Observing higher modes of gravitational radiation in future detectors

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Phys. Rev. D 104, 084080, arXiv: 2103.03241

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Chennai Symposium on Gravitation and Cosmology (CSGC)

February 3, 2022

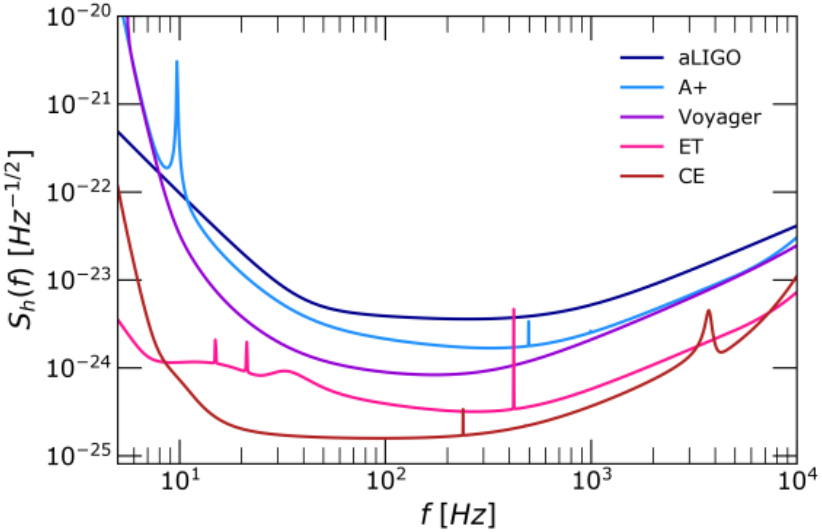
CHENNAI MATHEMATICAL INSTITUTE

Introduction

- In GWTC-2, LIGO-Virgo Collaboration reported the detection of Higher Modes (HMs) for two events: GW190412 and GW190814.
- A few more events with large mass ratios have been added in GWTC-3.
- Relative contribution of HMs increases for binary systems which are asymmetric in masses, or non-optimally oriented.
- Detection of HMs increases the mass reach of the detectors, leads to better parameter estimation and measurement of cosmological parameters.
- We have performed three studies:
  - Detectability of HMs in $q - \iota$ plane
  - Detection of HMs for GWTC-2 events if 3G detectors were operational
  - Population study using the next generation detector networks.

Detector networks

- Upgraded 2G detectors: LIGO-A+, Voyager
- 3G detectors:
  - Cosmic Explorer (CE): L-shaped, length of each arm = 40km.
  - Einstein telescope (ET): Equilateral triangle, length of each arm = 10km, setup will be underground.
  - Low frequency sensitivity in the range of 1-5Hz.



Label	Location	Type(s)
L	Louisiana, USA	CE/A+/Voyager
H	Washington, USA	CE/A+/Voyager
V	Cascina, Italy	CE/A+/Voyager
A	New South Wales, Australia	CE
E	Cascina, Italy	ET

Waveform and detection criteria

- Multipolar expansion of GW radiation:

$$h(t;\iota,\varphi_o) = \frac{1}{d_L}\sum_{\ell=2}^{\infty}\sum_{m=-\ell}^{\ell} h_{\ell m}(t,\lambda)\, Y^{-2}_{\ell m}(\iota,\varphi_o) \tag{1}$$

- Waveform: IMRPhenomHM, Modes (ℓ, m): 22, 33, 44, 21, 32, 43.
- Individual mode strain:

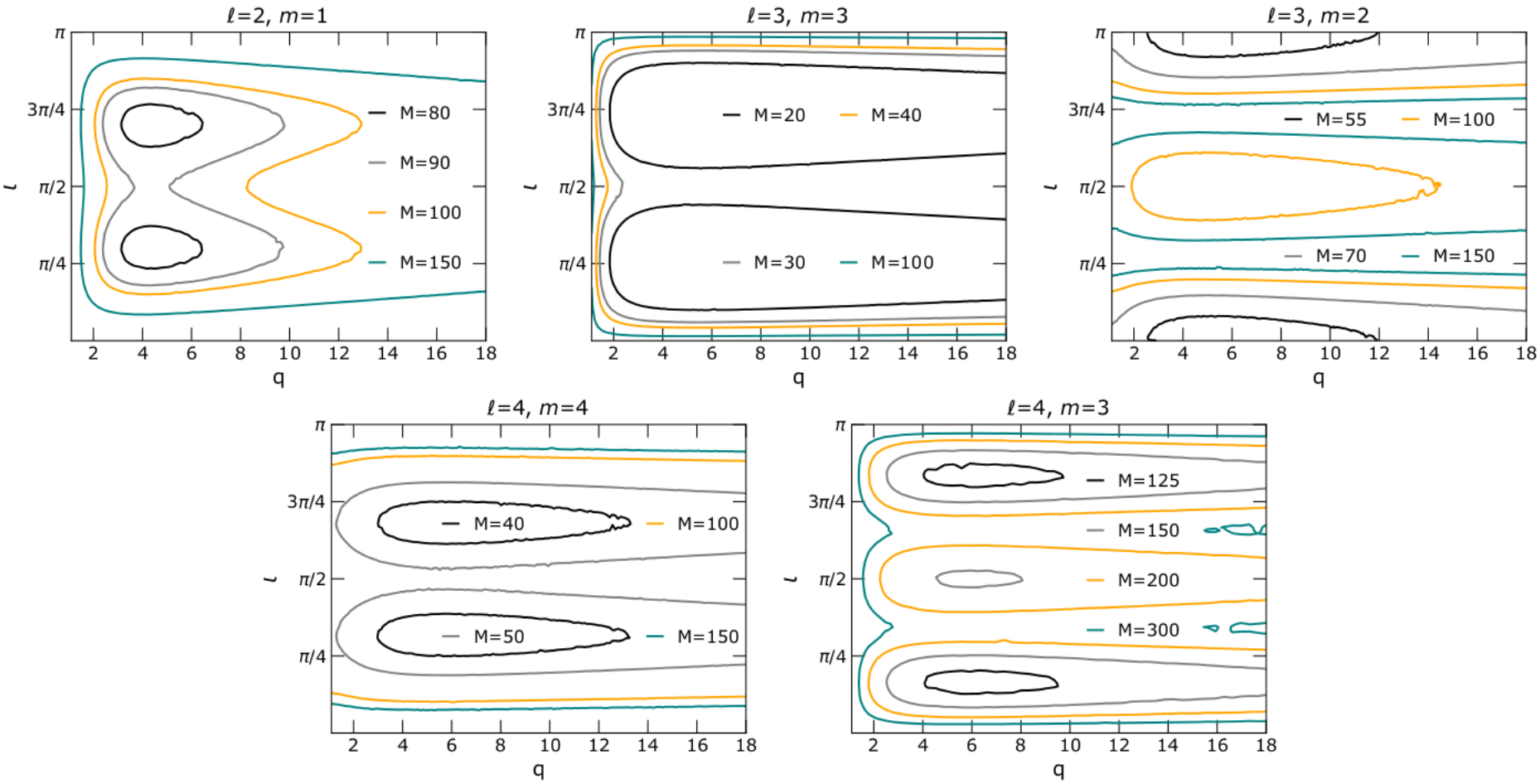
$$\tilde{h}_{\ell m}(f) = F_+(\theta,\phi,\psi)\,\tilde{h}^{\ell m}_+(f) + F_\times(\theta,\phi,\psi)\,\tilde{h}^{\ell m}_\times(f) \tag{2}$$

- Optimal SNR for each mode $(\rho_{\ell m})$ as:

$$\rho^2_{\ell m} = 4\int_{f_{\rm low}}^{f_{\rm cut}} \frac{|\tilde{h}_{\ell m}(f)|^2}{S_h(f)}\, df \tag{3}$$

- $f_{\rm low} = 5$Hz for all the detectors.
- Criteria for detection: 22 mode: SNR ≥ 10, HMs: SNR ≥ 3

Higher modes in the $q - \iota$ plane



Fixed SNR=3, $D_L = 3$ Gpc, $\chi_{1z} = 0.9$, $\chi_{2z} = 0.8$, Detector: CE

HM SNRs in CE for GWTC-2 events

Event	M	q	$\chi_{\rm eff}$	SNR in mode				
				22	33	44	21	32
GW190412	42.6	3.2	0.2	649	81	17	14	3.9
GW190519_153544	159.5	1.6	0.4	685	79	48	19	14
GW190521	279.8	1.4	0.1	424	22	19	7.1	7.5
GW190602_175927	173.8	1.4	0.1	330	15	9.4	4.3	4.7
GW190630_185205	69.9	1.5	0.1	708	31	14	7.9	5.8
GW190706_222641	183.5	1.7	0.3	223	18	7.6	3.4	3.3
GW190814	27.2	9.0	0	982	172	33	32	4.4
GW190828_065509	44.4	2.4	0.1	418	34	7.2	6.7	3.0

LIGO-Virgo quoted the 33 mode network SNR as ~ 6.6 for GW190814.

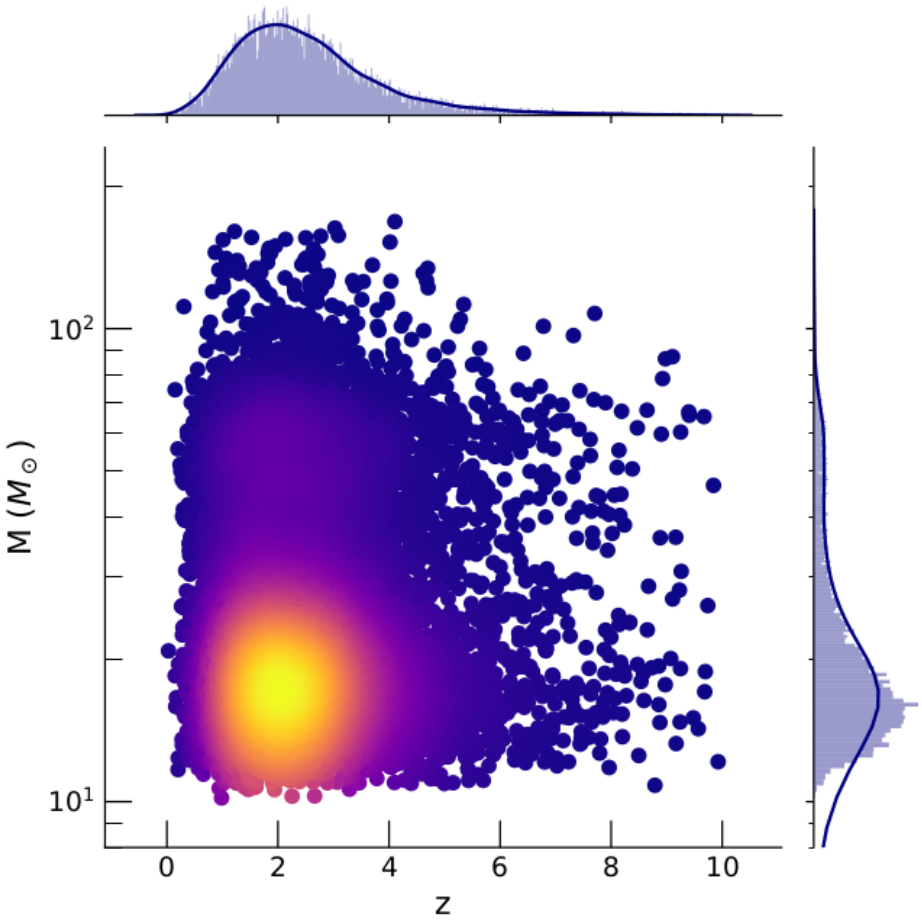
Population Study: Models

- Models (from GWTC-2[1]) for the parameter distributions chosen as:
  - Masses: Power Law + Peak and Broken Power Law models. $m_1 \in (5, 100)$, $q_{\max} = 18$.
  - Spins: Default Model for both χ_{1z} and χ_{2z}, range {-1,1}.
  - Luminosity Distance: Madau-Dickinson redshift evolution model[2], $z_{\max} = 10$.
  - Angles: cos(ι) and cos(θ) uniform between {-1,1}, ϕ and ψ uniform between {0,π}.
- Total number of population points for each mode: 10,000

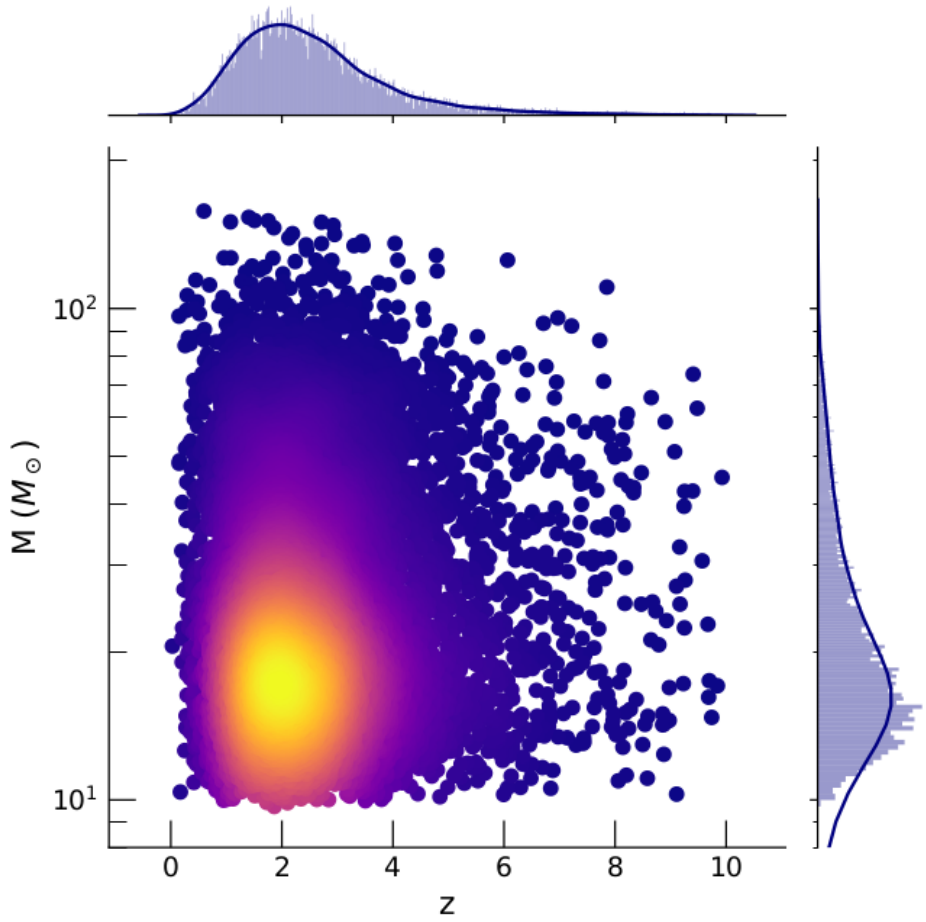
[1] R. Abbott et al. (LIGO Scientific, Virgo) (2020),arXiv:2010.14533.

[2] K. K. Y. Ng et al., Astrophys. J. Lett.913, L5 (2021), arXiv:2012.09876.

Injected Population

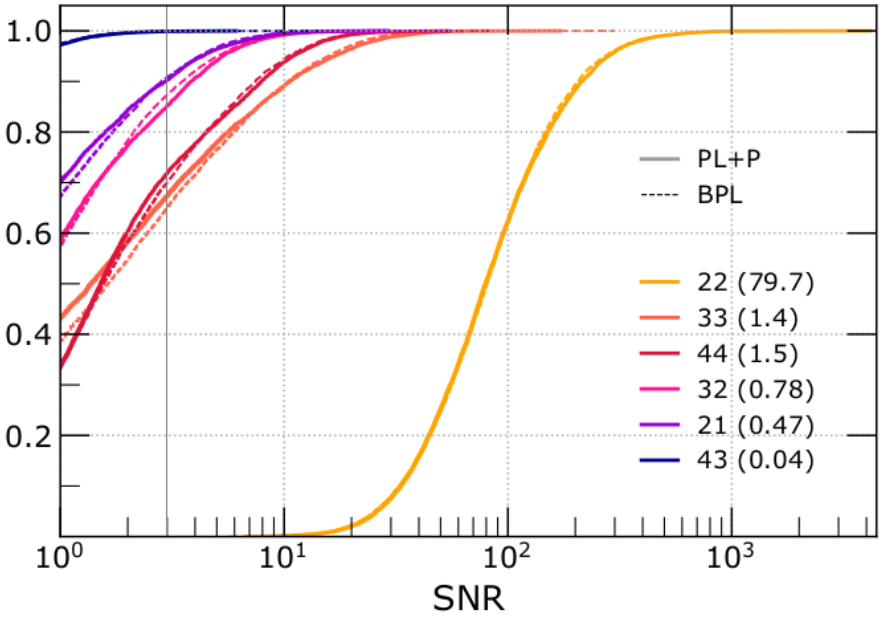


Power Law + Peak (PLP)

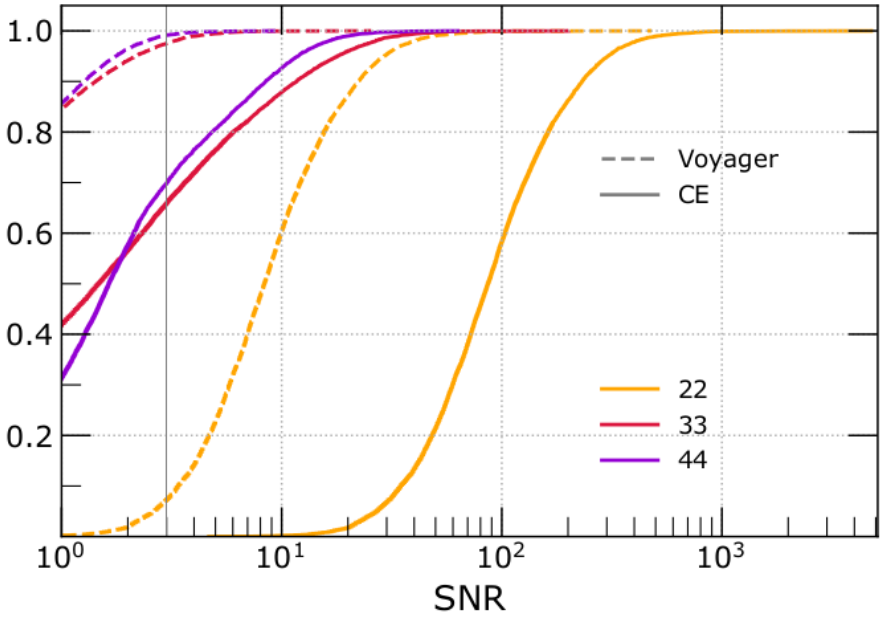


Broken Power Law (BPL)

Population histograms



Comparison between mass models (PL+P and BPL)
3G Detector network: LAE



Comparison between generations of detectors
Detector network: LHV for both the detectors (Voyager, CE)

Results and Summary

- Different HMs activate different regions of the parameter space, and show symmetries in ι leading to bi- and tri- modality of contours.
- Several of the GWTC-2 events would've led to the detection of HMs if 3G detectors were operational now.
- For 3G network, 33 and 44 modes are detectable in nearly 30% of the population.
- For 10% of the sources, all five leading modes are detectable.
- Comparison between generations: Less than 10% sources show detectability of 33 and 44 modes for upgraded 2G detectors, whereas for 3G, this number is $\sim 30\%$.

Thank You

Waveform

- Plus and cross polarizations associated with each mode:

$$\tilde{h}^{\ell m}_{+}(f) = \left[(-)^{\ell}\frac{d_2^{\ell,-m}(\iota)}{d_2^{\ell m}(\iota)} + 1\right] Y^{\ell m}_{-2}(\iota,\varphi_0)\tilde{h}^{\rm R}_{\ell m}(f)$$
$$\tilde{h}^{\ell m}_{\times}(f) = -{\rm i}\left[(-)^{\ell}\frac{d_2^{\ell,-m}(\iota)}{d_2^{\ell m}(\iota)} - 1\right] Y^{\ell m}_{-2}(\iota,\varphi_0)\tilde{h}^{\rm R}_{\ell m}(f) \quad (4)$$

  where $\tilde{h}^{\rm R}_{\ell m}(f) = A_{\ell m}(f)\, e^{i\varphi_{\ell m}(f)}$

- Combining them with the detector pattern functions:

$$\tilde{h}_{\ell m}(f) = F_{+}(\theta,\phi,\psi)\,\tilde{h}^{\ell m}_{+}(f) + F_{\times}(\theta,\phi,\psi)\,\tilde{h}^{\ell m}_{\times}(f) \quad (5)$$