Title: Exploring the phenomenology of black hole horizons using multi-modal gravitational wave observations

Speakers:

Series: Strong Gravity

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Abstract: At the event horizon of a black hole, gravity reaches its most extreme behaviour. Studying the dynamics of event horizons is key to understand gravity in is ultra-strong field regime and investigate the most fundamental properties of black holes. Black hole collisions provide a unique scenario to observe event horizons in a highly distorted and violently changing regime, which leads to a vast collection of phenomena that has not yet been detected by Advanced LIGO and Virgo. In this talk I will discuss the imprint that these phenomena leave in the gravitational-wave emission of black hole collisions and what it can teach us about the properties of black hole horizons.

Exploring the phenomenology of black hole horizons using multi-modal gravitational wave observations

Juan Calderón Bustillo

Strong Gravity Seminar

Perimeter Institute, March 2019

OzGrav

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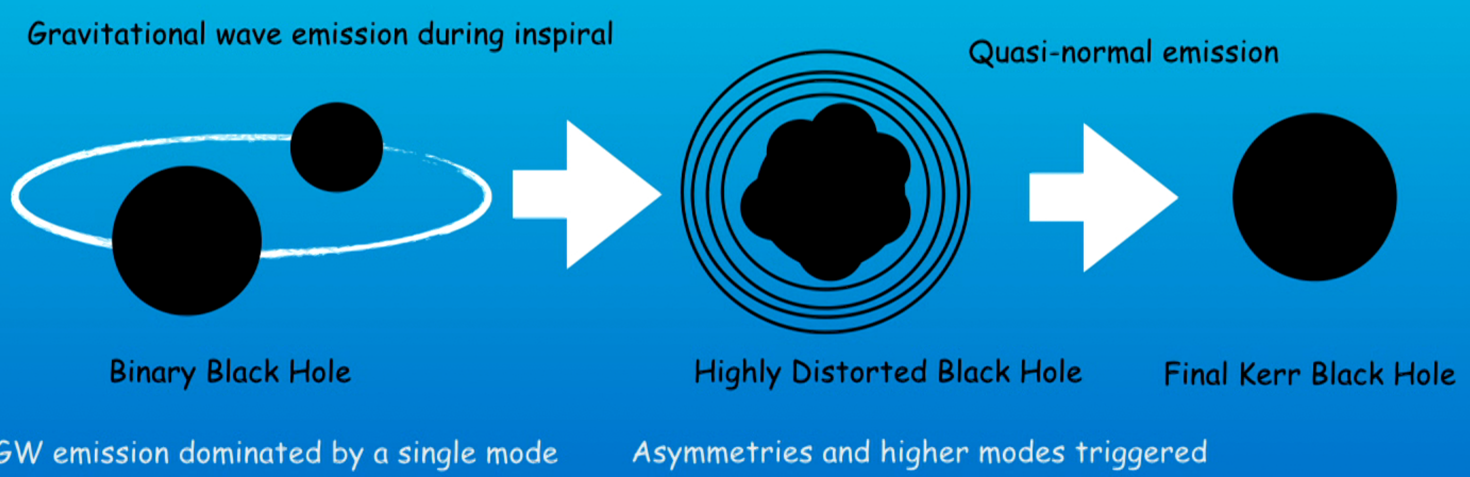
Outline

- Higher gravitational wave modes from binary black holes
  - I: What are these?
  - II: Where to find them?
- How do higher modes help us? Parameter estimation of binary black holes
  - Effect on GW170729: the "heavy" binary black hole (soon in arXiv!)
- Exploiting waveform morphology to spot strong field effects:
  - I: Black Hole Kicks: JCB+ Phys. Rev. Lett. 121, 191102 (2018)
  - II: Multi chirps: also coming soon
- Conclusions

Binary black hole mergers

- Inspiral: large distances, "weak" emission, fairly Kerr black holes.
- Merger: highly distorted horizons, study out of equilibrium horizon dynamics, strong field.
- Ringdown: quasinormal modes, test the no hair theorem.



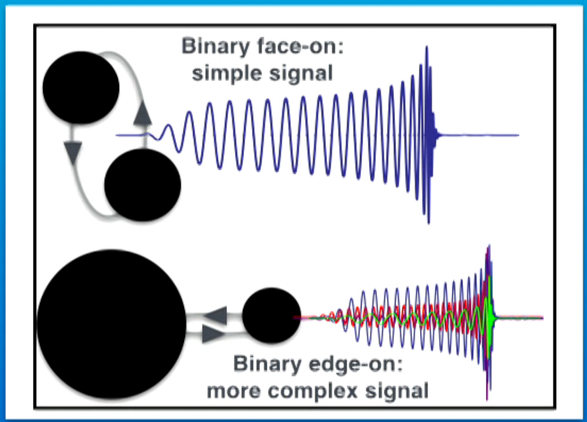
The Binary Black Hole Orchestra: higher modes

- The GW emission of a BBH consists on a superposition of GW modes hlm. How they are perceived depends on the observer location.

$$h = \sum_{\ell,m} {}^{-2}Y_{\ell,m}(\iota,\phi) h_{\ell,m}(t; m_1, m_2, \ldots)$$

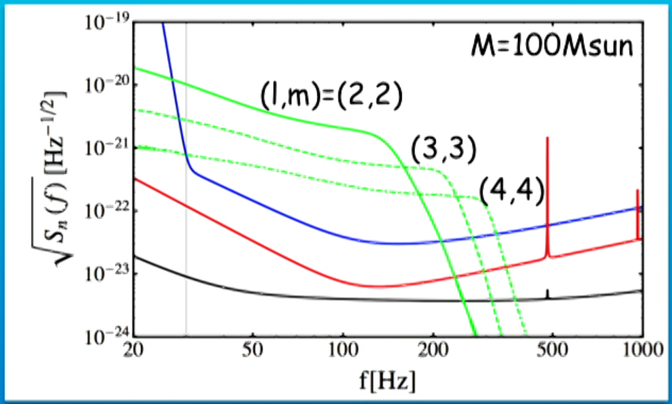
Location of the observer

Intrinsic properties of the source (Instruments <—> modes)

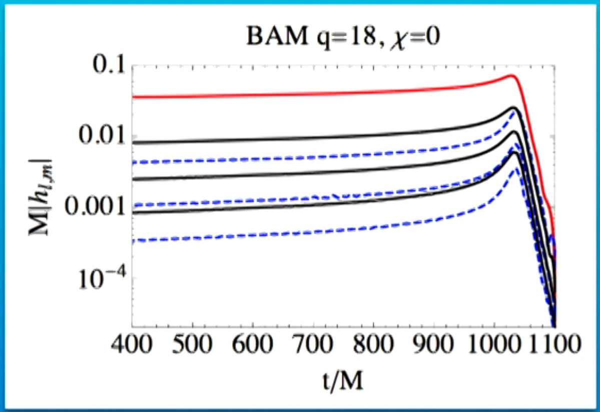


Higher modes from binary black holes

- Higher modes are stronger (in the detector band) for high mass sources



JCB+ Phys. Rev. D 93, 084019 (2016)

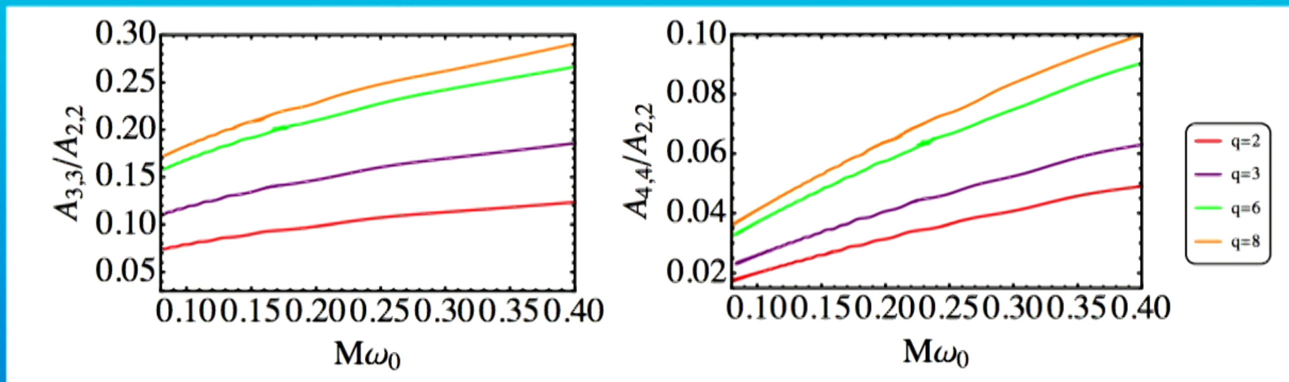


JCB+, arXiv:1501.00918 (2015)

- Frequency of each hlm(t) mode is proportional to m and to 1/M_total
- (2,2) mode dominates (by far) during the inspiral stage. Higher modes become relevant at merger.

Higher modes from binary black holes

- Higher modes are stronger for unequal mass binaries (and negative spins)

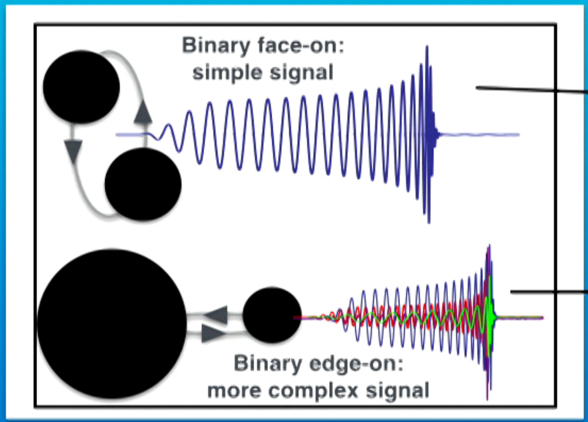


JCB+ Phys. Rev. D 93, 084019 (2016)

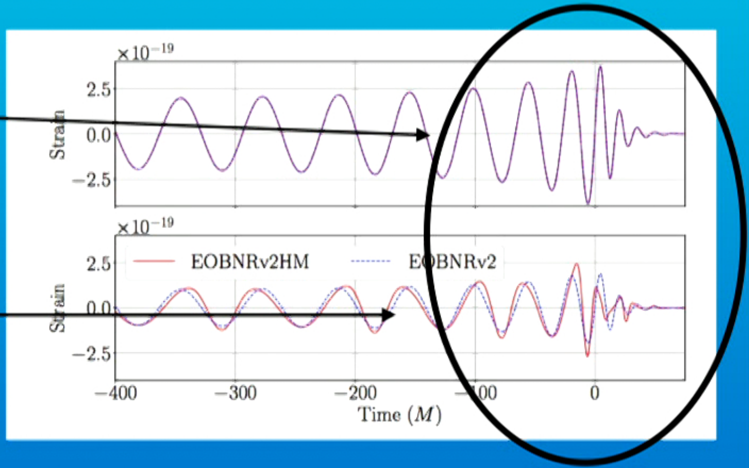
- (2,2) mode dominates (by far) during the inspiral stage. Higher modes become relevant at merger.
- Their magnitude grows as the masses get more unequal

Higher modes from binary black holes

- Almost irrelevant for equal mass sources and low mass ones
- Importance grows with mass ratio, total mass and inclination (close to the orbital plane)
- Spins, precession and eccentricity also triggers them.



Overlap between full signal and (2,2) mode as function of binary orientation



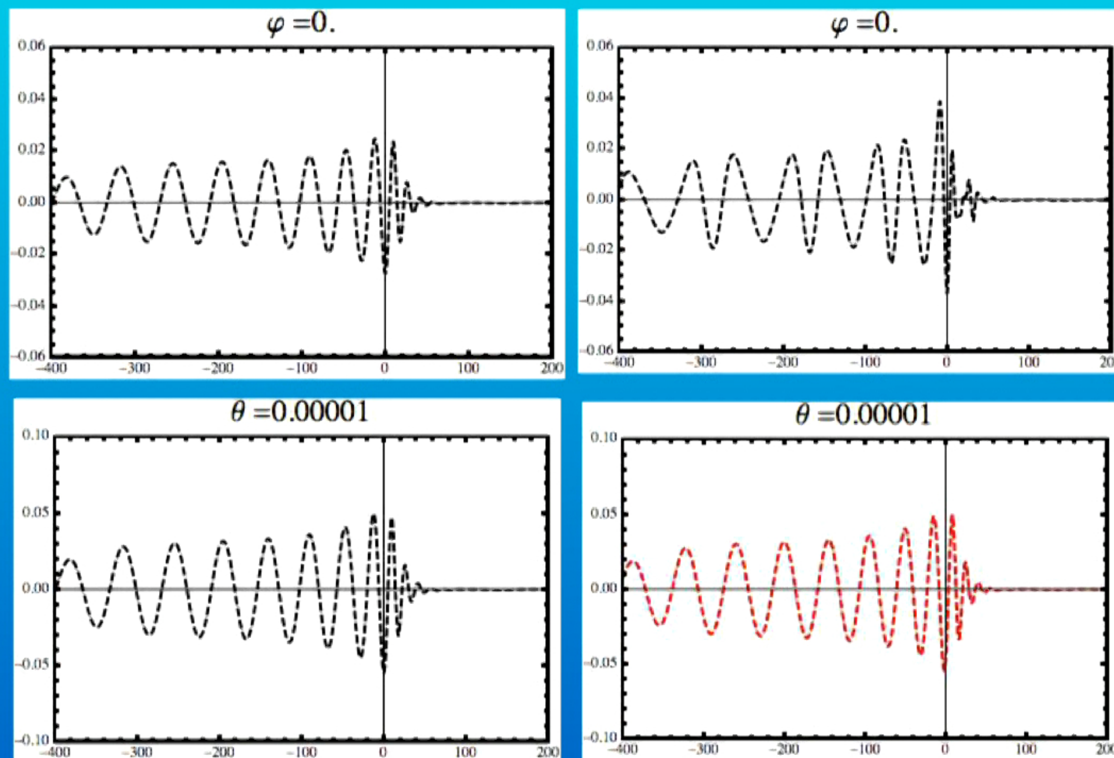
Effect stronger toward the end of the coalescence, when the binary is edge-on

The information in the higher order modes

2,2 mode | **All modes**

Azimuth impact (edge-on)

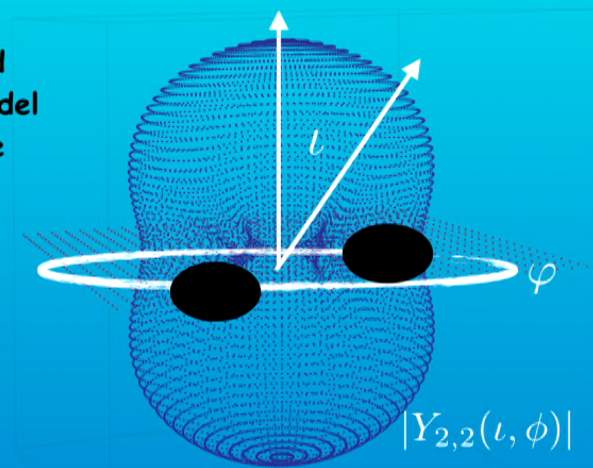
Inclination impact

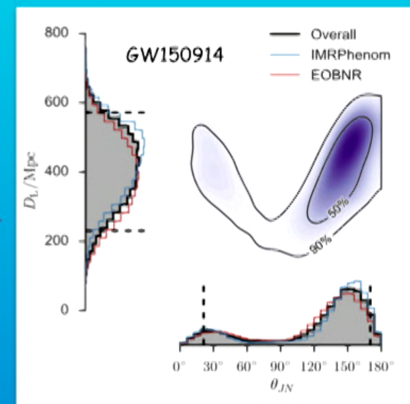


Breaking parameter degeneracies

Standard GW templates used for parameter estimation model only the dominant (2,2) mode

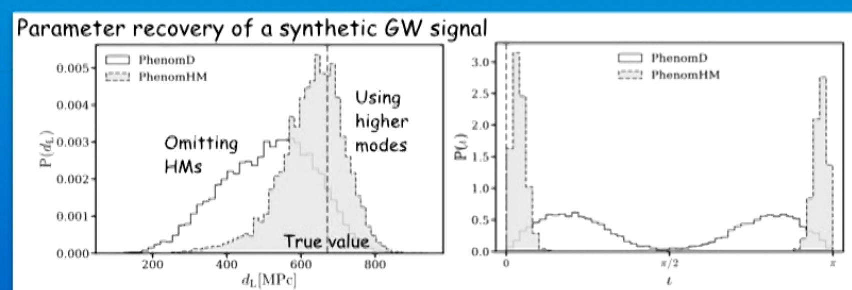
<u>Degeneracy</u>:
Distance <—>Inclination





LIGO+Virgo: Phys. Rev. Lett. 116, 061102

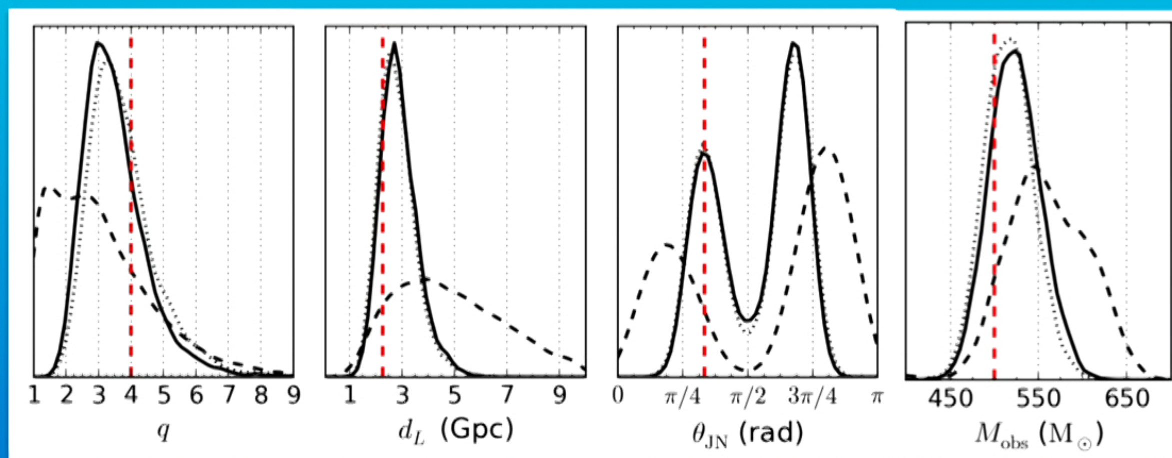
Higher modes make signal morphology depend on the inclination: better measurement



London +, Phys. Rev. Lett. 120, 161102 (2018)

Improving parameter estimation

The extra information provided by higher modes helps to identify the parameters of the binary. Furthermore, their omission can lead to parameter biases (Varma + '14, JCB + '15).

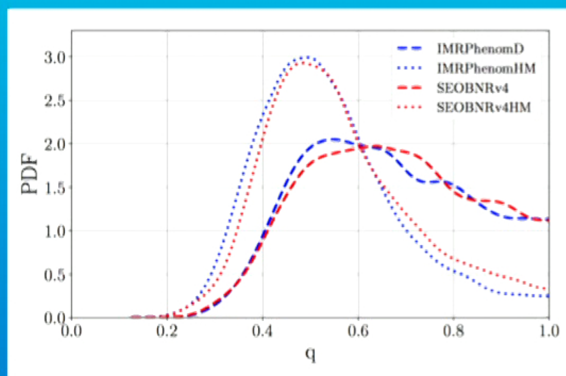


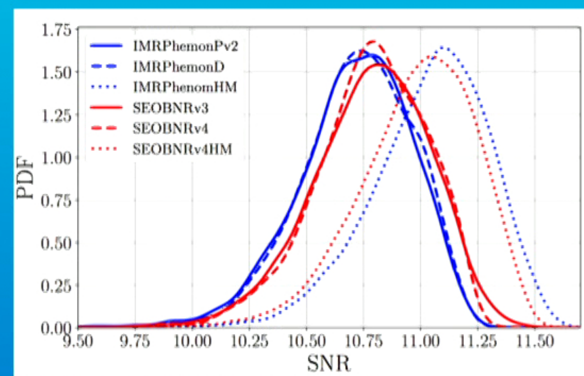
Graff et al '15

Parameter recovery of a signal emitted by a 400+100 Msun binary. Including higher modes (solid) and omitting them (dashed)

Impact on real observations: GW170729

- GW170729 is the heaviest binary black hole detected by Advanced LIGO
  - Standard PE reports a total mass of ~85Msun (LIGO + Virgo, O2 Catalogue)
  - Most reasonable candidate for observing higher modes

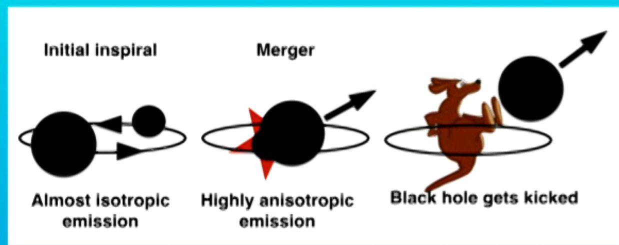




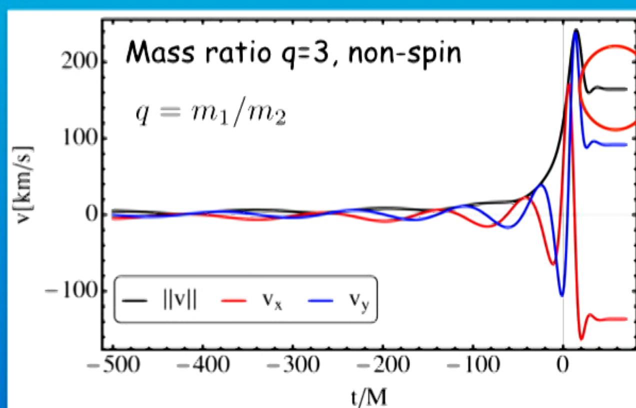
Chatziioannou + "On the properties of the heavy binary black hole GW170729", in prep.

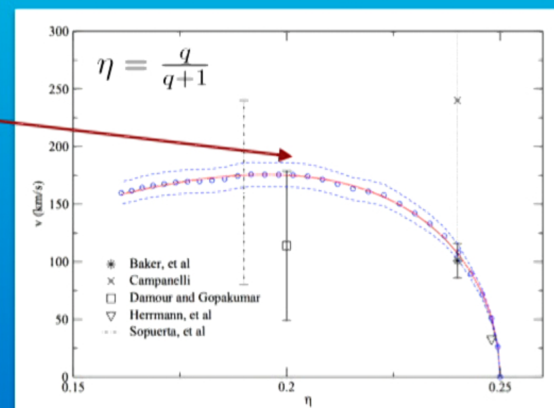
- Stronger preference for unequal masses
- We discard equal-mass at 90% confidence
- Slight increase of the SNR
- Not inconsistent with noise
- Also: Reduction of distance, increase of inclination, larger primary mass. Look at formation scenarios

Strong field phenomena: black hole kicks



- Interaction of GW modes leads to an **anisotropic GW emission** —> Net momentum emission
- The remnant black hole acquires a **characteristic recoil velocity or "kick"**





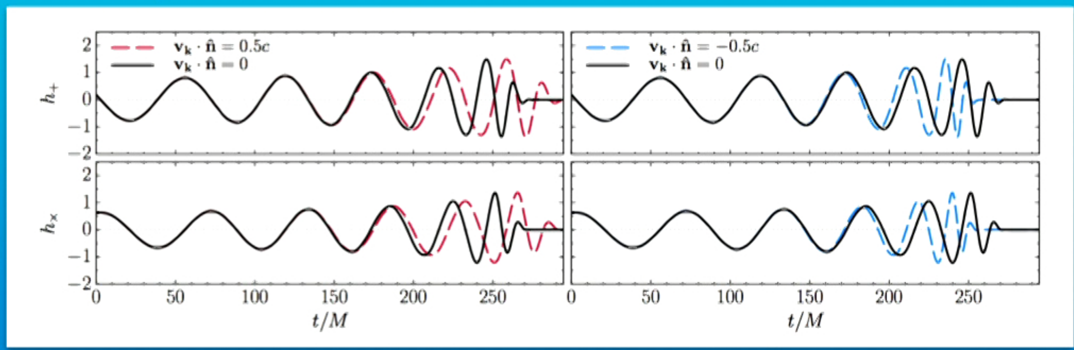
Gonzalez + 2007

- Final black hole inherits a recoil velocity or "kick".
- The kick is depends on the **total power emitted** and the size of **higher modes (anisotropy)**.

Kicks and Doppler shifts

- Incorporate kick effect to waveform models via Doppler shifts in the observed signal.
- Effect incorporated to 2,2 mode.

Away from Earth: red shift   Towards Earth: blue shift



Gerosa & Moore, Phys. Rev. Lett. 117, 011101 (2016)

Kicks and waveform morphology

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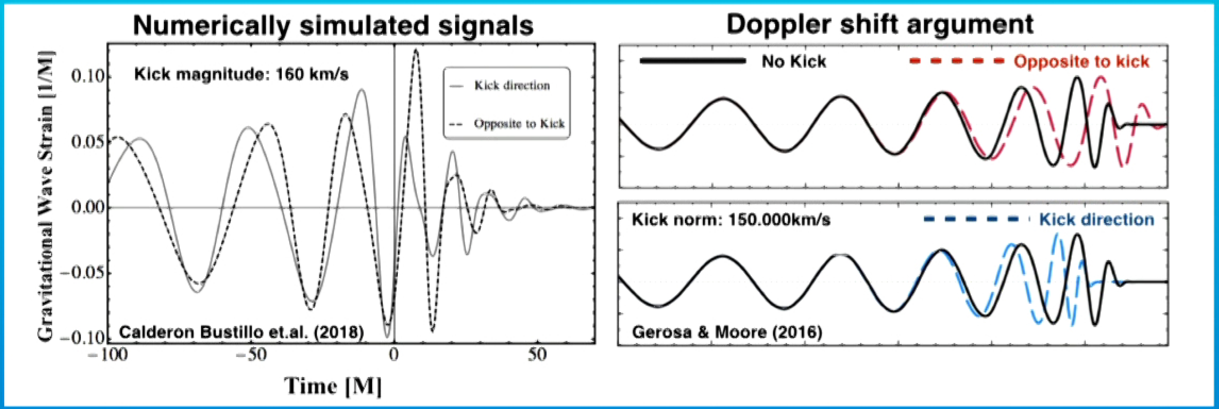


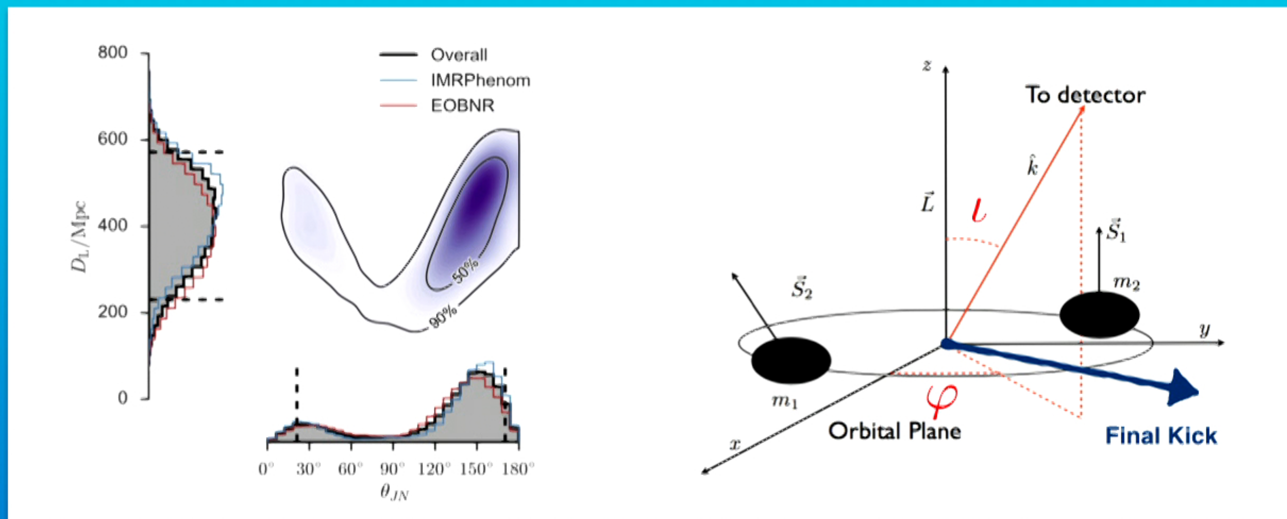
JCB+ (Phys. Rev. Lett. 121, 191102)

Gerosa & Moore, Phys. Rev. Lett. 117, 011101 (2016)

- **Kick effect is encoded in the higher modes:** no need to impart artificial Doppler shift. Imprint is much more dramatic than a simple Doppler shift.
- **Very subtle effect:** measure kicks of 500km/s with LISA.
- We exploit higher modes: can measure ~125km/s with Advanced LIGO.

Defining a reference frame

- Measuring a kick amounts to measuring the intrinsic parameters of the binary (magnitude) and its orientation (direction with respect to observer)



LVC+ Phys. Rev. Lett. 116, 241102 (2016)

- Location of the observer around the binary is defined by two angles:

  Inclination: ι Azimuth: φ

- ι is usually reported for GW observations but φ is treated as a nuisance parameter: lack of clear physical meaning

Defining a reference frame

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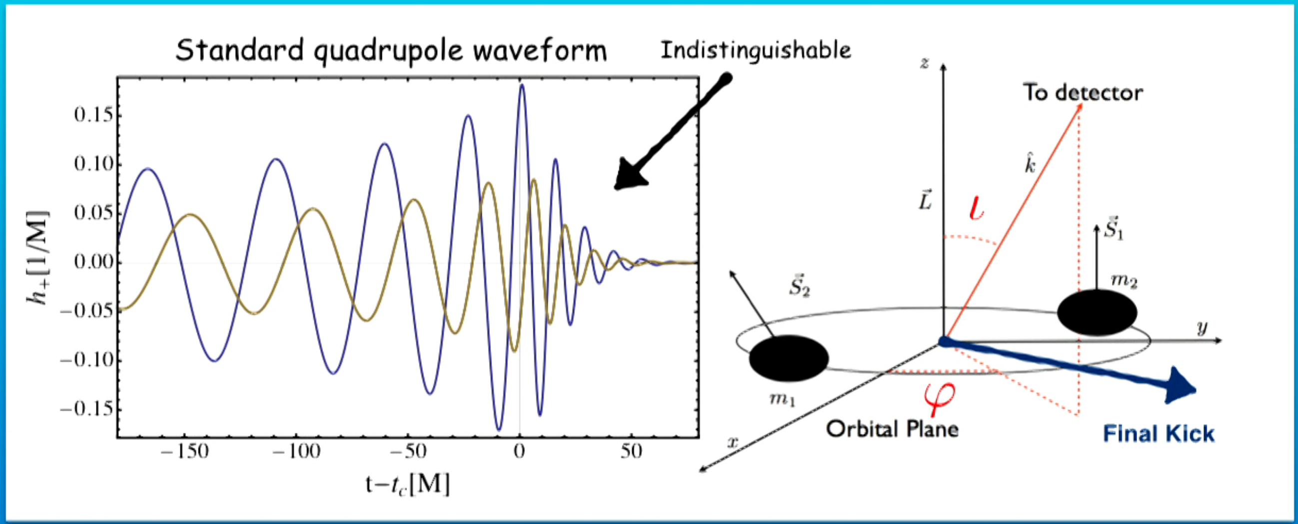

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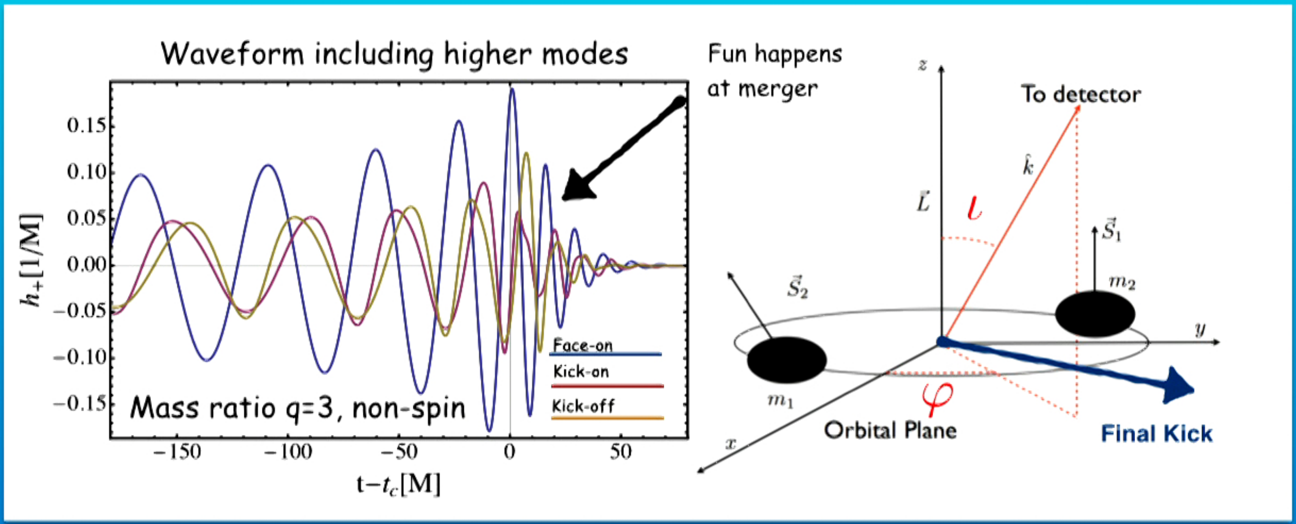

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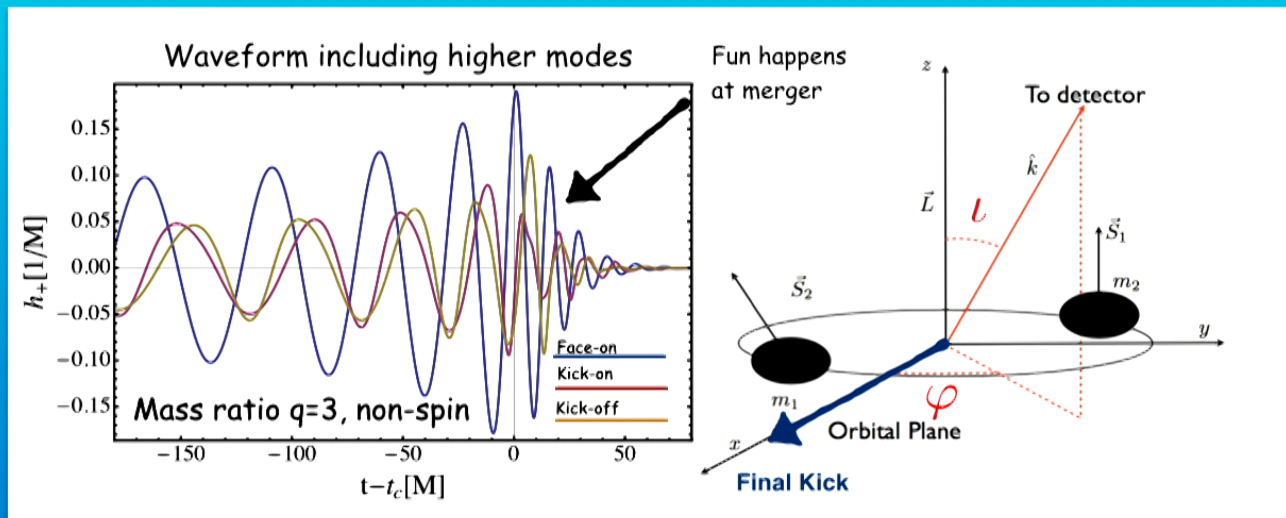
The “kick” frame

- Rotate our waveforms so that the origin of φ denotes the direction of the kick



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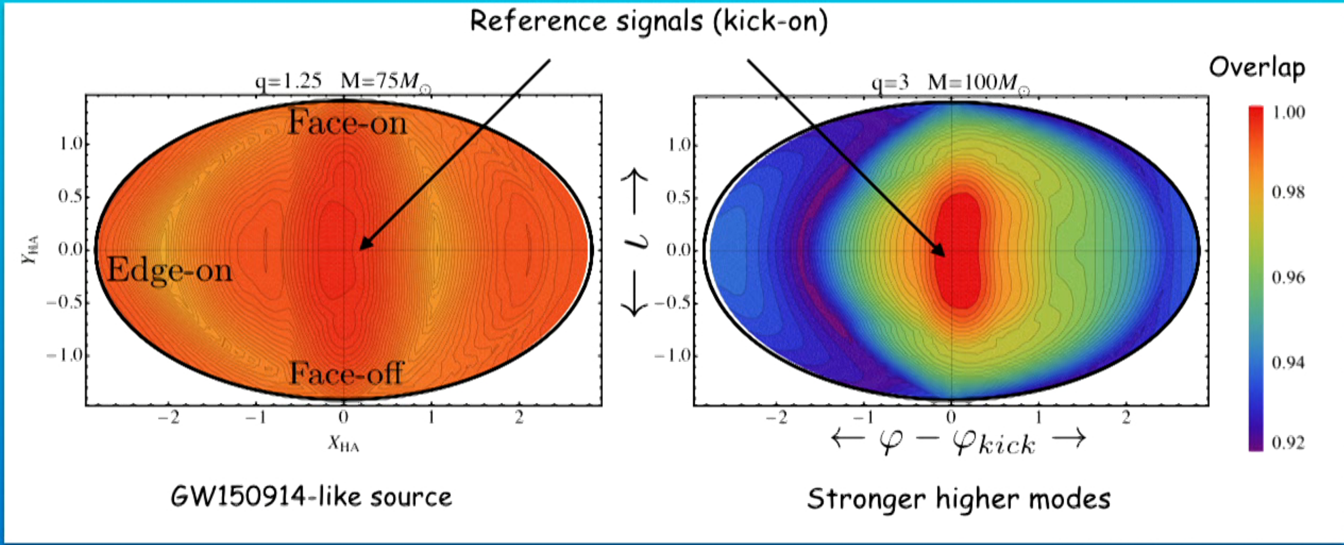
Resolving the orientation of the source

Measuring the orientation of a binary. Check how similar a signals emitted at arbitrary orientations are to a reference one.



JCB+ (Phys. Rev. Lett. 121, 191102)

Orientation is better resolved when higher modes are strong

- Overlap between k=160km/s and no-kick: ~0.92 ← Not a subtle effect
- Overlap between k~1000km/s and no-kick (Doppler shifts): ~0.9999X (Need LISA to see this)

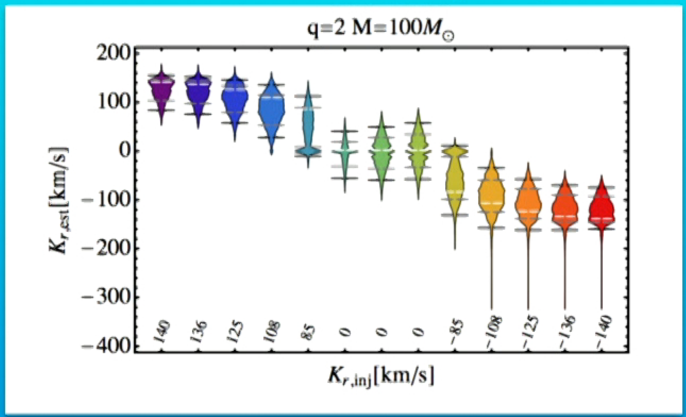
Measurement of kick projection

Kick projected onto line of sight $K_r = K \cos\alpha$

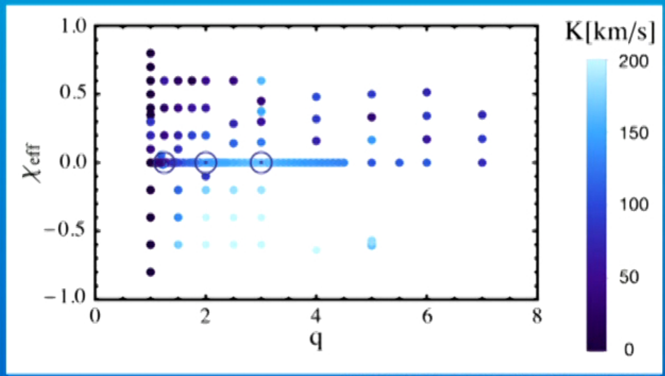
Kick magnitude: from masses and spins estimates

From source orientation

$$cos\alpha = cos(\pi/2 - \iota)\cos(\bar{\varphi})$$



- Better accuracy when the injected kick is large.
- Can rule out zero kick for Kr ~125km/s



- Perform parameter estimation on a grid of Numerical Relativity simulations. Georgia Tech catalogue of NR simulations (Jani+ 16)
- Application to real data will require continuous waveform families (Cotesta+ 18, London+17)

JCB+ (Phys. Rev. Lett. 121, 191102)

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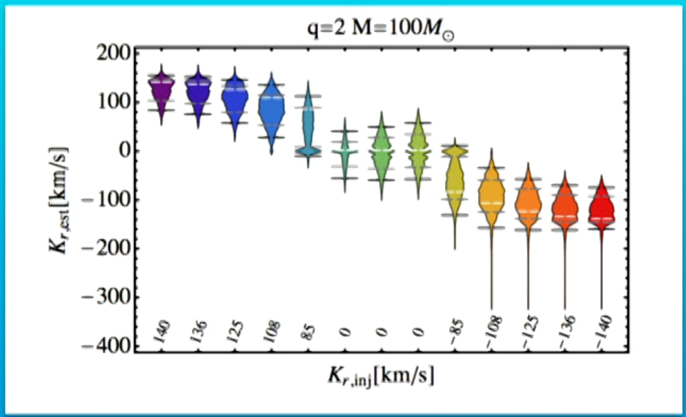

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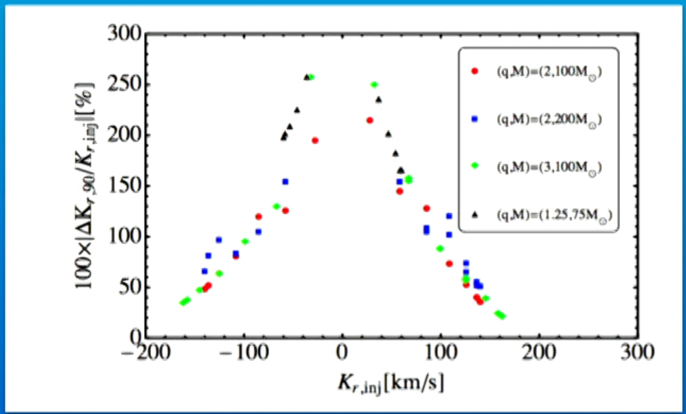
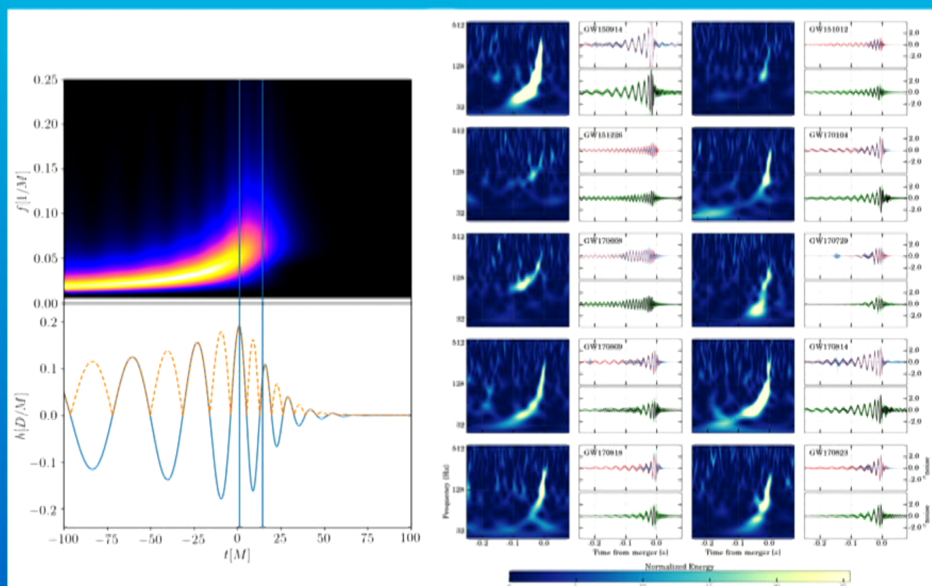


- Better accuracy for larger q and M due to the stronger higher modes. (Pekowsky+'13, JCB + '15,'16, Varma +'14,'17)
- Large uncertainties for GW150914-like source: **not likely to measure a non-zero kick with current BBH observations.**

JCB+ (Phys. Rev. Lett. 121, 191102)

Gravitational waves are simple......

- Inspiral: frequency rises monotonically and slowly. Reflects the increasing orbital frequency.
- Merger: frequency ramps-up: black hole speeds comparable to that of light
- Ringdown: frequency stays constant as the final black hole settles.



All BBH events consistent with this chirp morphology.

We conclude that the higher mode content of the GW signals is weak enough that models including them are not strongly preferred given our data. This is consistent with the fact that the contribution from higher modes is highly suppressed for signals emitted by binaries with mass ratio $q \gtrsim 0.5$, total masses $\lesssim 100M_{\odot}$, and weak support for edge on inclination $\theta_{JN} = 90°$, as is the case for the observed BBHs [239, 240]. Our results agree with those in

LIGO-Virgo O2 Catalogue: arXiv:1811.12907v1

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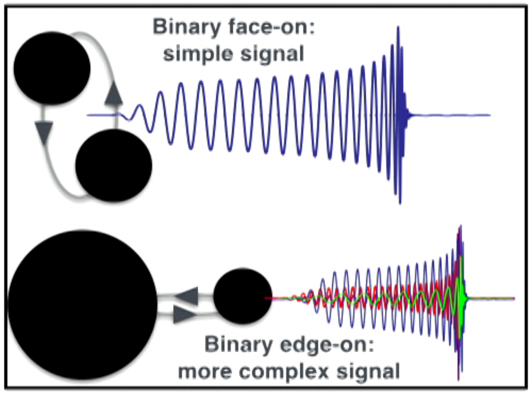
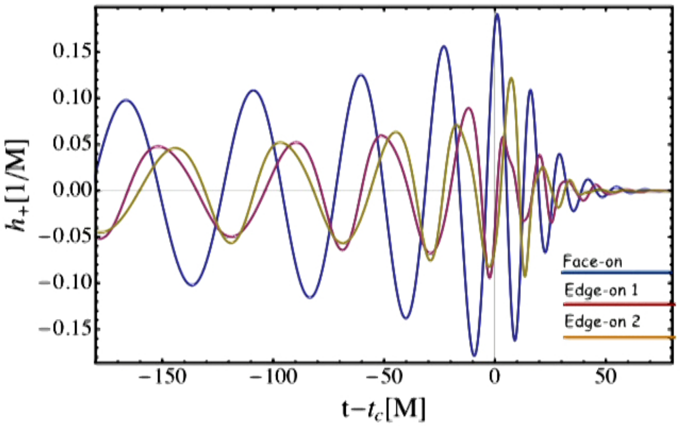
.... but not always

- Simple morphology is due to the signal being dominated by one GW mode
- When the source is edge-on, several modes impact the signal
- Higher modes make morphology depend strongly on the orientation of the source (or observer location)

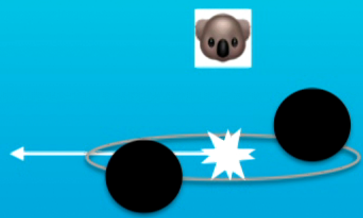


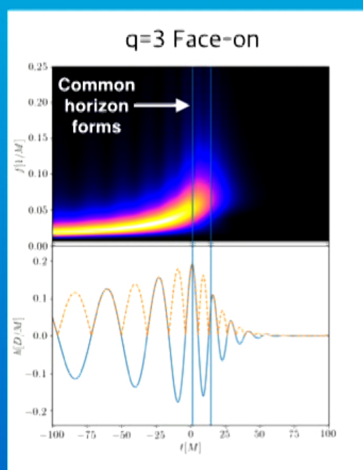


Mass ratio q=3, non-spin

Standard signals: the chirps

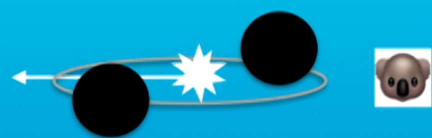
- Monotonic increase in frequency: reflects the increasing orbital frequency.

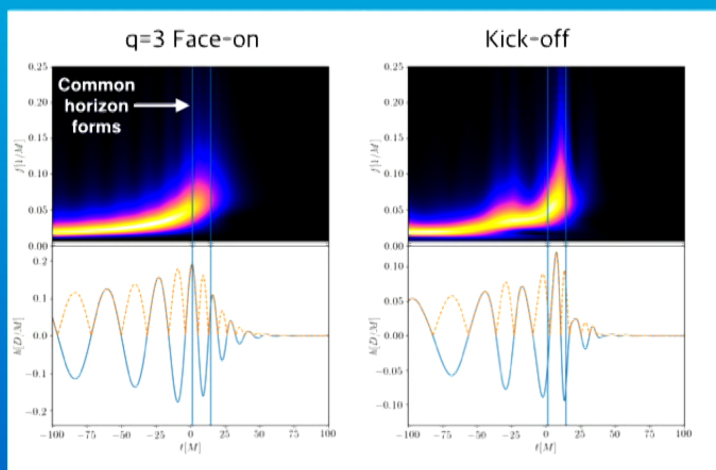




Let's explore other orientations

- Monotonic increase in frequency: reflects the increasing orbital frequency.
- Seems not to quite work for edge-on binaries





Mass ratio q=3, non-spin. GT0453

Let's explore other orientations

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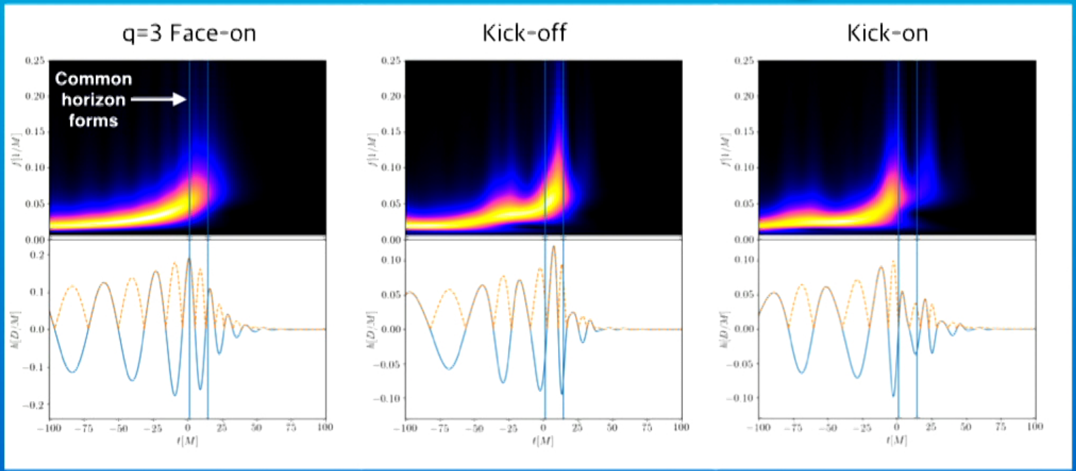
- A second frequency peak arises in some cases, after the final horizon has formed.



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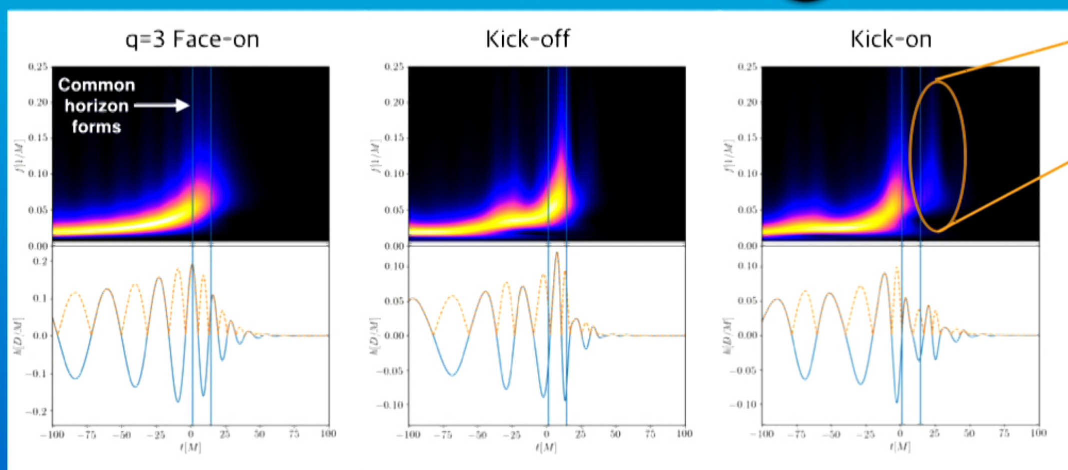

Mass ratio q=3, non-spin. GT0453

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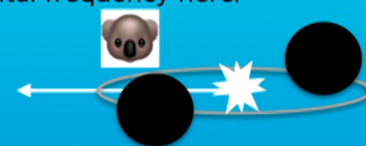
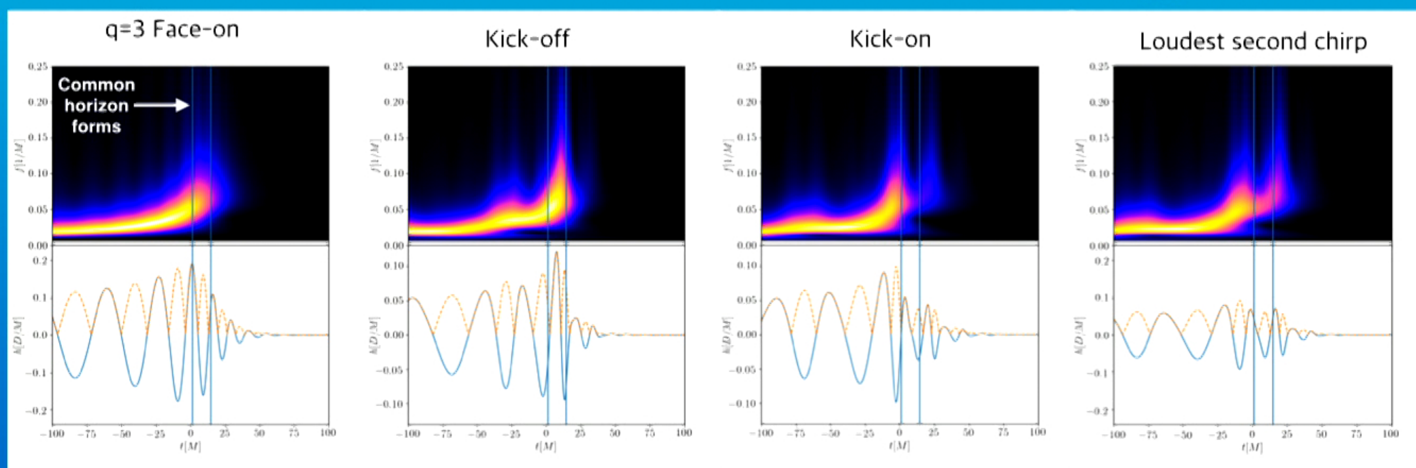
Double chirps!

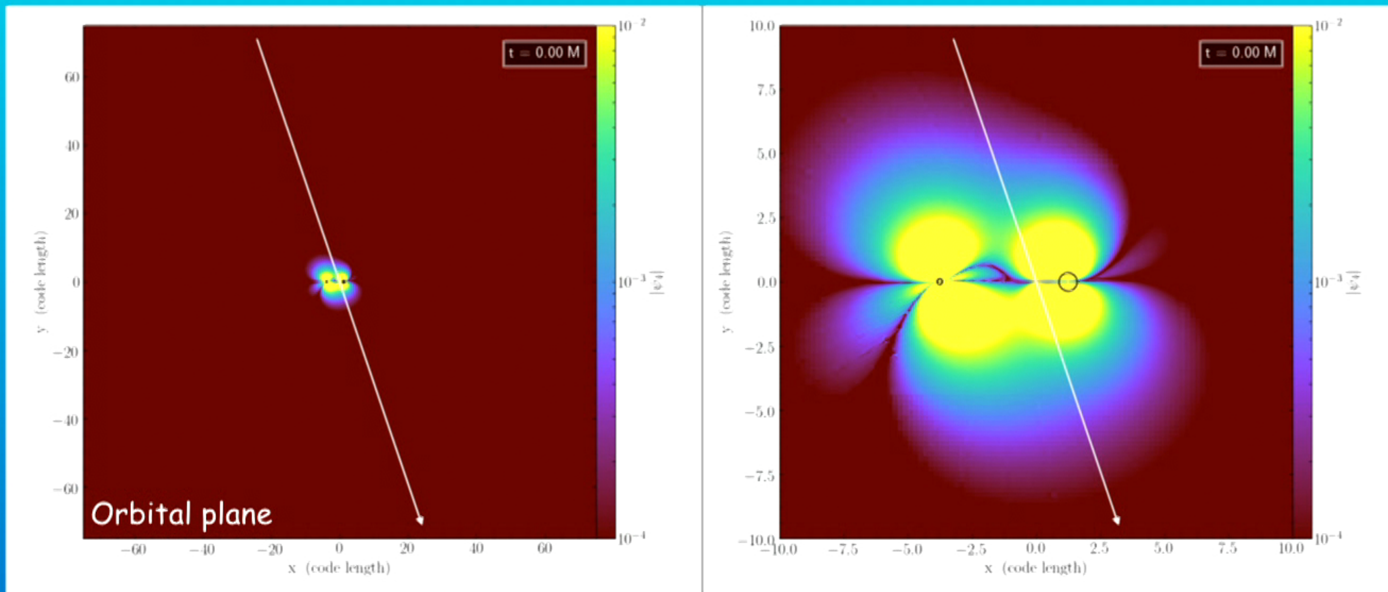
- A second raise of the frequency (chirp), and subsequent ones visible from the orbital plane (edge-on)
  - Differences in amplitude expected due to momentum conservation, what about frequency?
  - Second chirp happens after the common horizon has formed: no orbital frequency here.





Mass ratio q=3, non-spin. GT0453

Why double chirps: looking into the simulations

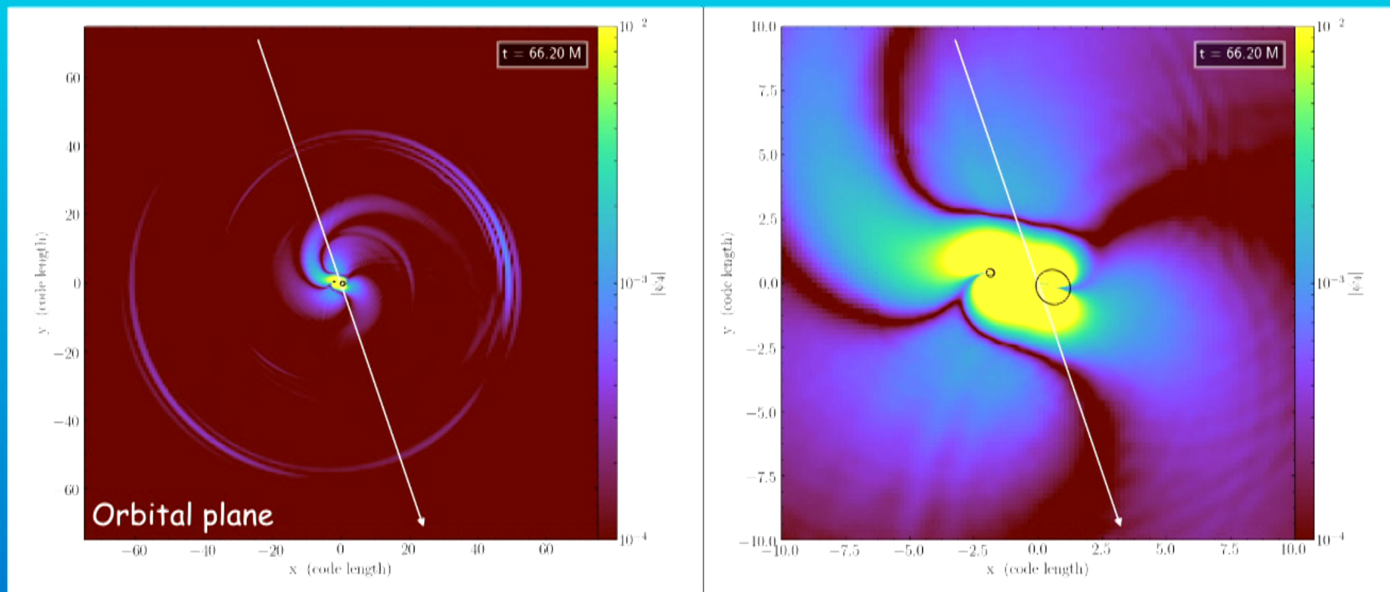


Simulation by Chris Evans (Georgia Tech)

Color code: $\psi_4 = \frac{d^2 h(t)}{dt^2}$

Newman - Penrose Scalar

Why double chirps: looking into the simulations



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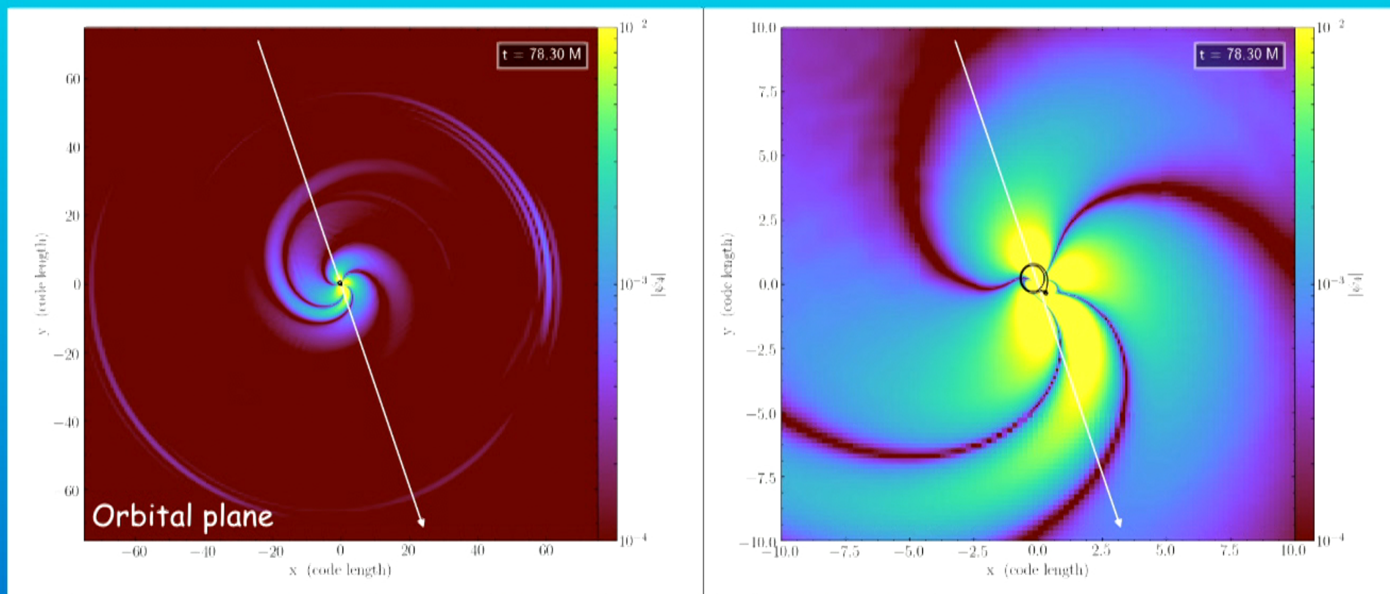

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Newman - Penrose Scalar

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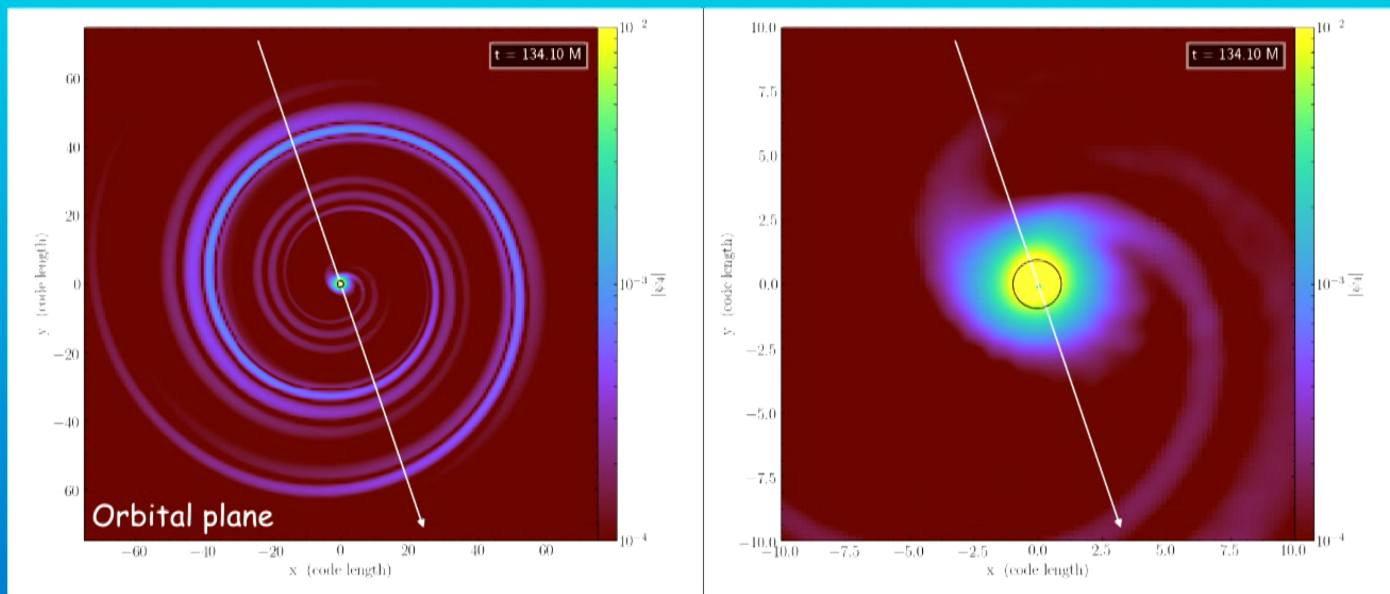

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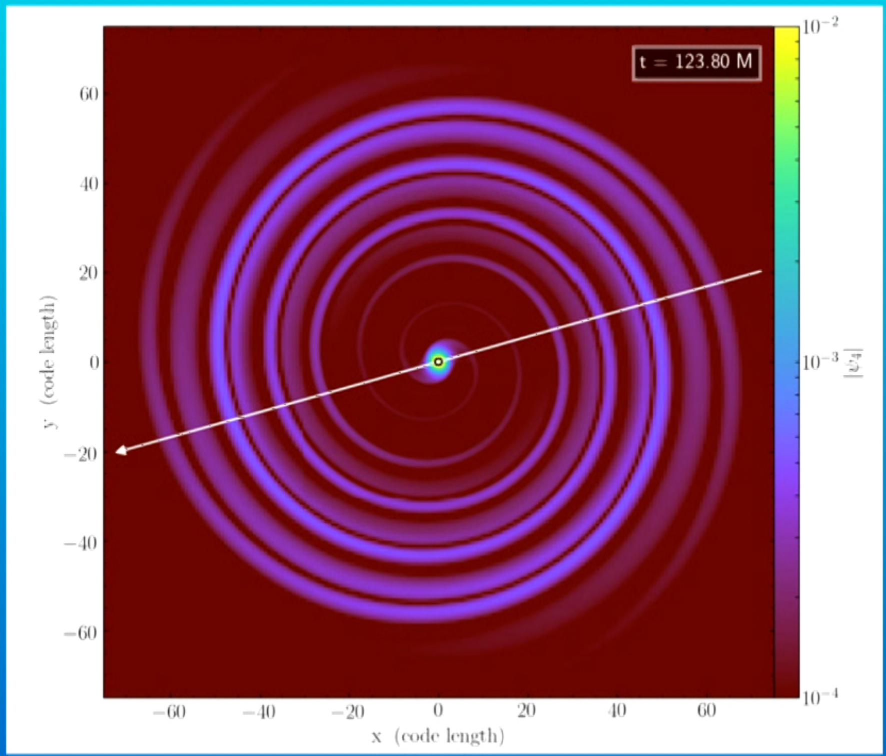
Newman - Penrose Scalar

Equal mass case: no double chirps



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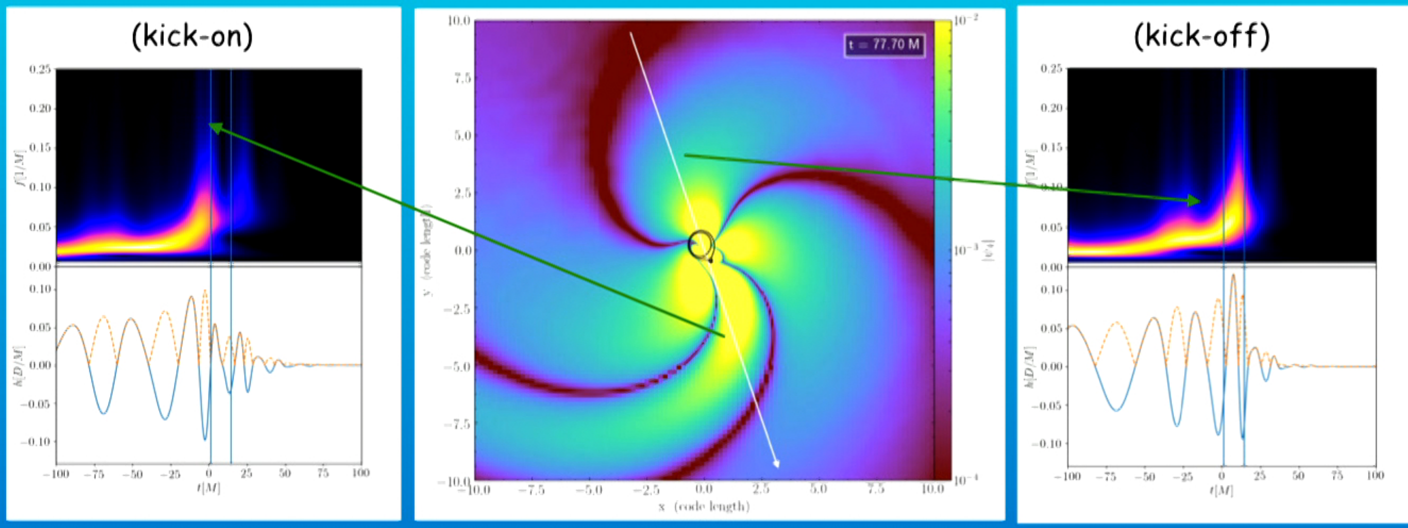
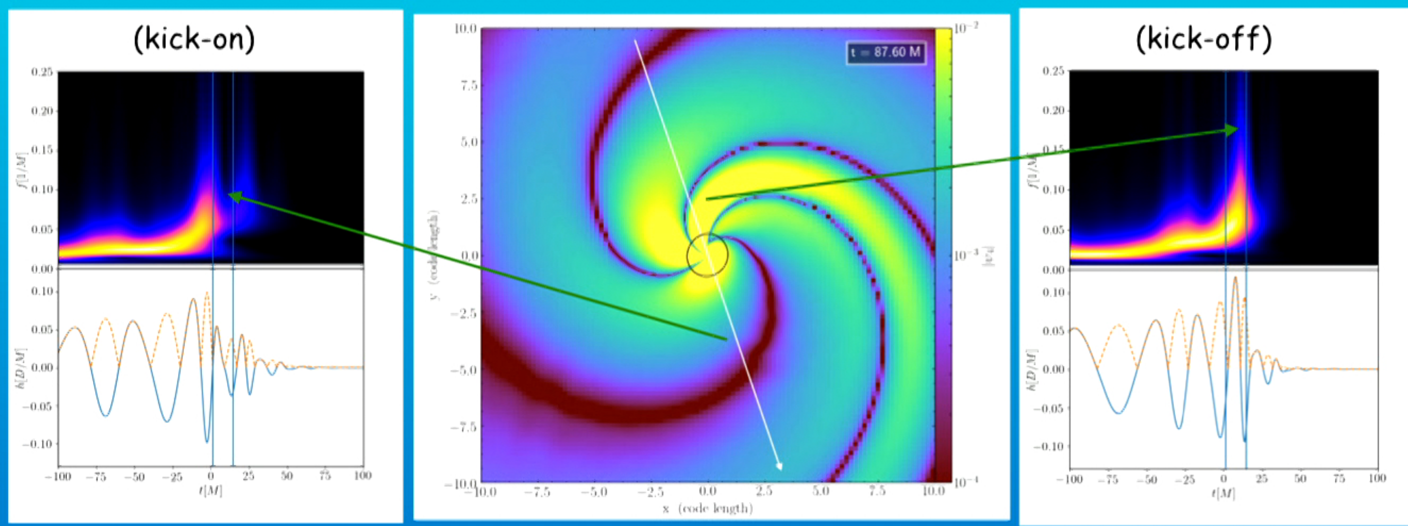
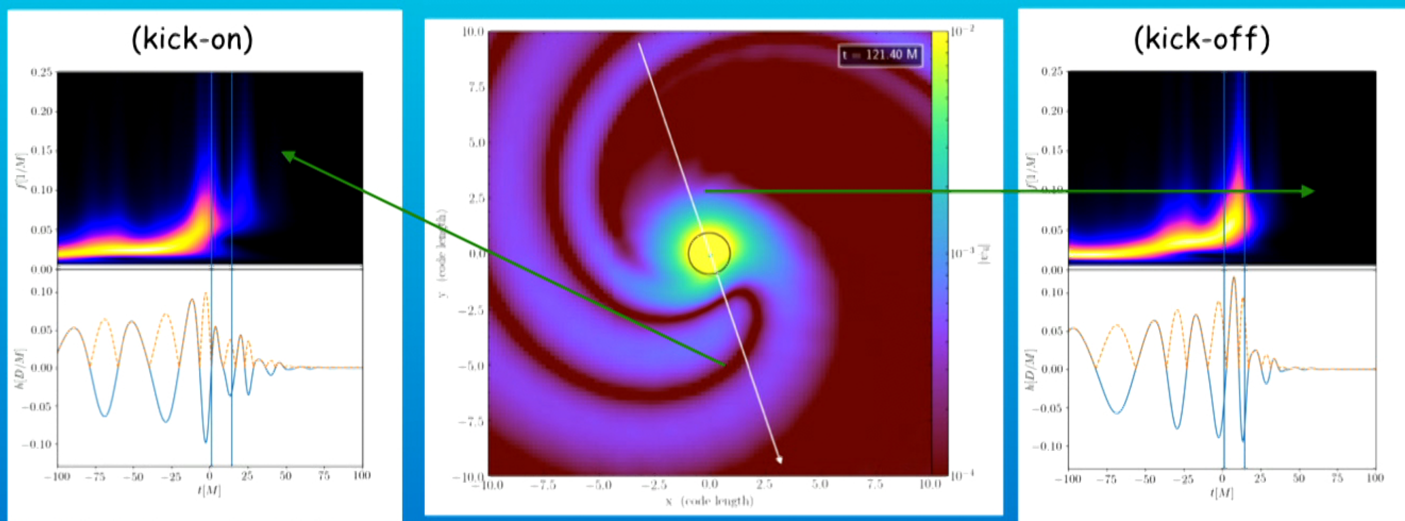
Kick-on vs. Kick-off observer



Kick-on vs. Kick-off observer



Kick-on vs. Kick-off observer



Strong Gravity Seminar
Perimeter Institute, March 2019

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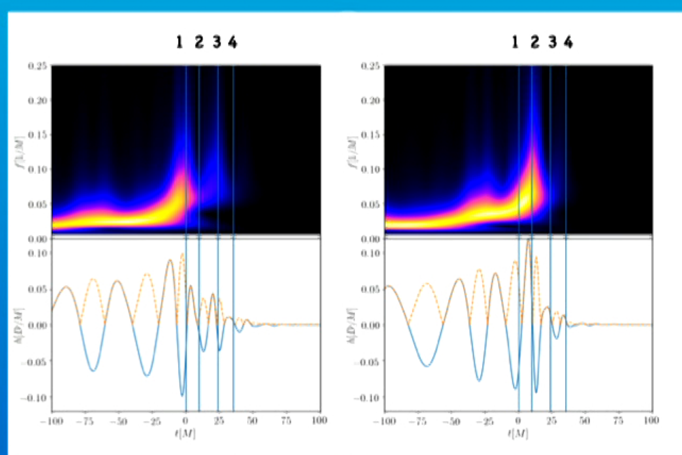
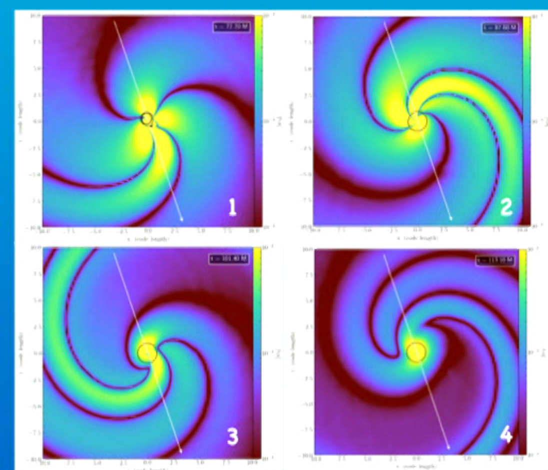
Correlating "tridents" and chirps

- Difference between simulation snapshots time and strain plots = 77M.
    - Check if chirps happen at consistent retarded time to establish correlation
    - Chirps and valleys happen at the right times (there is some ambiguity in choosing a given time)
    - The passage of the trident correlates with the occurrence of the chirps
    - We are comparing strain to psi4 though





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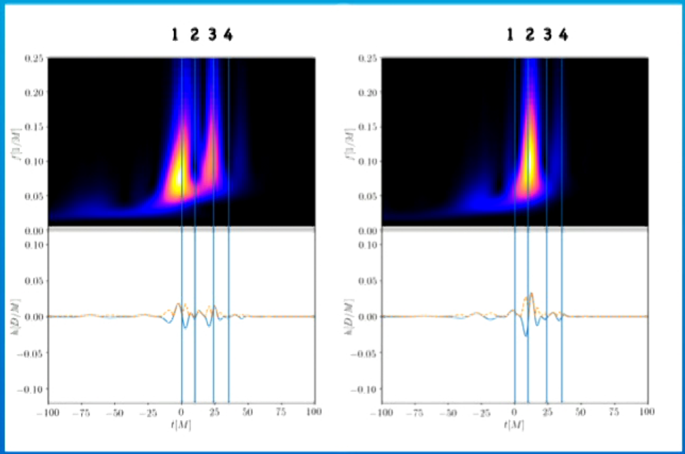
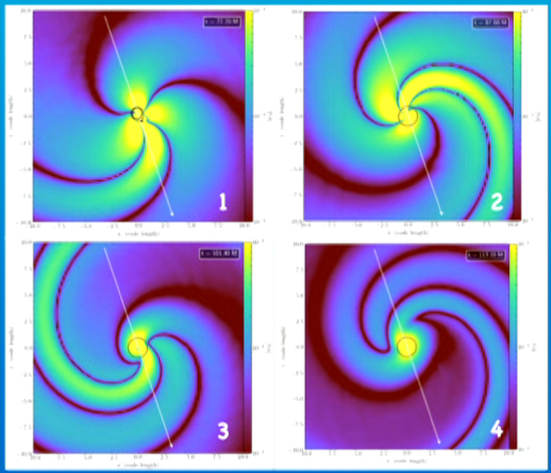
Correlating tridents and chirps (psi4)

- Difference between simulation snapshots time and strain plots = 77M. But we should be looking at psi4
  - Look at observed psi4 instead of strain
  - Better timing (expected)
  - In psi4, even the third chirp can be observed
  - Psi4 (post)merger emission is stronger than strain (compared to the inspiral)





Why the psi4 "trident" structure?

- Just after the horizon is formed: clear that the cusp surroundings radiate stronger
- Relation between curvature and momentum flux (Rezolla+ 2010).
- Highly curved regions radiate strongly. Curvature measured by **Gaussian Curvature**.

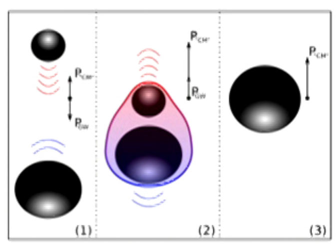
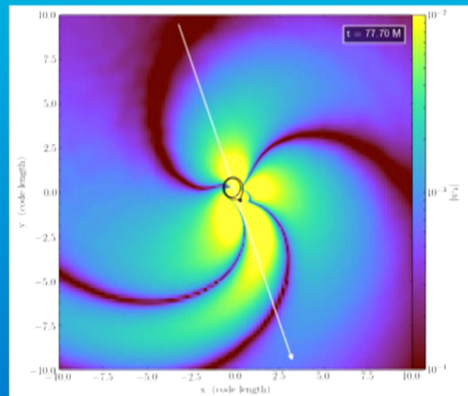
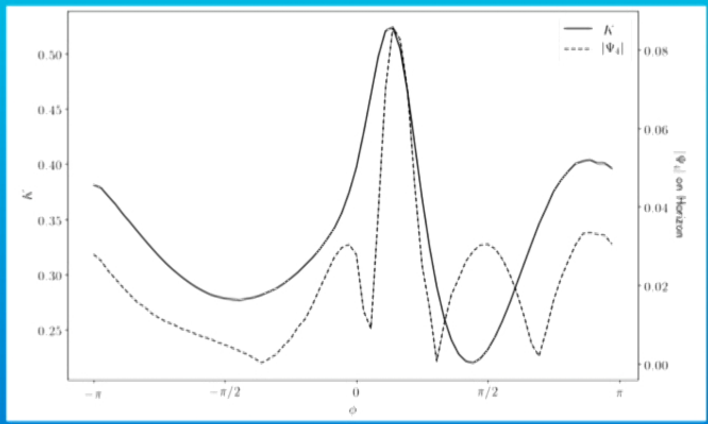


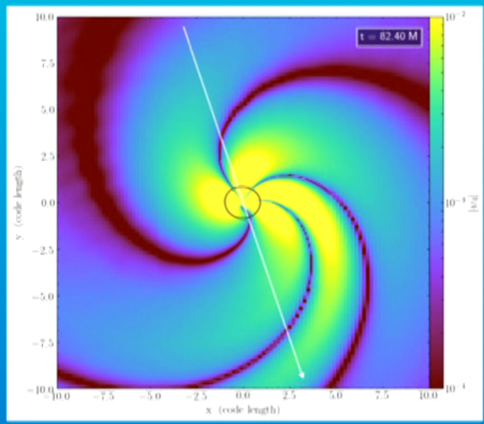
FIG. 1: Cartoon of the generation of the antikick in the head-on collision of two unequal-mass Schwarzschild BHs. Initially the smaller BH moves faster and linear momentum is radiated mostly downwards, thus leading to an upwards recoil of the system [stage (1)]. At the merger the curvature is higher in the upper hemisphere of the distorted BH (*cf.* shading) and linear momentum is radiated mostly upwards leading to the antikick [stage (2)]. The BH decelerates till a uniform curvature is restored on the horizon [stage (3)].



Let's look at Gaussian Curvature

- It captures the global maximum but can't explain the local maxima and minima
- True for the most part of the evolution of the final black hole





- We plot mean curvature vs. strain measured on the event horizon through the evolution.
  - It captures the peak
  - Cannot explain the local minima and maxima

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Another approach

- Since Gaussian curvature does not work….let's try something else:
  - Gaussian curvature is intrinsic to the surface, but radiation should depend on where the black hole is embedded: **use mean curvature.**

Independent on how the surface is embedded

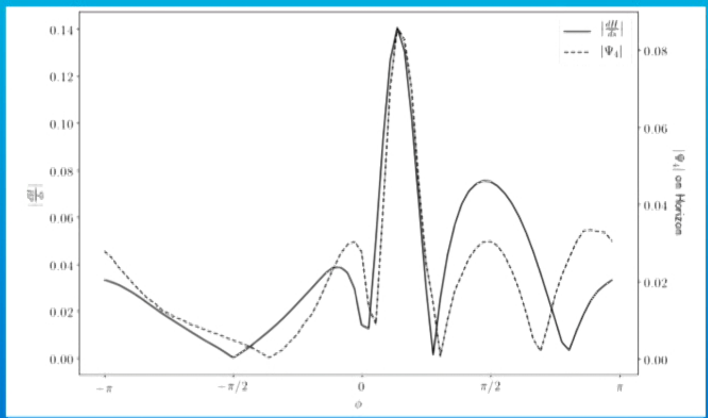
- **Gaussian Curvature:** $K = \kappa_1 \kappa_2$
- **Mean Curvature:** $H = \frac{1}{2}(\kappa_1 + \kappa_2)$

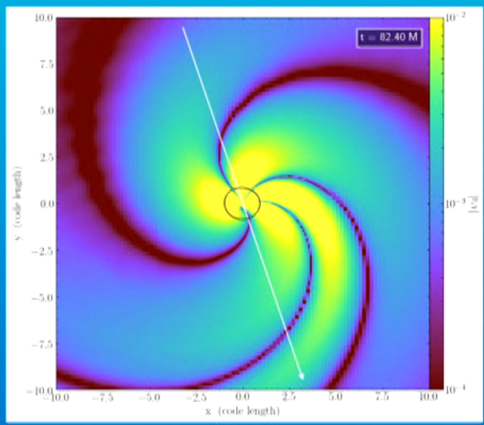
Another approach

- Since Gaussian curvature does not work….let's try something else:
  - Gaussian curvature is intrinsic to the surface, but radiation should depend on where the black hole is embedded: **use mean curvature.**
  - **Gaussian Curvature:** $K = \kappa_1 \kappa_2$ ← Independent on how the surface is embedded
  - **Mean Curvature:** $H = \frac{1}{2}(\kappa_1 + \kappa_2)$
- The black hole sheds hair via eliminating inhomogeneities on its horizon: look at **curvature derivative.**
  - **We look at:** dH/ds
  - **s:** ArcLength parameter on the intersection between horizon and orbital plane

Mean Curvature Gradient

- Since Gaussian curvature does not work….let's try something else:
  - Gaussian curvature is intrinsic to the surface, but radiation should depend on where the black hole is embedded: **use mean curvature.**
  - The black hole sheds hair via eliminating inhomogeneities on its horizon: look at **curvature derivative.**





- dH/ds captures both the global and local peaks and minima: **can correlate chirp to trident to "three close regions of large curvature gradient"**
- **Evidence for a tight psi4 vs. dH/ds relation** (we are missing time derivatives here)

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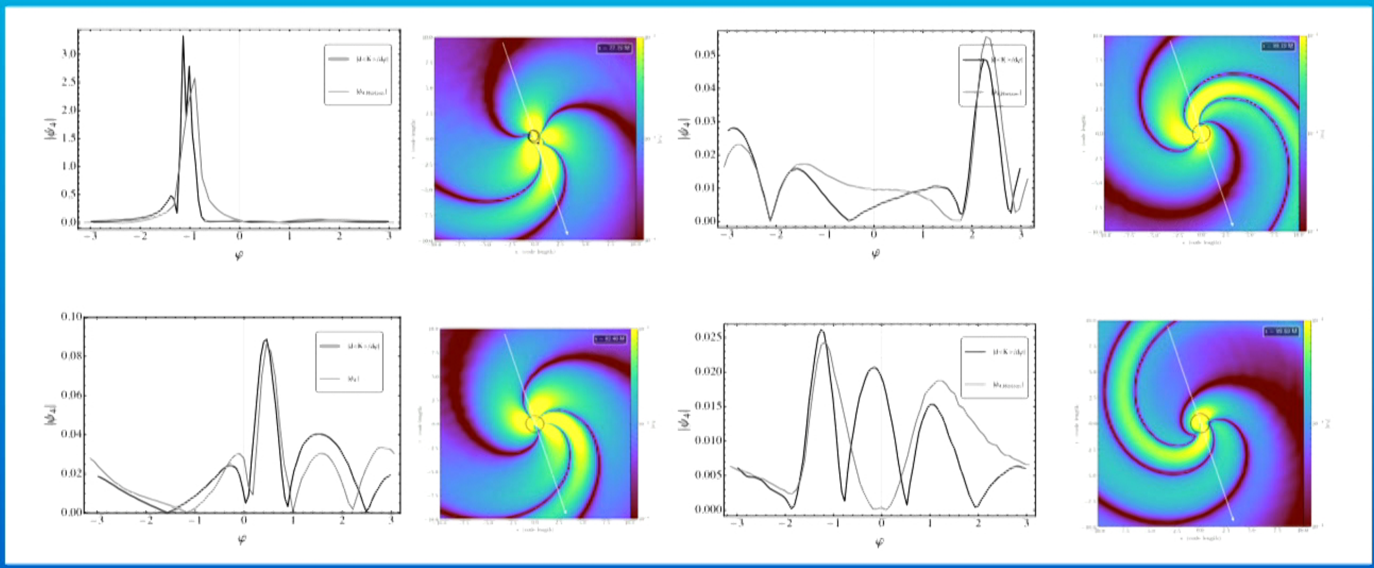
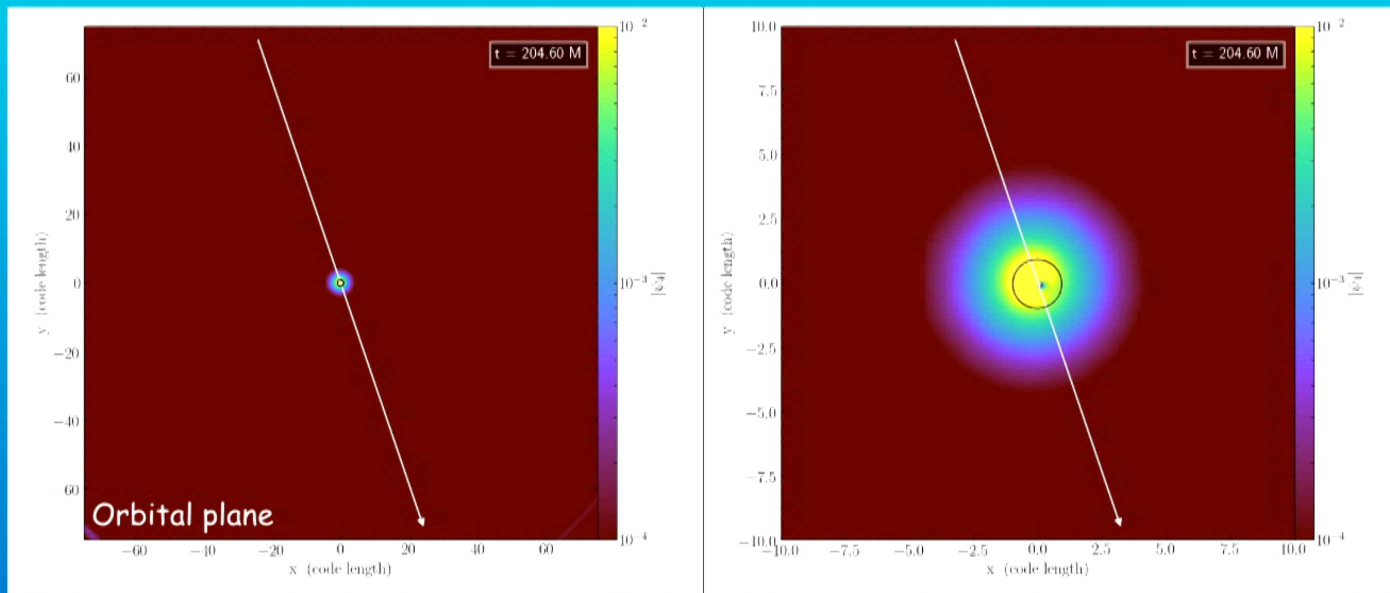
Event horizon curvature and gravitational waves

- Showed best case in previous slide.
- The relation does not work perfectly during the whole evolution. Still, there is a strong correlation between zeros and peaks of psi4 and curv. derivative.
- Chirps correlated to passage of trident and with the ``cusp'' of the horizon



Why double chirps: looking into the simulations



Color code: $\psi_4 = \frac{d^2 h(t)}{dt^2}$

Newman - Penrose Scalar

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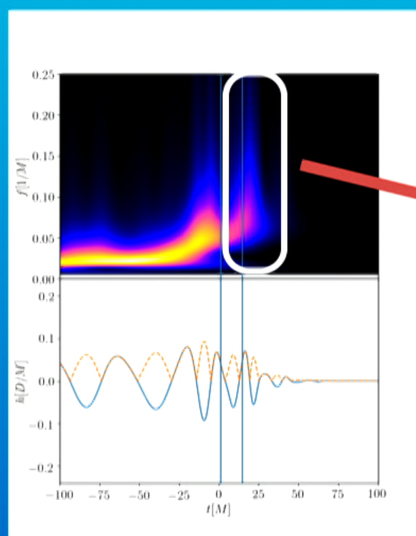
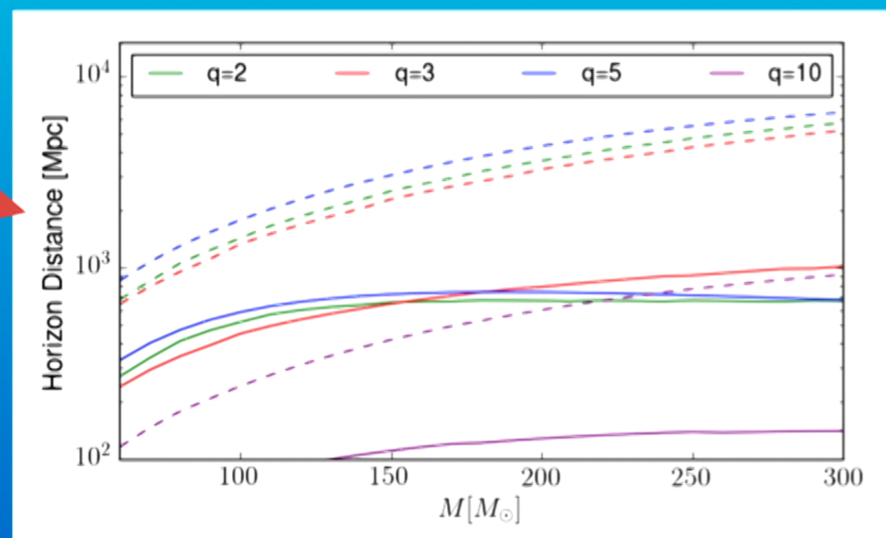
Observability of the second chirp

- Simple approach: compute the signal-to-noise ratio (SNR) of the second chirp
- Plot distance at which SNR reaches 5 (hence, 5 sigma deviation from Gaussian noise)
- Second chirp visible at ~800Mpc using design Advanced LIGO, for q=(2,5) and M=60Msun





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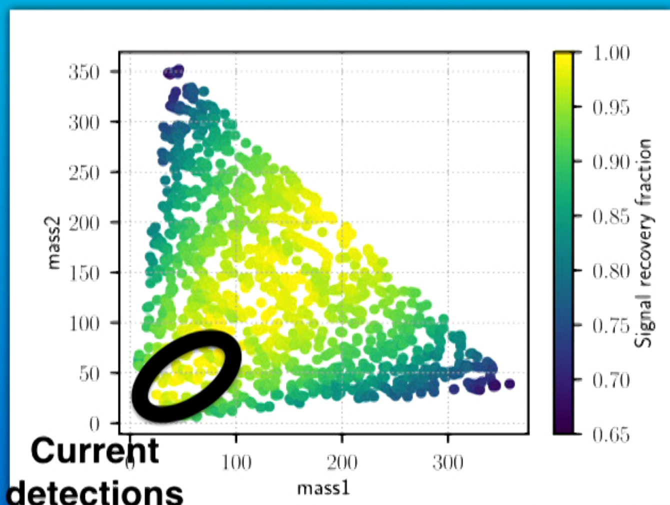
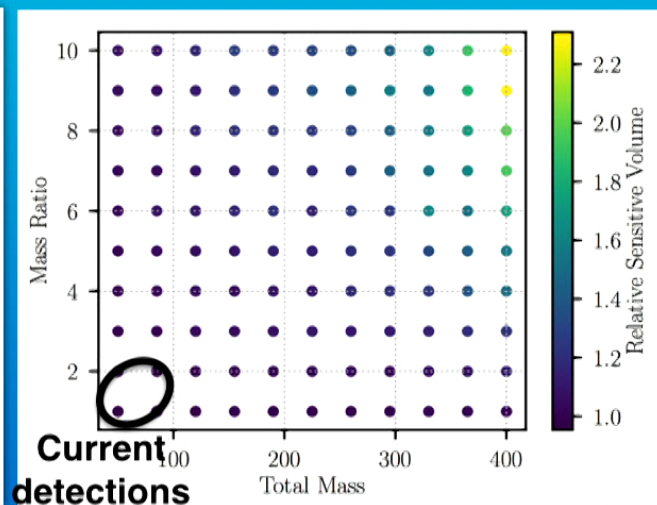
Why no higher modes yet?

- Large mass ratio binaries are weaker.
- No heavy binaries (M~100Msun) detected yet: difficult to distinguish from background noise.
- Crucial: our searches only include the dominant (2,2) mode. Developing new one including higher mdes, hopefully ready for O3 run.

Current searches



New search including higher modes



- **Decreased sensitivity to highly asymmetric and high mass binaries**

Harry, JCB & Nitz (2017)

Summary

- Current GW observations don't show strong higher modes
- Higher modes lead to rich post merger waveform morphologies.
- Help to improve parameter estimation and measure new observables
  - Kicks: emission of linear momentum
  - Multi-Chirps: horizon structure (Black holes chirp several times!)
- Correlation between the horizon curvature and psi4 measured on it.
  - Relate geometrical feature of the horizon to a feature of the waveform.
- Need to improve our searches to detect these fancy signals: we are on it!

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