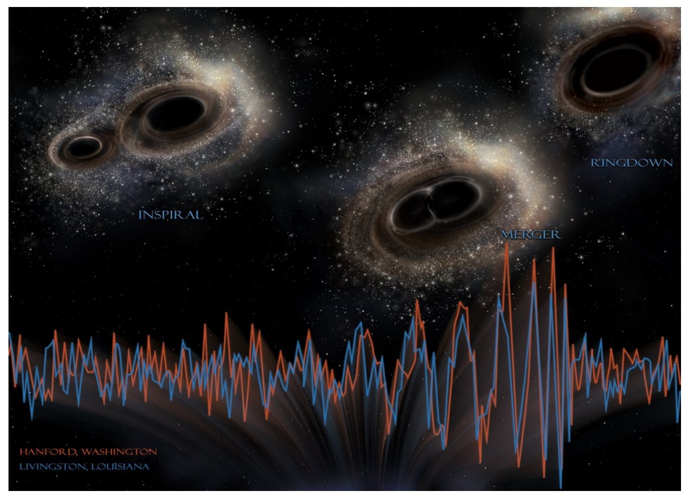
Observation of Gravitational Waves from a Binary Black Hole Merger In LIGO Hanford and Livingston detectors

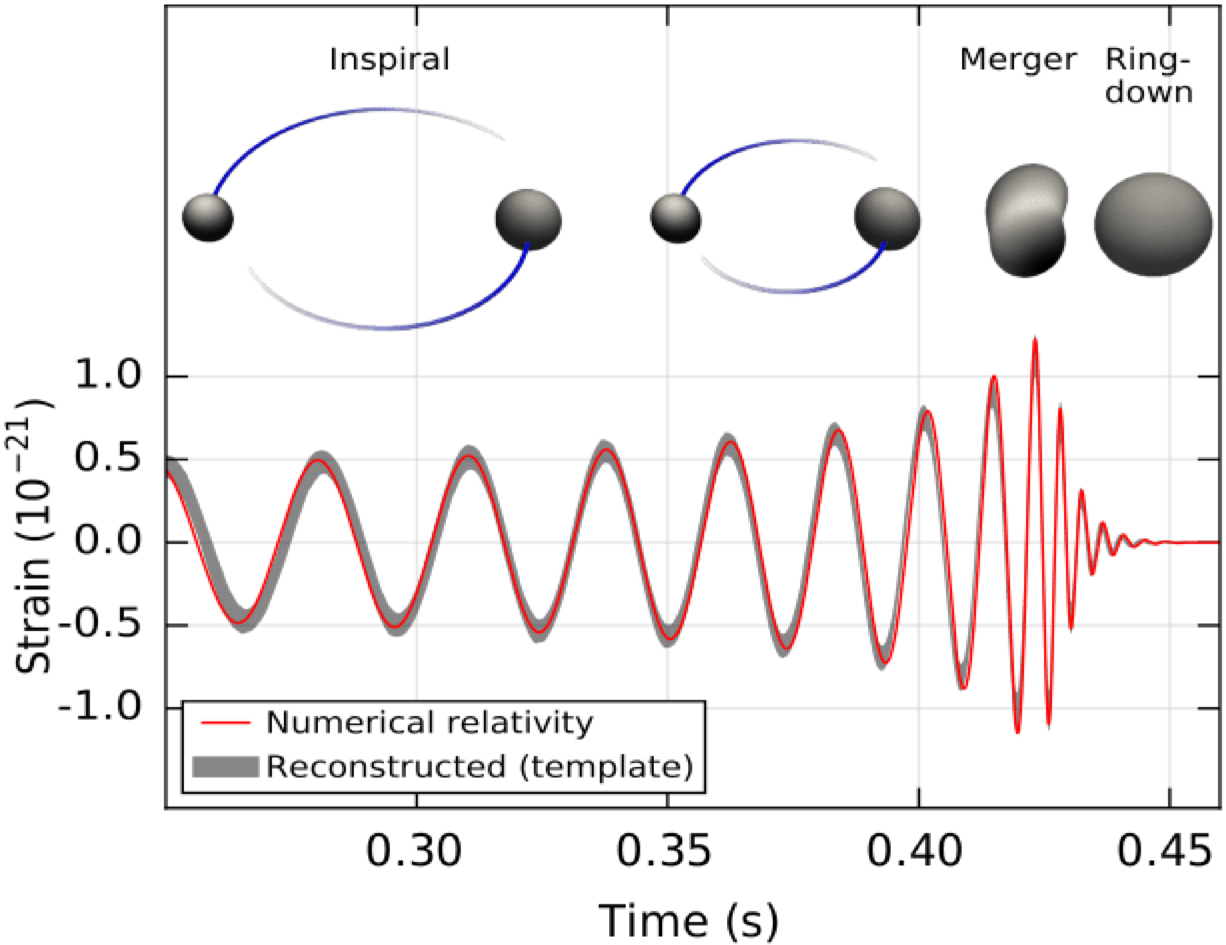


PRL 116, 061102 (2016)
link.aps.org/doi/10.1103/PhysRevLett.116.061102

The LIGO Scientific Collaboration & the Virgo Collaboration

What has been observed?

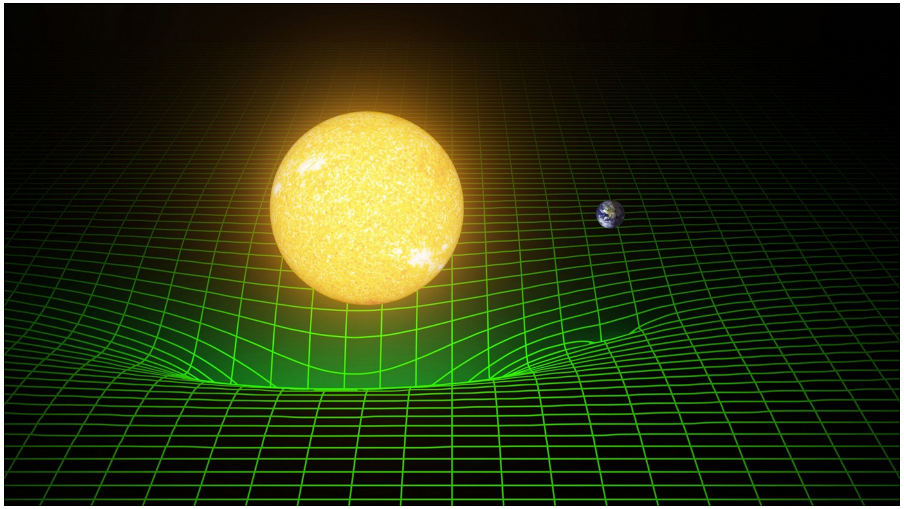
The final plunge of a 29+36 Msun binary black hole system forming a fast rotating (Kerr) black hole of 62 Msun.



What are we talking about? GW!

- General relativity prediction (1916).
- Gravity is no more a force in GR but a space-time deformation.
- Masses deformed locally the space-time.
- When masses are accelerated, they

emit GW that are ripples in space-time



- Space-time is rigid:

The amplitude of the deformation is tiny.

Need super cataclysmic events to expect to

measure something on Earth … (metric deformation/strain amplitude: $h \sim 10^{-21}$)

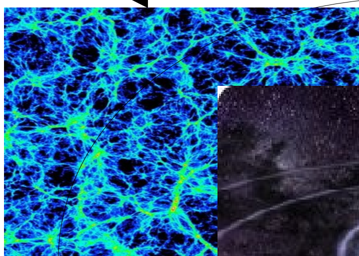
- LIGO/Virgo GW sources: mainly astrophysical in the 10 Hz -10 kHz bandwidth

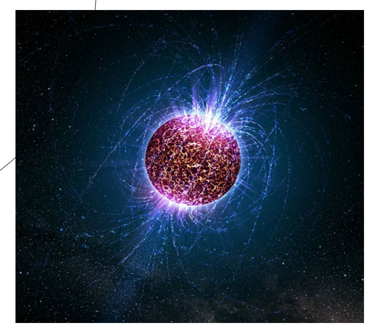
GW searches zoology

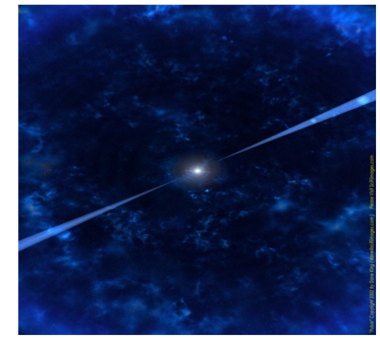
Short duration (~1s)

Long duration (∞)

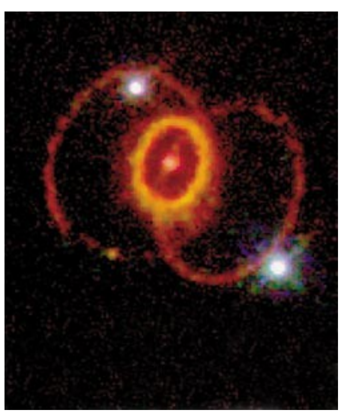
Waveform known







Waveform unknown



One century of developments that lead to GW150914

Theory

15: GR (Einstein)

16: GW prediction (Einstein)

52: Cauchy problem & Einstein equations (Choquet-Bruhat)

57: GWs can be detected (Pirani, Bondi, Feynman)

63: Rotating BH solution (Kerr)

90s: CBC PN waveforms (Blanchet, Iyer, Damour, Deruelle, Will, Wiseman, ...)

00s: CBC Effective One Body (Damour, Buonanno)

06: BBH numerical simulation (Pretorius, Baker, Loustos, Campanelli)

Experience

60s: Weber's resonant bar

70s: First interferometer prototypes (Forward)

72: Thorough noise studies (Weiss)

73: Hulse & Taylor binary pulsar discovery

80s: Few-meters interferometer prototypes (Weiss, Drever, Hough, Brillet, ...)

90s: LIGO (USA)-Virgo (Italy) funded

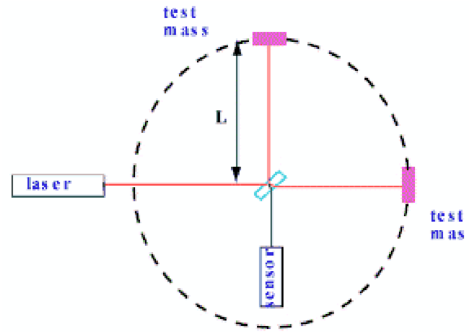
00s: Initial LIGO-Virgo runs

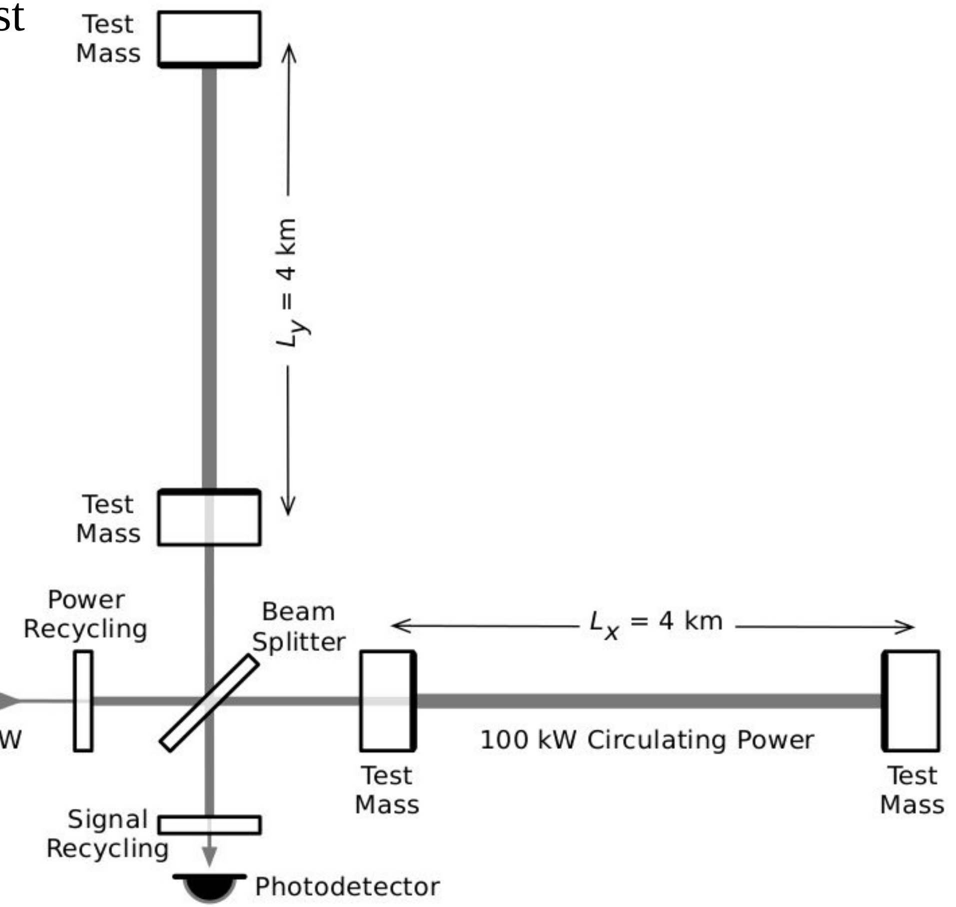
07: LIGO-Virgo MOU

10s: advanced LIGO – advanced Virgo construction

But how to detect GWs?

Passing GWs modulate the distance between the end test mass and the beam splitter



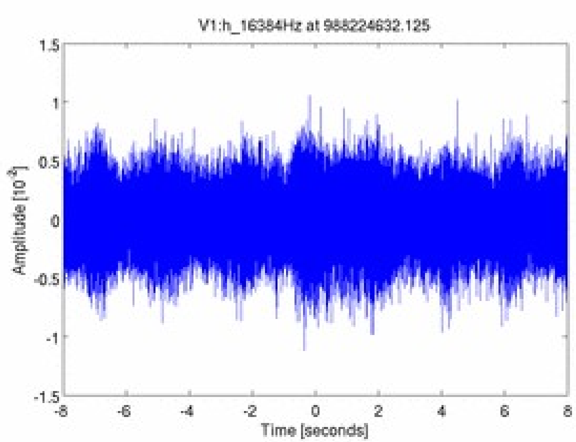


$$\frac{\Delta L}{L} = \frac{h}{2}$$

$$L = 4\ km\ ,\ h \sim 10^{-21} \rightarrow \Delta L \sim 10^{-18} m$$

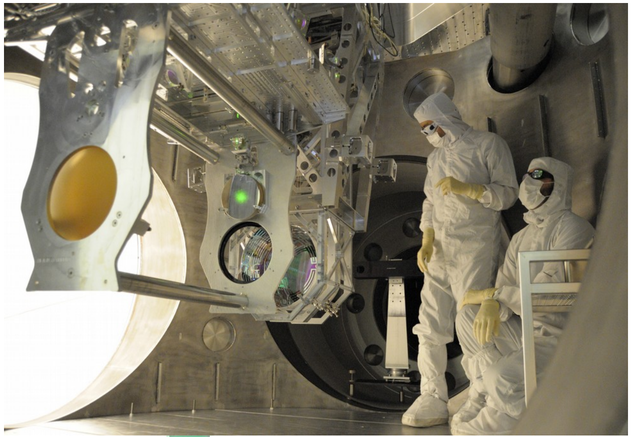
$$h(t) = F_+ \times h_+(t) + F_\times \times h_\times(t)$$

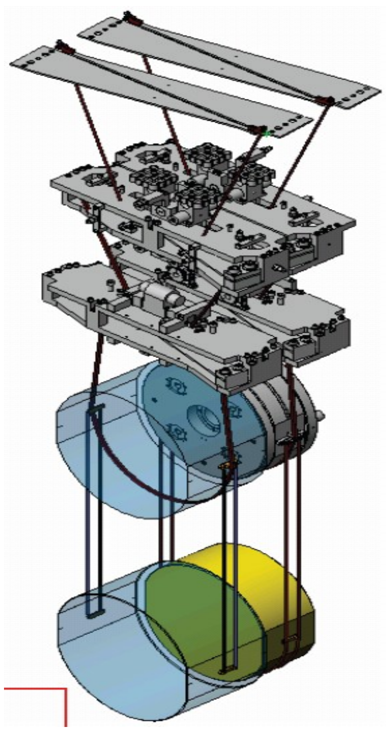
$$s(t) = n(t) + h(t)$$

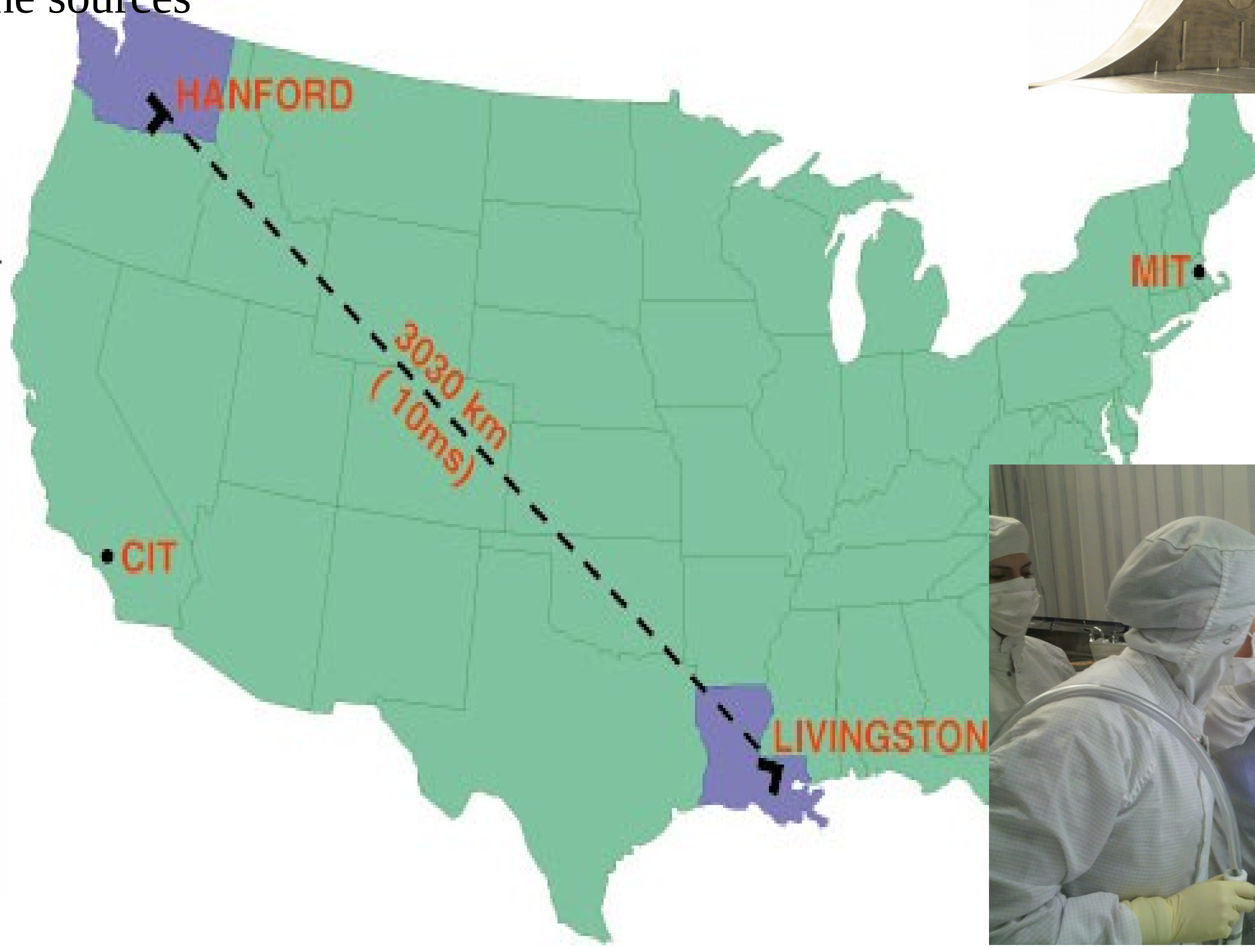


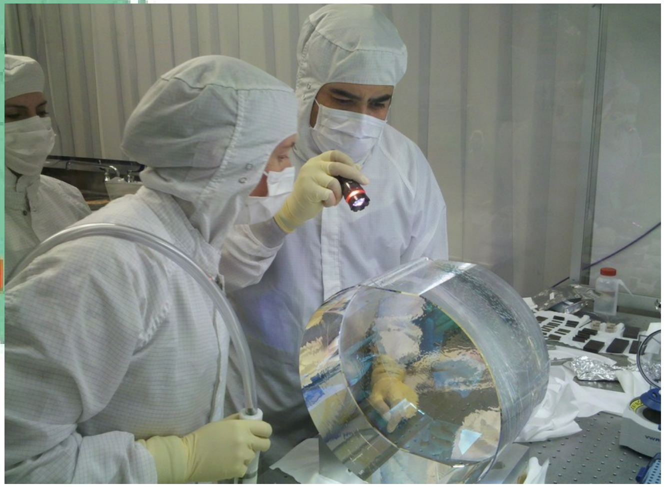
At least 2 (LIGO) interferometers to see GW150914

- Reduce the background (coincidence)
- Estimate the background (time slides)
- Source sky localization
- Source parameters inference
- GW polarization determination
- Astrophysics of the sources

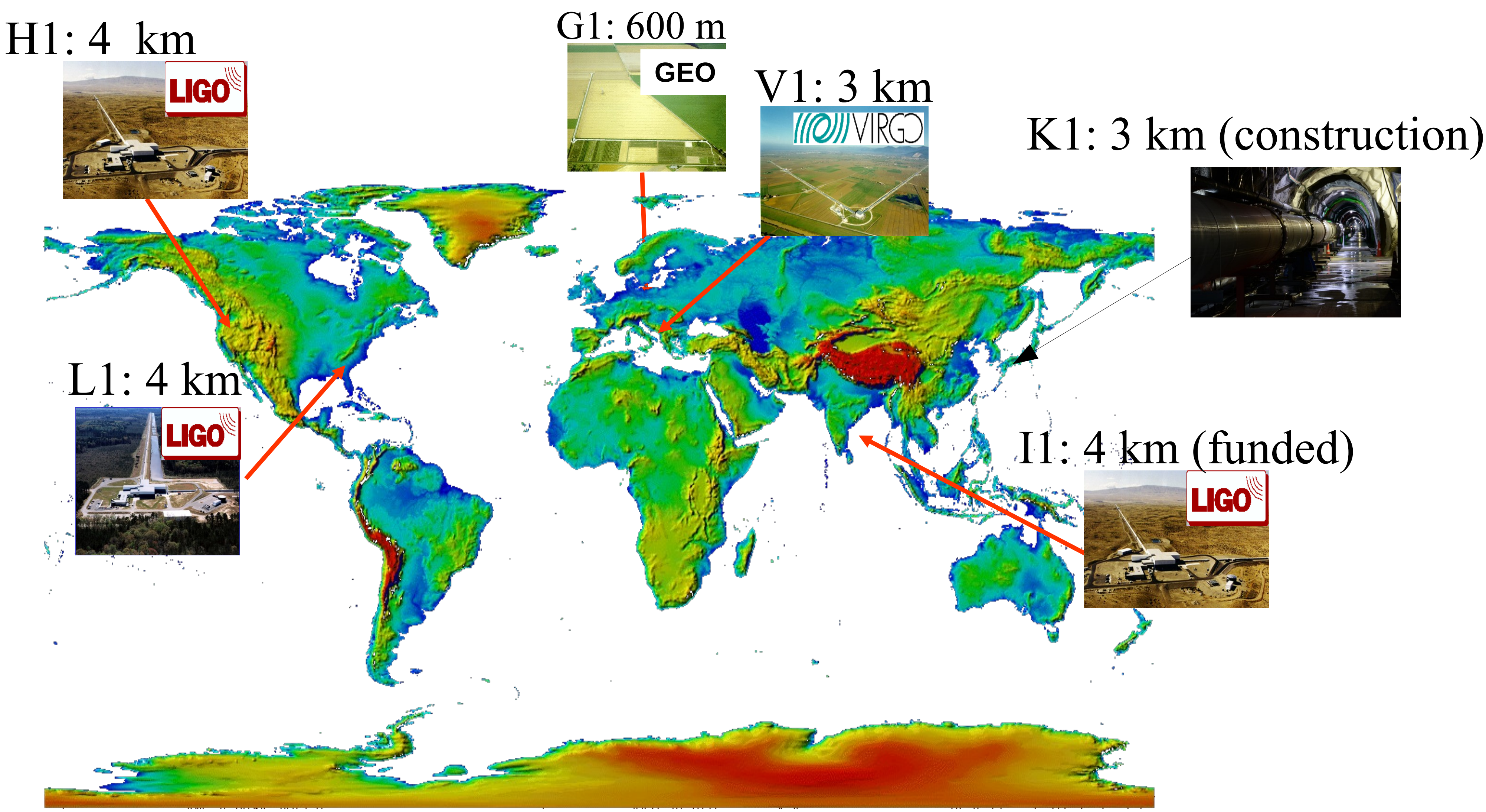






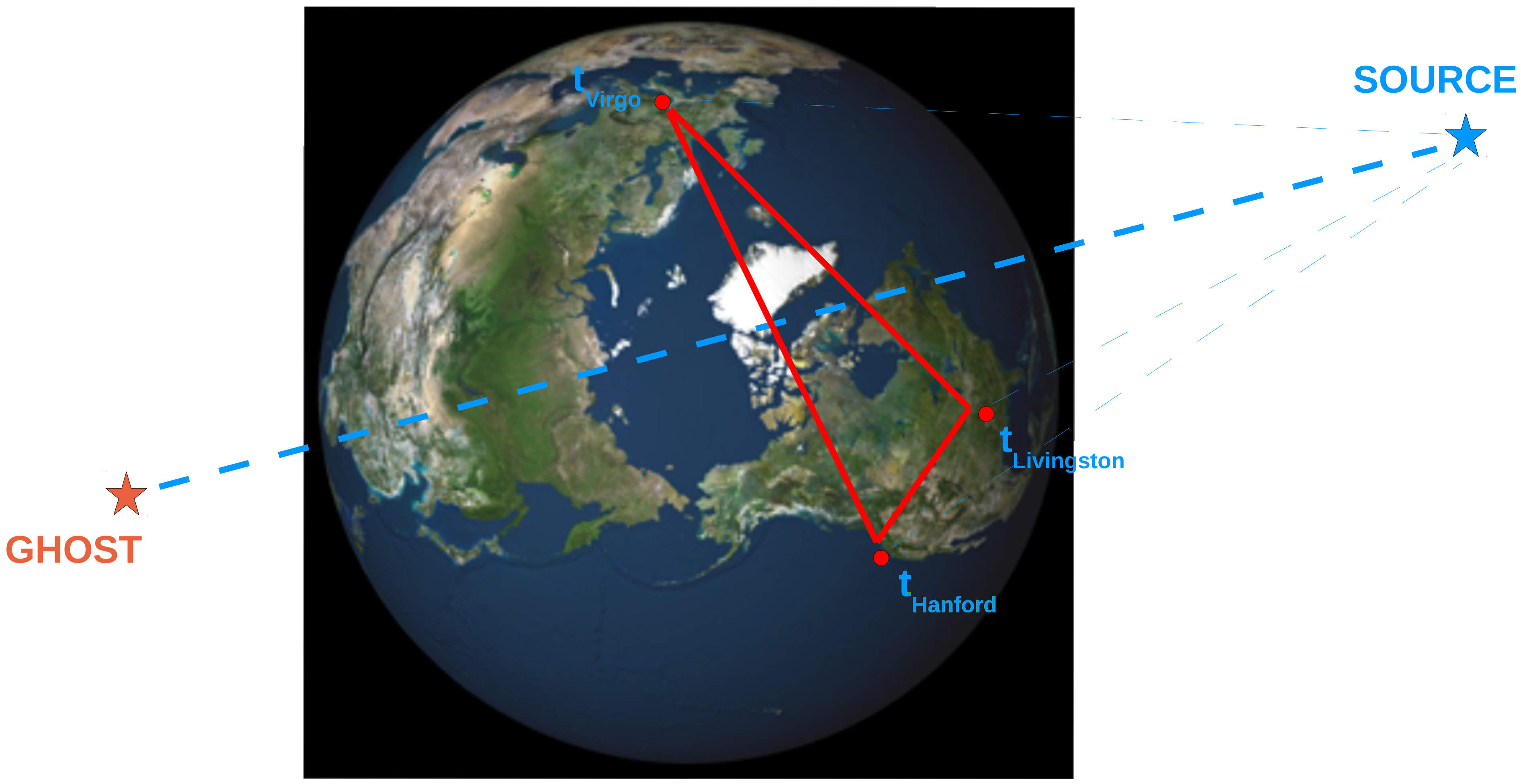


Network of ground based detectors

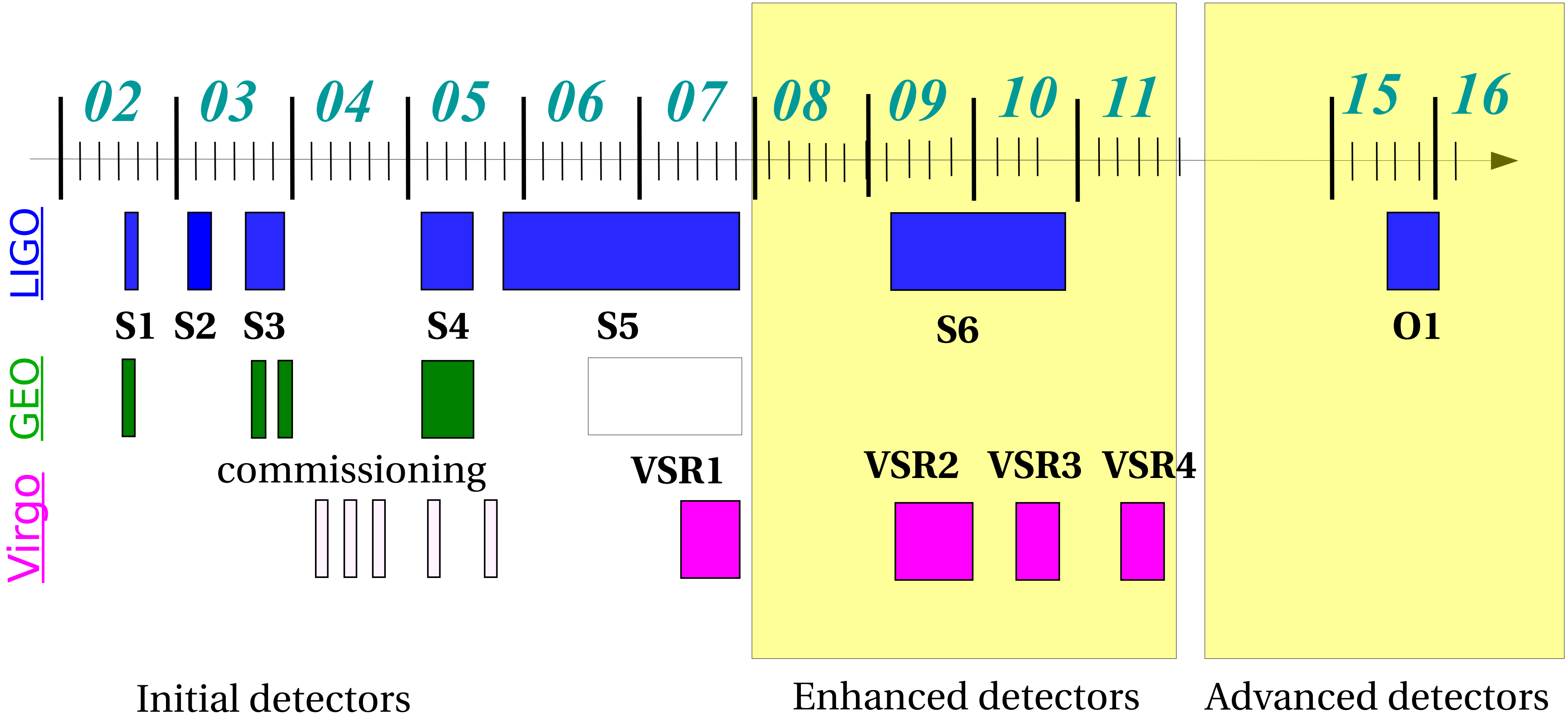


Since 2007, LIGO, GEO & Virgo data are jointly analyzed by the LIGO Scientific Collaboration and the Virgo Collaboration.

GW source sky localisation



LIGO-GEO-Virgo joint runs



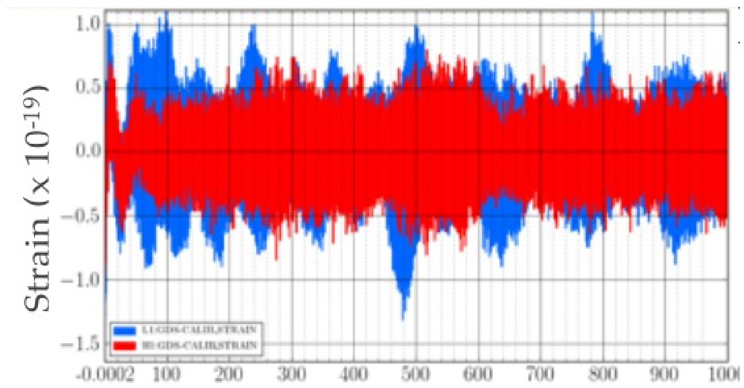
Searching for compact binary coalescence sources "modelled" searches

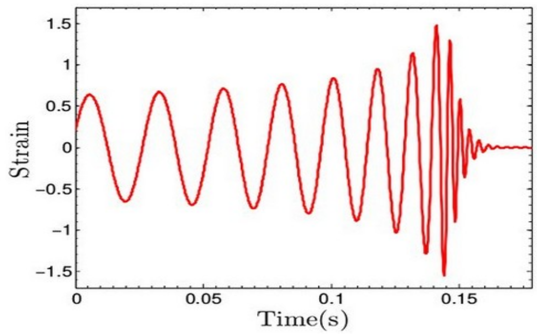
FFT of data

Template can be generated in frequency domain using stationary phase approximation

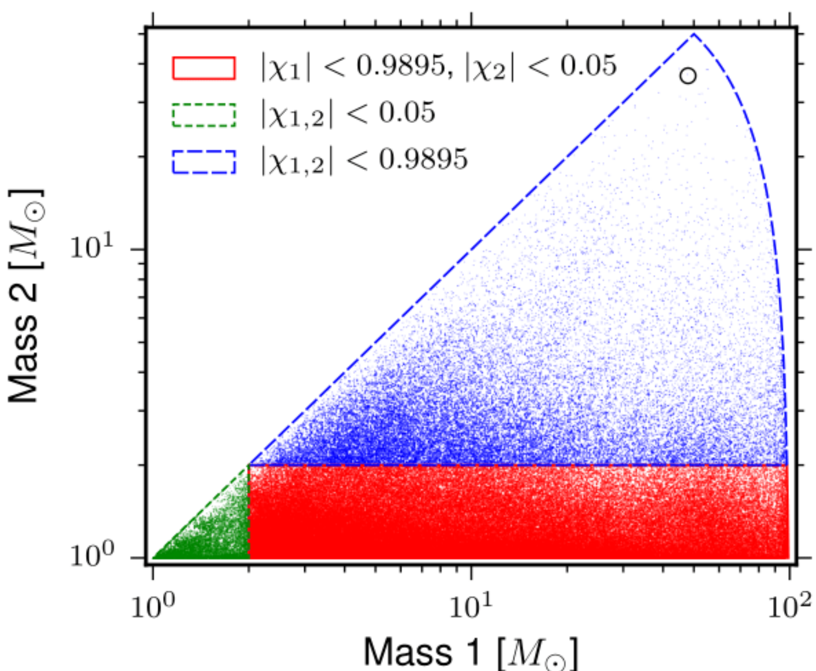
$$\mathcal{C}(t) = \int_{-\infty}^{\infty} \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

Noise power spectral density (in this case this is the two-sided Power spectrum)



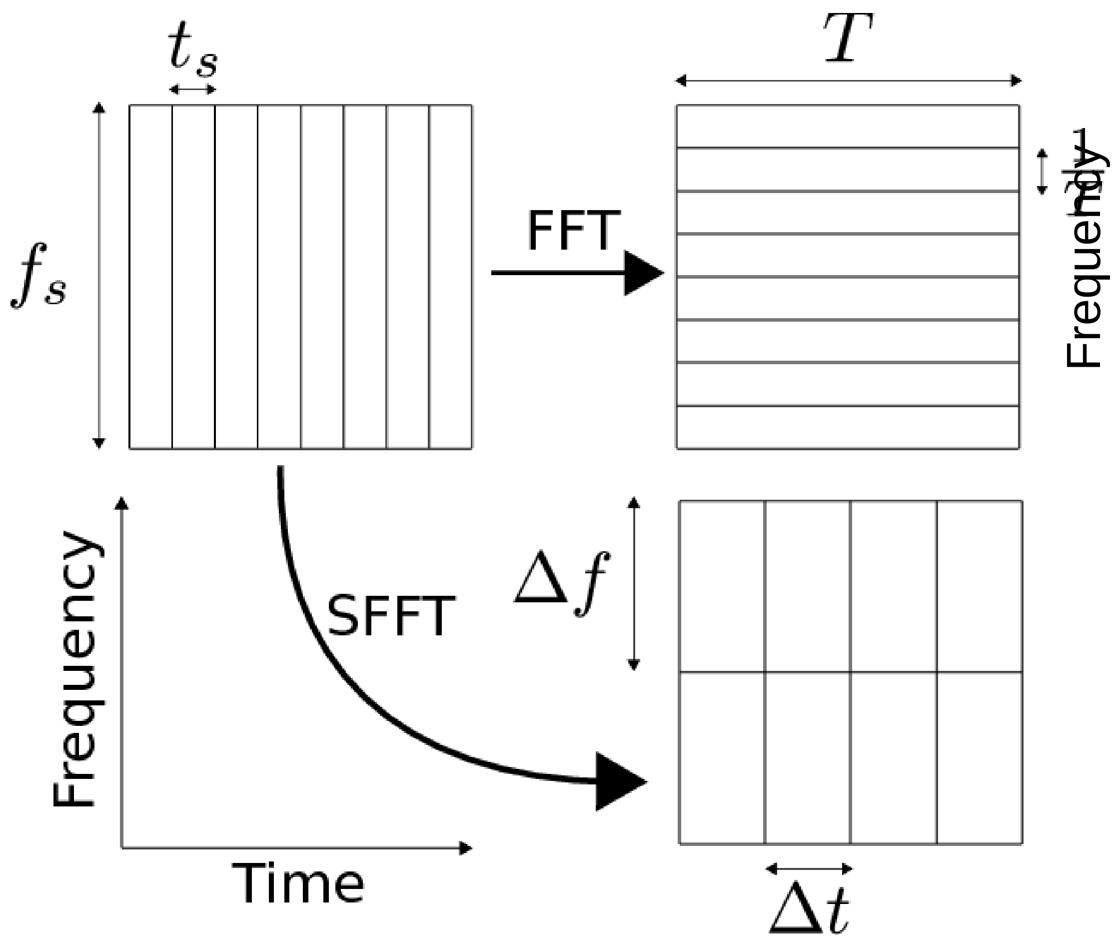


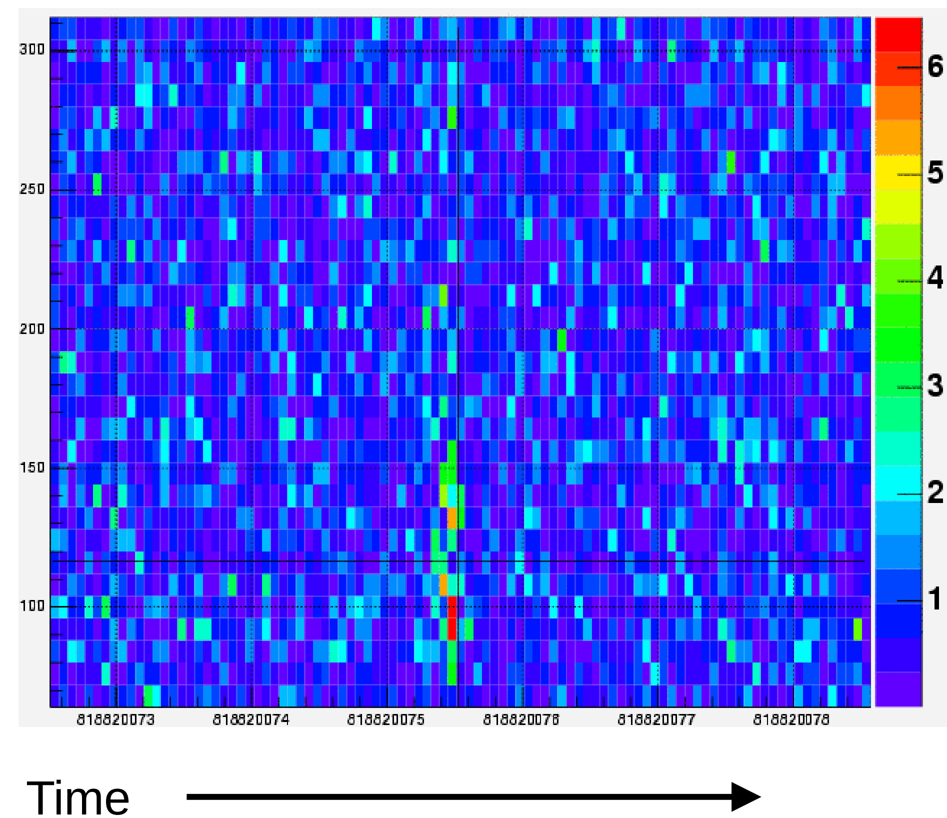
EOBNR-IHES waveform: m1=36Msun, m2=29Msun, nonspinning black holes



September 2015 configuration:
Waveform templates: EOBNR with aligned spins
Online: low mass regime (<20 Msun)
Offline: 1-100 Msun

Searching for compact binary coalescence sources “un modelled” searches



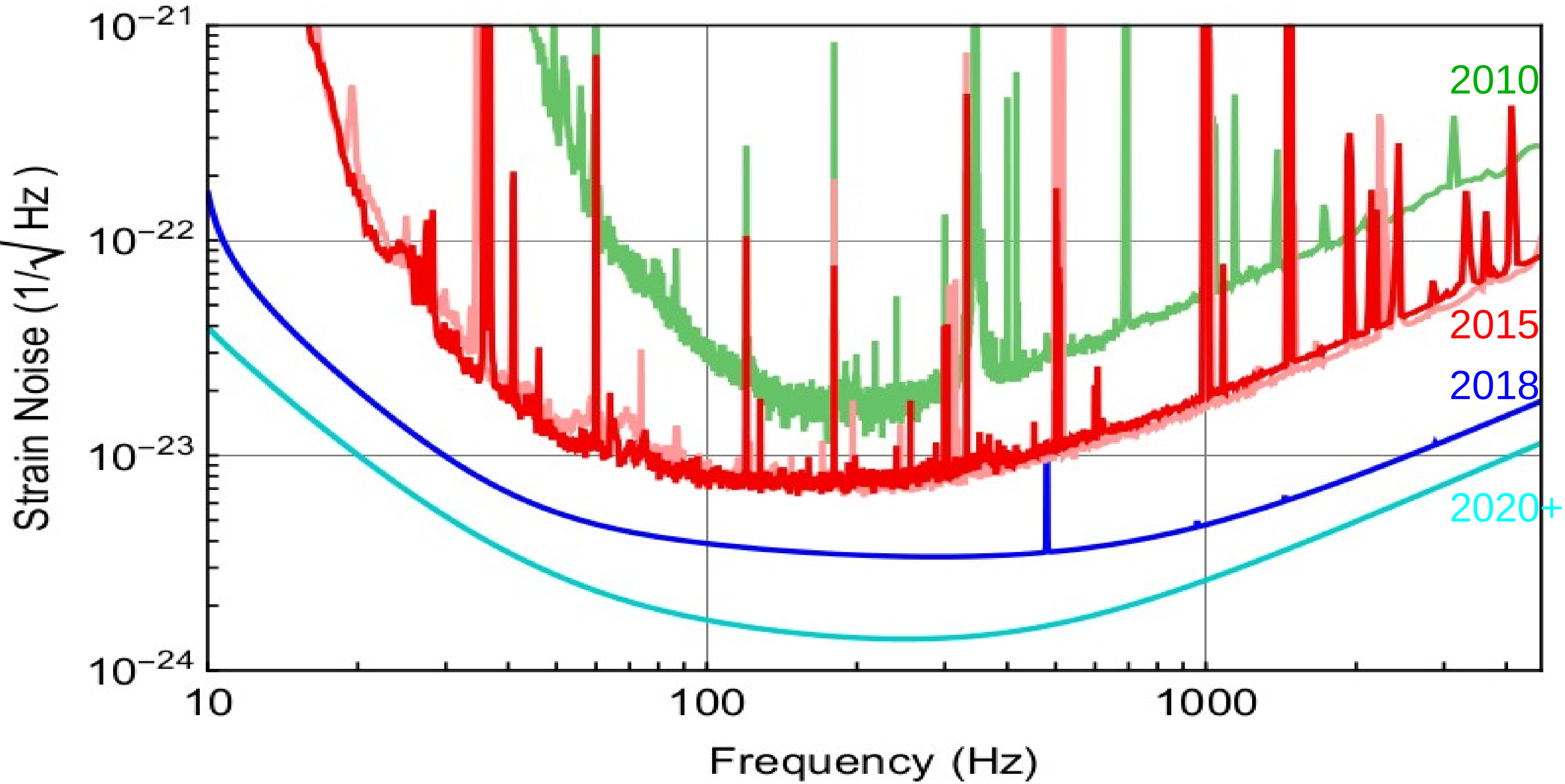


- Excess energy in time-frequency (wavelet transform)
- Efficiency similar to template based searches for BBH (masses > ~10 Msun)
- September 2015: online!

Advanced LIGO in September 2015

- 2010-2014: installation
- 2014-2015: commissioning
- September 2015: O1 run start!

- Horizon (BNS): 70 – 80 Mpc
- 3-4 times more sensitive than LIGO
- 30-60 times larger in volume



What happened on Sep 14th 2015?

GraceDB Processor
To: klimenko@phys.ufl.edu , reed.essick@ligo.org , Marco Drago
action required for GraceDB event : G184098 (burst_cwb_allsky)

September 14, 2015 5:54 AM
Details
Inbox - UF exchange

action required for GraceDB event : https://gracedb.ligo.org//events/view/G184098
(burst_cwb_allsky)
cwb_eventcreation

From Marco Drago
Subject **[CBC] Very interesting event on ER8**
Reply to cbc@ligo.org
To burst@sympa.ligo.org
Cc cbc@ligo.org BinariesGroup, The LIGO Data Analys

Hi all,
cWB has put on gracedb a very interesting event in the las
https://gracedb.ligo.org/events/view/G184098

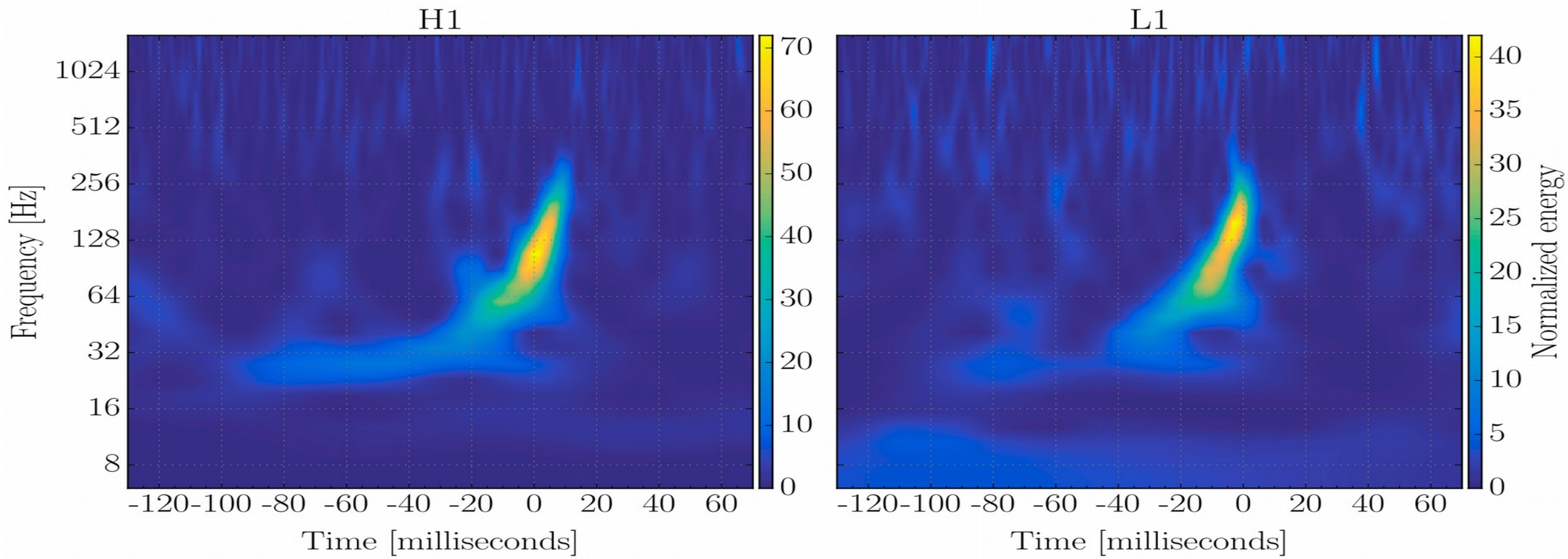
This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/11
/L1H1_1126259461.750_1126259461.750/

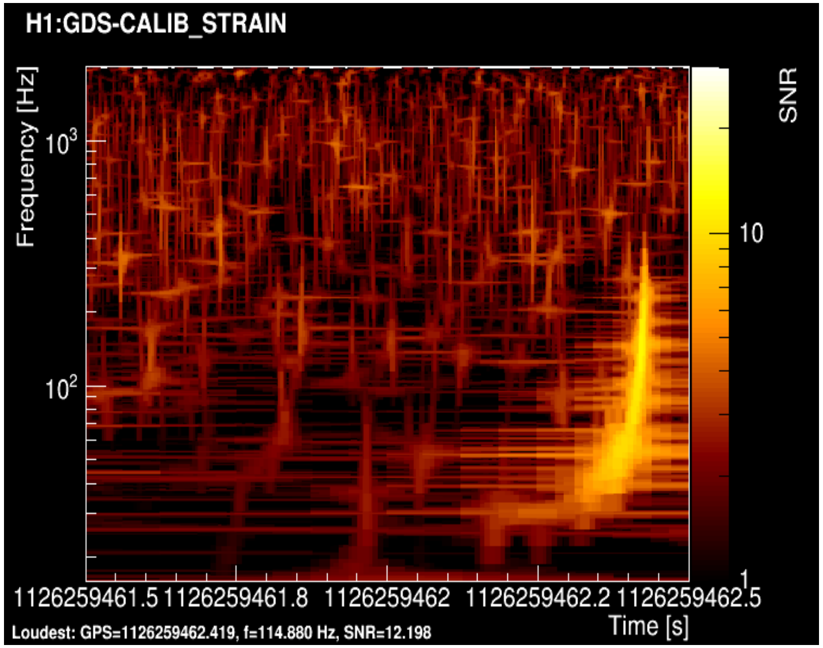
Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

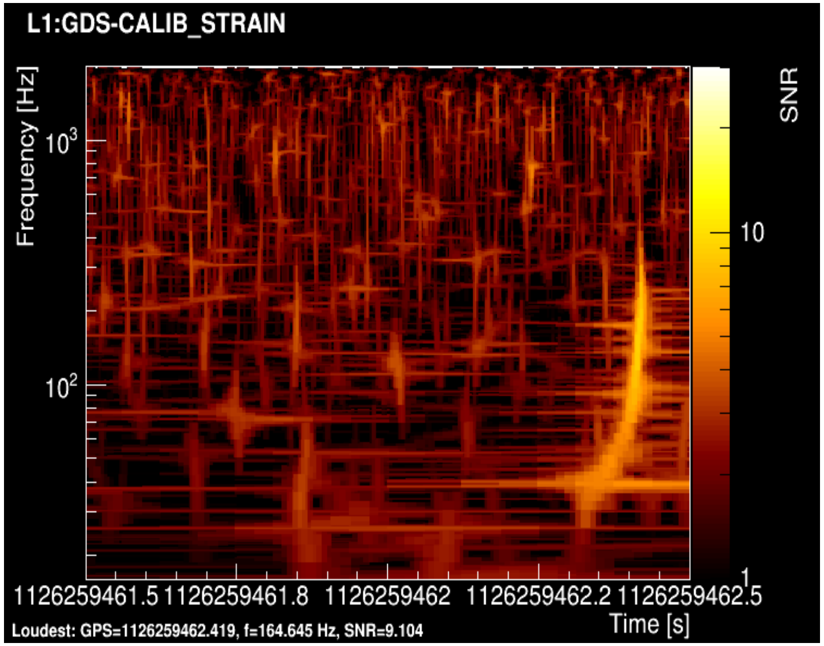
It is not flag as an hardware injection, as we understand after some

10h54 (Paris)
12h55: 1st email
+20mns: no injected signal
+30mns: BBH !
+55mns: data quality OK
+70mns: Mchirp ~27 Msun
FAR ~10^{-10} Hz

What happened on Sep 14th 2015?







On that ordinary monday

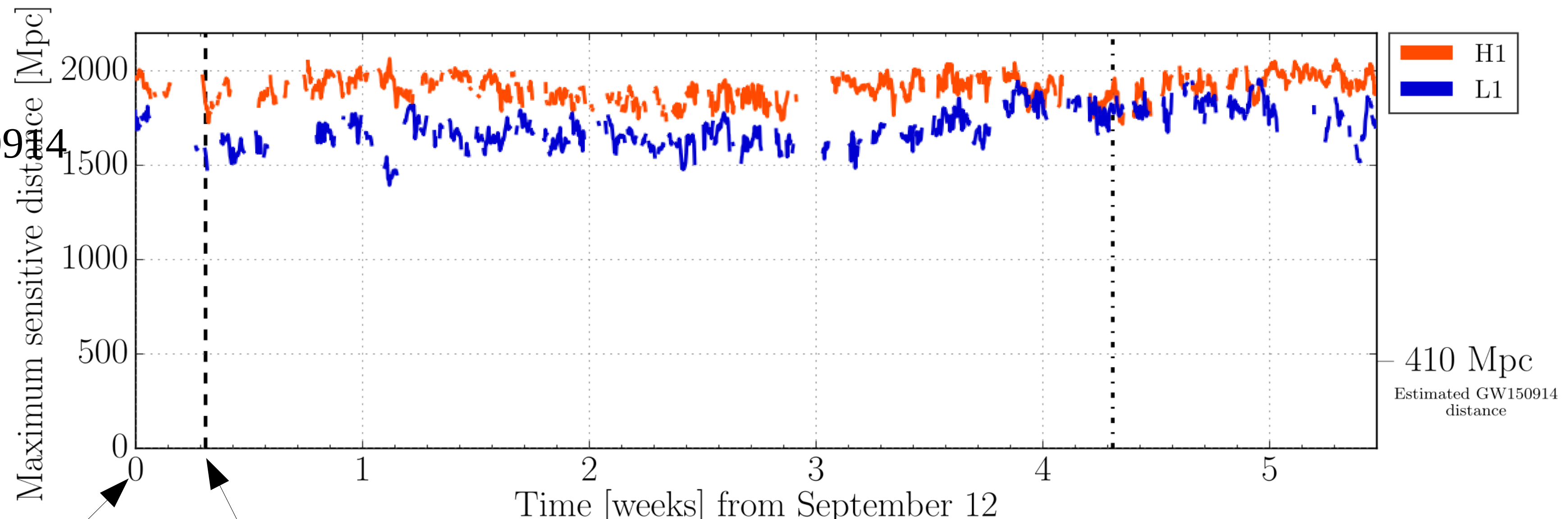
- Later that day, Dave Reitze (LIGO executive director) sent an email at 17h59 "The BI team has indicated that they have not carried out a blind injection nor an untagged hardware injection" ...
- Detectors / data quality check list procedure for GW alert sending to EM follow-up partners (MOU privacy)
- GCN (Gamma-ray Coordinate Network) alert sent on Sep 16th at 14h39 (Paris)

```
From: "Singer, Leo P. (GSFC-661.0)[OAK RIDGE ASSOCIATED UNIVERSITIES (ORAU)]" <leo.p.singer@nasa.gov>
Subject: [lv-em-observers] LIGO/Virgo G184098: Burst candidate in LIGO engineering run data
Date: 16 Sep 2015 07:39:44 CEST
To: "lv-em-observers@gw-astronomy.org" <lv-em-observers@gw-astronomy.org>
Reply-To: lv-em-observers@gw-astronomy.org
Dear colleagues,
We would like to bring to your attention a trigger identified by the
online Burst analysis during the ongoing Engineering Run 8 (ER8).
Normally, we would send this in the form of a private GCN Circular, but
the LIGO/Virgo GCN Circular list is not ready yet.
The LIGO Scientific Collaboration and Virgo report that the cWB unmodeled
burst analysis identified candidate G184098 during real-time processing of
data from LIGO Hanford Observatory (H1) and LIGO Livingston Observatory
(L1) at 2015-09-14 09:50:45 UTC (GPS time: 1126259462.3910). Alerts were
not sent in real-time because the candidate occurred in ER8 data; however,
we have now sent GCN notices through our normal channel.
G184098 is an unvetted event of interest, as the false alarm rate (FAR)
determined by the online analysis would have passed our stated alert
threshold of ~1/month. The event's properties can be found at this URL:
https://gracedb.ligo.org/events/G184098
```

The detection procedure

- Start immediately the “detection” procedure established years ago with a “detection committee” in charge of validating all steps up to the discovery announcement on Feb 11th 2016.
- In the mean time: detectors continue to take data in the same condition!
- All pipelines run with ~1 month of data (16 days of coincident data).

For BBH
Like GW150914



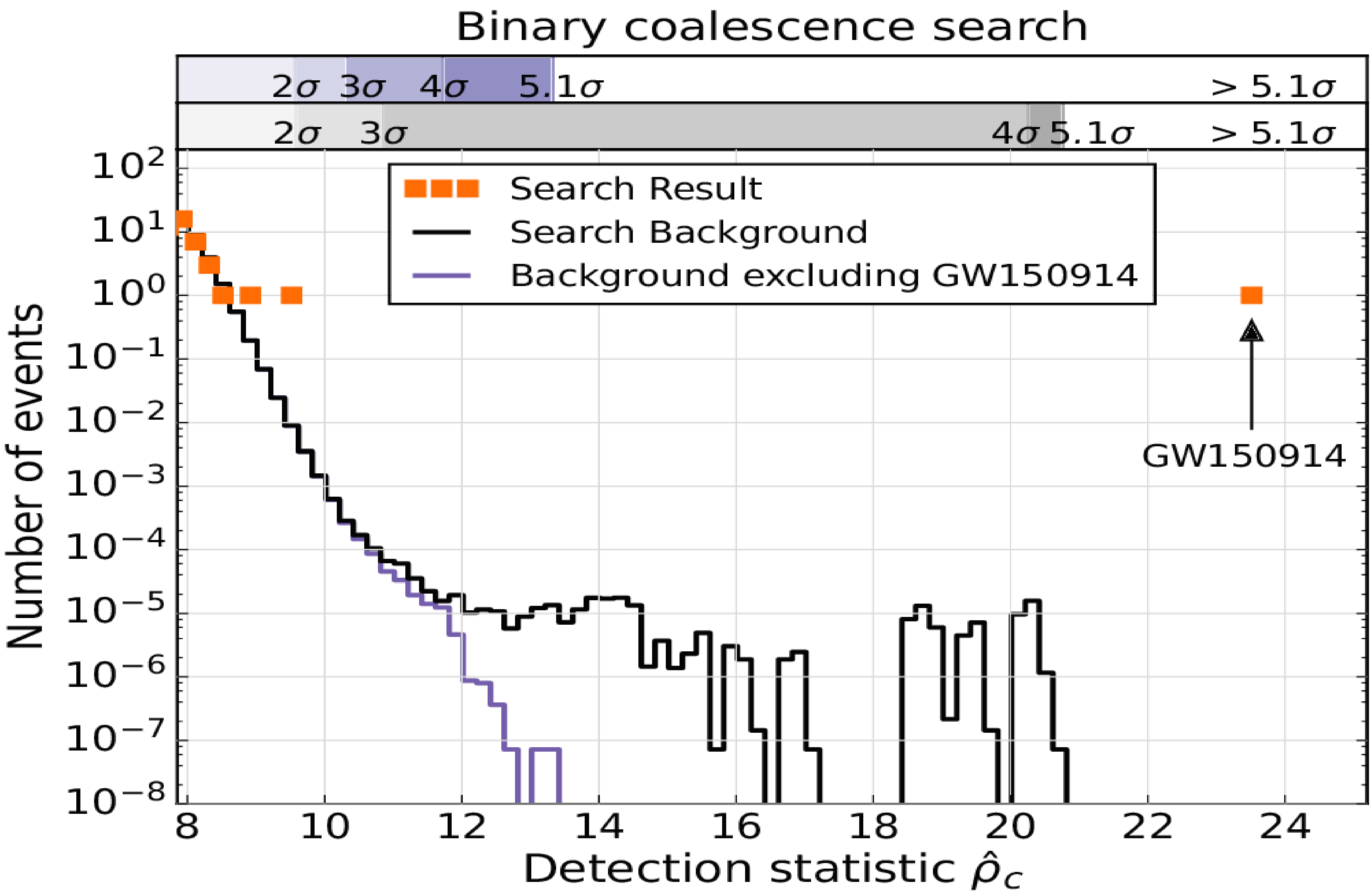
Calibration OK

GW150914

The detection: (modelled search)

FAR: < 1 event /200,000 years

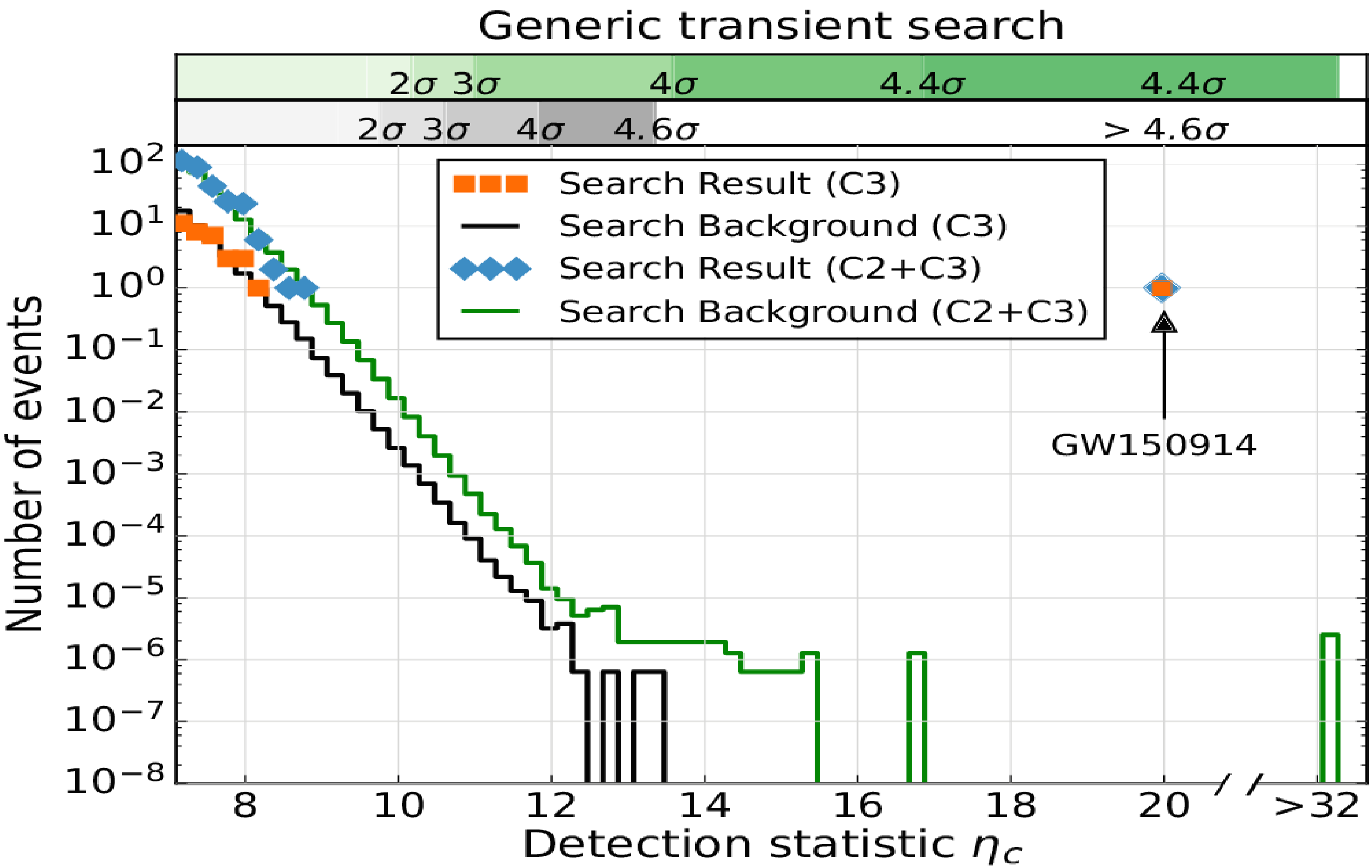
FAP: < 2x10^{-7} (> 5.1 sigma)



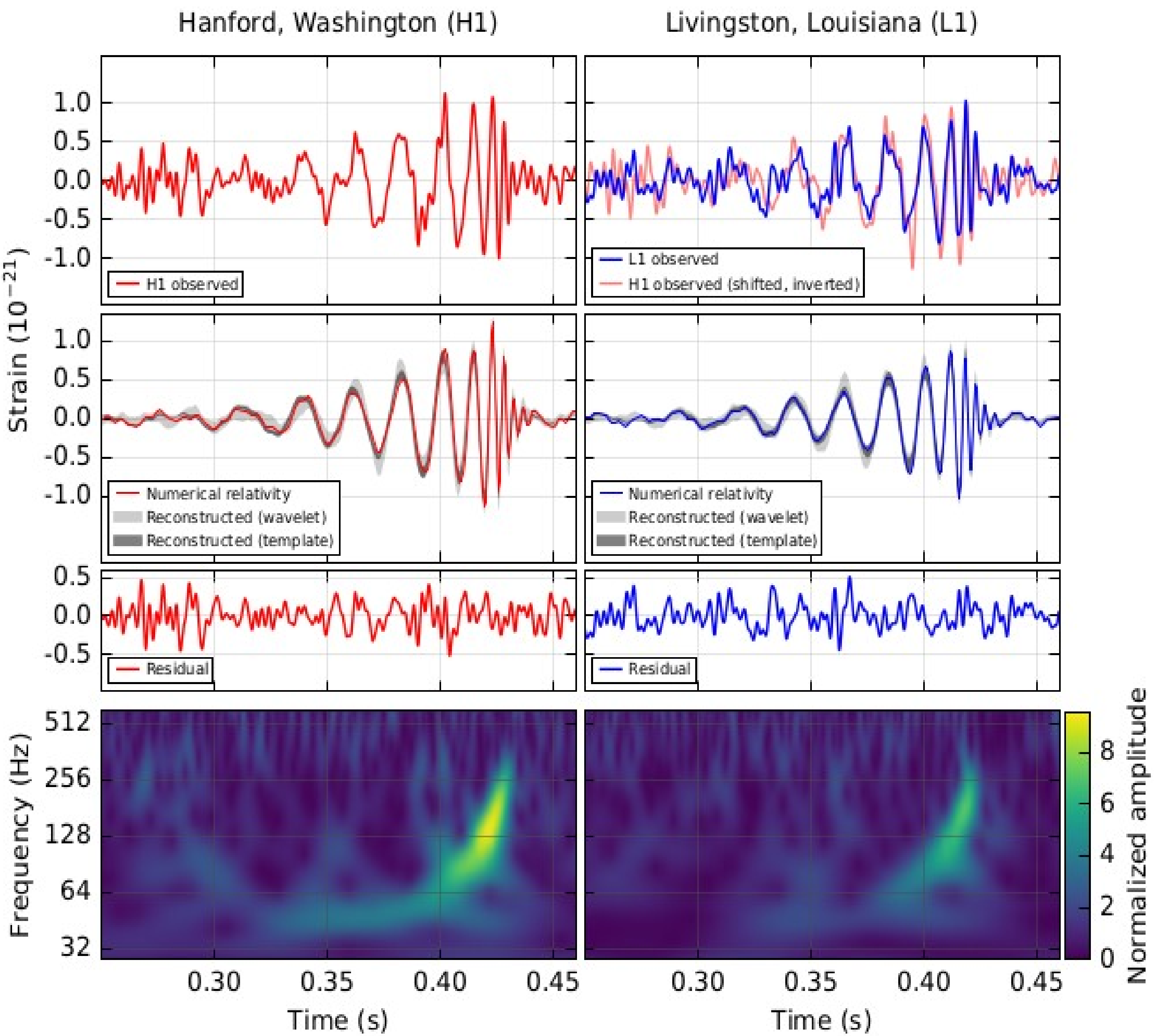
The detection: (un-modelled search)

FAR: < 1 event /67,400 years

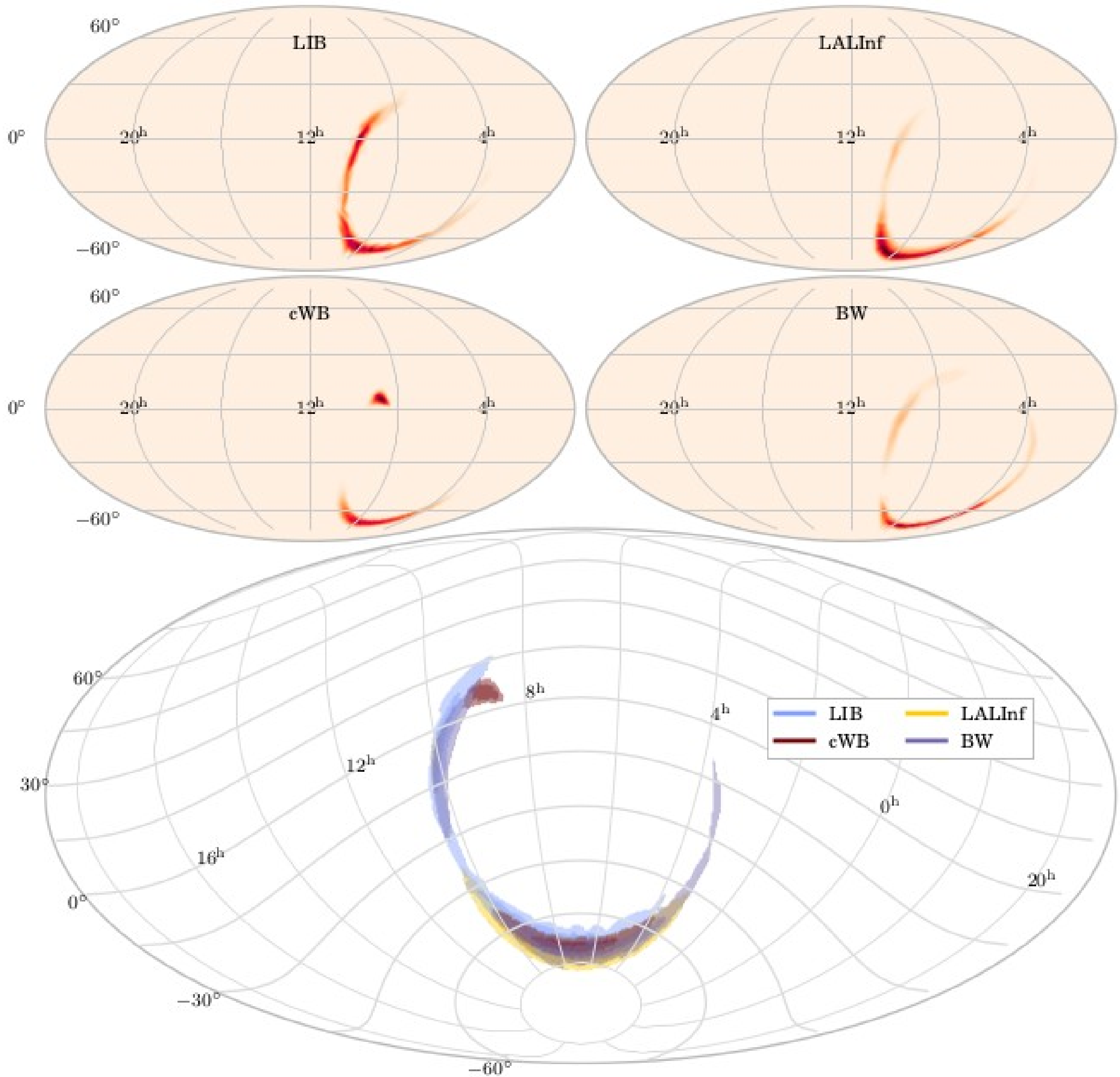
FAP: < 2×10^{-6} (> 4.6 sigma)



Signal reconstruction

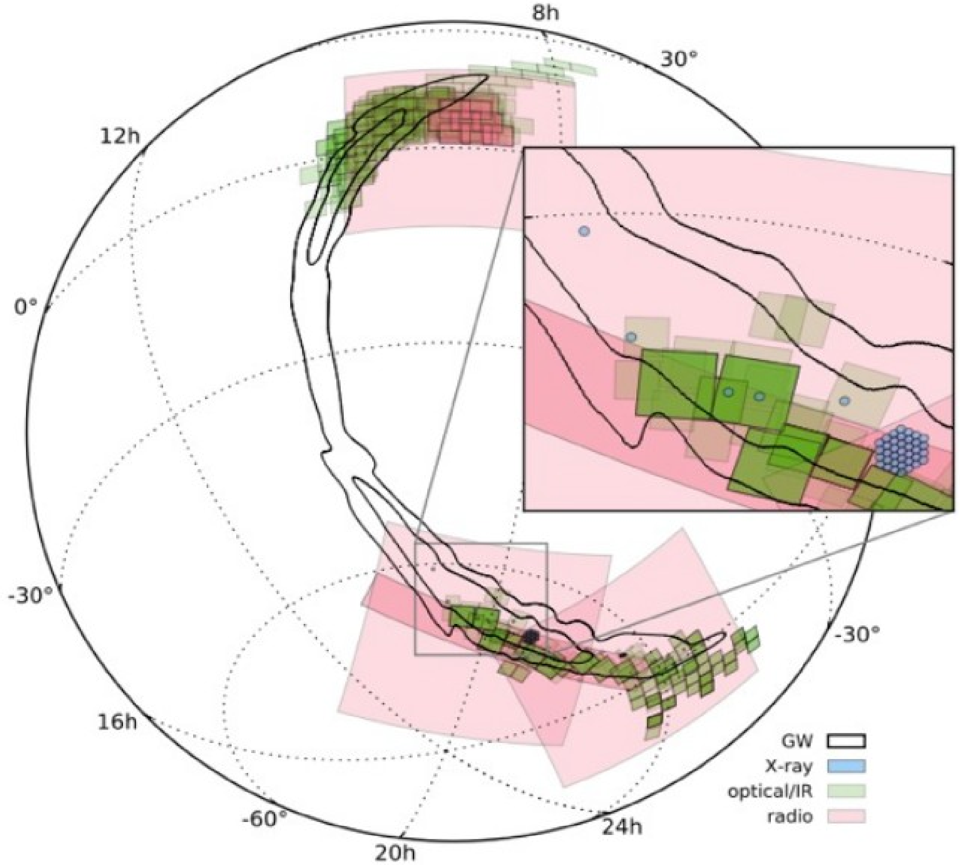


Sky location



Electro-magnetic follow-up

- 62 MOUs (radio, optical, IR, X-ray and γ-ray).
- GW150914 followed up by 21 teams (private GCN circulars).
- What can we learn … for a BBH?

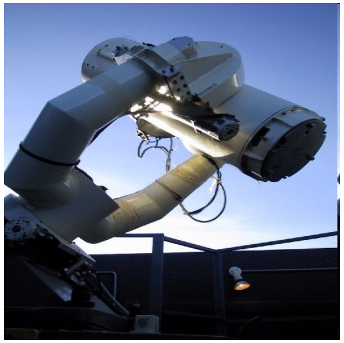


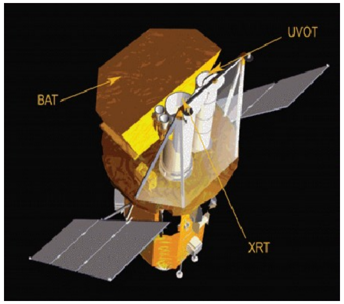
cWB sky map

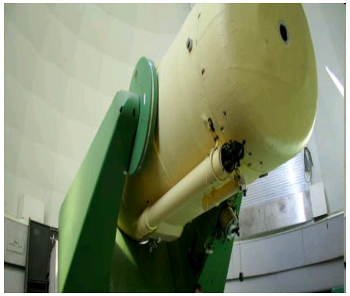
γ / X-ray observations

Optical observations

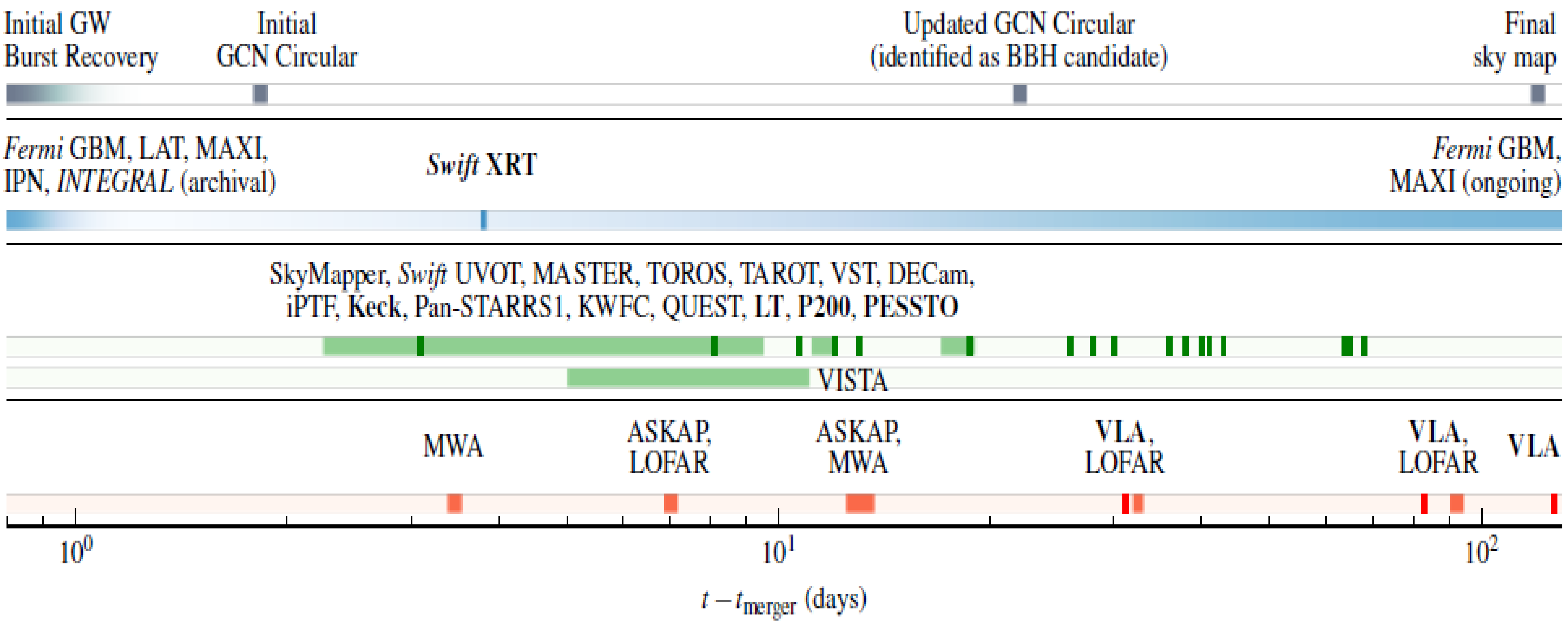
Radio Observations







Electro-magnetic follow-up

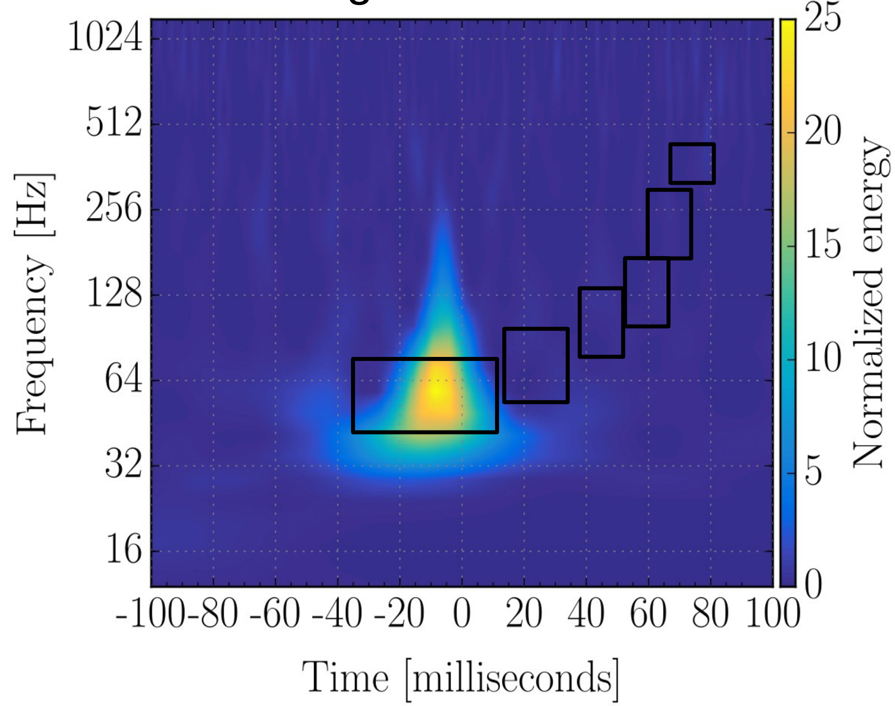


Why do we know GW150914 is not a noise artefact?

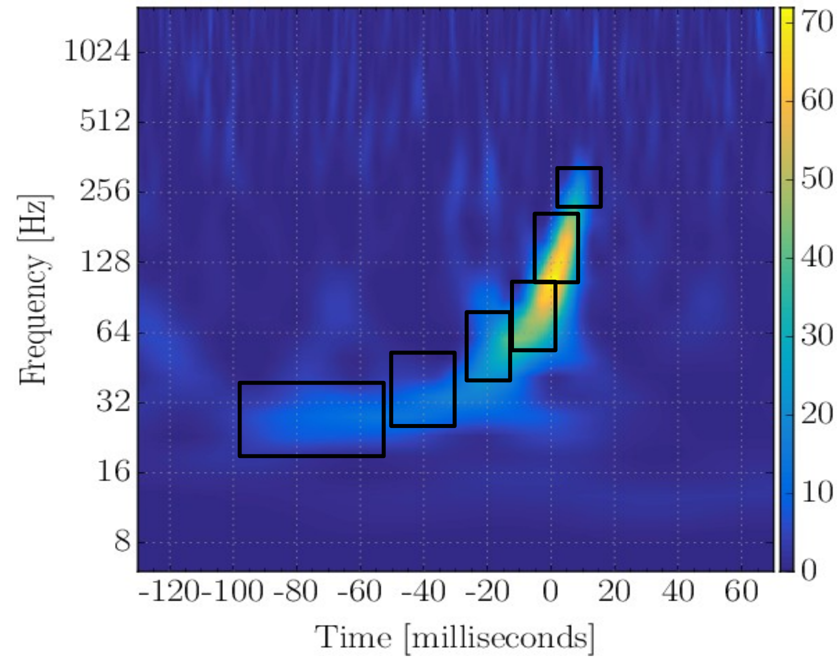
- Noise investigation: 200,000 auxiliary channels scrutinized
  - Un-correlated noise: anthropogenic, earthquakes, radio-frequency modulation, unknown origin / known family glitches.
  - Correlated noise: potential EM noise sources (lightning exciting Schumann resonances, solar wind, …).
- Detector's control systems have been checked for hacking hazard (thorough investigation to rule out that none has injected a signal).
- Data quality around GW150914: rather good + stable over weeks.
- Detection committee : in charge of establishing a complete check list.

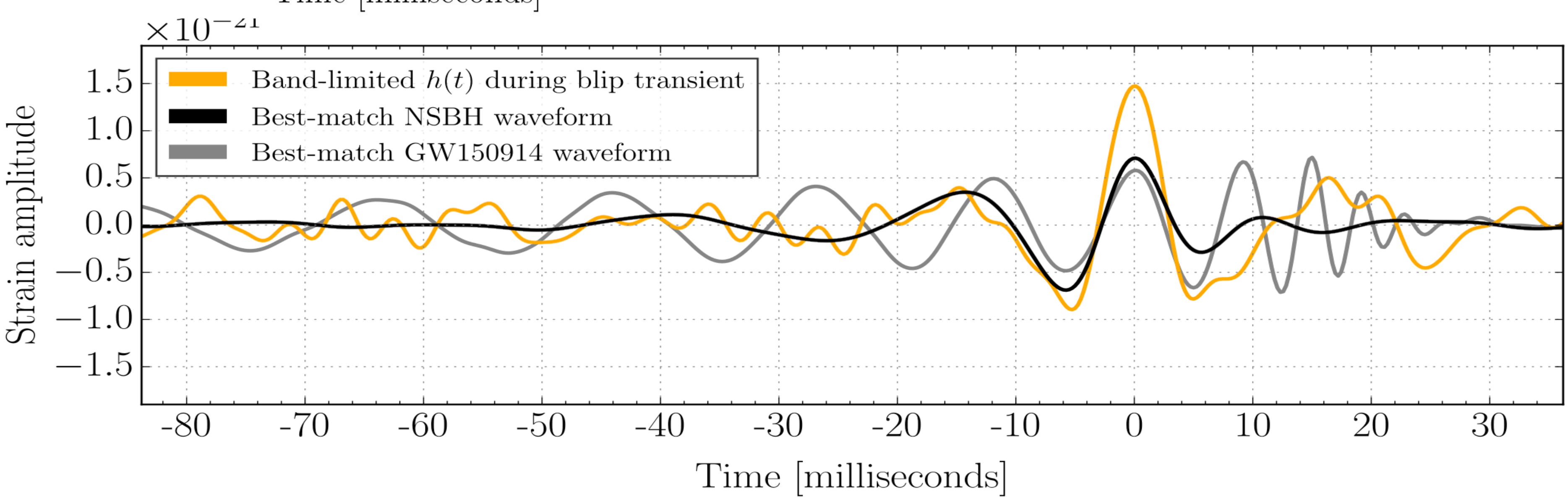
Why do we know this is not a noise artefact?

A glitch in L1

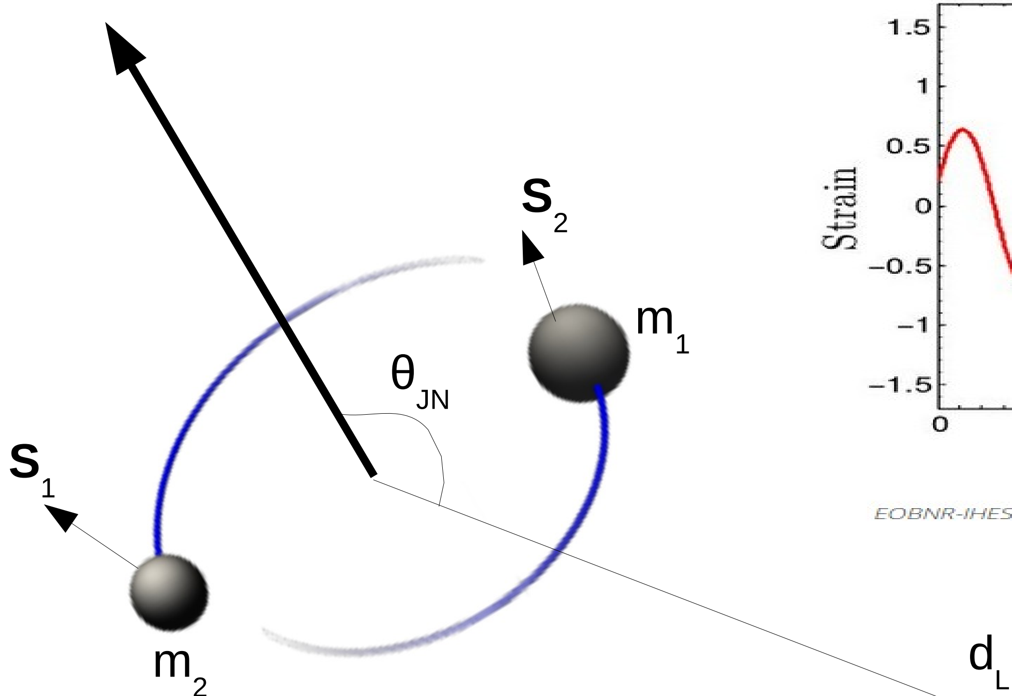


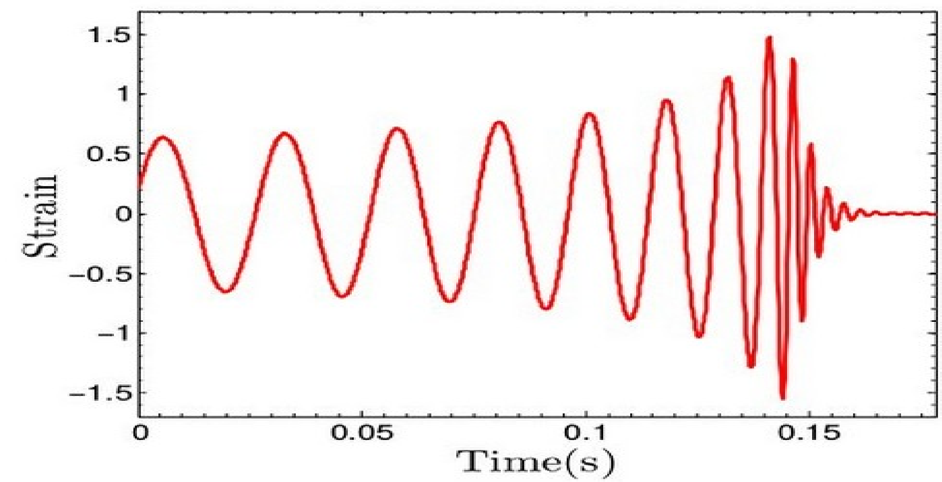
GW150914 in H1





Source parameter estimation: Bayesian inference





EOBNR-IHES waveform: m1=36Msun, m2=29Msun, nonspinning black holes

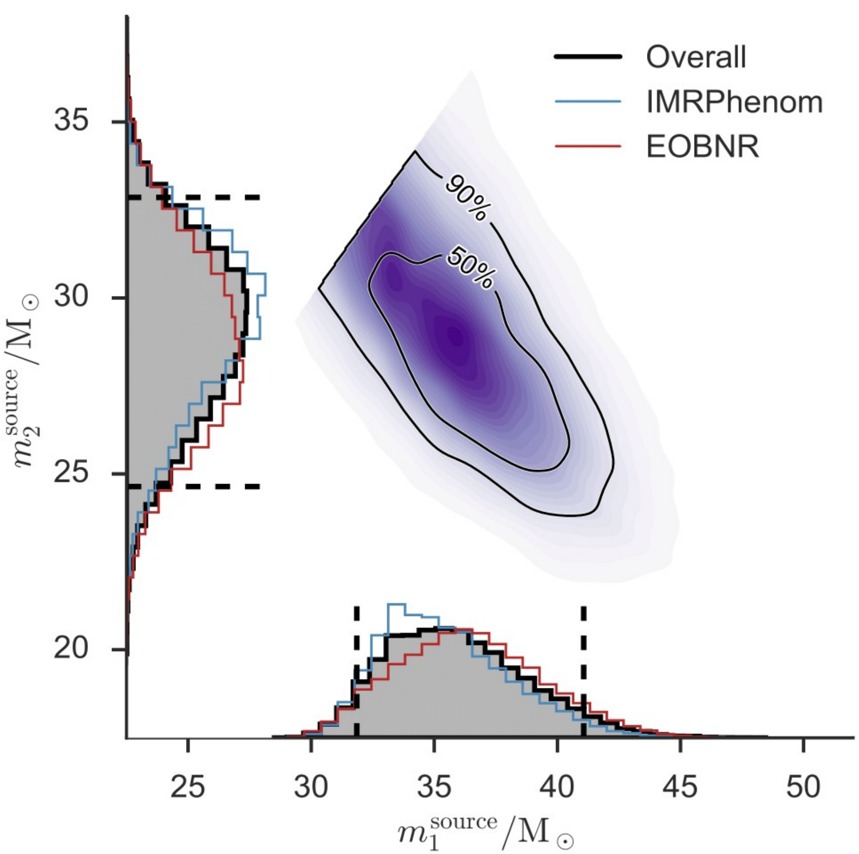
GWs (?) noise data from multiple instruments

$$\tilde{d}^{(D)}(f) = \tilde{h}^{(D)}(f) + \tilde{n}^{(D)}(f) \qquad \vec{d} = \{d^{(H)}, d^{(L)}, ...\}$$

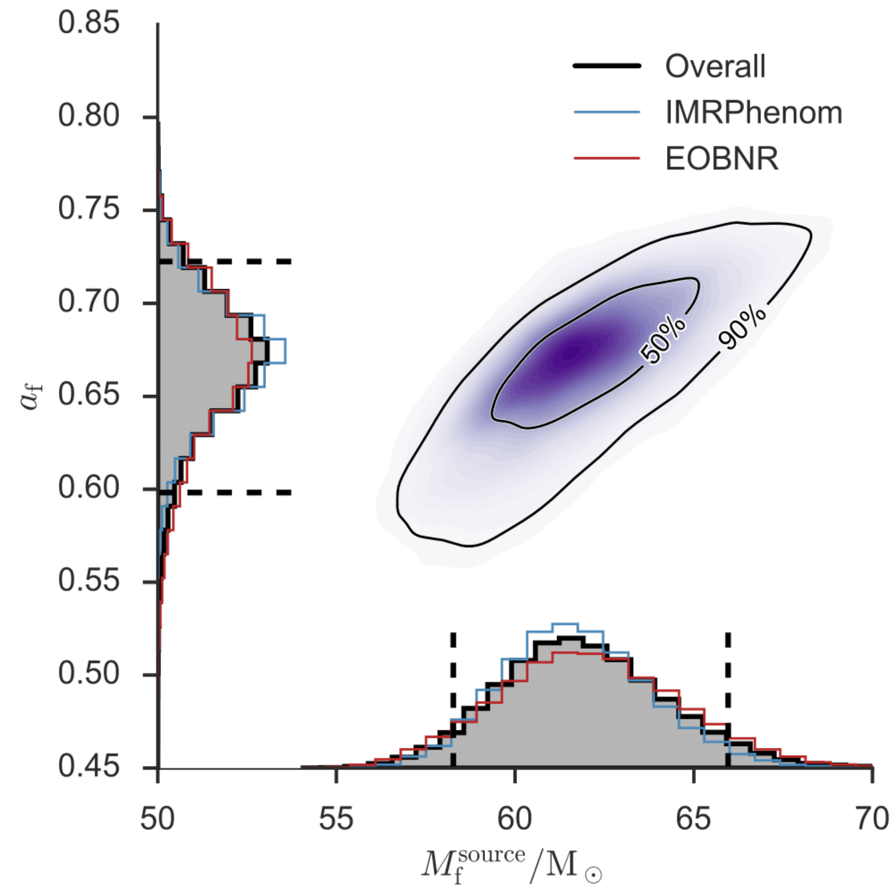
$$Z = P(\vec{d}|\mathcal{H}, I) = \int_{\Theta} p(\vec{\theta}|\mathcal{H}, I) p(\vec{d}|\mathcal{H}, \vec{\theta}, I) d\vec{\theta} \qquad O_{i,j} = \frac{P(\mathcal{H}_i|I)}{P(\mathcal{H}_j|I)} \frac{P(\vec{d}|\mathcal{H}_i, I)}{P(\vec{d}|\mathcal{H}_j, I)} = \frac{P(\mathcal{H}_i|I)}{P(\mathcal{H}_j|I)} B_{ij}$$

PDF $$p(\vec{\theta}|\vec{d}, \mathcal{H}, I) = \frac{p(\vec{\theta}|\mathcal{H}, I) p(\vec{d}|\vec{\theta}, \mathcal{H}, I)}{p(\vec{d}|\mathcal{H}, I)} \qquad p(\vec{\theta}_A|\vec{d}, \mathcal{H}, I) = \int_{\Theta_B} p(\vec{\theta}|\vec{d}, \mathcal{H}, I) d\vec{\theta}_B$$

Source parameters estimation: Bayesian inference

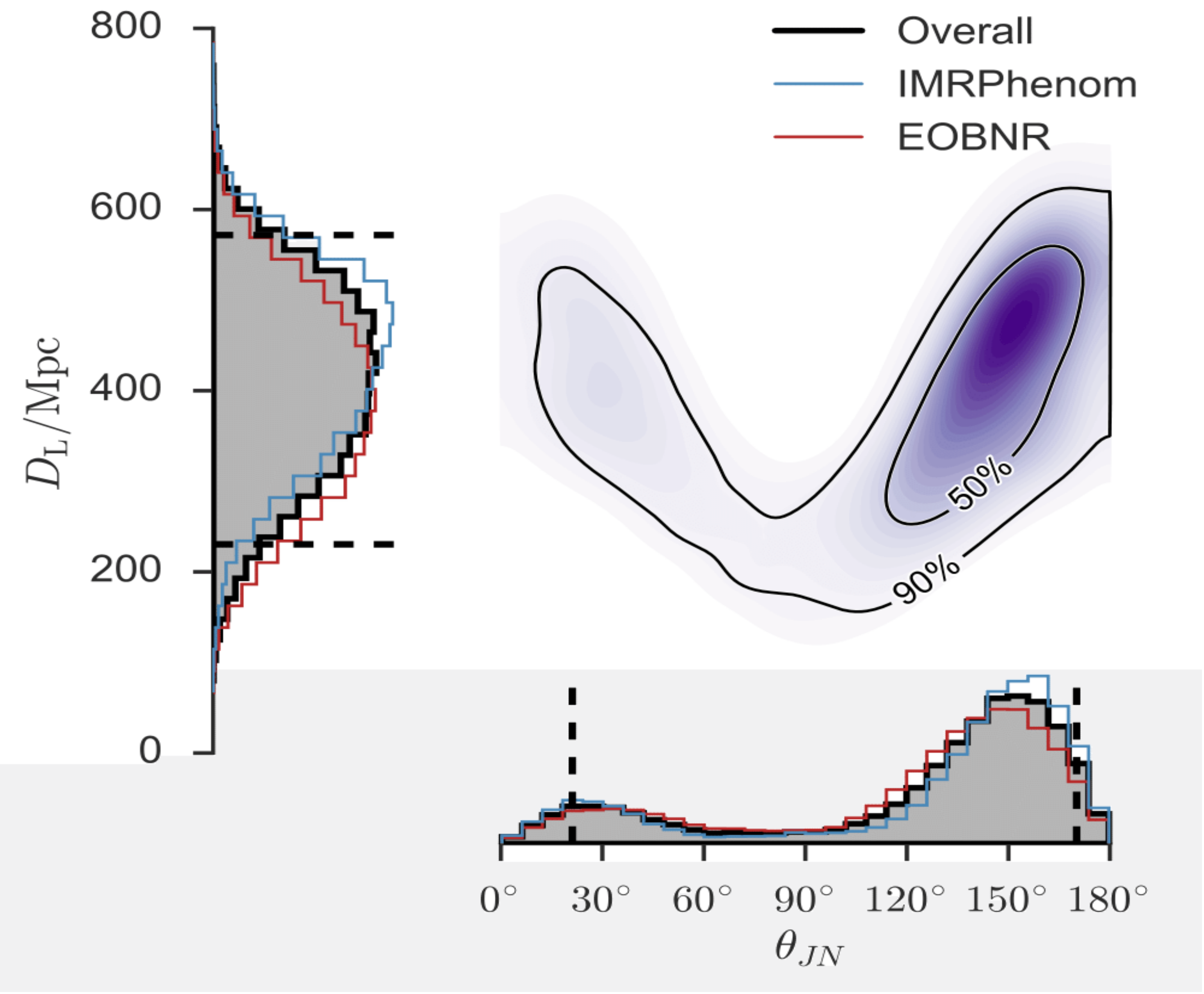


Individual masses

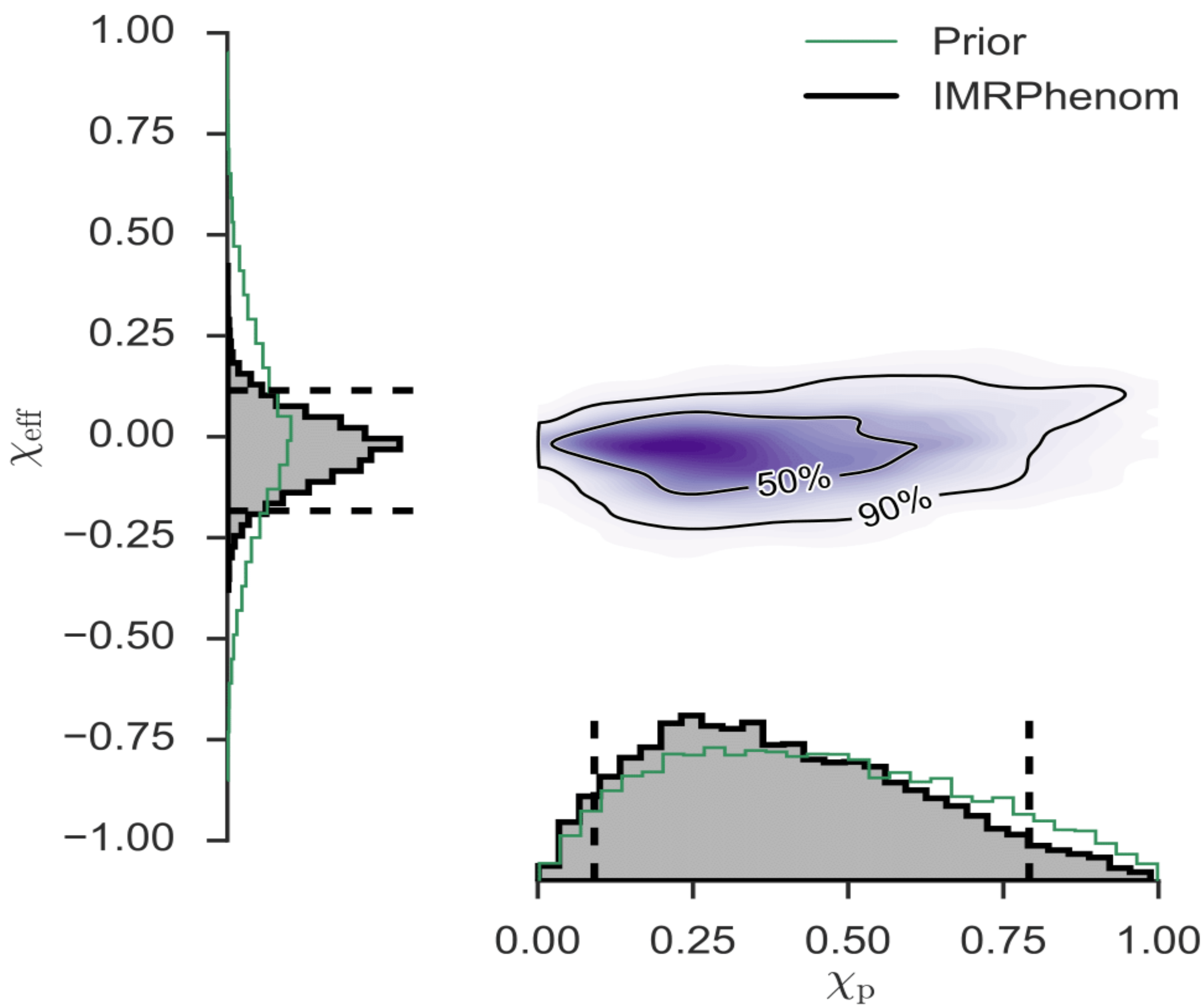


Final BH mass and spin

Source parameters estimation: Bayesian inference



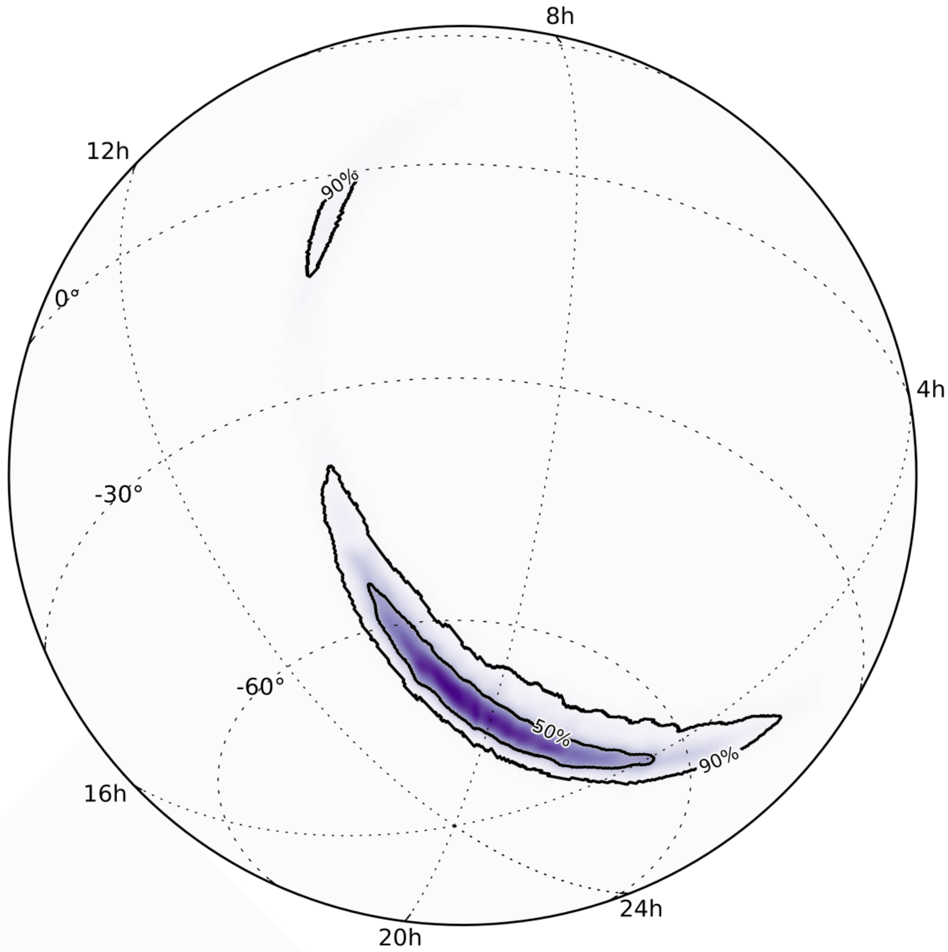
Source parameters estimation: Bayesian inference



Spins aligned with orb. angular momentum constrained to be small

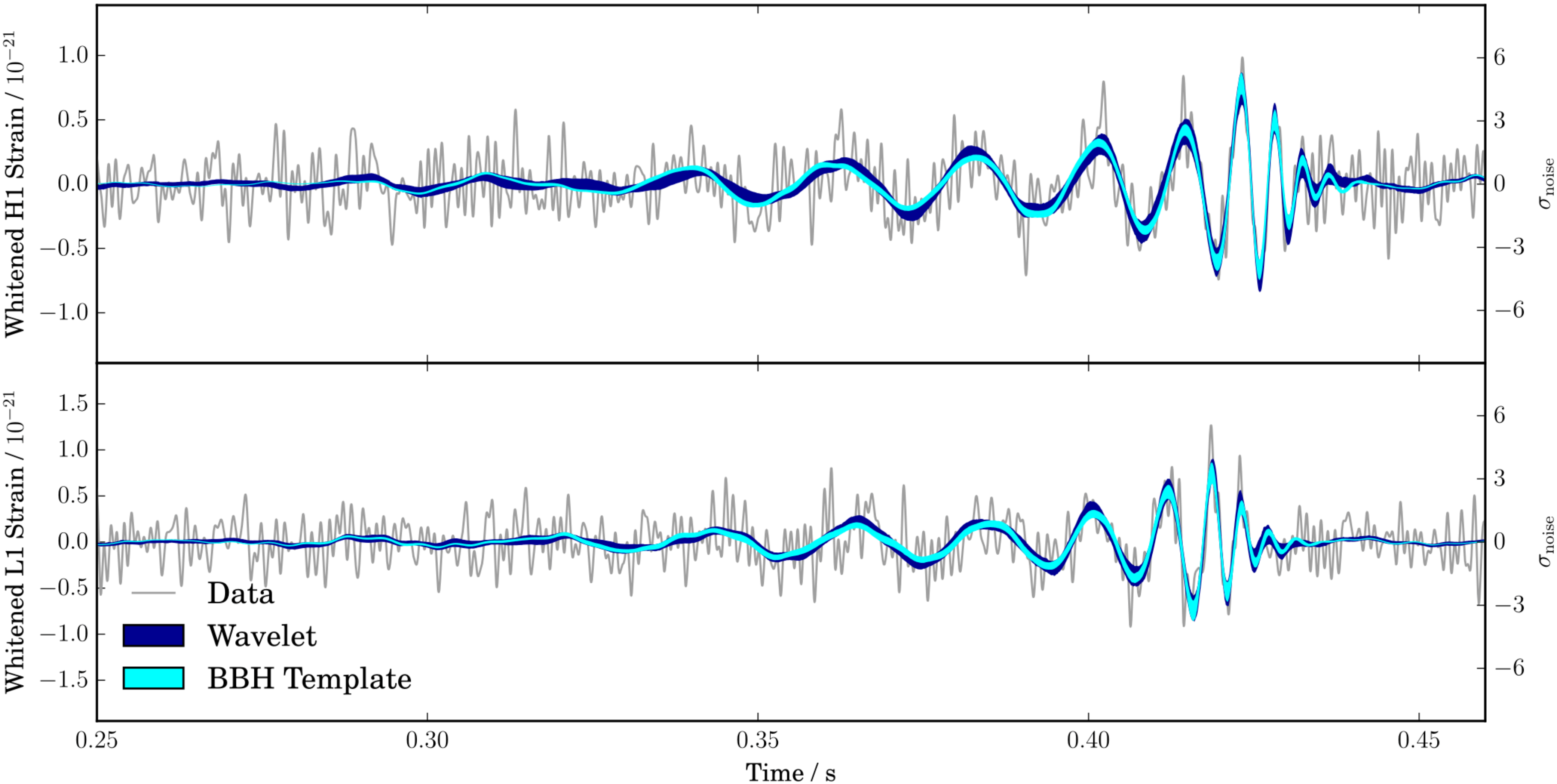
Precession un-constrained

Source parameters estimation: Bayesian inference



90% contour: 590 deg^2
50% contour: 140 deg^2

Source parameters estimation: Bayesian inference



EOBNR / IMRPhenom waveforms

Source parameters (summary table)

	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_{\mathrm{s/n}}$	288.7 ± 0.2	290.1 ± 0.2	—

Source parameters (summary table)

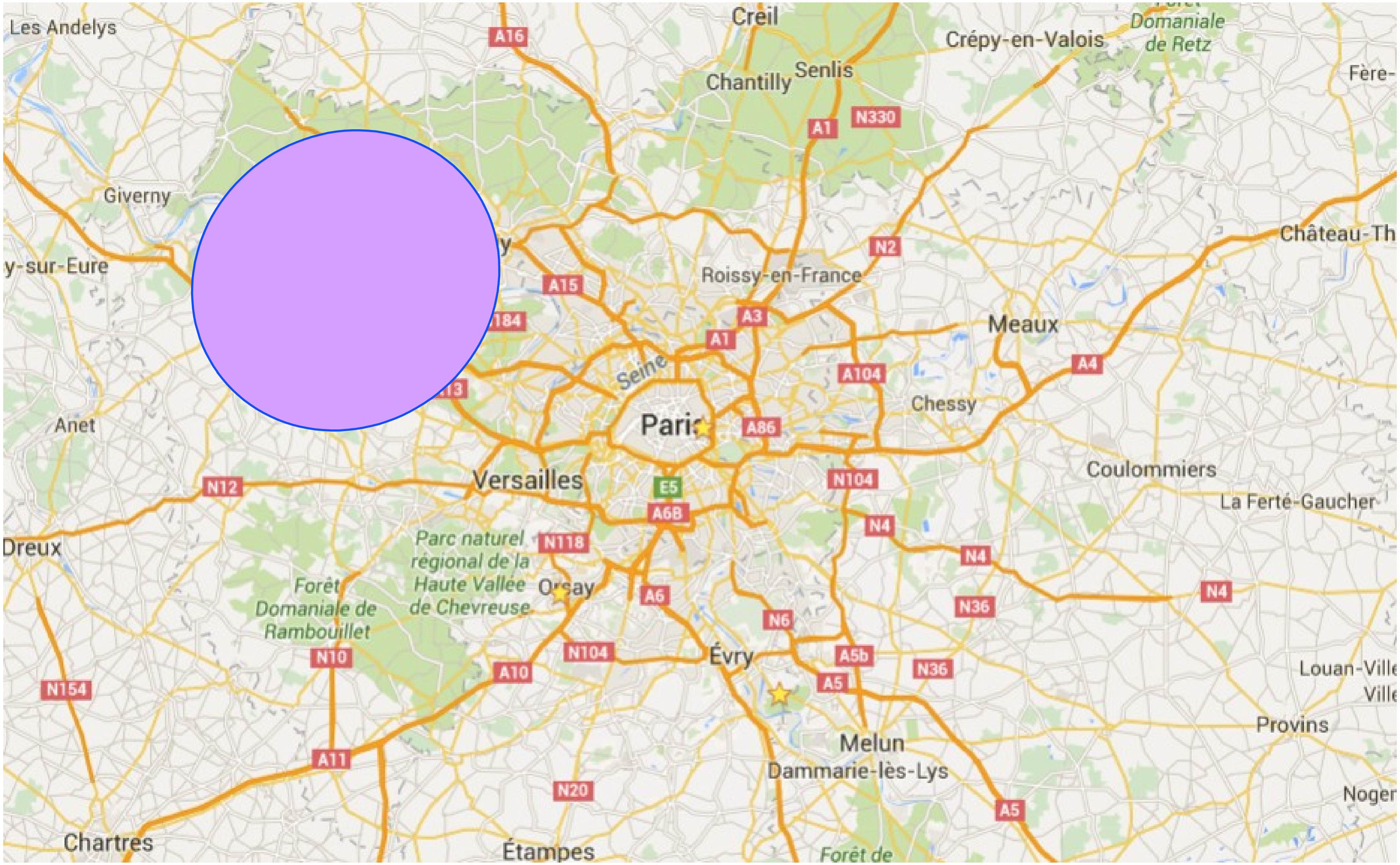
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 190 to 590 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	$M_\odot$
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 $M_\odot$
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Highest luminosity ever observed !

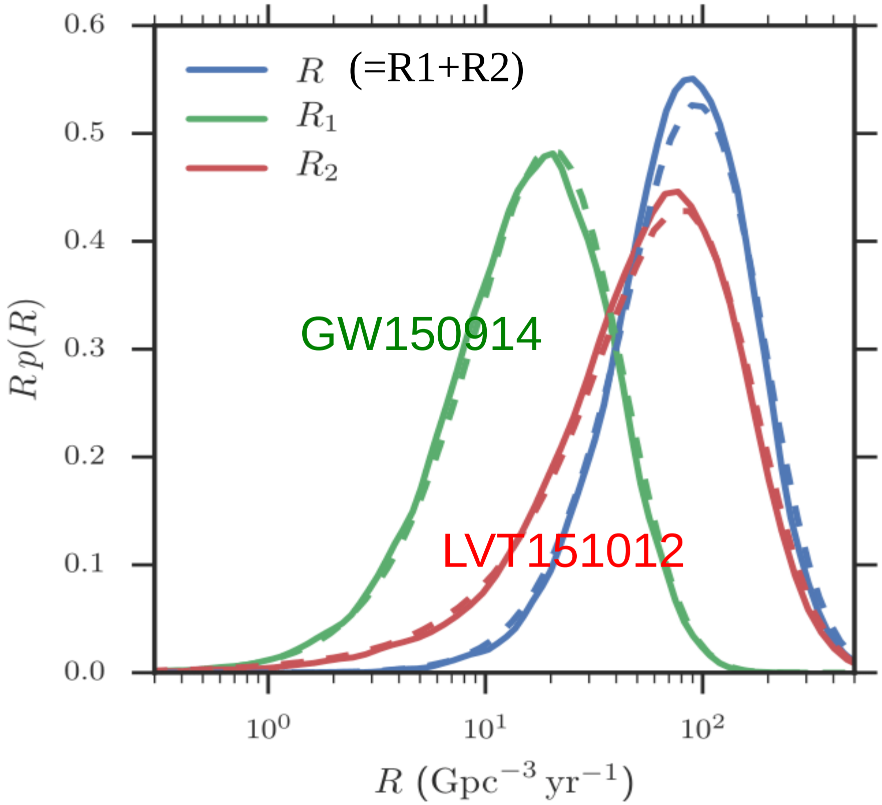
~3 Msun emitted during the merger

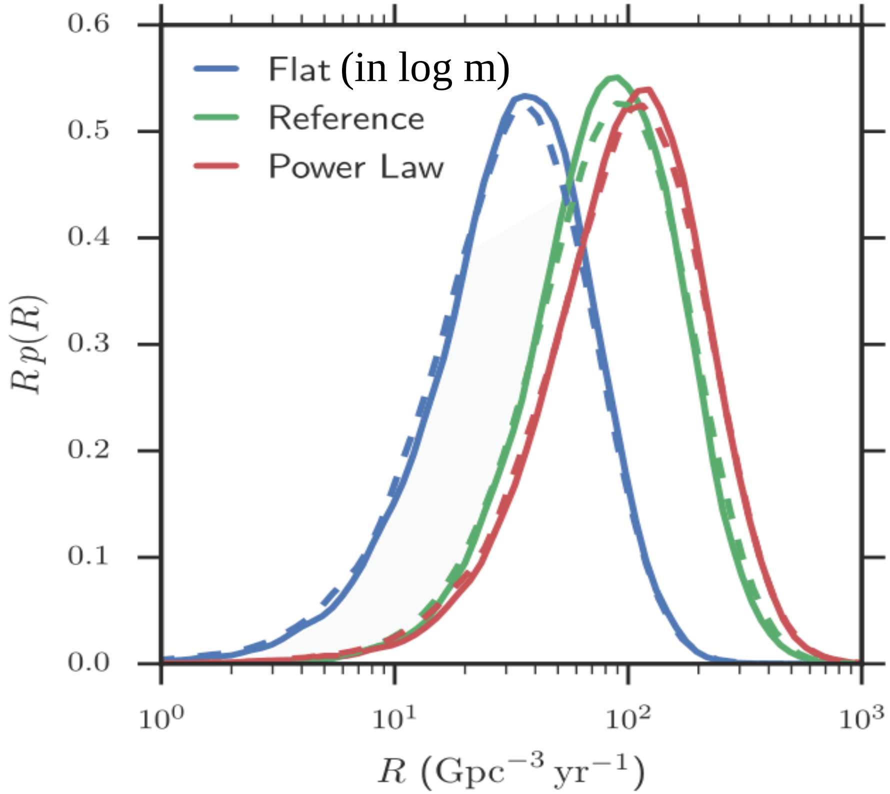
Scales comparison: 62 Msun Kerr BH horizon



BBH merger rate

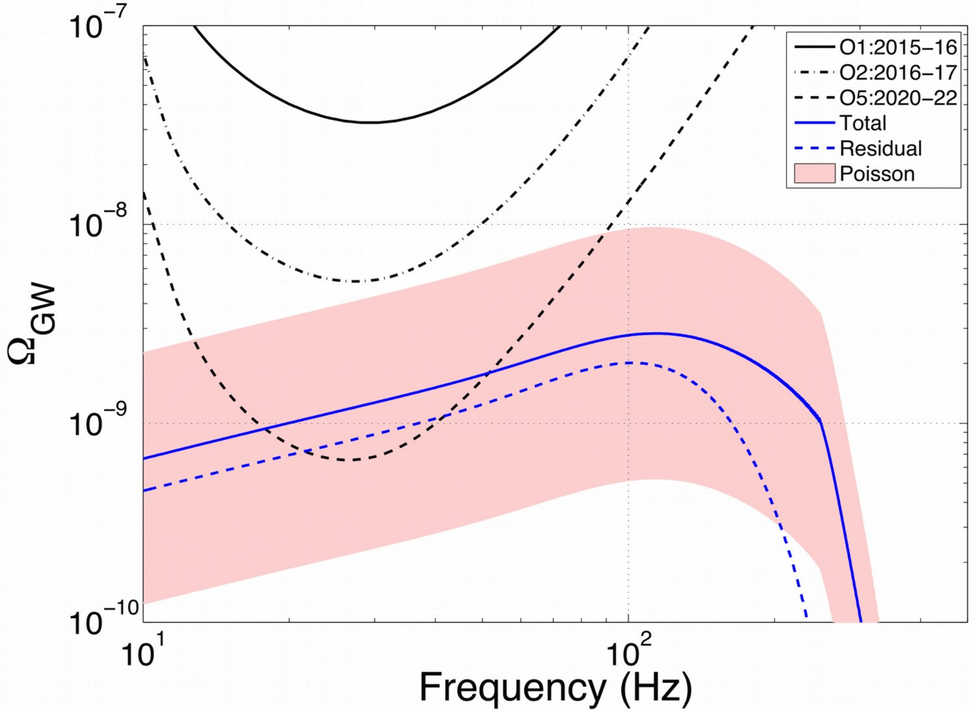
- Assumed to be constant within current sensitive volume out to z~0.5
- For GW150914-like BBH mergers: 2-53 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- But, there are a few other triggers (<2 σ) : 6-400 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$



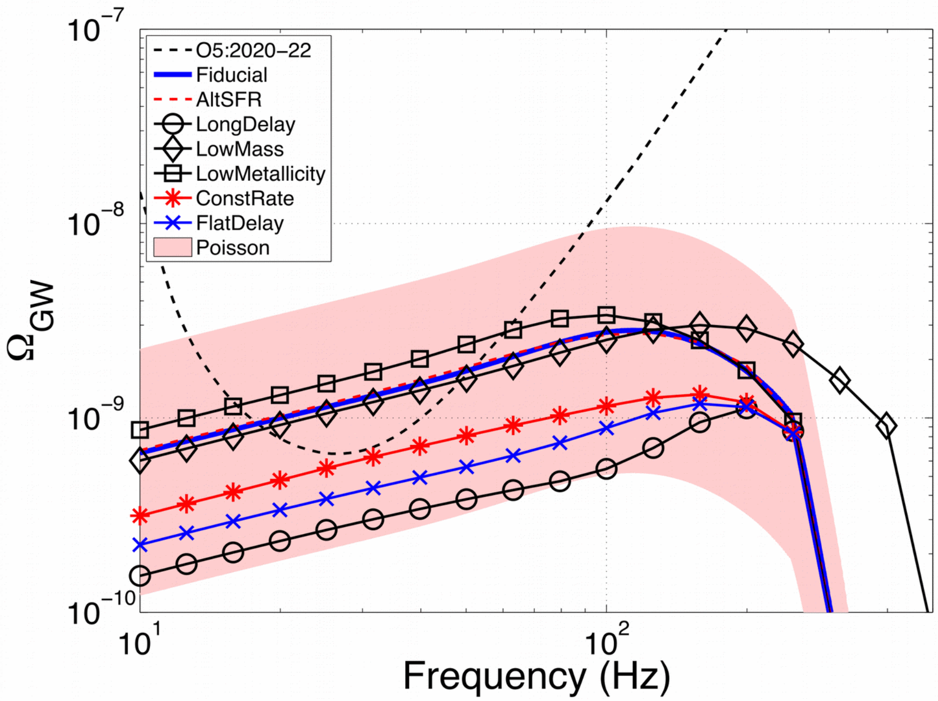


Stochastic background from BBH mergers

Assuming a BBH merger rate of 6-400 Gpc^{-3} yr^{-1}

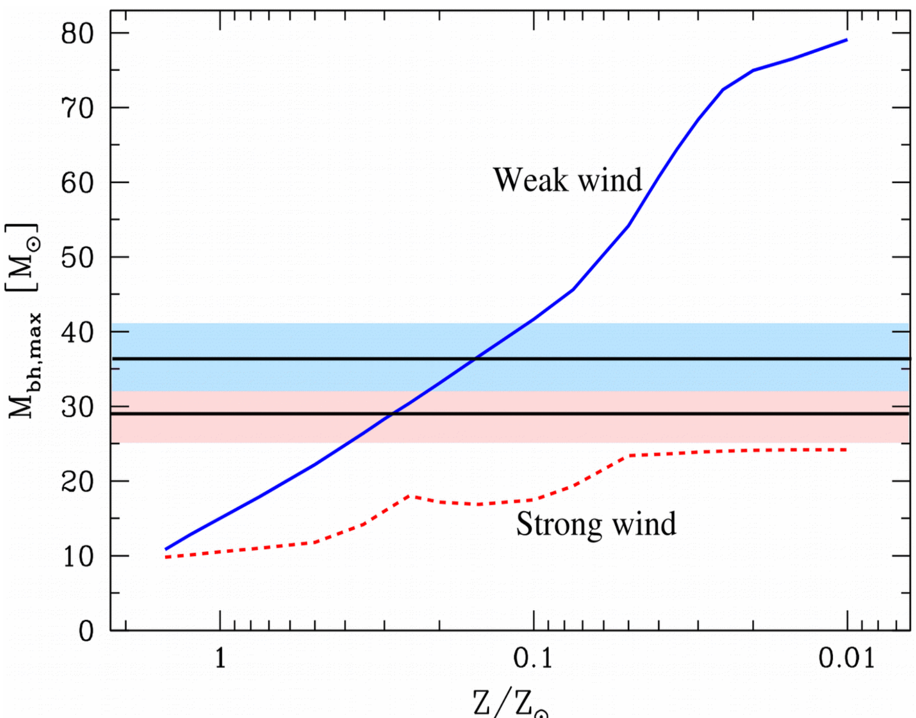


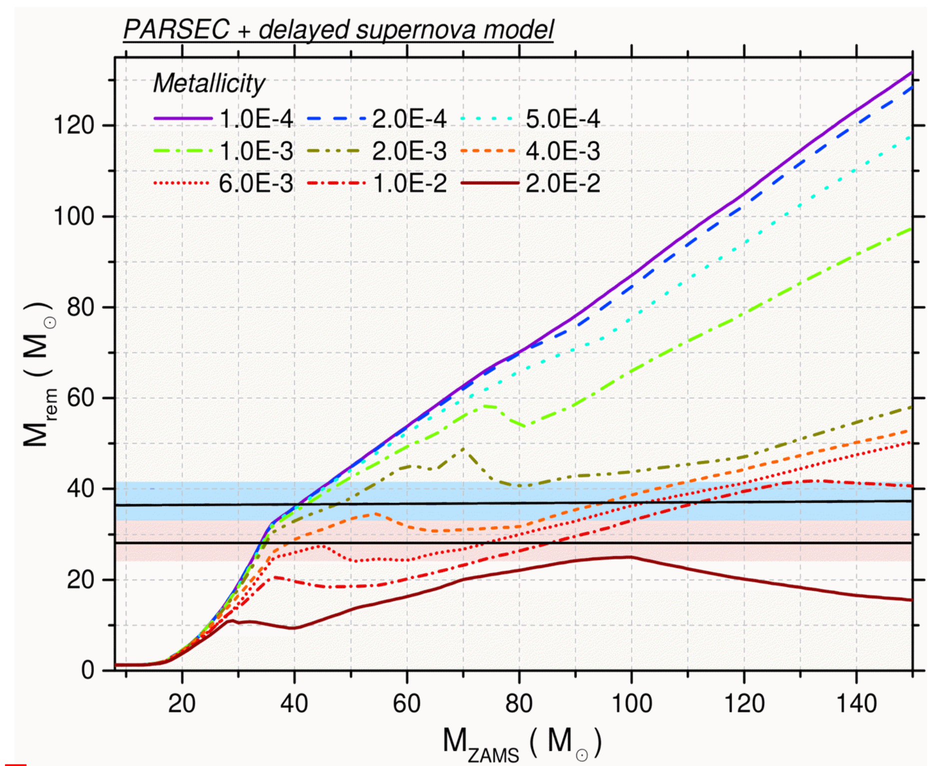
Alternative star formation models dependence



Star formation astrophysics

- First BBH system ever observed & heaviest stellar mass black holes (>25 Msun).



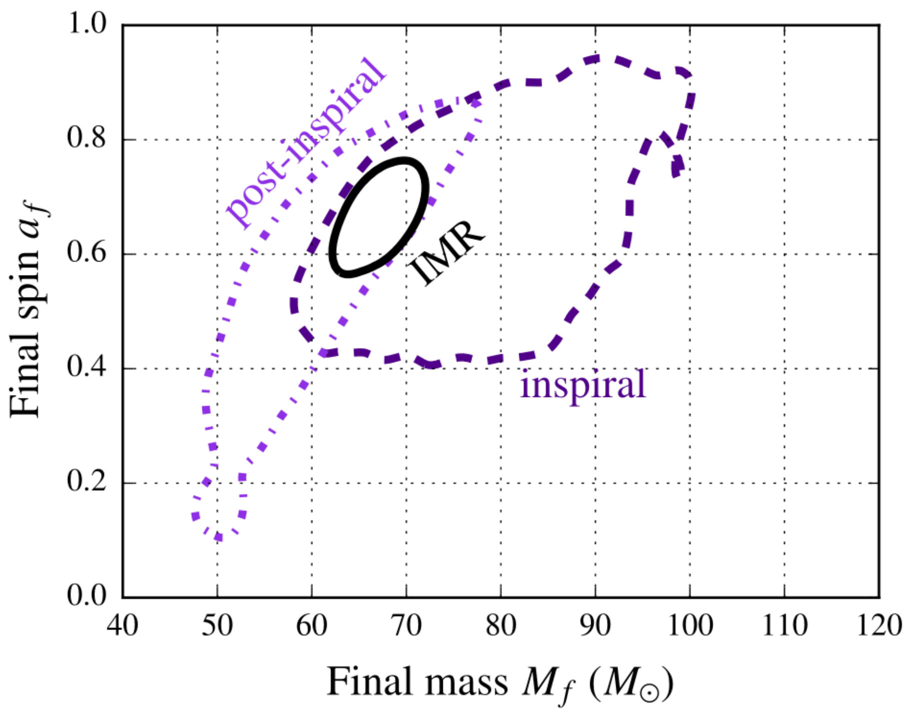


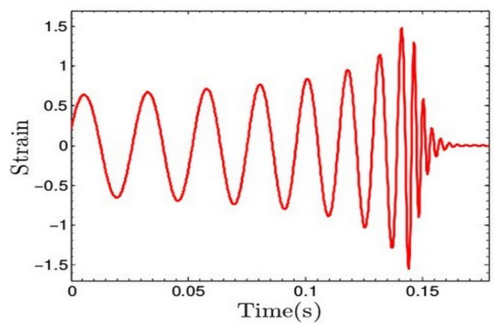
High mass stellar BH → low metalicity Z < ½ Zsun
→ weak massive-star winds

- BBH formation: isolated binaries (low-Z to popIII) vs capture in dense clusters (globular clusters, galactic centers, …): no way to discriminate between the 2 scenarios with GW150914.

Testing GR in strong field regime

- Solar-system experiments, binary pulsar & cosmological tests: low velocity, quasi static, weak field, linear regime tests: all in agreement with GR ...
- Tests with GW150914 (highly relativistic & highly non linear)
  - Data subtracted from the maximum a posteriori waveform (EOBNR). Search for a residual signal using a burst pipeline : results compatible with Gaussian noise--> if deviations to GR exist, they are smaller than 4%
  - Inspiral-merger-ringdown consistency test

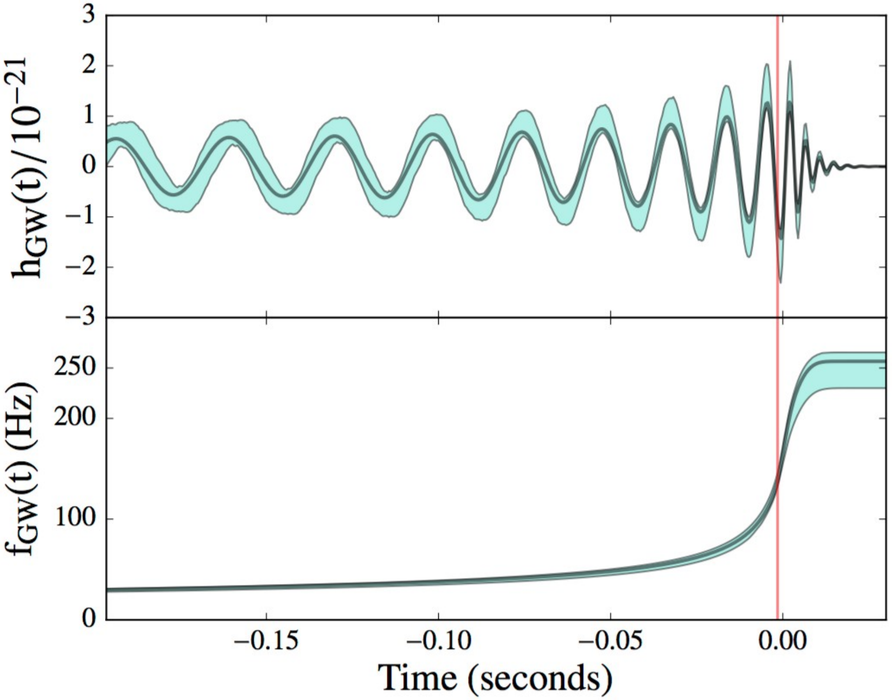


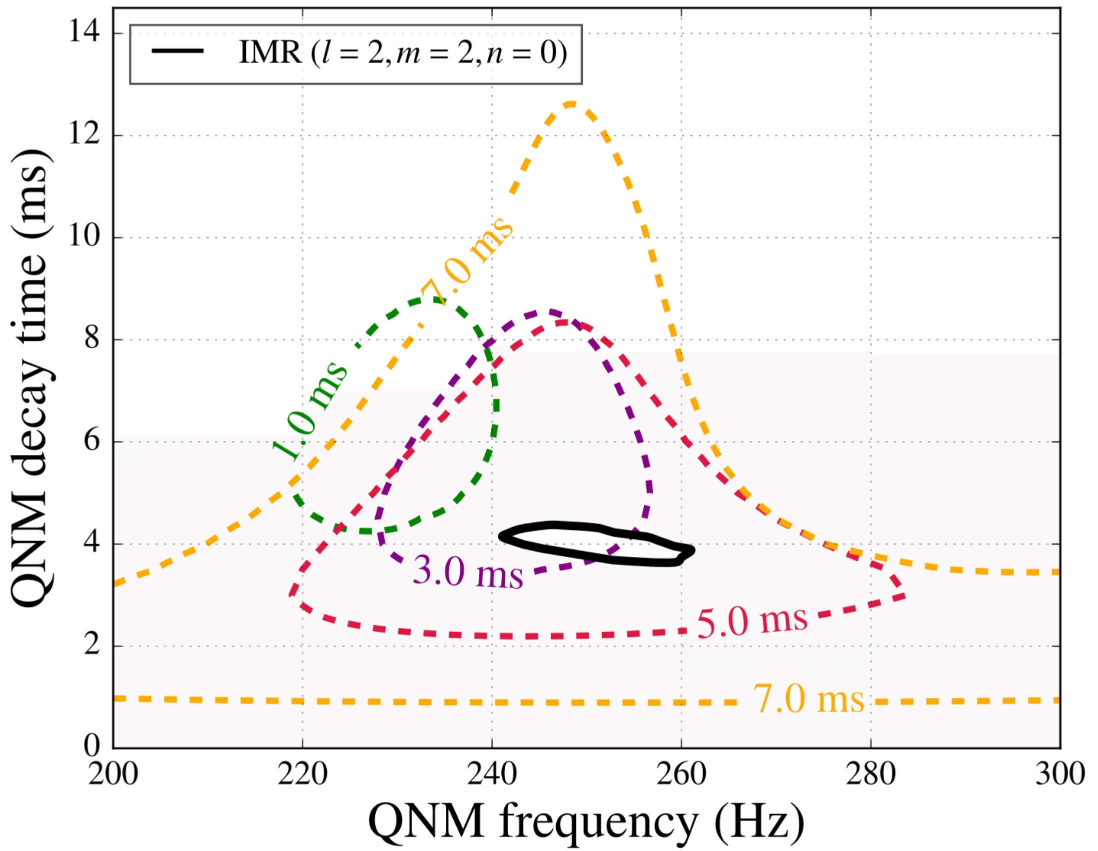


EOBNR-IHES waveform: m1=36Msun, m2=29Msun, nonspinning black holes

Testing the QNM of the final BH

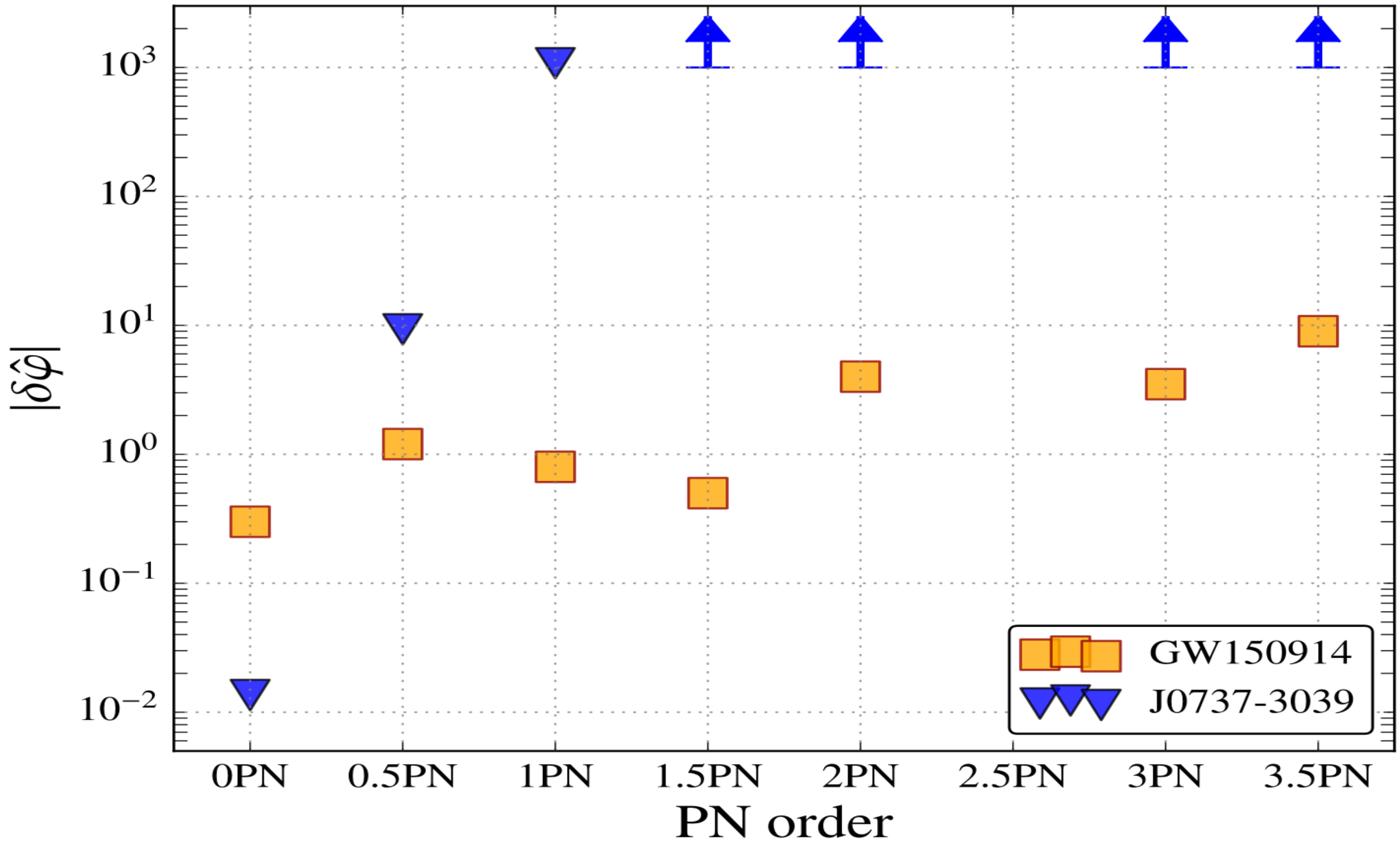
- From the IMR parameter estimation, the l=2,m=2,n=0 f^{QNM} = 251 Hz & τ=4 ms @90% CL.
- Bayesian test with $h(t) = Ae^{-t(t-t_0)/\tau} cos(2\pi f_0(t-t_0)+\phi_0)$



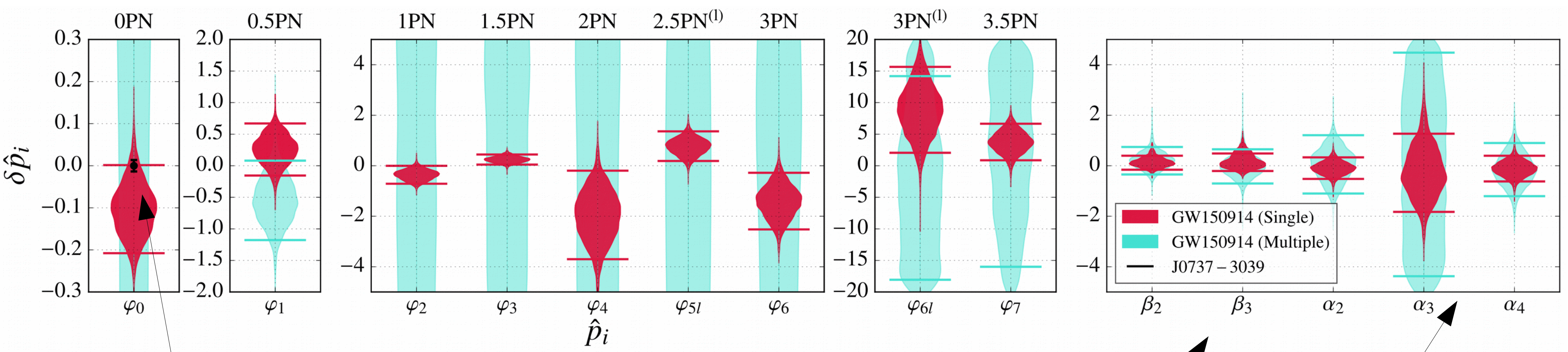


Constraining parametrization deviations from IMR waveforms

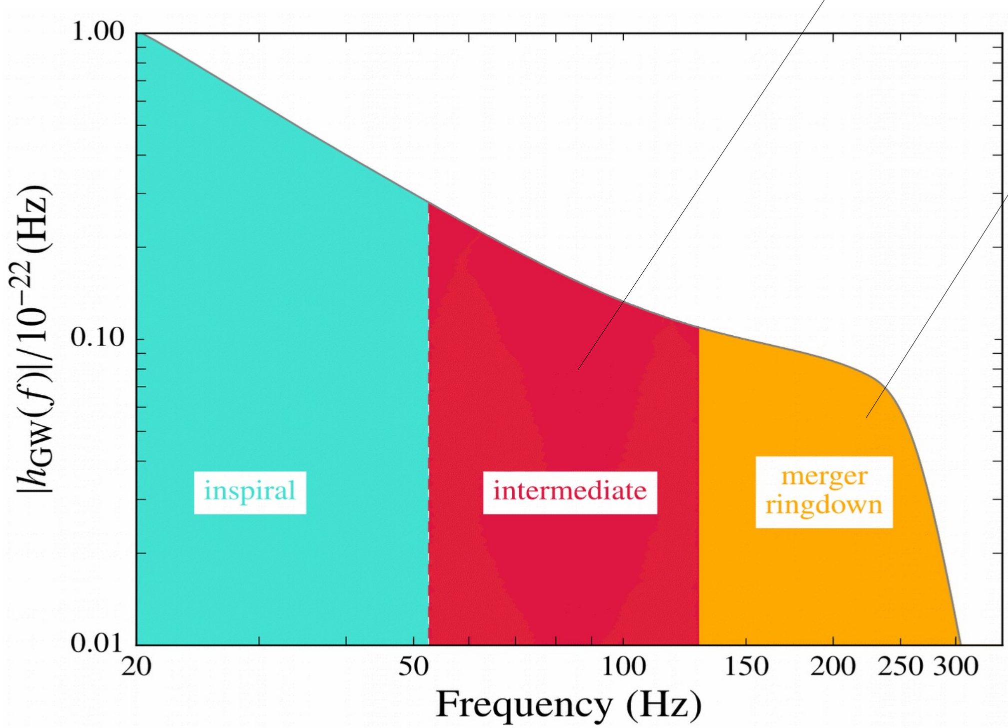
- Testing non linear deviation to GR (tails of radiation back-scattering in curved background, tails of tails, spin-orbit, spin-spin couplings, …)
- Constrain deviation of all parameters that describe the waveform phase evolution at all PN orders.



Constraining parametrization deviations from IMR waveforms

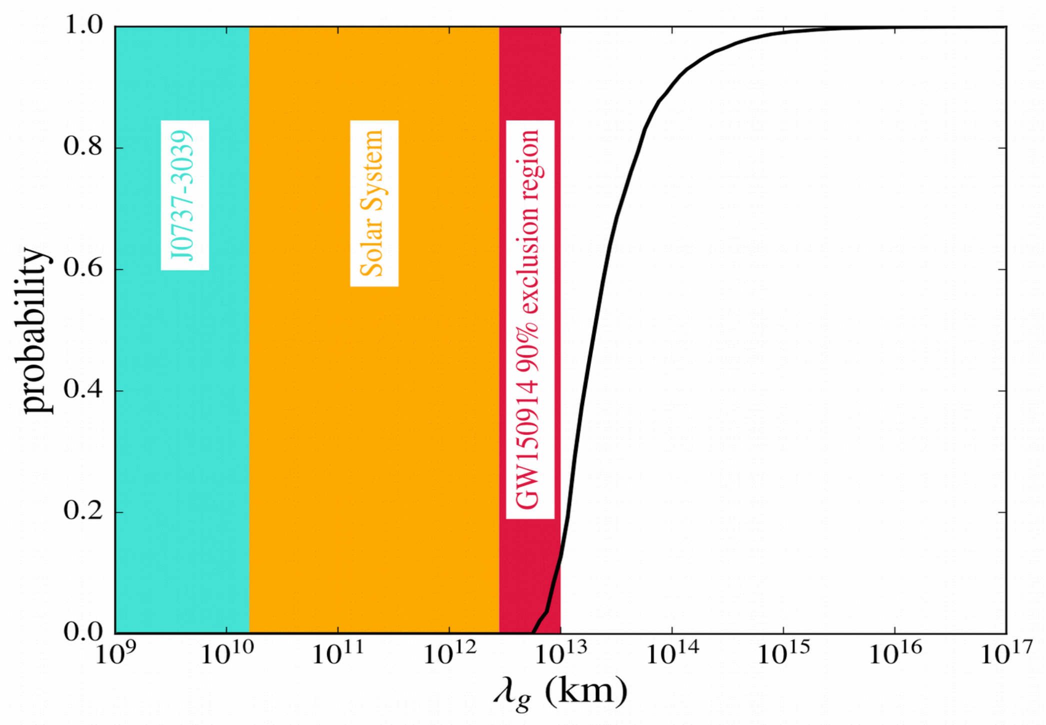


J0737-3039



Constraining the graviton Compton wavelength

- Hypothetical massive graviton theory: Yukawa type correction in the Newtonian potential.
- Massive graviton propagates at speed that depends on the frequency/energy (dispersion: lower frequencies propagate slower than high frequencies → phase distortion at 1PN order).



$$\frac{v_g^2}{c^2} = 1 - \frac{h^2 c^2}{\lambda_g^2 E^2}$$

$$\lambda_g = \frac{h}{m_g c}$$

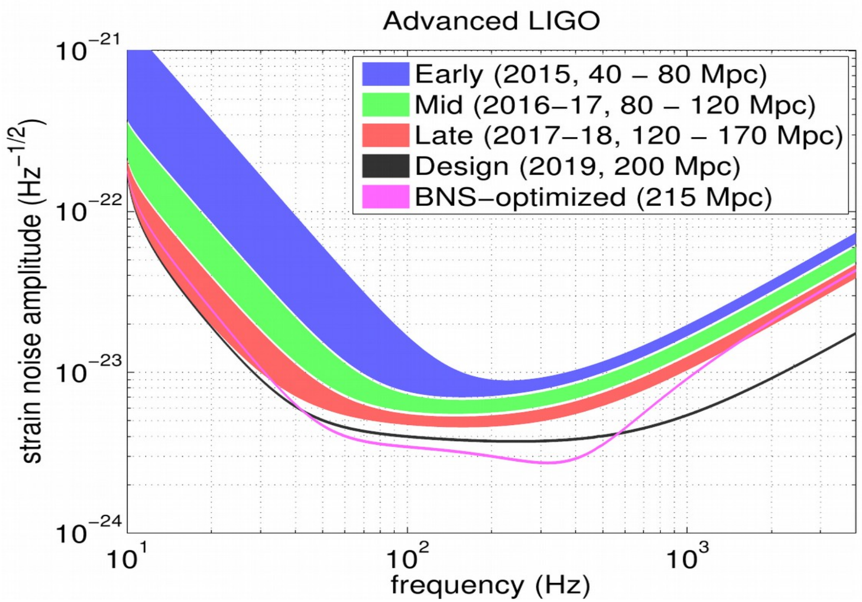
$$\lambda_g > 10^{13} km$$

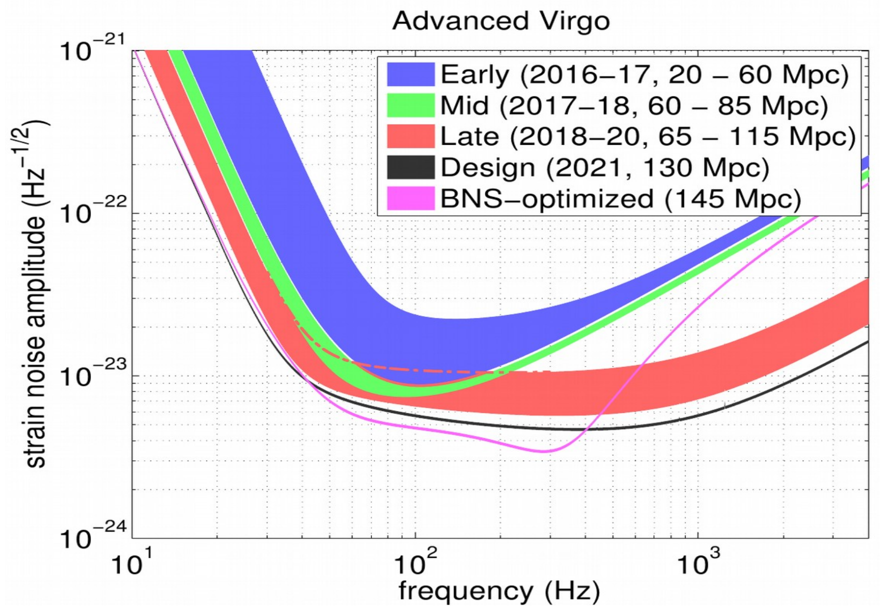
$$m_g < 10^{-22} eV$$

(3 orders of magnitude better than binary pulsar tests)

And Virgo?

- Virgo is contributing to the analysis of the LIGO/Virgo data since 2007.
- Advanced Virgo installation should finish in the coming months:
  - ~ 1 year of commissioning is foreseen,
  - will join LIGO for science runs in 2017.
- 3 detectors: mandatory to
  - better localize sources (~X00 deg^2 → ~X0 deg^2),
  - constrain polarization prediction of GR.





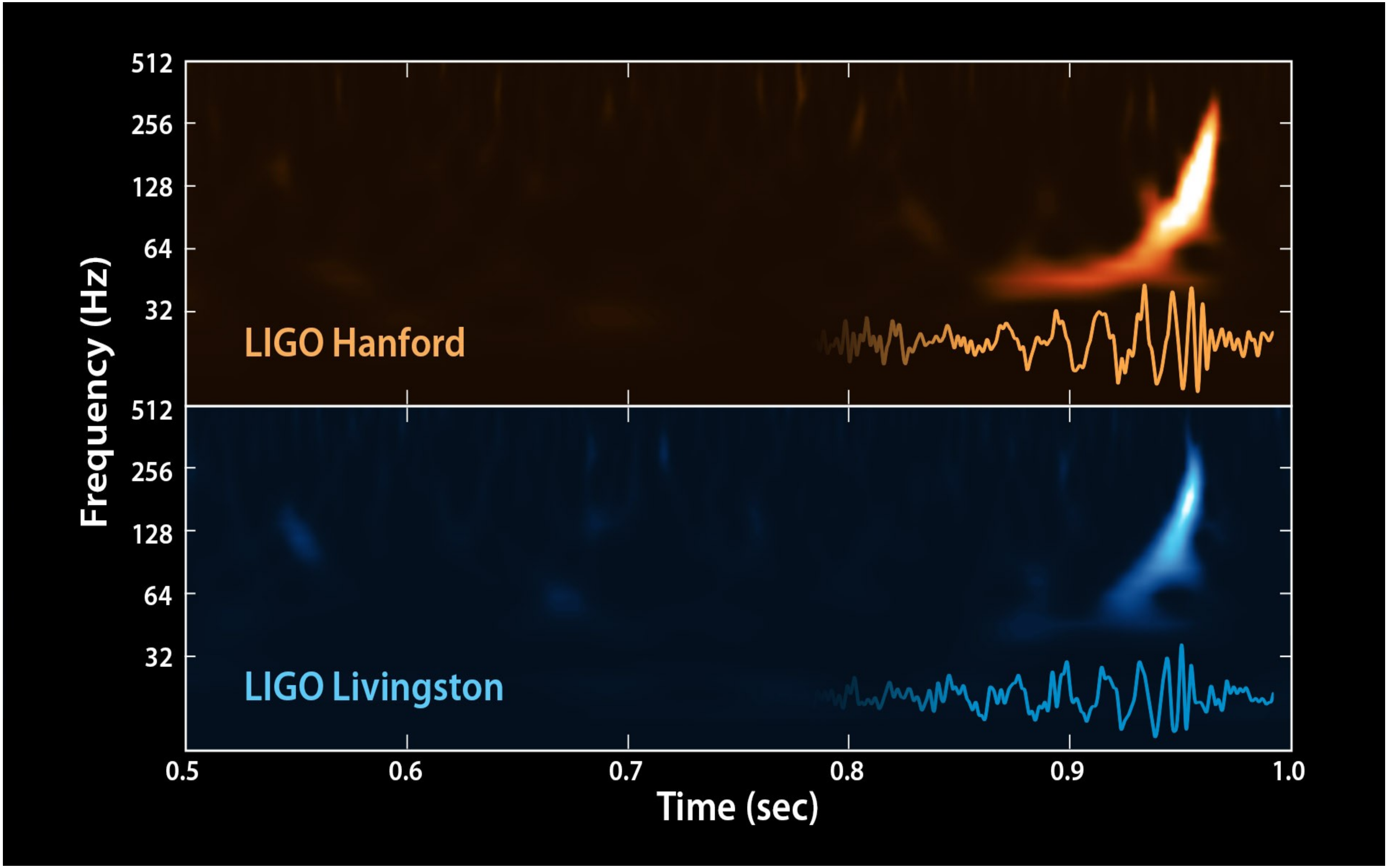
Why this is a fundamental discovery?

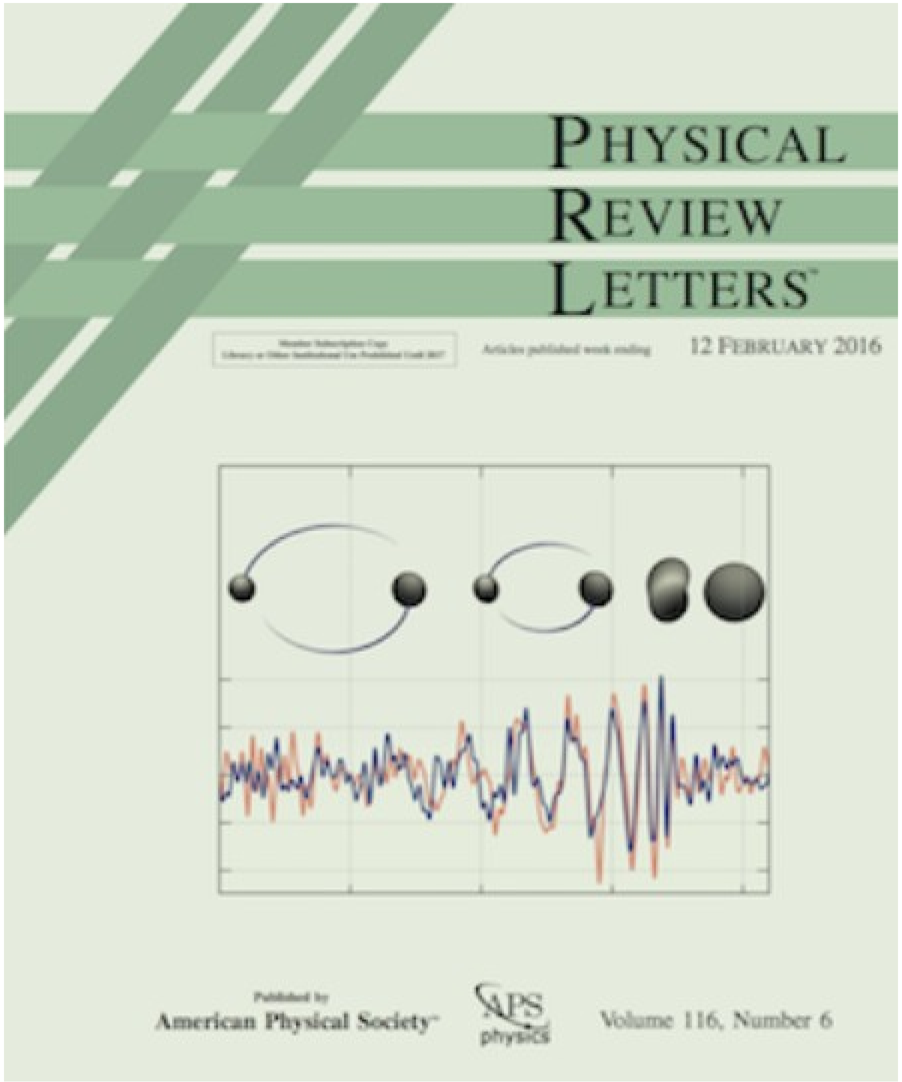
- First direct detection of GW emitted from an astrophysical source.
- First evidence that stellar mass BH with M>15 Msun exist.
- First observation of a BBH system.
- First discovery of a binary black hole merger (within the Hubble time).

What can we learn from this event?

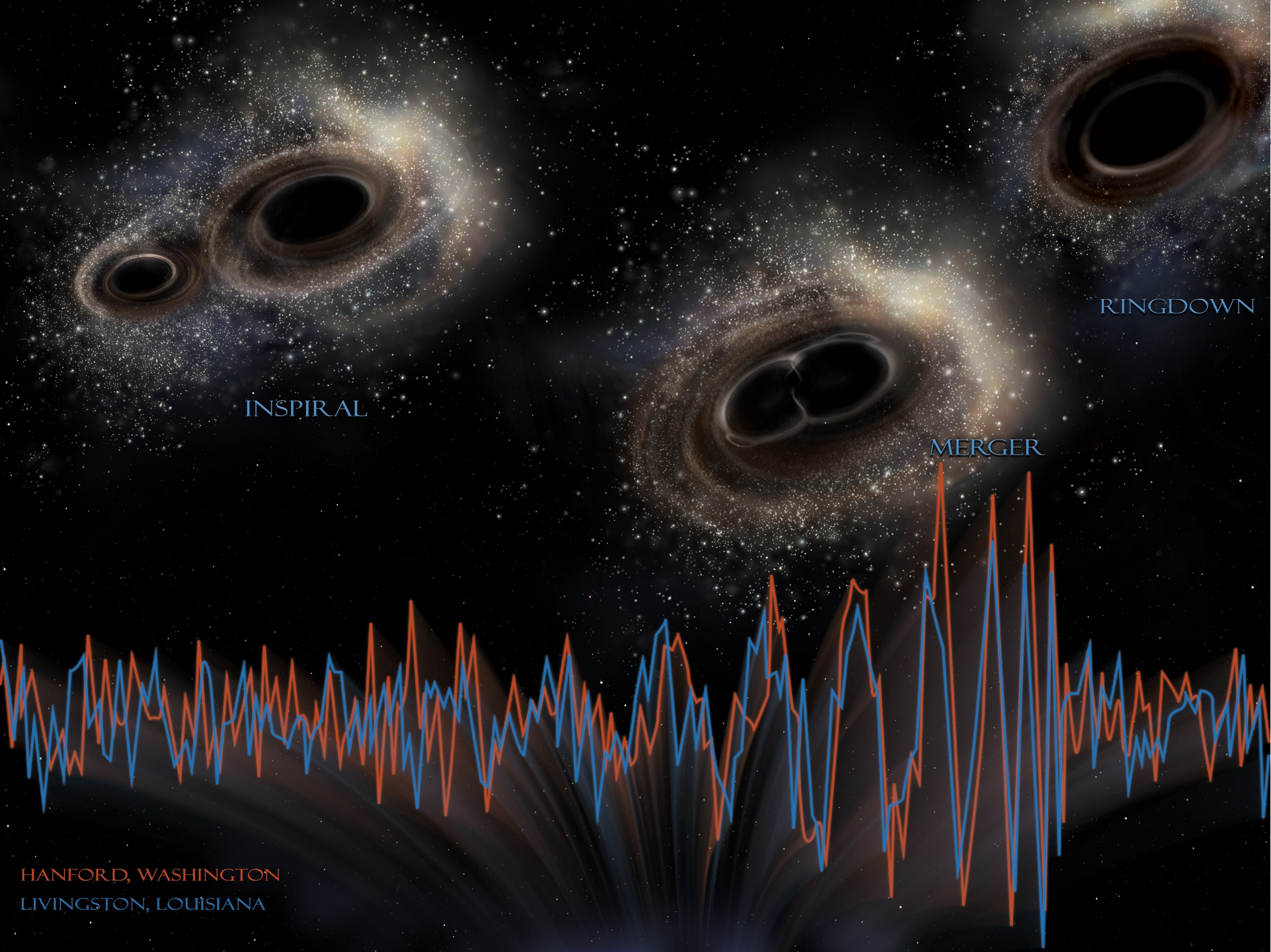
- BBH formation mechanism (low metallicity / weak winds).
- Constrain deviation to general relativity in the strong field regime.
- BBH rates measurement.
- ….

Five centuries after the telescope invention, LIGO/Virgo have opened a new way to do astronomy and probe the Universe ...

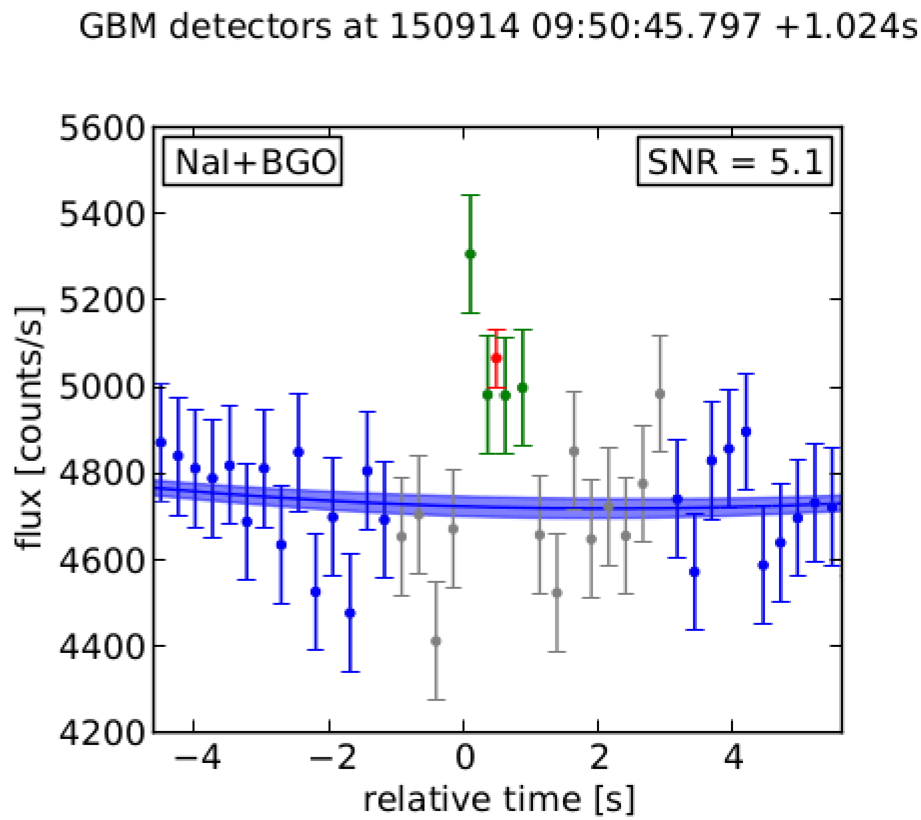

Frequency (Hz)
512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



+12 other LVC papers
Posted on arXiv


INSPIRAL
MERGER
RINGDOWN
HANFORD, WASHINGTON
LIVINGSTON, LOUISIANA

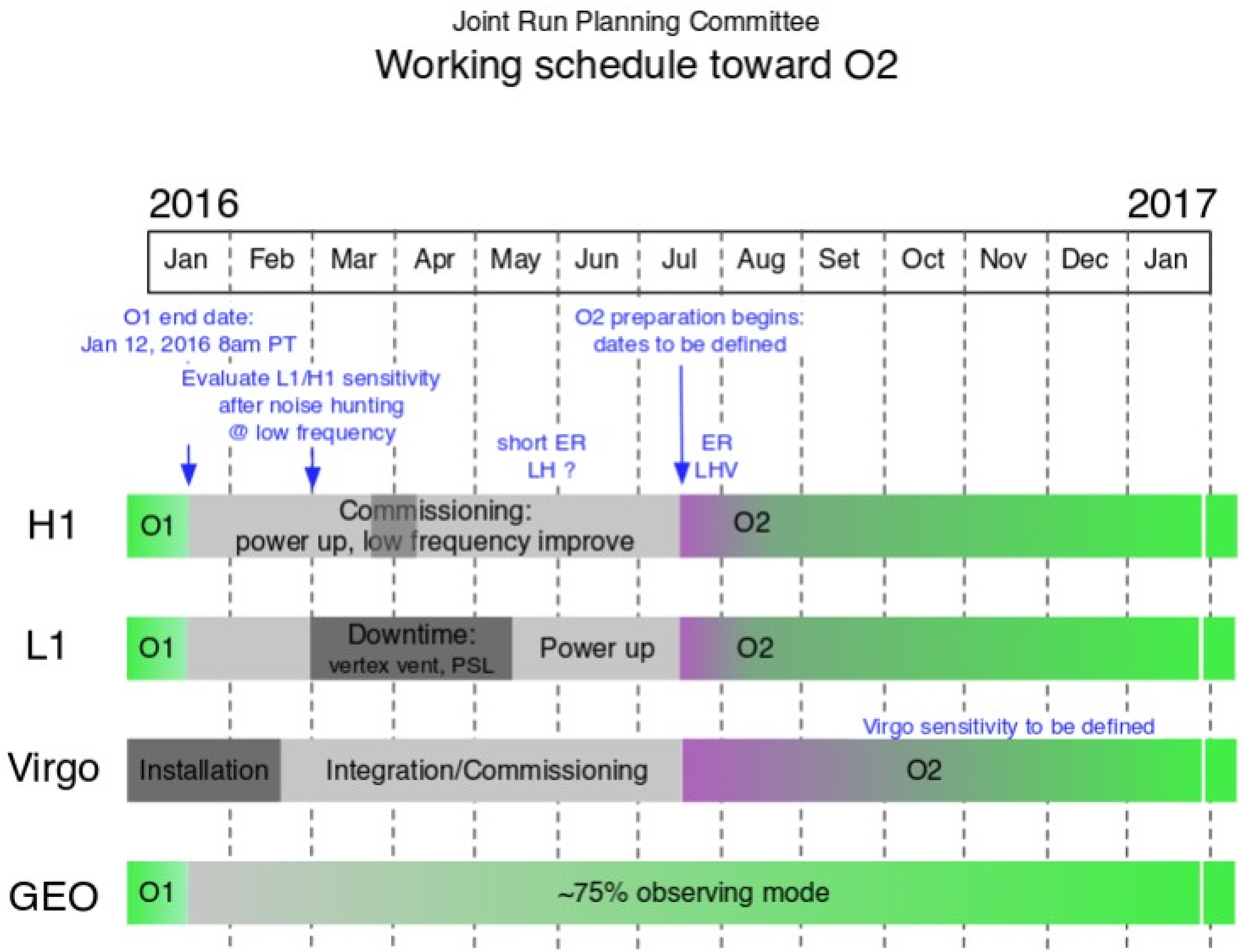
Fermi-GBM faint signal 0.4s after GW150914



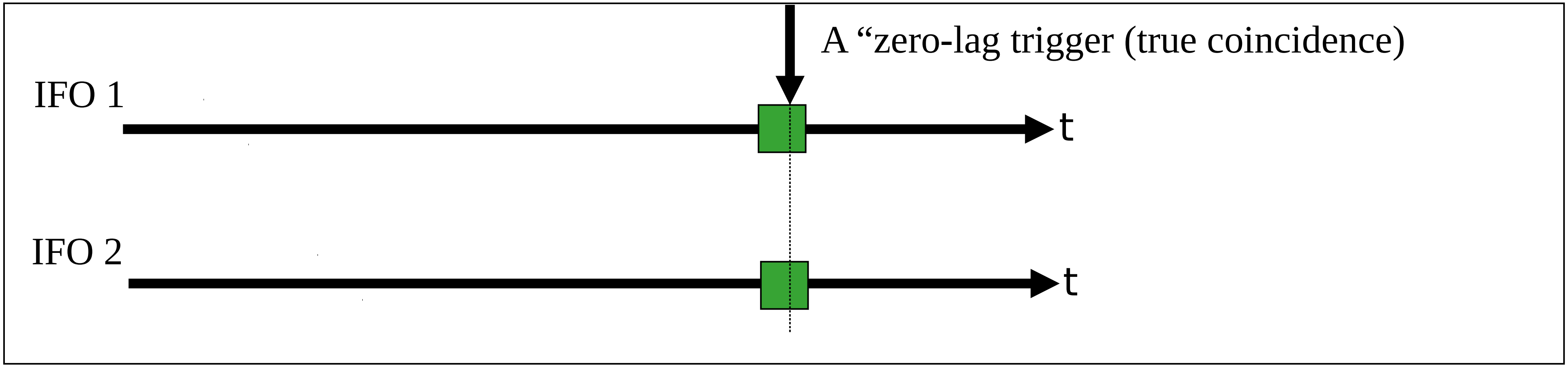
FAP : 0.0022

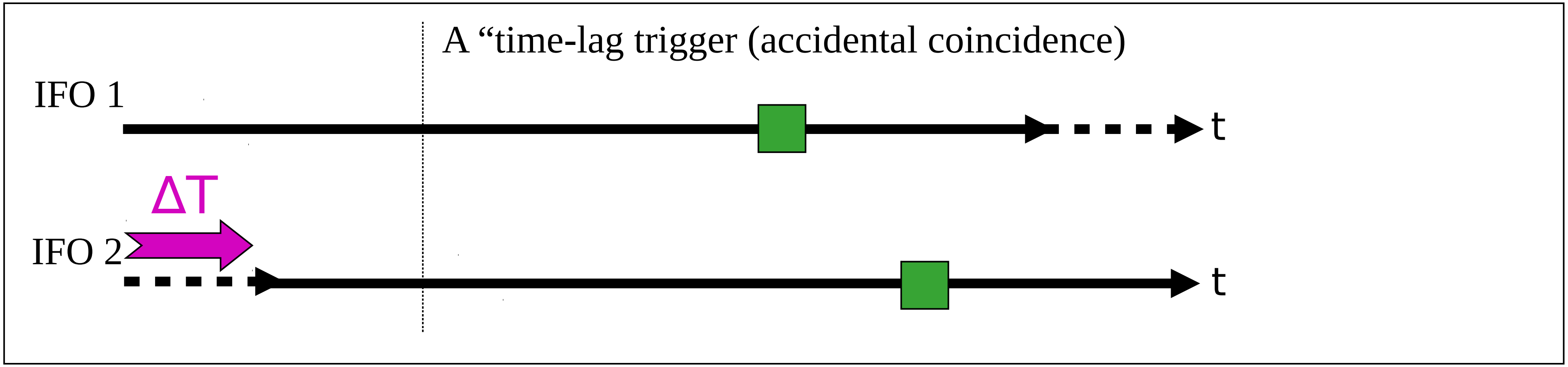
Fig. 2.— Count rates detected as a function of time relative to the start of GW150914-GBM, ~0.4 s after the GW event GW150914, weighted and summed to maximize signal-to-noise for a modeled source. CTIME time bins are 0.256 s wide. The blue data points are used in the background fit. The green points are the counts in the time period determined to be significant, the grey points are outside this time period, and the red points show the 1.024 s average over the green points. For a single spectrum and sky location, detector counts for each energy channel are weighted according to the modeled rate and inverse noise variance due to background. The weighted counts from all NaI and BGO detectors are then summed to obtain a signal-to-noise optimized light curve for that model. Each model is also assigned a likelihood by the targeted search based on the foreground counts (in the region of time spanned by the green points), and this is used to marginalize the light

Toward next scientific run : O2

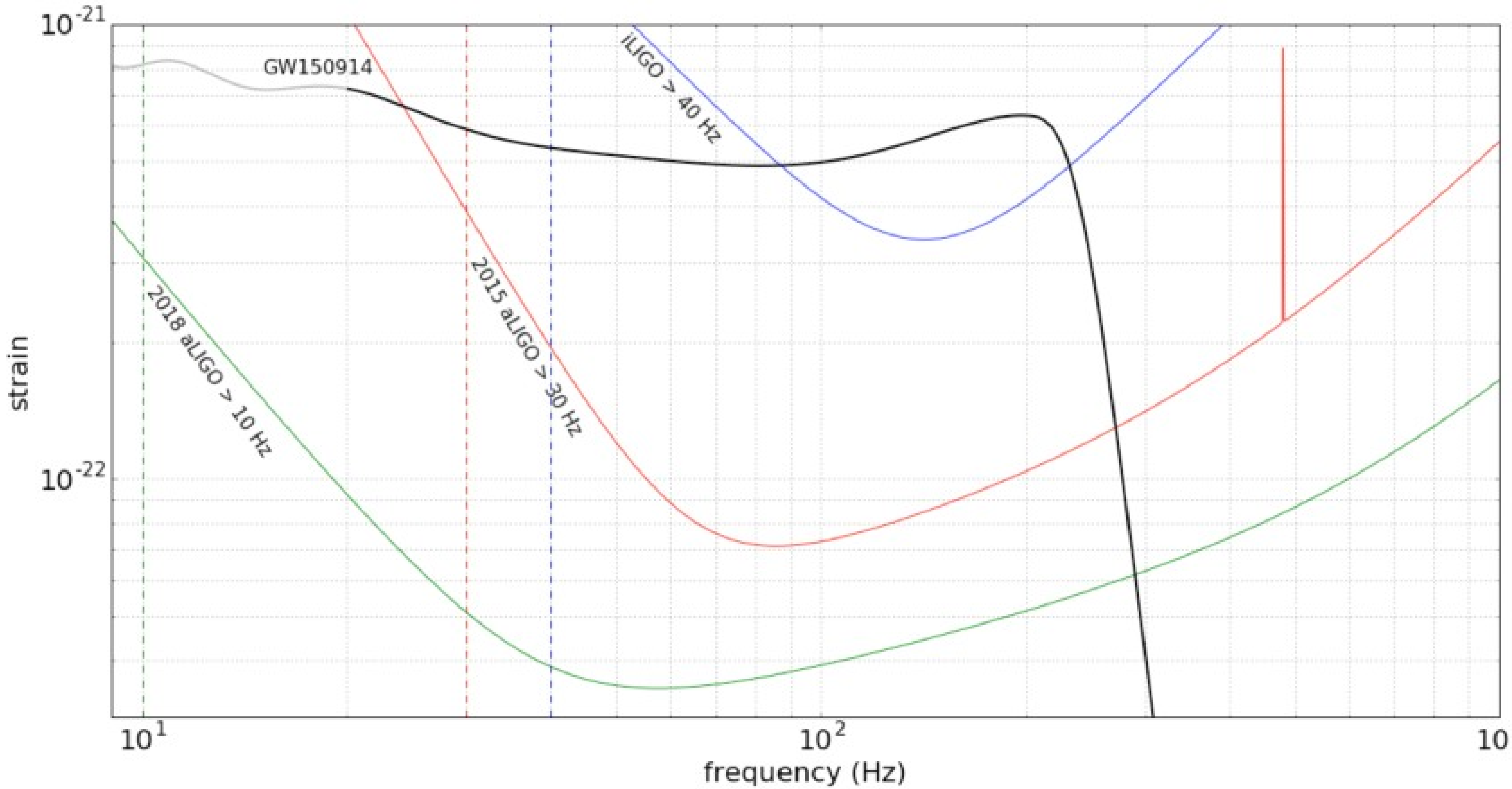


Background estimation





Chris Pankow



Source parameters estimation: Bayesian inference