Un-modeled search for stellar mass binary black hole mergers in LIGO-VIRGO interferometers

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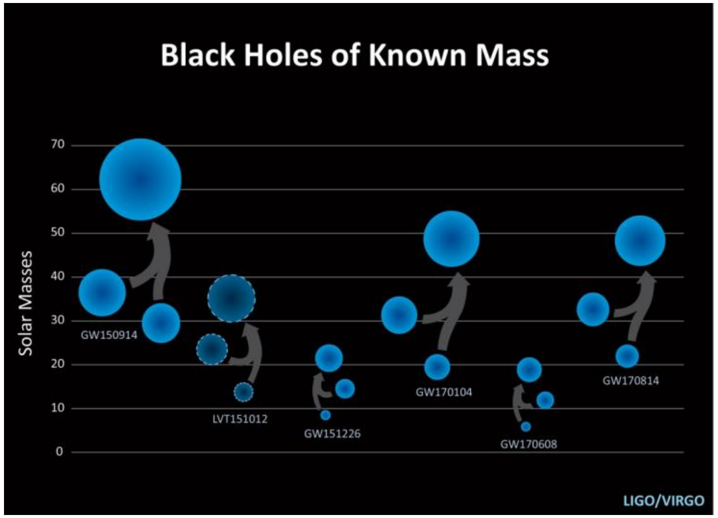
Outline

- Un-modeled search for BBH
  - Motivation
  - Methods
- Search for IMBHB using un-modeled search
- Search for eBBH using un-modeled search

BBH searches

- We now know that BBHs exists in nature and merge in Hubble time
- Detected 5 confirmed BBHs mergers
- Interesting non-vanilla BBH sources:
  - binaries with eccentricities (e>0.1) in LIGO band (dynamical capture in dense stellar environments, three body interaction etc)
  - binaries with intermediate mass (>100 $M_{\odot}$) companion

- The searches for BBHs can be divided into
  - Modelled search
  - Un-Modelled search



Modeled searches

The analyses correlated detector data with template waveforms that model the expected signals

Candidate events that are detected at both observatories with the same template and consistent with the 10ms inter-site propagation time are identified

A detection-statistic value ranks likelihood event of being a GW signal
Detection statistic is compared to background to determine the probability that a candidate is due to detector noise

Three pipelines running low-latency in O2

T. Dal Canton et al., Phys. Rev. D 90, 082004 (2014)
C. Messick et al., Phys. Rev. D 95, 042001 (2017)
Adams et al. CQG 33, 175012, 2016

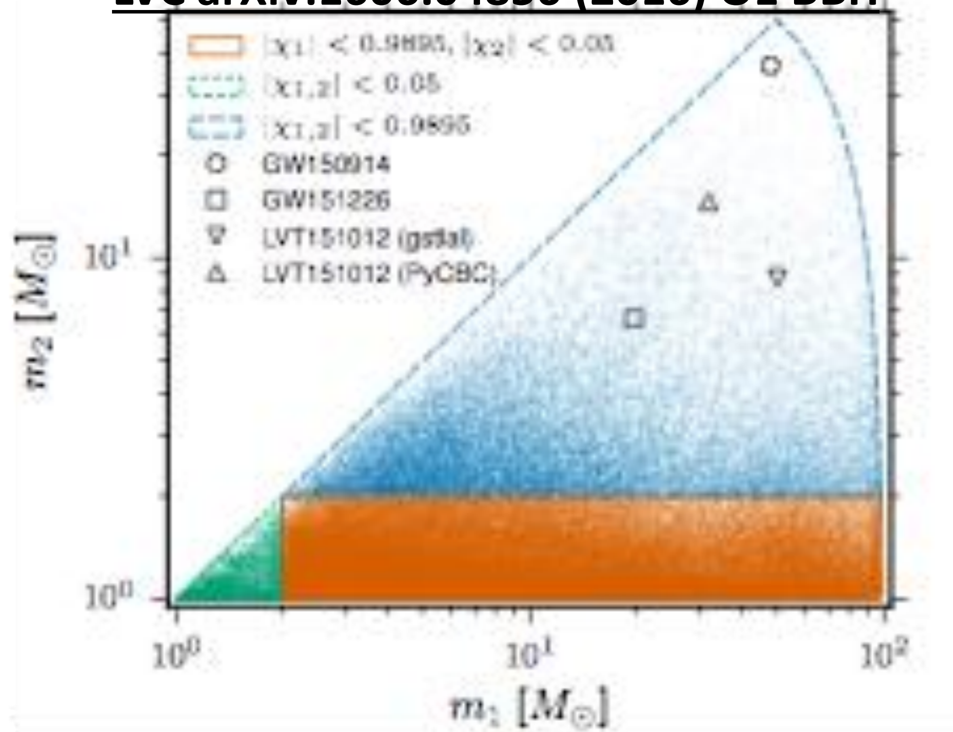
Limitation of modeled search for BBH

- In modeled search signals are matched filtered using the a bank of template waveforms.
- Four-dimensional search parameter space (component masses and spins) is covered by the template bank

- Template bank covers a huge part of the parameter space and most likely BBHs signals , it assumes
  - circular orbits (no eccentricity)
  - no contribution from higher modes (can be important in high mass ratio systems)
  - only aligned spin (no precession)

- *Note : the template bank for BBHs search is an evolving process dependent on the detector sensitivity*

LVC arXiv:1606.04856 (2016) O1 BBH



The colours indicate mass regions with different limits on the dimensionless spin parameters χ1 and χ2.

Un-modeled searches

Search for excess power in time-frequency domain
(Wavelet, Q-transform, …)

↓

Combine coherently the selected TF pixels of different detector in a unique data stream
Consider time-delay between detectors
Include antenna pattern factors

↓

Calculate a detection statistic and compare the one of each candidate to the background distribution

Two pipelines and one follow-up algorithm running low-latency for O2

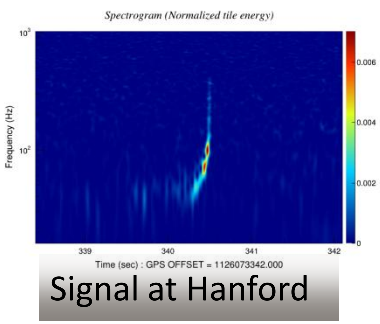
S. Klimenko et al., Phys. Rev. D 93, 042004, 2015
R. Lynch et al., Phys. Rev. D 95, 104046 (2017)
T. B. Littenberg et al., Phys. Rev. D 91, 084034 (2015)

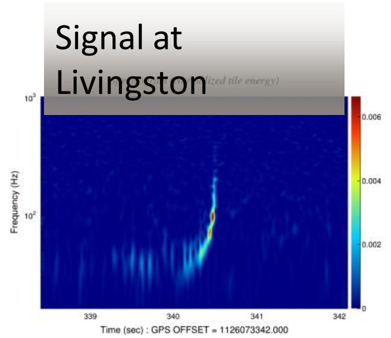
Coherent WaveBurst algorithm

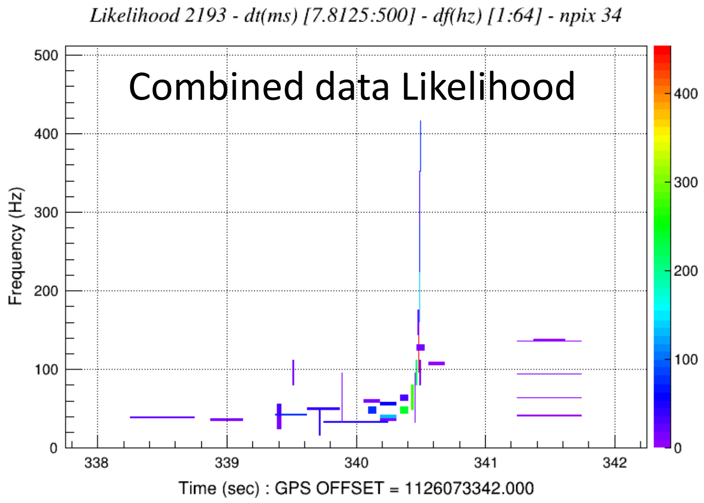
- Coherent Waveburst is an algorithm of Burst search developed at LVC

Klimenko+ PhysRevD.93.042004

- Interesting features:
  - Characterization of signal both in time and frequency (Wavelet)
  - Coherent analysis (Likelihood approach)
  - Reconstruction of waveforms and source coordinates

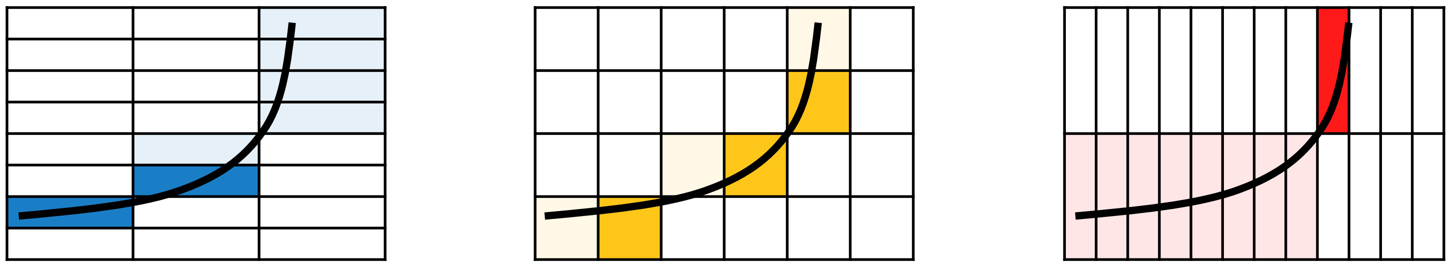


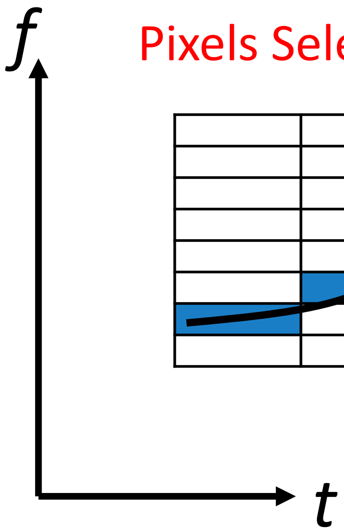




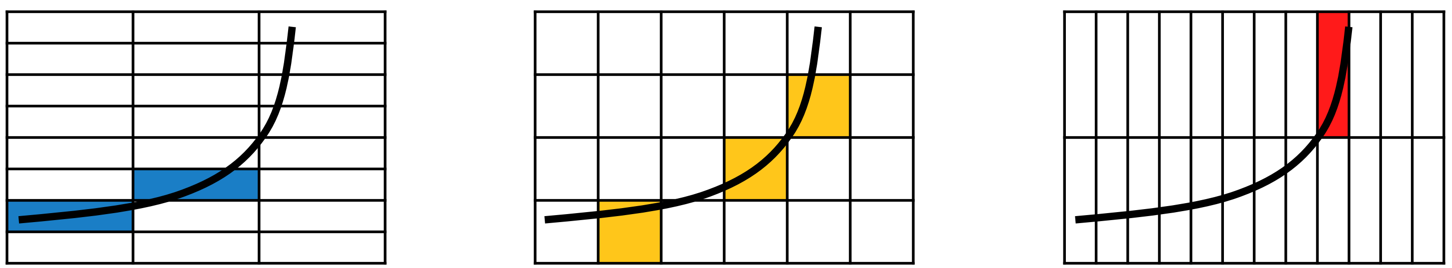
Time-Frequency selection

Multi resolution Time-Frequency decomposition & Pixel Energy (**Single Pixel**)

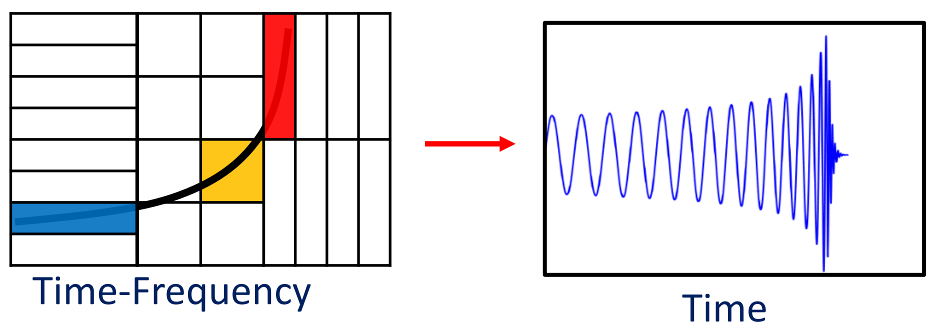




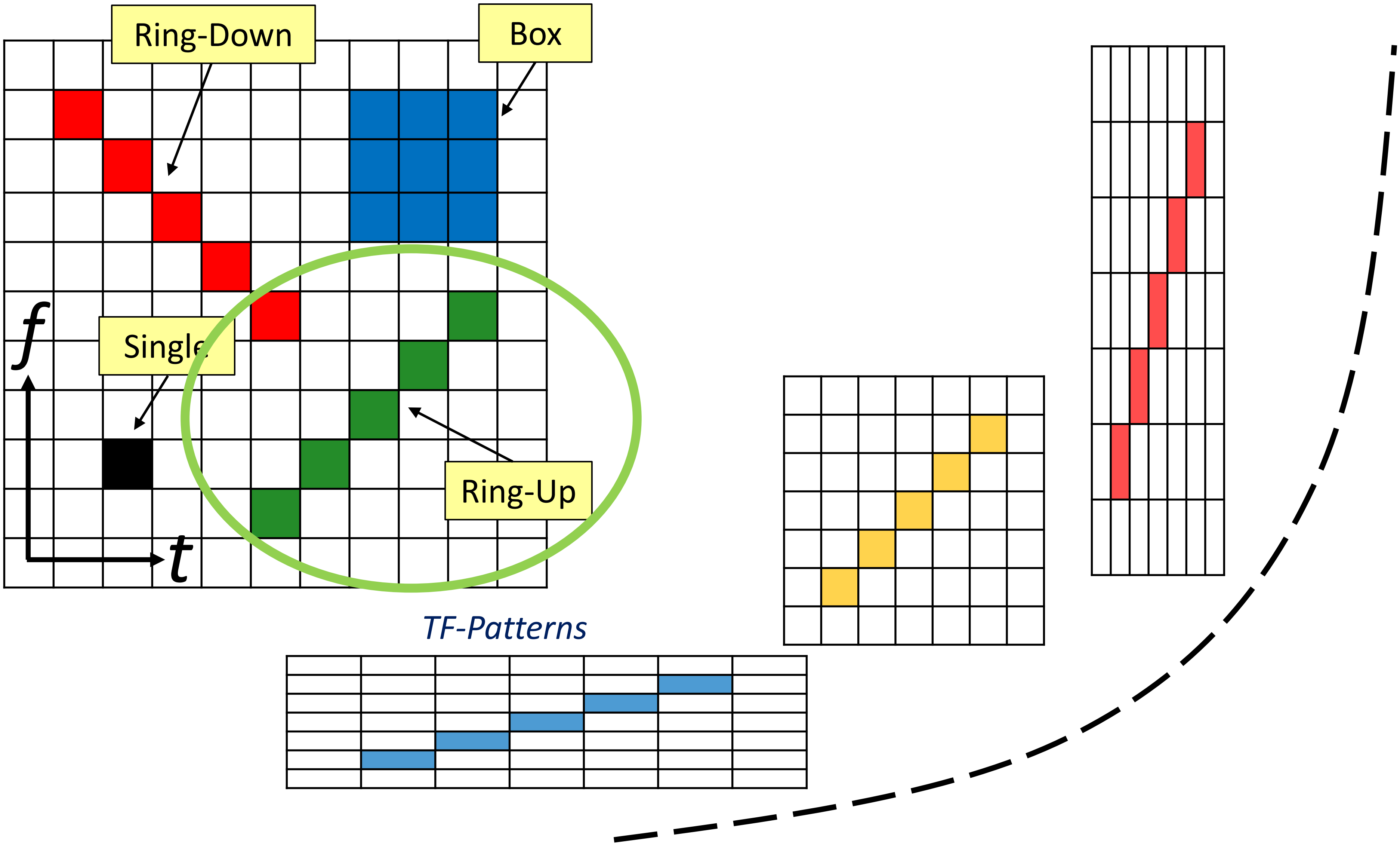
Pixels Selection (pixels with energy above the threshold) & Clustering



Reconstruction (**Principal Components**)

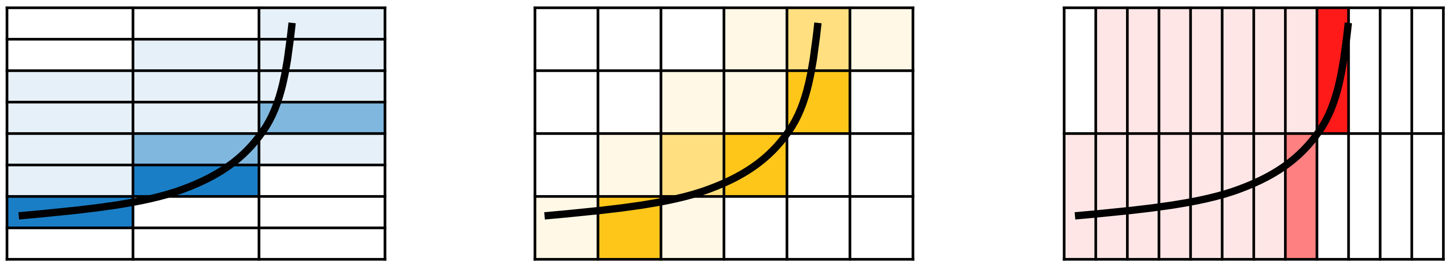


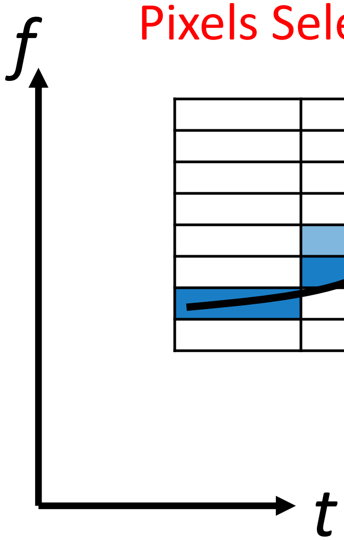
Dedicated pixel selection



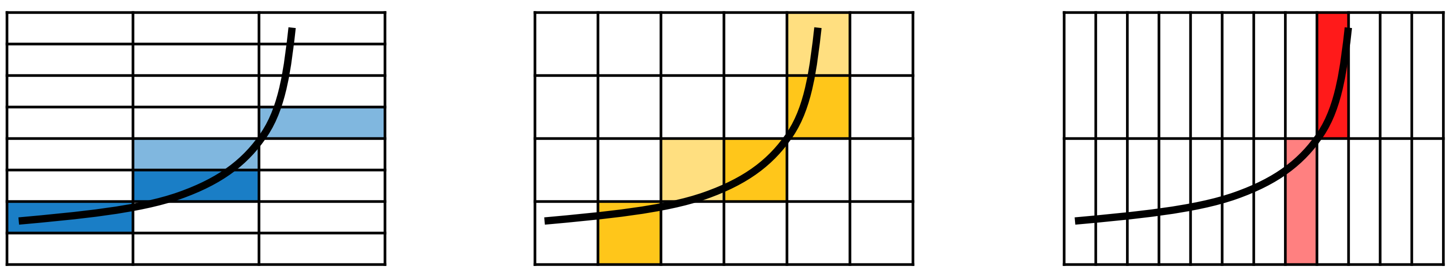
Multi level pixel

Multi resolution Time-Frequency decomposition & Pixel Energy (**Wavelet Packet**)

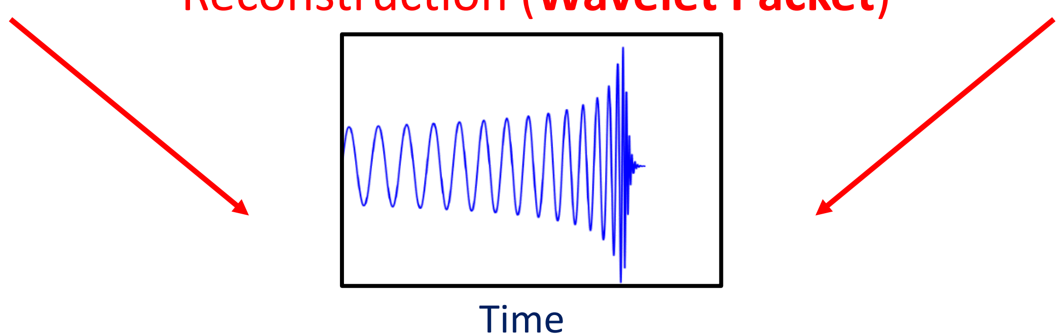




Pixels Selection (pixels with energy above the **threshold**) & Clustering

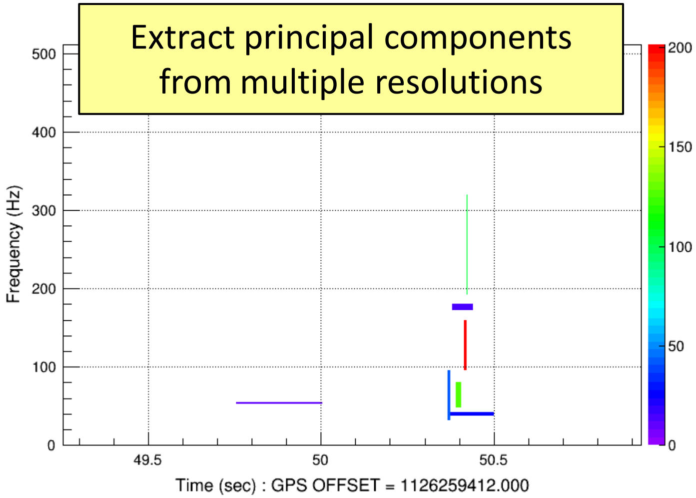


Reconstruction (**Wavelet Packet**)

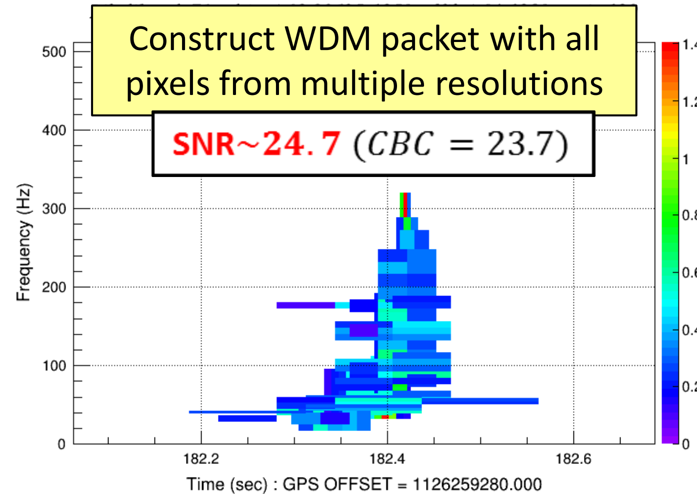


GW150914 improvement

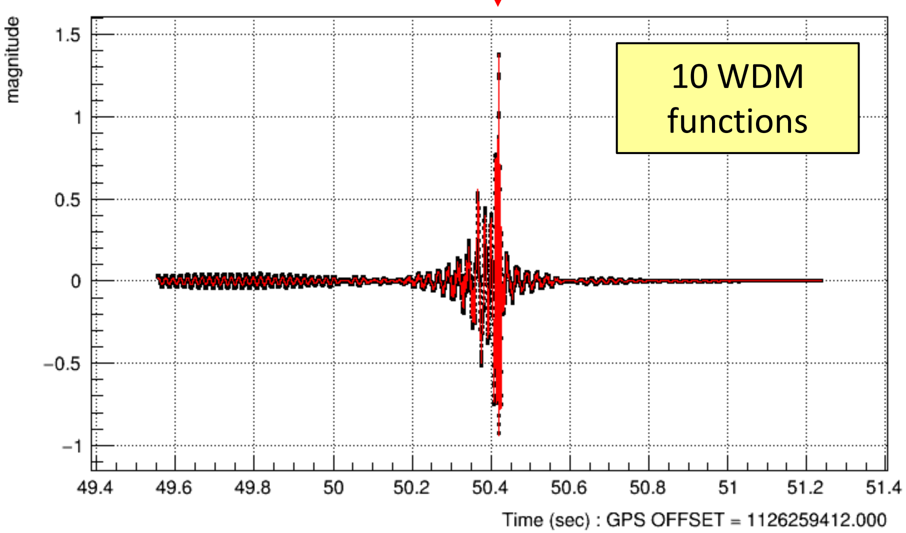
No dedicated selection

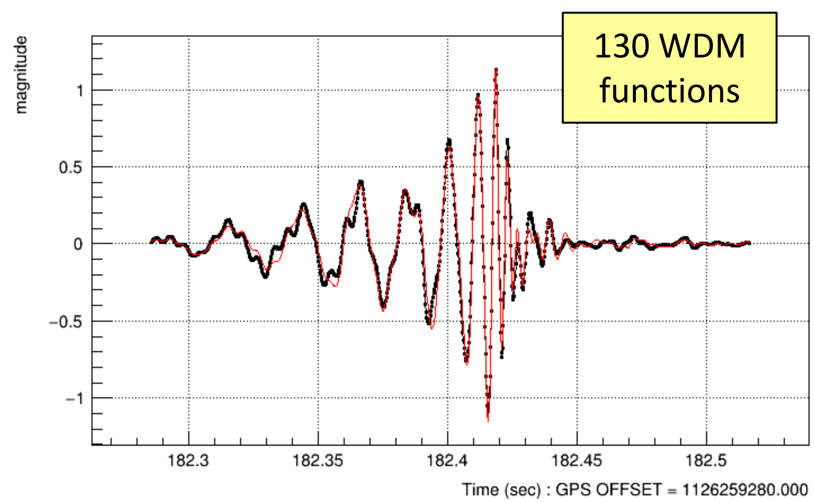


Dedicated selection



L1 – Whitened Reconstructed Waveform

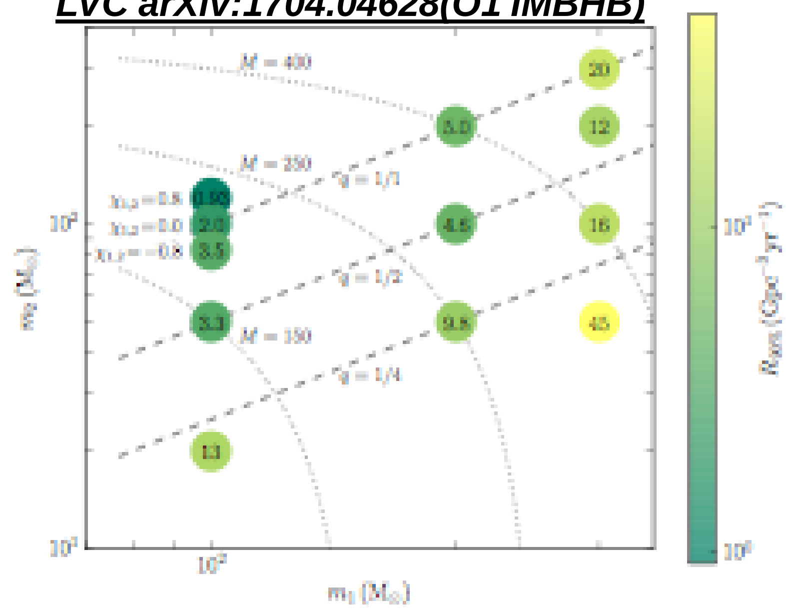




Search for IMBHB

- Search for Intermediate mass BBH is done using both the methods
  - Modeled search : using inspiral merger ringdown template bank with aligned spins till total mass between 50-600 $M_\odot$ and effective spins -0.99 and 0.99 and mass ratio less extreme than 1:10
  - Un-modeled search tuned in the parameter space of IMBHB (lower frequency, requires signal to be chirping up etc)

LVC arXiv:1704.04628(O1 IMBHB)



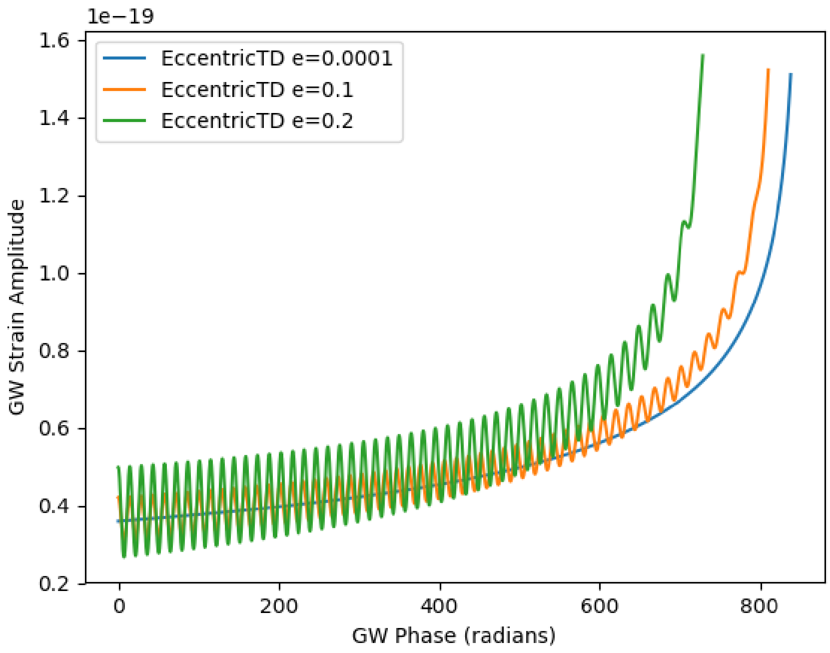
Rate upper limit

- Results for this search for O1 is now published, highlights:
  - There were no GWs found from IMBHB
  - The rate upper limit at 90% confidence was found to be 0.93 for 100-100 $M_\odot$ at 0.8 aligned effective spin

Gravitational wave from eccentric BBH

- Binaries with orbital eccentricity will have periastron advance, this feature is translated as the phase modulation in the GWs waveform
- The waveform are shorter in time, i.e. time to merge is smaller as the eccentricity increases

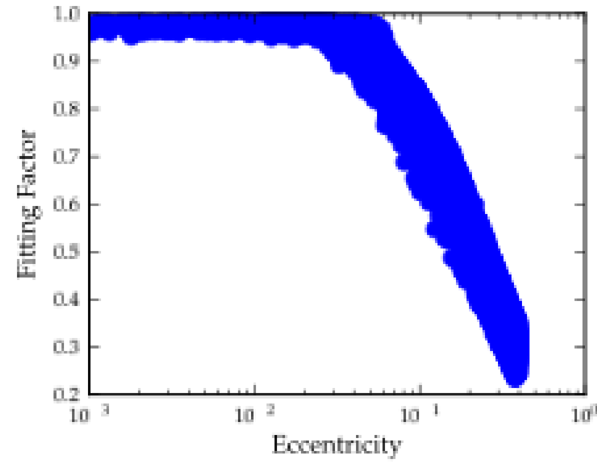
- The relative power in the higher harmonics are proportional to the eccentricity



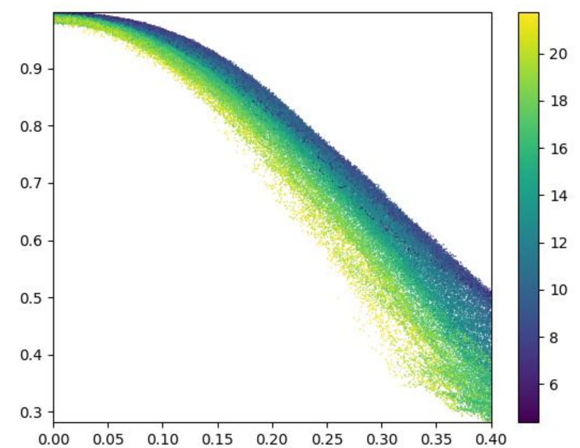
Peter Mathews (1964) PRL

Effect of eccentricity on the templated search for BBHs

- Fitting factor (FF) is the measure of how much waveform accuracy contributes to the collection of optimal SNR
  - Not a good match for the binary neutron star (BNS) having eccentricity, e > 0.05
    Huerta, E. A. and Brown, Duncan A. PRD (2013)
  - For BBH, we can conclude for ~ e > 0.2 the FF falls below 0.9
    (this is done with the inspiral only waveform and templates, full inspiral merger ringdown models are not available yet)
    Tiwari et al in preparation



fitting factor (FF) as a function of eccentricity for BNS (top) and BBH (bottom)

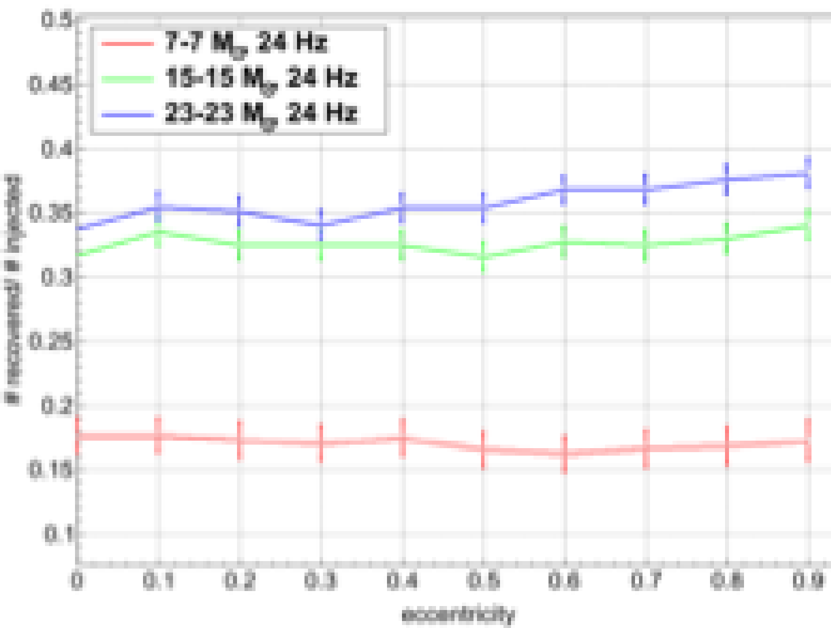


- Hence, searching for eBBH with the circular template bank will be quite suboptimal
- For such scenarios un-modelled search targeted for BBHs can complement the modelled searches

Search for BBH using un-templated analysis : eBBH

- Only un-modeled search (no templates)
  - the efficiency of this algorithm is invariant of the eccentricity
- If detected such sources can enrich our understanding of the dense stellar environments and formation channels of BBH

- Early LIGO -VIRGO sensitivity results published
- Working on search for advanced LIGO-Virgo first and second observing run



<u>Phys.Rev. D93 (2016) no.4, 043007</u>

Conclusions

- Un-modeled searches are complementary to the modeled searches for BBHs and can potentially help to extend the search parameter space
- Un-modeled searches can find vanilla BBH with high significance
(although lower than the modeled search)
- Some of the interesting formation channels can predict binaries with parameters such eccentricity, extreme precession … where un-modeled searches play an important role