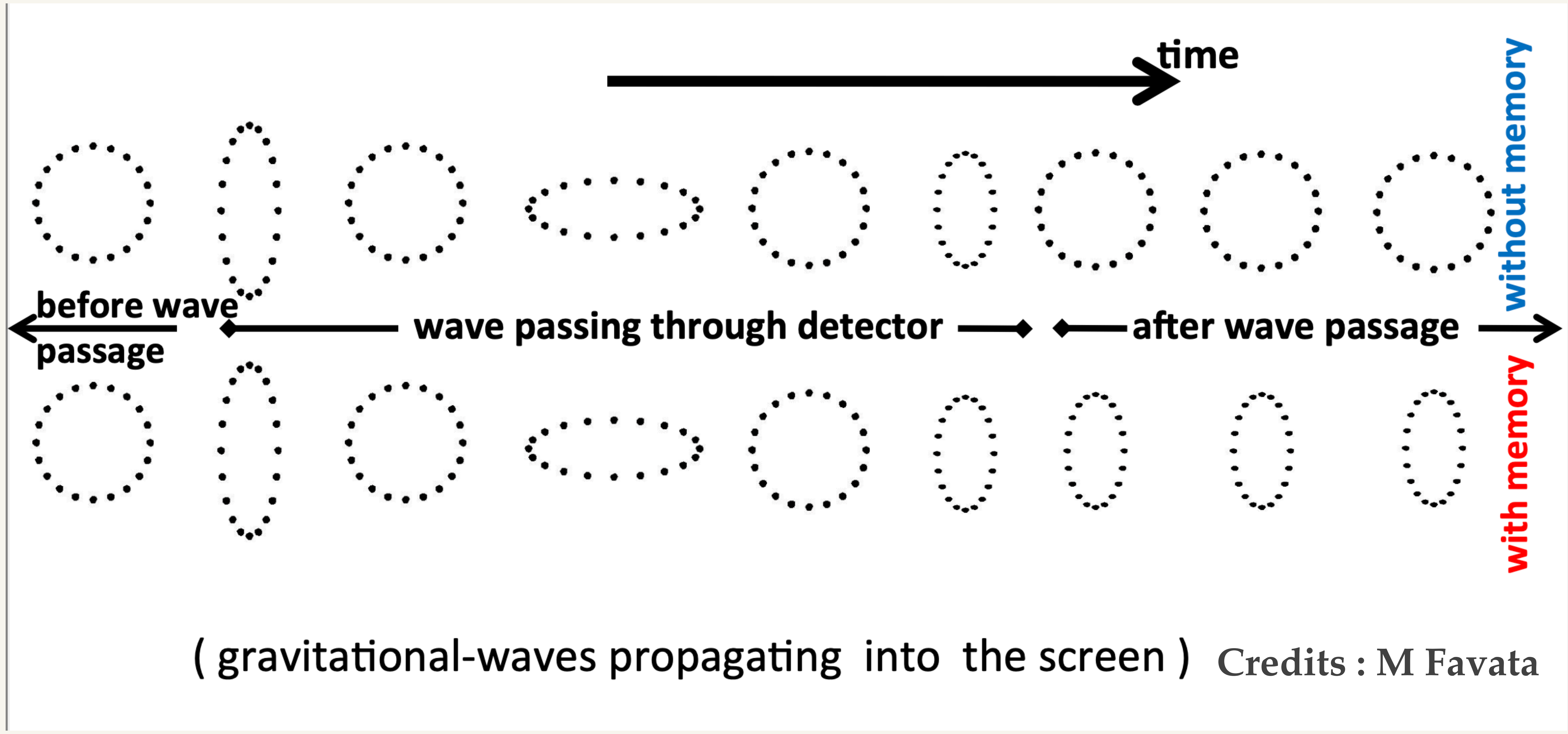
3 Sep 2024, Fundamental Physics meets waveforms with LISA, Potsdam, Germany

Observational consequences of gravitational waves non-linear* memory

Michael Ebersold, Dixeena Lopez, Eleanor Hamilton, Yumeng Xu, Henri Inchauspe, *Shubhanshu Tiwari* and others

*little bit linear memory as well

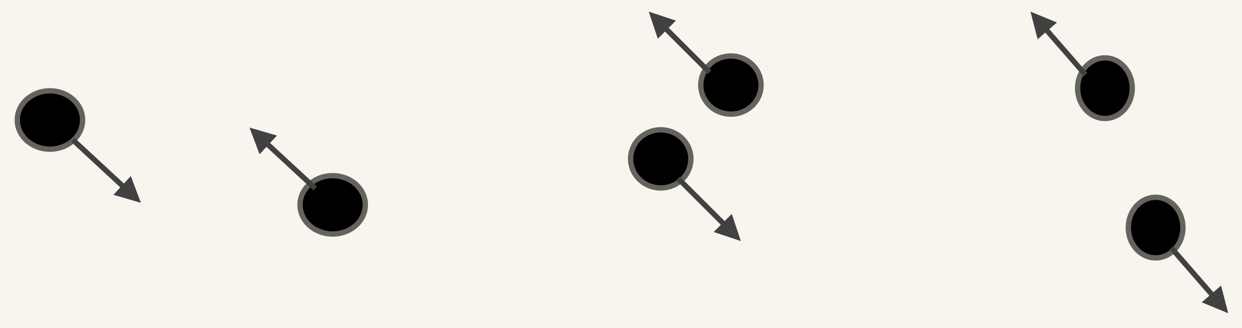
Heuristic: Memory of gravitational waves



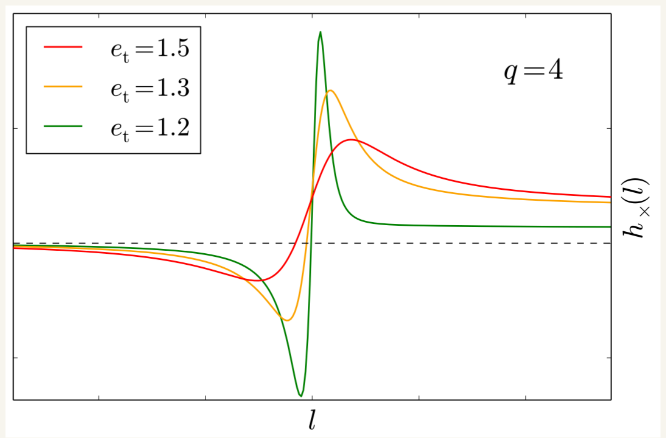
- GWs can permanently deform the space time
- When a GWs passes through an interferometer causes a permanent displacement of the mirrors.
  - We refer to this permanent deformation as "**memory**"
- The wave does not return to its zero point

Persistence of memory, S Dali, 1931

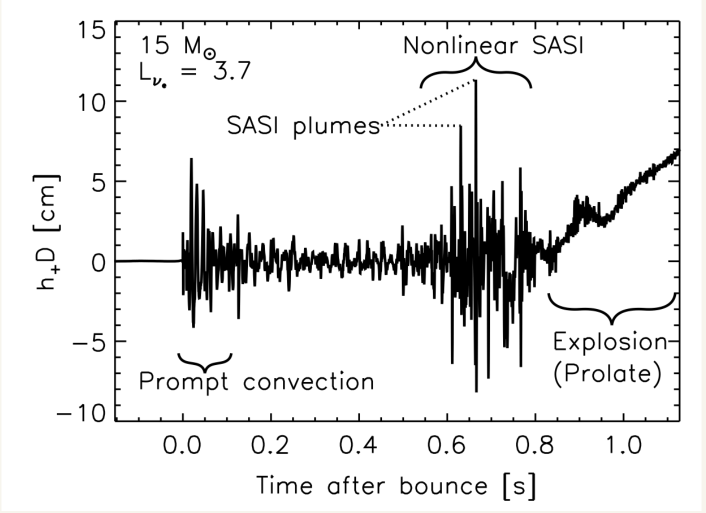
Heuristic: Linear and non-linear memory



Fly By Encounter

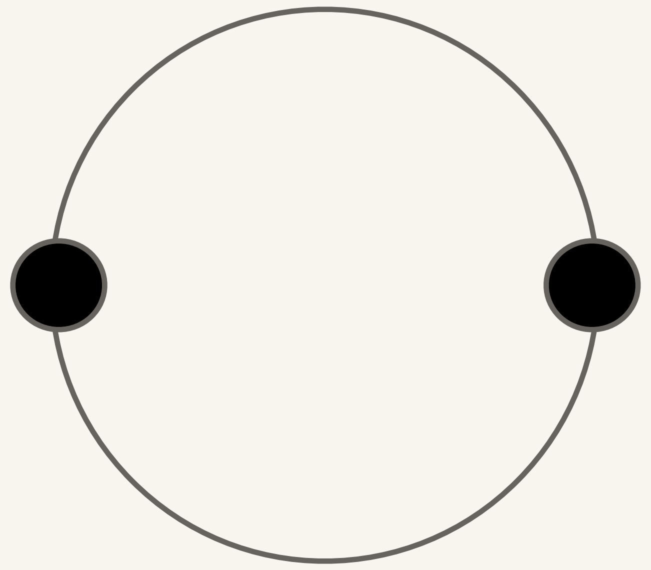


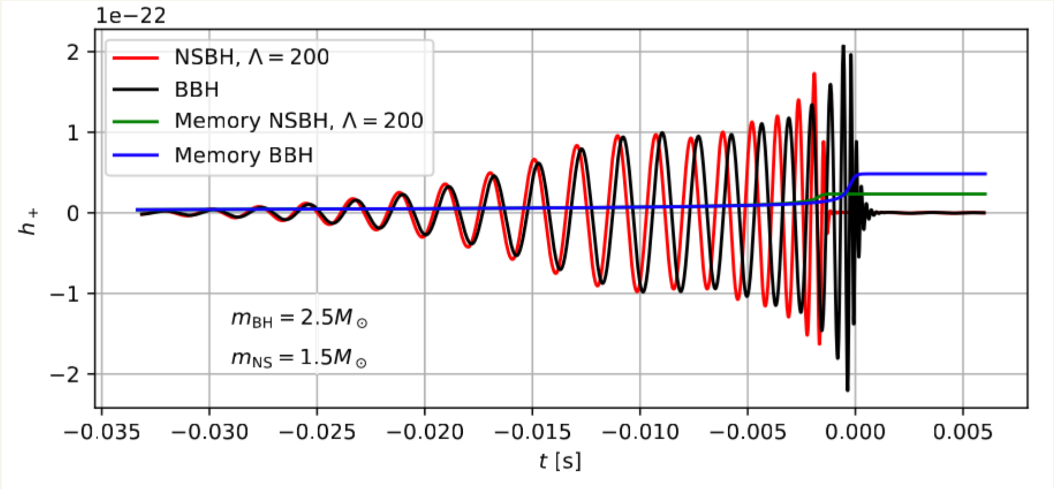
Asymmetric Core Collapse Supernovae



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





Compact Binary Coalescence

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

Memory 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, or change in the spin of a gyroscope

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

About memory

- Memory is a fundamental prediction of any theory which has non linear wave solutions
  - Its not limited to GR but also EM has memory*
- In GR however its comes with understanding of asymptotic symmetries
  - While recovering the Poincaré group of special relativity, Bondi, van der Burg, Metzner, and Sachs (BMS) discovered an infinite-dimensional group of transformations in GR.
  - Originally the BMS group was just extending the Poincaré group with an infinite number of transformations called *supertranslations*
  - Later it was understood to be extended group including the super rotations and super boosts creating extended BMS group

* series of papers by L Bieri and D Garfinkle, and possibly others as well

BMS: Memory of gravitational waves

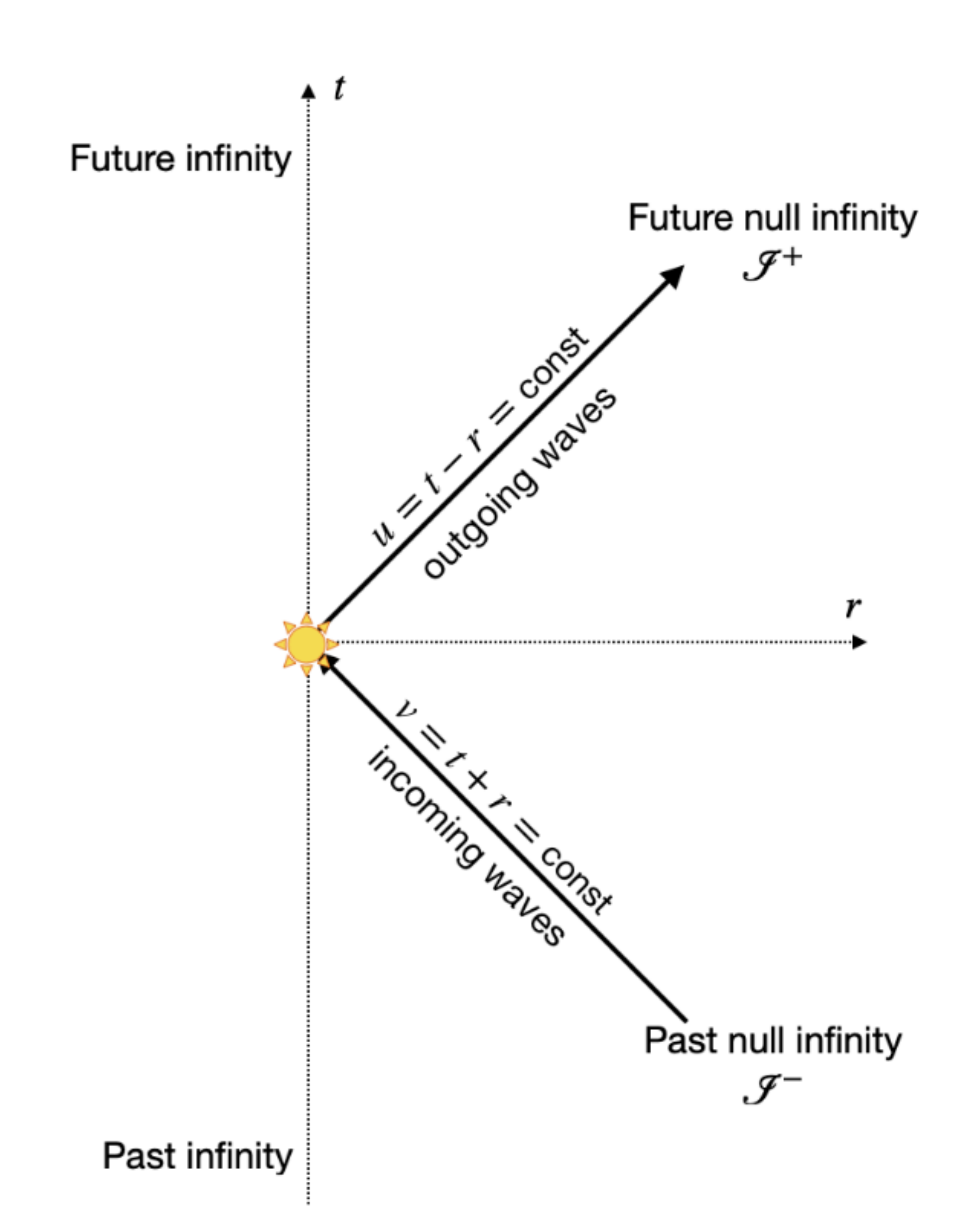
- In Bondi Framework where we use set of coordinates (u,r, θ^A), with u retarded time, r some affine parameter along the outgoing null rays and θ^A with A=1,2 arbitrary coordinates on 2-sphere, the metric expanded in 1/r while imposing Einstein's equations can be written as $ds^2 = -du^2 - 2dudr + r^2 h_{AB} d\theta^A d\theta^B + \frac{2m}{r} du^2 + rC_{AB} d\theta^A d\theta^B$ $-D^B C_{AB} d\theta^A du + \frac{1}{24r}\left[32N_A + 3D_A(C_{BC}C^{BC}) + 24C_{AB}D_C C^{BC}\right] dud\theta^A + \ldots$ where there are 3 major leading order terms m the Bondi Mass aspect, N the angular moment aspect and C_{AB} is the shear/strain (Bondi news N_{AB} is the rate of change of shear)
- With appropriate gauge conditions (symmetric trace-free) the shear can be decomposed in electric Φ and magnetic parts Ψ

$$C_{AB} = D_A D_B\ \Phi + D_A \epsilon_{BC} D^C\ \Psi$$

Bondi Mass aspect is given by $\dot{m} = -4\pi \hat{T}_{uu} - \frac{1}{8} N_{AB} N^{AB} + \frac{1}{4} D_A D_B N^{AB}$

Angular moment aspect is given by

$$\dot{N}_A = -8\pi \hat{T}_{uA} + \pi D_A \partial_u \hat{T}_{rr} + D_A m + \frac{1}{4} D_B D_A D_C C^{BC} - \frac{1}{4} D_B D^B D^C C_{CA} + \frac{1}{4} D_B (N^{BC} C_{CA}) + \frac{1}{2} D_B N^{BC} C_{CA}$$



* mostly following Flanagan, Nicols arXiv:1510.03386 and references within

BMS: Memory of gravitational waves

- We plug the electric and magnetic decomposes shear C_{AB} in the mass and angular momentum aspects and integrate it for all times and applying appropriate projection operator on the sphere one can write the electric parity piece

$$\Delta\Phi = \mathscr{D}^{-1}\mathscr{P}\Delta m + 4\pi\mathscr{D}^{-1}\mathscr{P}\int_{u_1}^{u_2} du\left[\hat{T}_{uu} + \frac{1}{32\pi}N_{AB}N^{AB}\right]$$

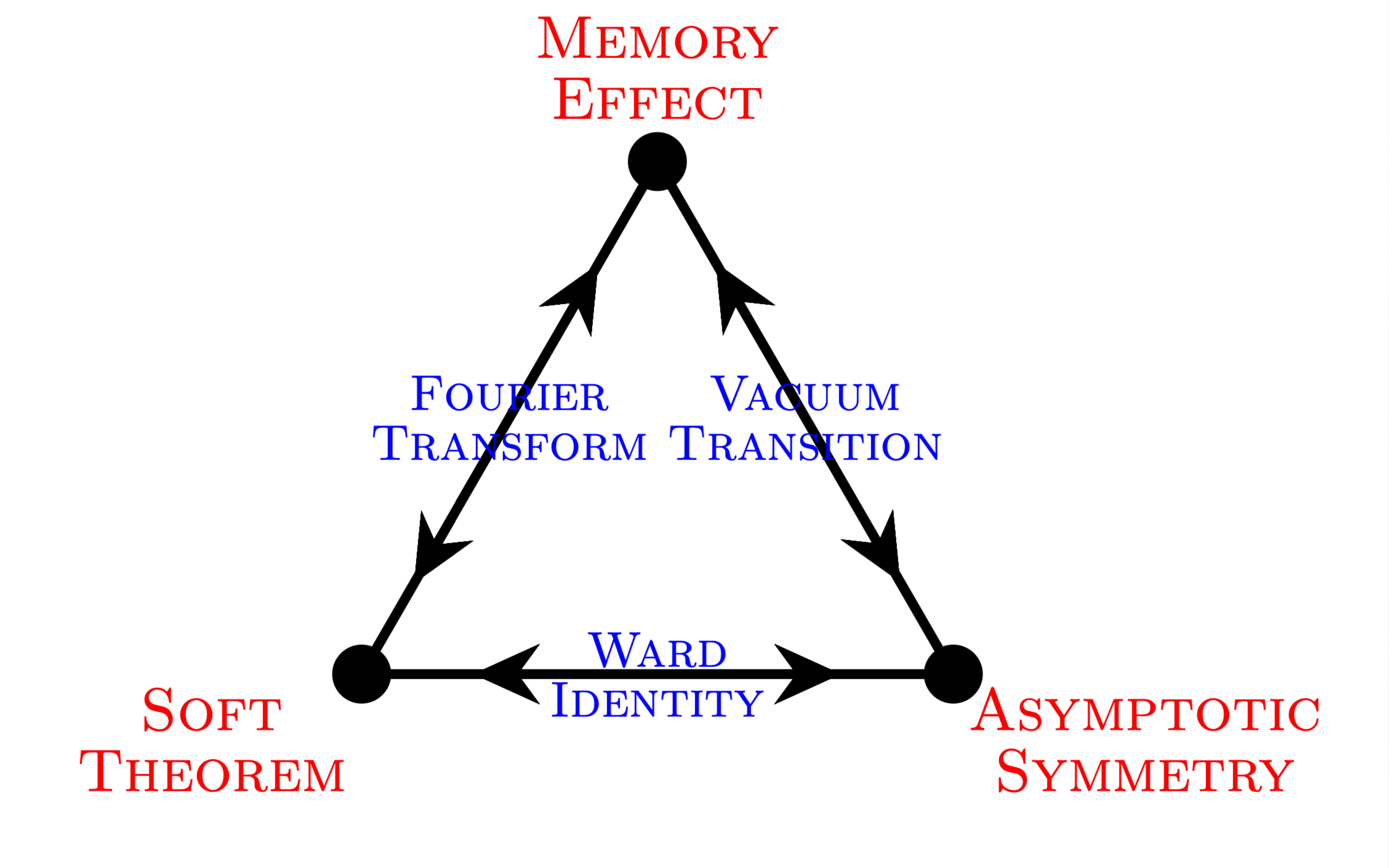
Linear "ordinary" Memory

Non-linear "null" Memory

- Similar argument/calculations follows for the magnetic parity piece, with both null and ordinary memories

Memory and soft theorems

- It is understood that memory is mathematically equivalent to the so-called Weinberg soft theorem via Ward Identities and this is part of the infrared triangle *series of papers by Pasterski–Strominger–Zhiboedov*
- Recently *Daniel, Sathischandran, Wald 2023* showed that quantum states decoder with the mere presence of killing horizons, the mechanism proposed is harvesting of soft photons/gravitons (which is equivalent to memory)



Computing memory: Throne formula

- One way to compute displacement (electric) null memory is through the Throne formula (Favata formula) which we write as

$$h_{\rm mem}^{\ell m} = -\frac{R}{c}\sqrt{\frac{(\ell-2)!}{(\ell+2)!}}\sum_{\ell'=2}^{\infty}\sum_{\ell''=2}^{\infty}\sum_{m'=-\ell'}^{\ell'}\sum_{m''=-\ell''}^{\ell''} \times G_{mm'm''}^{\ell\ell'\ell''}\int_{-\infty}^{T_R} dt\, \dot{h}^{\ell' m'}\dot{\bar{h}}^{\ell'' m''},$$

- Details
  - Here the integral is taken some reasonable time before merger, we can ignore other modes and "deeper" memory contributions results the memory signal amplitude to be accurate up to a few percentage
  - Cross checking this result with the recent work where the memory is extracted from numerical relativity simulations exploiting the BMS conservation laws, the results are within 10% of the amplitude (for most cases within 1%)
  - The amplitude of memory signal is much(much) fainter as compared to the oscillatory signal
  - Simple analysis reveals that the leading contribution lives in the (2,0) mode for displacement null memory coming from (2,2) x (2,2) oscillatory mode

*Expression taken from Ebersold Tiwari 2020

Computing spin memory: Nichols formula

- Similar handy formula can be derived for the spin memory following Nichols (2017) and Grant,Nichols (2022)

$$h_{lm}^{\mathrm{spin}} = \sum_{\substack{l'\geq 2,\\ |m'|\leq l'}} \sum_{\substack{l''\in {}_2I_{ll'mm'},\\ m''=m-m'}} \frac{\xi^{l}_{l'l''m'm''} + (-1)^{l+l'+l''}\xi^{l}_{l''l'm''m'}}{l(l+1)\sqrt{(l+2)(l-1)}}\omega_{l'm'l''m''},$$

$$\xi^{l}_{l'l''m'm''} \equiv \frac{1}{4}\left[\sqrt{(l'-2)(l'+3)}\,{}_{(-3)2}\mathcal{C}^{l}{}_{l'l''m'm''} + 3\sqrt{(l''+2)(l''-1)}\,{}_{(-2)1}\mathcal{C}^{l}{}_{l'l''m'm''}\right]$$

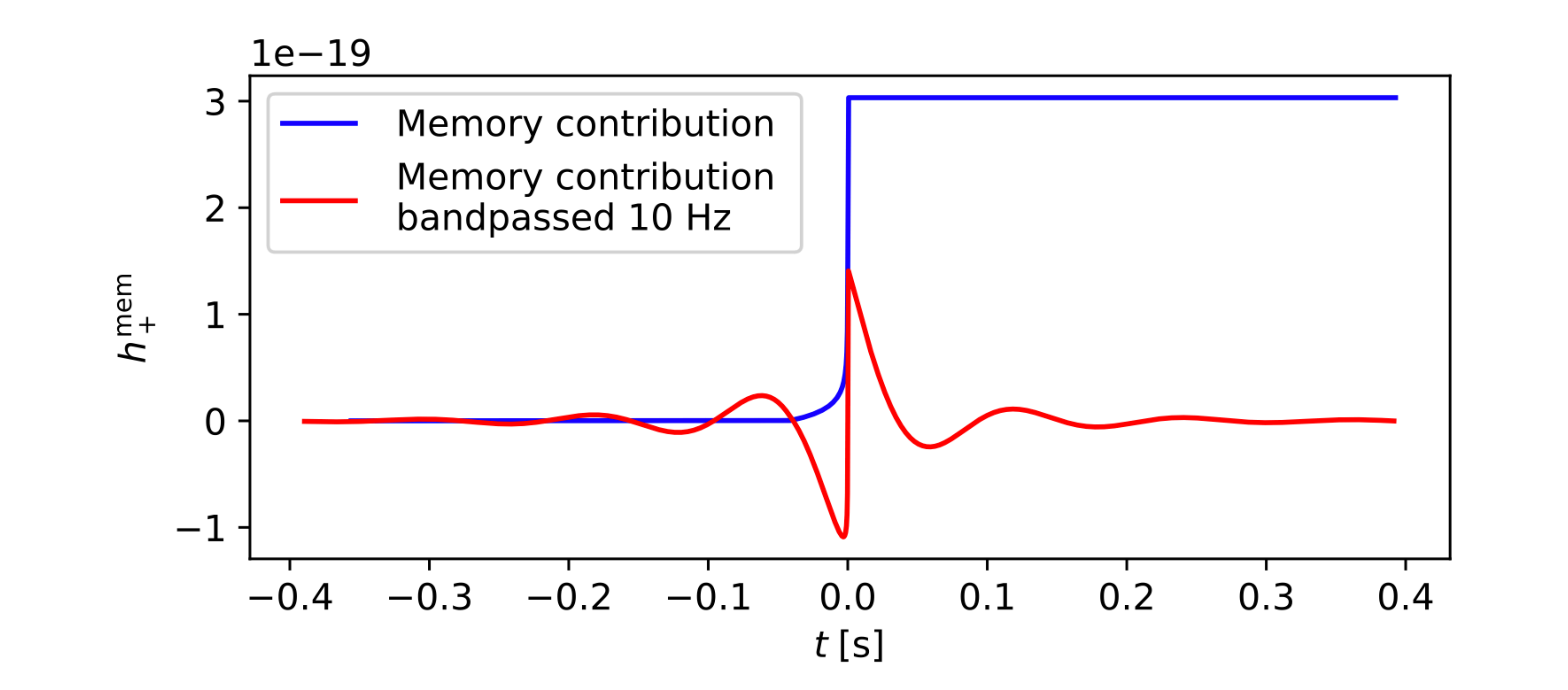
$$\omega_{lml'm'} \equiv (-1)^{m'}\left(h^{\mathrm{osc.}}_{lm}\overline{\dot{h}^{\mathrm{osc.}}_{l'(-m')}} - \dot{h}^{\mathrm{osc.}}_{lm}\overline{h^{\mathrm{osc.}}_{l'(-m')}}\right).$$

- The leading order harmonic is (3,0)

Waveforms models with memory

- Adding memory using Throne formula
  - Several works by Lasky, Huber, Tiwari, Ebersold etc
- Numerical relativity simulations with memory and surrogate
  - Along with the extraction of h and the weyl scalar ψ_2 and ψ_1 *Mitman, Moxon et al* generate NR waveforms with memory along with the Bondi Mass and Angular momentum aspects
  - NRSurrogate waveforms are also created *Yoo, Mitman et al arXiv:2306.03148*
- PhenomT with full (2,0) mode included is also available *Rosselló-Sastre, Husa et al arXiv:2405.17302*

Michelson Interferometer displacement memory



- 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

Time frequency visualisation

- 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

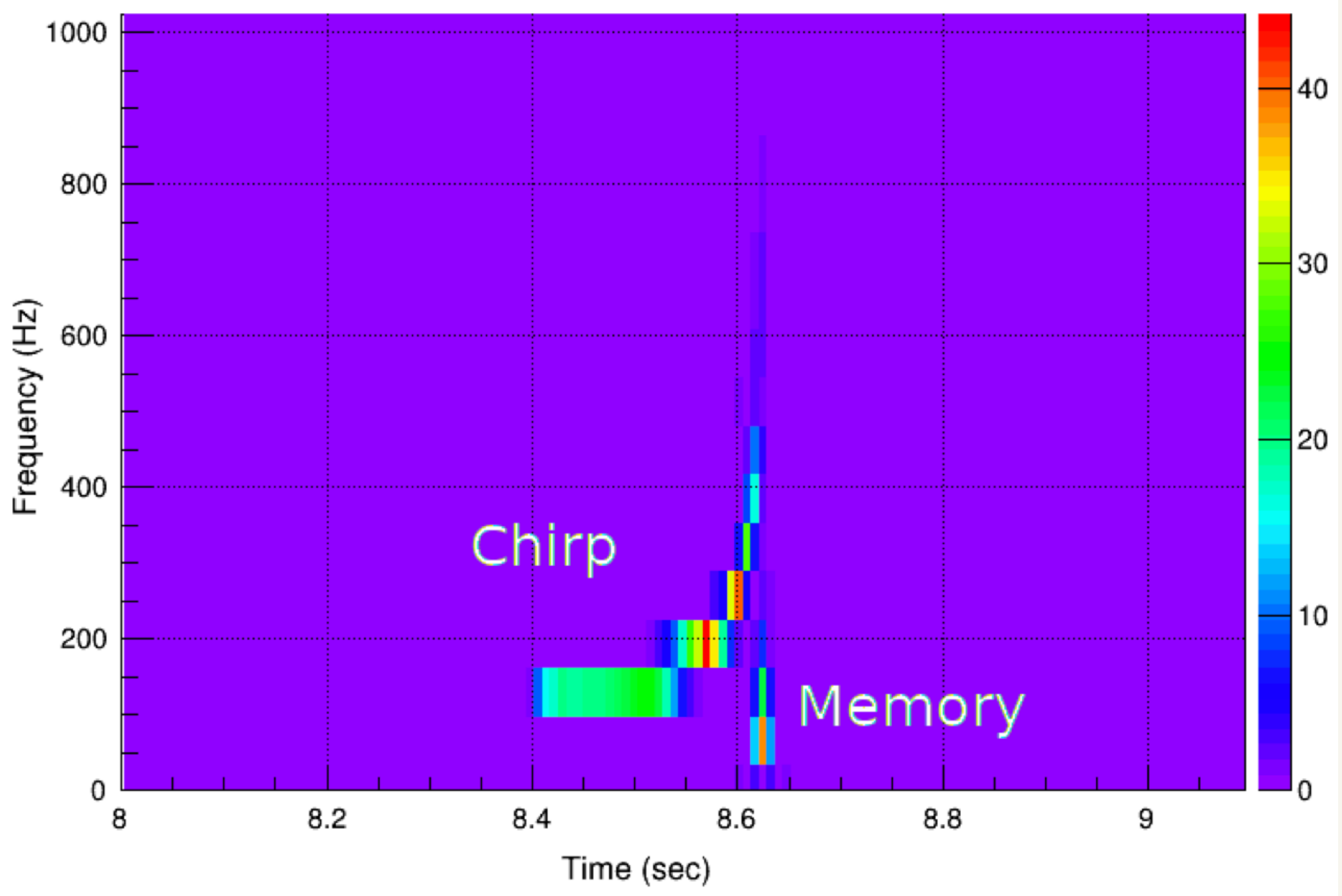
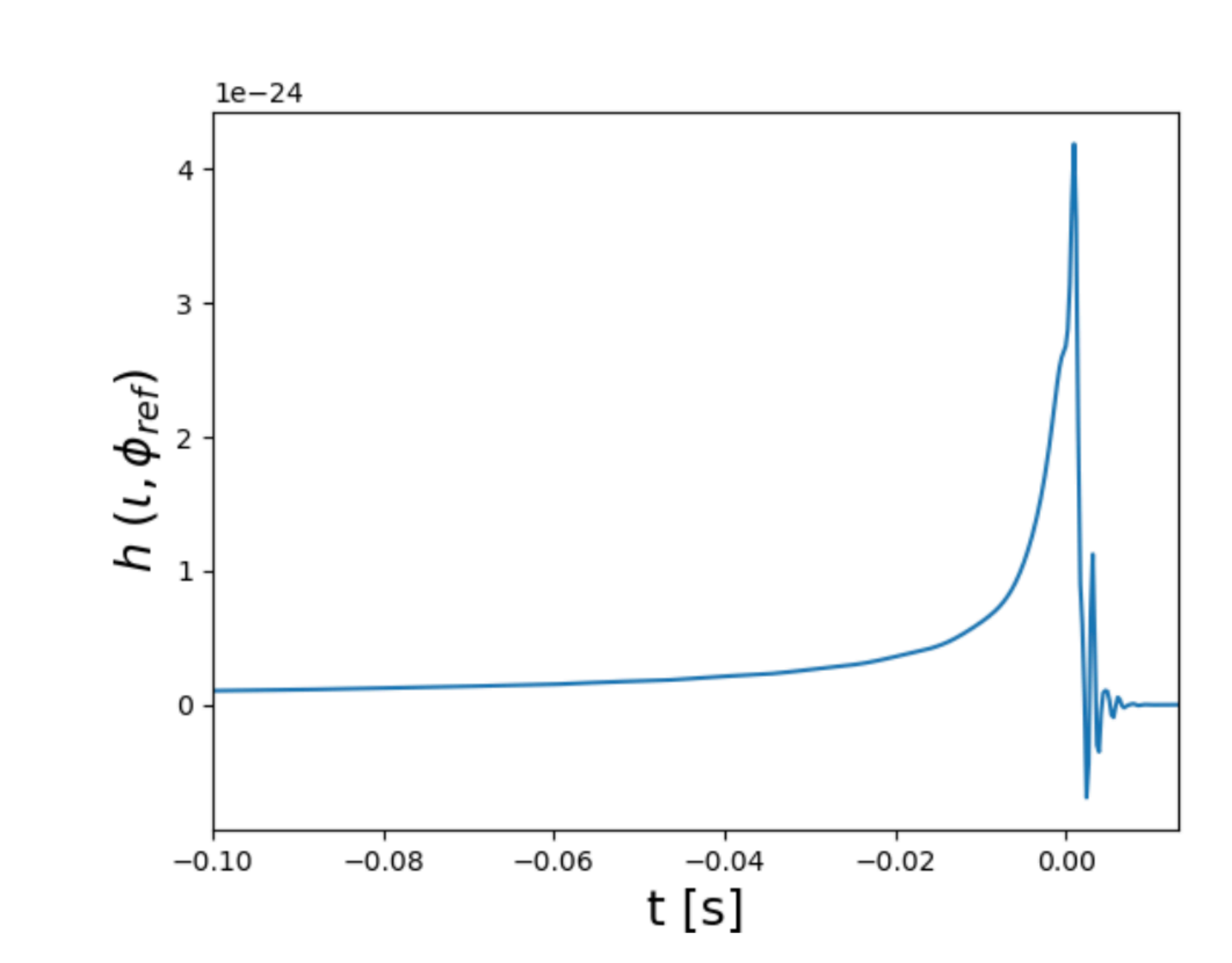


Fig 2: *Whitened spectrogram with O2 noise PSD of a GW signal from a $5-5M_\odot$ BBH at SNR ≈ 100 with enhanced memory signal*

Michelson interferometer : spin memory



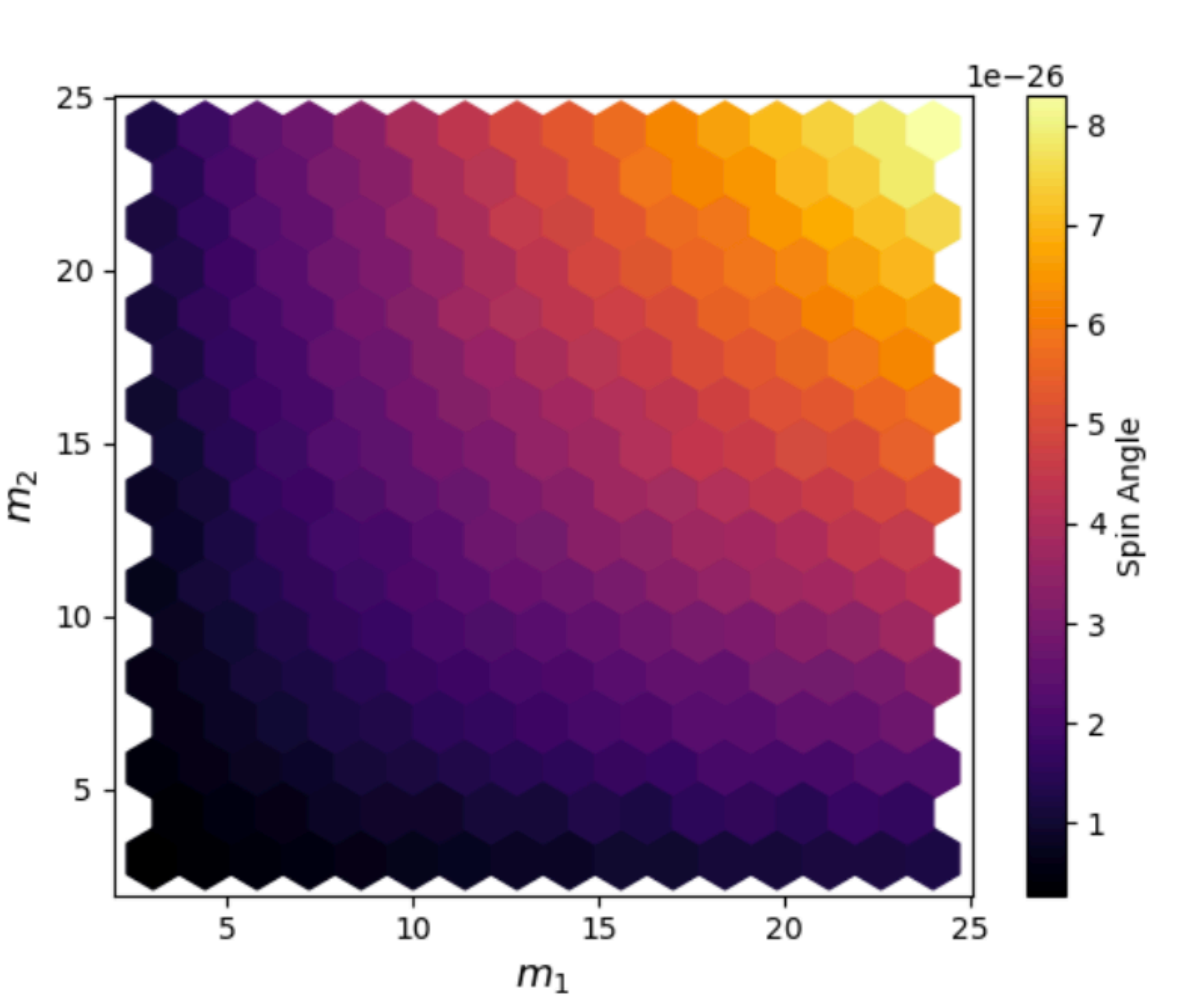
- Spin memory in Michelson interferometer behaves like an oscillatory signal, it is broadband due to sharp peak at merger but not saturated at low frequencies
  - Spin memory is ~2 orders of magnitude smaller than displacement memory
- Spin memory contains full signal unlike the displacement memory for Michelson interferometer

Spin memory : Angular observable

- Effect of spin memory can also be measured in terms of effective spin orientation change of a free falling gyroscope (we assume point-like)
- For the angular memory shift the expression including the sub-leading terms is given as Mesiura, Tiwari (in prep)

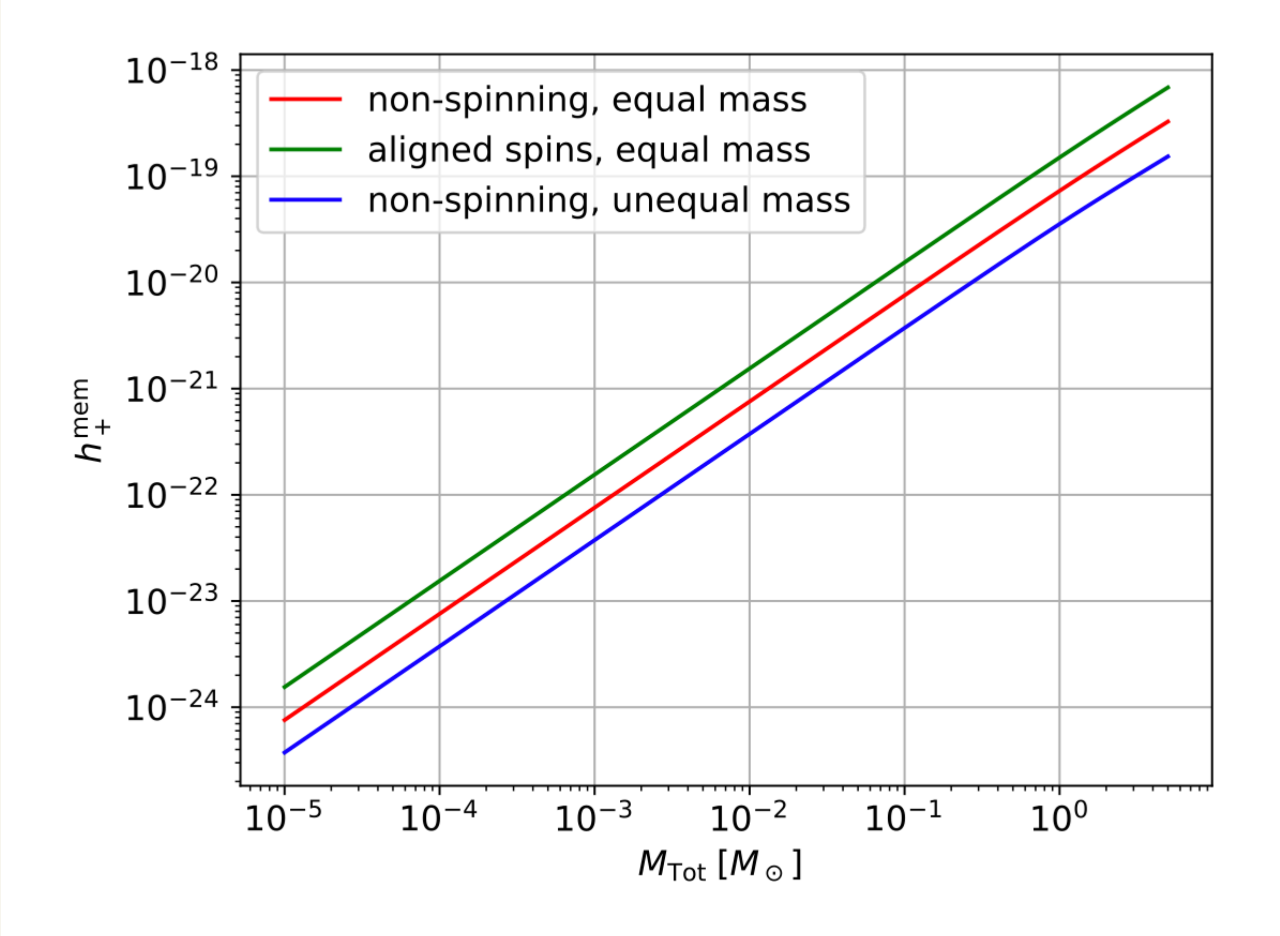
$$\Phi = \int du \frac{\tilde{\mathscr{M}}}{r^2} = -\frac{1}{2r}\int du h_\times + \frac{1}{4}\left[\int du h_\times h_+ - \int du h_\times \dot{h}_+\right].$$

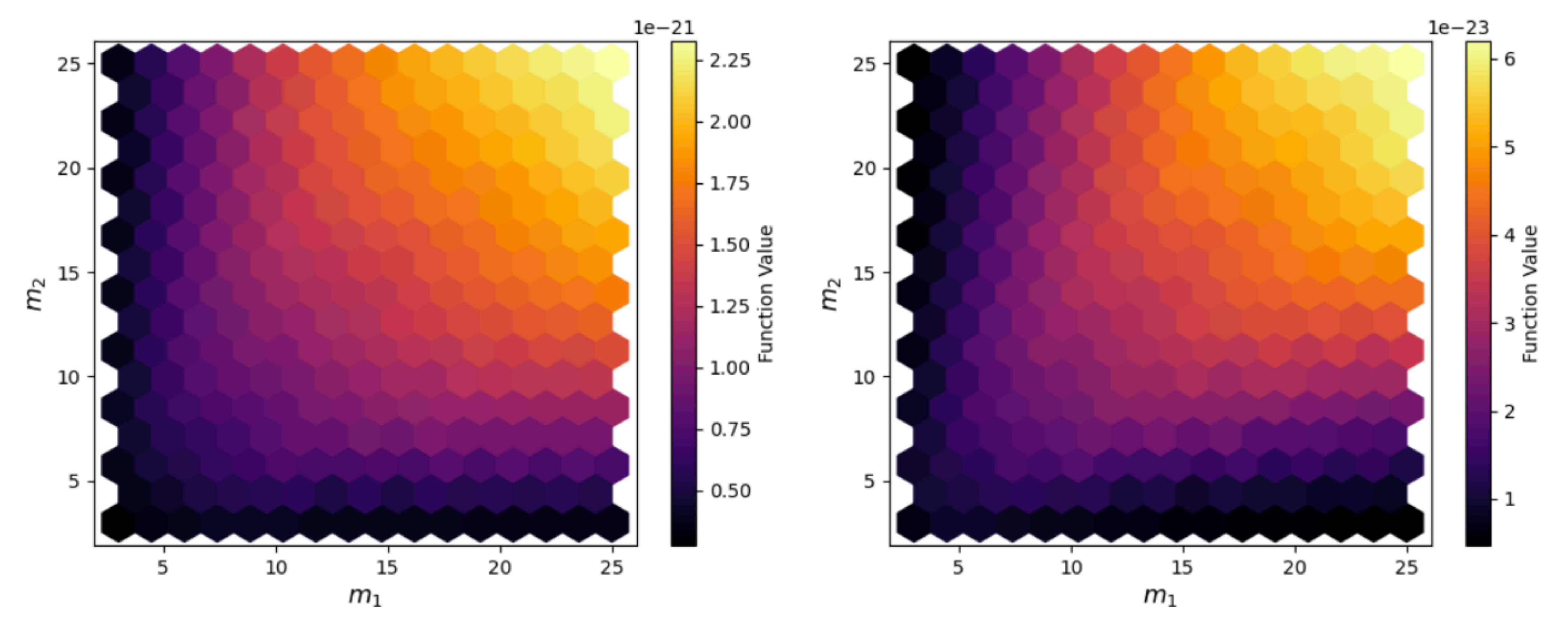
- The plot is shown for the optimally oriented (optimal for spin memory) Binary black hole merger at 400 Mpc
  - Z-axis is the angle in radian that a free falling gyroscope will have at earth



Features 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
  - Due to its dependency on $\dot{h}$ similar trend is restored for spin memory as well



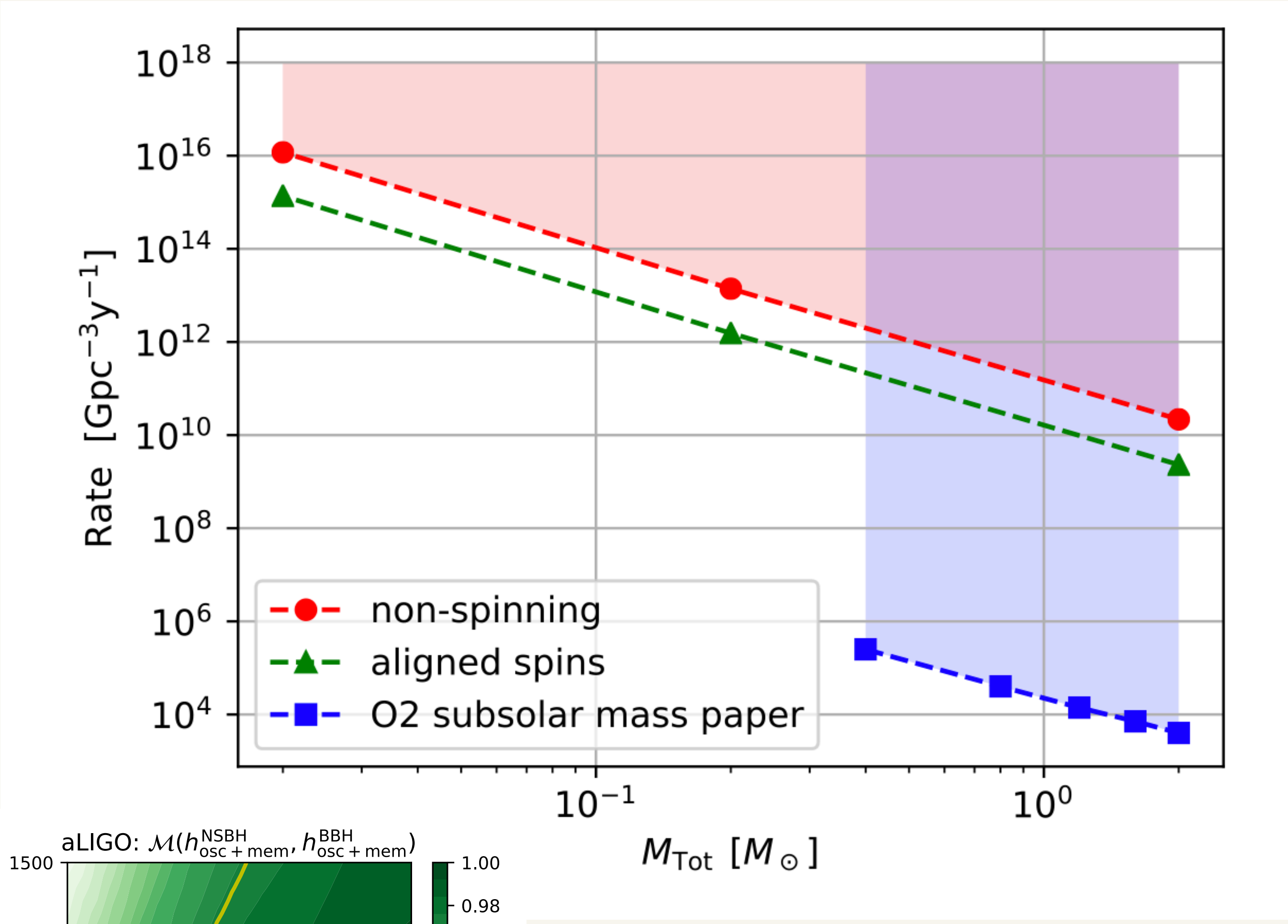


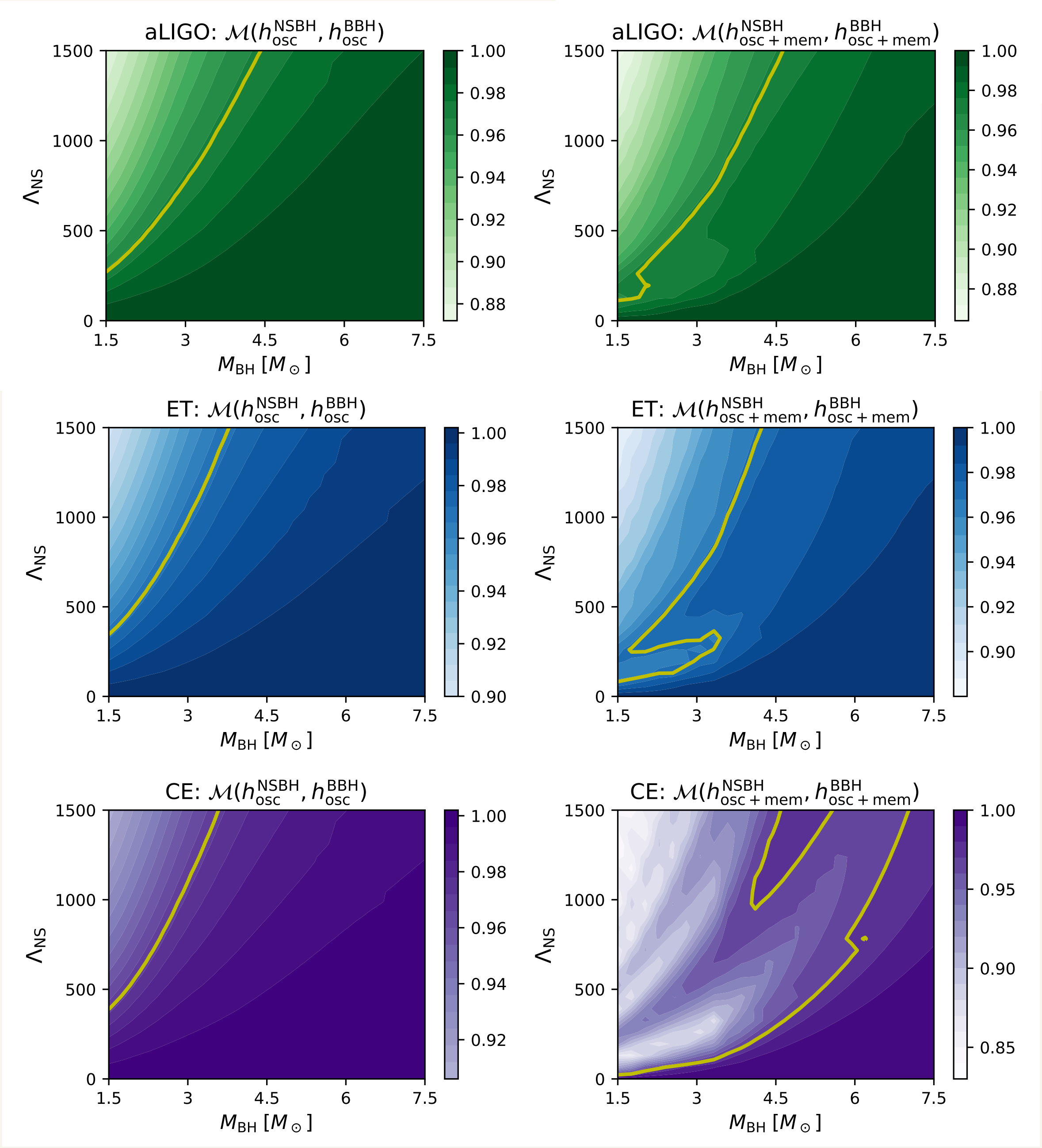
(a) Displacement memory.

(b) Spin memory.

Utility of displacement null 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 [see papers by Lasky, Huber, Cheung et al]
- For LVK like detectors displacement memory can be used for various high frequency sources
    - We present how memory can aid the detection of **tidal disruption** event in the case of neutron star black hole binary *Tiwari, Ebersold, Hamilton PRD*
    - We present how the various **EoS effect the BNS post merger** signal memory and their detection prospects *Lopez, Tiwari, Ebersold PRD*
    - We present the search for **ultra-light CBC** made possible only through memory *Ebersold, Tiwari PRD*
    - And also can be used to break the distance-inclination degeneracy *Xu, Sastre, Tiwari et al PRD*
- For LISA *Gasparotto et al PRD* show that adding memory can help with constraining parameters of lighter SMBHB mergers in LISA



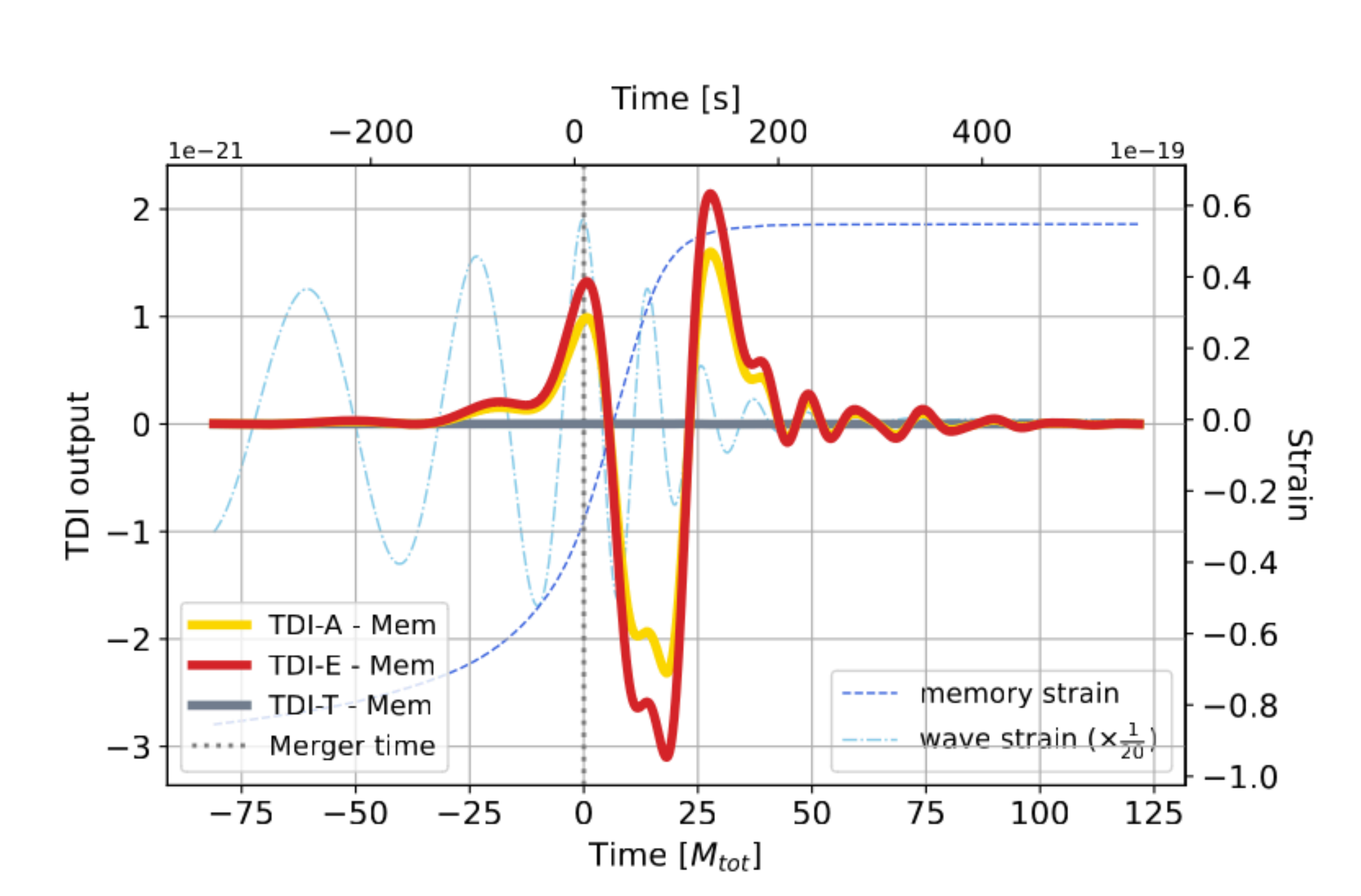


Sources of linear memory (ordinary electric memory)

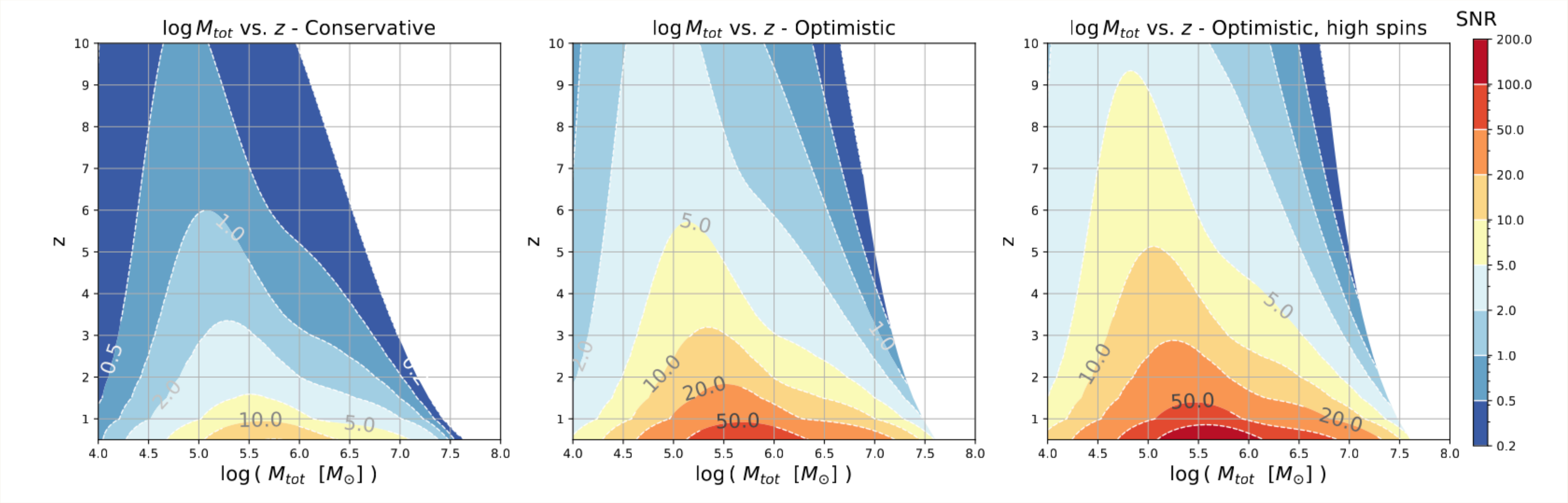
- Well down sources include
  - Hyperbolic encounters (searches are done in LVK for hyperbolic encounters of compact objects) *Bini, Tiwari et al 2023 PRD*
  - GRB jet - very weak not detectable anytime soon *Birnholz, Piran PRD 2013* and *Lopez, Tiwari, Ebersold PRD*
  - Core collapse supernova, detectable for some CCSN model out to 10 Kpc *Richardson et al arXiv:2404.02131v1*
- No perceivable vanilla source for LISA(?)

Prospects of memory detection : LISA

- As part of collaborative project we have conducted detectability study of displacement null memory for SMBHBs in LISA *Inchasupe, Gasparotto et al arXiv:2406.09228*
- The full time domain TDI response is computed using the LISA simulation suite, and the waveform model used for this study is the NRSurrogate_CCE
- Comprehensive study in terms of Signal to noise ratio in various slices of parameters is done



Prospects of memory detection : LISA



- Memory is a weak signature, as compared to the main oscillatory signal
- However, for nearby sources memory can be detected even for a single event
- Careful summation of multiple sources will be desirable

Baseline	q	χ
1. Conservative	2.5	0.0
2. Optimistic	1.0	0.0
3. Opt. & Spin.	1.0	0.8

Memory with LISA : future projects

- PE and Bayesian analysis to evaluate evidence of memory detection with full memory data (extending [Gasparotto et al, 2023])
- Stacking coherently memory for various SMBHB mergers (like how its done by *Lasky et al PRL*)
- Agnostic search of the memory / Consistency Test of GR combining parametrized waveform model with template-free representation (following [Heisenberg et al.,2023])
- Effect of the memory in the ringdown analysis
- Additional memory effects: spin, Center of mass…

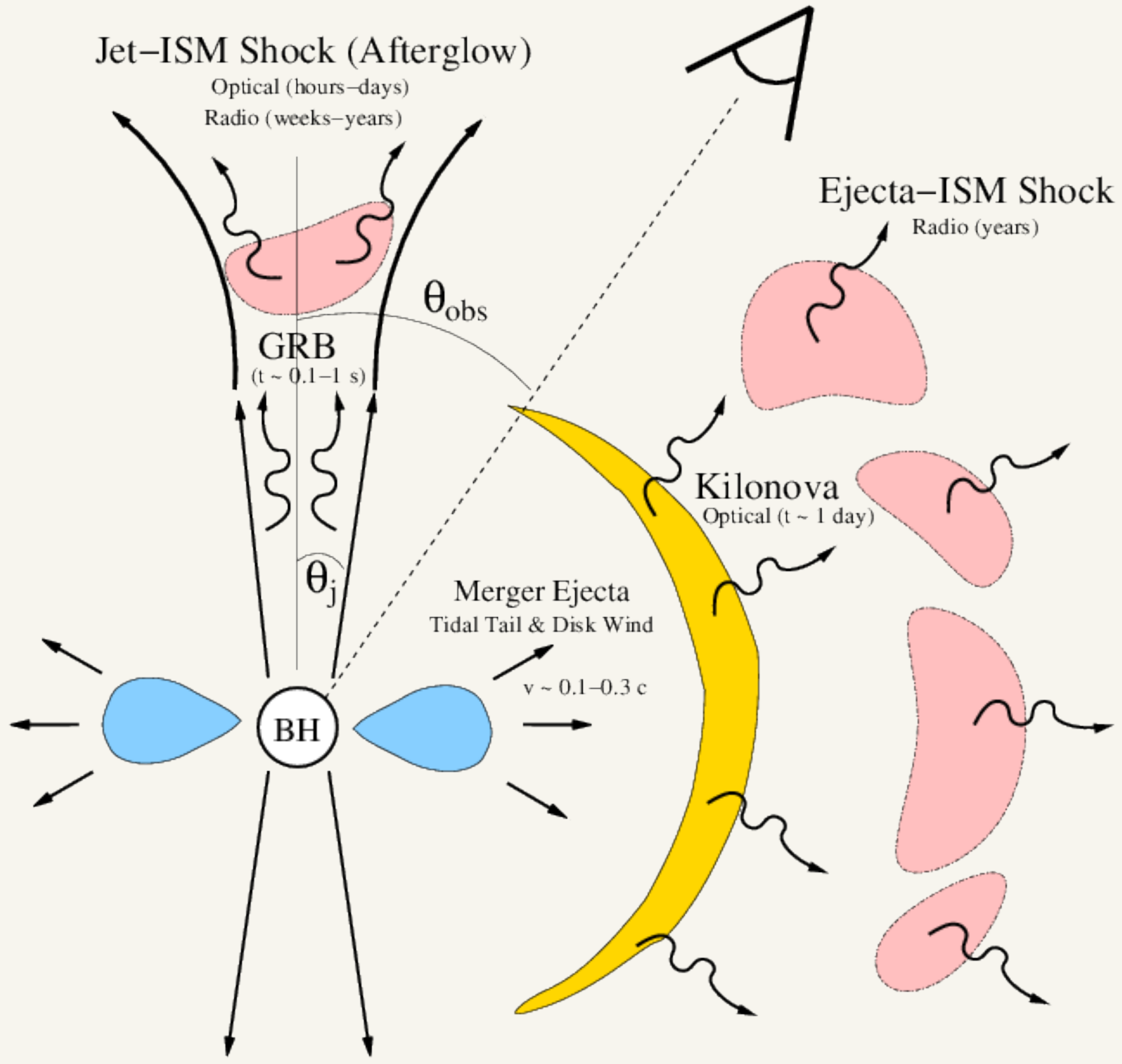
Conclusions

- 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 is just a matter of time
- We have explored the various consequences that memory in LVK, we need to do the same for LISA
- Studies of spins (precessing) and eccentricity with non-linear memory is underway
- Looking into some peculiarities of memory like linear polarisation to test parity violating theories of gravity (Tiwari, Zosso in prep)

Thanks for your attention

Leveraging memory to infer the nature of compact objects: Idea

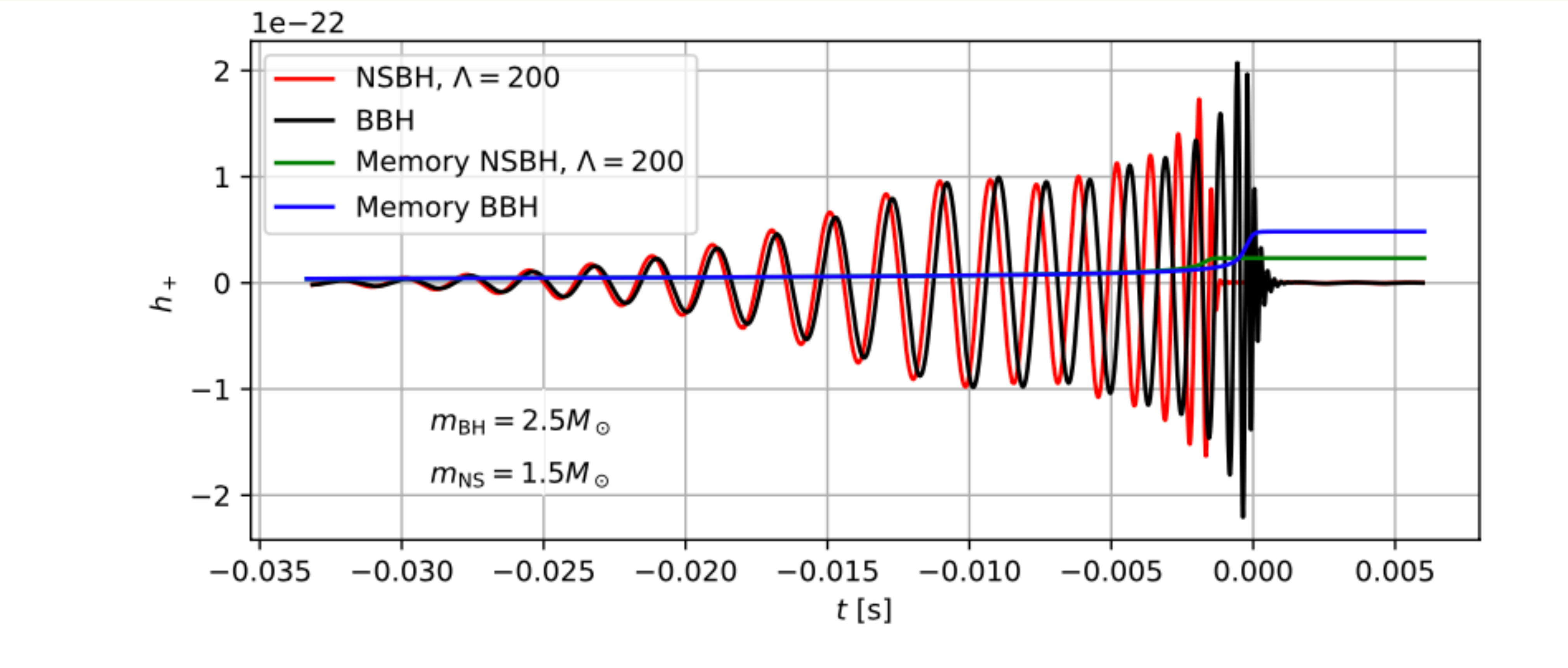
- Distinguishing between NSBH and BBH systems challenging (more challenging than distinguishing between BNS and BBH systems as two components show tidal deformation)
- A smoking gun for a NSBH detection apart from just the mass estimate would be a *tidal disruption event* : Neutron star disrupted by 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

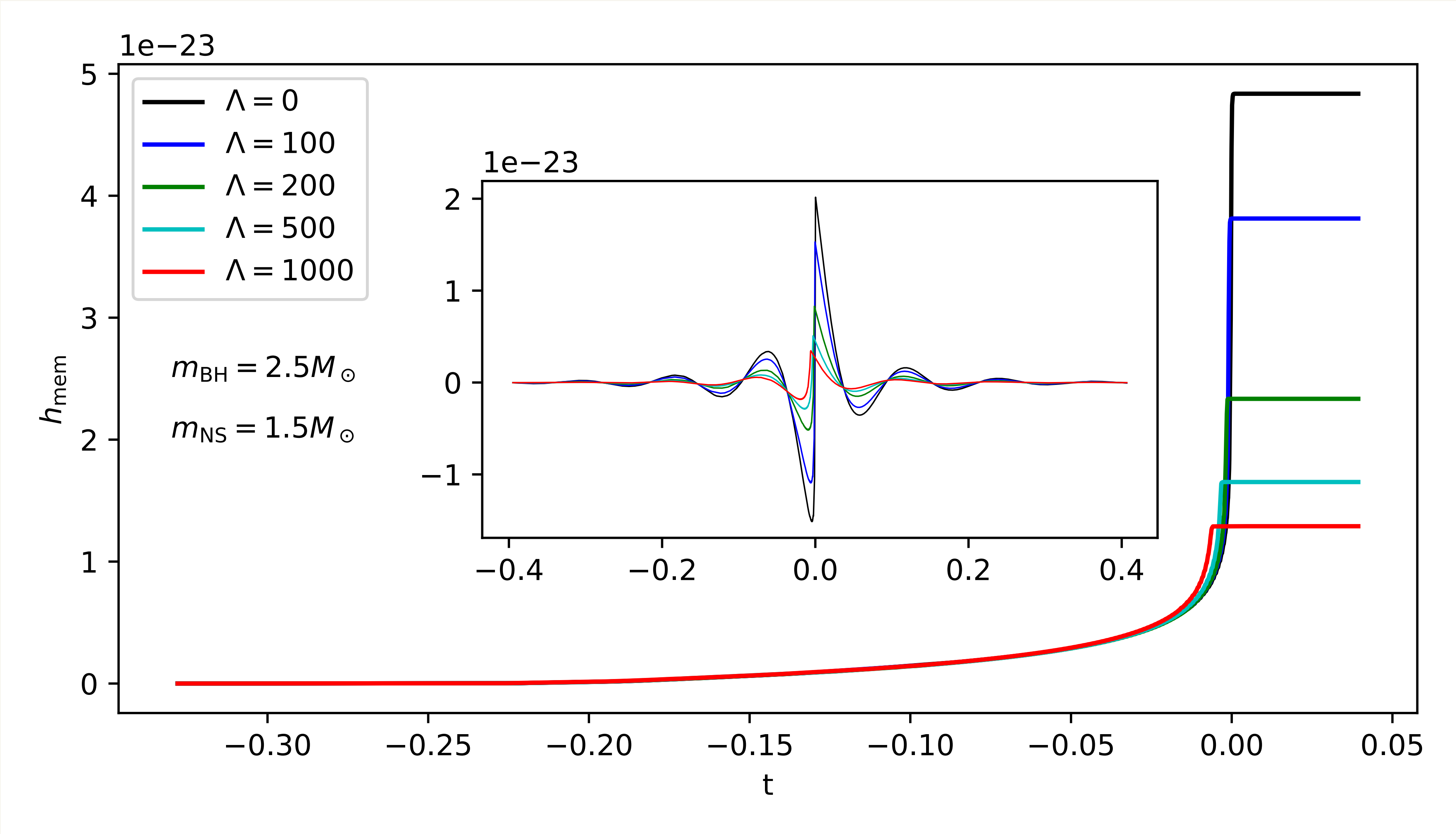


Taken from Metzger & Berger

Leveraging memory to infer the nature of compact objects

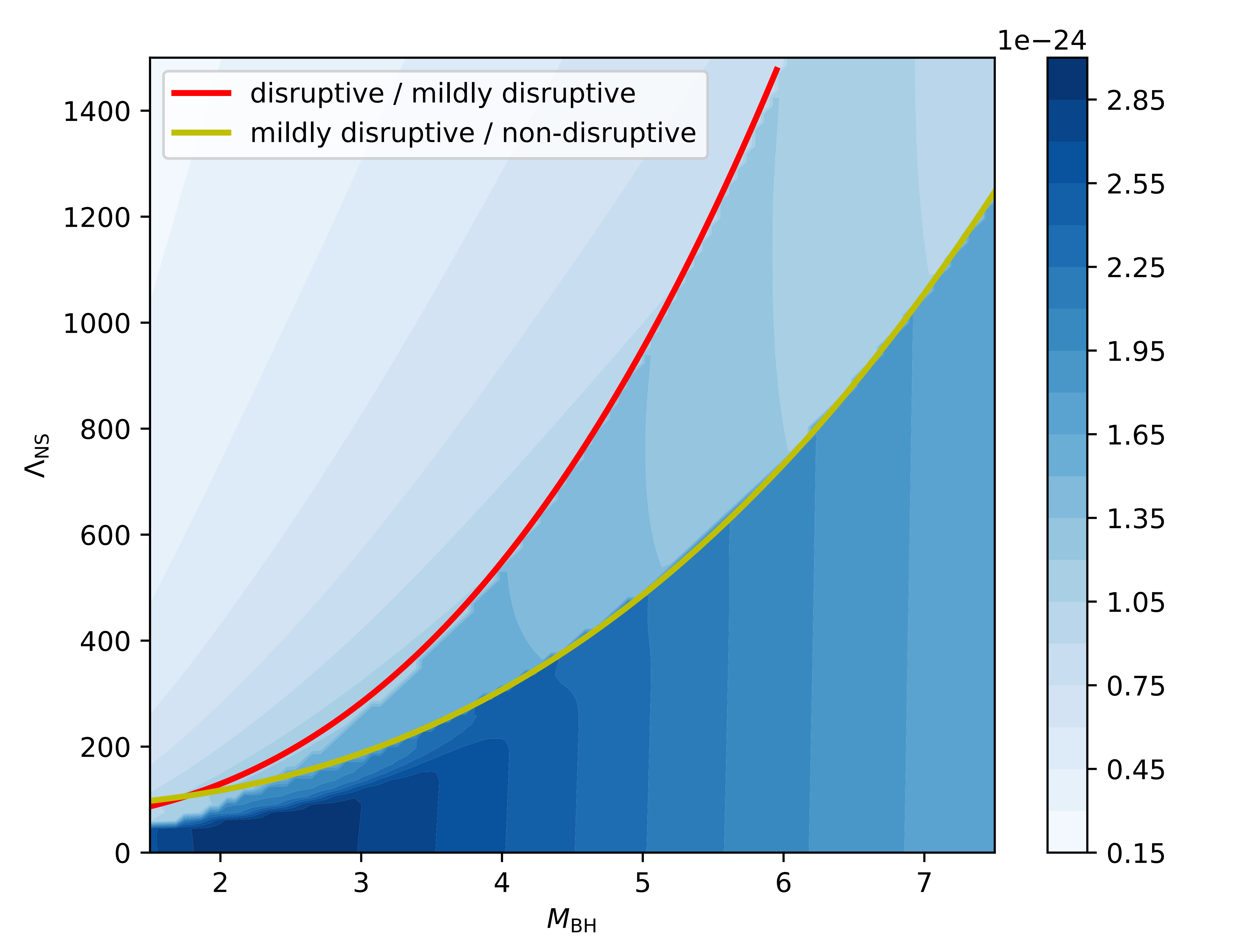
- We compute the memory from the NSBH model SEOBNR_NSBH which has tidal disruption physics
- We show that memory signal is sensitive in amplitude to the nature of the system BBH (no tidal disruption, maximum memory) NSBH (tidal disruption, minimum memory)





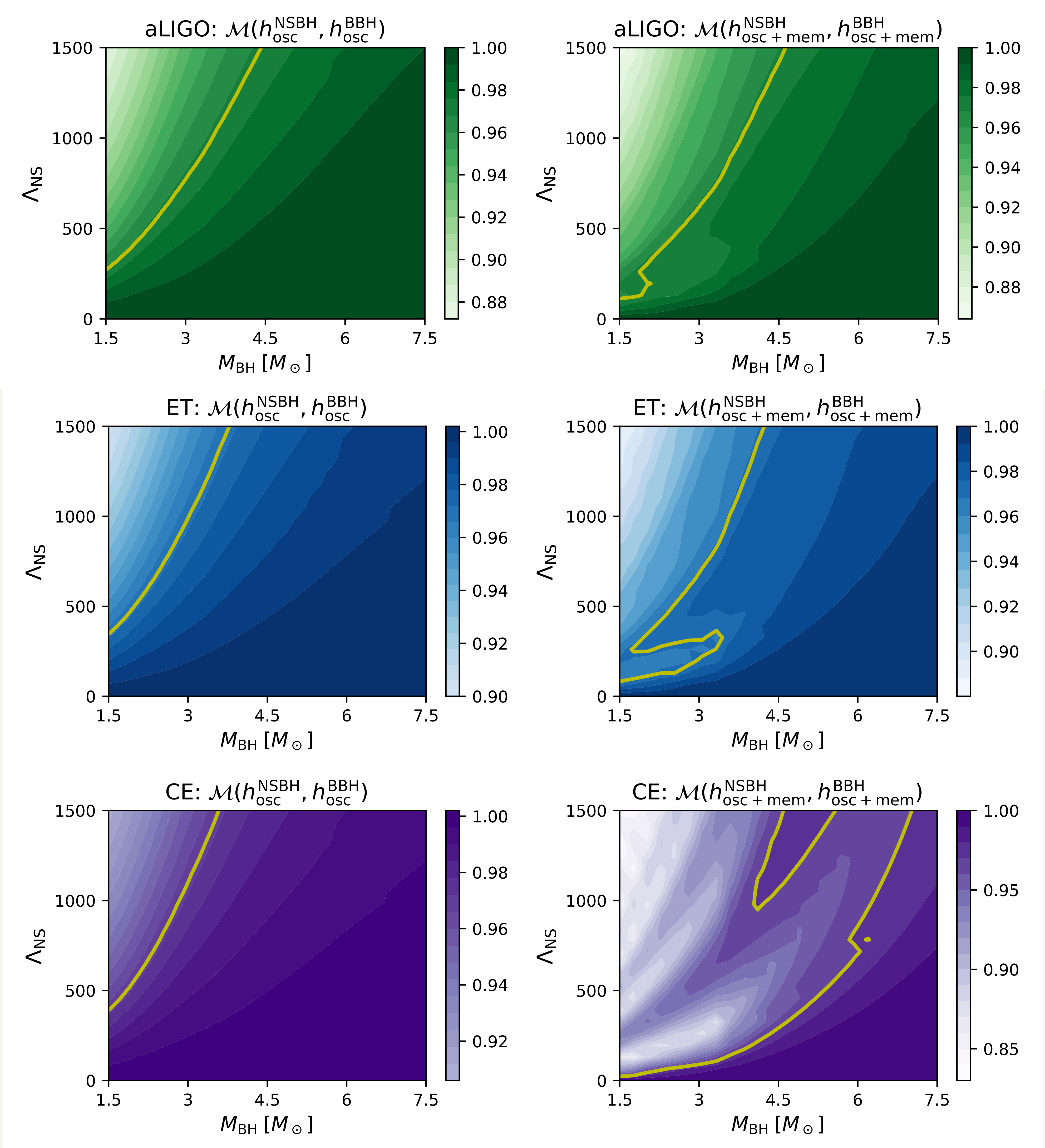
Leveraging memory to infer the nature of compact objects

- 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

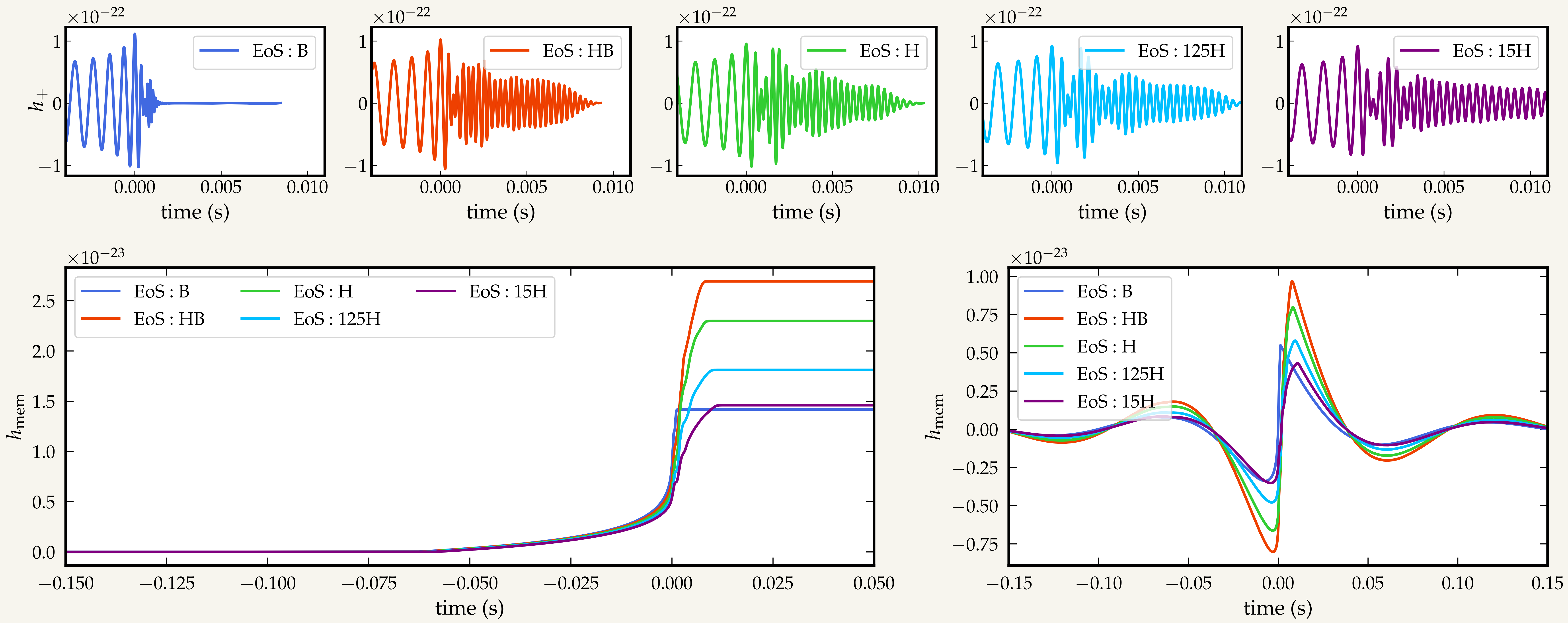


Tiwari, Ebersold, Hamilton PRD 2021

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

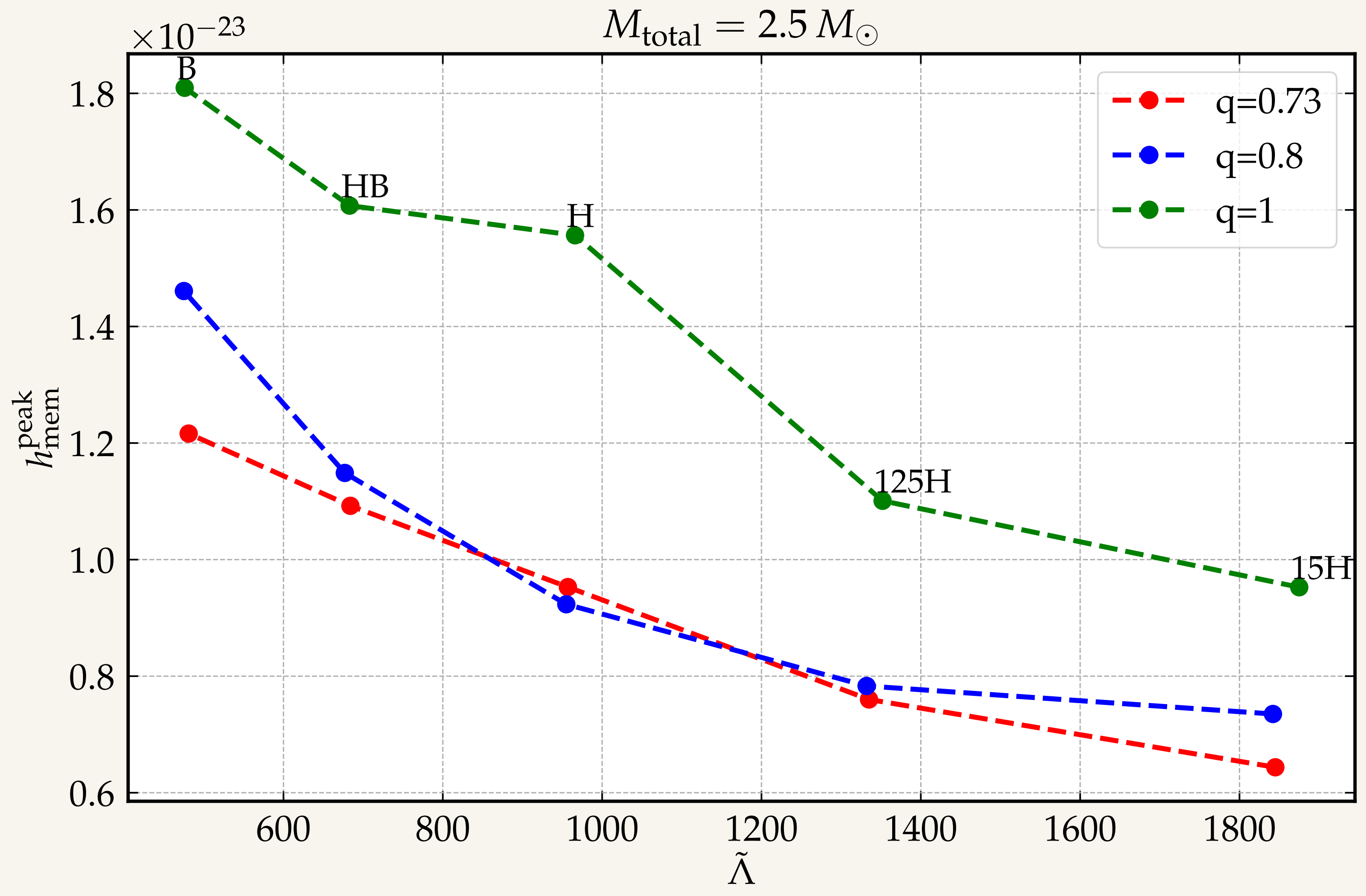
Binary neutron star post merger memory

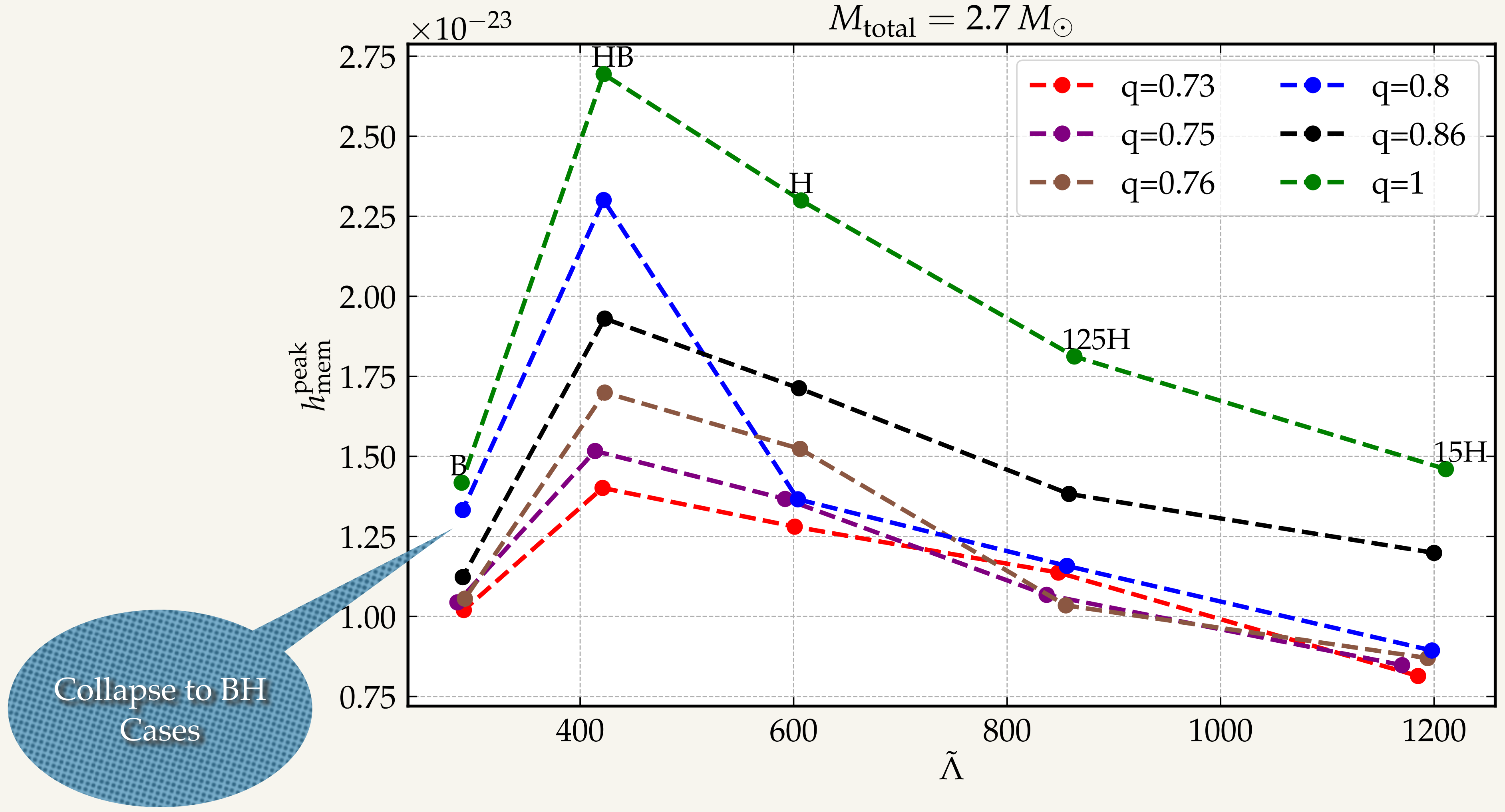


- We illustrate some oscillatory post merger NS signal with various EoSs, from softer to harder (low tidal deformability to high)
- This part of the talk is based on in work by *Lopez, Tiwari, Ebersold 2305.04761*

Binary neutron star post merger memory

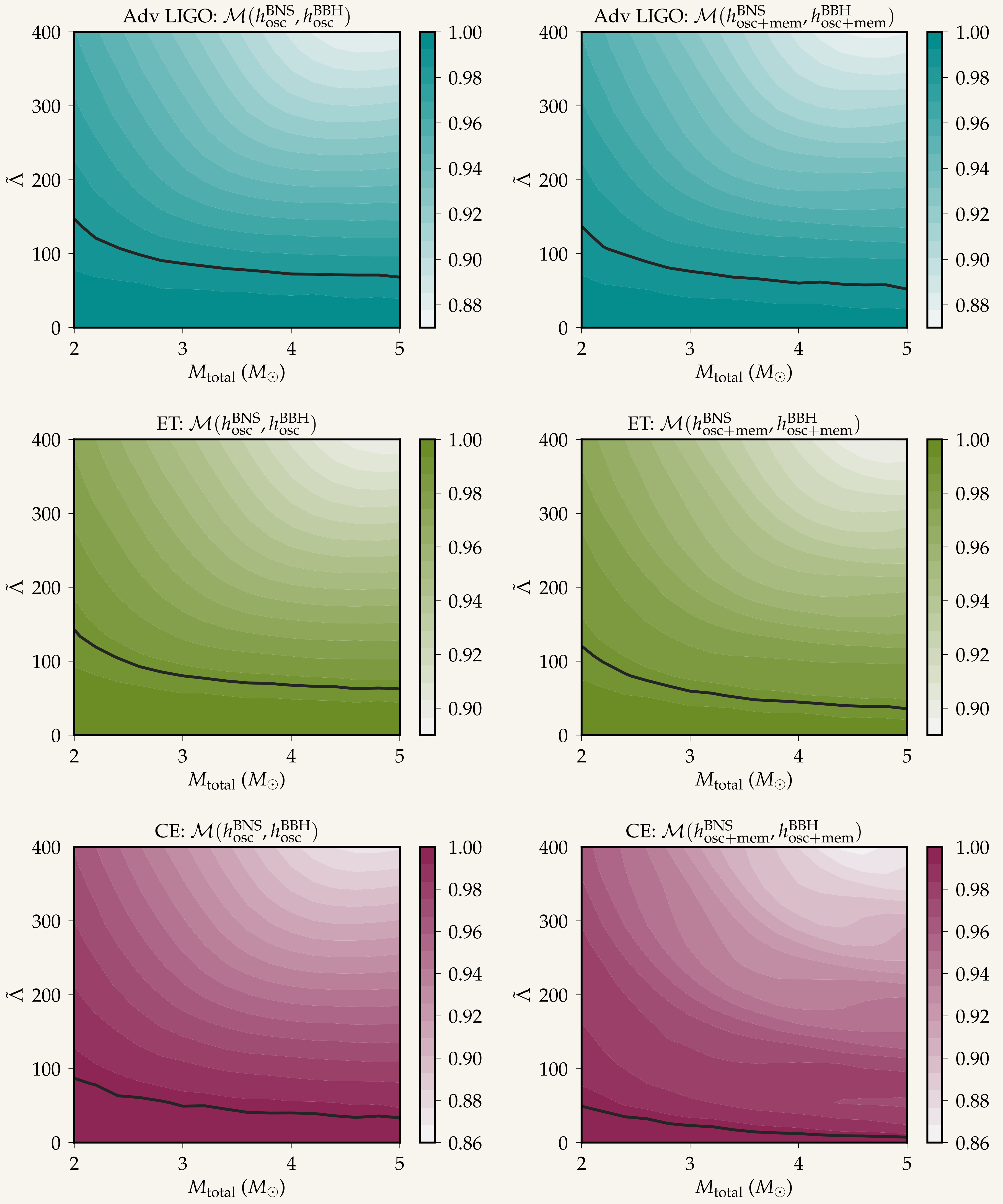
- Binary neutron stars when they have low enough mass and hard (large Lambda) enough EoS will show post merger signal post merger
  - The memory content of post merger signal is not negligible
  - If after merger the remnant collapse quasi-instantaneously to a BH then there is no post merger signal and 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





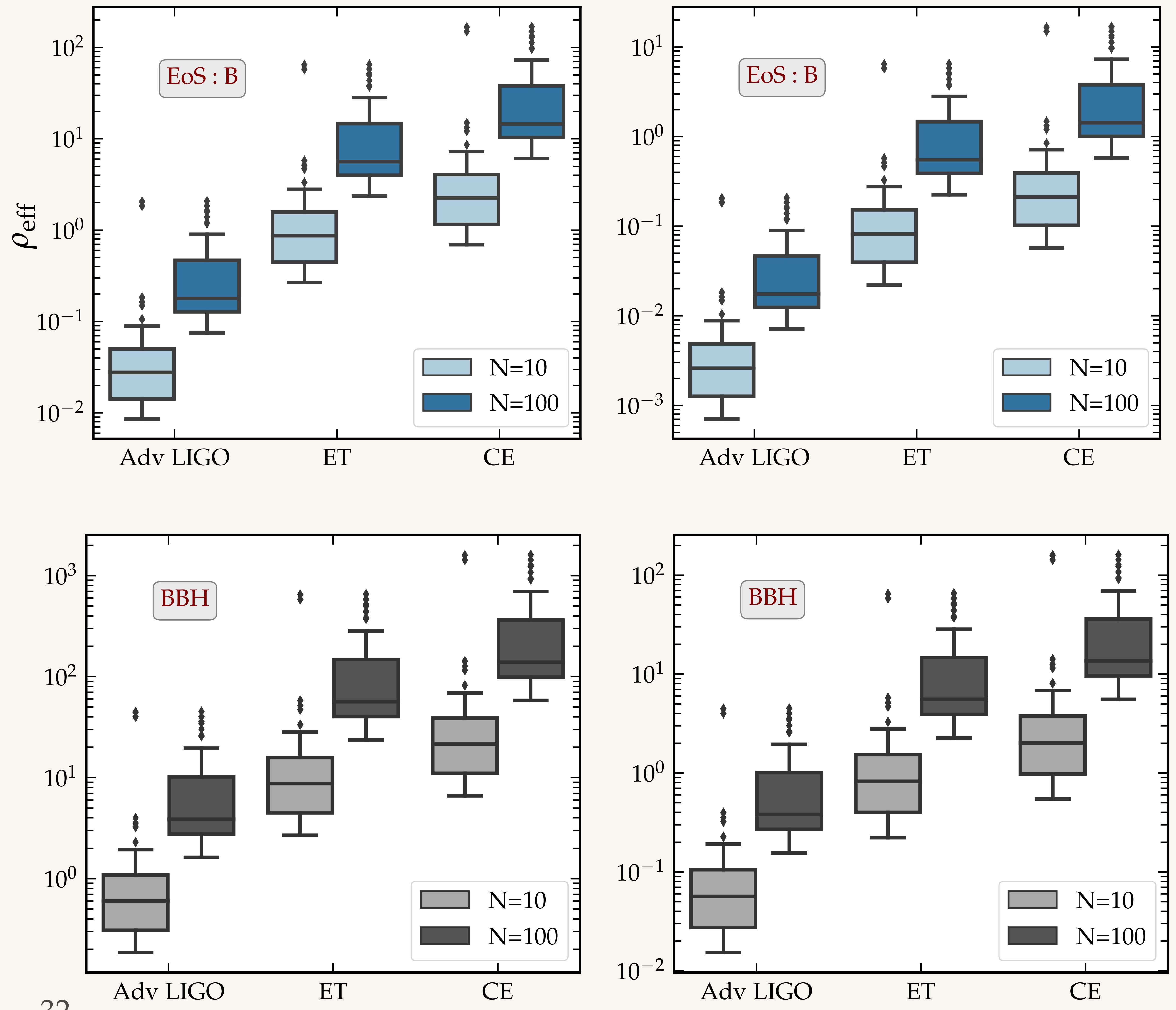
Binary Neutron star post merger memory

- 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

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

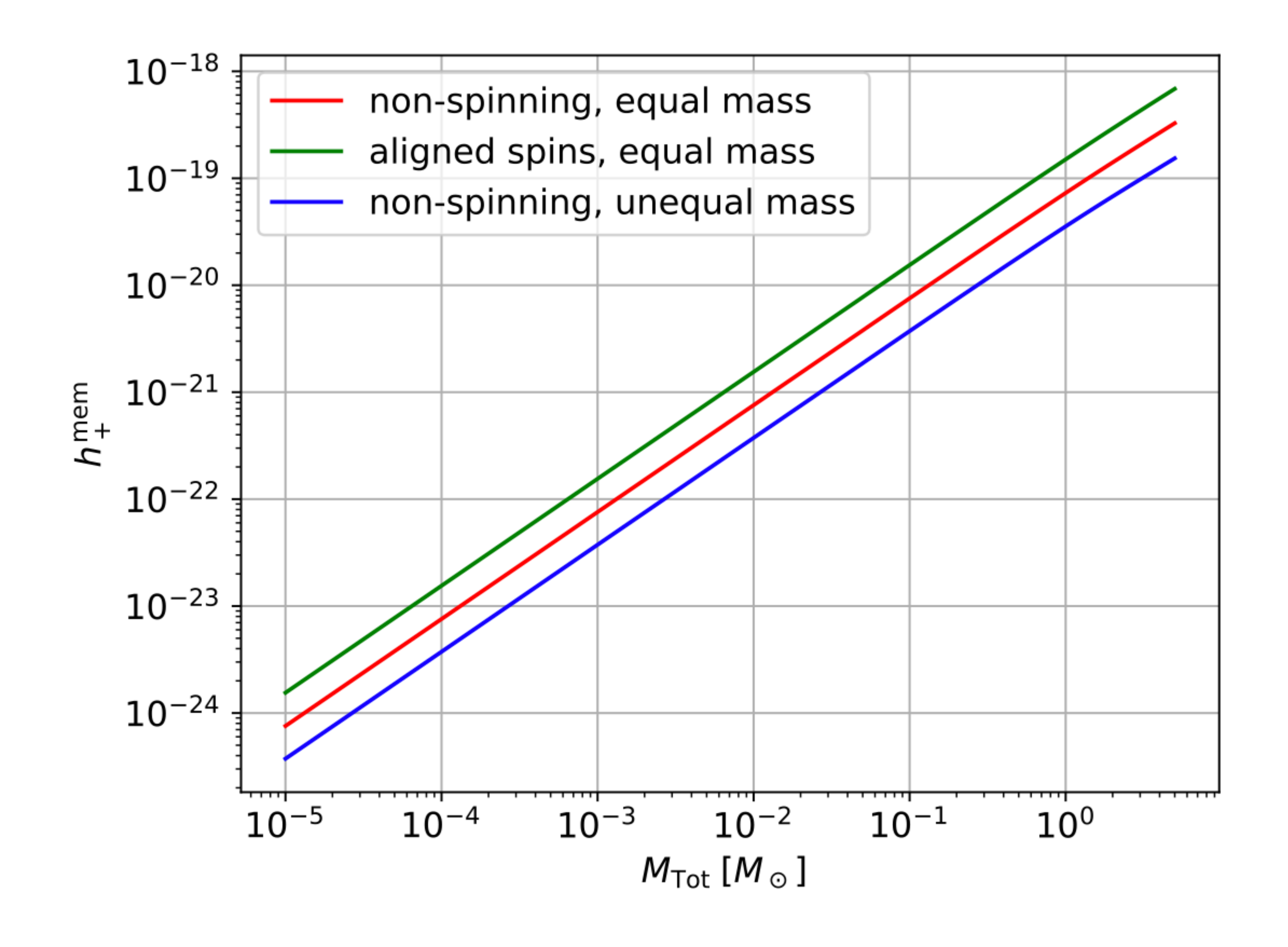
- Not detectable even with ET and CE

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

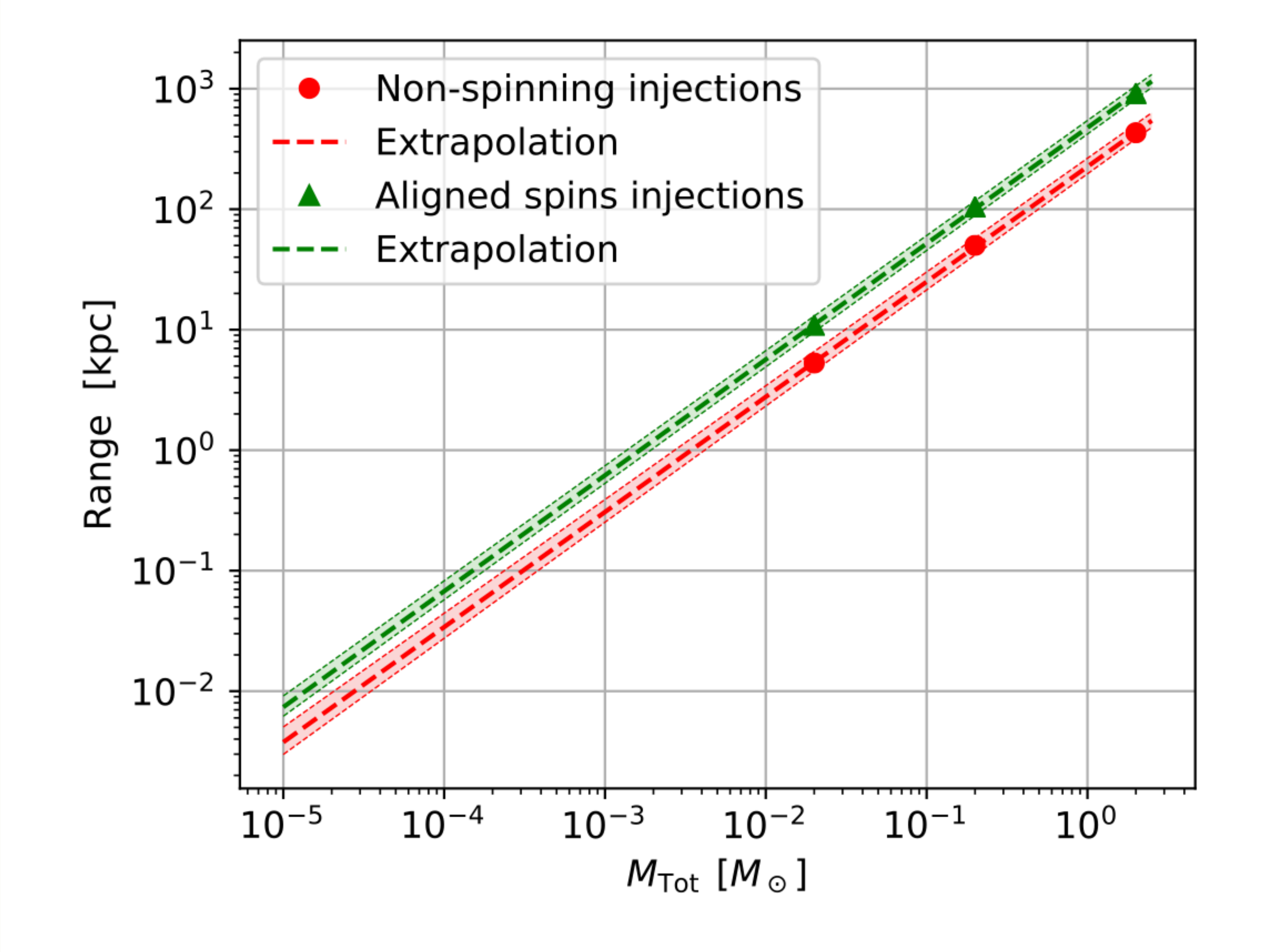
- We use the NRSur waveform model for the oscillatory waveform and compute the memory for only the merger part of the signal
  - The memory contribution from early time inspiral is negligible as the memory amplitude is directly related to emitted GW radiation
- We study the dependancy of the memory amplitude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



Unequal mass
Mass ratio 3

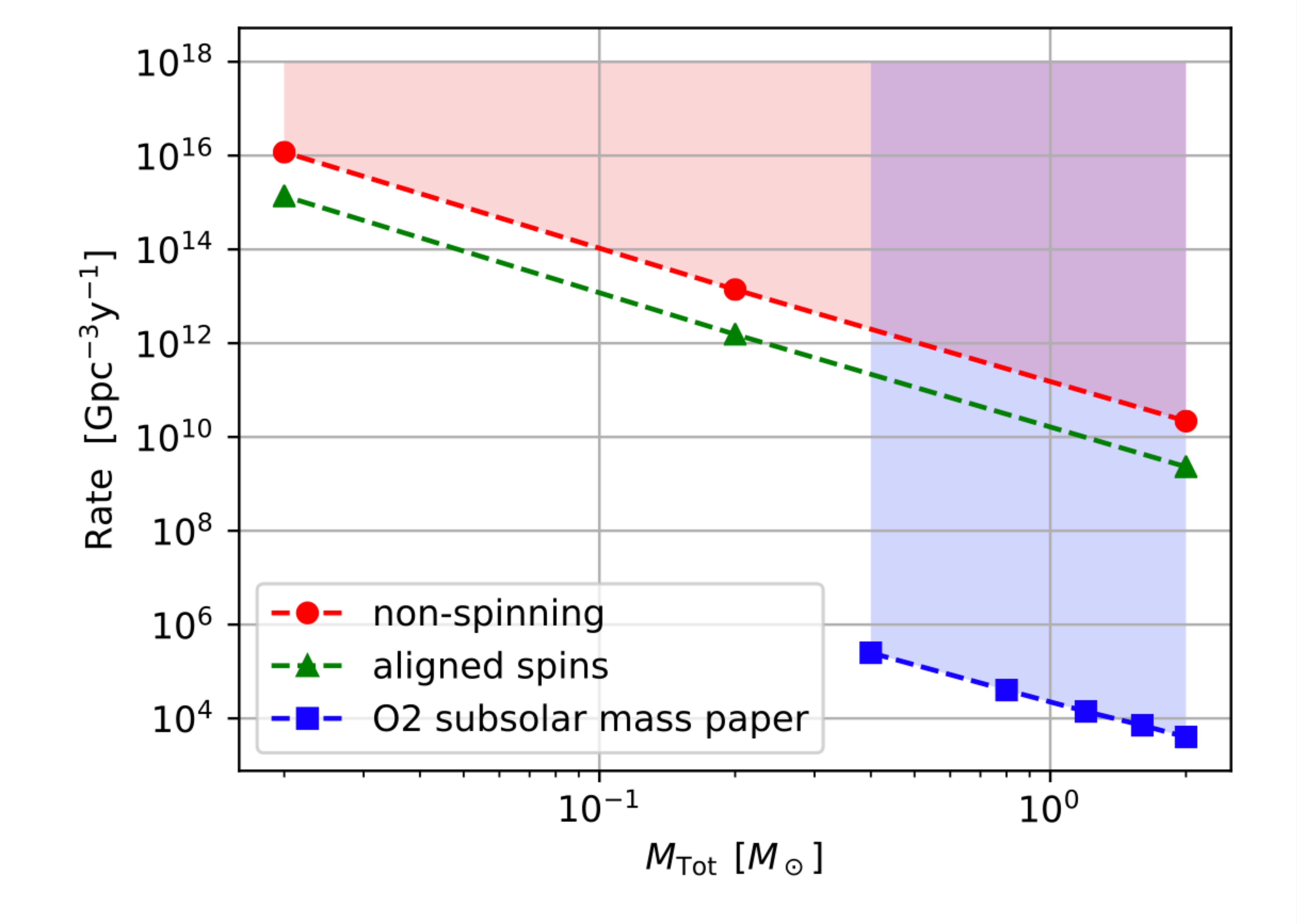
Search for non-linear memory from ultra light CBC

- 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 $M_{Tot} \leq 0.4 M_\odot$

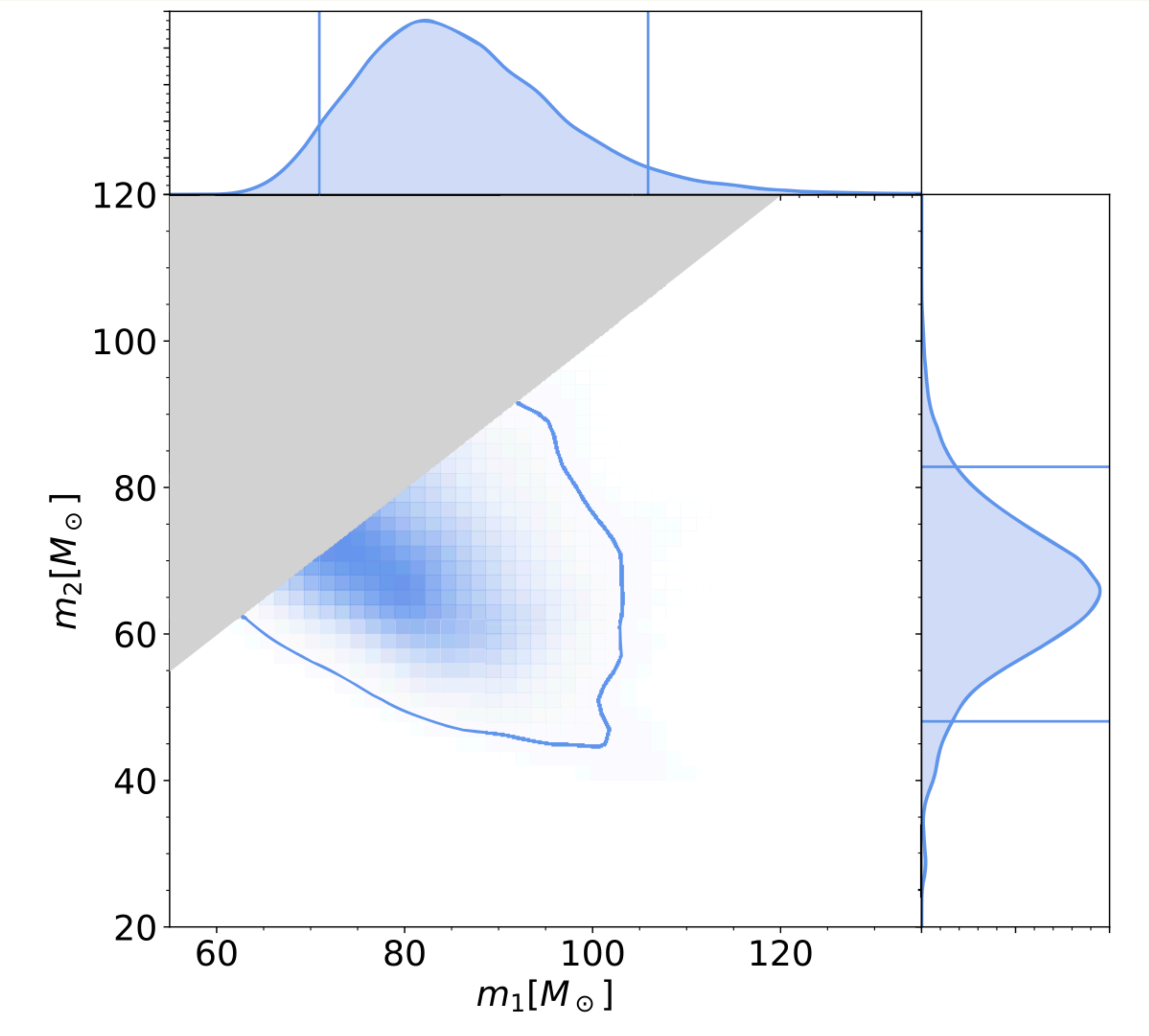


Upper limit on binary merger rate

Ebersold and Tiwari PRD 2020

Gravitational waves : “Interesting” events

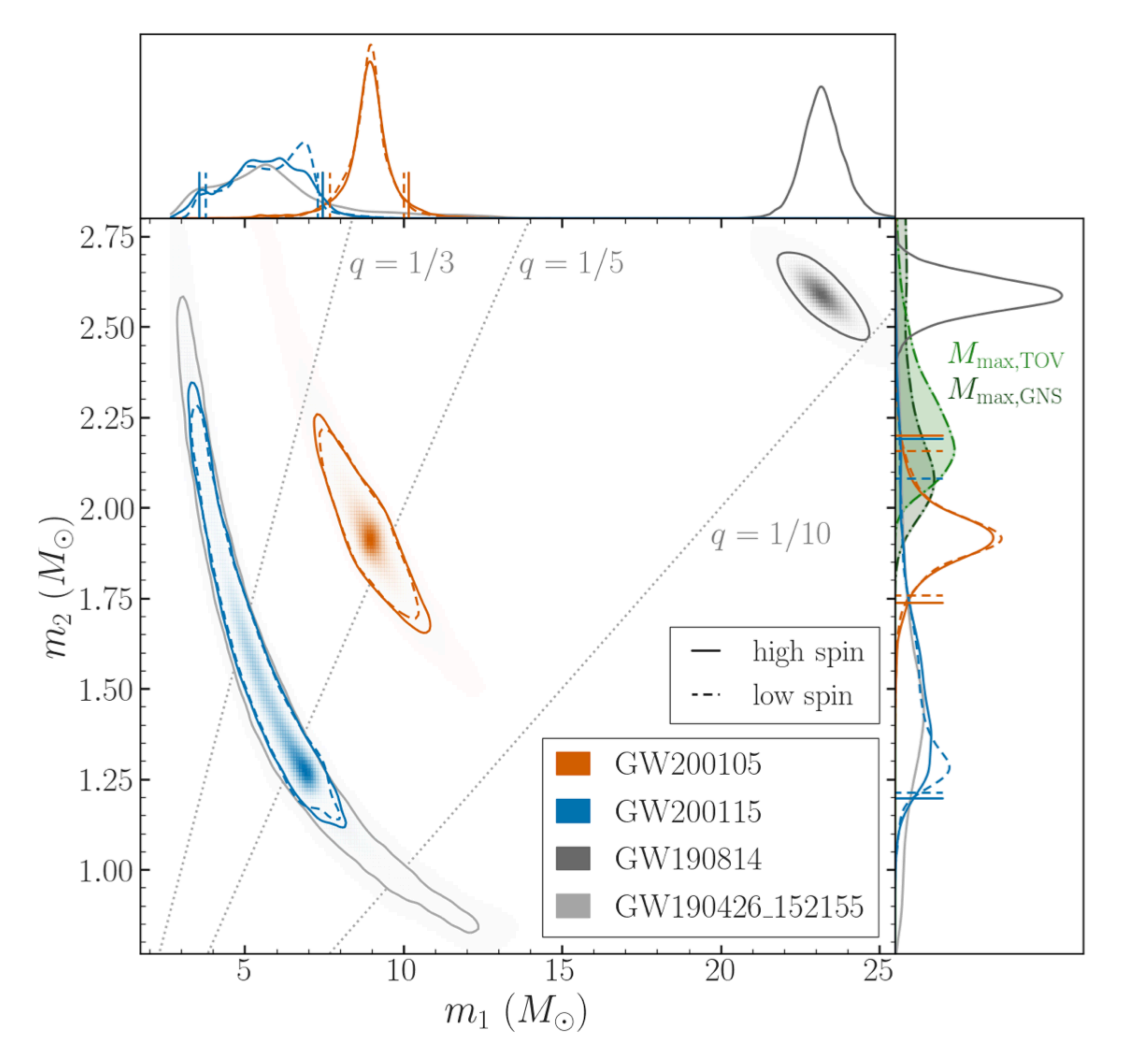
- GW190521 under the assumption of CBC has un-ambiguously both components way above 3 solar masses
  - There is a hint for in-plane spin*
  - The heavier component’s mass has probability of only 0.32% of being lower than 65 solar masses (within the gap of pair instability supernova)
  - The remnant is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



PHYSICAL REVIEW LETTERS 125, 101102 (2020)

Gravitational waves : “Interesting” events

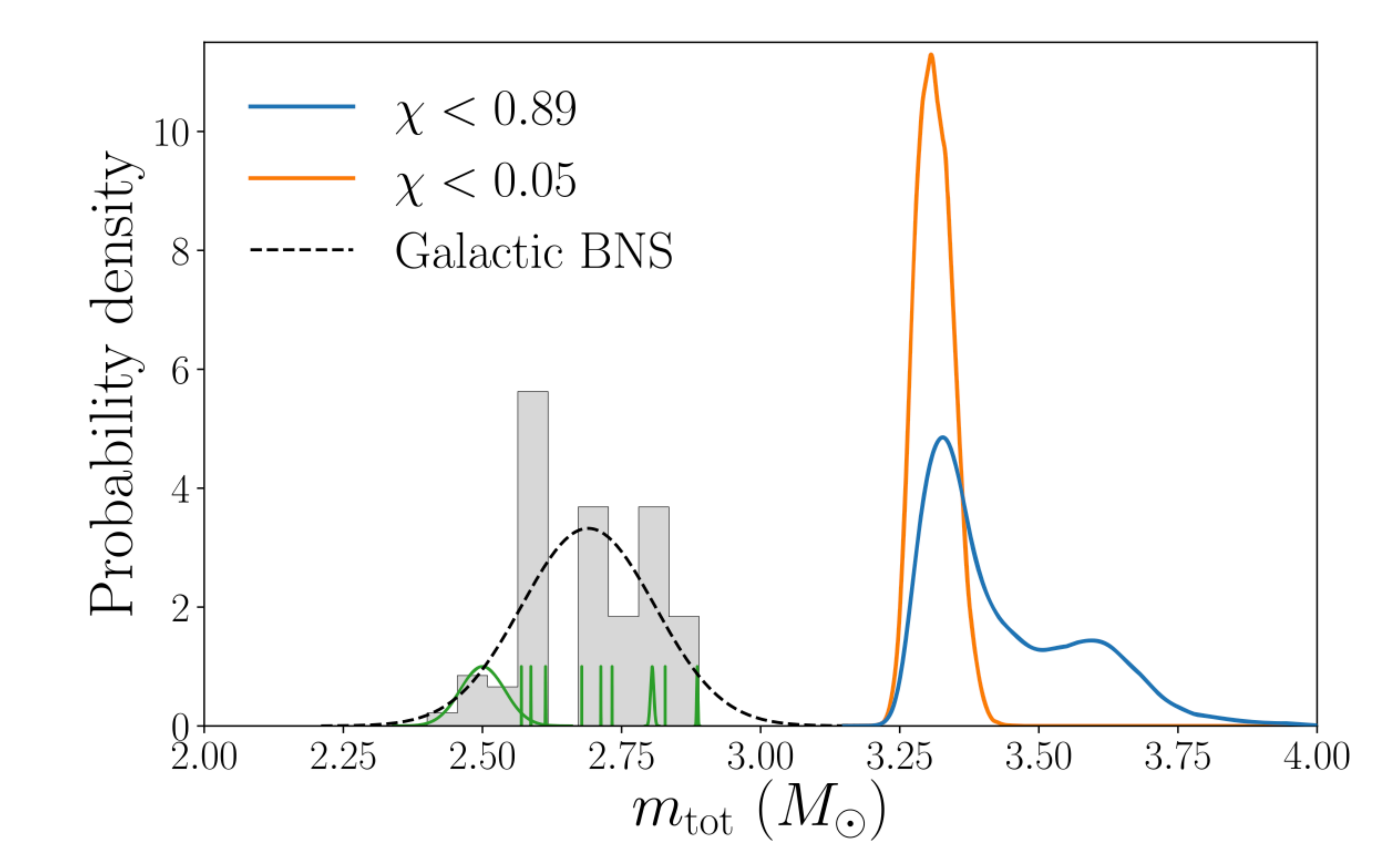
- The two NSBH events (blue and orange) in the picture both have the lighter component less than 3 solar masses and the heavier greater than 3 solar masses
  - We consider objects less than 3 solar masses to be a candidate for neutron stars conservatively
- GW190814 was also an event (grey) with lighter 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



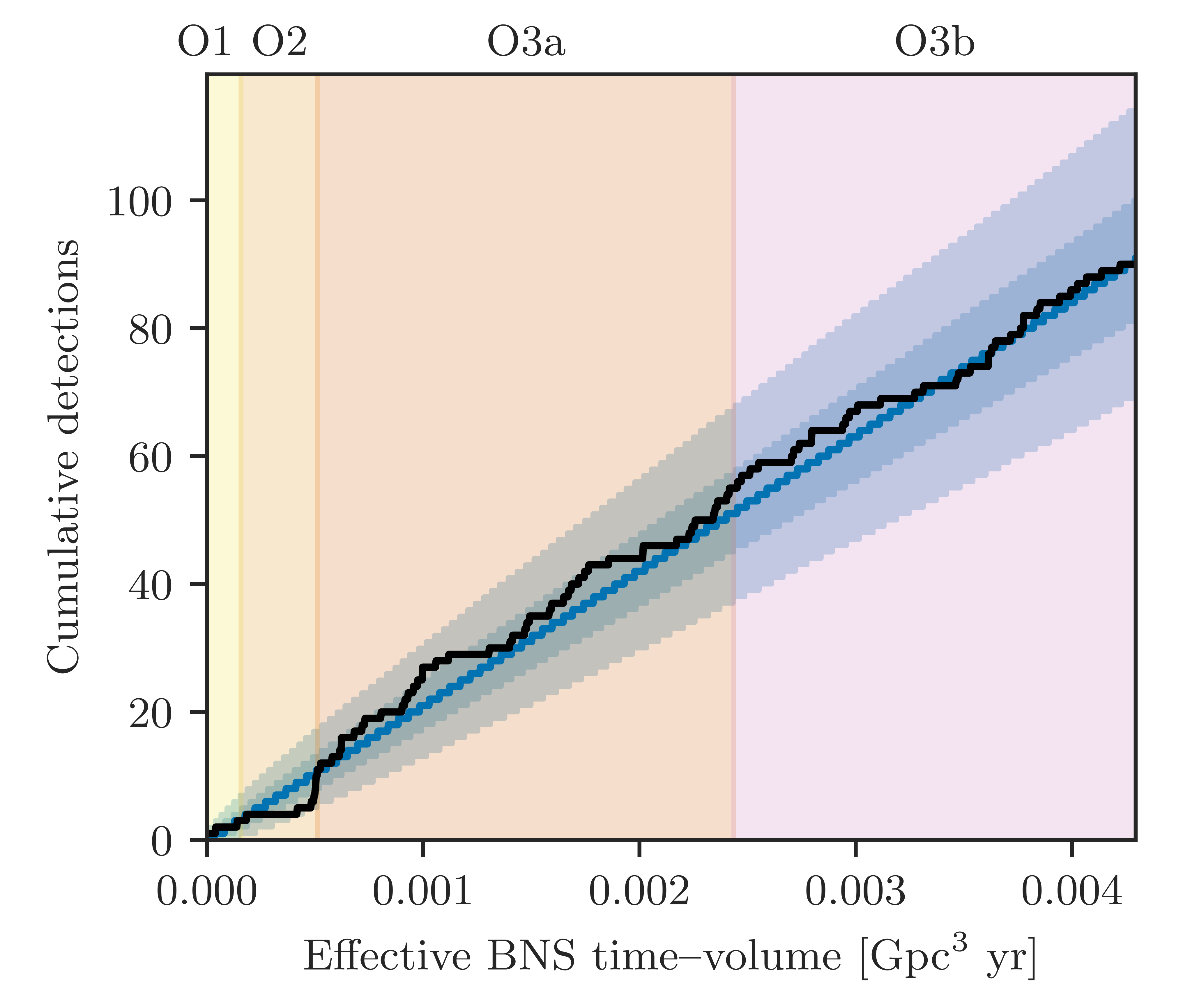
The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20

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

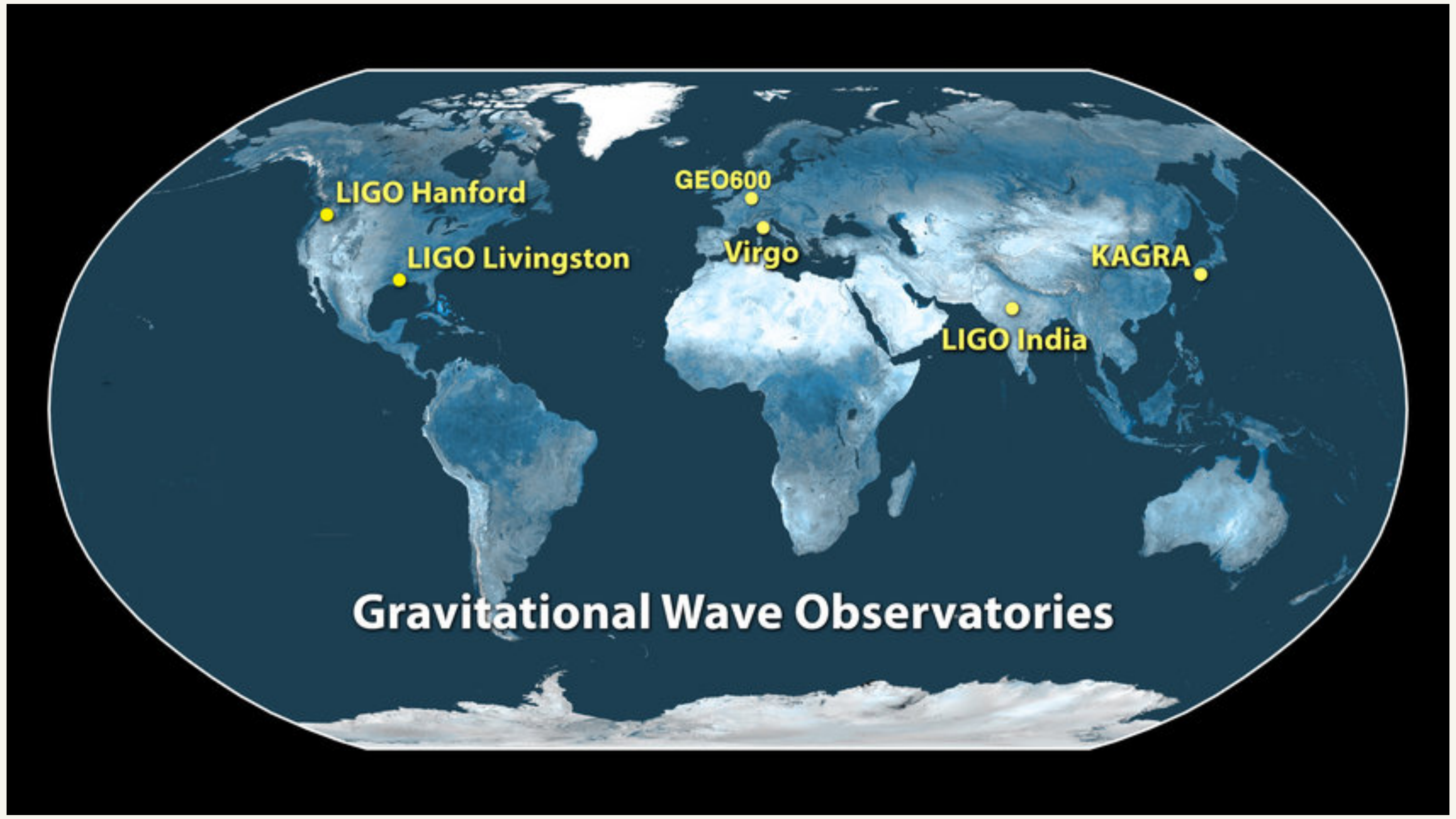
*exceptional for me

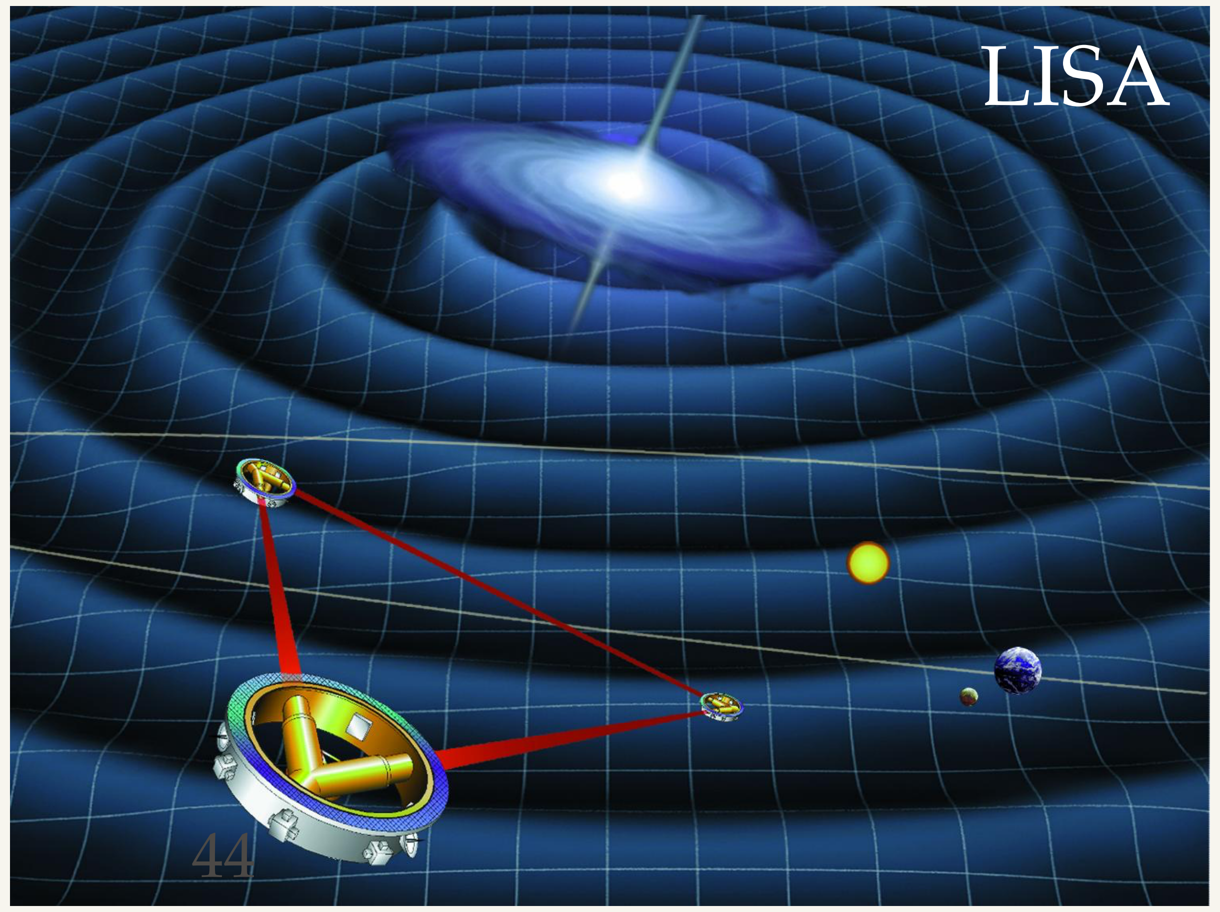
Gravitational waves : “Interesting” events

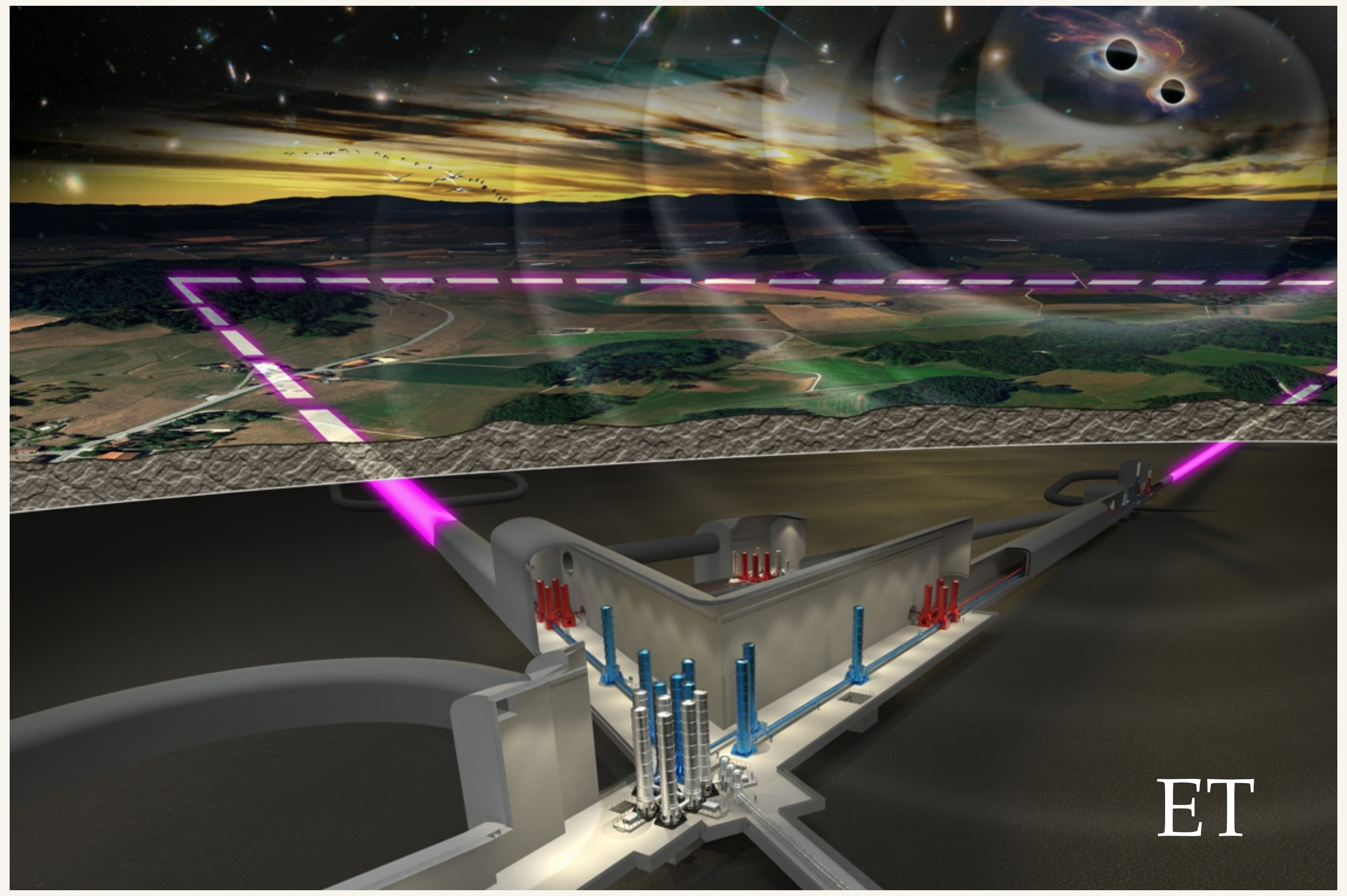
- Henceforth I call these events interesting
  - **GW200105, GW200115** : 2 Neutron Star Black Hole binaries,
  - **GW190814** : Ambiguous lighter companion,
  - **GW190425** : Heavy double Neutron Star event with no electromagnetic counter part
- I leave alone **GW190521** as the masses are so high 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!!!

Gravitational waves

- 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

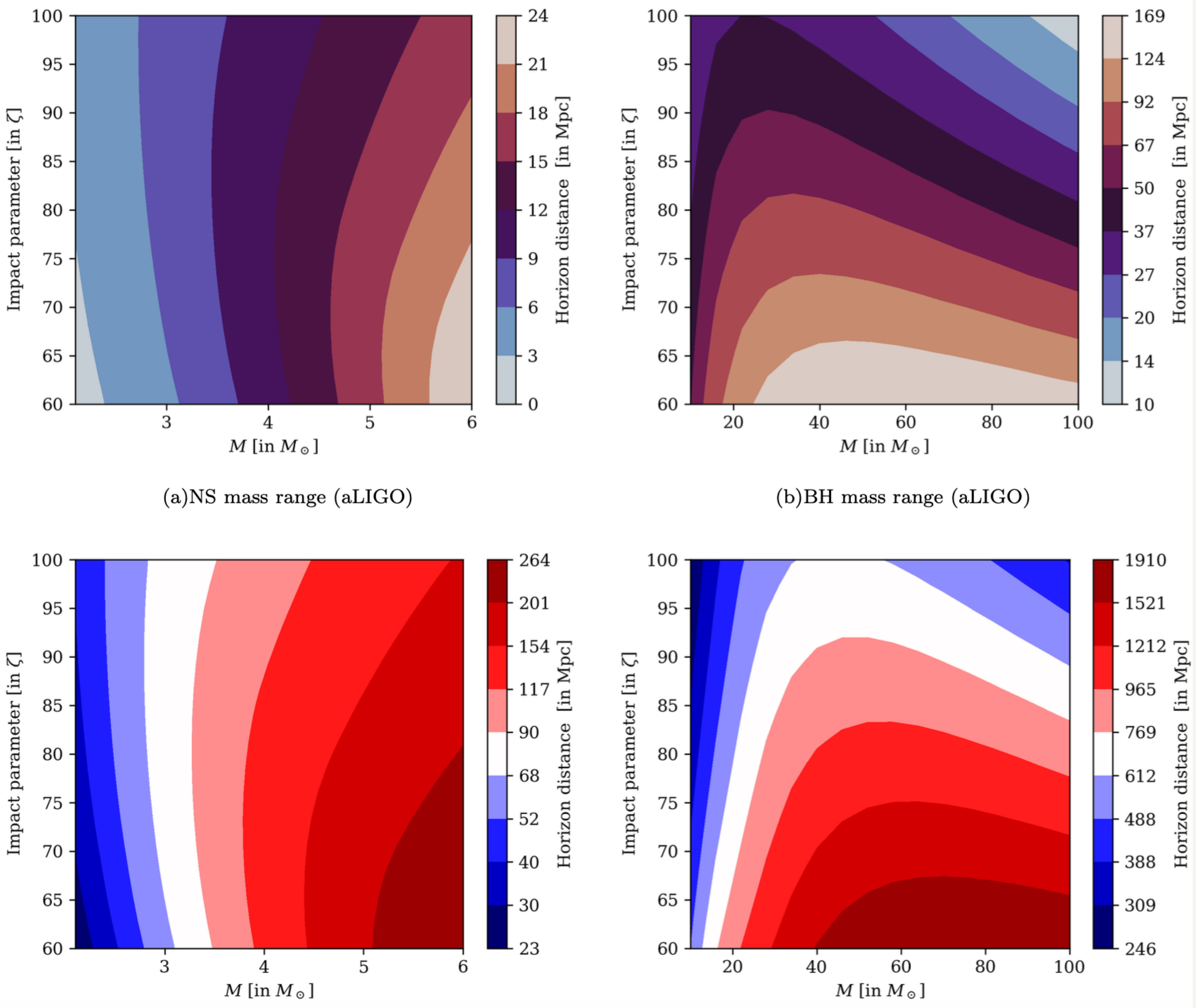






Linear memory : Detectability of hyperbolic encounters of binaries

- 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