GW transient searches to probe Neutron star physics

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GW transients from neutron stars

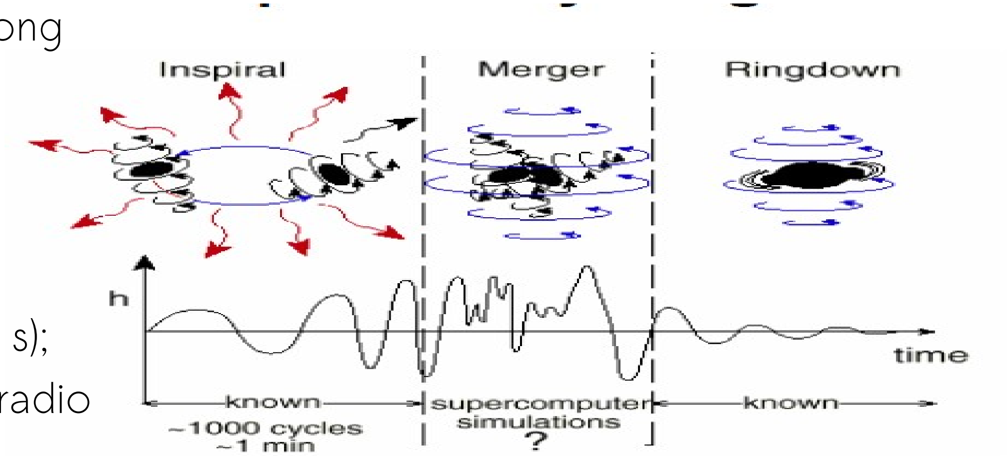
<u>Coalescence of binary systems of NSs and/or BHs:</u> strong emitters of gravitational waves (GW) signals:

-inspiral

-merger

-post merger, ringdown

→EM emission: short GRBs: prompt γ-ray emission (< 2 s); multi wavelength afterglow emission: X-ray, optical and radio (minutes, hours, days, months).

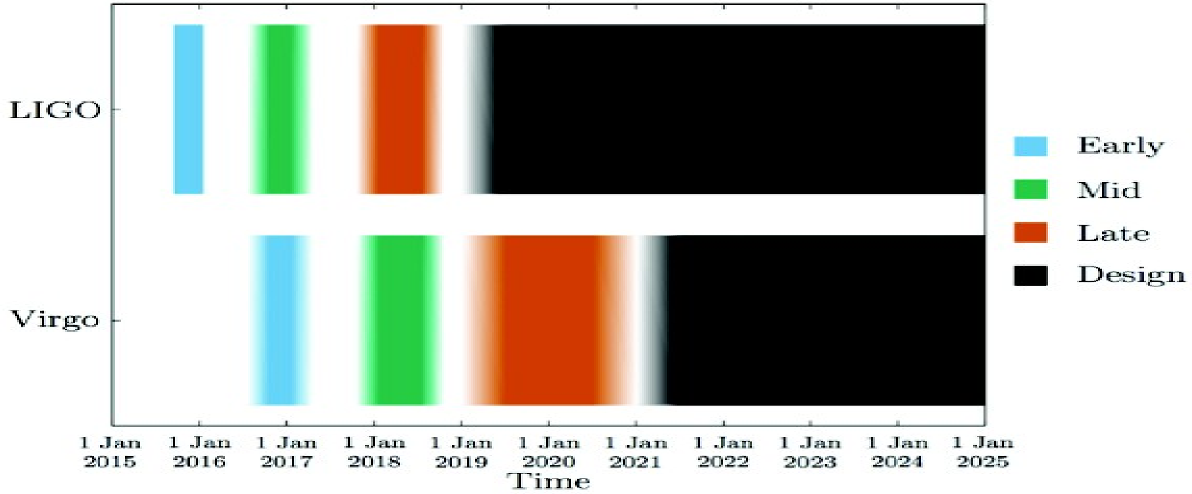


<u>Isolated neutron stars:</u>

the excitation of various oscillatory modes leads to transient gravitational wave emission (e.g. flaring activity in magnetars)→ not well known morphologies

→ EM emission: soft γ–ray repeaters, -radio/X-ray pulsar glitches

Near Future



Performance upgrades by steps, interleaved by scientific observation runs: O2, O3, design

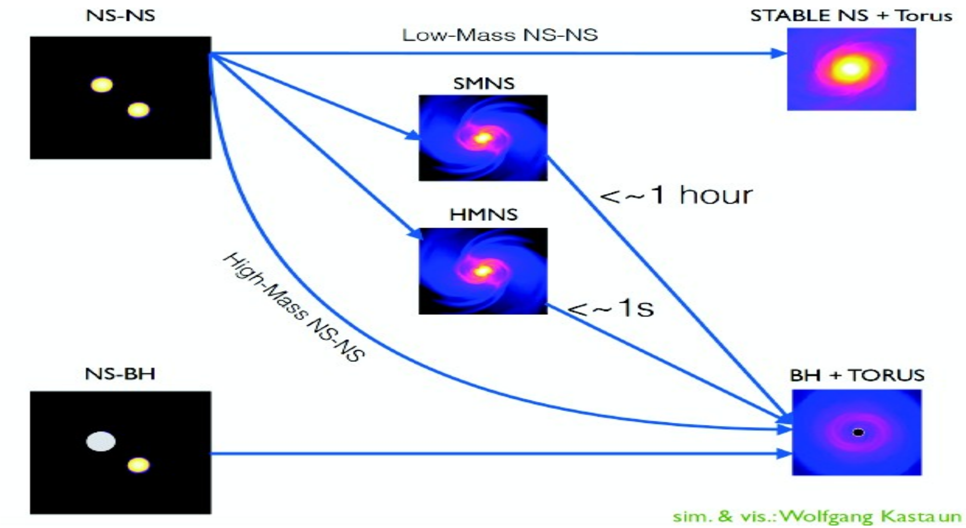
Data taking O2: ongoing

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

Living Rev Relativ (2016) 19: 1

Design sensitivity:
Binary NS detection rate:
0.2-200 /year

Binary neutron star mergers

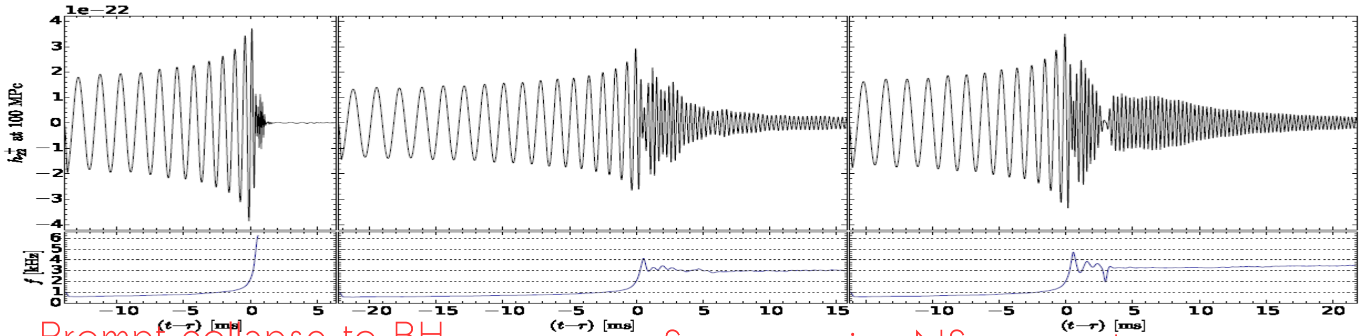


BNS merger possible outcome:
-stable NS
-supramassive or hypermassive neutron star (SMNS,HMNS) → delay collapse to BH
-prompt collapse to BH

} Post merger neutron star (PMNS)

Endrizzi et al. 2016, CQG 33, 164001

-PMNS emits short (tens to hundreds ms) GWs burst signals, dominant power in freq ~2-4 kHz.
-BH ringdown will be ~6-7 kHz (no detectable by Ligo-Virgo sensitivity)

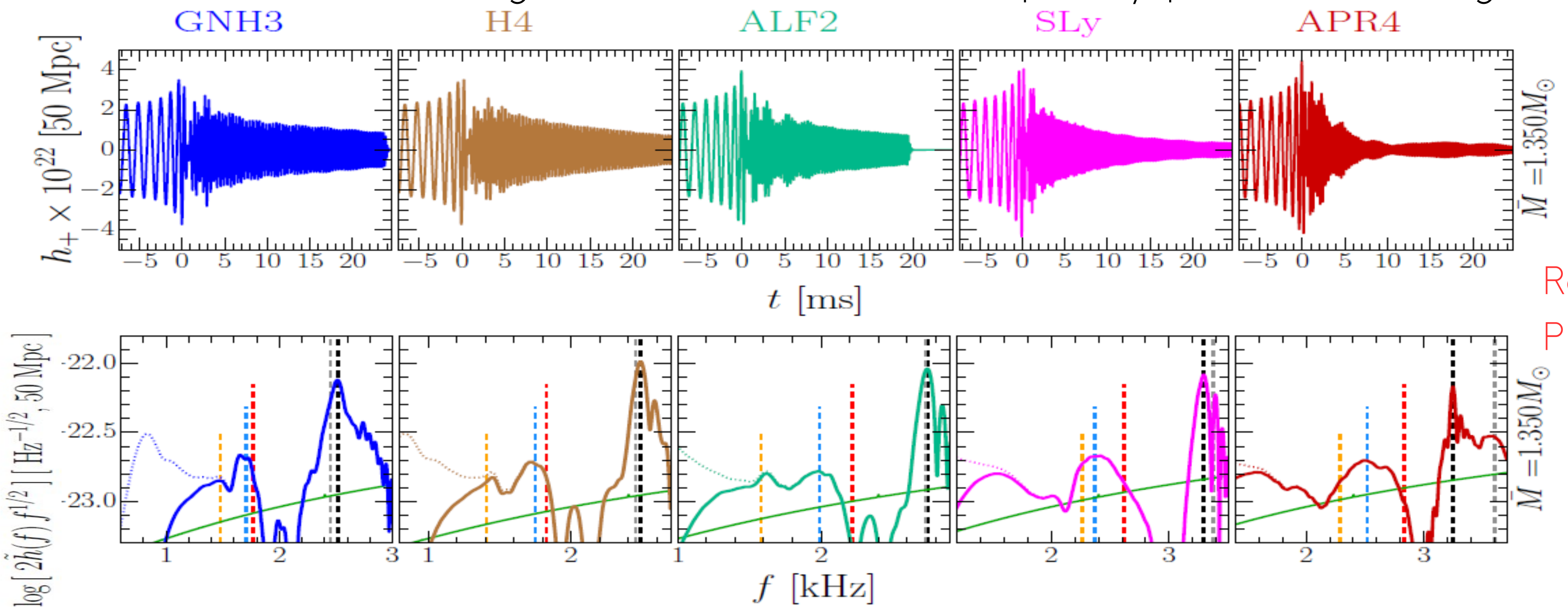


Prompt collapse to BH — 1.43+1.43 $M_\odot$

Supramassive NS remnants — 1.22+1.22 $M_\odot$ — 1.29+1.42 $M_\odot$

Gravitational waves - PMNS

GW PMNS signals has a dominant frequency peak in the range 2-4 kHz



Gravitational waveforms for some EOSs

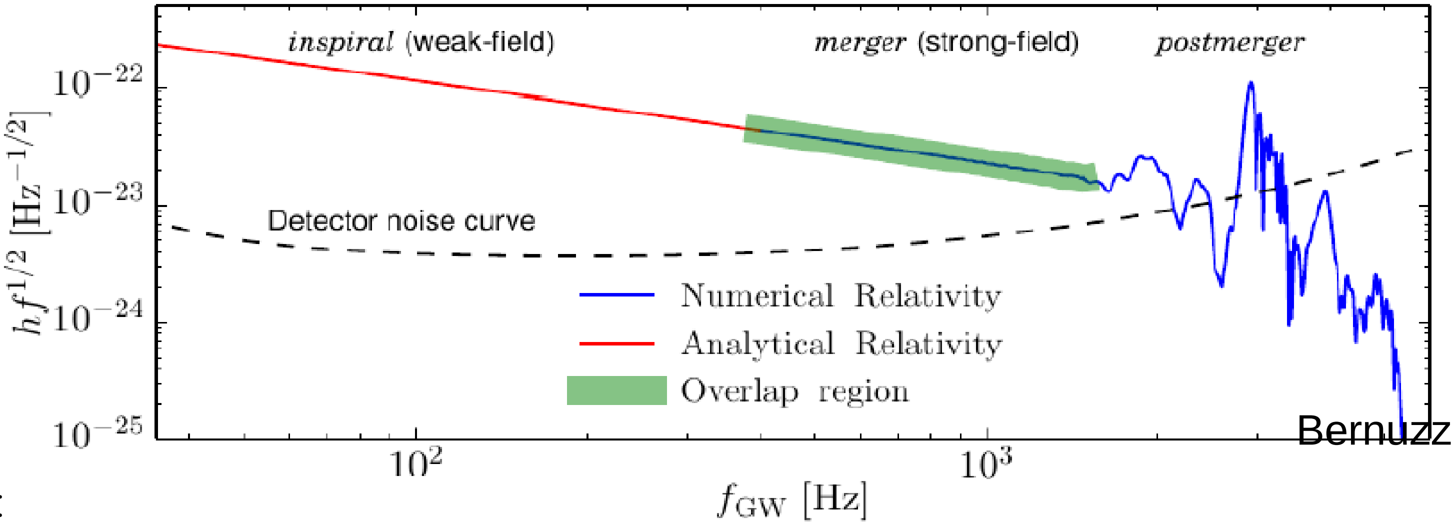
Rezzolla & Takami 2016, PRD 93, 124051

PSDs of the GW signals for some EOSs

Frequencies of main spectral features correlate with NS properties: quadrupolar tidal deformability, compactness and mass ratios of progenitors. e.g. main PM frequency peak correlates with radius of NS (across many EoS)

PRD 91, 064001 (2015)
arXiv:1604.00246v2
PRD 91, 124056 (2015)
..many other works

Gravitational waves - PMNS (2)



Bernuzzi

GW signal:

-Inspiral: well approximated by PN/EOB; tidal effects can be important at high PN order

-merger: analytic description possible, tidal effect are important, signature of neutron star EoS

-post merger: among the excited modes, the fundamental mode of the NS is expected to produce a strong peak in the emitted GW, strong signature of neutron star EoS. Numerical relativity is needed

High computational cost to have full bank of templates

Accurate waveform models

Search for generic burst transients

Searches for gravitational-wave bursts do not require knowledge about the morphology of the signal (time-frequency (TF) and phase evolution)

↓

suitable when waveform morphologies are too uncertain to build a template bank (or the uncertainties of the template waveform are relevant)

Burst searches aim to cover a broad parameter space, complement and extend searches for well modeled signals, potential for discovering new sources of gravitational waves

<u>Algorithm key points</u>:

- Data conditioning, TF representation of the data and whitening
- Search for excess power in TF domain coincidently/coherently in different detectors data (considering time delay between detector sites and different antenna patterns of interferometers for any incoming direction)

Short transient, all sky search → 3 pipelines: cWB, oLIB, BayesWave

PMNS detection using cWB

cWB (Coherent WaveBurst): Klimenko et al. 2016, PRD 93, 042004

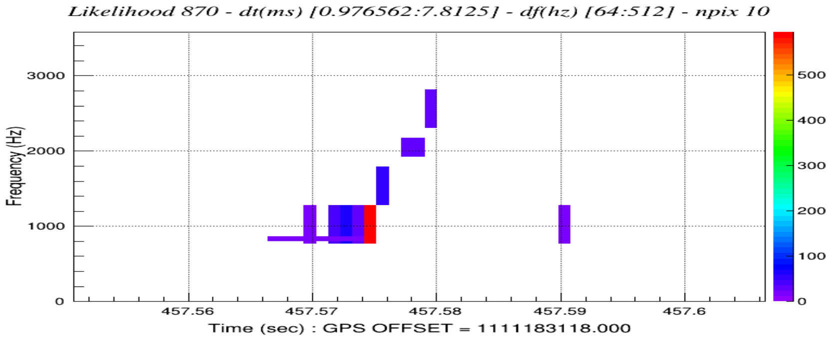
- Excess power selected in time frequency (TF) maps are combined in unique coherent cluster trigger considering multi-resolution TF representation.
- Triggers are analyzed coherently to estimate signal waveform, wave polarization, source location, using a constrained likelihood method (maximization over sky position loop)

Hierarchical procedure:

In case of BNS detected, follow up cWB analysis optimized is performed in the frequency band [768Hz-4kHz] → waveform signal reconstructed at the detector

Tool to discriminate NS post merger candidates versus prompt collapse to BH

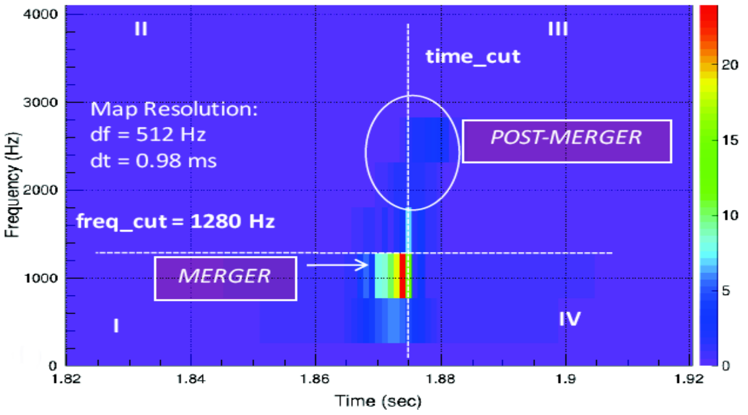
In case of post merger candidate, characterization of its spectral properties



Example of reconstructed signals, injected BNS, EOS: SHT mass 2.0 M
SNR -reconstructed: 32

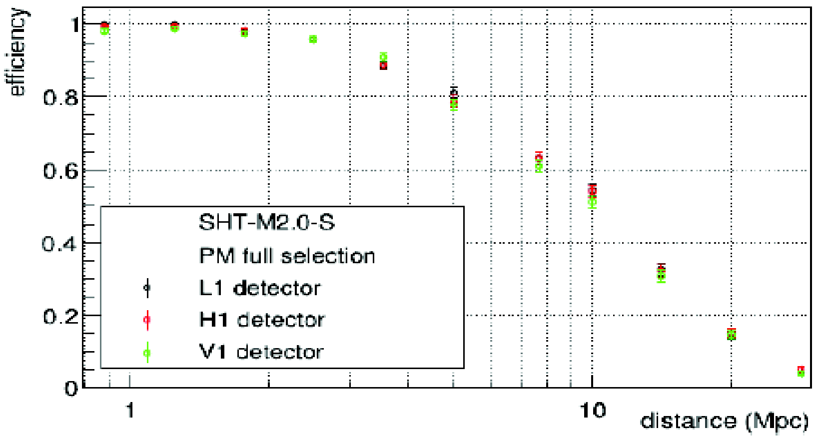
PMNS detection using cWB (2)

TF map of the waveform signal reconstructed
df=512 Hz, dt=0.98 ms



The tool classifies the event according to the energy distribution in different region of TF map.
Simulations have been performed injecting BNS waveform of both scenario: PMS with delayed collapse and prompt collapse to BH, for different EoS.

Efficiency for SHT 2.0 M simulation



Estimate: efficiency, false alarm probability and posterior probability of the discrimination's tool

Parameter estimation of PMNS

→ brightness (luminosity profile) and duration of the PM signal
→ main frequency peak of the spectra of post merger signal

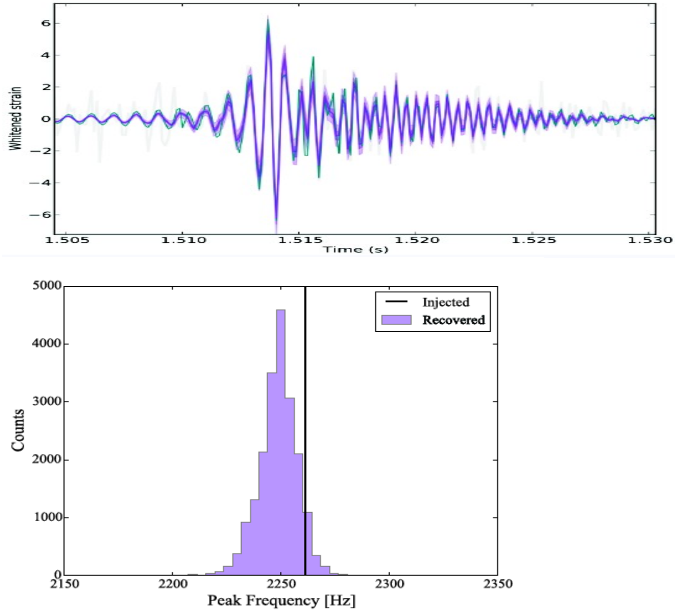
PMNS detection using BayesWave

CWB + BayesWave: CQG 32(13):135012, 2015

- Bayesian model selection using a liner combination of sine Gaussian templates (it marginalizes over the number of wavelets using a reversible jump Markov chain Monte Carlo). Posterior distributions for estimation parameters and waveform reconstruction

Chatziioannou,Clark

Example of injected signal reconstructed, Waveform posterior with 50% and 90% credible intervals



Dominant peaks are extracted directly form the reconstructed signal. Extract also multiple subdominant peaks, width of peaks. Introducing model dependencies to infer physical NS properties (e.g. radius)

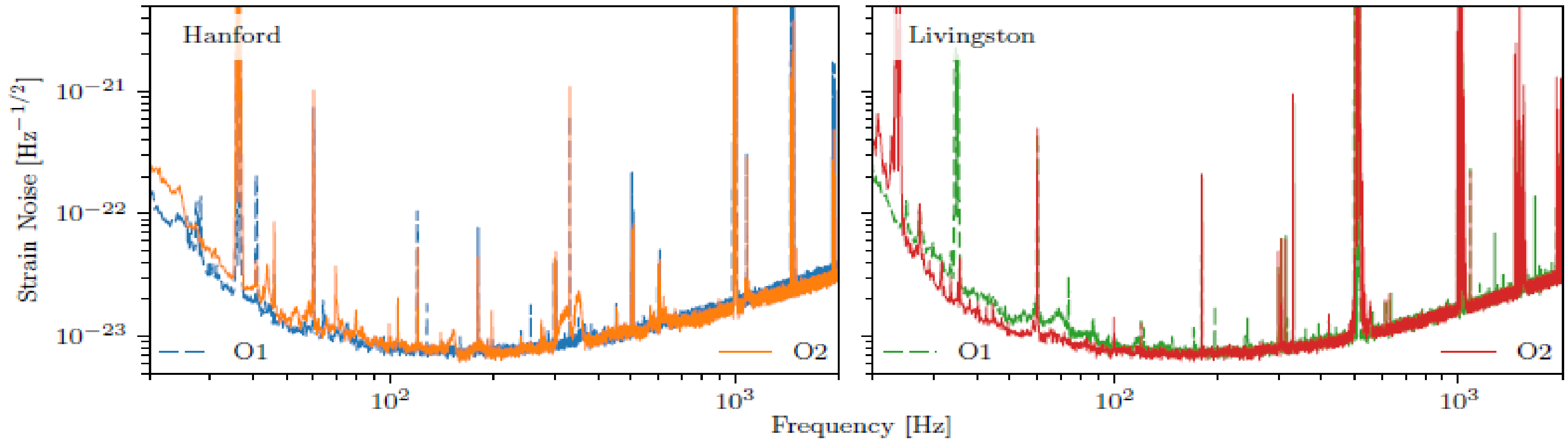
Conclusion

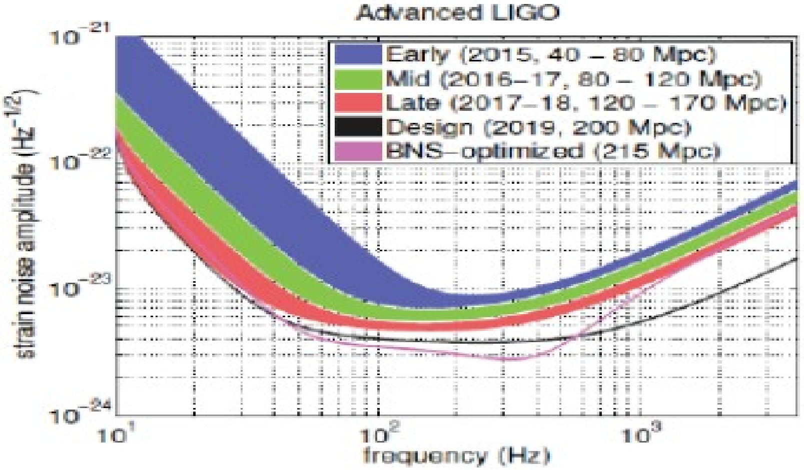
LIGO Virgo interferometers network is expected to detect GW from NS in the near future (Advanced designed sensitivity needed):

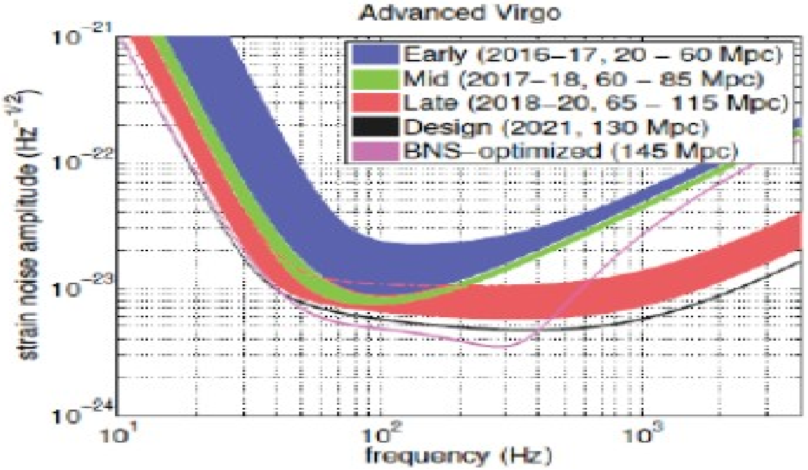
- Targeted offline search for gravitational waves associated with magnetar flaring activity are foreseen
- Studies of extreme matter with GWs are possible; signature of EoSs are imprinted in the post-merger GW signal from BNS coalescences
- Burst waveform reconstruction tools, based on un-modeled approach, are under development to extract post merger signal features

Back up

Interferometers sensitivity





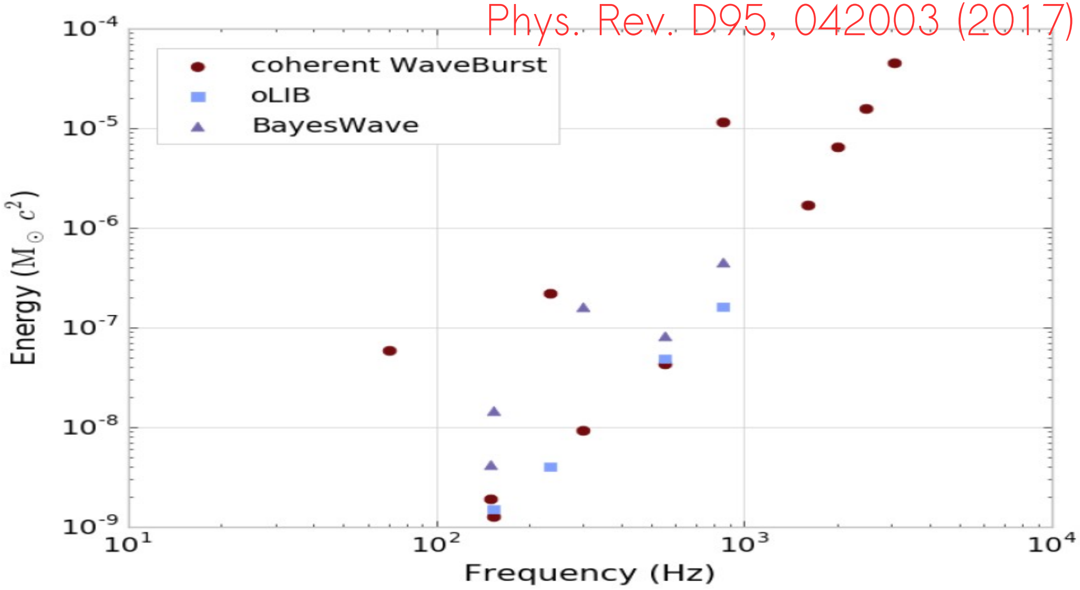


All-sky search for generic transient- O1

All-sky search for 'unmodelled' GW transients search for transients:
with short (up to a few seconds) and long durations (~10-500s) (short transient searches also run in low-latency mode)
In the frequency bandwidth 40Hz-4kHz

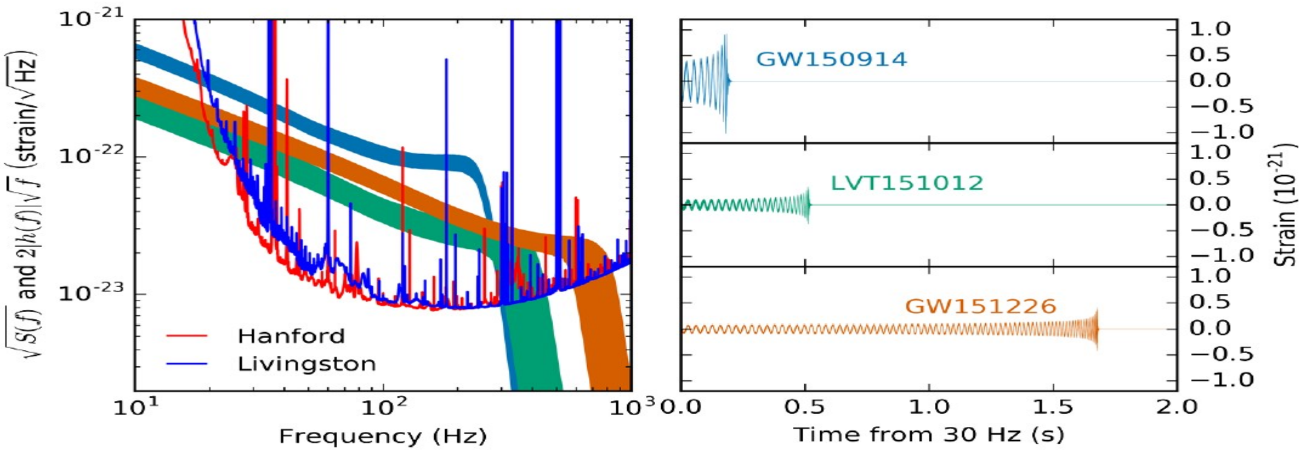
Phys. Rev. D95, 042003 (2017)

Short duration search
~48 days of data (O1)
GW energy in short pulses, detectable with 50% efficiency for standard-candle sources emitting at 10 kpc
False alarm < 1/100yr



Different waveform morphologies

LIGO interferometers network -O1



GW150914 (significance >5.3σ)
LVT151012 (Candidate 1.7σ)
GW151226 (significance>5.3σ)

Amplitude spectral density of the total strain noise of the H1 and L1 and the recovered signals

Phys. Rev. X 6, 041015