TRANSIENT SEARCH IN GW ASTRONOMY

CASE STUDY OF GW150914

-ARCHANA PAI, IISER TRIVANDRUM

MARCH 20, 2017 ICTS-TIFR BANGALORE
TIME SERIES ANALYSIS FOR SYNOPTIC SURVEYS AND GRAVITATIONAL WAVE ASTRONOMY

On behalf LSC-VIRGO Collaboration

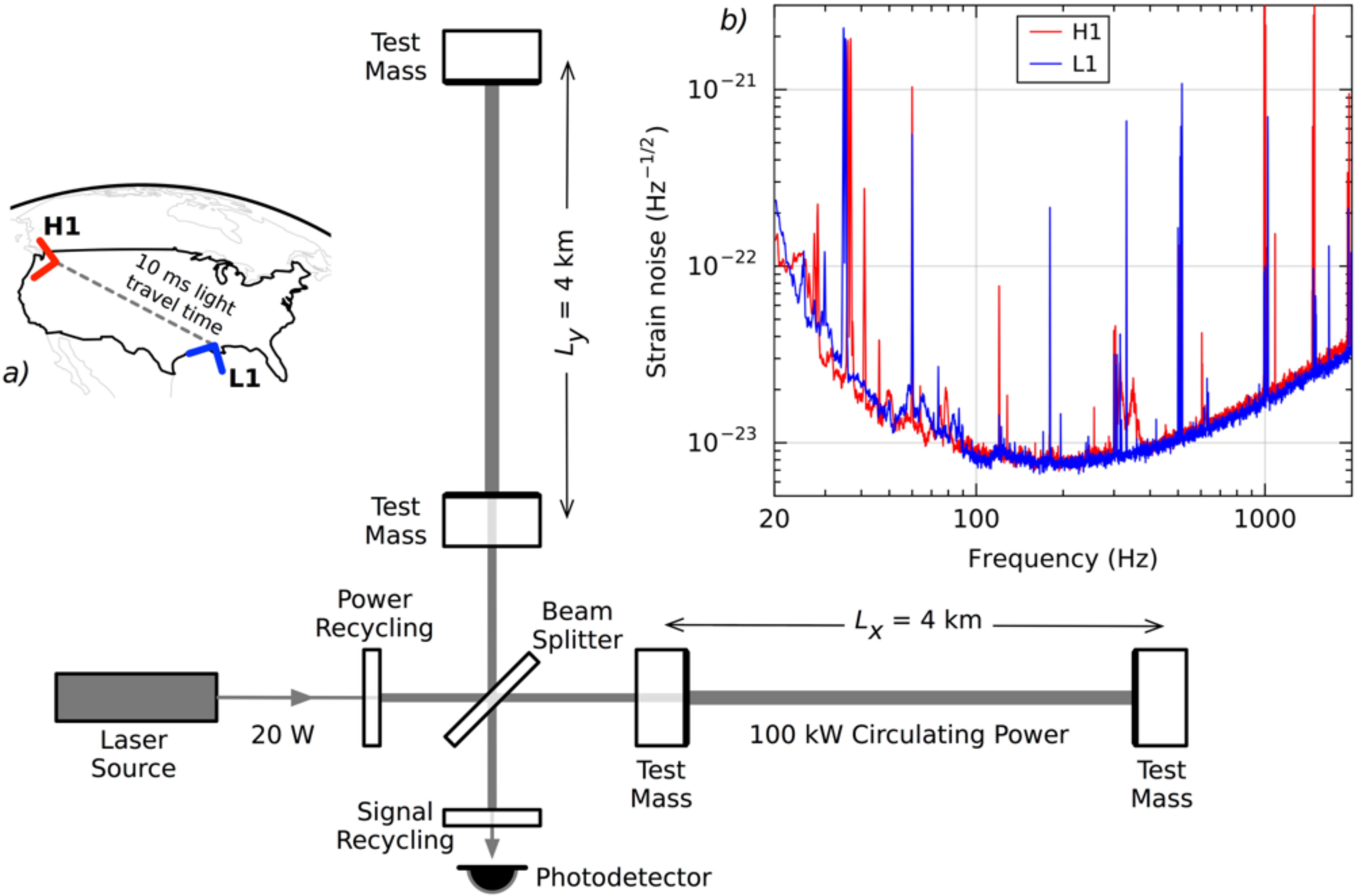
based on LIGO-G1601052

NEW ERA OF GRAVITATIONAL WAVE ASTRONOMY HAS BEGUN

Laser Interferometric Gravitational Wave Observatory (LIGO)

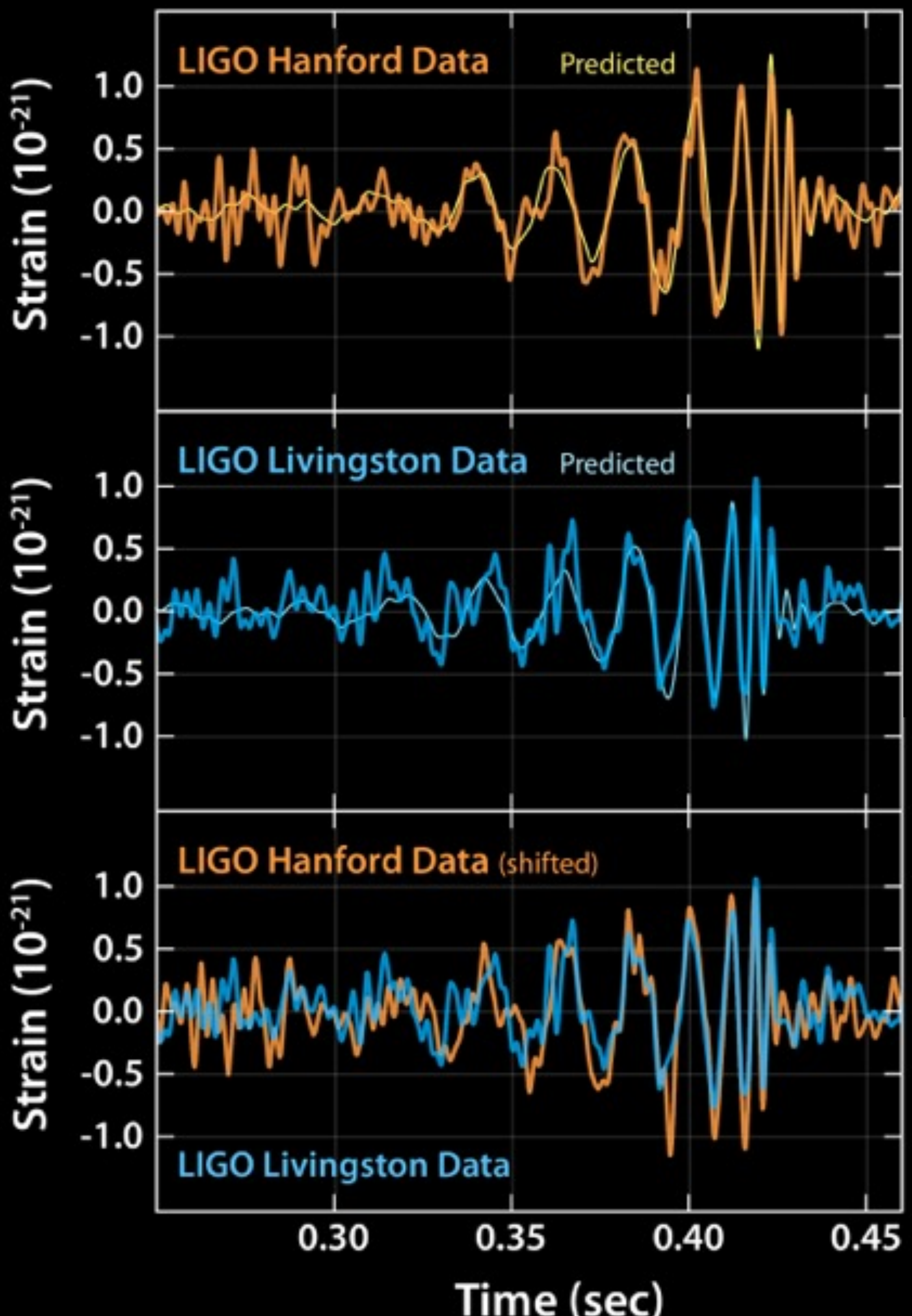
$$h = h_+ F_+ + h_\times F_\times$$

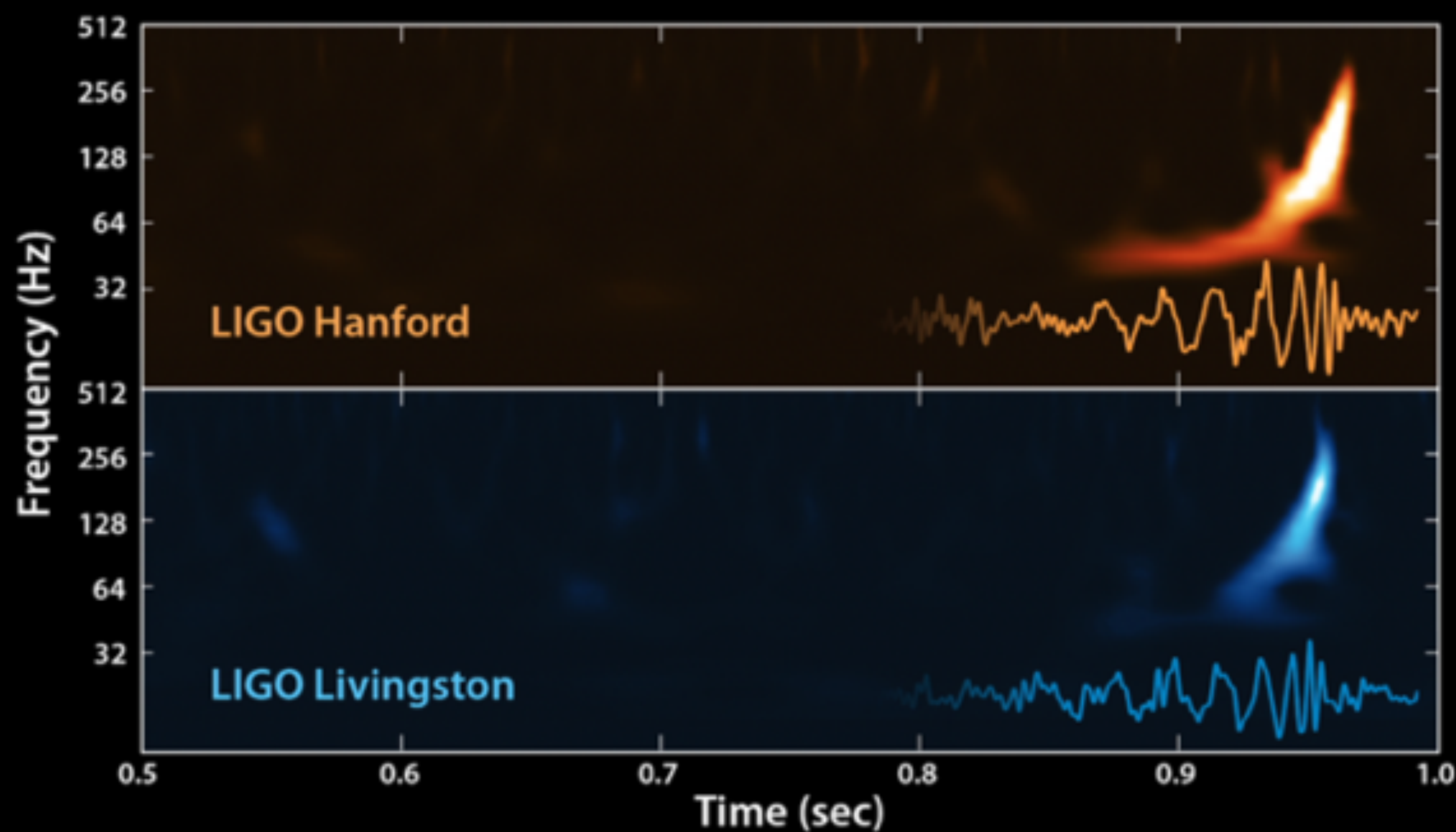
Credit: Larson


a)
H1
10 ms light travel time
L1
b)
H1
L1
10^{-21}
10^{-22}
10^{-23}
Strain noise ($Hz^{-1/2}$)
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
100 kW Circulating Power
Test Mass
Test Mass
Signal Recycling
Photodetector

LVC, PRL 116, 061102 (2016)

GW150914: FIRST GW TRANSIENT EVENT

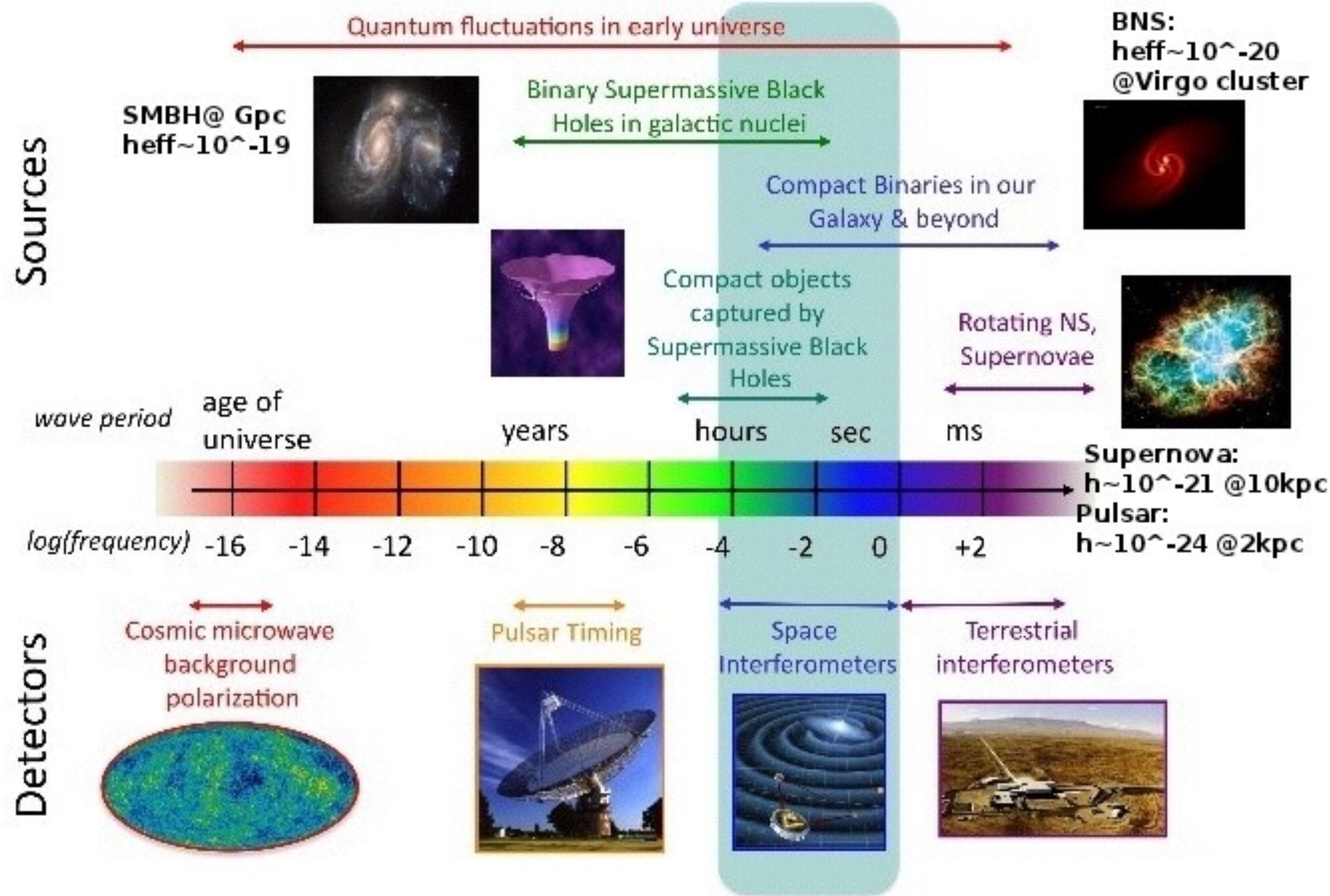




The signal swept in frequency
(35-300 Hz)
as time progresses

The signal duration is 200 msec from
30 Hz.

The Gravitational Wave Spectrum



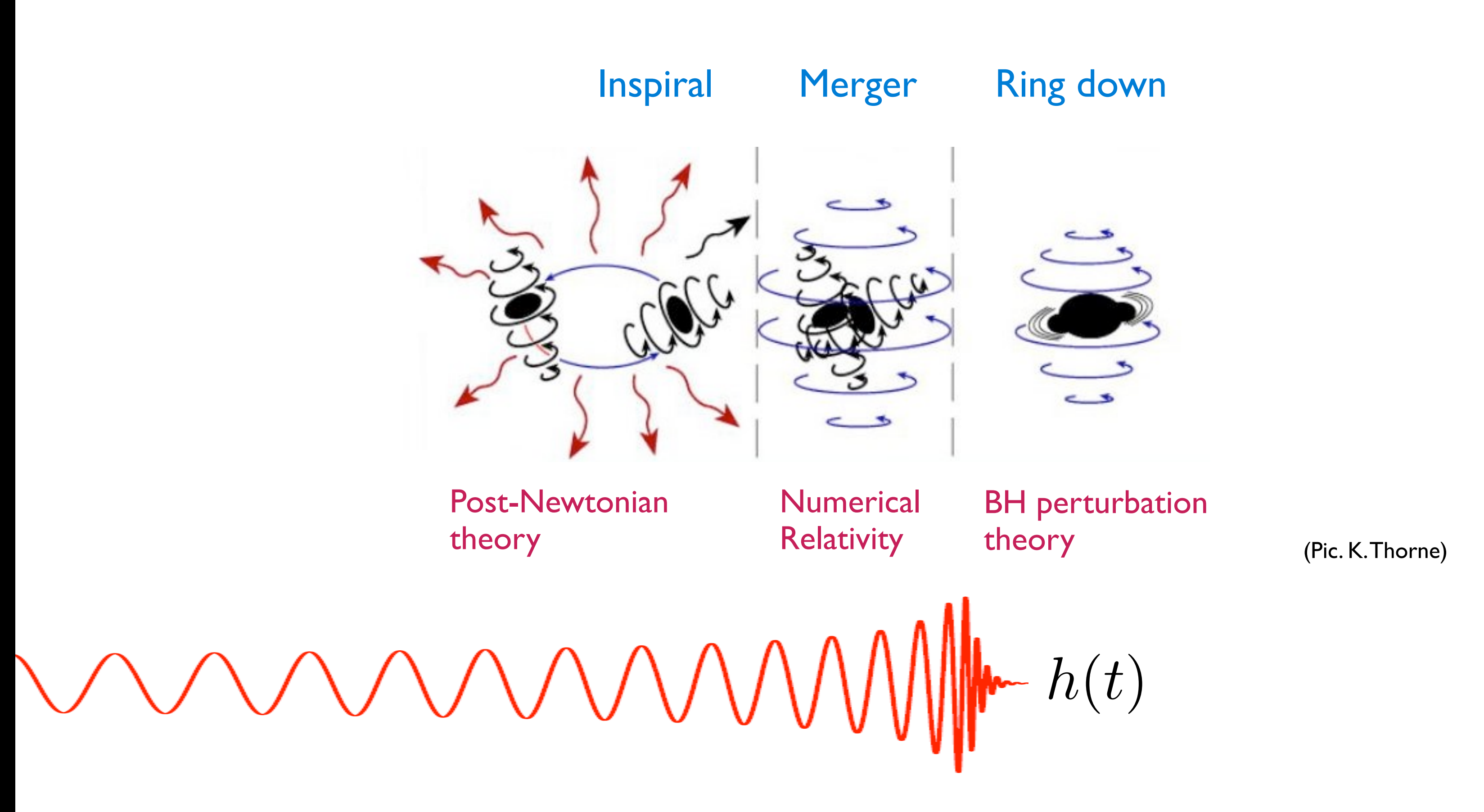
GW TRANSIENTS

SHORT DURATION (FEW MILLISEC TO FEW TENS OF SECS)

FREQUENCY MODULATED SIGNALS

FREQUENCY BAND — 20 HZ - 2-3KHZ

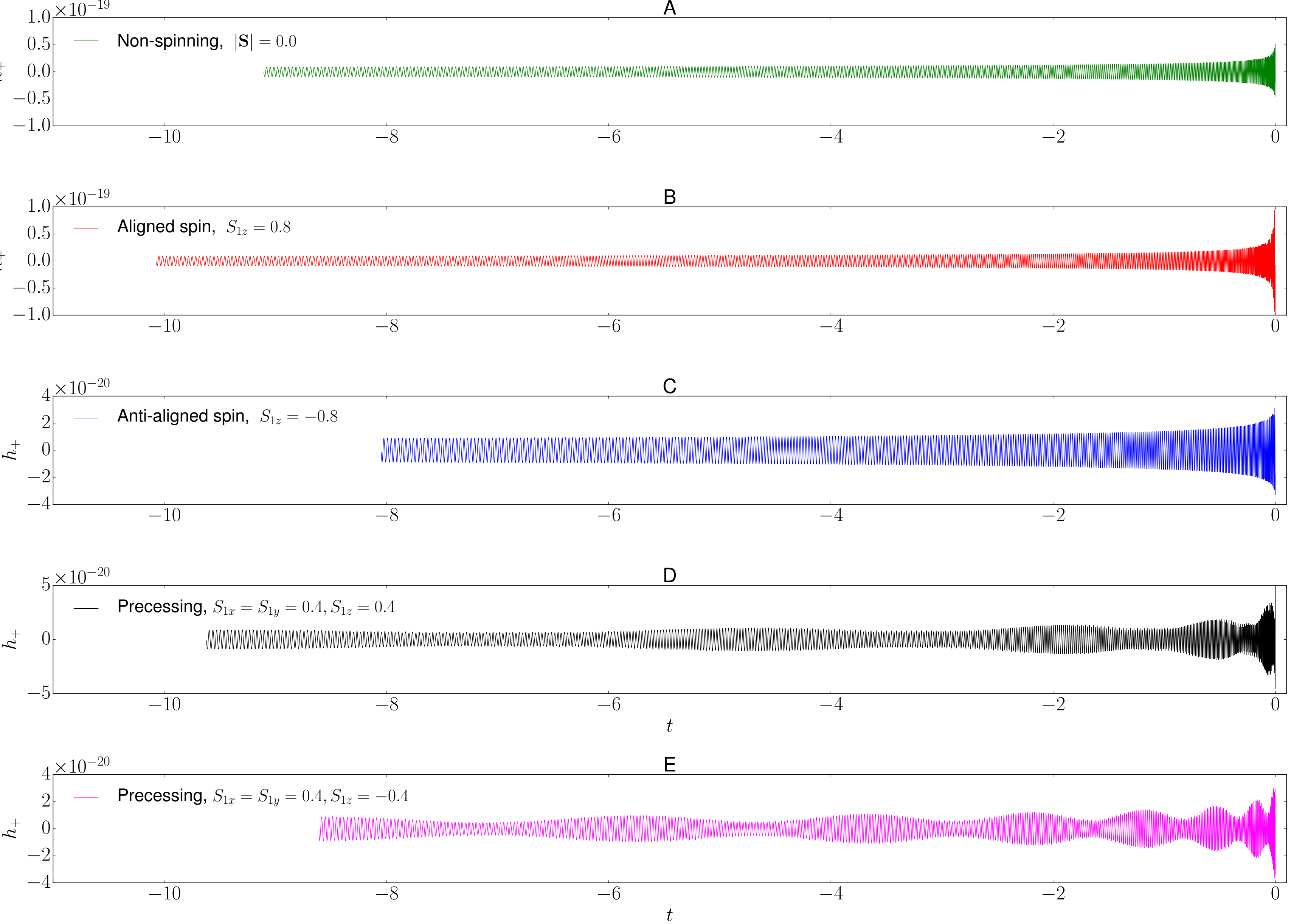
GW TRANSIENTS



COMPACT BINARY COALESCENCE (CBC)

DOUBLE NEUTRON STARS (DNS)
NEUTRON STAR-BLACK HOLES (NSBH)
BLACK HOLE-BLACK HOLE (BBH)

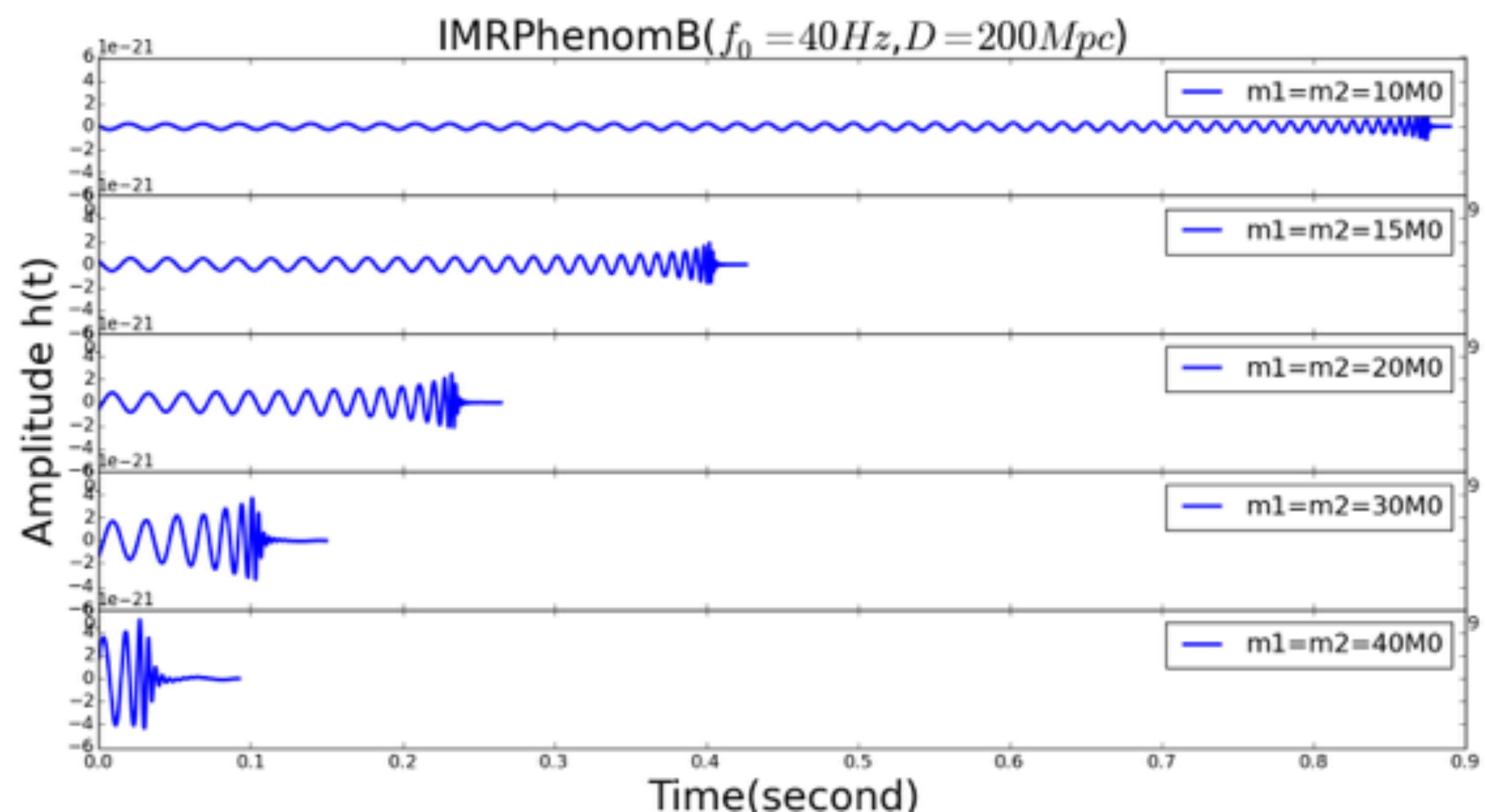
DURING END STAGES OF BINARY EVOLUTION GW SIGNAL ENTERS THE DETECTOR BAND
(20HZ < F < 1HZ)



Different types of GW transients from CBCs

Lower masses spend more time in the detector

Aligned spin system spends more time compared to anti-aligned spins

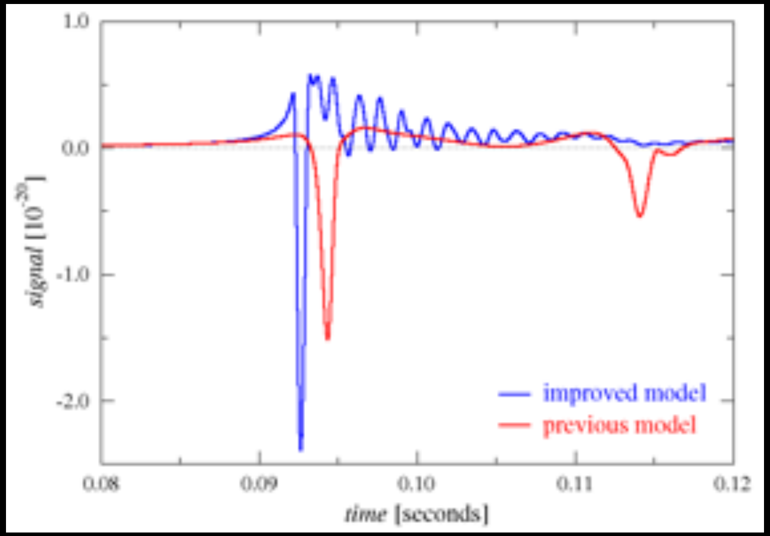


GW TRANSIENTS

UNMODELLED
COMPLEX PHYSICS

Crab

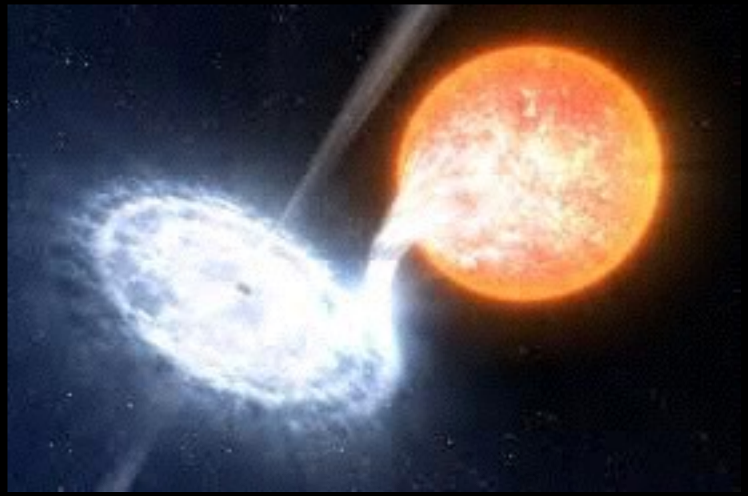
SUPERNOVA CORE
COLLAPSE EVENT



Dimmelmeier Catelogue

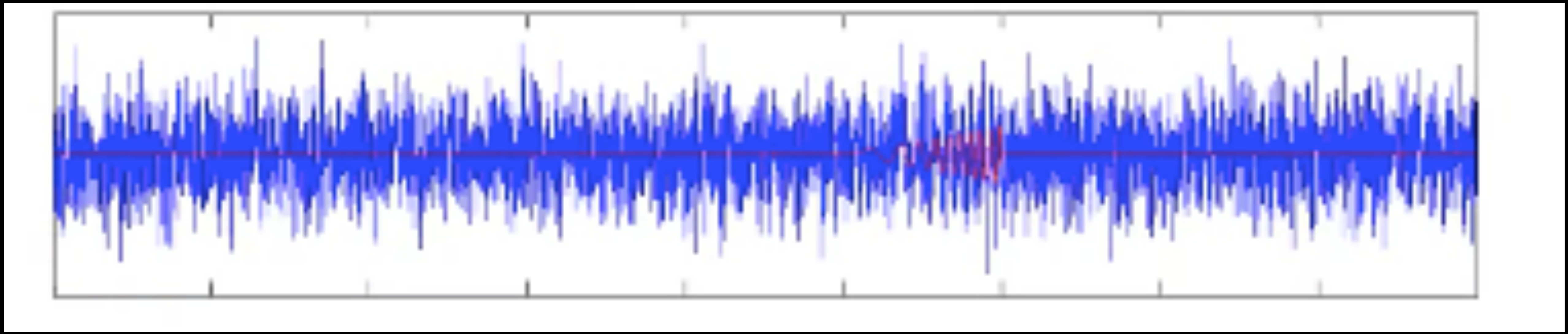
BURSTS IN ECCENTRIC
BINARY ORBITS
LOUTREL ETAL PRD 2014

ACCRETING SYSTEMS
PIRO-THRANE ARXIV-2012



UNKNOWN SOURCES...

DETECTION OF GW TRANSIENT
===
NEEDLE IN A HAYSTACK



MODEL BASED SEARCH:MATCHED FILTERING

UN-MODELLED SEARCH: LARGELY BASED ON THE BROAD SIGNAL FEATURES IN TIME-FREQUENCY DOMAIN

MATCHED FILTERING TECHNIQUE

Fetching weak signal in the noisy data (x(t)=h(t)+n(t))

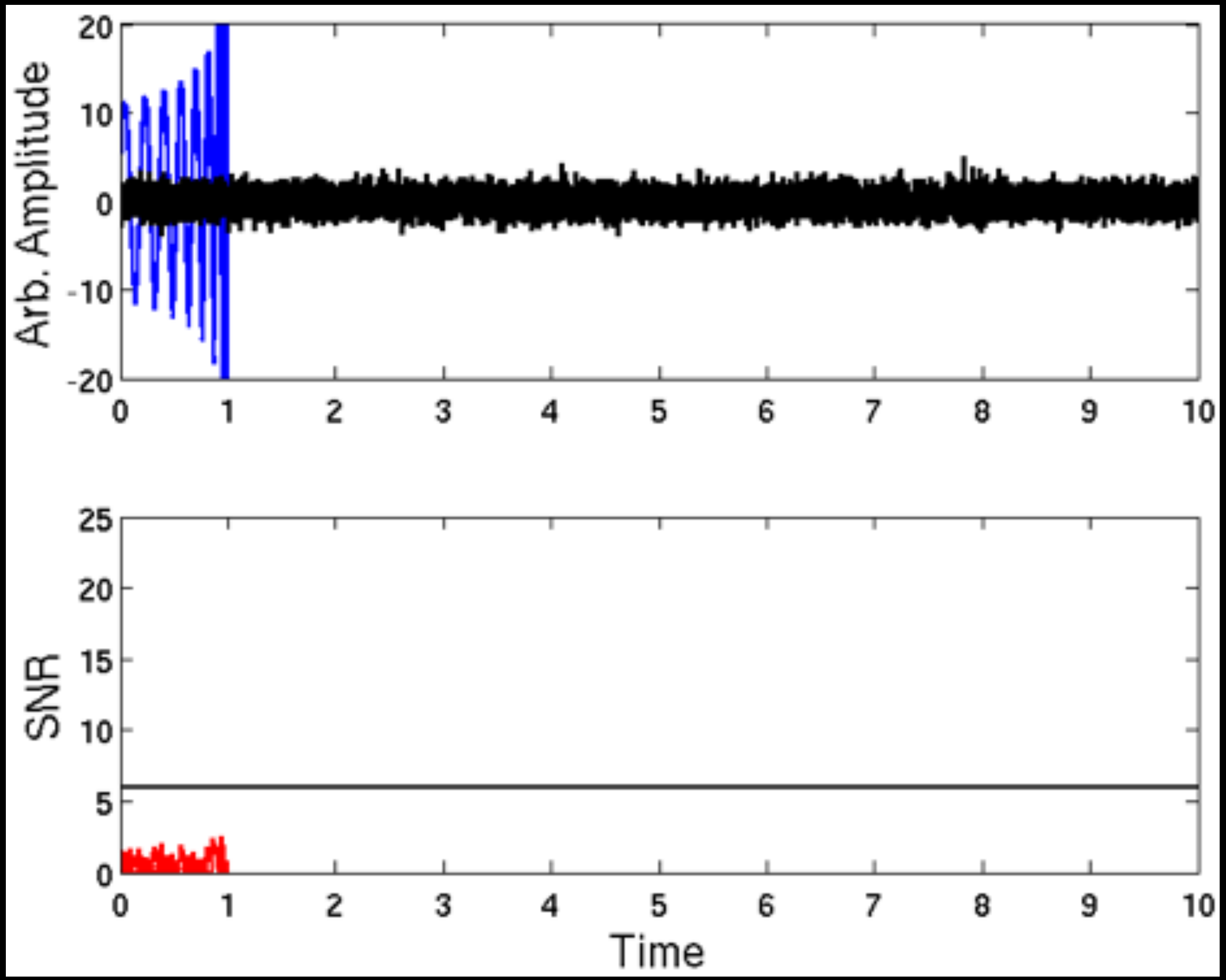
Shape matching technique

Coherent addition of Signal

Incoherent addition of Noise

Filtered Output

$$< x|\hat{h} >$$



Optimal

Signal-To-Noise Ratio

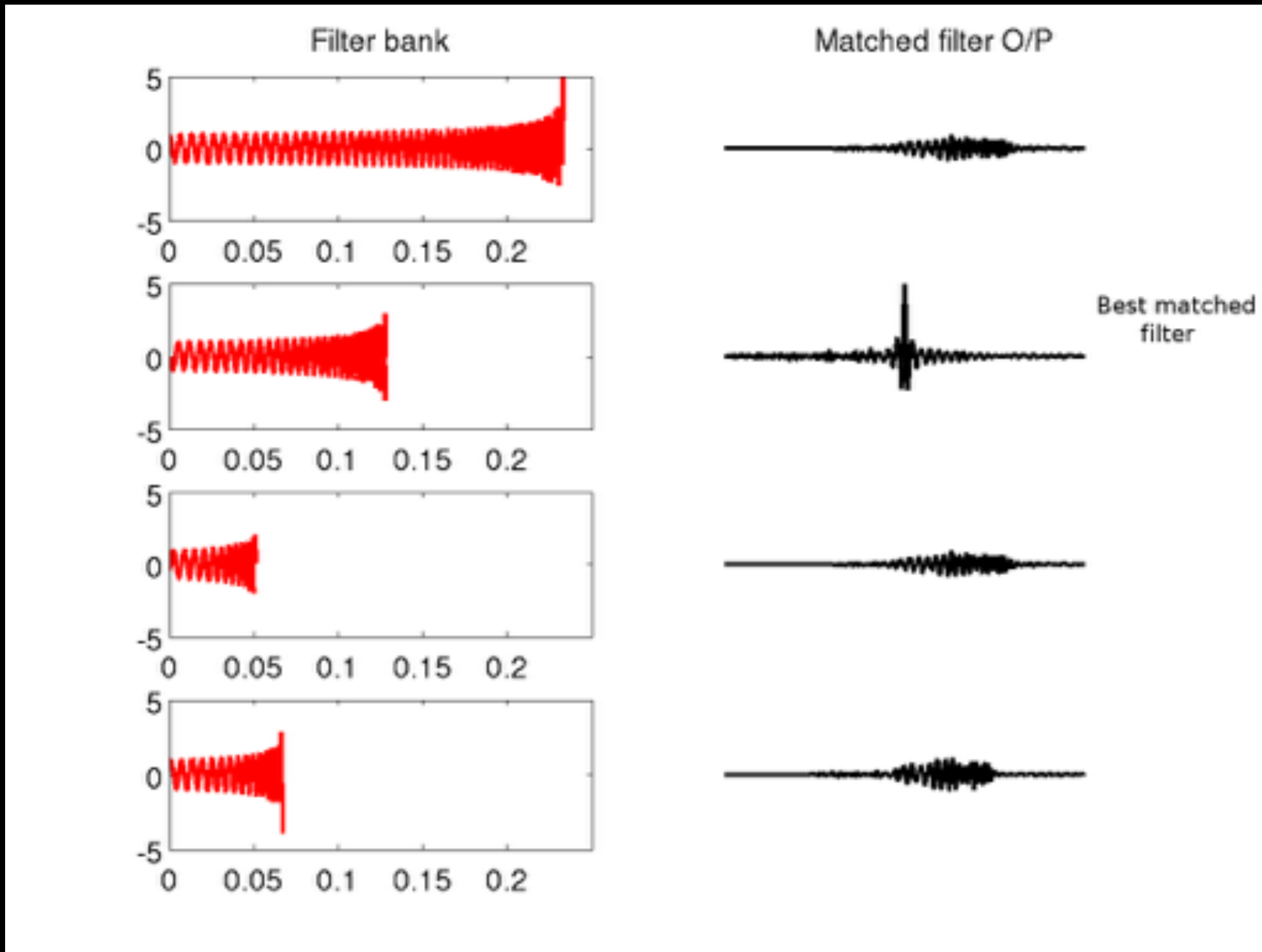
$$(< x|\hat{h} >_{av})^2 =< h|h >\equiv \rho^2$$

$$< a|b >= 4\Re \int_{fs}^{f_{LSO}} \frac{\tilde{a}^*(f)\tilde{b}(f)}{Sn(f)} df$$

Dhurandhar and Sathyaprakash-PRD 1991

FEATURES OF THE MATCHED FILTERING

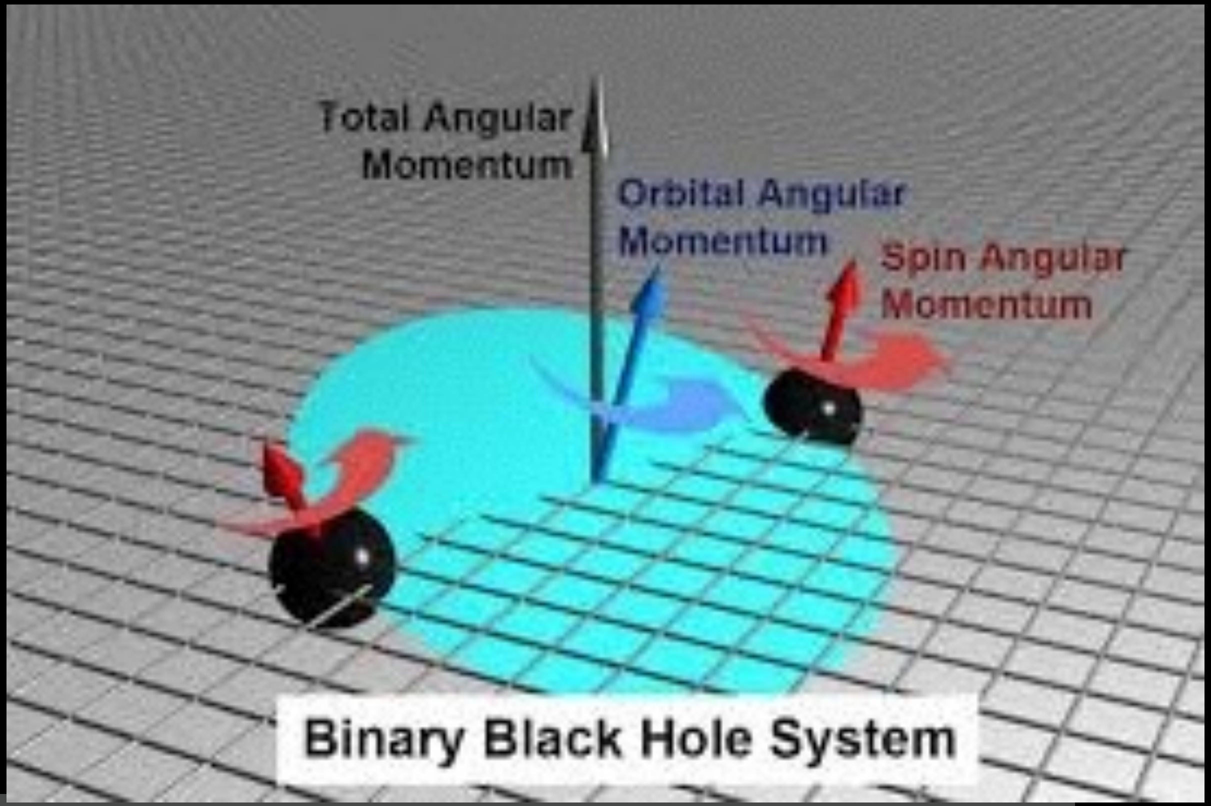
- Accurate waveform model is crucial.
- Sensitive to small phase mismatch =large number of templates
- Identification of signal parameters which govern the phase (signal shape) = Intrinsic parameters
- Physical parameters may not always be the best choice.



TEMPLATE PARAMETERS FOR CBC

DNS: SHORTEST KNOWN PULSAR PERIOD IS 22MS GIVES LOW SPIN [BURGAY ET.AL., NATURE 2003]

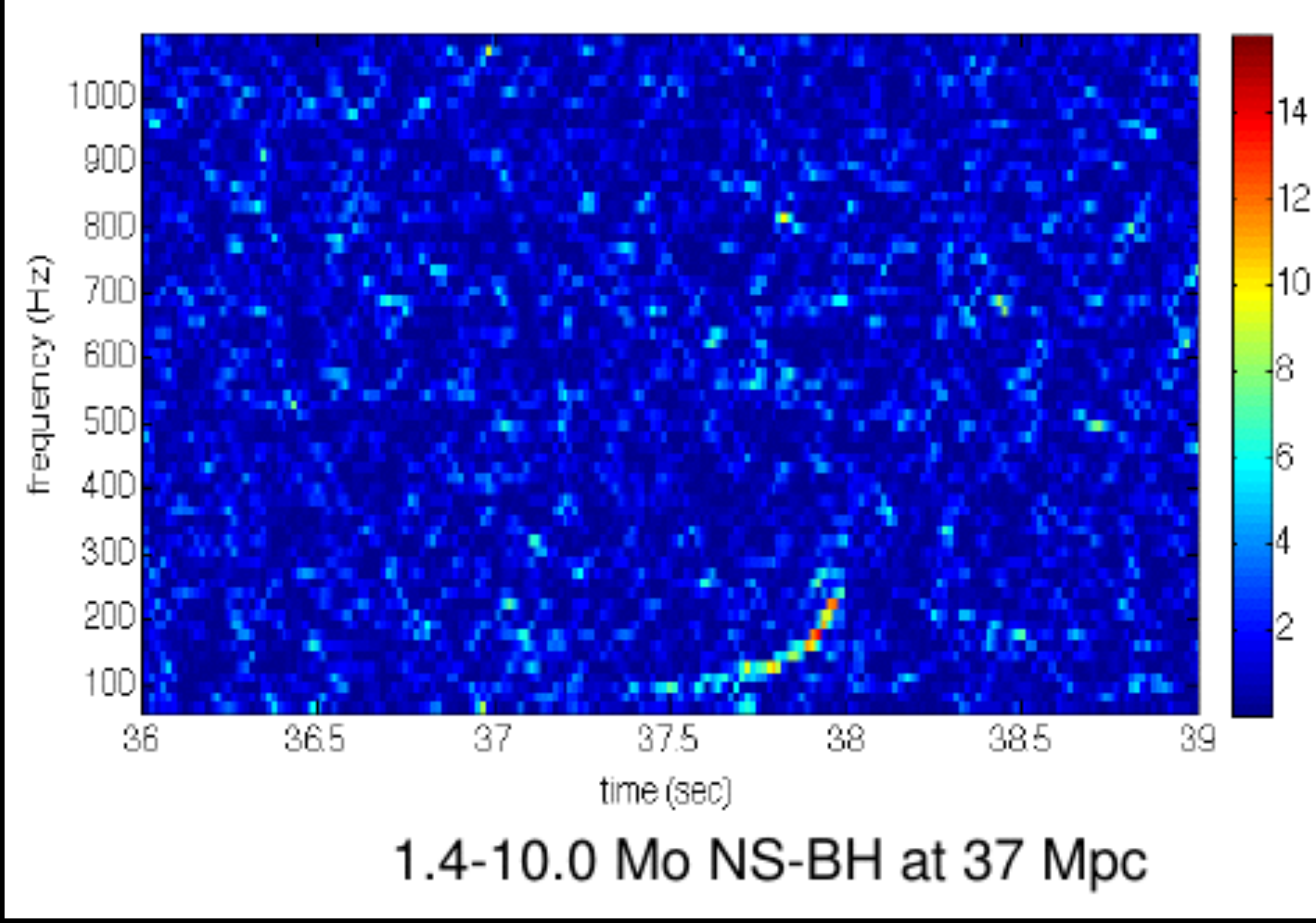
- DNS: Masses (#2) (NS has negligible spin)
- NSBH: Masses and 1 spin vector (#5)
- BBH: Masses and 2 Spin vectors (# 8)



QUESTIONS:
OPTIMUM TEMPLATE PLACEMENT IN THE MULTI-DIMENSIONAL SPACE — TILING PROBLEM
WHAT IS THE BEST PARAMETER FOR PRECESSING SYSTEMS FOR DETECTION?

GENERIC TRANSIENT SEARCH

- Sensitive to short duration transients
- Do not rely on precise signal model or GR
- Minimum assumptions on the signal
- Excess power in the time-frequency map
- Multi-detector statistic



cWB:chirp in Gaussian noise

GENERIC TRANSIENT SEARCH

COHERENT WAVE BURST (CWB) —
WAVELET BASED TIME-FREQUENCY CLUSTERING
MULTI-DETECTOR COHERENT SEARCH
S. KLIMENKO ET AL., CQG 25:114029, 2008

OMICRON-LALINFERENCE-BURSTS (OLIB) —
MULTI-RESOLUTION TIME-FREQUENCY MAP OF EACH DETECTOR
COINCIDENCE EVENTS IN EACH DETECTOR
FOLLOWED BY BAYESIAN INFERENCE SCHEME
R. LYNCH ET AL., ARXIV:1511.05955

BAYESWAVE —
SIGNAL MODEL: LINEAR COMBINATION OF MORLET WAVELETS
PRESENCE/ABSENCE OF SIGNAL WITHIN BAYESIAN FRAMEWORK
CORNISH-LITTENBERG, CQG, 32(13):135012, 2015

SALIENT FEATURES OF GW TRANSIENT SEARCHES

- Device the search method, detection statistic based on type of transient, efficient as well reduces the false alarm
- Draw the candidate event list after/before applying noise veto for noisy transients
- Enforce that events are consistent with the inter-site separation between the detectors and SNR is computed.
- Rank the candidate events
- Assess the noise background using the time-slide method

TIME-SLIDE METHOD TO ASSESS THE NOISE BACKGROUND

- The strain data exhibits non-Stationary and non-Gaussian noise features.
- Estimation of chance coincidence of noisy events = Background estimation
- Maximum light travel between 2 LIGOs is 10 ms. Obtain candidates by combining information from unphysical delays (greater than 15 ms)
- Effective for uncorrelated instrumental noises

http://arxiv.org/abs/1602.03844

“GW150914 appeared in modelled as well as Generic transient search pipeline”

ON SEPTEMBER 14, 2015

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION | AUTHENTICATED AS: ARCHANA PAI

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G184098	H1OK L1OK	Burst	CWB	AllSky	H1,L1	1126259462.3910	1.178e-08	Data	2015-09-14 09:53:51 UTC

Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

GraceDB sends an Event alert at 9:53:51 UTC

Search pipeline used was — Generic transient Burst

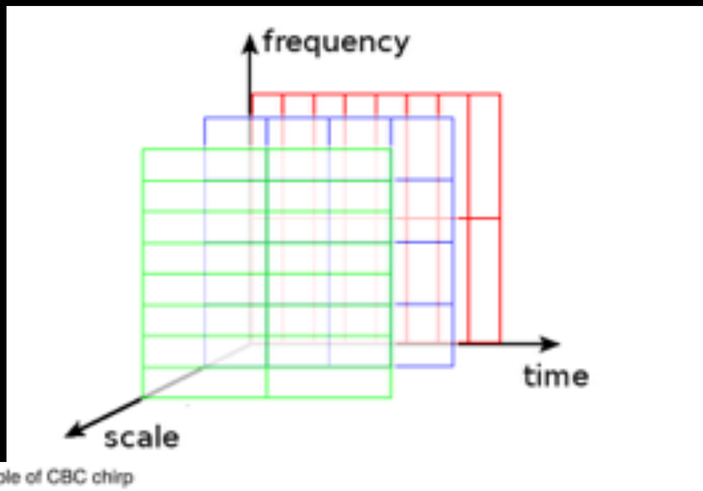
Klimenko et al, PRD, 93, 2016

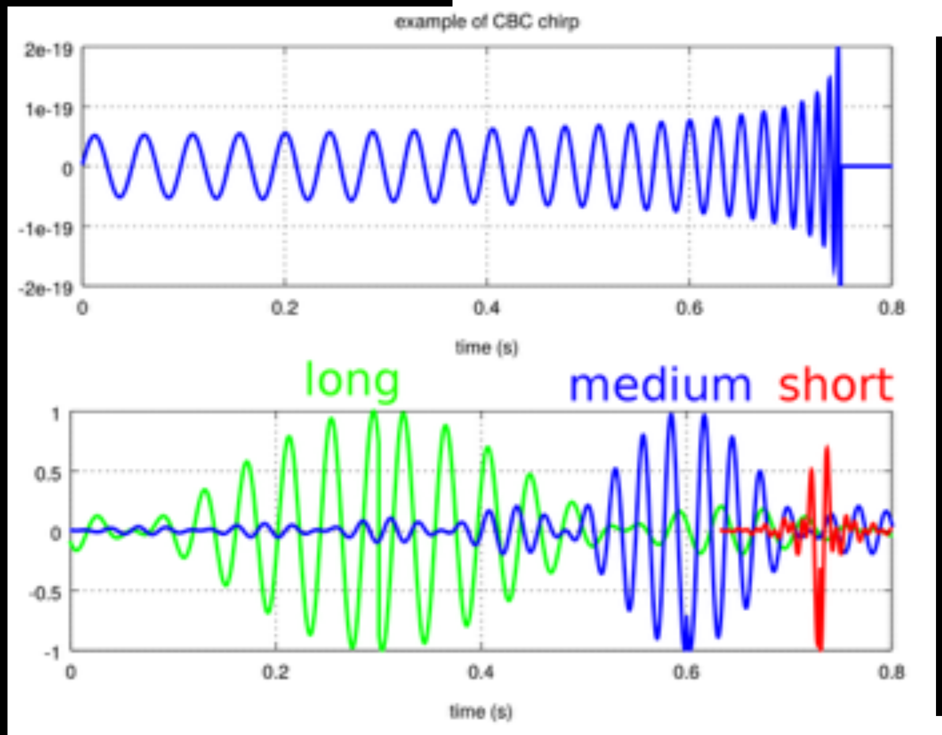
COHERENT WAVEBURST

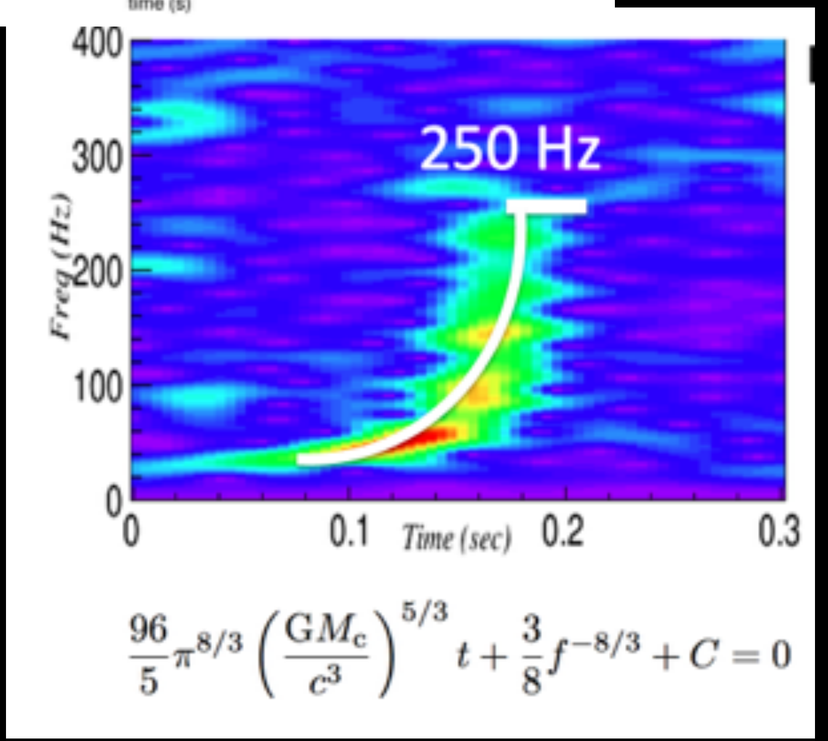
- Coherent WaveBurst (cWB) - For GW up to duration of few seconds.
- Project the data on the WDM wavelets.
- Combine the TF output from 2 detectors to obtain energy (incorporating possible delays).
- Clustering scheme combines the TF pixels from different scales. Gives the signal energy.
- LIGO-H and LIGO-L are parallel =>
  High correlation Ec (Used in the constraint likelihood approach)
- Detection Statistic:

$$\eta = \sqrt{\frac{2E_c^2}{E_c + E_n}}$$

For GW150914 = 20



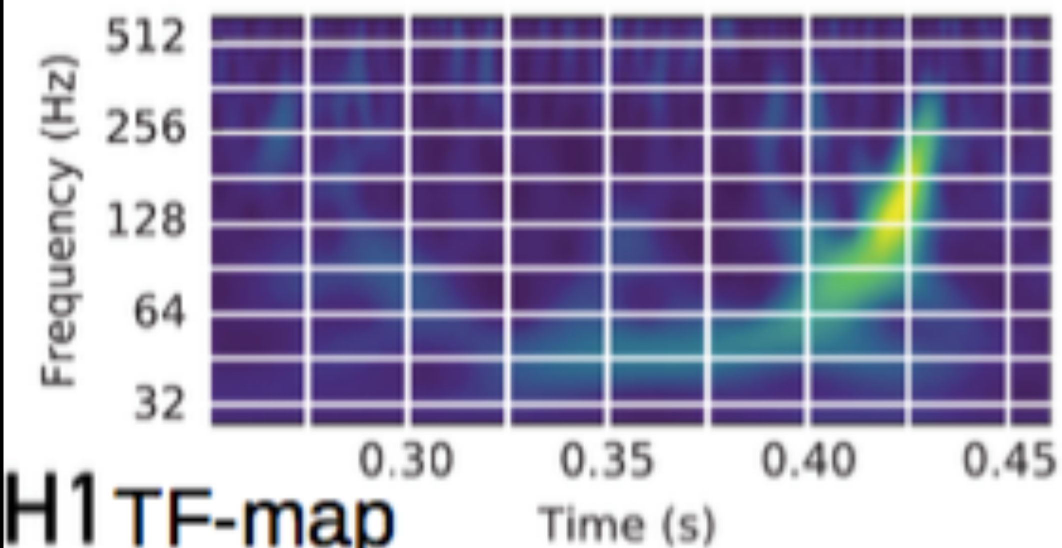




Mc ~ 27.2 Msun

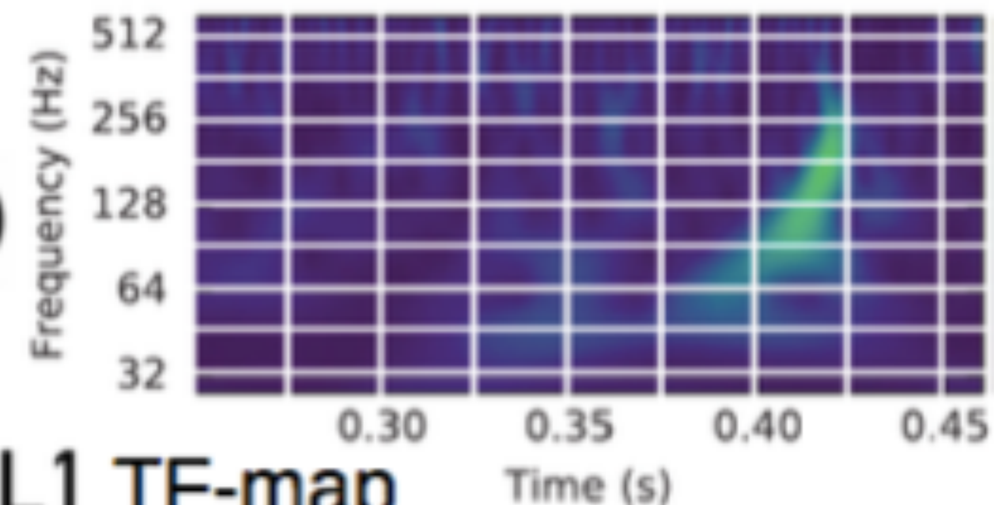
Klimenko

GW150914 : First GW detection was made by low-latency cWB searches within three minutes of the data acquisition on September 14,2015.



H1 TF-map

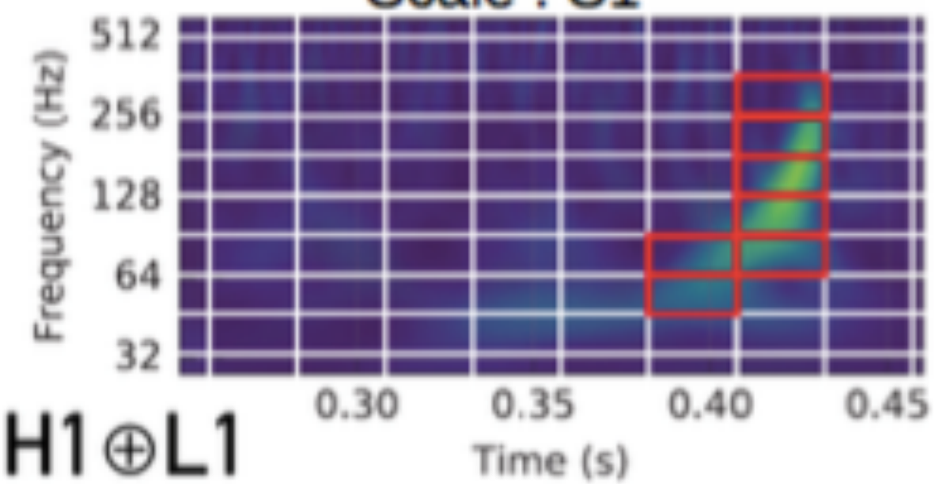
⊕



L1 TF-map

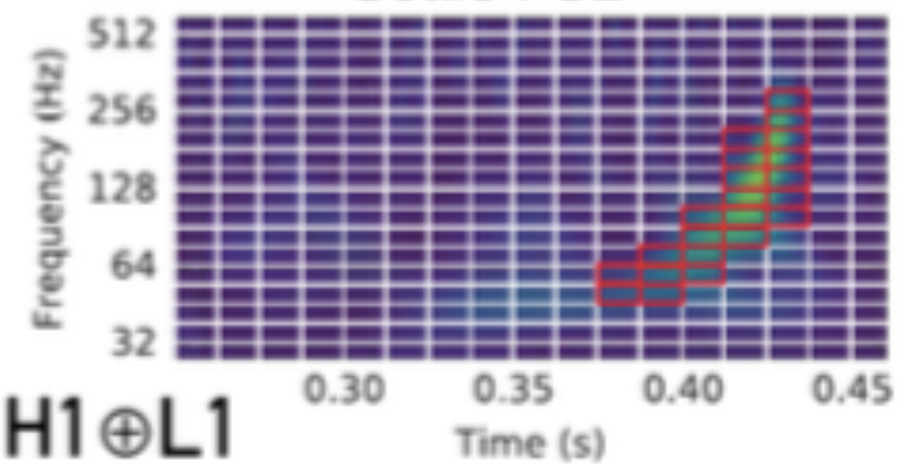
Collecting excess power pixels

Scale : S1



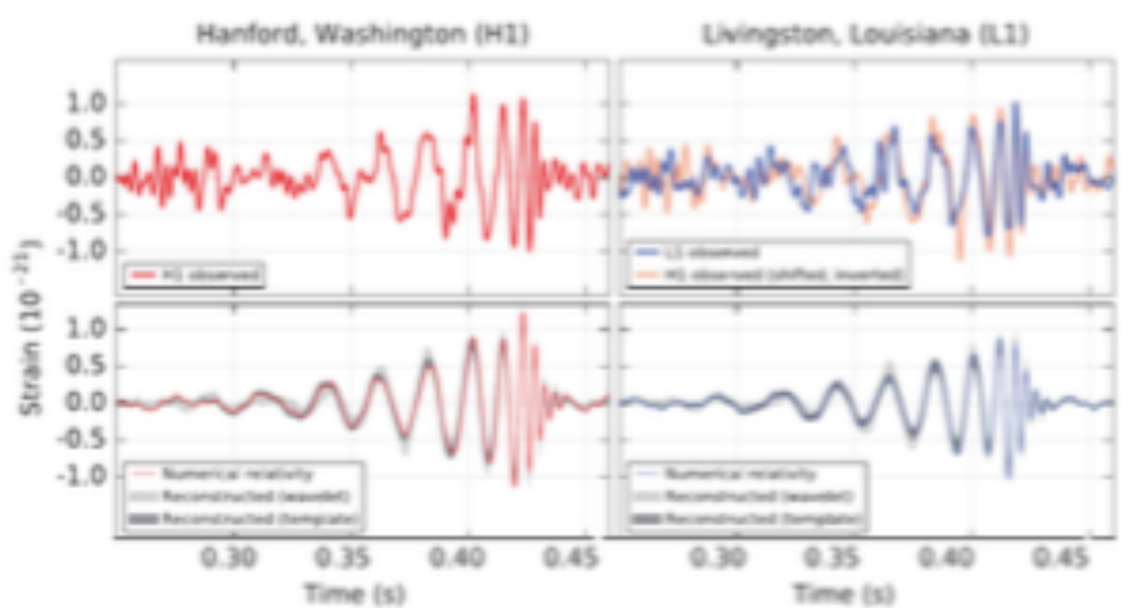
H1⊕L1

Scale : S2



H1⊕L1

Reconstructed waveform



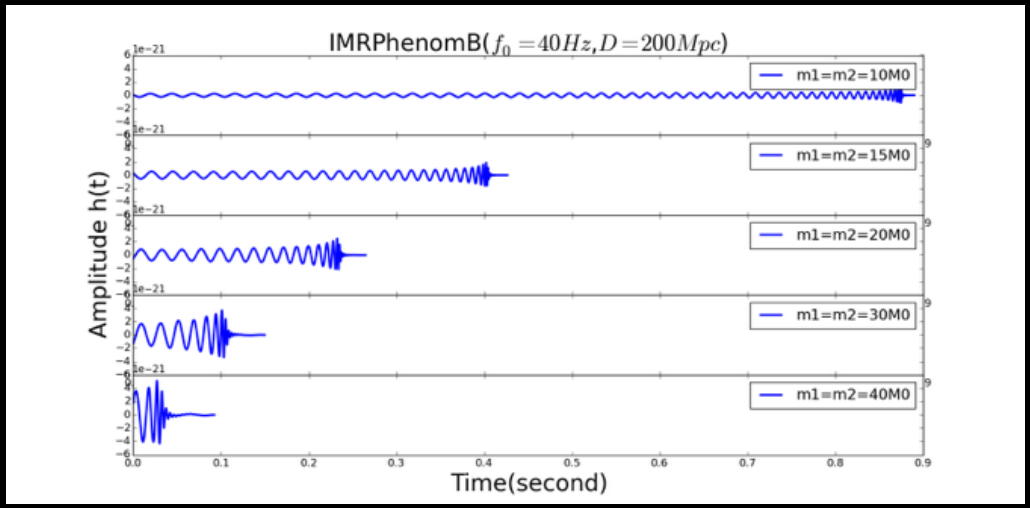
Multidetector SNR
$\rho = 20$
$Cc > 0.7$

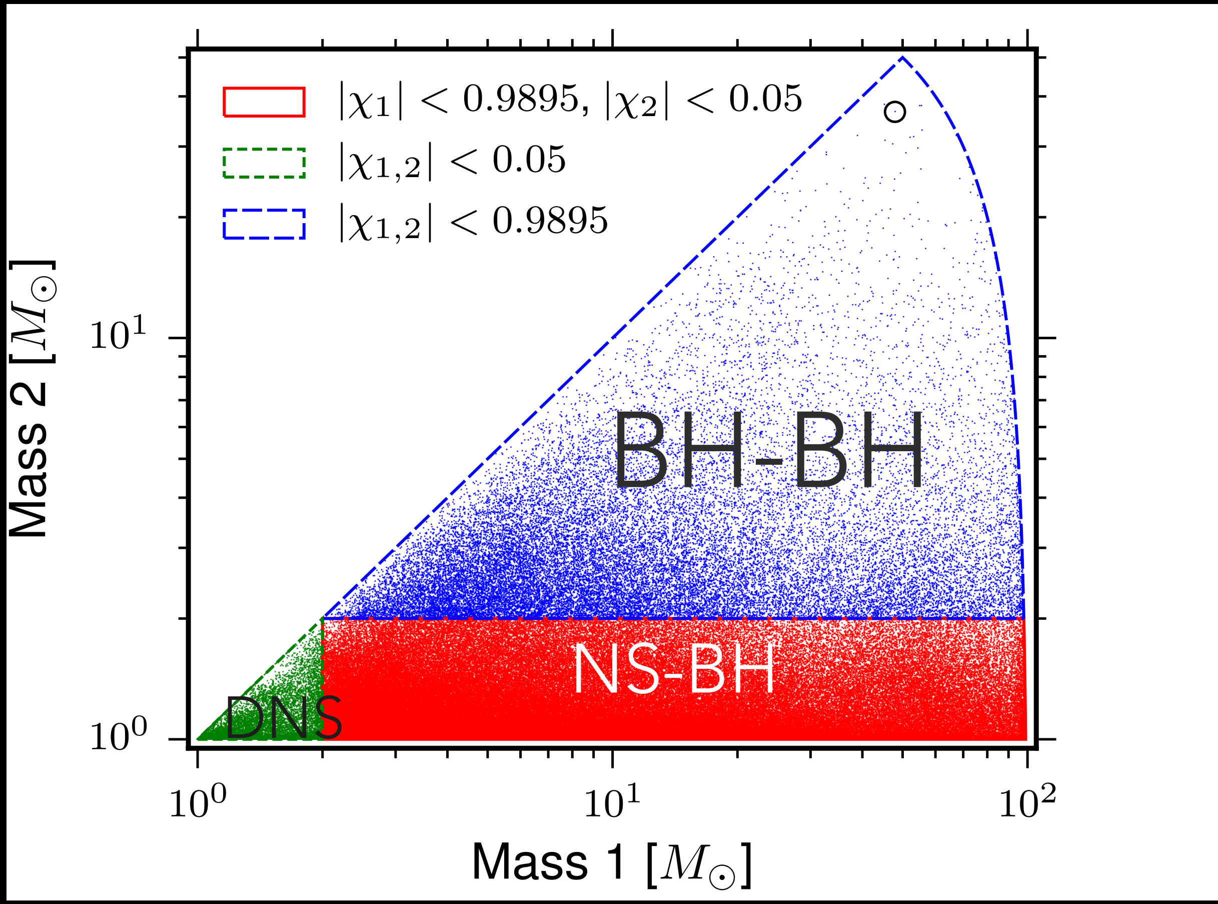
LVC.et al. Phys. Rev. D 93, 122004 (2016)

http://arxiv.org/abs/1602.03839

CBC SEARCHES: DNS, NS-BH AND BH-BH

- Search with individual masses 1 - 99 Msun and dimensionless spins up to 0.99. $\chi_i = \frac{cS_i}{Gm_i^2}$
- Effective one body Templates: Combines Post-Newtonian approach with BH perturbation theory and Numerical relativity.
- No precession in the templates
- Total number of templates used 250000.

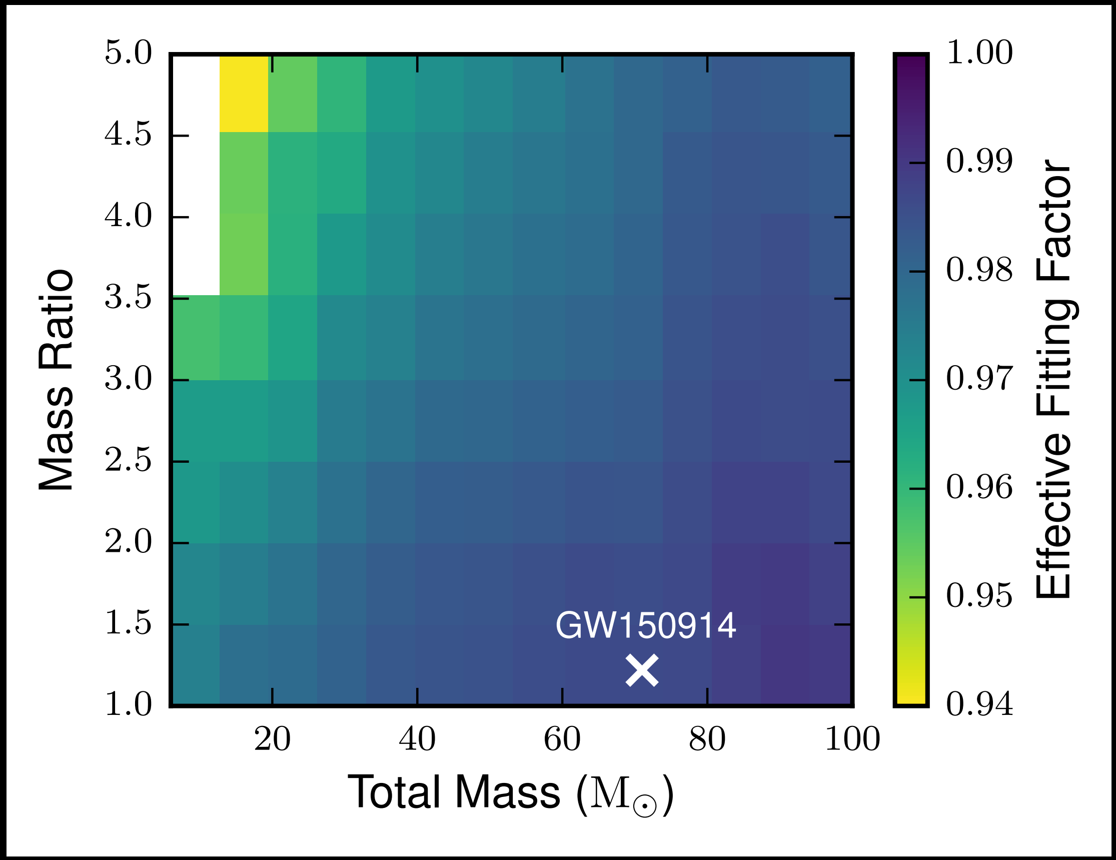




CBC SEARCH

arxiv.org/abs/1602.03839

- Matched filter SNR $\rho^2(t) \equiv |< s|\hat{h} >|^2$
- Maximised over the time of arrival.
- Model dependent veto is applied which compares if the signal power is consistent with the template.
- The best mass and effective spin template is obtained.
- Follow-up Bayesian inference based parameter estimation gives more accurate parameters.



GW150914

$\rho_{L1} = 13, \rho_{H1} = 20 \rightarrow \rho = 24$

Effective spin ~ 0.2

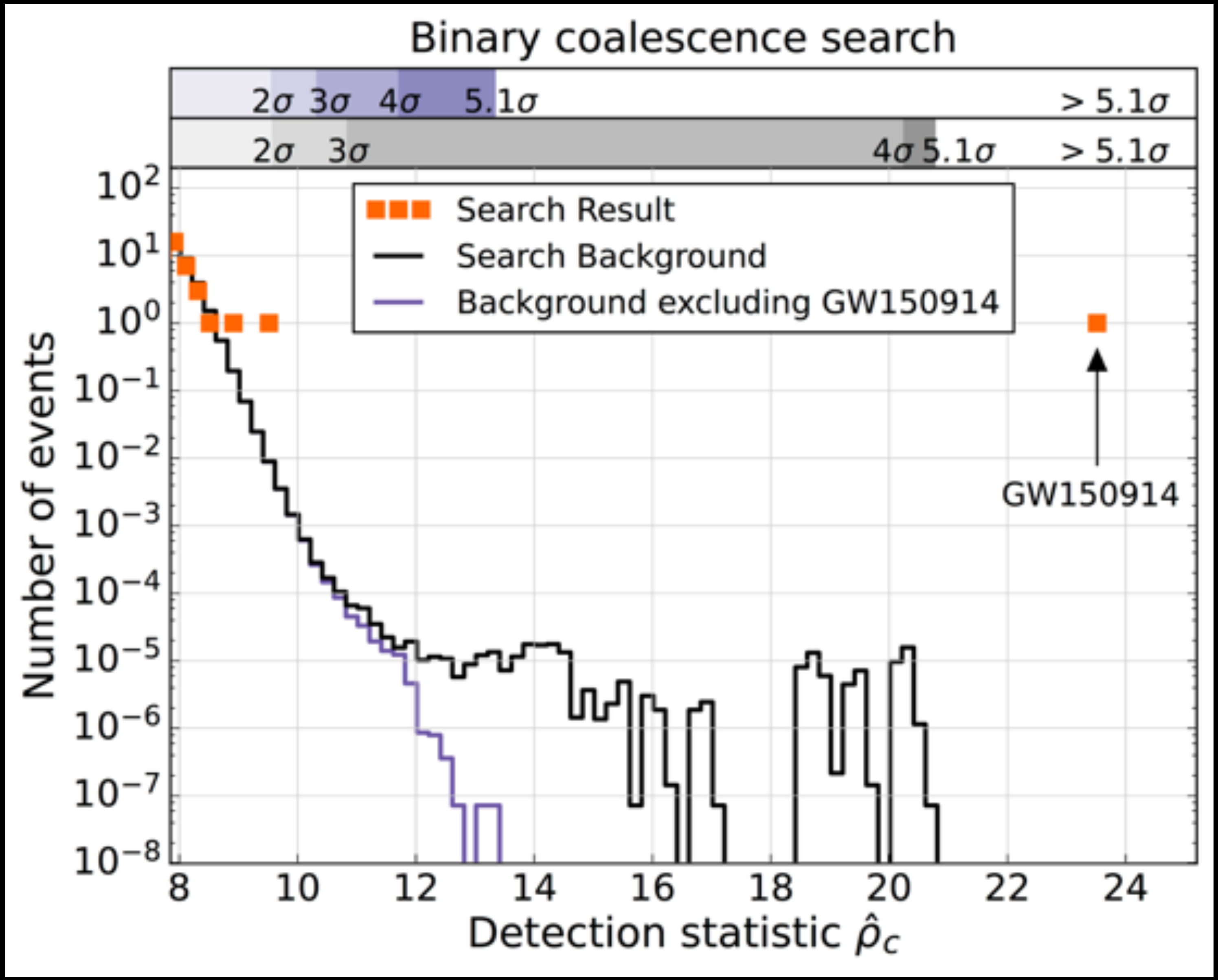
Template masses 47.9 and 36.3 Msun.

Time delay from search ~ 7.1 msec.

LVC, PRL 116, 061102 (2016)

BACKGROUND STATISTICS

CBC SEARCH WITH TEMPLATES



16 days of coincidence data (Sept 12-Oct 20),

608000 yrs of observation time

Significance of GW150914:

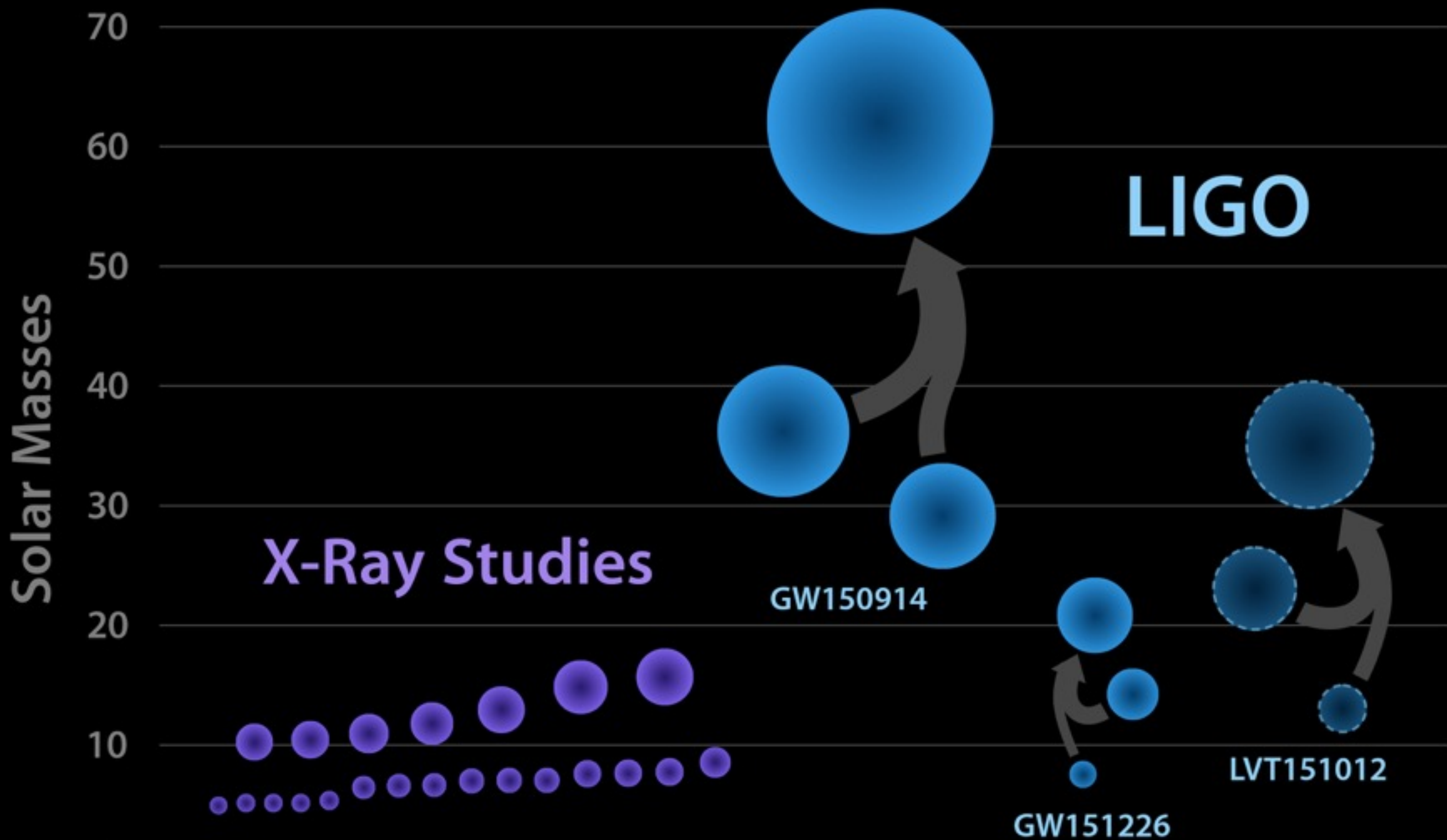
Number of classes (DNS,NS-BH,BBH) 3 =>FAR of 1 in 203000 yrs

Confidence level 5.1 sigma level

Once significant confidence level is achieved for the astrophysical nature
Extensive parameter estimation study was carried out for GW150914 to understand the source

Rajesh Nayak's talk on Parameter Estimation
Sukanta bose's talk on Source localisation
Anand Sengupta's talk on hybrid geometric and stochastic bank
Varun Bhalerao's' talk on EM follow up

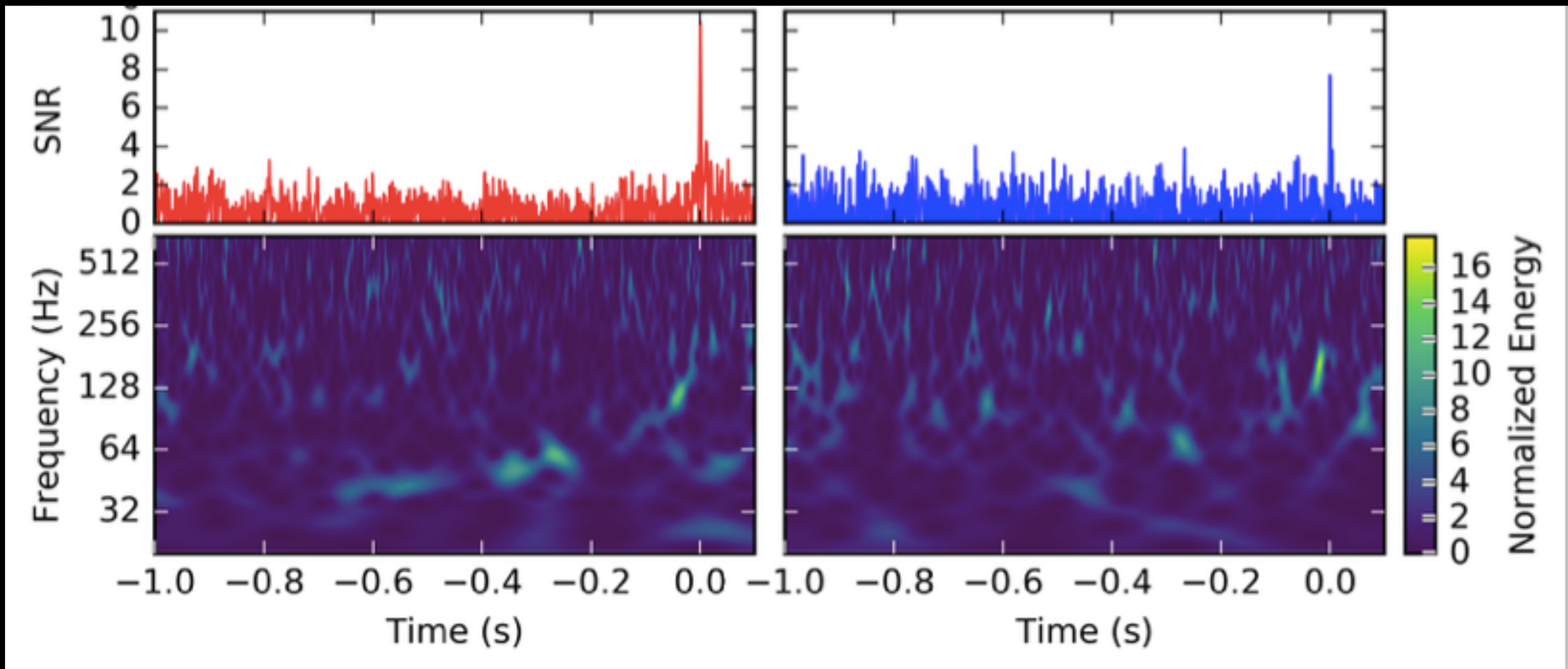
Black Holes of Known Mass



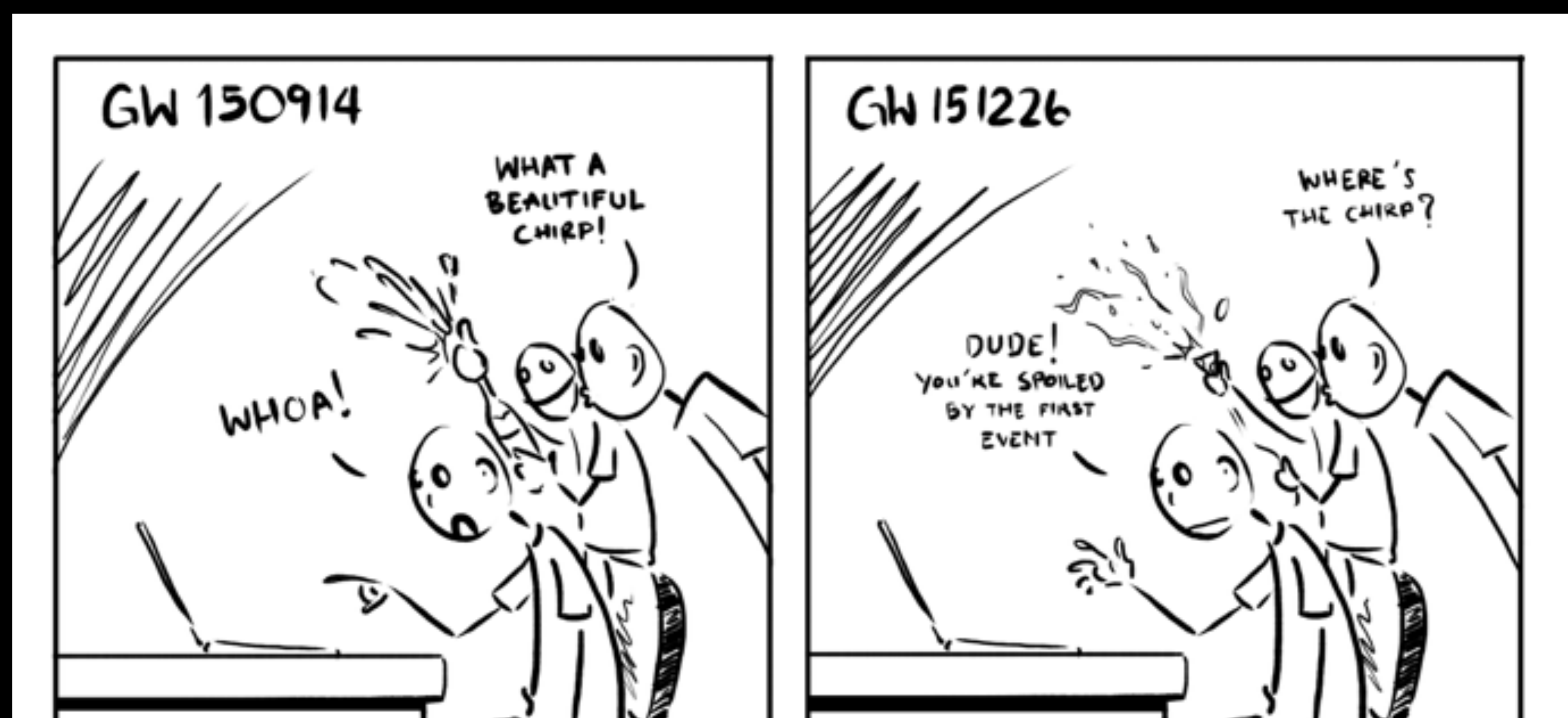
Cardiff Univ

LVC, PRL 116, 241103 (2016)

GW151226: Transient of 1 sec duration

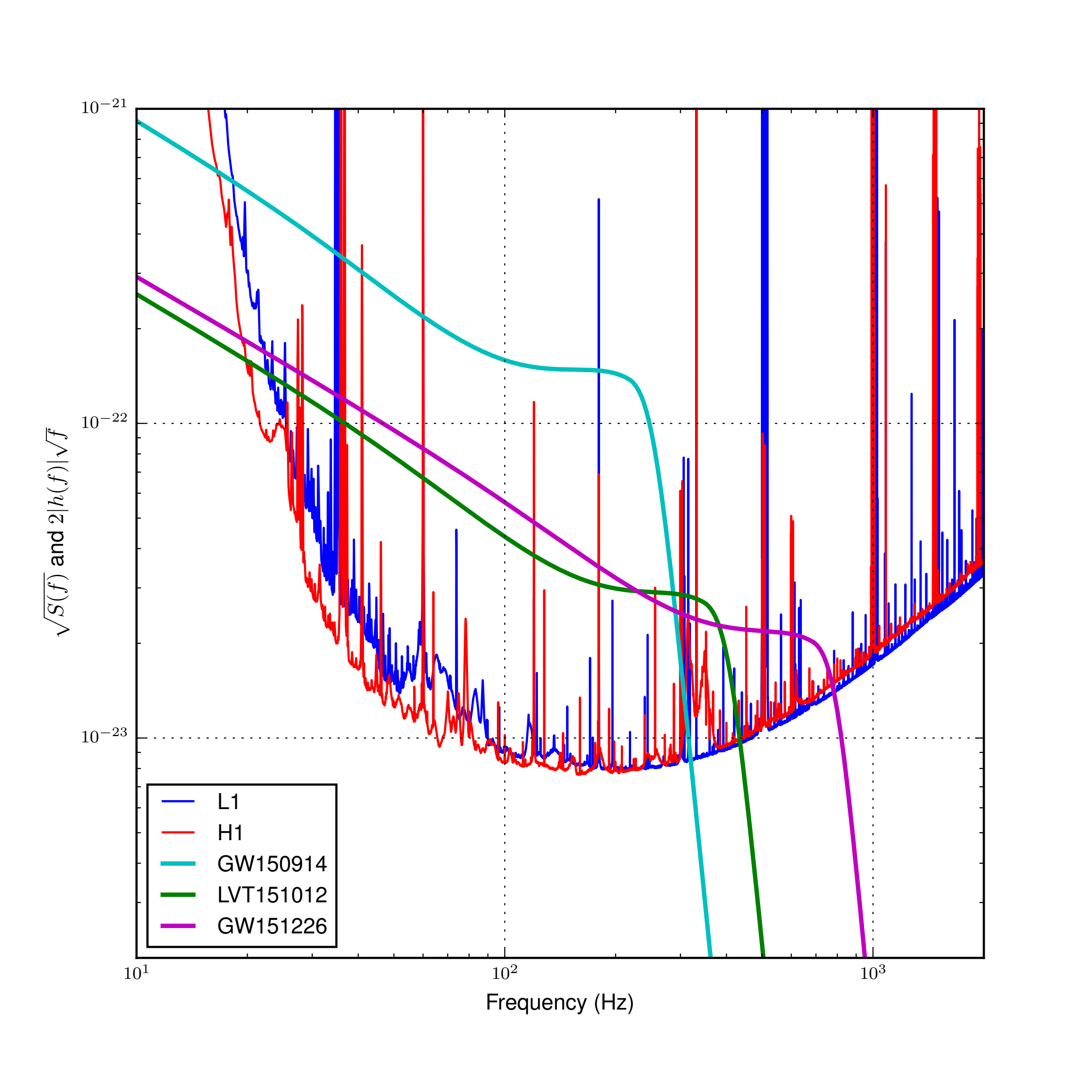


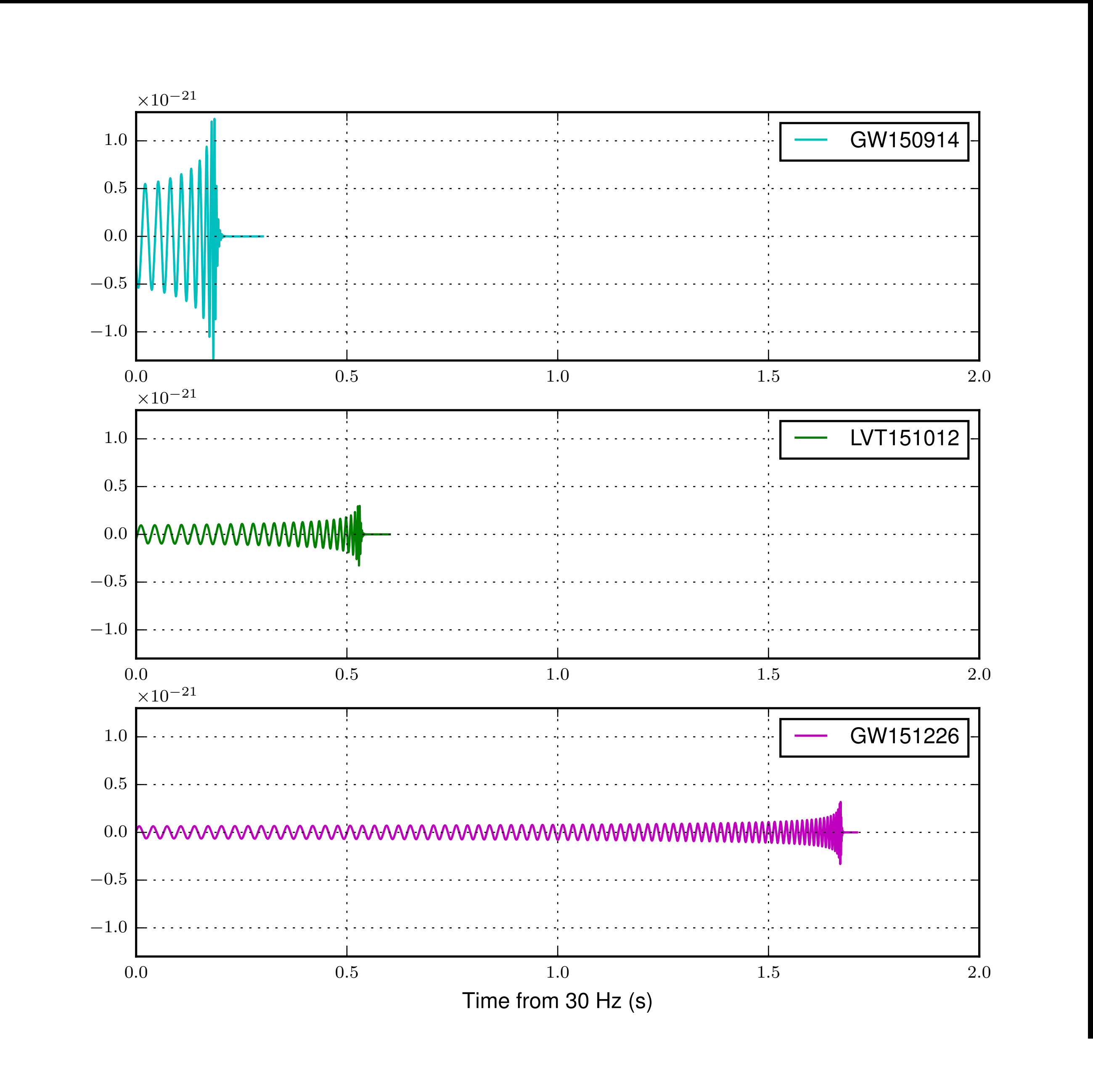
Triumph of Matched Filtering

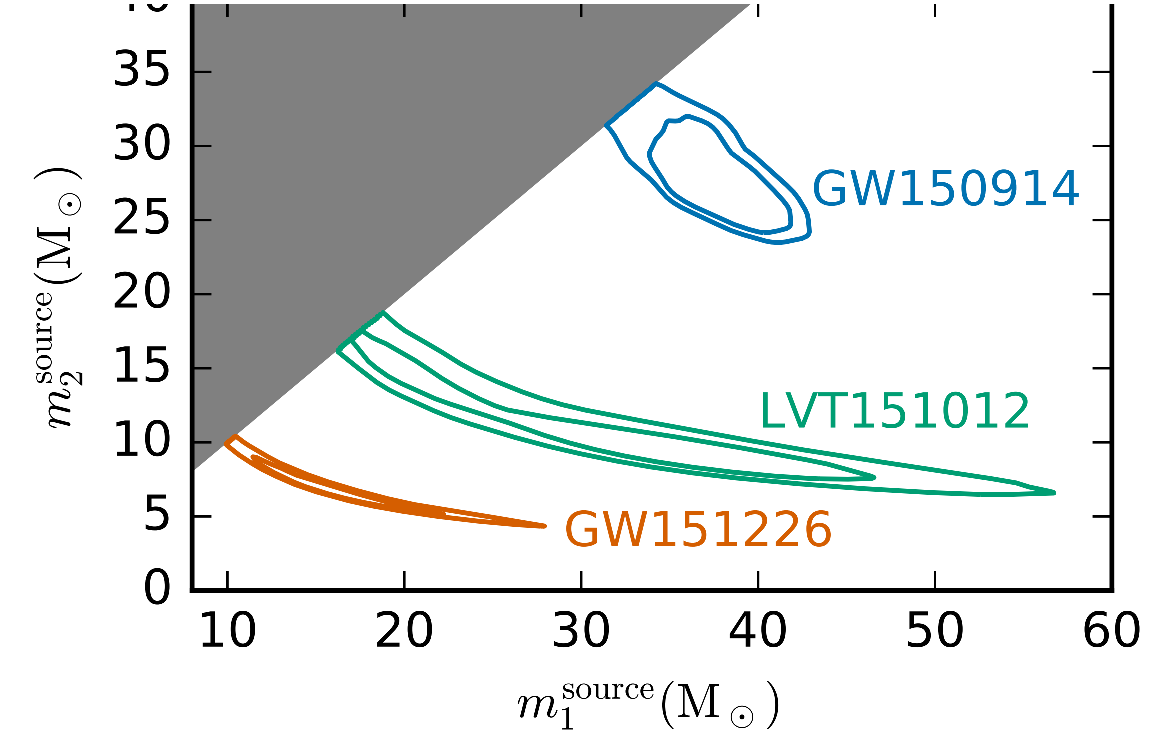


GW events in First observation run of LIGO September 12, 2015 - January 12, 2016

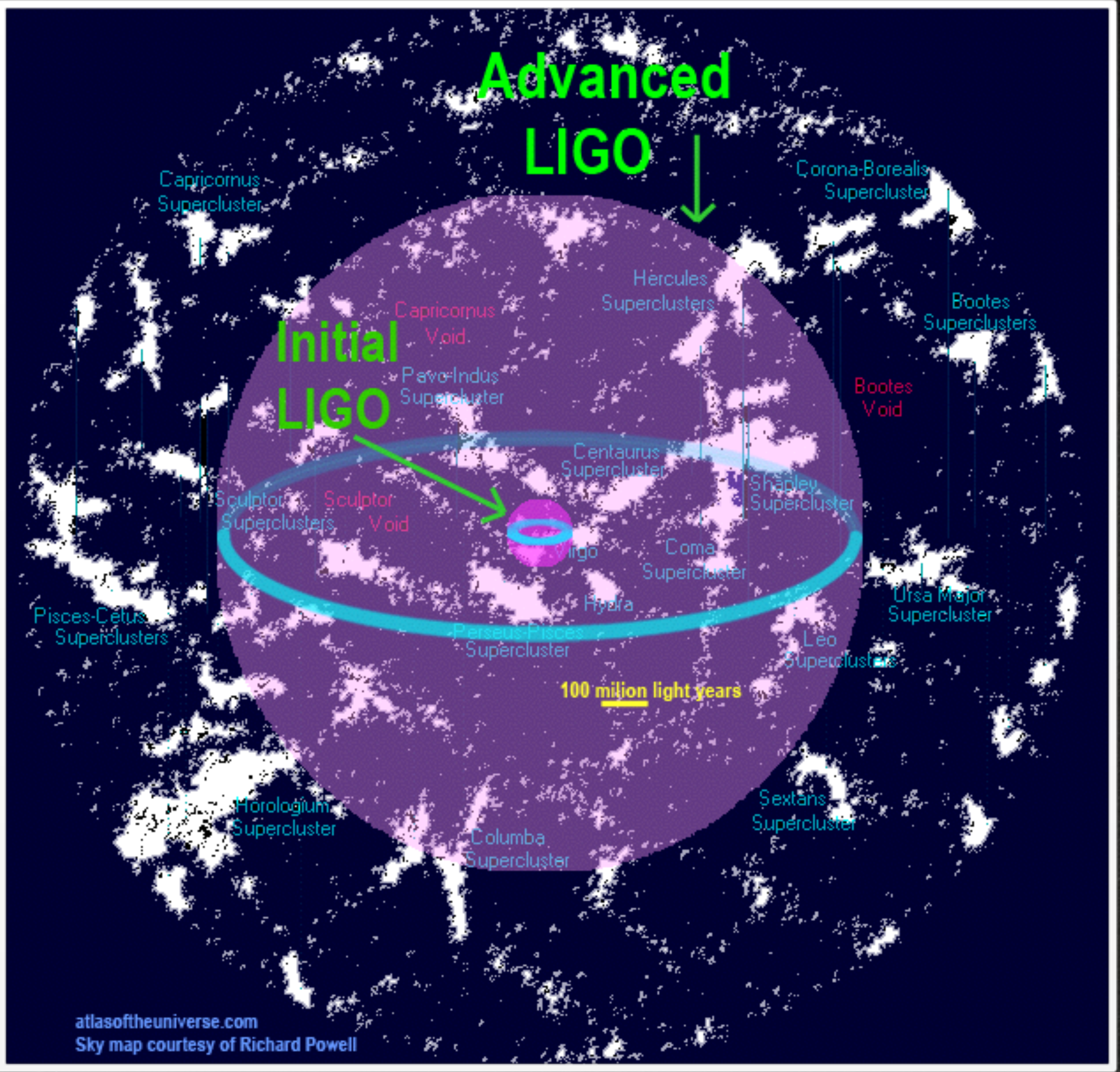
Open data @ https://losc.ligo.org/







Credit: LVC, PRD 2016



LIGO's distance reach in O1

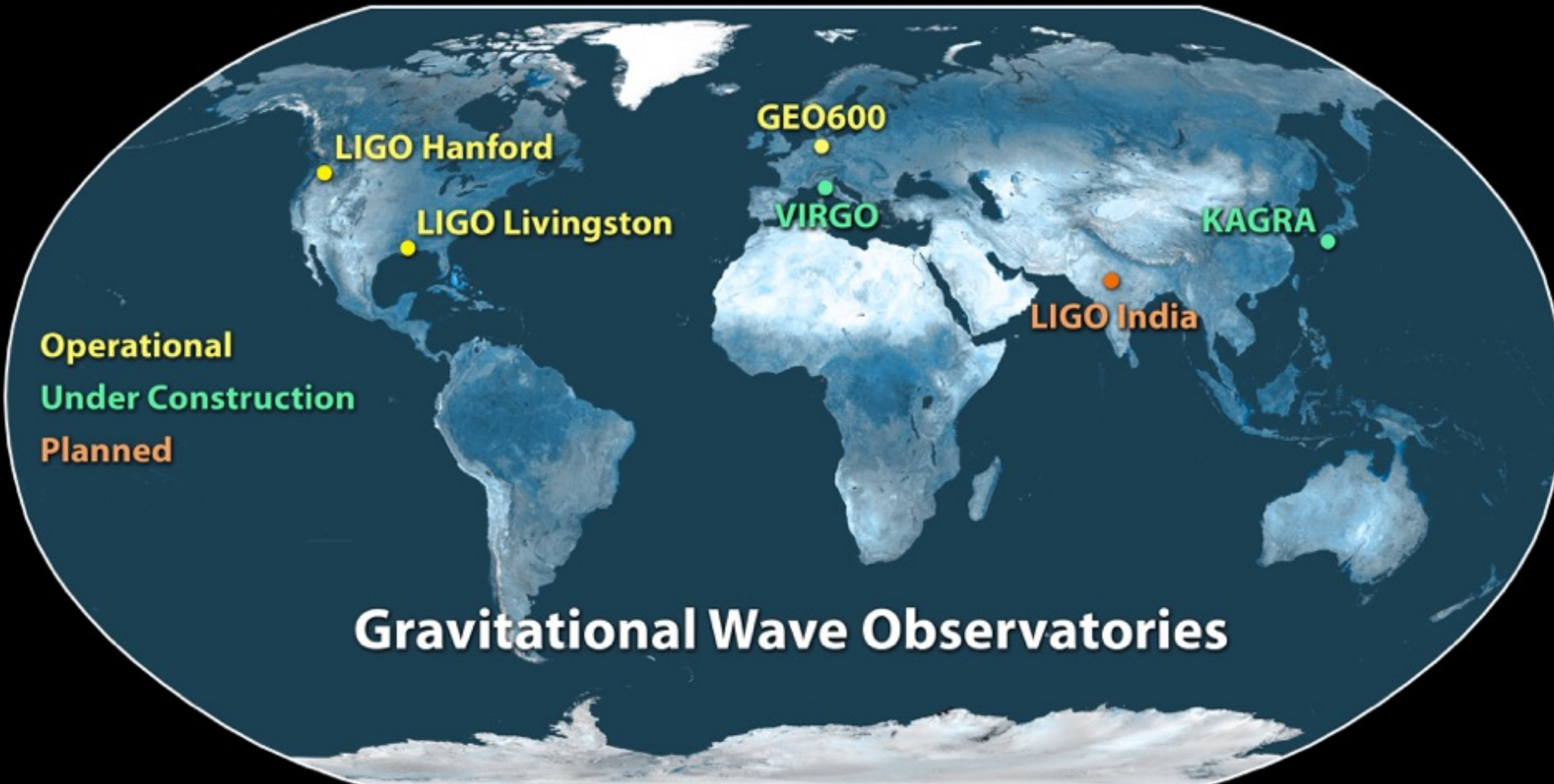
Initial LIGO: probed little further Virgo cluster (15 Mpc) for DNS

Advanced LIGO = 10 times deeper in sky =1000 more volume

O1 Rates: LVC, Astrophys. J. 832 L2, 2016

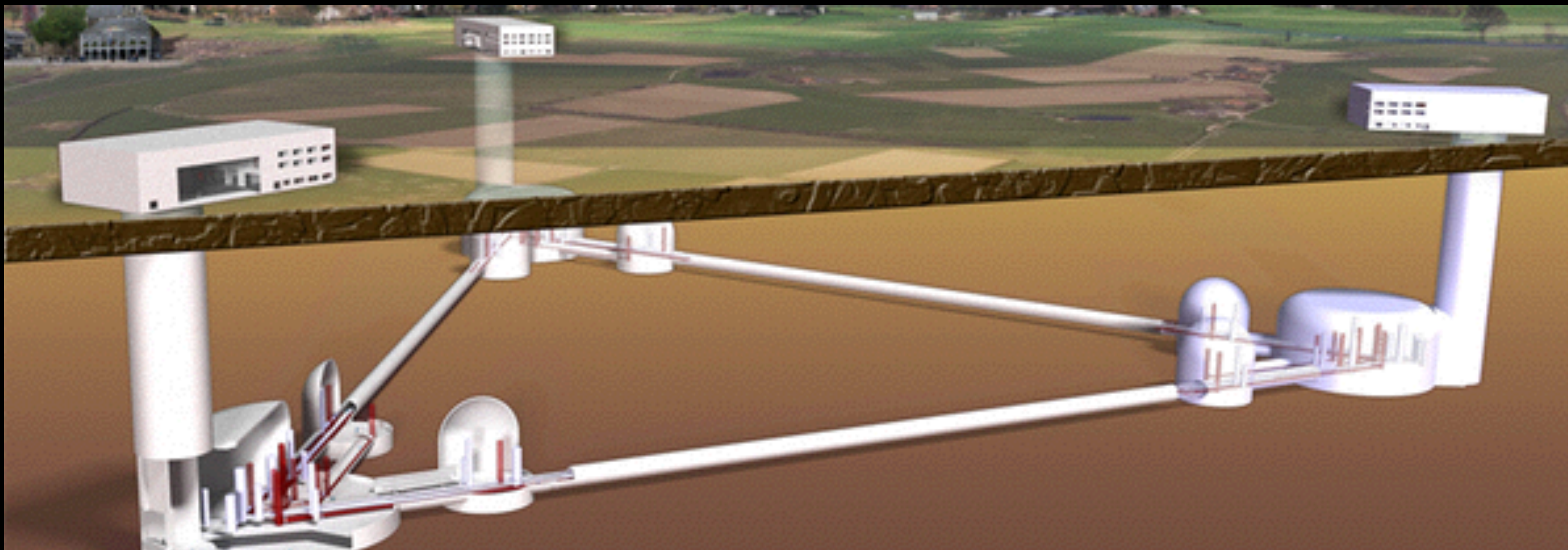
Distance reach: DNS upto 70Mpc , NSBH upto 110 Mpc

Rate <12600 Gpc^-3/yr (DNS) , < 3600 Gpc^-3/yr (NSBH), 2-600 Gpc^-3/yr (BBH)



Global network of ground based interferometers
2024+

FUTURE: EINSTEIN TELESCOPE



Underground, cryogenic, triangular interferometer,
10 km arm length
GW150914: SNR 20 times (~500)
Signal duration 25 seconds

WHAT DID WE LEARN?

- Discovery of stellar mass BH > 25 Msun opens up new questions
- More events will shine light on formation channels, BBH populations, BH spin distributions, BH mass distribution etc
- Expected to observe DNS and NSBH systems == direct implication on the EM follow-up and Short GRB progenitors, Neutron star physics
- GW transient search is wel-devloped. Still work is needed for precessing and eccentric binaries as well as all sky CBC search.

CHALLENGES IN THE TRANSIENT SEARCH: COMPACT BINARIES

- Template bank for precessing binaries is a challenge.

- Stochastic banks: Harry etal PRD 2016

Parameter space	Minimal match	Spin	Templates	Eff. FF
NSBH	0.97	Aligned	146,315	0.948
	0.90	Precessing	1,583,079	0.976
BBH	0.97	Aligned	23,948	0.984
	0.90	Precessing	237,909	0.988

PRECESSING BANK INCREASES THE TEMPLATES BY FACTOR OF 10
> MILLION TEMPLATES

- Face on bank Indik etal arXiv:1612.05173
  NSBH bank, precessing but face on system: Template bank of size 6 miillion. Shown definite improvement in sensitivity of detection but need to run online! (if we want to send EM alerts)

CHALLENGES IN THE TRANSIENT SEARCH: COMPACT BINARIES

Increase in the number of templates

- increases the computational cost
- increases the false alarm as there is high probability for noise to mimic as template shape

HIGH MASS RATIO AND HIGH SPIN PRECESSION IS NOT ADDRESSED

SEARCHES FOR ECCENTRIC BINARIES WHICH EMIT GW TRANSIENTS

ONE APPROACH: TIME FREQUENCY BASED CLUSTERING SCHEME WHICH FOLDS SIGNAL MORPHOLOGY

भारतीय विज्ञान शिक्षा एवं अनुसंधान संस्थान तिरुवनंतपुरम

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Department of Science and Technology

Max Planck Institute, Germany

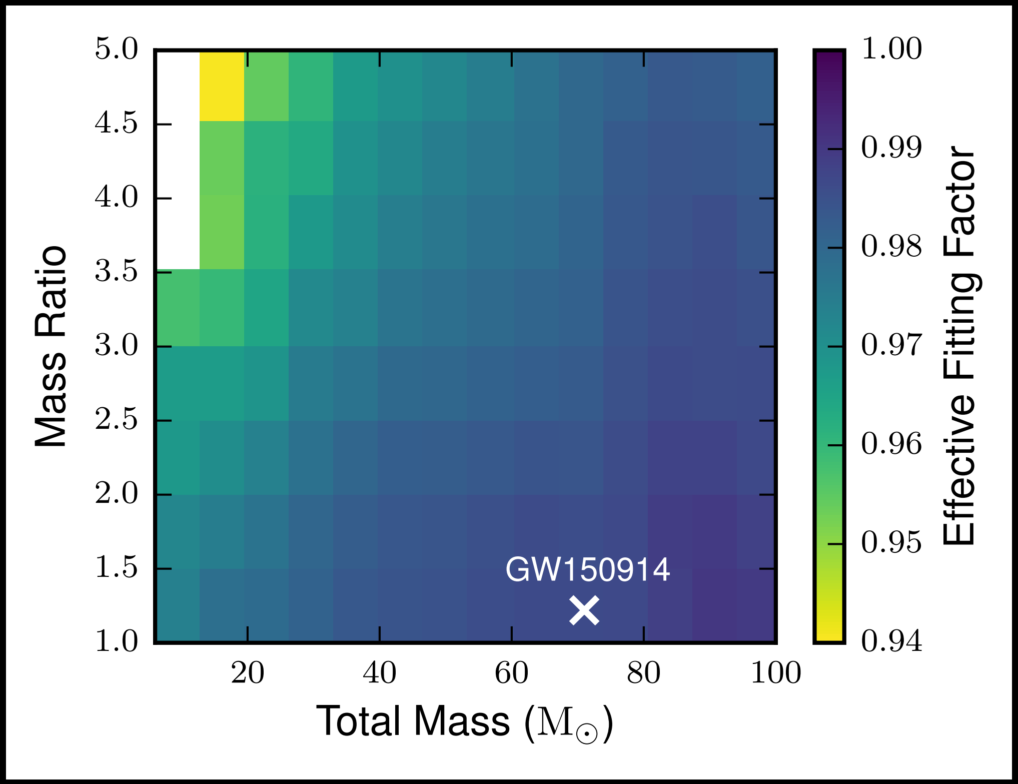
Advanced LIGO — 1411.4547

Table 1. Main parameters of the Advanced LIGO interferometers. PRC: power recycling cavity; SRC: signal recycling cavity.

Parameter	Value
Arm cavity length	3994.5 m
Arm cavity finesse	450
Laser type and wavelength	Nd:YAG, $\lambda = 1064$ nm
Input power, at PRM	up to 125 W
Beam polarization	linear, horizontal
Test mass material	Fused silica
Test mass size & mass	34cm diam. x 20cm, 40 kg
Beam radius ($1/e^2$), ITM / ETM	5.3 cm / 6.2 cm
Radius of curvature, ITM / ETM	1934 m / 2245 m
Input mode cleaner length & finesse	32.9 m (round trip), 500
Recycling cavity lengths, PRC / SRC	57.6 m / 56.0 m

GOODNESS OF THE BANK

- Fitting factor : Fraction of SNR recovered by the bank
- Simulation:
  Injected signals precessing binaries — Recovered with the bank
- The effective FF is lowest at low total mass and high mass ratio.



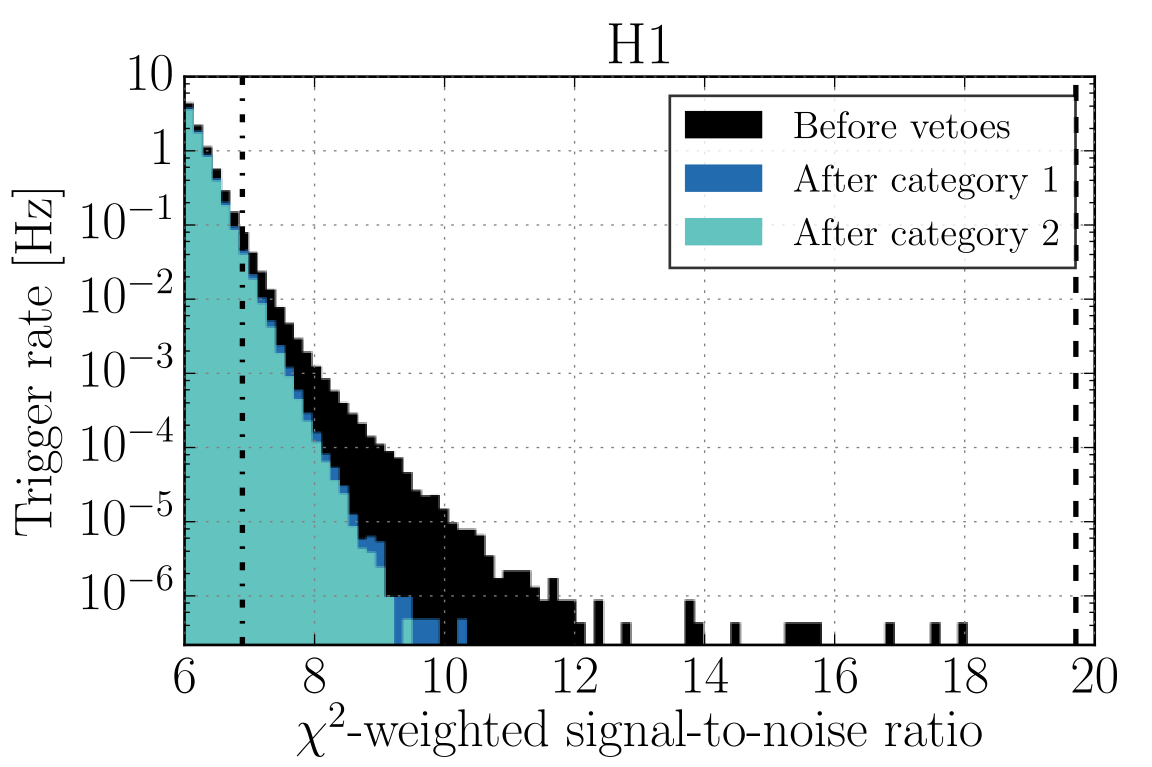
THE TEMPLATE BANK IS GOOD FOR MASS RATIO OF 1 AND HIGH TOTAL MASS

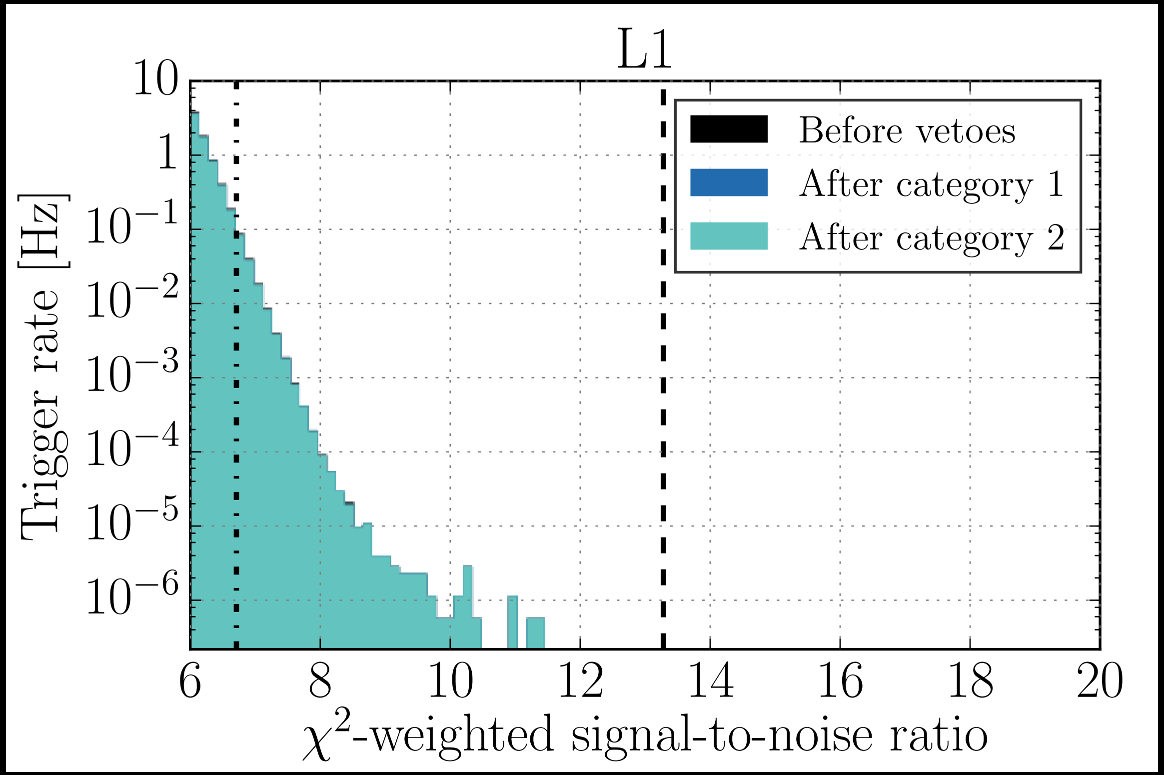
http://arxiv.org/abs/1602.03839

Vetos:

CAT1 - known instrumental problems

CAT2 - known physical coupling with the noise

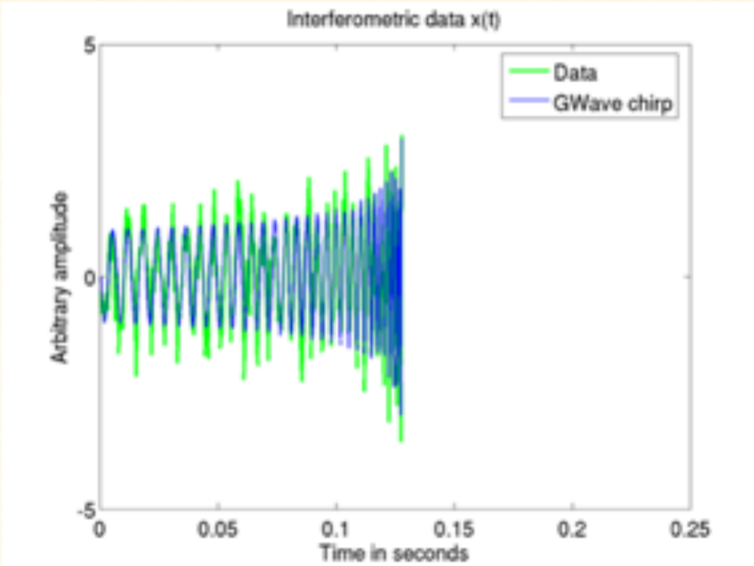


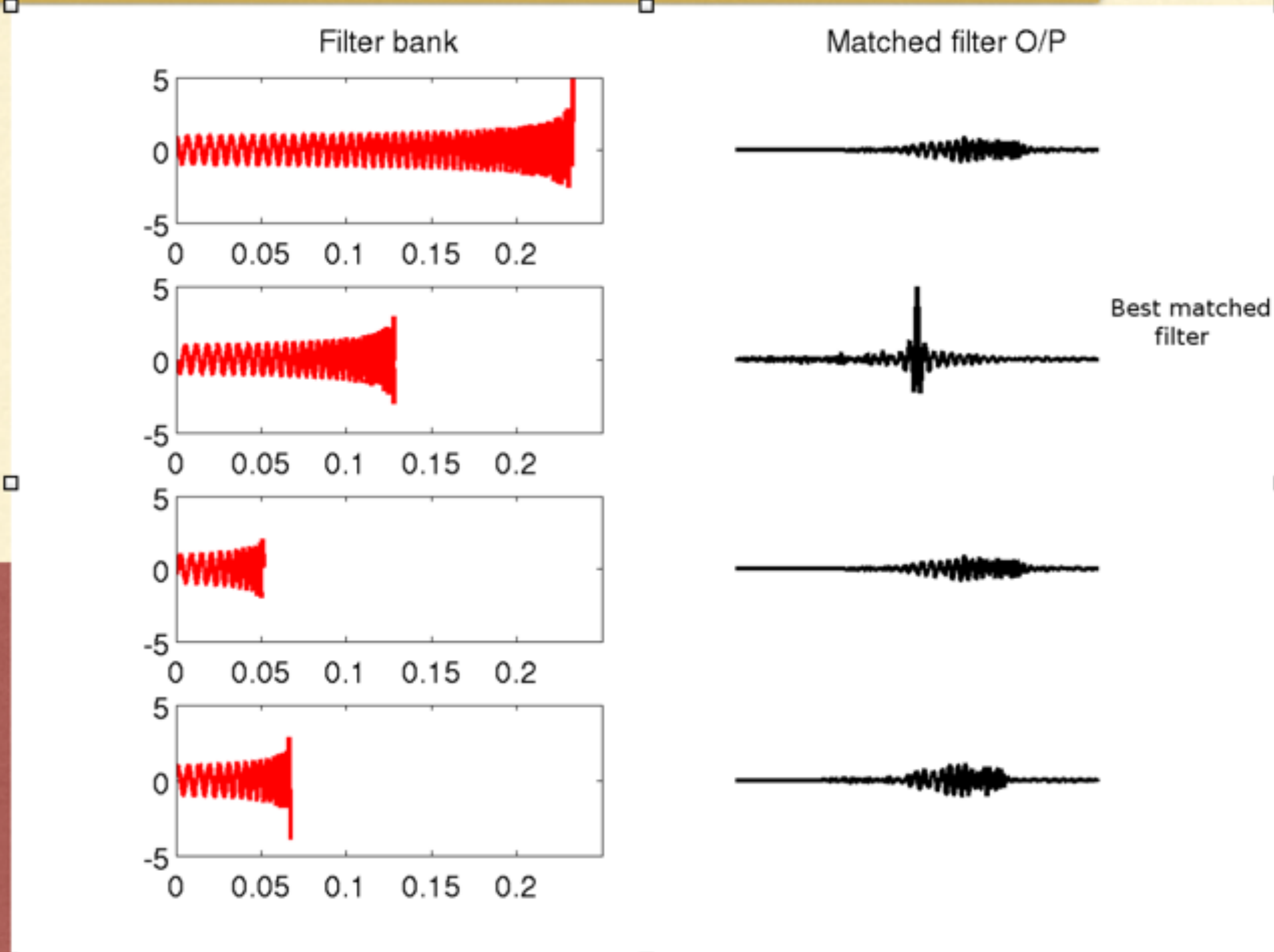


GW150914 EVENT WAS FAR LOUDER THAN ANY BACKGROUND TRIGGER

http://arxiv.org/abs/1602.03844

Compact Binary Coalescence Search in LIGO data





Matched Filtering Technique

Coherent addition of Signal
Incoherent addition of Noise

Accurate knowledge of waveform
phase is crucial

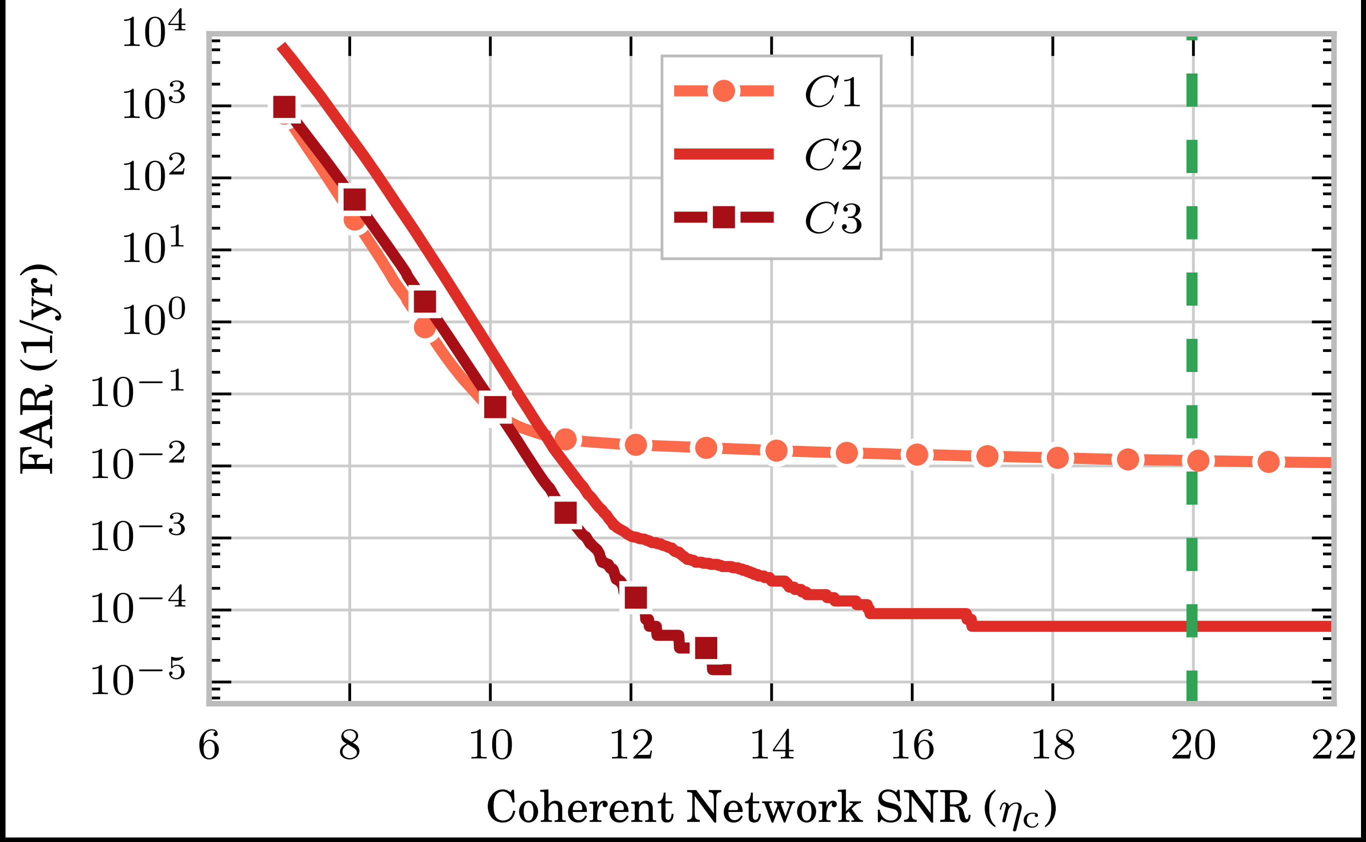
A century long history towards the Gravitational Wave detection

1916: Einstein General Theory of Relativity Predicts GWaves
1961: J. Weber proposed Resonant bar detector to detect GWaves
1970s: Development of precision measurement laser technology, Feasibility studies for km arm length interferometer and possible noise sources
Early 1980s: Prototype interferometers in Glasgow, Garching and MIT
1992 : National Scientific Foundation approves LIGO
1993: Hulse and Taylor receives Nobel prize for the discovery of PSR 1913+16
1994 : LIGO Site construction begins at Livingston and Hanford
1997 : LIGO Scientific Collaboration (LSC) was established.
2001: First coincidence run between 3LIGOs, GEO600, LSU bar detector
2002-2007: Joint Science Run data with GEO600, TAMA300, Virgo
No GWaves detected with initial interferometers
2008: Advanced detector construction started
2011-2014: Installation and Testing of LIGO
Sept 2015- January 2016: First Observation Run

CLASSIFICATION OF EVENTS:

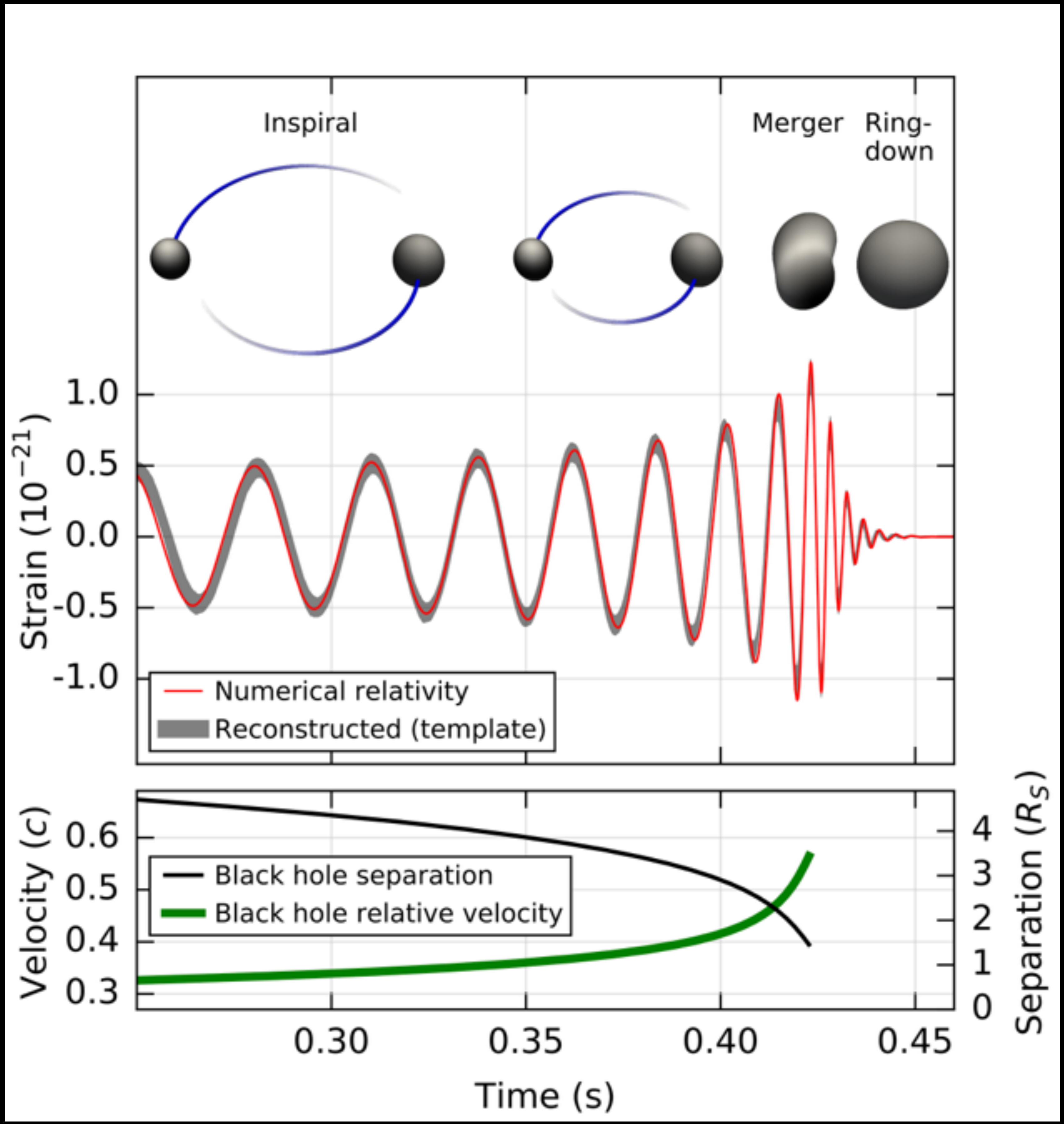
Noise features and characteristics, the background events are classified

- C1 — Known population of noise transients e.g. power line or mechanical resonances
- C3 — Events with increase in frequency as the time increases
- C2 — Not C1 nor C3.



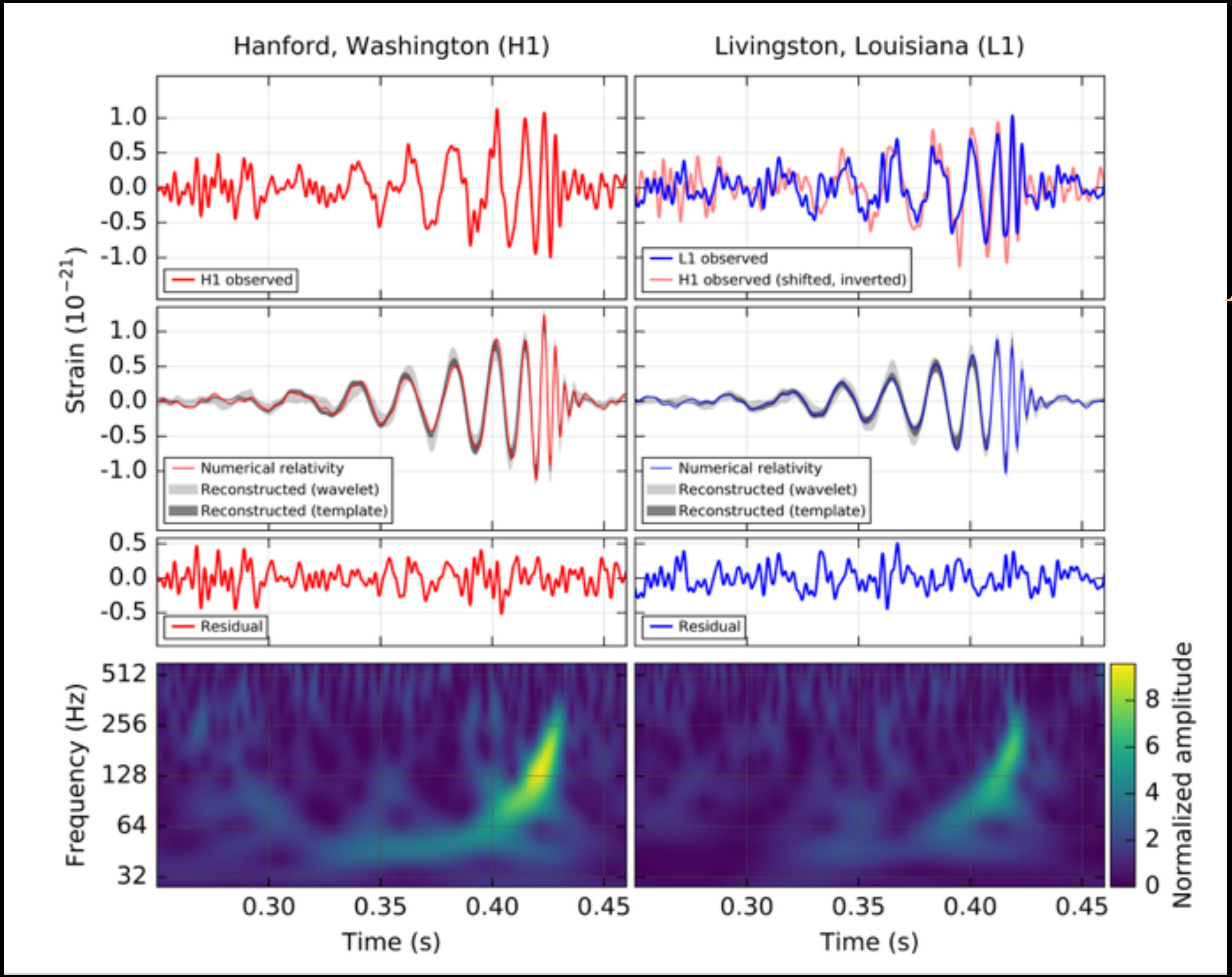
The SNR level of GW150914 corresponds to green line

http://arxiv.org/abs/1602.03843



Inspiral
Merger
Ring-
down
1.0
0.5
0.0
-0.5
-1.0
Strain (10^{-21})
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
4
3
2
1
0
Separation (R_S)
0.30
0.35
0.40
0.45
Time (s)

Is it a NS-BH or BBH?



TF path

Mc~ 27Msun

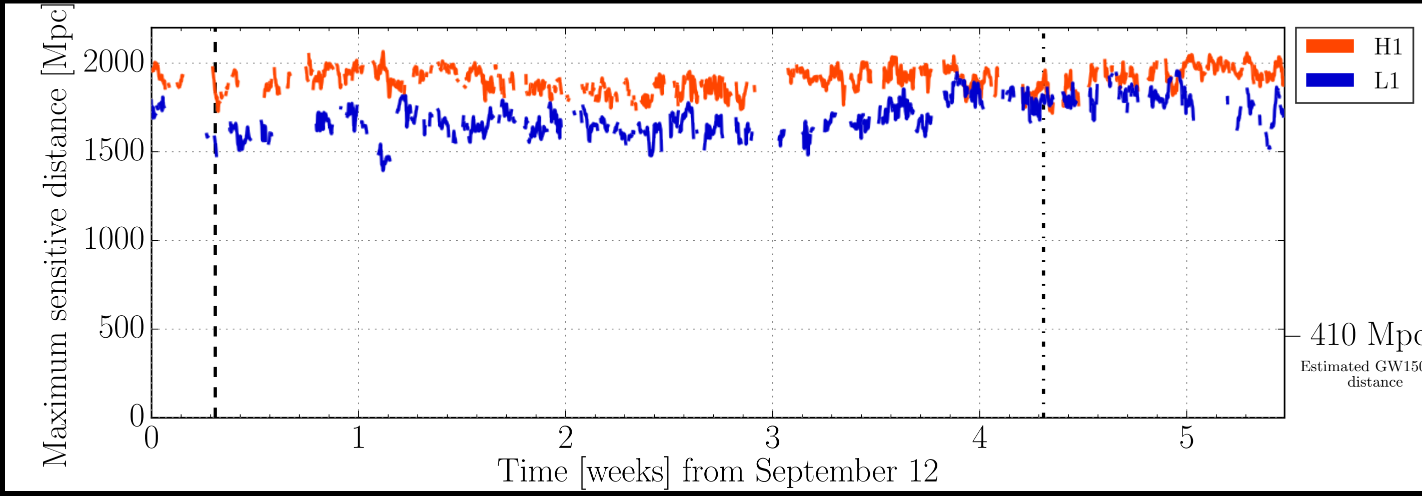
$$M_c = (m_1 m_2)^{3/5} / M^{1/5}$$

If the binary is NS-BH

BH mass > 900 Msun

Signal freq < 300 Hz

DETECTOR VALIDATION AROUND GW150914



- Both the detectors were in steady operation around the event

Sept 12 — Oct 20, 2015

- Extensive investigations of instrumental, environmental disturbance shows no evidence for instrumental artifact

- No indication of frequency evolution of external disturbance as observed in the event

- No evidence of instrumental disturbance which has temporal correlation between the two sites.

https://dcc.ligo.org/public/0122/P1500238/022/P1500238_GW150914_noise_characterization.pdf

GW 150914: FACTSHEET

date	14 Sept 2015
time	09:50:45 UTC
observatory	LIGO WA, LA
source type	black hole binary
SNR	24
false alarm prob.	$< 2 \times 10^{-7}$
false alarm rate	1 in 200,000 yr
chirptime at 35 Hz	200 ms
cycles from 35 Hz	8
remnant size, area	210 km,
inferred rate	2-400 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
BH spins	
primary	< 0.7
secondary	< 0.9
remnant	0.7
graviton mass	$< 1.2 \times 10^{-22}$ eV
resolved to	600 sq. deg.
orientation	face-on/off
sky location	southern hemisphere
CPU hours used	~ 50 million

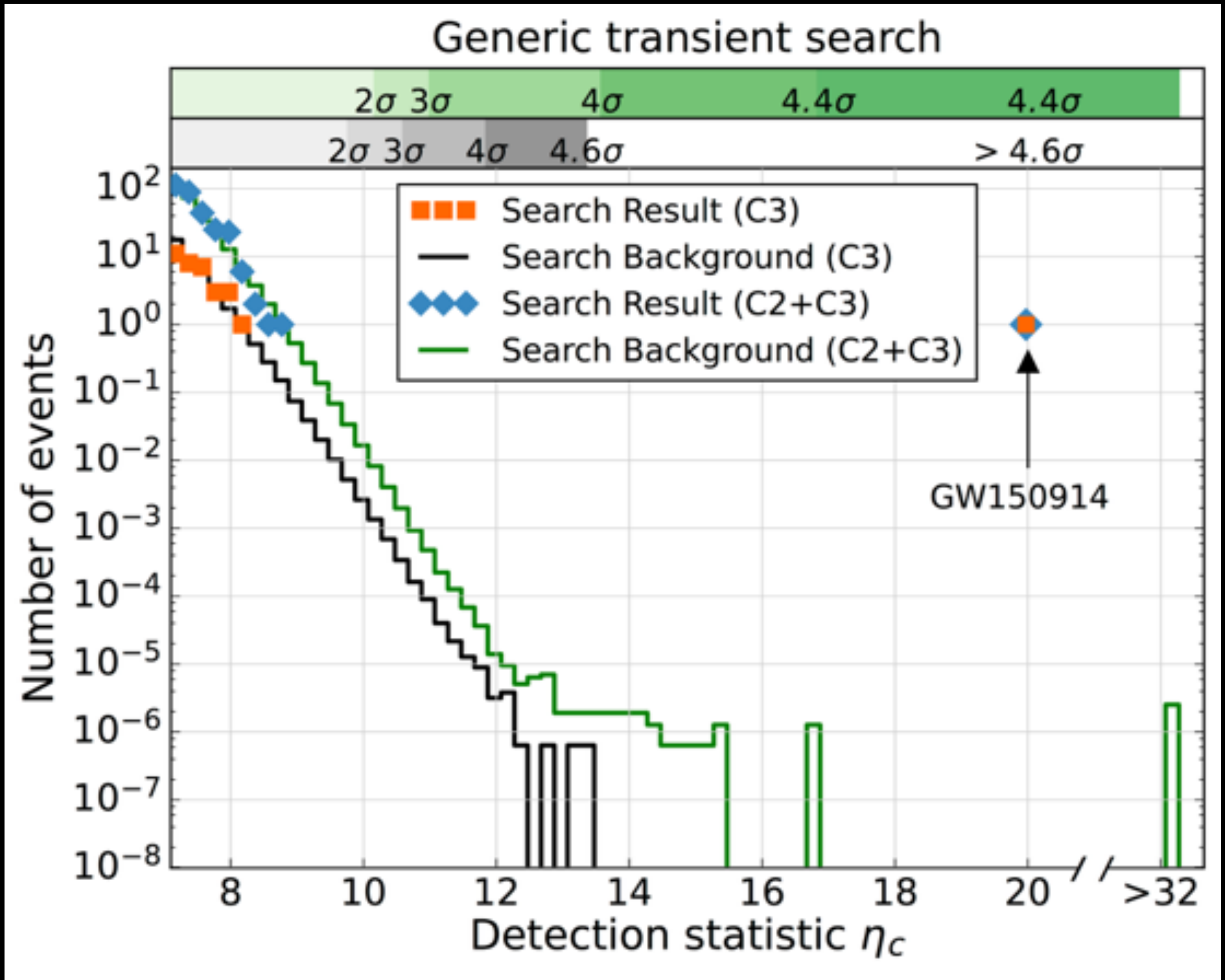
distance, redshift	410 Mpc, 0.09
peak frequency	150 Hz
QNM frequency	250 Hz
peak strain	10^{-21}
peak luminosity	3.6×10^{56} erg s^{-1}
peak speed	0.6 c
radiated energy	3 $M_\odot$, 5% of mass
Detector Frame Masses $M_\odot$	
total mass	70
chirpmass	30
primary BH	39
secondary BH	31
remnant BH	67
Source Frame Masses $M_\odot$	
total mass	65
chirpmass	28
primary BH	36
secondary BH	29
remnant BH	62
mass ratio	0.8

http://arxiv.org/abs/1602.03843

LVC, PRL 116, 061102 (2016)

BACKGROUND STATISTICS

GENERIC TRANSIENT SEARCH



16 days of coincidence data in Sept 12-Oct 20,

1.6 x 10e6 time instances= 67,400 yrs of observation time

Significance of GW150914:

Number of classes 3 => FAR of 1 in 22,500 yrs.

Significance level 4.6 sigma

Salient Features of advanced LIGO upgrades:

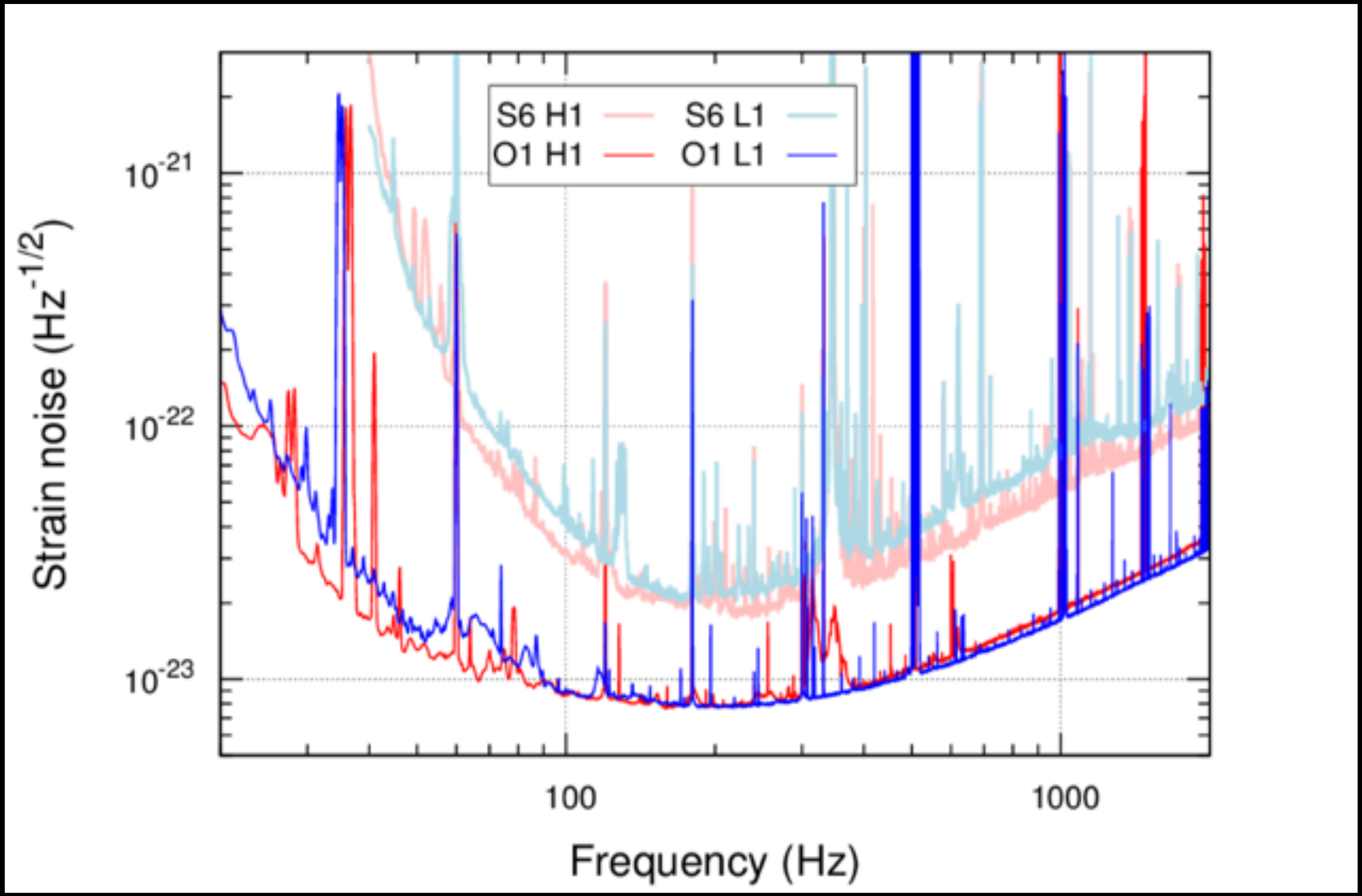
1/ Increased laser power — reduces high frequency noise

2/ Heavier test masses — reduces random mirror motions

3/ Suspension with fused silica fibre — reduction in thermal noise

4/ 4 stage suspension — reduces seismic noise

http://tinyurl.com/ALIGO-upgrades-pdf



Observation Run (O1) — Sept'15-Jan'16

Sensitivity is 3-5 times of iLIGO (~100 Mpc)

100-300 Hz is the most sensitive band

Volume of 27-125 times larger