Title: Gravitational-wave memory effects from binary-black-hole mergers

Speakers: David Nichols

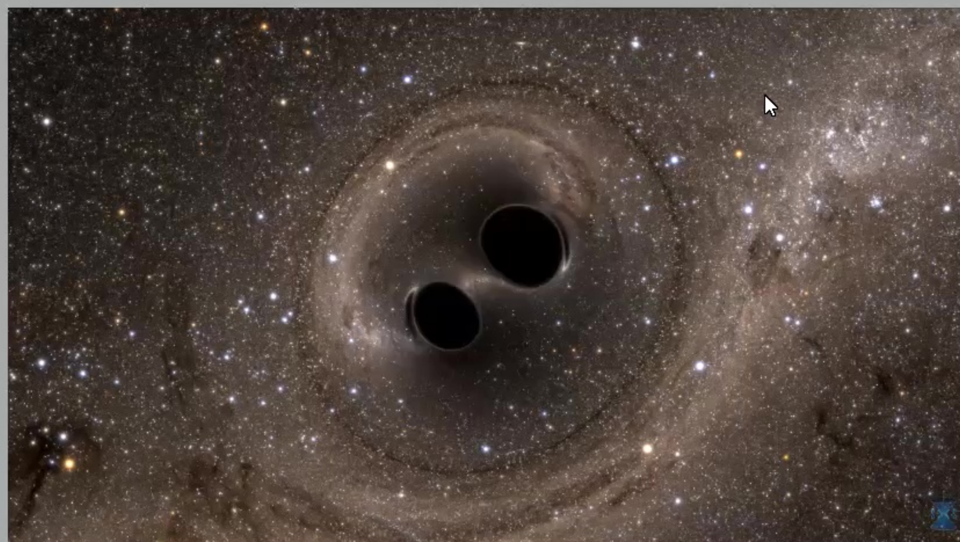
Series: Strong Gravity

Date: April 29, 2021 - 1:00 PM

URL: http://pirsa.org/21040034

Abstract: Over forty detections of binary-black-hole mergers have been made during the first three observing runs of the LIGO and Virgo detectors. With this larger number of measurements of increasing accuracy, many of the remarkable predictions of general relativity for strongly curved, dynamical spacetimes will be able to be studied observationally. In this talk, I will discuss one class of strong-gravity phenomena, called gravitational-wave memory effects, which are predictions of general relativity that are most prominent in systems with high gravitational-wave luminosities, like binary black holes. Memory effects are characterized by changes in the gravitational-wave strain and its time integrals that persist after a transient signal passes by a detector. I will summarize the computation of these effects and the prospects for current and planned future gravitational-wave detectors to detect memory effects from black-hole mergers; in particular, there could be evidence for the memory effect in just a few years of advanced LIGO, Virgo, and KAGRA data at their design sensitivities. I will also review what observing gravitational-wave memory effects can teach us about the symmetries and conserved quantities around isolated systems like binary-black-hole mergers. Time permitting, I will present results on memory effects in scalar-tensor theories of gravity and on subleading memory effects.

Gravitational-wave memory effects from binary-black-hole mergers

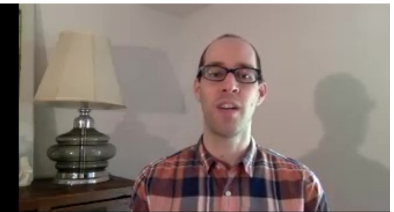


David A. Nichols, University of Virginia, Dept. of Physics

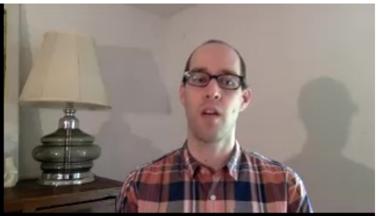
Strong Gravity Seminar

Perimeter Institute (via Zoom)

April 29, 2021



Outline



1. Review/summary of gravitational wave (GW) detections
2. GW memory effect and its detection prospects
3. Implications of detecting GW memory
4. New types of GW memory effects and detection prospects
5. Future directions and conclusions

1. LIGO, Virgo, and KAGRA detectors

LIGO Hanford

LIGO Livingston

Virgo

KAGRA

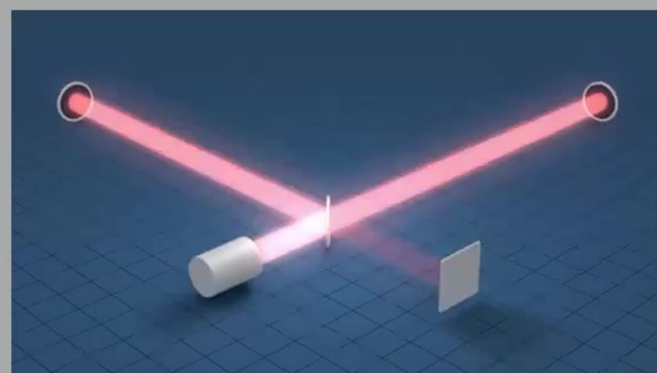


Image Credits: LIGO/Virgo/KAGRA

1. LIGO, Virgo, and KAGRA detectors

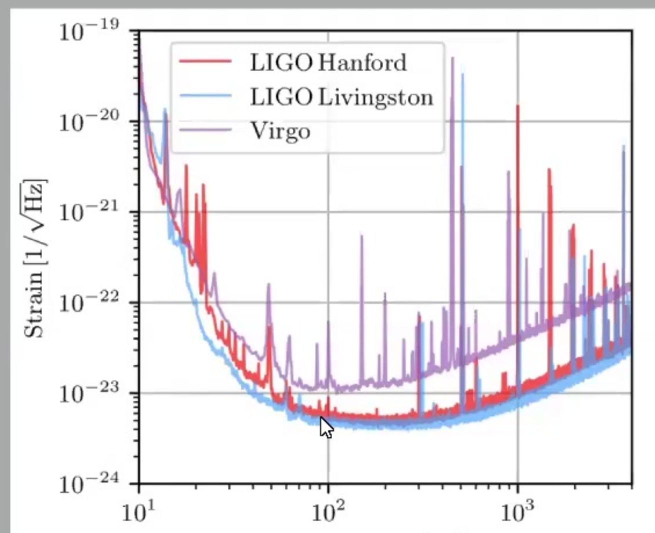
LIGO Hanford

LIGO Livingston

Virgo

KAGRA

Image Credits: LIGO/Virgo/KAGRA



LVC, GWTC-2, 2020

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GWs from binary-black-hole (BBH) mergers

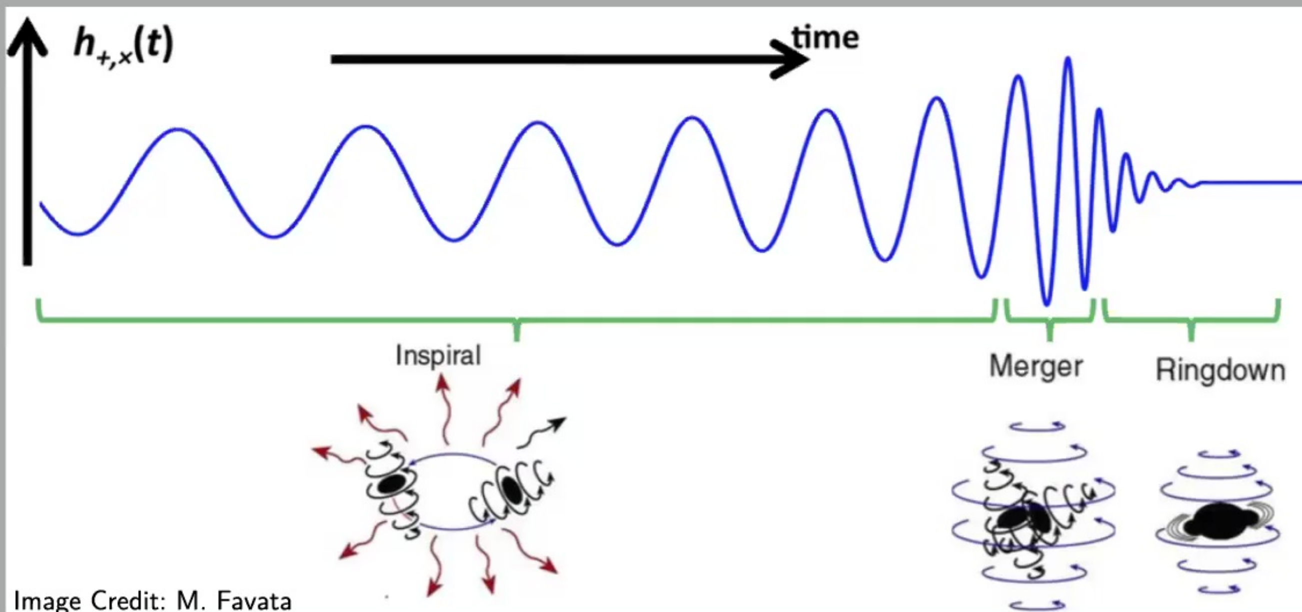
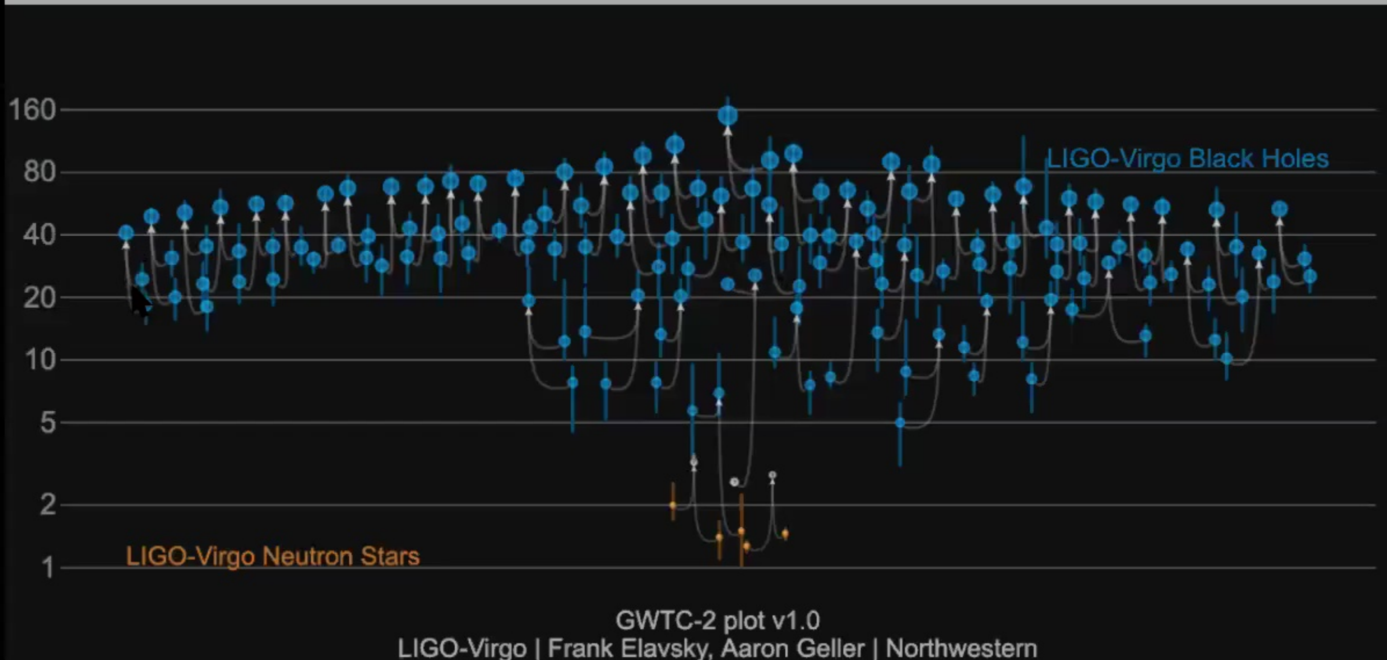
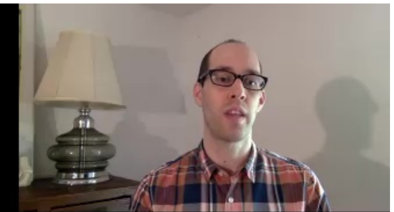


Image Credit: M. Favata

Evolution of frequency and amplitude encodes information about the masses and spins of the individual BHs

LIGO and Virgo Detections





- First observing run (O1): 3 binary black holes (BBH)
- O2: 7 BBH and 1 binary neutron star (BNS)
- O3a: 36 BBH, 1 BNS, 1 BH-NS (marginal), 1 BBH or BH-NS

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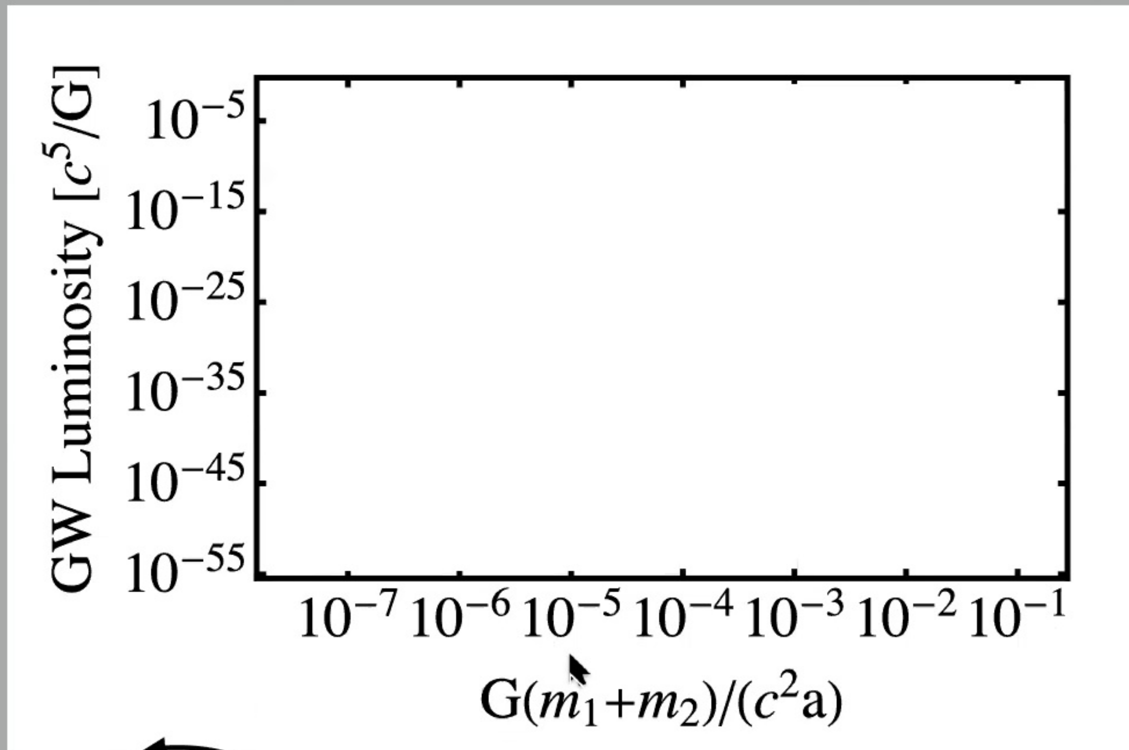
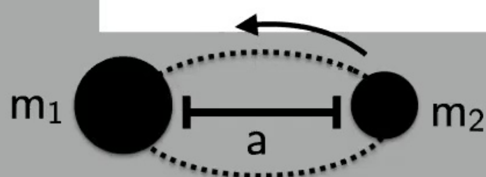
Binary BHs probe nonlinear & dynamical GR

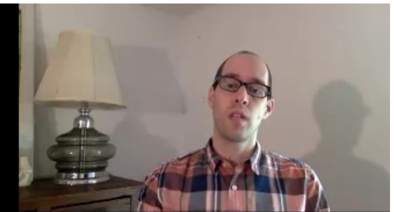




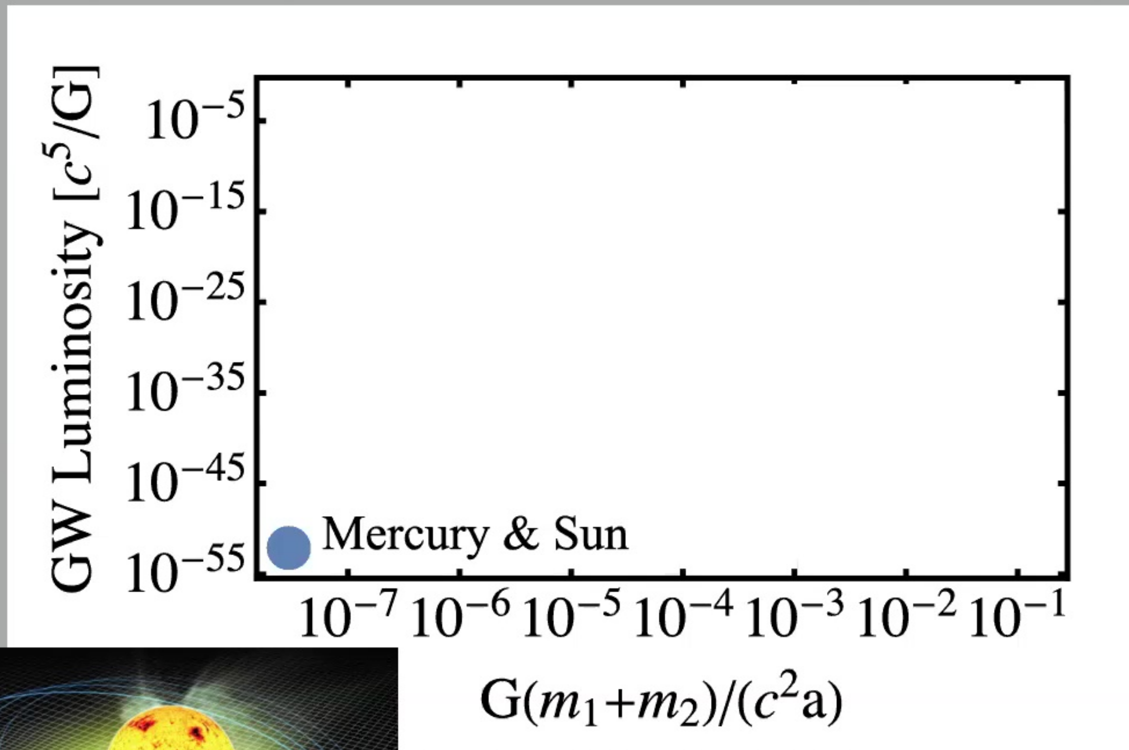
"Planck luminosity"

$$\frac{c^5}{G} \approx 3.6 \times 10^{52} \mathrm{W}$$

6



Binary BHs probe nonlinear & dynamical GR



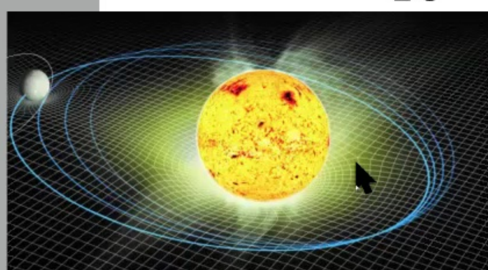


Image Credit: NASA

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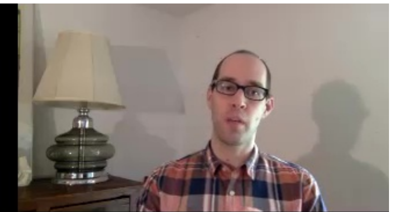
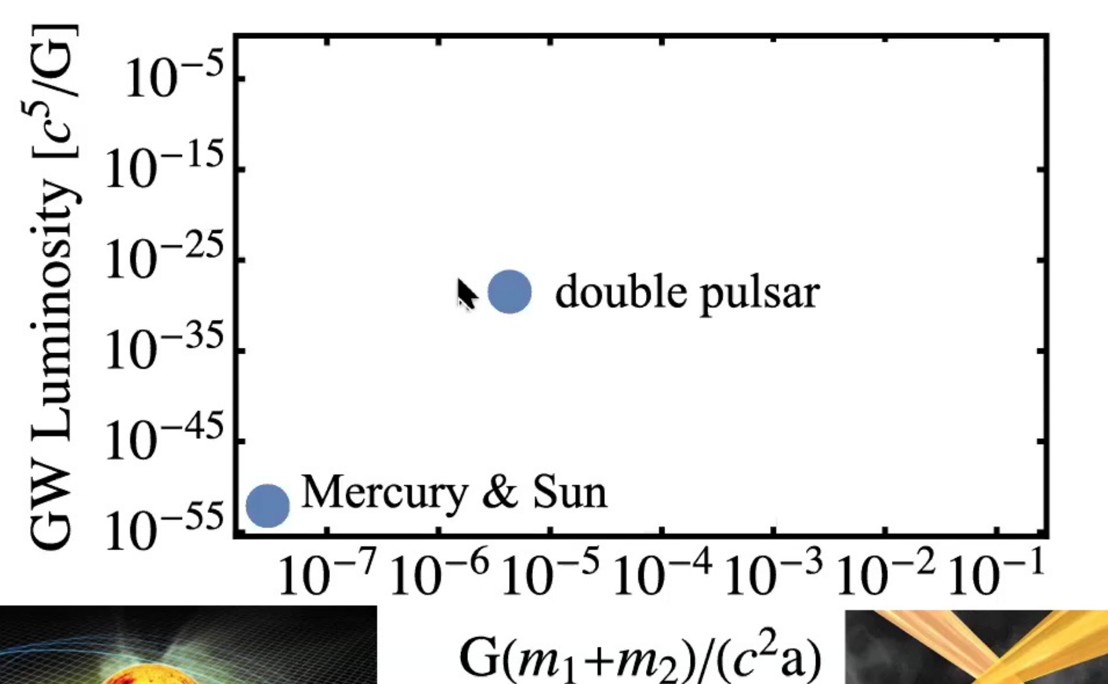
Binary BHs probe nonlinear & dynamical GR





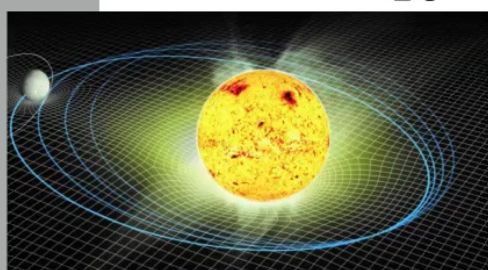


Image Credit: NASA

"Planck luminosity"

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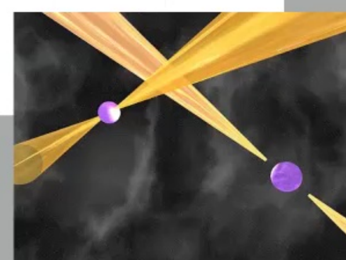

Image Credit: M. Kramer

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Binary BHs probe nonlinear & dynamical GR

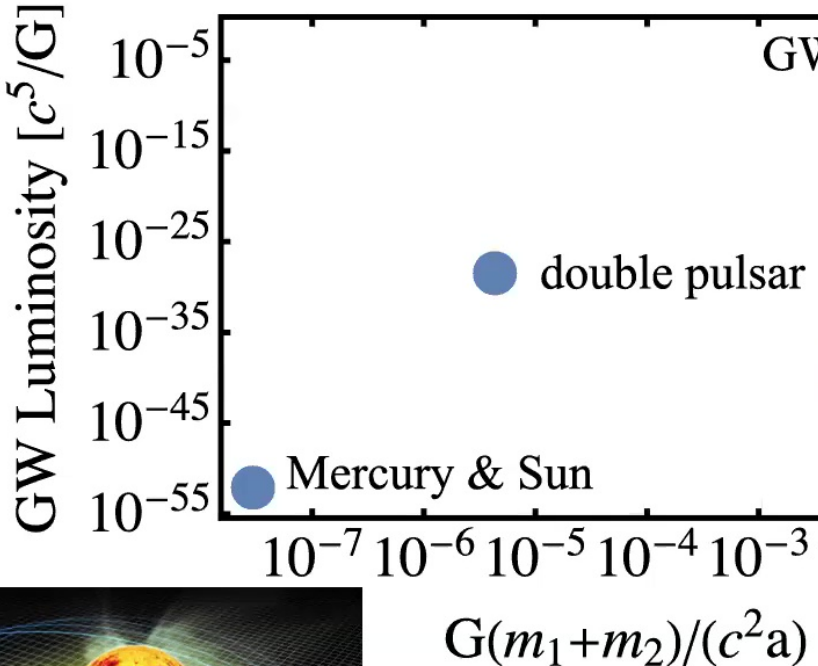


Image Credit: LIGO

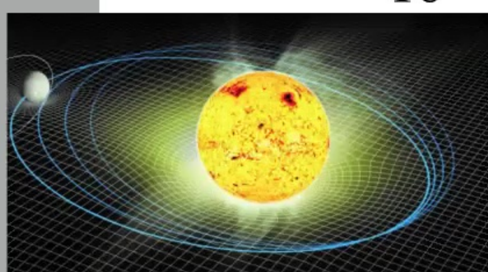
Image Credit: NASA

"Planck luminosity"

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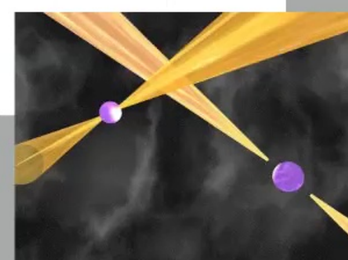
Image Credit: M. Kramer

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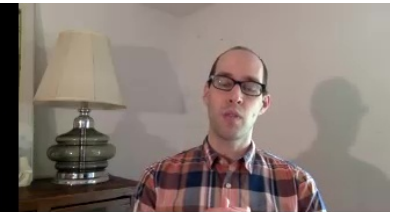
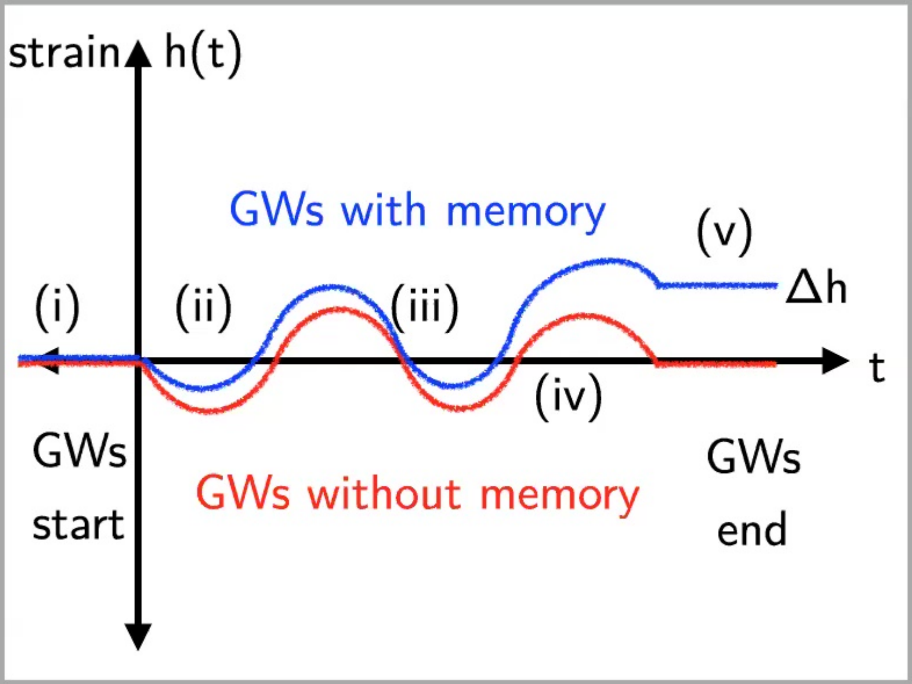
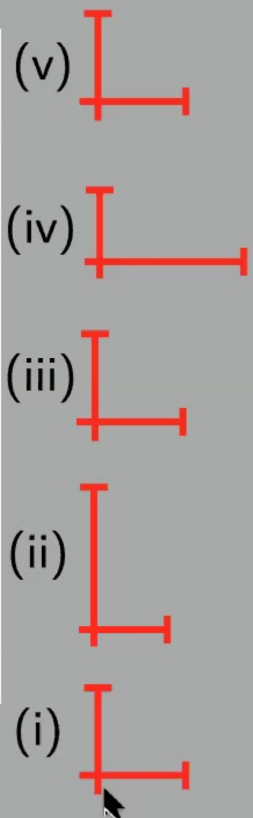
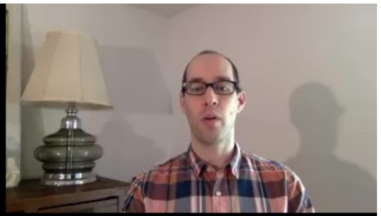


2. Gravitational-wave (GW) memory effect







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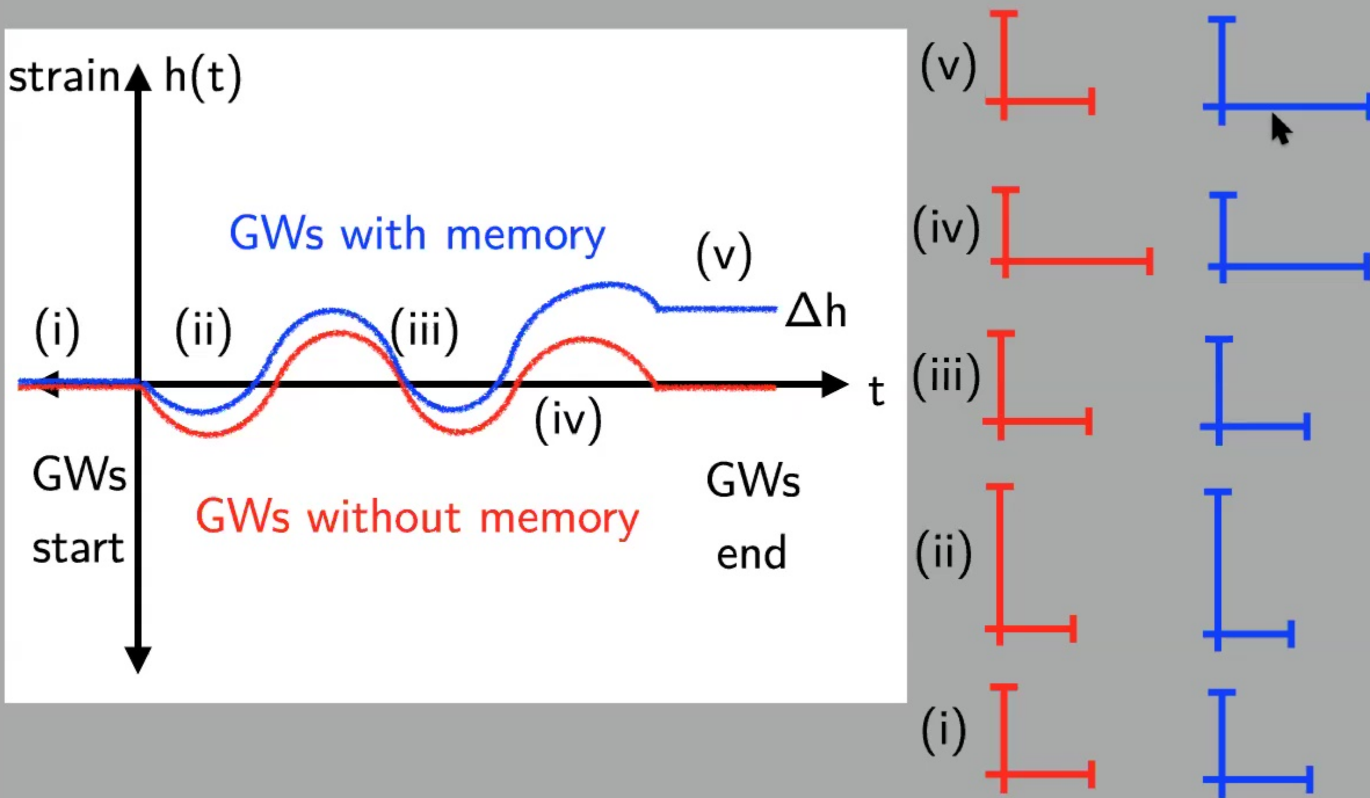

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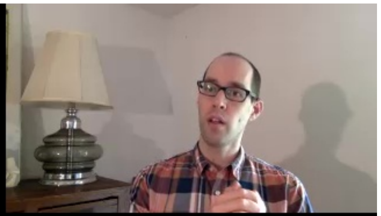

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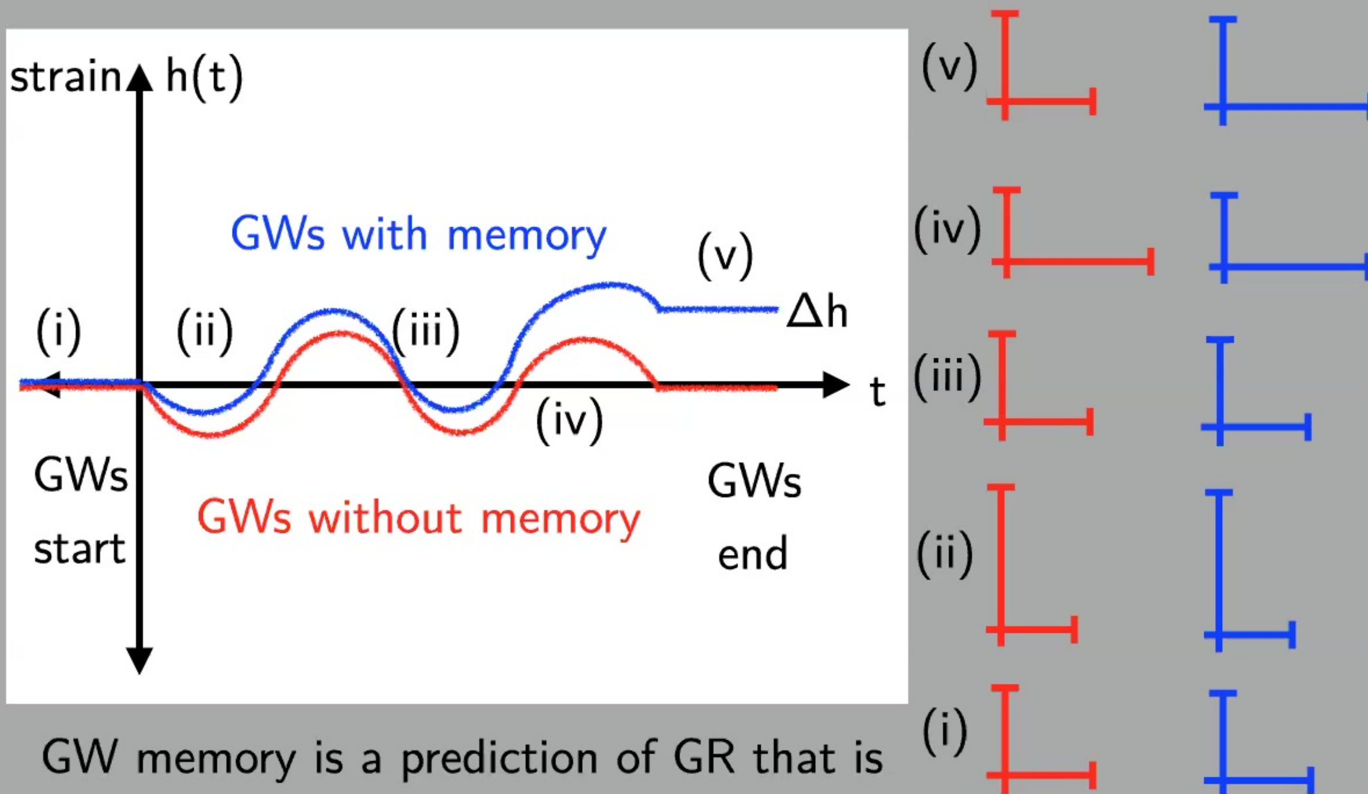
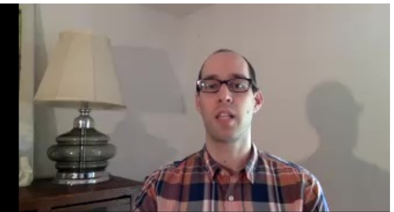
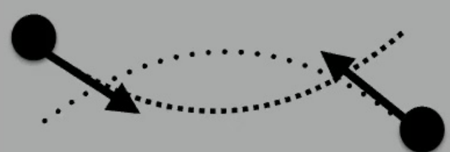


GW memory is a prediction of GR that is expected for most transient GW sources



Sources of GW memory

$$\Delta h \propto \begin{array}{c}\text{Changes in}\\ \text{“conserved”}\\ \text{quantities}\end{array} + \int dt \left(\begin{array}{c}\text{Energy flux}\\ \text{from massless}\\ \text{particles}\end{array} + \begin{array}{c}\text{Energy flux}\\ \text{from GWs}\end{array} \right)$$



Ex. NSs/BHs Scattering

Zeldovich & Polnarev, (1974)

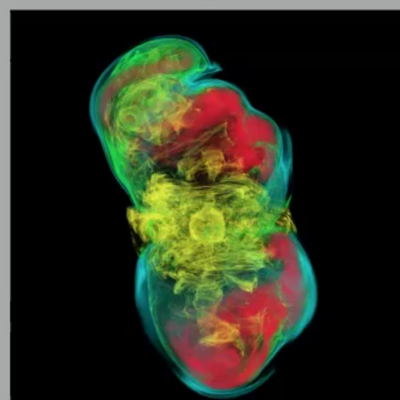


Image Credit: P. Moesta

Ex. SNe neutrinos

Epstein, (1978)

Image Credit: SXS

Ex: BBH mergers

Christodoulou, (1992)

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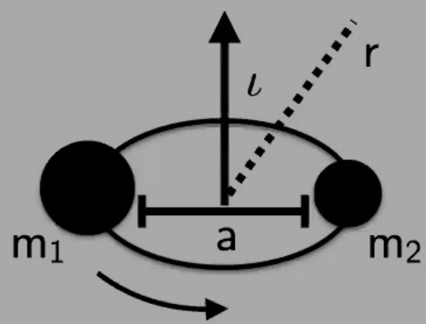
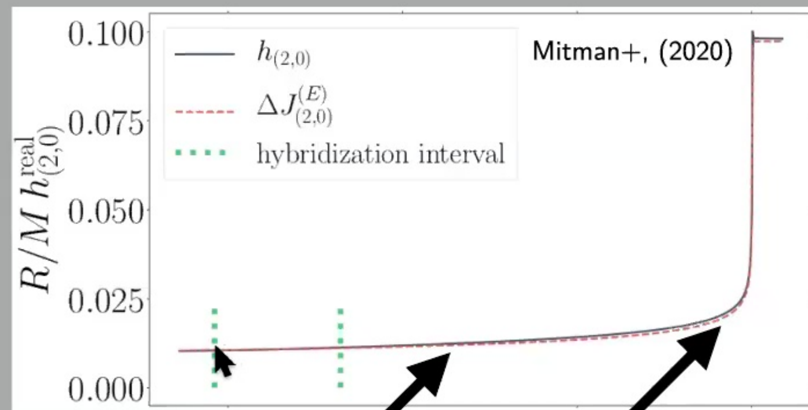
Memory effect from BBH mergers





Inspiral

Merger/ Ringdown

Time

"Newtonian" expectations

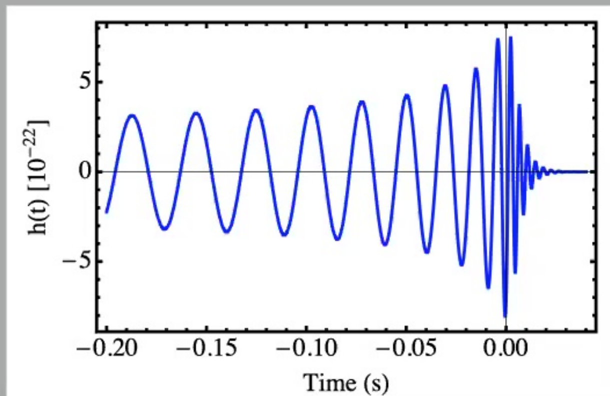
$$\Delta h_+ = \frac{G}{c^4}\frac{1}{48r}\Delta\left(\frac{Gm_1m_2}{a}\right)$$
$$\times \sin^2\iota(17+\cos^2\iota)$$
$$+ \text{ post-Newtonian corrections}$$

Numerical Relativity (NR)

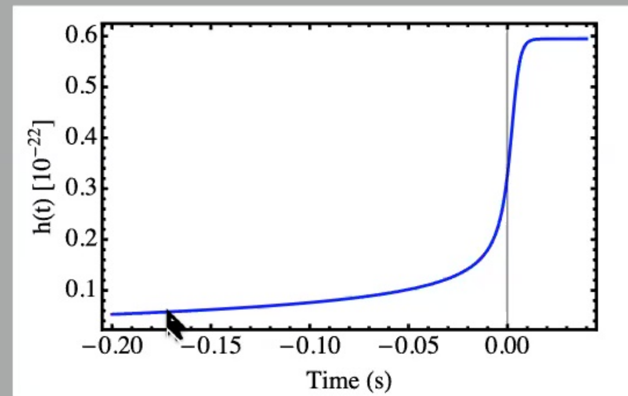
Memory computed "exactly" and approximately agree well

Wiseman & Will (1992)

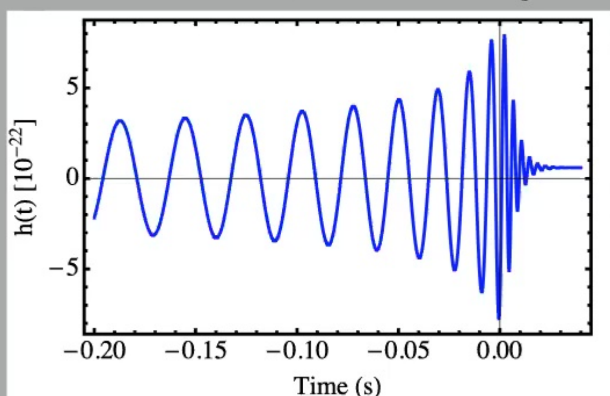
Detecting GW memory (GW150914)



Waveform, no memory



GW memory waveform



Complete waveform

- Want to determine if waveform w/ vs. w/o memory is preferred by the data
- Will use additional signal-to-noise (S/N) in memory waveform to assess

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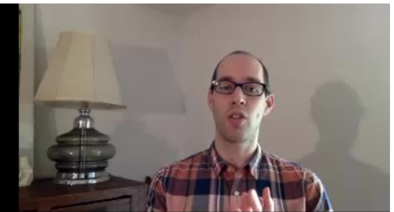
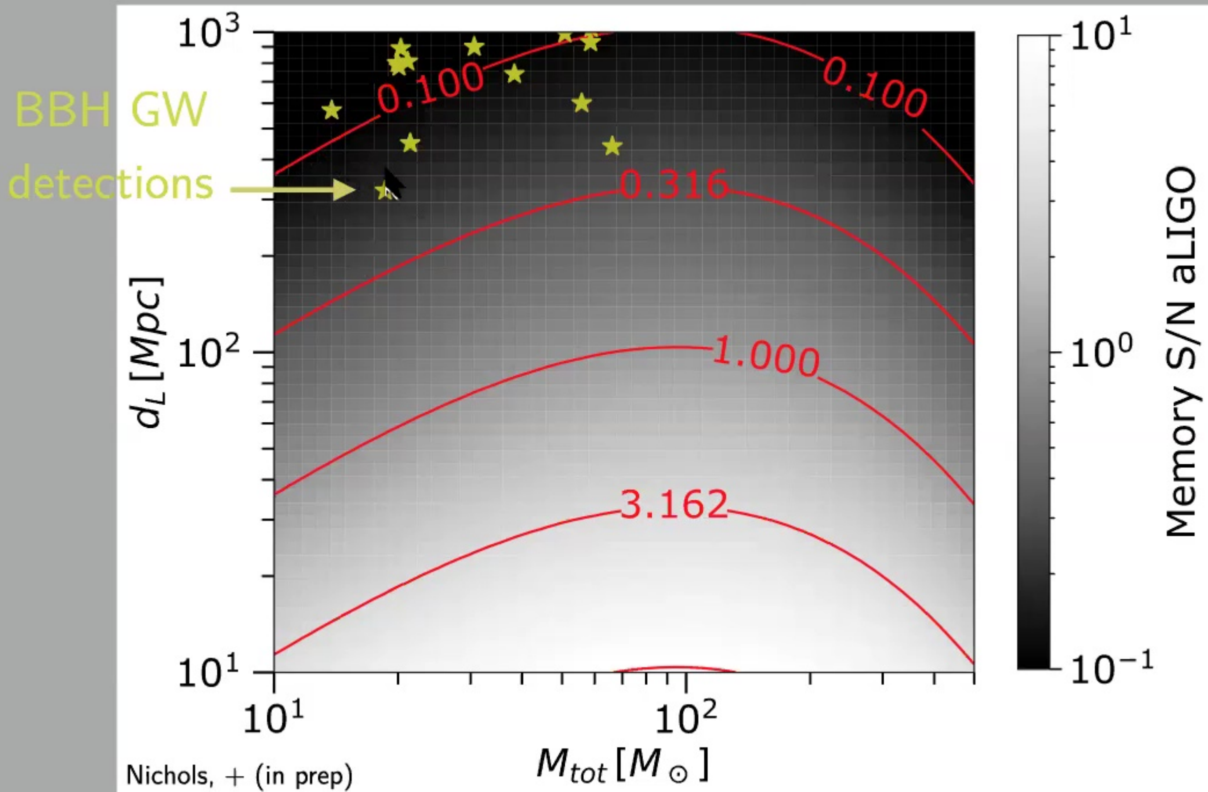
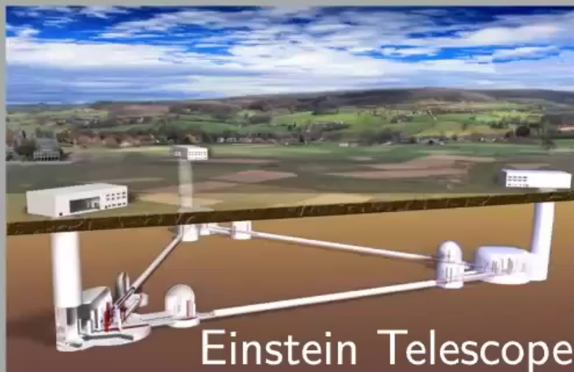


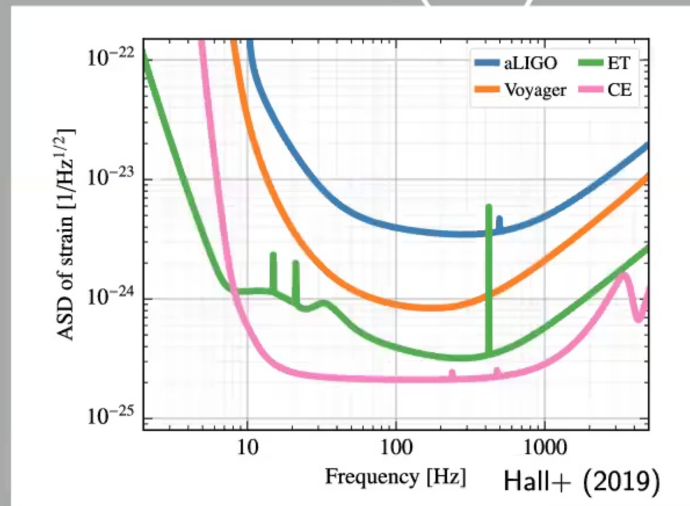
Prospects for measuring GW memory



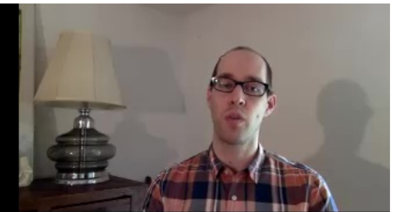
- Advanced LIGO design sensitivity, single detector, angle averaged, equal mass; prospects for detection not promising

Planned GW detectors on Earth (3G)





- ET: 10km, underground, EU, operational early 2030s
- CE: 40km, above ground, US, stage 1 mid 2030s, stage 2 2040s



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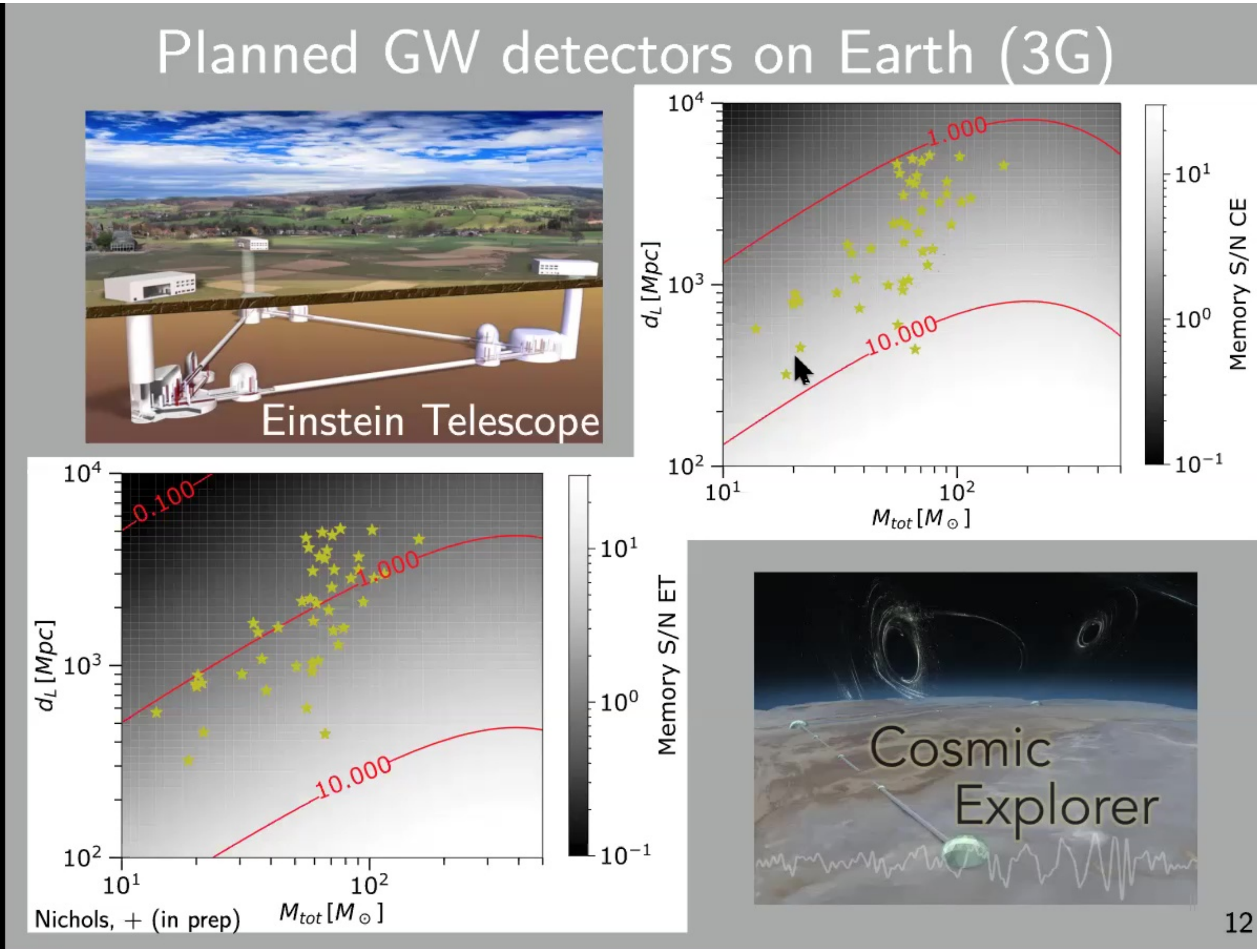
Planned GW detectors on Earth (3G)
Einstein Telescope
10^4
10^3
10^2
$d_L\,[Mpc]$
10^1
10^2
$M_{tot}\,[M_\odot]$
1.000
10.000
10^1
10^0
10^{-1}
Memory S/N CE
0.100
1.000
10.000
Memory S/N ET
Nichols, + (in prep)
Cosmic Explorer
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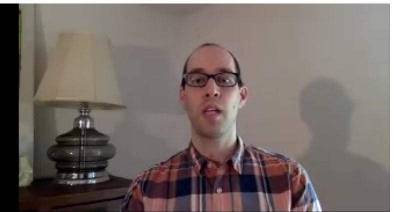
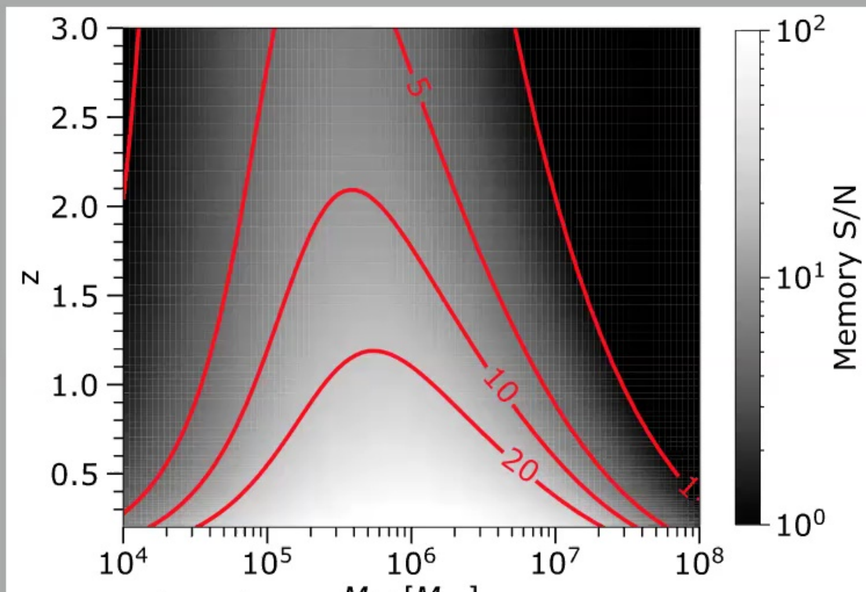


Detecting memory with LISA from SMBBHs

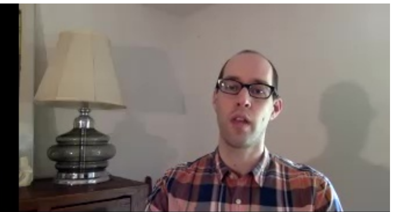


Nichols, + (in prep)

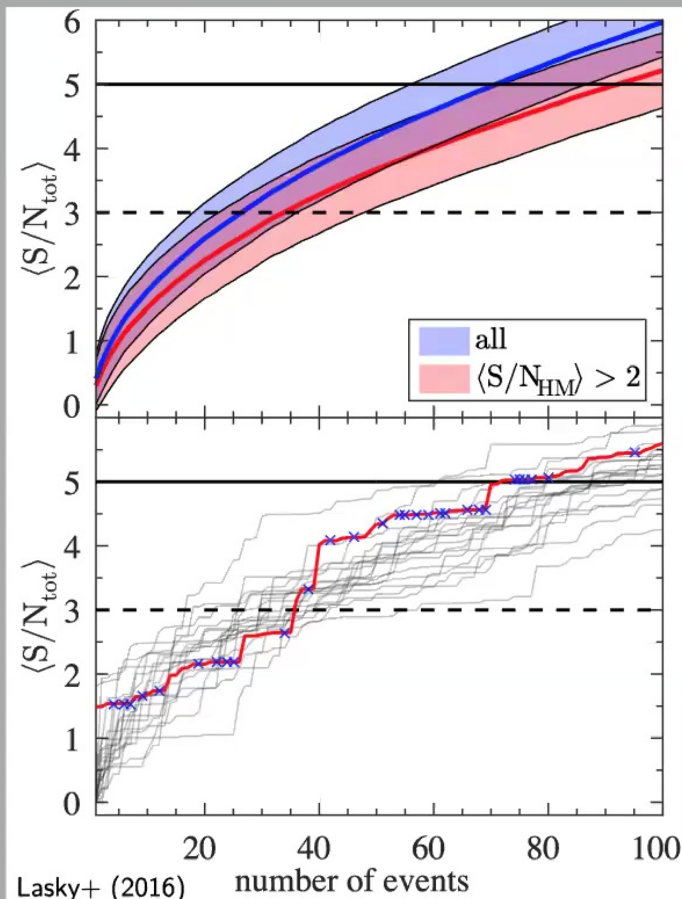
Credit: LISA

- 10^6 km arms
- 10^{-4}–10^{-1} Hz best sensitivity
- Planned launch: 2034

- Expect O(1) SMBBH merger with measurable GW memory effect during LISA mission lifetime Islo+, (2019)



Detecting memory in populations with LIGO



S/N of memory in population:

$$\langle S/N_{tot} \rangle = \left(\sum_{i=1}^{n} \langle S/N_{\Delta h_i} \rangle^2 \right)^{1/2}$$

$$\langle S/N_{tot} \rangle \sim \sqrt{n}$$

- Population consists of GW150914-like events
- Make multiple realizations of this population
- Only count events with measurable higher harmonics of the GWs

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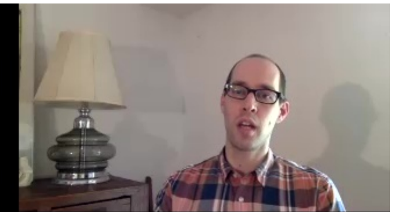
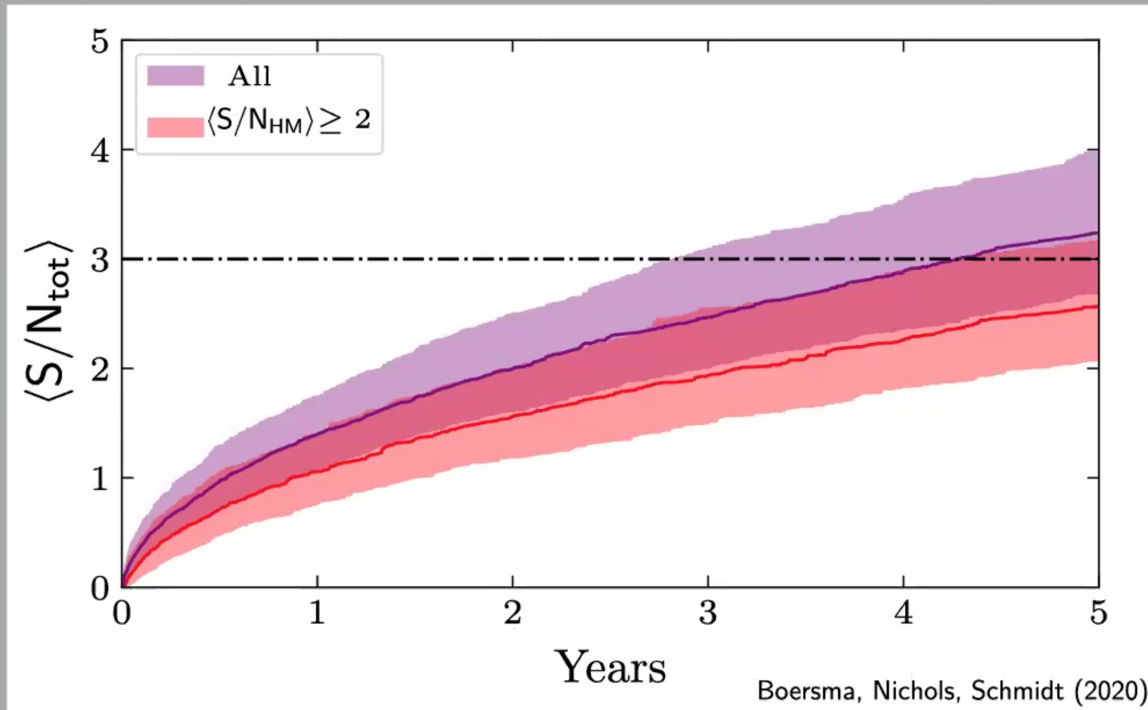


Populations and time to memory detection



- Simulate multiple realizations of a BBH population consistent with O1 & O2 LIGO BBHs; take median and 1-sigma error
- aLIGO and AdVirgo design sensitivity; with 50% duty cycle

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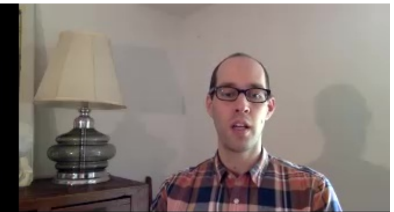
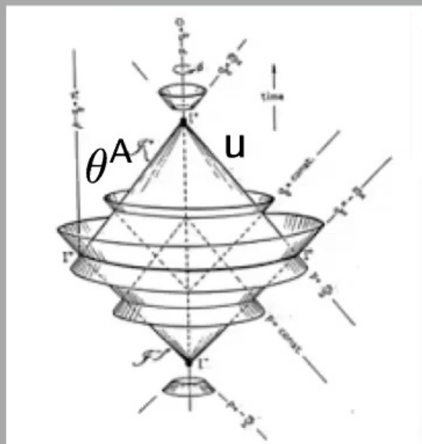


3. Asymptotic flatness and symmetries



Penrose (1963)

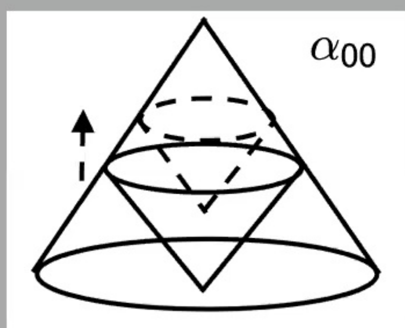
Bondi-Metzner-Sachs (BMS) algebra

Bondi, van der Burg, Metzner (1962), Sachs (1962)

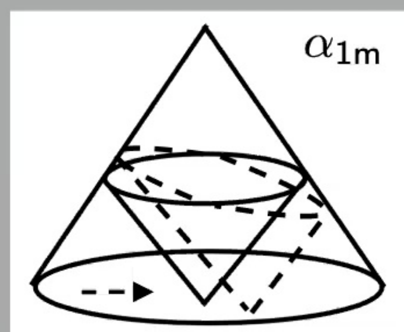
Symmetry (u=0): $\vec{\zeta} = \alpha(\theta^A)\vec{\partial}_u + Y^A\vec{\partial}_A$

$\alpha(\theta^A)$, supertranslation; Y^A, Lorentz

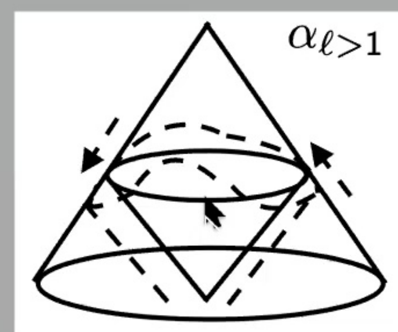
$$u' = u + \alpha(\theta^A), \quad \alpha(\theta^A) = \sum_{\ell m} \alpha_{\ell m} Y_{\ell m}(\theta^A)$$



Time translation



Spatial translation



Supertranslation

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Symmetries and conserved quantities

Noether's theorem: symmetry $\longrightarrow$ conserved quantity

Bondi-Metzner-Sachs (BMS) group   Bondi+, Sachs (1962)

Time translations $\longrightarrow$ Energy

Spatial translations $\longrightarrow$ Linear momentum

Rotations $\longrightarrow$ Angular momentum (spin)

Lorentz boosts $\longrightarrow$ "Center-of-mass" angular momentum: mass times CM position in rest frame

Supertranslations $\longrightarrow$ Supermomentum

- GWs change charges, but change in charges = net flux

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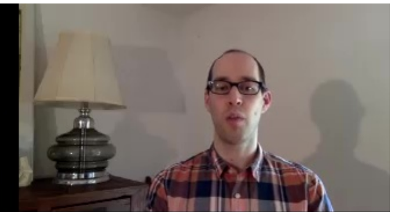
GW memory and conserved quantities



$$\Delta \mathrm{h} \propto \begin{array}{c}\text{Changes in}\\ \text{super-}\\ \text{momentum}\end{array} + \int du \left(\begin{array}{c}\text{Energy flux}\\ \text{from massless}\\ \text{particles}\end{array} + \begin{array}{c}\text{Energy flux}\\ \text{from GWs}\end{array} \right)$$

- Memory computed from supermomentum balance law and is required for supermomentum flux law to hold!

Measuring GW memory will show:

- Energy in GWs radiates like any other quadrupolar source
- Supermomentum conservation applies to BBH mergers
- Final BH is a Kerr BH without supermomentum “hair”
- Initial & final “rest frames” are supertranslated

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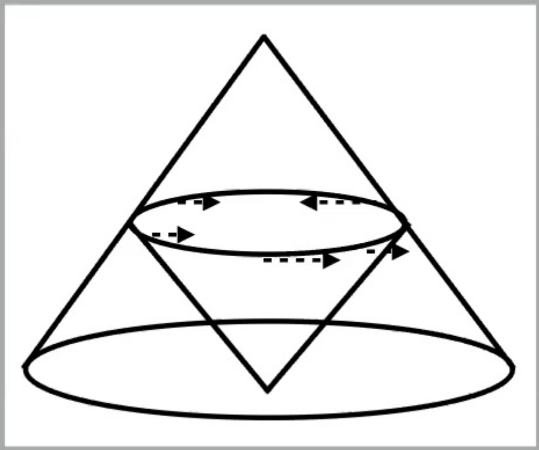
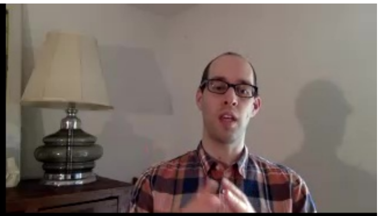
New symmetries and conserved quantities

- New symmetries proposed: super-rotations/super Lorentz
  Barnich & Troessaert (2010), Campiglia & Laddha (2015)
- Y^A a local conformal KV or a diffeomorphism of the 2-sphere

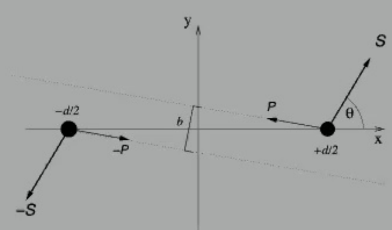


- Related conserved quantities: "super CM" and "super spin"
- Are there new memory effects related to these conserved quantities and are they measurable? A: Yes (eventually)
- Are these new memory effects related to the initial and final frames being super Lorentz transformed? A: Not for BBHs



4. First new memory effect: Spin memory

$$\text{Change in time-integrated GW strain} \propto \text{Changes in super-spin} + \int du \left(\text{Angular momentum flux, matter} + \text{Angular momentum flux, GWs} \right)$$



Ex. Unbound spinning objects

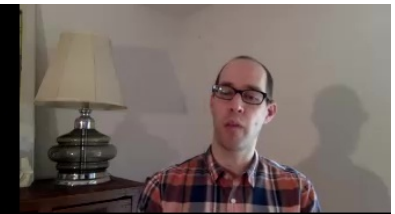
Pasterski+ (2015)

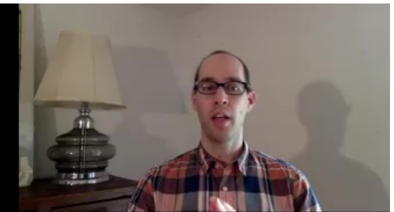
?

SNe neutrinos possible; need rotating CC with neutrinos

Ex: BBH mergers

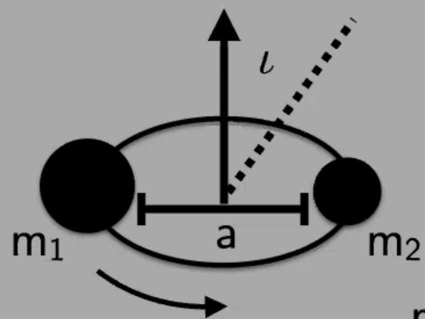
Nichols (2017)





Spin memory effect: Non-spinning binaries

"Newtonian" expectations



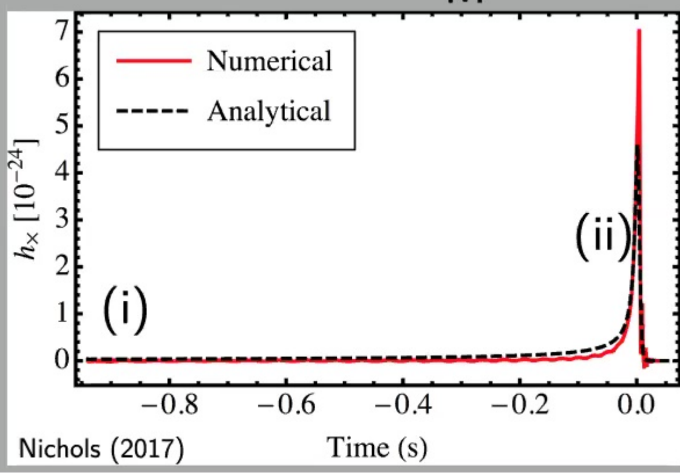
$$\int du\, h_\times^{smm} = \frac{G}{c^4}\frac{3}{8r}\Delta(\mu\sqrt{GMa})\sin^2\iota\cos\iota$$

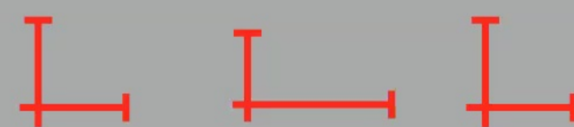
$+$ higher PN terms Nichols (2017)

$h_\times^{smm}$ found before at 2.5PN order Arun (2005)

$M = m_1 + m_2 \quad \mu = \frac{m_1 m_2}{M}$

LIGO does not measure integrated $h_\times^{smm}$ but can measure $h_\times^{smm}$





(i) (ii) (iii)

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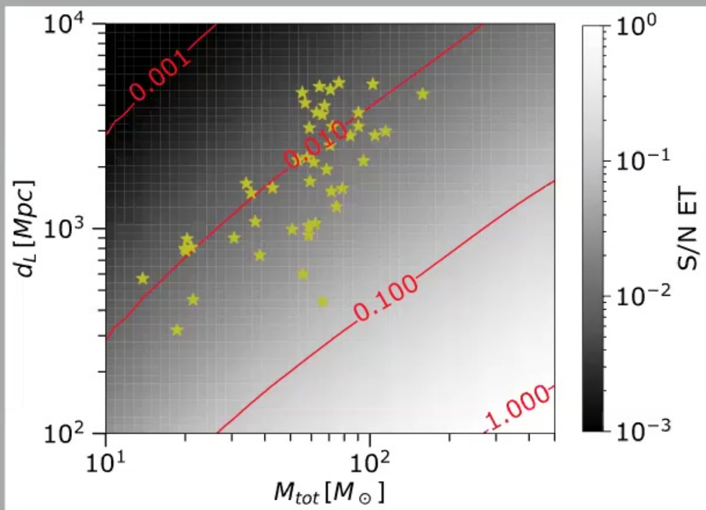
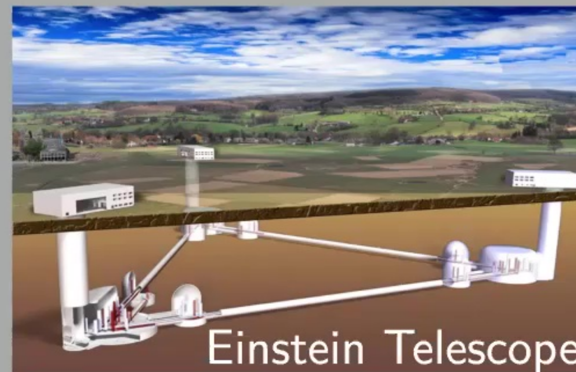
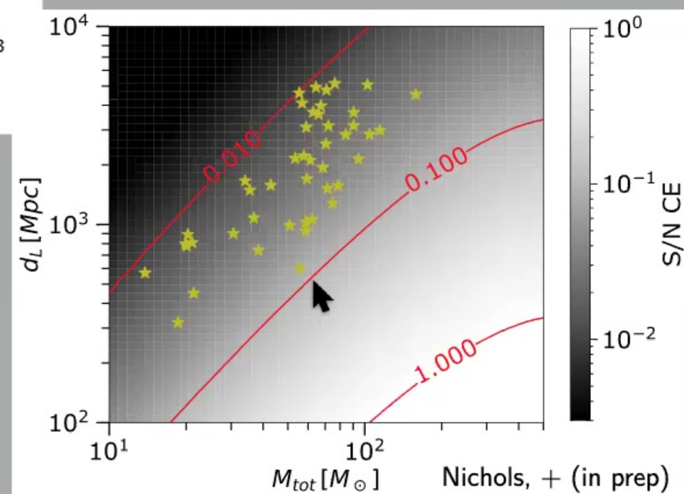
Detecting spin memory with ET and CE







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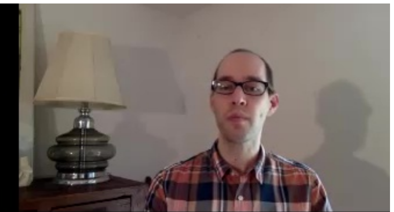
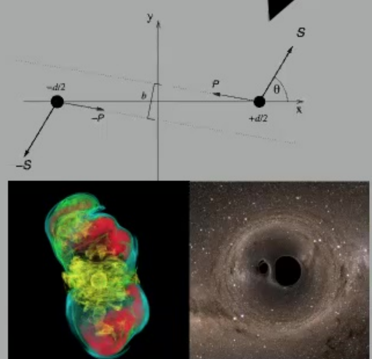


Second new memory effect: CM memory

$$\text{Change in time-integrated GW strain} \propto \text{Changes in super-CM charges} + \int du \left(\text{CM angular momentum flux, massless fields} + \text{CM angular momentum flux, GWs} \right)$$



Ex. Any source of GW memory

Nichols (2018)

?

No sources computed yet; SNe neutrinos are possible

Ex: BBH mergers

Nichols (2018)

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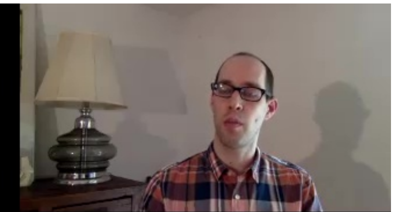
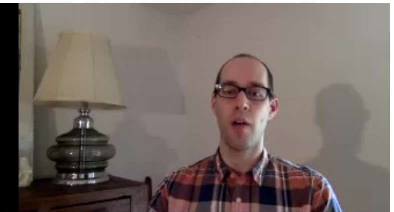




CM memory effect: non-spinning binaries

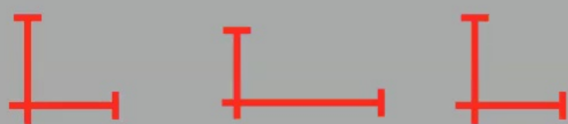
Charge part:

$$\int du\, h_+^{CM} = \frac{GM}{c^3}\Delta\left(\frac{G^2\mu}{c^4 r}\frac{M}{a}\right)\frac{\sin^2\iota}{1440}(257+\cos^2\iota)$$

$+$ higher PN terms Nichols (2018)

Flux part: Proportional to $|m_1 - m_2|$; vanishes for equal masses

Cannot measure integrated h_+^{CM} with LIGO, but can measure h_+^{CM}



(i) (ii) (iii)

- h^{CM} a 4PN term for charge part and 2.5PN for flux part
- Both effects weaker than spin memory; detection prospects less optimistic

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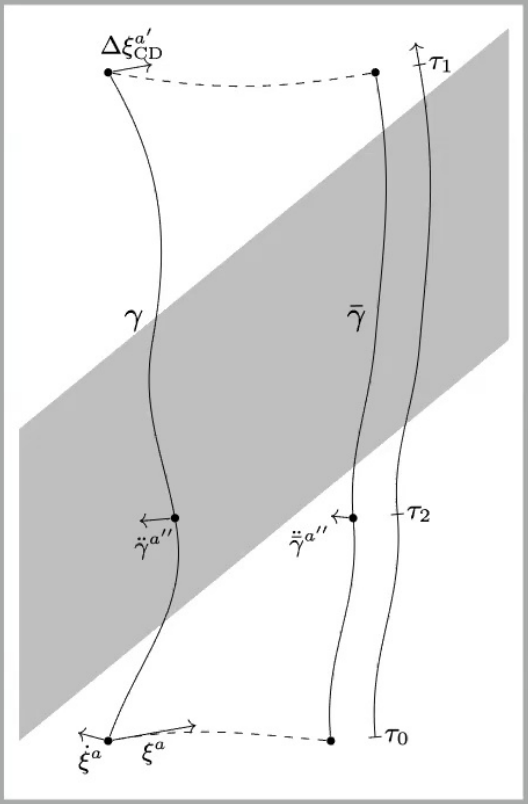
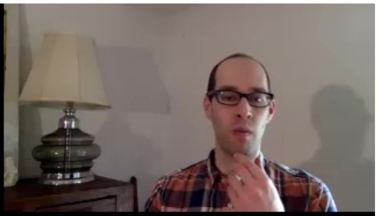
5. Ongoing & Future Directions

Persistent Observables:

- 3 types of memory: "standard," spin, & CM;
- other memory-like effects: lasting velocity, proper-time, and rotation
- Can all these effects be measured through one procedure?
- A: Yes! Multiple procedures: nearby accelerating curves, spinning test particles, angular momentum transport



Flanagan, Grant, Harte, Nichols (2019, 2020, in prep)



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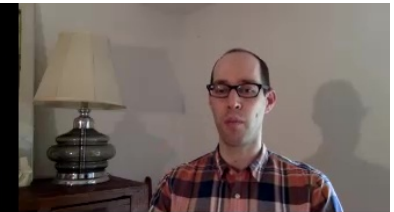
Persistent Observables



- Solve for change in deviation vector for nearby curves $\Delta\vec{\xi}_{\mathsf{CD}}$

$$\Delta\xi^\alpha_{\mathsf{CD}} \sim \underbrace{\xi^\beta_0 \int d\tau \int d\tau\, R^\alpha{}_{\mu\beta\nu}\dot{\gamma}^\mu\dot{\gamma}^\nu}_{\text{Contains standard GW memory at O(1/r) in } \Delta h}$$

$$+ \underbrace{\dot{\xi}^\beta_0 \int d\tau \int d\tau' \int d\tau''\, R^\alpha{}_{\mu\beta\nu}\dot{\gamma}^\mu\dot{\gamma}^\nu}_{\text{Contains spin and CM memory at O(1/r) in } \int d\tau\, \Delta h}$$

$$+ \underbrace{\ddot{\xi}^\beta_0 \int d\tau \int d\tau' \int d\tau'' \int d\tau'''\, R^\alpha{}_{\mu\beta\nu}\dot{\gamma}^\mu\dot{\gamma}^\nu}_{\substack{\text{Contains new memory-like effects at O(1/r)} \\ \text{to be further investigated in } \int d\tau \int d\tau' \Delta h}}$$

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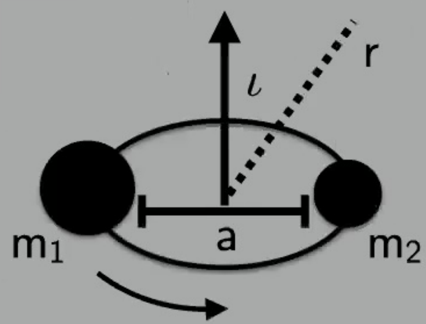
Memory effect from compact binary mergers



$M = m_1 + m_2$

$\xi \sim 1/\omega \ll M/a$

"Newtonian" expectations

$$\Delta h_+ = \frac{G}{c^4}\frac{1}{48r}\Delta\left(\frac{Gm_1m_2}{a}\right)$$
$$\times \sin^2\iota(17+\cos^2\iota)$$
$$\times\left[1-\xi\frac{\Delta a}{M}\Delta\log(a/M)\right]$$

\+ higher harmonics at 0PN

\+ higher PN terms

Tahura, Nichols, Yagi (in prep)

- BBHs same as in GR
- Work in limit in which quadrupole radiation dominates and scalar (dipole) radiation is a small correction to energy flux
- Scalar memory not present through 2PN Lang (2014)

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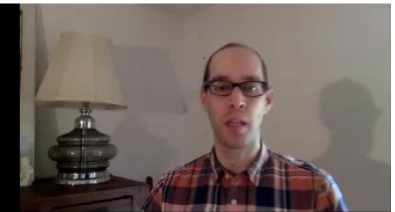

Conclusions

- GW memory from BBH mergers is a nonlinear, dynamical spacetime effect that can be detected with LIGO/Virgo
- Memory is required for supermomentum balance, and is an observational consequence of BMS symmetry
- Future GW detectors (CE/ET) will study it more precisely

- Two new types of memory effects related to new conservation laws: spin memory and center-of-mass (CM) memory
- Spin memory possibly measurable by ET/CE with stacking
- CM memory is most likely too weak even for 3G detectors

- More subleading memory effects in GR, and new effects in modified gravity theories to be explored

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