Effect of the inclusion of sub-dominant modes of gravitational-waves emitted from binary black hole mergers - measured by a gravitational-wave burst search algorithm

Amaldi 10 **GR 20**

Warszawa 2013

Satya Mohapatra[§], James Clark[¶], Laura Cadonati[¶]

[§]Rochester Institute of Technology (USA), [§]Syracuse University (USA), [¶]University of Massachusetts – Amherst (USA)

Sub-Dominant Modes of Binary Black Hole Merger Signal

❖ Gravitational waves are expressed in the basis of spin weighted spherical harmonics, ${}^{s}Y_{\ell m}$, with spin weight $s = -2$.

❖ For the gravitational wave from the merger a binary black hole, the dominant contributions come from the modes: **(ℓ, m): (2 ± 2).**

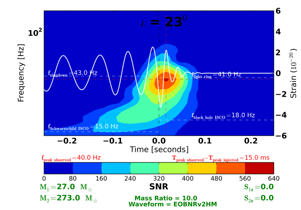
❖ Until now gravitational-wave searches, have only utilized the dominant modes for the full **Inspiral-Merger-Ringdown** waveform model, such as the **E**ffective **O**ne **B**ody tuned to **N**umerical **R**elativity (**EOBNRv2** - *Buonanno et al. 2009*) waveform.

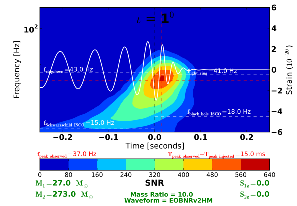
❖ Recently an analytical model extension of EOBNRv2 with the inclusion sub-dominant modes (up to ℓ = **5)** has become available – **EOBNRv2HM** (*Pan et al. 2012*).

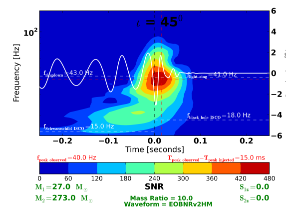
❖ Sub-dominant modes contribute towards the luminosity of the emitted gravitational wave – hence a gravitational-wave burst search can be sensitive to the inclusion of sub-dominant modes in addition to the dominant modes.

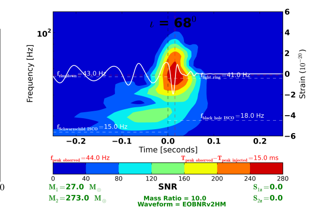
❖ In this poster we show the effect of the inclusion of sub-dominant modes in addition to the dominant modes in a gravitational-wave burst search for binary black holes. We utilize a burst search which uses **sine-Gaussian** basis to filter and then finds statistically significant excess energy in the time-frequency representation of the strain data.

(ℓ, m): (2 ± 2) : Dominant Modes
Other Modes: Sub-dominant Modes

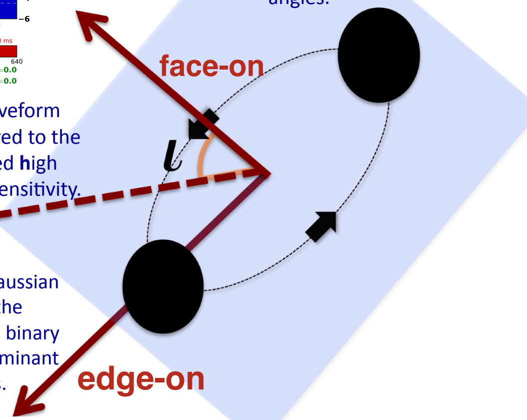






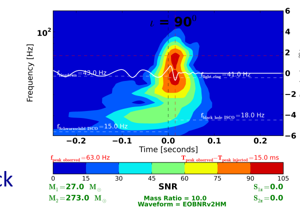


Inclination angle (ι) is the angle between the line of sight and the orbital angular momentum of a binary black hole system. In this diagram, examples are shown of observation made at different inclination angles.



EOBNRv2HM analytical waveform added to Gaussian noise colored to the advanced LIGO **z**ero **d**etuned **h**igh **p**ower (**ZDHP**) target design sensitivity.

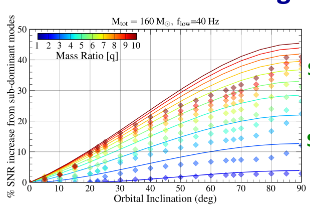
Time-frequency scans in sine-Gaussian basis, super-imposed with the gravitational-wave strain from a binary black hole merger with both dominant and sub-dominant modes.



The amplitude of gravitational-wave strain is maximum when observed at the face-on direction . The strain amplitude decreases as the point of observation moves towards the edge-on direction.

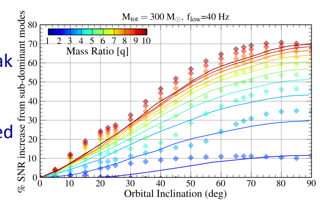
The inclusion of sub-dominant modes in the signal brings additional modulation in the strain. This effect is visible on the time-frequency profile as measured by a burst search. The measured peak frequency by a burst search is pushed up to a higher value at the edge-on orientation compared to the face-on orientation.

Inclination Angle and Mass Asymmetry



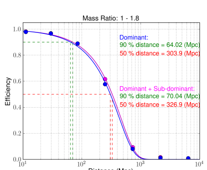
Scatter points: peak SNR difference

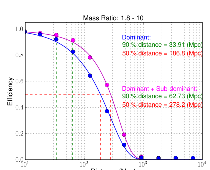
Solid lines: matched filtering SNR difference



Examples of **peak SNR difference** (scatter points), measured by the above mentioned burst search, between binary black hole merger gravitational-wave signal with dominant modes only and signal with both dominant modes and sub-dominant modes, added to the **5th Science run of LIGO Hanford (H1)** noise, at different inclination angles.

Detection Efficiency: Mass Ratio

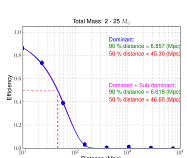


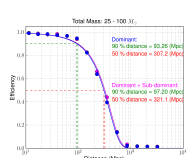


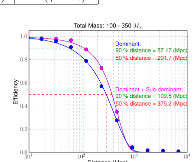
Measured detection efficiency (estimated by counting missed and found signals at a distance), averaged over **inclination angle** and **total mass**, of a burst search with simulation that includes sub-dominant modes compared with signal that includes dominant modes only. 2 months of the 5th science run of LIGO Hanford (H1) noise is used. A single detector **SNR threshold of 5.5** is the criterion for found signal in this study.

Set	(2, ±2) $D_{\rm eff}^{50\%}$ (Mpc)	(2, ±2) $D_{\rm eff}^{90\%}$ (Mpc)	ℓ up to 5 $D_{\rm eff}^{50\%}$ (Mpc)	ℓ up to 5 $D_{\rm eff}^{90\%}$ (Mpc)
Mass ratio: 1 – 1.8	304	64	327 (↑ 8%)	70 (↑ 9%)
Mass ratio: 1.8 – 10.0	187	34	278 (↑ 48%)	63 (↑ 85%)

Detection Efficiency: Total Mass







Measured detection efficiency for the above set of signals but averaged over **mass ratios** and **inclination angles**.

Set	(2, ±2) $D_{\rm eff}^{50\%}$ (Mpc)	(2, ±2) $D_{\rm eff}^{90\%}$ (Mpc)	ℓ up to 5 $D_{\rm eff}^{50\%}$ (Mpc)	ℓ up to 5 $D_{\rm eff}^{90\%}$ (Mpc)
2 – 25 $M_\odot$	45	7	47 (↑ 4%)	7 (0%)
25 – 100 $M_\odot$	307	93	321 (↑ 5%)	97 (↑ 4%)
100 – 350 $M_\odot$	292	57	375 (↑ 28%)	110 (↑ 92%)

Implications

❖ The contributions from the sub-dominant modes increase with the inclination angle. No effect of the sub-dominant modes measured at the **face-on** direction.

❖ The maximum contribution as measured by a burst search need not occur right at the edge-on but *near* the **edge-on** direction.

❖ For asymmetric mass binary black hole system, sub-dominant modes are more important than symmetric mass binary black hole system.

❖ Sub-dominant mode effect is negligible for stellar mass binary black holes. But it is important for intermediate mass binary black holes measured in a burst search.

❖ Any burst search upper limits drawn on dominant mode models are possibly under estimated.

❖ Time frequency properties measured by a burst search change with the inclusion of the sub-dominant modes. Measured signal energy is pushed up to higher frequency when observed away from the **face-on** orientation.

LIGO DCC G1300130