

Title: Gravitational waves: Exploring the strongly curved side of the Universe

Date: Feb 08, 2018 11:00 AM

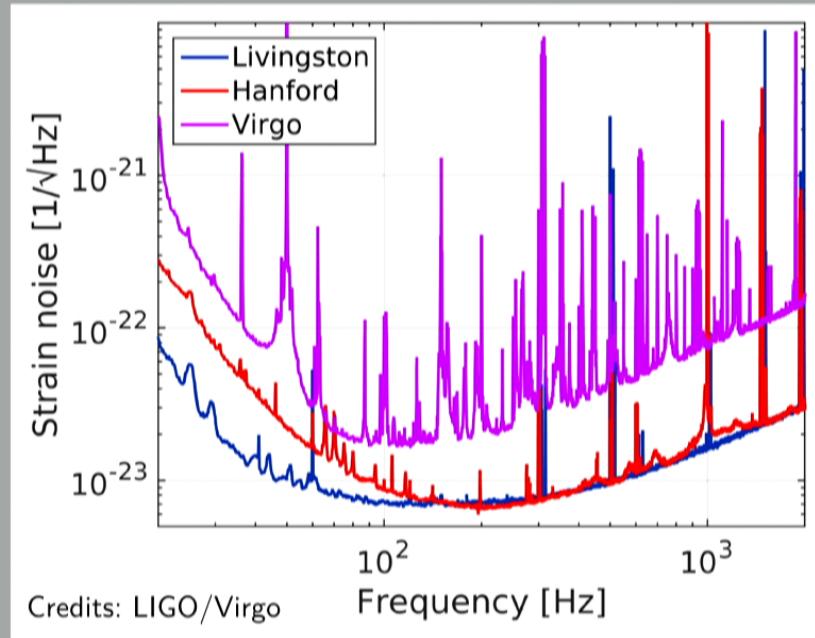
URL: <http://pirsa.org/18020090>

Abstract: <p>Gravitational waves from the mergers of five binary black holes and one binary neutron star were detected in the past two years by the advanced LIGO and Virgo detectors. These detections allowed our Universe to be observed in gravitational waves for the first time, and they have tested the predictions of general relativity for dynamical and strongly gravitating systems. I will discuss these results and also highlight a few additional examples of ways in which gravitational waves can shed light on open questions in theoretical physics and astrophysics. One involves the gravitational-wave memory effect, which is a constant change in the gravitational-wave strain produced by the energy that gravitational waves and matter carry away from an isolated system. I will describe the challenges in detecting the memory with LIGO and Virgo, and how the memory is related to the symmetries and conserved quantities of isolated gravitating systems. A second involves using precision astrometry to detect a stochastic background of gravitational waves from astrophysical, and potentially even cosmological, sources. With the upcoming data release from the Gaia mission, it will likely be possible to place improved constraints on the stochastic background at frequencies higher than those coming from the cosmic microwave background, but below those of pulsar timing searches. I will show how these constraints can be determined. Finally, I will discuss gravitational waves from a compact object orbiting an intermediate mass black hole surrounded by a dark matter spike. I will describe how details about the dark matter distribution can be imprinted in the emitted gravitational waves.</p>

Outline of this talk

1. Binary black holes (BBH): LIGO-Virgo detections, testing the predictions of GR, and GW memory effects
2. Binary neutron star (BNS) detection: A few highlights
3. Stochastic background of gravitational waves (GWs)
4. Influence of dark matter on GW inspirals

LIGO and Virgo detectors



Detector sensitivity at end
of O2 run, August 2017

BNS horizons

- Hanford: ~ 100 Mpc
- Livingston: ~ 200 Mpc
- Virgo: ~ 60 Mpc



Hanford

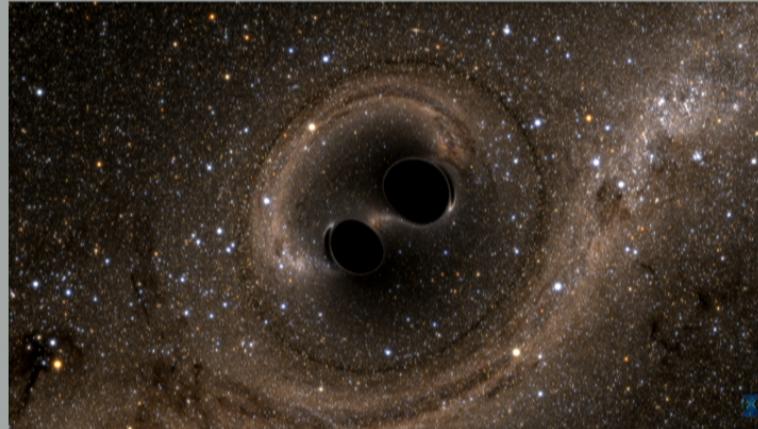
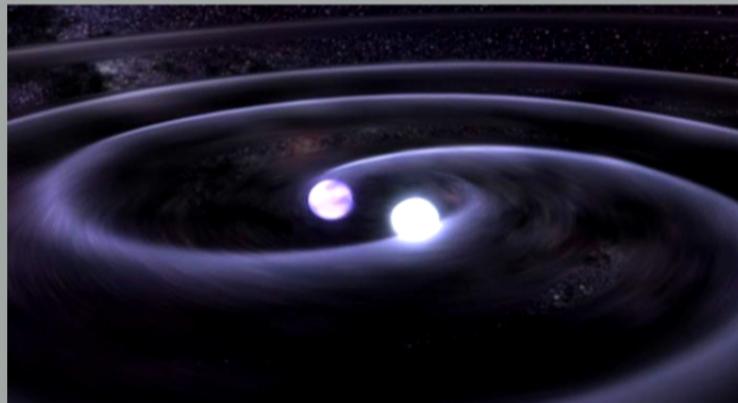
Livingston

Virgo

3

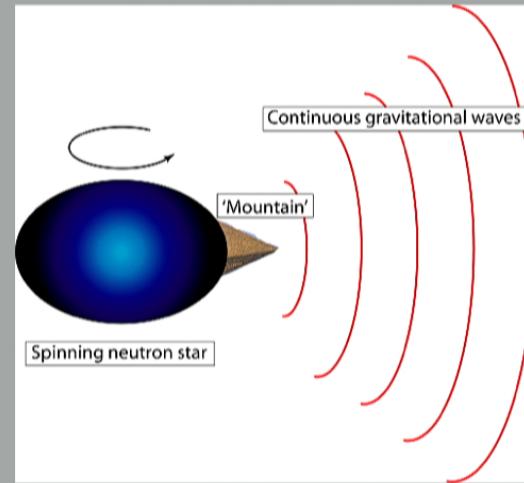
LIGO/Virgo sources of GWs

“compact binaries”
black holes (BH)/neutron stars (NS)

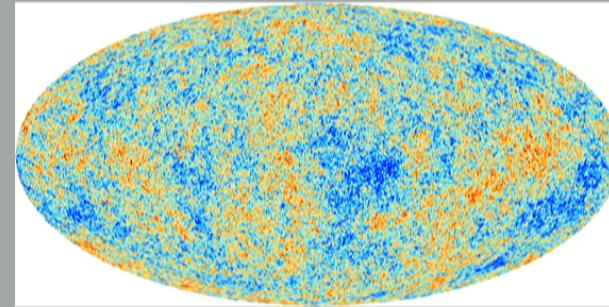


Credits: NASA, SXS, ESA/Planck, ANU

Continuous waves



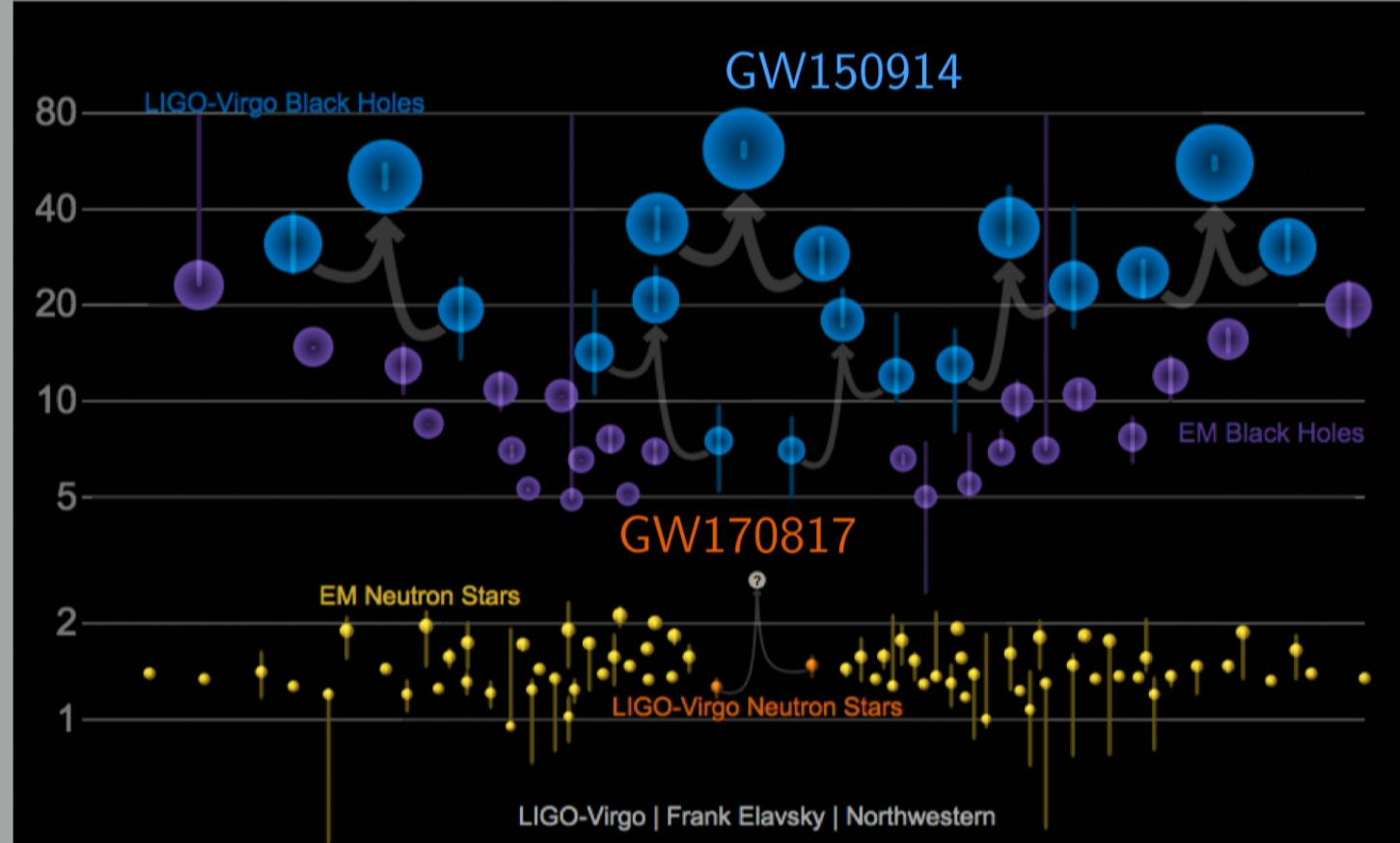
Stochastic background



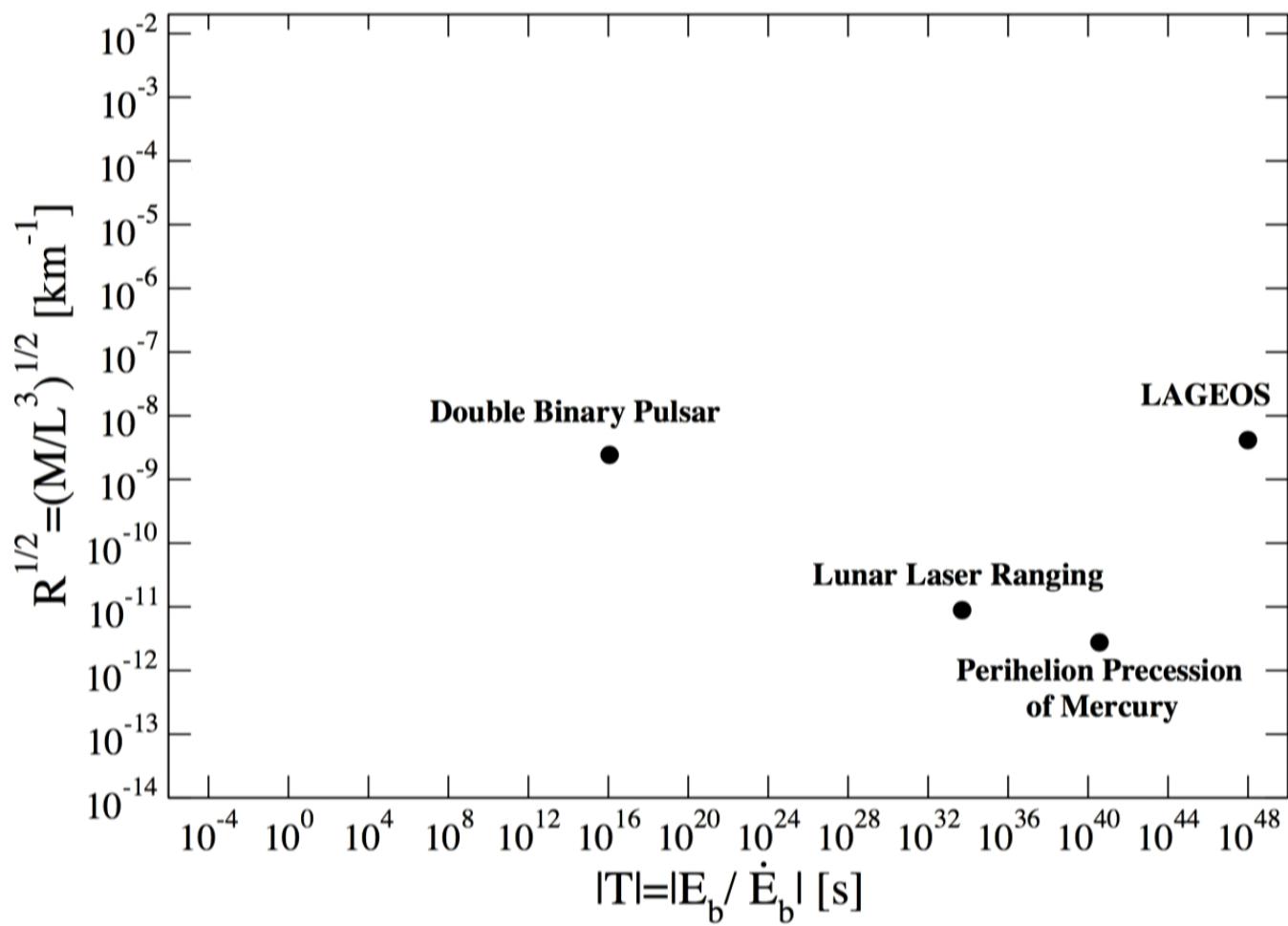
Unmodeled sources

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LIGO/Virgo results: Summary



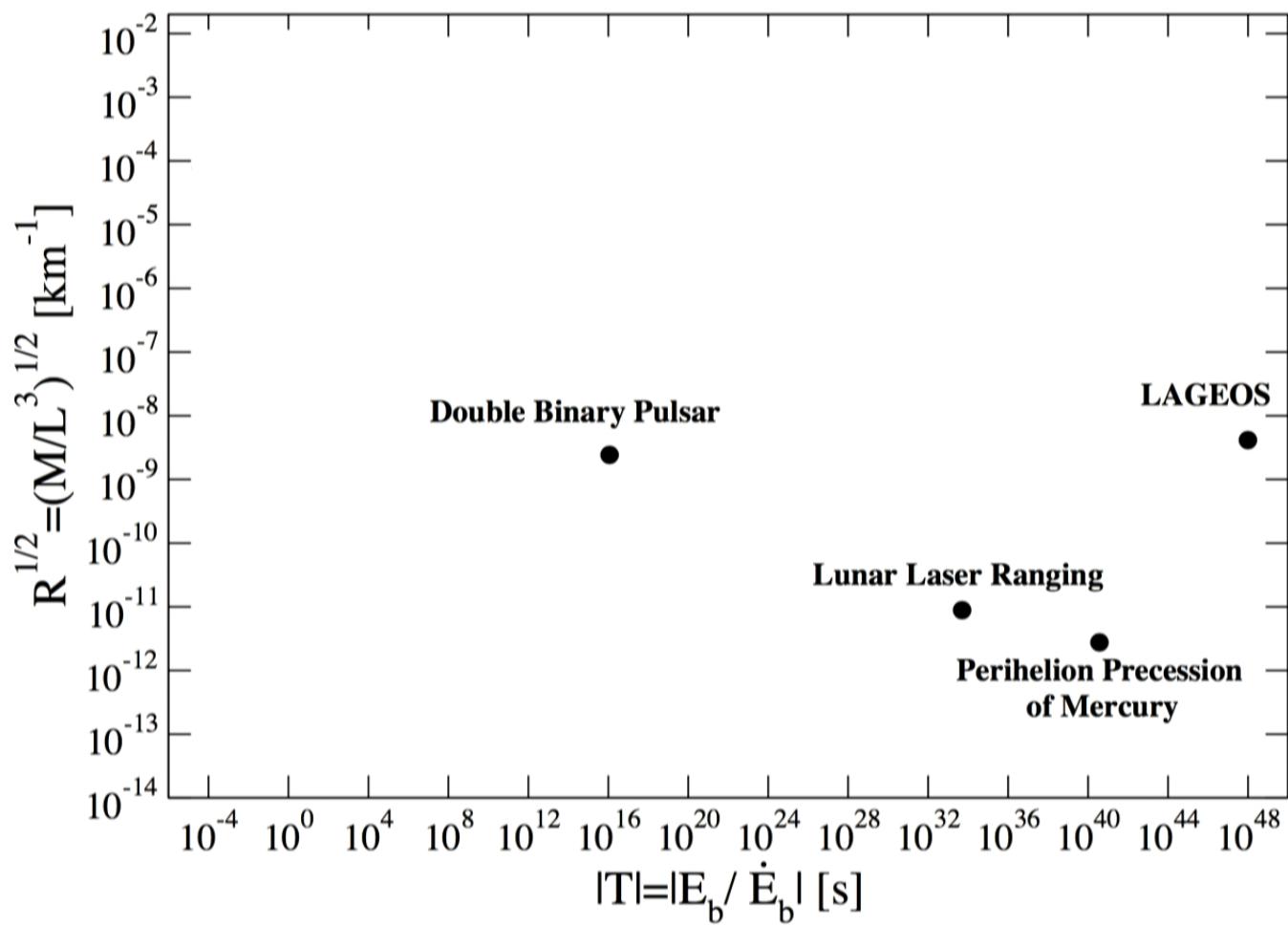
BBHs probe dynamical & nonlinear GR



Adapted from Yagi+ (2016)

6

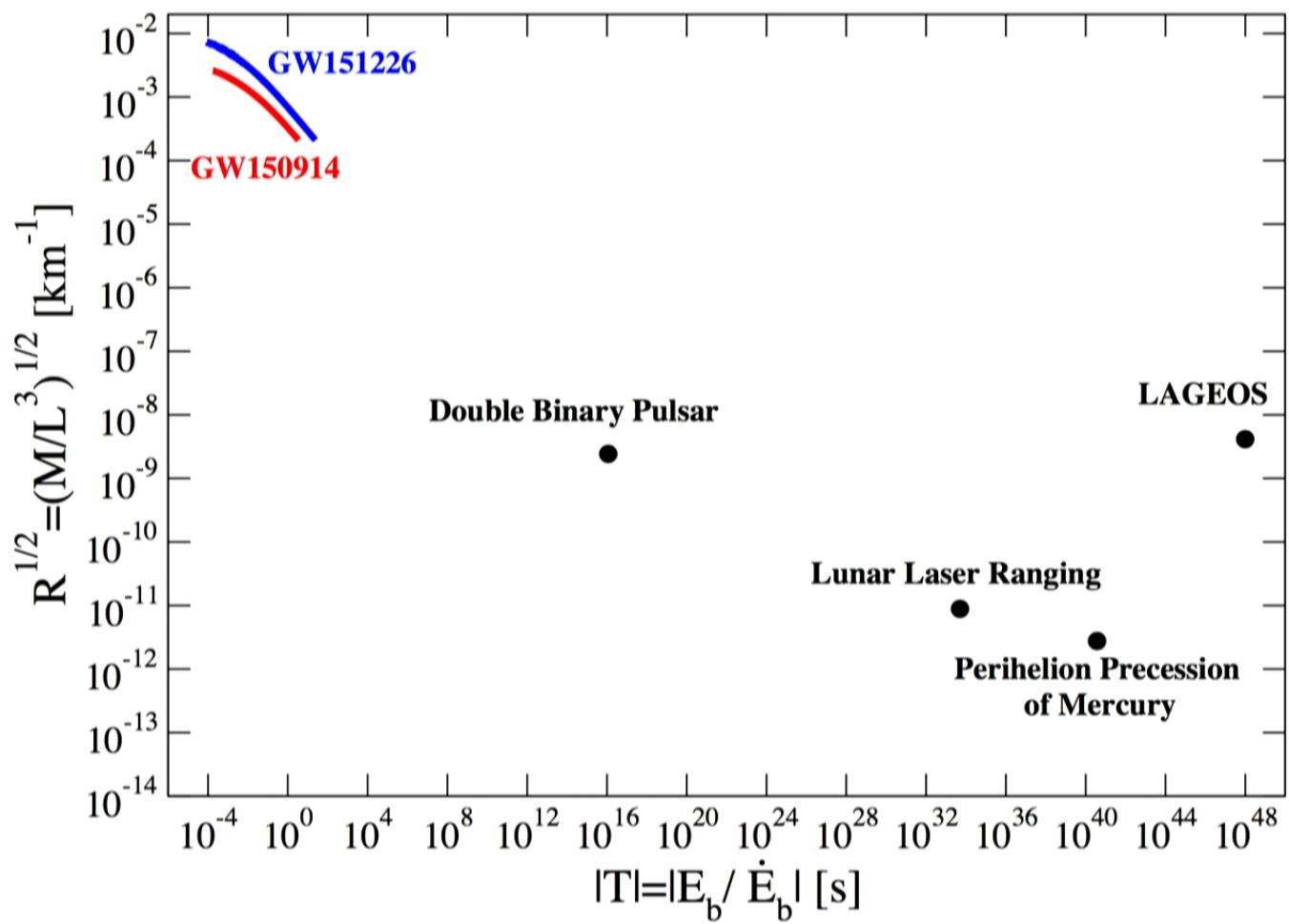
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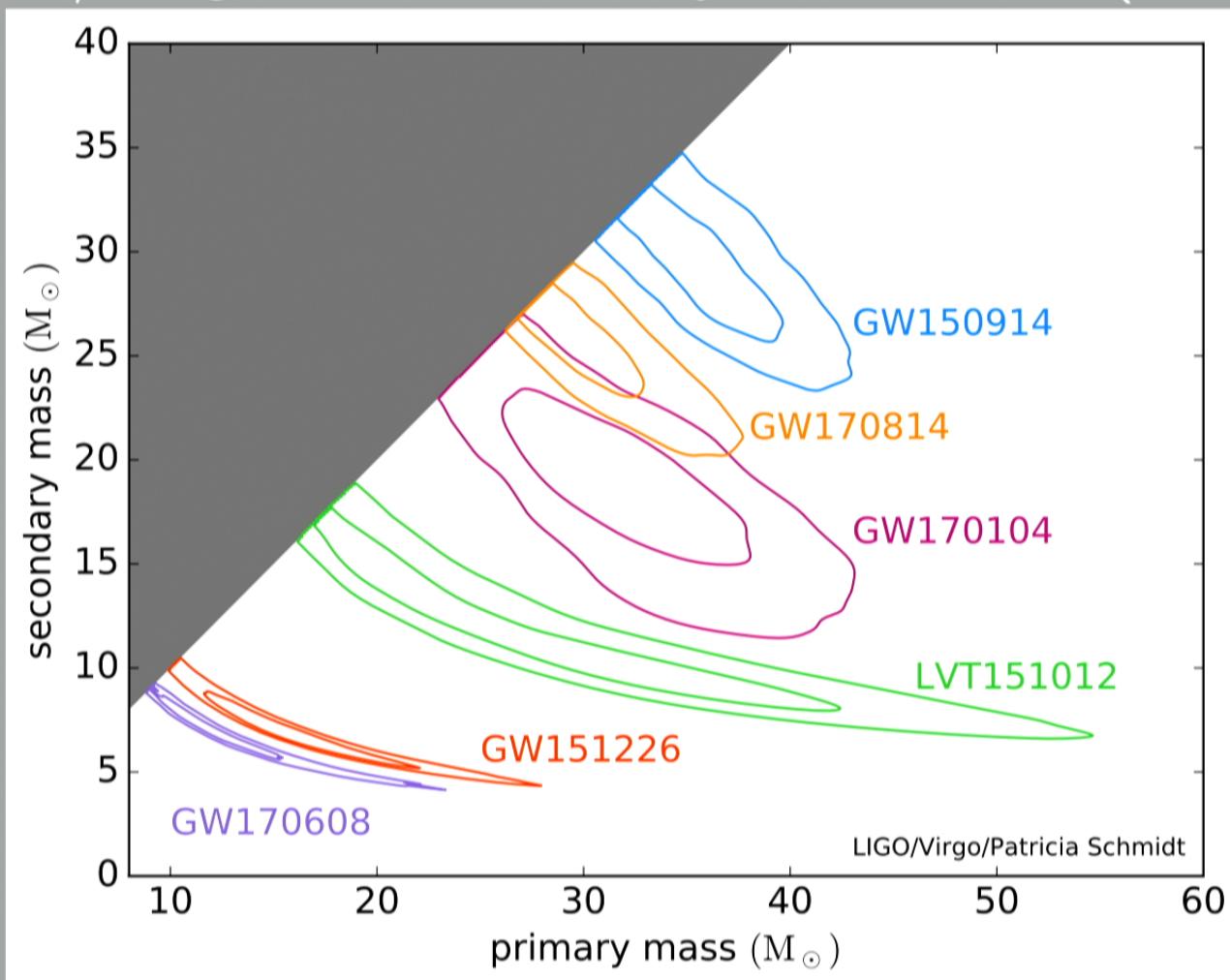
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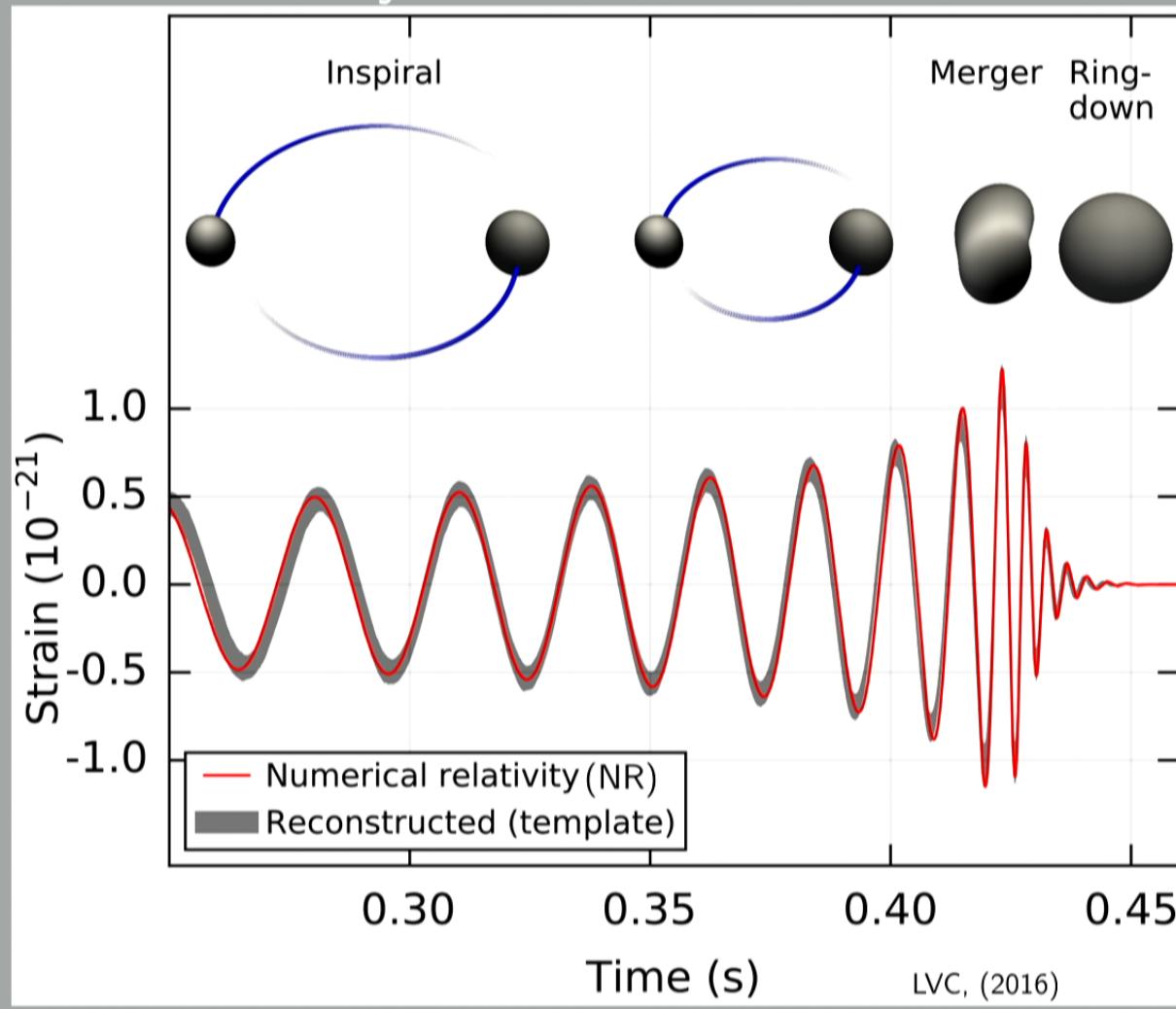
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LIGO/Virgo results: Binary black holes (BBHs)



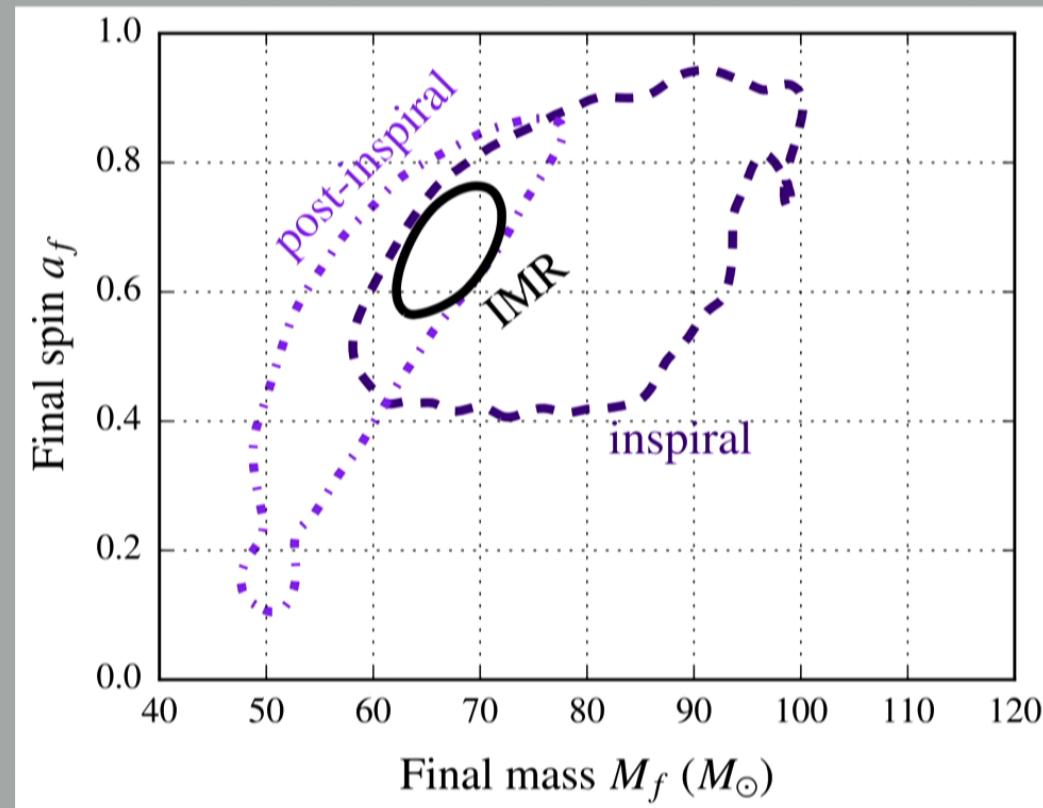
Nonlinear dynamics in GWs: GW150914



Inspiral merger-ringdown consistency test

GW150914

- NR predicts M_f and a_f from m_1 , m_2 , a_1 , and a_2
- Can determine M_f and a_f from inspiral and post-inspiral

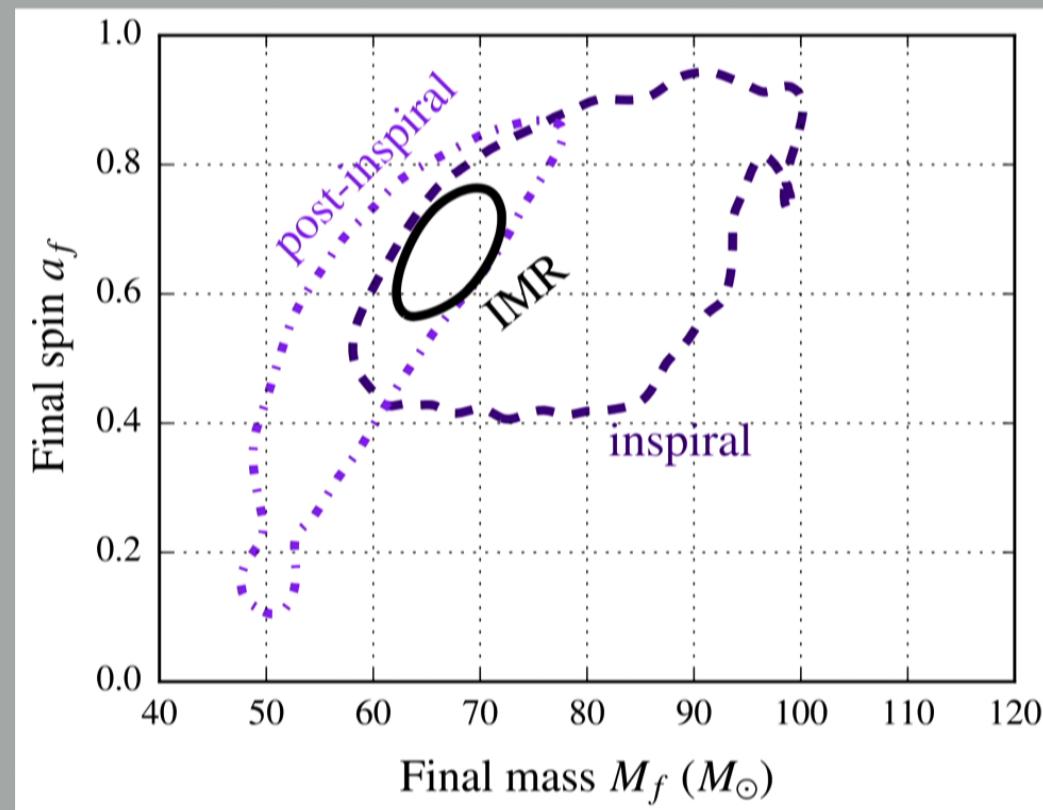


LVC, (2016), See also Ghosh,...,Nichols+ (2016)

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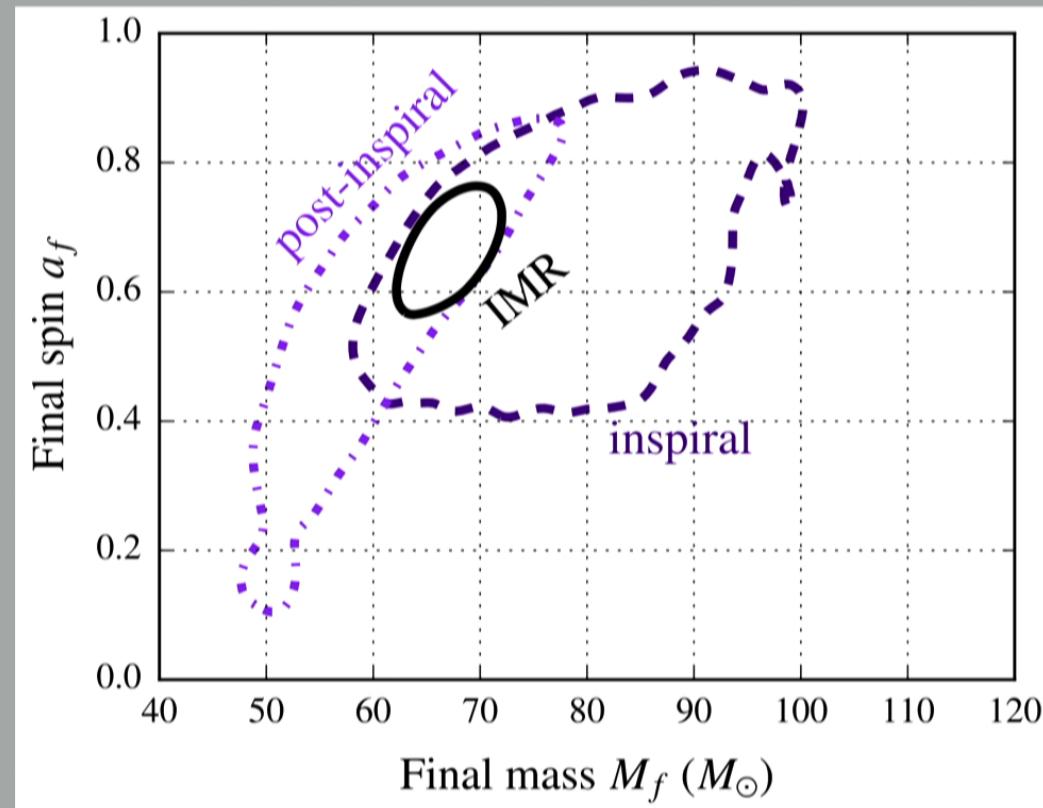


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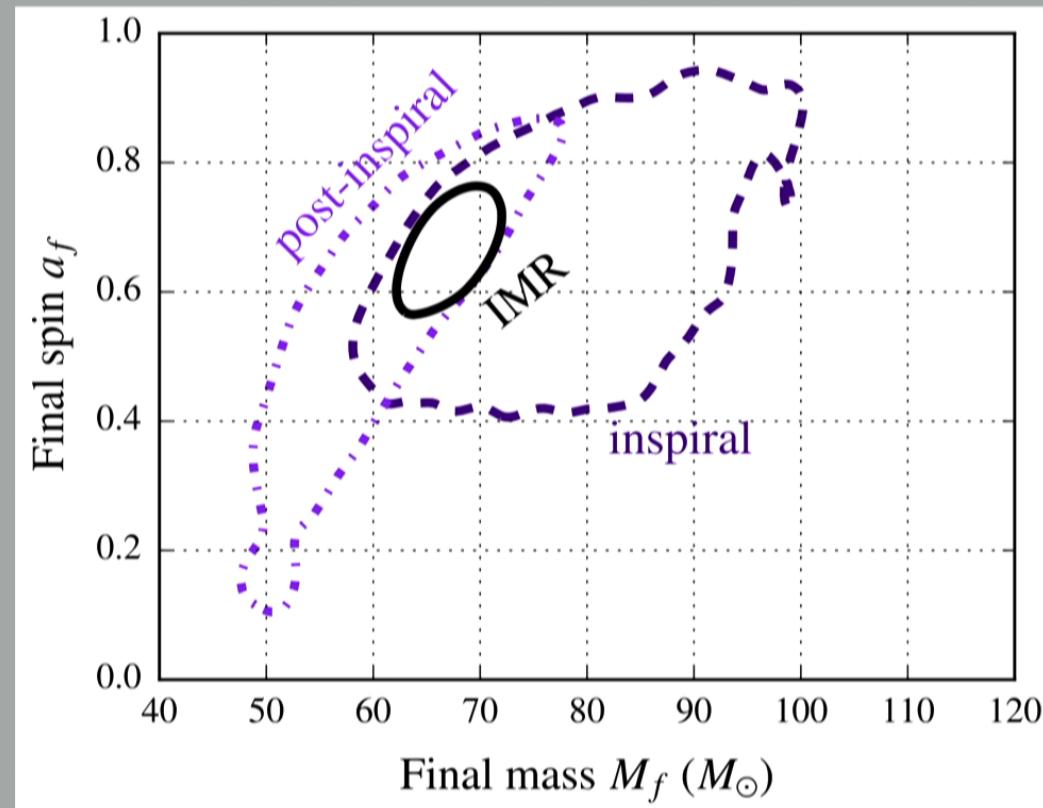


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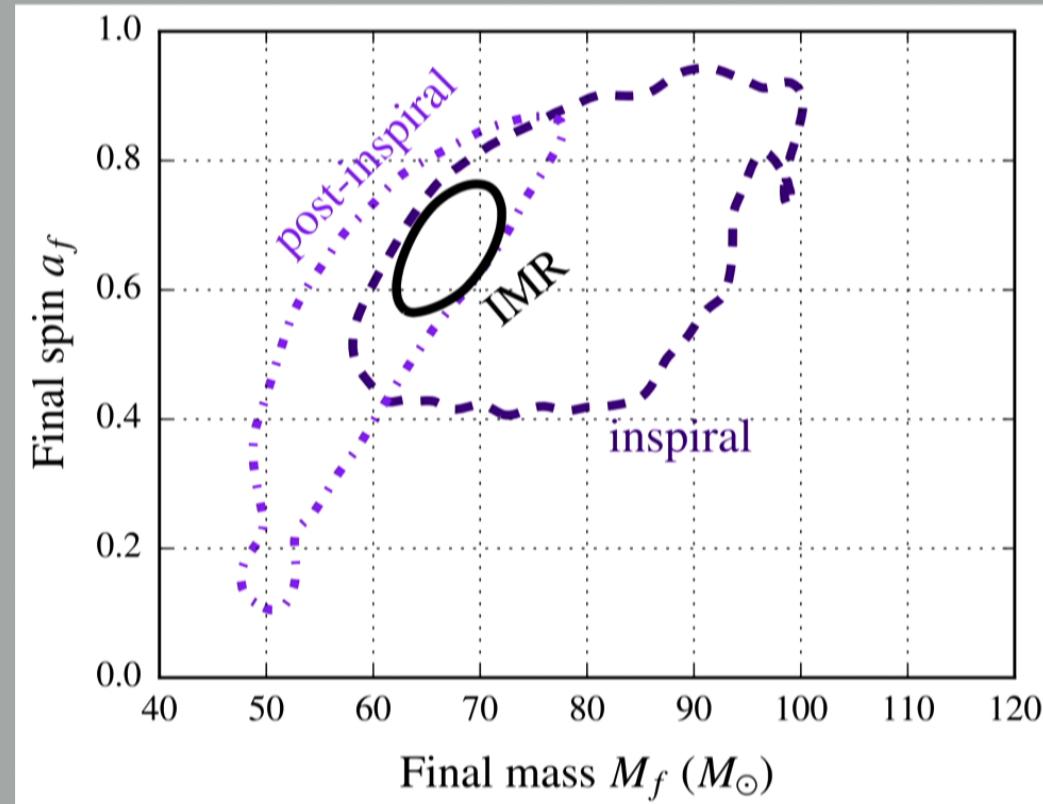


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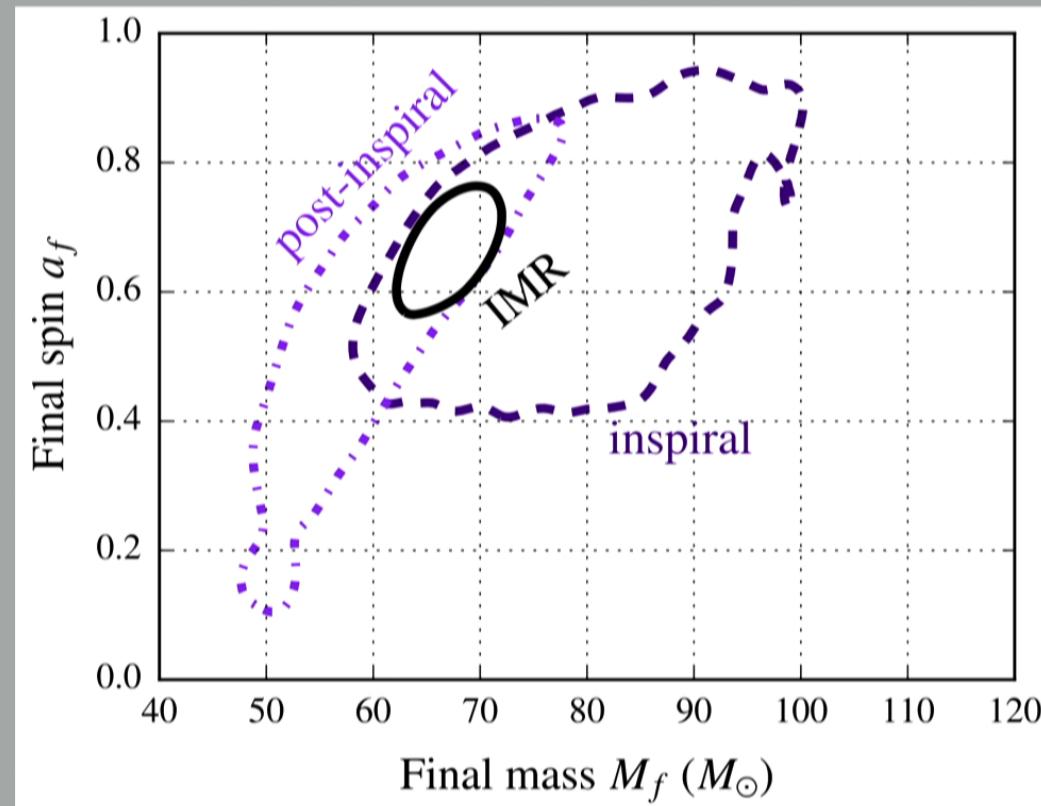


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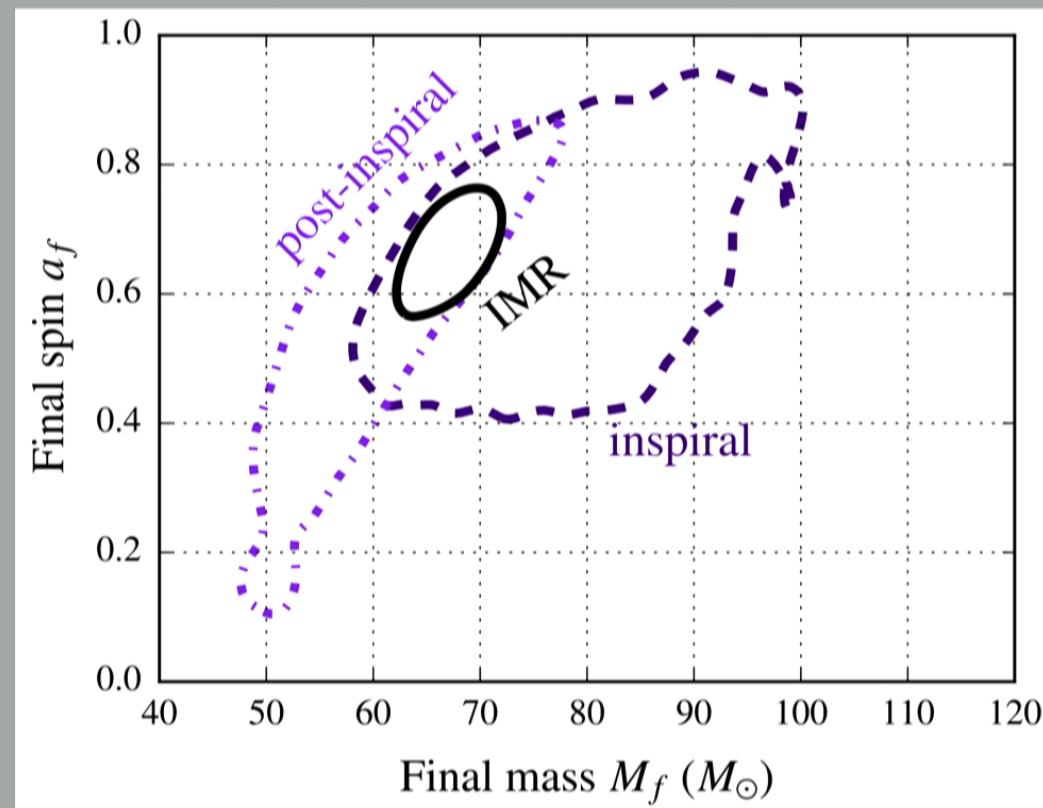


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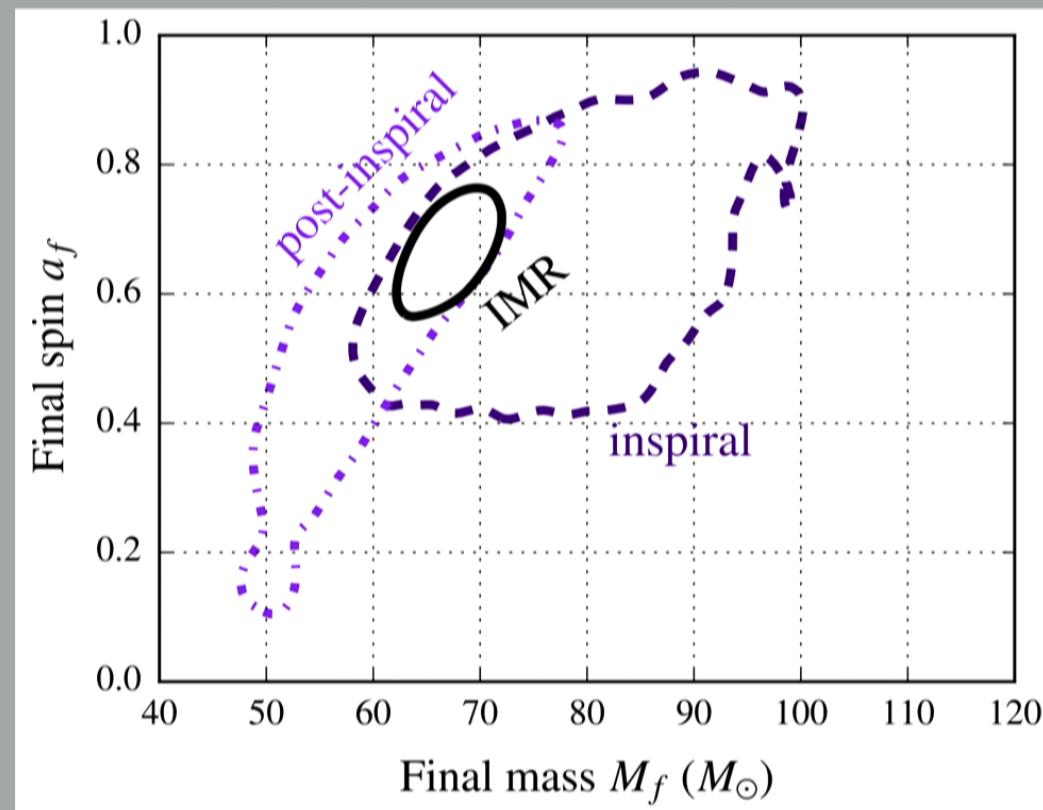


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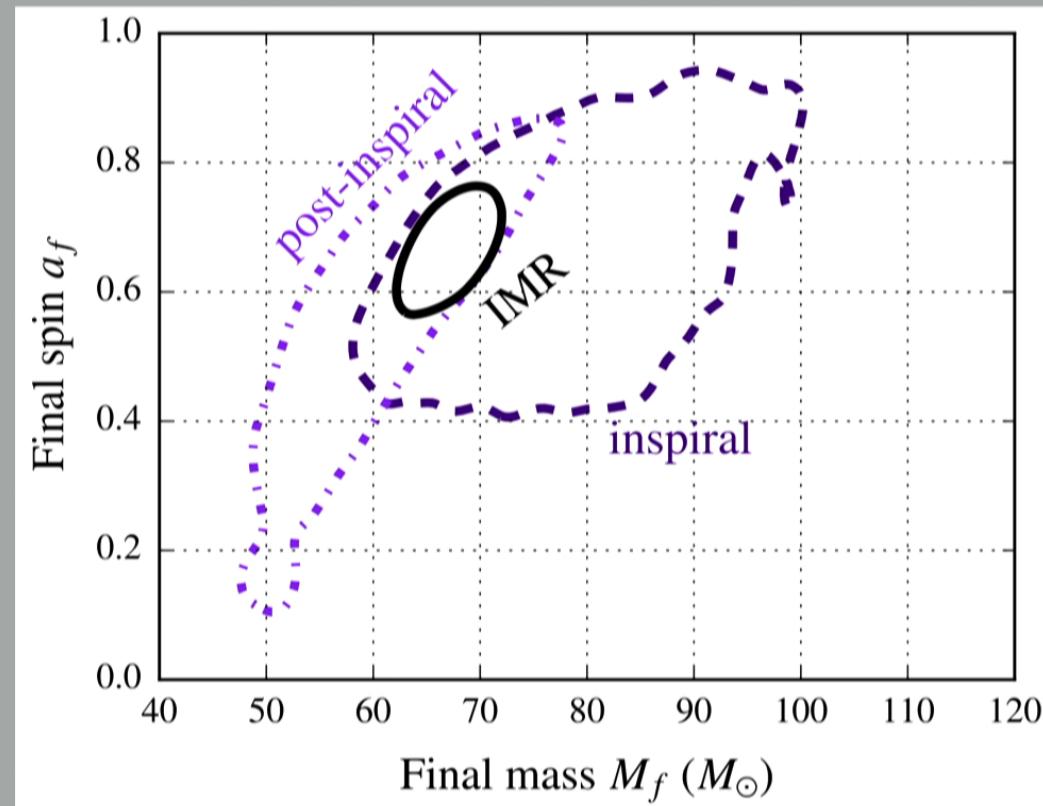


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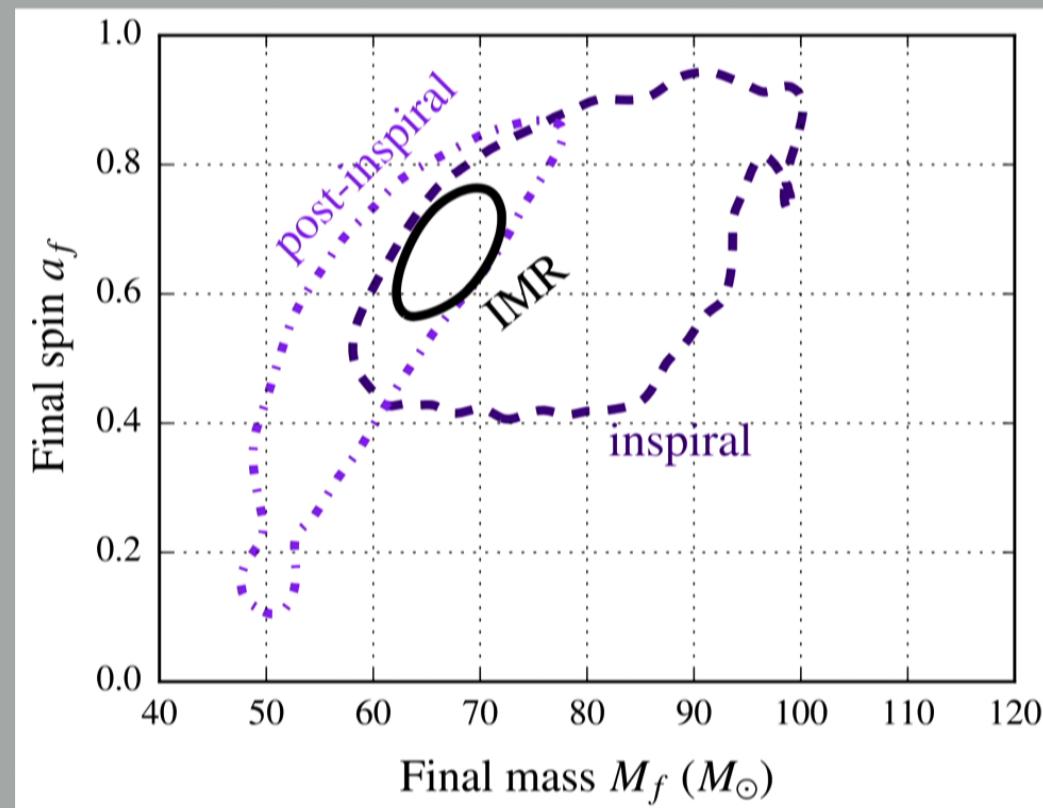


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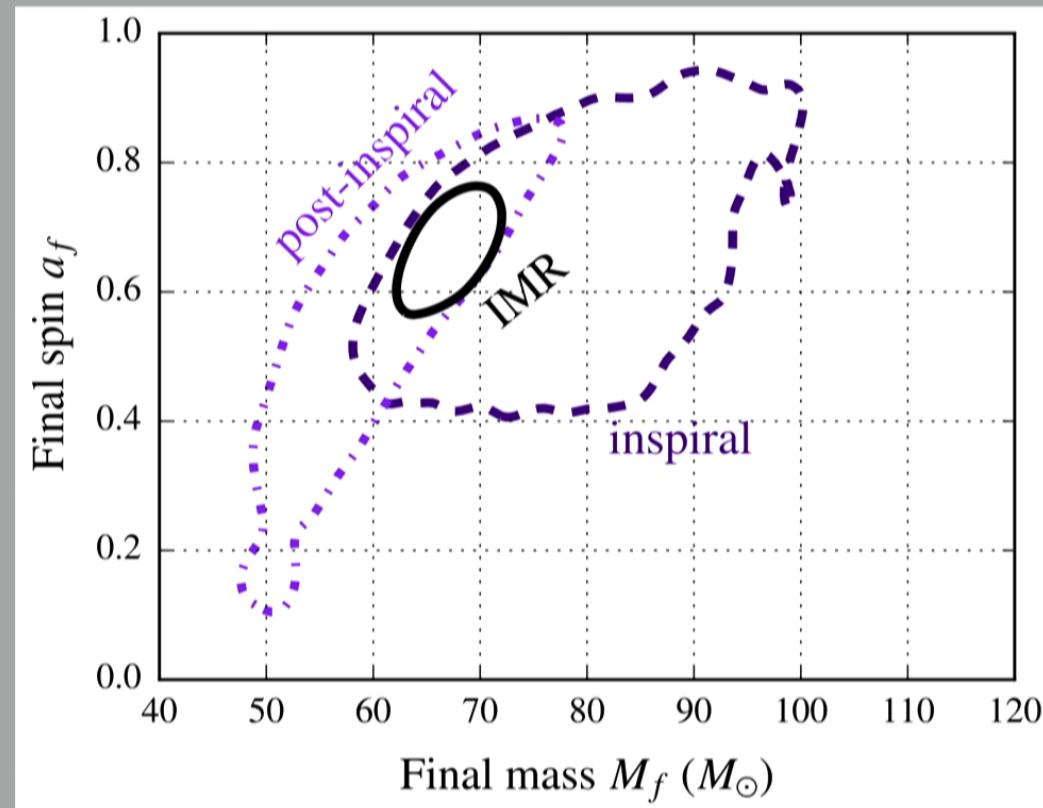


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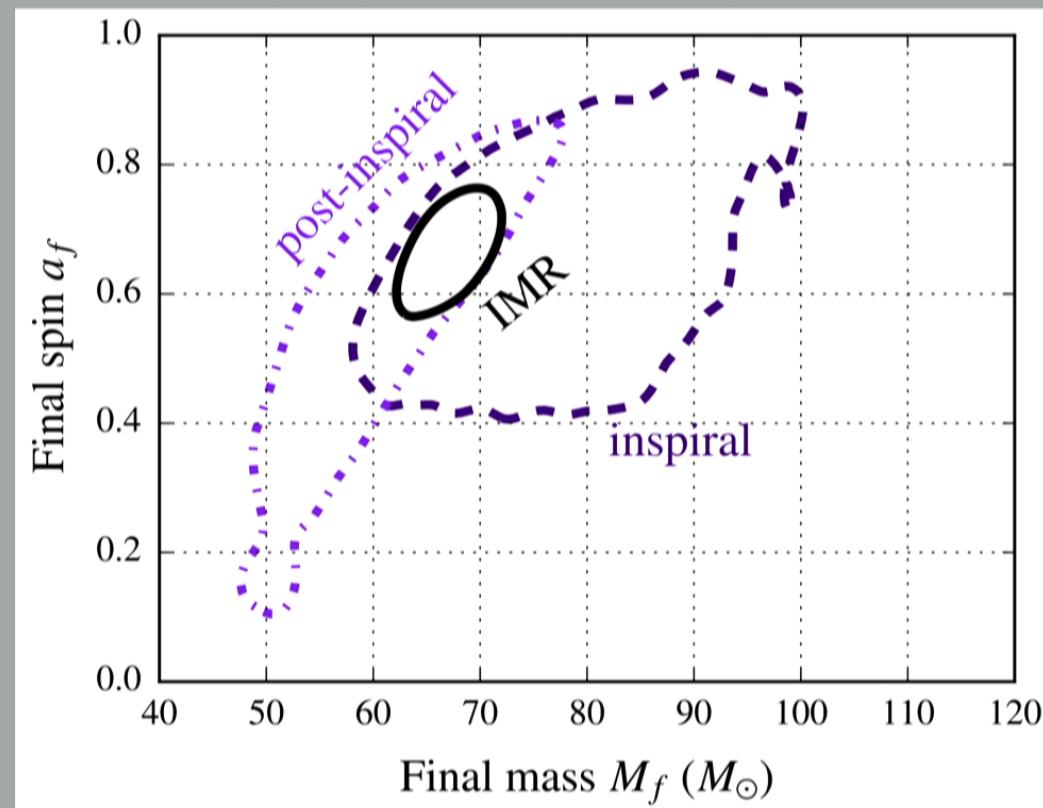


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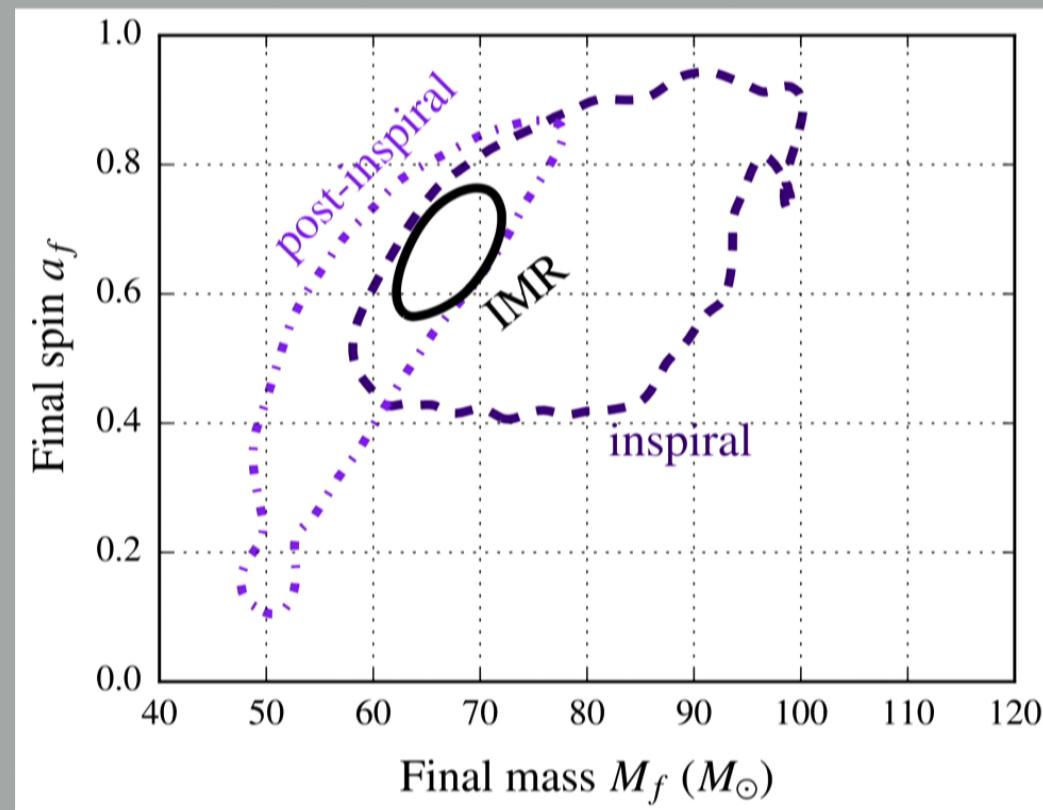


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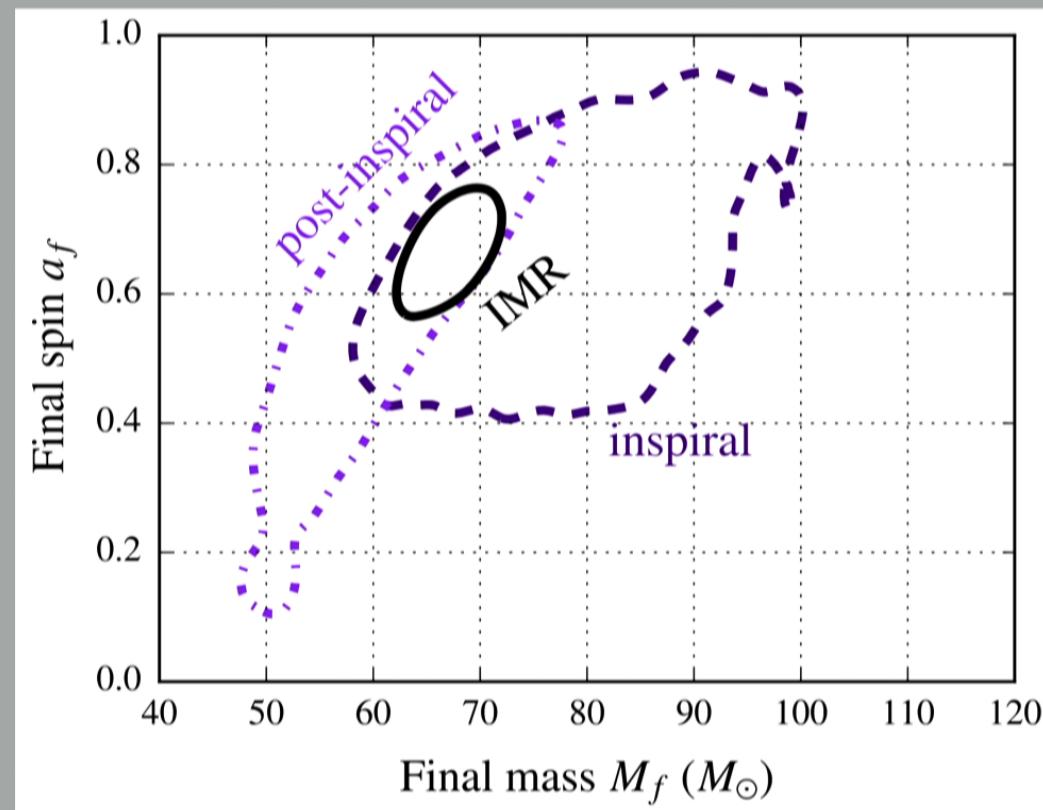


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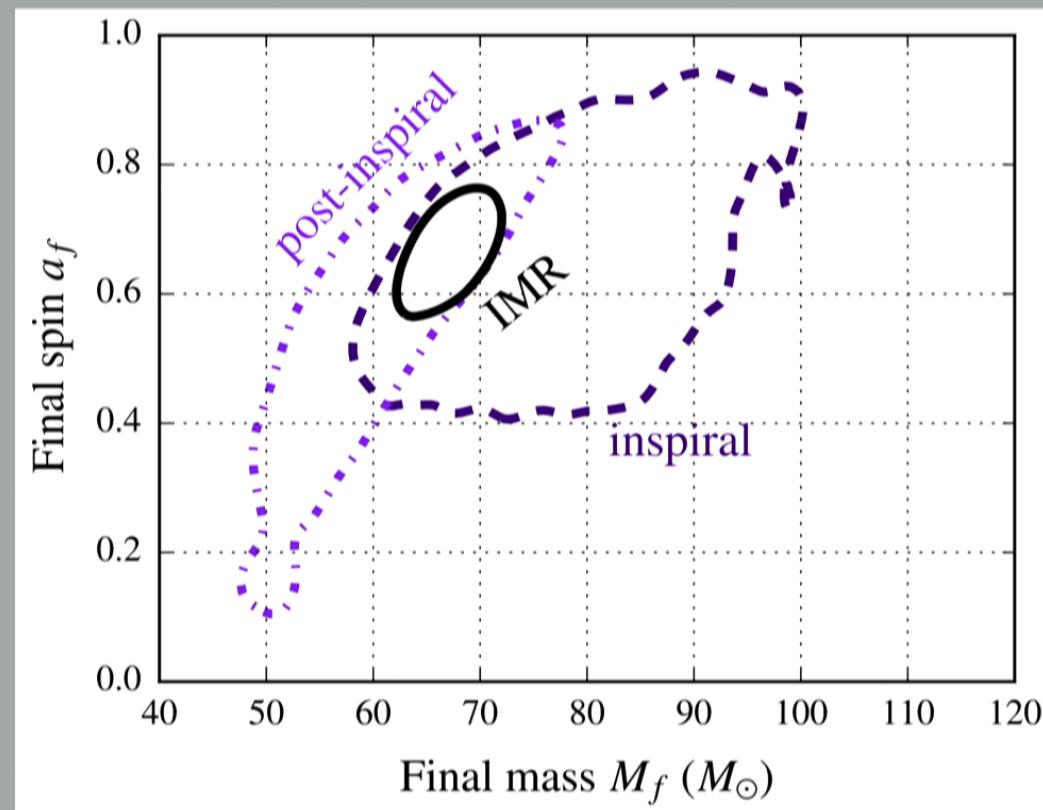


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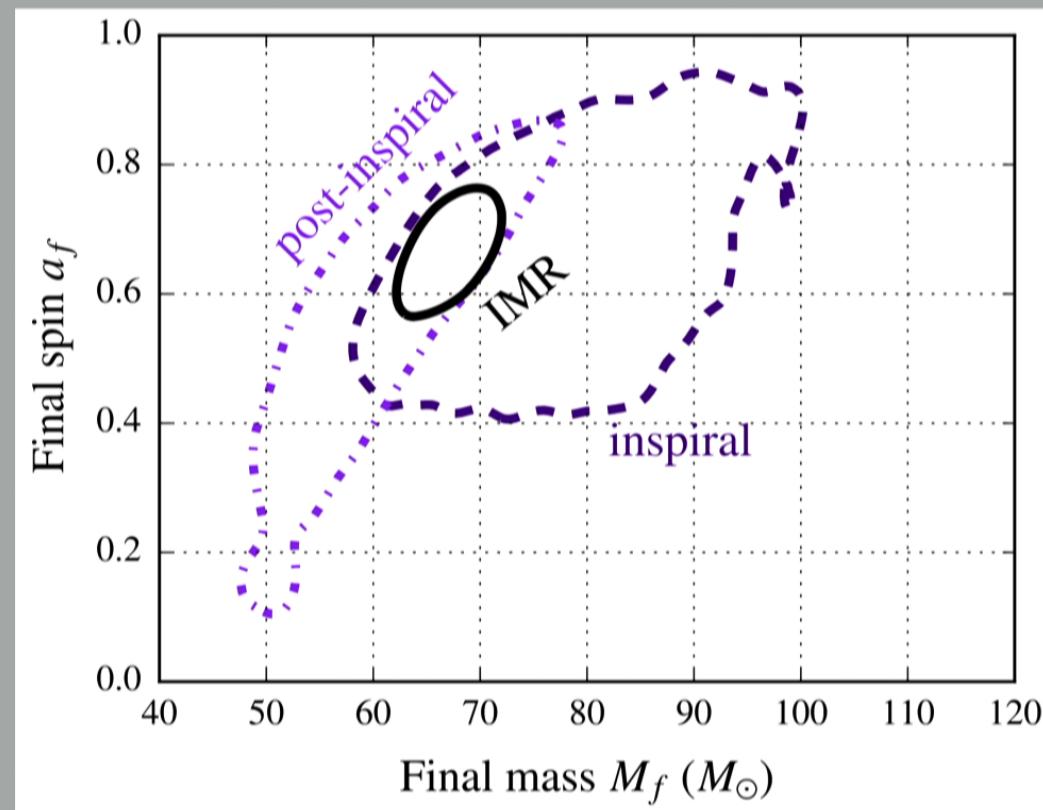


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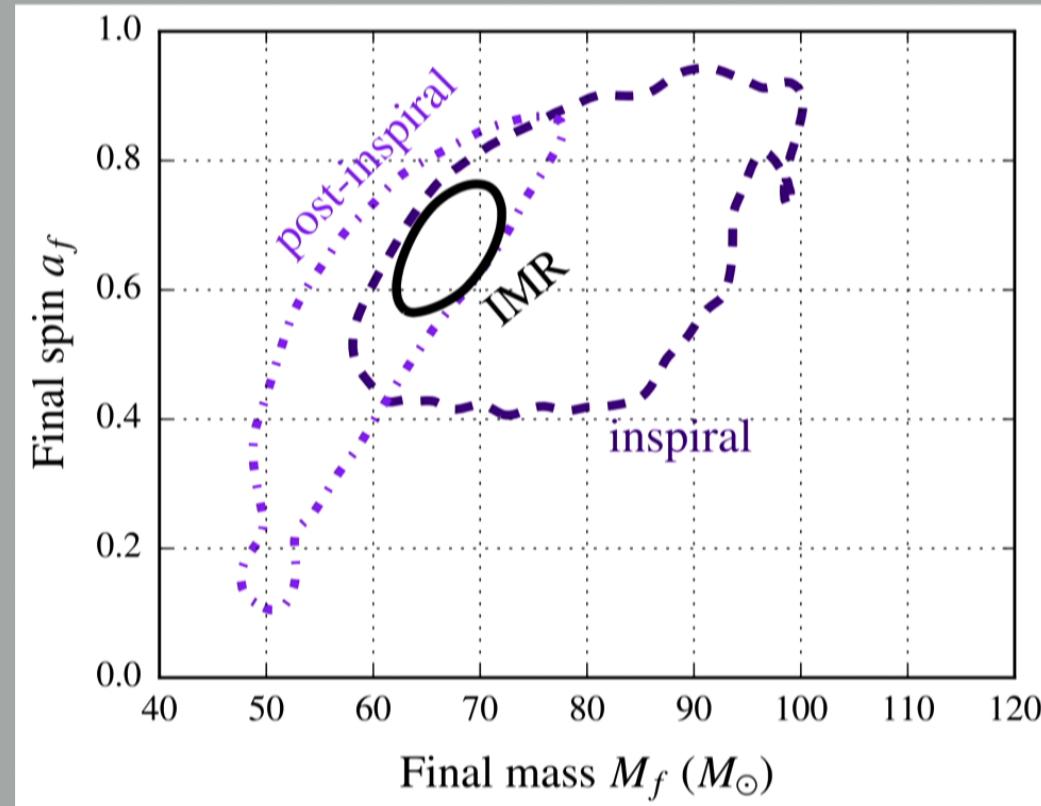


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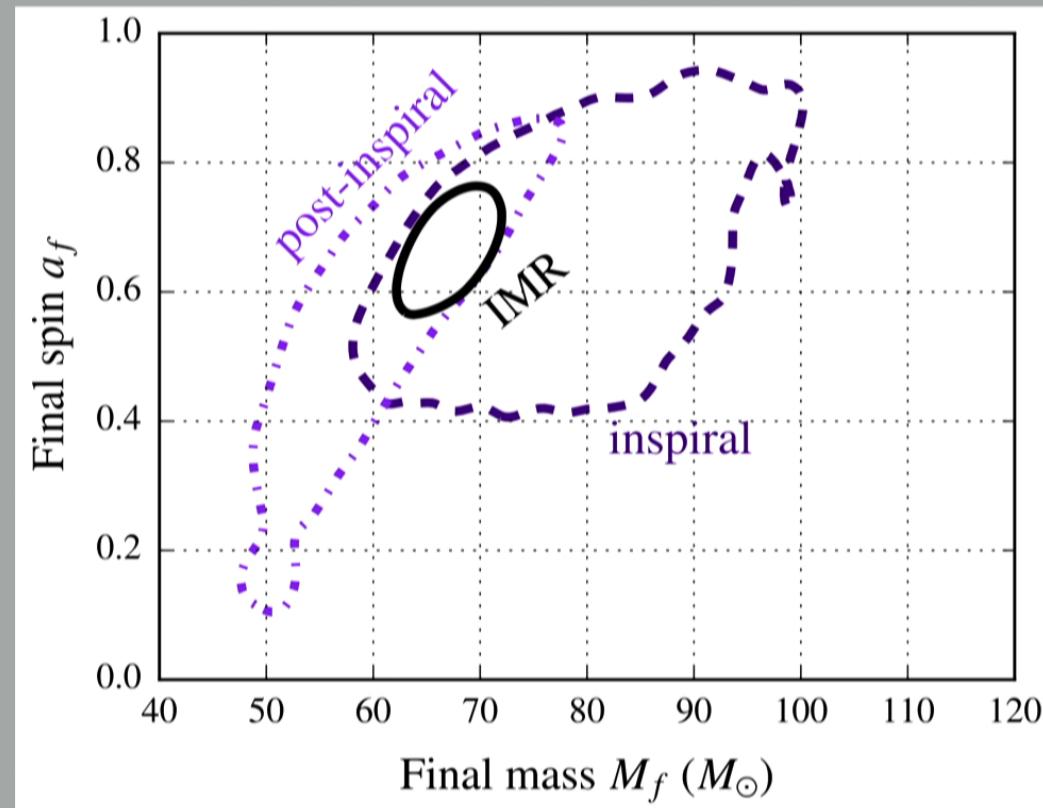


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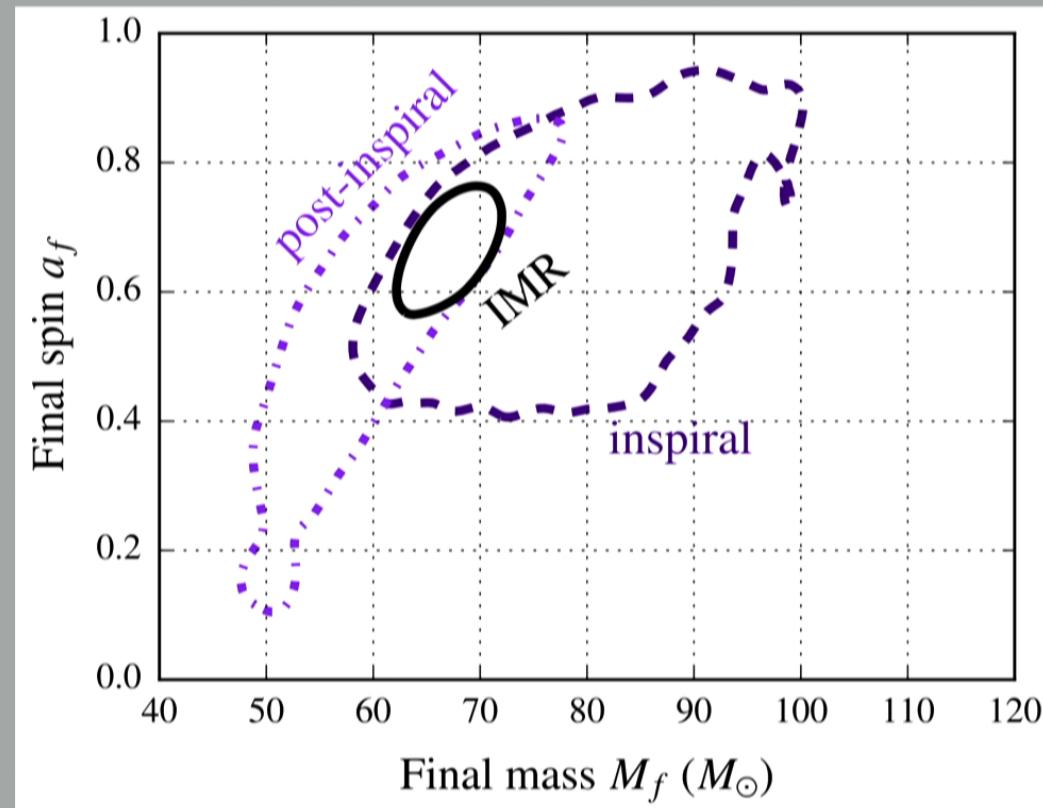


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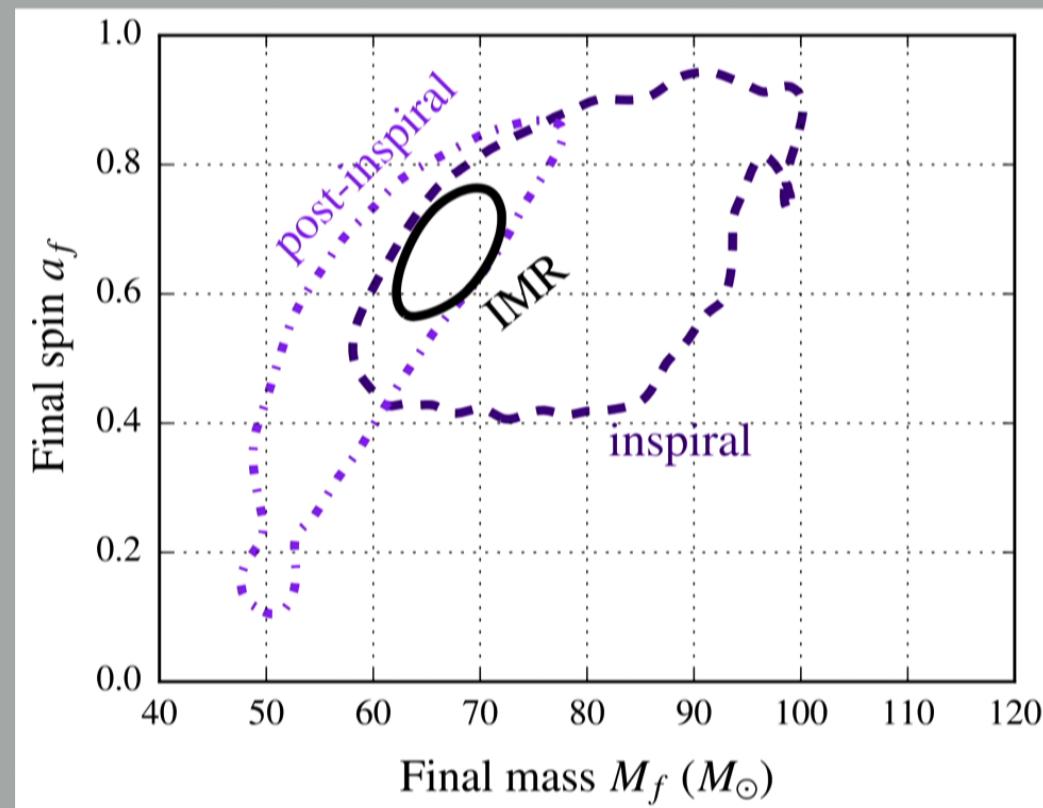


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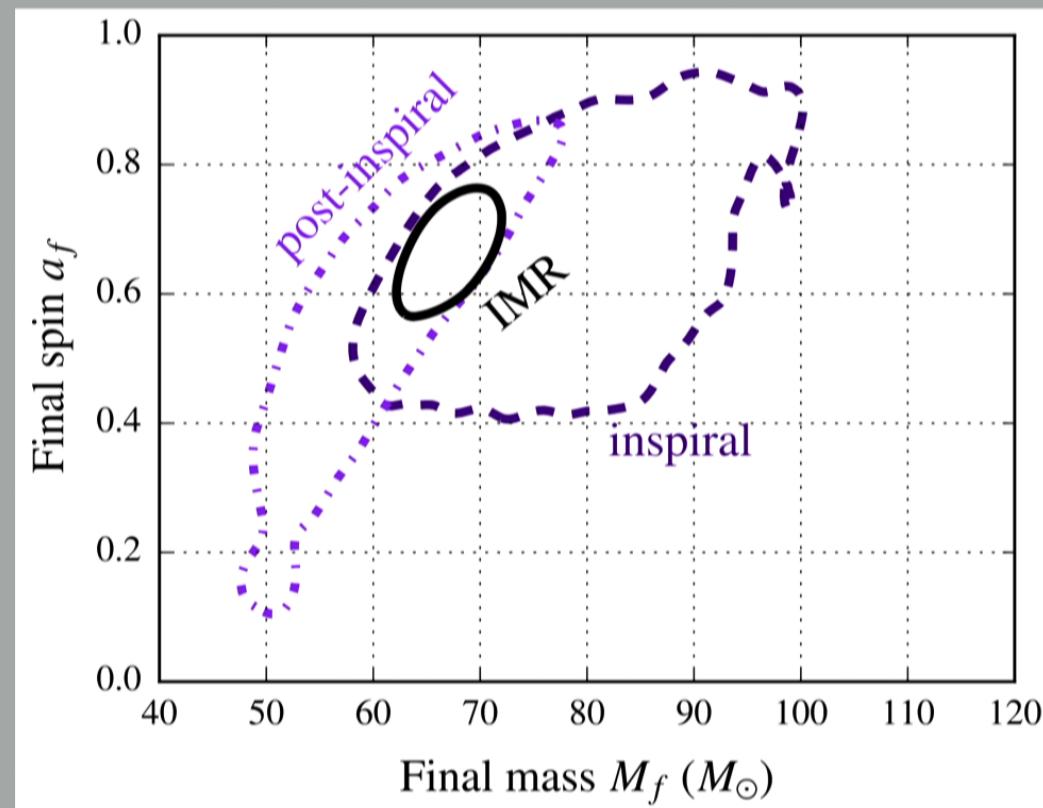


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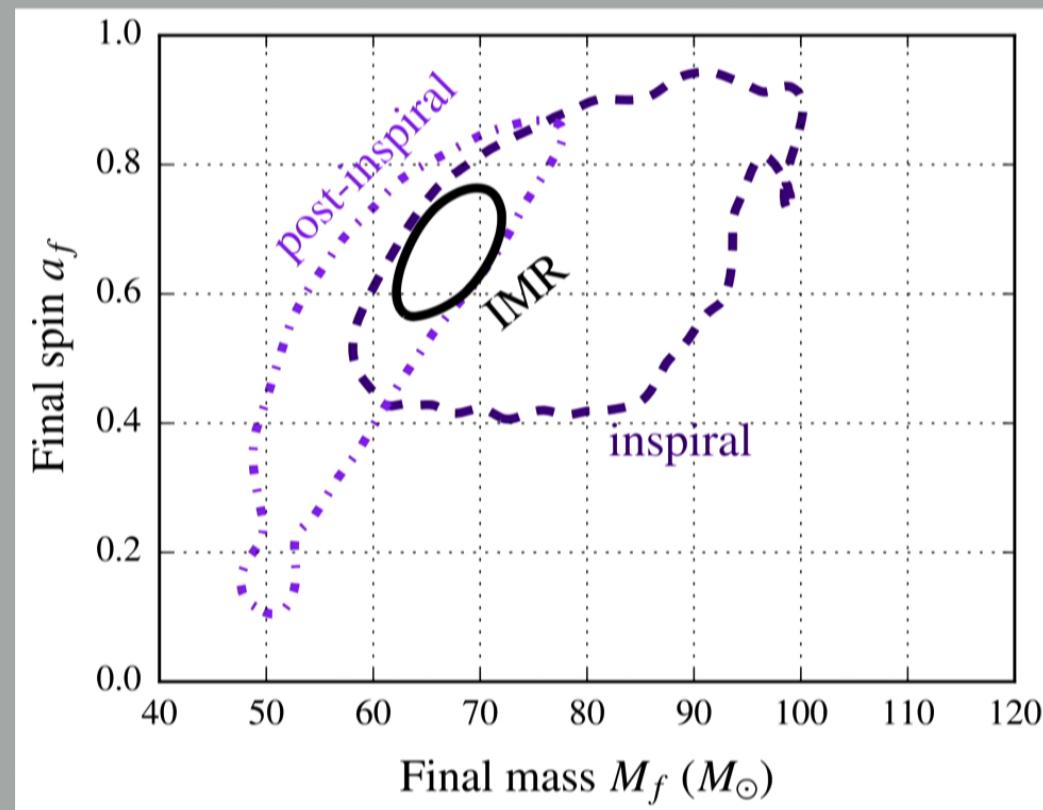


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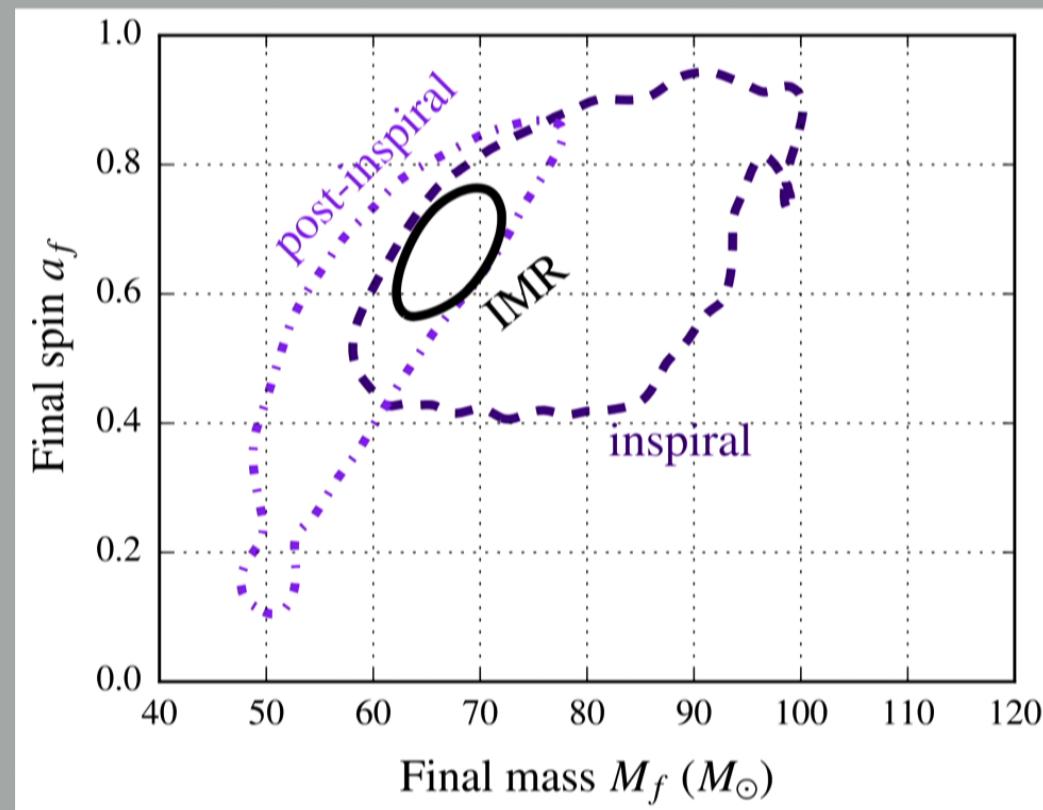


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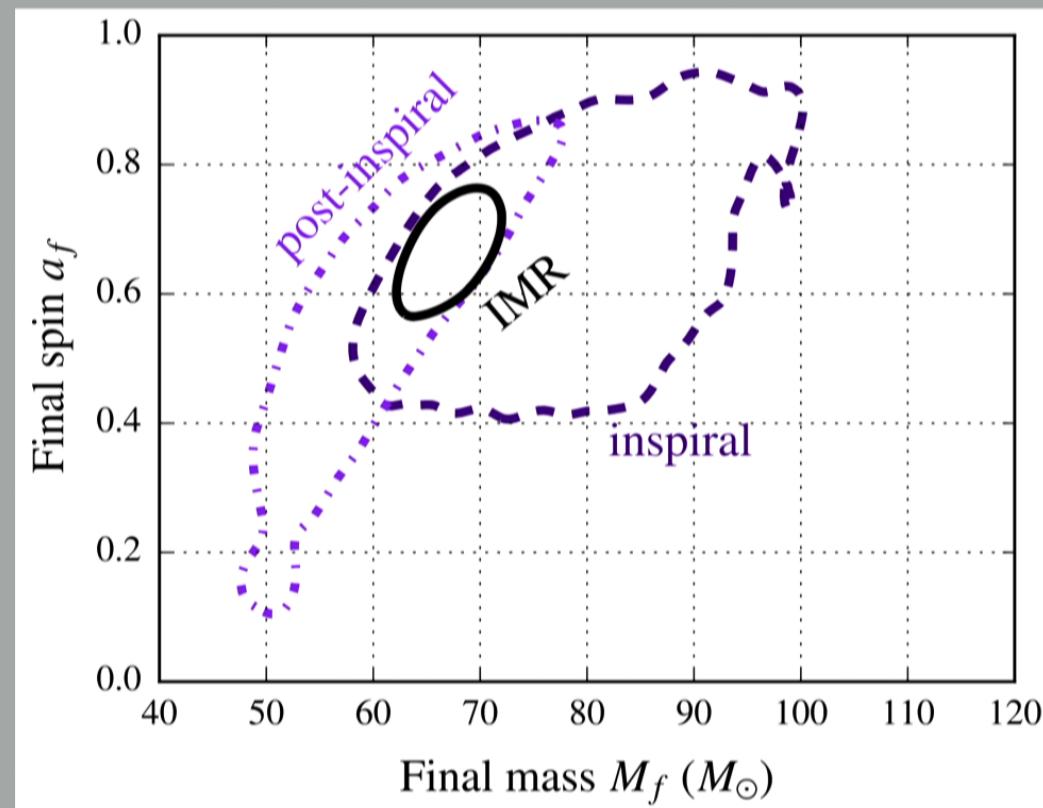


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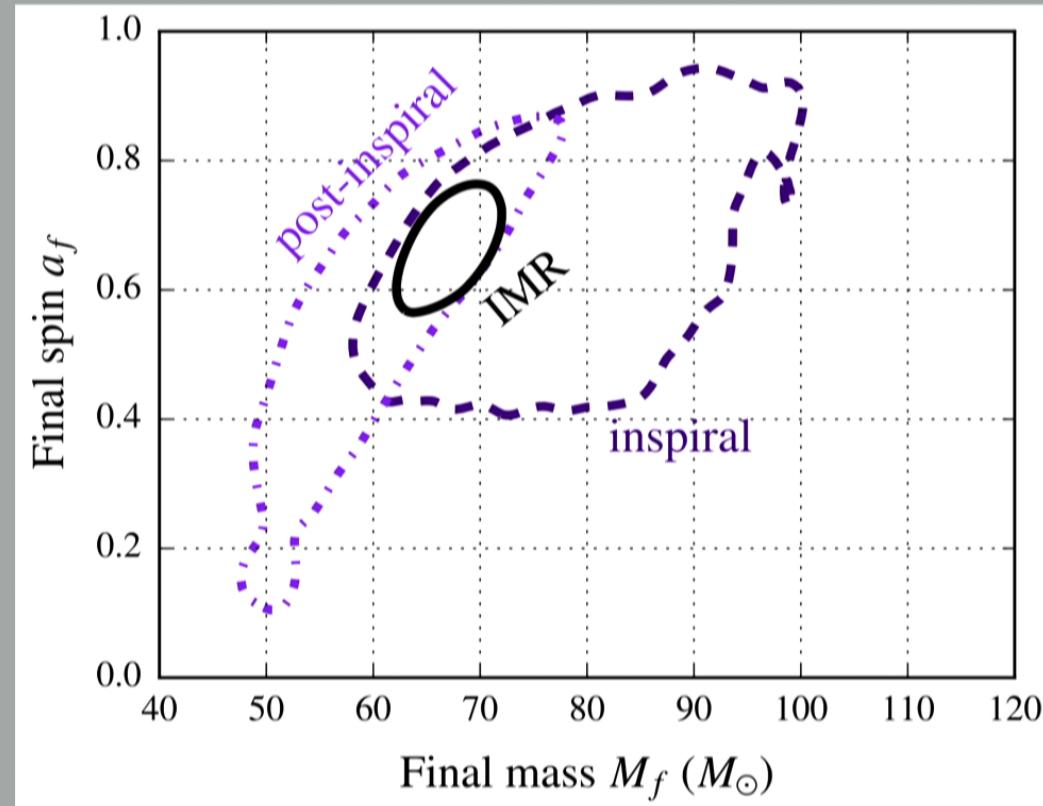


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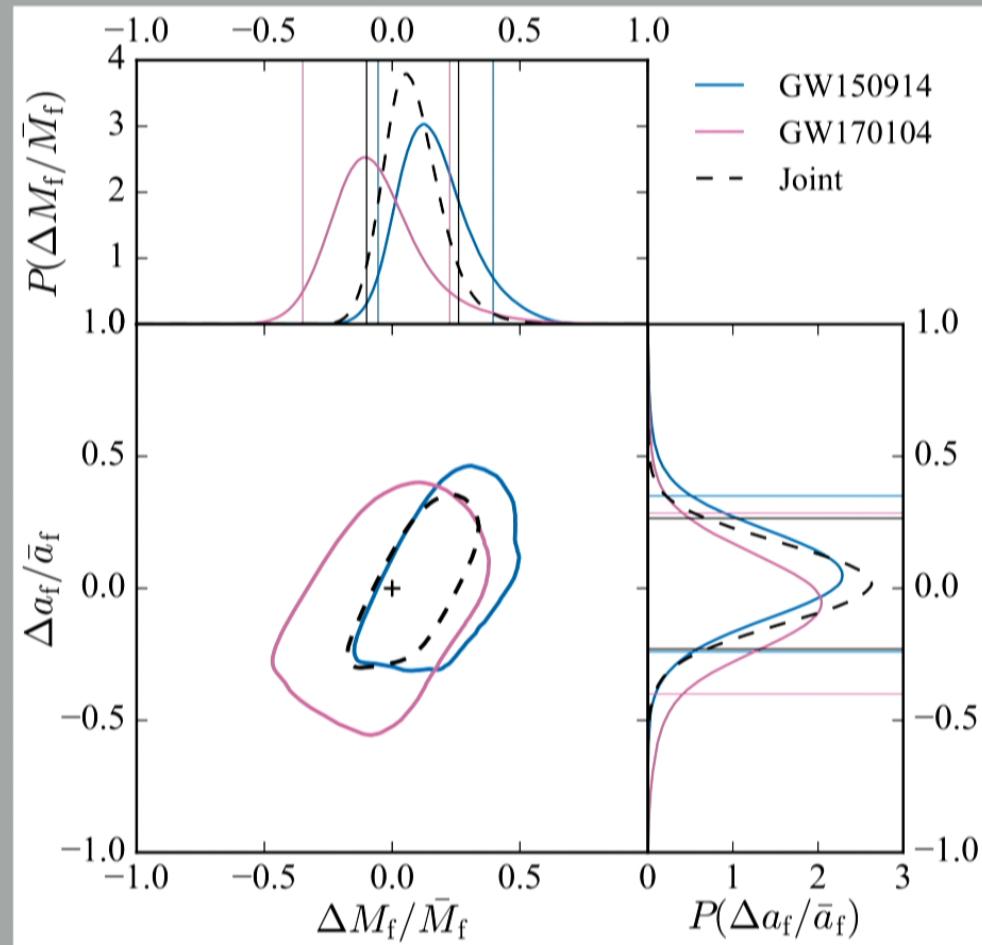
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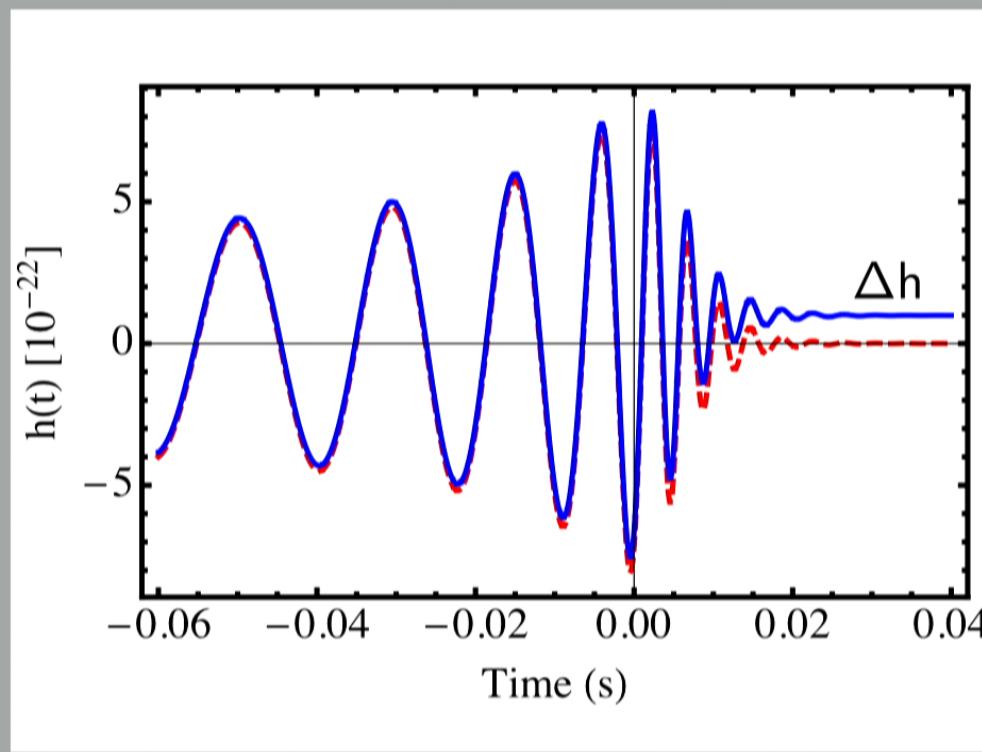


LVC (...Nichols...), PRL 118, 221101 (2017)

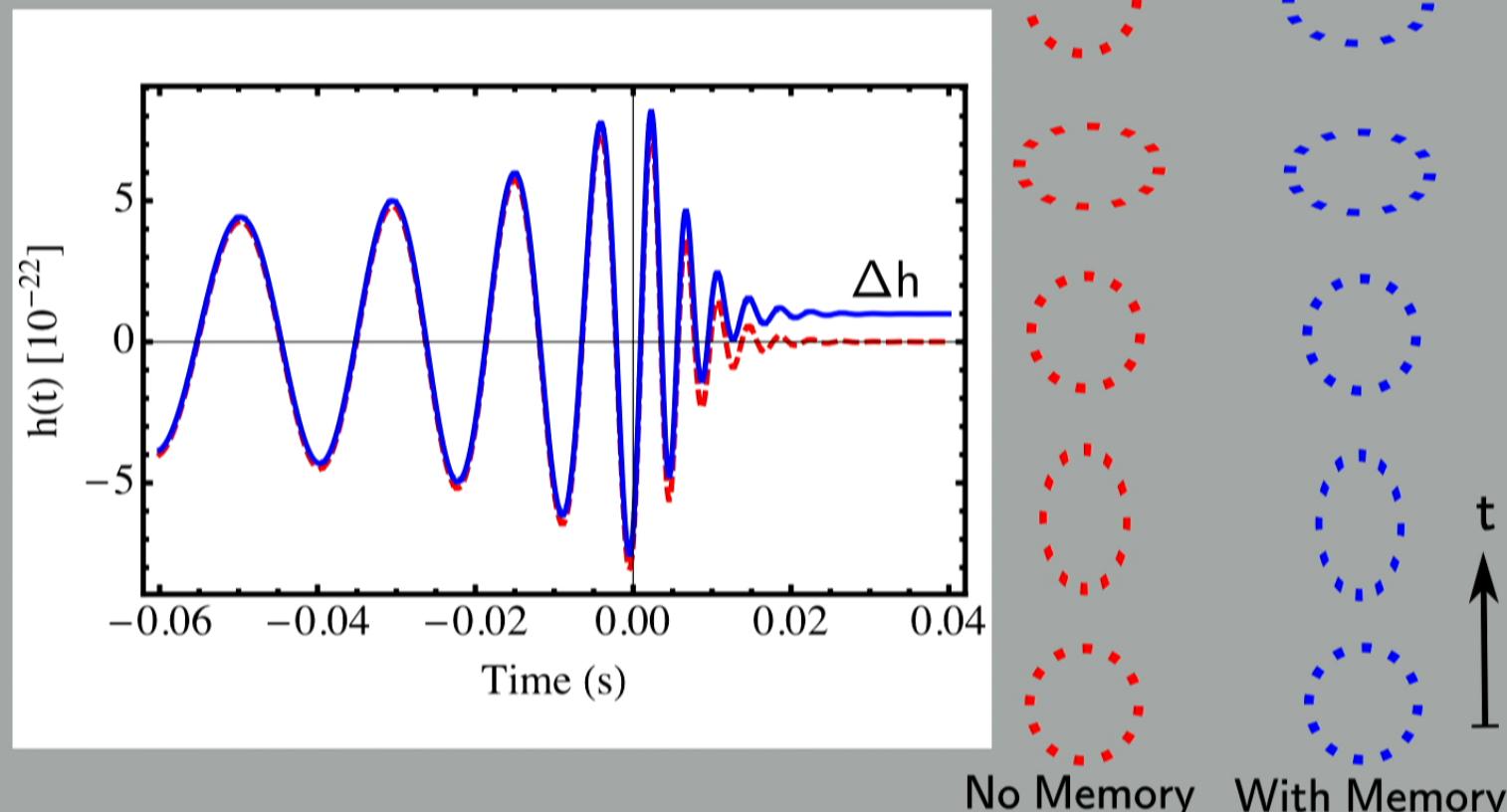
10

- $\Delta M_f = M_f^{\text{insp}} - M_f^{\text{post}}$
- $\Delta a_f = a_f^{\text{insp}} - a_f^{\text{post}}$
- Normalize by most probable
- Compare between different mergers
- Consistent with GR at $\sim 10\text{-}20\%$ level
- Expect errors shrink as $n^{-1/2}$

GW memory effect: GW150914

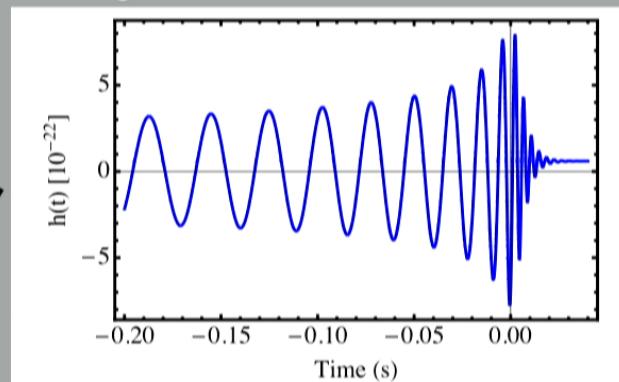


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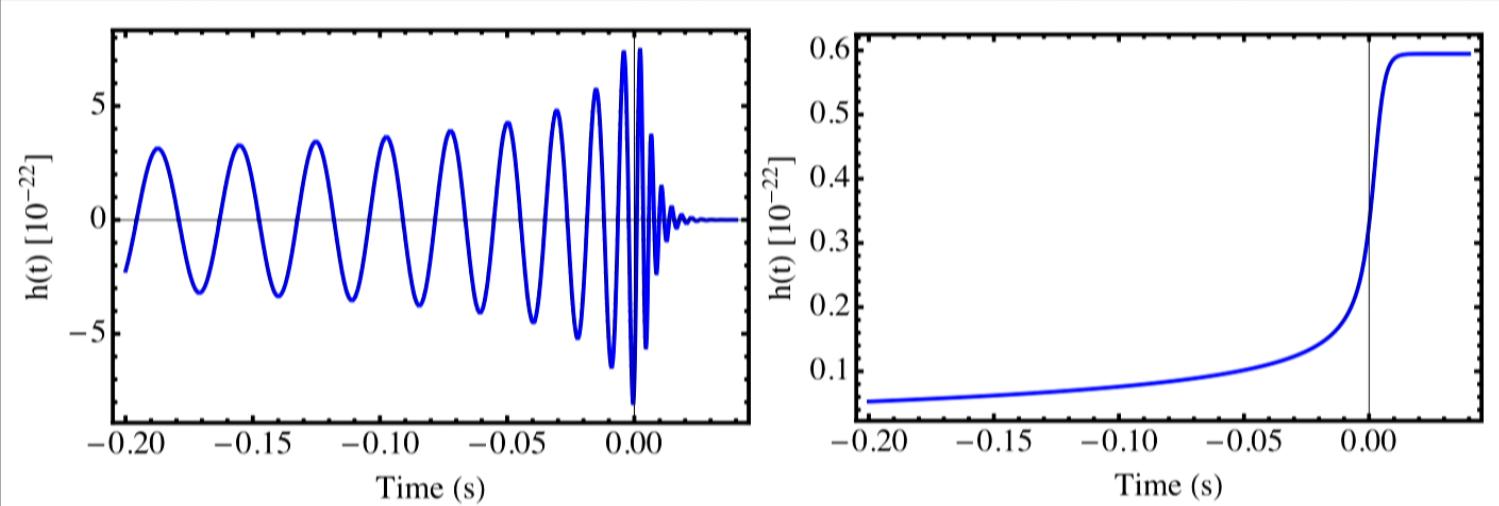


GW memory effect from GW150914

Oscillatory part



Memory part

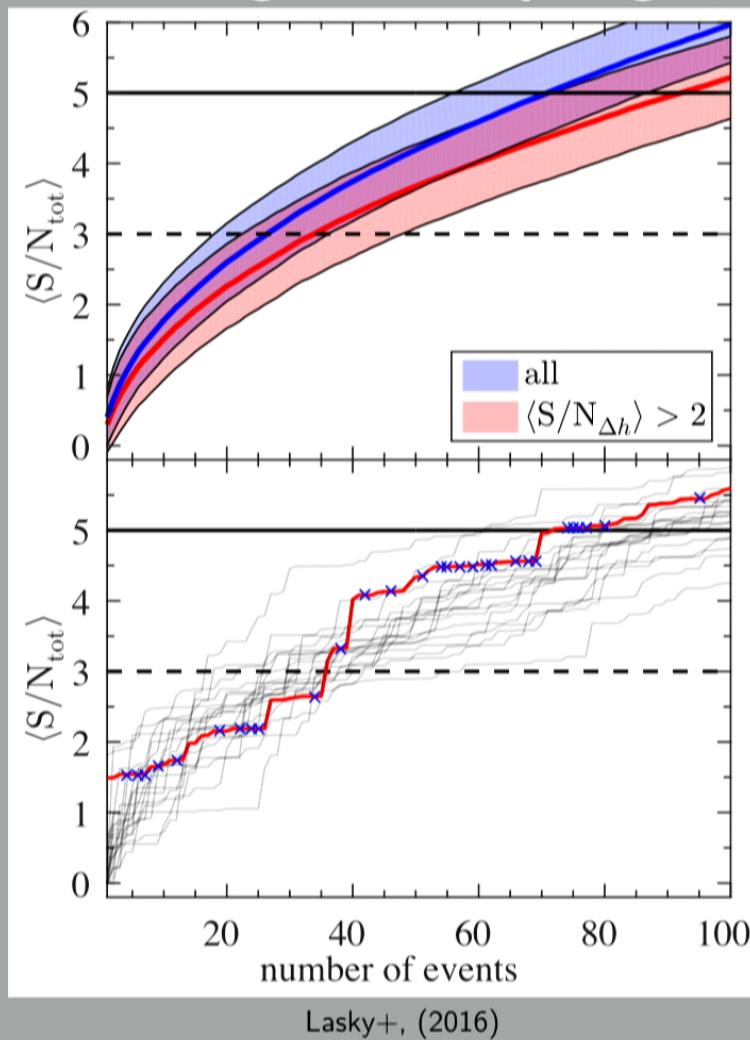


Signal to noise (S/N) ~ 25

$S/N \sim 0.5$

13

Stacking memory signals to detect with LIGO



Optimal estimator:

$$\widehat{S/N_{\text{tot}}} = \left(\sum_{i=1}^n \frac{\hat{h}_i}{\sigma_i^2} \right) \sigma_{\text{tot}}$$
$$\sigma_{\text{tot}} = \left(\sum_{i=1}^n \sigma_i^{-2} \right)^{-1/2}$$

With higher multipoles, can coherently add events and

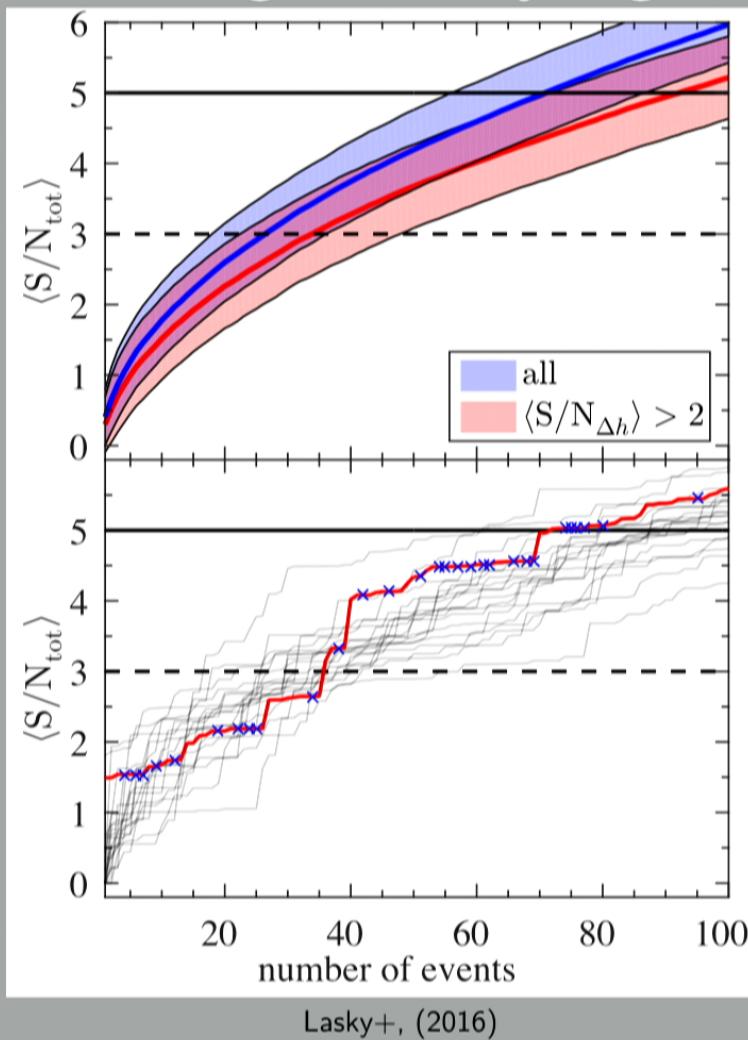
$$\langle S/N_{\text{tot}} \rangle \sim \sqrt{n}$$

Studying how well can be done with different BBH populations

Boersma, Nichols+, (in prep)

14

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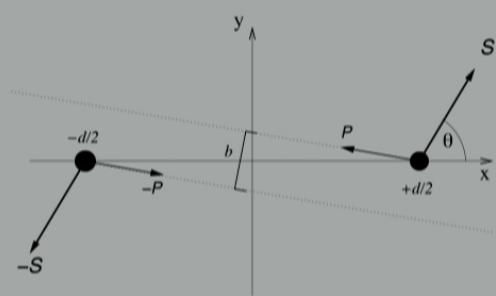
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Sources of GW memory

Changes in
“ Δh ” \propto “conserved” + $\int du \left(\begin{array}{l} \text{Energy flux} \\ \text{from massless} \\ \text{particles} \end{array} + \begin{array}{l} \text{Energy flux} \\ \text{from GWs} \end{array} \right)$

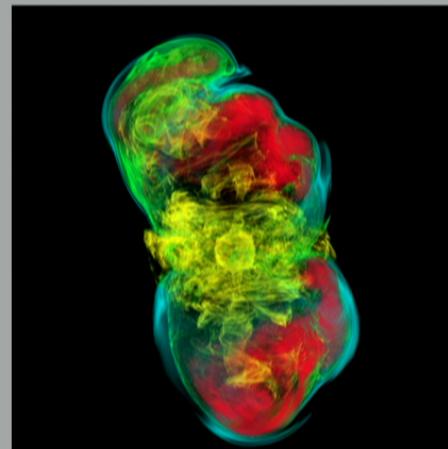
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Ex. Stars/BHs
Scattering

Zel'dovich & Polnarev, (1974)

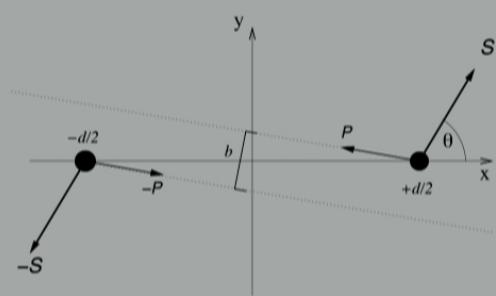


Ex. SNe neutrinos

Turner, (1978)

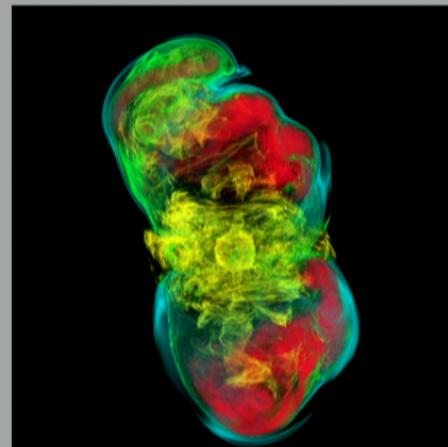
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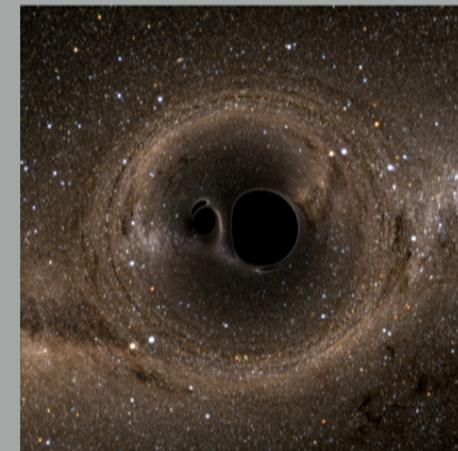
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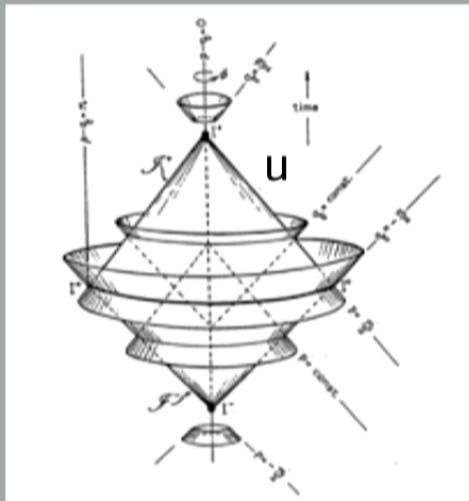
Turner, (1978)



Ex: BBH mergers

Christodoulou, (1992) 15

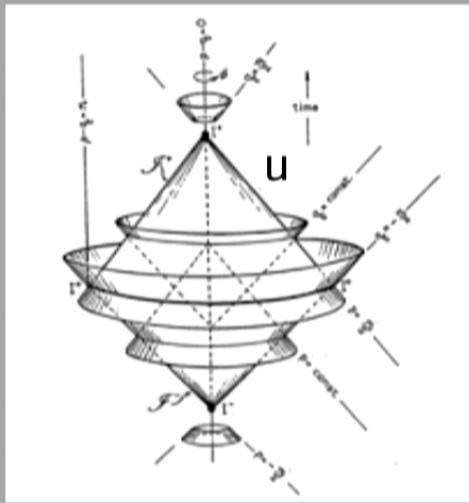
GW memory & Bondi-Metzner-Sachs symmetry



Penrose (1963)

\mathcal{I}^+ : Null surface $S^2 \times \mathbb{R}$
Endpoint of outgoing null rays

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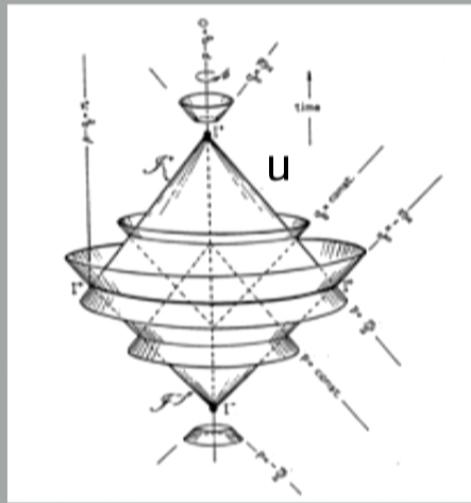
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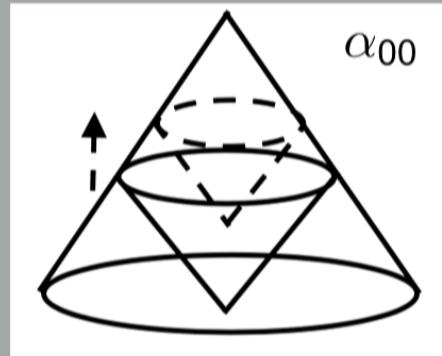


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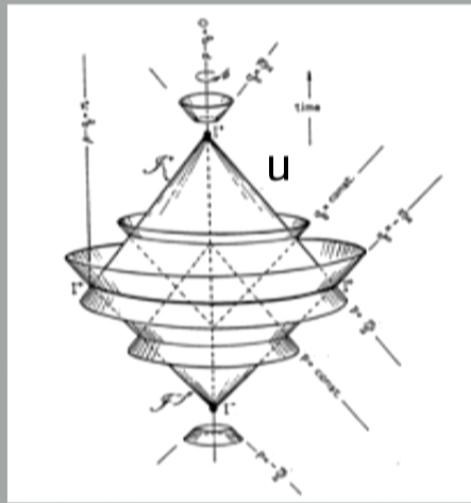
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Time translation

16

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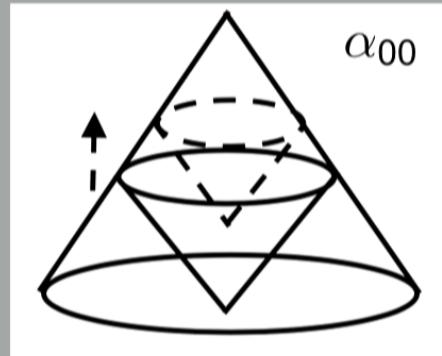


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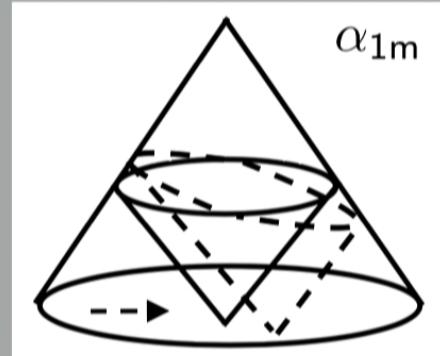
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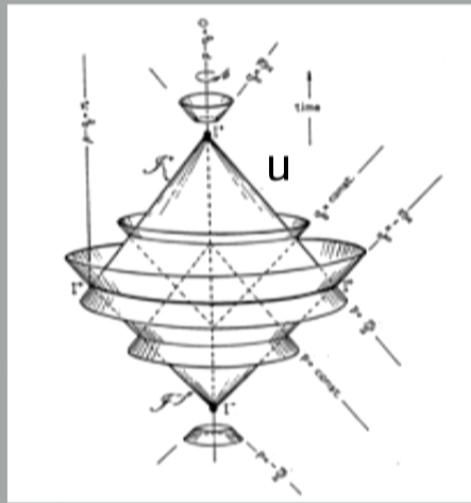
Time translation



Spatial translation

16

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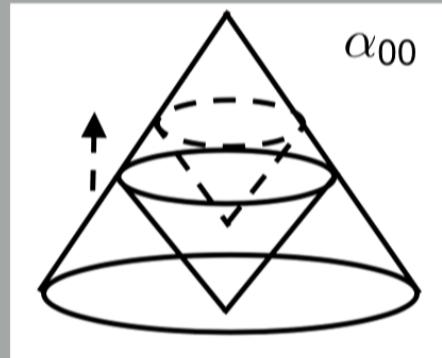


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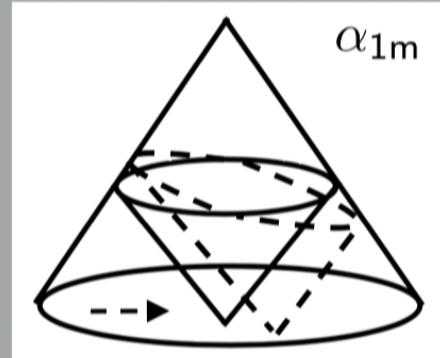
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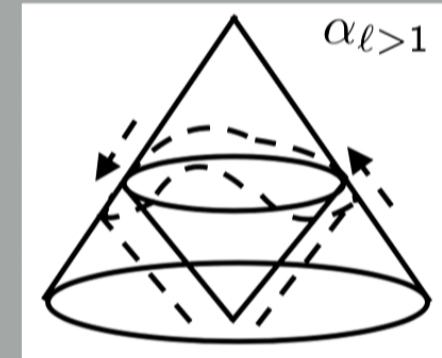
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Time translation



Spatial translation



Supertranslation

16

Memory and conserved quantities

- Symmetries → conserved quantities by Noether's theorem
- With GWs, changes in charges related to flux of charge

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Supertranslations



- Supermomentum:
changes in charges only
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Memory and conserved quantities

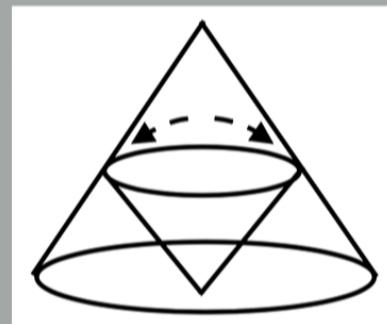
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Super-rotations Barnich & Troessaert (2009)



- Two conserved quantities: “super center-of-mass” contain full GW memory and “superspin” charges

Flanagan & Nichols (2016)

Virasoro algebra

$$l_m = -z^{m+1} \partial_z$$
$$\bar{l}_m = -\bar{z}^{m+1} \partial_{\bar{z}}$$

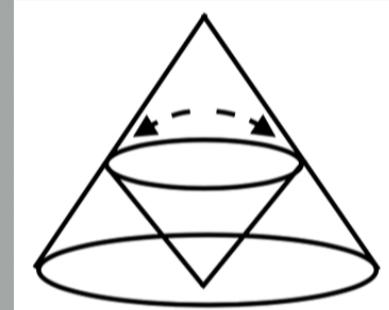
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Super-rotations Barnich & Troessaert (2009)



- Supermomentum:
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- Super center of mass an important ingredient in proposed
solution to BH information paradox! Hawking, Perry, Strominger (2017)

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Charges and fluxes: non-radiative transitions

Bondi 4-momentum loss formula

$$\Delta(\text{4-momentum}) \propto \int d^2\Omega \alpha_{\ell=0,1} \Delta \mathcal{E}$$

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New memory effect: Spin memory

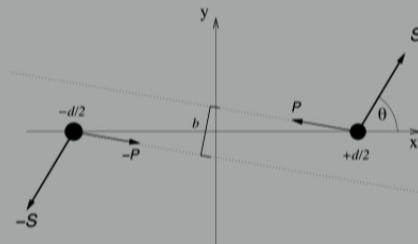
New “spin memory” effect related to extended symmetries

$$\text{“} \int du h \text{”} \propto \frac{\text{Changes in}}{\text{super-spin}} + \int du \left(\begin{array}{c} \text{Angular} \\ \text{momentum} \\ \text{flux, matter} \end{array} + \begin{array}{c} \text{Angular} \\ \text{momentum} \\ \text{flux GWs} \end{array} \right)$$

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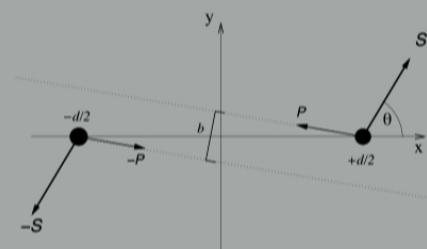
Ex. Spinning objects
scattering

Pasterski+, (2015)

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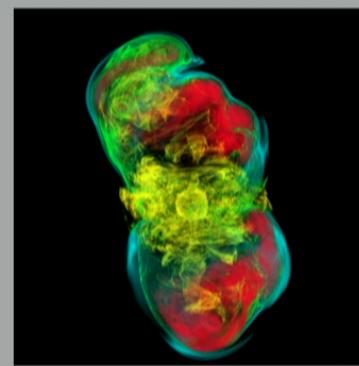
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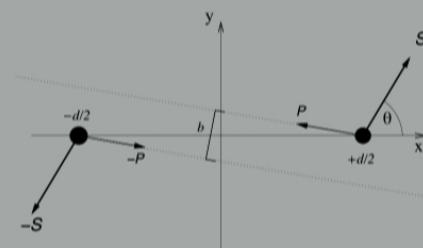
Ex. SNe neutrinos

Presumably, not yet computed

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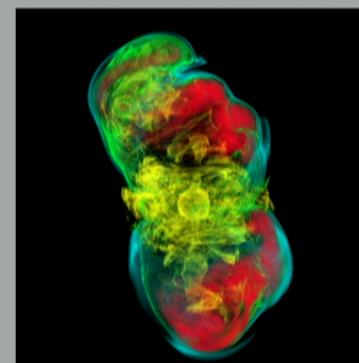
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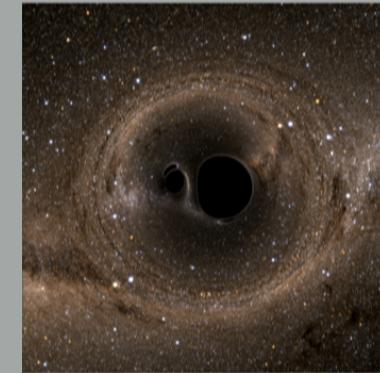
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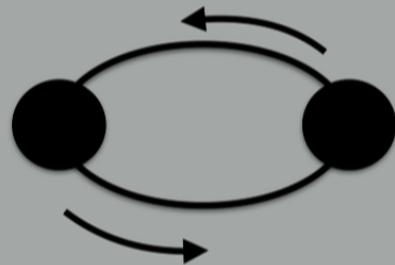
Nichols, (2017)

Spin memory effect: Post-Newtonian binaries

Non-spinning compact binaries, spin memory in $(L,m)=(3,0)$ mode

$$\Delta\Sigma = \int du h_x^{\text{smm}} = \frac{3}{64\pi r} \int du \Im[\bar{U}_{2,2} \dot{U}_{2,2}] \sin^2 \theta \cos \theta + \dots$$

Expand for quasi-circular binaries in terms of $x = (M\omega)^{2/3}$

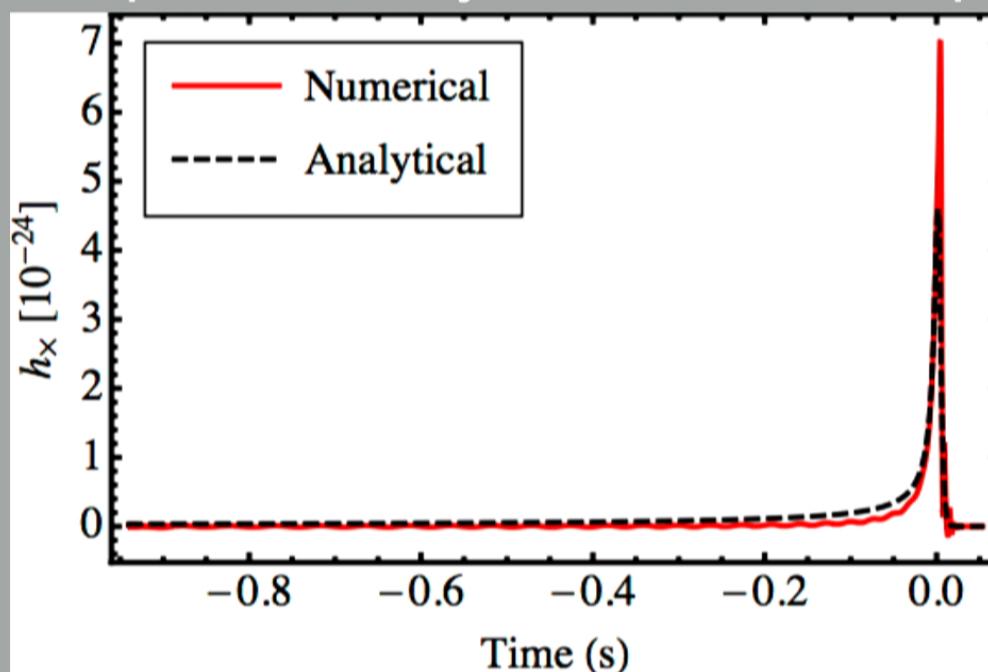


$$\Delta\Sigma = \frac{3M\eta^2}{8r} x^{-1/2} \Big|_{x=x_0}^{x=x_f} \sin^2 \theta \cos \theta$$

Cannot measure $\Delta\Sigma$ with LIGO, but can measure h_x

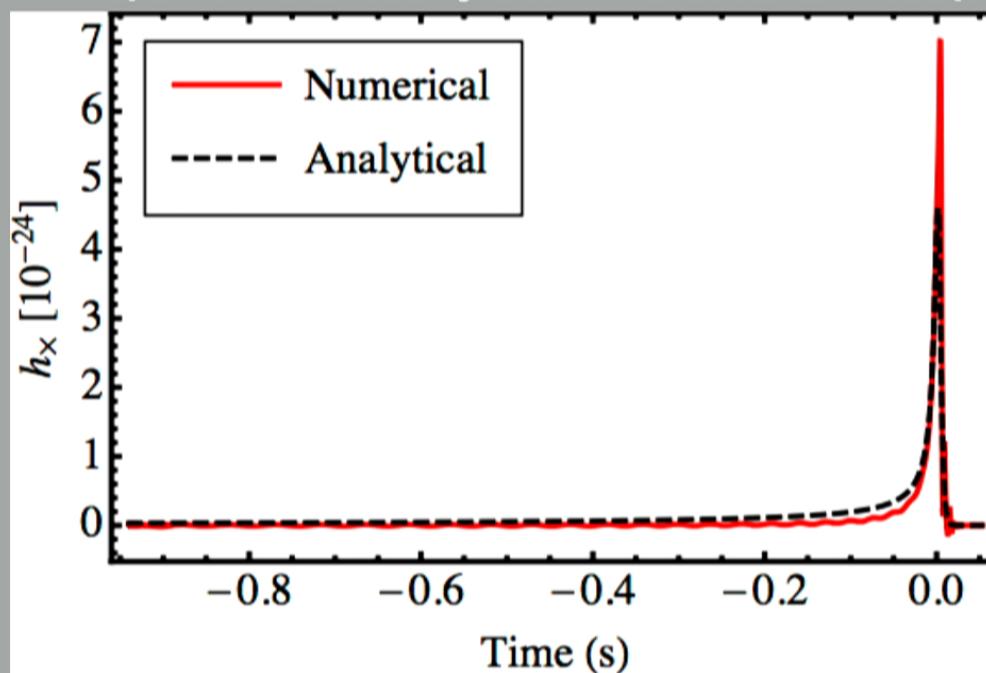
$$\begin{aligned} h_x^{\text{smm}} &= \frac{3}{64\pi r} \Im[\bar{U}_{2,2} \dot{U}_{2,2}] \sin^2 \theta \cos \theta + \dots \\ &= -\frac{12M\eta^2}{5r} x^{7/2} \sin^2 \theta \cos \theta + \dots \end{aligned}$$

Spin memory effect for compact binaries



Nichols (2017)

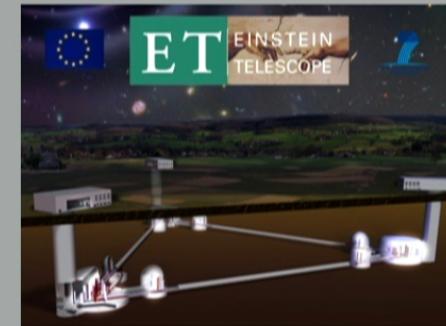
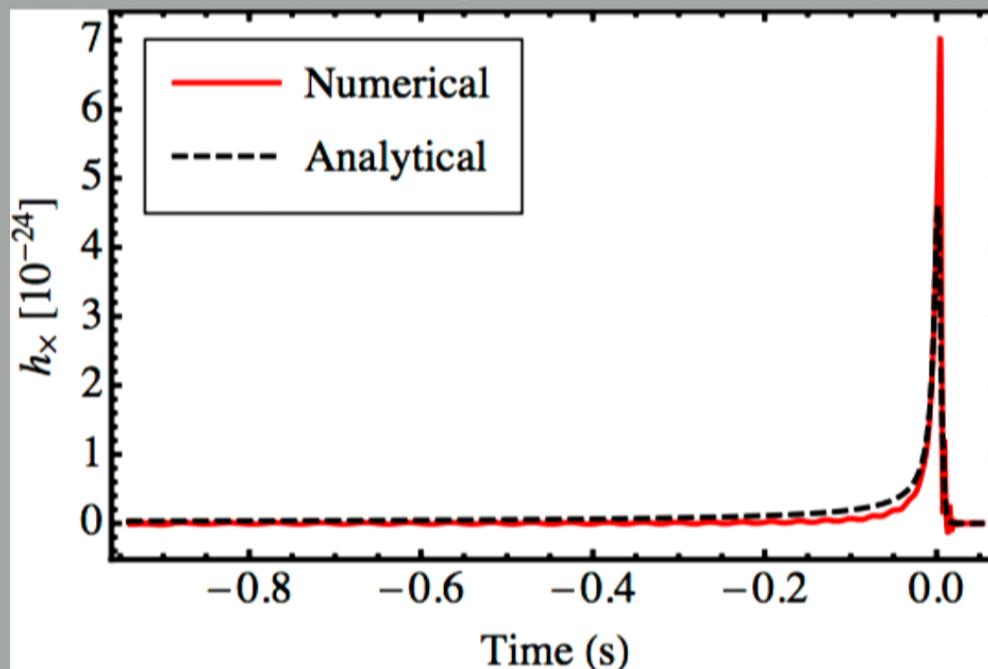
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Nichols (2017)

Mode	SNR in LIGO
Quadrupole	$\sim 1 \times 10^2$
Displacement Memory	~ 1
Spin Memory	~ 0.03

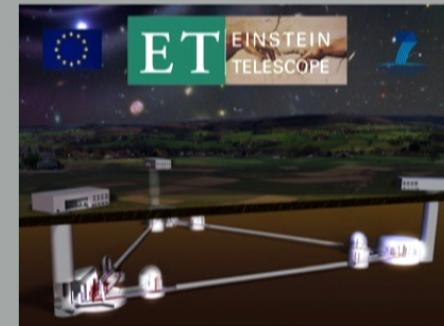
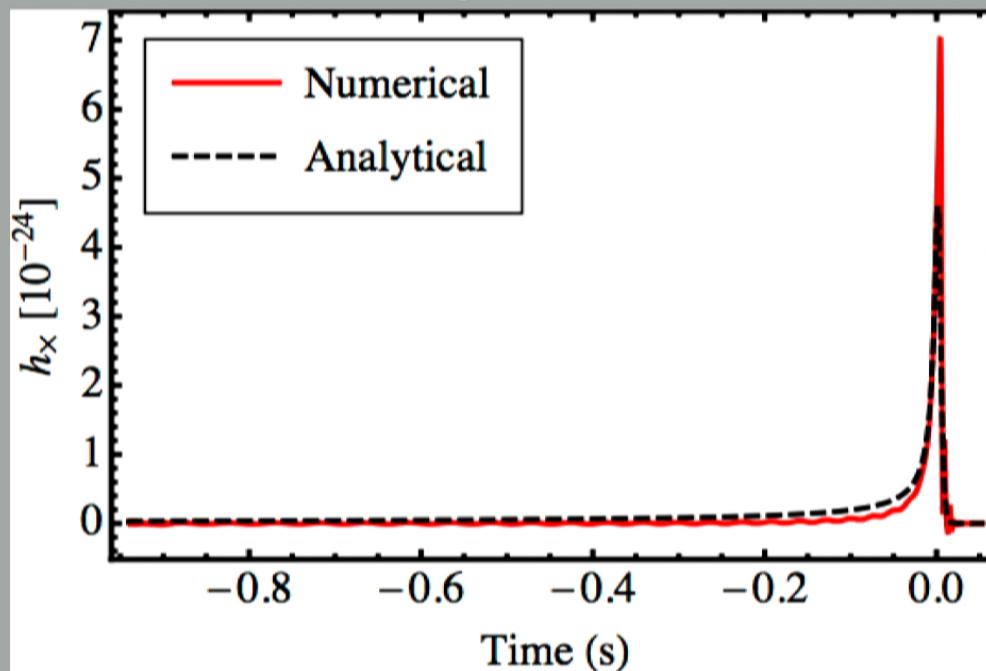
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- 10 km arms
- Planned for
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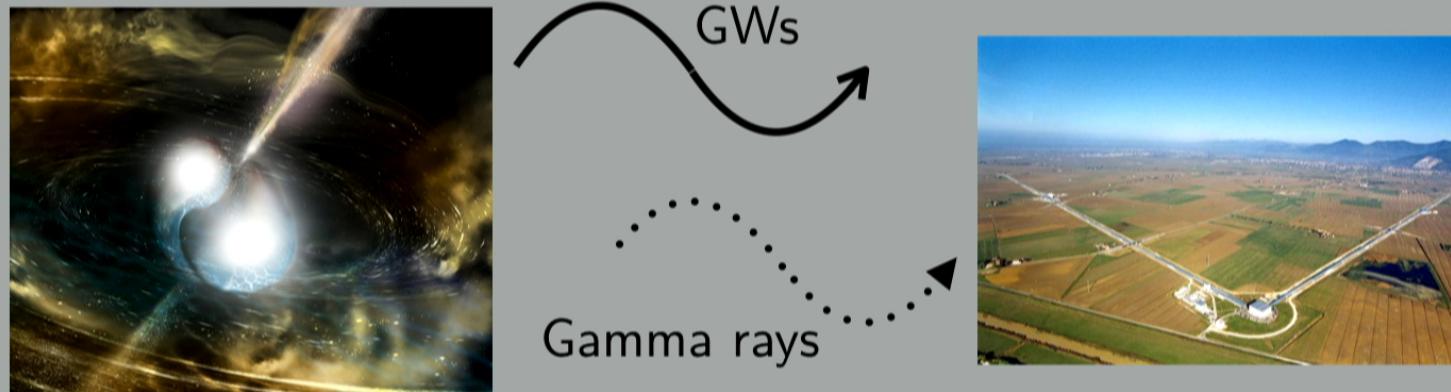
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Mode	SNR in LIGO	SNR in ET
Quadrupole	$\sim 1 \times 10^2$	$\sim 5 \times 10^3$
Displacement Memory	~ 1	~ 30
Spin Memory	~ 0.03	~ 1

21

LIGO/Virgo+Fermi results: Speed of GWs

1. GWs and GRB emitted at same time; 1.7s delay because GWs faster than light (upper bound).
2. GRB delayed by 10s; GWs slower than light (lower bound)

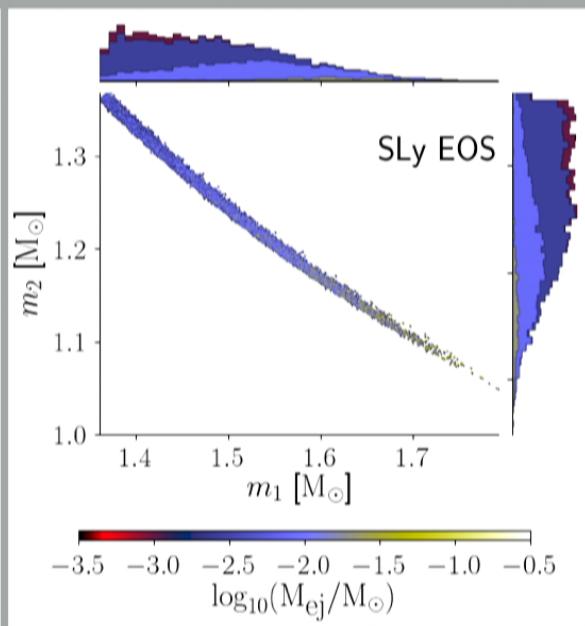
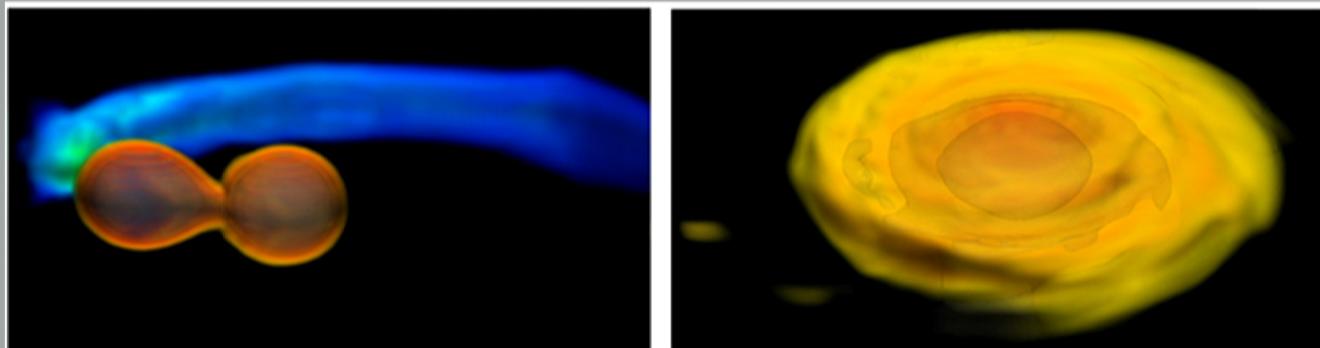


Gives constraint: $-3 \times 10^{-15} \leq \frac{v_{\text{gw}}}{v_{\text{em}}} - 1 \leq 7 \times 10^{-16}$
LVC (...Nichols...), Fermi, Integral, (2017)

Improved constraints on Lorentz violation by 10^{10} in one case!

Constrains modified gravity theories (e.g., galileons) Sakstein+ (2017) 23

Ejected mass from GW170817



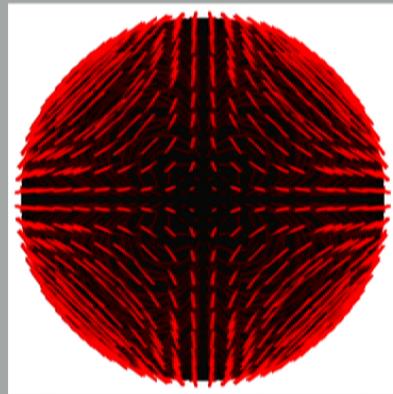
LVC (...Nichols...), (2017)

Credit: AEI Potsdam

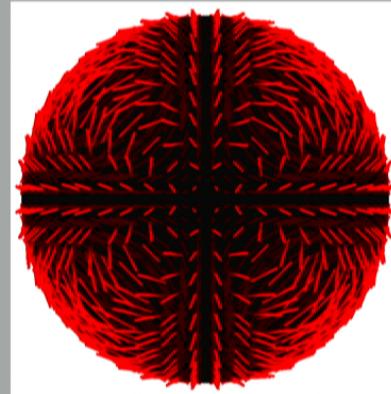
- Ejected neutron-rich material produces kilonova and forms heavy elements via r-process
- GW estimates consistent with galactic abundances
- Can use to compare with kilonova light curves

Future direction: Measuring GWs via astrometry

GWs passing Earth cause stars' positions to be deflected Pyne+ (1996)



Northern hemisphere



Southern

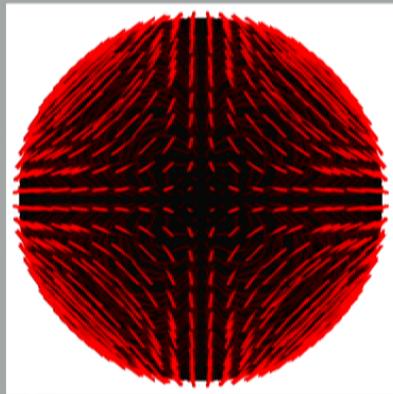
$$\delta n \propto h$$

Possible to look for GWs
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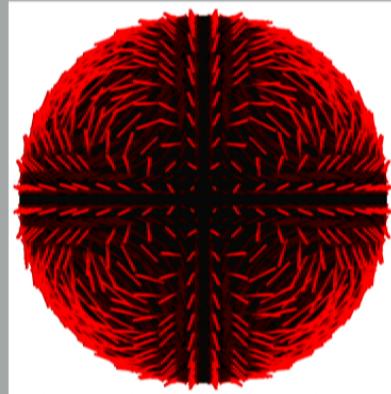
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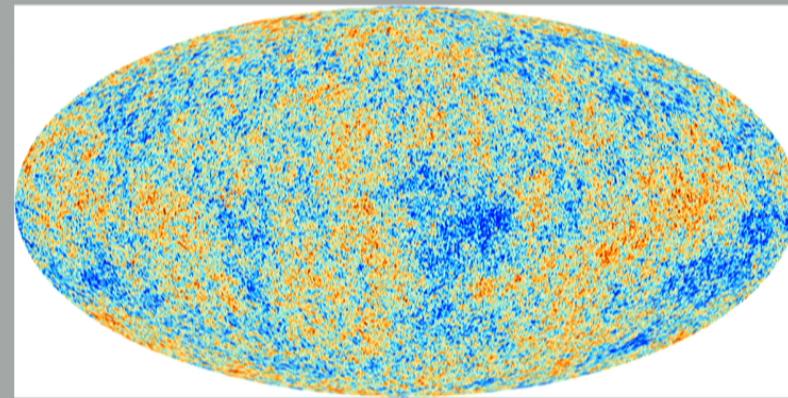
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Moore+, (2017)

A stochastic background of GWs (stationary, Gaussian, isotropic, GW fluctuations) produces correlated stellar motion
e.g., Book+ (2011)



Credit: ESA/Planck

26

Stochastic background of GWs

$$\langle \delta n^2 \rangle \sim (f h_{\text{rms}})^2 \sim (H_0)^2 \Omega_{\text{gw}}(f) \quad \text{where} \quad \Omega_{\text{gw}} \equiv \frac{1}{\rho_c} \frac{d\rho_{\text{gw}}}{d \ln f}$$

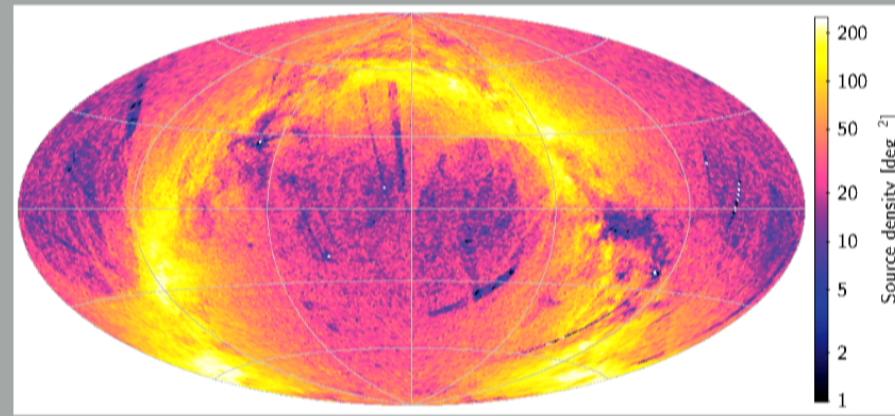
Can measure $h_{\text{rms}} \sim \frac{\Delta\theta}{\sqrt{n}}$ at $f \sim \frac{1}{T}$ constrain $\Omega_{\text{gw}} \lesssim \frac{\Delta\theta^2}{n(H_0 T)^2}$
Book+ (2011)

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Credits: ESA/Gaia



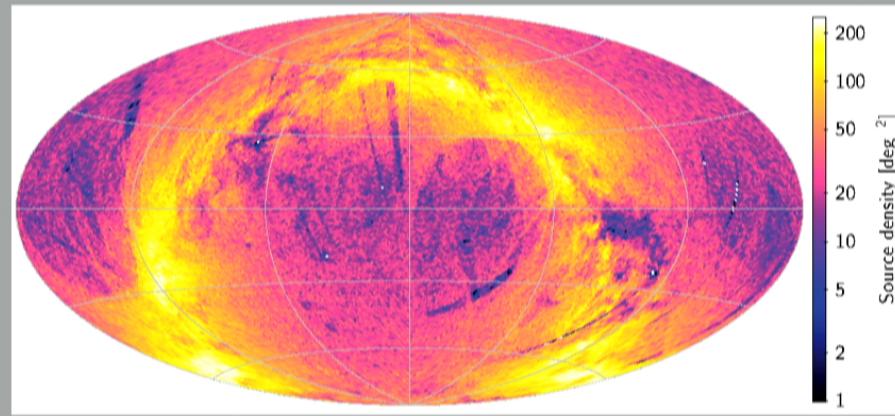
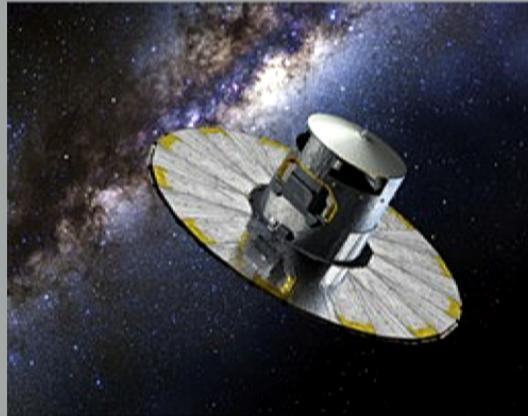
Gaia: measure $n \sim 10^9$ stars $\sim 10^6$ quasars for $T \sim 5$ yr with $\Delta\theta \sim 10 \mu\text{as}$

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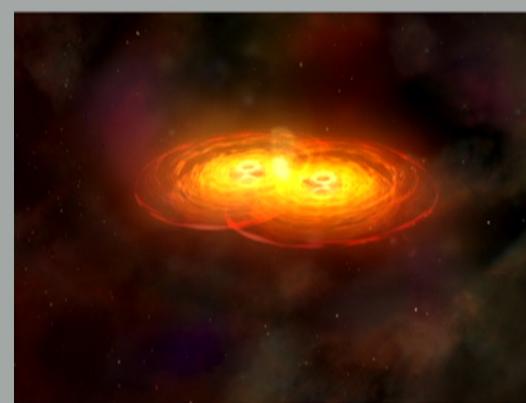
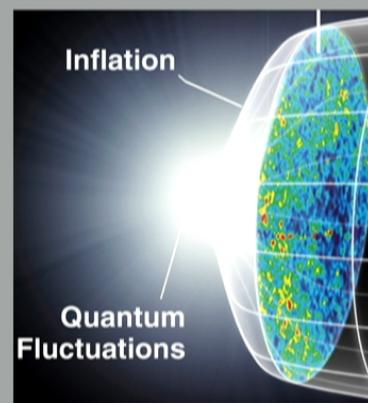
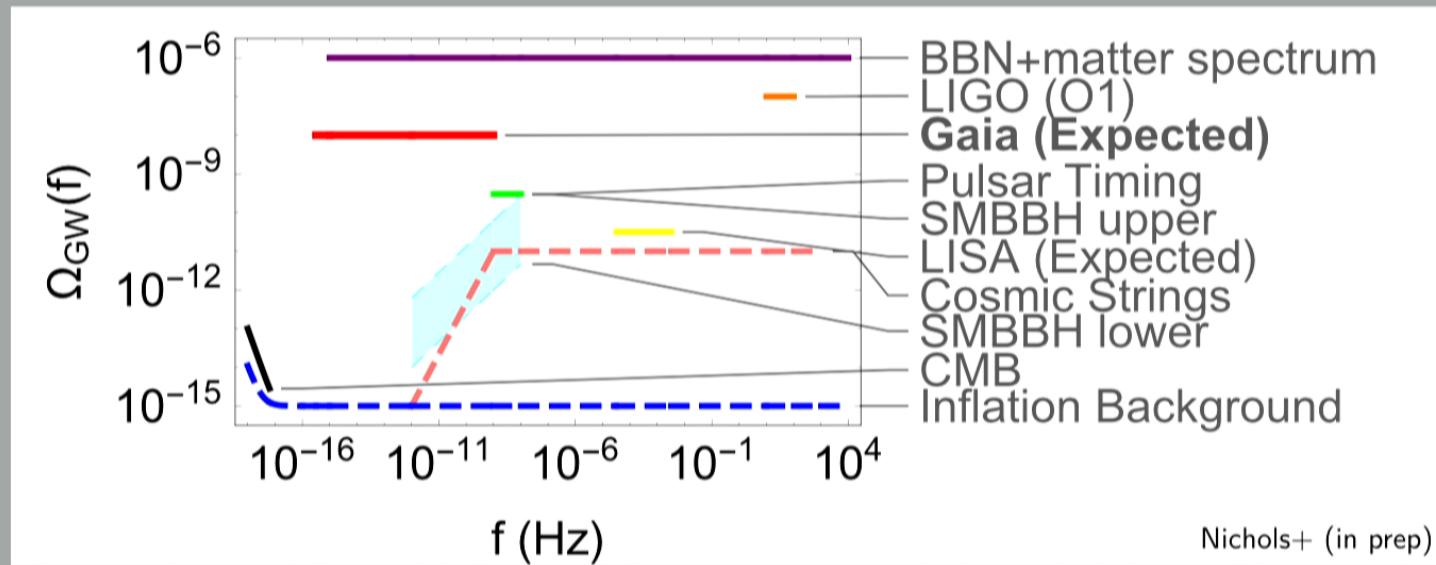


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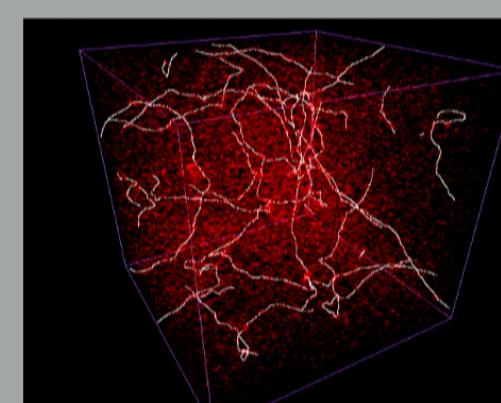
$$\text{For quasars: } \Omega_{\text{gw}} \lesssim 10^{-8} \left(\frac{\Delta\theta}{10 \mu\text{as}} \right)^2 \left(\frac{10^6}{n} \right) \left(\frac{5 \text{yr}}{T} \right)^2$$

27

Future directions: GWs with astrometry



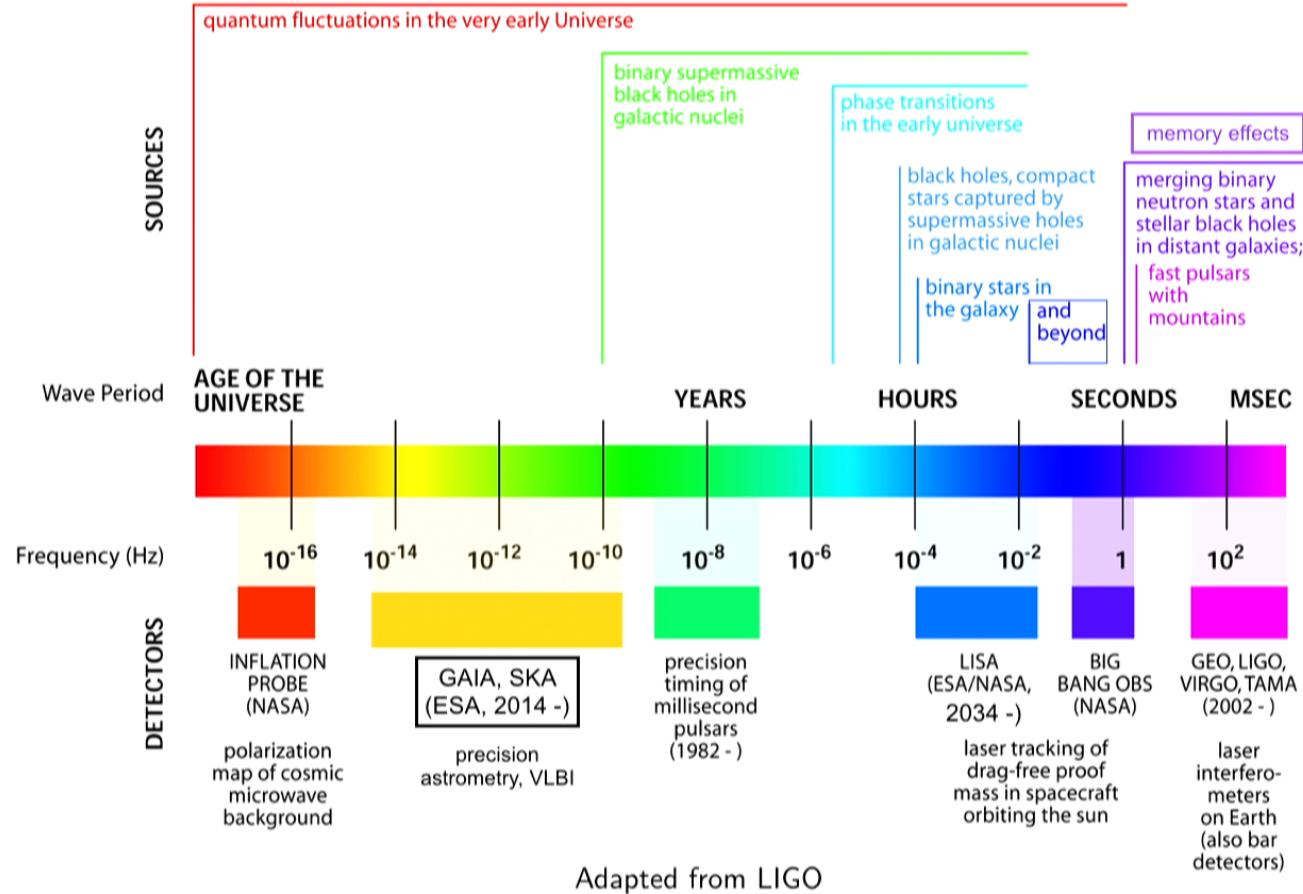
Credits: NASA, DAMTP



28

Conclusions

THE GRAVITATIONAL WAVE SPECTRUM



33