The First Observation of a Gravitational Wave Event

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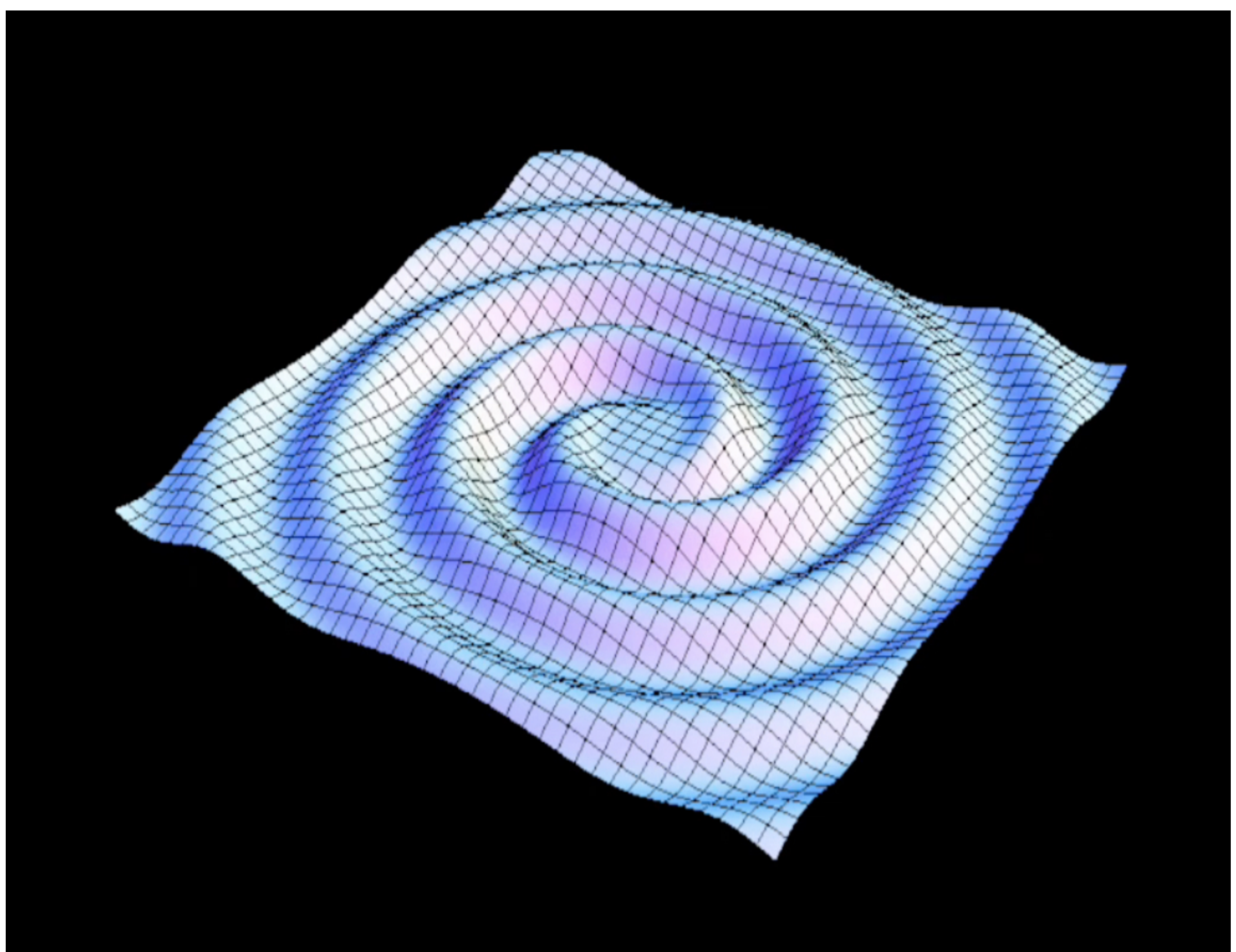
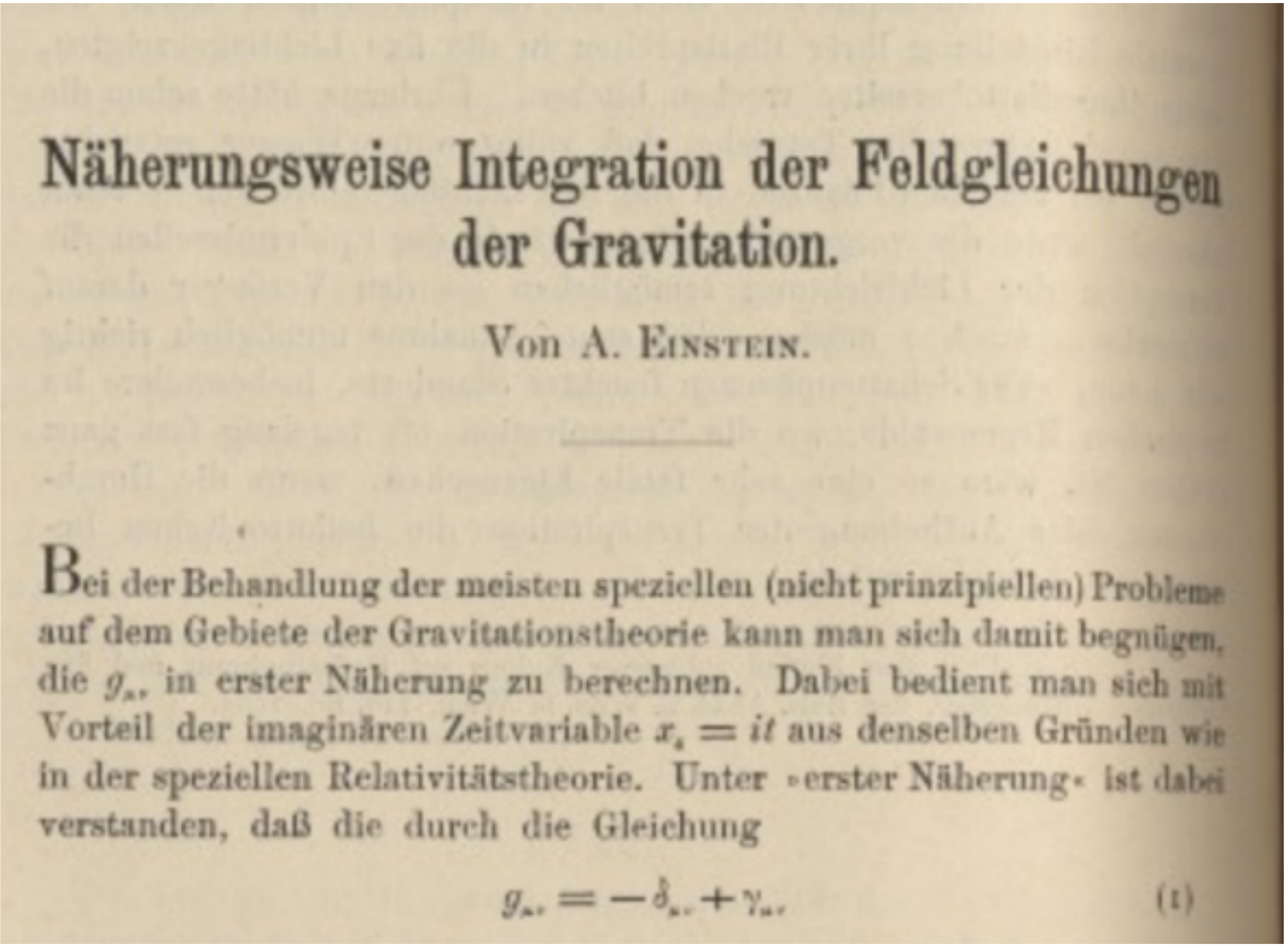


1916



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

Albert Einstein
Näherungsweise Integration der Feldgleichungen der Gravitation, Berlin 22.6.1916
Approximate integration of the field equations of gravitation

2016

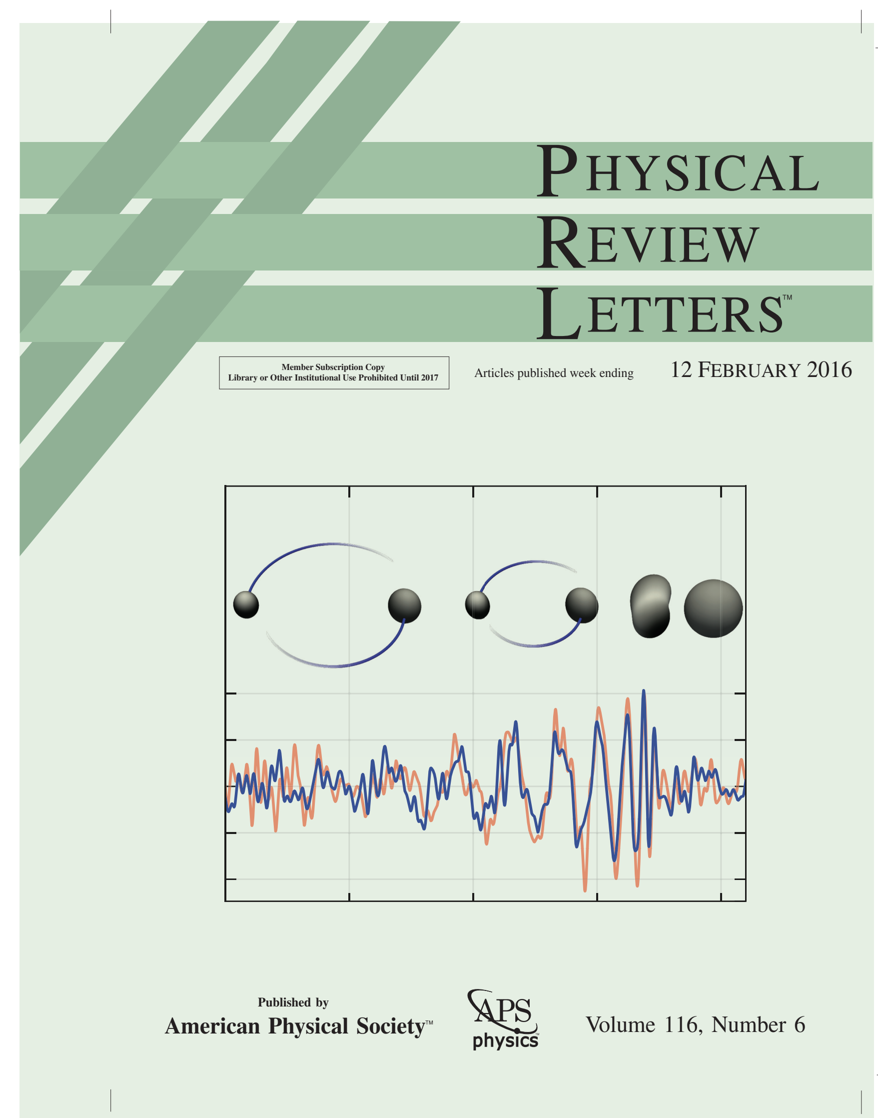
Selected for a Viewpoint in *Physics*
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102



229,000 paper downloads from APS in the first 24 hours

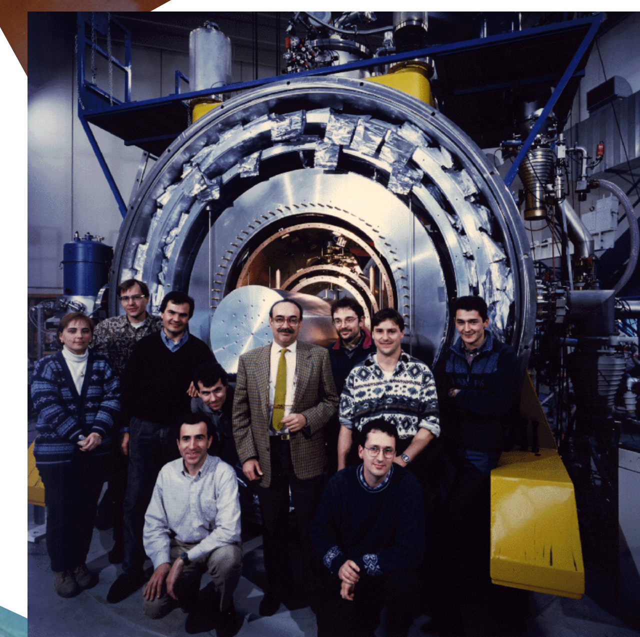
[Phys. Rev. Lett. 116, 061102 (2016)]

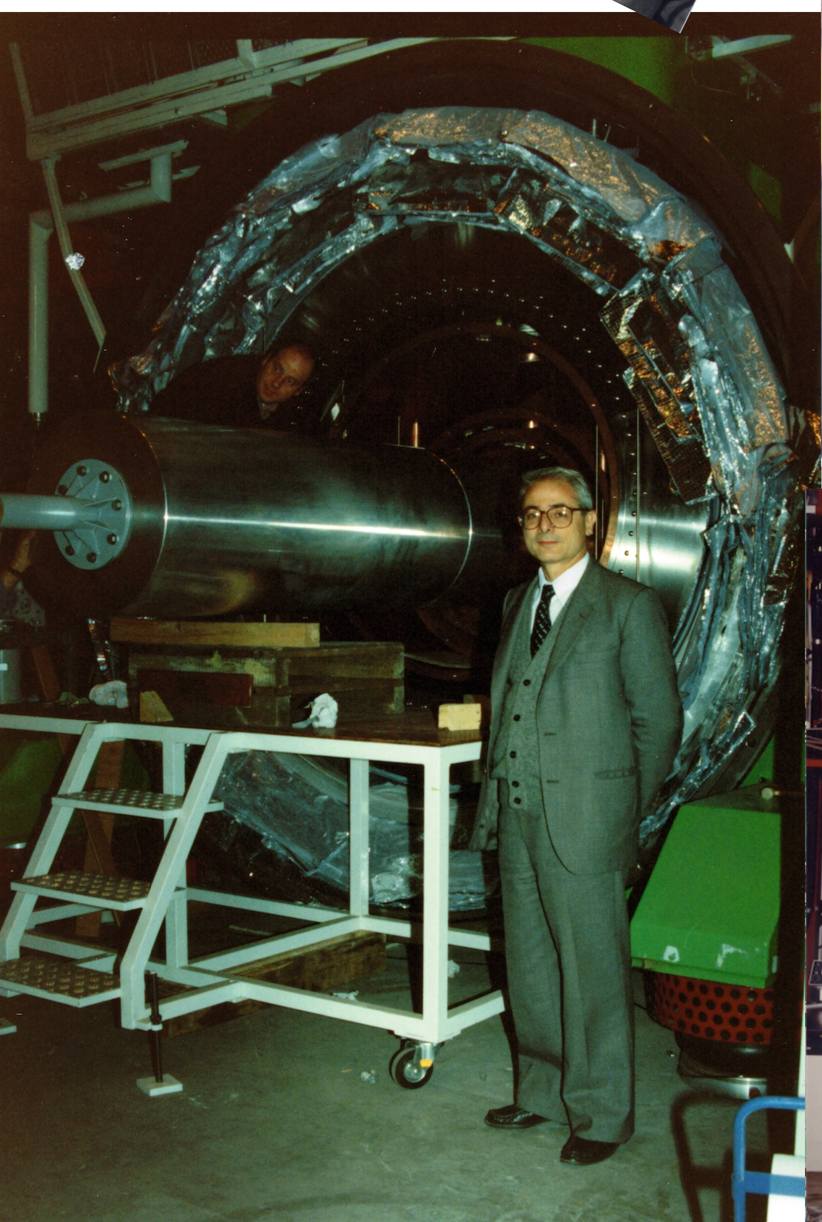
GW150914 papers

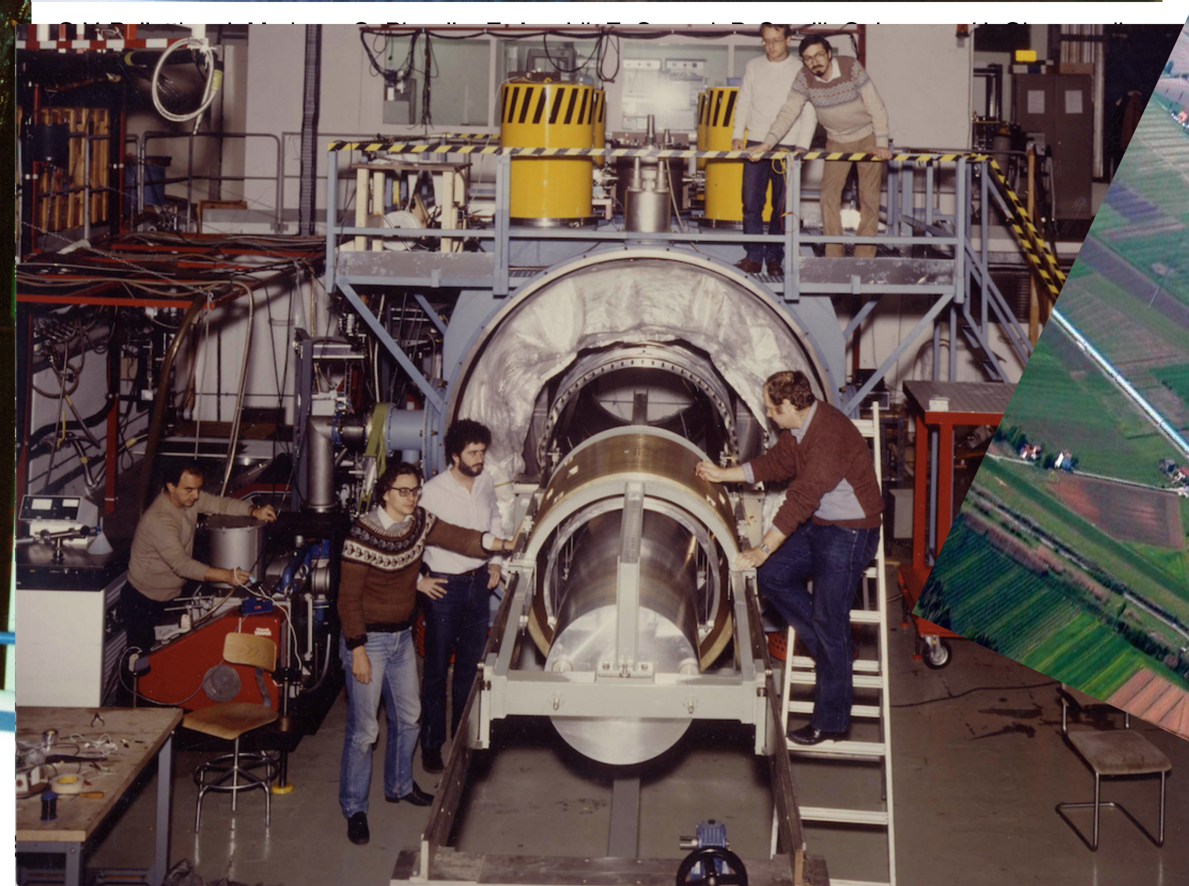
- **Detection Paper**
  Phys. Rev. Lett. 116, 061102 (2016) arXiv:1602.03837
- **Astrophysics implications**
  ApJL, 818, L22, 2016
  arXiv:1602.03846
- **Test of GR**
  arXiv:1602.03841
- **Rates**
  arXiv:1602.03842
- **Stochastic Background**
  arXiv:1602.03847
- **EM follow-up**
  arxiv.org/abs/1602.08492
- **High Energy Neutrinos**
  arxiv.org/abs/1602.05411
- **CBC searches**
  arXiv:1602.03839
- **Unmodeled searches**
  arXiv:1602.03843
- **Parameter Estimation**
  arXiv:1602.03840
- **Instrument**
  arXiv:1602.03838
- **DetChar**
  arXiv:1602.03844
- **Calibration**
  arXiv:1602.03845
- **Public data release**
  https://losc.ligo.org/events/GW150914

40 years of experimental effort

Il gruppo gravitazionale romano, 1973.



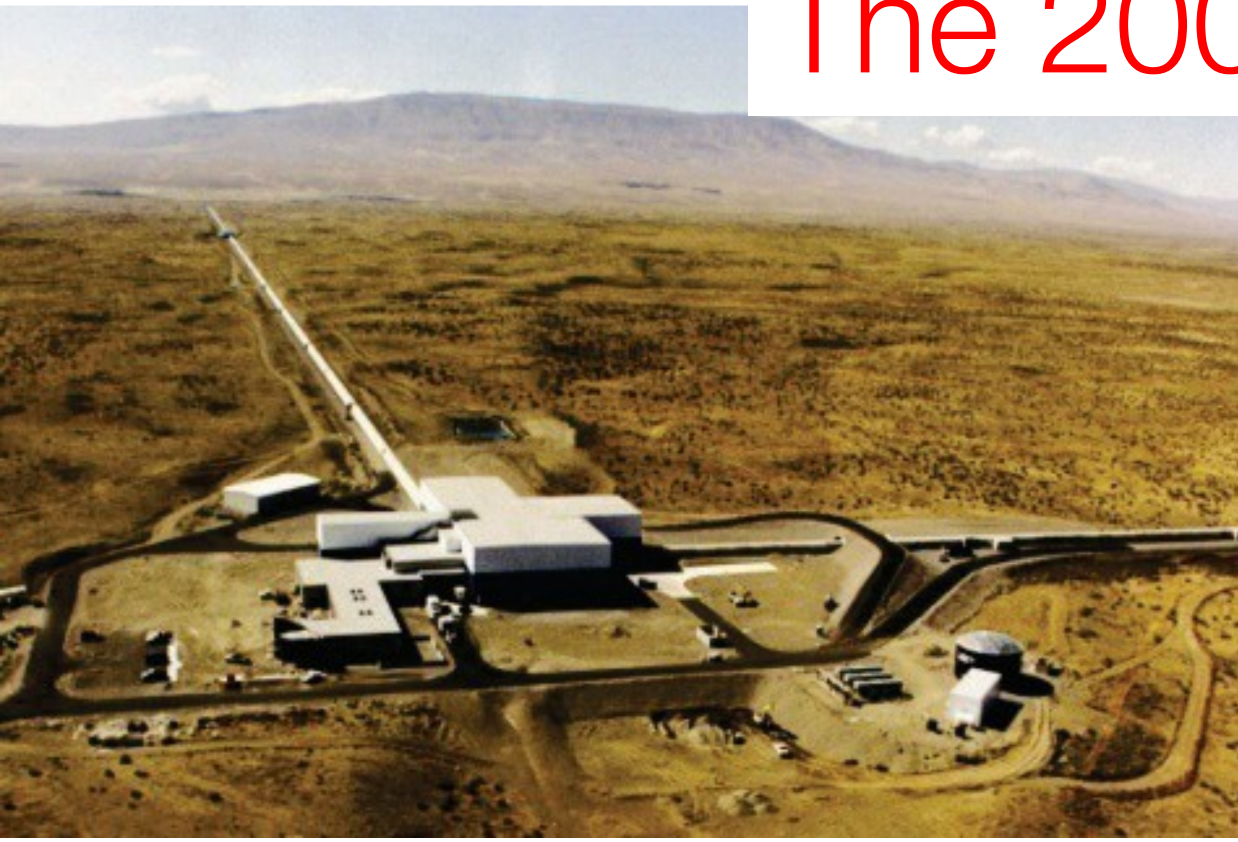




A bit of history of the GW interferometers

- The LIGO project was approved in 1992 and inaugurated in 1999. Built at a cost of almost $3x10^8$ \$, LIGO was the largest single enterprise ever undertaken by the foundation. It started the operation in 2002.
- VIRGO was formally proposed in 1989 and approved in 1993. The construction was divided in two step: it started in 1996 and then completed in 2003. The first science run is date 2007. The total investment done by CNRS and INFN was almost 8×10^7 \$.
- GEO600 was proposed in 1994. Since September 1995 this British-German GW detector was under construction. The first science run was performed in 2002. In 2013 Squeezing light was used over one complete year!
- First attempt to exchange data and mix the data analysis groups started in 2004. The formal MoU of data sharing and common analysis among GEO-LIGO-VIRGO was signed in 2007.

The 2007 GW network



H1- Hanford – Washington state

Virgo – Cascina (Pisa) – EGO site

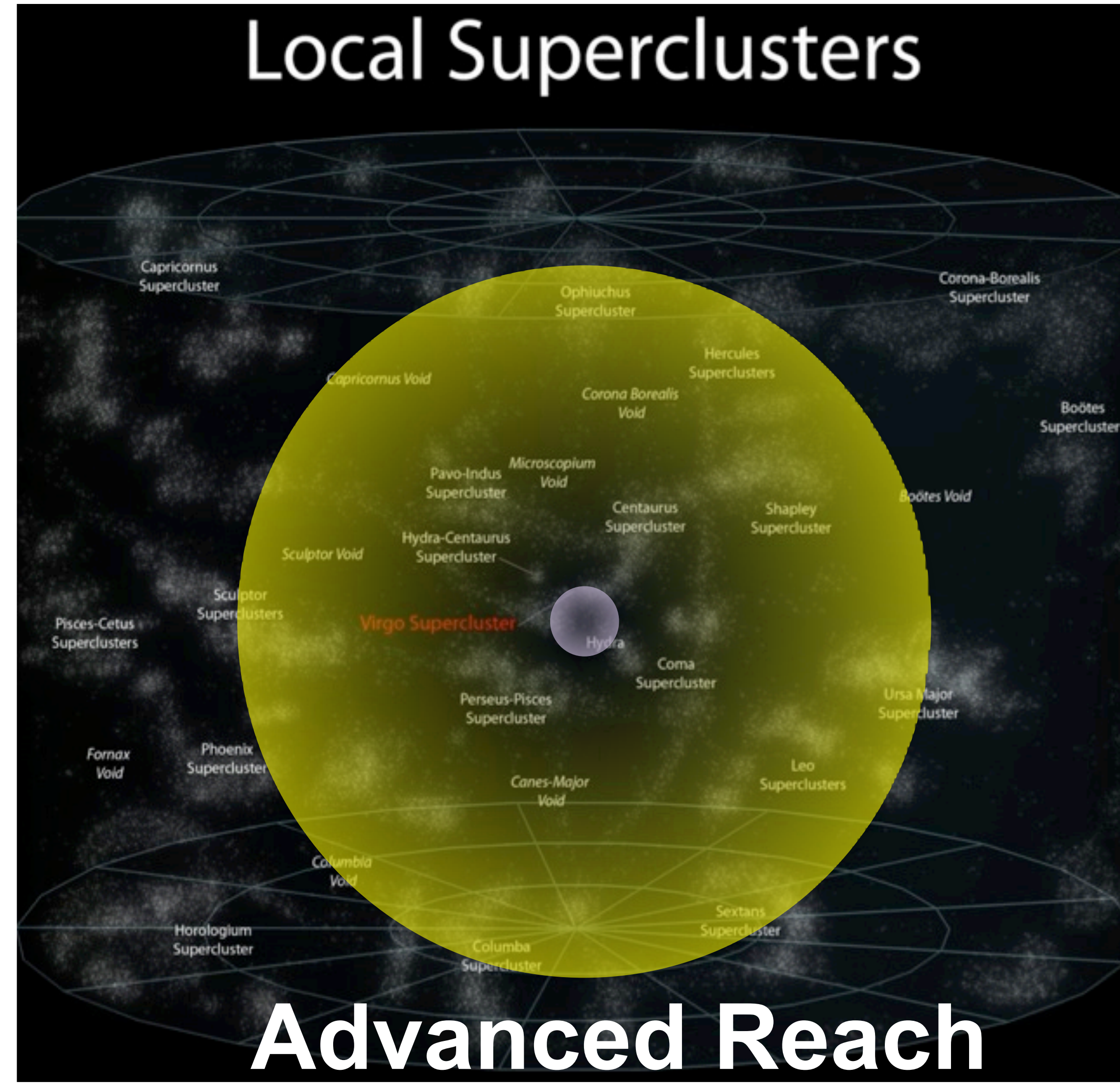
GEO600 – Hannover - Germany

L1- Livingston – Louisiana state

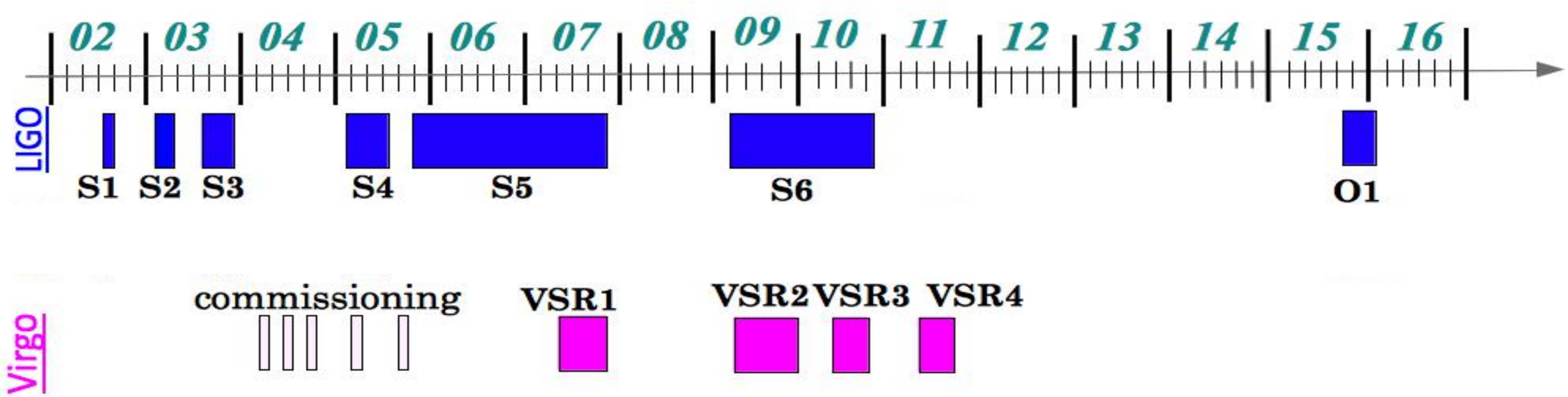
Advanced detectors

- Upgrade of the LIGO
- LIGO cost: $205M (NSF) and $16M in hardware from partners in Germany, UK, and Australia
- aLIGO approved in 2008, inauguration May 2015
- First observing run O1 from mid-September 2015 to mid-January 2016.

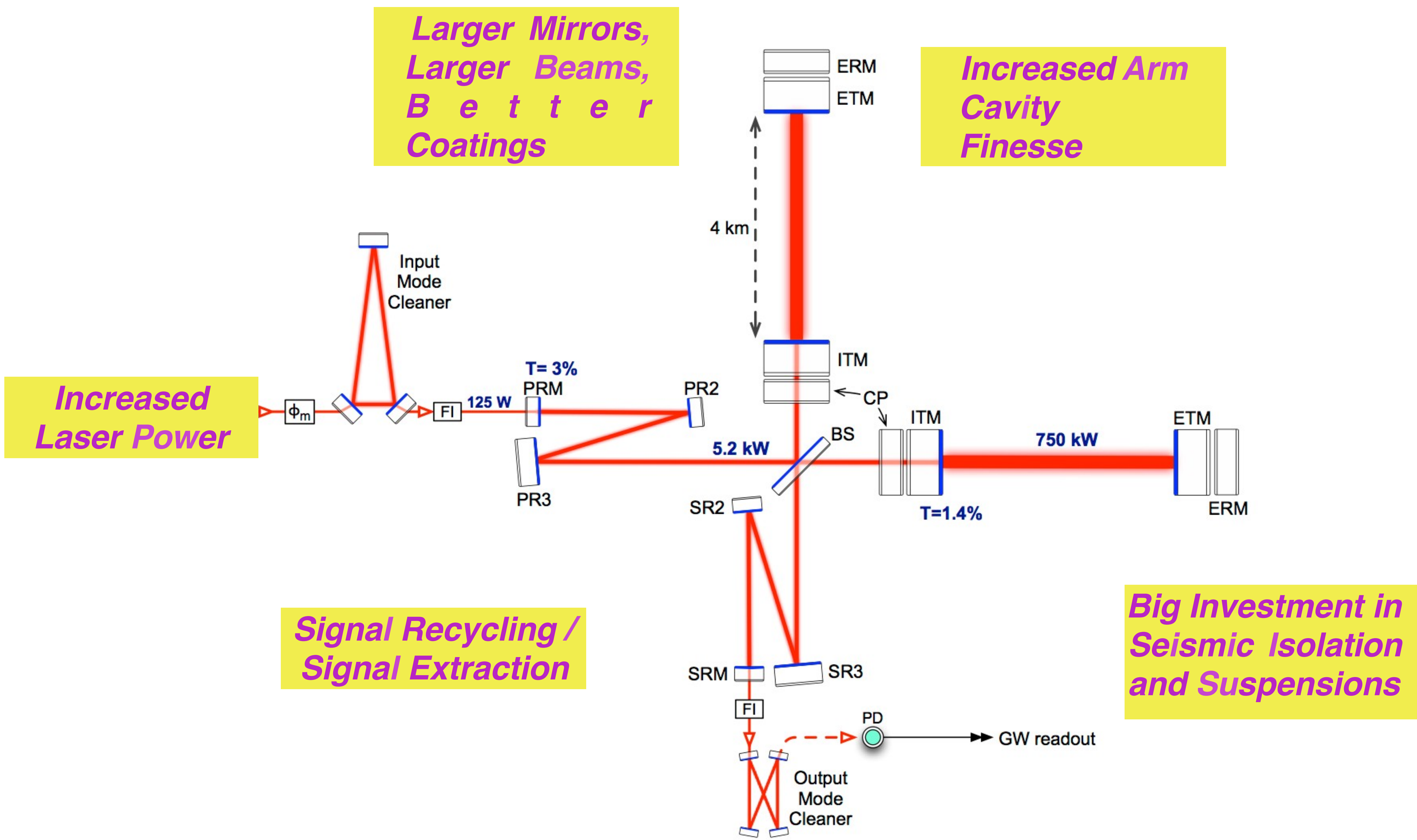
- Upgrade of Virgo
- aVirgo cost: 23 M from CNRS,INFN and NIKHEF
- aVirgo approved in 2011 and project started in 2012
- Installation to be completed in the first half of 2016



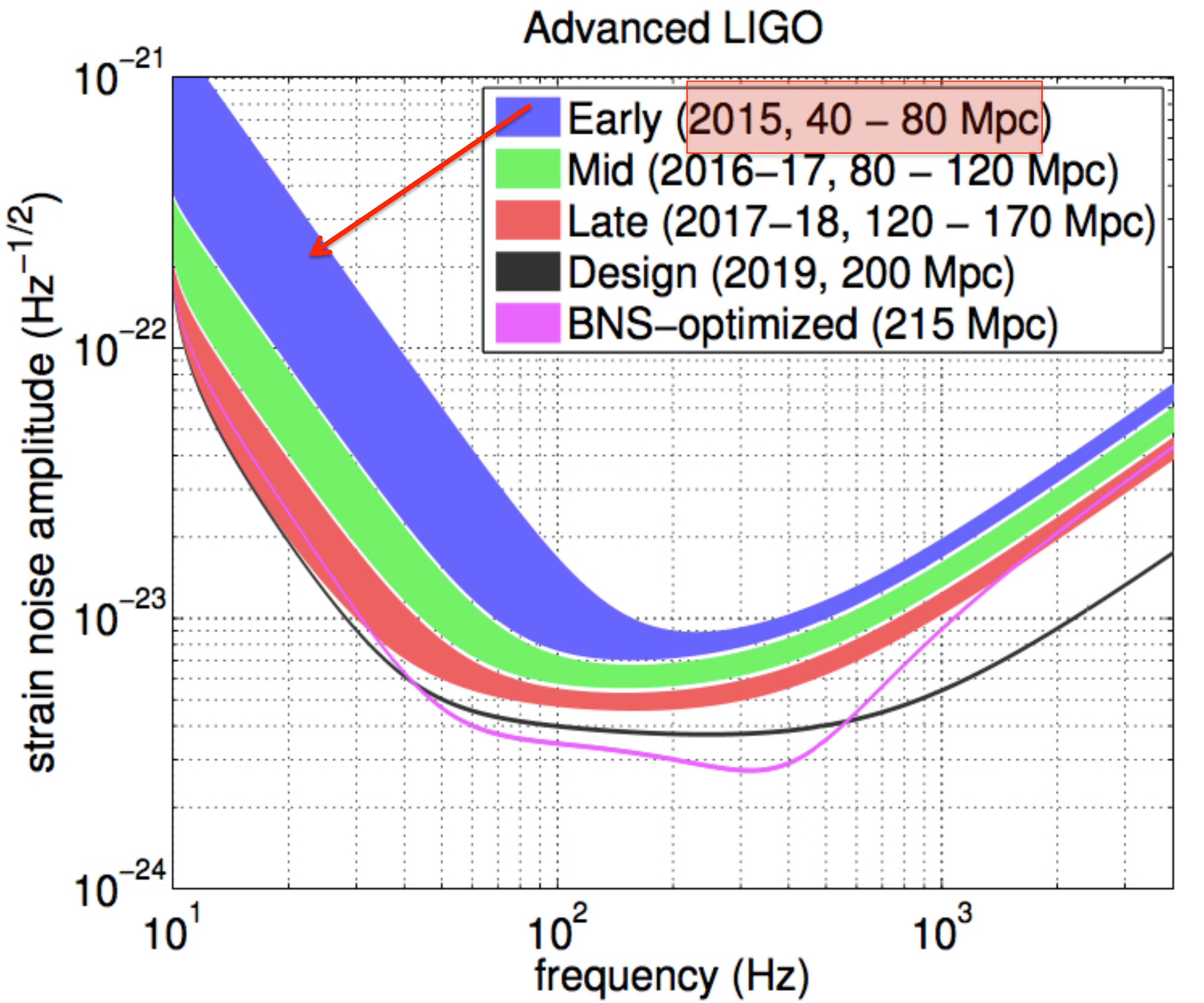
Ultimately 10x more sensitive
→1000x more volume probed



From the first generation to the second one



First sensitivity target achieved already !



Compact Binary Coalescence: The Primer

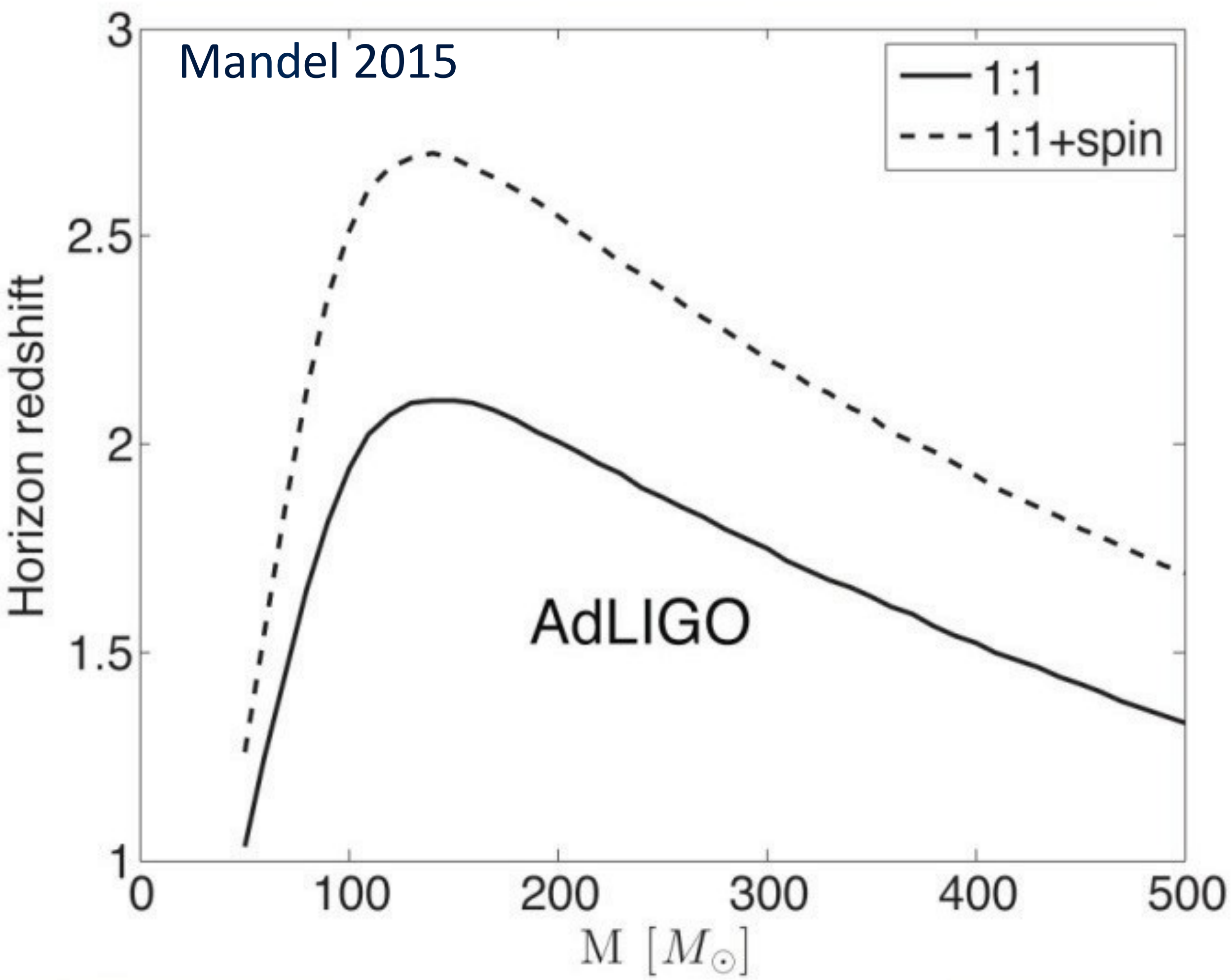
- Compact objects form in the galaxy: we have observations of (at least) binary neutron stars
- All binaries emit gravitational radiation (just as accelerated charges emit electromagnetic radiation) $P_{GW} \sim M^3/r^5$, so binaries have to be close and very massive in order to emit non-negligible amounts
- Unstable process: loss of energy implies smaller orbits, smaller orbits imply smaller radial separation, smaller radial separation implies larger energy loss, rinse, repeat ad nauseum
- Strong field general relativity takes over at some point, and the objects can only occupy stable orbits, they plunge together and merge, forming a single compact object

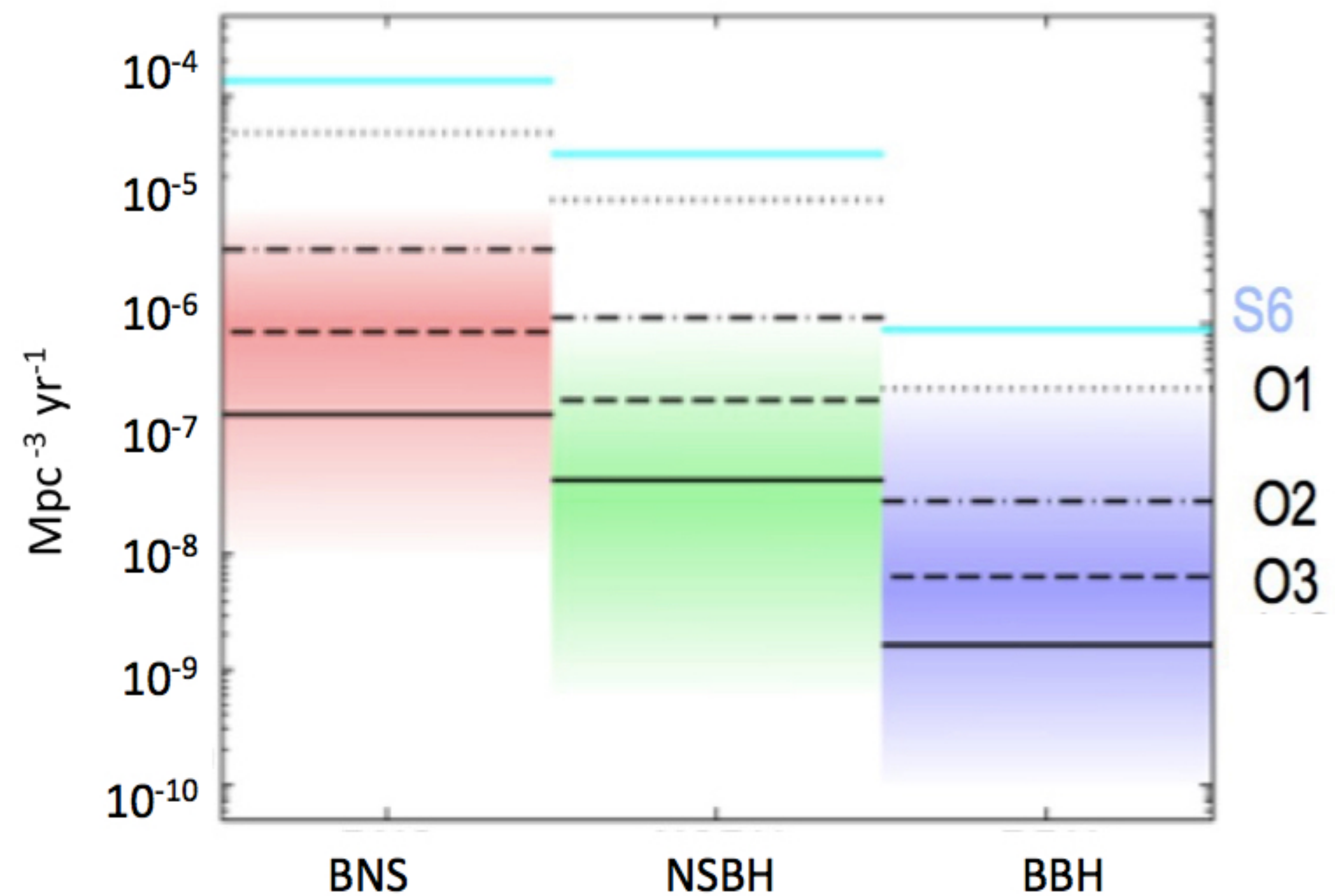
	Earth / Sun system	1.4 + 1.4 neutron star binary just before merger
P_{GW}	$\sim 10^2$ W	$\sim 10^{48}$ W
$\dot{\omega}/\omega$	10^{-33} Hz	10^2 Hz

Compact Coalescing Binaries

Detection perspectives with advanced detectors

Phys. Rev D85 (2012) 082002

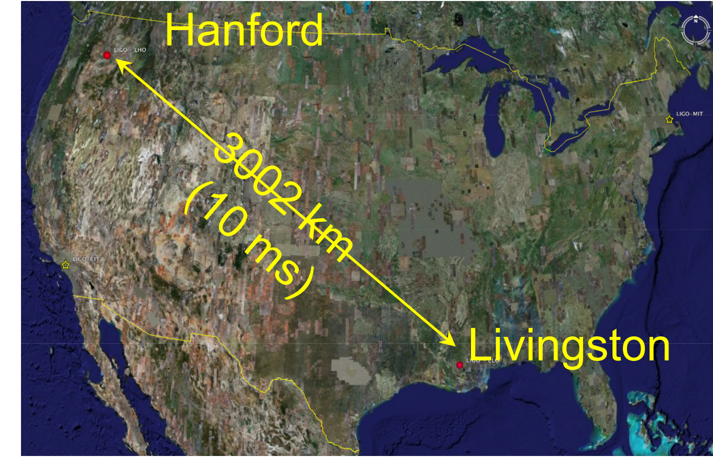


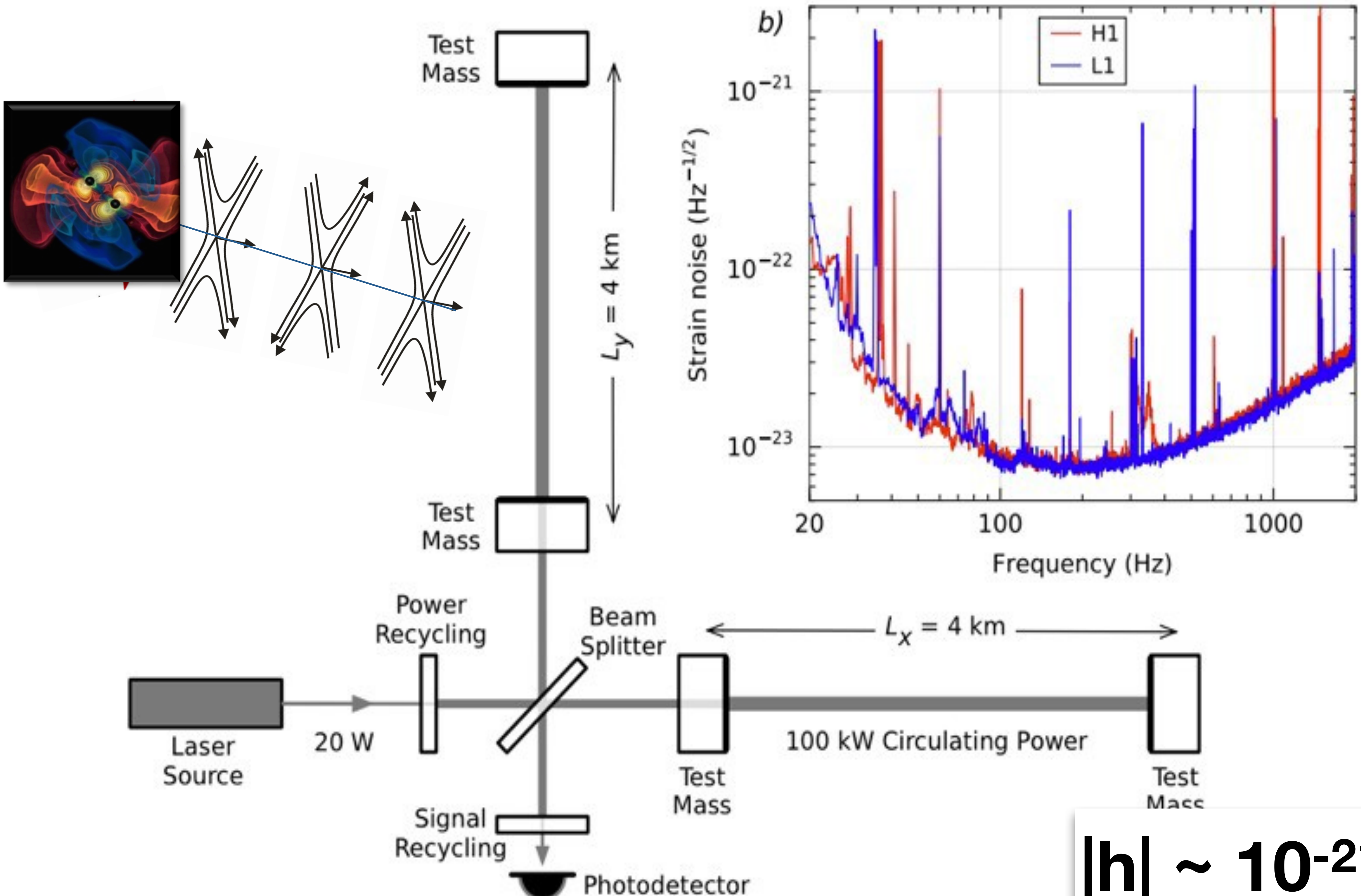


Epoch		2015	2016–2017	2017–2018	2019+	2022+ (India)
Estimated run duration		3 months	6 months	9 months	(per year)	(per year)
BNS range/Mpc	LIGO	40–80	80–120	120–170	200	200
	Virgo	—	20–60	60–85	65–130	130
BNS detections		0.0004–3	0.006–20	0.04–100	0.2–200	0.4–400

Probe beyond local universe100 $M_\odot$ + 100 $M_\odot$ BBH visible out to ~16 Gpc at design sensitivity (~5 Gpc in O1), even further if the source is spinning

The first run of the advanced detectors

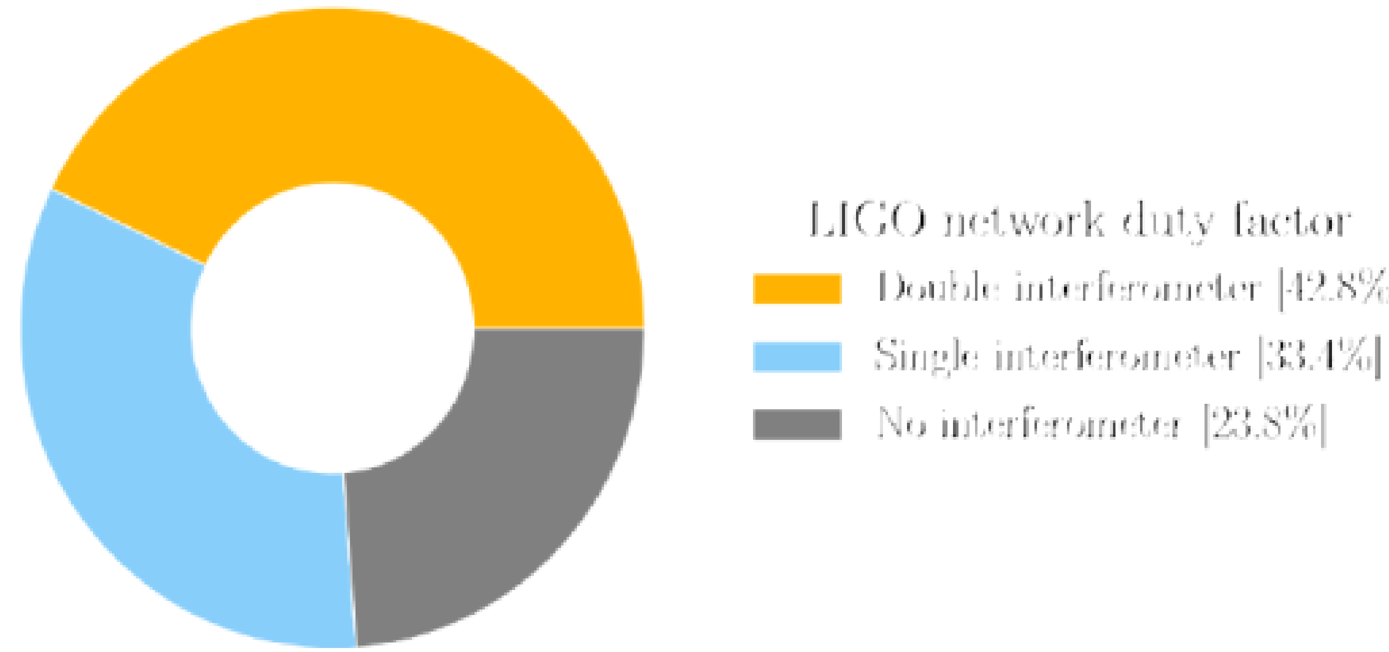




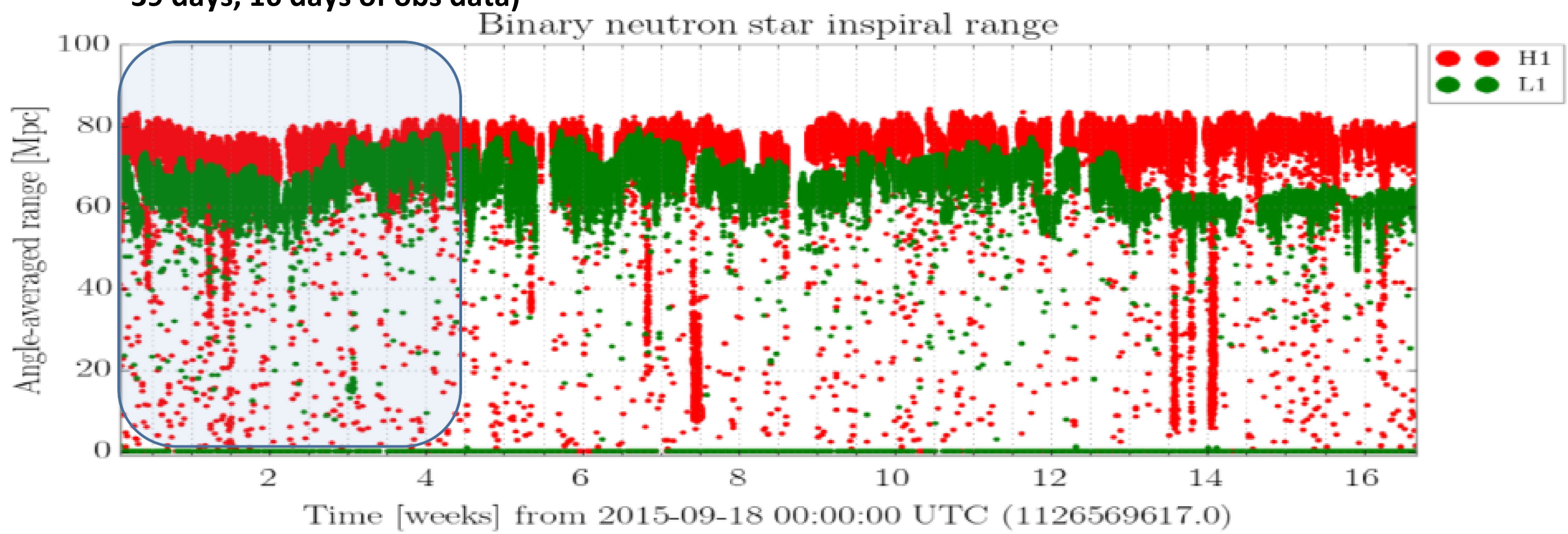
$|h| \sim 10^{-21}$

O1 in a nutshell

- Official dates : 18th of September 2015 to 12th of January 2016
- Dates with very good confidence : from the 12th of September to the 15th of January 2016
- H1 livetime : 62.6 %
- L1 livetime : 55.3 %



time analyzed to determine the significance of GW150914
(Sept 12 - Oct 20, 2015,
39 days, 16 days of obs data)



Hanford (H1) and Livingston (L1) in action

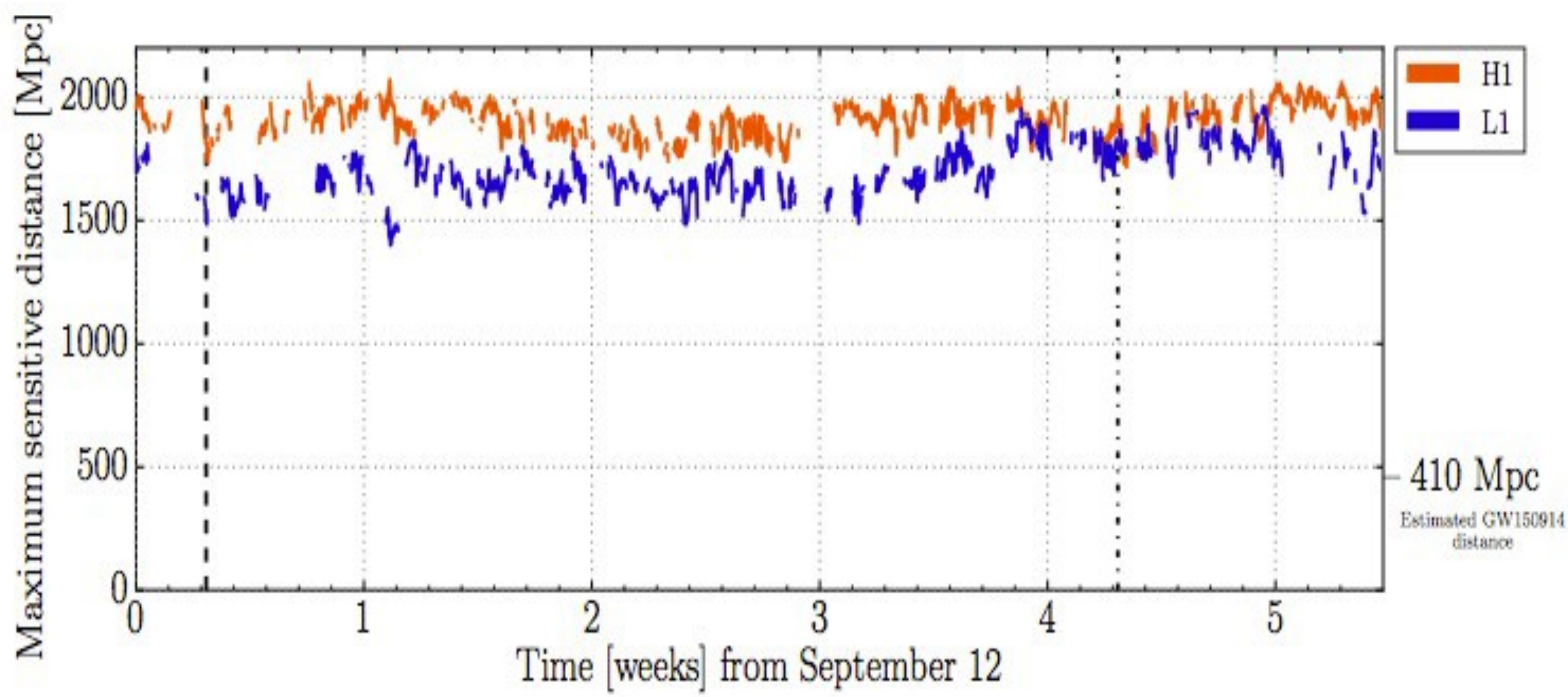
The detector was in a rather stable conditions from the beginning of September 2015 and took data until January 2016

Here we present just the analysis of the data taken in the period from September 12 to October 20, 2015

16 days of coincident data taking !!

16 days of data produced by 2 interferometers:

$5x10^{7}$ hours of CPU time ➔ 69444 months of CPU time !



The First Month of Observation Run 1

- Accumulated more space-time volume surveyed in first ~30 days than all previous data taking **combined**.

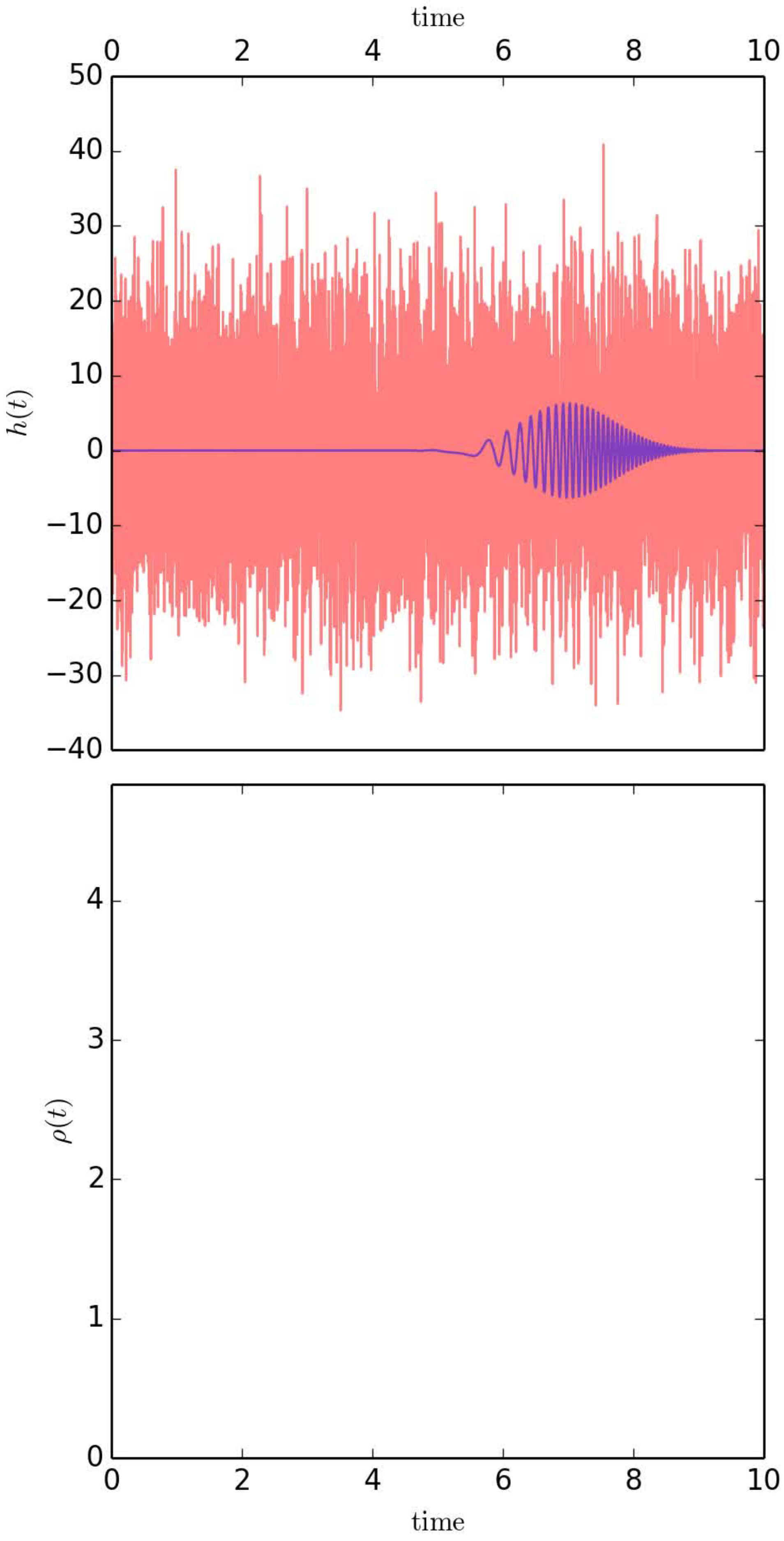
  - 1.4 + 1.4 horizon: 130 Mpc
  - 1.4 + 5 horizon: 200 Mpc
  - 20 + 20 horizon: ~1 Gpc

Signal-to-Noise ratio (SNR)

$$\rho = 4 \int_0^\infty \frac{\tilde{h}(f)\tilde{d}(f)^*}{S(f)} df$$

horizon distance (luminosity)

$$d_h = \frac{4}{\bar{\rho}} \int_0^\infty \frac{\tilde{h}_{1\ \mathrm{Mpc}}(f)\tilde{d}(f)^*}{S(f)} df$$

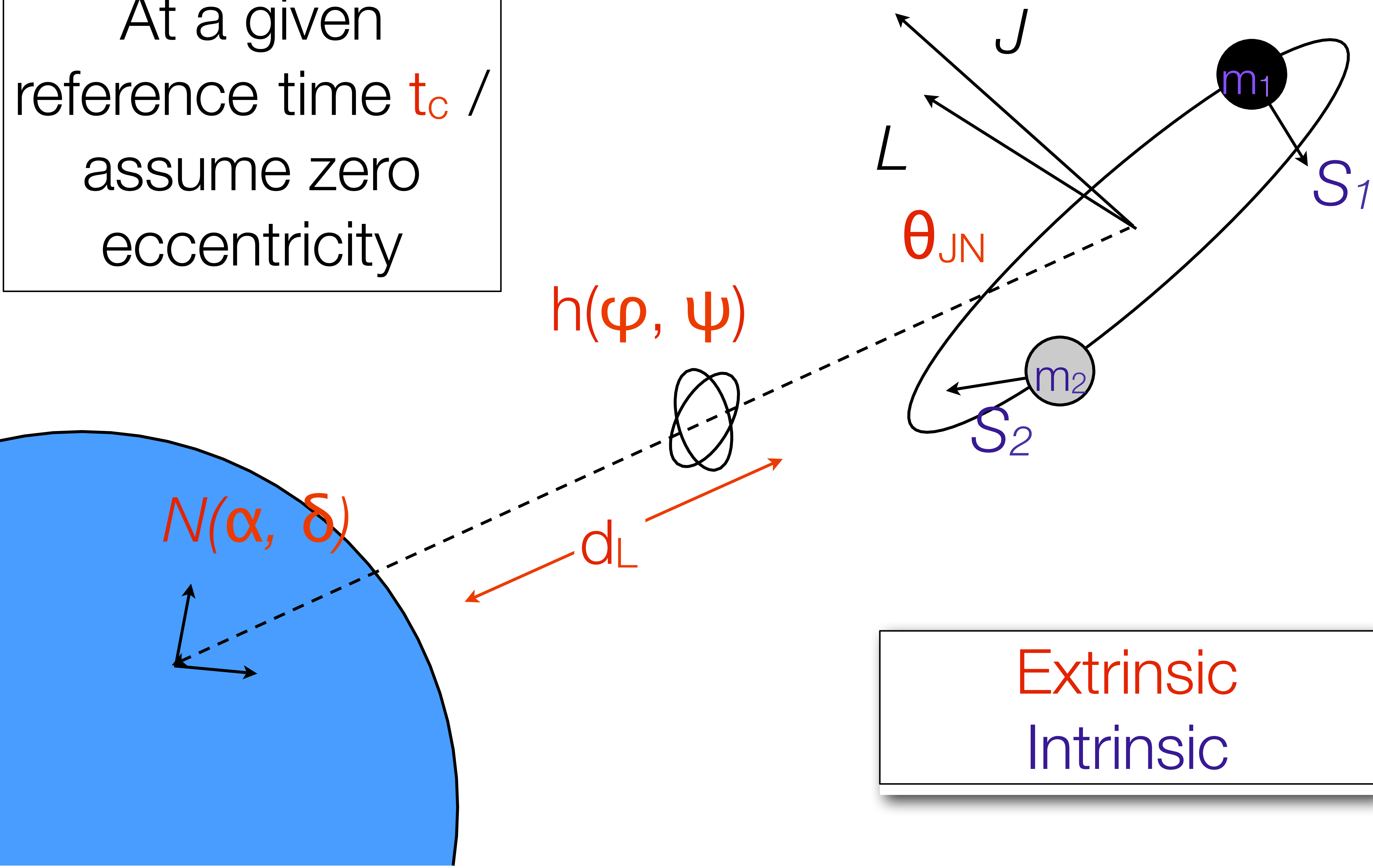


Matched filtering

- Calculate matched filter signal/noise as function of time ρ(t) and identify maxima and calculate χ^2 to test consistency with matched template, then apply detector coincidence within 15 msec
- Calculate quadrature sum ρ_c of the signal to noise of each detector
- Background: Time shift and recalculate 10^7 times equivalent to 608,000 years

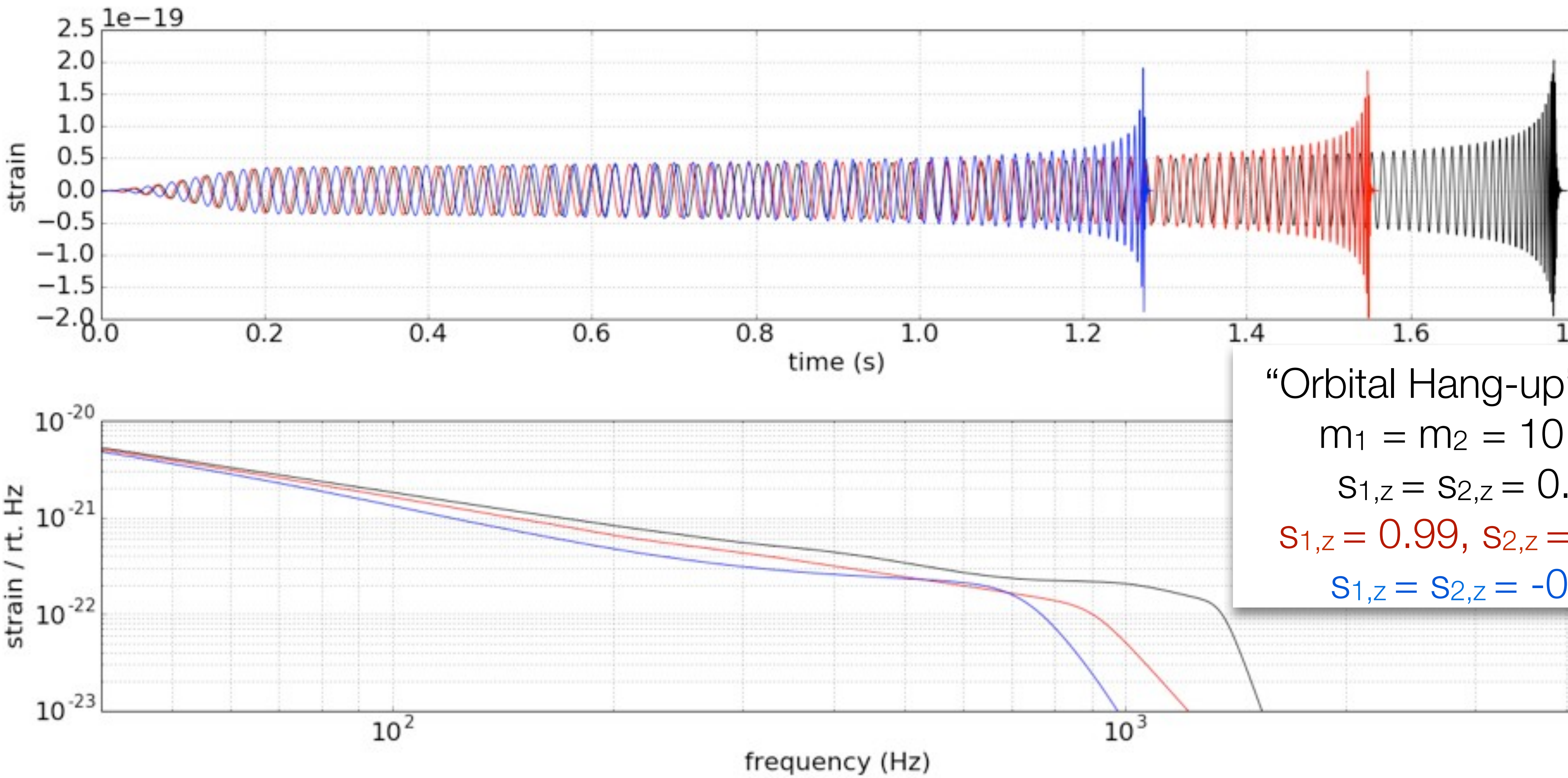
System Parameterization

At a given reference time t_c / assume zero eccentricity



Extrinsic
Intrinsic

Compact Binary Coalescence: Waveforms



"Orbital Hang-up" Effect

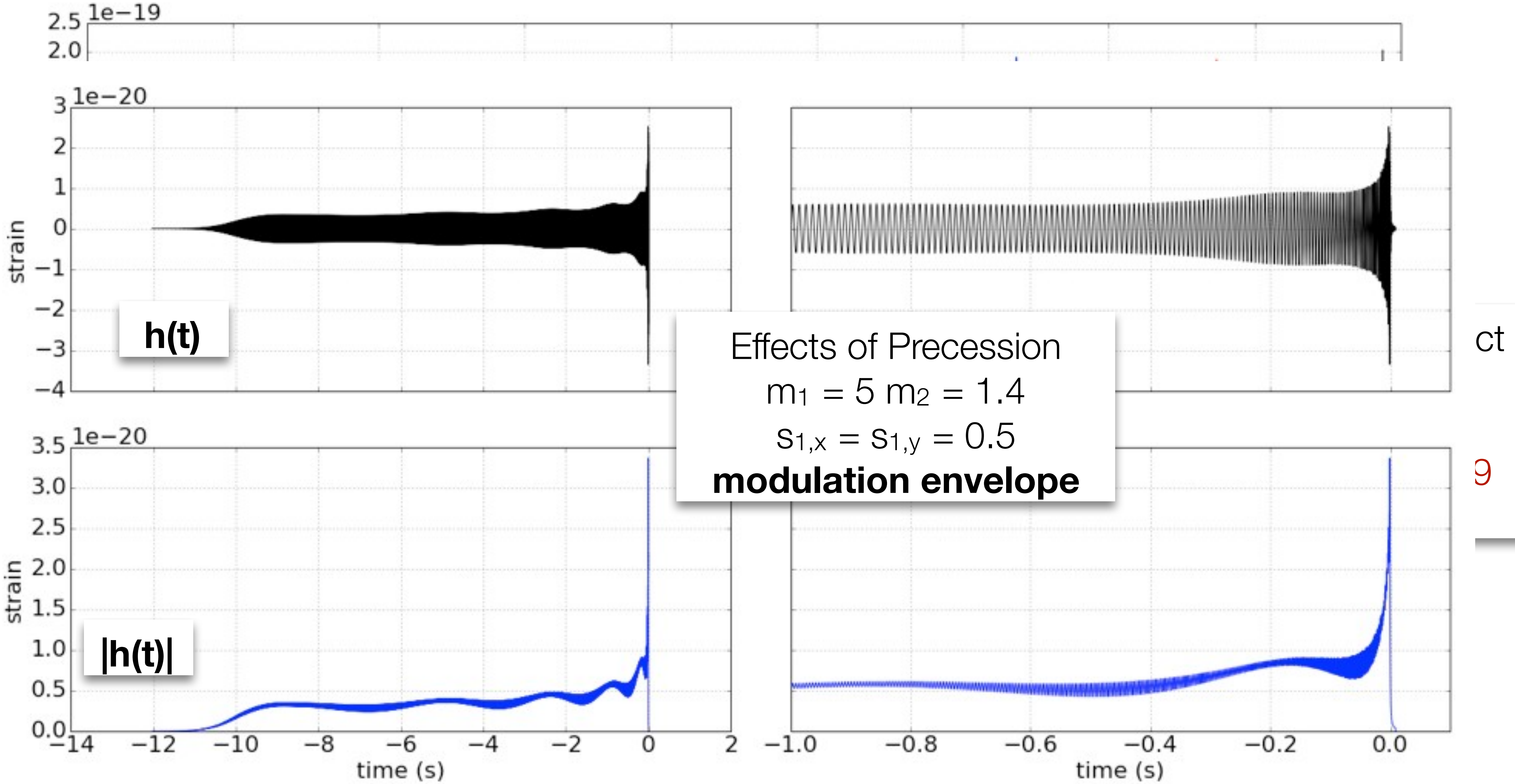
$m_1 = m_2 = 10\ M_\odot$

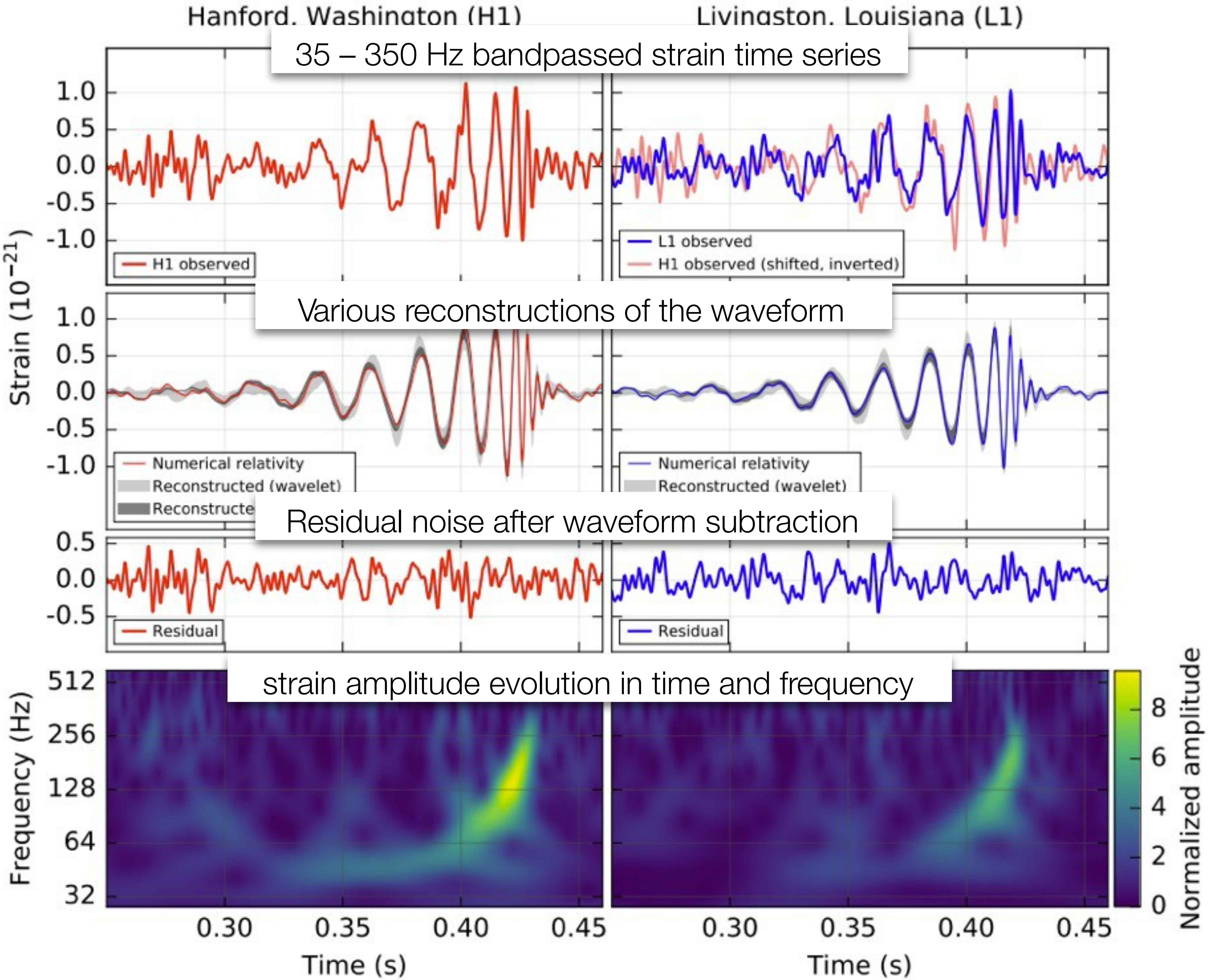
$s_{1,z} = s_{2,z} = 0.99$

$s_{1,z} = 0.99$, $s_{2,z} = -0.99$

$s_{1,z} = s_{2,z} = -0.99$

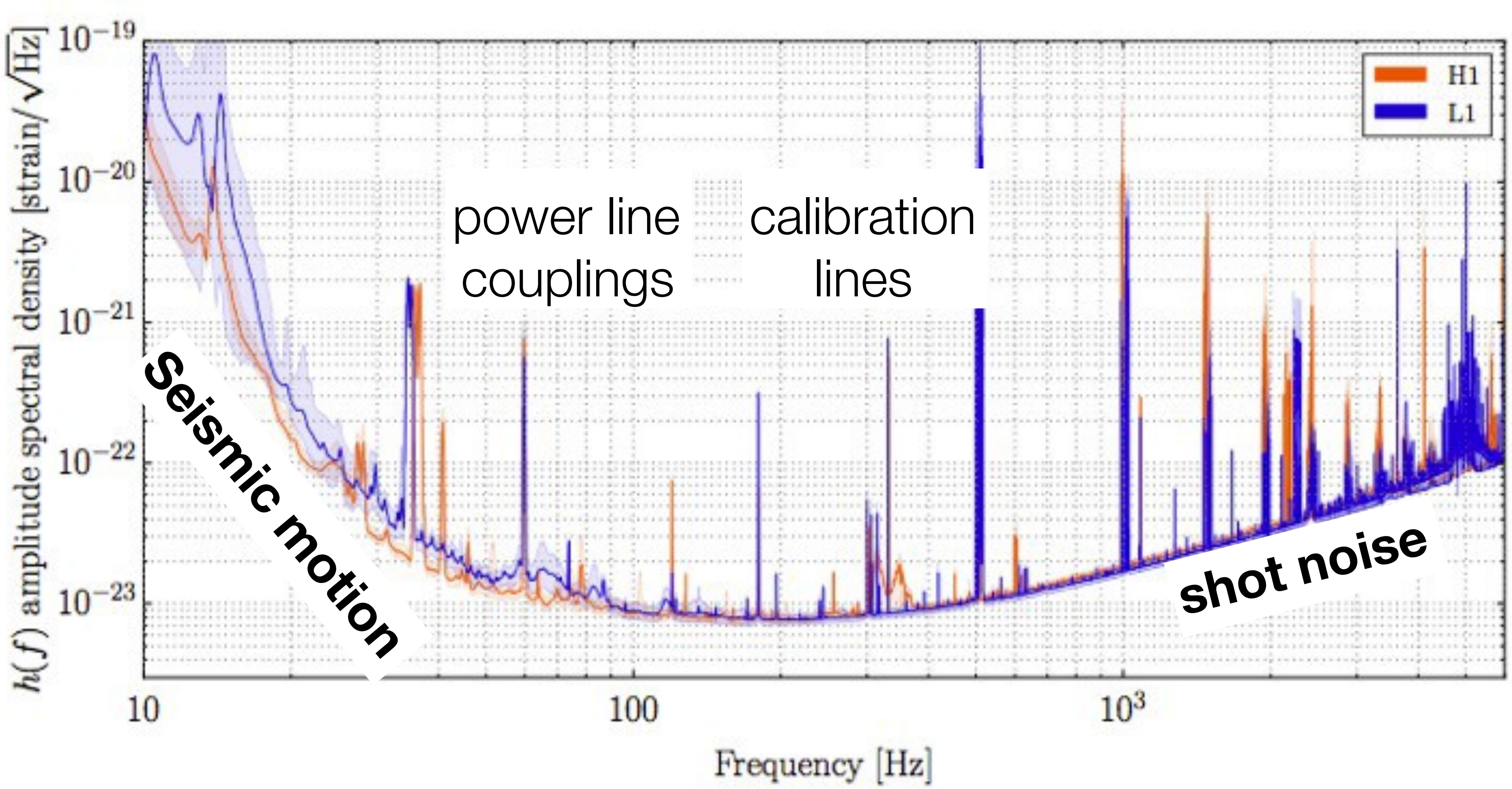
Compact Binary Coalescence: Waveforms





Hanford, Washington (H1)
Livingston, Louisiana (L1)
35 – 350 Hz bandpassed strain time series
H1 observed
L1 observed
H1 observed (shifted, inverted)
Various reconstructions of the waveform
Numerical relativity
Reconstructed (wavelet)
Reconstructe
Residual noise after waveform subtraction
Residual
strain amplitude evolution in time and frequency
Strain (10^{-21})
Frequency (Hz)
Time (s)
Normalized amplitude

Data Quality and Sanity Checks



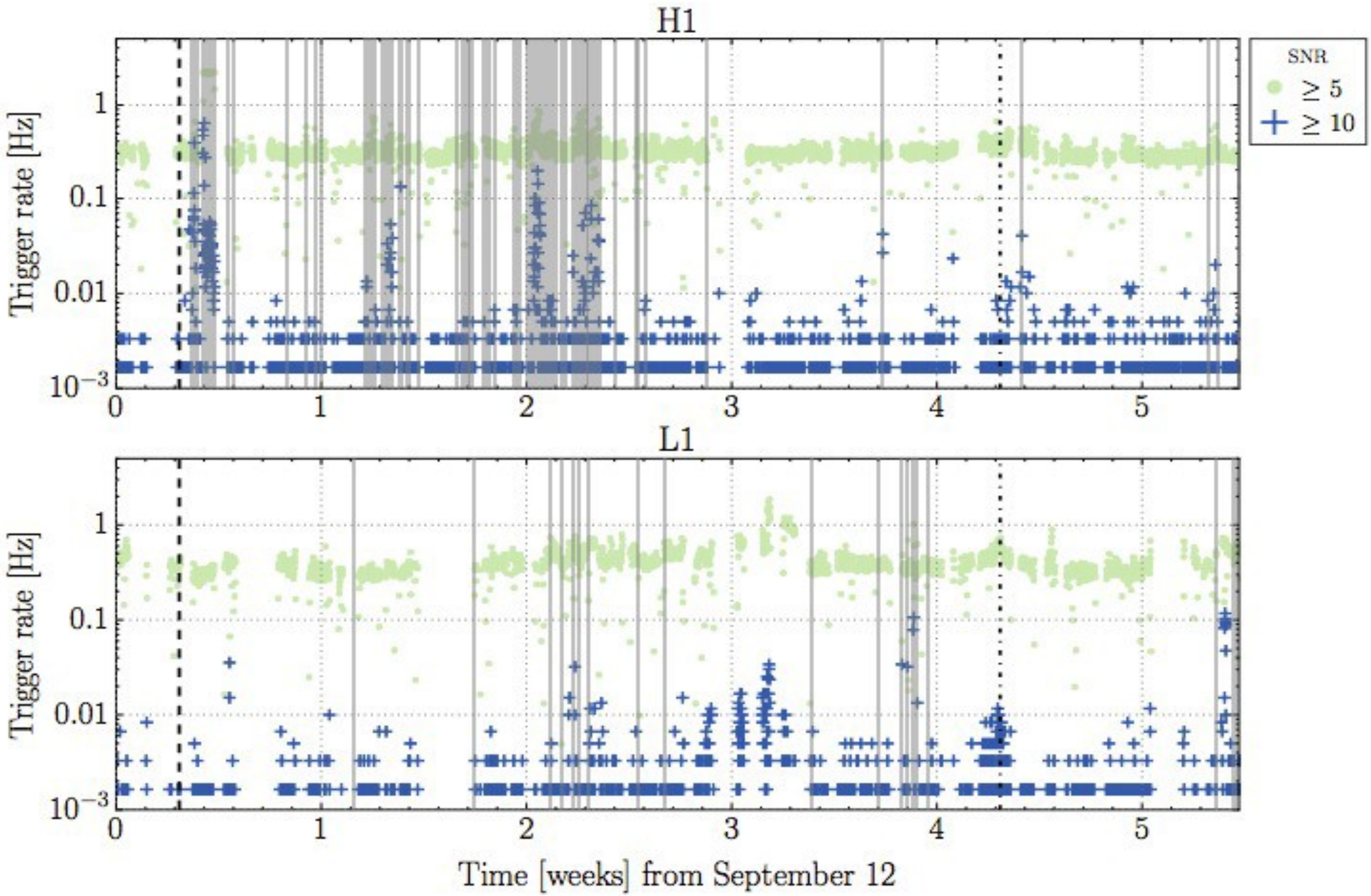
- Tens of thousands of **environmental**, **magnetic**, **optical path**, and **seismic** measurements from both instruments

- Channels are checked for spectral correlations as well as statistical correlations between transients in the channel and the gravitational-wave strain measurement channel

Data Quality and Sanity Checks

- **Candidates are vetoed if a correlation is detected**

Data near GW150914 is **very clean**, no *a priori* or *a posteriori* vetoes would have indicated non- astrophysical origin



GW150914: a Binary Black Hole Coalescence

- The generic analysis provided a characterization of the time-frequency track of the event: the first blush was that this was a binary coalescence with a peak energy at a frequency of ~200 Hz, bandwidth between 30-300 Hz: consistent with a system containing **at least** one black hole and **probably** two

- Signal-to-noise ratio recorded from the generic analysis: ~19 from Hanford and ~16 from Livingston -> *preliminary* upper limit on the false alarm rate of these events of **$<10^{-8}$ Hz (1 / 30 yrs)**

- Time-frequency track **very** indicative of a compact binary signal, preliminary fits showed total mass > 50

- Low-latency searches tailored for binary coalescences were looking for EM- bright signals and were not searching in this region at the time

Measuring the parameters

- Orbits decay due to emission of gravitational waves
  - Leading order determined by “chirp mass”

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{M^{1/5}} \simeq \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

  - Next orders allow for measurement of mass ratio and spins
  - We directly measure the red-shifted masses (1+z)m
  - Amplitude inversely proportional to luminosity distance
- Orbital precession occurs when spins are misaligned with orbital angular momentum – no evidence for precession
- Sky location, and binary orientation information extracted from time-delays and differences in observed amplitude and phase in the detectors

Timeline: from low latency to followup

- Followup began immediately: given highly suggestive waveform morphology, Markov Chain Monte Carlo methods began probing the compact binary parameter space

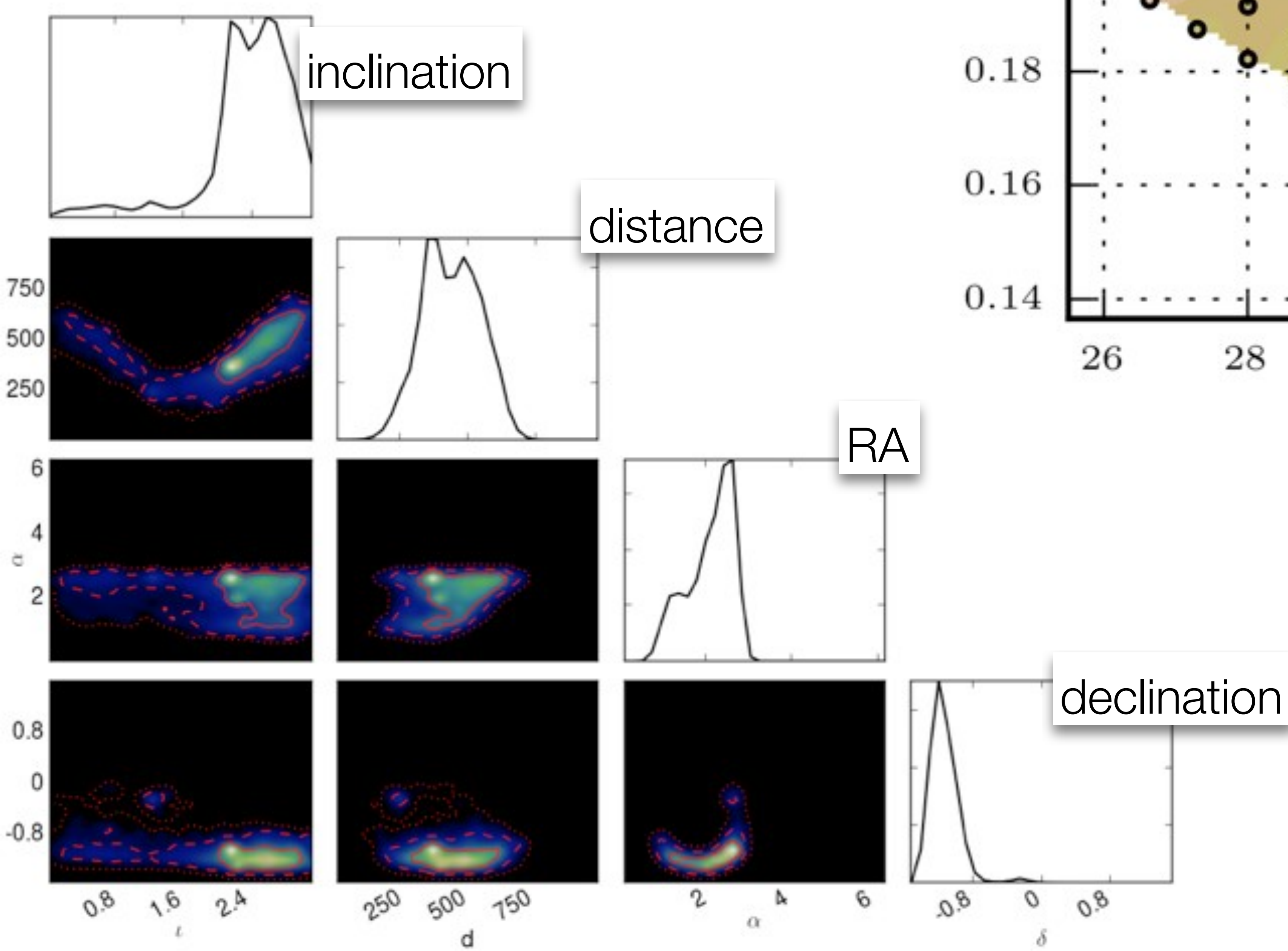
  - Within a day, those methods showed **very** clear confirmation: pending data quality / data calibration checks the evidence for the astrophysical origin of the signal was **overwhelming** (SNR ~25!)

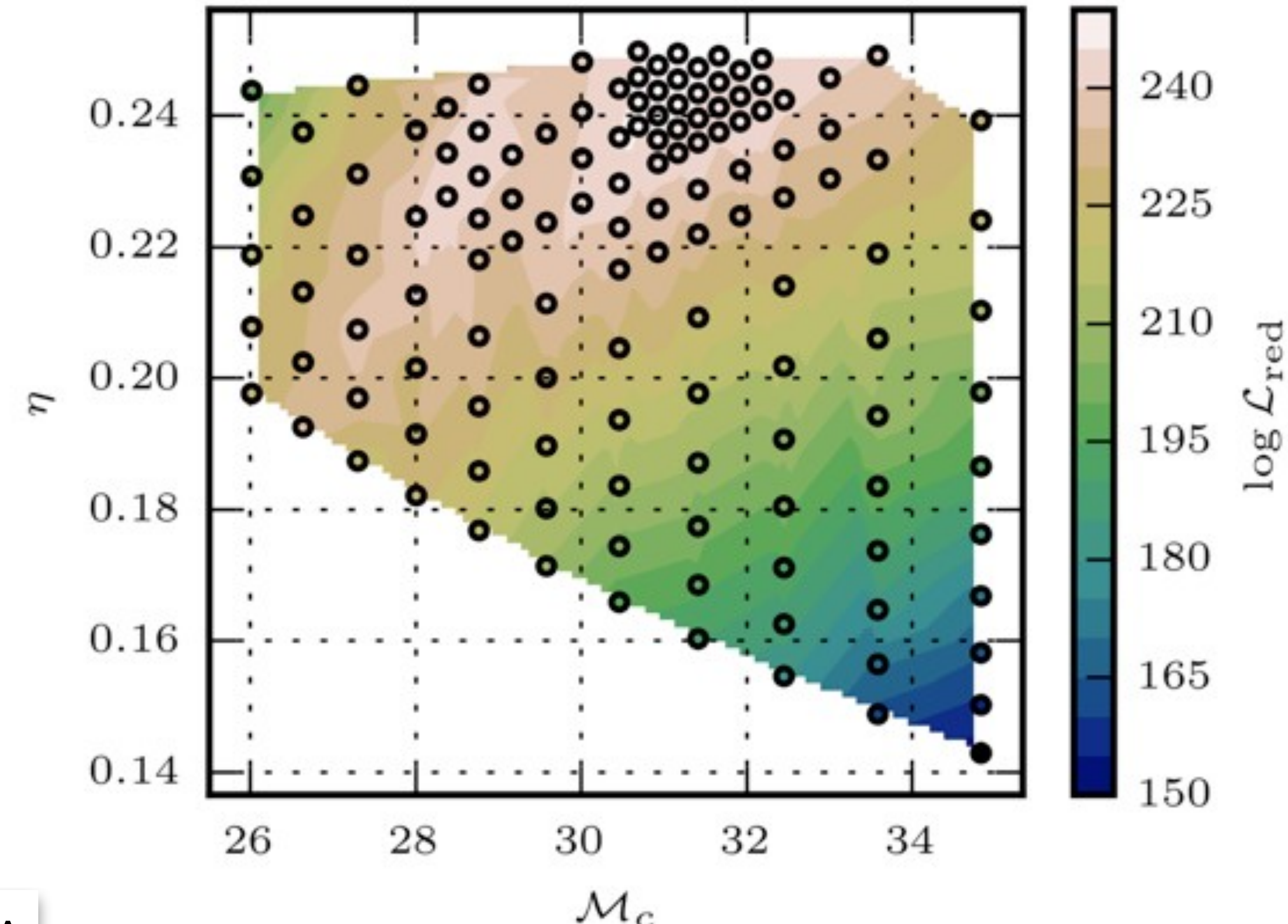
- Bayesian posterior probability over the sky position released to other observatories for electromagnetic facility follow up after about 48 hours

  - Unfortunately, given the nature of the signal, there are few believable scenarios where electromagnetic emission is expected: most require a medium of matter around the event to be present and would likely be weak

Rapid Parameter Estimation

Mass estimates
and source orientation
in less than an hour



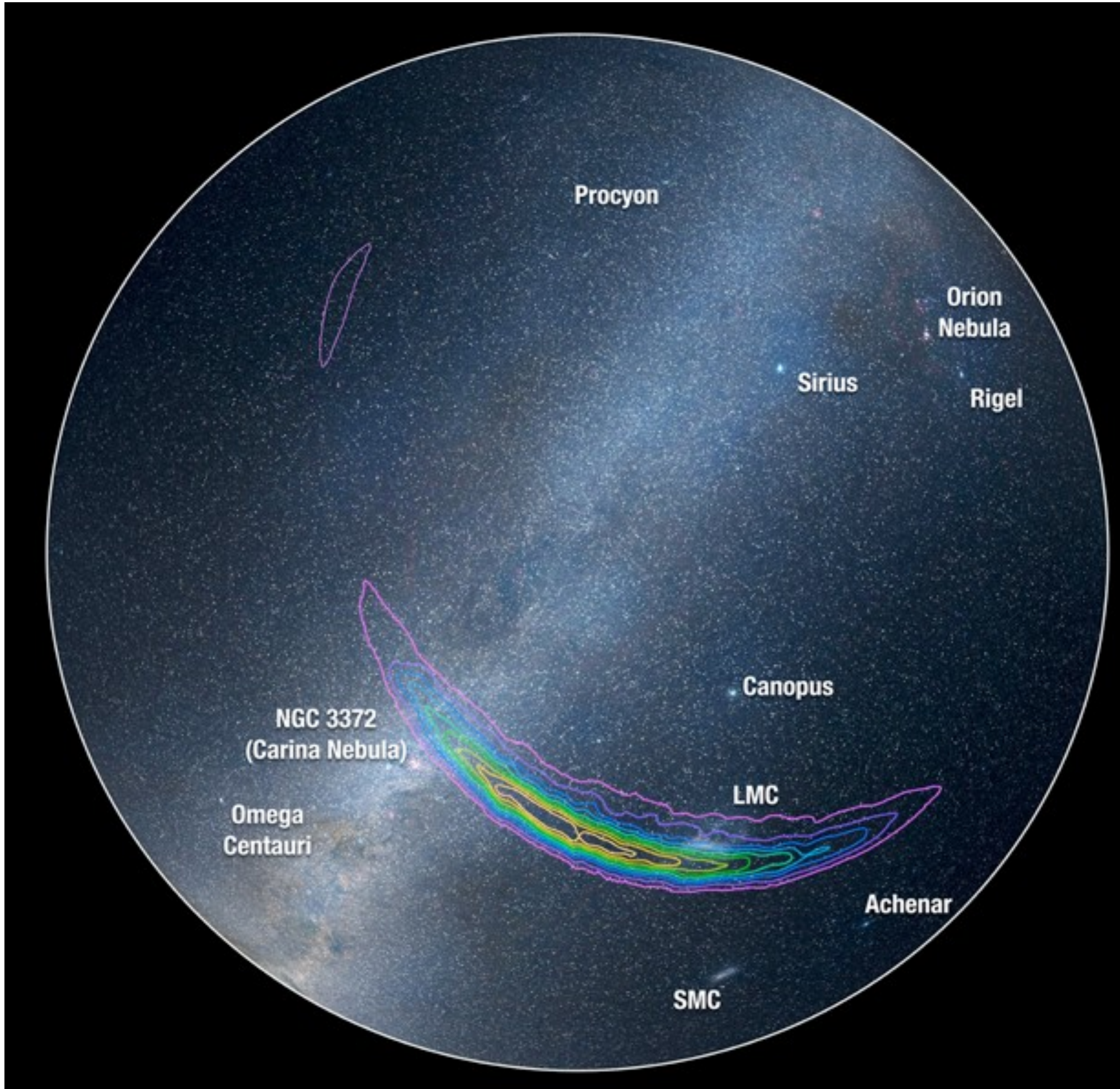


Gravitational-Wave Sky Posteriors

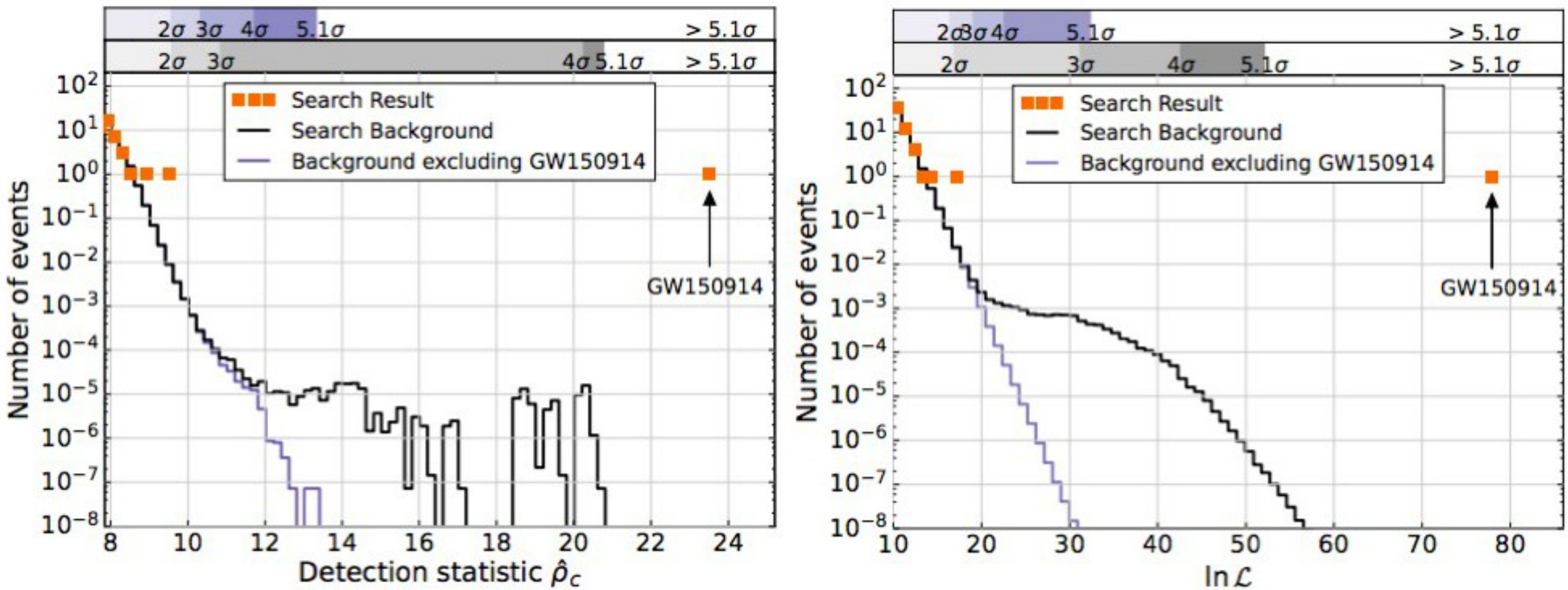
Sky areas broadly consistent with simply triangulation, and mostly cross-consistent

Triangulation ring consistent with time delay of about ~7 ms

Search area: 620 sq. degrees to cover:



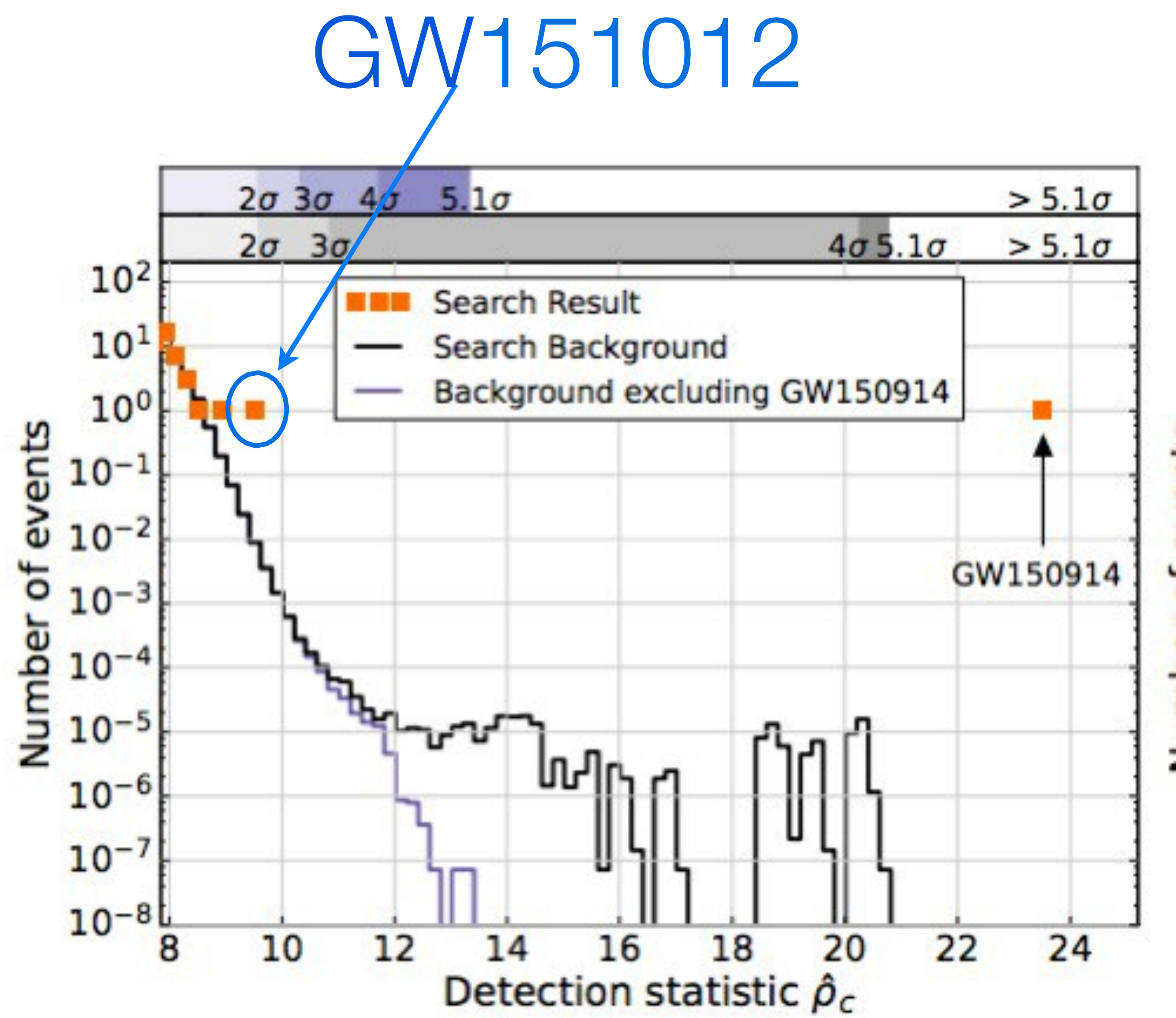
Statistical significance over 38 (16 effective) Days of observation



- Upshot: all (modeled and generic) searches identified the candidate, CBC search SNR of 24 (CBC), with masses and spins that were consistent with the initial CBC parameter estimation posterior results
  - Significance was off the charts (literally), upper limit on FAP of ~10^{-7}

GW151012

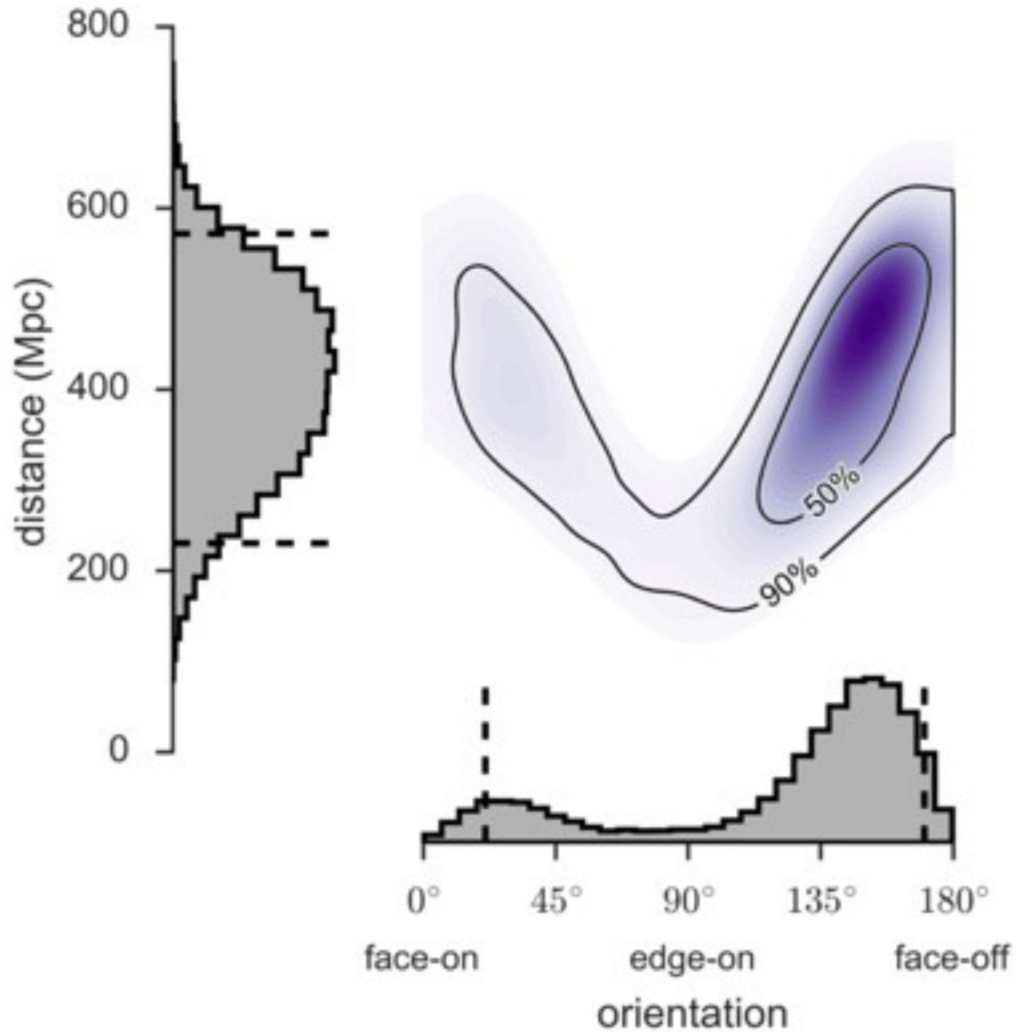
- Full offline deep search revealed a second event on October 12, 2015: false alarm probability of ~2%
    - Much less significant: if it is interpreted as a candidate of astrophysical origin it contribute to event rate eveluation and it can increases confidence in detection
- Event properties are quantitatively different, but still very likely a binary black hole coalescence



Parameter Estimation

- May be the most energetic astronomical event ever observed: **10^{56} ergs, 3 $M_\odot c^2$** very briefly outshone the universe... by a factor of **50**
- Online search pipelines have some biases in parameter recovery, and marginalize others for speed — full parameter measurement comes from Markov Chain Monte Carlo algorithms
- Two waveform models (both full inspiral-merger-ringdown families):
    - **Effective One-Body Numerical Relativity w/spin (SEOBNR)**: numerical evolution of GR equations, with tuning to result of numerical relativity and appropriate ringdown attachment — component spins are aligned to the orbital angular momentum vector
    - **IMRPhenomP**: Phenomenologically motivated family, simple precession effects embodied in a single effective spin parameter — excludes extreme and misaligned spin effects

Source Distance and Orientation



- GW directional emission intensity is invariant to reflections across the plane of the rotation if non-spinning

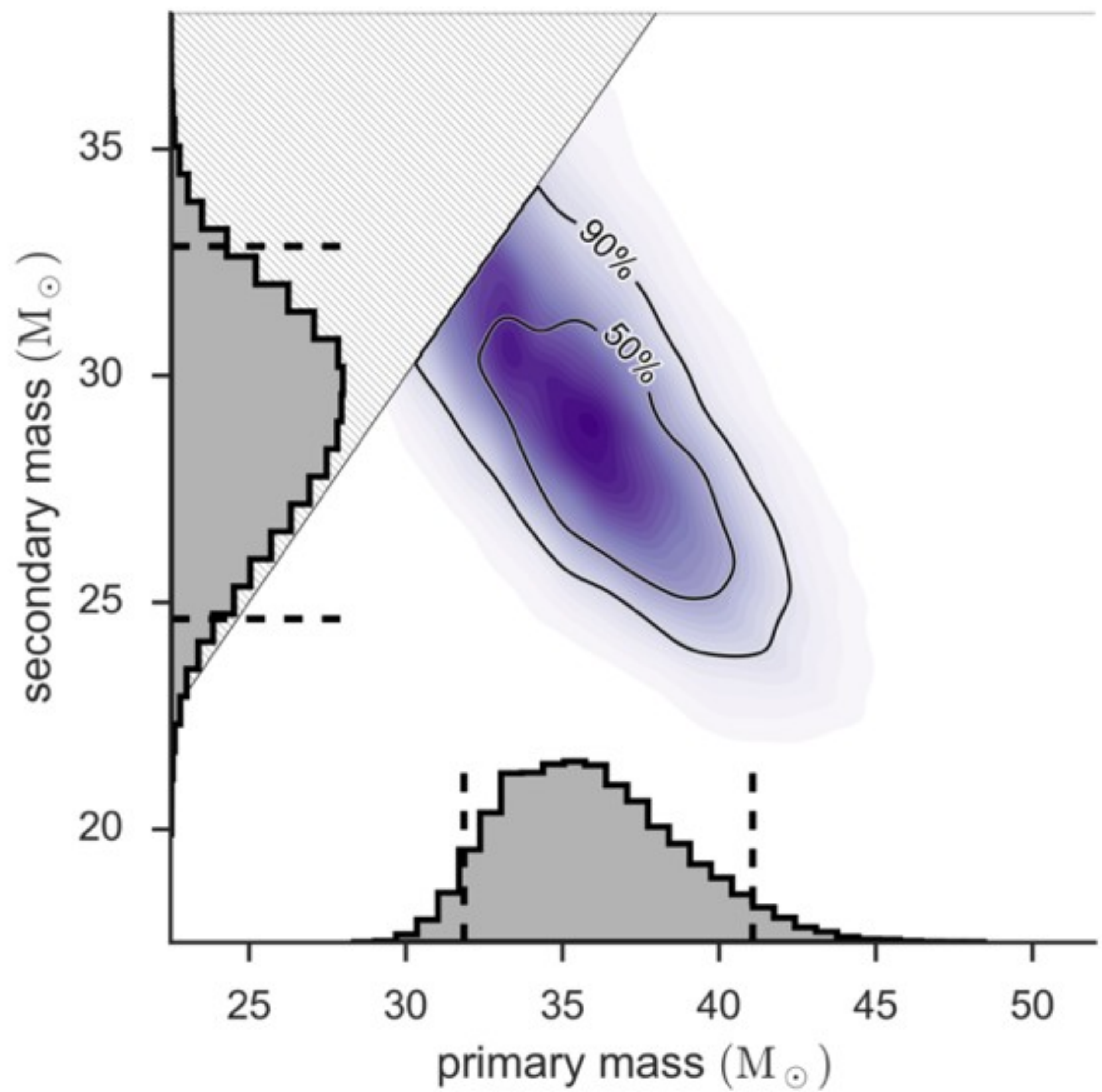
- Typical distance / inclination degeneracy could be broken by spin effects, now favoring a “face on” orientation

- Luminosity distance peaks ~400 ± 100 Mpc, bringing cosmological effects into play, redshift estimated near z ~0.1 ± 0.04 (ΛCDM cosmology)

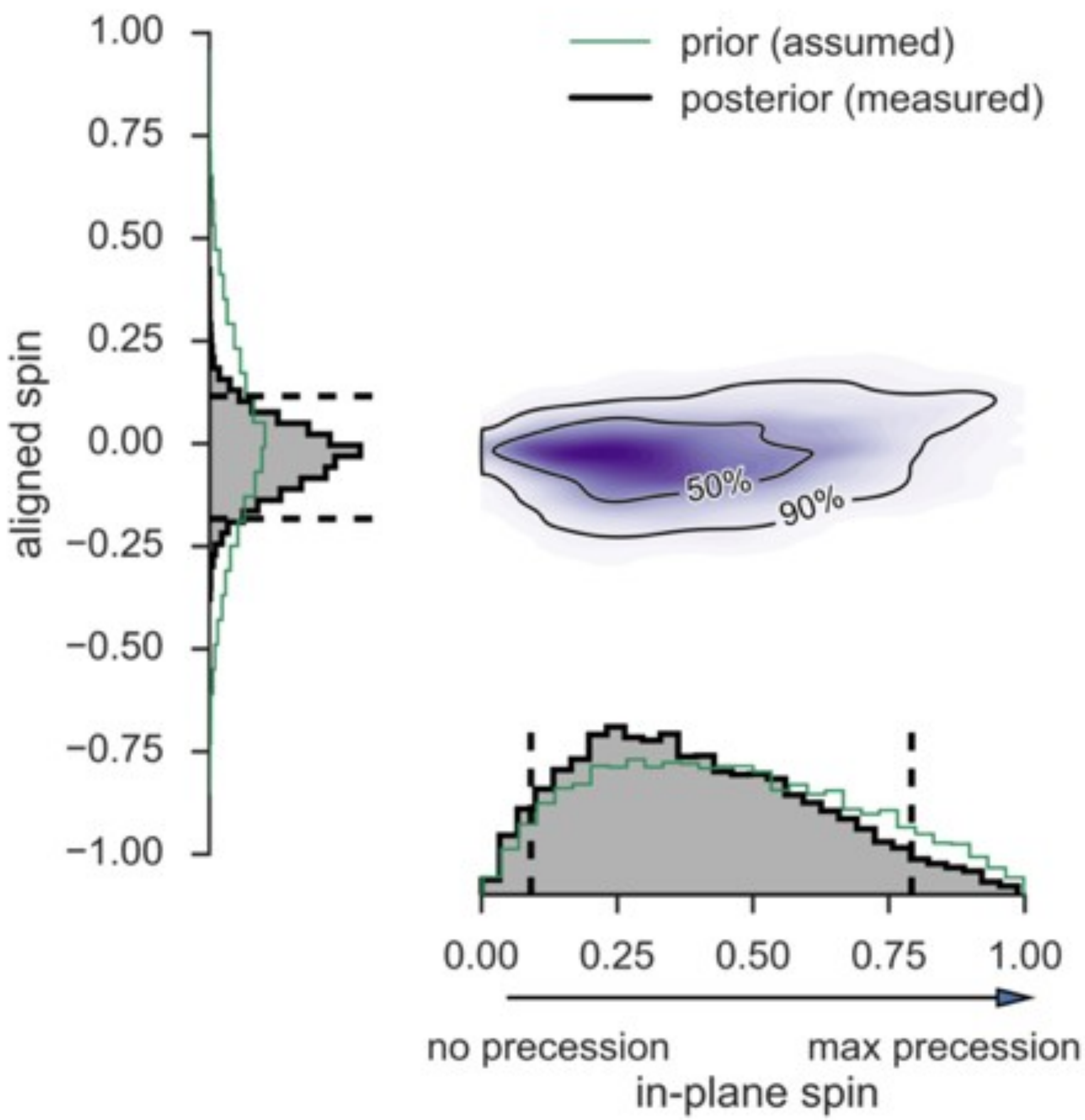
- Redshift affects not only the distance measurement, but also redshifts the frequencies received at the instrument, and hence the phasing of the waveform, we infer different source masses, modulated by our current understand of cosmology

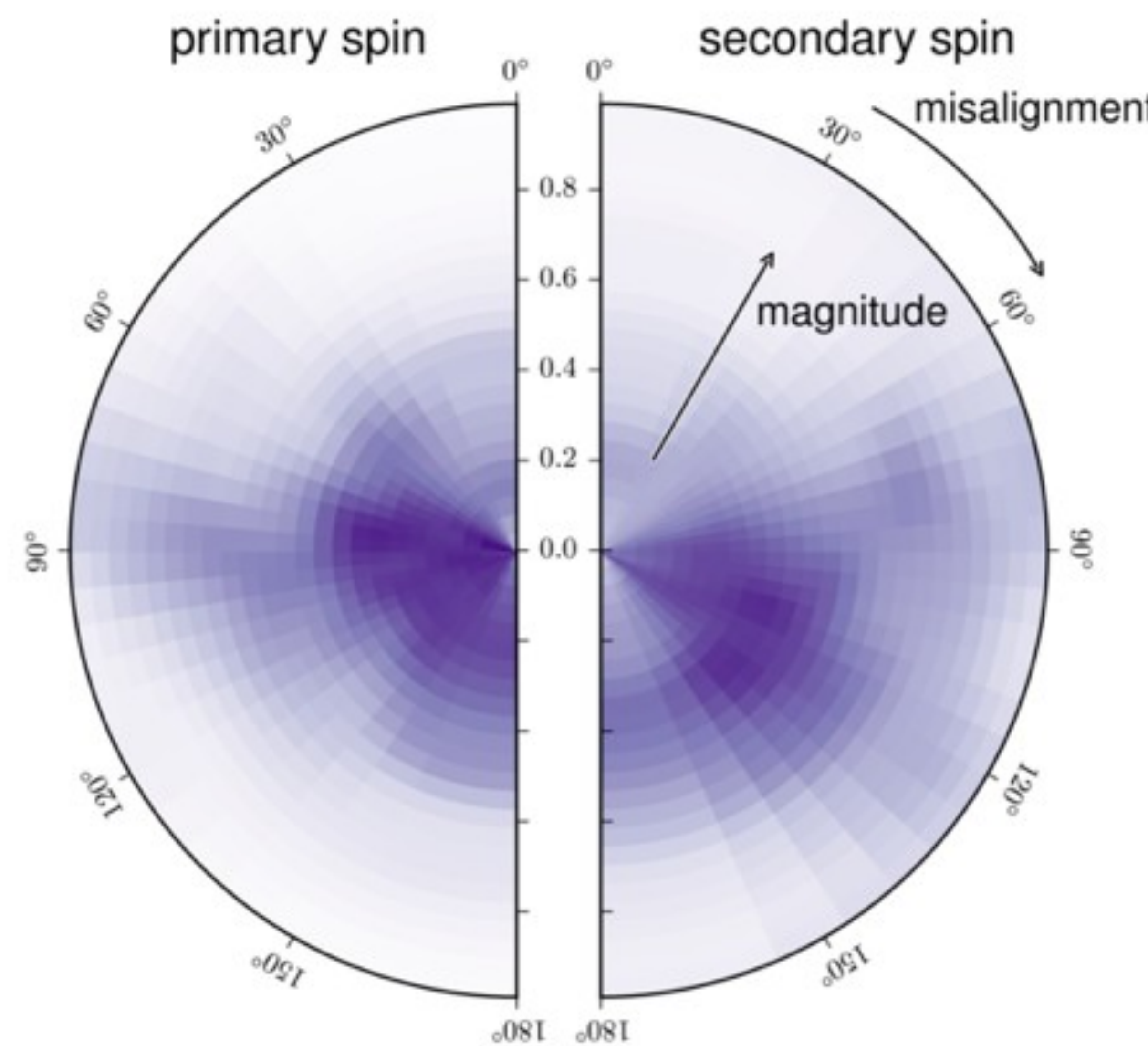
Black Hole Masses

- Degeneracies in waveform morphology arise along equal chirp mass lines in m_1/m_2 space
- Since M_c (or total mass) is the better measured quantity m_1/m_2 is anticorrelated
- Detected masses are redshifted, lower frequency implies higher masses are "detected" than source frame: Detector frame masses are ~39 + 32 Ms



Source Spin Parameters / Precession?

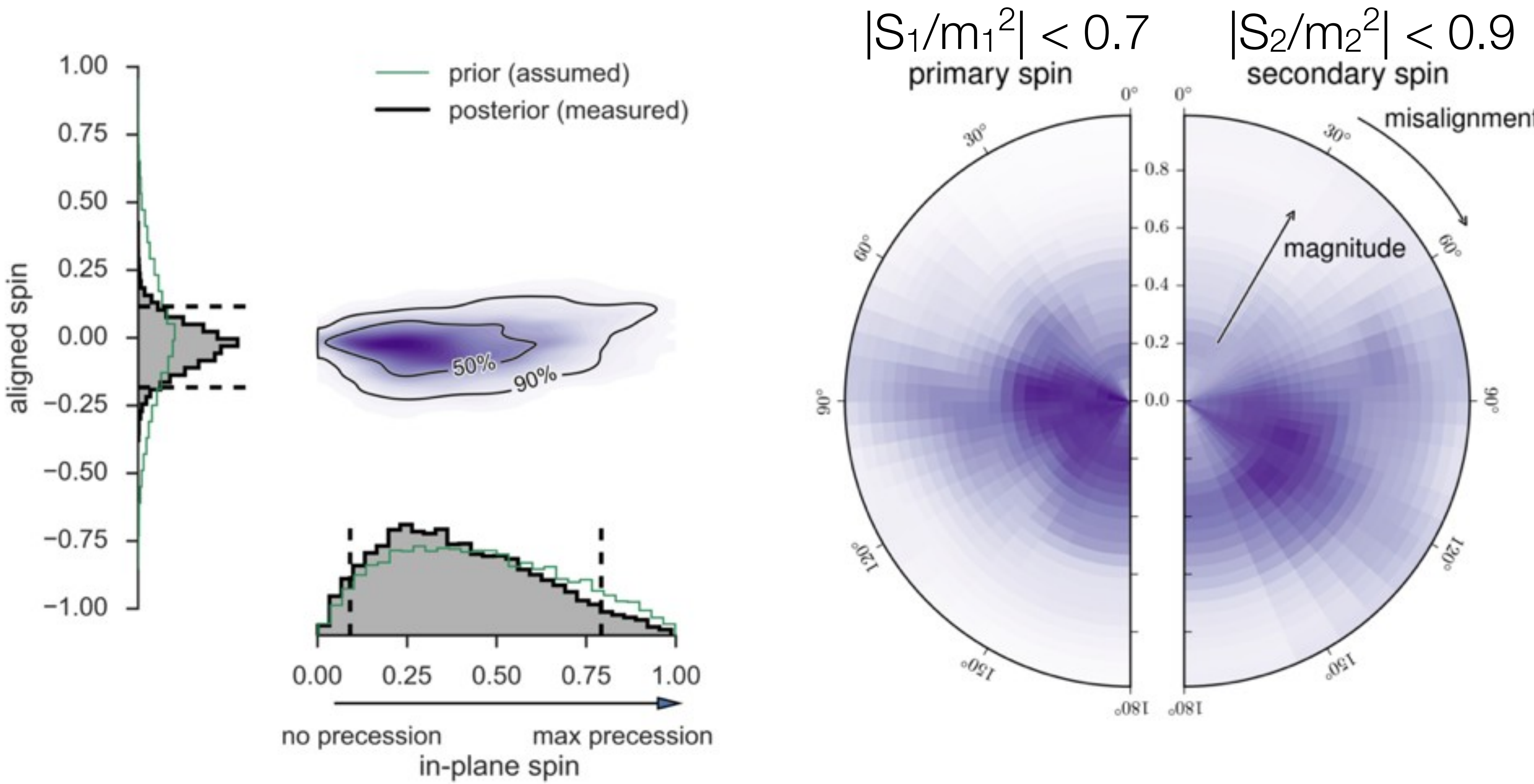




aligned spin measures components of $S_{1,2}$ along the orbital angular momentum

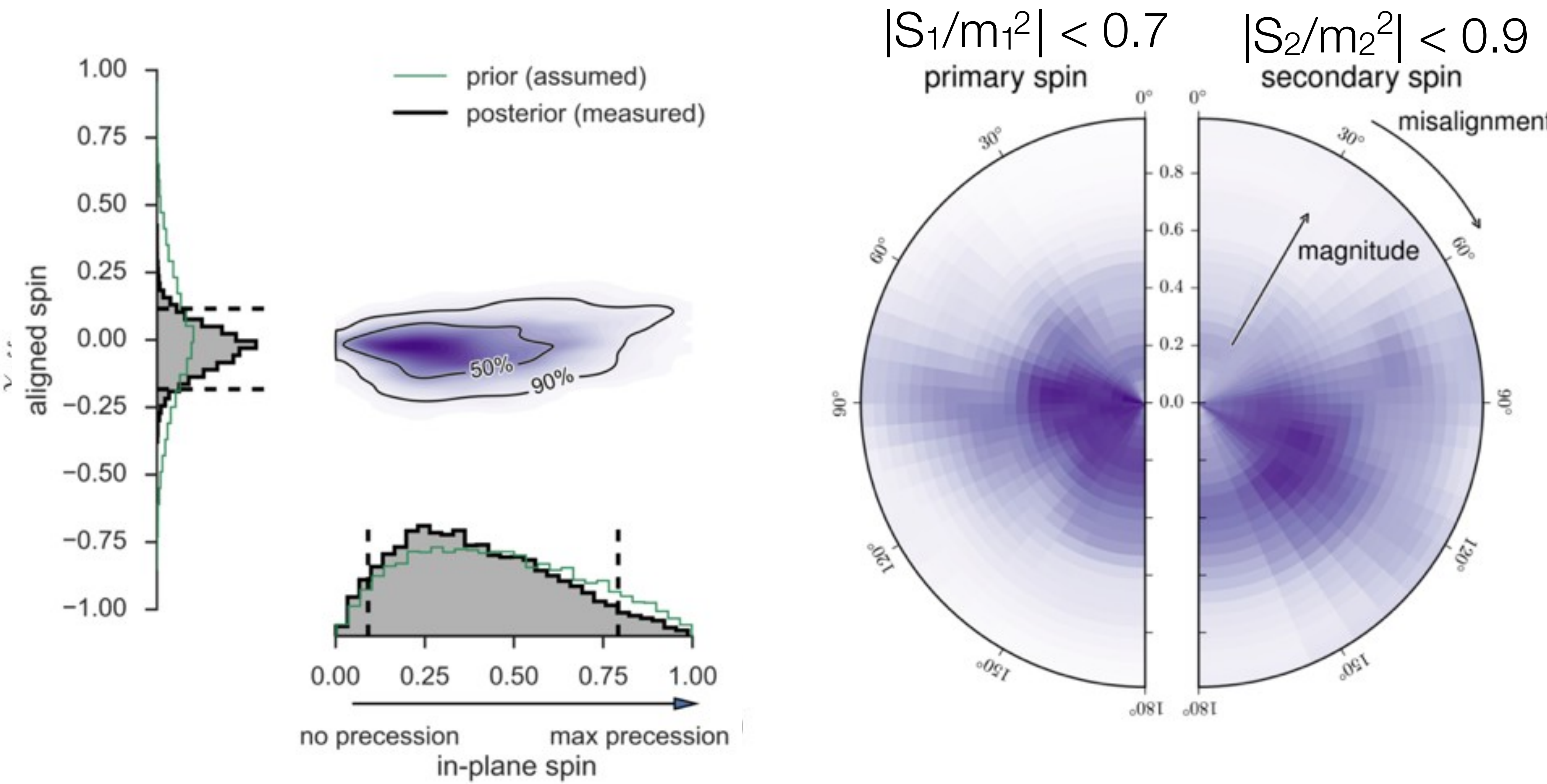
in plane spin measures components of $S_{1,2}$ in the plane of the instantaneous orbit

Source Spin Parameters / Precession?



Upshot: constrained aligned spin values to be small (and slightly negative) — not really able to measure the precessional component

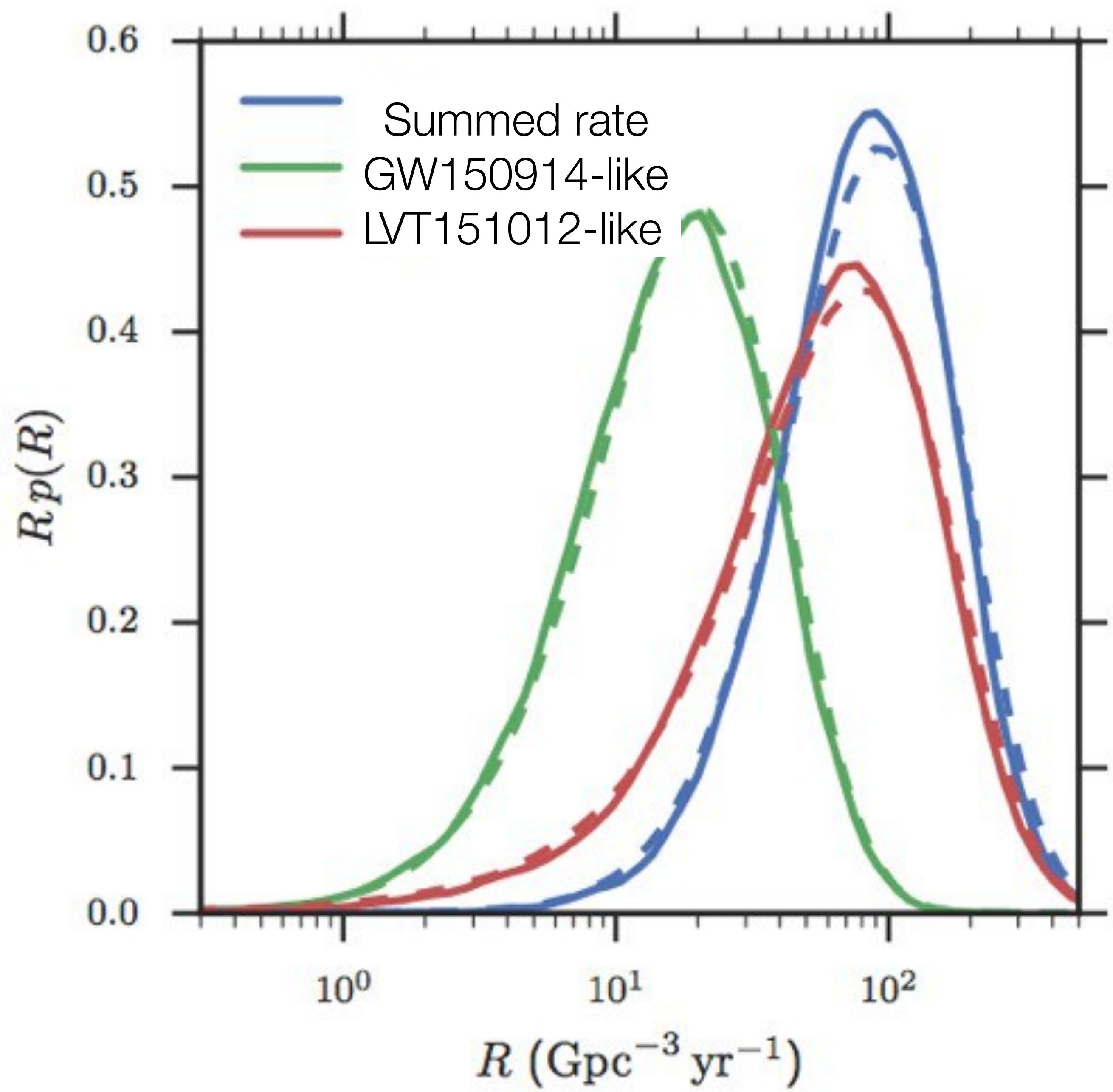
Source Spin Parameters / Precession?



Caveat: If the system is "face on" (L aligned with line of sight) precessional effects are mostly unobservable

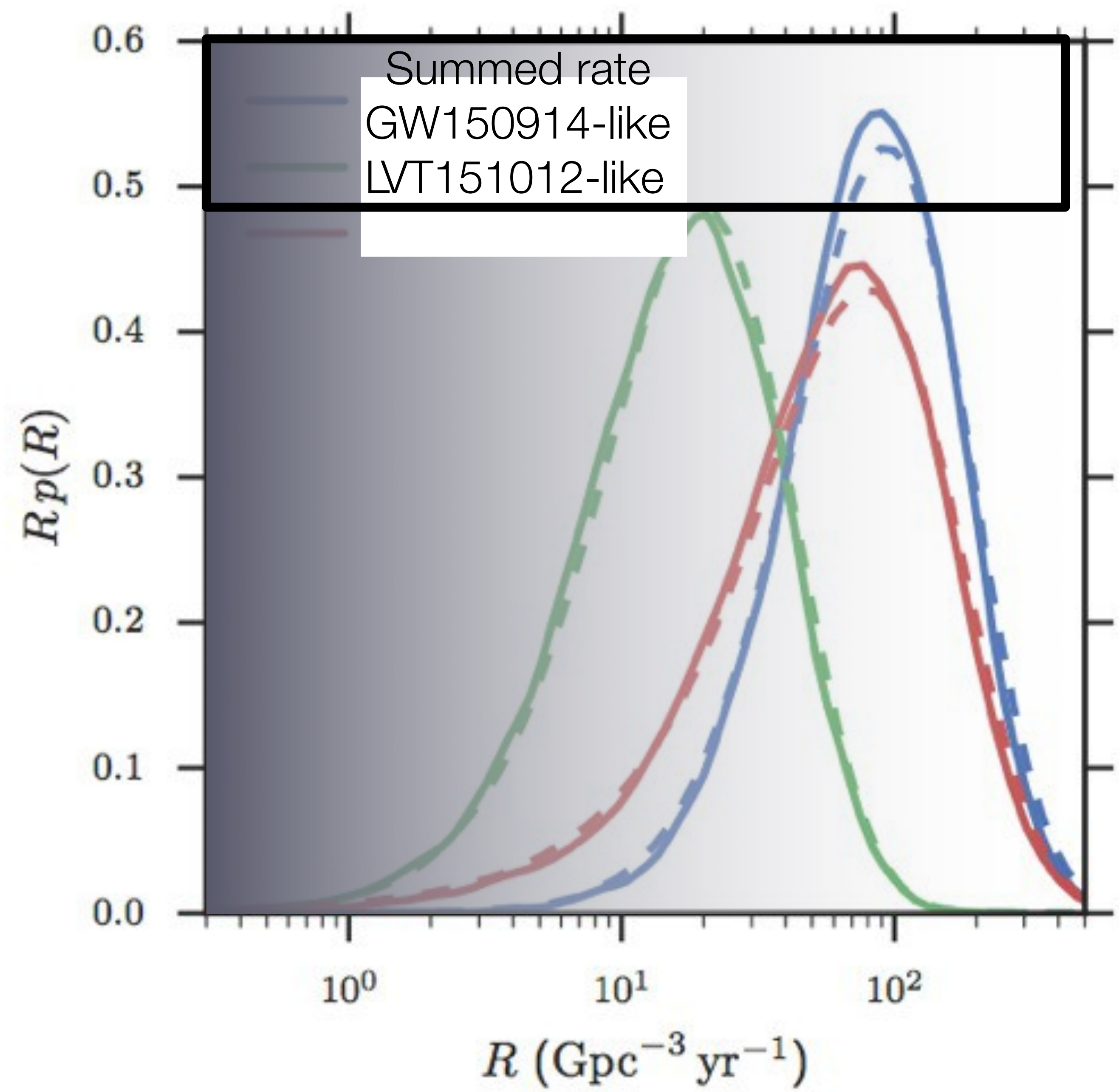
Astrophysical Event Rate Implications

- Difficult to be **very** specific with rates, we still don't have a definitive handle o BBH formation scenarios, only simulations from stellar evolution modeling
  - *If you use only GW150914 (FAP ~4e-7)*: the rate for a "class of even with astrophysical features like this one" is between 2-53 $Gpc^{-3}yr^{-1}$ (median 14)
  - *If you use both events (LVT151012 FAP ~0.02)*: the rate for BBHs "including these two classes" is between 6-400 $Gpc^{-3}yr^{-1}$

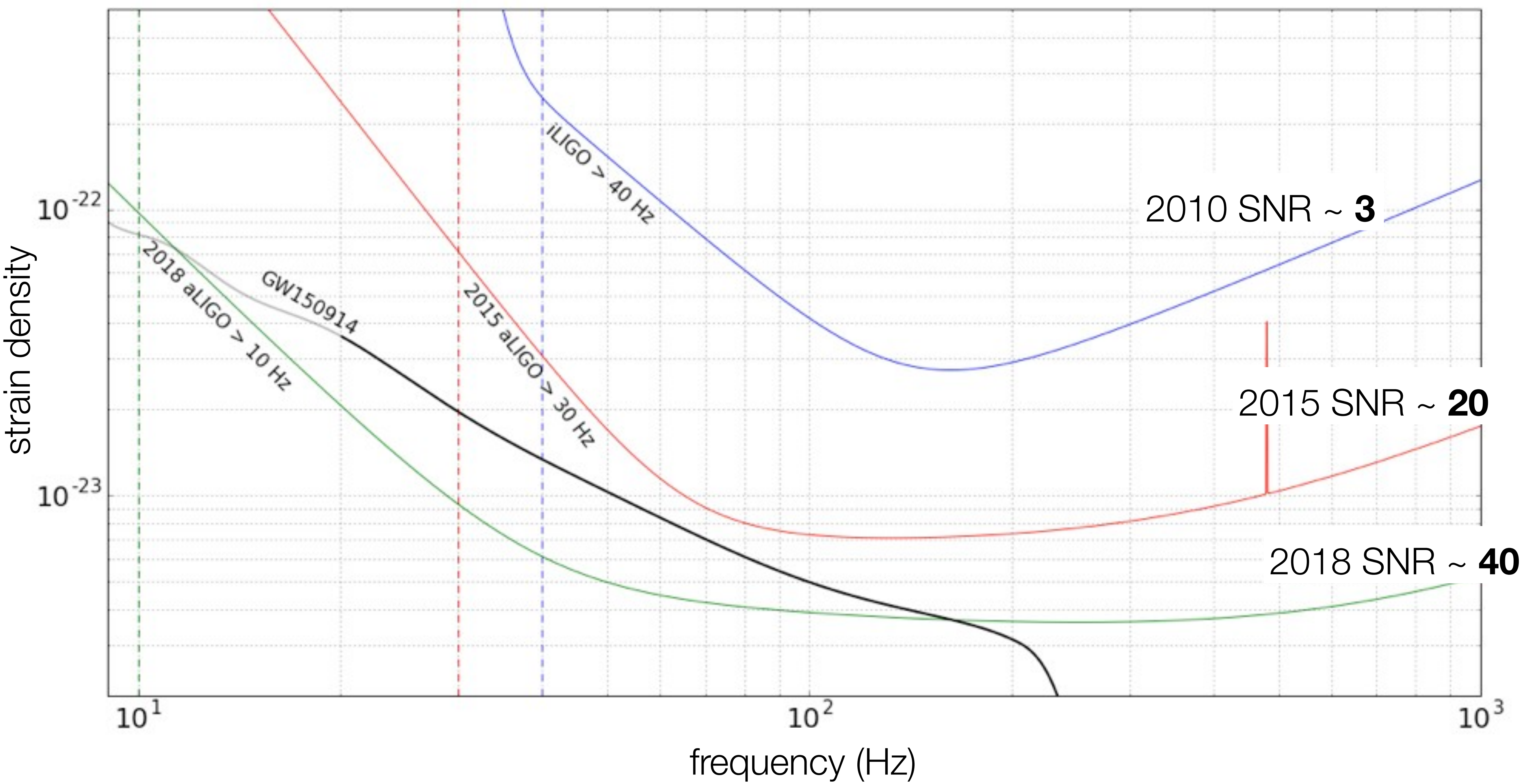


Astrophysical Event Rate Implications

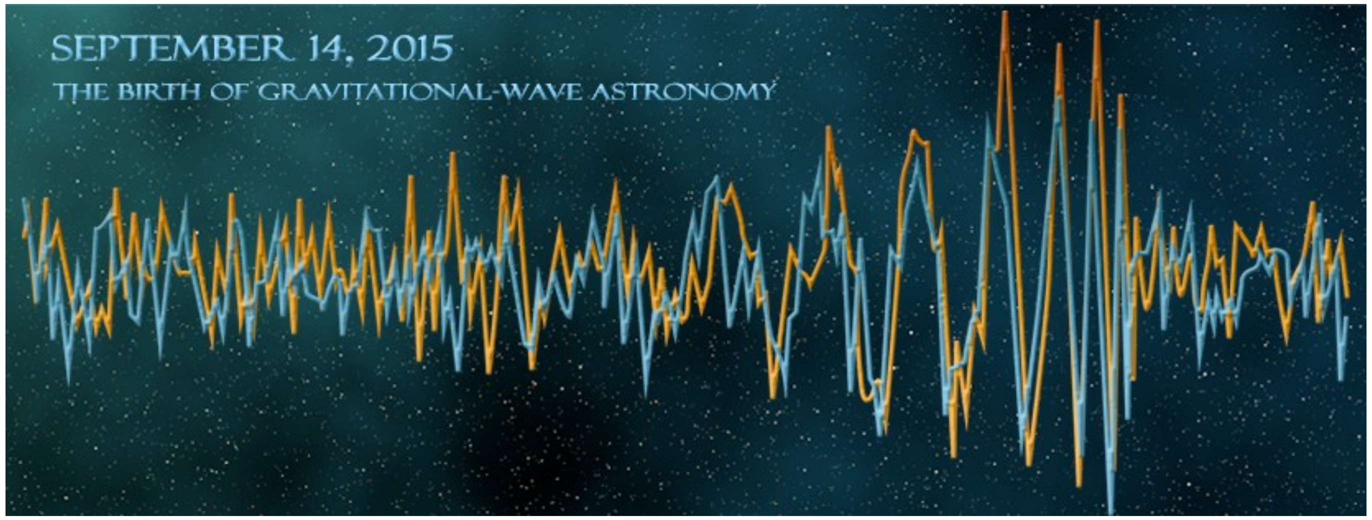
- Difficult to be **very** specific with rates, we still don't have a definitive handle on BBH formation scenarios, only simulations from stellar evolution modeling
  - Compare to previous rate limits set by 2009-2010 LIGO-Virgo run: ≤ 330 $Gpc^{-3}yr^{-1}$ (all BBH) ≤ 420 (GW150914)
  - Rate intervals **are consistent** with astrophysically motivated rate predictions**, excluding only those models with R ~ 0**.

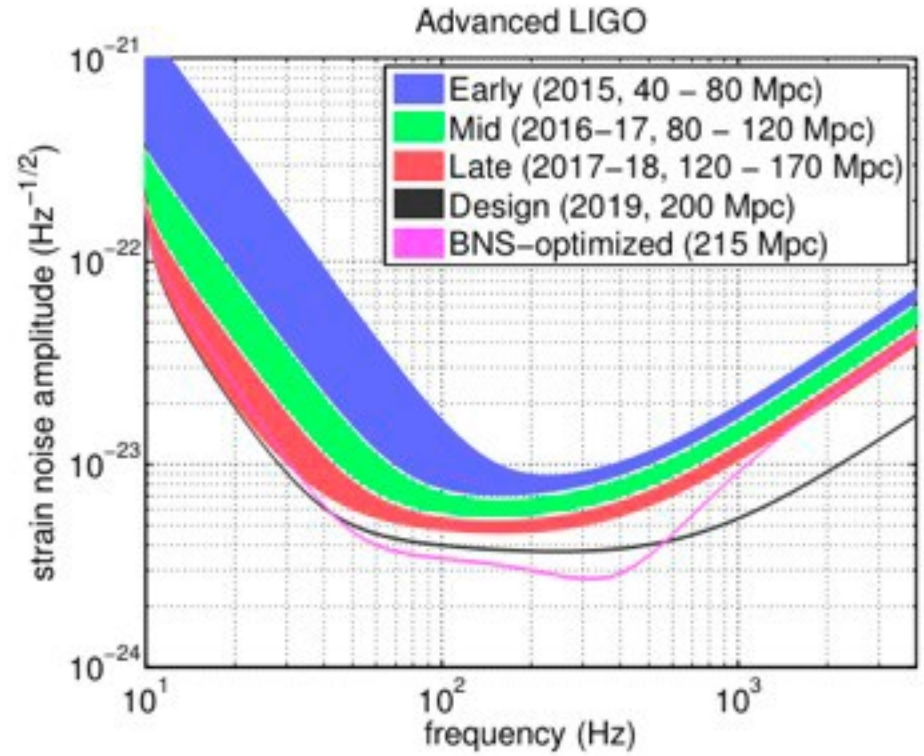


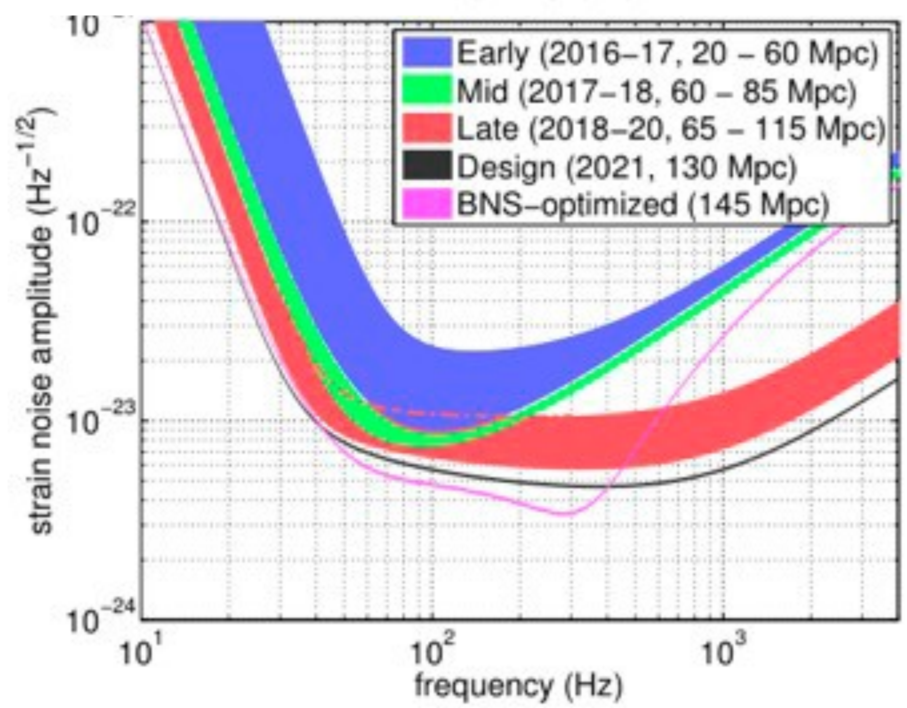
The role of the low frequency sensitivity



Conclusion







- Further upgrades in sensitivity over a broad bandwidth, double the observation time
- Virgo will join the observation run
  - Great improvement in the sky localization, decreased uncertainty in posterior distributions
- If the rates extrapolation holds, O2 will have about **one event per week** from BBH **alone** (still waiting for that NSBH, BNS, SN, etc…!)
- Should begin some time during fall 2016…