Unmodeled characterization of post-merger gravitational wave emission from binary neutron stars coalescence

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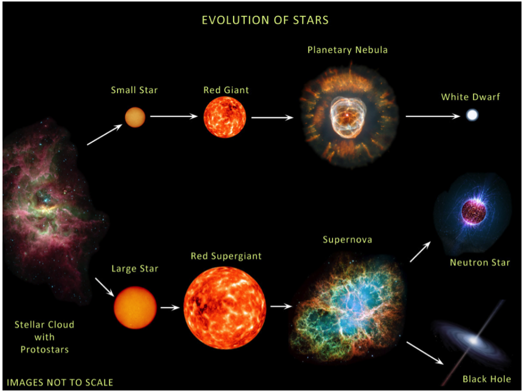
Neutron stars

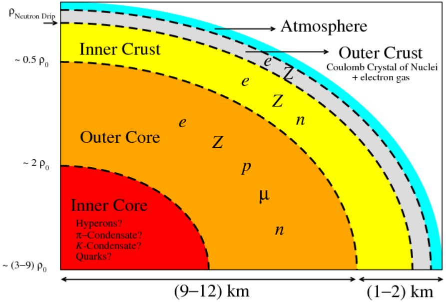
- One of the possible fates of stars



https : //blackholecam.org/

- Very compact matter: $M \sim 1 - 3M_{\odot}$, $R \sim 10km$
- Complicated structure: inner core $\rho > \rho_{nucl}$

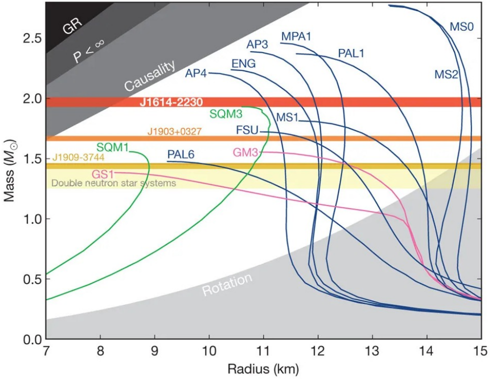
Cannot be recreated in laboratory!



X.Roca-Maza et al. (2011)

Neutron stars equation of state

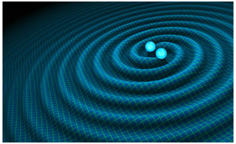
- Equation of state, different predictions: $p(\rho)$, m(R), Λ(m)
- We do not know the equation of state for matter at such high densities
- Large variety: hyperons, three-body interactions, liquid drop model, relativistic mean field...



P.B.Demorest et al. (2010)

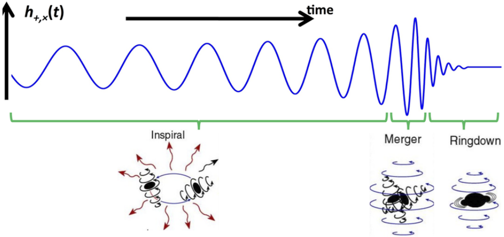
- Astronomical measurements, nuclear matter studies, **gravitational waves**

Gravitational waves



- General Relativity, gravity as curvature of spacetime.
- GW as ripples in spacetime, travelling at the speed of light
- Away from the source: solutions of Einstein eq. in vacuum $\Box \bar{h}_{\alpha\beta} = 0$
- Produced by mass quadrupole moment variations: $\bar{h}_{ij}(t, \vec{x}) = \frac{2}{r}\ddot{q}_{ij}$

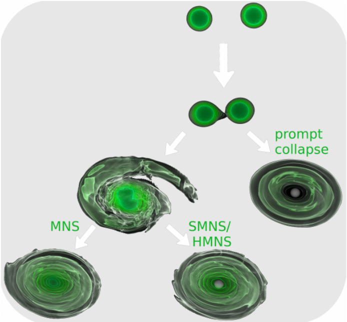
  Example: neutron stars binaries coalescence, inspiral or highly excited remnant



- Now we can detect them!
- August 17, 2017: first detection of a gravitational wave signal from a binary neutron star

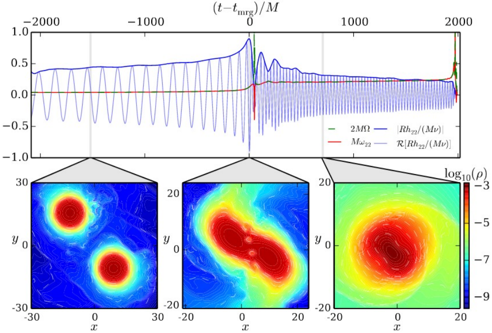
Neutron stars binaries coalescence: post merger

Un-modeled characterization, both in time and frequency domain, of gravitational wave signal emitted by binary neutron stars during the post-merger phase.



After the merger, depending on initial mass and equation of state:

- Prompt collapse to a black hole
- Massive neutron star remnant

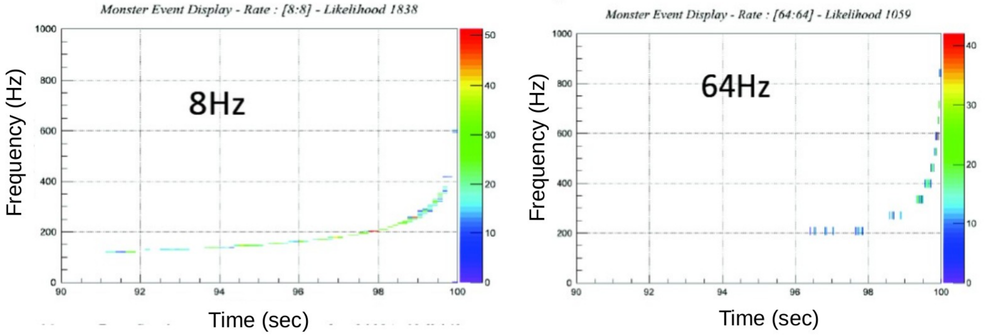


S.Bernuzzi, T.Dietrich, A.Nagar (2015)

Post-merger: different information with respect to inspiral because different physical regime

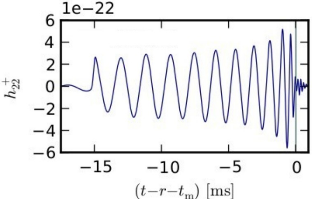
cWB

- Coherent WaveBurst algorithm: no a-priori assumptions
- Reconstruction of signal based on coherent power in output from different detectors
- Analysis in Time-Frequency domain: different resolutions

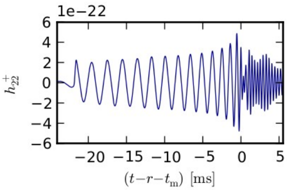


Waveforms

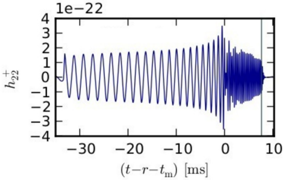
- Simulated signals: sources population randomly distributed in sky, at different fixed distances between [0.88, 56.56] Mpc.
- Assuming LIGO-Virgo network at design sensitivity
- Simulated (gaussian) noise for O4



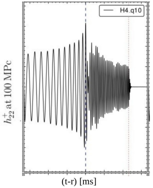
SHT-M2.2-I, [1], prompt collapse to black hole



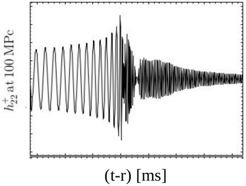
SHT-M2.0-S [1],
neutron star remnant



LS220-M1.5-S, [1]
neutron star remnant



H4-M1.5 [2],
neutron star remnant

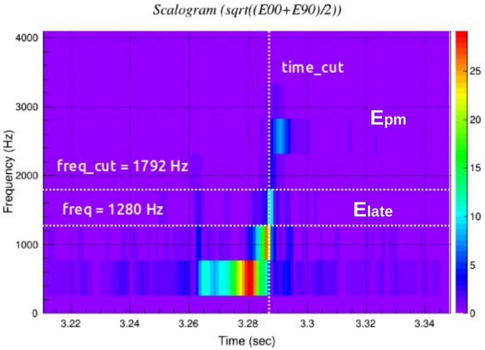


APR4-UM [3]
neutron star remnant

[1] Phys. Rev. D, 91:064027 [2] Phys. Rev. D, 94:064012 [3] arXiv:1604.03445v2 [astro-ph.HE]

Post-merger identification

First step of the analysis: identify post-merger on reconstructed event time-frequency map



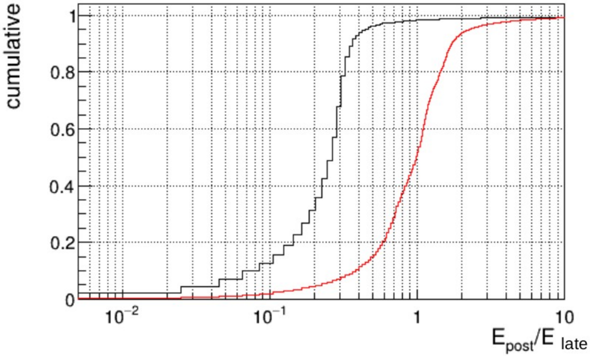
Many simulations within the same model, then study the distributions of various parameters computed from the reconstructed events.

First parameter: E_{pm}/E_{late}

with E_{late} energy in the frequency band 1280-1792 Hz.

Energy

Starting from populations of reconstructed post-merger GW signal, discriminate between prompt collapse to BH or formation of a NS remnant: decision threshold on $\frac{E_{PM}}{E_{late}}$



Black = prompt collapse to BH (reference: SHT-M2.2-I)

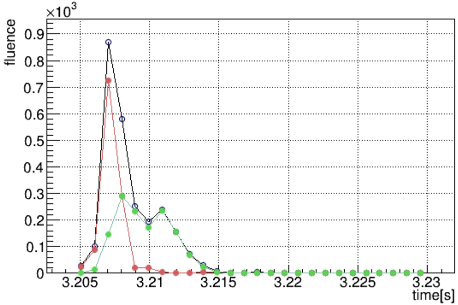
Red = NS remnant (reference: all other models, flat prior)

The E_{PM}/E_{late} cut controls false alarm probability and determines false dismissal probability.

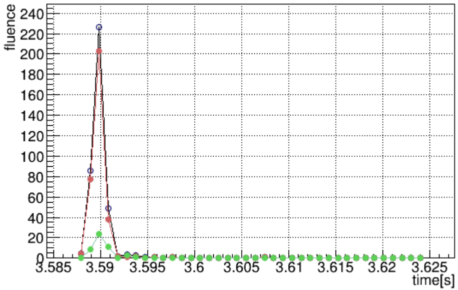
Luminosity profile

$$\mathcal{F} = \frac{dE}{dt}$$

Investigate it in different frequency regions: green = post-merger ($f > 1792$ Hz), red = $1280 < f < 1792$ Hz, black = total. Reconstructions from two sample events:



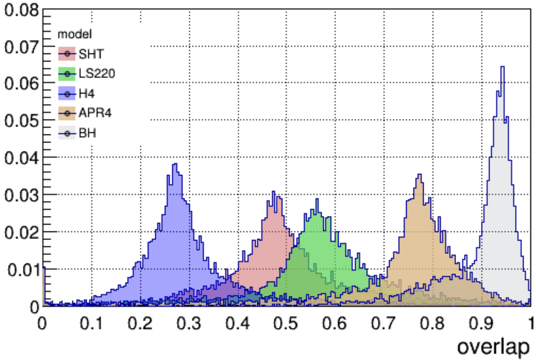
NS remnant



Prompt collapse to BH

Luminosity profile overlap function

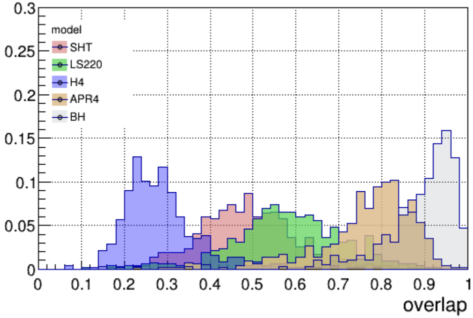
$$\mathcal{O} = \frac{\sum_i \mathcal{F}_3[i] \cdot \mathcal{F}_{pm}[i]}{\left(\sum_i \mathcal{F}_3[i]^2 \sum_i \mathcal{F}_{pm}[i]^2\right)^{1/2}}$$



Reference populations of four NS remnant models (color) and one BH prompt-collapse model (gray)

Luminosity profile overlap function

Events with signal to noise ratio between 55-65



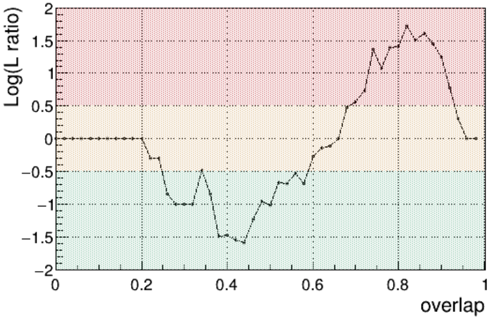
Reference distributions for different models:

Calibration of the method

Likelihood ratio

$$L_{ratio} = \frac{PDF(Model_i)}{PDF(Model_{ref})}$$

We choose a threshold $|Log(L_{ratio})| = 0.5$

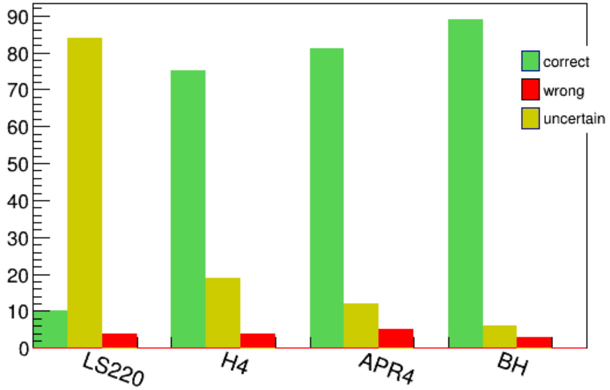


Luminosity profile overlap function

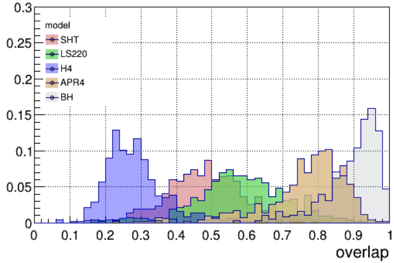
Simulating an observation: new simulation of $\sim$ 100 events with signal to noise ratio 55-65, SHT waveform

$$\mathcal{O} = \frac{\sum_i \mathcal{F}_3[i] \cdot \mathcal{F}_{pm}[i]}{\left(\sum_i \mathcal{F}_3[i]^2 \sum_i \mathcal{F}_{pm}[i]^2\right)^{1/2}}$$

Model exclusion results



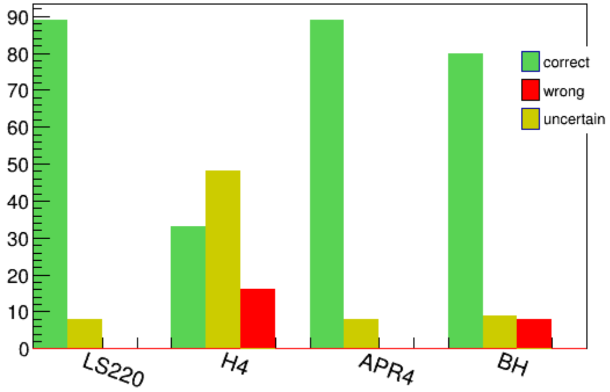
Reference distribution:



Prompt-collapse to BH is excluded very well, as models H4 and APR4.
LS220 uncertain.
Very few wrong assignments!

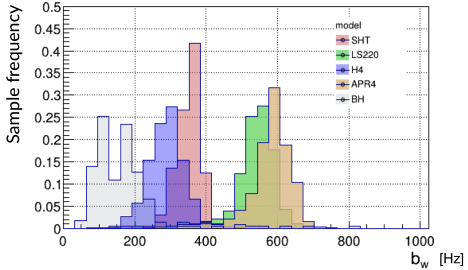
Spectral characterization

Simulating an observation Model exclusion results



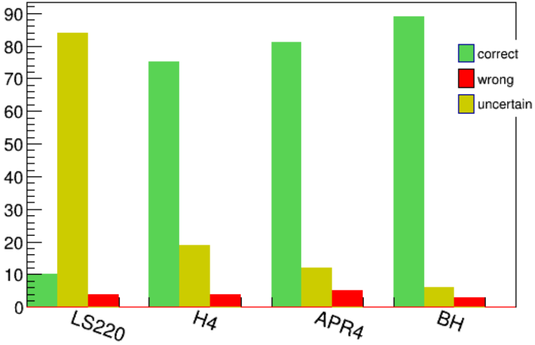
$$b_w = \frac{\sum_{i=1}^{N} f_{c,i}^2 en_i}{\sum_{i=1}^{N} en_i} - \left(\frac{\sum_{i=1}^{N} f_{c,i} en_i}{\sum_{i=1}^{N} en_i} \right)^2 .$$

Reference distribution:

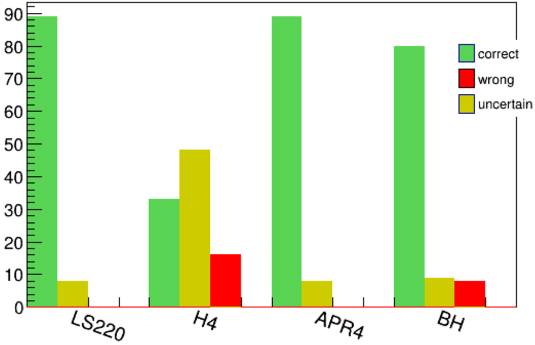


H4 is uncertain, but for LS220 and APR4 no wrong assignments!

Adding information



Overlap function



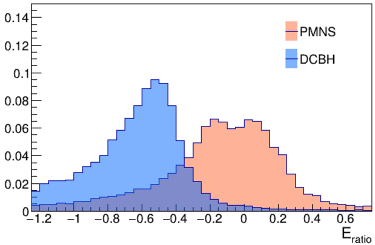
Energy-weighted bandwidth

The joint use of spectral parameters and luminosity profile can greatly enhance the capability to identify the EOS model

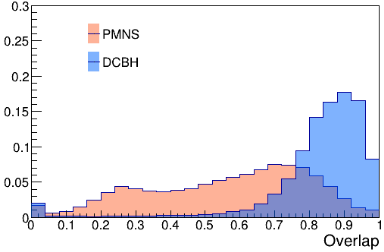
More developed study: add waveforms

- More systematic study: add waveform models, total 10, 3 expected to collapse promptly to a black hole
- **Aim**: after BNS merger, discriminate between prompt collapse to BH and delayed collapse to BH in which the merger outcome could be a massive NS remnant

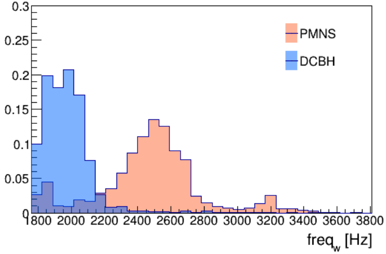
Testing for NS remnant



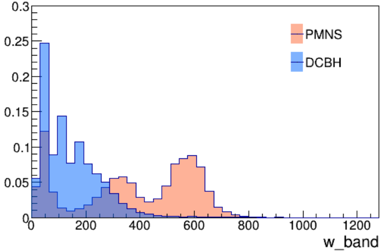
$E_{ratio} = log_{10}\left(\frac{E_{PM}}{E_3}\right)$



Luminosity profile overlap



Energy-weighted frequency



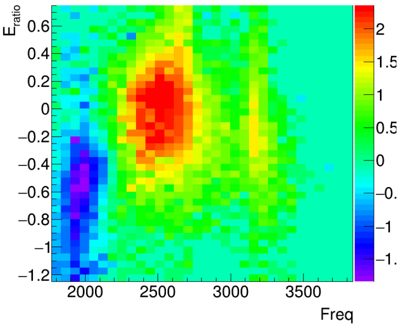
Energy-weighted bandwidth

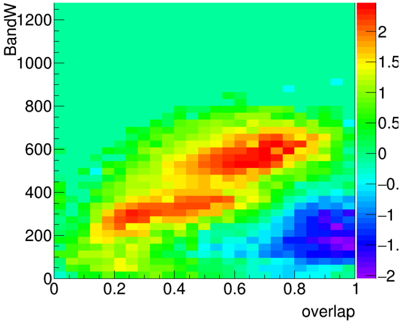
Procedure

Work on E_{ratio} *vs* $Freq_w$ and *BW vs overlap*. Likelihood ratio, define

$$z_1 = log\left[\frac{pdf\left(E_{ratio},\ Freq_w | NS\right)}{pdf\left(E_{ratio},\ Freq_w | BH\right)}\right]$$

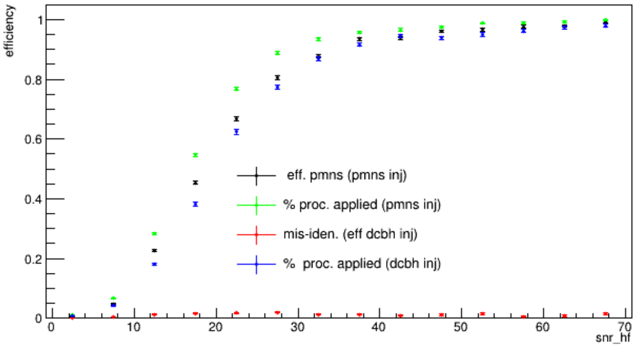
$$z_2 = log\left[\frac{pdf\left(BW,\ overlap | NS\right)}{pdf\left(BW,\ overlap | BH\right)}\right]$$





Red: formation of NS remnant scenario favored, Blu: prompt collapse to BH scenario favored

Procedure

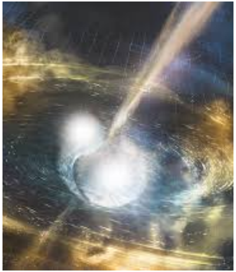


WORK IN PROGRESS

Example of efficiencies obtained setting as a cut to select the null hypothesis $(z1 \leq 0)||(z2 \leq 0)$. While the procedure is implemented on all the simulated events for every waveform, efficiencies are computed on a sub-sample of events ($\sim 15\%$).

Note: Injected waveforms include only late few cycles of inspiral. We characterize the signal with SNR_{HF}, the reconstructed signal SNR for frequency $> 768Hz$

Conclusions



- Pilot study to see if we can gain information about neutron stars equation of state
- Development of a new method for discriminating different remnant scenarios

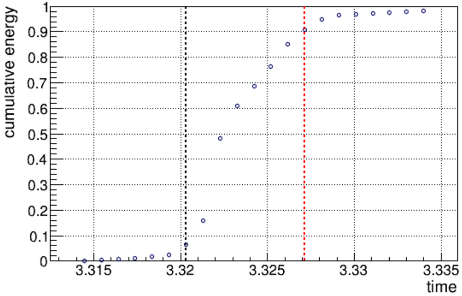
Future possible developments:

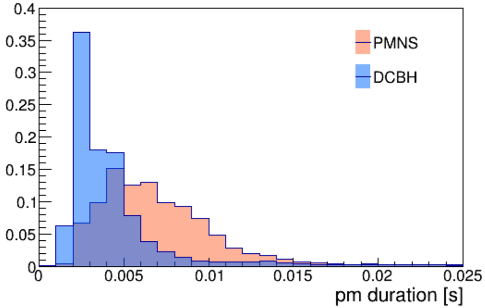
- Include other parameters we estimated, like time-duration or peak frequency of post merger signal
- Exploit the full detector network information (now our analysis is implemented on data projected only onto one detector)
- Possibly, more systematic study also on neutron star equation of state discrimination

Thank you for your attention

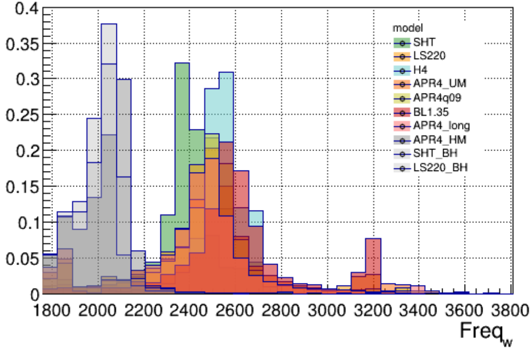
Extra 1: Post-merger duration

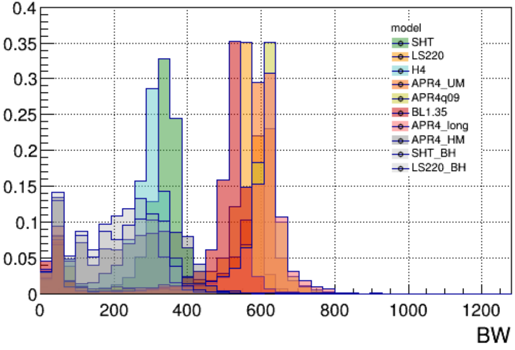
Time at which the cumulative energy distribution in the post-merger quadrant reaches 10% and 90%, called respectively $\mathbf{t_{10}}$ and t_{90}. We define $\Delta t = t_{90} - t_{10}$





Extra 2: Energy weighted frequency and bandwidth





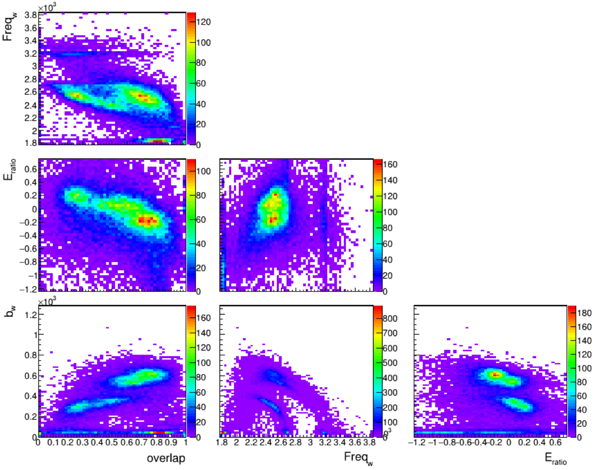
Extra 3: add waveforms

Model	M_b	M_∞	τ_{MNS} [ms]	f_{peak} [kHz]	M_{BH}	Ref.
SHT-M2.0-S	4.01	1.80	>9.4	2.66	...	[1]
SHT-M2.2-I	4.39	1.95	< 1	...	3.73	[1]
LS220-M1.5-S	3.12	1.41	7.7	3.17	2.67	[1]
H4-M1.5	3.04	1.40	12	2.67	2.47	[2]
APR4-UM	3.01	1.42, 1.29	SMNS	3.30	...	[3]
LS220-M1.7-I	3.46	1.54	< 1	...	2.98	[1]
APR4-HM	3.18	1.43	1	...	2.79	[3]
BL	2.95	1.35	> 20	3.17	...	[4]
APR4 1.35 Long	2.98	1.35	...	3.35	...	[5]
APR4-q09	2.98	1.42,1.28	SMNS	3.24	...	[6]

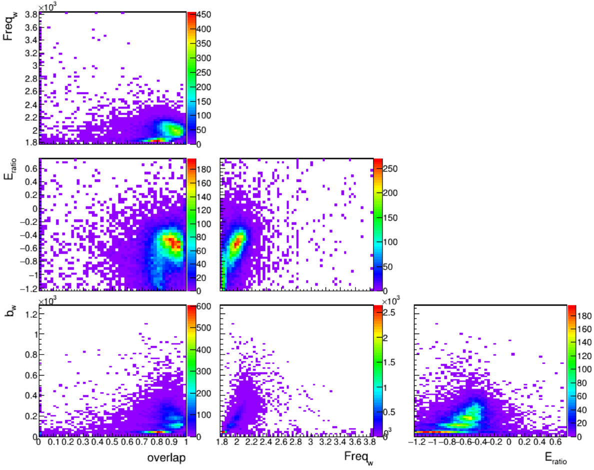
[1] Phys. Rev. D, 91:064027 [2] Phys. Rev. D, 94:064012 [3] arXiv:1604.03445v2 [astro-ph.HE]

[4] Phys.Rev.D, 98:043015 [5] arxiv:1904.10222 [6] arXiv:1701.08738 [astro-ph.HE]

Extra 4: Different scenarios

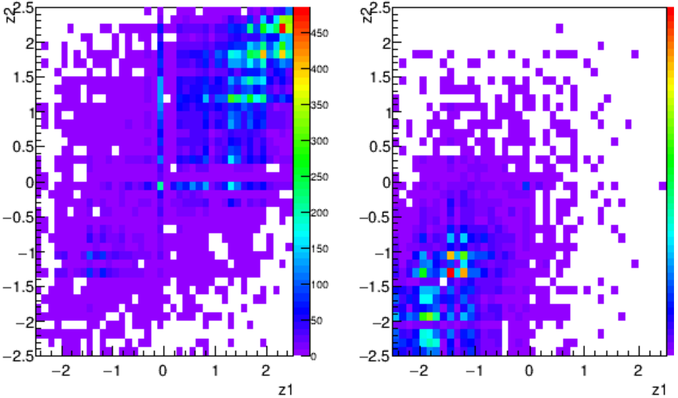


NS remnant



Prompt collapse to BH

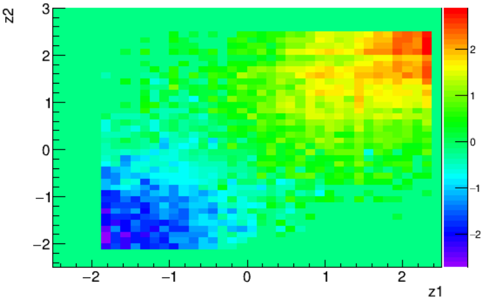
Extra 5: z1z2 for NS and BH



Extra 6: second level likelihood

Find the distribution of $z2$ *vs* $z1$ both for NS and BH cases, then define

$$z12 = log\left[\frac{pdf\,(z1, z2|NS)}{pdf\,(z1, z2|BH)}\right]$$



Decide a cut on z1 and z2 or a cut on z12 to discriminate the two scenarios.