13 July 2023, Quantum gravity phenomenology in the multi-messenger approach, Rijeka, Croatia

Observational consequences of non-linear* memory of gravitational waves from coalescing compact binary mergers

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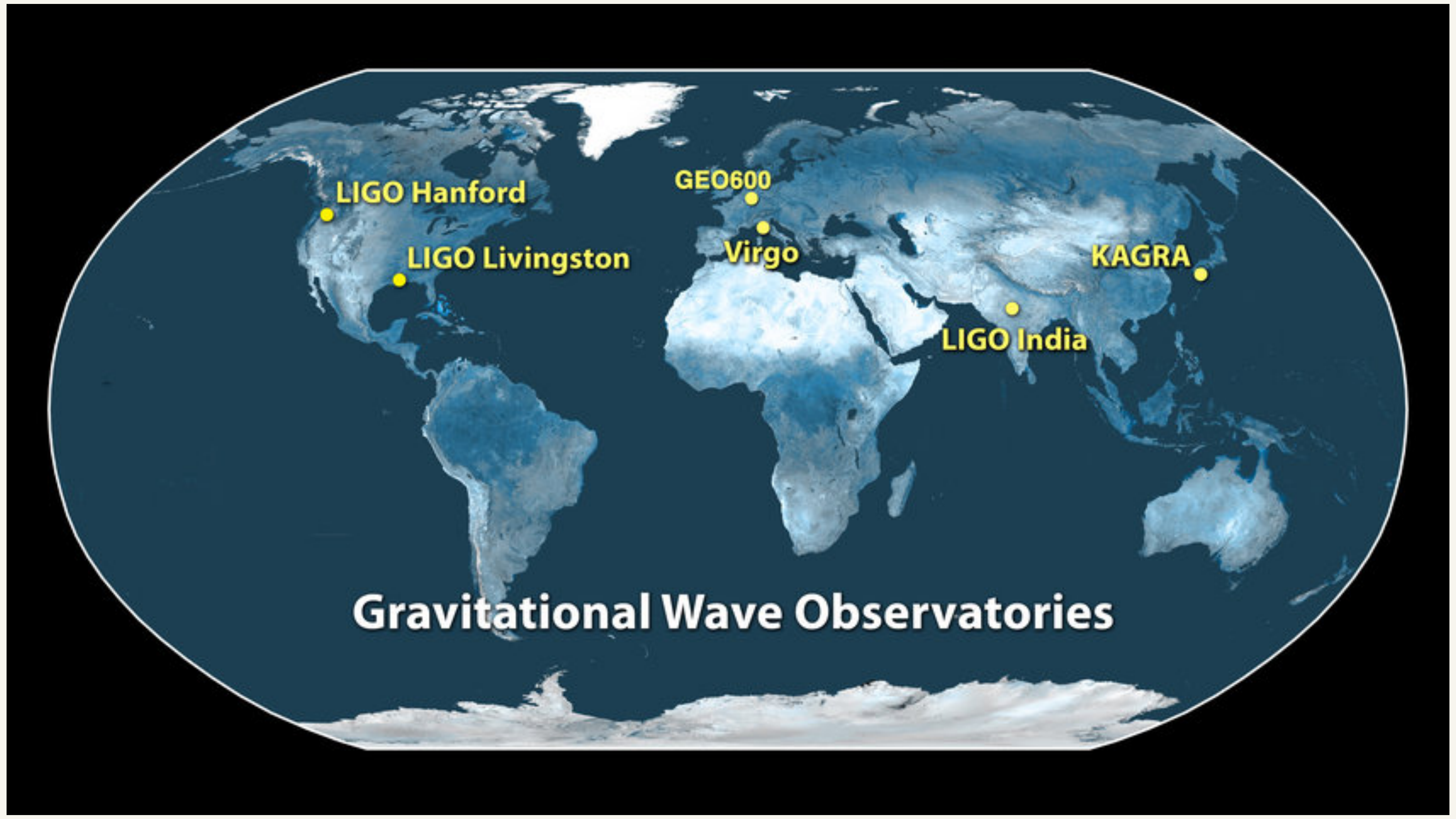
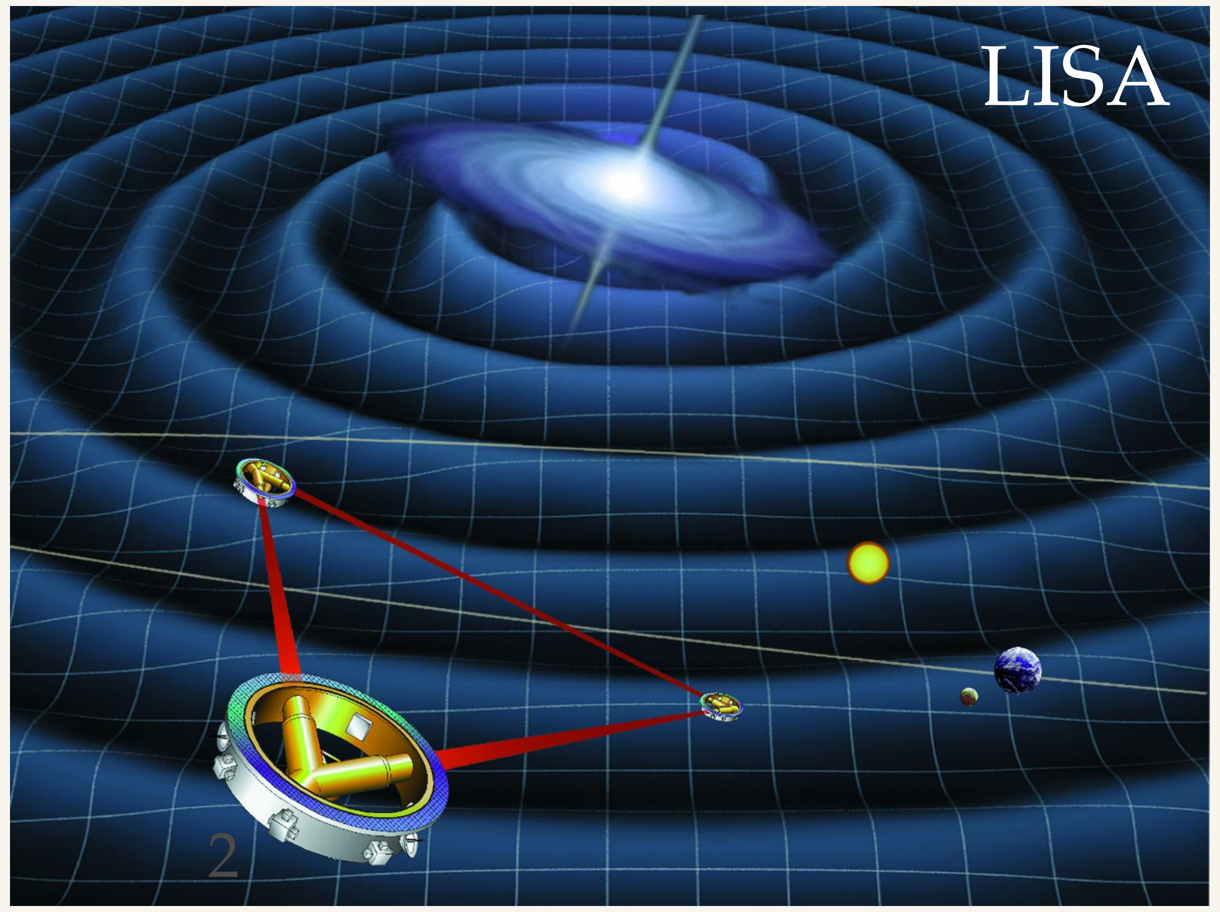
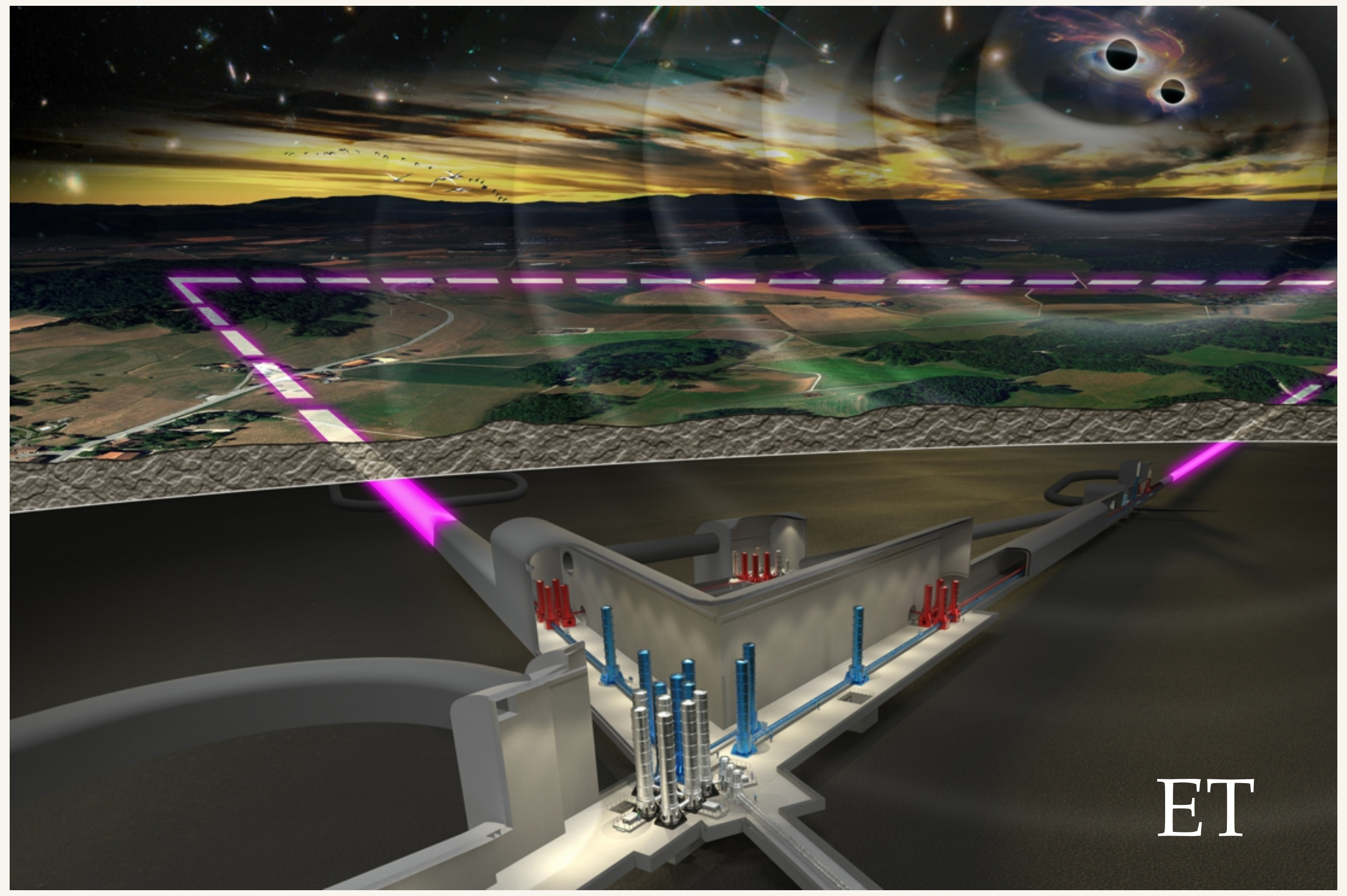
*very briefly also linear

Gravitational waves : detectors

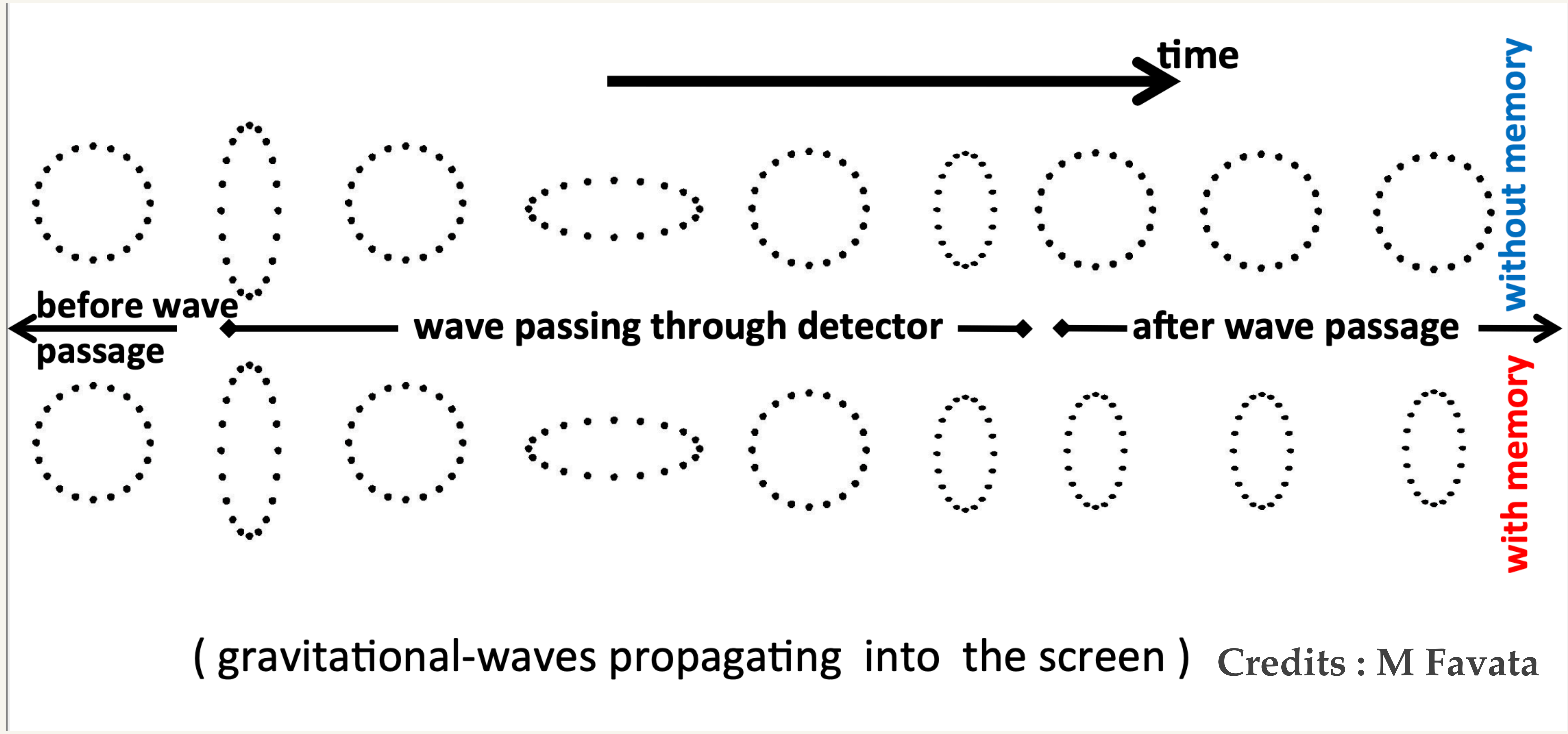
- Gravitational Waves (GWs) are a fundamental prediction of General Relativity (GR) which are now confirmed
- Current generation of interferometers include 2 in the US, LIGO Hanford and Livingston, 1 in Pisa : Virgo. Japanese detector KAGRA is also joining the network and Indian detector LIGO-India is also expected to join in the coming years probing 10-4000 Hz GW universe
- There will also be a space based GW detector called LISA that will be launched in 2030s, probing 10^{-4} - 10^{-2} Hz GW universe
- In future the upgrades to the current generation ground based detectors are also foreseen like the Einstein Telescope (ET), Cosmic Explorer (CE)
  - There are also efforts in China for space based detectors like TIAN-QIN, TAIJI
  - There are proposal for the GW detectors on moon







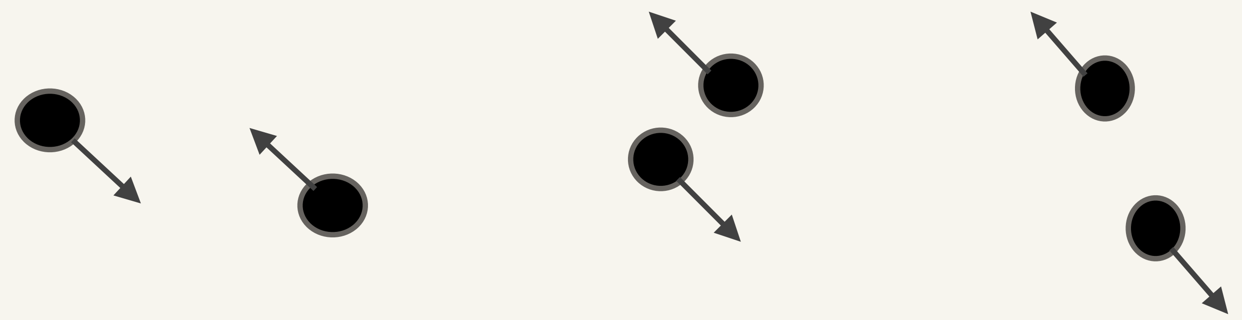
Memory of gravitational waves

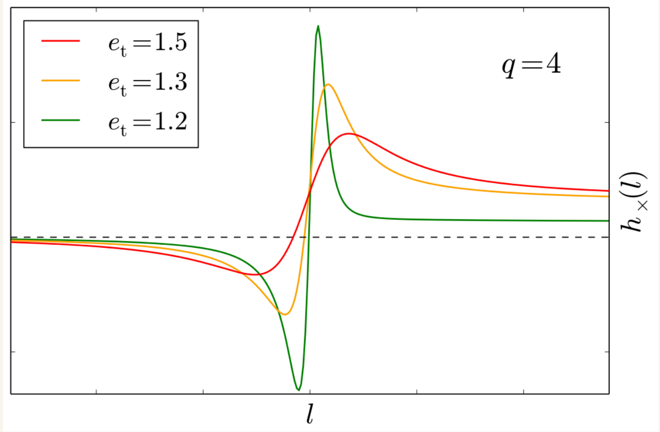


- GWs can permanently deform the space time
- When a GWs passes through an interferometer causes a permanent displacement of the mirrors.
  - We refer to this permanent deformation as “**memory**”
- The wave does not return to its zero point

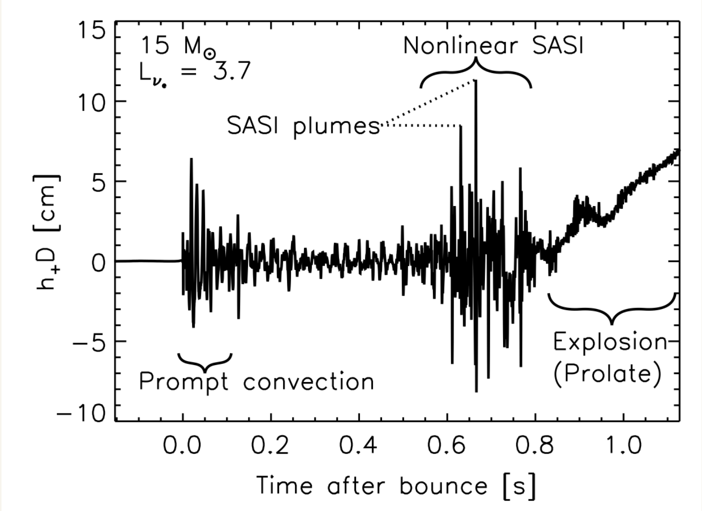
Persistence of memory, S Dali

Linear and non-linear memory

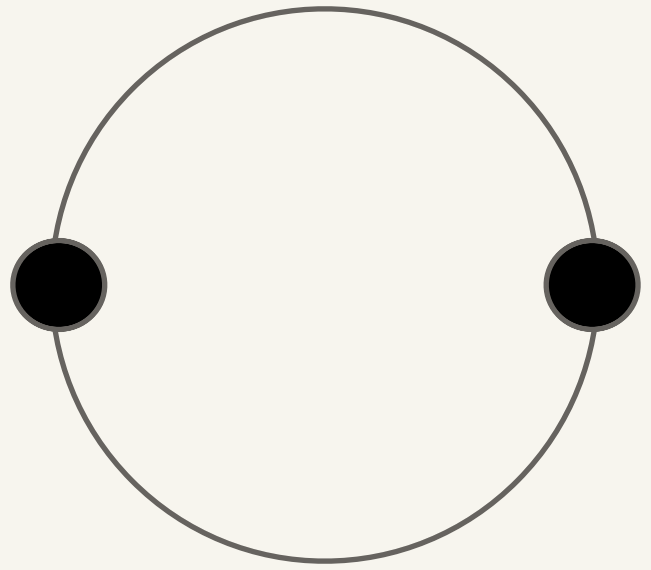


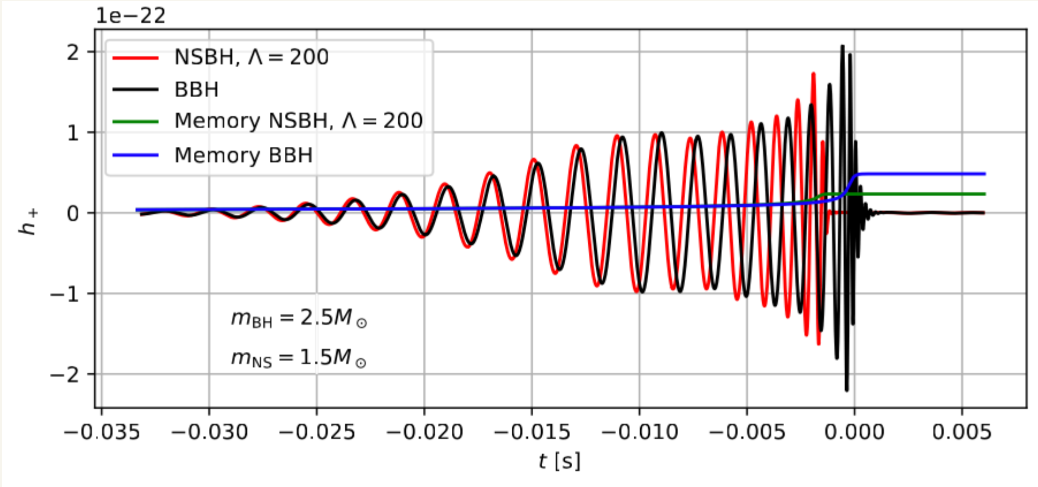


Fly By Encounter



Asymmetric Core Collapse Supernovae





Compact Binary Coalescence

Linear Memory

Braginskii, Grishchuck, Thorne, Zeldovich, Polnarev

- Arises when GWs are emitted from unbounded, non-oscillatory motion of objects
  - Hyperbolic encounters of compact objects lead to linear memory
  - Asymmetry in core collapse supernovae due to neutrino emission induced linear memory
  - GRB jets (ejecta) also have linear memory component

Non-linear Memory

Throne, Christodoulou, Blanchet, Damour, Favata

- Is produced by GWs itself (GWs produced by GWs)
- All sources of GWs will produce non-linear memory as well
- Memory scales likes the radiated GWs energy
- Effect is hereditary and is integrated over the full past history of the system

“Better” Classification

Displacement Memory

Permanent change in the arm length of Michelson interferometer

BMS transformation : Supertranslation

Spin Memory

Permanent change in the rotation observable of Sagnac interferometer

BMS transformation : Superrotation

Center of mass Memory

Related to the time delay acquired by the freely-falling objects on antiparallel paths

BMS transformation : Superboost

S Pasterski et al arXiv:1502.06120
David A. Nichols arXiv:1702.03300
David A. Nichols arXiv:1807.08767
K Mitman et al 2021 arXiv:2007.11562

BMS: Bondi, van Der Burg, Metzner, Sachs group

$$\dot{m} = -\frac{1}{4}\dot{h}\dot{\bar{h}} + \frac{1}{4}\mathrm{Re}\left[\eth^2 \dot{h}\right]$$

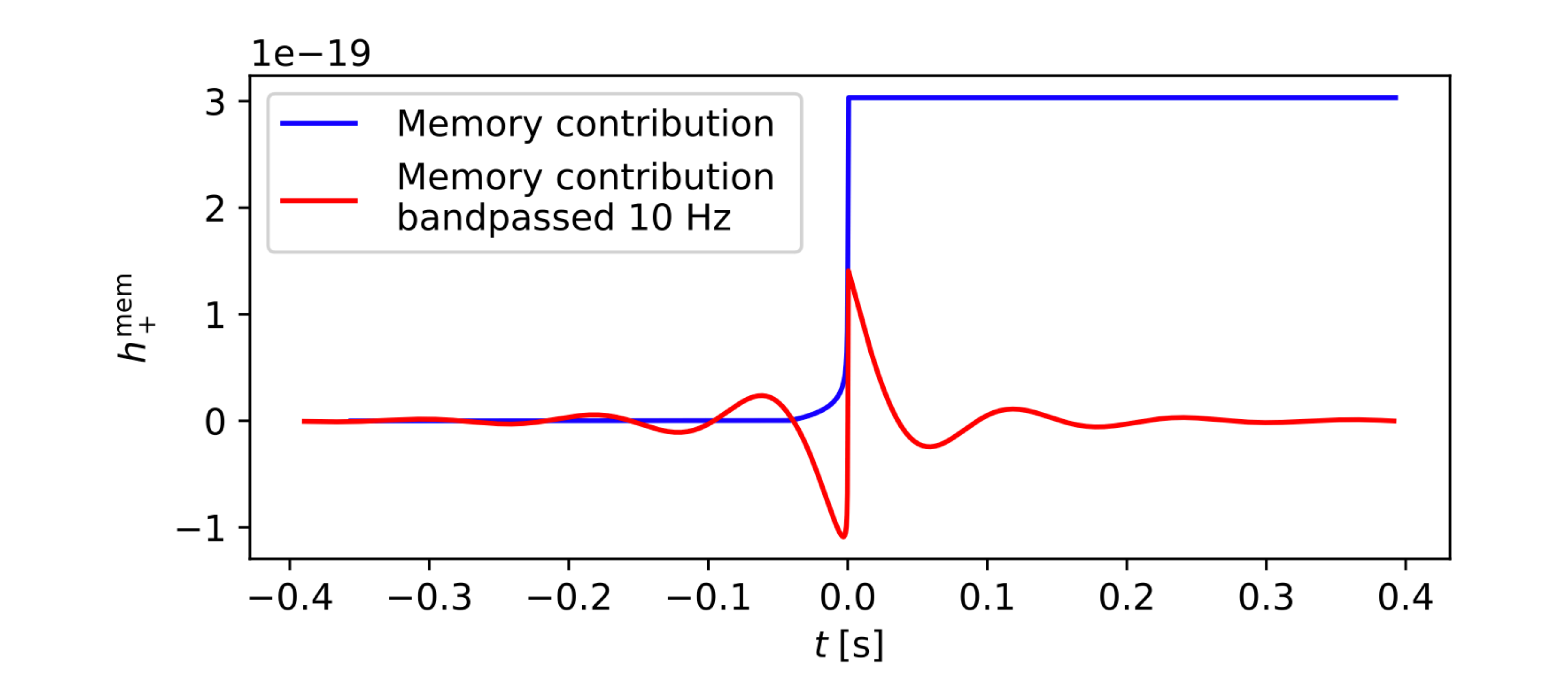
Computing Non-Linear memory (displacement)

- We compute the memory using only the (2,2) component of the oscillatory waveform (formula of Throne)

$$h_+^{\rm mem}(T_R) = -\frac{R}{7c}\sqrt{\frac{5}{6\pi}}\int_{-\infty}^{T_R} dt\,|\dot{h}_{22}(t)|^2\ {}_{-2}Y_{20}(\iota,\Phi)$$

- Details
  - Here the integral is taken from 500M before merger and not the real , ignoring other modes and "deeper" memory contributions results the memory signal amplitude to be accurate up to a few percentage
  - We have also cross checked this result with the recent work where the memory is extracted from numerical relativity simulations exploiting the BMS conservation laws, our results are within 10% of the amplitude (for most cases we within 1%)
  - The amplitude of memory signal is much fainter as compared to the oscillatory signal

Response of interferometer to a memory signal



- Memory signal behaves like a growing step function with finite rise time.
- The frequency spectra of memory will peak at 0 Hz which is beyond the reach of any detectors
- In frequency domain memory signal will saturate at the low-frequency cut off of the detector
- In time domain the band passed memory will look like a single cycle **bursts** signal with linear polarisation*

*in detector frame precession can make memory elliptically polarised

Response of interferometer to a memory signal

- In the time-frequency domain one can visualise how memory appears in the full (oscillatory + memory) signal
  - NOTE : Memory amplitude has been artificially enhanced for better visualisation
- A few things to note here
  - The peak amplitude of memory in the detector just follows the power spectral density, f_{peak} around 100 Hz
  - The main signal is extremely short, ideally one cycle and few sidebands

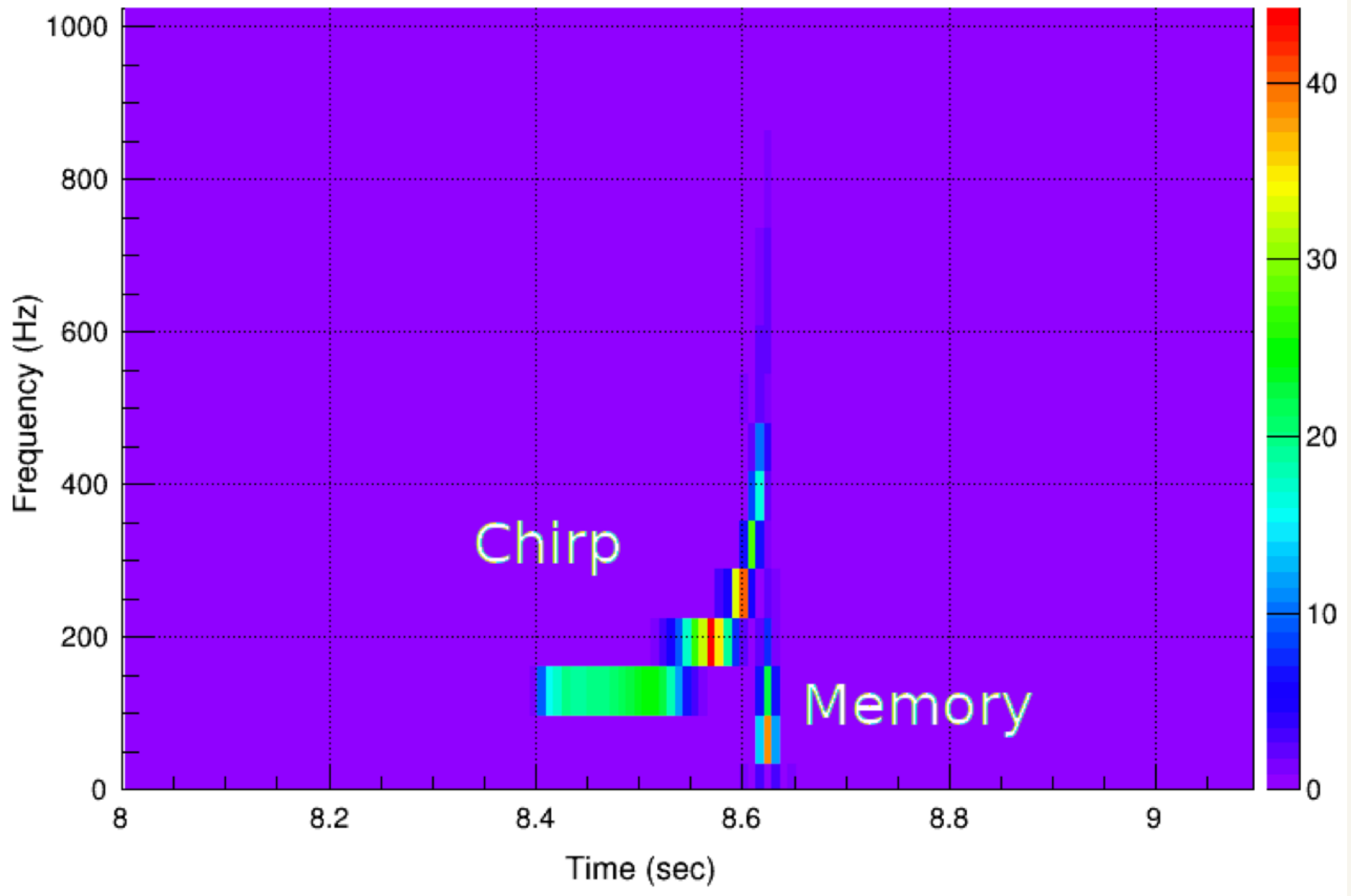


Fig 2: *Whitened spectrogram with O2 noise PSD of a GW signal from a* $5-5M_\odot$ *BBH at SNR* ≈ 100 *with enhanced memory signal*

Properties of memory from CBC

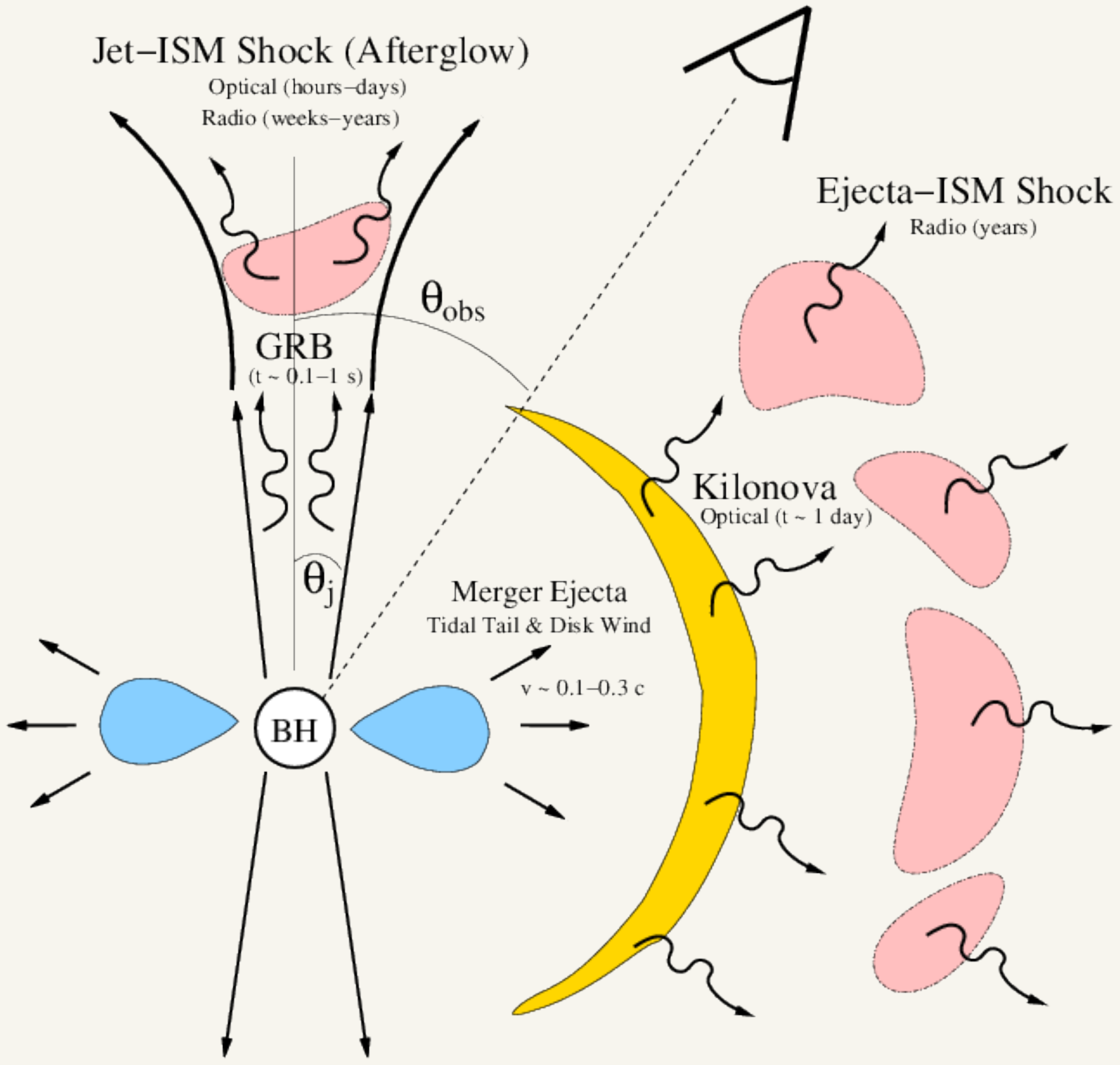
- Features of memory signal :
  - Memory of the sources which have very high frequency (>3-5KHz) oscillatory signal will also peak at lower frequency cutoff of the detectors, in fact the spectra is broadband
  - Memory likes symmetrical systems (equal mass systems, aligned spins, circular orbits) have more memory than asymmetric systems [this is only merger memory]
  - Memory has a different dependancy on the binary's orientation, memory peaks when the plane of the orbit is edge-on, this is orthogonal to what we get from the dominant oscillatory signal
    - The interplay of mass ratio and inclination angle estimate is especially interesting use case for memory

Utility of memory

- Detection of displacement memory will in itself be a proof of BMS symmetries and soft theorem validity. There are several efforts ongoing, till date memory is not detected.
- Here we present some consequences/utility of memory for GW astronomy
  - We present how memory can aid the detection of **tidal disruption** event in the case of neutron star black hole binary
  - We present how the various **EoS effect the BNS post merger** signal memory and their detection prospects
  - We present the search for **ultra-light CBC** made possible only through memory

Leveraging memory to infer the nature of compact objects: Idea

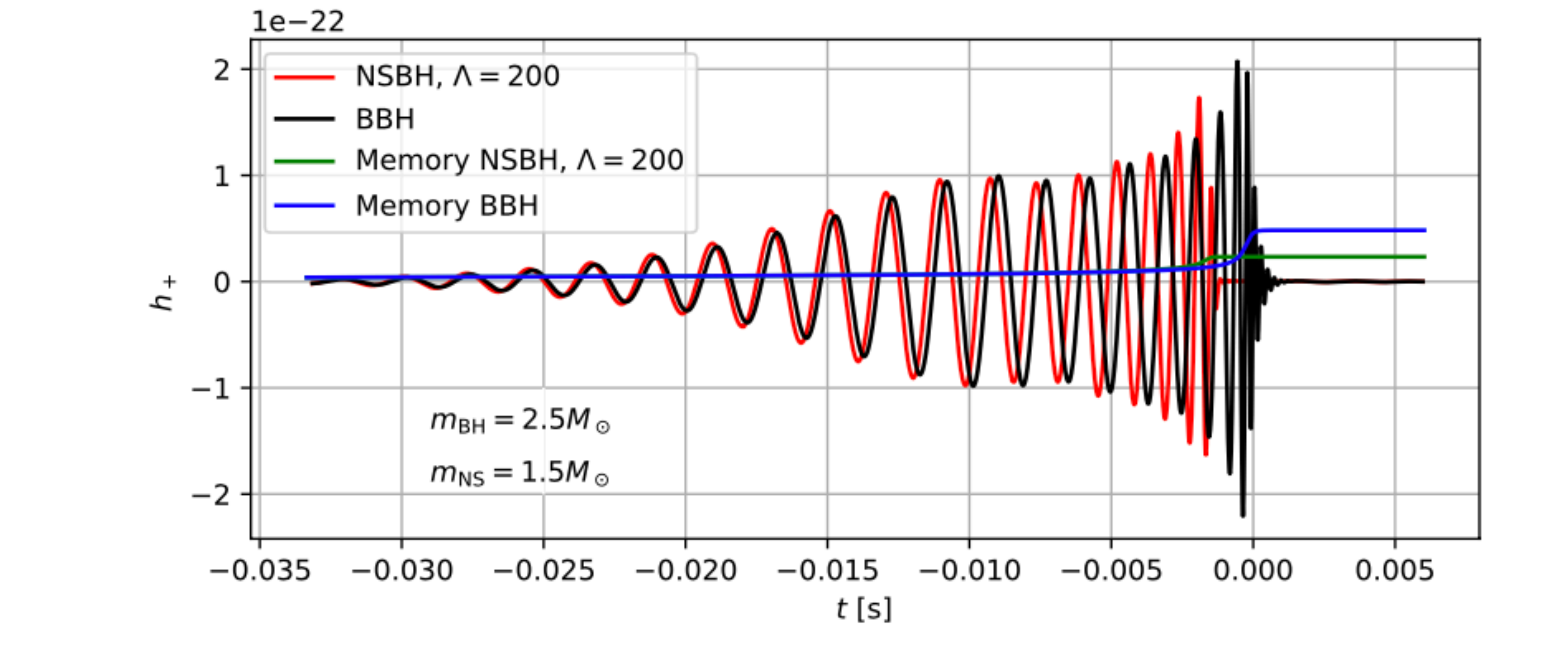
- Distinguishing between NSBH and BBH systems challenging (more challenging than distinguishing between BNS and BBH systems as two components show tidal deformation)
- A smoking gun for a NSBH detection apart from just the mass estimate would be a *tidal disruption event* : Neutron star disrupted by the black hole around or before the inner most stable circular orbit
- Memory signal is very subdued for tidal disruption events when compared to non tidal disruption events (GW radiation)
- Memory provides a near perfect complement, as it peaks for the edge-on systems where masses are equal to help distinguish between a tidal disruption event with a non tidal disruption event

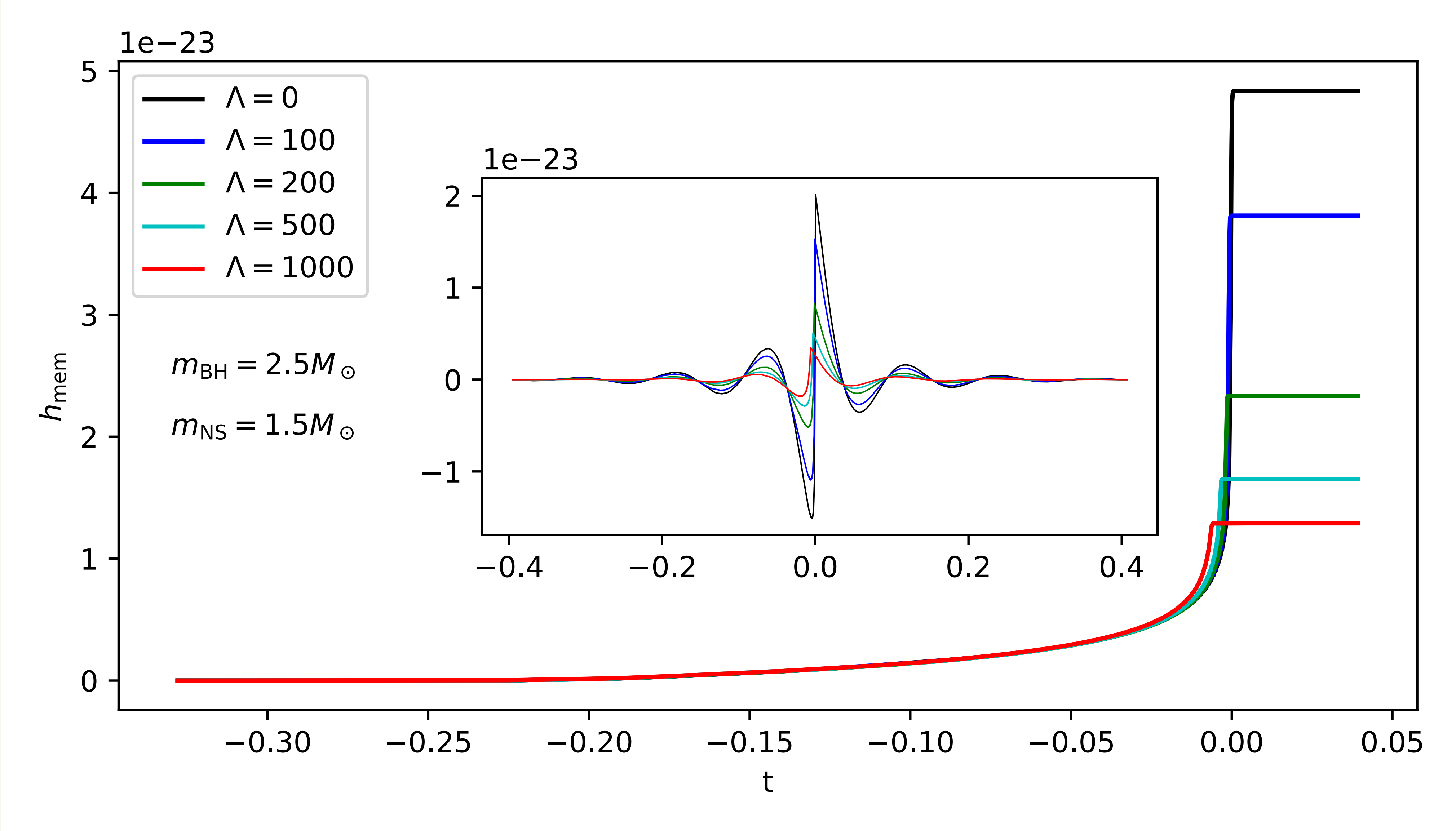


Taken from Metzger & Berger

Leveraging memory to infer the nature of compact objects

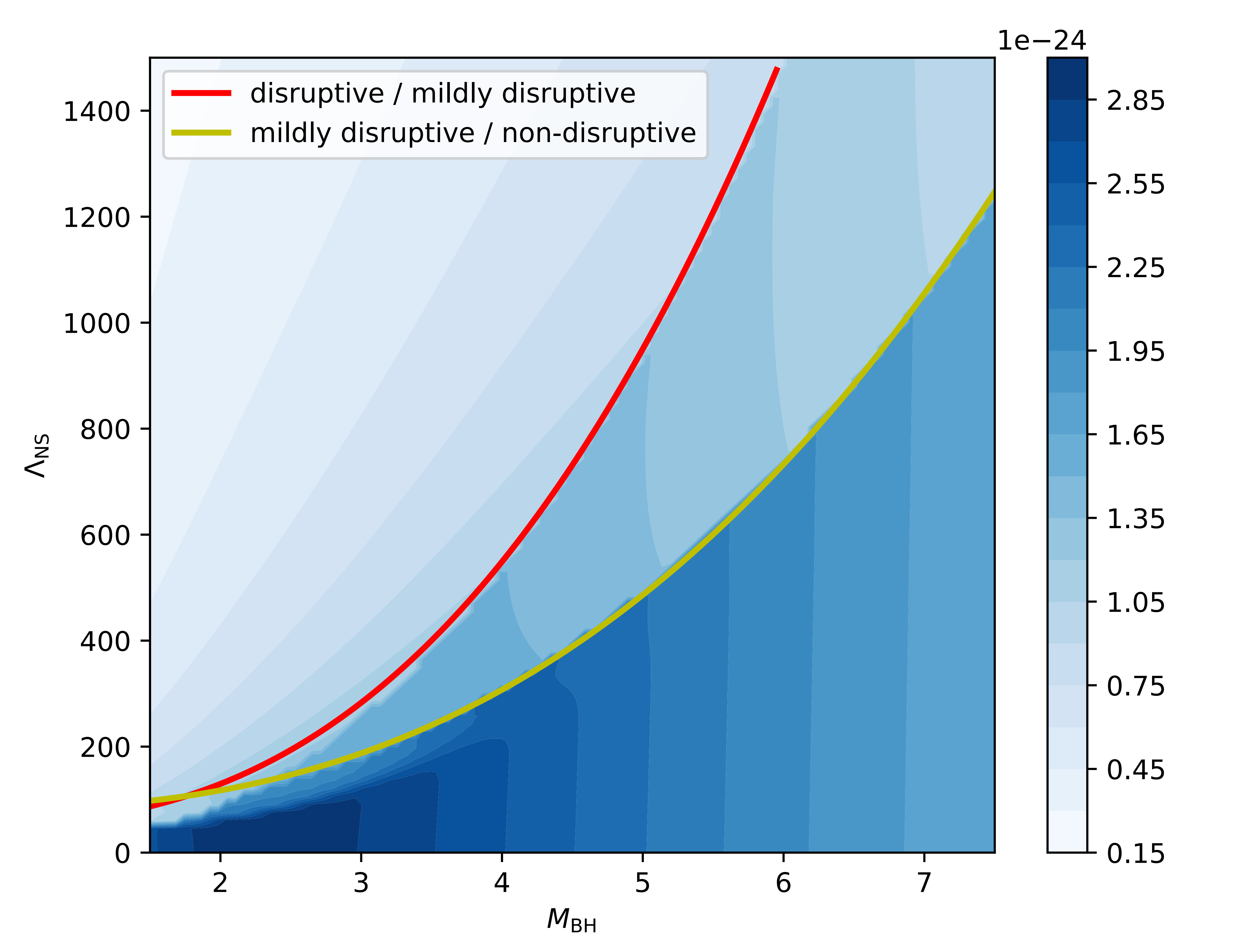
- We compute the memory from the NSBH model SEOBNR_NSBH which has tidal disruption physics
- We show that memory signal is sensitive in amplitude to the nature of the system BBH (no tidal disruption, maximum memory) NSBH (tidal disruption, minimum memory)





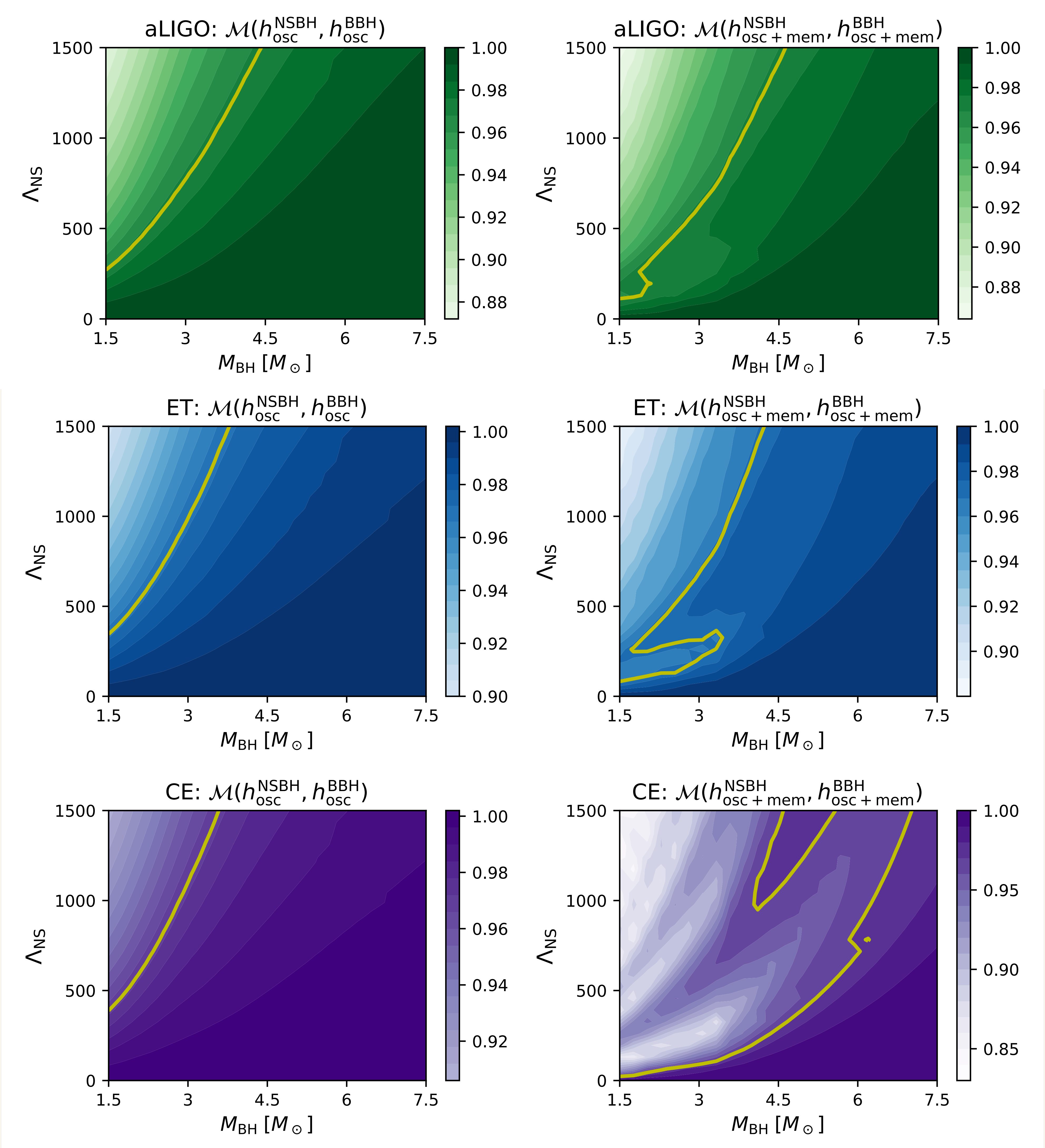
Leveraging memory to infer the nature of compact objects

- Memory signal almost is fully correlated to the oscillatory signal definition of the three cases of tidal disruption
  - NOTE : Memory peaks at more edge-on systems so EM counterpart is not expected there



Leveraging memory to infer the nature of compact objects

- We add the memory to the full oscillatory waveform of NSBH system and compare how memory can aid
- The contours are the matches (overlaps between waveforms) on the left its only the oscillatory signal on right its the full oscillatory with memory
- The yellow line define the 90% distinguishability criteria
- We clearly see that for the upcoming generations of detectors memory will increase the parameter space significantly where we can find a tidal disruption event

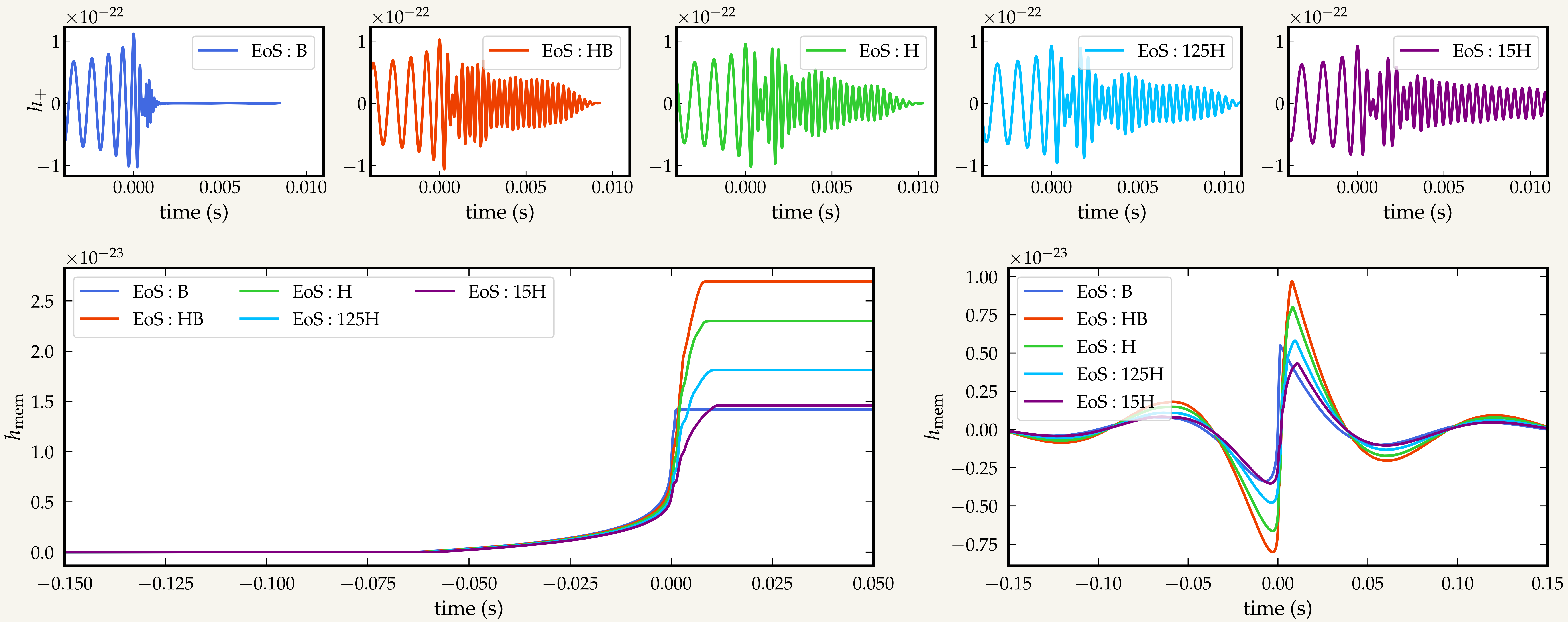


Tiwari, Ebersold, Hamilton PRD 2021

Binary neutron star : post merger memory

- In this work we further move ahead in the direction of matter effects and work on memory from the binary neutron star systems
  - While thinking about the BNS systems one can not ignore the post merger part of the signal while considering the non linear memory contribution.
  - NSBH systems always form remnant black holes, this makes NSBH simpler in this regard.
- Thanks to very high quality and numerous NR waveforms from CORE and SCARA databases we have done “extensive” work on categorising non-linear memory from BNS post merger signal

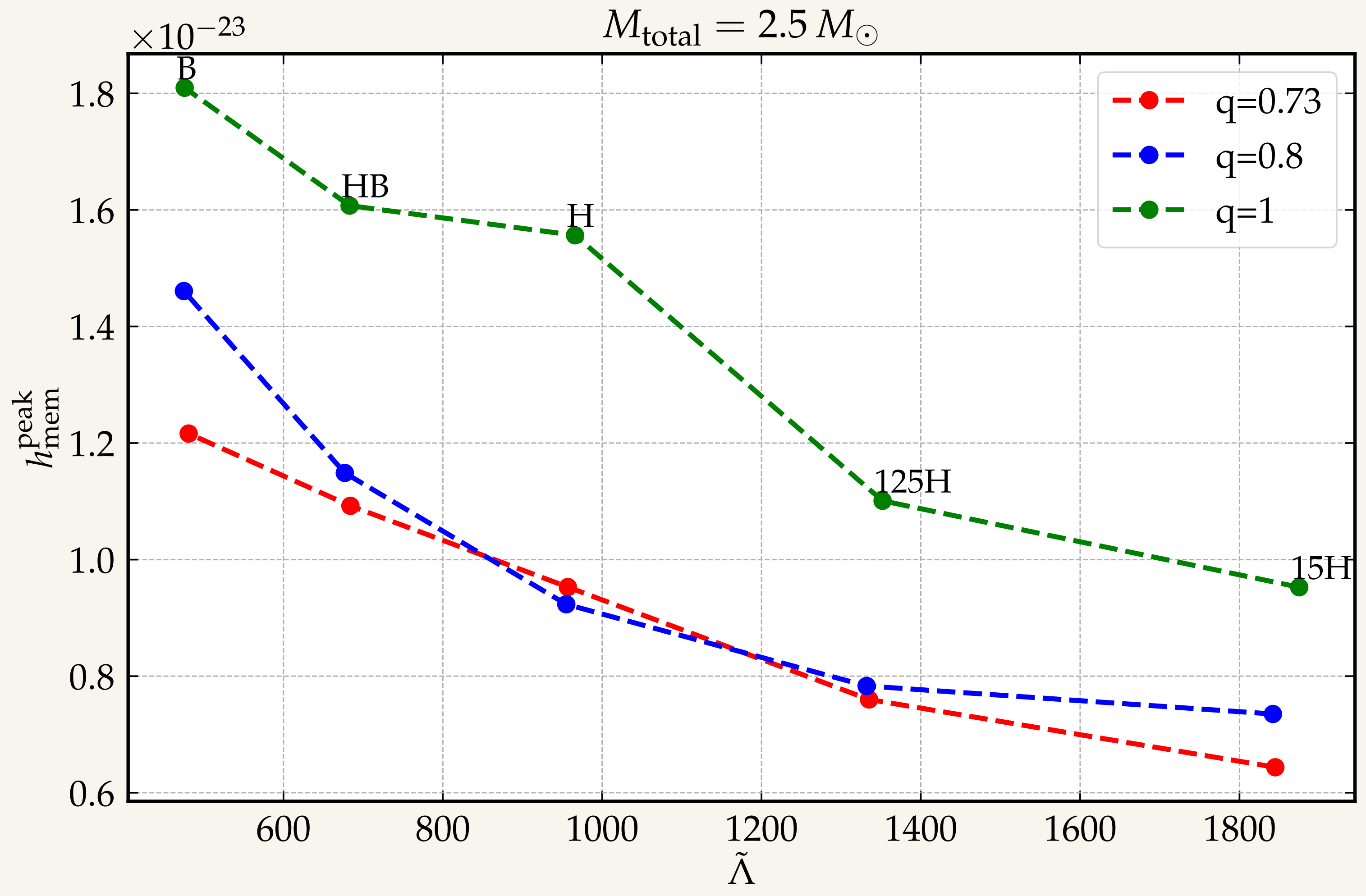
Binary neutron star post merger memory

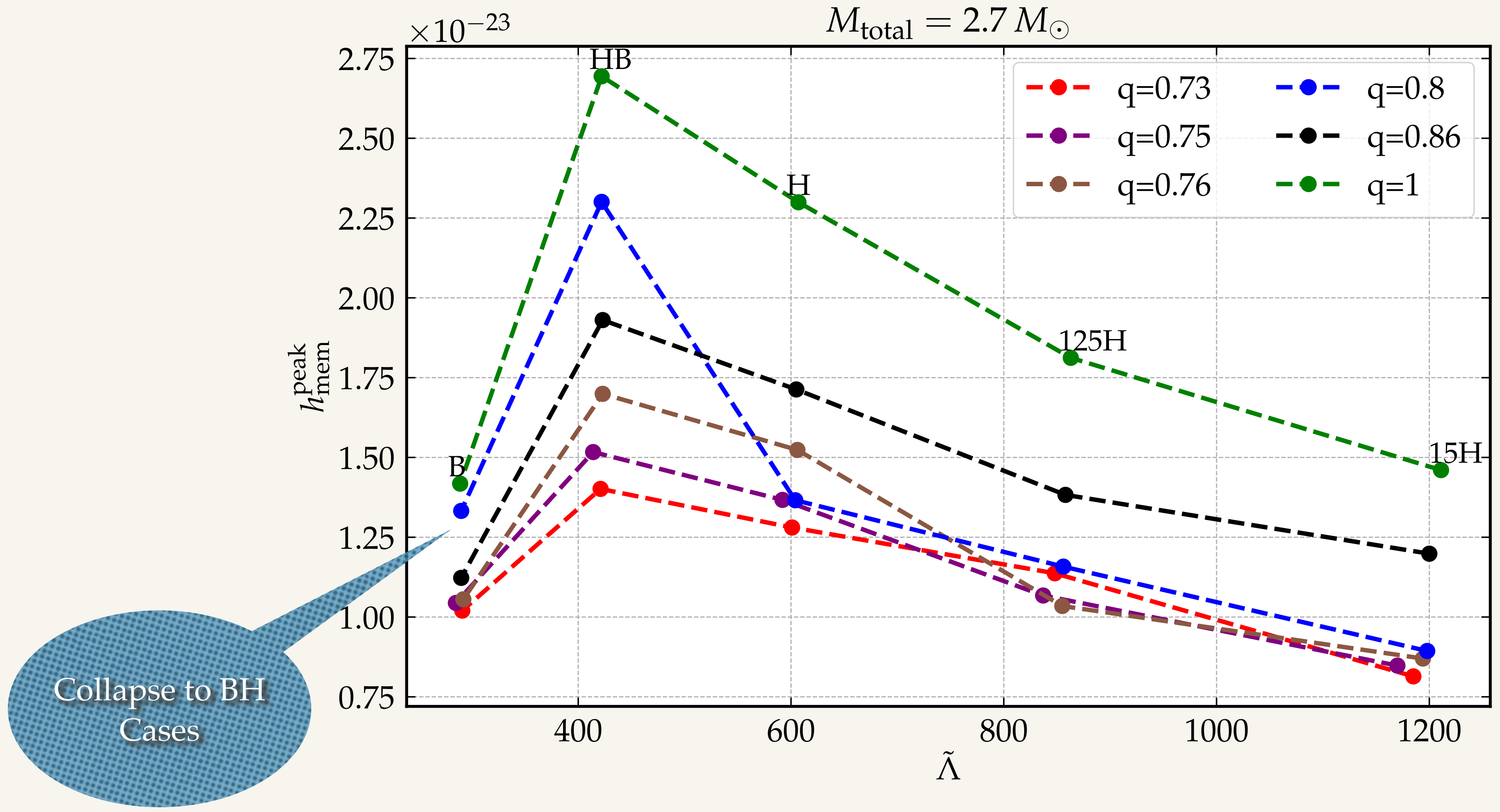


- We illustrate some oscillatory post merger NS signal with various EoSs, from softer to harder (low tidal deformability to high)
- This part of the talk is based on in work by *Lopez, Tiwari, Ebersold 2305.04761*

Binary neutron star post merger memory

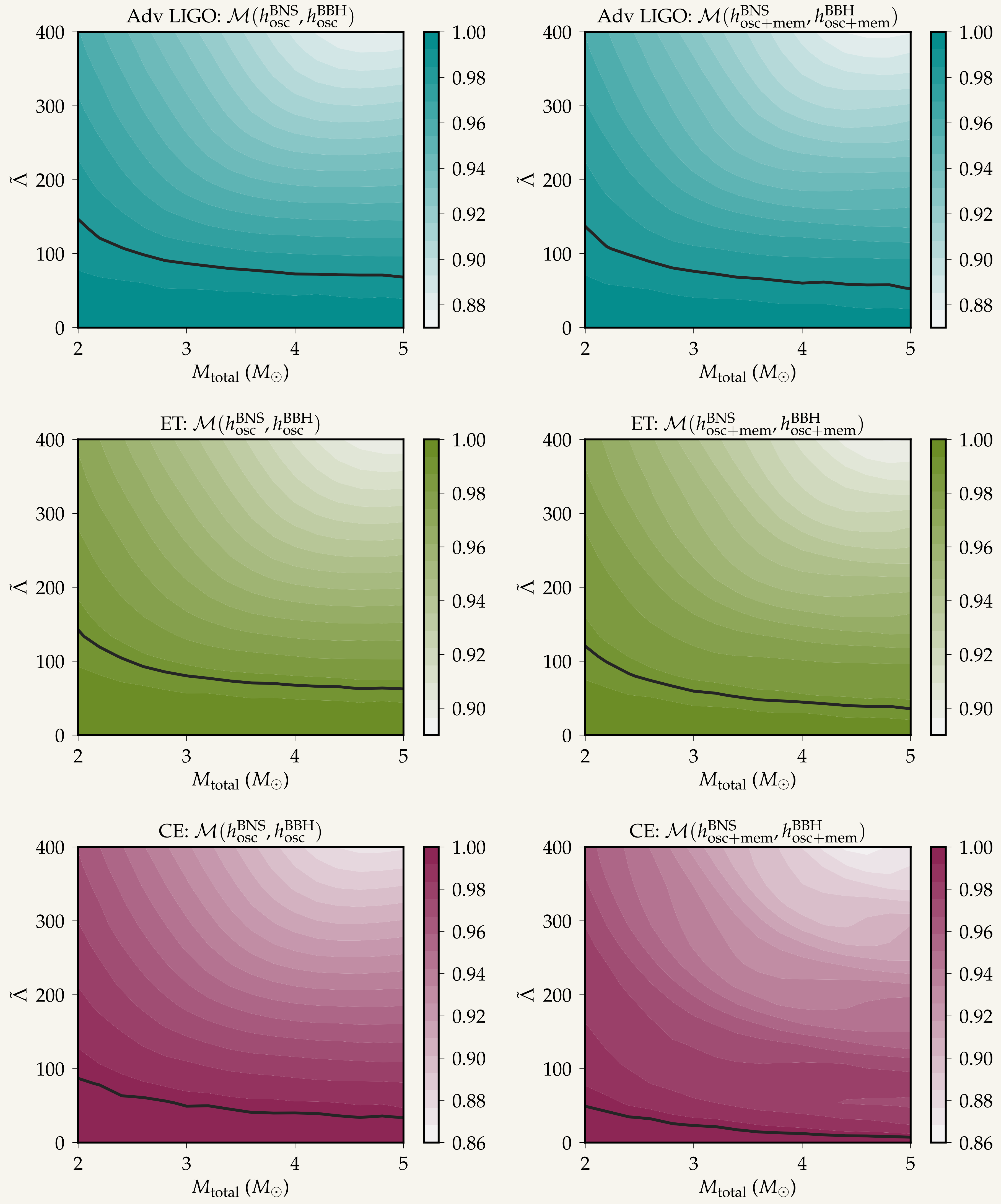
- Binary neutron stars when they have low enough mass and hard (large Lambda) enough EoS will show post merger signal post merger
    - The memory content of post merger signal is not negligible
    - If after merger the remnant collapse quasi-instantaneously to a BH then there is no post merger signal and no post merger memory
- We find that as a function of tidal deformability parameter (softer - harder EoS) the memory monotonically decreases
    - The memory signal is proportional to the energy emitted and hence we can also infer that the post merger signal energy also decreases as a function of tidal deformability parameter





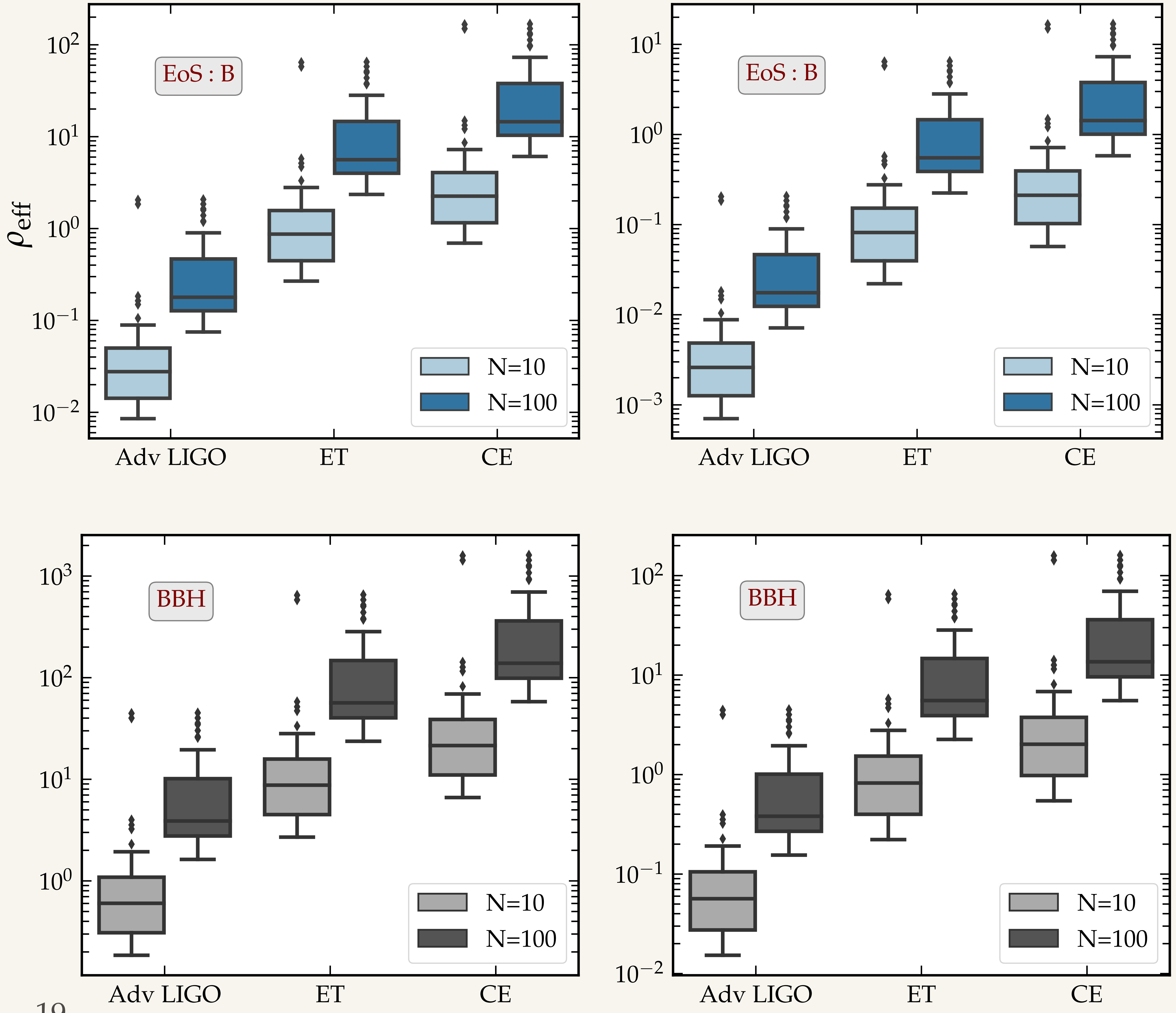
Binary Neutron star post merger memory

- The cases when the post merger part of the signal is available (and detected) it is smoking gun for a BNS system.
    - The utility of memory in this case is limited as compared to the NSBH case and the post merger part will have much higher SNR
- Memory is useful only in the so called lower mass gap $(3 - 5M_{\odot})$
    - In this case memory can help in distinguishing between BBH and BNS systems as the BNS system will also directly collapse to BH with no post merger signal



Binary Neutron star post merger memory : Population of events

- We further study if a population of BNS events will allow us to detect post merger NS memory and can in principle lead to distinguishing from the BBH system
- Cumulative memory SNR of 10 and 100 events corresponds to advanced LIGO, Einstein telescope, and cosmic explorer design sensitivity.



Linear memory : Detectability of GRB jet

- Unbounded ejecta from BNS/BHNS merger must produce a GW signal in form linear memory (*Birnholtz and Piran 2013*)
  - But now we have NR and we know more about the properties of ejecta.
  - We know the velocity distribution of the ejecta and the fraction of it being unbounded
- We compute the linear memory for all the NR waveforms that we considered using ejecta mass and velocity from NR simulations, we found that amplitude of linear memory will be at least 2 orders of magnitude smaller than non-linear memory of the BNS merger/post-merger

$$\Delta h = \frac{2G\, m_{\rm ej}\, v_{\rm ej}^2}{c^4\, r}$$

- Not detectable even with ET and CE

Conclusions

- Memory is a particularly resourceful feature in GW, which can be used to extract a lot of interesting and sometimes unreachable physics!
  - Memory is not yet detected but this is just a matter of time*
- We have explored the various consequences that memory especially the matter effects
  - These by no means completes the utility of memory in this regime
- We are now moving on with the studies of spin and eccentricity with non-linear memory

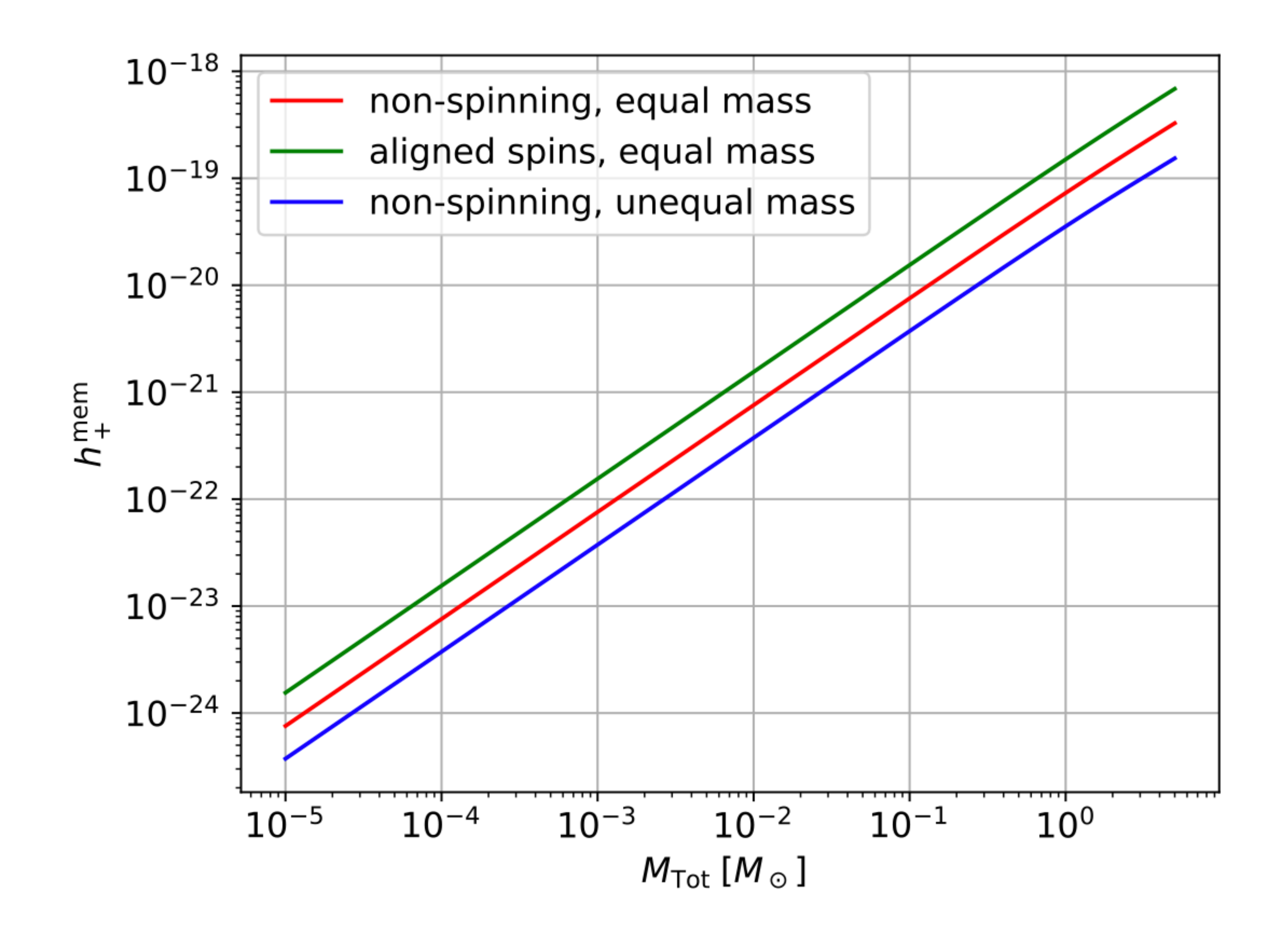
Thanks for your attention

Search for non-linear memory from ultra light CBC: Idea

- Sub-Solar mass CBC can be visible during the inspiral phase if the components are sufficiently massive (> 0.4 solar mass)
- Sub-solar mass matched filter search is computationally very demanding (very long signal !!)
- We note that the merger of CBC which are less than 0.4 solar masses the memory will lie in the band of out present day detectors for very nearby events

Search for non-linear memory from ultra light CBC

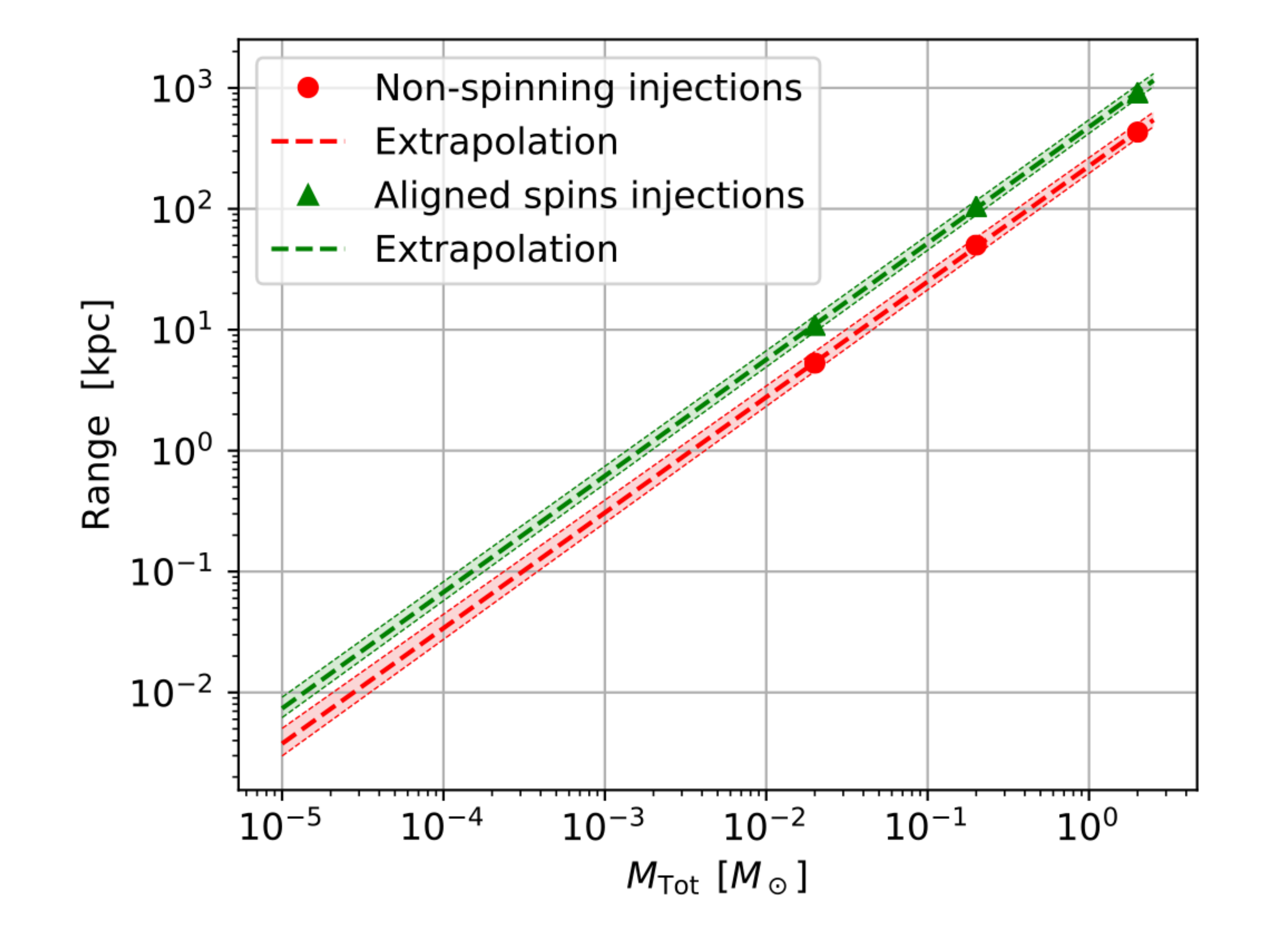
- We use the NRSur waveform model for the oscillatory waveform and compute the memory for only the merger part of the signal
    - The memory contribution from early time inspiral is directly related to emitted GW radiation
- We study the dependancy of the memory amplitude as a function of mass ratio and spins for very light BBH waveforms



Unequal mass
Mass ratio 3

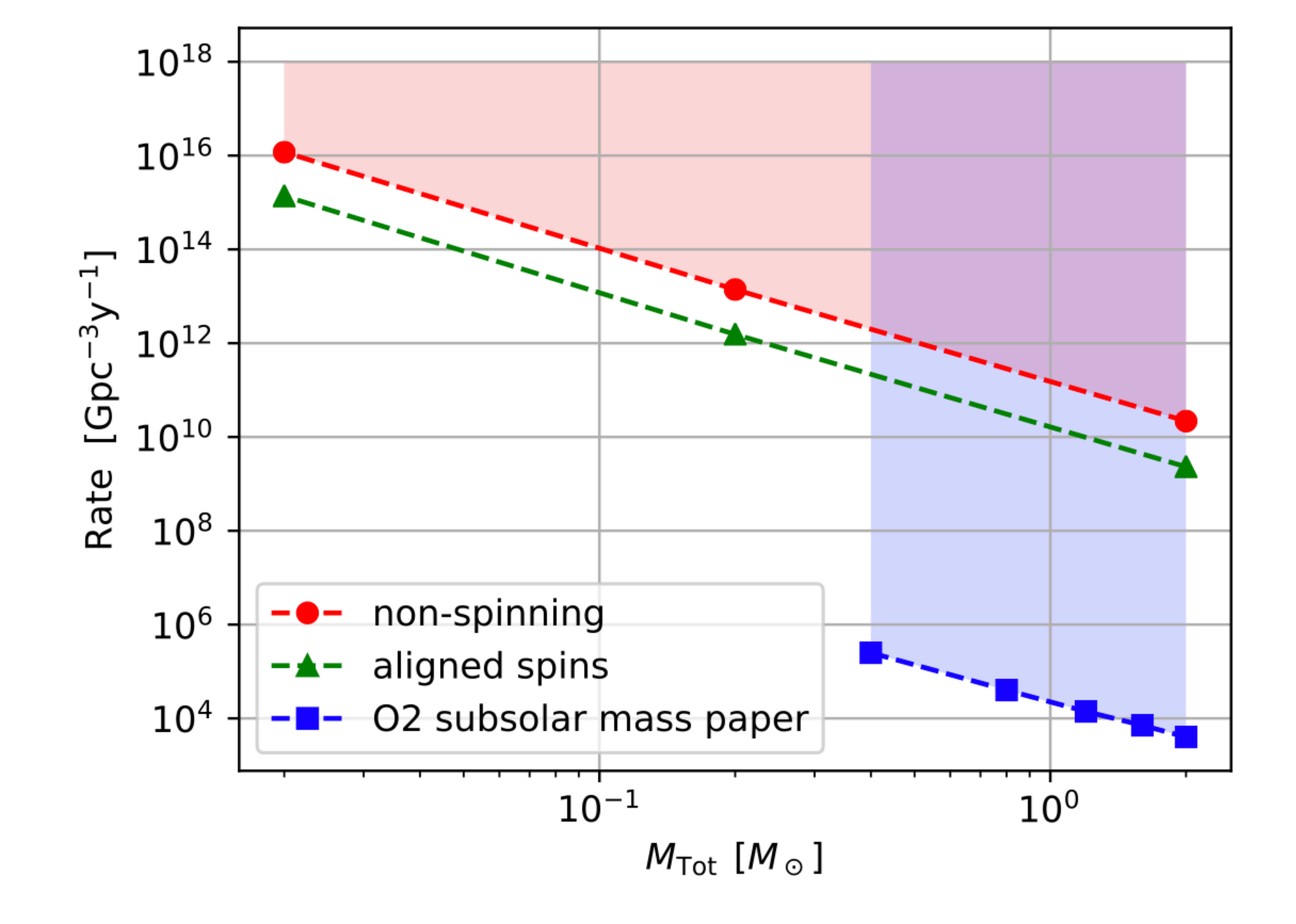
Search for non-linear memory from ultra light CBC

- cWB search is indeed sensitive to memory bursts
- We find the range (iFAR ≥ 1yr) of the search by injecting 6 different memory signals in O2 data (equal masses, 3 non-spinning, 3 with 0.8 aligned spins)
- Range scales linearly with total mass of the system, can be extrapolated to arbitrarily low masses



Search for non-linear memory from ultra light CBC

- Constraints from memory are not competitive with matched-filter searches for the corresponding oscillatory signal (reported e.g. in LIGO O2 subsolar mass paper, arXiv:1904.08976)
- However, memory only search expands the parameter space to masses below $M_{Tot} \leq 0.4 M_{\odot}$

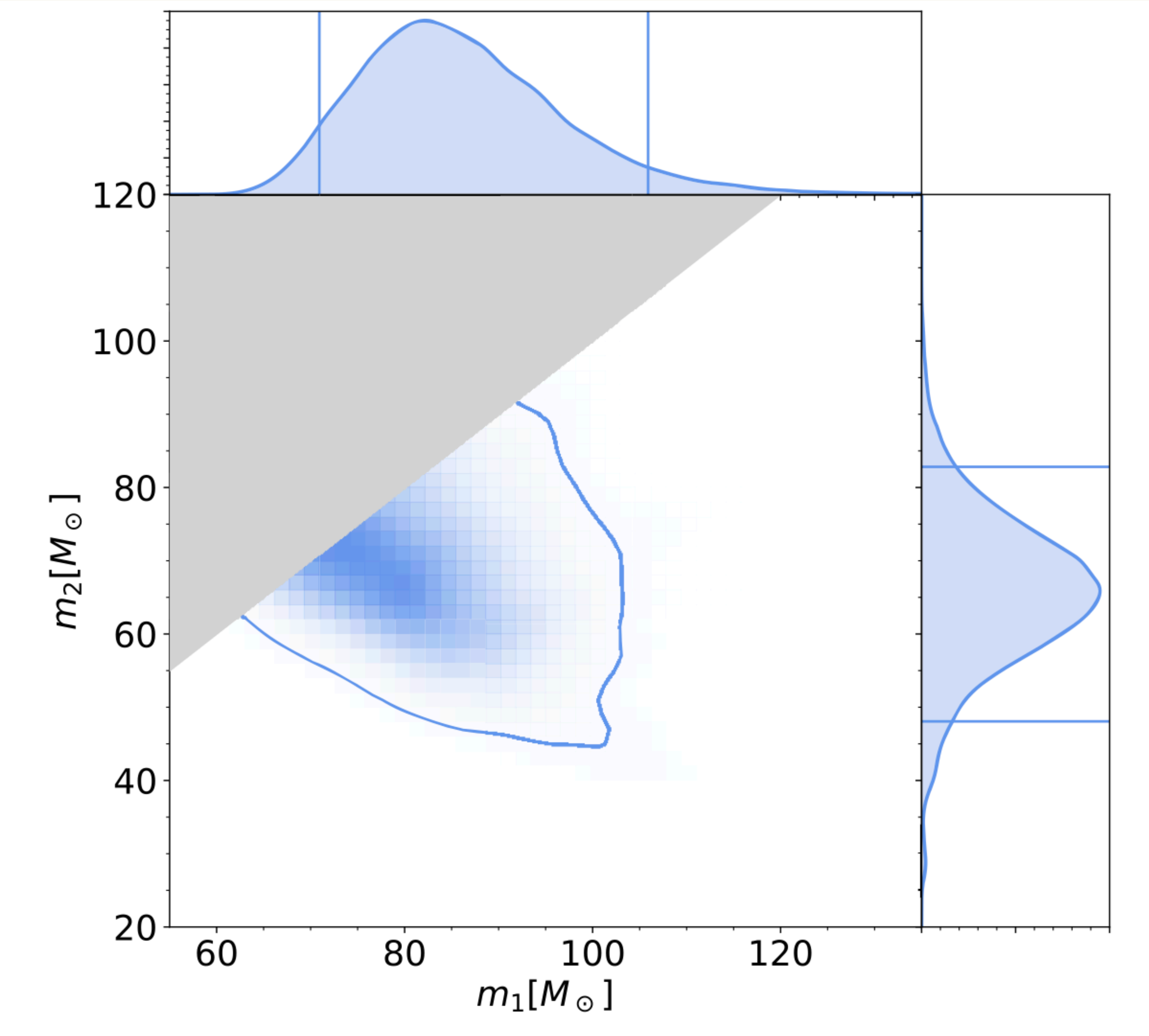


Upper limit on binary merger rate

Ebersold and Tiwari PRD 2020

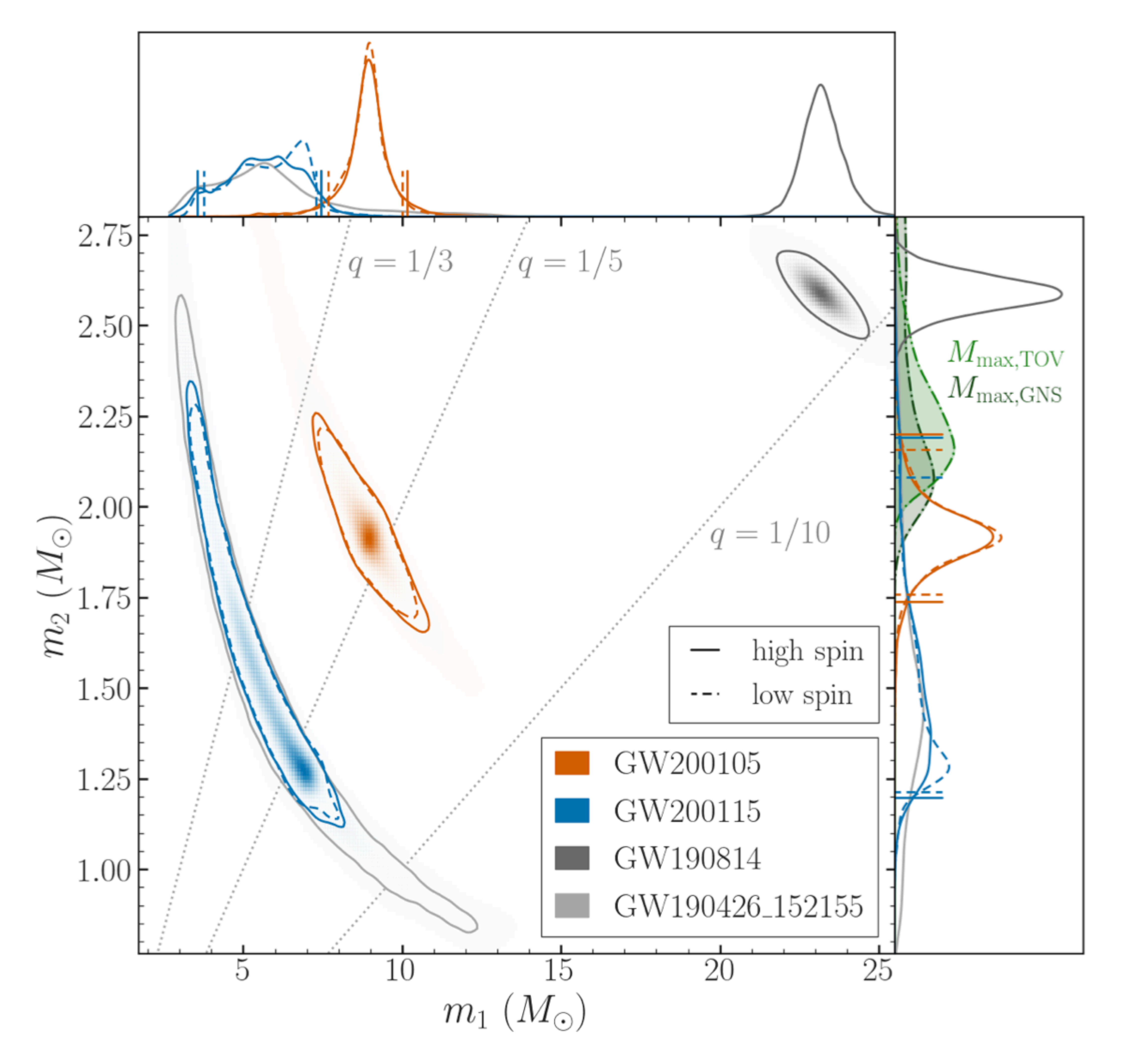
Gravitational waves : “Interesting” events

- GW190521 under the assumption of CBC has un-ambiguously both components way above 3 solar masses
  - There is a hint for in-plane spin*
  - The heavier component’s mass has probability of only 0.32% of being lower than 65 solar masses (within the gap of pair instability supernova)
  - The remnant is confidently above 100 solar masses (our definition of intermediate mass black hole)



Gravitational waves : “Interesting” events

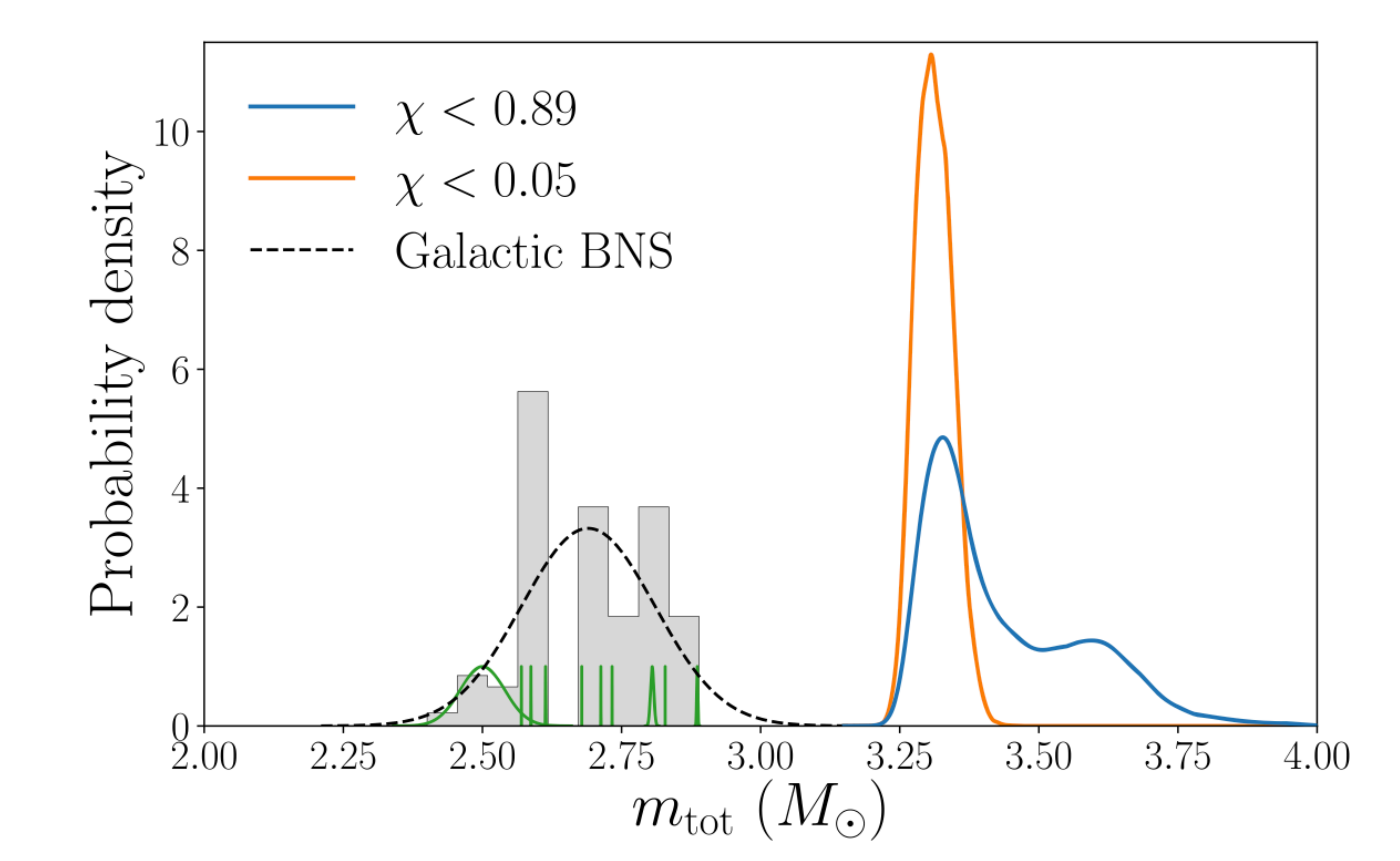
- The two NSBH events (blue and orange) in the picture both have the lighter component less than 3 solar masses and the heavier greater than 3 solar masses
  - We consider objects less than 3 solar masses to be a candidate for neutron stars conservatively
- GW190814 was also an event (grey) with lighter component less than 3 solar mass and the heavier much larger than 3
- In the absence of the tidal deformation parameters we rely on masses for the lighter components



The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20
Astrophys.J.Lett. 915 (2021) 1, L5

Gravitational waves : "Interesting" events

- The BNS event GW190425 was also peculiar the total mass of the detected BNS event was confidently larger than the total mass of other double NS systems that we have observed
- This BNS detection was not accompanied by any electromagnetic counterparts



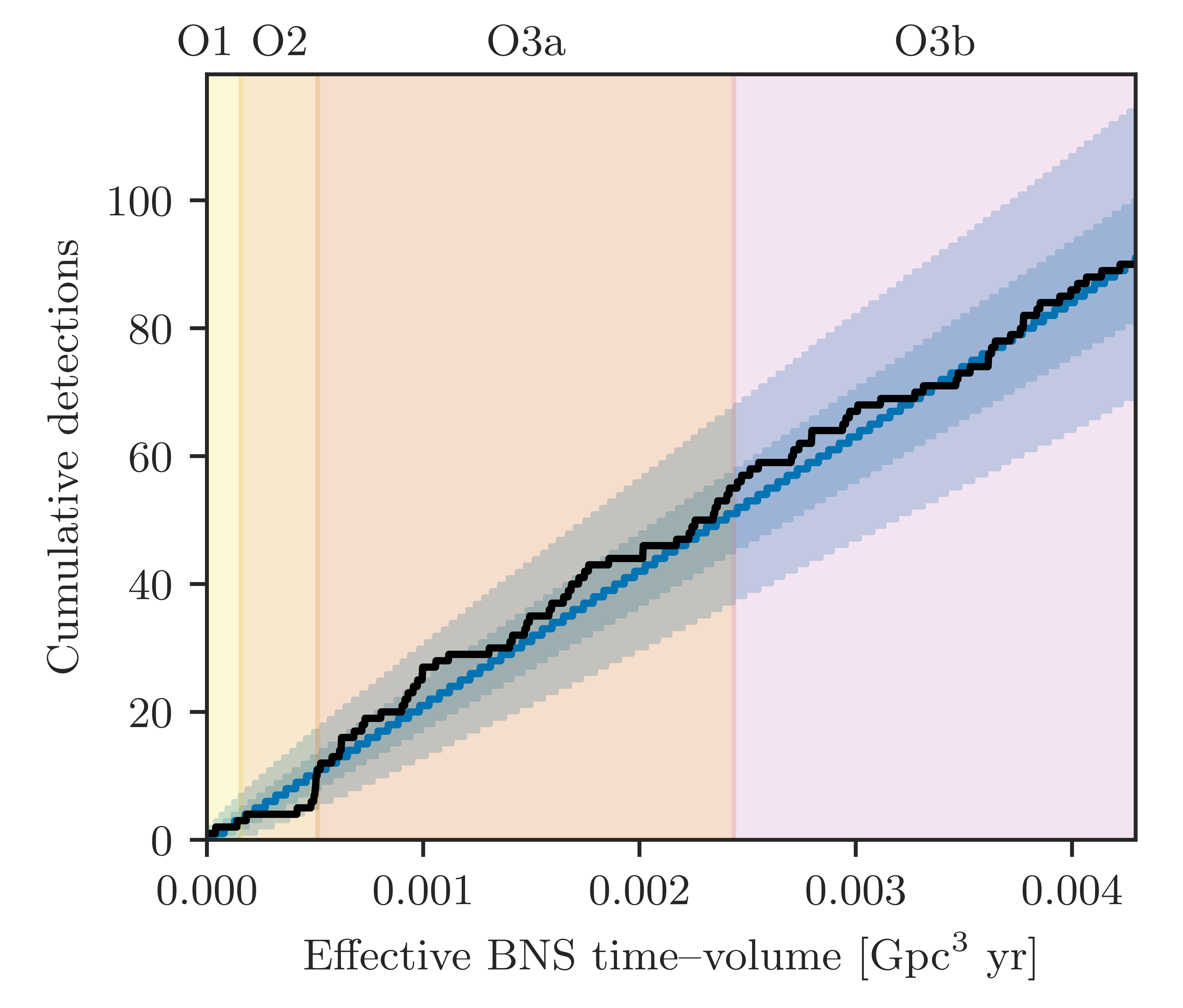
The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20

Leveraging memory to infer the nature of compact objects

- For the interesting events (red bold events before) we ran cWB in the targeted reconstruction setting to find any memory signal
- For the 2 NSBH and the one with ambiguous companion the mass ratio is too high for tidal disruption and also for the memory signal
- For the BNS we find the loudest on-source event with p-value 0.4 (too high), for a detection we would have need the binary at 2 Mpc !
- NOTE : The poor sensitivity is not only because of the detector sensitivity but for the BNS it was only one detector which was operating making it hard to remove false alarms.

Gravitational waves : Current status

- LIGO and Virgo interferometers have finished their third observing run, the fourth run started in May
- They have detected over 50 gravitational waves events all associated with compact binary coalescence (CBC) mergers till date
- The third observing run saw some exceptional* events, these include
  - **GW190521** : Intermediate mass binary black hole
  - **GW200105, GW200115** : 2 Neutron Star Black Hole binaries
  - **GW190814** : Ambiguous lighter companion
  - **GW190425** : Heavy double Neutron Star event with no electromagnetic counter part



Black curve shows the detected events, blue is the expected curve

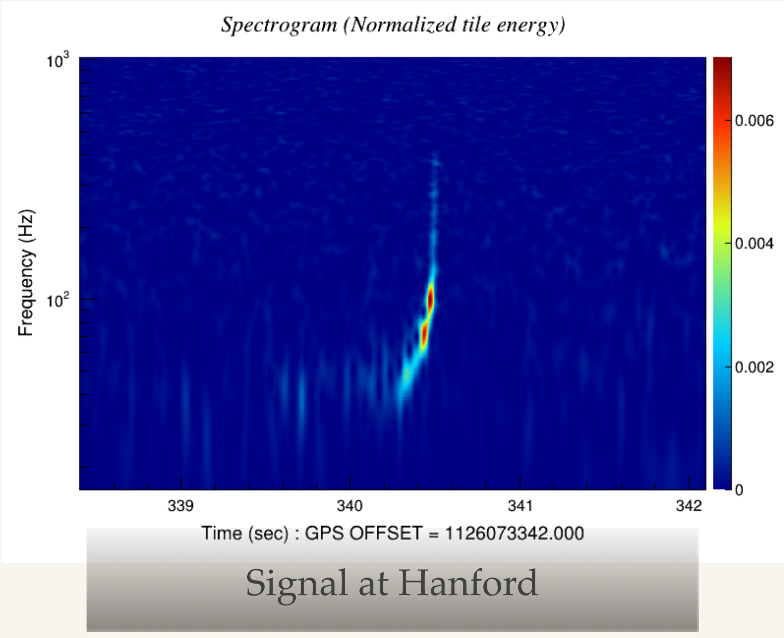
*exceptional for me

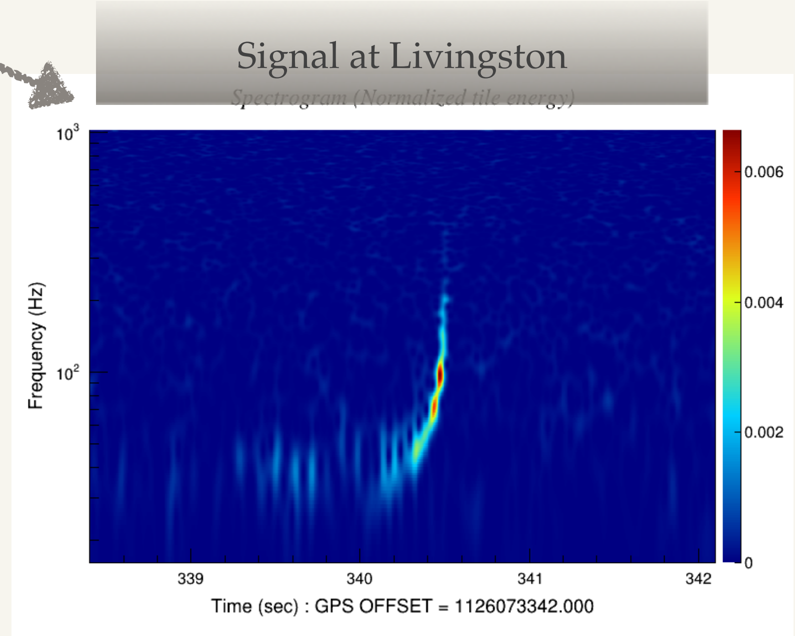
Gravitational waves : “Interesting” events

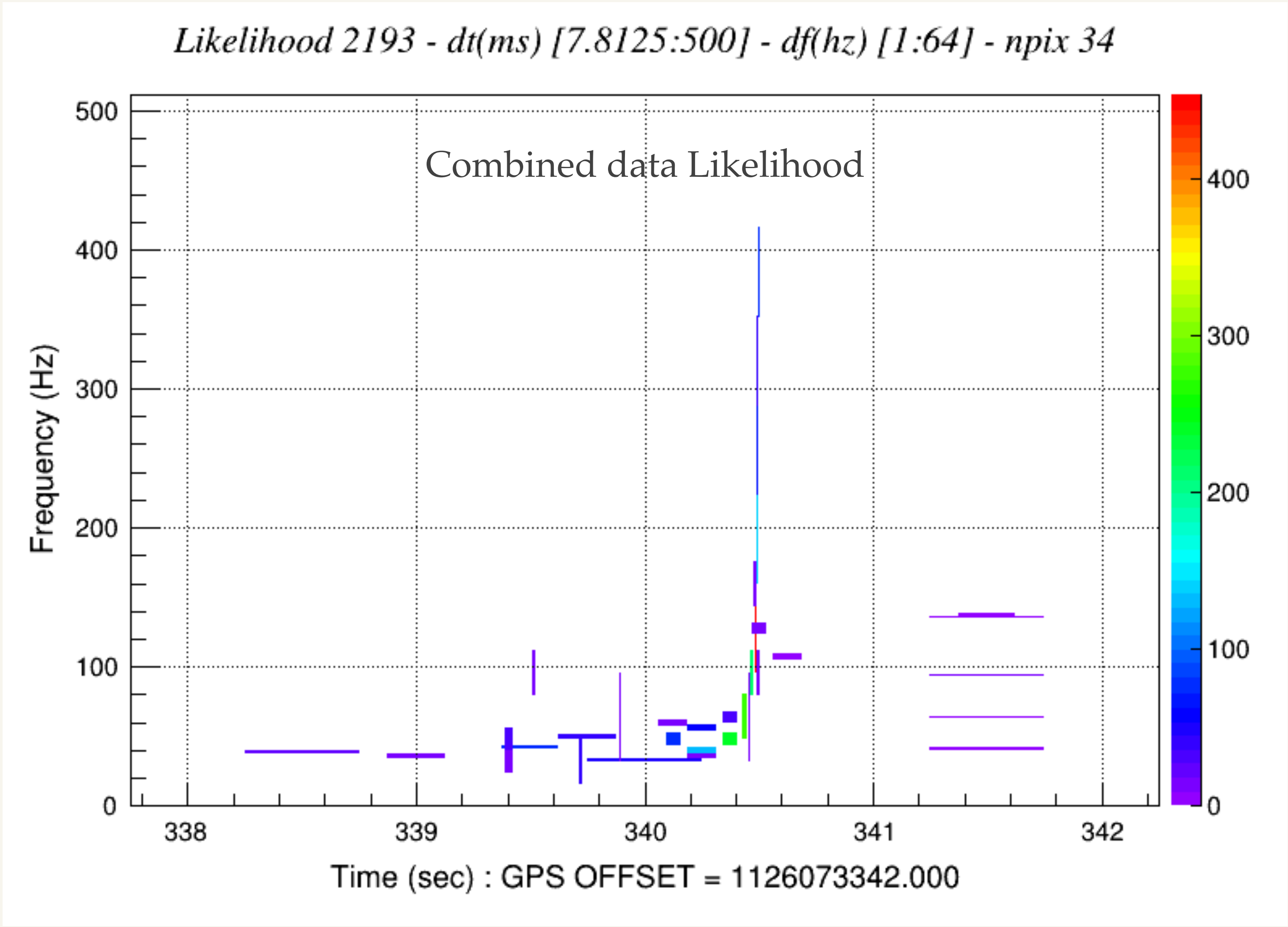
- Henceforth I call these events interesting
  - **GW200105, GW200115** : 2 Neutron Star Black Hole binaries,
  - **GW190814** : Ambiguous lighter companion,
  - **GW190425** : Heavy double Neutron Star event with no electromagnetic counter part
- I leave alone **GW190521** as the masses are so high that in any non-exotic sense they should be a BH (BH-like)
- With the detection of event with light mass companions less than 3 solar masses, we are beginning to uncover a population of such events which are not yet un-ambiguously Neutron Stars
- To confidently claim an object to be a NS one relies on mass but is not the safest option
  - The safest option is to prove that the object shows tidal deformation, measuring tidal deformation effects are challenging since they are weak and also they occur at high frequencies where detectors are not most sensitive
  - In this case non linear memory can play a role!!!

Detection methods for GW memory : The generic search algorithm

- Memory manifests itself as a bursts like single cycle event
- We employ bursts search called as *coherent Wavebursts* (cWB) to detect and reconstruct the memory signal
- cWB relies on the excess power above the noise floor of the network of detectors to make a pre-selection of time frequency pixels
- Exploits the presence of signal (energy) in multiple detectors to appear coherently i.e. consistent in time and sky location







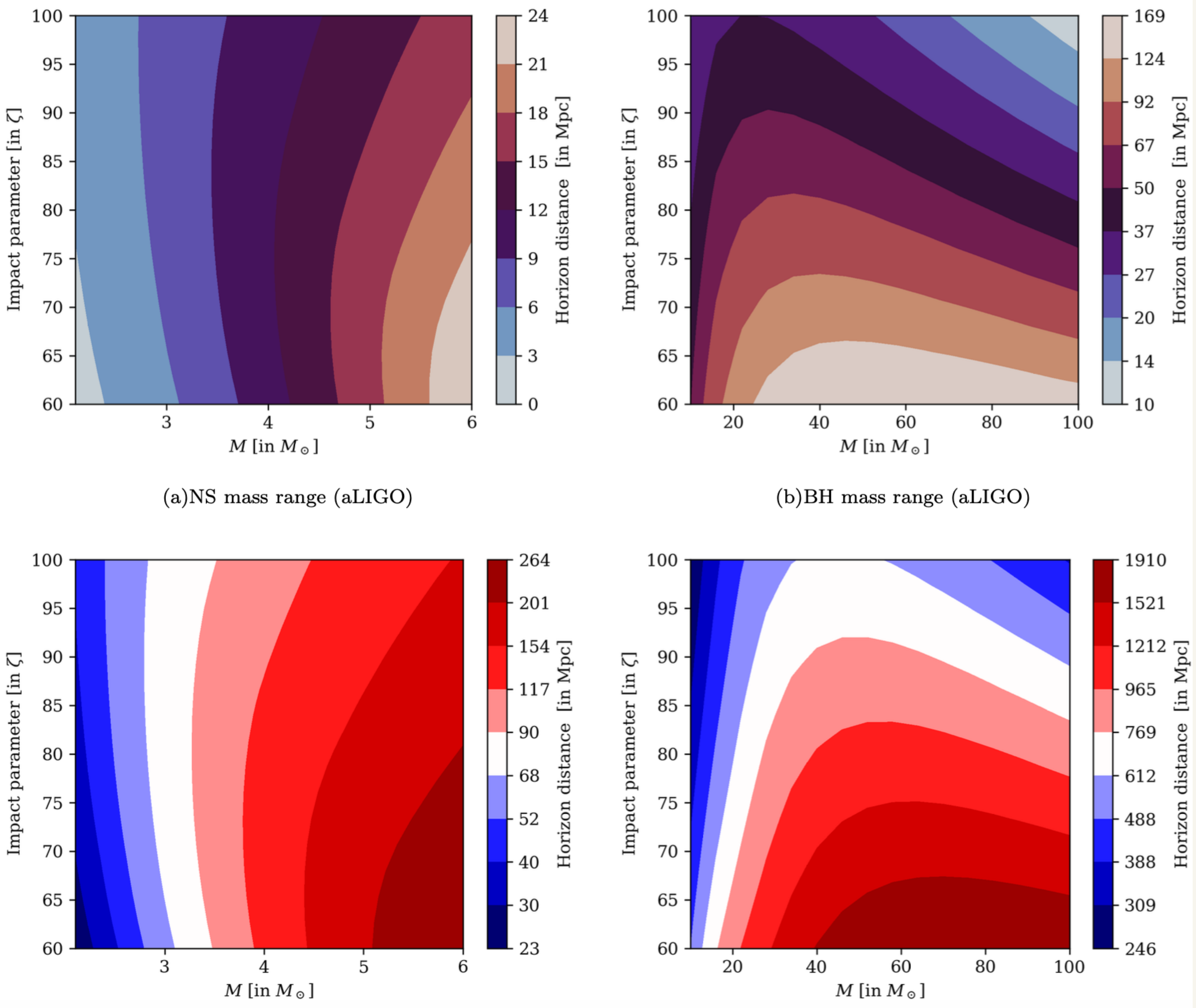
Detection methods for GW memory

- For the search of memory only signal in data we just run cWB throughout the data set to find events which resemble memory signal
- In order to reconstruct memory signal from already detected events we restrict cWB analysis to an on-source window of time and frequency and then compare the results with the surround off-source window to get the confidence estimate
    - A dedicated work in this direction is also underway*
- Our approach is frequentist
- Of course there are bayesian methods to detected memory see works by *Hubner,Lasky et al 2020*

*Andrea Miani PhD Thesis

Linear memory : Detectability of hyperbolic encounters of binaries

- We used the 3PN hyperbolic encounter waveform and studied the detectability of BNS and BBH hyperbolic encounters
    - We consider the usual SNR~8 to be the detection threshold the luminosity distance at this SNR we call this *horizon distance*
    - We consider LIGO as representative of current generation of ground based detectors and ET as the representative of next generation.
- The binaries are at fixed e=1.15 and mass ratio unity.



Based on Dhandapat, Ebersold, … Tiwari .. et al arXiv: 2305.19318