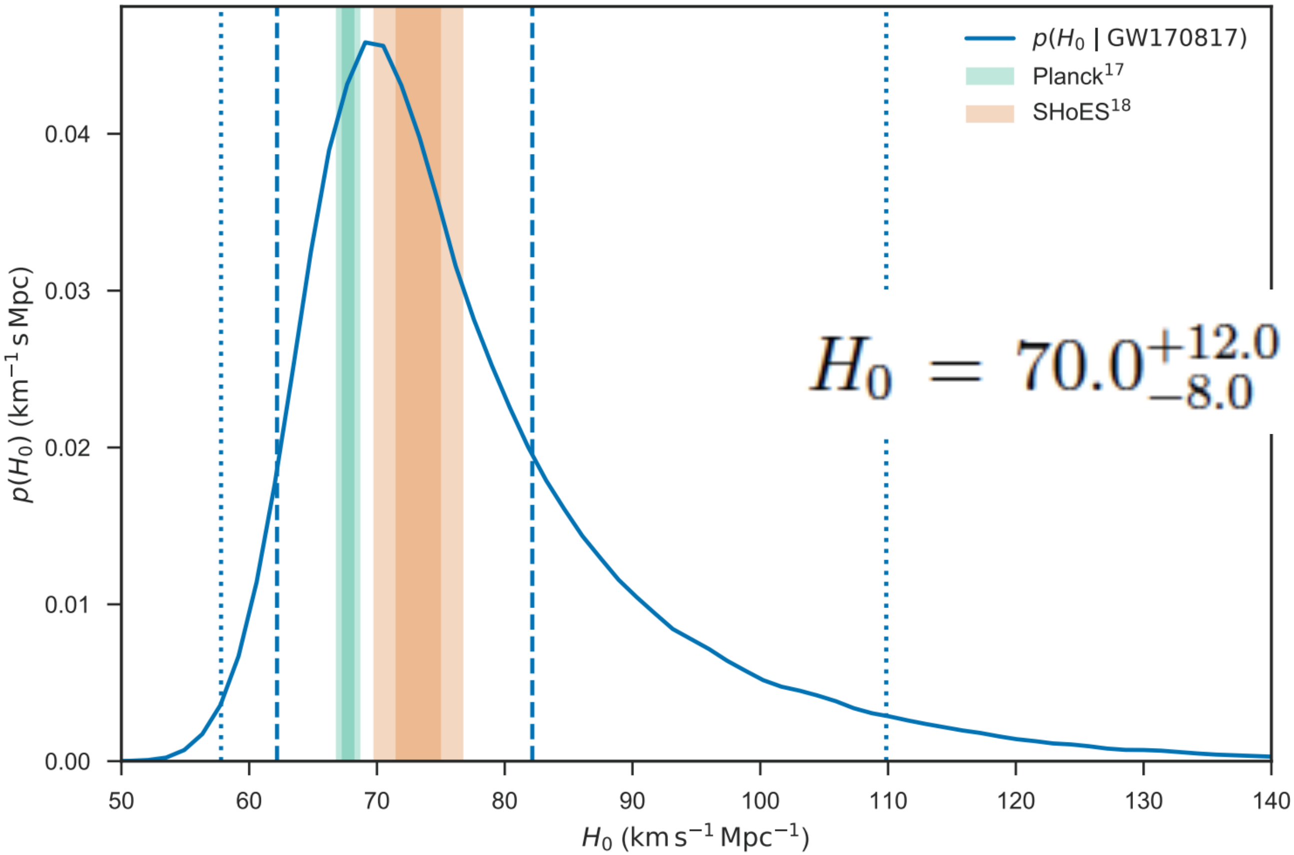
from the GW170817 data is $-2.6\times 10^{-7} \leq \Delta\gamma \leq 1.2\times 10^{-6}$

Newer result (Boran et al, 1710.06168) using more sophisticated dark matter halo model gives $\Delta\gamma \leq 3.9\times 10^{-8}$

This implies that MOND-like dark matter emulator theories are ruled out, as the GWs would have arrived 1000 days before the EM emission. [Boran et al's figure is 400 days.]

Measuring H_0 from GW170817 as a standard siren

GW170817 can be used as a **"standard siren"**: combining the **distance** (inferred from the inspiral GW signal) with the recession **velocity** of the source (redshift; inferred from EM signal) the **Hubble constant** can be measured.



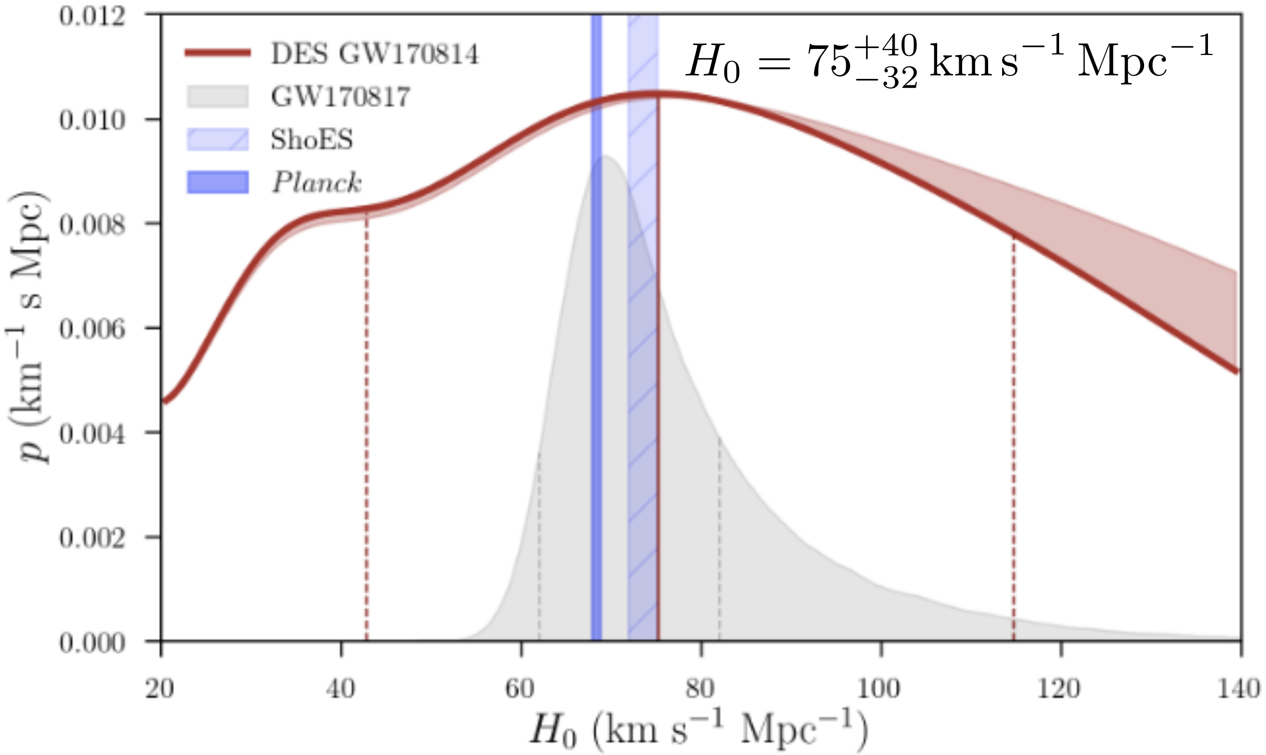
$$v_H = H_0\, d$$

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

Abbot et al, Nature, **551**, 85–88 (2017)

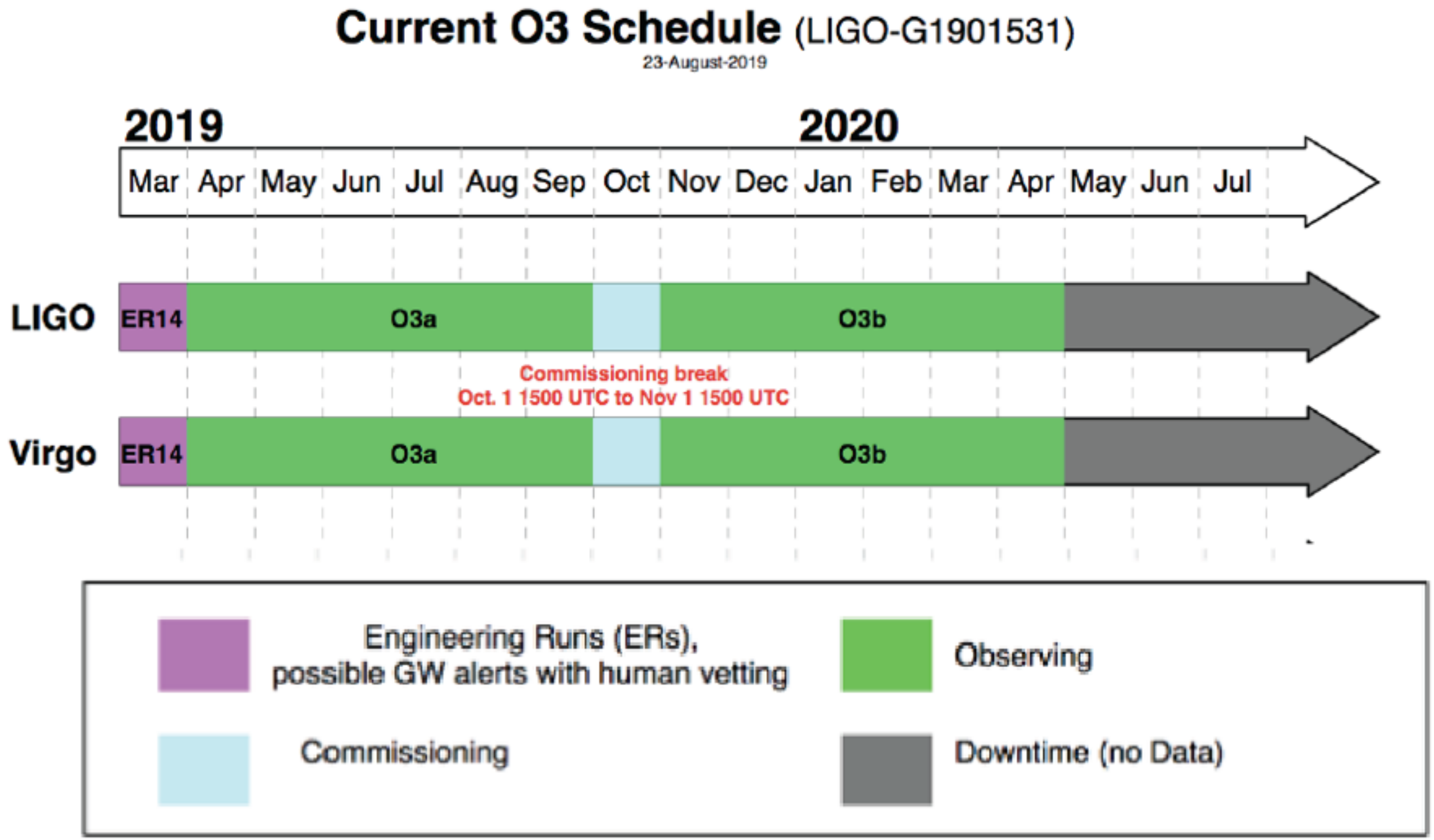
Measuring H_0 from a *dark* standard siren

Soares-Santos et al (2019): First measurement of the Hubble constant using a GW detection of a BBH merger (**GW170814**) as a **dark standard siren** and the DES galaxies as a sample of potential host galaxies.



Improved dark siren measurements will require complete galaxy catalogs. Combinations of many sirens will lead to improved constraints on H_0.

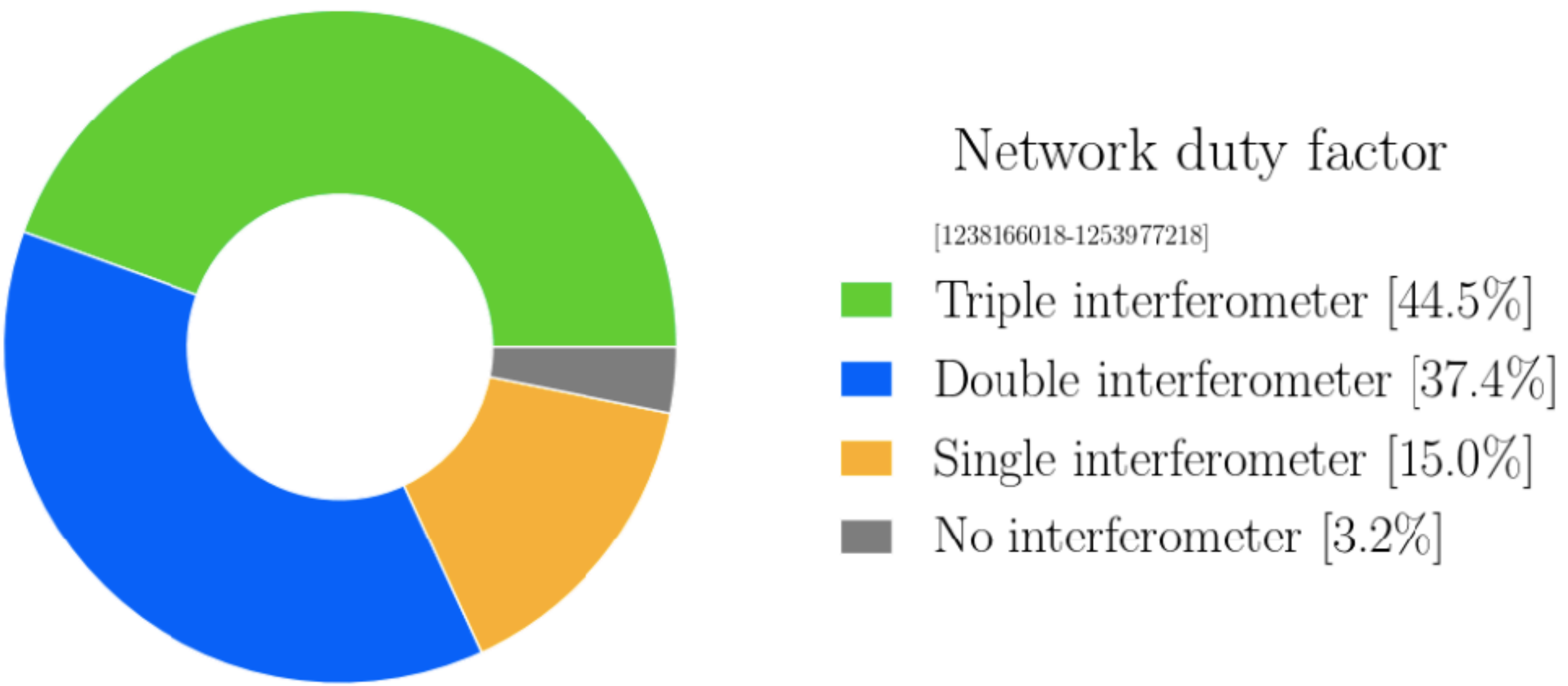
Current O3 schedule



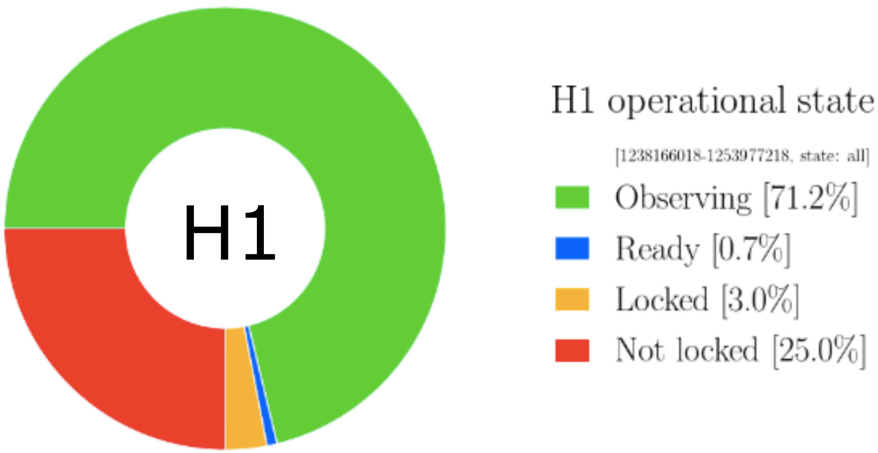
Detector network performance during O3a

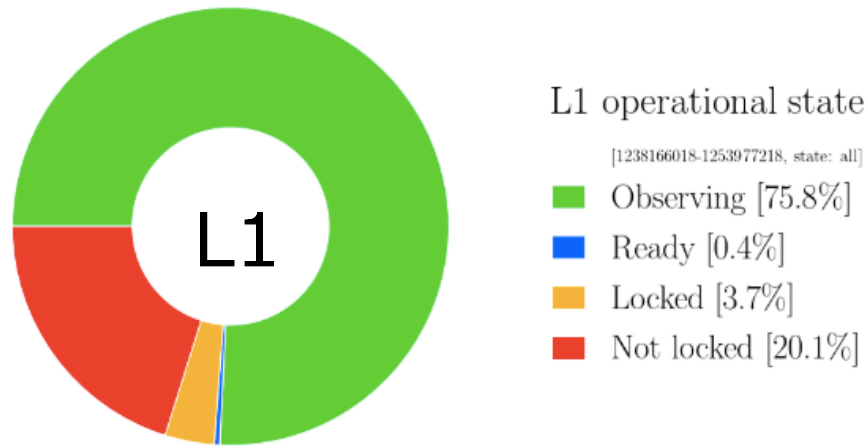
O3a: 6 months with 44.5% triple IFO cumulative duty cicle.

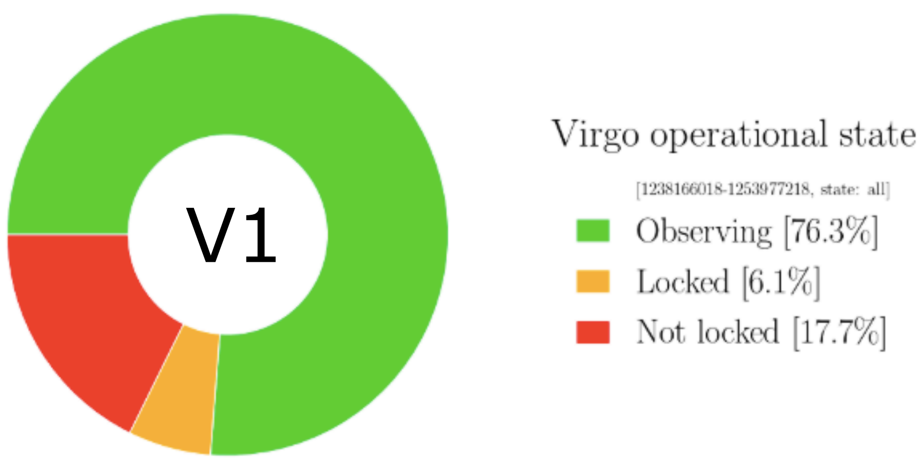
81.9% at double or triple IFO.
3.2% zero IFO coverage.



Individual IFO performance during O3a







Detector ranges

Ranges corresponding to orientation-averaged spacetime volumes surveyed per unit detector time. SNR=8 in each detector.

		O1	O2	O3
BNS Range (Mpc)	aLIGO	80	100	110 – 130
1.4 Mo+1.4 Mo	AdV	-	30	50
	KAGRA	-	-	8 – 25
BBH Range (Mpc)	aLIGO	740	910	990 – 1200
30 Mo+30 Mo	AdV	-	270	500
	KAGRA	-	-	80 – 260
NSBH Range (Mpc)	aLIGO	140	180	190 – 240
1.4 Mo+10 Mo	AdV	-	50	90
	KAGRA	-	-	15 – 45
Burst Range (Mpc)	aLIGO	50	60	80 – 90
$[E_{GW} = 10^{-2} M_\odot c^2]$	AdV	-	25	35
	KAGRA	-	-	5 – 25
Burst Range (kpc)	aLIGO	15	20	25 – 30
$[E_{GW} = 10^{-9} M_\odot c^2]$	AdV	-	10	10
	KAGRA	-	-	0 – 10

Abbott et al 1304.0670
(updated Sep 2019)

Low-latency searches

As LIGO and Virgo data is collected, the data are immediately analyzed to search for compact binary coalescence (CBC) and GW burst signals.

- Four low-latency CBC search pipelines: GstLAL, MBTAOnline, PyCBC Live, and SPIIR.
- One GW burst search pipeline: cWB (Coherent WaveBurst)

Each pipeline assesses the significance of any signal candidate, assigning it a false alarm rate (FAR) based on empirically measured noise properties.

The initial searches focus on detection, not on estimating the parameters of the source.

The RAVEN pipeline is used to check for coincidences of reported GRBs and GW triggers, even sub-threshold ones.

GW alerts during O1 and O2

During O1 and O2, GW candidate alerts were sent **privately** to groups of astronomers who signed an **MOU with the LVC**.

At the end of O2, the follow-up program included **95 groups**, with capabilities to search for EM counterparts from very high-energy to the radio band, and to search for neutrino counterparts.

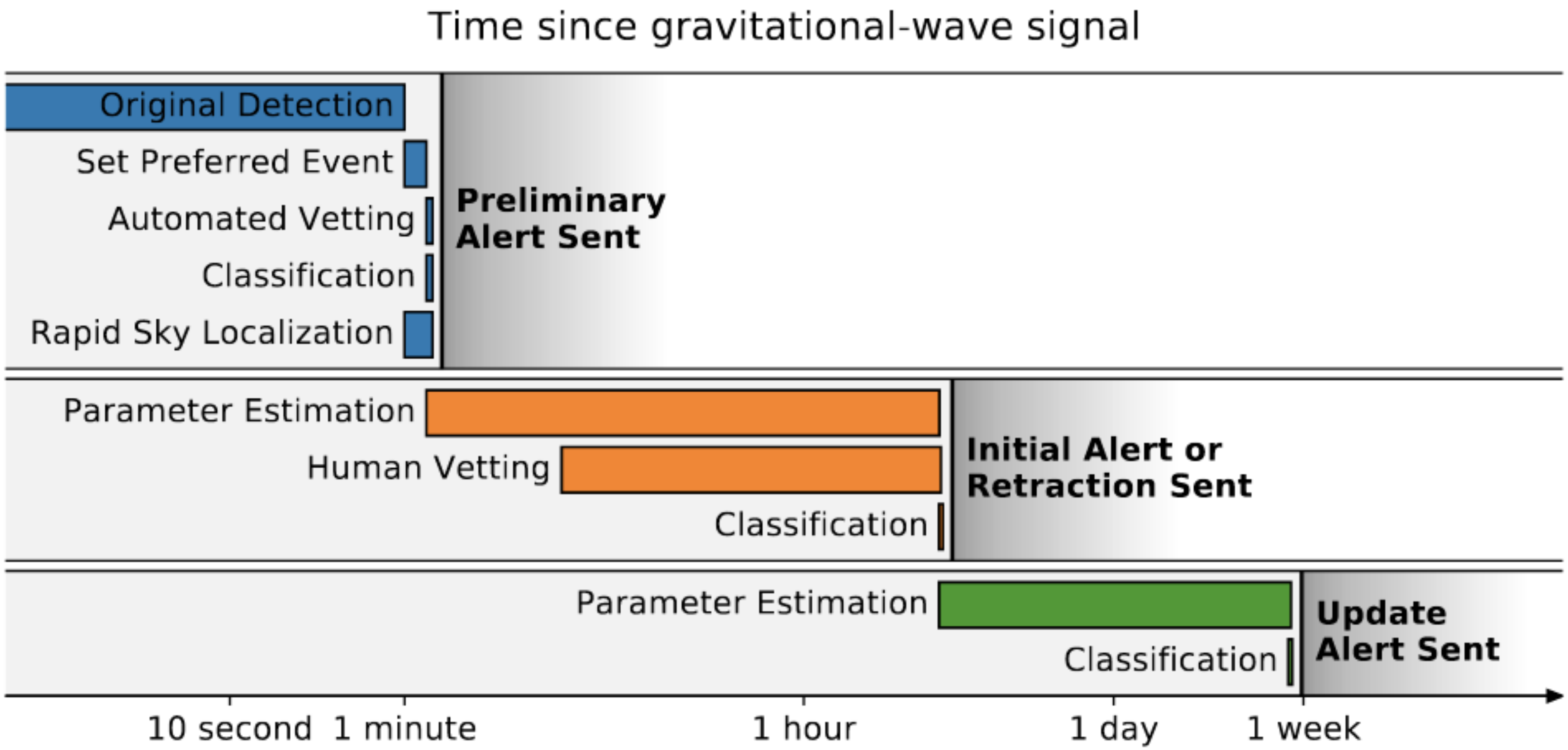
Only candidates with a **FAR below a threshold of 1/(2 months)** were selected to trigger the search for counterparts. Properties of the GW candidates were distributed using the Gamma-ray Coordinates Network (**GCN**) system, widely used in the astronomical community for multi-wavelength follow-up of GRBs.

GCNs info: event time, sky localization probability map, estimated FARs. For CBC candidates, also included volume localization (3D sky map), probability to contain a NS and probability to be EM bright .

17 alerts were sent to the astronomers during O1 and O2

O3: Public alerts for GW candidates

To facilitate the rapid identification of EM or neutrino counterparts to GW detections, and to maximize the science that the entire scientific community can do with them, GW candidate events are released as **public alerts** since the start of O3.



LIGO/Virgo Public Alerts User Guide

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

LSC LIGO Scientific Collaboration

VIRGO

Public Alerts

User Guide

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

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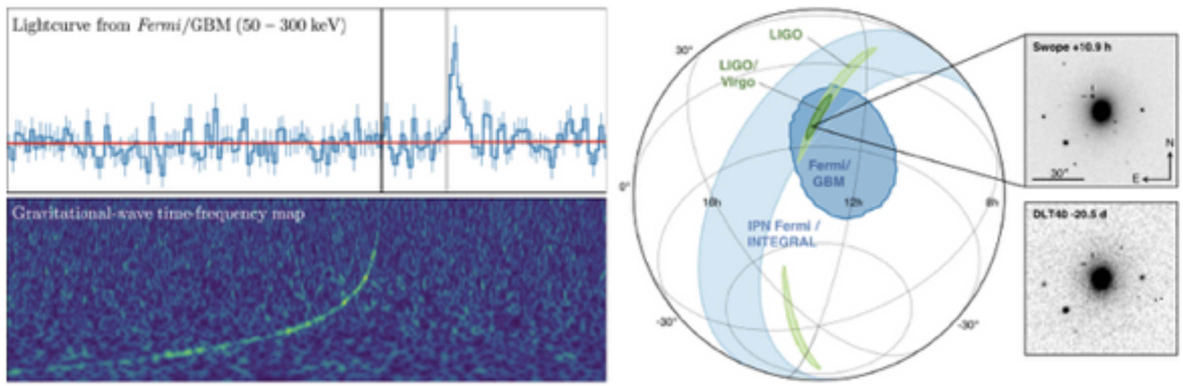
LIGO/Virgo Public Alerts User Guide



Welcome to the LIGO/Virgo Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

Three sites (LHO, LLO, Virgo) together form a global network of ground-based GW detectors. The LIGO Scientific Collaboration and the Virgo Collaboration jointly analyze the data in real time to detect and localize transients from compact binary mergers and other sources. When a signal candidate is found, an alert is sent to astronomers in order to search for counterparts (electromagnetic waves or neutrinos).

O3: Public alerts for GW candidates

Threshold to release automatic alerts:

- For CBC, FAR threshold to target an overall astrophysical purity (p_astro) of 90% across all categories of mergers.
- This translates into a FAR threshold of 1/(2 months) for CBC.
- For unmodeled burst events the FAR threshold is 1/yr

Contents of the alert:

- Estimate of False Alarm Rate (FAR) of the event candidate.
- Event time and sky localization given as a posterior probability distribution of the source's sky position.

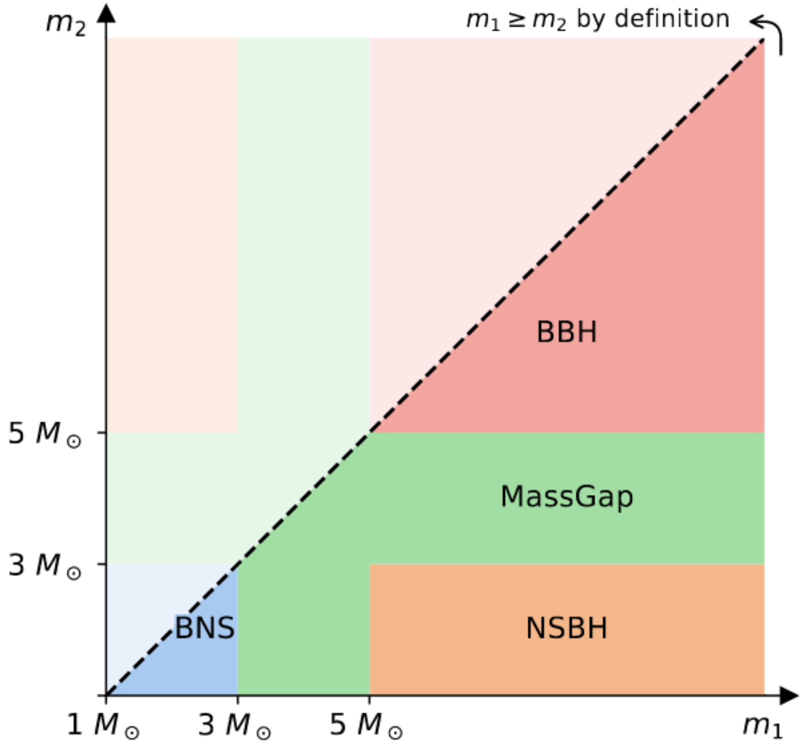
- For CBC candidates:

- 3-D skymap with direction dependent luminosity distance.
- Luminosity distance marginalized over whole sky.

O3: Public alerts for GW candidates

Contents of the alert:

- For burst candidates, central frequency in Hz, duration in seconds and the GW fluence in erg/cm^2.
- For CBC candidates, classification and properties.



Classification (p_astro):
probability signal is astrophysical

BNS: both masses < $3M_{sun}$
MassGap: $3M_{sun}$ < one mass < $5M_{sun}$
NSBH: one mass <$3M_{sun}$, other mass > $5M_{sun}$
BBH; both masses > $5M_{sun}$
Terrestrial: noise

Properties:

HasNS: probability one mass consistent with NS.
HasRemnant: probability system ejected NS matter.

p_astro measured by comparing differential rates of GW and background events at a given value of a search statistic (Abbott et al 2016).

GraceDB - GW Candidate Event Database

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

GraceDB — Gravitational-Wave Candidate Event Database

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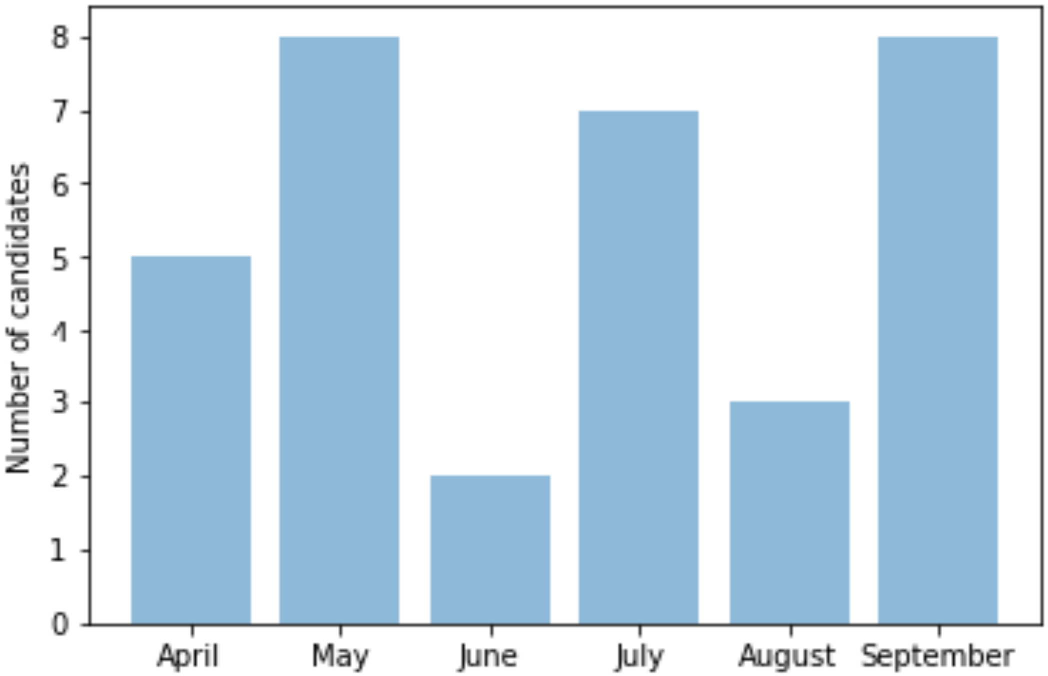
LIGO/Virgo O3 Public Alerts

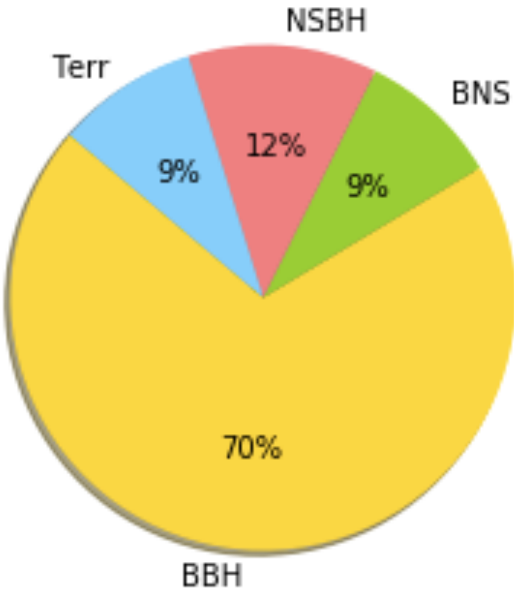
Detection candidates: 26

SORT: EVENT ID (A-Z) ▼

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190901ap	BNS (86%), Terrestrial (14%)	Sept. 1, 2019 23:31:01 UTC	GCN Circulars Notices | VOE		1 per 4.5093 years	
S190829u	MassGap (90%), Terrestrial (10%)	Aug. 29, 2019 21:05:56 UTC	GCN Circulars Notices | VOE		1 per 6.1522 years	RETRACTED
S190828l	BBH (>99%)	Aug. 28, 2019 06:55:09 UTC	GCN Circulars Notices | VOE		1 per 684.54 years	
S190828j	BBH (>99%)	Aug. 28, 2019 06:34:05 UTC	GCN Circulars Notices | VOE		1 per 3.7395e+13 years	
S190822c	BNS (>99%)	Aug. 22, 2019 01:29:59 UTC	GCN Circulars Notices | VOE		1 per 5.1566e+09 years	RETRACTED
S190816i	NSBH (83%), Terrestrial (17%)	Aug. 16, 2019 13:04:31 UTC	GCN Circulars Notices | VOE		1 per 2.2067 years	RETRACTED
		Aug. 14,	GCN			

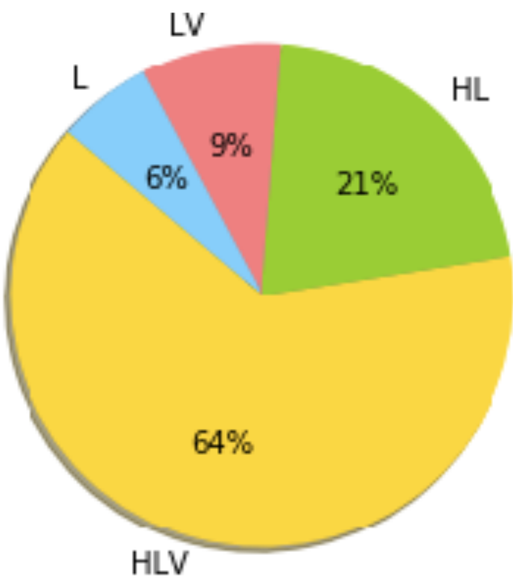
O3a: Public alerts



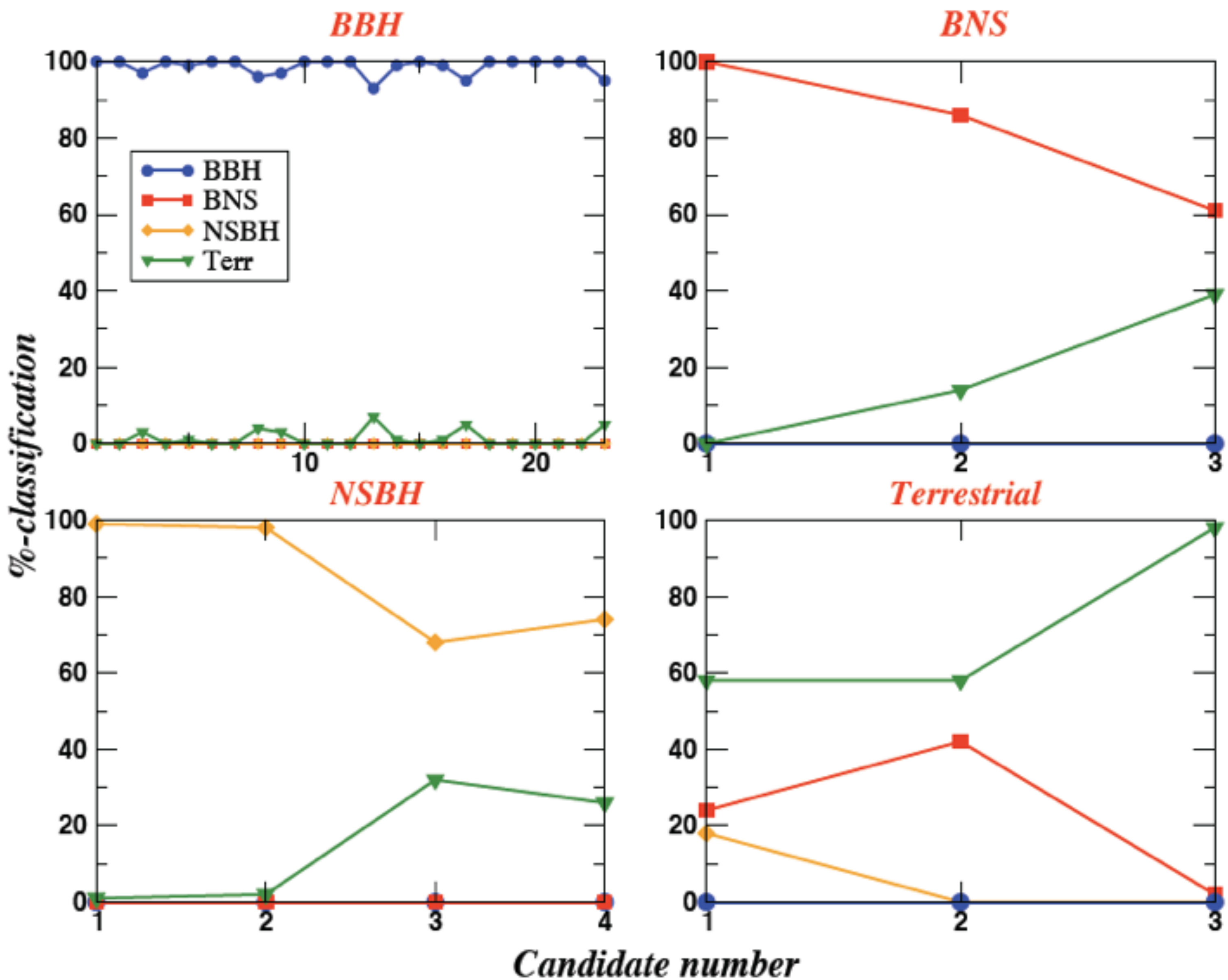


41 alerts
8 retractions

33 candidates



O3a: Source classification



O3a candidates + O1 + O2 detections

Number of candidates: 41 (excluding retractions)

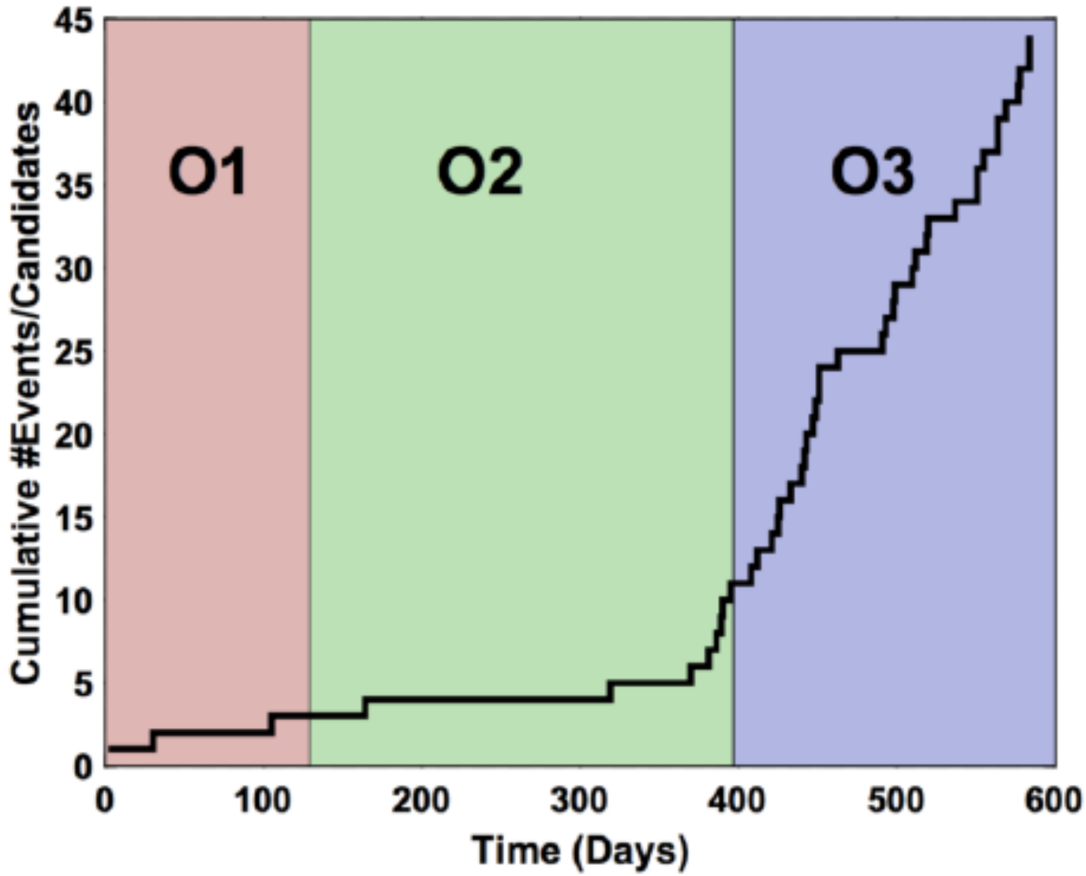
False alarm rate (FAR):

26 with FAR > 1/100 yr
15 with FAR < 1/100 yr

Number of retractions: 8

O3a candidate types:

21 BBH
3 BNS
2 Mass Gap
4 NSBH
3 Terrestrial



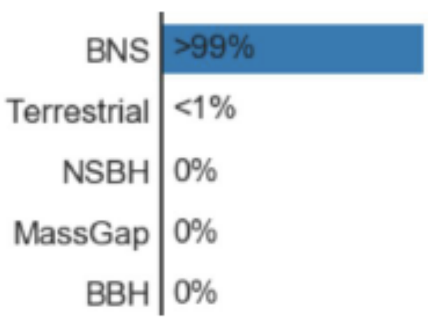
Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}

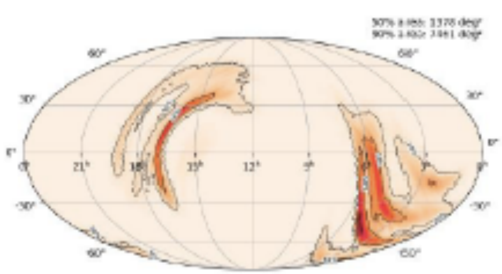
O3a: BNS candidates

Three candidates have significant probability of being BNS events.
Poor sky localization: despite extensive EM follow-up campaign no counterparts found.

S190425z
FAR < 1/100 yrs

7461 deg2 in 90% c.r.
Distance 156±41 Mpc
L, V

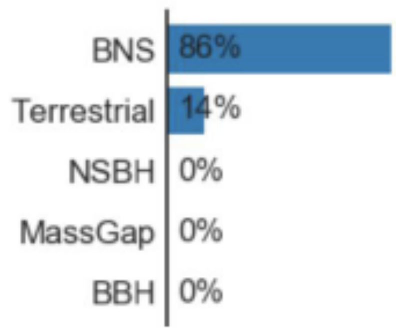


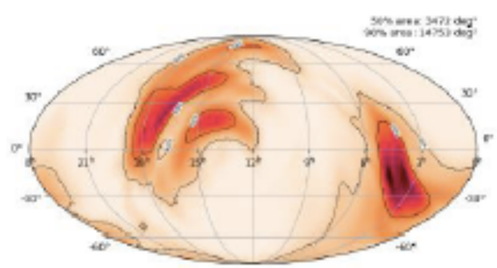


GCN 24168, 24228

S190901ap
FAR: 1 in 4.5 yrs

14753 deg2
241±79 Mpc
L, V

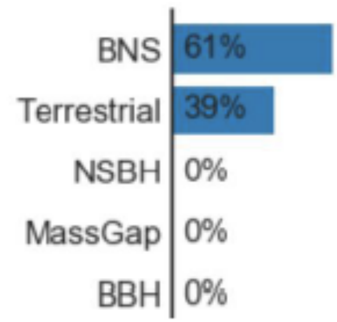


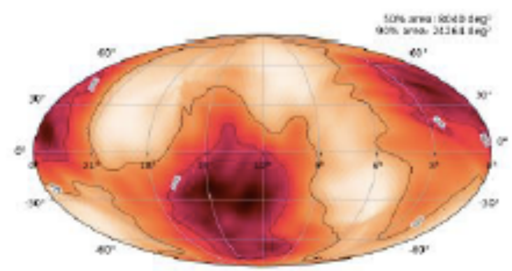


25606, 25614

S190910h
FAR: 1.13 per year

24264 deg2
230±88 Mpc
L



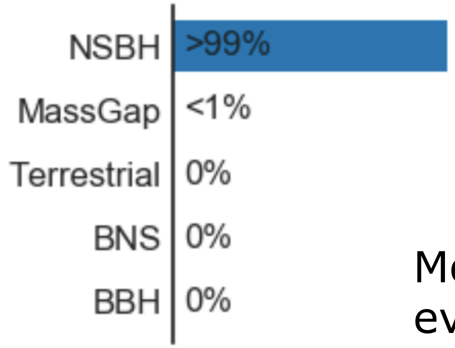


25707, 25778

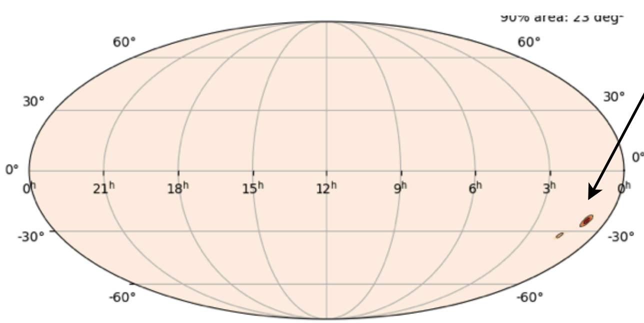
O3a: NSBH candidates

No NSBH detections in O1/O2. 4 candidates in O3. First detection of a new class of GW events.

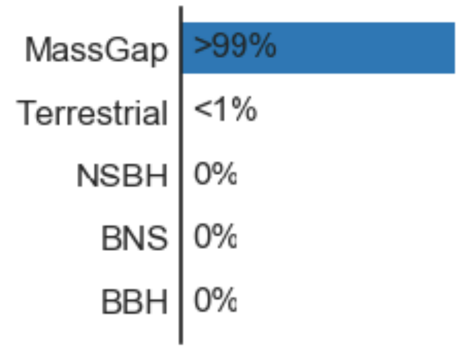
S190814bv
FAR < 1/100 yrs
90% c.r. 23 deg^2
Distance 267±52 Mpc
L,H,V

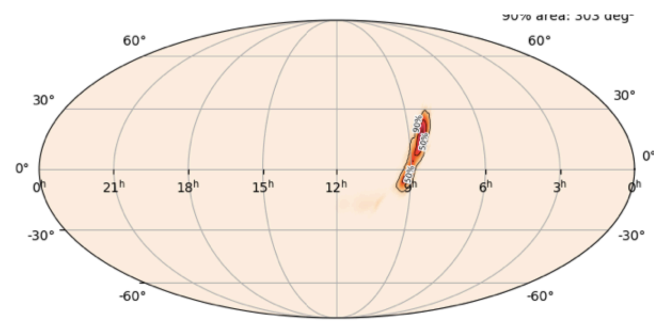


Most localised event thus far.



S190814h
FAR < 1/100 yrs
90% c.r. 303 deg^2
Distance 548±112 Mpc
L,H,V





GCN 25324, 25333

Conclusions

- **GW Astronomy** and **Multi-Messenger Astrophysics** started in O1 and O2: large community of scientists interested in GW detections.
- **Scientific impact** of GW detections growing.
- Since O3 we are in the **Public Alerts** era.

- O3a has been a very successful run:
  - **33 open candidate alerts** have been **sent**: 23 BBH, 3 BNS, 4 NSBH
  - No EM counterparts announced thus far.

- O3b started on Nov 1st.

- KAGRA to hopefully join O3b with BNS range of a few Mpc.

- **Public data**: 18 months after the end of each run

These are very exciting times ...