LIGO-Virgo observational results with the O1 run & O2 run status



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On behalf of the LIGO Scientific Collaboration & the Virgo Collaboration

Outline

Introduction

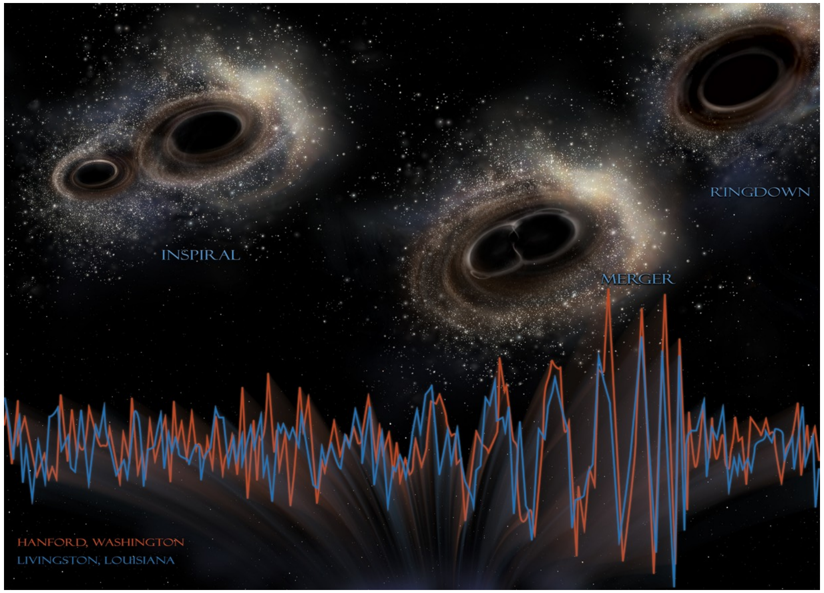
O1 results

- Binary black holes discovery
- Other transient searches
- Stochastic background searches

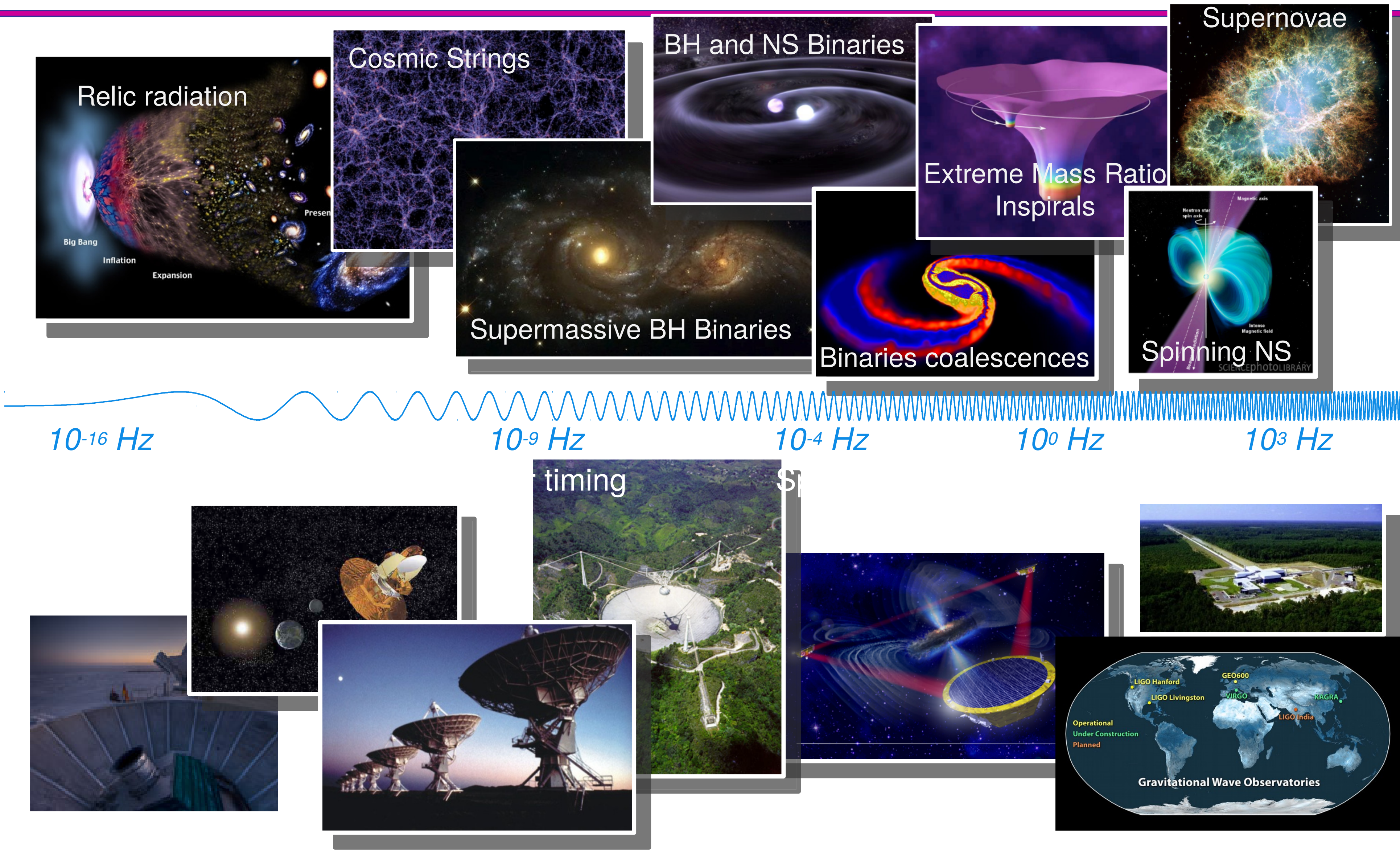
O2 run : now !

O3 preparation

- LIGO detectors readiness
- Virgo detector status



The gravitational wave spectrum

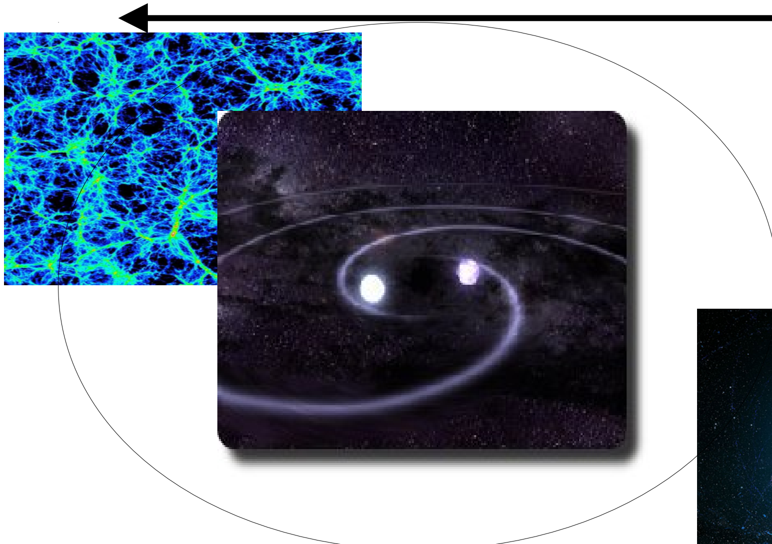


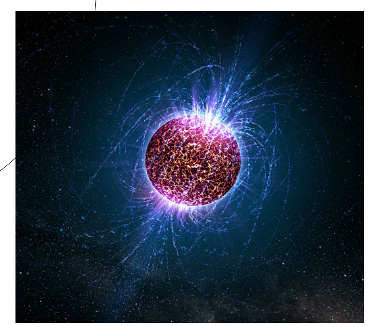
LIGO-Virgo GW searches zoology

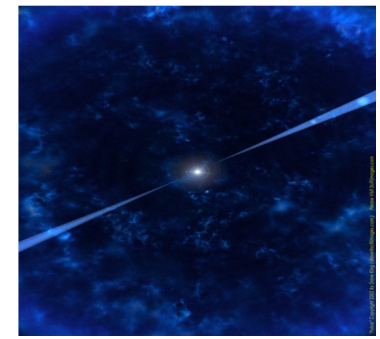
Short duration (~1s)

Long duration (∞)

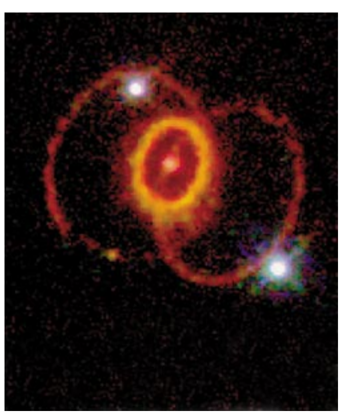
Waveform known





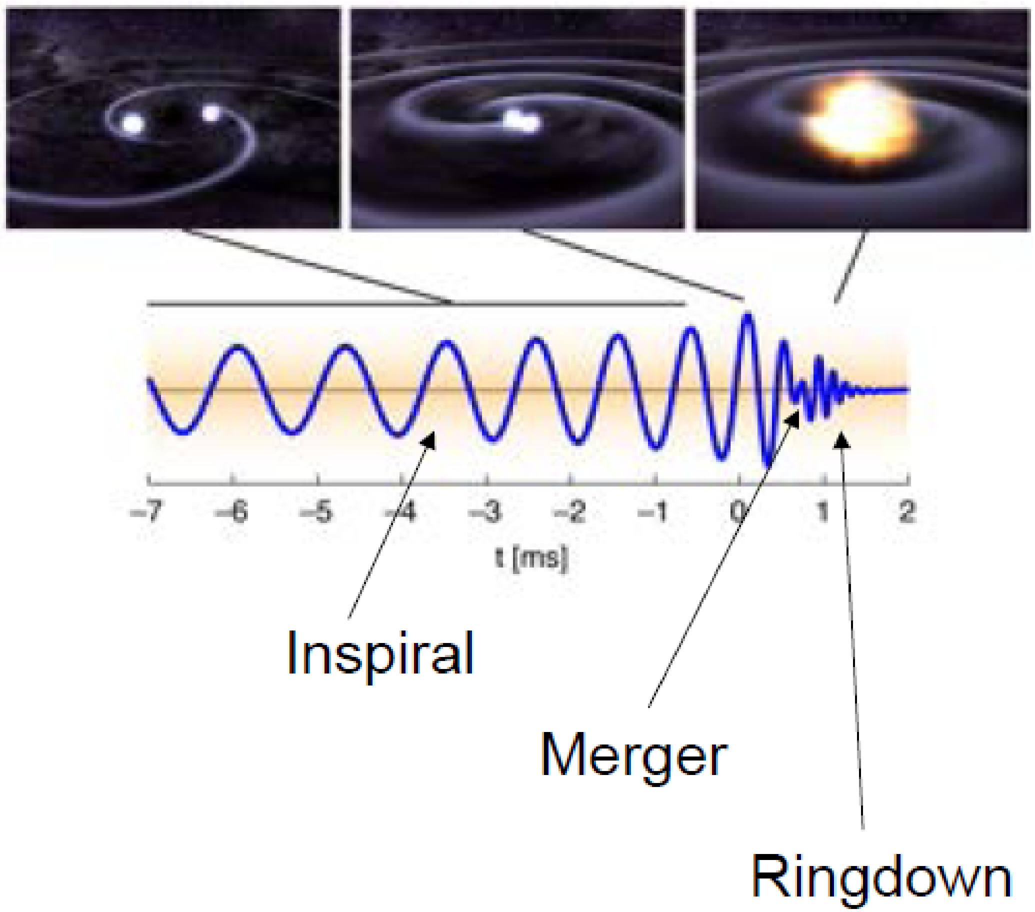


Waveform unknown



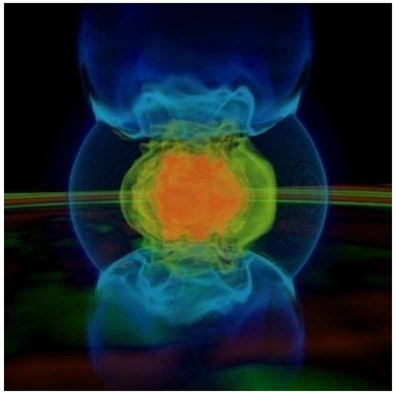
Compact Binary Coalescence

- Compact binary objects:
  - » Two neutron stars and/or black holes.
- Inspiral toward each other.
  - » Emit gravitational waves as they inspiral.
- Amplitude and frequency of the waves increases over time, until the merger.
- Waveform well understood, matched template searches.



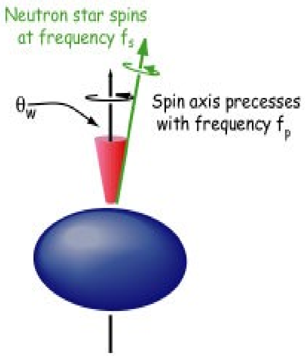
Other sources

- Transient
  - Stellar core collapse (probe the supernova mechanism)
  - Pulsar glitches
  - Magnetars
  - Cosmic string cusps

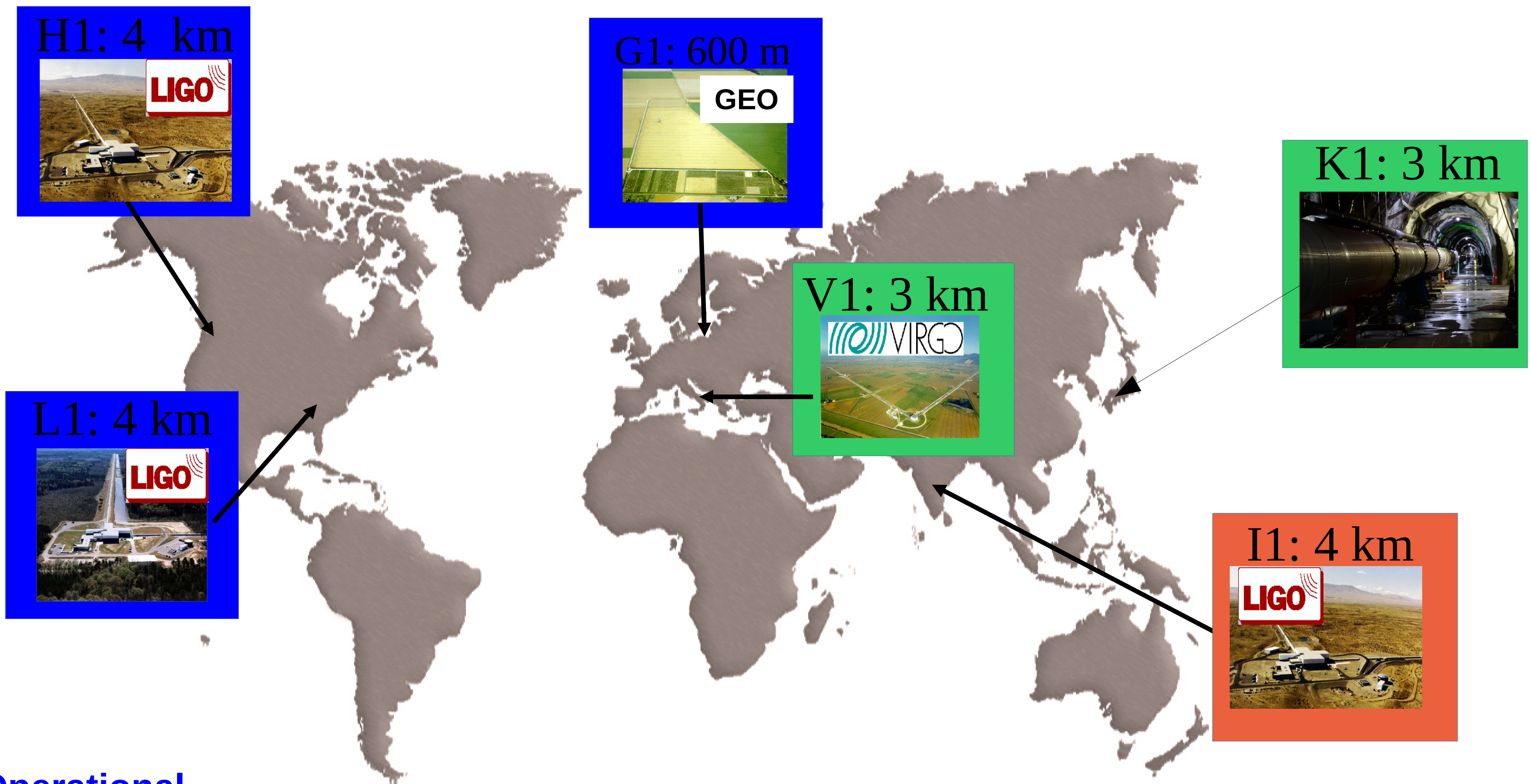


- Stochastic background
  - Cosmological (inflation reheating, phase transitions, cosmic strings, ...)
  - Astrophysical (compact binary coalescence, neutron star instablities, …)

- Periodic
  - Rotating neutron star with small mass non uniformity



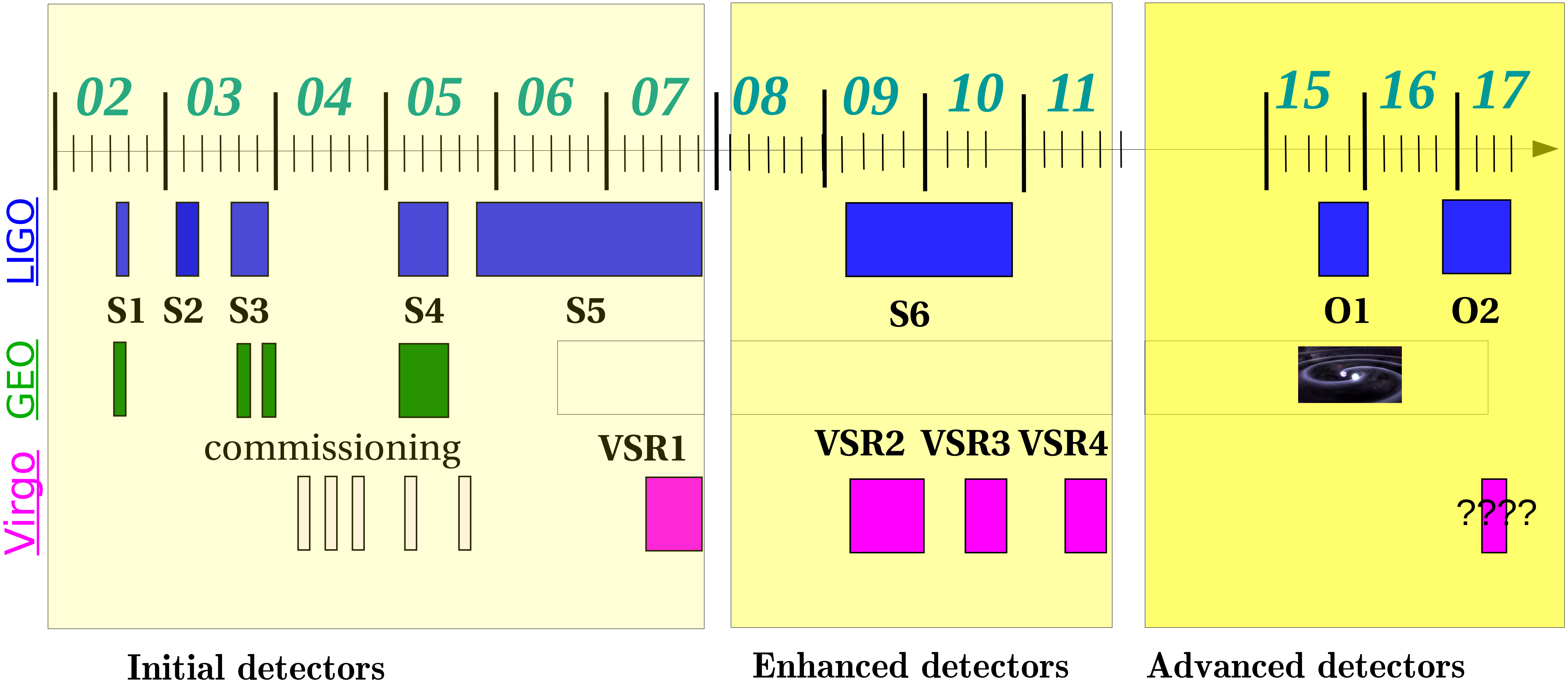
Network of ground based advanced detectors



Operational
Commissioning/construction
Planned

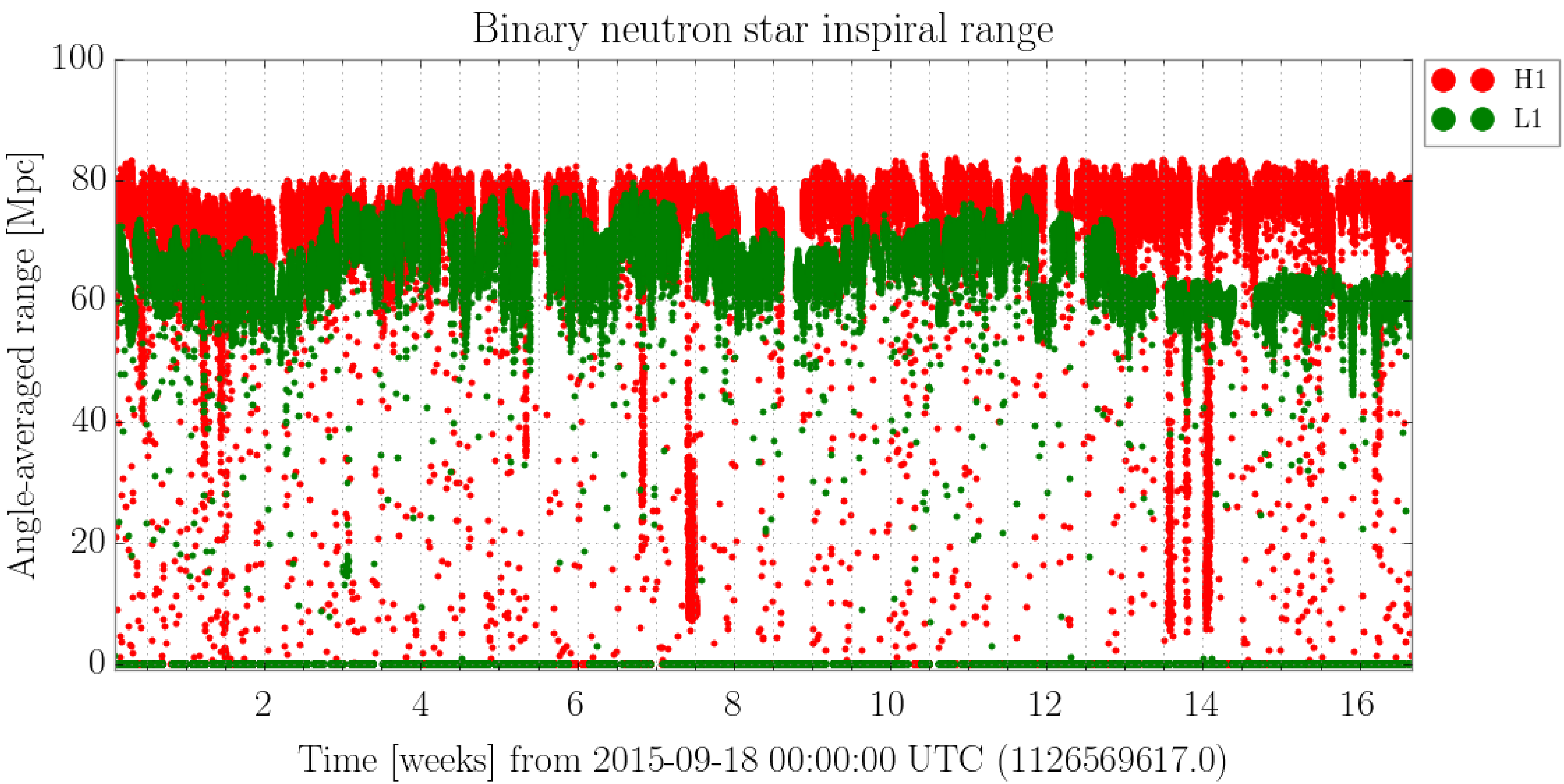
Since 2007, LIGO, GEO & Virgo data are jointly analyzed by the LIGO Scientific Collaboration and the Virgo Collaboration.

LIGO-GEO-Virgo joint runs



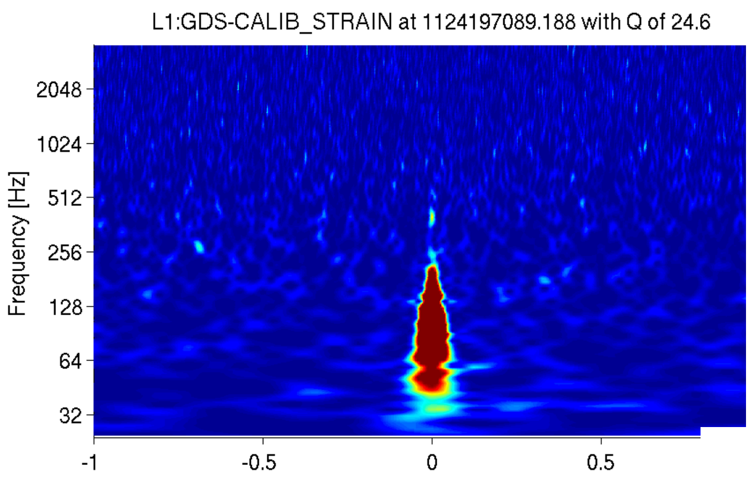
O1 data quality

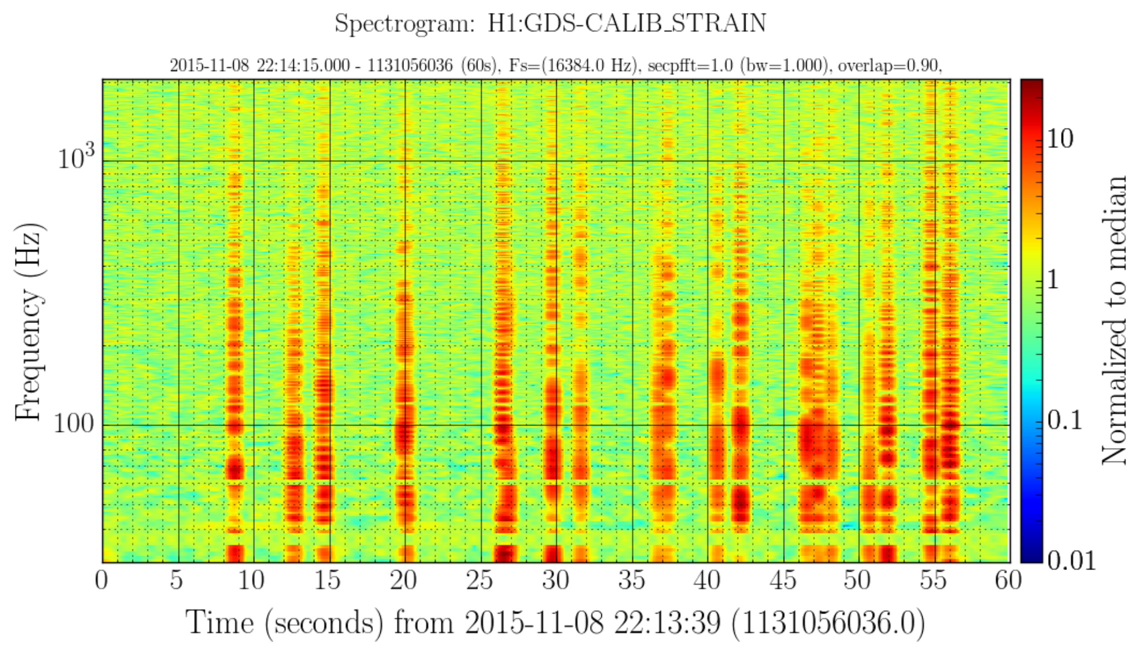
- Stable performance of both detectors during O1
- The product of observation volume X time exceeded that of previous runs after 16 coincident days in O1.

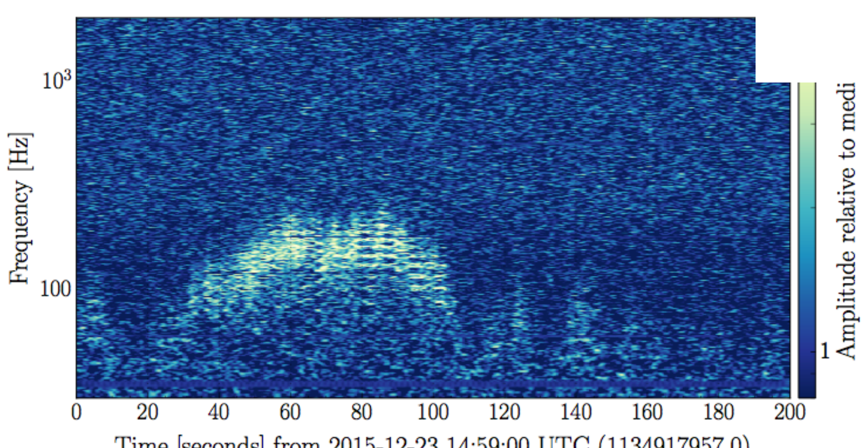


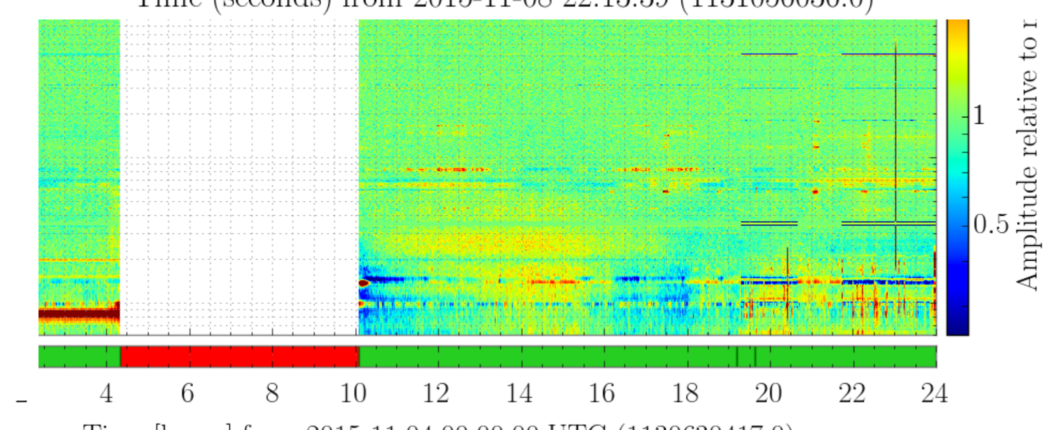
O1 data quality

- Many glitch sources (RF-modulation electronics fault, « blip » glitches, …) : either correlation in auxiliary channels → vetoes
- Spectral lines : wandering, 1Hz combs, breathing effects



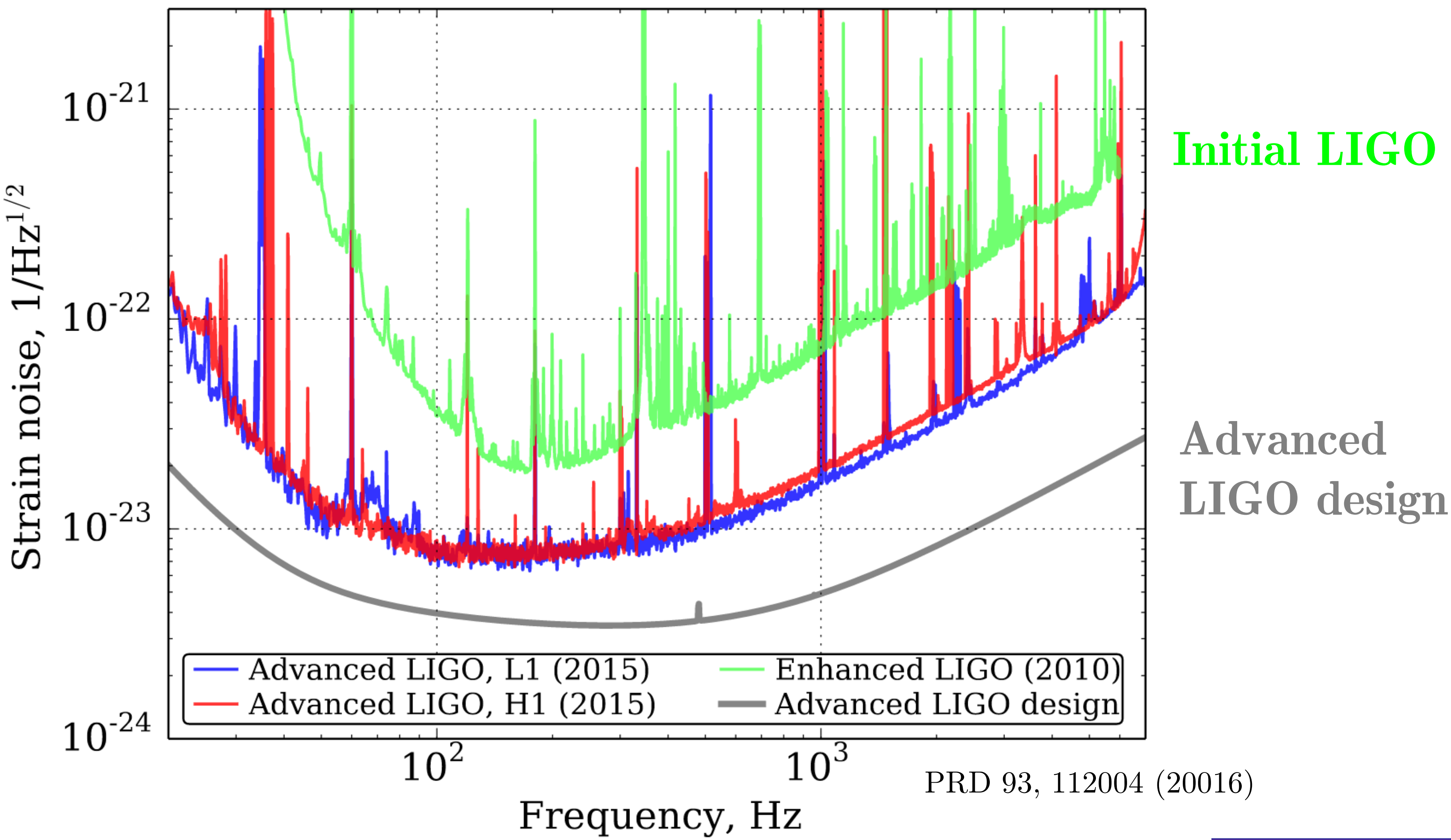






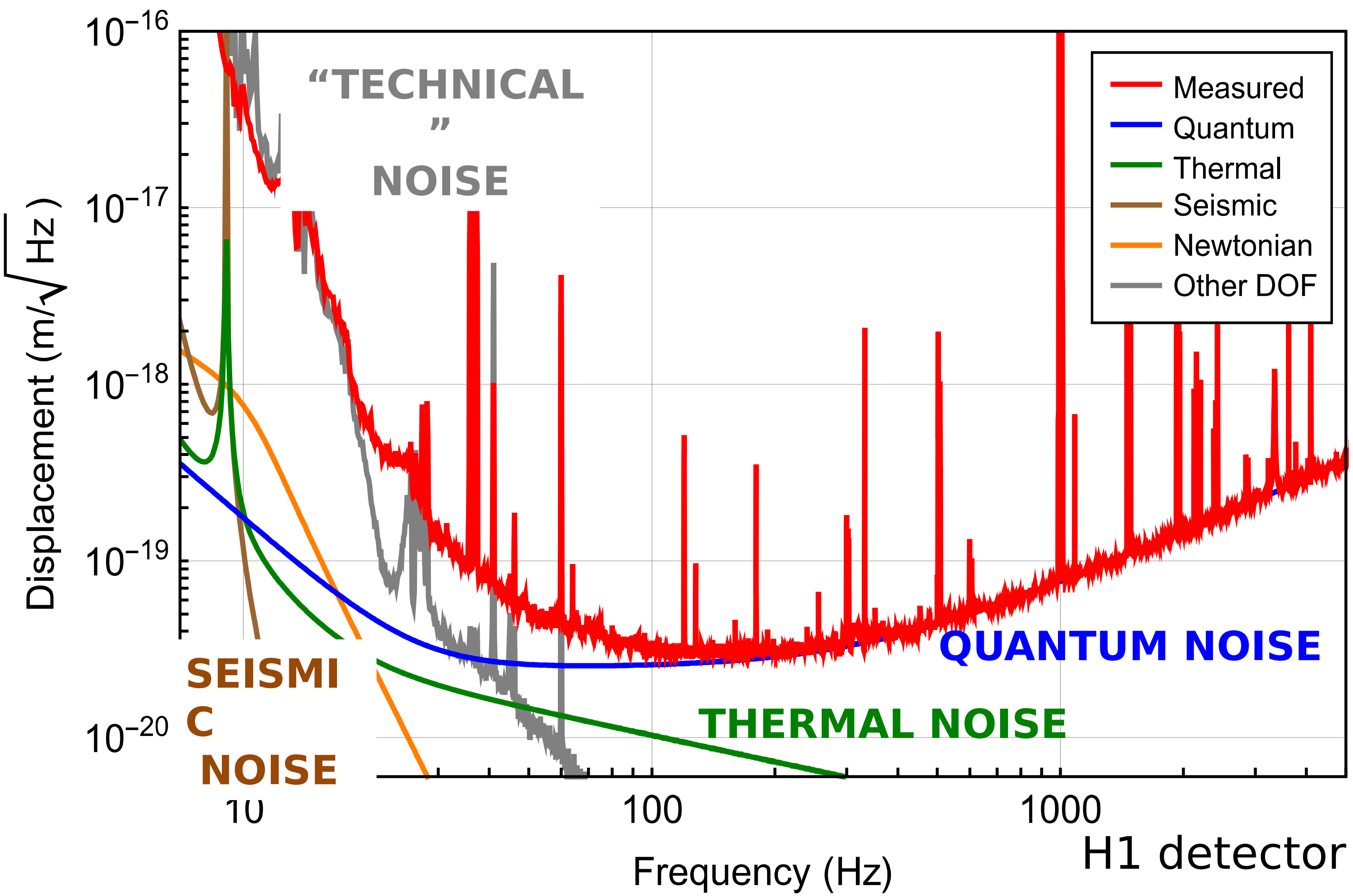
Strain noise during O1

Better than ever not yet at sensitivity !

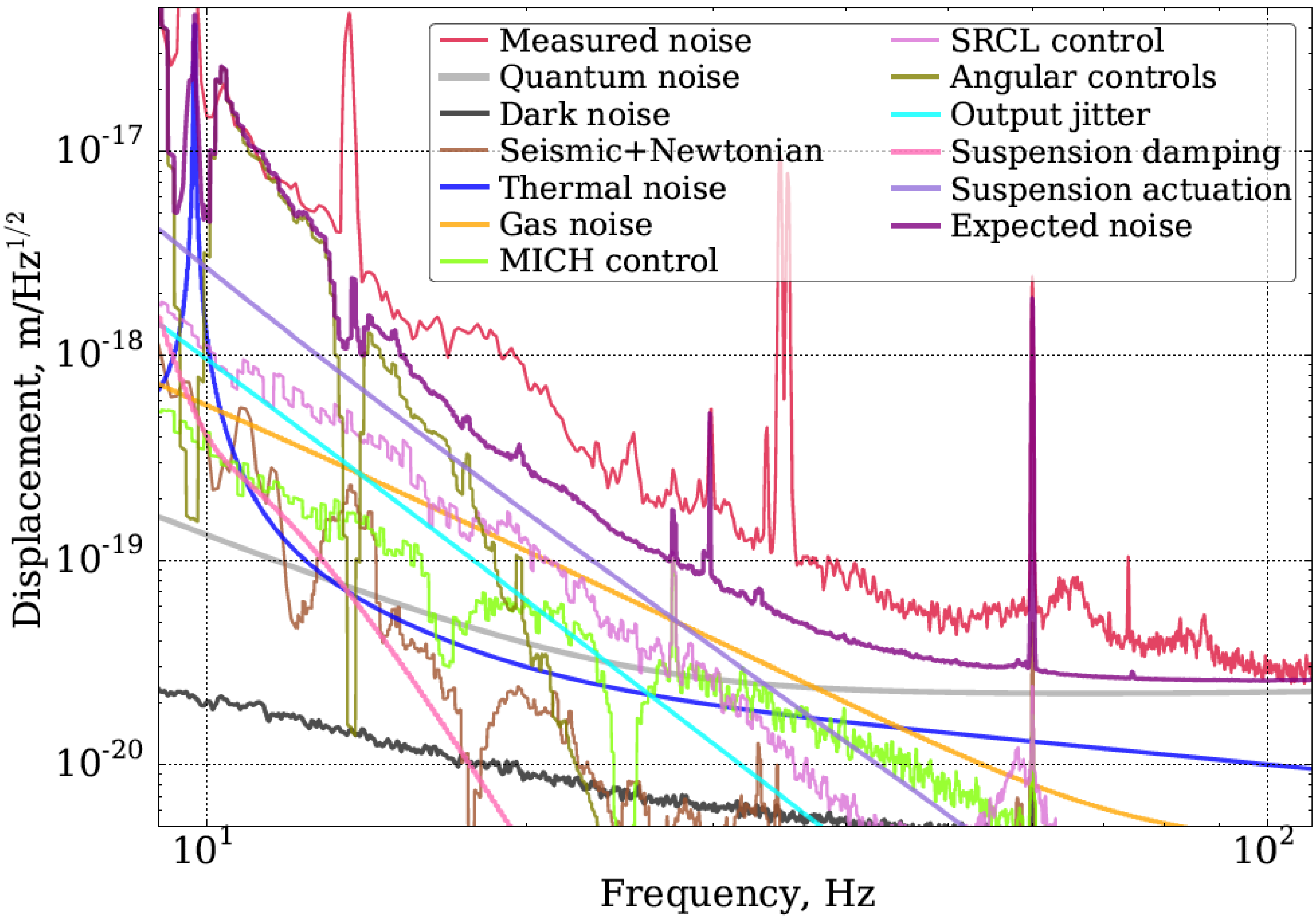


PRD 93, 112004 (20016)

O1 displacement noise



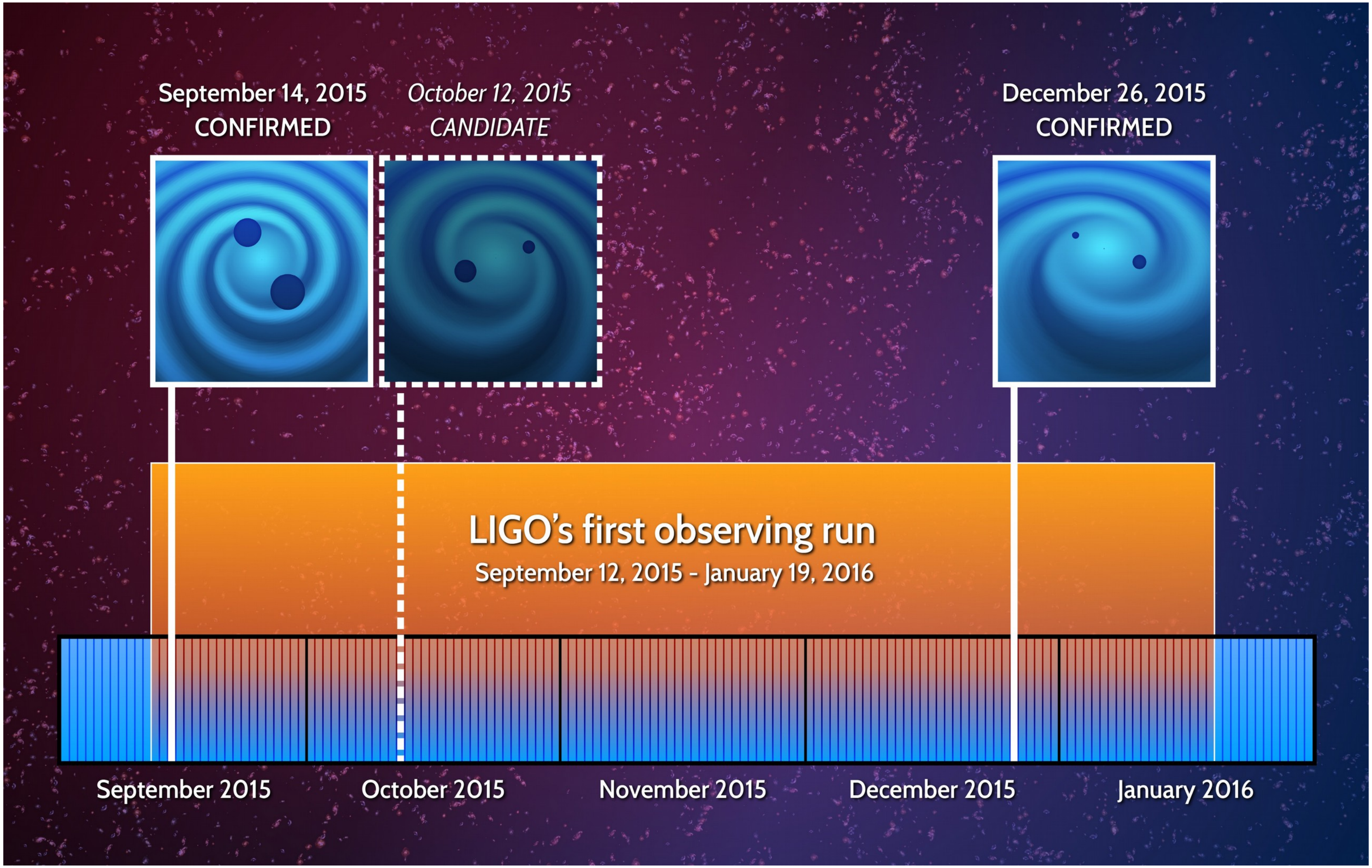
Low-frequency noise sources



(a) LIGO Livingston Observatory

O1 results

Binary black holes discovery : a summary

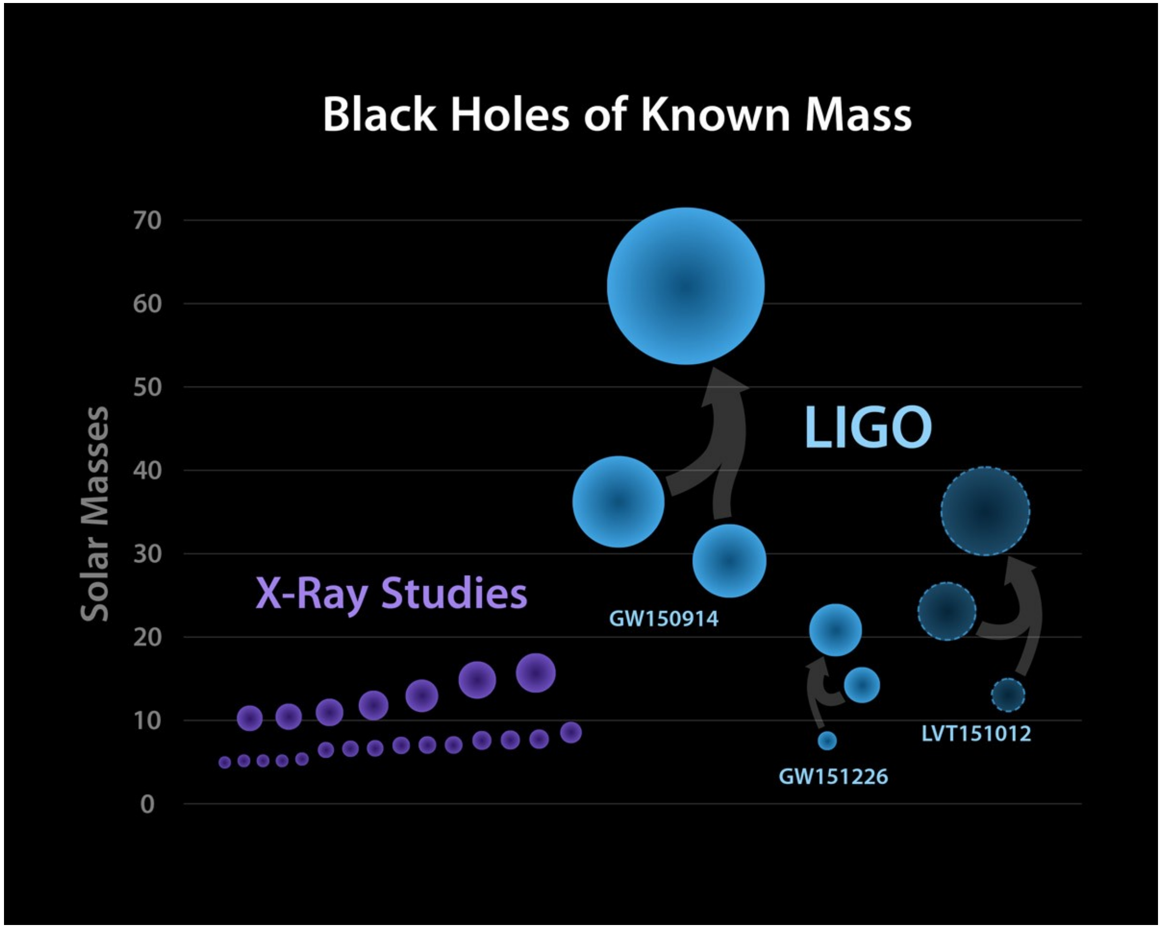


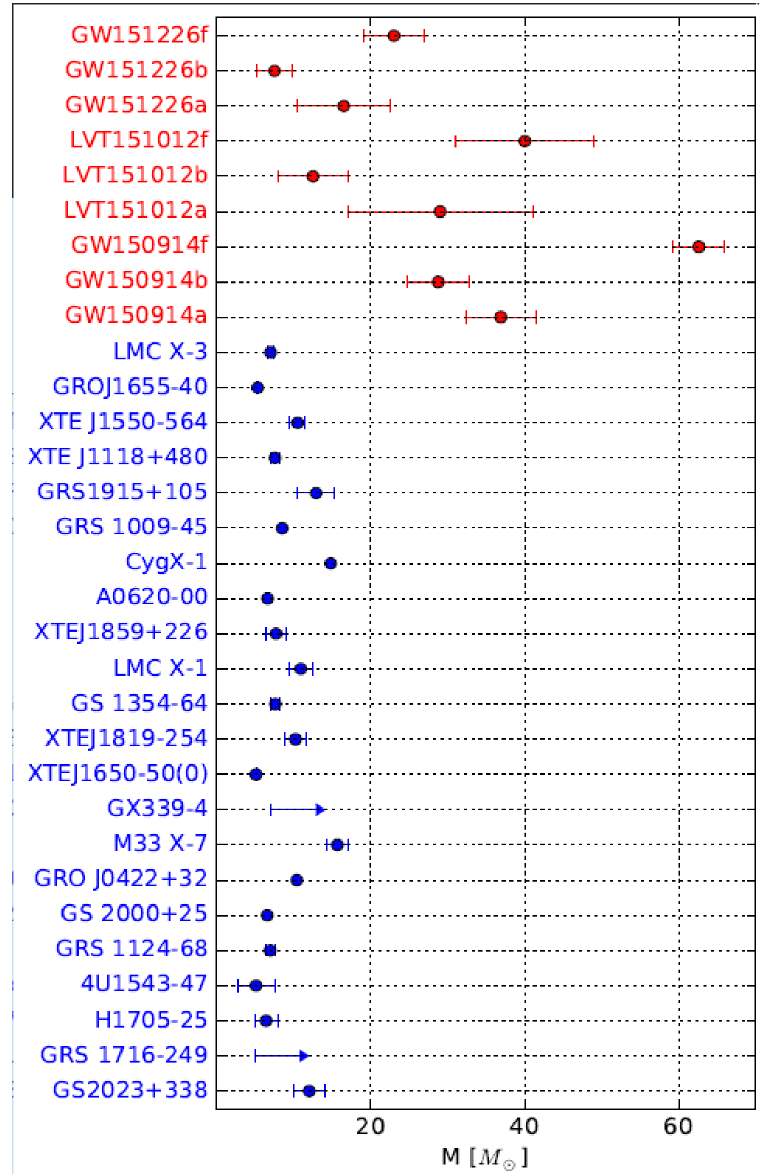
O1 BBH: Two Golds and a Silver

[gr-qc:1606.04856]

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR/yr^{-1}	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\rm source}/{\rm M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/{\rm M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\rm source}/{\rm M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\rm source}/{\rm M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin $\chi_{\rm eff}$	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin $a_{\rm f}$	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$	$0.20^{+0.09}_{-0.09}$
Sky localization $\Delta\Omega/{\rm deg}^2$	230	850	1600

Black hole population





Three BBH GW signals

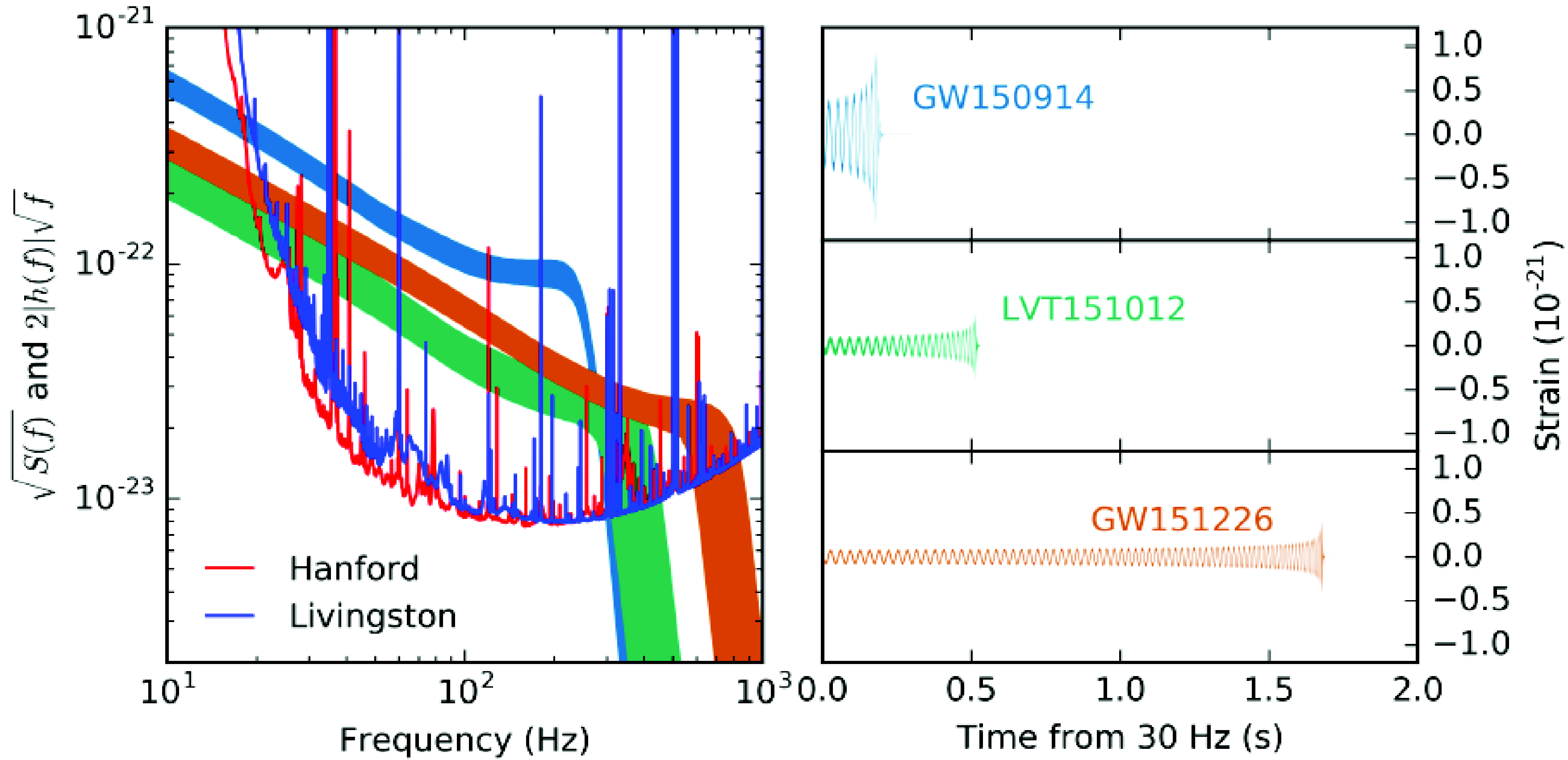
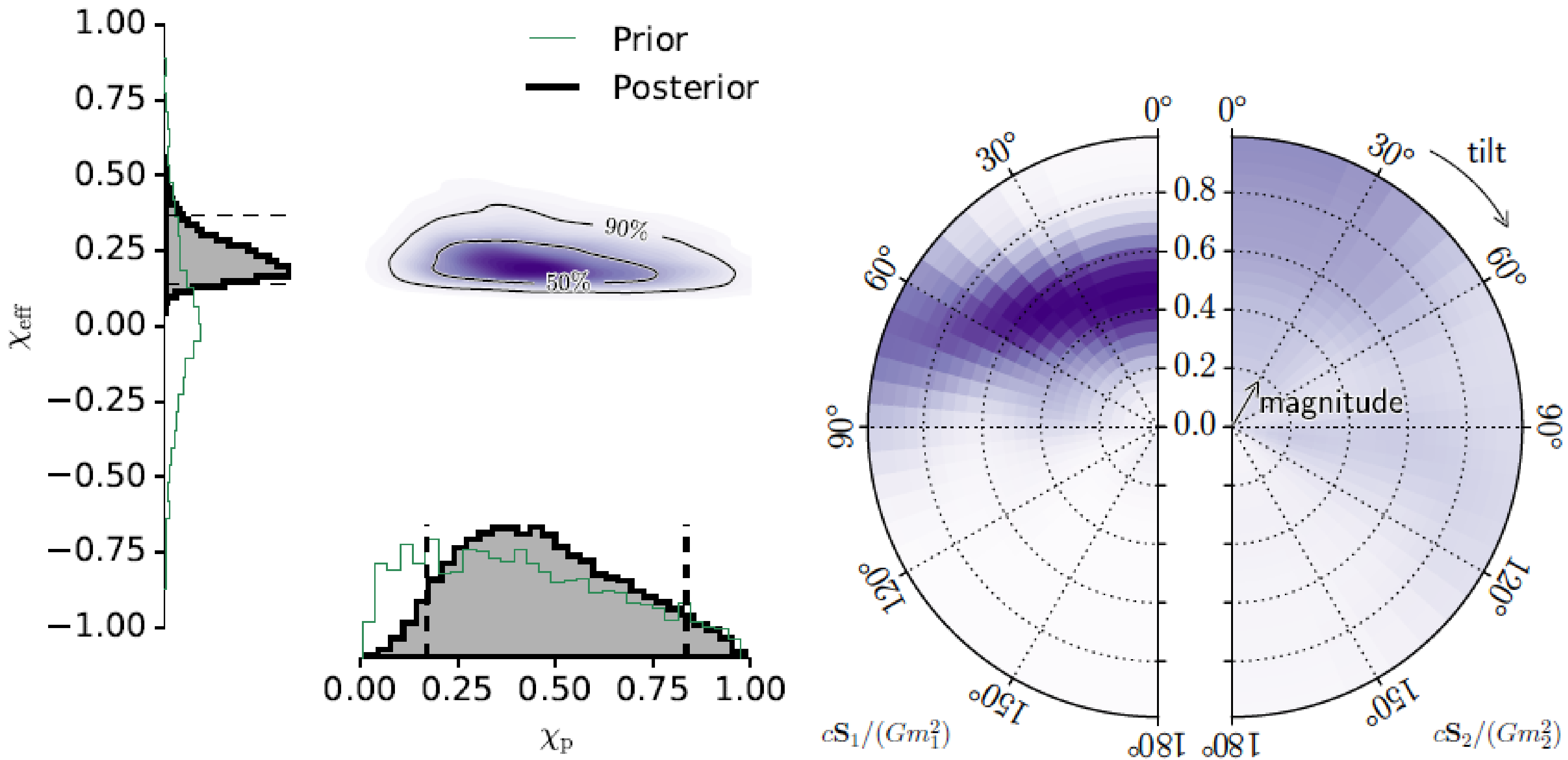


FIG. 1. Left: amplitude spectral density of the total strain noise of the H1 and L1 detectors, $\sqrt{S(f)}$, in units of strain per $\sqrt{\mathrm{Hz}}$, and the recovered signals of GW150914, GW151226 and LVT151012 plotted so that the relative amplitudes can be directly related to the SNR of the signal (as described in the text). Right: the time evolution of the waveforms from when they enter the detectors' sensitive band at 30 Hz. All bands show the 90% credible regions of the LIGO Hanford signal reconstructions from a coherent Bayesian analysis using a non-precessing spin waveform model [44].

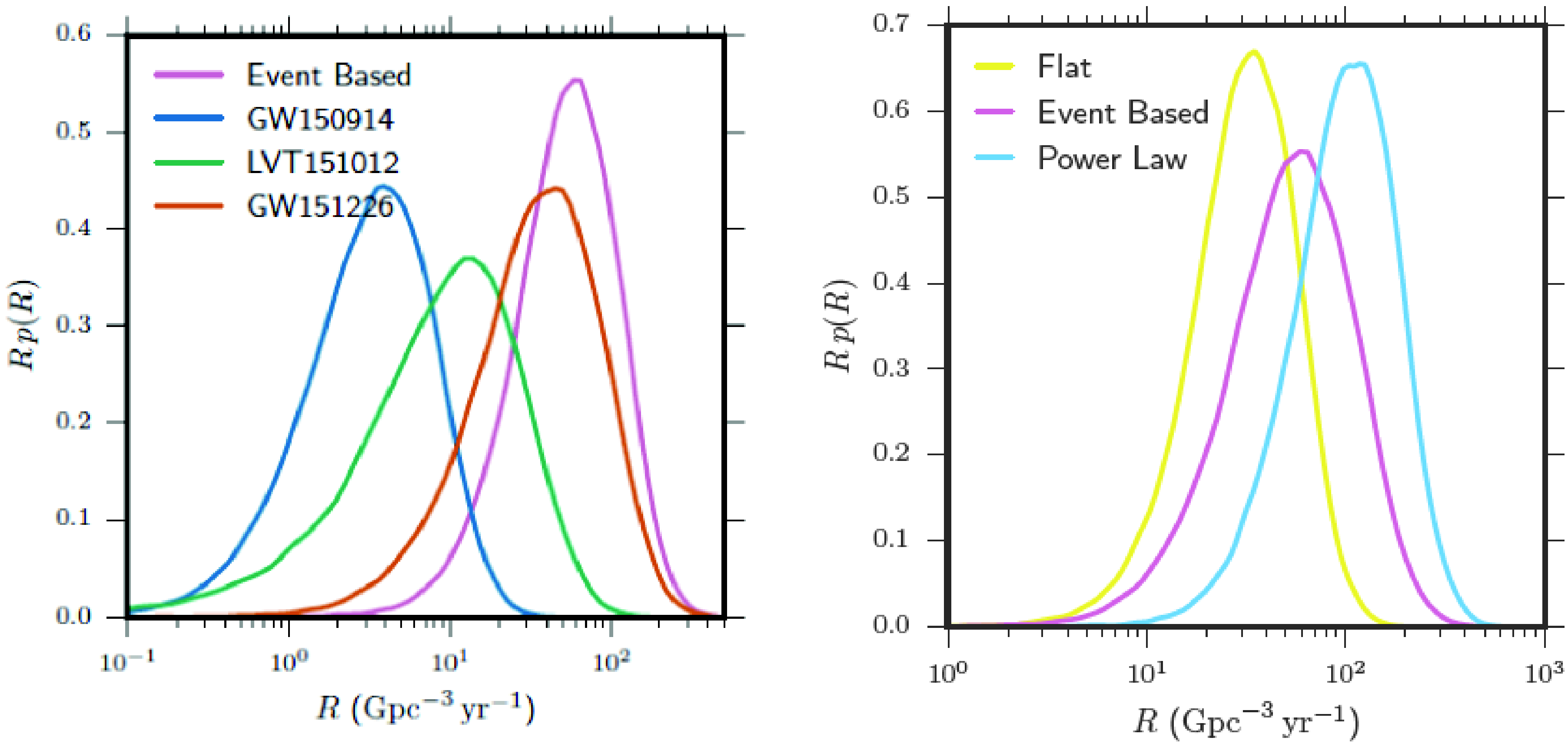
GW151226 – At least one BH had spin



At least one black hole has spin greater than 0.2. Spins of the primary and secondary black holes are constrained to be positive.

Mass-weighted combinations of orbit-aligned spins χ_{eff} and in-plane spins χ_{p} (weak constraints only, non-informative).

Binary Black Hole Merger Rate



90% allowed range: [9-240] /Gpc^3/yr

Binary black hole merger rate

- Assuming that all binaries are like these 3 events is not realistic.
- Try two alternative models:
  - Flat distribution in log m1 – log m2
  - (m1) ∝ $m_1^{-2.35}$ with a uniform distribution for the second mass.
- Significantly different rate estimates.
- Altogether: 9 – 240 Gpc^{-3} yr^{-1}.
- Lower limit comes from the flat in log mass population and the upper limit from the power law population distribution.

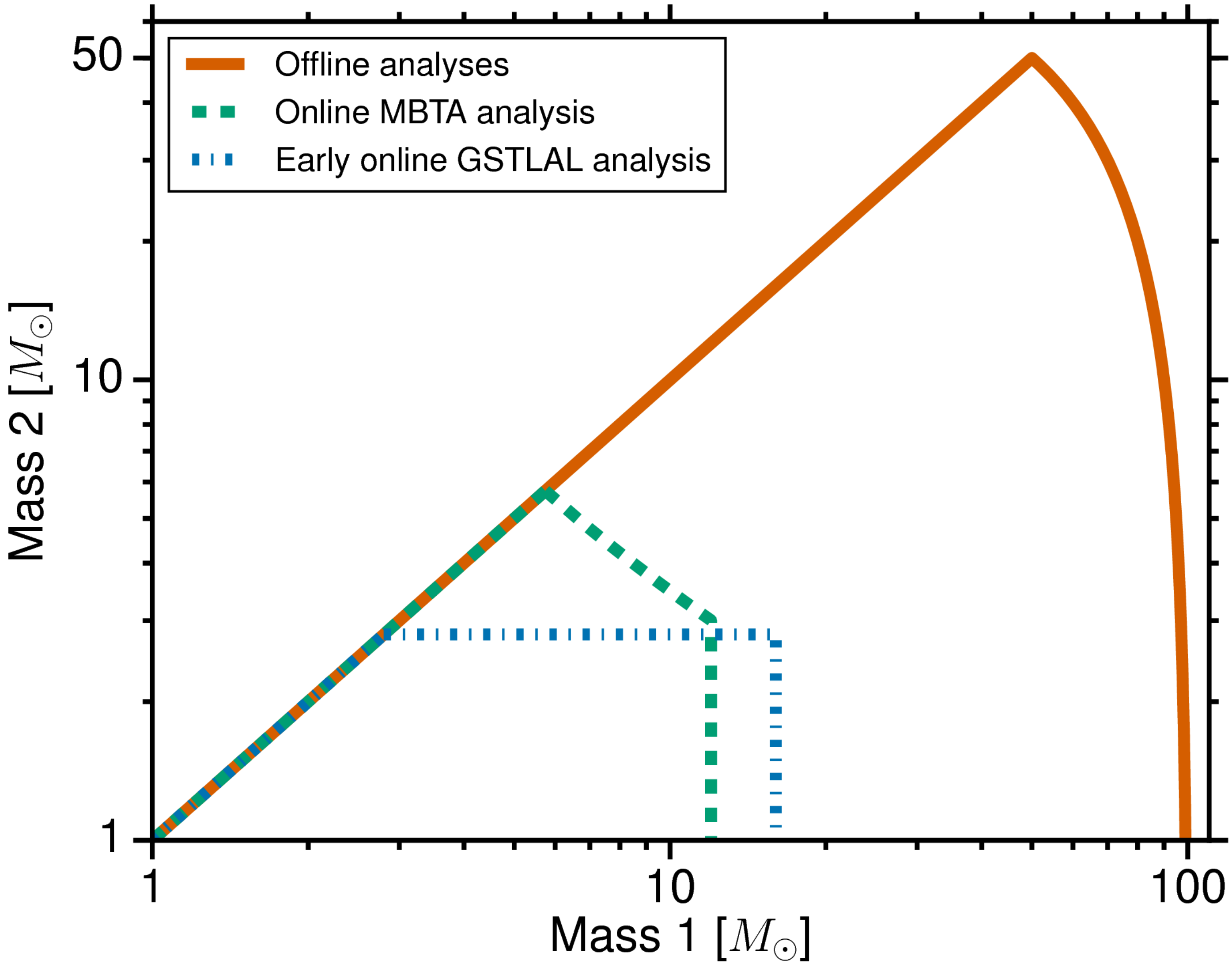
- Rules out <9 Gpc^{-3} yr^{-1}, which were previously allowed.

The birth of GW astronomy

- Testing GR in strong field regime
- Unveiling the black hole merger dynamics and the post-merger phase
- Checking consistency between waveform predictions (analytical/numerical)
- Understanding binary black hole formation mechanisms

Binary neutron stars & neutron star-black hole

gr-qc:1607.07456



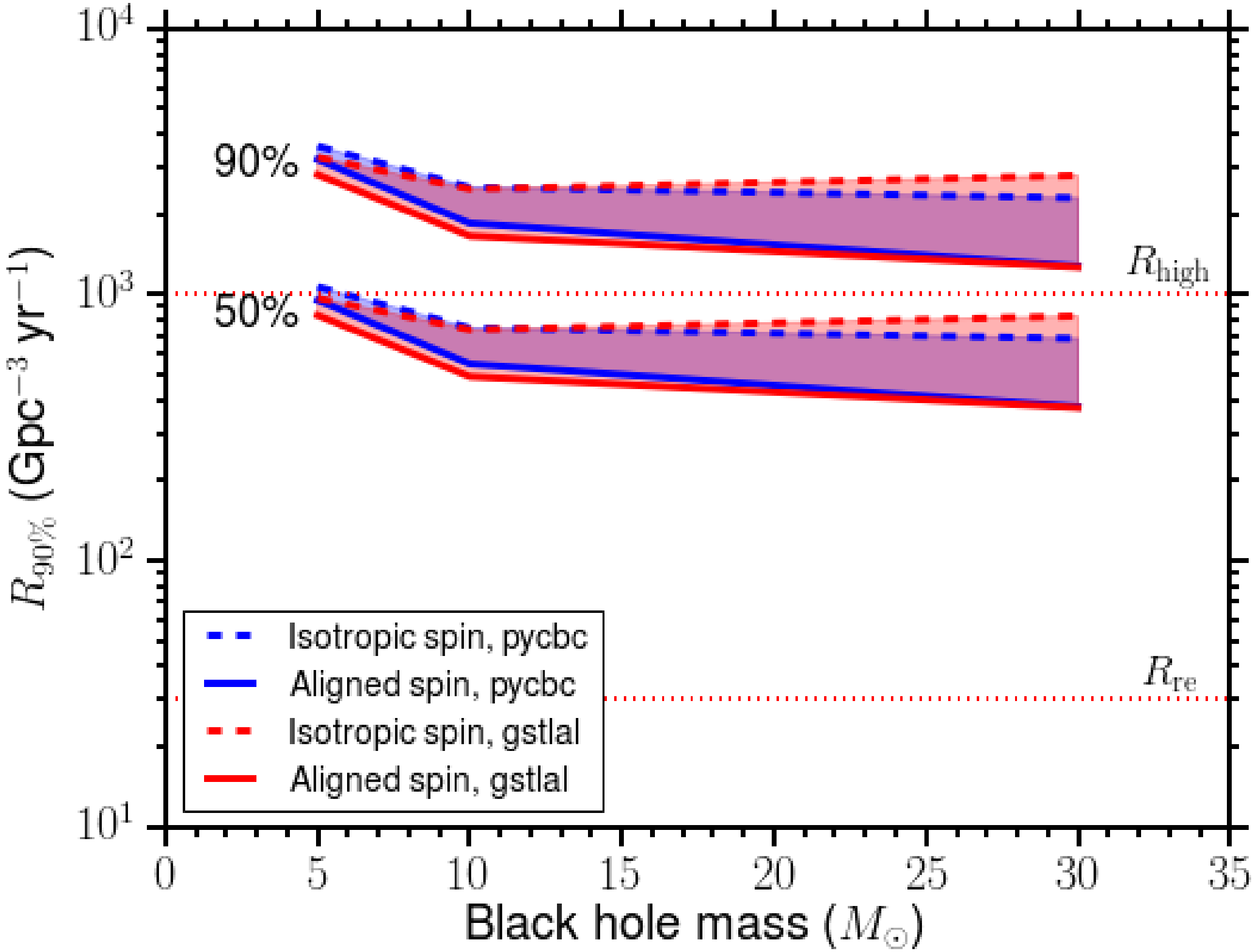
Spins :

Neutron star : [0 – 0.04]

Black hole : [0 – 1]

Binary neutron stars & neutron star-black hole

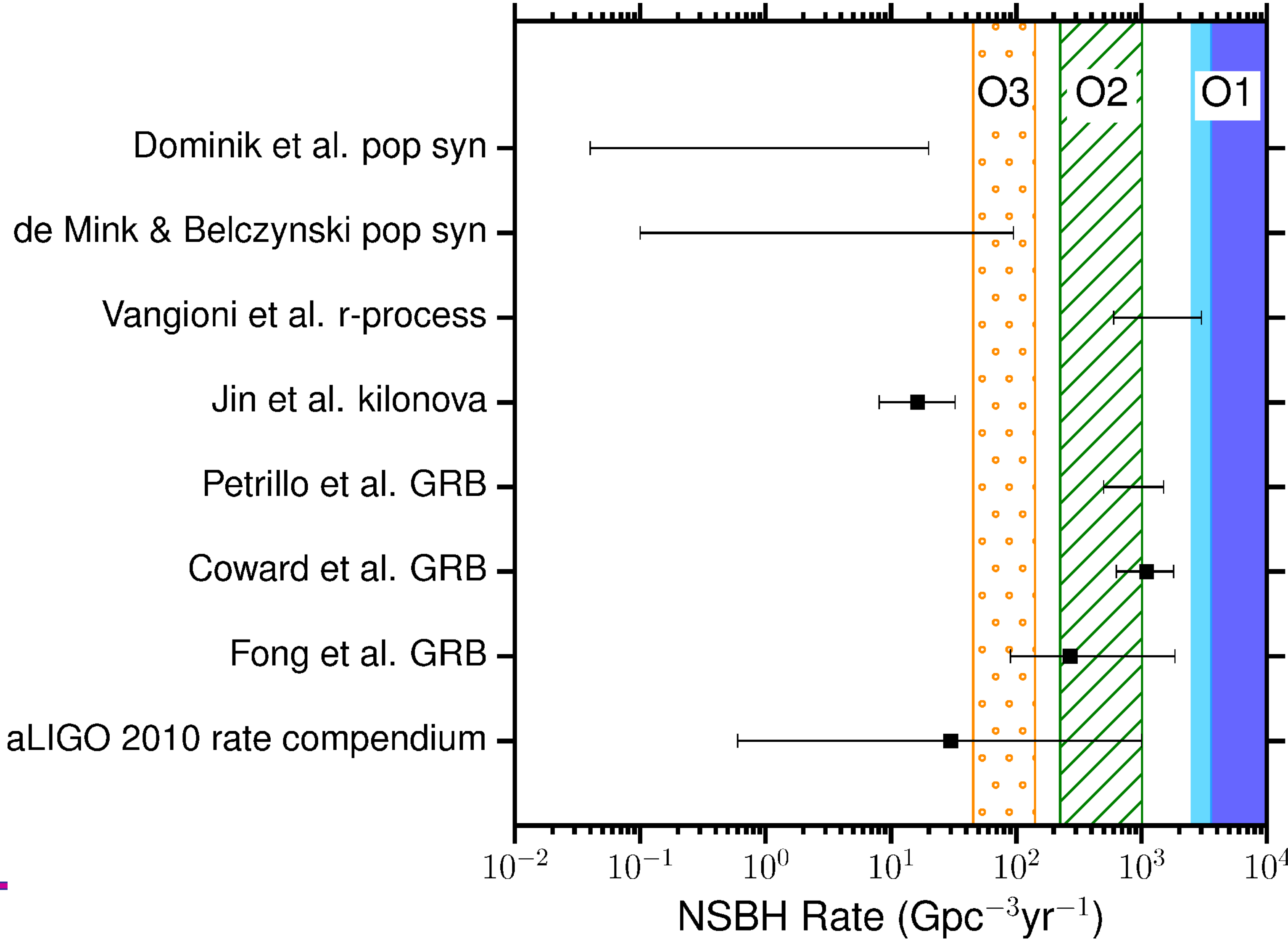
gr-qc:1607.07456



Binary neutron stars & neutron star-black hole

gr-qc:1607.07456

NS-BH predictions



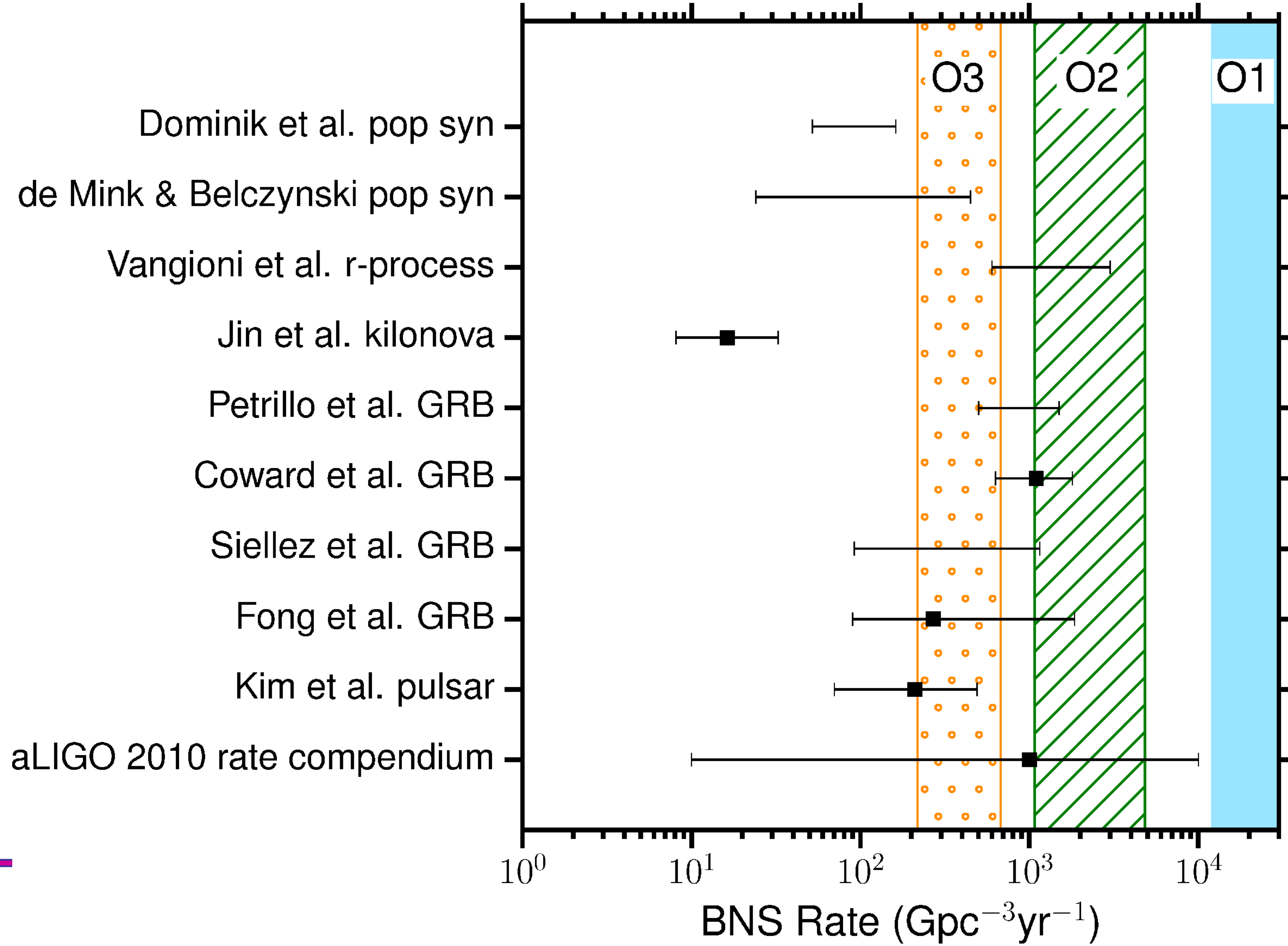
10-1.4 Msun

5-1.4 Msun

Binary neutron stars & neutron star-black hole

gr-qc:1607.07456

BNS predictions



Implications for a stochastic background of GWs

- For every detected binary merger, there are many more that are too distant and too faint.

- They generate a stochastic background of gravitational waves.

Source Energy Spectrum

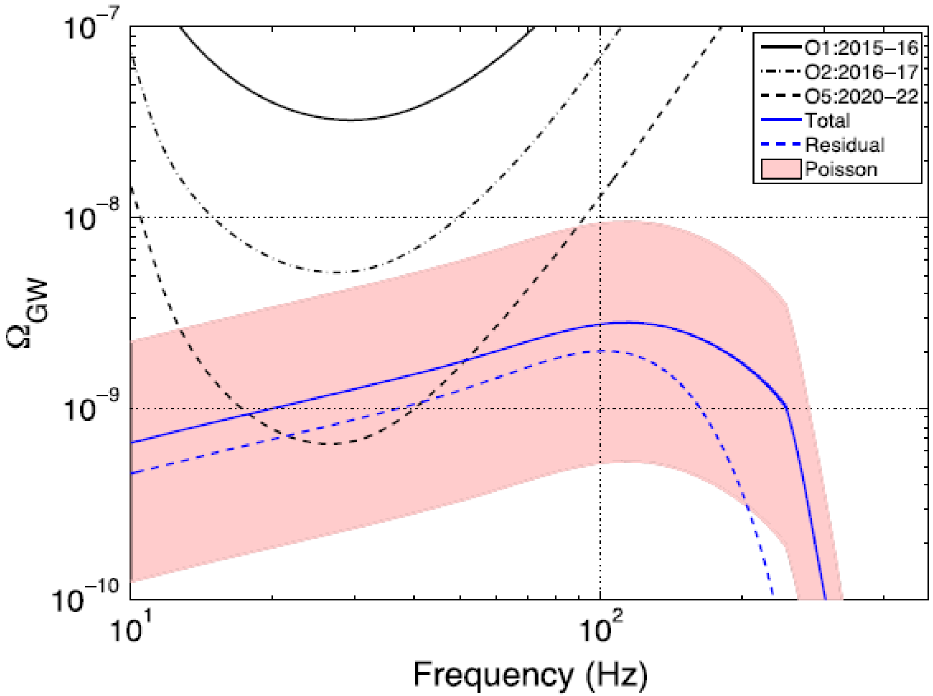
Merger Rate

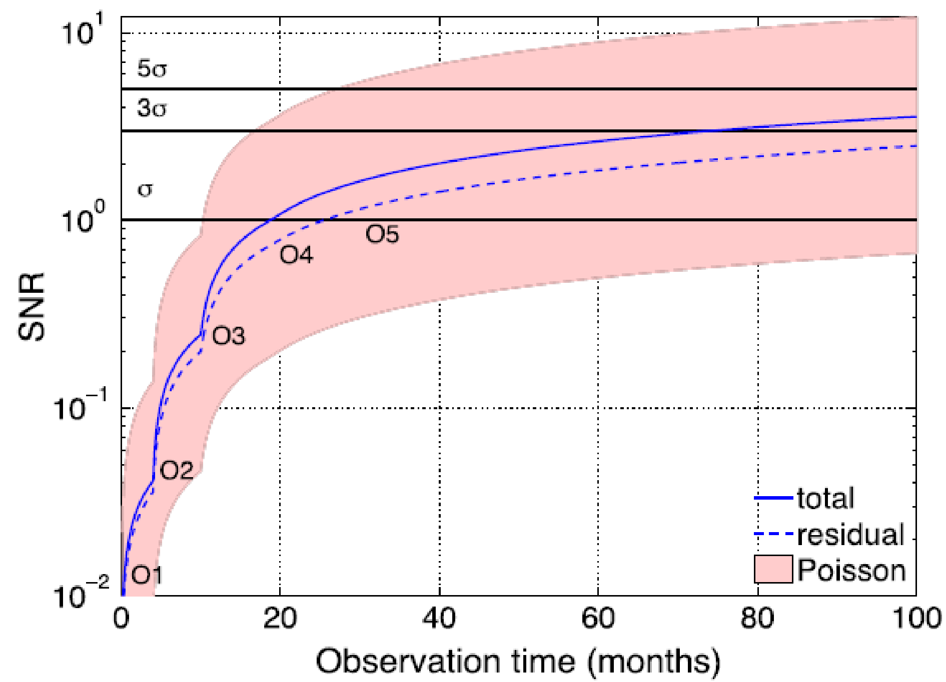
$$\Omega_{\mathrm{GW}}(f;\theta_k) = \frac{f}{\rho_c H_0} \int_0^{z_{\max}} dz \frac{R_m(z,\theta_k)\frac{dE_{\mathrm{GW}}}{df_s}(f_s,\theta_k)}{(1+z)E(\Omega_{\mathrm{M}},\Omega_\Lambda,z)}$$

Cosmology

- Relatively high rate and masses of observed systems prefer a relatively strong stochastic background.

Fiducial models

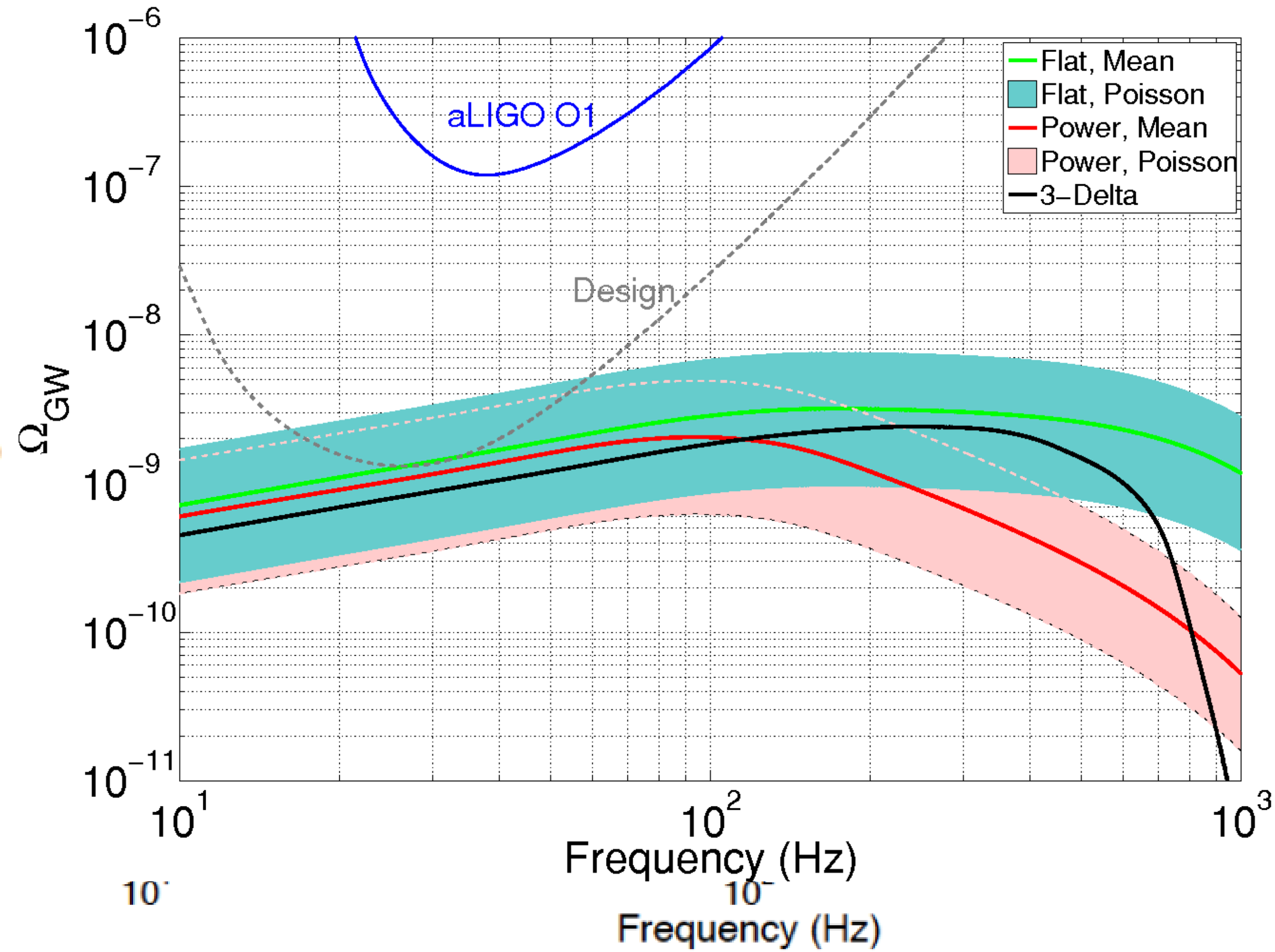




PRL 116, 131102 (2016)

- Many assumptions :
  - Field binary formation mechanism,
  - Assuming only GW150914 parameters.
  - Using chirp mass and merger rate distributions.
  - Formation-merger time delay distribution.
  - Metallicity distribution

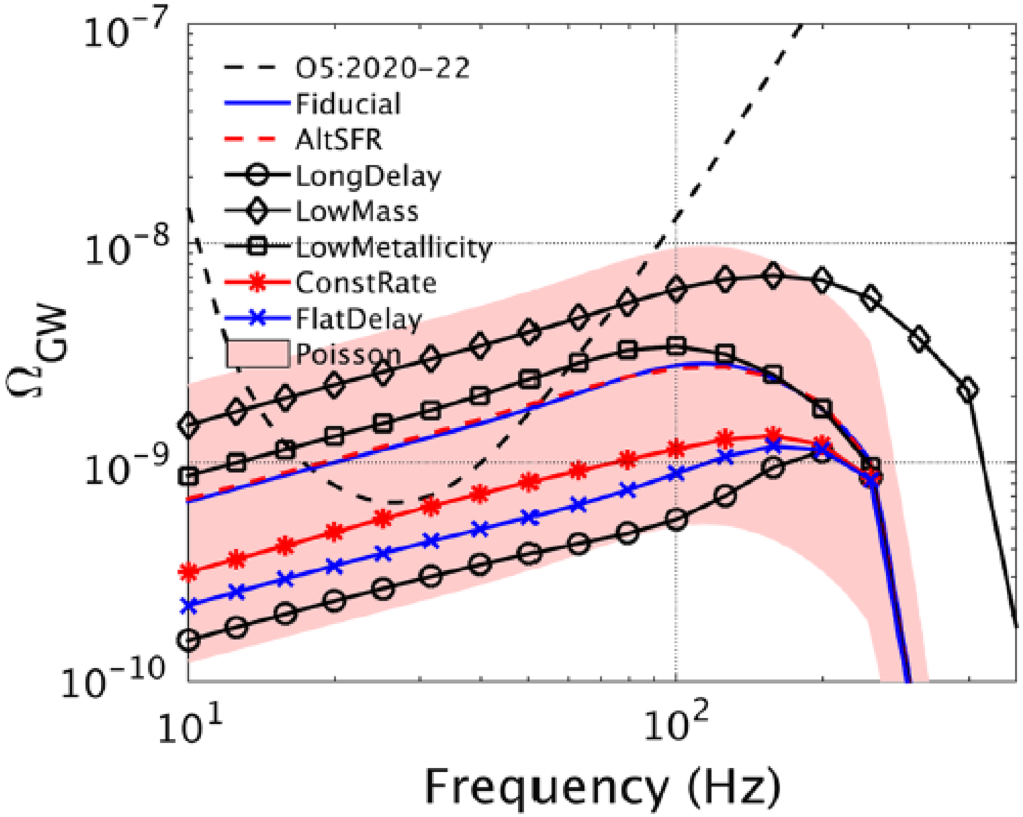
Fiducial models (all of O1)



- 3 events
- Same mean value Ω_{gw} (25Hz)~ 10^{-9}
- Less uncertainty

There is a very real probability that LIGO-Virgo will observe this BBH produced stochastic background in the next 3 to 5 years.

Alternative models



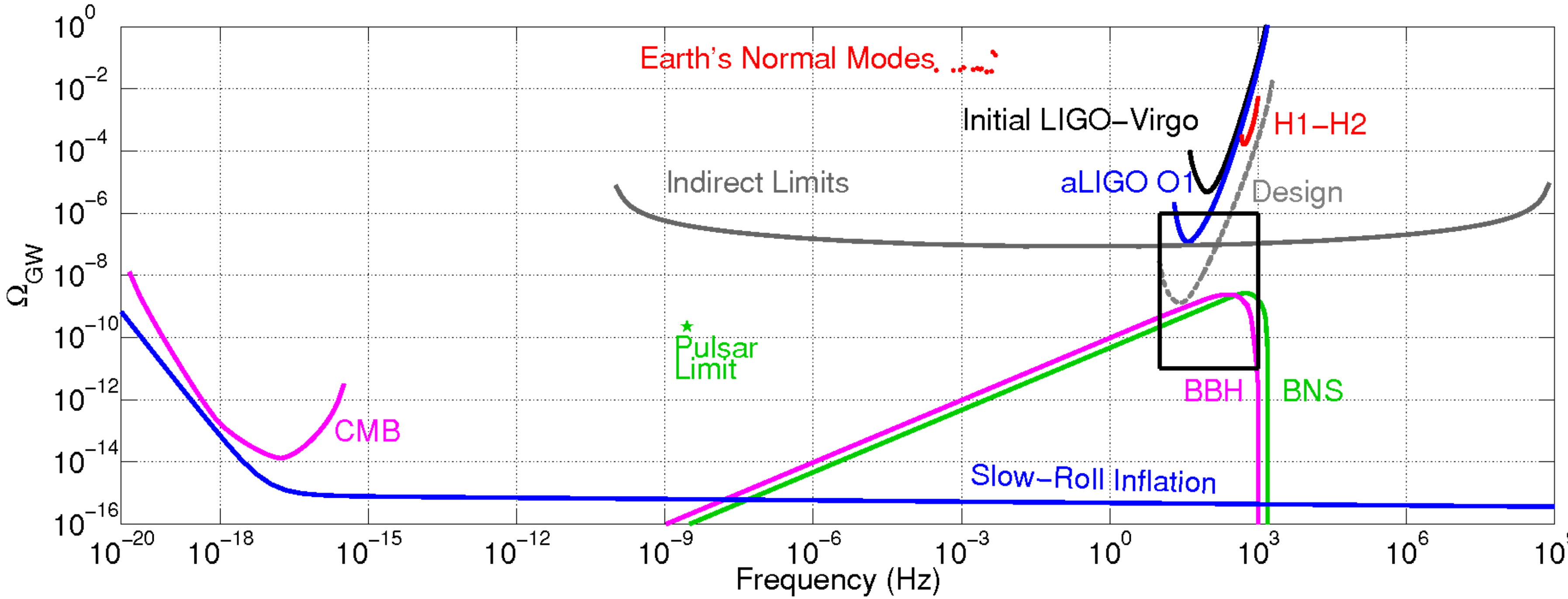
- Model variations imply relatively small changes in the energy spectrum.
- Large Poisson statistical uncertainty.
- Dominated by z ~1-2 contributions.
- Conservative estimates.
- A foreground to cosmological models of stochastic background.

O1 stochastic background search

- Cross-correlating H1 & L1
- 95 % confidence upper limit :
  - $\Omega_o < 1.7 \times 10^{-7}$ (previous : 5.6×10^{-6})

$$Y = \int_{-T/2}^{+T/2} dt_1 \int_{-T/2}^{+T/2} dt_2\, s_1(t_1)\, s_2(t_2)\, Q(t_2 - t_1)$$

$$\tilde{Q}(f) = \frac{1}{N} \frac{\gamma(f)\, \Omega_t(f)}{f^3\, P_1(f)\, P_2(f)}$$

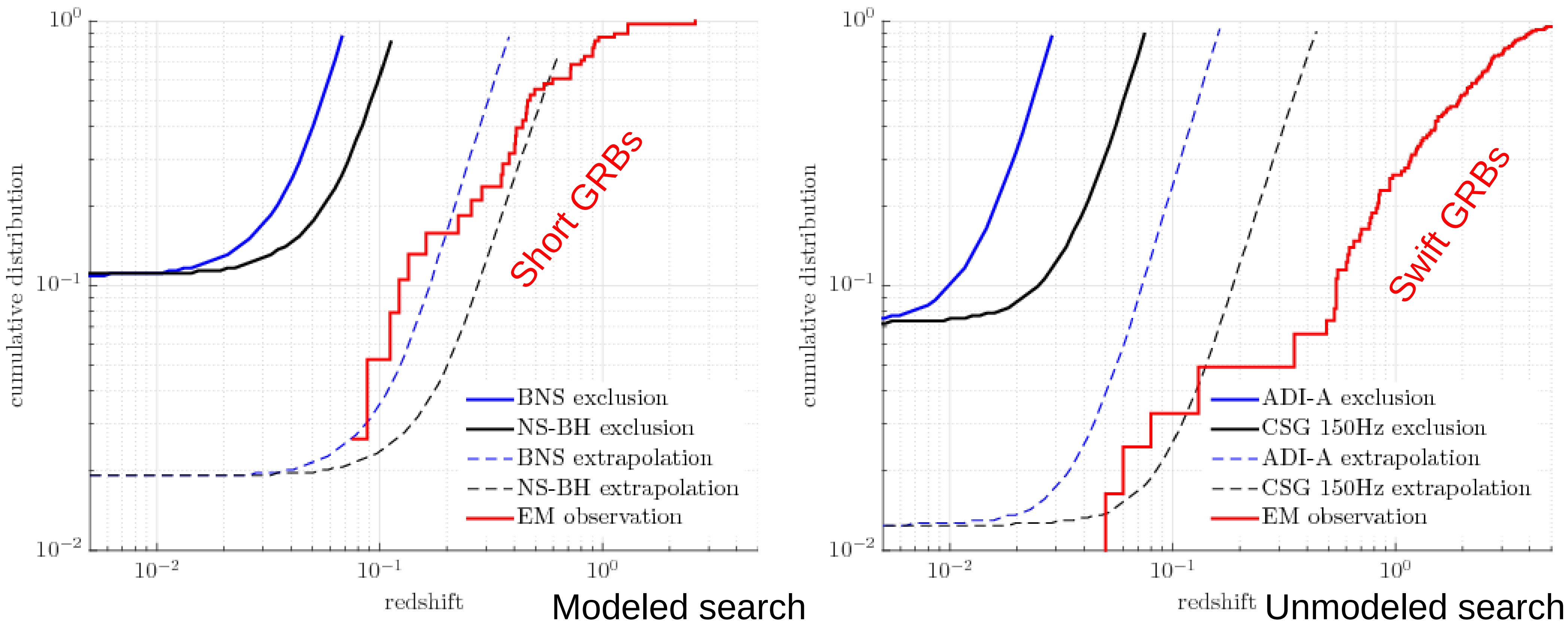


O1 un-modelled transient searches

- Have detected first (online) GW150914 because of the large masses.
- O1 data have been search for any un-modelled events in a large parameter space :
  - Short : 1 ms – 10s x 32 Hz – 4 kHz
  - Long : 10s – 500s x 24 Hz – 2kHz
- Search sensitivity estimated : ~3 times better than previous run → an order of magnitude better on the rate of events.
- No additional GW found.

GW associated with GRBs

arXiv:1611.07947

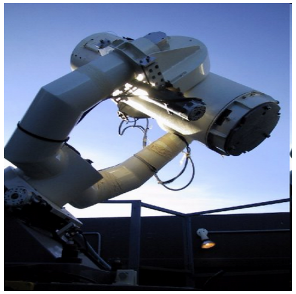


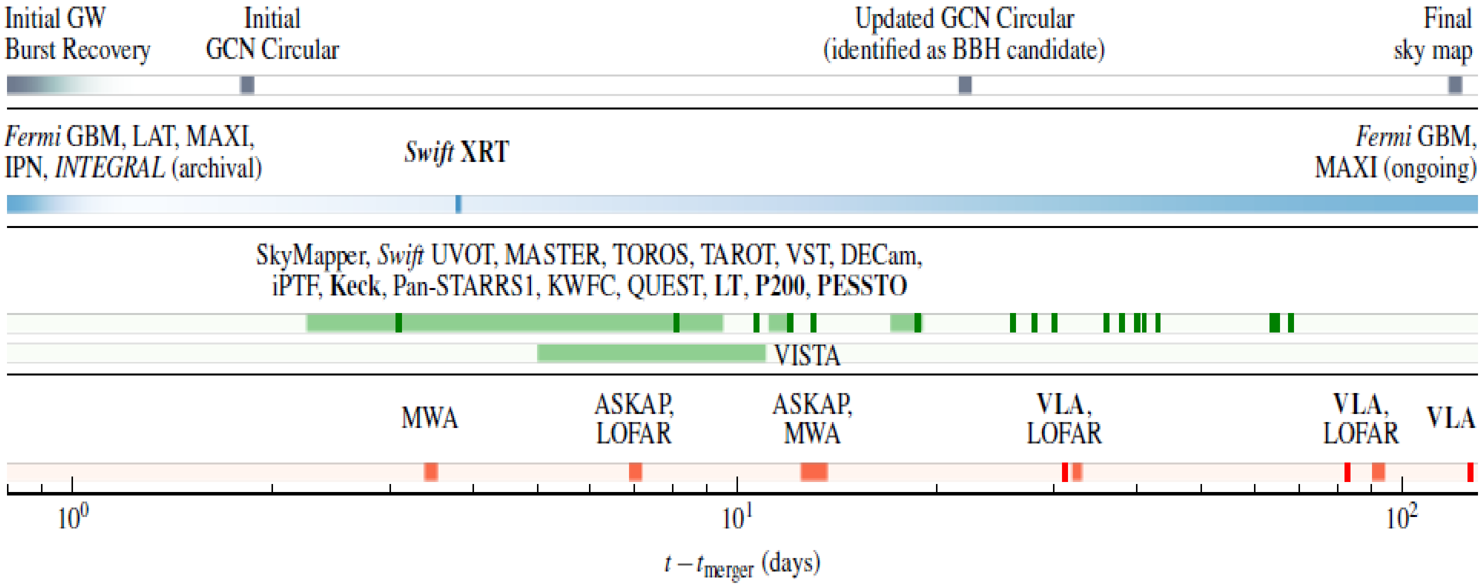
Extrapolation : 2 years of operation @ aLIGO sensitivity

With 2 years of observation at design sensitivity, Advanced LIGO will probe the observed redshift distribution

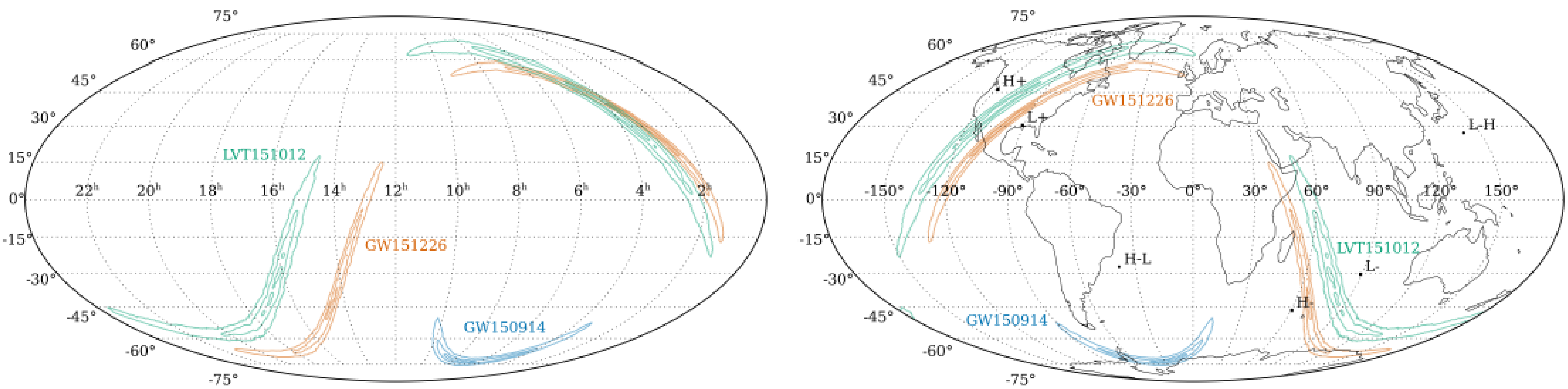
O1 data set

- Observation run O1 : September 12, 2015 – January 19, 2016
- Only LIGO Hanford (62%) & LIGO Livingston (55%) online
- ~50 days of coincident data to be analyzed
- Online transient searches & electro-magnetic follow-up program
  - Matched filtering CBC searches & un-modelled short transient searches
  - 62 MOUs (radio, optical, IR, X-ray and γ-ray).
  - 20 groups reacted to the first alert



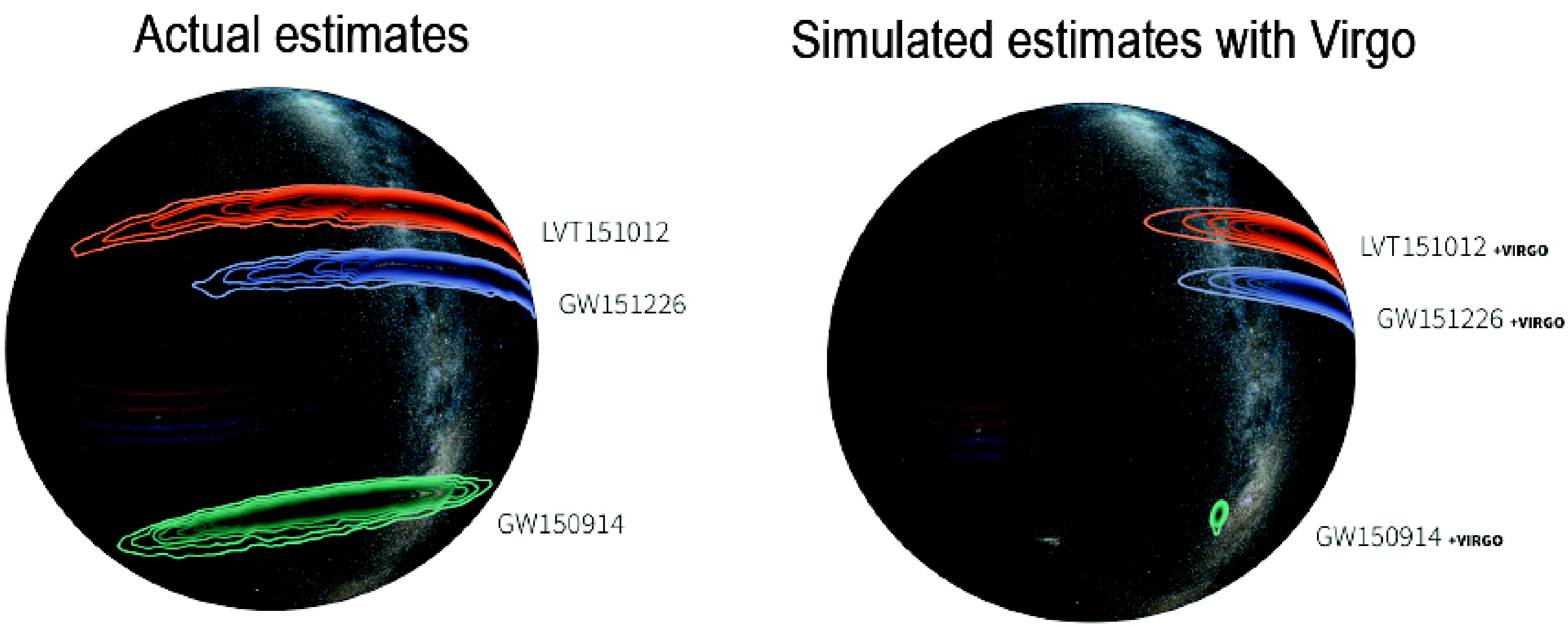


Sky position estimates



Event	GW150914	GW151226	LVT151012
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

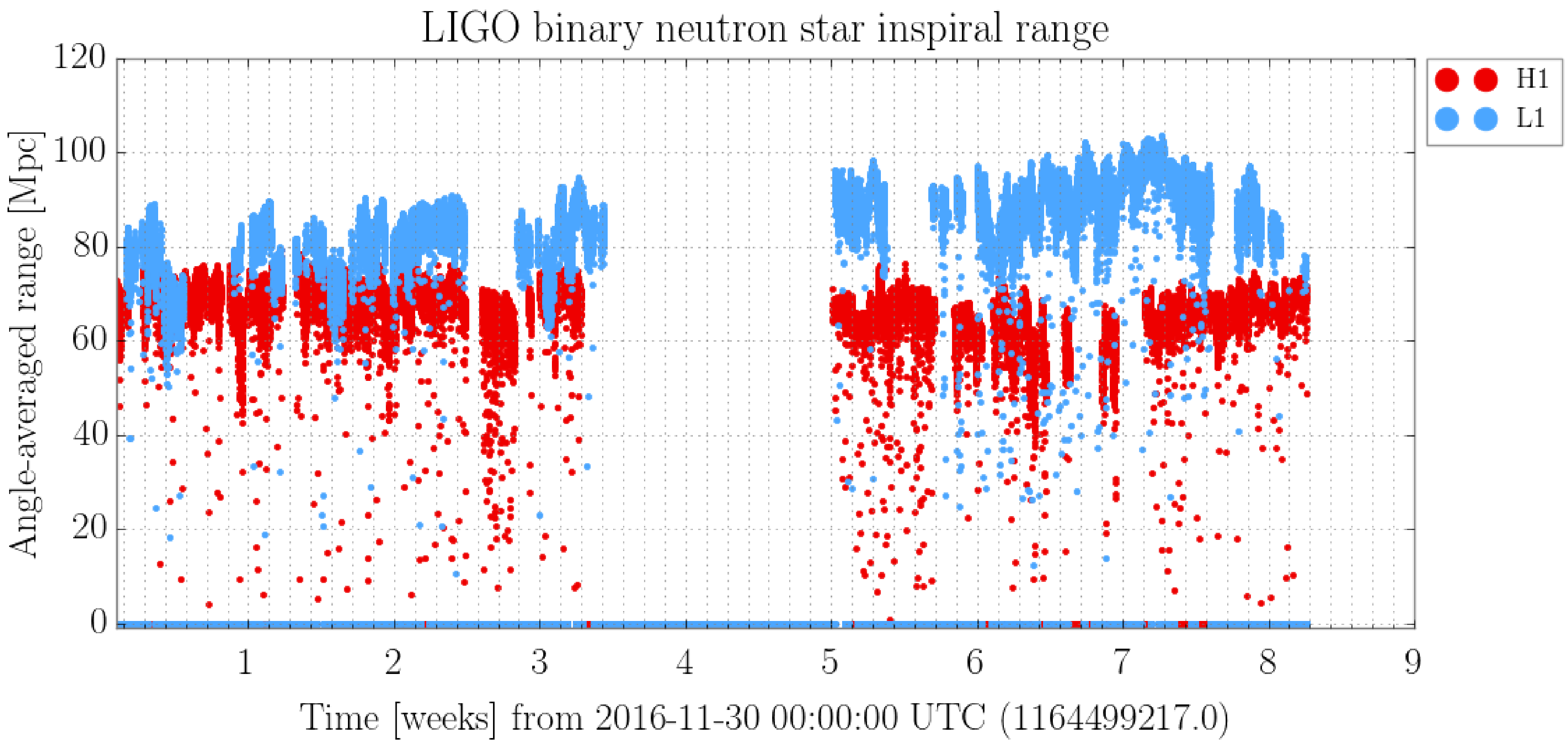
Sky localization: more detectors needed!



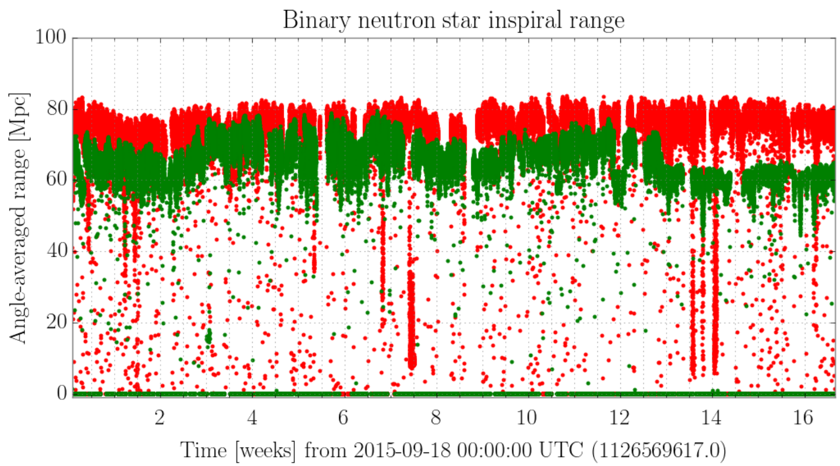
3-D projection of the Milky Way onto a transparent globe shows the probable locations of confirmed detections GW150914 (green), and GW151226 (blue), and the candidate LVT151012 (red). The outer contour for each represents the 90 percent confidence region while the innermost contour is the 10 percent region.
Image credit: LIGO/Axel Mellinger

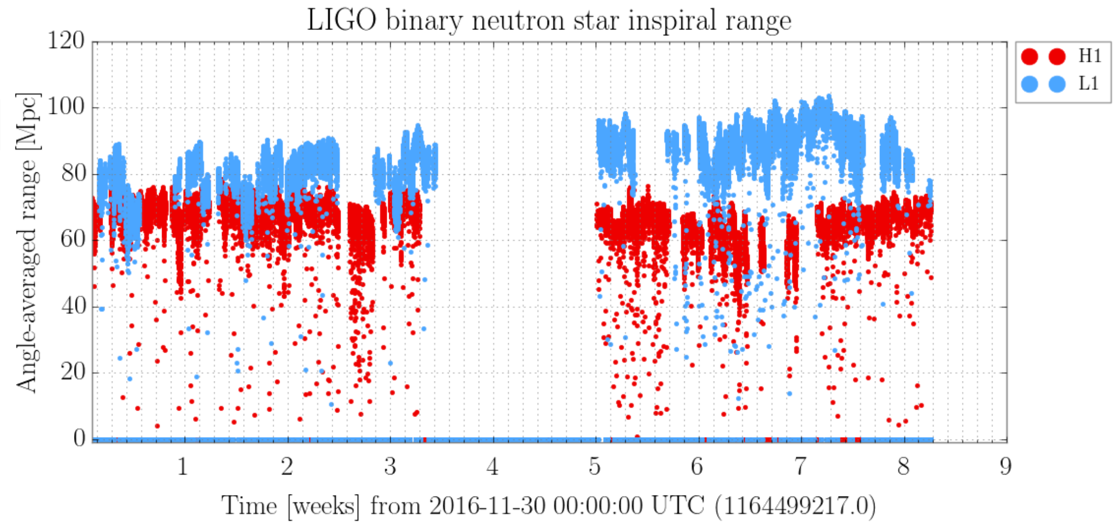
O2 run

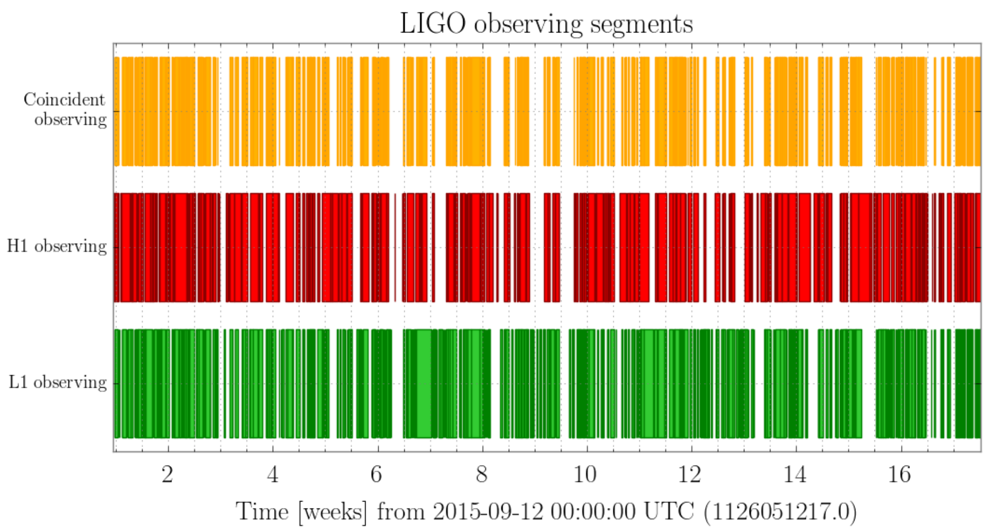
O2 data quality

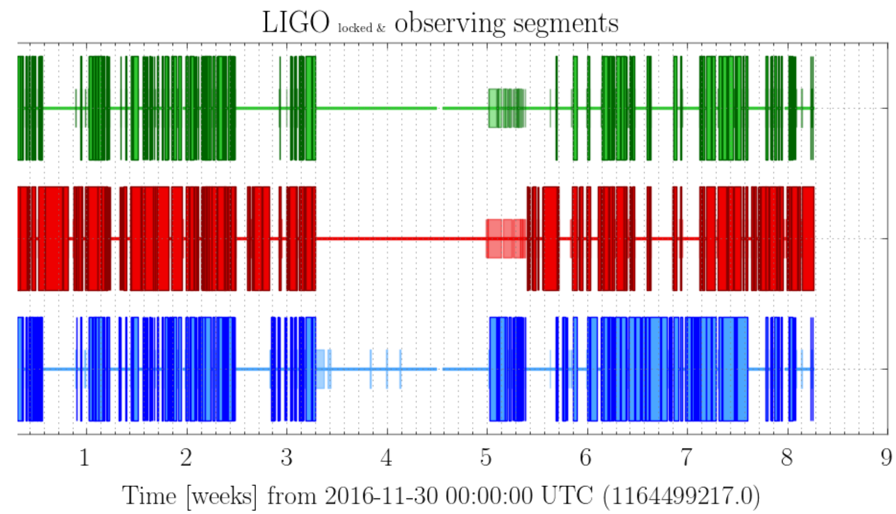


O1 / O2 data quality









BBHs expectations in next runs

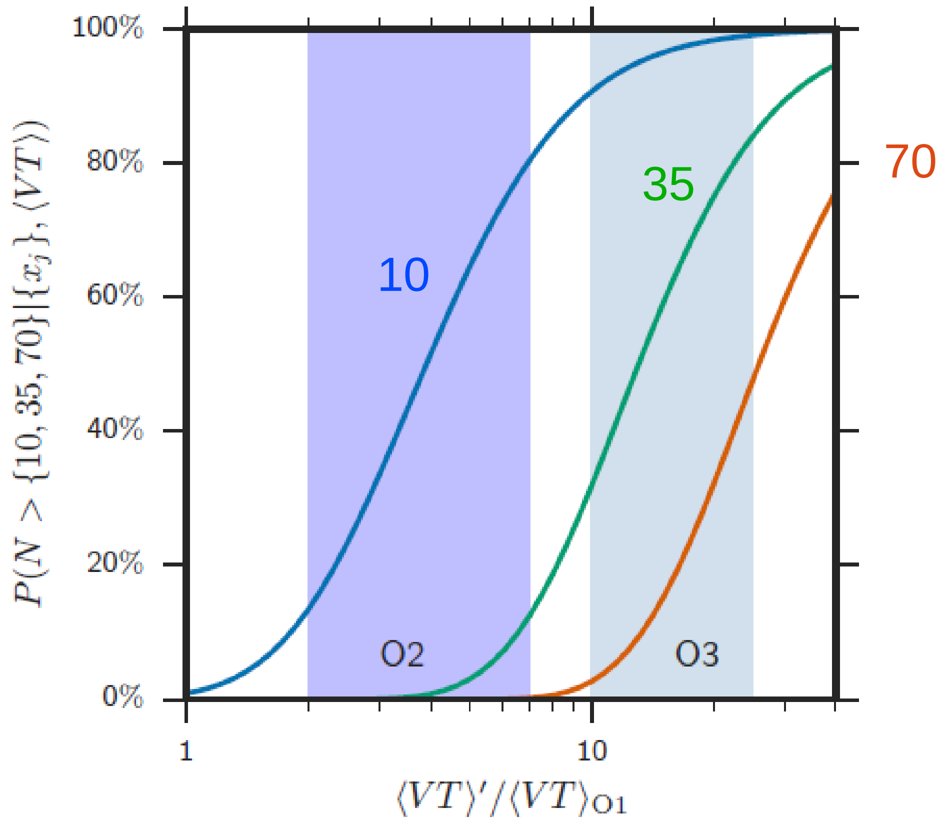


FIG. 12. The probability of observing $N > 10$, $N > 35$, and $N > 70$ highly significant events, as a function of surveyed time-volume. The vertical line and bands show, from left to right, the expected sensitive time-volume for the second (O2) and third (O3) advanced detector observing runs.

Towards O3

Future observing runs

Living Rev. Relativity, **19**, (2016), 1
DOI 10.1007/lrr-2016-1

LIVING REVIEWS *in relativity*

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

Abbott, B. P. et al.
The LIGO Scientific Collaboration and the Virgo Collaboration
(The full author list and affiliations are given at the end of paper.)
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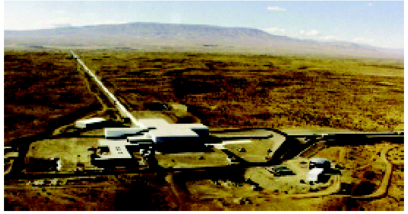


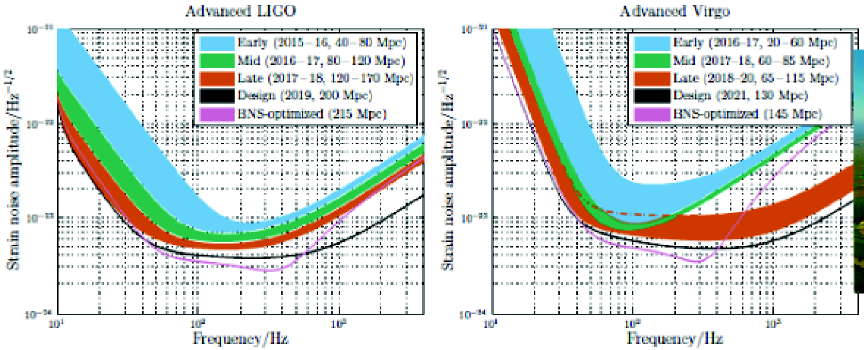


Figure 1: aLIGO (*left*) and AdV (*right*) target strain sensitivity as a function of frequency. The binary neutron-star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late commissioning phases, as well as the final design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.

2015 – 2016 (O1) A four-month run (beginning 18 September 2015 and ending 12 January 2016) with the two-detector H1L1 network at early aLIGO sensitivity (40 – 80 Mpc BNS range).

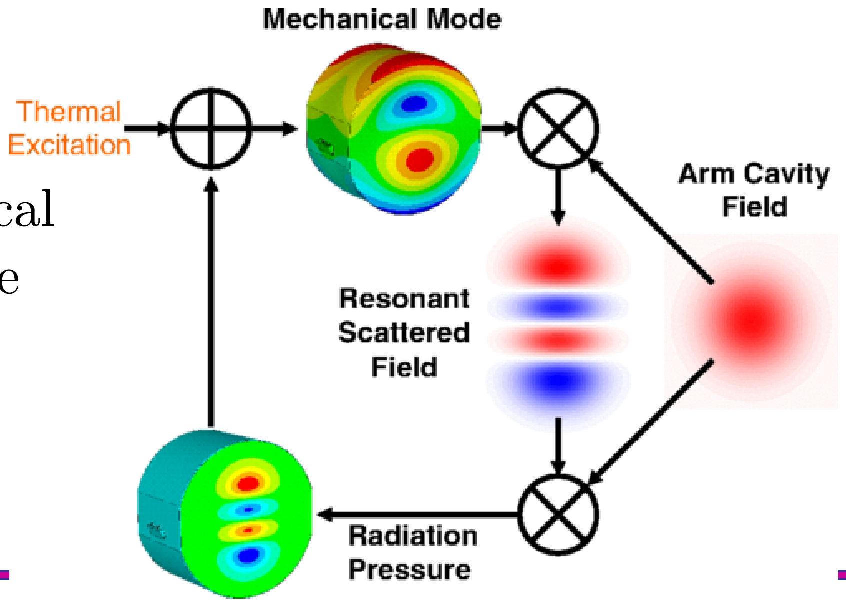
2016 – 2017 (O2) A six-month run with H1L1 at 80 – 120 Mpc and V1 at 20 – 60 Mpc.

2017 – 2018 (O3) A nine-month run with H1L1 at 120 – 170 Mpc and V1 at 60 – 85 Mpc.

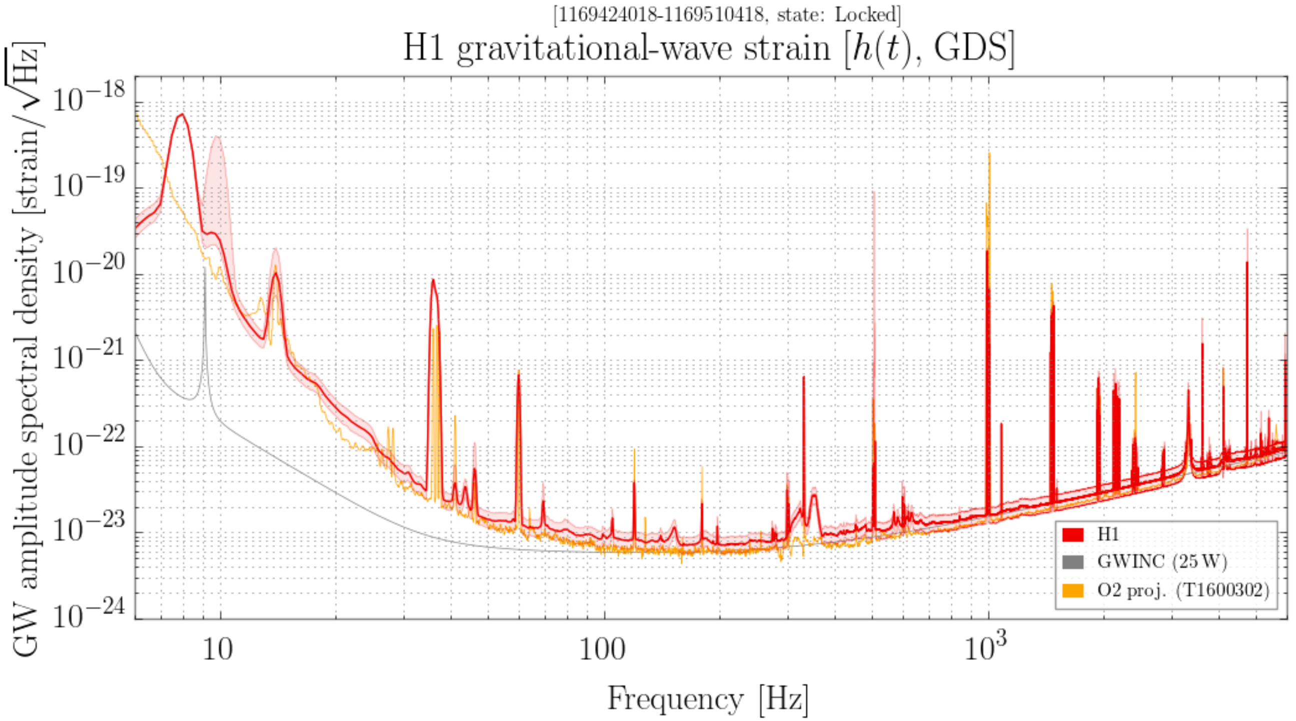
2019+ Three-detector network with H1L1 at full sensitivity of 200 Mpc and V1 at 65 – 115 Mpc.

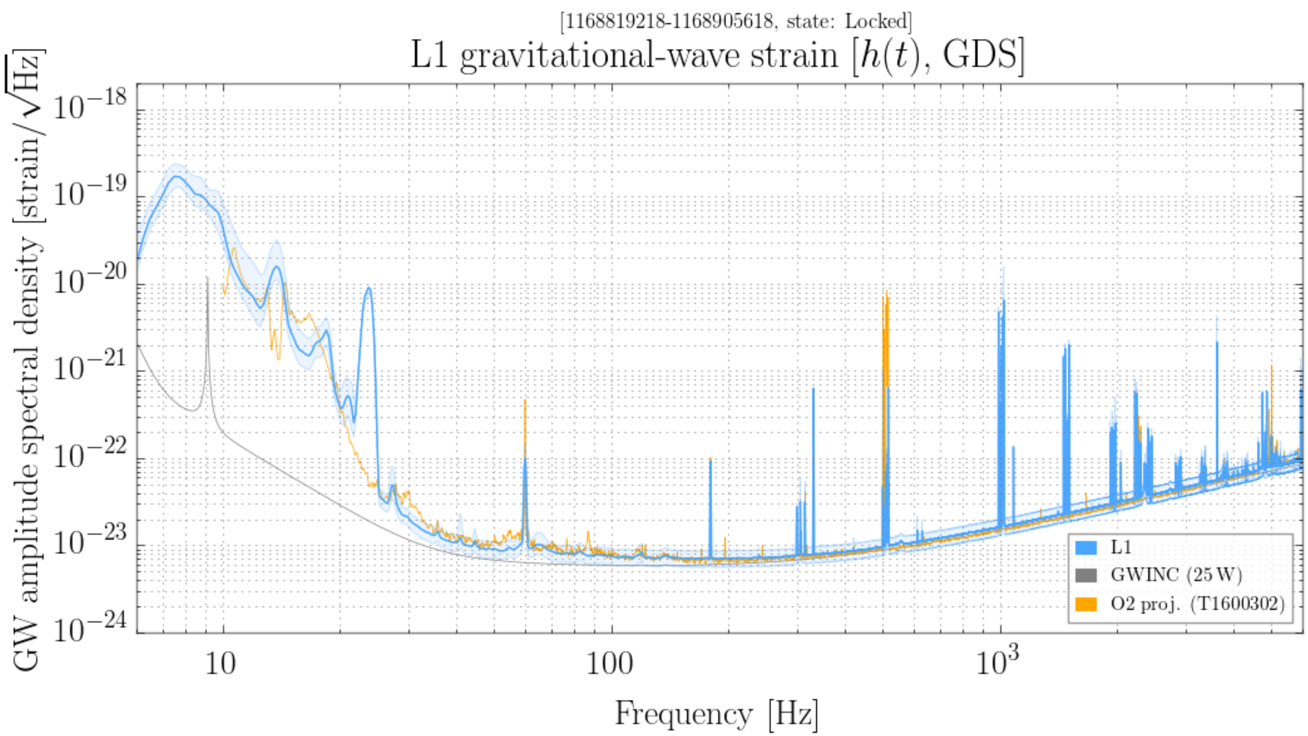
aLIGO status

- Since O1 :
  - Noise hunting at low-frequency to reduce « technical » noise
  - Increase laser power (35 W @ L1 – 50 W → 25 W @ H1)
- Challenges :
  - Thermal lens in mirrors require more active thermal compensation
  - Mirror alignment control
  - Parametric instabilities : acoustic modes of the mirrors get excited and pump light in high order optical modes that become resonant in the arms.



Many unknown sources of noise @ Hanford


[1169424018-1169510418, state: Locked]
H1 gravitational-wave strain [h(t), GDS]
GW amplitude spectral density [strain/√Hz]
Frequency [Hz]
H1
GWINC (25 W)
O2 proj. (T1600302)


[1168819218-1168905618, state: Locked]
L1 gravitational-wave strain [h(t), GDS]
GW amplitude spectral density [strain/√Hz]
Frequency [Hz]
L1
GWINC (25 W)
O2 proj. (T1600302)

Advanced Virgo preparation

- Accumulated a serie of unexpected problems/accidents
  - Broken suspension blades due to H embrittlement
    - 160/260 blades changed
    - ~ 4 months of delay
  - Monolitic suspensions breaking : anchors culprit
    - Suspected cause : adV anchor glass contains OH that are eliminated through heating generating H_2 that migrates and creates bubbles during welding
    - 3/4 replaced with steel wires
    - Several months of delay
- Almost all hardware installed & commissioning has started !

Recently : PR-ITF locked with MICH offset = 0.1 (90% of dark fringe)

  - Unfortunately, still many tasks (controls & noise hunting) before measuring a sensitivity curve. Very unlikely Virgo will join O2.

AdV installatioin in a nutshell

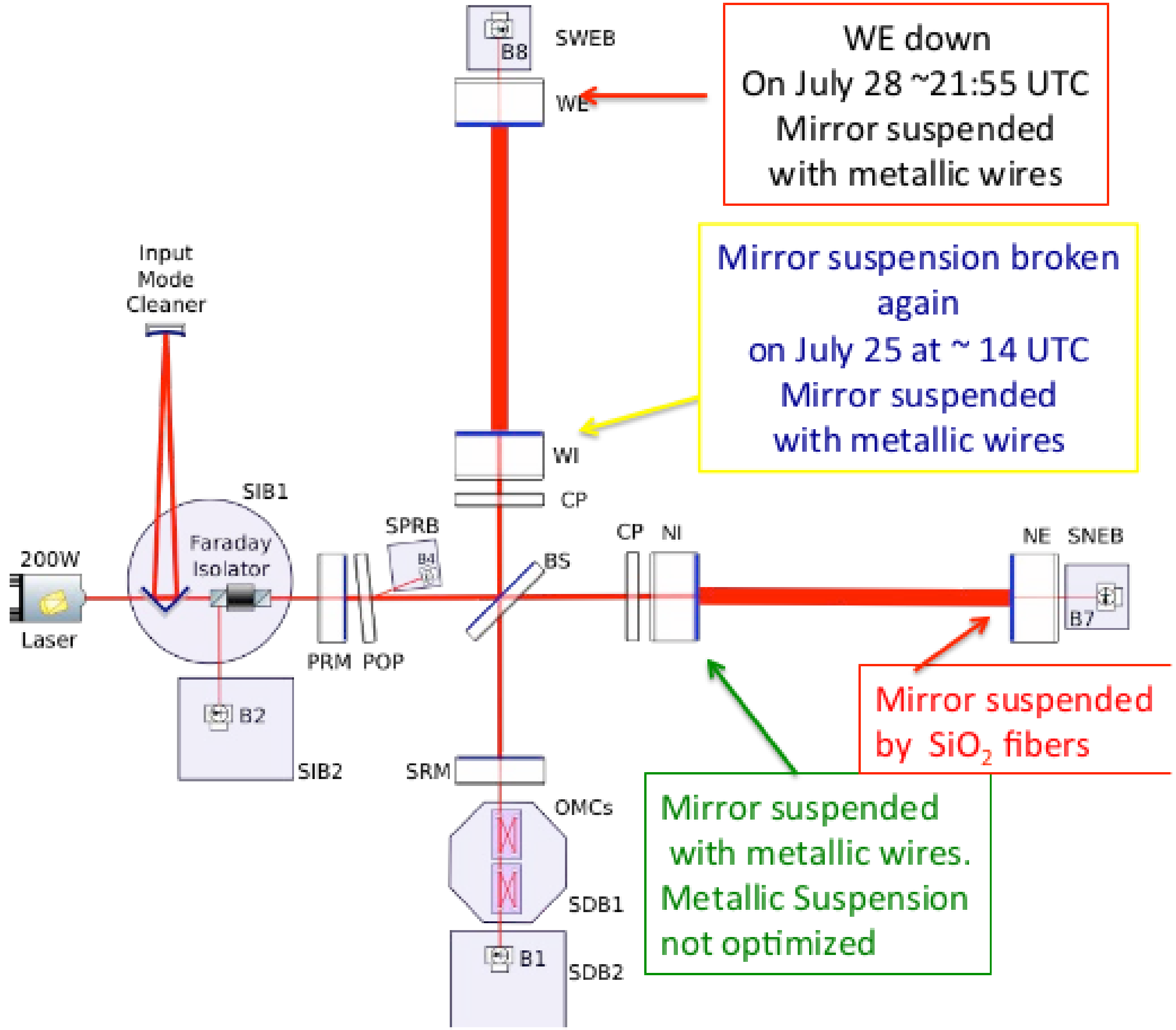
All the main parts of hardware are on-site and are installed

Final NI payload installation TBD soon

Failure of a NIKHEF blade solved promptly

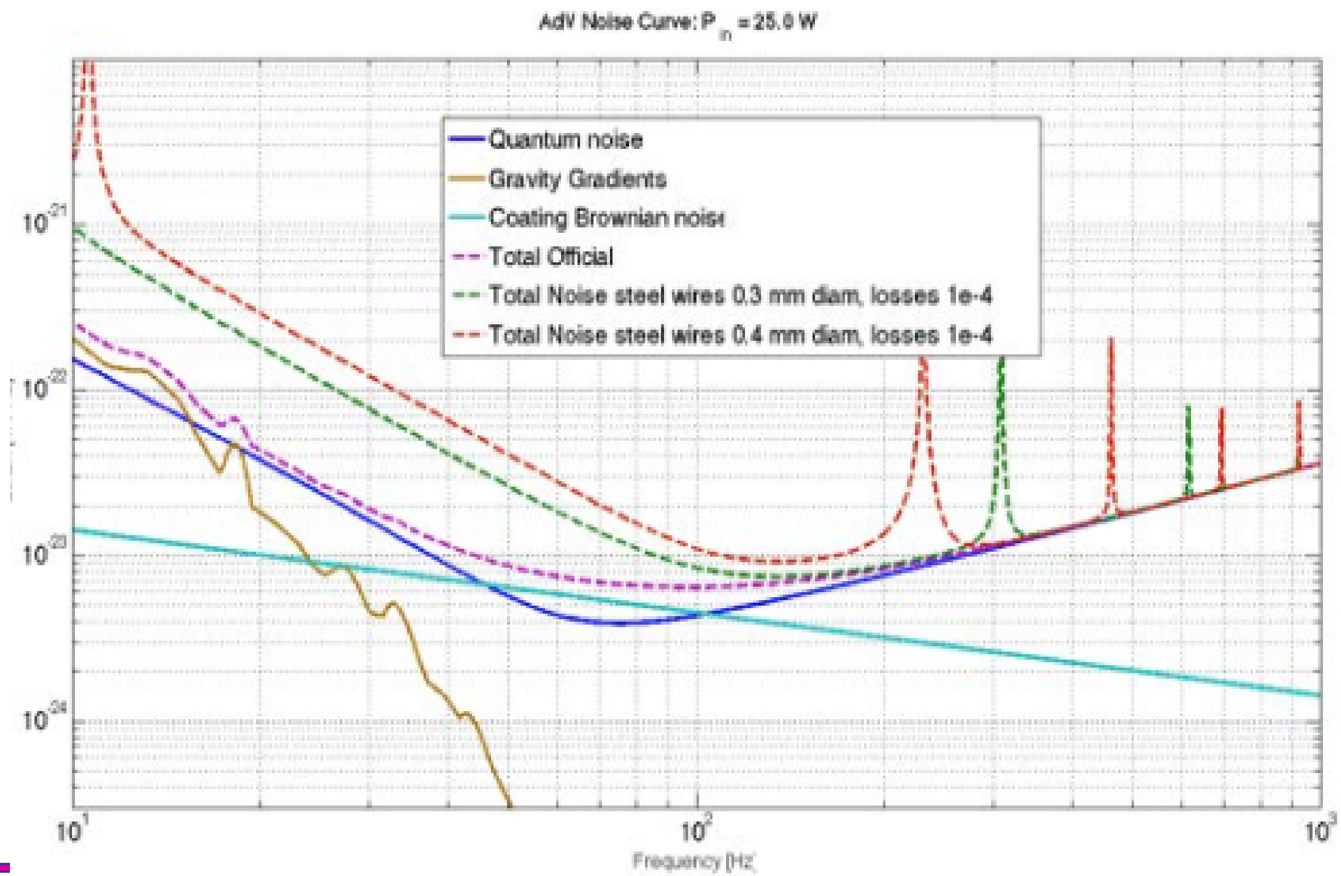
Commissioning of the North arm done. Arm locked. Light circulating also on CITF

West Input down again: action lan TBD



Which sensitivity for O2 ?

- Keep steel wires suspensions
- Join O2b with « relevant » sensitivity



	Steel 300 µm $\phi=10^{-4}$ ($\phi=10^{-3}$)
Violin [Hz]	307
Bouncing [Hz]	8.3
BNS Horizon [Mpc]	60 (45)
BBH Horizon [Mpc]	**313 (202)**

Conclusions

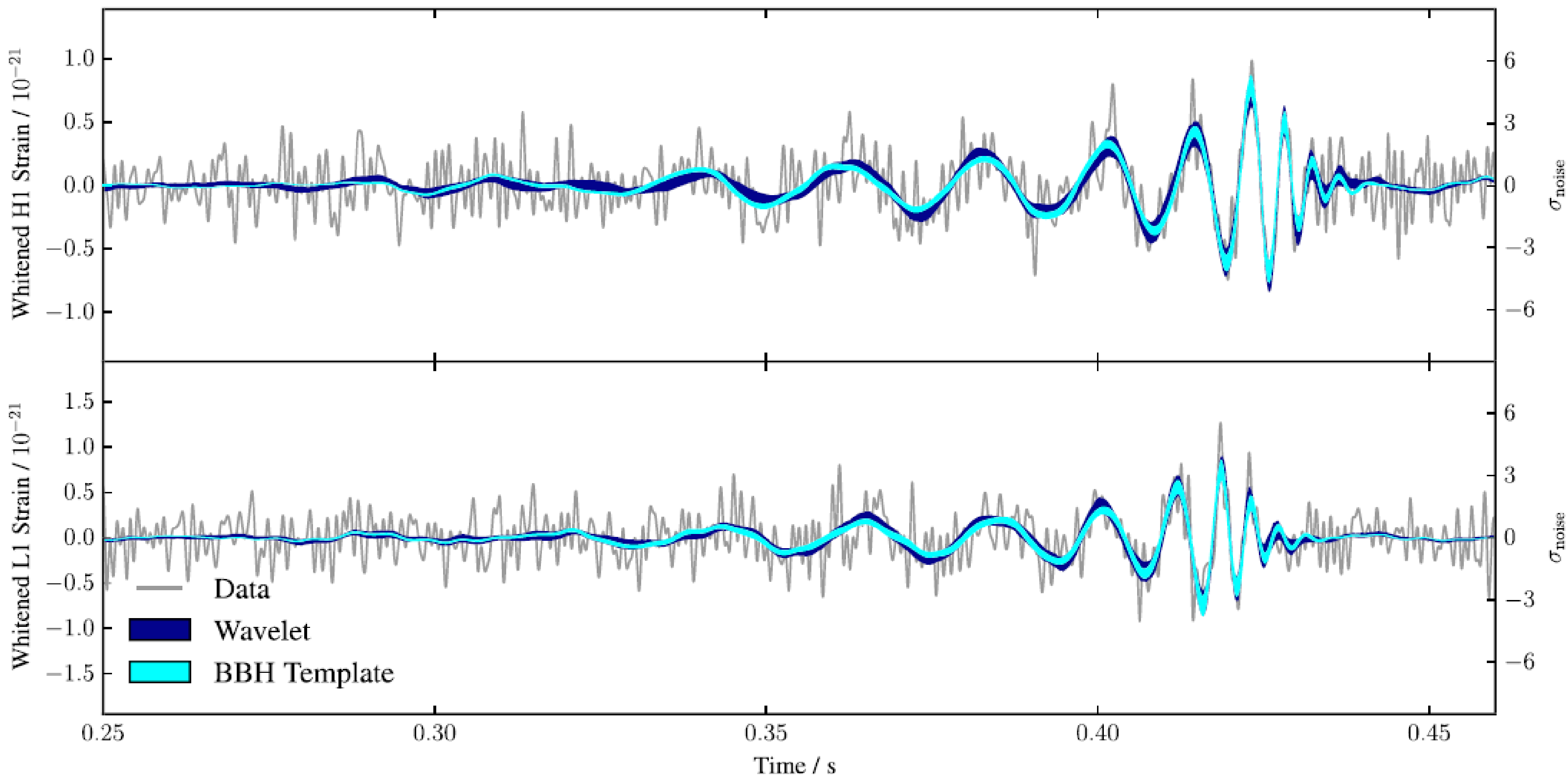
- We are already in the post-discovery era
  - Direct GW discovery
  - First observation of massive black holes
  - First observation of binary black hole mergers
  - Outcome :
    - Strong field tests of GR
    - Constrain binary system formation mechanisms
- More observation runs planned 2016-2020 (+KAGRA online 2018)
  - O2 : more BBH events expected and maybe first NSBH event ?
  - O3 : with Virgo hopefully
- New call for partnerships with EM partners

Additional slides

Testing general relativity

- Past tests done on binary
  - Typical speed : 10^{-3} c
  - Typical dP_{orb}/dt : 10^{-12} or less
- GW150914
  - Speed of black holes before merger : 0.5 c
  - dP_{orb}/dt : 0.1 – 1
- Unique opportunity to test general relativity in the strong field regime

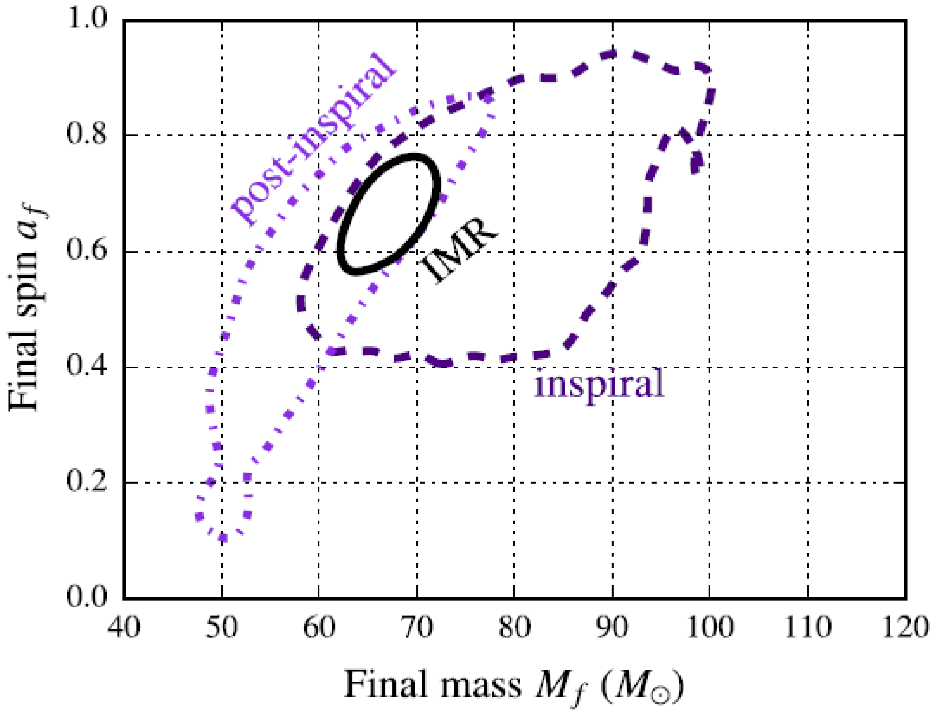
Consistency between observed waveform and GR



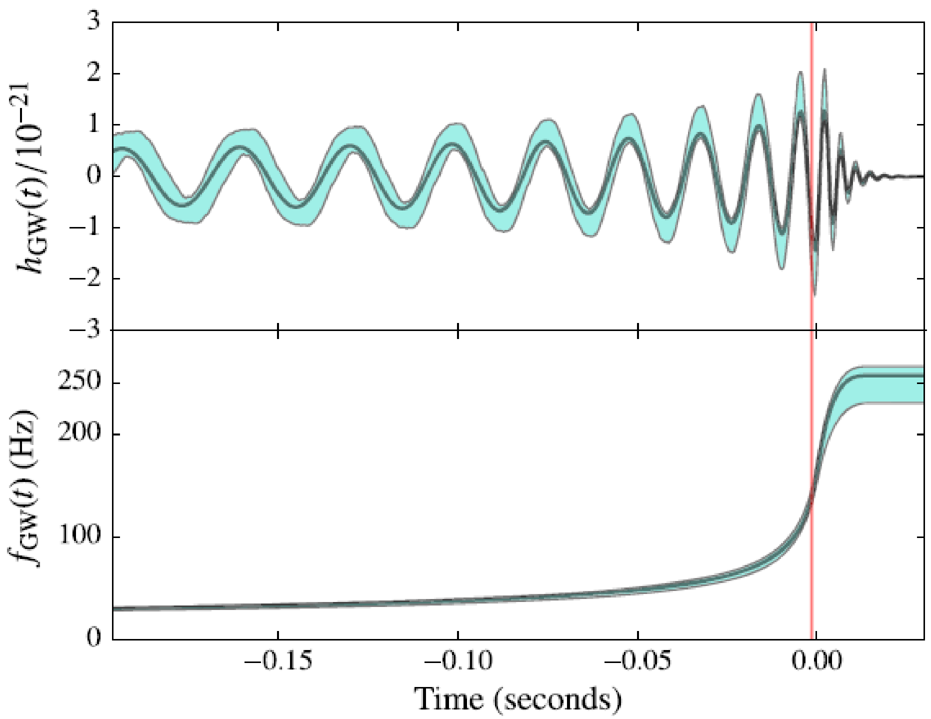
After subtracting the best-fit waveform, the residual is not statistically distinguishable from instrumental noise around the event time.

Inspiral – Merger - Ringdown

- Use the inspiral part of the waveform to predict the mass and spin of the final black hole.
- Compare it to the actual measurement using the post-inspiral part of the waveform.
- Robust against the definition of the inspiral and post-inspiral components.



90% confidence contours.
Observe good agreement.



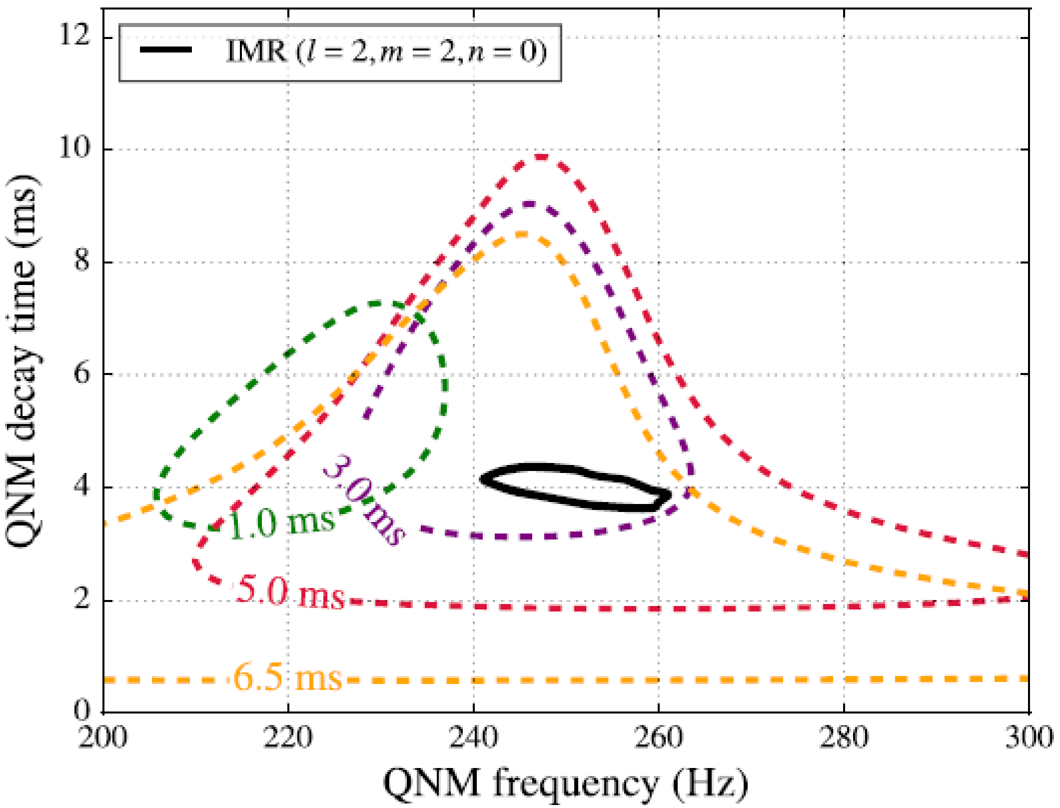
Quasinormal mode

- Measure the (single) least-damped quasinormal mode (l=m=2) of the remnant black hole.

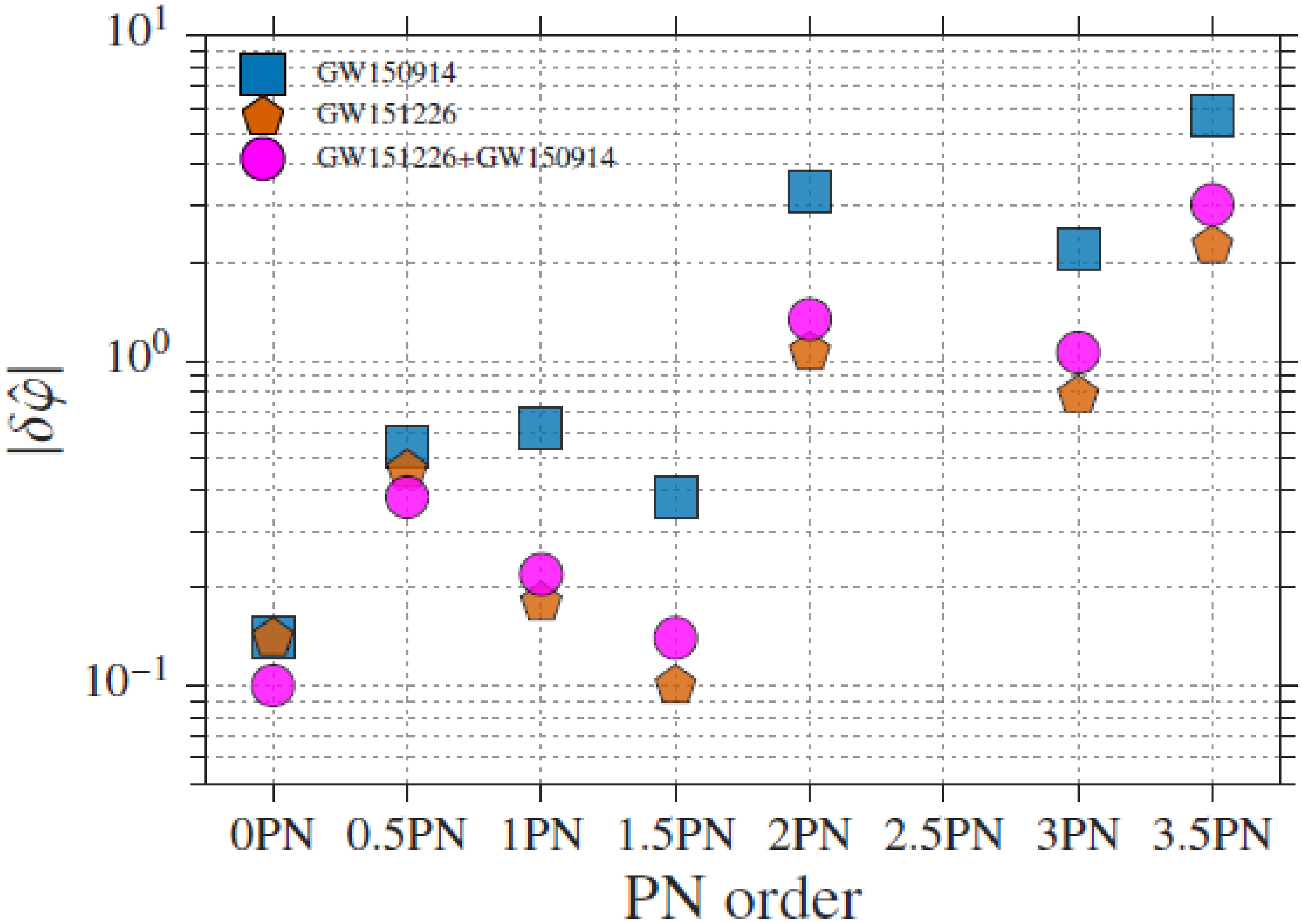
- Try different offsets relative to the merger time.

- Compare to the QNM estimate based on the final spin and mass of the remnant black hole.

- Reasonable agreement of the 90% confidence contours.



Testing general relativity
Deviations in post-Newtonian waveforms



The 90% credible upper bounds on deviations in the PN coefficients, from GW150914 and GW151226. Also shown are joint upper bounds from the two detections; the main contributor is GW151226, which had many more inspiral cycles in band than GW150914.

Graviton Compton Wavelength

- Massive graviton obeys a different dispersion relation.
- Graviton speed is energy and frequency dependent.
- This introduces a different phasing of the chirp waveform.
- Results at 90% confidence:
  $\lambda_g > 10^{13}$ km.
  $m_g < 1.2 \times 10^{-22}$ eV/c^2.
- 1000x better than previous dynamic bounds based on binary pulsars.
- Weaker than model-dependent bounds based on weak gravitational-lensing observations.

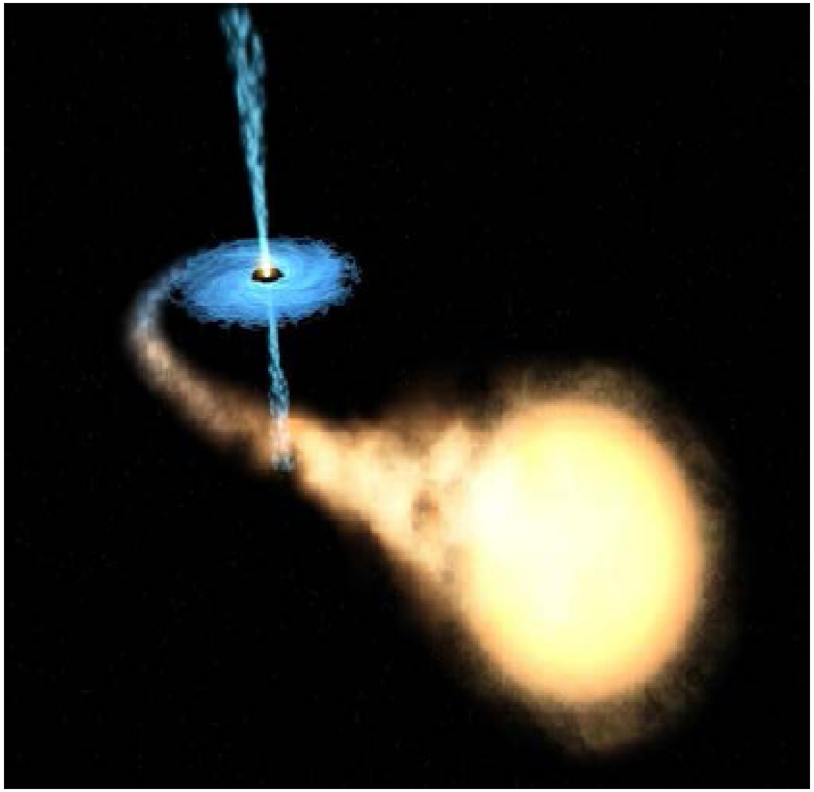
$$E^2 = p^2 c^2 + m_g^2 c^4$$

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

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

Astrophysics: Masses

- Past black-hole observations based on X-ray binaries:
  - Compact object accretes matter from a companion.
  - Measure orbital period, velocity etc. to estimate mass of the compact object.
  - Most estimates 5-10 Msolar, some higher (up to ~35 Msolar, some debated).
- GW150914 reveals that heavy stellar-mass black holes exist.
  They can also live in binaries and merge in the lifetime of the universe.



Astrophysics: Binary formation

- Two binary formation mechanisms have been proposed.
- Field:
  - » Starting from a binary star system, with each star going through the core-collapse to a black hole.
  - » Spins likely aligned with the orbital angular momentum.

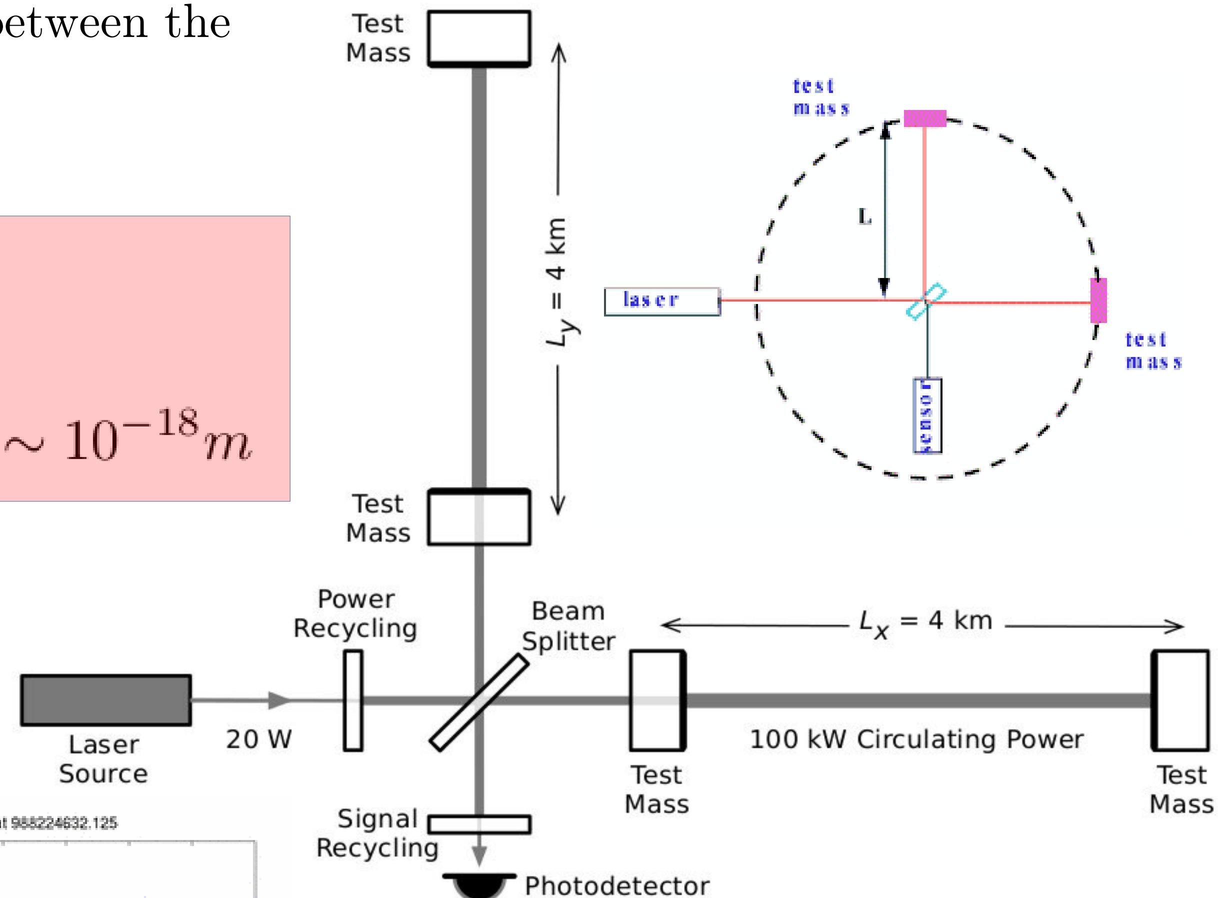
- Dynamic:
  - » Individually formed black holes in dense environments (globular clusters) fall toward the center of the potential well, where they dynamically form binaries (and are often ejected).
  - » Spins not expected to be correlated.

- GW150914 and GW151226 spin parameter estimates are consistent with either formation mechanism.

- Future observations could distinguish between the two:
  - » For example, a precessing binary would indicate dynamic formation.

GW detection with ground based laser interferometry detectors

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



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

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

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

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