Based on LIGO-G1900073

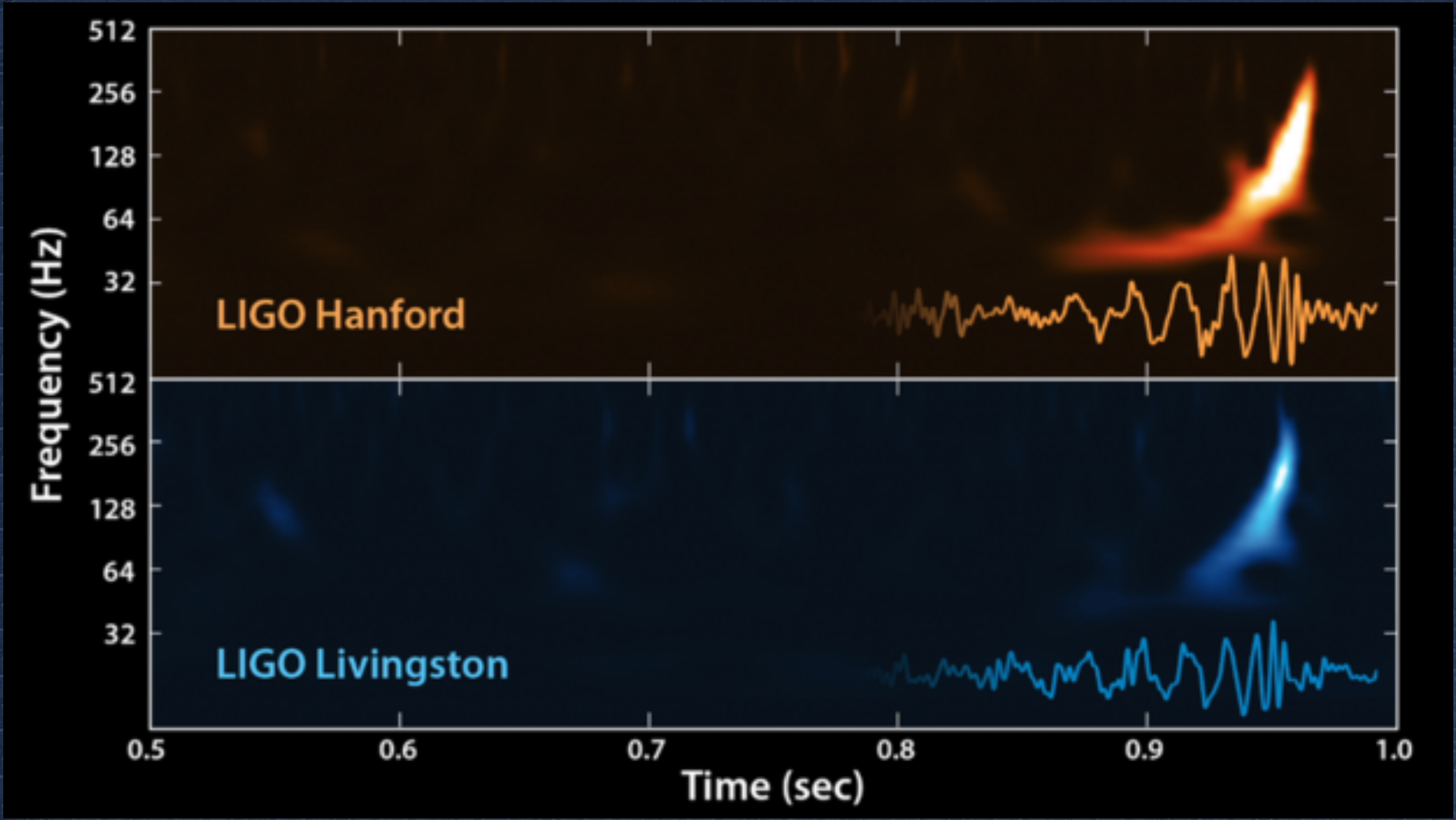
Updates from LIGO-Virgo Observing Runs

(for LIGO Scientific and Virgo Collaboration)

Archana Pai

IIT Bombay

Chennai Symposium on Gravity and Cosmology, January 24,2020



Era of gravitational wave astronomy begun on September 14, 2015 when gravitational wave detectors observed the first signal from the Universe

LVC, PRL 116, 061102 (2016)

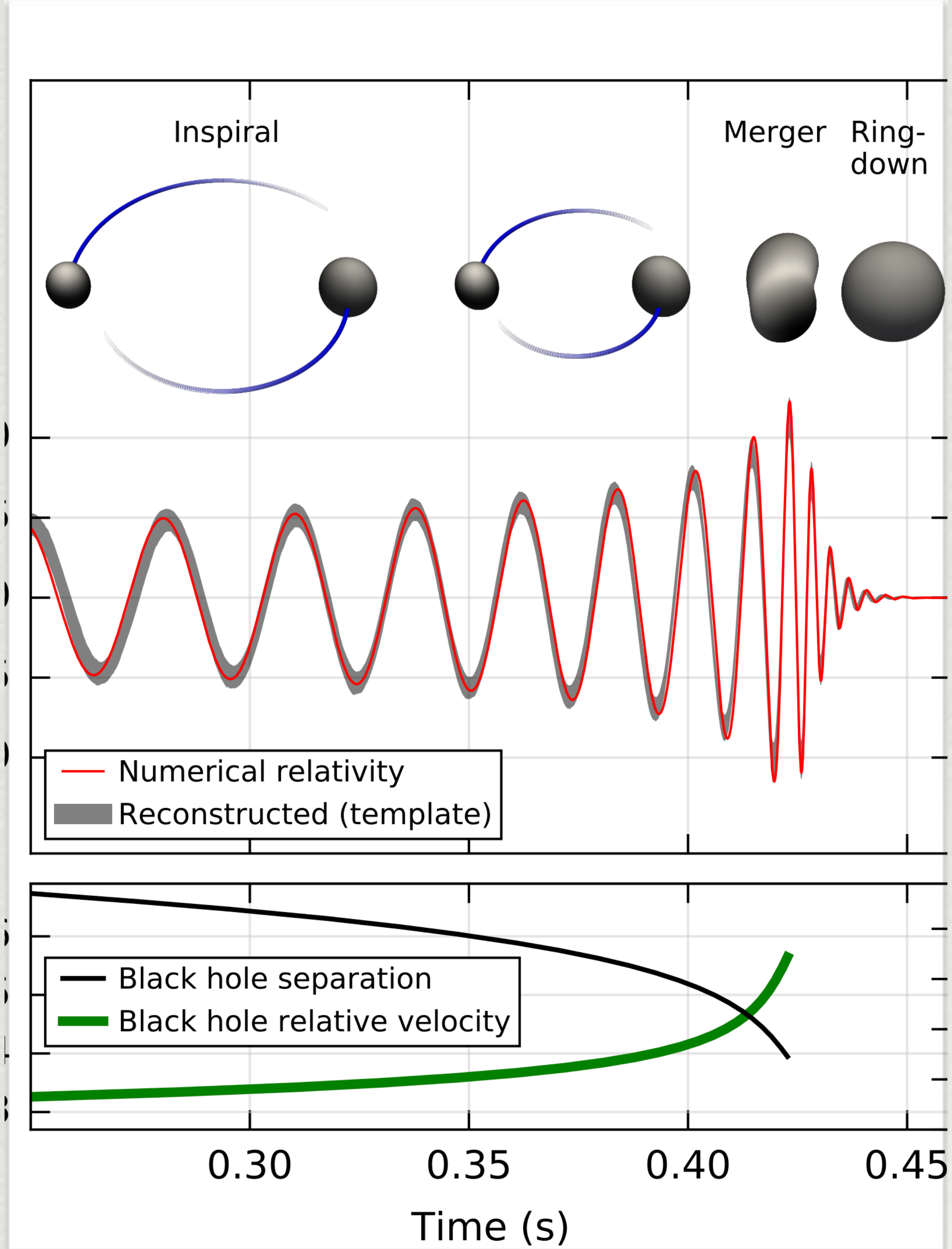
GW150914

Collision of two stellar mass BHs into a kerr BH
Signal to Noise Ratio : 24 in two LIGO detectors
Peak strain produced 10e-21.
Signal duration 200 msec from 30 Hz

Masses: 29 Msun + 36 Msun
Distance: 1.33 Billion Light Years (450Mpc)
Power radiated: Equivalent to 3Msun

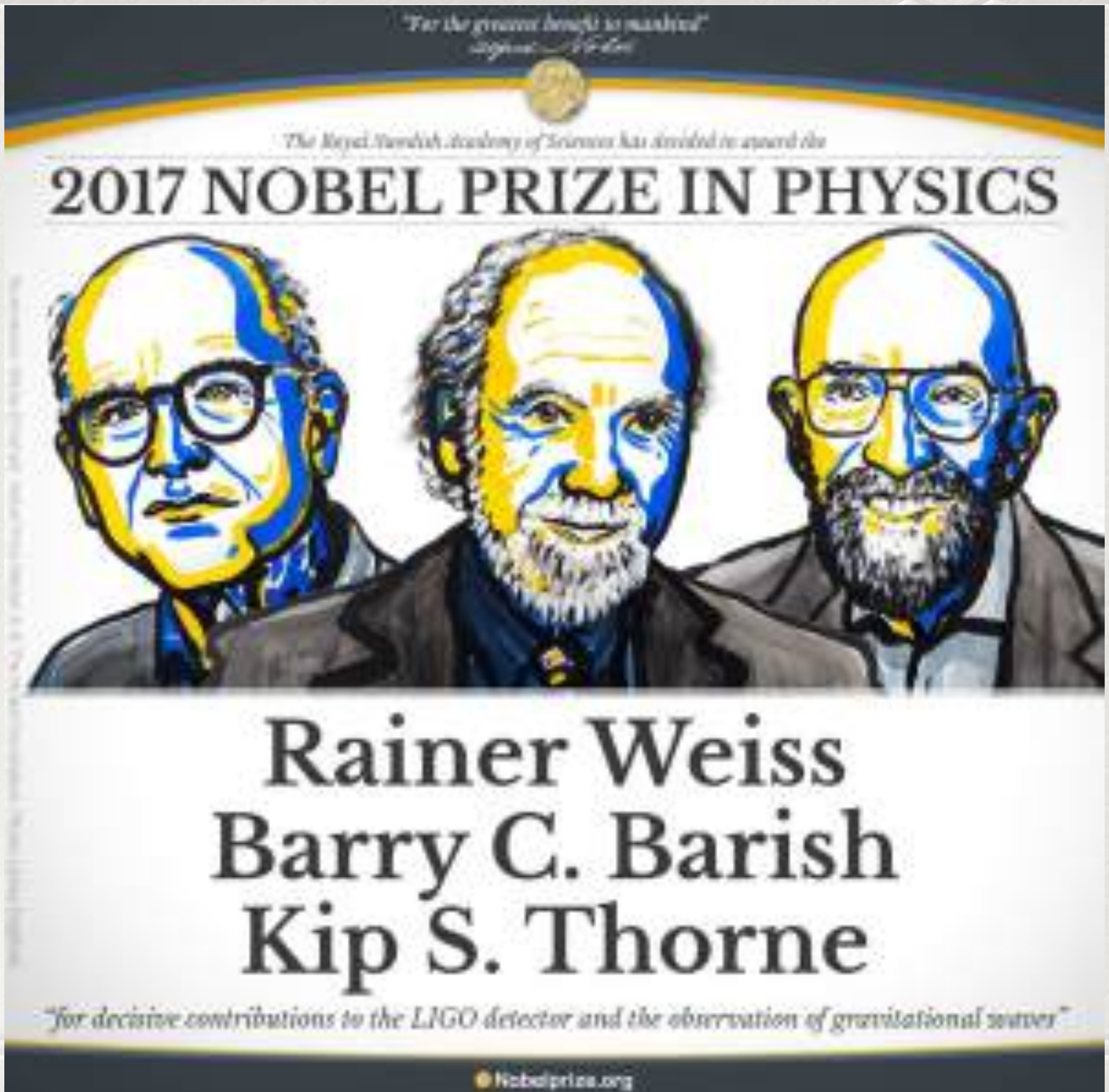
Final black hole mass: 62 Msun
Final black hole spin: 0.67

Highly relativistic



LVC, PRL 116, 061102 (2016)

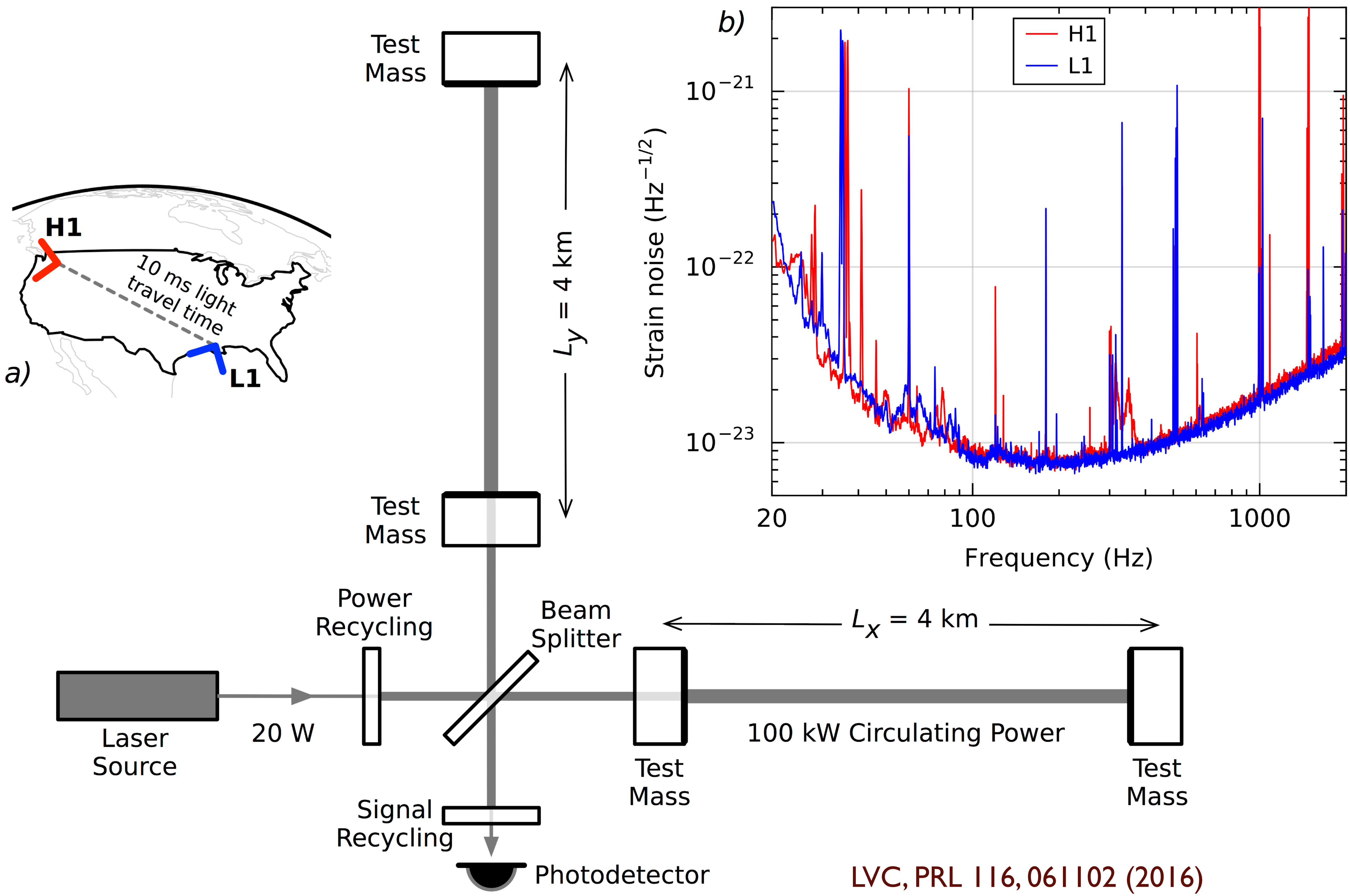
Nobel Prize in Physics for the year 2017



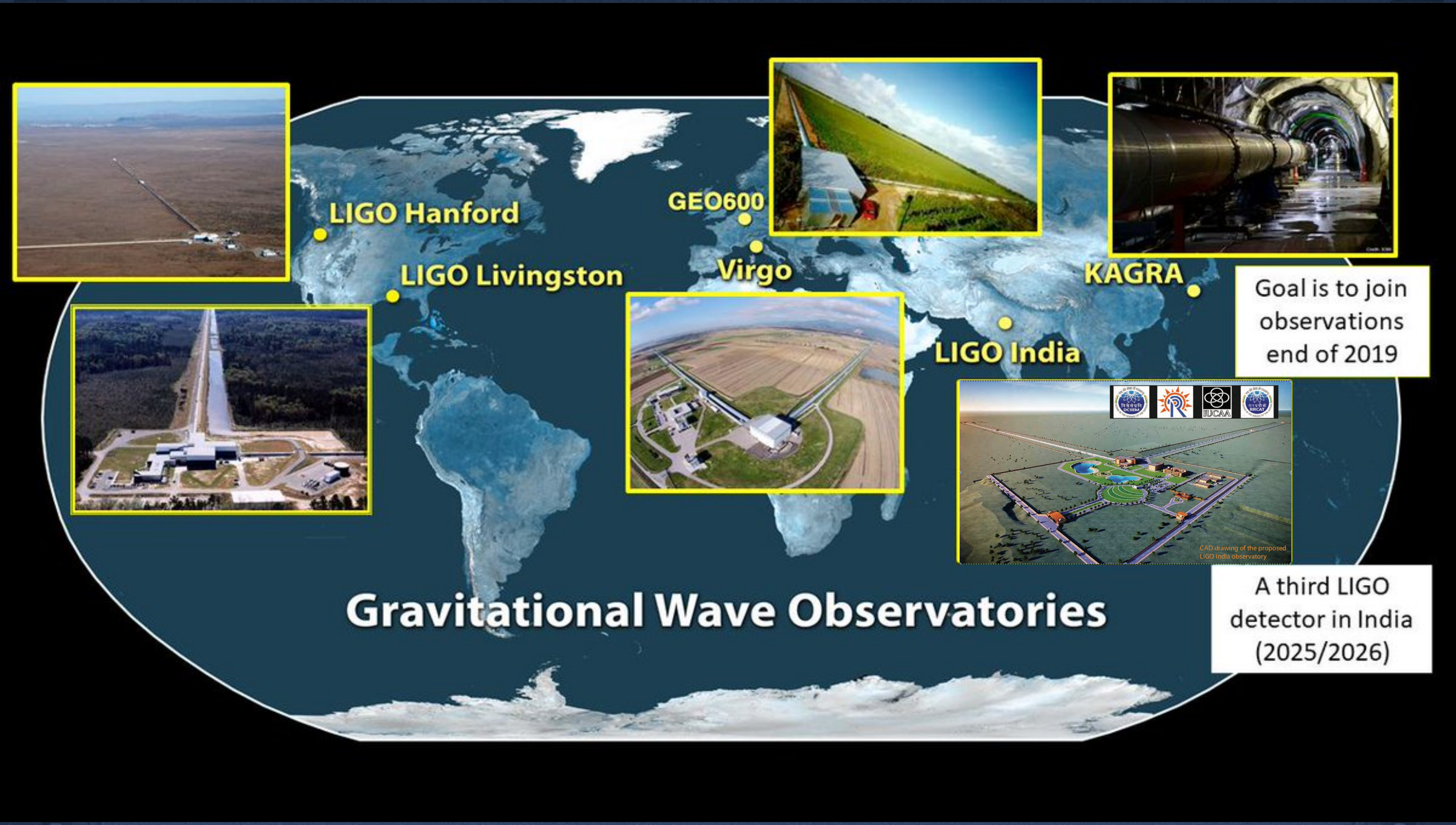
- *For the decisive contributions to the LIGO detector and the observation of gravitational waves*
- *Uniqueness of the discovery:*
  First direct observation of GW,
  First direct probe to binary BHs,
  First probe to strong gravity,
  First evidence of stellar mass BHs above 20 Msun.

Laser Interferometric Gravitational Wave Observatories (LIGO)

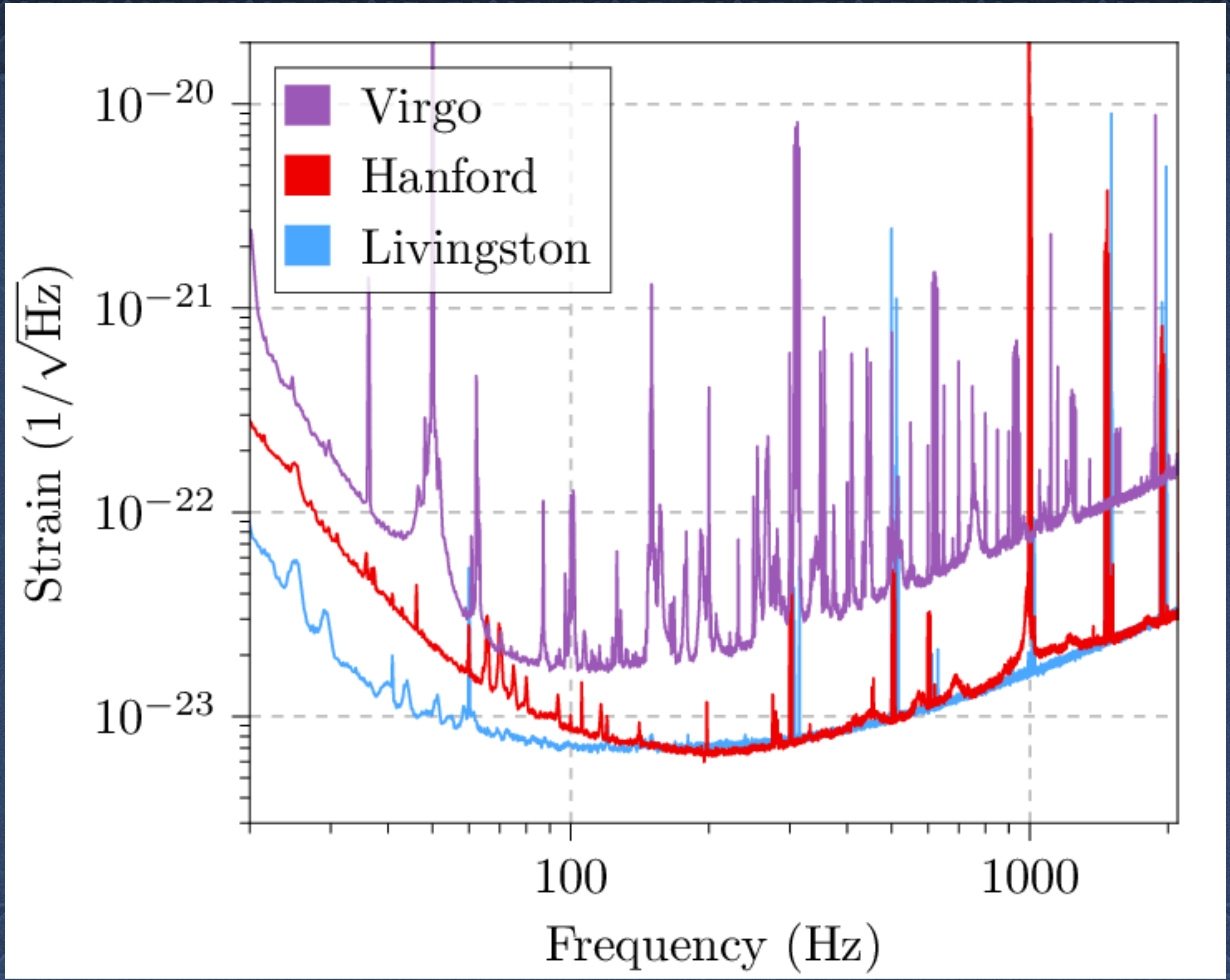
Km arm length Suspended Optical Laser Interferometer with Fabry Perot Cavities



LVC, PRL 116, 061102 (2016)

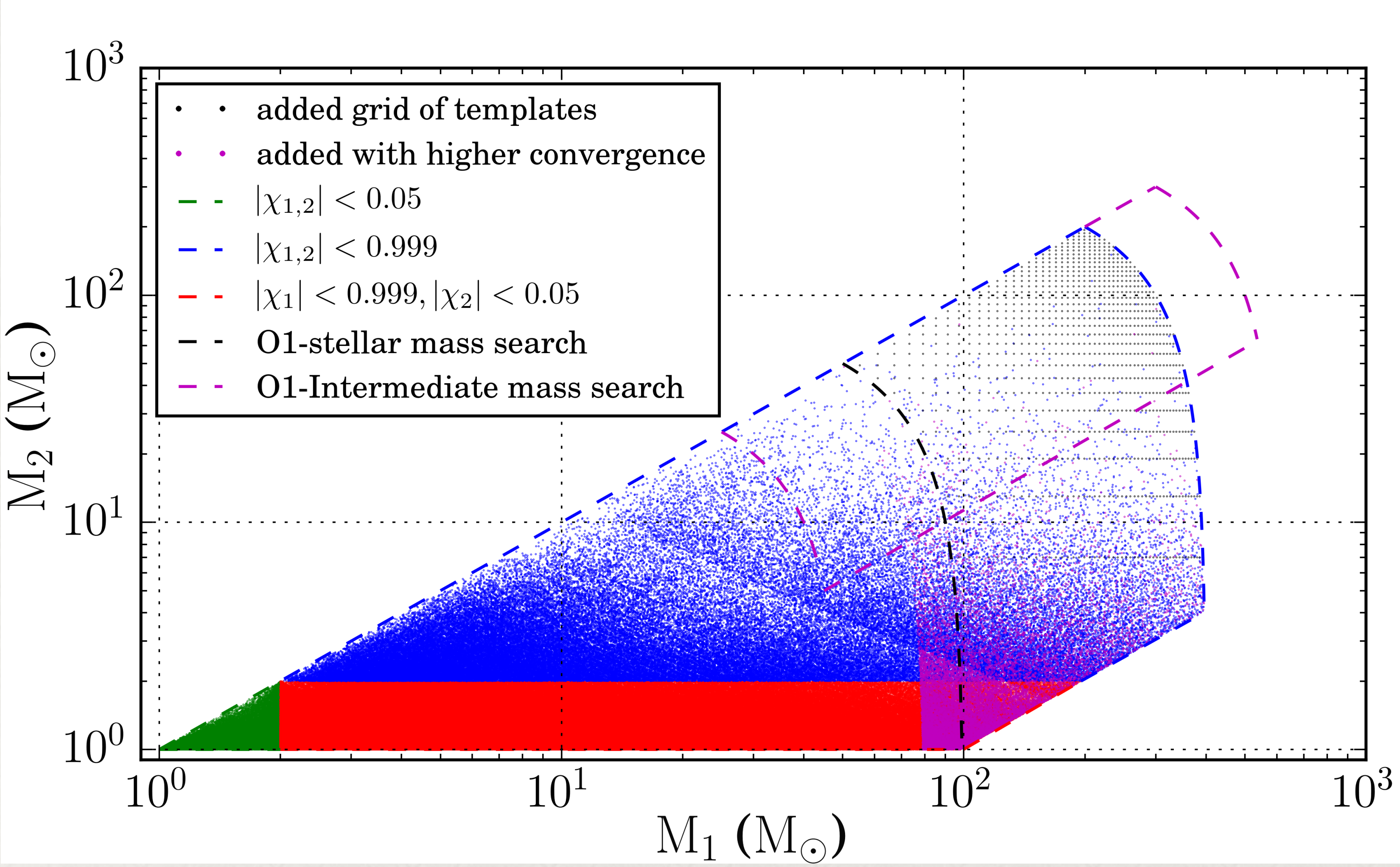


Global network of ground based laser interferometric gravitational wave observatories



Sensitivity of Advanced LIGO-Virgo during second observing run O2(Nov2016-Aug2017)

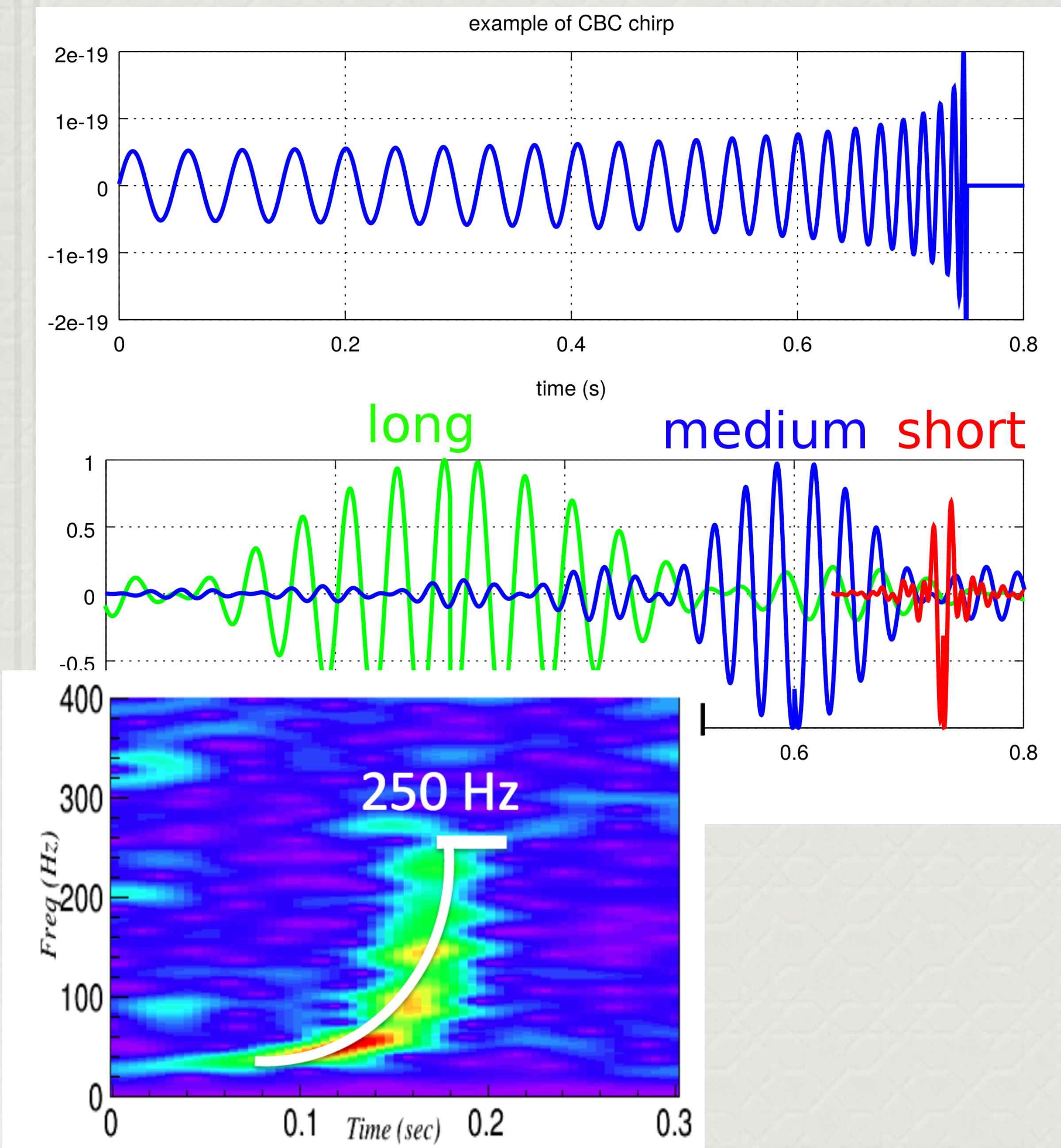
GW transient searches-modeled



- *Matched filtering: Cross-correlation of the data with the GR template*
- *Templates from general relativity waveforms with BH spins aligned with the orbital angular momentum*
- *GstLAL (M: 2-400 Msun) [Messik etal. PRD 2017] PyCBC (M:2-500 Msun) [Canton etal, PRD 2014]*

LVC, GWTC1, PRX 2019

GW transient searches-unmodeled

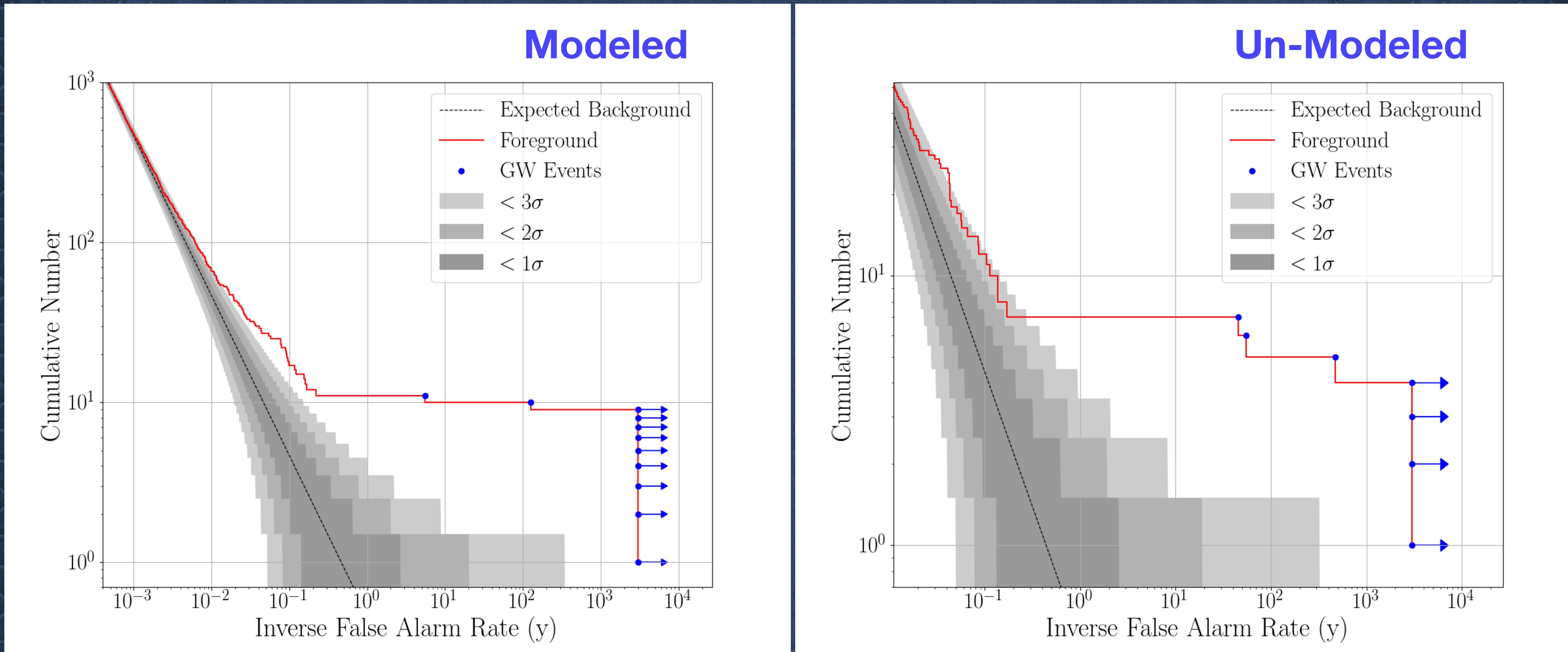


$$\frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} t + \frac{3}{8} f^{-8/3} + C = 0$$

- *Coherent Wave-Burst: Project the data on the wavelet domain characterised by (time,freq,scale).*
- *Combine the time-frequency energy from detectors (incorporating possible delays) and obtain pixel energy for each scale.*
- *Obtain energetic pixels.*
- *Clustering scheme combines the TF pixels from different scales which constructs clusters.*
- *Maximum likelihood ratio statistic is used for each cluster to obtain multi-detector statistic.*

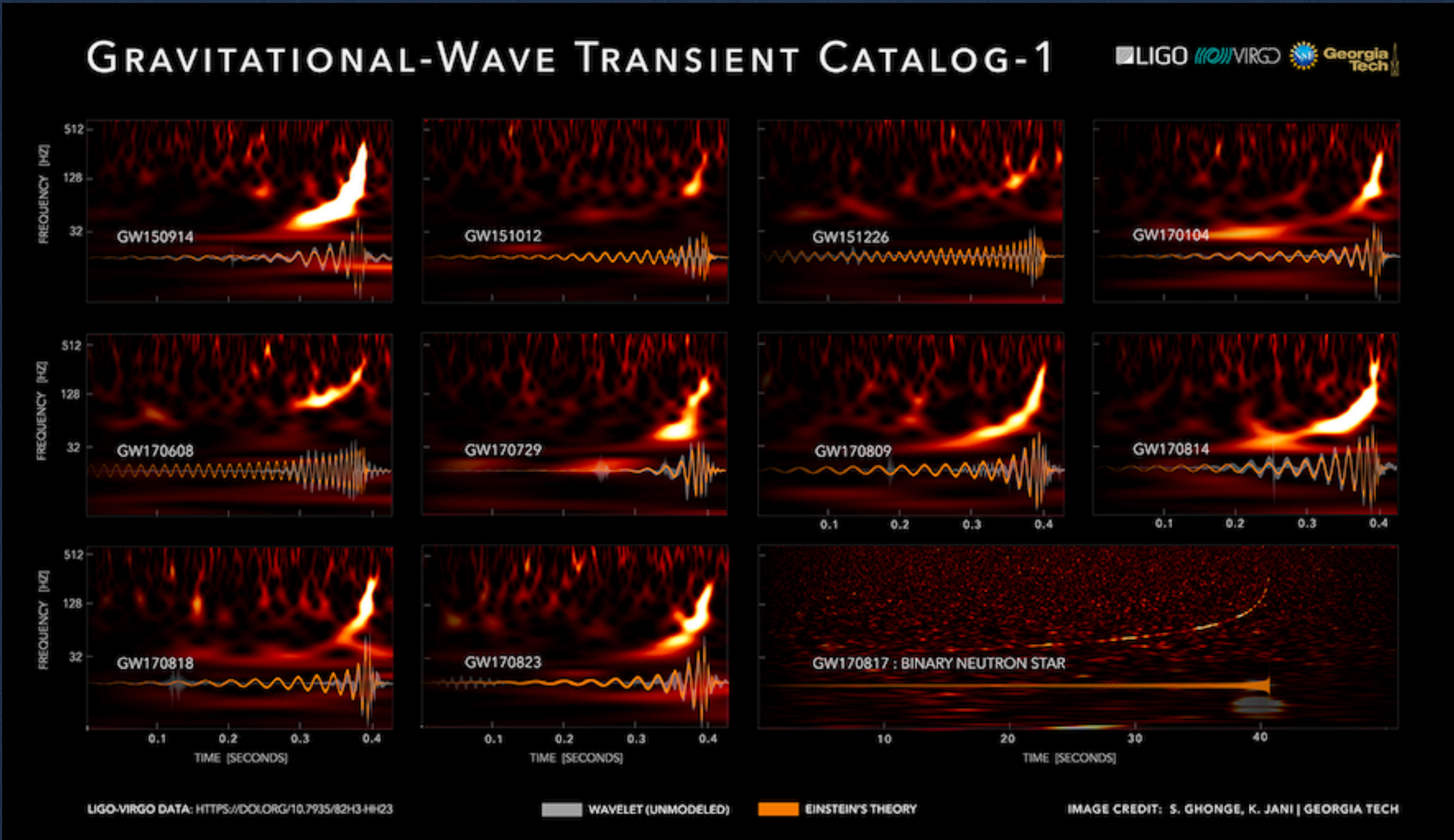
[Klimenko etal PRD 2016]

Significance of the GW triggers

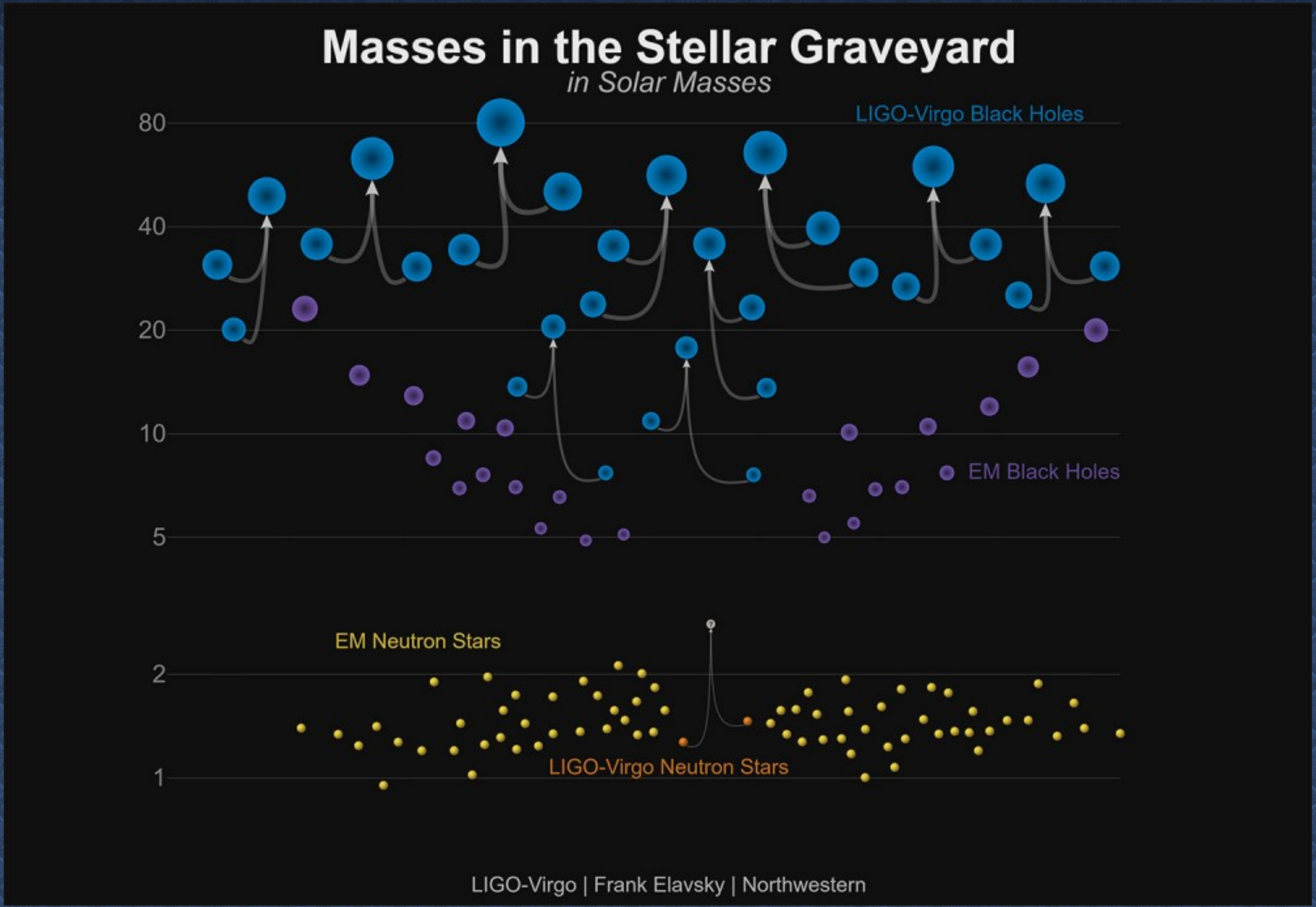


LVC, GWTC1, PRX 2019

Foreground trigger with (FAR below 1 in 30 days) and probability of astrophysical origin > 50% is termed as GW event



Result of first two observing runs of LIGO-Virgo detectors
O1(Sept2015-Jan2016) O2(Nov2016-Aug2017)

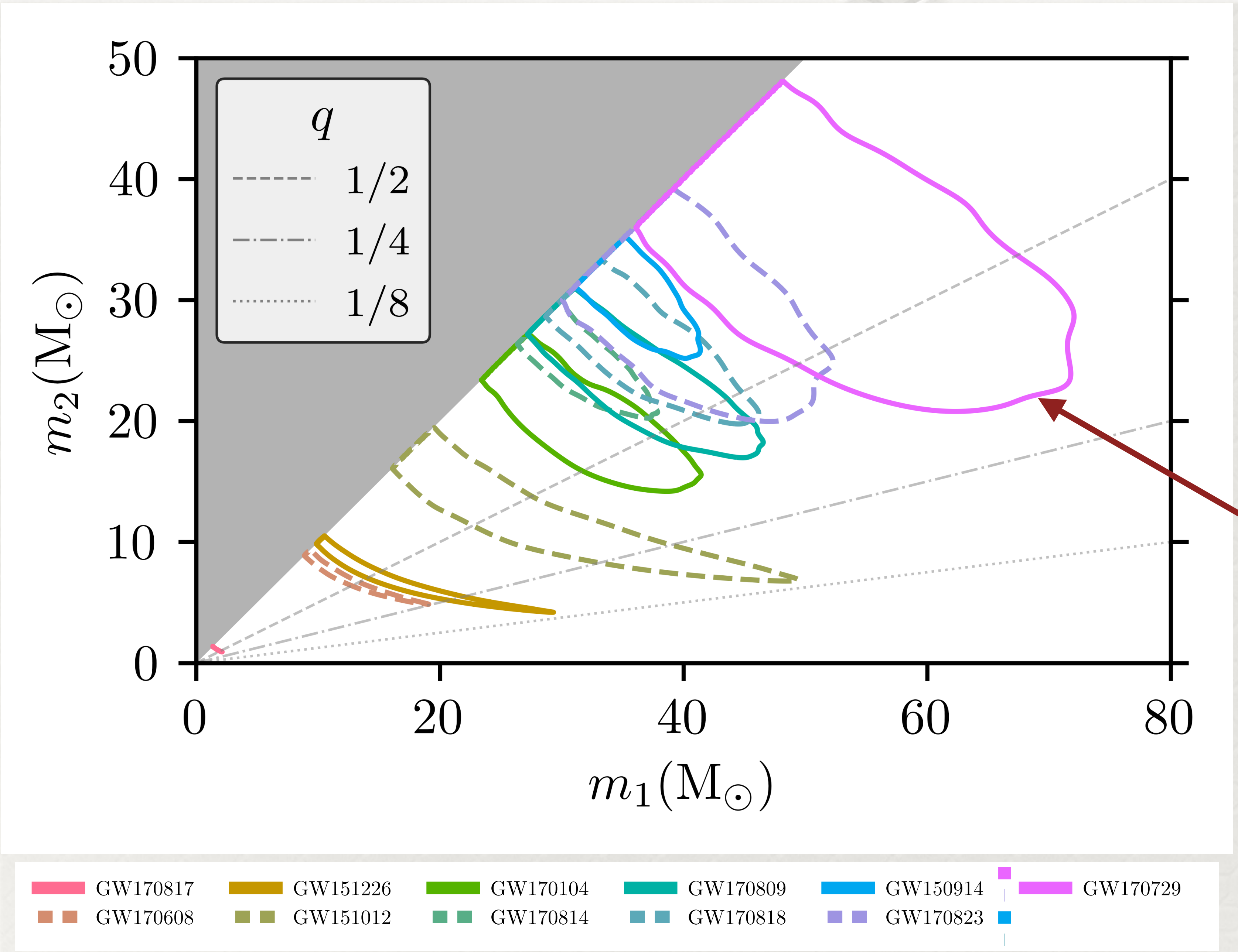


Ten binary binary BHs and one binary NS observed

A population of high mass stellar BHs is observed

What did we learn from compact binary mergers?

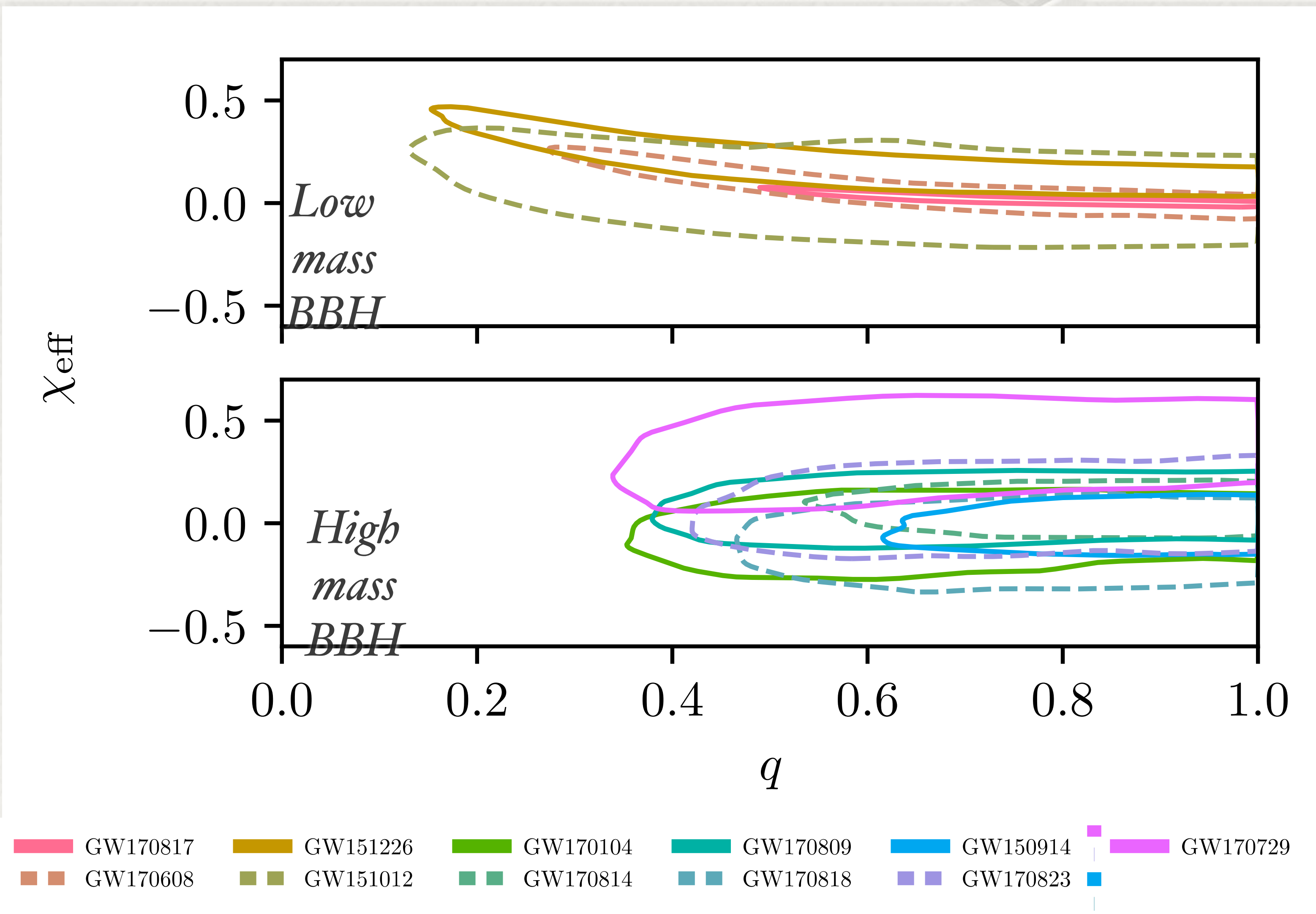
Observed component masses



- *Comparable masses , Component mass range 5-70 Msun, above the 2-5Msun mass gap.*
- *Most massive system is GW170729 with mass ratio q ~ 0.3-0.8*

LVC, GWTC1, PRX 2019

Spin components

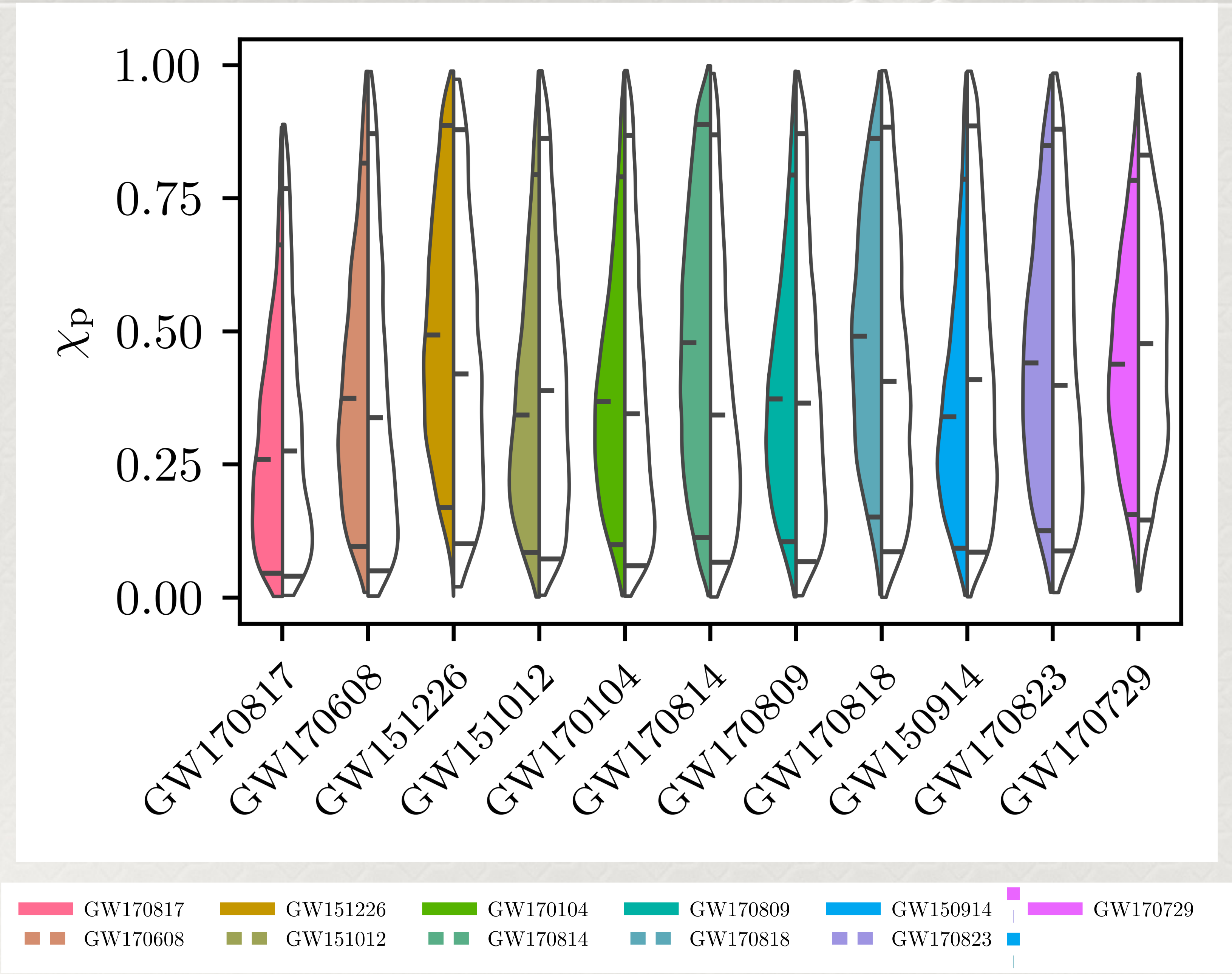


$$\chi_p = \max\left(\chi_1^{\perp}, \frac{2+3q/2}{q^2}\chi_2^{\perp}\right), \quad \chi_{eff} = \frac{\chi_1^{\parallel} m_1 + \chi_2^{\parallel} m_2}{m_1 + m_2}.$$

- *No correlation between the effective spin and the mass ratio (comparable mass binaries)*
- *Measures moderate spins centred around zero.*
- *Massive systems estimate mass ratio better due to high SNR.*

LVC, GWTC1, PRX 2019

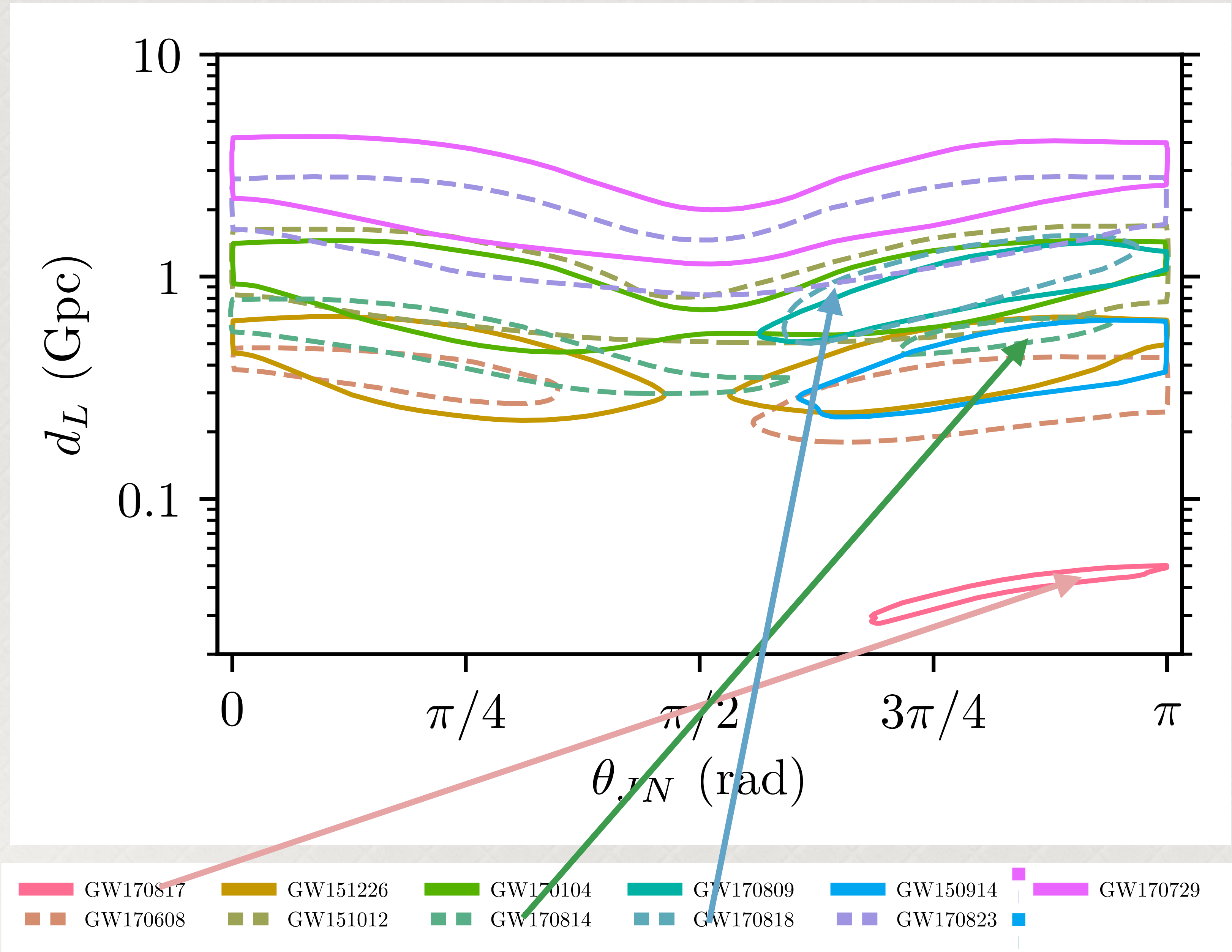
Spin precession



- Isolated binaries gets aligned with the angular momentum
- Binaries formed in the dense environment can have isotropic spin distributions
- Observations show no precession so far and less extreme spins (Vanilla BBH)
- Consistent with the prior distribution

LVC, GWTC1, PRX 2019

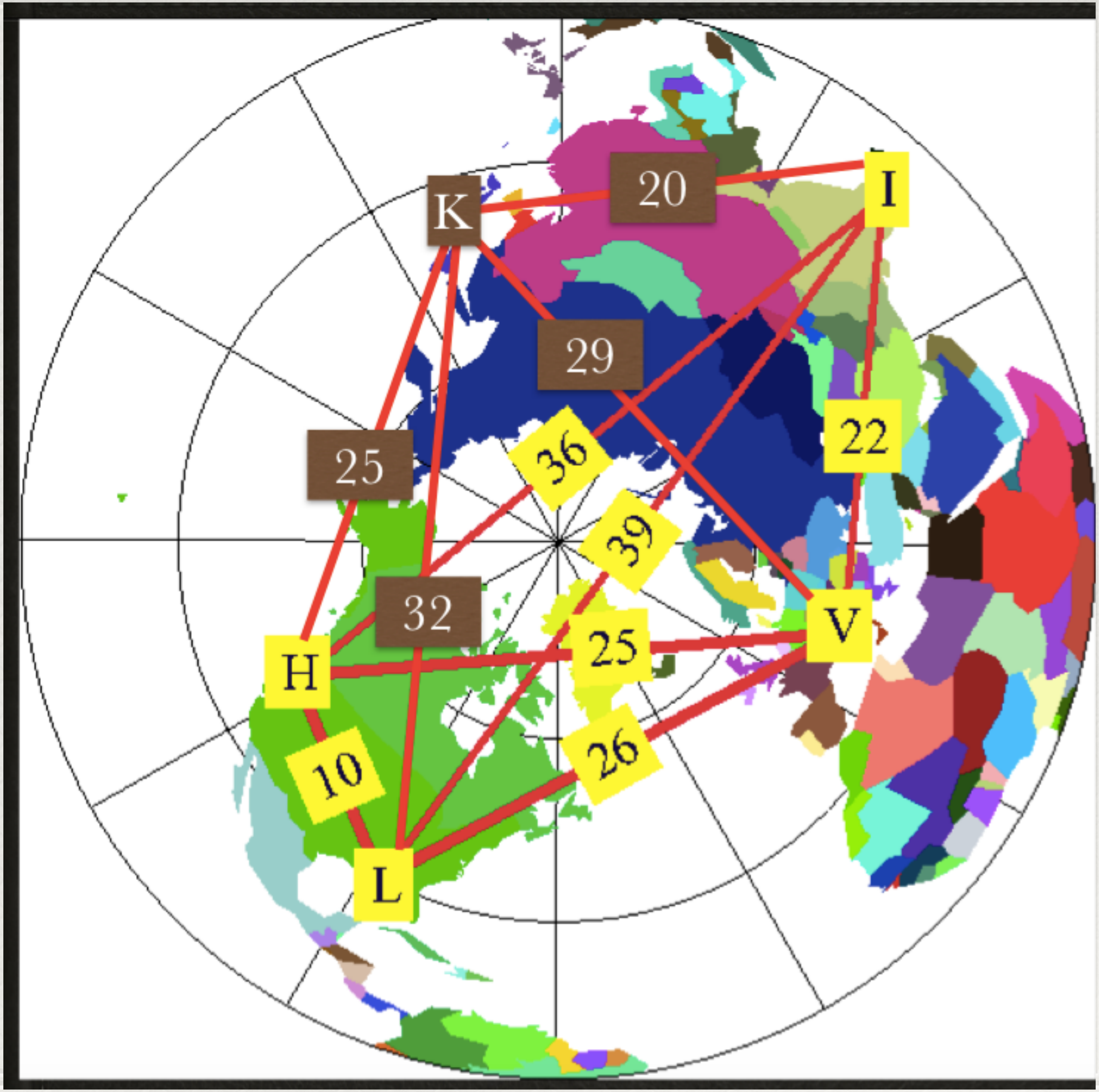
Distance and Inclination



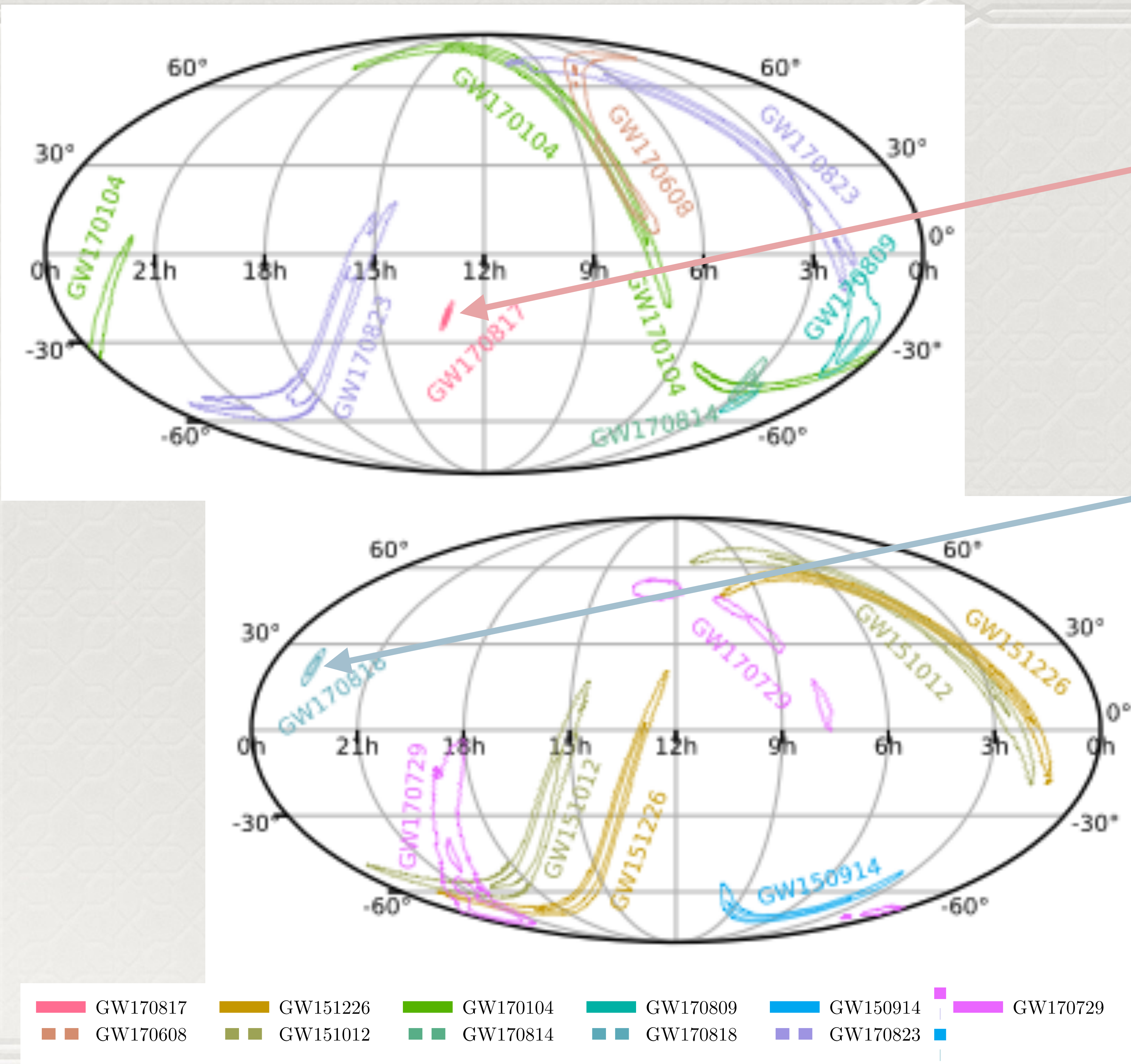
- ✦ *Strong correlation between inclination and distance*
- ✦ *Identification of the EM counterpart e.g GW170817 reduces this correlation*
- ✦ *More detectors will improve the accuracy*

LVC, GWTC1, PRX 2019

Light travel time between the two sites LLO-LIO has longest baseline of 39 msec



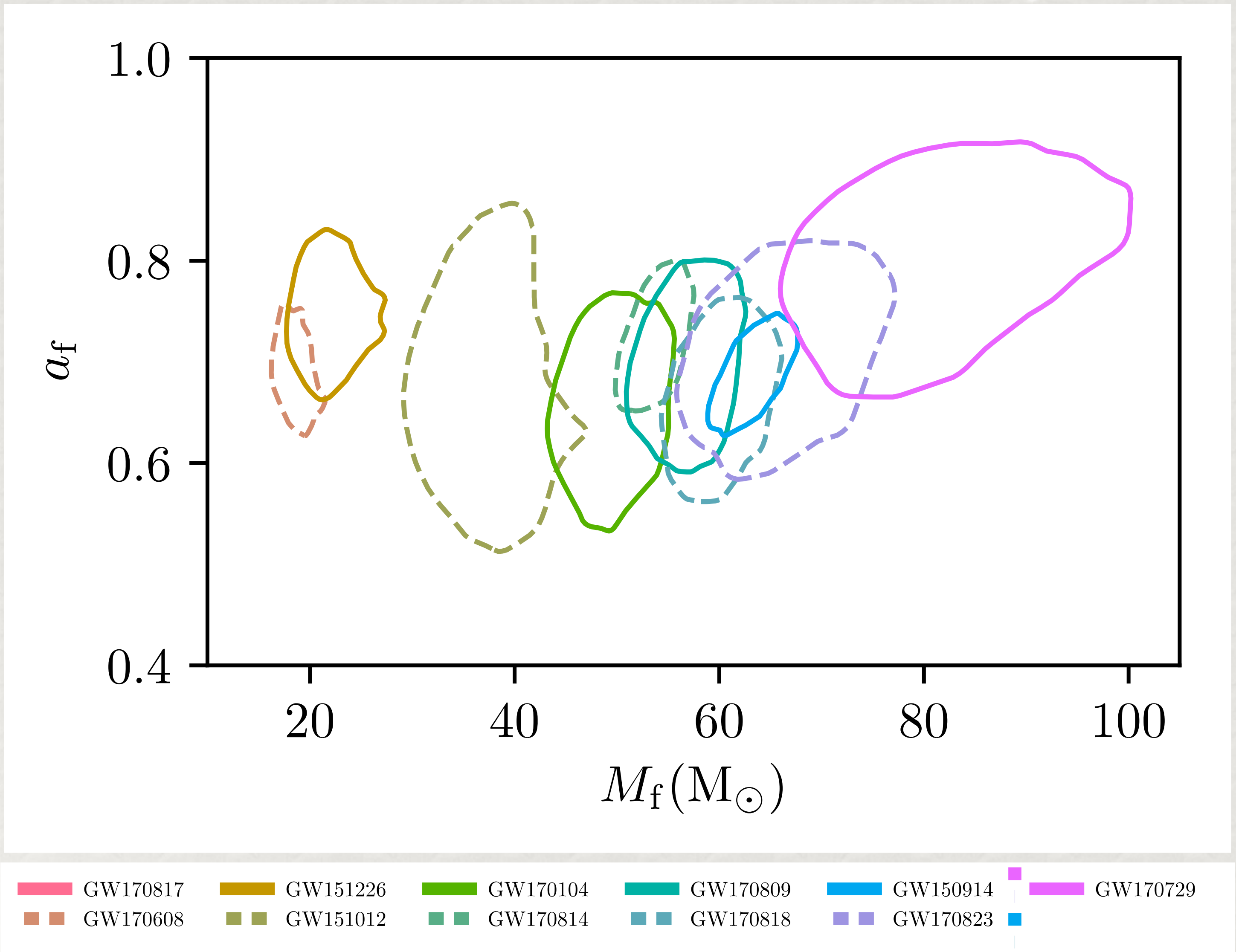
Sky Localization



- *Best sky localization GW170817 (16square degrees)*
- *Best binary BH localised GW170818 (39 square degrees)*
- *Both LHV events*
- *Longer separation, better sky localisation*

LVC, GWTC1, PRX 2019

Mass and spin of the final BH



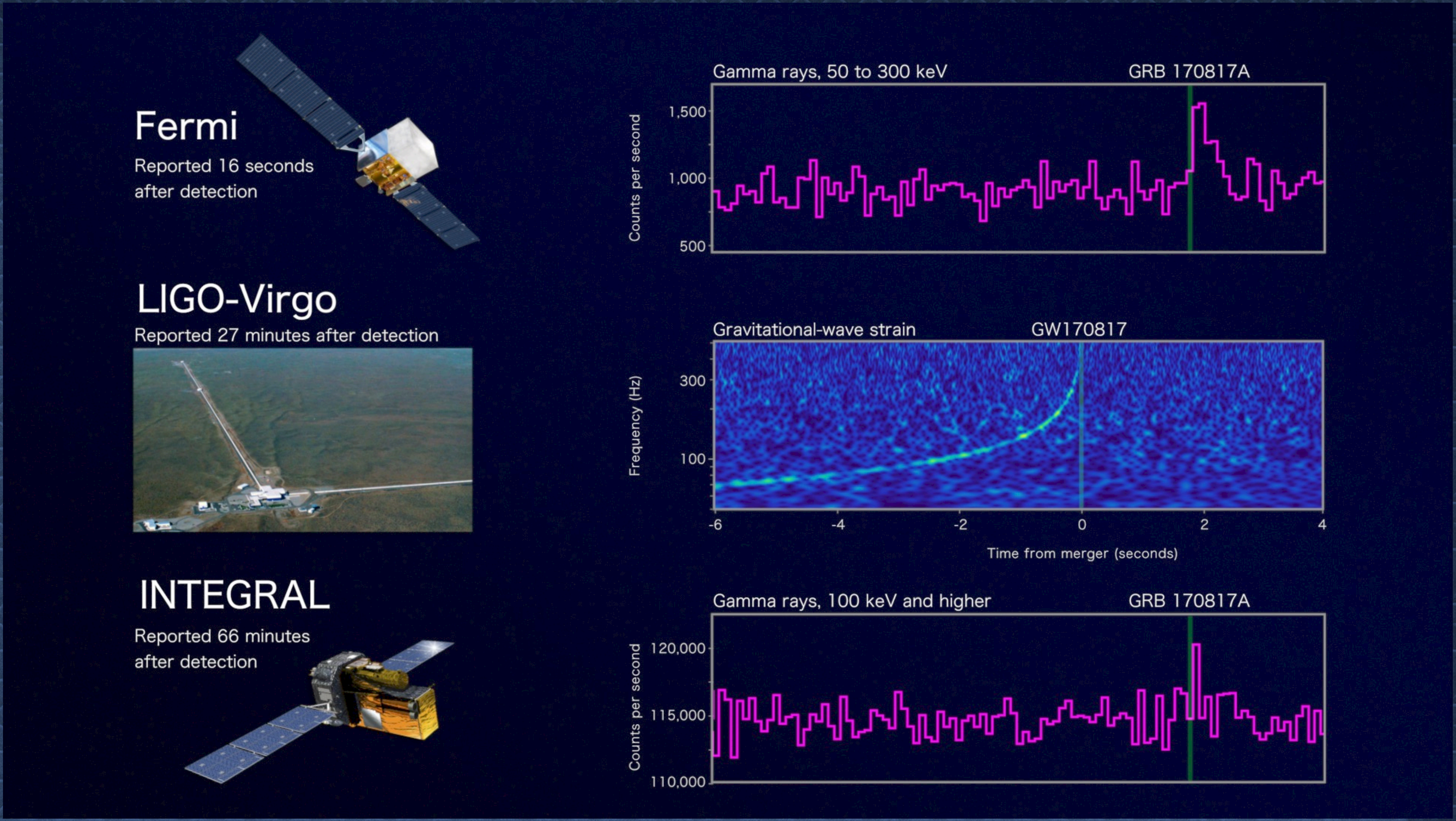
- For non-spinning equal mass systems, the spin of the final BH ~0.7
- All the observed BBH systems show the median final BH spin value close to 0.7 or consistent with 0.7 @ the 90% CI
- Distribution of mass and spin of BH shine light on the stellar evolutionary pathways

LVC, GWTC1, PRX 2019

LVC, GWTC1, PRX 2019

Event	Properties			
	D_L [Mpc]	M_{tot} [$M_\odot$]	M_f [$M_\odot$]	a_f
GW150914[b]	430^{+150}_{-170}	$66.2^{+3.7}_{-3.3}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$
GW151012[b]	1060^{+550}_{-480}	$37.3^{+10.6}_{-3.9}$	$35.7^{+10.7}_{-3.8}$	$0.67^{+0.13}_{-0.11}$
GW151226[b,c]	440^{+180}_{-190}	$21.5^{+6.2}_{-1.5}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$
GW170104	960^{+440}_{-420}	$51.3^{+5.3}_{-4.2}$	$49.1^{+5.2}_{-4.0}$	$0.66^{+0.08}_{-0.11}$
GW170608	320^{+120}_{-110}	$18.6^{+3.1}_{-0.7}$	$17.8^{+3.2}_{-0.7}$	$0.69^{+0.04}_{-0.04}$
GW170729[d]	2760^{+1380}_{-1340}	$85.2^{+15.6}_{-11.1}$	$80.3^{+14.6}_{-10.2}$	$0.81^{+0.07}_{-0.13}$
GW170809	990^{+320}_{-380}	$59.2^{+5.4}_{-3.9}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$
GW170814	580^{+160}_{-210}	$56.1^{+3.4}_{-2.7}$	$53.4^{+3.2}_{-2.4}$	$0.72^{+0.07}_{-0.05}$
GW170818	1020^{+430}_{-360}	$62.5^{+5.1}_{-4.0}$	$59.8^{+4.8}_{-3.8}$	$0.67^{+0.07}_{-0.08}$
GW170823	1850^{+840}_{-840}	$68.9^{+9.9}_{-7.1}$	$65.6^{+9.4}_{-6.6}$	$0.71^{+0.08}_{-0.10}$

Black Hole binary source properties



GW170817 : First binary NS merger

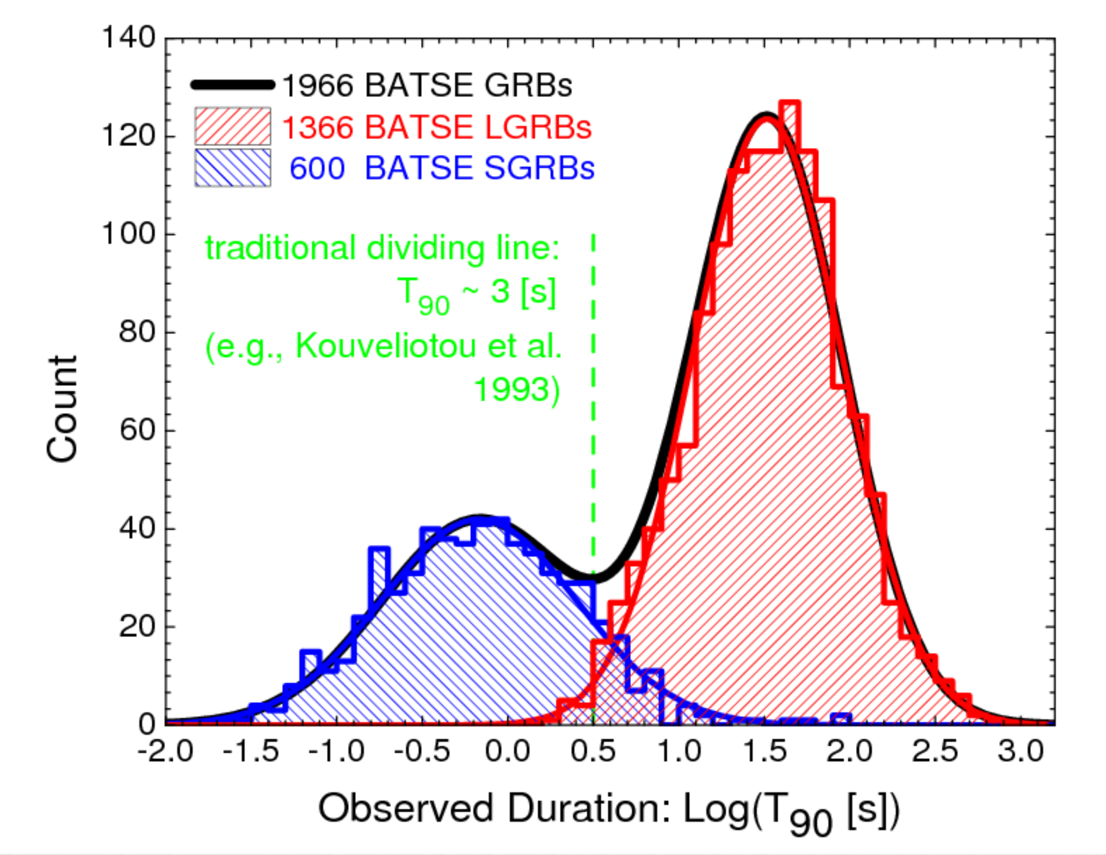
First joint observation in GW+EM window

Short Gamma ray burst puzzle solved !!

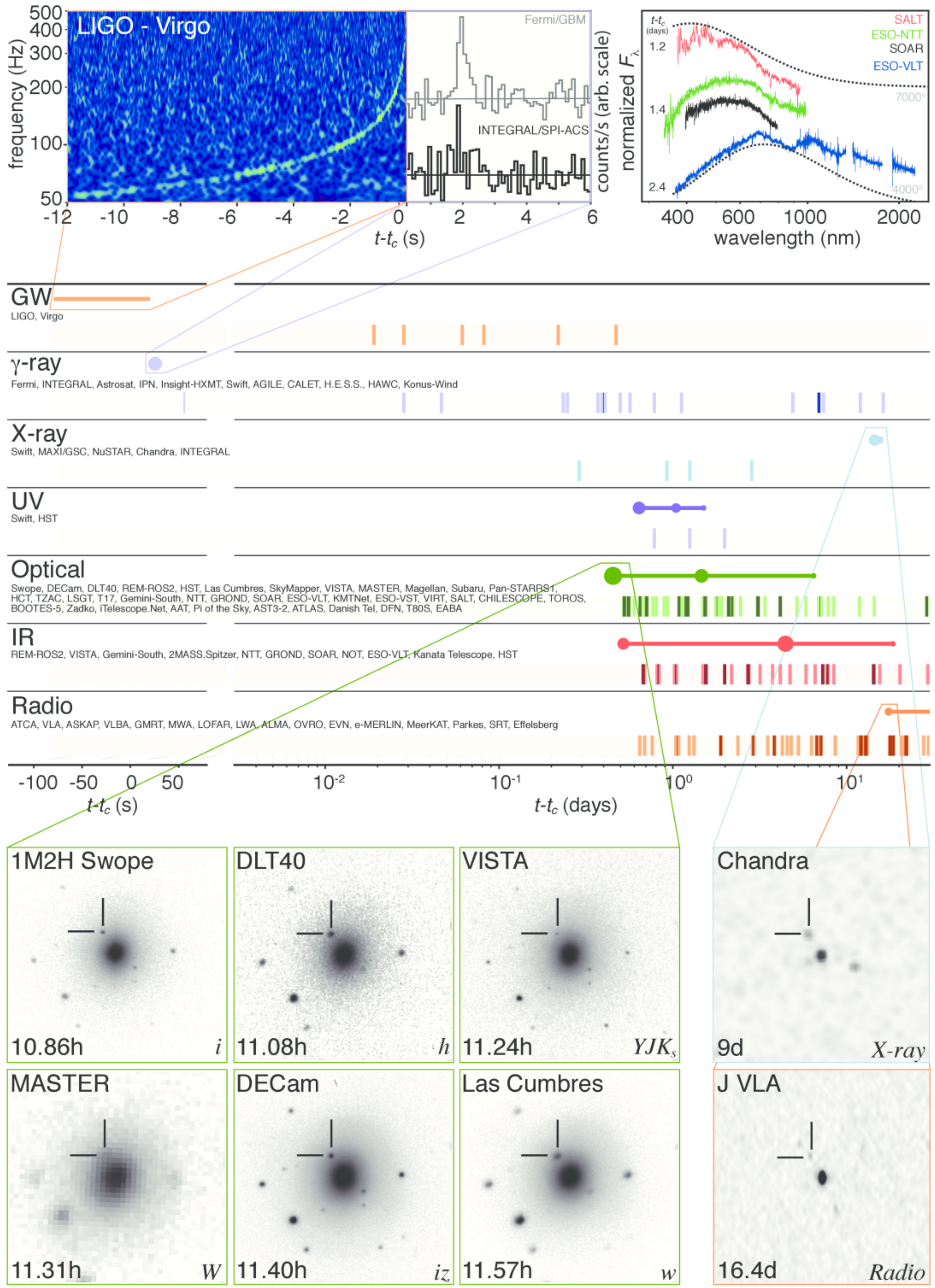
Gamma ray bursts are highly energetic sources with 10e49-10e53 ergs in few secs , quite frequent
Ultra relativistic and highly beamed

Two types:
Long T> 2secs and short T< 2 sec.
Long GRBs: Supernova core collapse
Short GRB: Progenitor not known till 2017.

Eichler etal 1989 — Binary NS as progenitors of a subclass of bursts
Numerical simulations indicated binary NS as the progenitor for ShortGRB
[Aloy et al. 2005; Rezzolla et al. 2011; Kiuchi et al. 2015; Baiotti & Rezzolla 2017; Kawamura et al. 2016; Ruiz et al. 2016]

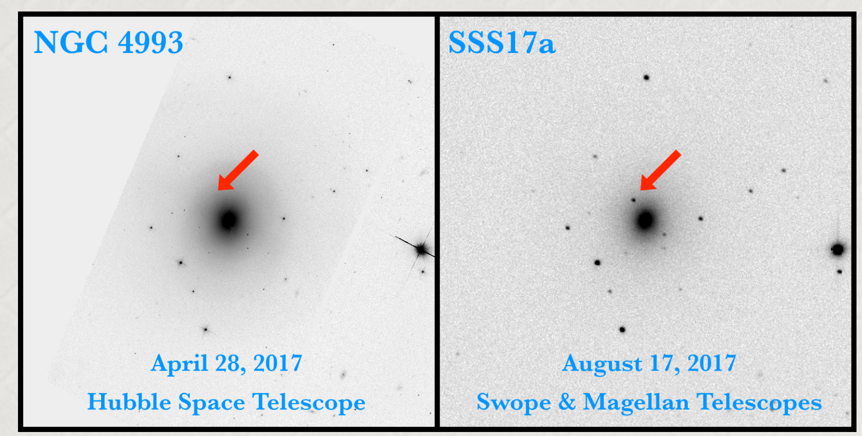


Joint observation of GW170817-GRB170817A confirmed binary NS merger as a progenitor of ShortGRBs



Follow-up with ~ 70 EM Observatories Gamma To Radio

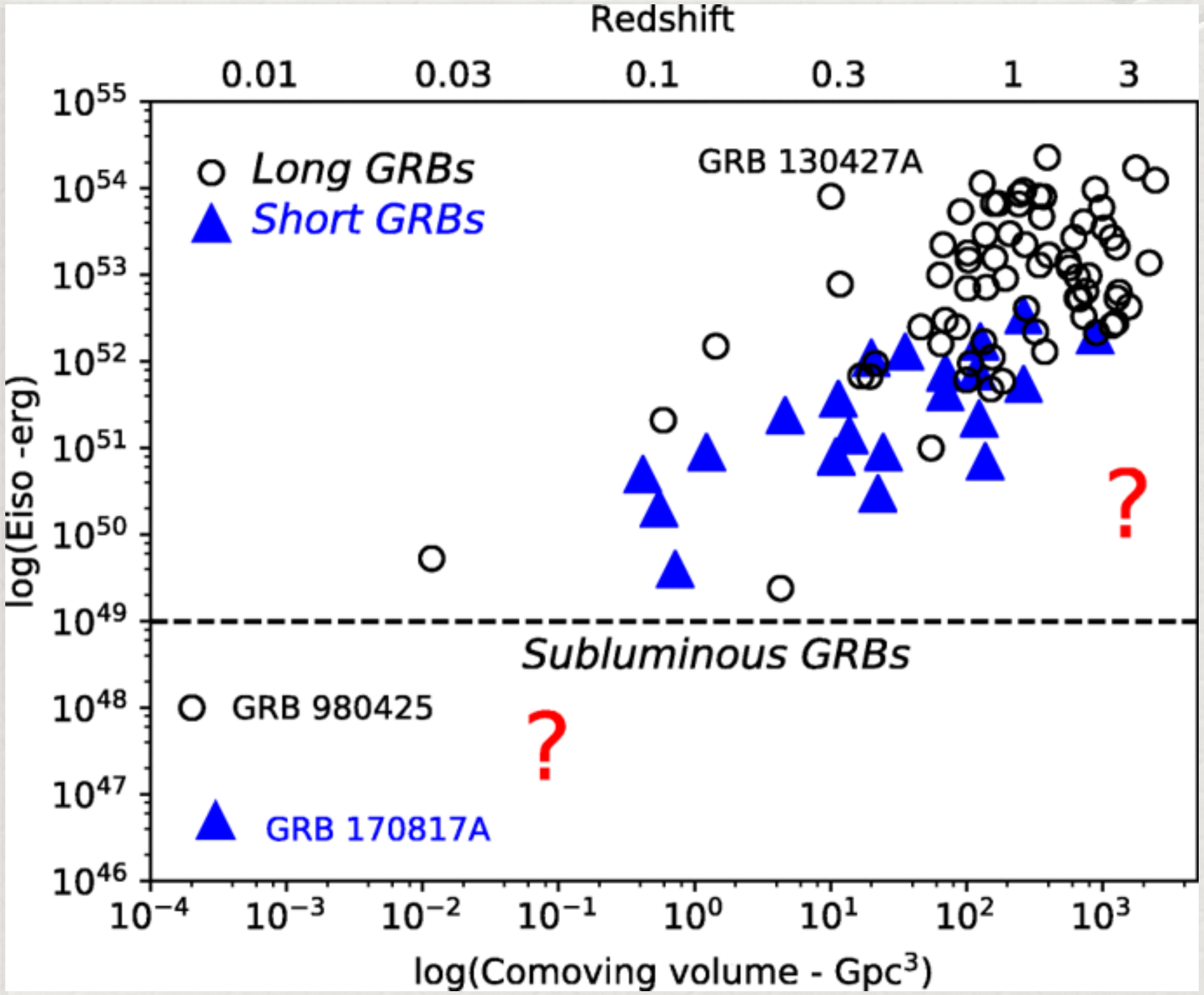
Biggest ToO campaign



Galaxy identification by NGC4993 ~ 40 Mpc

Coulter etal Science 2017

Peculiarity of the GRB170817



Lacombe étal Exp Astro (2019)

- *Few orders of magnitude fainter than classical ShortGRBs*
- *Closest ShortGRB - 40 Mpc (fainter)*
- *GRB170817A was after 9 days in X-rays and 16 days in radio window.*
- *Challenges for the model development.*
- *Current understanding:*
  Earlier emission: Cholked Jet+Cocoon
  Late time Afterglow: Successful jet

[Kasliwal + Science 2017, Troja + Nature 2017, Mooley + Nature 2018, Nakkar, Piran,....]

More details in Saleem's talk

Synthesis of heavier elements

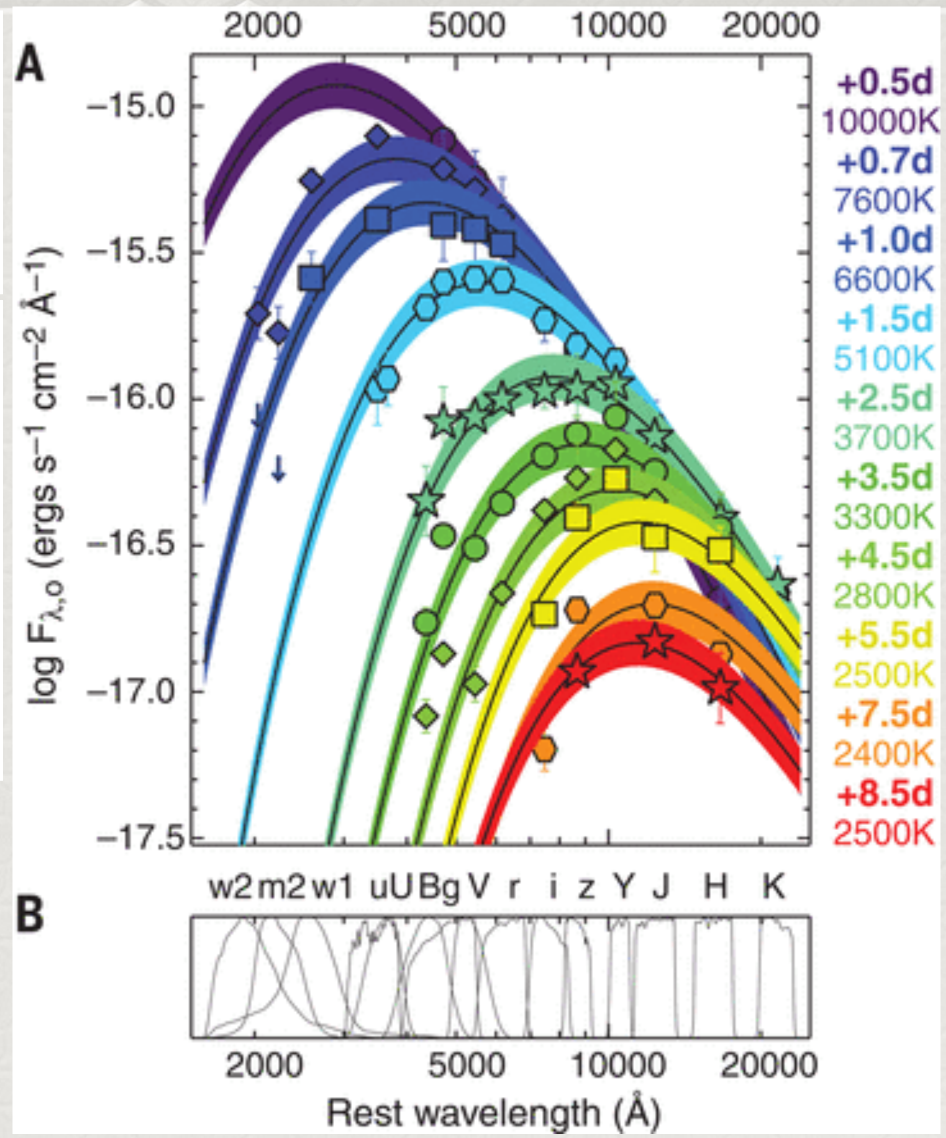
Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

David Eichler, Mario Livio, Tsvi Piran & David N. Schramm

Nature **340**, 126–128(1989) | Cite this article

Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process

Direct proof of synthesis of heavier elements via r-process during binary NS merger

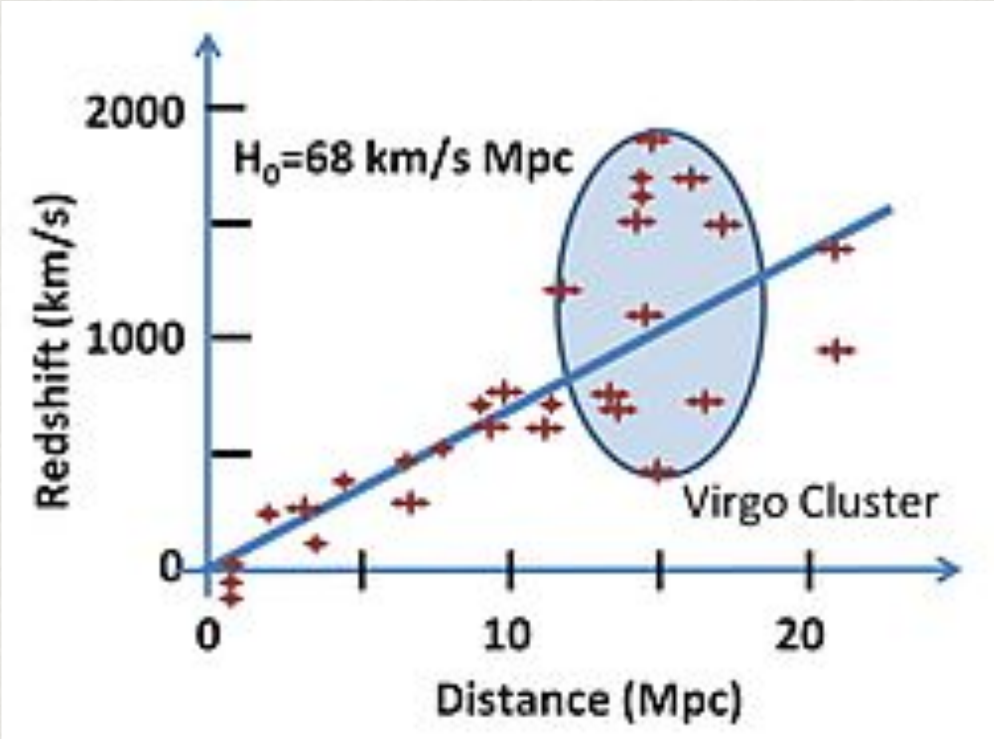


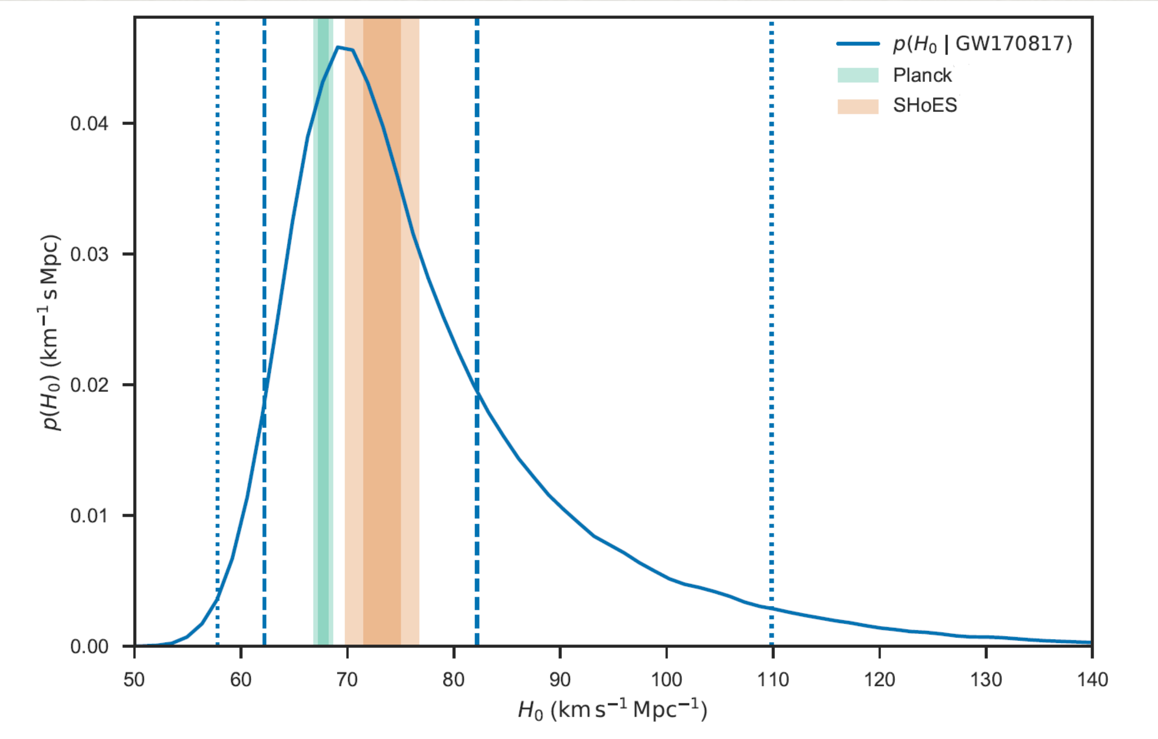
0.5 days to 8.5days after the merger, near UV to IR Clear indication of presence of heavy elements

Lanthanides have high opacity => long duration diffusion time, long duration optical curves
Progression towards red spectra with time

Kasen et al Nature 2017, Drout et al Science 2017

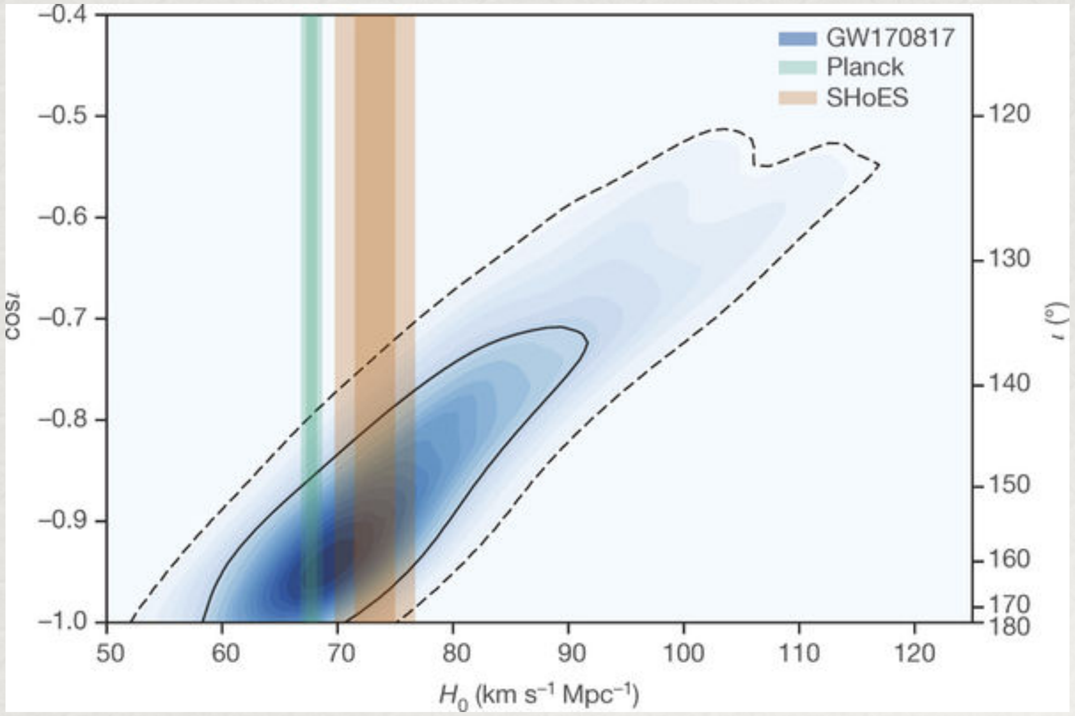
Measurement of Hubble constant from GW observations





Optical counterpart from Swope NGC4993 — redshift, distance Include in the Bayesian inference of GW170817 and obtain Hubble's constant ~70 km/sec/Mpc

LVC Nature,2017



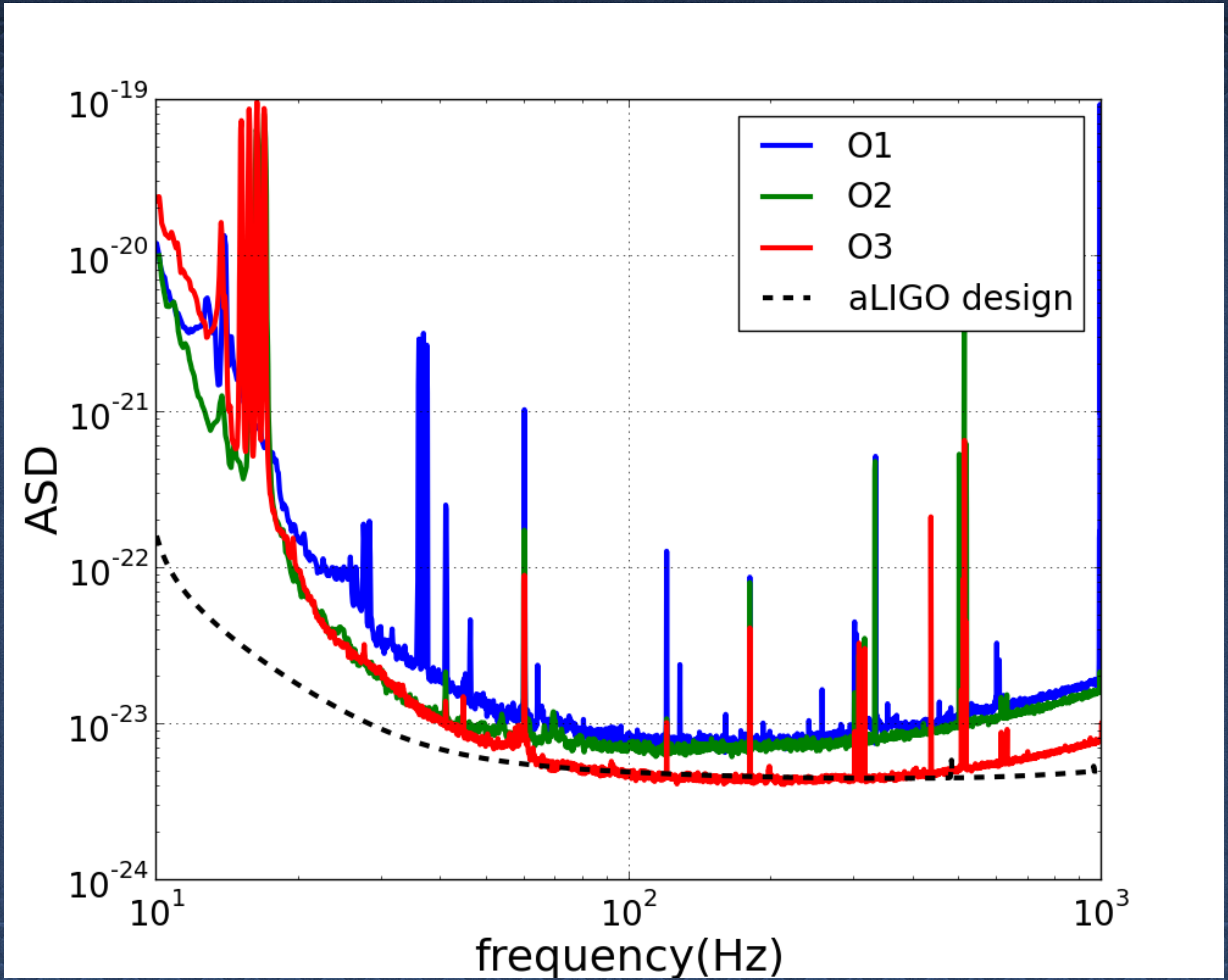
Tests of GR with GW events

- *Parametrized post-newtonian tests* *[LVC, PRL 2019]*
- *Inspiral-Merger-Ringdown consistency test* *[LVC, PRL 2019]*
- *Polarisation test with GW170814: tensor mode vs scalar mode and tensor mode vs vector mode GW models are tested. Tensor mode was favoured.* *[LVC, PRL 2017]*
- *Dispersion relation and bound on the graviton mass < 7.7 *10^-23 eV/c^2 from GW170104* *[LVC, PRL 2017]*
- *GW speed measurement with GW170817: Arrival time difference between the GW and ShortGRB in gamma rays is 1.7 sec. Distance to the source 40Mpc.* *[LVC, ApJ Lett. 2017]*

$$-3 \times 10^{-15} \leq \frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq 7 \times 10^{-16}$$

More details in Chandra Kant Mishra's talk

Updates from the Third observing run of Advanced LIGO and Virgo detectors
April 1, 2019 —-



Sensitivity improvement in O3

SEVERAL COMPACT BINARY MERGER CANDIDATES SINCE APRIL 2019

GraceDB — Gravitational-Wave Candidate Event Database

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LIGO/Virgo O3 Public Alerts

Detection candidates: 46

S190924h	MassGap (>99%)	Sept. 24, 2019 02:18:46 UTC	GCN Circulars Notices | VOE	1 per 3.5493e+10 years
S190923y	NSBH (68%), Terrestrial (32%)	Sept. 23, 2019 12:55:59 UTC	GCN Circulars Notices | VOE	...4 per year
S190915ak	BBH (99%)	Sept. 15, 2019 23:57:02 UTC	GCN Circulars Notices | V...	1 per 32.55 years
S190910h	BNS (61%), Terrestrial (39%)	Sept. 10, 2019 08:29:58 ...	...CN Circulars Notices | VOE	1.1312 per year
S190910d	NSBH (98%), Terrestr...	...ept. 10, 2019 01:26:19 UTC	GCN Circulars Notices | VOE	1 per 8.5248 years
S190901ap	...(86%), Terrestrial (14%)	Sept. 1, 2019 23:31:01 UTC	GCN Circulars Notices | VOE	1 per 4.5093 years

O3 has begun few months ago!!!

EXPECT MANY MORE GW EVENTS

GraceDB — Gravitational-Wave Candidate Event Database

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Superevent Info

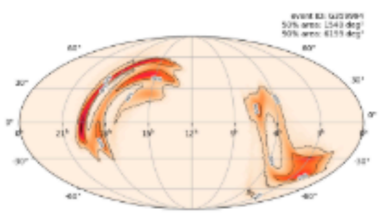
Superevent ID	Category	Labels	FAR (Hz)	FAR (yr⁻¹)	t_start	t_0	t_end	UTC Submission time	Links
S200112r	Production	DQOK ADVOK EM_READY EM_Selected EMBRIGHT_READY PASTRO_READY SKYMAP_READY GCN_PRELIM_SENT PE_READY	1.283e-11	1 per 2469.9 years	1262879935.091777	1262879936.093931	1262879937.093931	2020-01-12 15:59:06 UTC	Data

Preferred Event Info

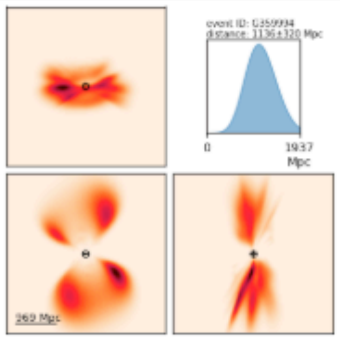
Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	gstlal	AllSky	L1,V1	1262879936.0939	2020-01-12 15:59:05 UTC

Superevent Log Messages

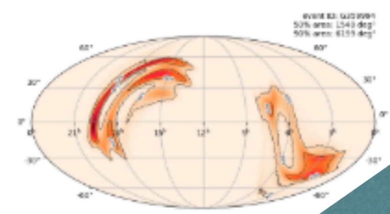
Sky Localization



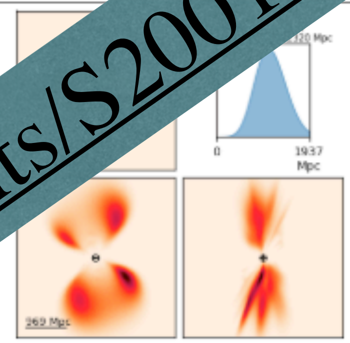
Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Jan 12, 2020 16:00:59 UTC



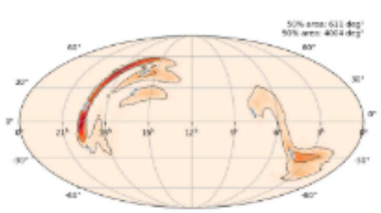
Volume rendering of bayestar.fits.gz bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Jan 12, 2020 16:01:05 UTC

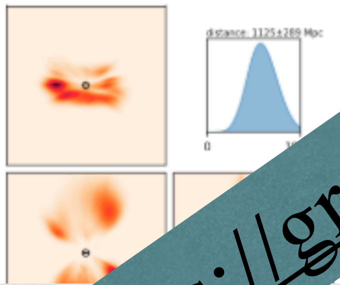


Mollweide projection o… bayestar.png. Sub… EM Follow-Up on J… UTC

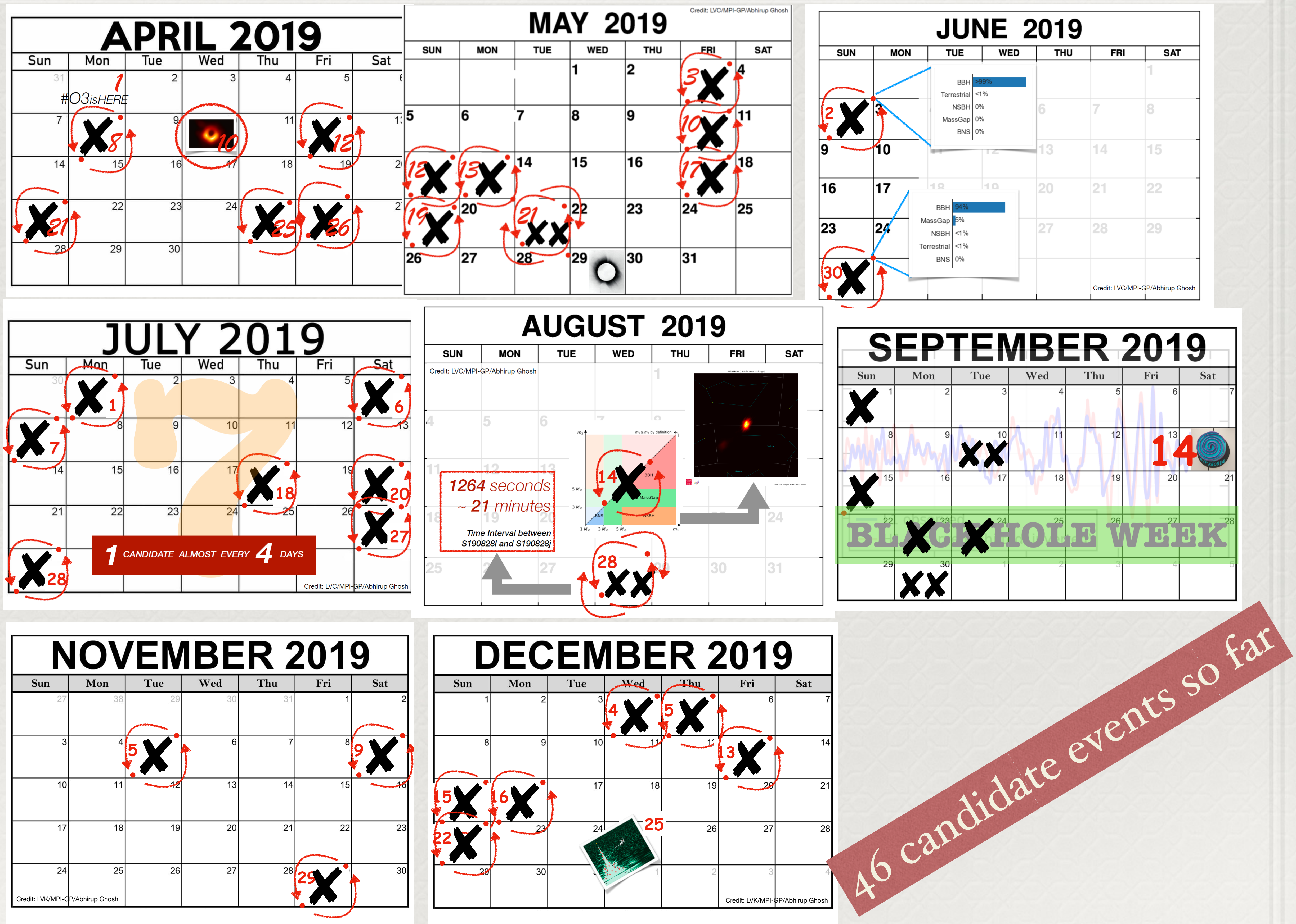


Volume rendering of bayestar.fits.gz bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Jan 12, 2020 16:06:52 UTC

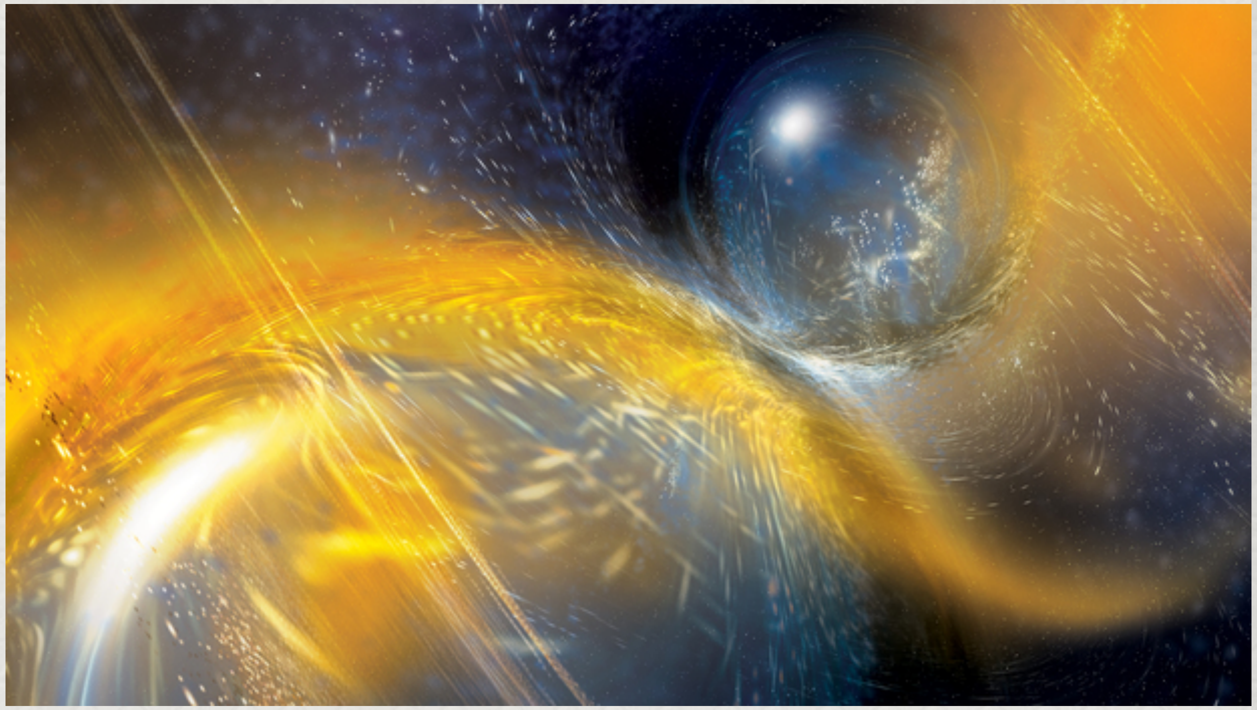




https://gracedb.ligo.org/superevents/S200112r/view/

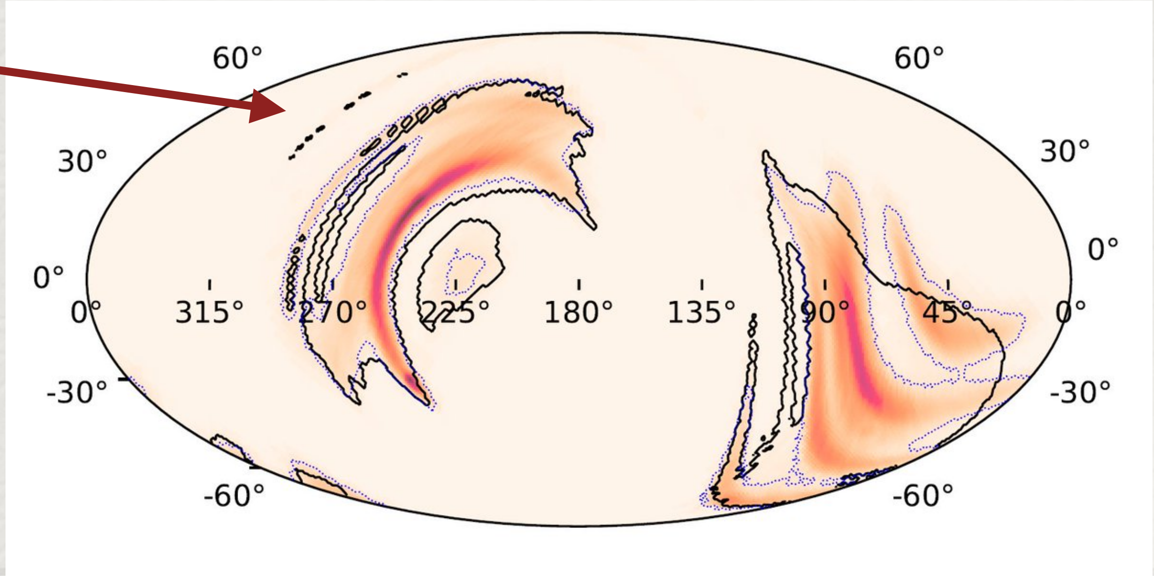

APRIL 2019
#O3isHERE
MAY 2019
Credit: LVC/MPI-GP/Abhirup Ghosh
JUNE 2019
BBH >99%
Terrestrial <1%
NSBH 0%
MassGap 0%
BNS 0%
BBH 94%
MassGap 5%
NSBH <1%
Terrestrial <1%
BNS 0%
Credit: LVC/MPI-GP/Abhirup Ghosh
JULY 2019
1 CANDIDATE ALMOST EVERY 4 DAYS
Credit: LVC/MPI-GP/Abhirup Ghosh
AUGUST 2019
Credit: LVC/MPI-GP/Abhirup Ghosh
1264 seconds
~ 21 minutes
Time Interval between S190828l and S190828j
SEPTEMBER 2019
BLACK HOLE WEEK
NOVEMBER 2019
Credit: LVK/MPI-GP/Abhirup Ghosh
DECEMBER 2019
Credit: LVK/MPI-GP/Abhirup Ghosh
46 candidate events so far

GW190425 Heaviest NS binary observed so far

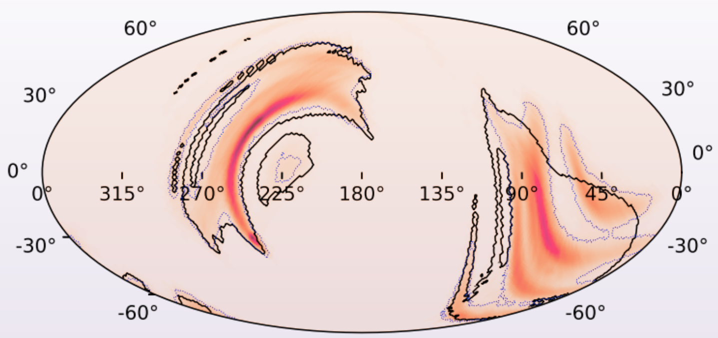


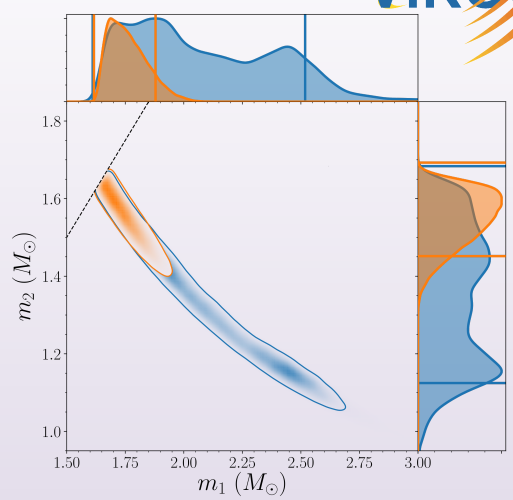
- *Trigger in LIGO-Livingston with SNR~12.9*
- *LIGO-Hanford: Not operational*
- *Virgo SNR ~ 2.5 not loud but useful for significance*
- *Large sky map 8000sq deg~16% of the sky!!*
- *No confirmed electromagnetic as well as neutrinos observed so far.*
- *Distance: 150 Mpc [More distant than GW170817]*

LVC, arXiv 2001:01761



GW190425 FACTSHEET





observed by	LIGO Livingston, Virgo
source type	most likely a binary neutron star merger
date	25 April 2019
time of merger	08:18:05 UTC
Livingston signal-to-noise ratio	12.9
Virgo signal-to-noise ratio	2.5
false alarm rate	1 in 69 000 years
distance	287 to 744 million light-years
redshift	0.01 to 0.04
total mass	3.3 to 3.7 $M_\odot$
primary NS mass	1.61 to 2.52 $M_\odot$
secondary NS mass	1.12 to 1.68 $M_\odot$
mass ratio	0.4 to 1.0
effective inspiral spin parameter	0.01 to 0.17
effective precession spin parameter	unconstrained

core density of primary NS	70 to 140 trillion times density of lead
inferred # of GW cycles from 19.4 Hz to 2048 Hz*	~ 3900
initial astronomer alert latency**	~43 min
sky area†	8284 deg^2
improved binary NS merger rate	7 to 81 mergers per year per cubic billion light-years

Images: **GW sky map** (left): initial (black contours) and final (red and orange with grey contours) regions where source is likely to be located. Darker shading indicates increased likelihood source is in that region of sky. **Component mass distribution** (right): darker shading indicates an increased likelihood the pair of stars had that set of masses. The blue and orange lines denote 90% confidence intervals for two different assumptions —NS spins are allowed to be large (blue) and NS spins are constrained to be small (orange). The black diagonal line is the line m_1=m_2.

GW=gravitational wave, NS=neutron star, $M_\odot$=1 solar mass=2x10^{30} kg

Parameter ranges are 90% credible intervals.
*maximum likelihood estimate
**referenced to the time of merger
†90% credible region

The first confirmed detection from O3 run

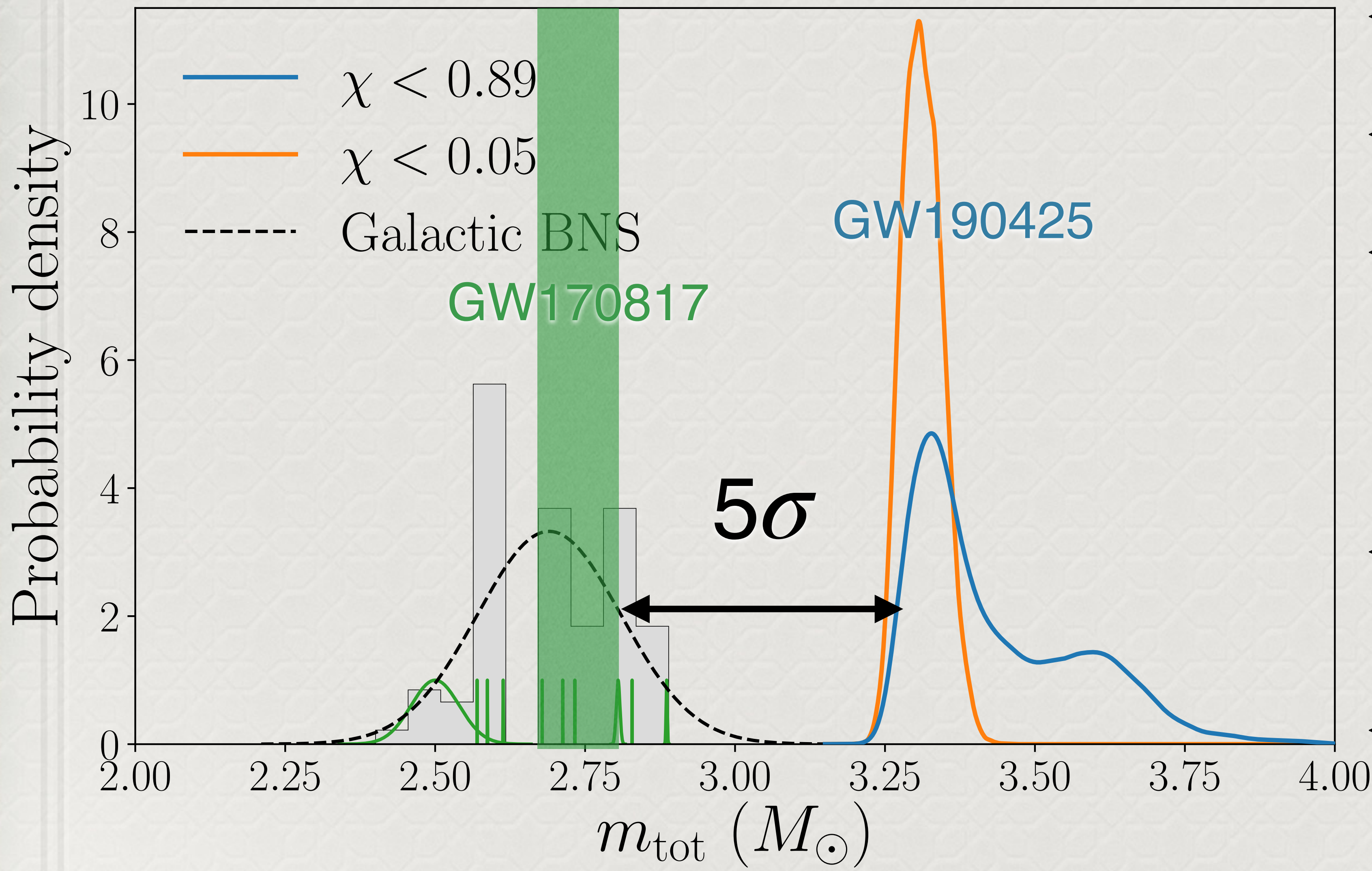
Heaviest NS binary observed so far!

No confirmed EM counterpart

3-4 times distant than GW170817

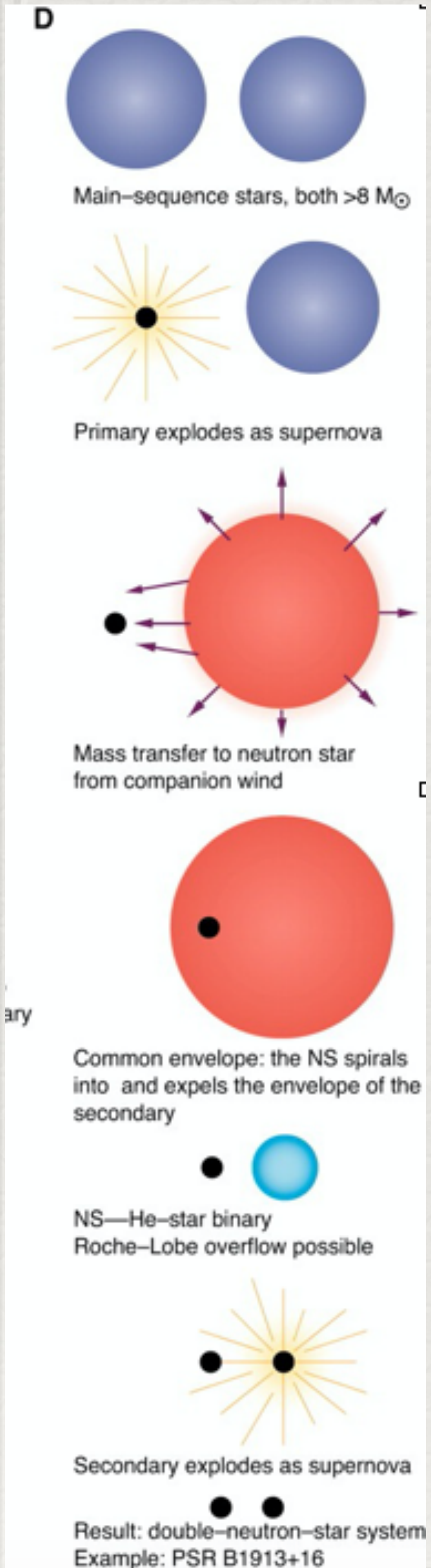
LVC, arXiv 2001:01761

Heaviest NS binary system so far



- *Primary mass: 1.6- 2.5Msun*
- *Secondary mass: 1.12-1.68 Msun*
- *Primary mass is on the higher end. Most massive pulsar is PSRJ0740-6620 with mass 2.05-2.24Msun*
- *Total mass: 3.3-3.7 Msun. Heaviest total mass binary NS.*
- *Large deviation from the distribution of observed total mass of the galactic NS binaries.*

Abbott+ arXiv2001.01761 Under review in ApJL



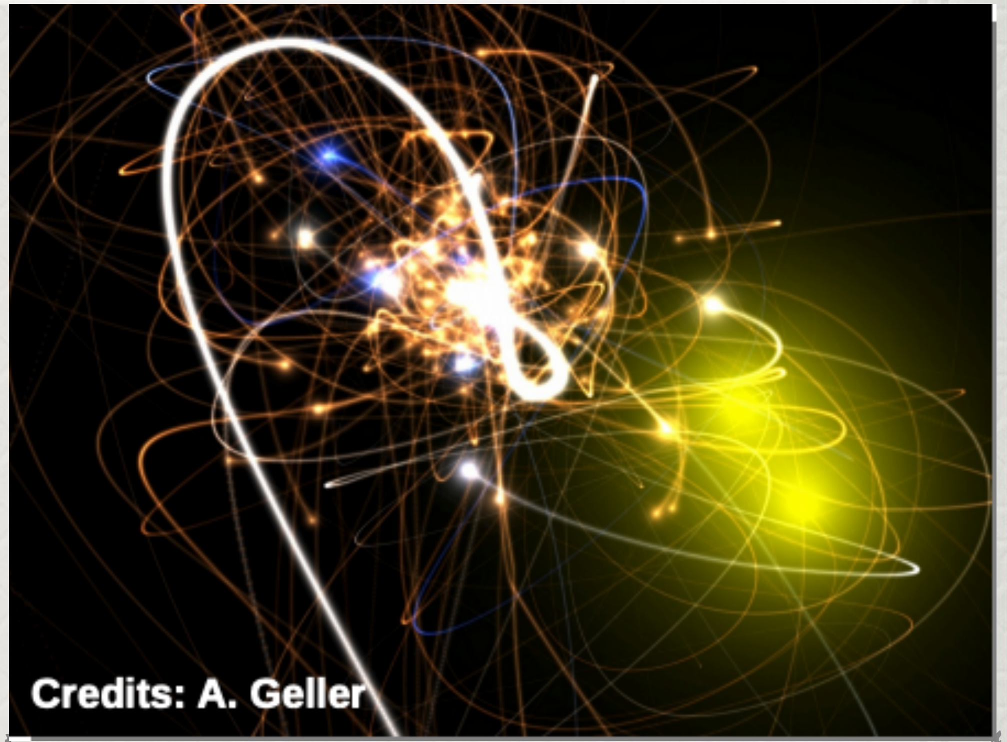
Science 2004

Channel1 :
Isolated compact binaries - Possibly formed from the same cloud and evolve as two compact objects in a binary

How do you get high mass NS?

New challenges to the NS binary formation channels

How does the GW190425 form?
Why such systems not observed in the radio band?

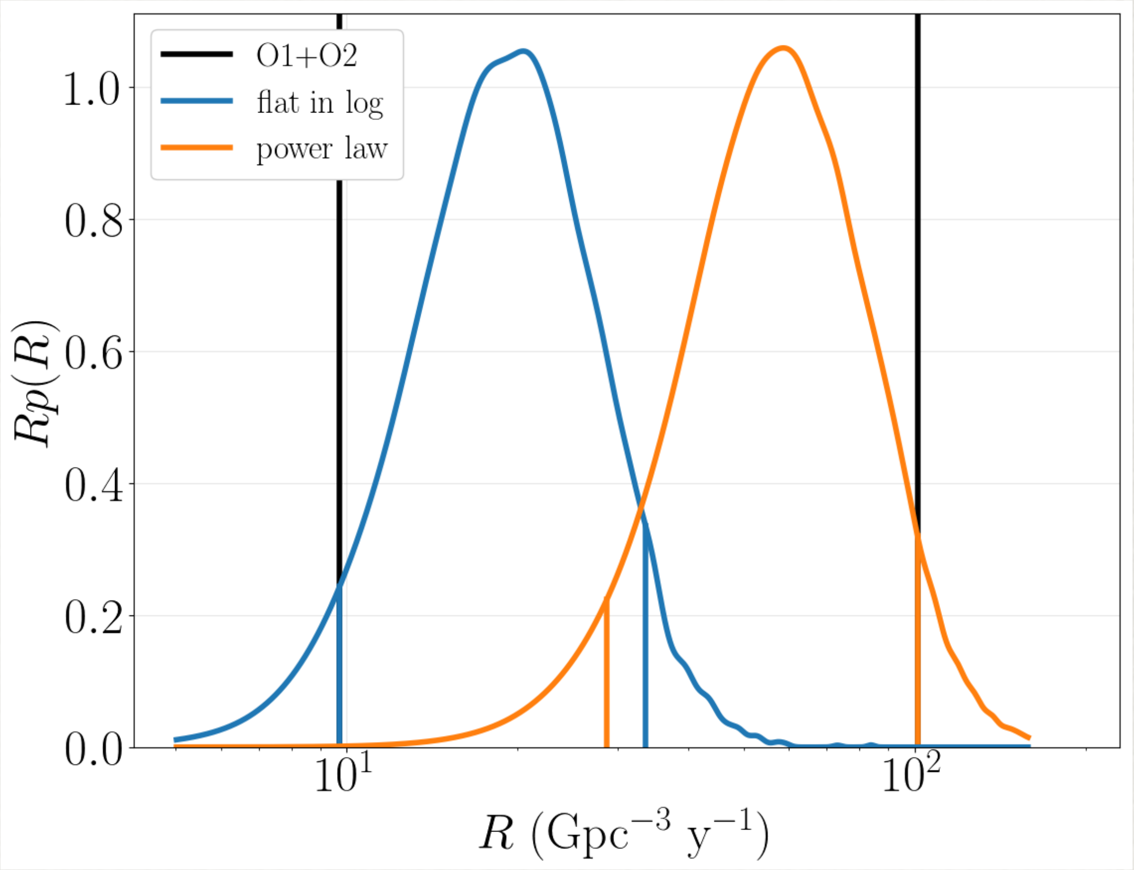


Channel 2
Dynamical binaries: Compact object binaries form and evolve due to dynamics in the dense stellar environment

Merger rates are high for high mass compact objects such as massive BBH

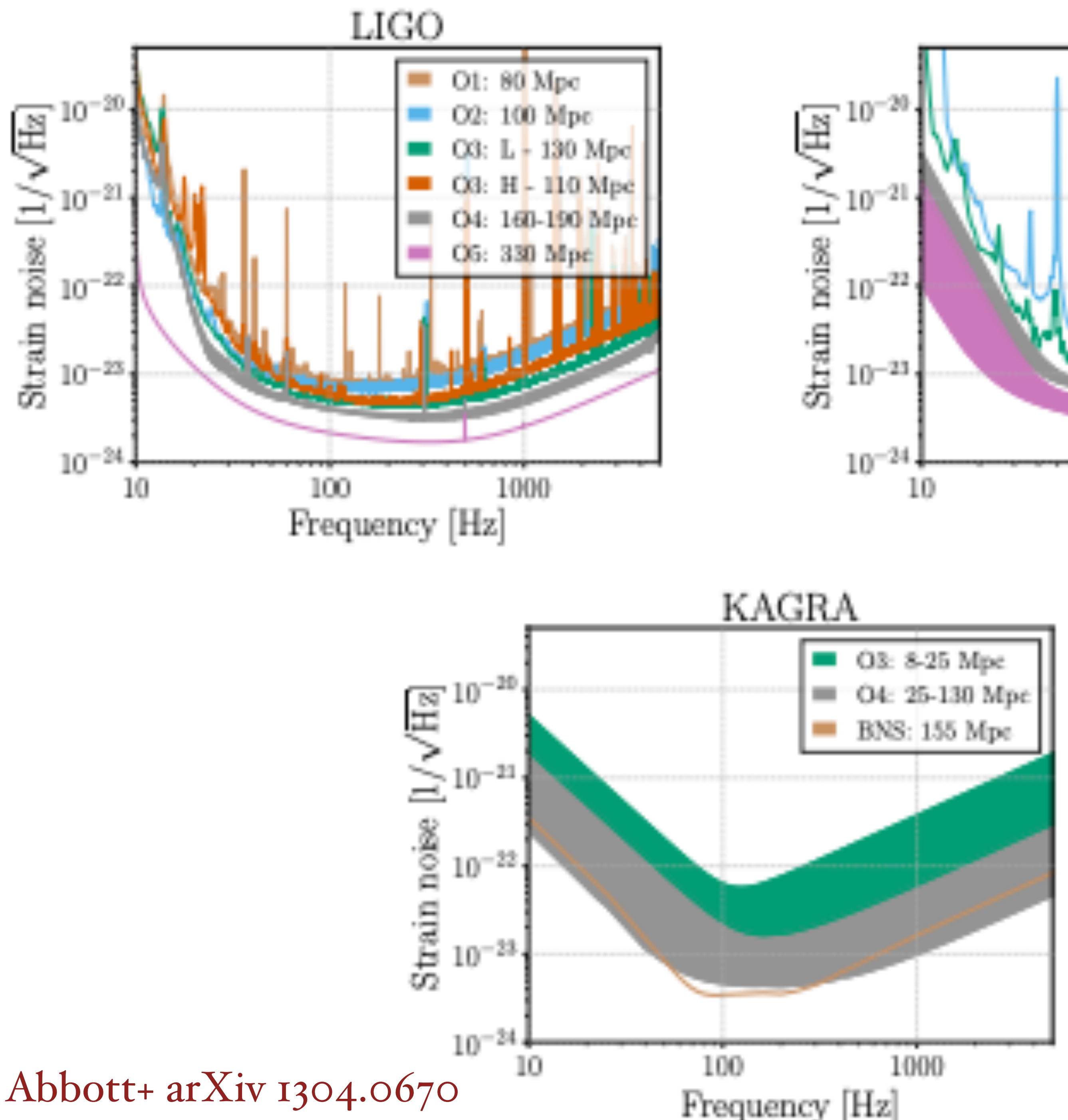
Rates estimates

- Binary NS merger rate density: 250-2810 per Gpc^3 per year
- Binary BH merger rate density: 9.7-101 per Gpc^3 per year
- IMBH binary (100-100) merger rate density: 0.2 per Gpc^3 per year



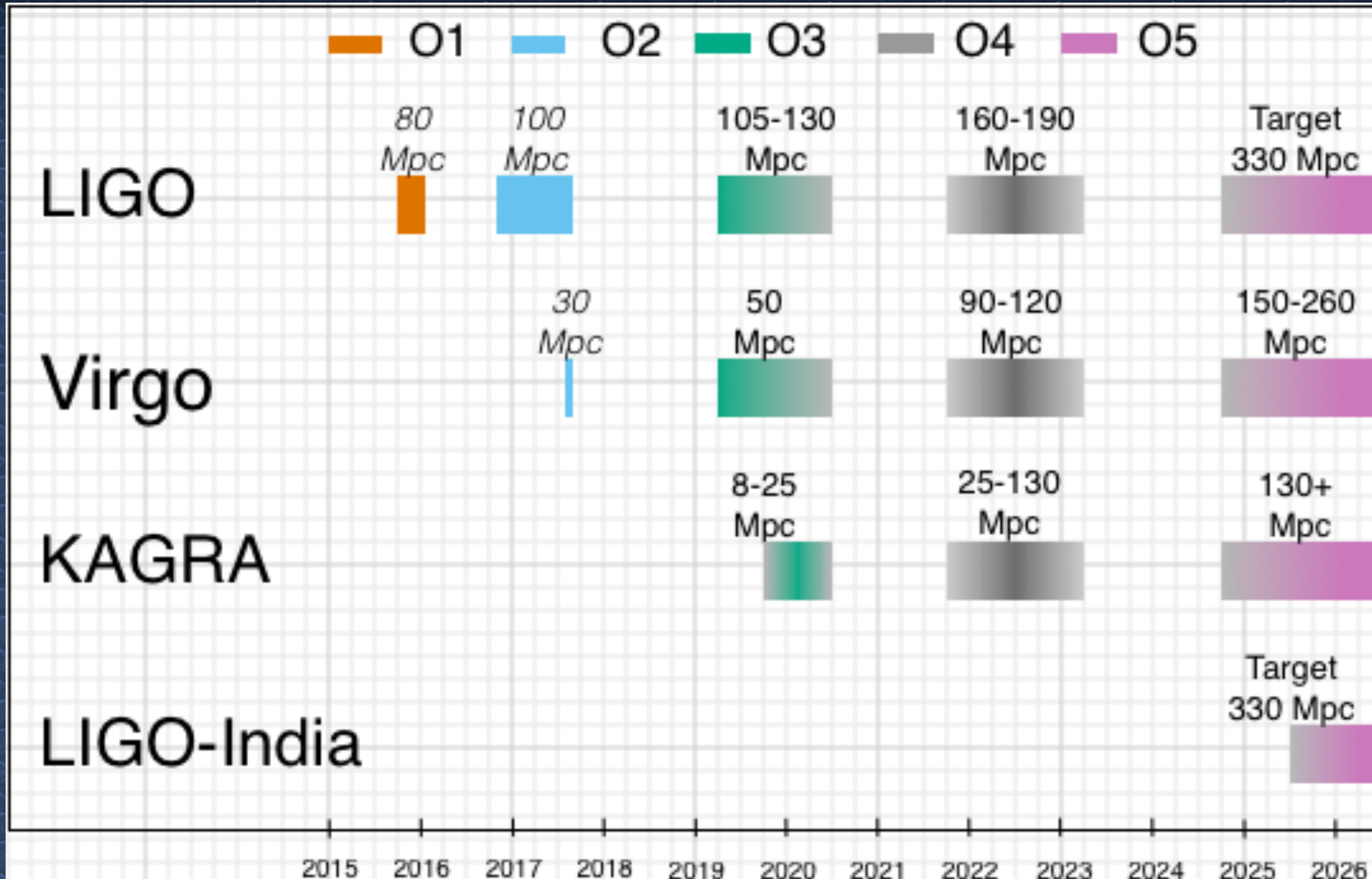
Abbott+ arXiv2001.01761, GWTC1 — Abbott+ PRX 2019, O1-O2 IMBHB Abbott+ PRD 2019

Future projections of the observations



Abbott+ arXiv 1304.0670

Expected Sensitivity improvement



Timeline of distance reach for binary NS

		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
$[E_{GW} = 10^{-2} M_{\odot} c^2]$	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc)	aLIGO	15	20	25 – 30	35 – 40	70
$[E_{GW} = 10^{-9} M_{\odot} c^2]$	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

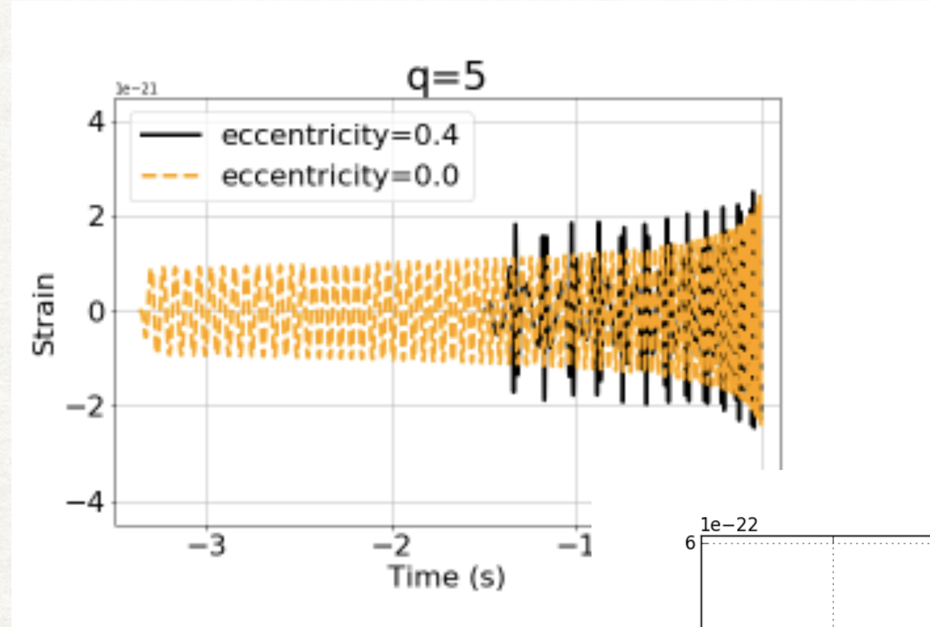
Abbott+ arXiv 1304.0670

Expected compact binary merger events in the advanced GW detector era

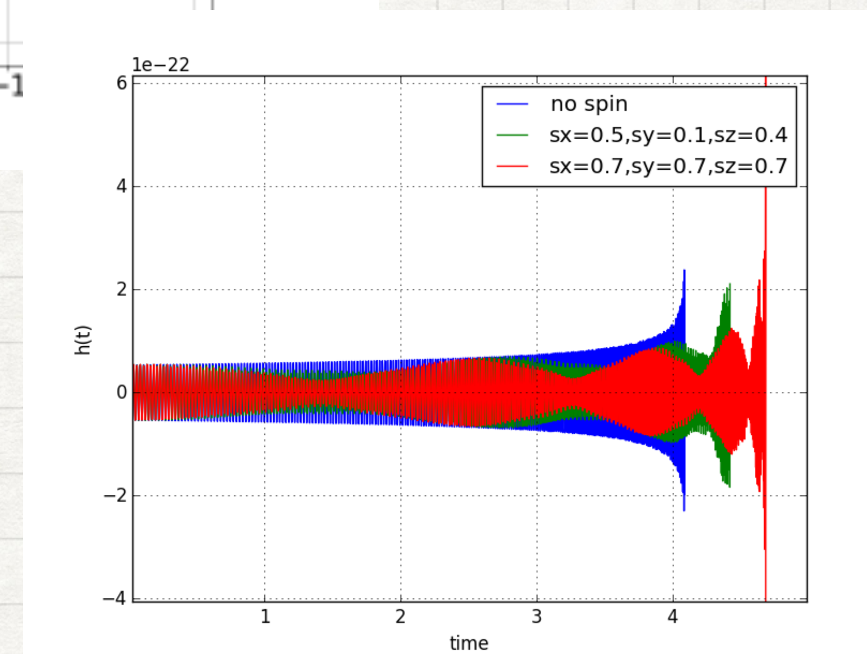
BNS: 16(O4), 75(O5) BBH: 170(O4), >500 (O5)

MODEL BASED SEARCHES : CHALLENGES

- *Phase can be degenerate with respect to many parameters*
- *Increase in waveform complexity with spins, eccentricity, higher modes etc*
- *Increased false alarm rates*
- *Higher computational cost*
- *Challenge: To capture effective parameter which reduces this degeneracy*
- *Challenge: Construct methods to veto out the noisy transients*

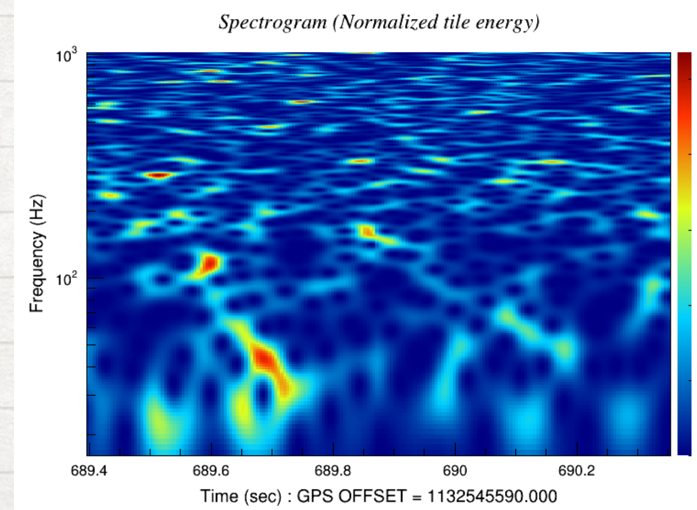


Eccentricity

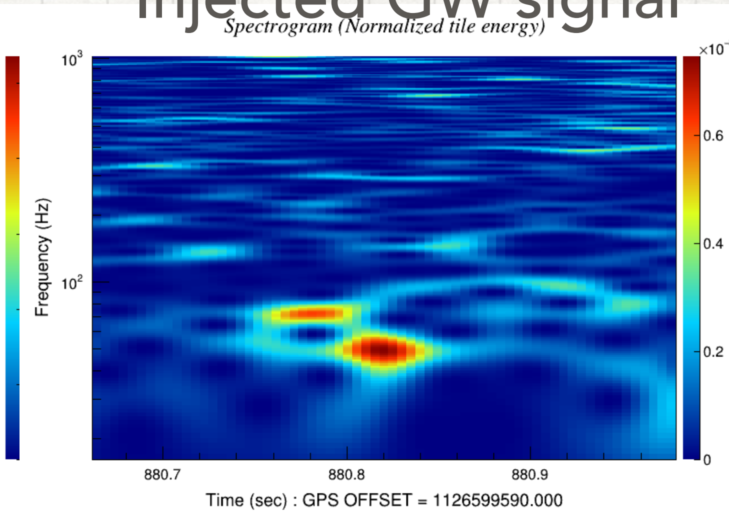


Precession

Noisy transient



Injected GW signal

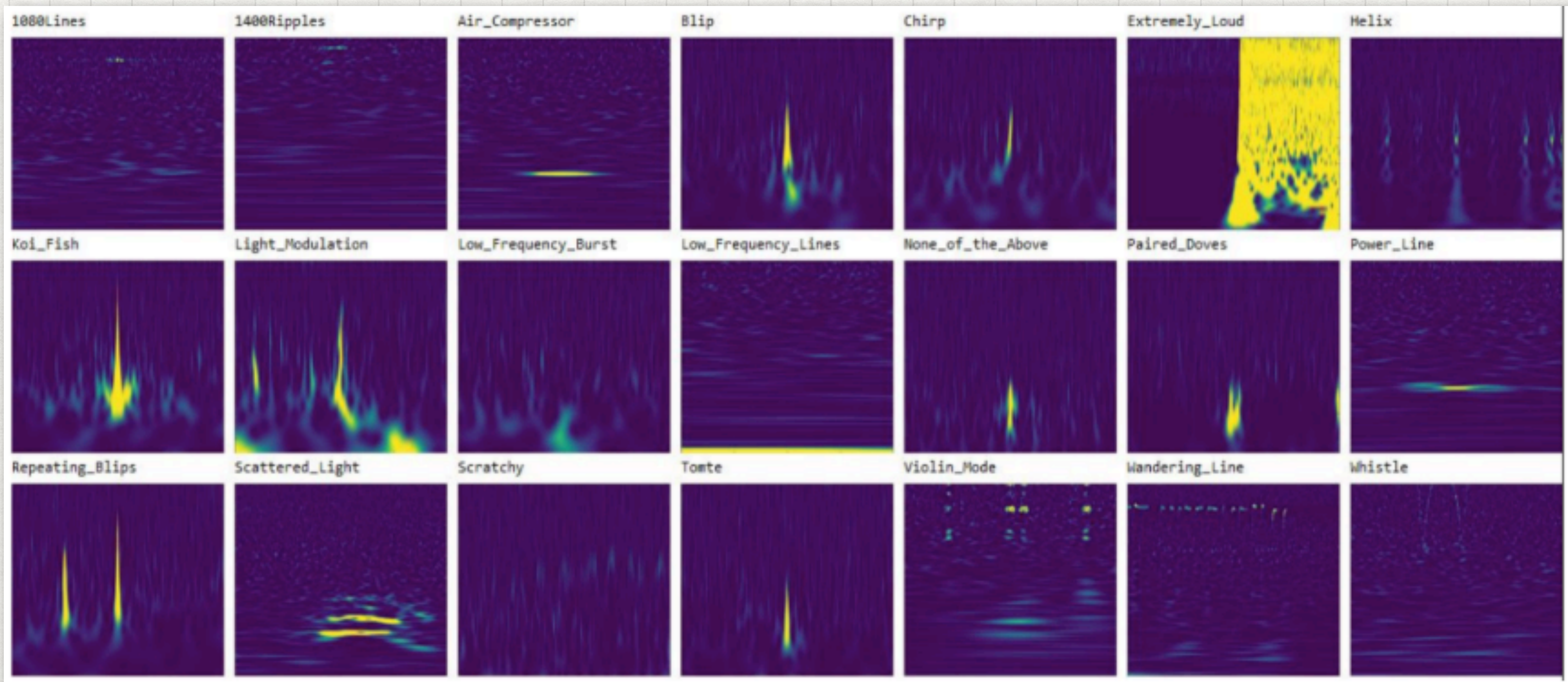


UNMODELED SEARCHES:CHALLENGES

INCREASED NUMBER OF NOISY TRANSIENTS WITH INCREASED SENSITIVITY

No of auxiliary channels ~ 100000

Identify the noisy features by correlation —— large number of unknowns



Challenge: Classification of noisy features based on the type of signal

Tens of BNS

Hundreds of BBH

Gravitational-wave sky

population of BHs, distribution of BHs, EoS of NS, formation channel of binaries, formation of SMBHs, test of GR, Hubble constant tension……

Within next decade

Few NSBH???

IMBHBs???

Unknown/exotic sources???

Thank you for your attention

Stay tuned !

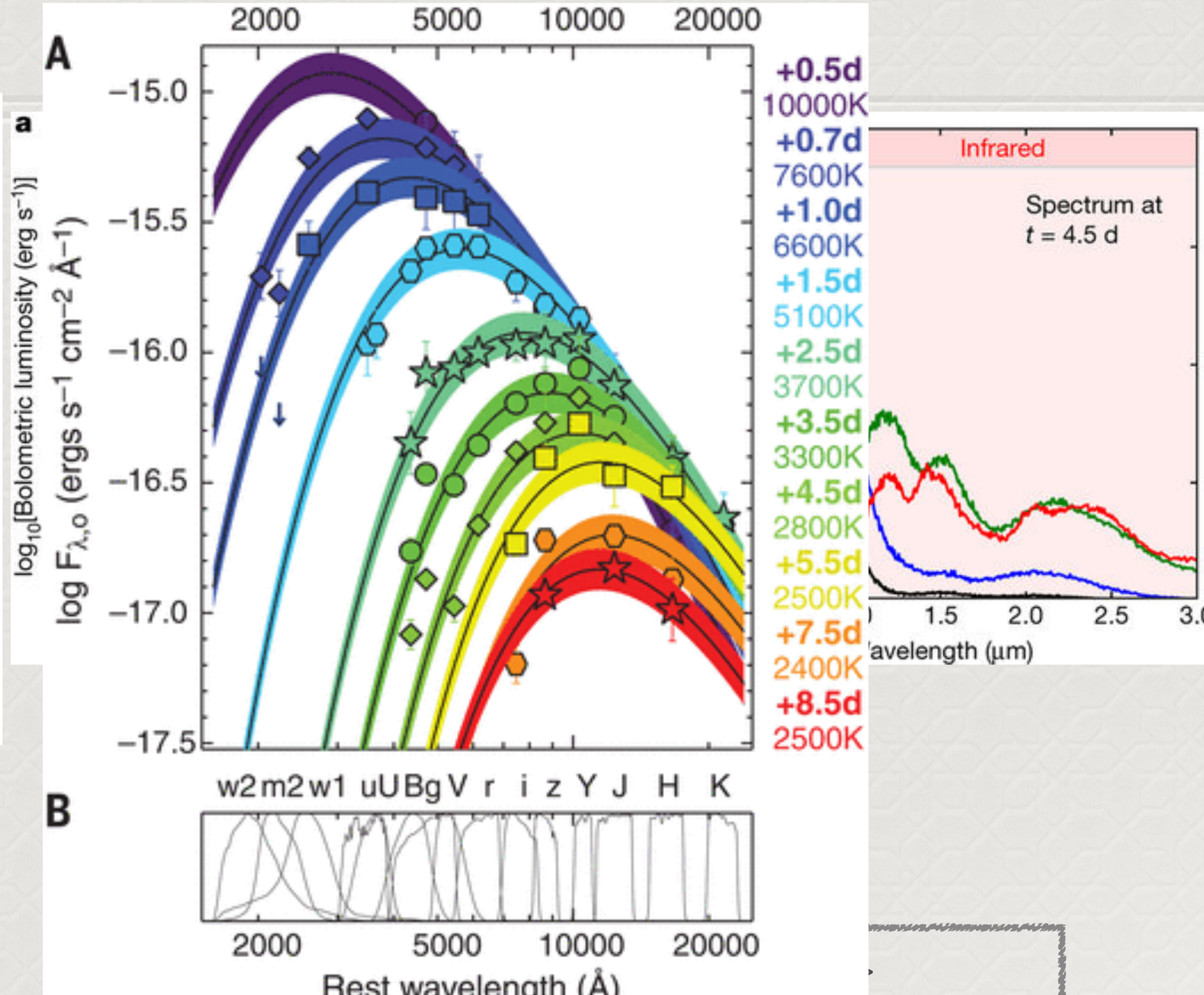
Synthesis of heavier elements

Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

David Eichler, Mario Livio, Tsvi Piran & David N. Schramm

Nature **340**, 126–128(1989) | Cite this article

Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process



Direct proof of synthesis of heavier elements via r-process during binary NS merger 0.05 Msun mass is

long duration diffusion time, long duration optical curves
Progression towards red spectra with time

Kasen et al Nature 2017, Drout et al Science 2017

Thank you for your attention

Stay tuned !