GW150914
Observation of Gravitational Waves from a Binary Black Hole Merger

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Introduction

Gravitation

Sources

Universe

- GW generated by powerful mass acceleration
  - Very energetic events in the Universe
  - Gravitational waves probe event dynamics
- Gravitation only clue to 96% of Universe contents
  - Gravitational waves probe gravitation in new regime

General Relativity

Astrophysics

Cosmology

Ground-based GW detectors

- 1st generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
First rate upper limits
Set up network observation

  - Enhanced LIGO, Virgo+

Improved sensitivity

Laid ground for multi-messenger astronomy

- 2nd generation detectors
  - Advanced LIGO, Advanced Virgo, GEO-HF, KAGRA

VOUS ÊTES ICI

First detection

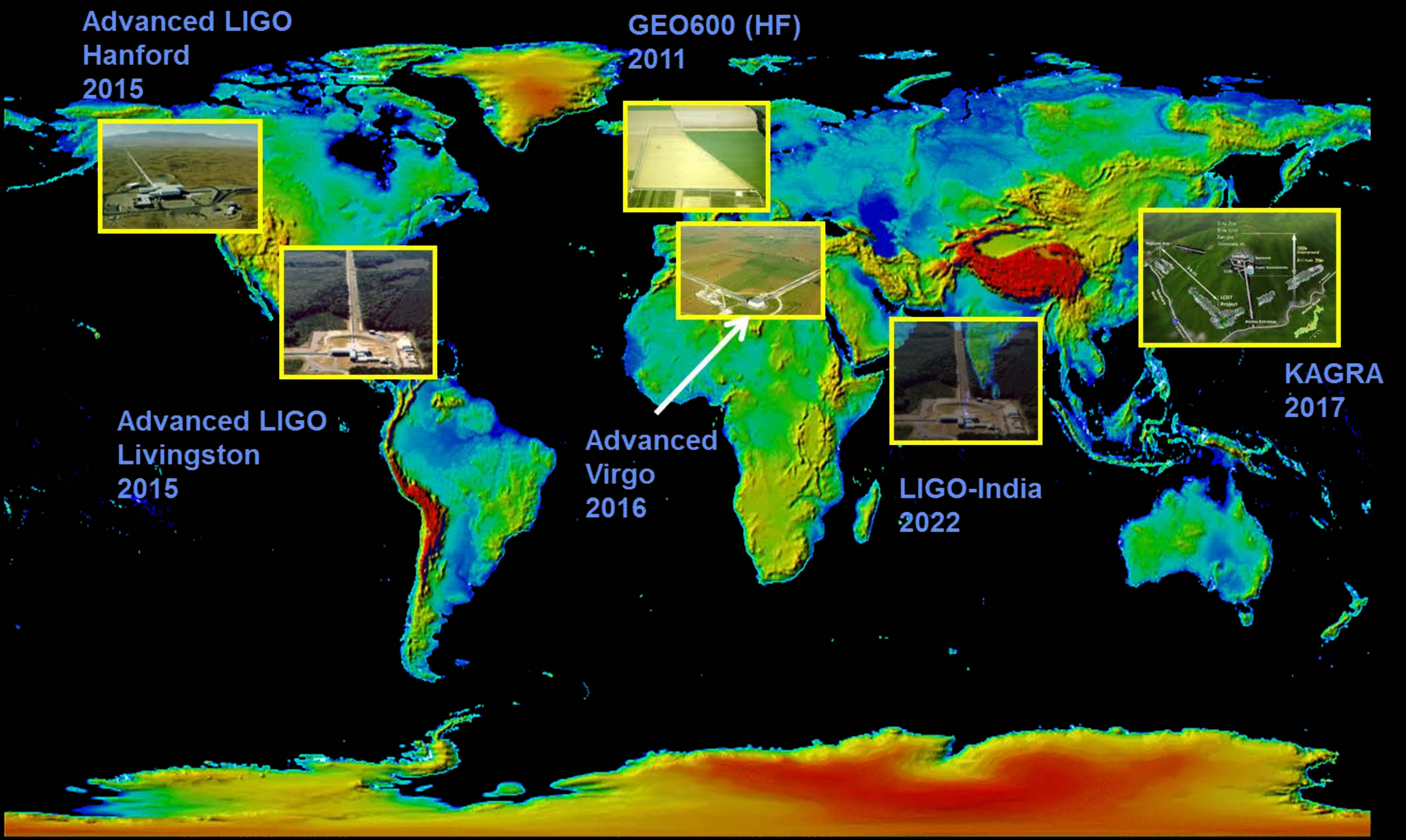
Toward routine observation
GW astronomy

2.5 G

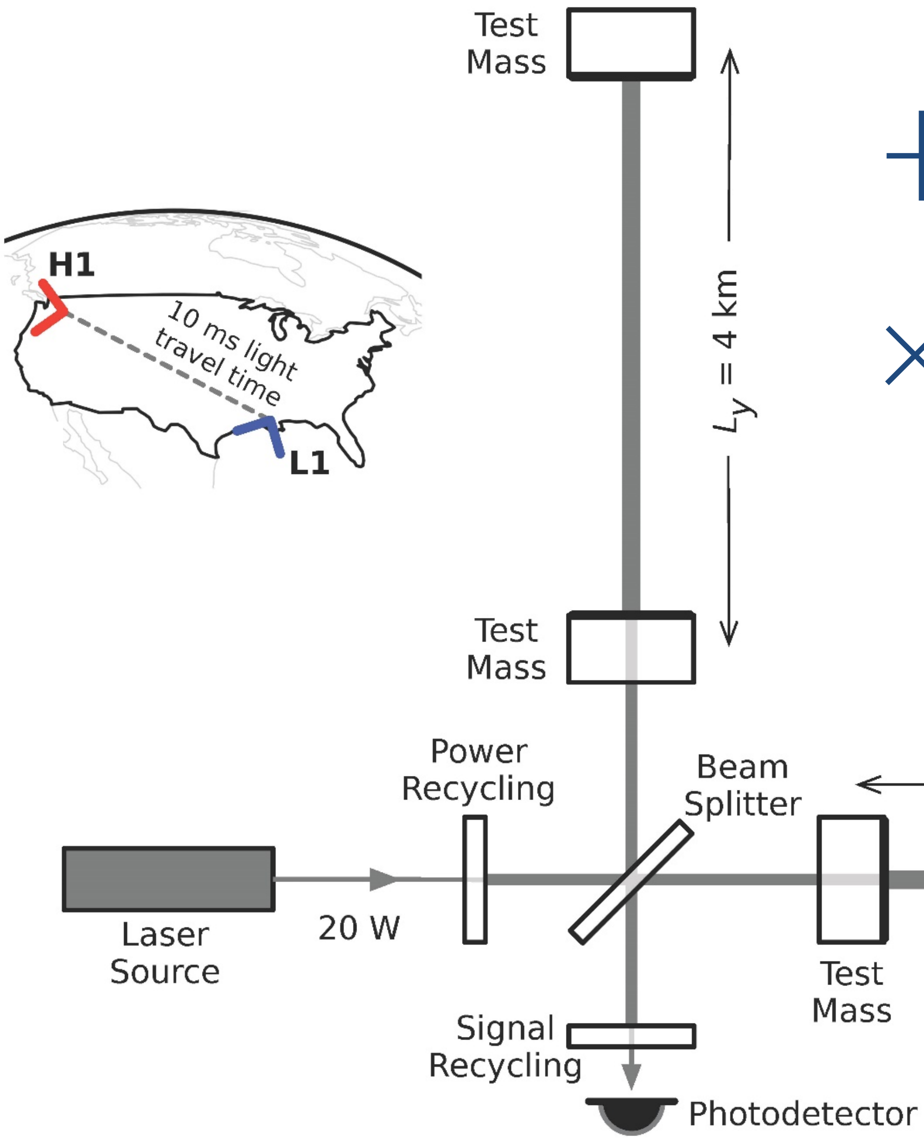
- 3rd generation detectors
  - Einstein Telescope, Cosmic Explorer

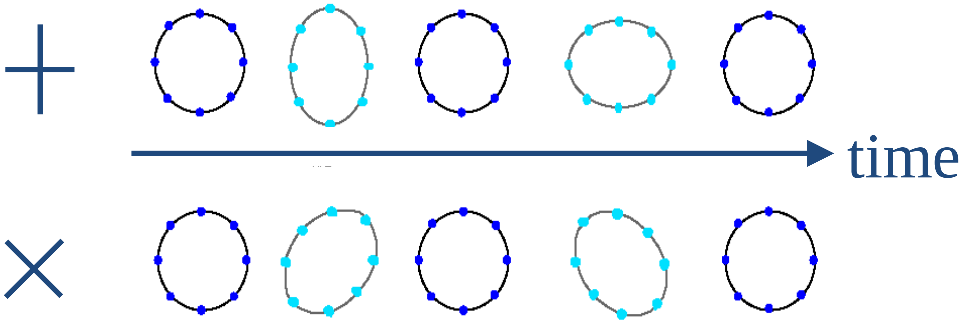
Thorough observation of Universe with GW

2^{nd} Generation Network



Instruments

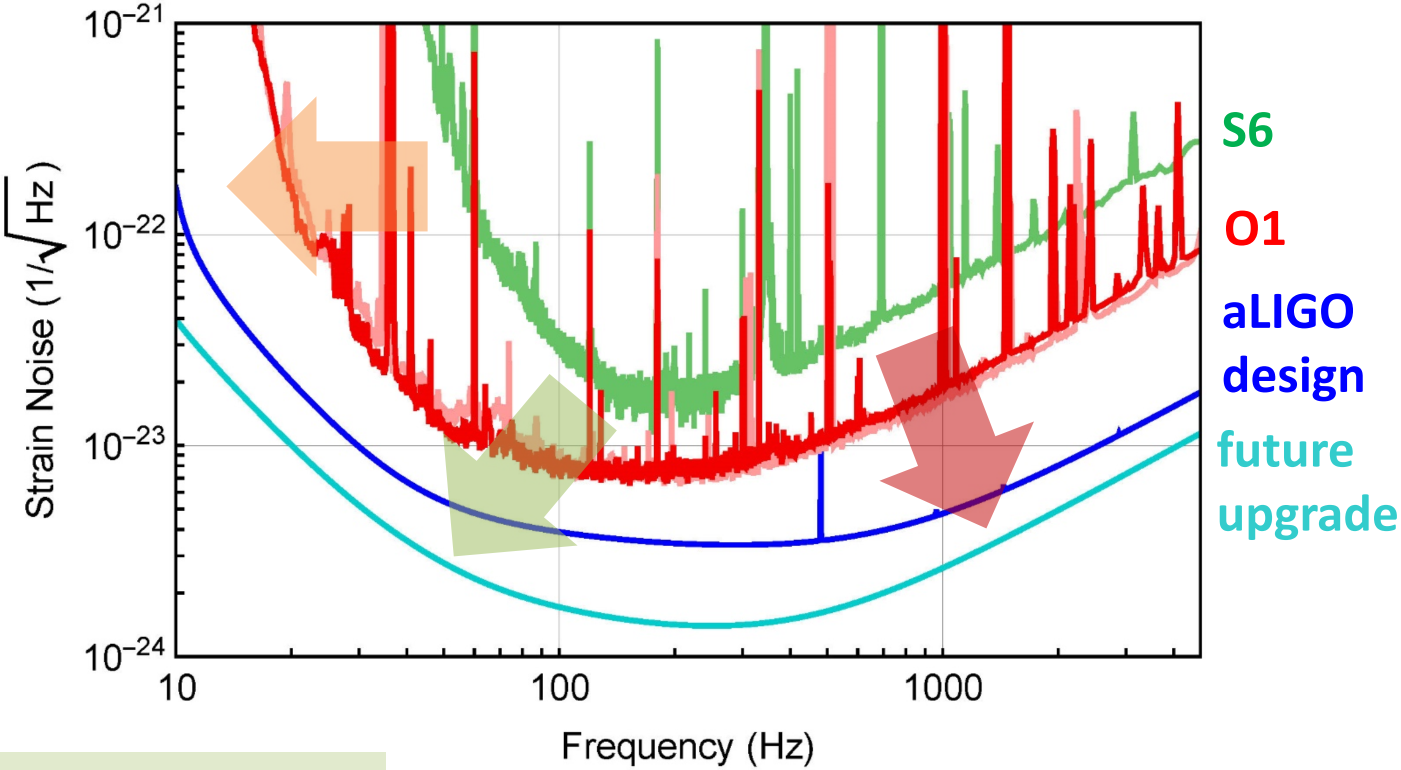




$$h = 2\frac{\delta L}{L}$$

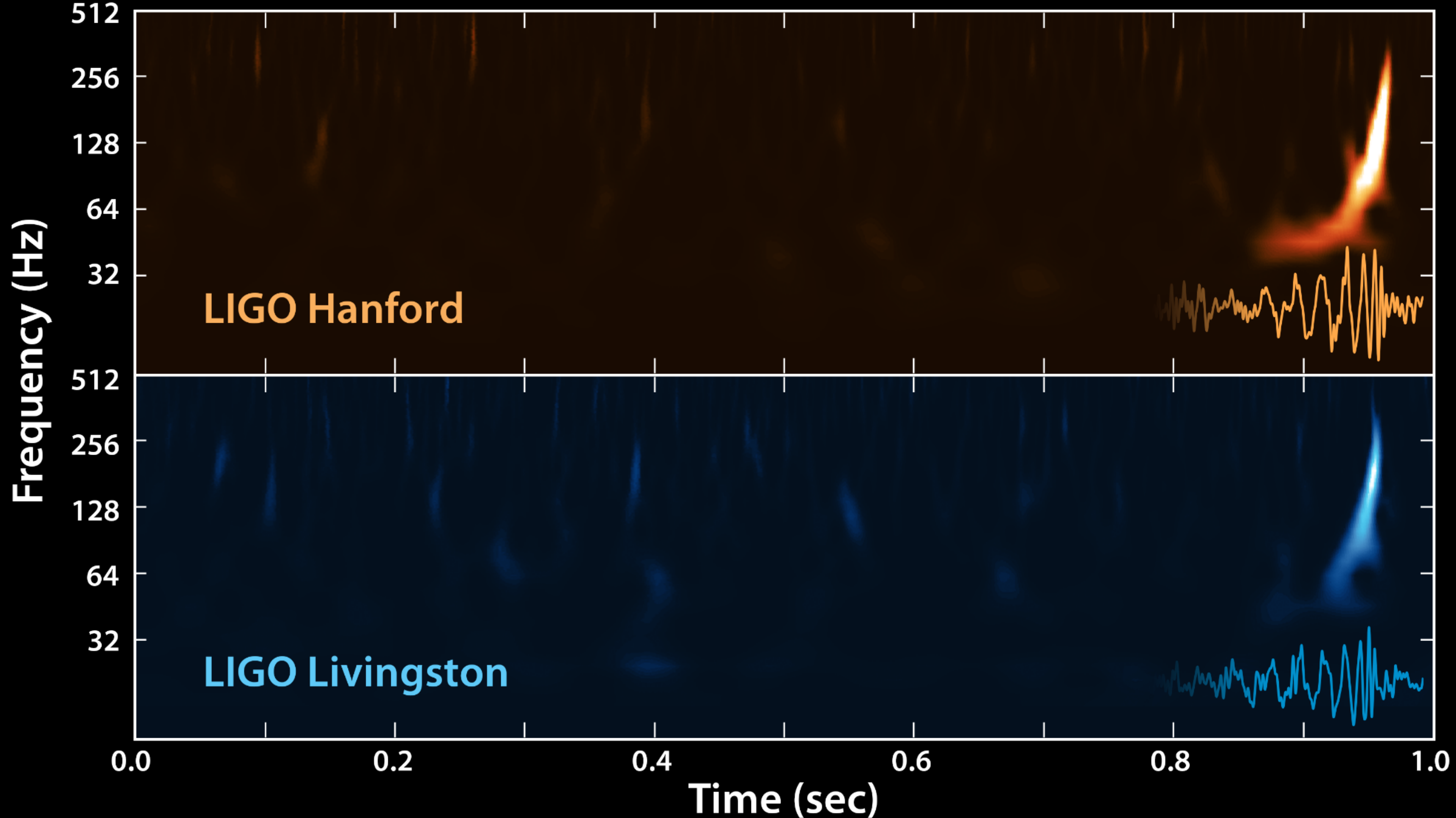
From 1st to 2nd generation

Seismic noise
Improved seismic isolation



Thermal noise
Monolithic suspensions
Improved mirror coatings
Larger beam size

Quantum noise
Higher laser power
Thermal compensation
Signal recycling
DC detection



INTRODUCING

GW150914

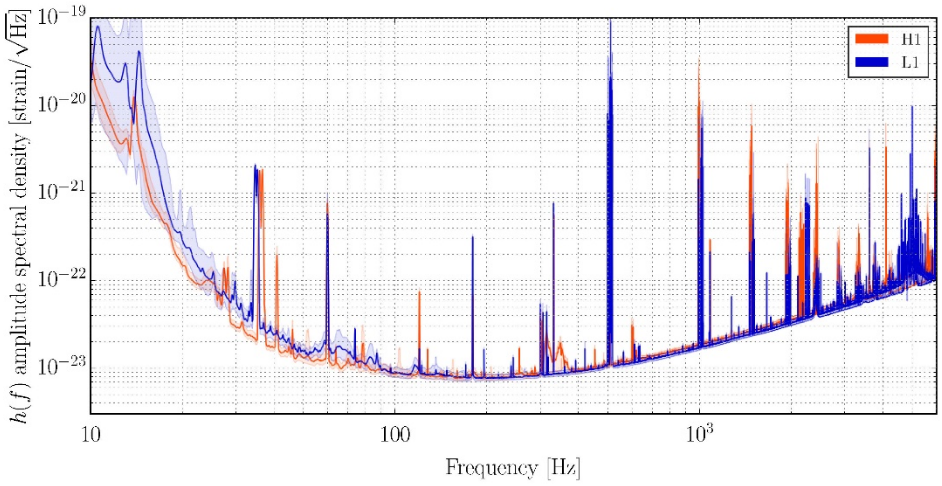
09.14.15 | 09:50:45 UTC | 29 +36 $M_{\odot}$, SNR 24 | proud parents, LIGO & Virgo Collaborations

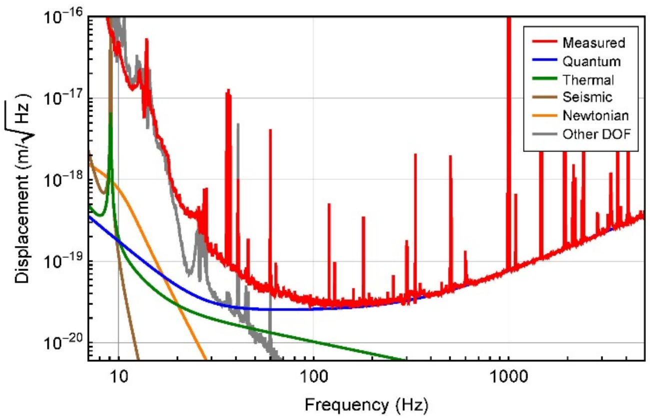
O1 run

- September 2015 – January 2016
  - Preceded by engineering run ER8 – from Aug 17
  - Stable data taking from Sep 12
  - O1 scheduled to start on Sep 18
    - When fully ready with calibration / hardware injections / EM follow-up alerts / computing
- Results on period Sep 12 – Oct 20
  - Detectors maintained in same configuration
  - Duty cycle: H1 70%, L1 55%, H1 + L1 48%
  - 16 days of coincident data

Detector operation

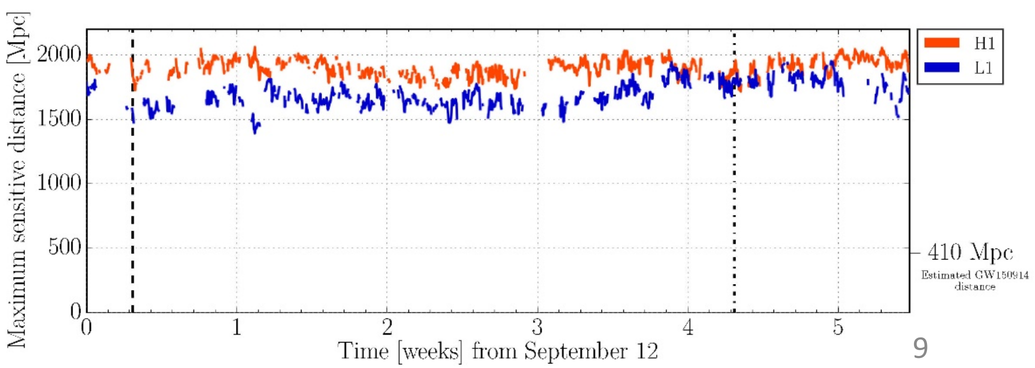
- Similar strain sensitivities for H1 and L1
  - $10^{-23}/\sqrt{Hz}$ @ 100 Hz
  - 3-4 times better than in 2010 in 100 Hz – 300 Hz band





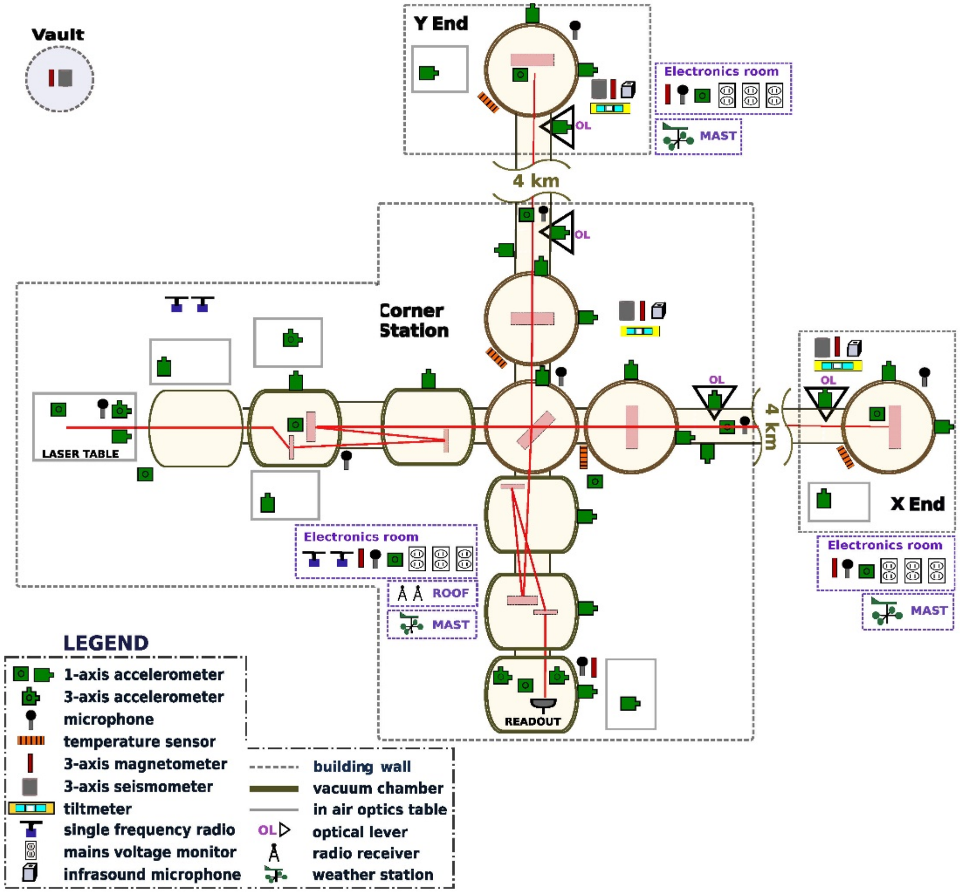
- Sum of known noise sources accounts for most of observed sensitivity curve
  - Excess noise in 20 Hz – 100 Hz band

- Homogeneous data taking on Sep 12 – Oct 20 period
- In observation mode for ~30 min (H1), > 1 hour (L1) at time of GW150914



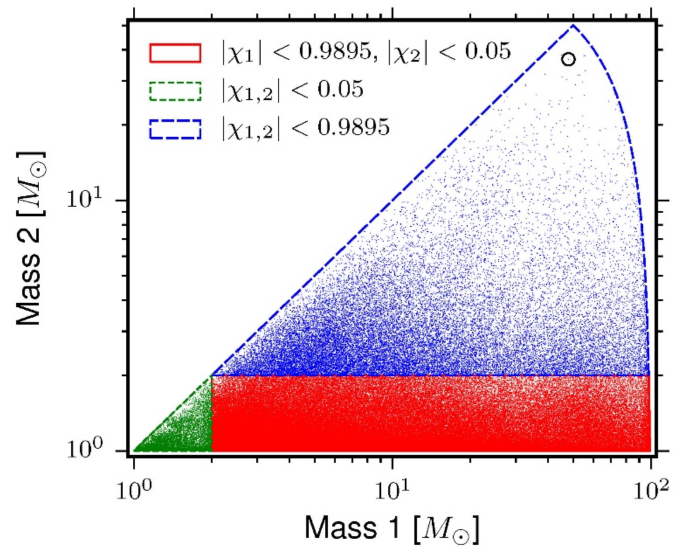
Environment vetting

- Monitoring of detectors physical environment performed with array of sensors
  - Seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, AC-power line monitors, cosmic ray detector
    - ~10^5 channels for each detector
  - Used to characterize couplings and identify / veto transient disturbances
  - Special attention to possible correlated sources of noise
    - Global electromagnetic noise
- Environmental origin for GW150914 ruled out
  - Excess power in any auxiliary channel too small by factor > 17 to account for GW150914 amplitude
    - Would not match signal morphology anyway

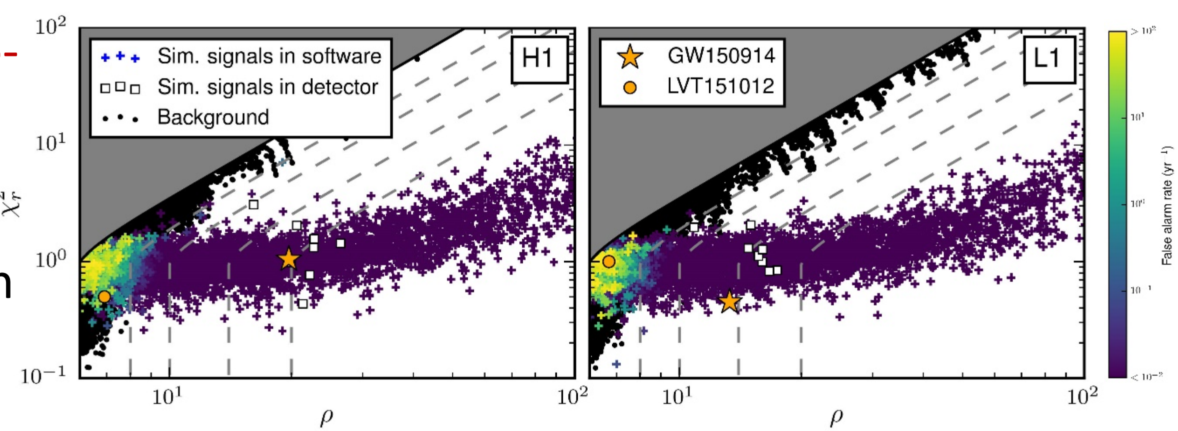


Compact Binary Coalescence Search

- Targets signals from BNS, NS-BH, BBH sources
- Relies on accurate model of waveform to perform matched filtering
  - Cross-correlates h(t) data with expected waveform
  - h(t) calibrated to 10% amplitude and 10° in phase
- Intrinsic parameters – masses, (aligned) spins – drive system dynamics and waveform evolution
  - 4-D space scanned with ~250,000 templates
- Extrinsic parameters impact signal arrival time, overall amplitude and phase
  - Maximized over

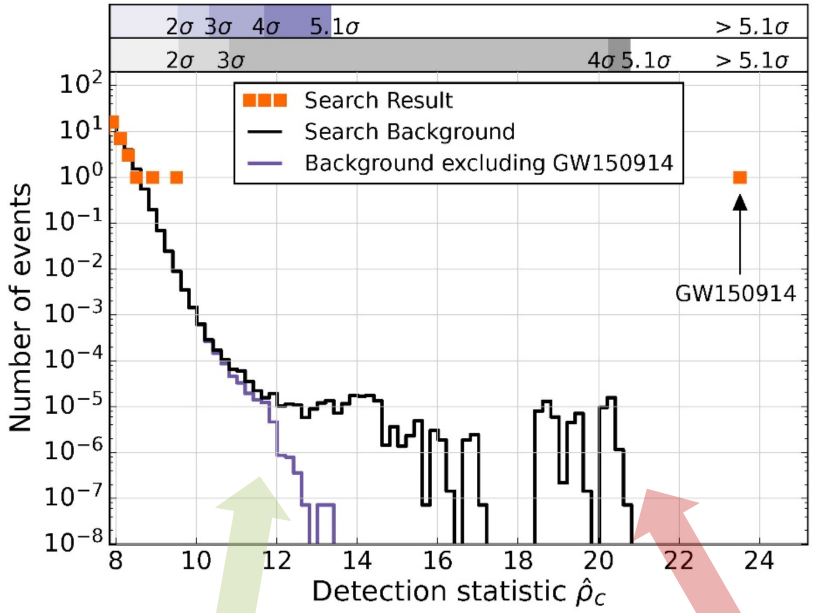


- Extracts maxima in signal-to-noise ratio time series $\rho(t)$
- Computes χ_r^2 to test consistency with template
- Extract triggers coincident in both detectors
  - Time and parameters
- Apply data quality vetoes



CBC BBH search result

- Detection statistic
  - $\hat{\rho} = \rho / \{[1 + (\chi_r^2)^3]/2\}^{1/6}$
  - $\hat{\rho}_c = \sqrt{\hat{\rho}_{H1}^2 + \hat{\rho}_{L1}^2}$
- Significance
  - GW150914 loudest event in search, $\hat{\rho}_c$ = 23.6
  - H1 and L1 triggers forming GW150914: largest $\hat{\rho}$ in each detector
  - False alarm rate measured from background estimated on data
    - Analysis repeated on detector streams time-shifted by 0.1 s ~10^7 times, T_{bckd} = 608,000 yr
    - Account for trial factors
    - GW150914 louder than all background ➔ lower limit on significance



Coincidences between single detector triggers from GW150914 and noise in other detector

Background excluding contribution from GW150914 to gauge significance of other triggers

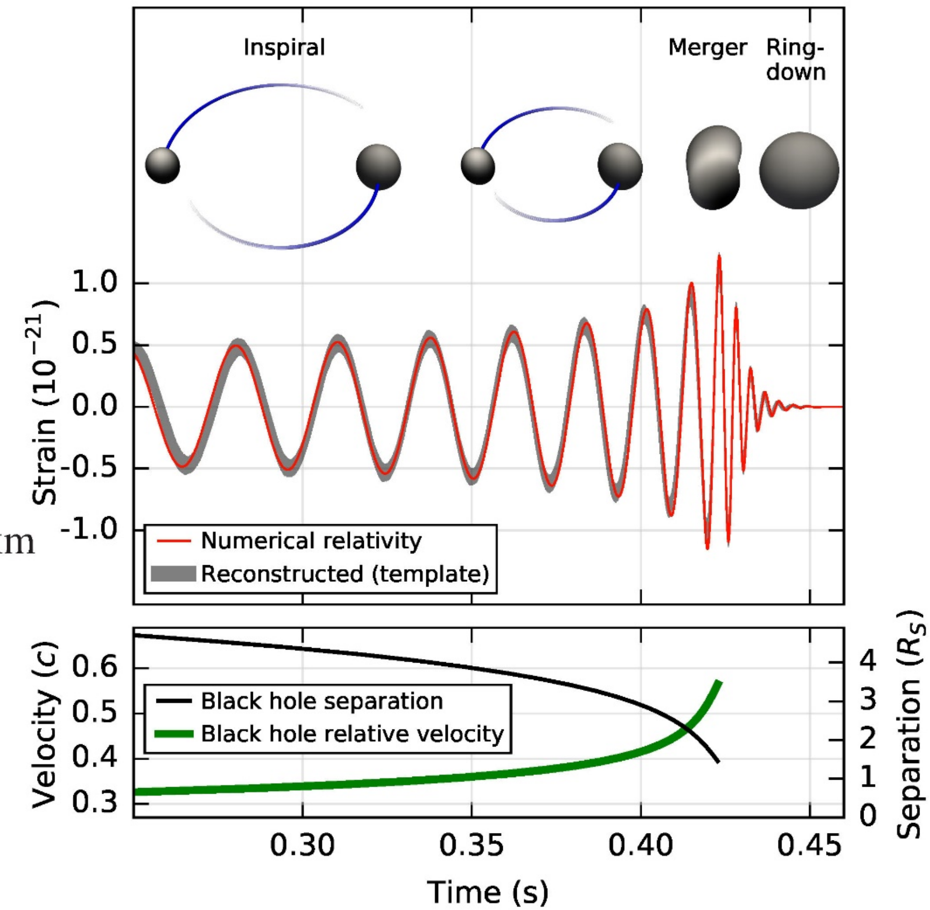
Event	Time (UTC)	FAR (yr^{-1})	$\mathscr{F}$	$\mathscr{M}$ (M$_\odot$)	m_1 (M$_\odot$)	m_2 (M$_\odot$)	$\chi_{\rm eff}$	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\,\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 ($2.1\,\sigma$)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}

Evidence for BBH merger

- Over 0.2 s, frequency and amplitude increase from 35 Hz to f_{peak} = 150 Hz (~ 8 cycles)
  - GW-driven inspiral of two orbiting masses m_1 and m_2
  - Inspiral evolution characterized by chirp mass

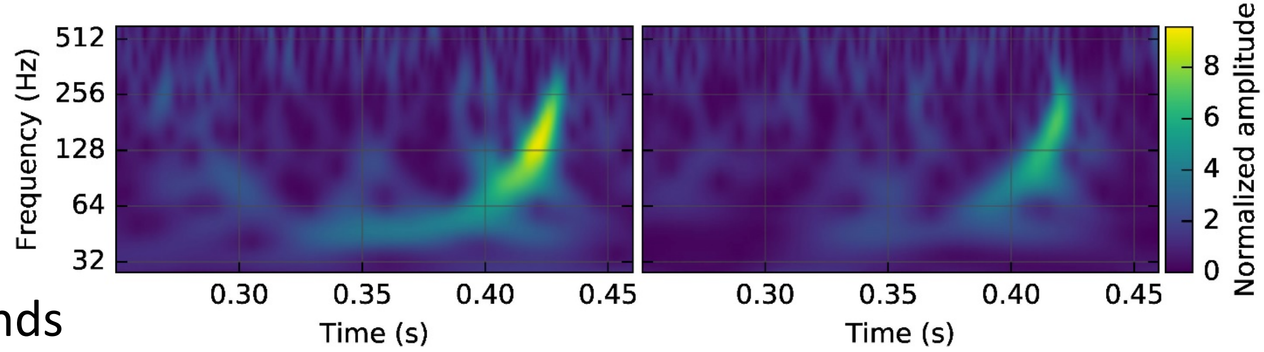
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

  - $\mathcal{M} \simeq 30 M_\odot \quad M = m_1 + m_2 \gtrsim 70 M_\odot$
  - Keplerian separation gets close to Schwarzschild radius $R_S = 2GM/c^2 \gtrsim 210$ km
  - Very close and very compact objects
    - BNS too light, NSBH would merge at lower frequencies
- Decay of waveform after peak consistent with damped oscillations of BH relaxing to final stationary Kerr configuration
  - But SNR too low to claim observation of quasi normal modes



Generic Transient Search

- Operates without a specific search model
- Identifies coincident excess power in time-frequency representations of h(t)
  - Frequency < 1 kHz
  - Duration < a few seconds



- Reconstructs signal waveforms consistent with common GW signal in both detectors using multi-detector maximum likelihood method
- Detection statistic
  - $$\eta_c = \sqrt{\frac{2E_c}{(1 + E_n/E_c)}}$$

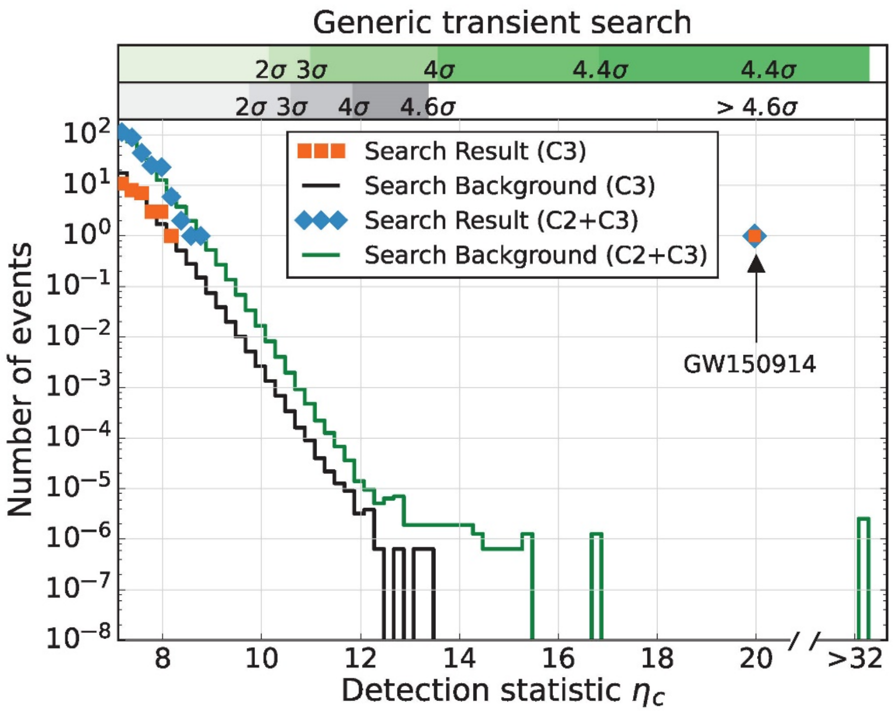
E_c: dimensionless coherent signal energy obtained by cross-correlating the two reconstructed waveforms

E_n: dimensionless residual noise energy after reconstructed signal is subtracted from data

- Signals divided into 3 search classes based on their time-frequency morphology
  - C3 : Events with frequency increasing with time – CBC like

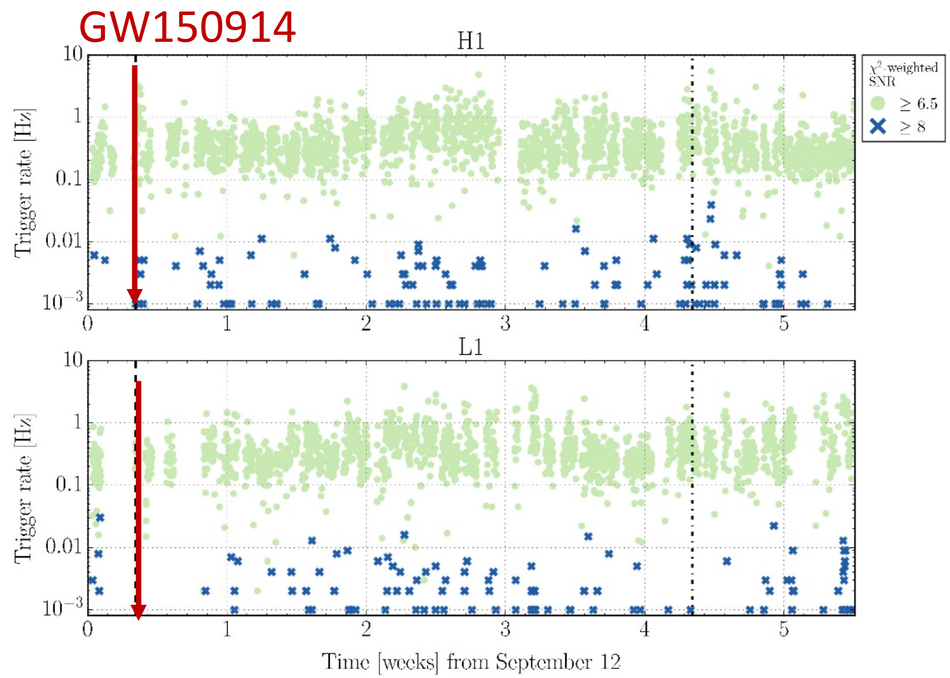
Generic Transient Search Result

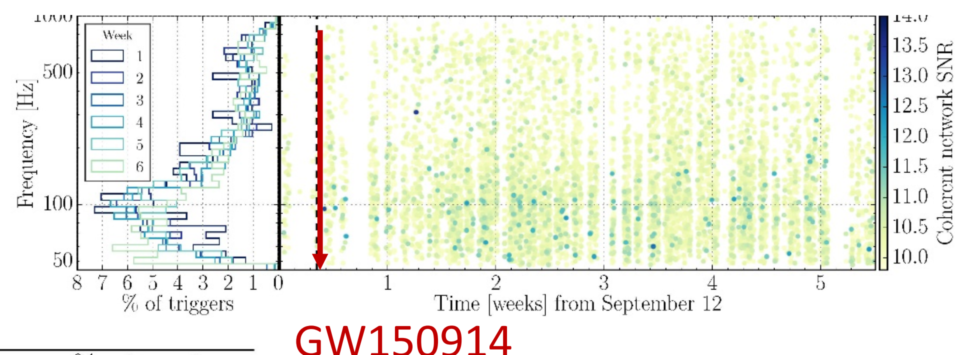
- GW150914 loudest event in C3 search class, $\eta_c = 20$
- Significance also measured from time slides
  - T_{bckd} = 67,400 yr , trial factors
  - FAR < 1 per 22,500 yr
  - FAP < 2 10^{-6} ➔ > 4.6 σ



Data Quality

- Data quality figures of merit show clean data set, with homogeneous background on analyzed period, for both transient analyses
- Data quality vetoes remove times with identified instrumental or environmental issues, improve search background
  - GW150914 >> every background event even without DQ vetoes





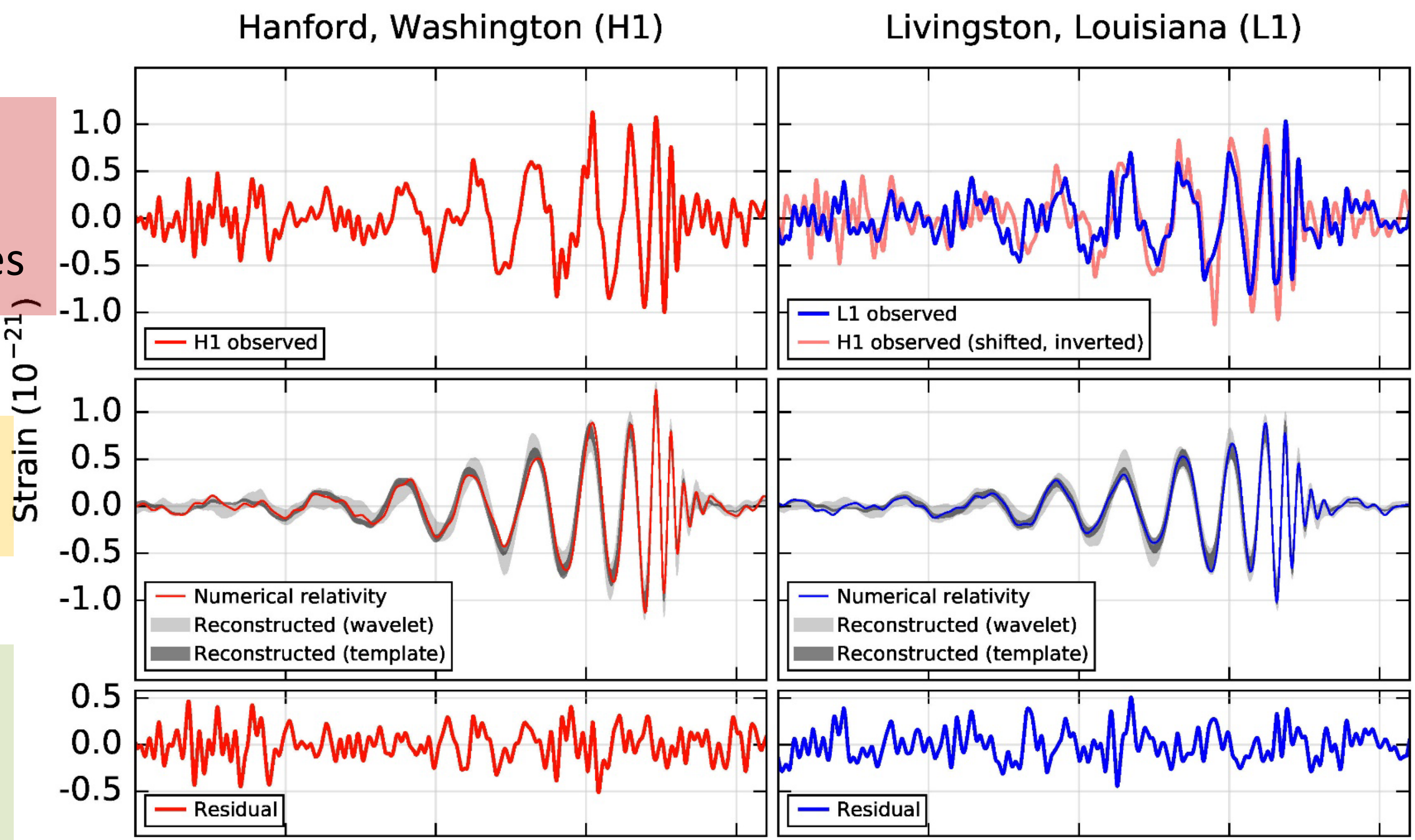
Hanford			Livingston		
DQ veto category	Total deadtime (s)	% of total coincident time	DQ veto category	Total deadtime (s)	% of total coincident time
1	73446	4.62%	1	1066	0.07%
2	5522	0.35%	2	87	0.01%

Naked eye, CBC and Burst Views

35 – 350 Hz band-passed strain time series

Waveform reconstructions

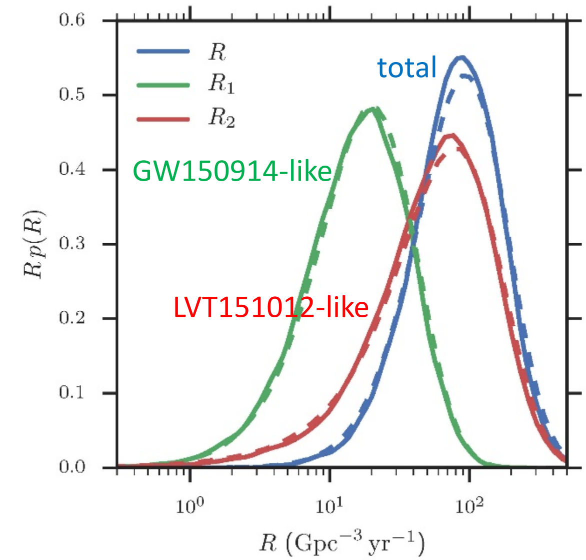
Residual noise after waveform subtraction

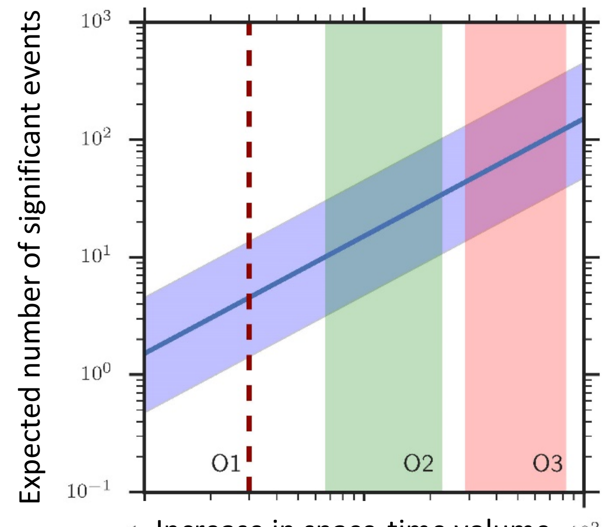


- Waveform reconstructed from coherent signal in both detectors agrees with best-fit CBC waveform and NR, agrees with data

Rate of BBH mergers

- Previous rate estimates based on EM observations and population modelling
  - $R \sim 0.1 - 300\ Gpc^{-3}\ yr^{-1}$
- Previous LIGO-Virgo rate upper limits
  - $R < 140\ Gpc^{-3}\ yr^{-1}$ for GW150914 parameters
- Astrophysical rate inference involves
  - Counting signals in experiment
  - Estimating sensitivity to population of sources
    - Depends on (hardly known) mass distribution
- Low statistics and variety of assumptions yield broad rate range
  - $R \sim 2 - 400\ Gpc^{-3}\ yr^{-1}$
- Can project expected number of highly significant events as a function of surveyed time-volume





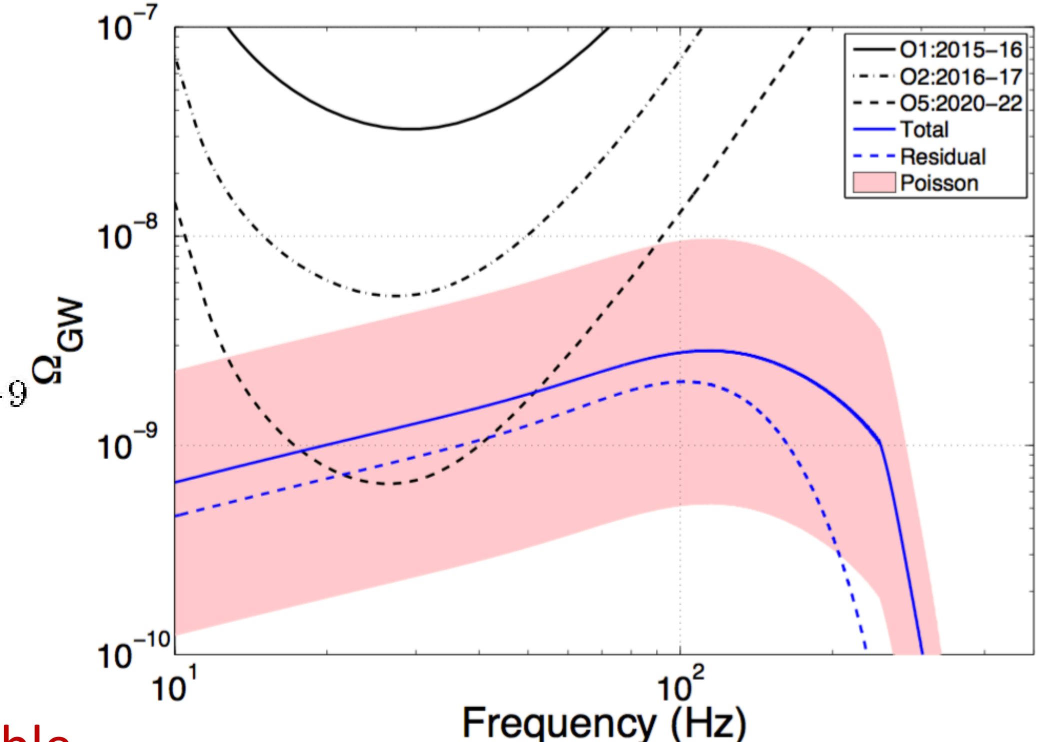
Expected BBH Stochastic Background

- GW150914 suggests population of BBH with relatively high mass
- Stochastic GW background from BBH could be higher than expected
  - Incoherent superposition of all merging binaries in Universe
  - Dominated by inspiral phase
- Estimated energy density

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df}$$

$$\Omega_{\rm GW}(f = 25\,{\rm Hz}) = 1.1^{+2.7}_{-0.9} \times 10^{-9}$$

- Statistical uncertainty due to poorly constrained merger rate currently dominates model uncertainties
- Background potentially detectable by Advanced LIGO / Advanced Virgo at projected final sensitivity

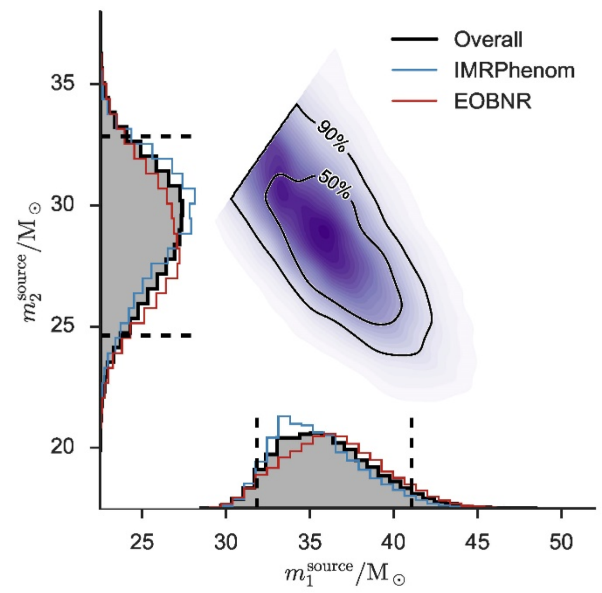


Parameter Estimation

- Intrinsic parameters (8)
  - Masses (2) + Spins (6)
- Extrinsic parameters (9)
  - Location : luminosity distance, right ascension, declination (3)
  - Orientation: inclination, polarization (2)
  - Time and phase of coalescence (2)
  - Eccentricity (2)
- PE based on coherent analysis across detector network
  - Bayesian framework: Computes likelihood of data given parameters, based on match between data and predicted waveform
  - Explores full multidimensional parameter space with fine stochastic sampling
- PE relies on accurate waveform models
  - Crucial progress over past decade to model all phases of BBH coalescence: inspiral, merger, ringdown
  - Waveform models combine perturbative theory and numerical relativity
  - Still missing: eccentricity, higher order gravitational modes, full spin generality
    - EOBNR: Aligned spins (11 parameters)
    - IMRPhenom: Aligned spins + one effective precession spin parameter (12 parameters)

GW150914 Intrinsic Parameters

- Encoded in GW signal
  - Inspiral
    - Leading order: chirp mass
    - Next to leading order: mass ratio, spin components // orbital angular momentum
    - Higher orders: full spin DOF
  - Additional spin effect
    - If not // orbital angular momentum: orbital plane precession
      ➔ Amplitude and phase modulation
  - Merger and ringdown
    - Primarily governed by final black hole mass and spin
    - Masses and spins of binary fully determine mass and spin of final black hole in general relativity



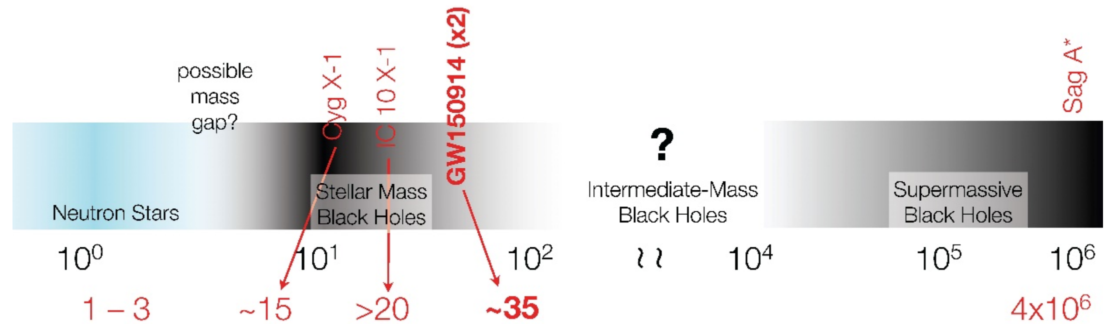
- Masses

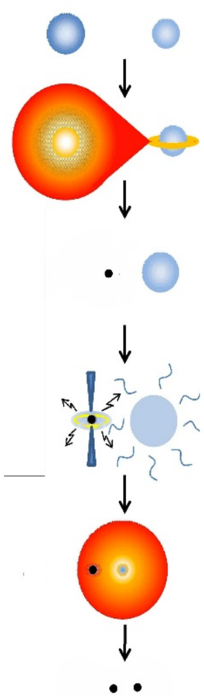
Source-frame total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$

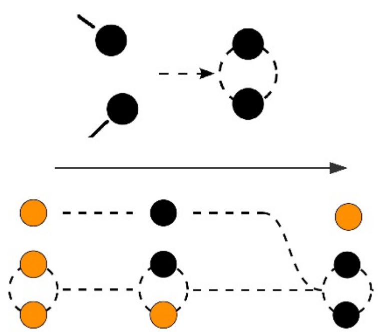
- Spins $a_{\mathrm{f}} = 0.67^{+0.05}_{-0.07}$
  - Weak/tight constraints on individual/final
- Radiated energy $3.0^{+0.5}_{-0.5}\ \mathrm{M}_\odot c^2$
- Peak luminosity $3.6^{+0.5}_{-0.4} \times 10^{56}\ \mathrm{erg\,s^{-1}} = 200^{+30}_{-20}\ \mathrm{M}_\odot c^2/\mathrm{s}$

Astrophysical Implications

- Relatively heavy stellar-mass black holes (> 25 $M_{\odot}$) exist in nature
  - Implies weak massive-star winds
  - Formation in environment with low metallicity





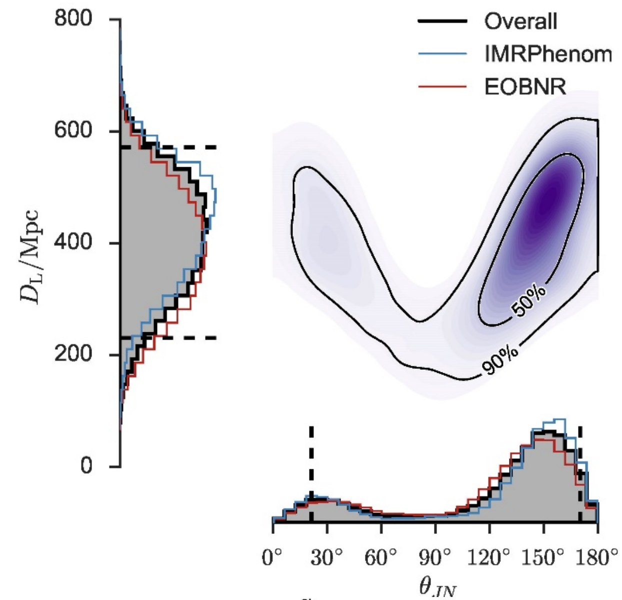


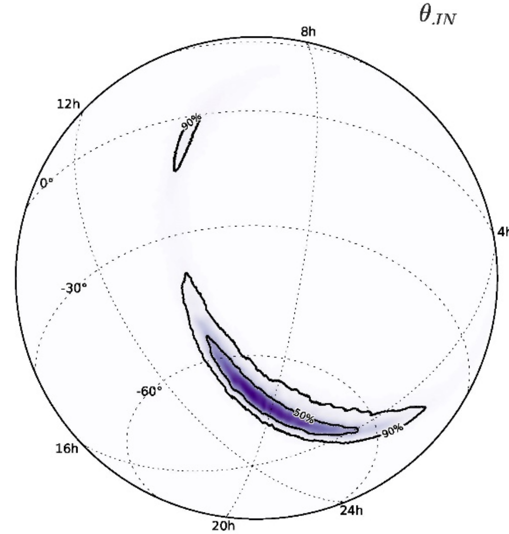
- Binary black holes form in nature
  - GW150914 does not allow to identify formation path
  - From isolated binaries vs dynamical capture in dense star clusters
    - Spin information may be able to tell in the future

- BBHs merge within age of Universe at detectable rate
  - Inferred rate consistent with higher end of rate predictions (> 1 $Gpc^{-3}\ yr^{-1}$)

GW150914 Extrinsic Parameters

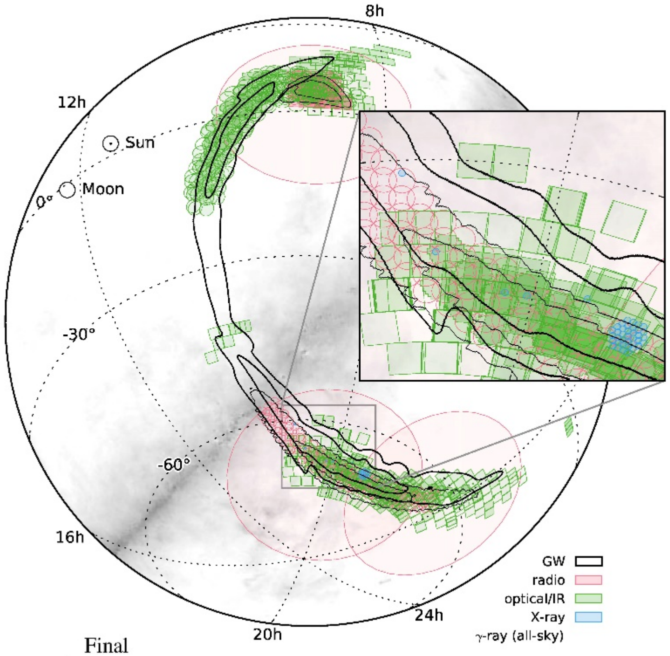
- A mix of things we can measure and things we can guess
  - Amplitude depends on masses, distance, and geometrical factors
    - Distance – inclination degeneracy
    - Distant sources with favorable orientations are preferred
    - $D_{\mathrm{L}} = 410^{+160}_{-180}\ \mathrm{Mpc} \qquad z = 0.09^{+0.03}_{-0.04}$
  - Source location inferred primarily from time of flight $6.9^{+0.5}_{-0.4}\ \mathrm{ms}$, amplitude and phase consistency
    - Limited accuracy with two detector network
    - Sky locations with good detector response are preferred
    - 2-D 90% credible region is 590 deg^2
    - 3-D uncertainty volume is $10^{-2}\ \mathrm{Gpc}^3$ $\sim 10^5$ Milky Way equivalent galaxies

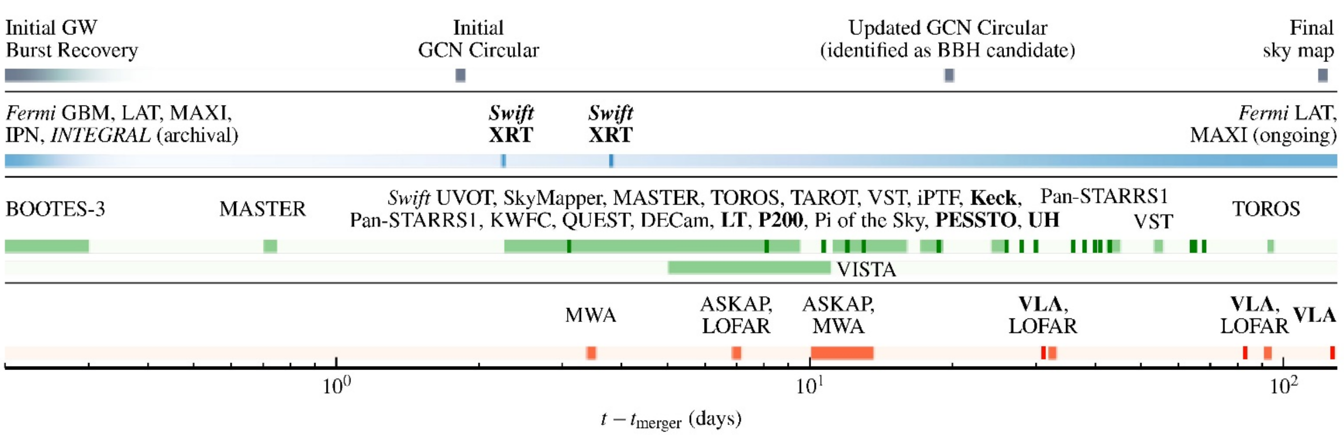




Electromagnetic follow-up

- LVC called for EM observers to join a follow-up program
  - LIGO and Virgo share promptly interesting triggers
  - 70 MoUs, 160 instruments covering full spectrum from radio to very high energy gamma-rays
- 25 teams reported follow-up observation of GW150914

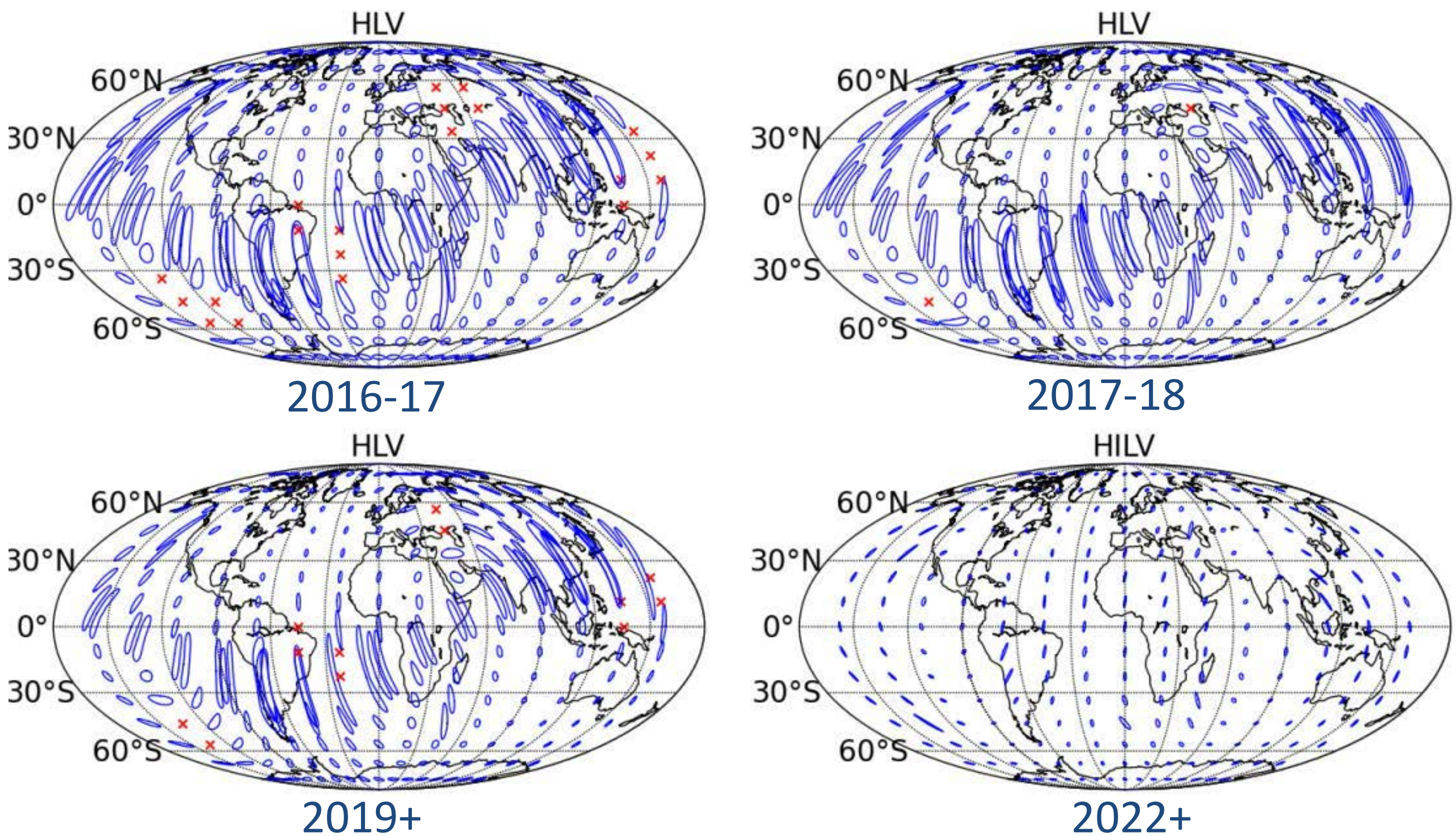




Future Localization Prospects

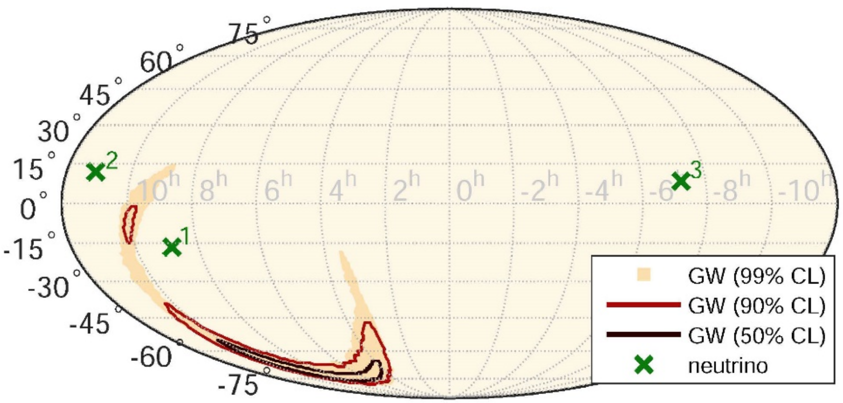
Face-on BNS
@ 80 Mpc

Face-on BNS
@ 160 Mpc



High-Energy Neutrino Follow-up

- Search for coincident high energy neutrino candidates in IceCube and ANTARES data
  - HEN ν expected in (unlikely) scenario of BH + accretion disk system
  - Search window ± 500 s



- No ν candidate in both temporal and spatial coincidence
  - 3 ν candidates in IceCube
  - 0 ν candidate in ANTARES
  - Consistent with expected atmospheric background
  - None of ν candidates directionally coincident with GW150914

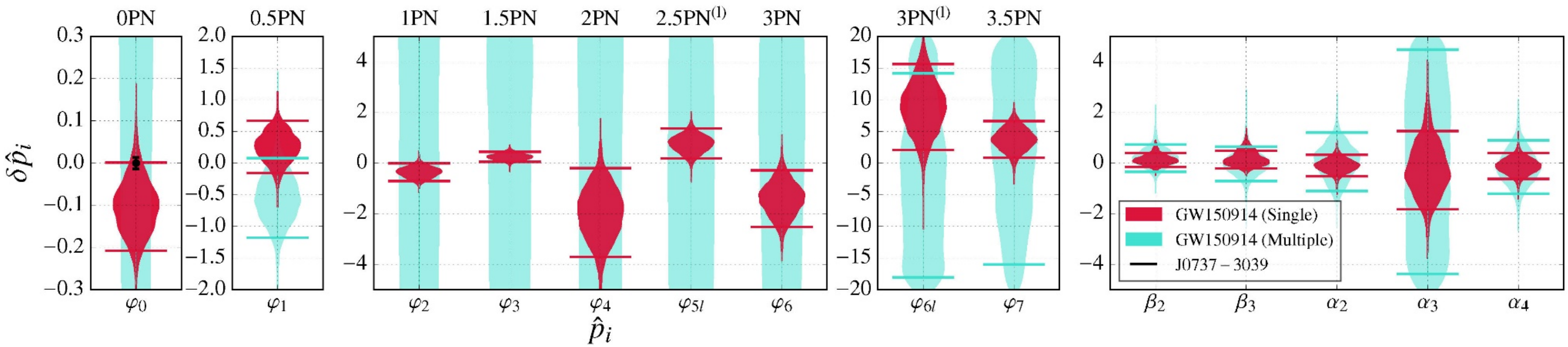
- Derive direction dependent ν fluence upper limit
- Derive constraint on total energy emitted in ν by the source
  - $$\mathrm{E}^{\mathrm{ul}}_{\nu,\mathrm{tot}} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{\mathrm{gw}}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

Testing GR with GW150914 (I)

- Most relativistic binary pulsar known today
  - J0737-3039, orbital velocity $v/c \sim 2 \times 10^{-3}$
- GW150914
  - Strong field, non linear, high velocity regime $v/c \sim 0.5$
- Loud-*ish* SNR allows some coarse tests
  - Check residuals after subtraction of best-fit waveform are consistent with instrumental noise
  - Waveform internal consistency check
  - Evidence for deviation from General Relativity in waveform ?
  - Bound on graviton mass

Testing GR with GW150914 (II)

- No evidence for deviation from GR in waveform

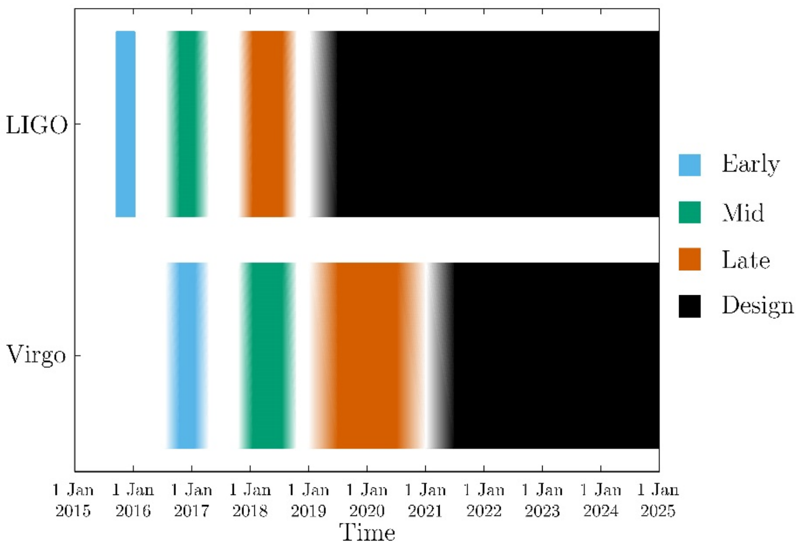


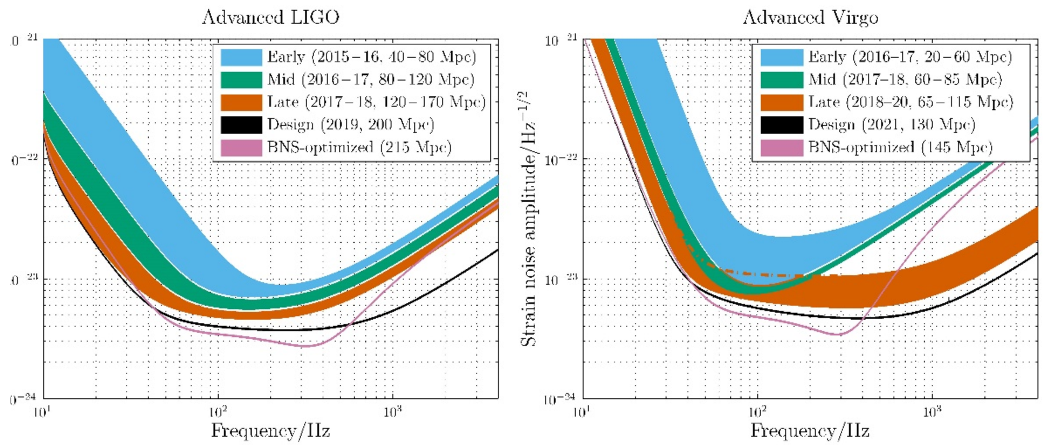
- No evidence for dispersion in signal propagation
  - $\left(\frac{v}{c}\right)^2 = 1 - \left(\frac{hc}{\lambda_g E}\right)^2$ $\quad \lambda_g > 10^{13}$ km
  - $m_g \leq 1.2 \times 10^{-22}$ eV/c^2
  - More constraining than bounds from Solar System and binary pulsar observations
  - Less constraining than model dependent bounds from large scale dynamics of galactic clusters and weak gravitational lensing observations

Outlook: Other Searches

- BBH search results presented on first part of O1
  - Full O1 results to be published in a few months
- Other transient searches on-going
  - BNS, NSBH, IMBH, cosmic strings, generic transients
  - Triggered searches: GRBs…
- Continuous wave sources
  - Non axisymmetric rotating neutron stars
- Stochastic background

Outlook: Future Data





Epoch		2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration		4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc	LIGO	40 – 60	60 – 75	75 – 90	105	105
	Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200	200
	Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections		0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400
90% CR — % within	5 deg^2	< 1	2	*> 1 – 2*	*> 3 – 8*	*> 20*
	20 deg^2	< 1	14	*> 10*	*> 8 – 30*	*> 50*
	median/deg^2	480	230	—	—	—
searched area — % within	5 deg^2	6	20	—	—	—
	20 deg^2	16	44	—	—	—
	median/deg^2	88	29	—	—	—

Conclusion

- Second generation ground-based GW detectors came back online, with amazing sensitivity
- The LIGO detectors observed the beautifully clear and loud signal GW150914
- This discovery opens up two new paths
  - Testing gravitation in uncharted territory
  - Gravitational wave astronomy
- Eagerly waiting for – and striving for – Advanced Virgo to join the network and the fun

LIGO-Virgo GW150914 papers

- Can be downloaded from https://papers.ligo.org/

- LIGO-P1500229: Observing gravitational-wave transient GW150914 with minimal assumptions
- LIGO-P1500269: GW150914: First results from the search for binary black hole coalescence with Advanced LIGO
- LIGO-P1500218: Properties of the binary black hole merger GW150914
- LIGO-P1500217: The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914
- LIGO-P1500262: Astrophysical Implications of the Binary Black-Hole Merger GW150914
- LIGO-P1500213: Tests of general relativity with GW150914
- LIGO-P1500222: GW150914: Implications for the stochastic gravitational-wave background from binary black holes
- LIGO-P1500248: Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914
- LIGO-P1500238: Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914
- LIGO-P1500227: Localization and broadband follow-up of the gravitational-wave transient GW150914
- LIGO-P1500271: High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES
- LIGO-P1500237: GW150914: The Advanced LIGO Detectors in the Era of First Discoveries