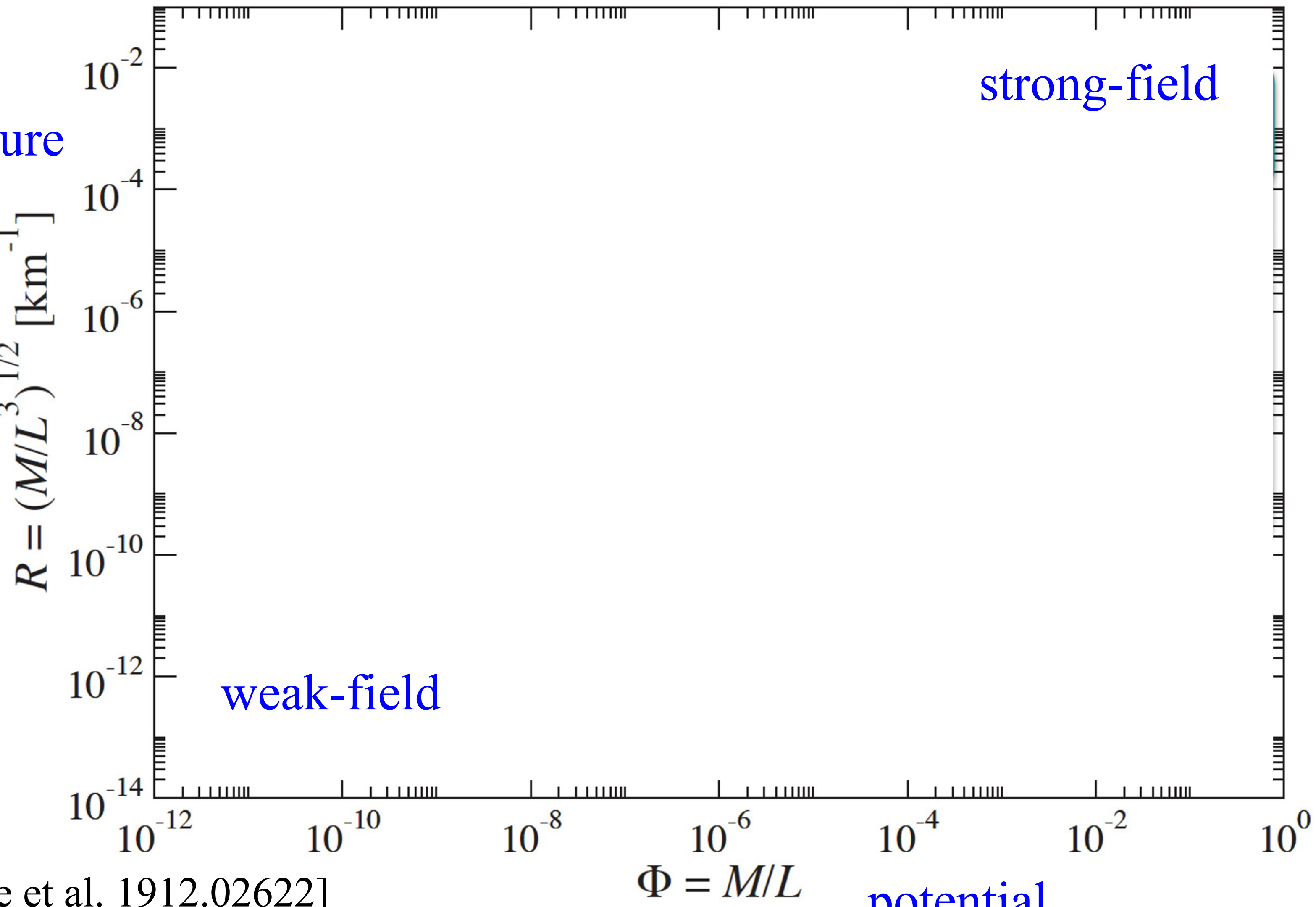
Strong-field Tests of Gravity with Gravitational Waves: Current Status & Future Directions

Kent Yagi
University of Virginia

P2I Conference @ U. of Tokyo
November 21, 2025

Various Tests of Gravity

curvature



potential

[Maggiore et al. 1912.02622]

[Yunes, KY & Pretorius 1603.08955]

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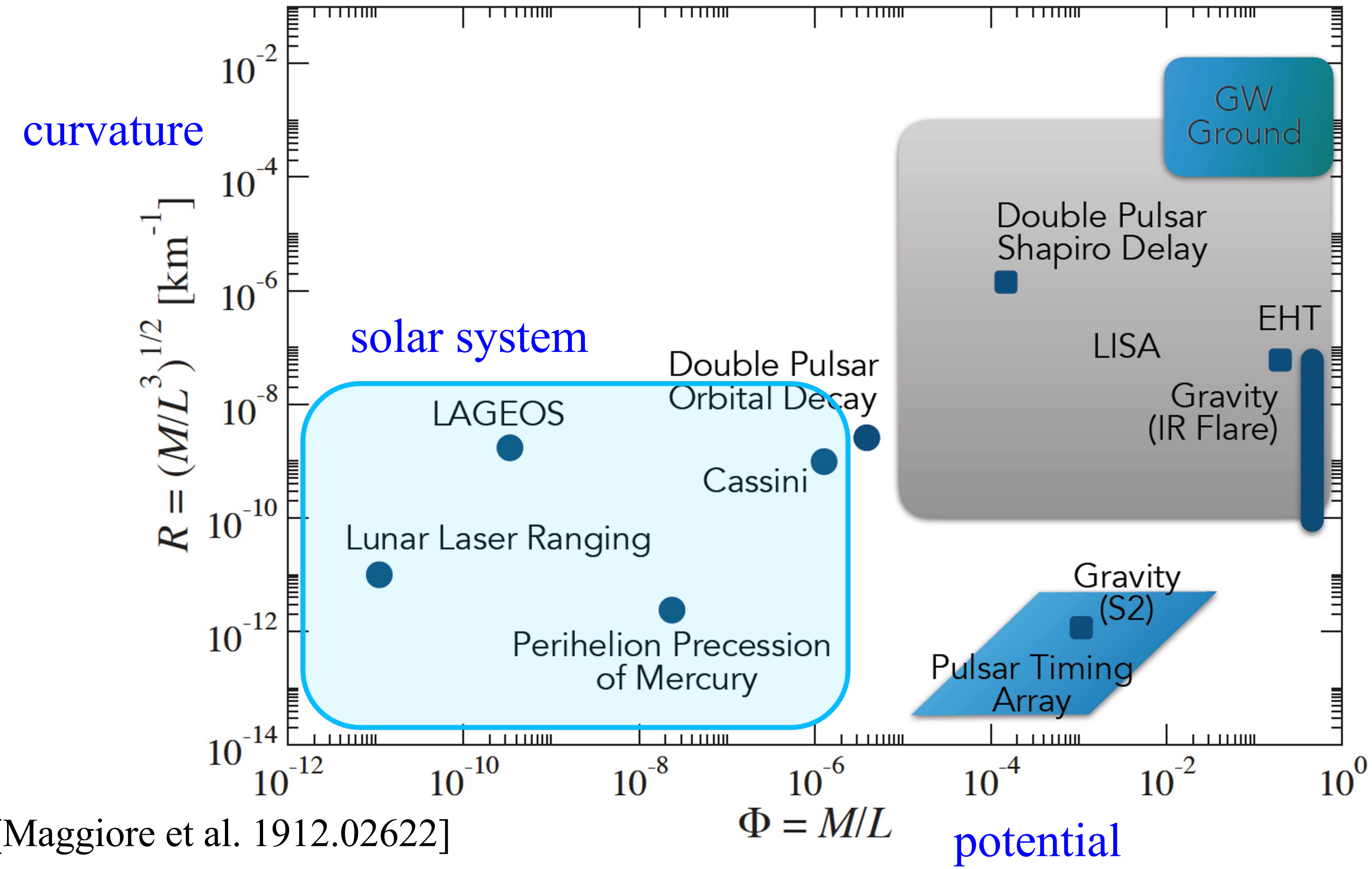
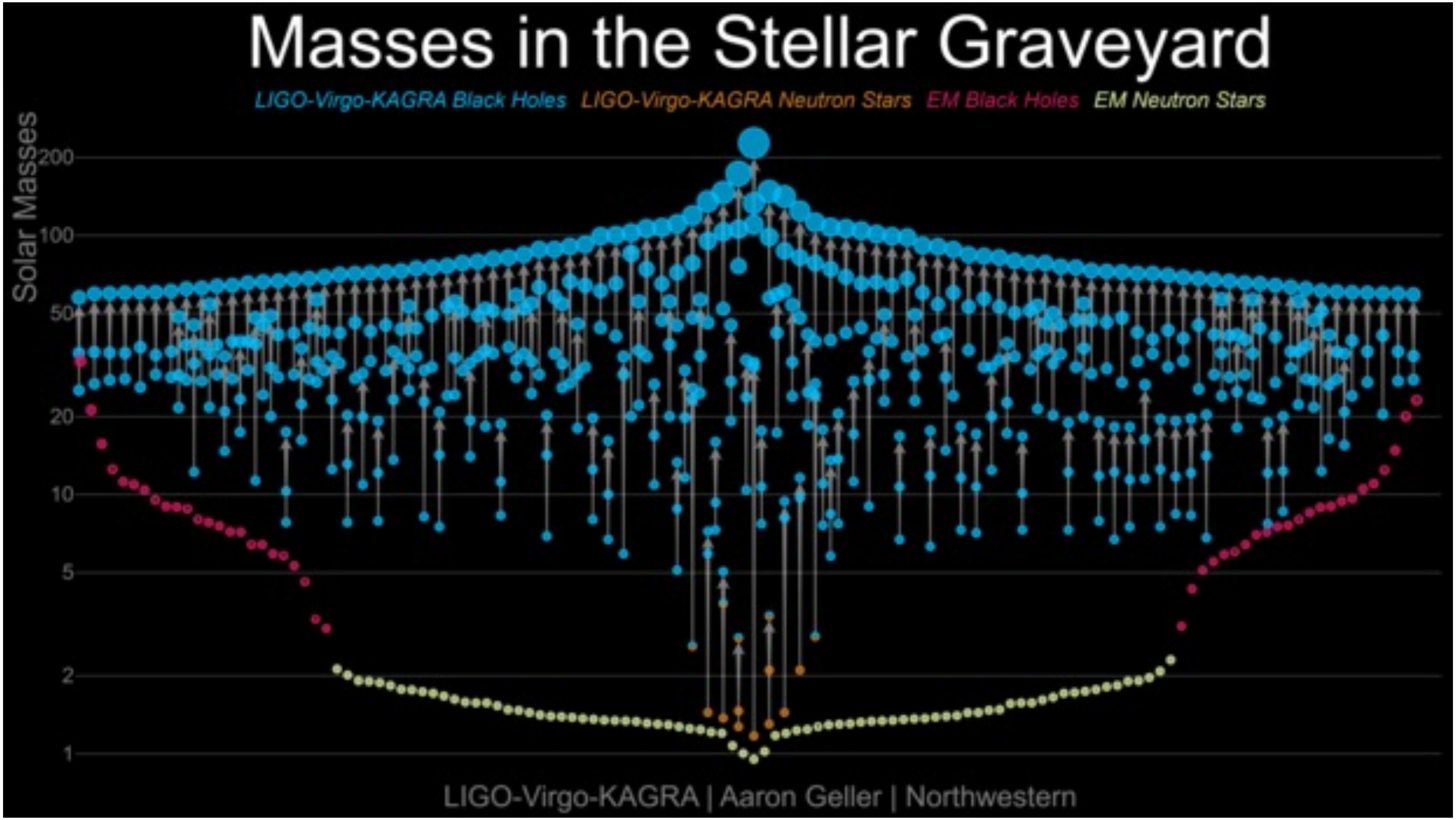


[Maggiore et al. 1912.02622]

[Yunes, KY & Pretorius 1603.08955]

Current Status

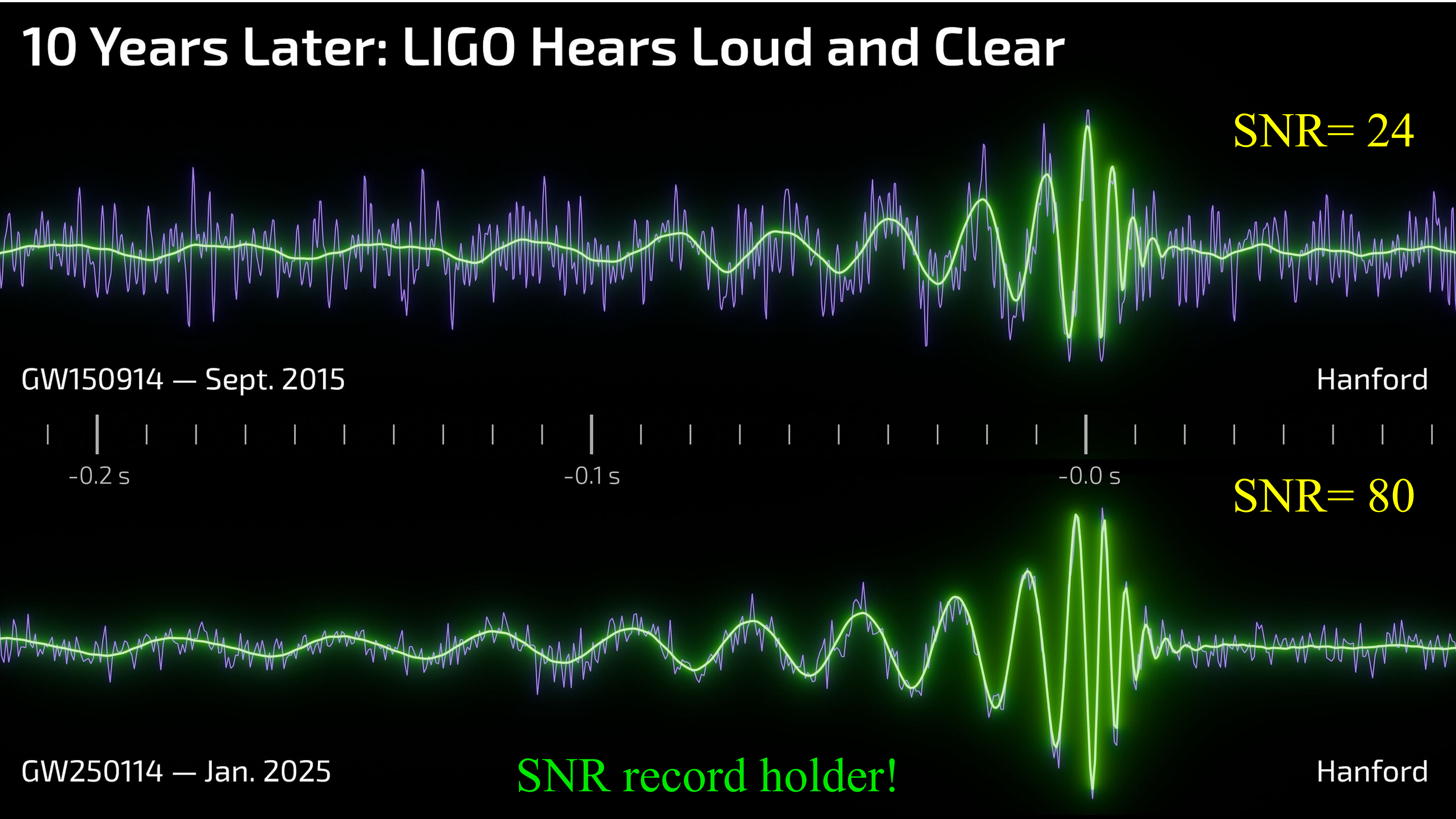
GWTC-4



[Parameswaran's talk]

[LIGO]

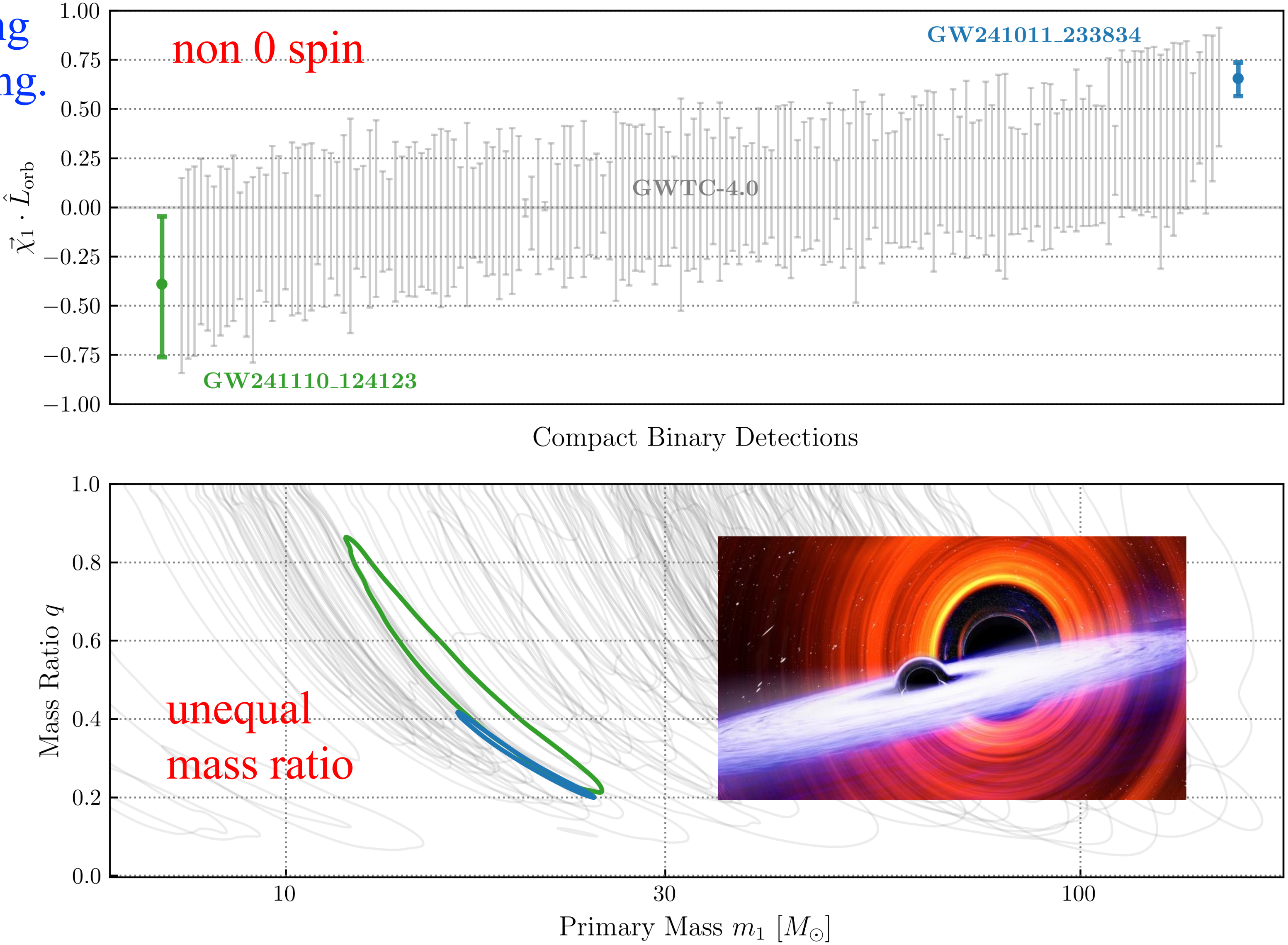
GW150914 & GW250114



GW241011 & GW241110

[LVK, arXiv:2510.26931]

spin along orbital ang. mom.

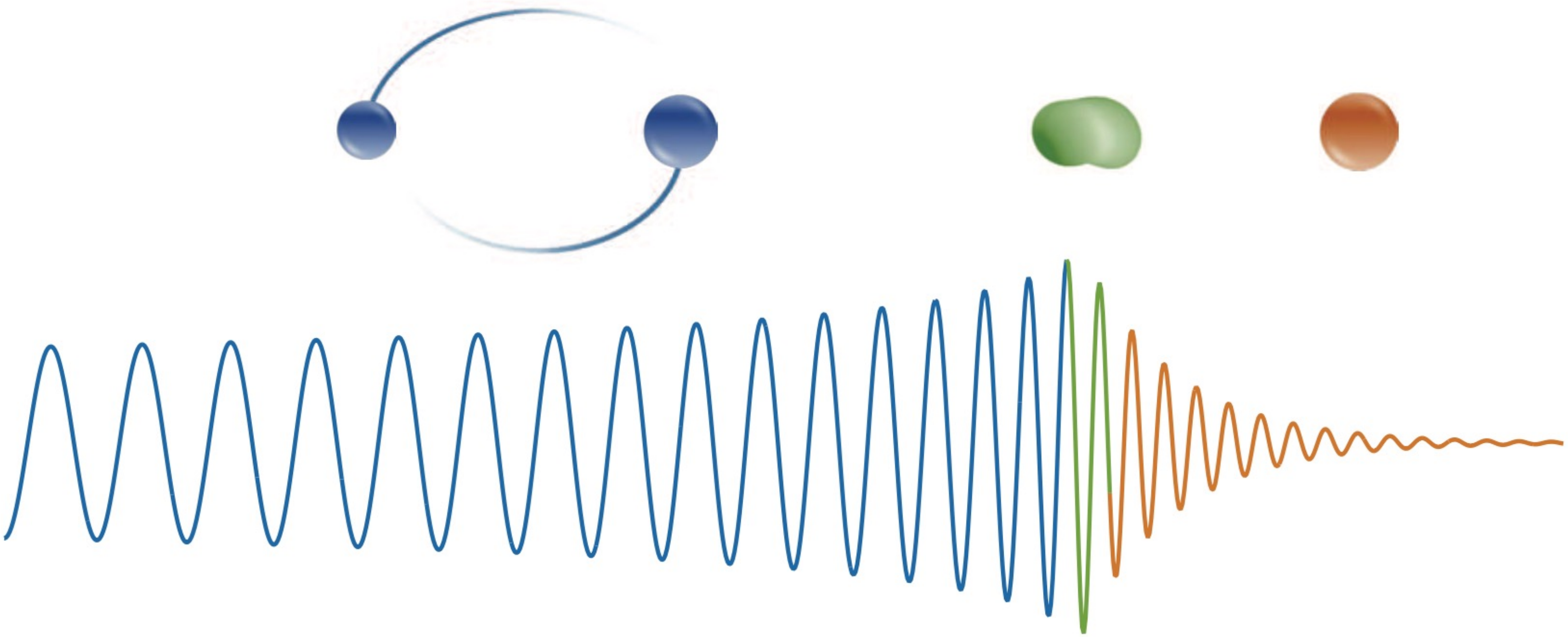


Tests of Gravity with Gravitational Waves

1-1. Parameterized tests

1-2. No-hair tests (inspiral)

2-1. No-hair tests (ringdown)



3-1. Hawking's area law

3-2. Inspiral-merger-ringdown consistency tests

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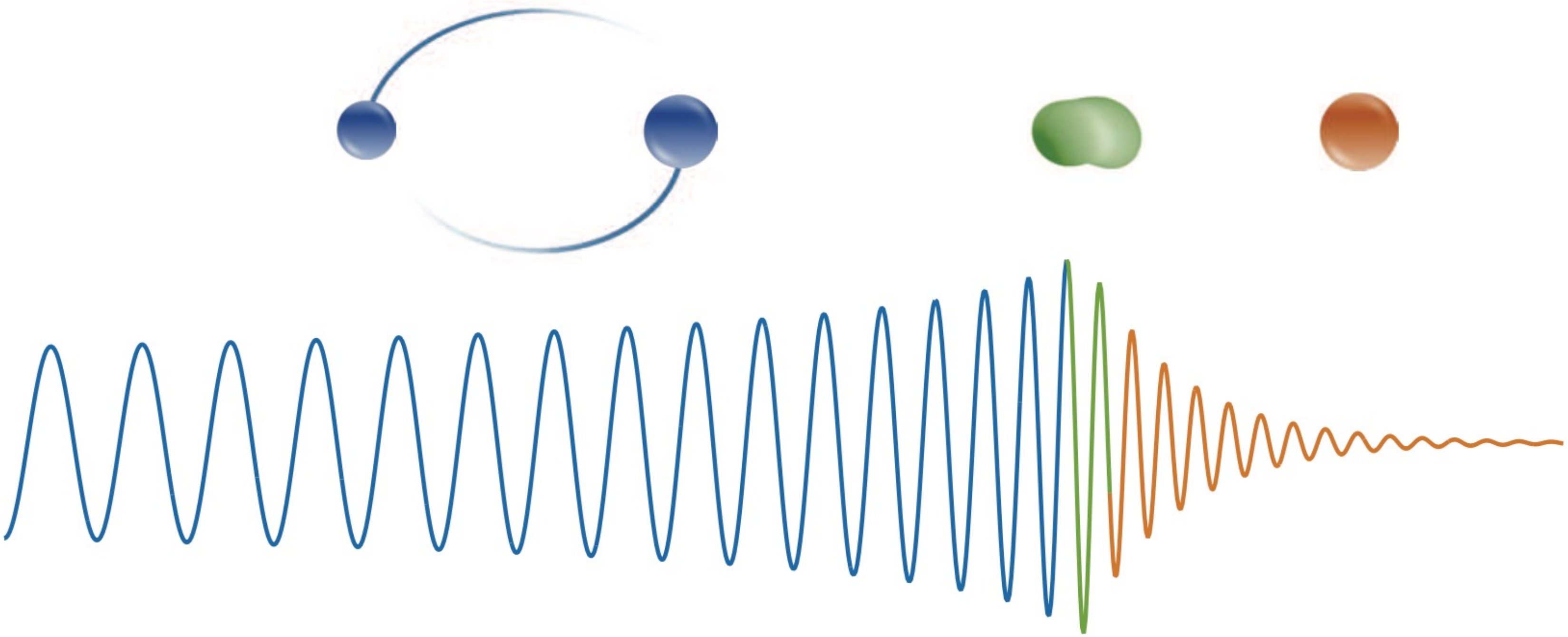

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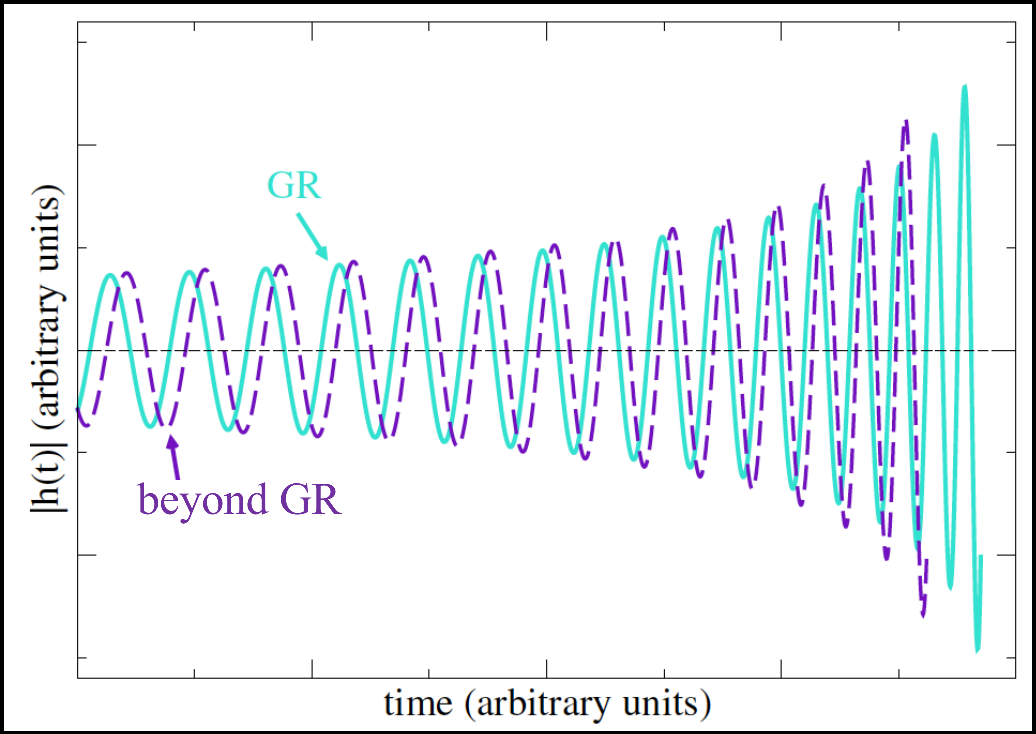
parameterized post-Einsteinian (ppE) Formalism



[Yunes & Pretorius (2009)]
[LVC, PRL 116, 221101 (2016)]

waveform phase:

ppE parameter

relative velocity

nth post-Newton (PN) correction

$$\Psi^{(\mathrm{insp})} = \Psi^{(\mathrm{insp})}_{\mathrm{GR}} + \beta\,(v/c)^{2n-5}$$

PN approximation:

$$v/c \ll 1$$

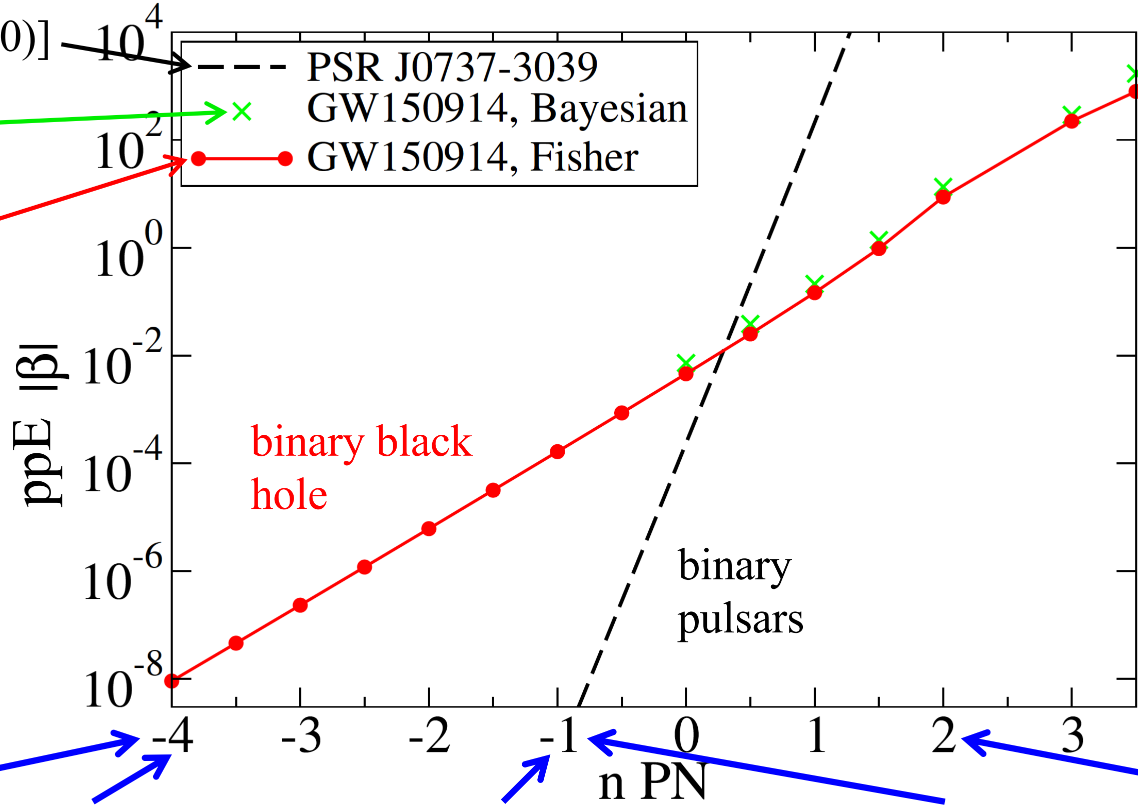
Kent Yagi

Parameterized tests with GW150914

[Yunes & Hughes (2010)]

[LIGO-Virgo Collaboration (2016)]

[Yunes, KY & Pretorius (2016)]



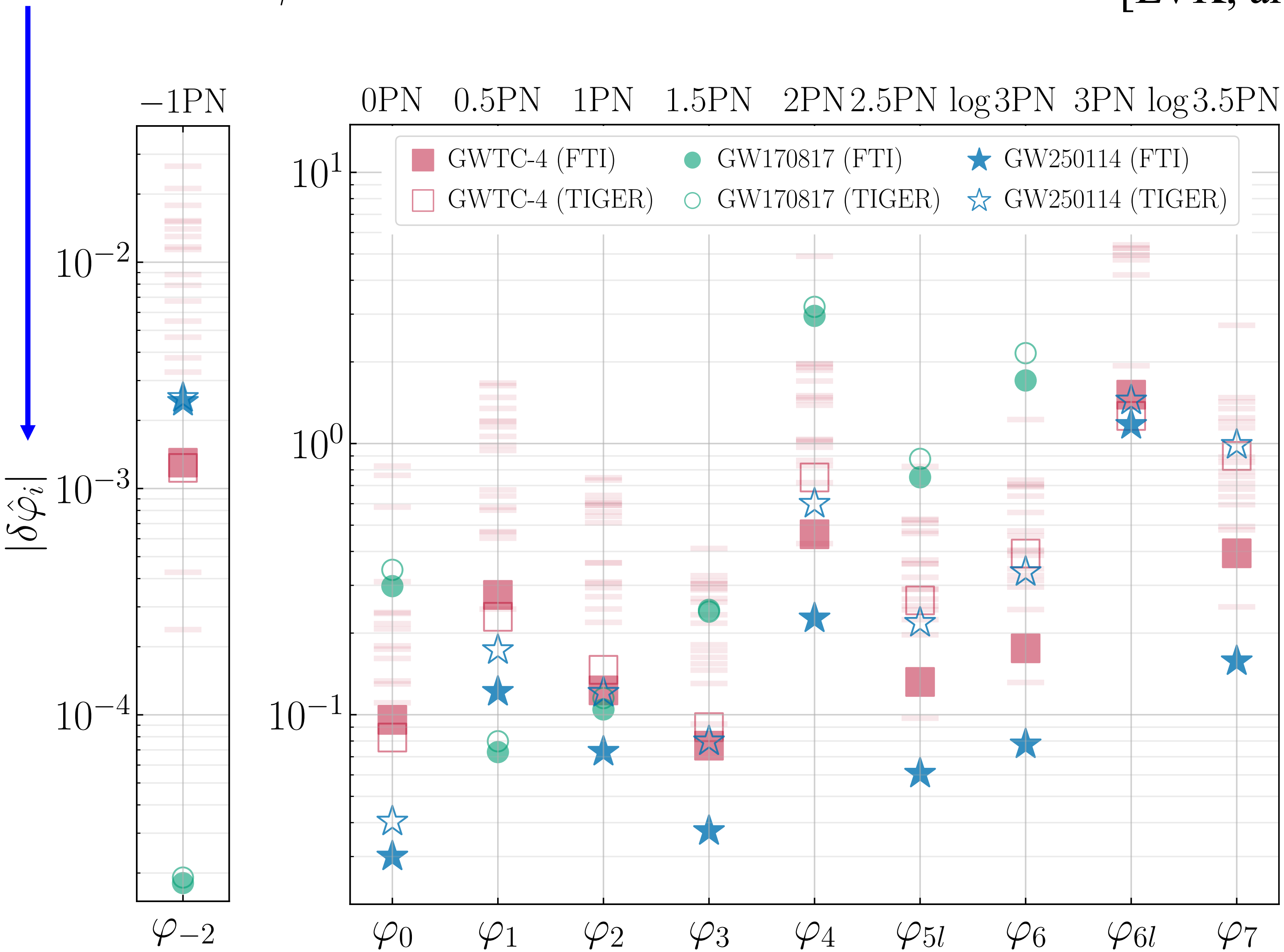
$$\delta\Psi = \beta\, v^{2n-5}$$

extra dimension	time varying G	scalar monopole activation	vector field activation	scalar dipole activation
4D	equivalence principle	equivalence principle	Lorentz invariance	parity invariance

Parameterized tests with GWTC-4

related to PPE β

[LVK, arXiv:2509.08099]



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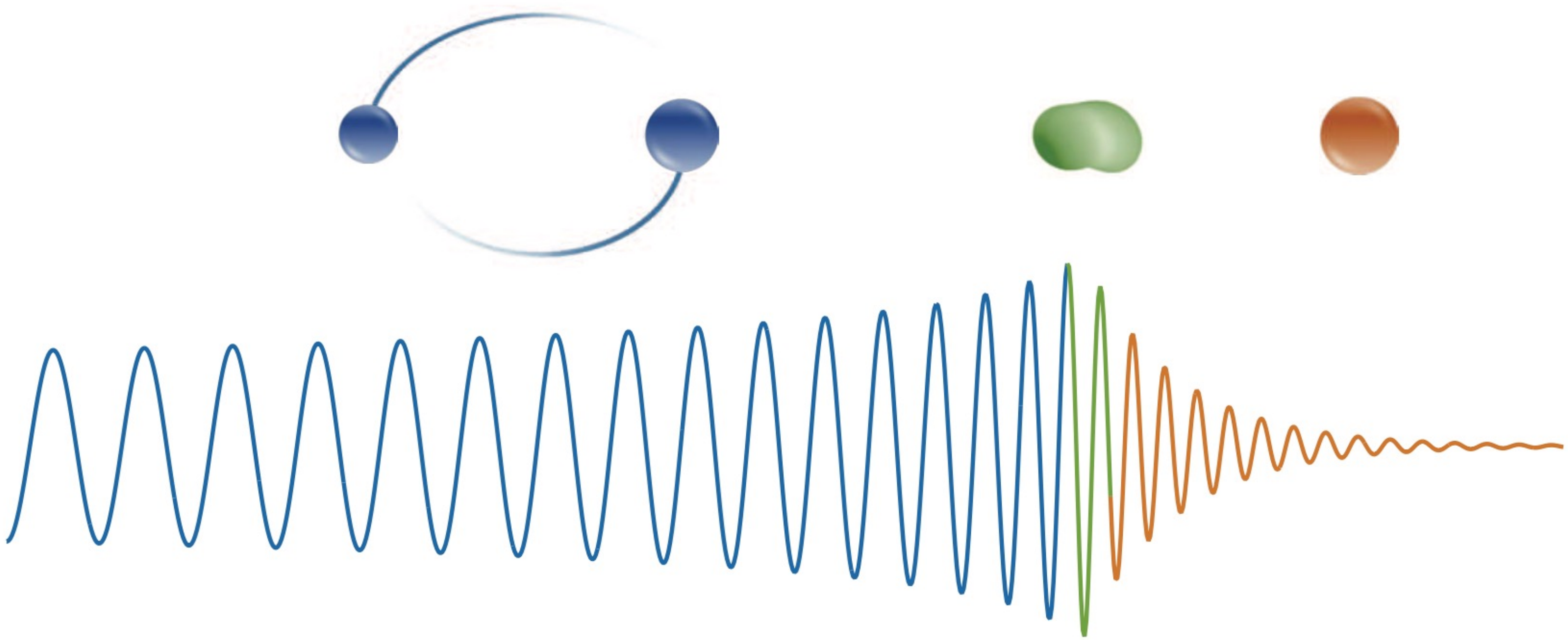

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Black Hole No-Hair Property

Astrophysical (Kerr) black holes have only **2 hairs**:

- mass M
- spin $\chi \; (= a/M)$

<u>Multiple Moments</u>

$$M_\ell + i S_\ell = M (ia)^\ell$$

e.g. quadrupole moment $(\ell = 2)$

$$M_2 = -M a^2$$

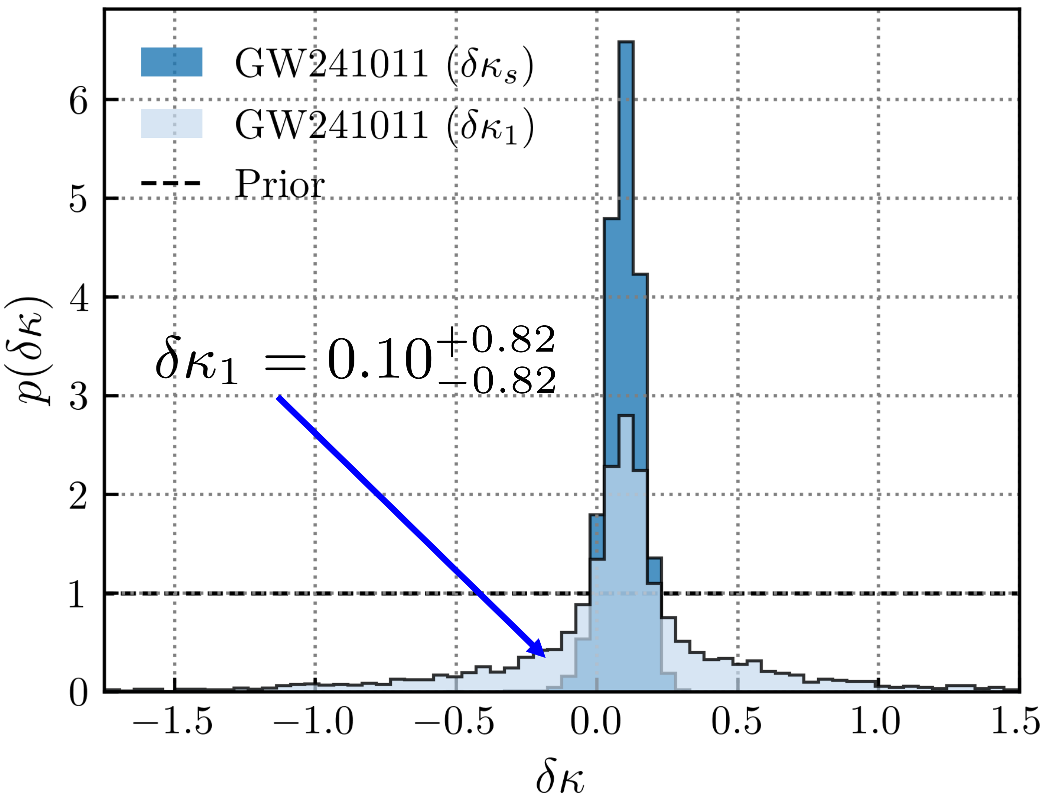
No-hair Test with GW241011

$$\kappa \equiv -M_2/(Ma^2) \qquad \kappa_{\mathrm{Kerr}} = 1$$

[LVK, arXiv:2510.26931]

$$\kappa_A = 1 + \delta\kappa_A$$

$$\kappa_s = (\kappa_1 + \kappa_2)/2$$



most stringent bound on $\delta\kappa_1$

- ✓ high SNR (~35)
- ✓ large primary spin
- ✓ unequal mass ratio

rules out certain exotic compact object, like massive boson stars

$$\kappa \sim 10 - 150$$

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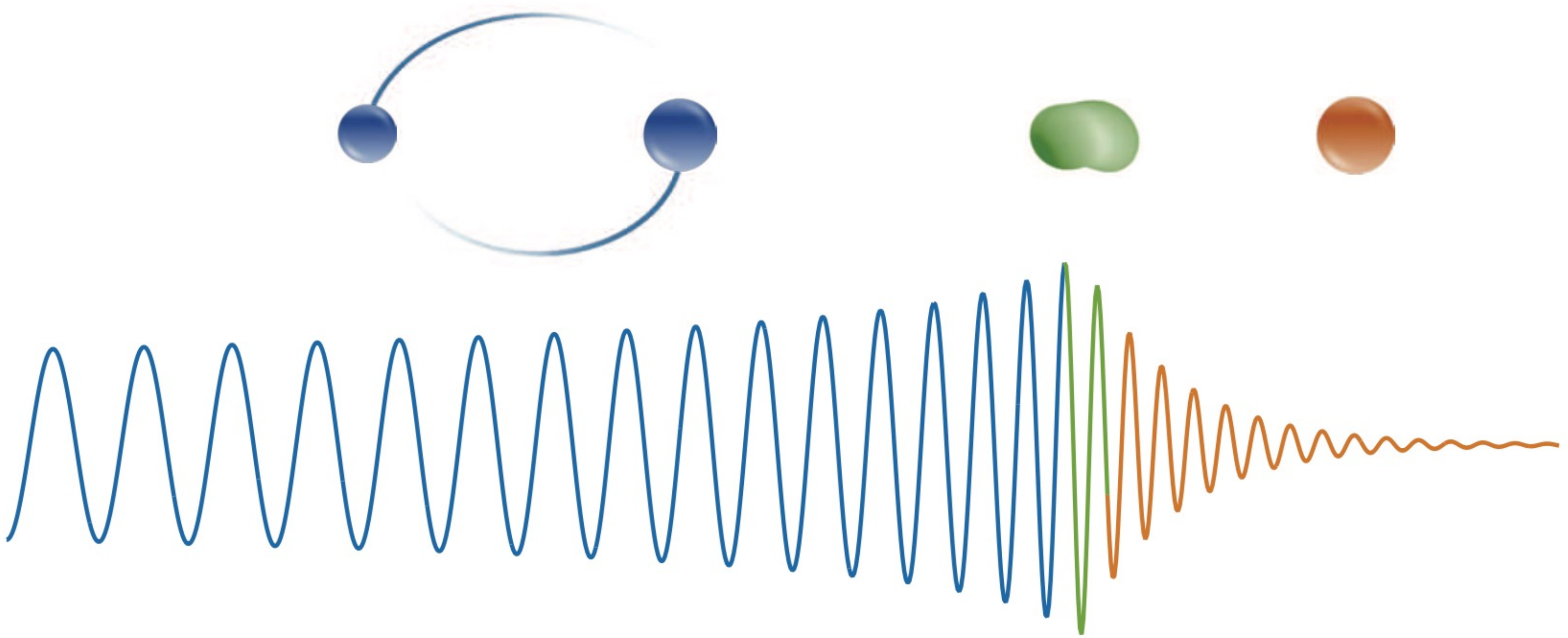

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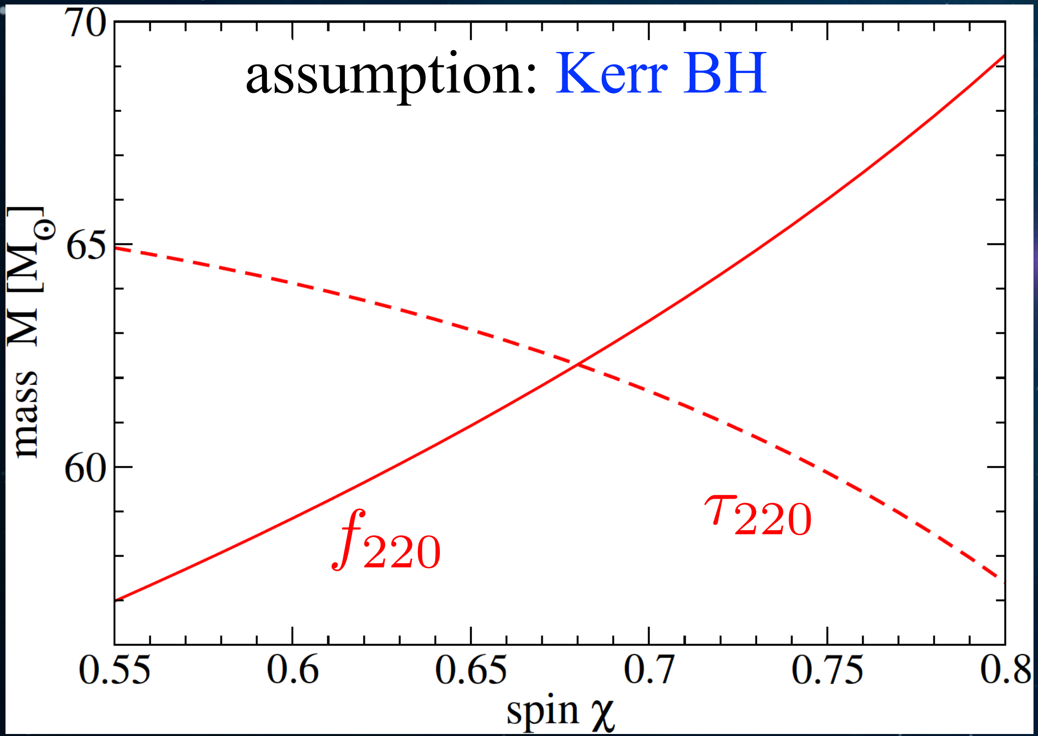
Black Hole Spectroscopy

black hole no-hair property

ringdown frequency: $f_{\ell mn}(M,\chi)$

damping time: $\tau_{\ell mn}(M,\chi)$



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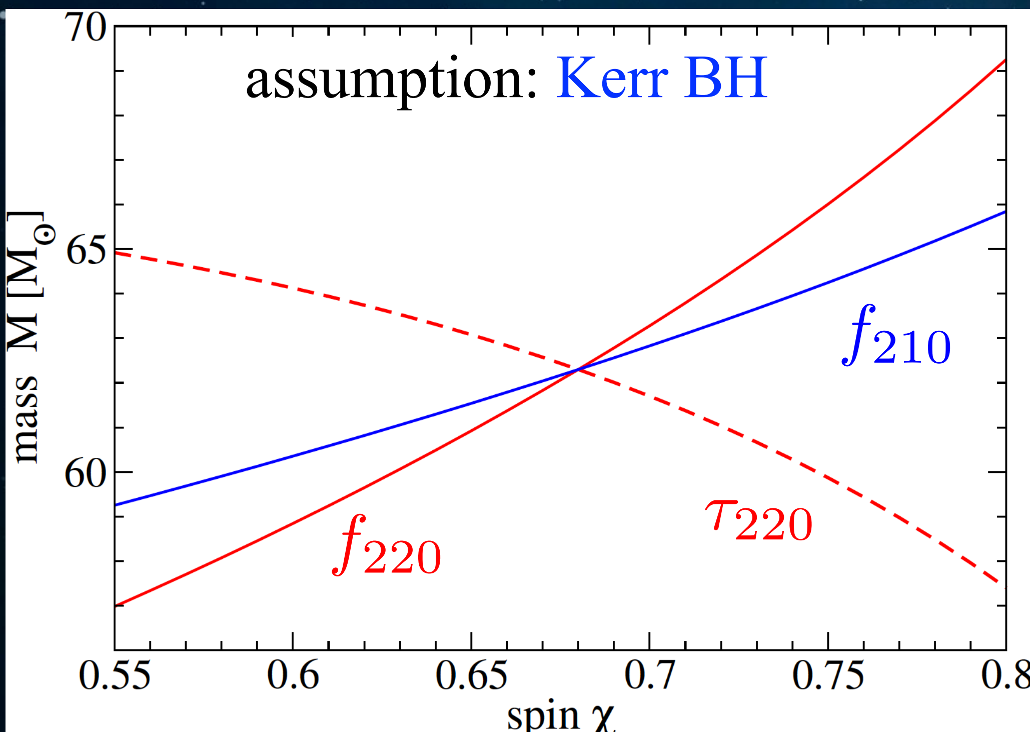
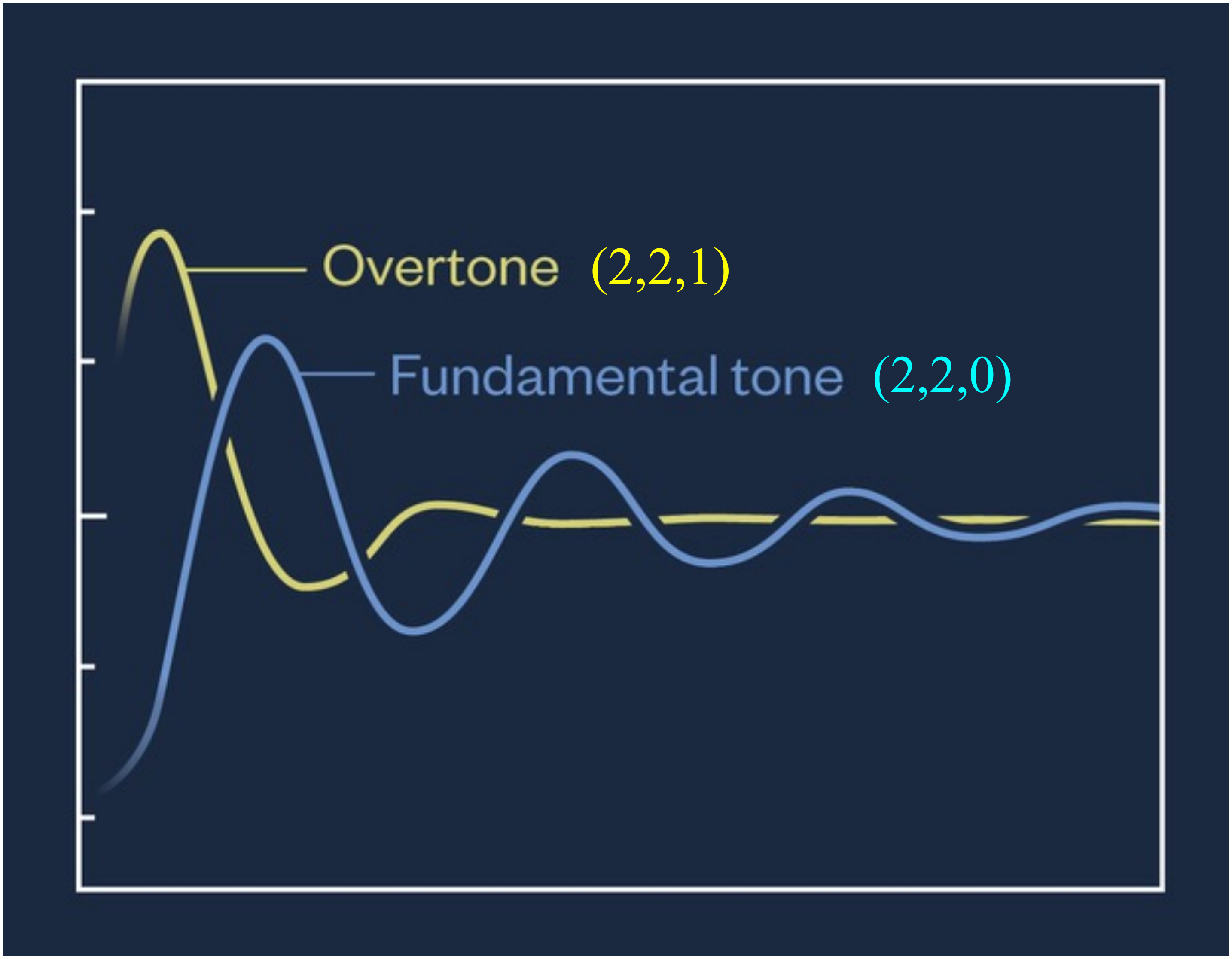
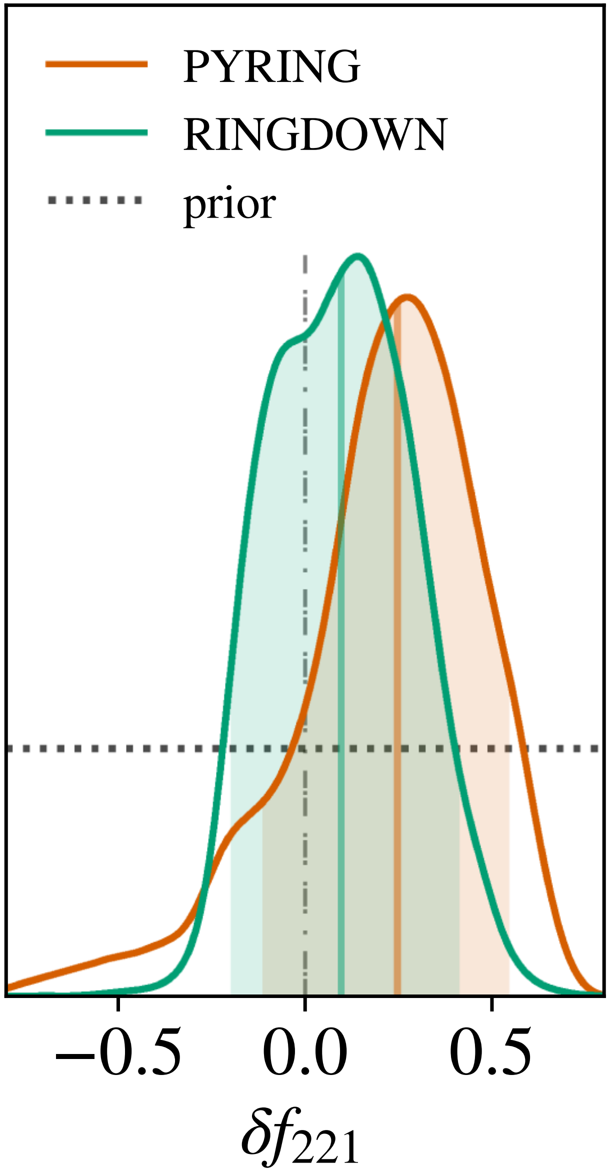


Overtone Detection with GW250114!



No-hair Test with GW250114



[LVK, arXiv:2509.08054]

$$f_{221} = f_{221}^{\mathrm{Kerr}}\boxed{(M_f, \chi_f)}\exp(\delta f_{221})$$

from fundamental (2,2,0) mode

$$\boxed{\delta f_{221} = 0.1^{+0.3}_{-0.3}}$$

consistent with Kerr overtone frequency to ~30%

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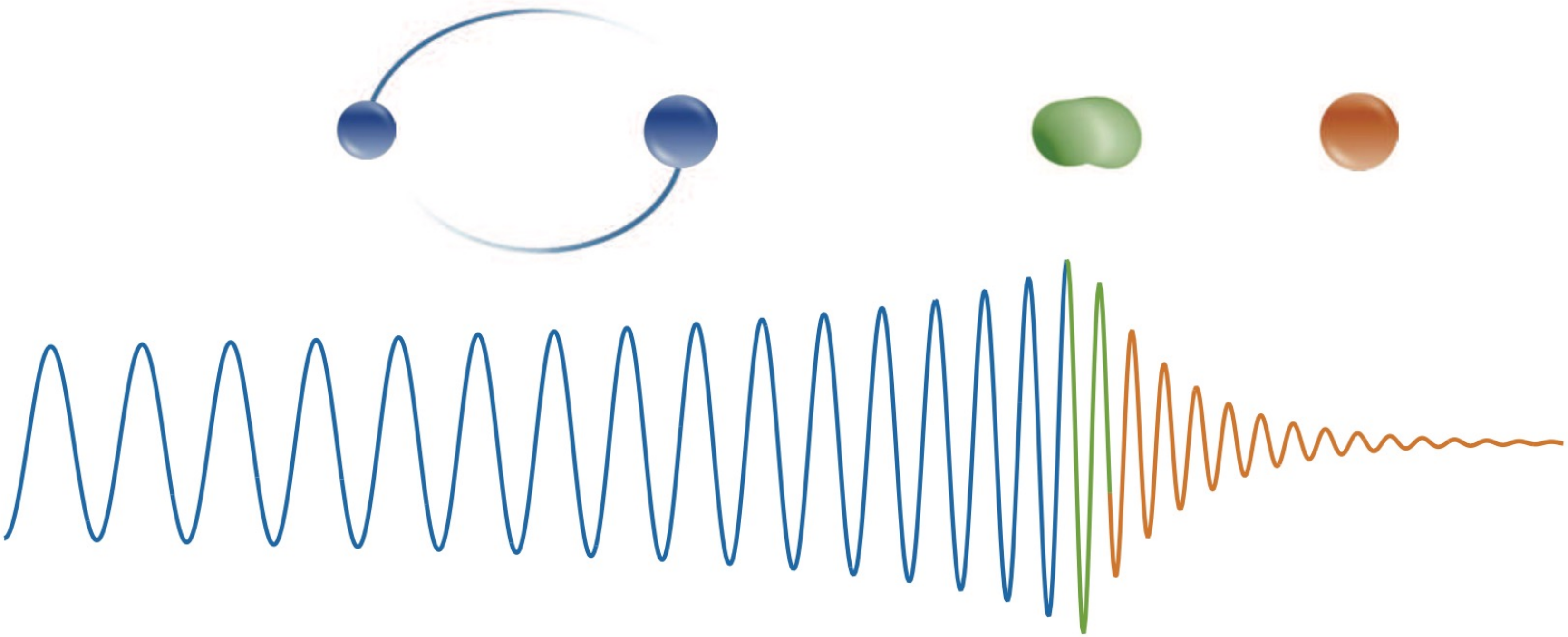

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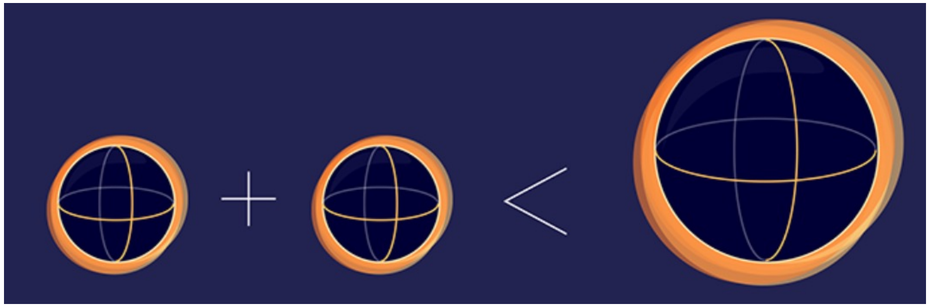
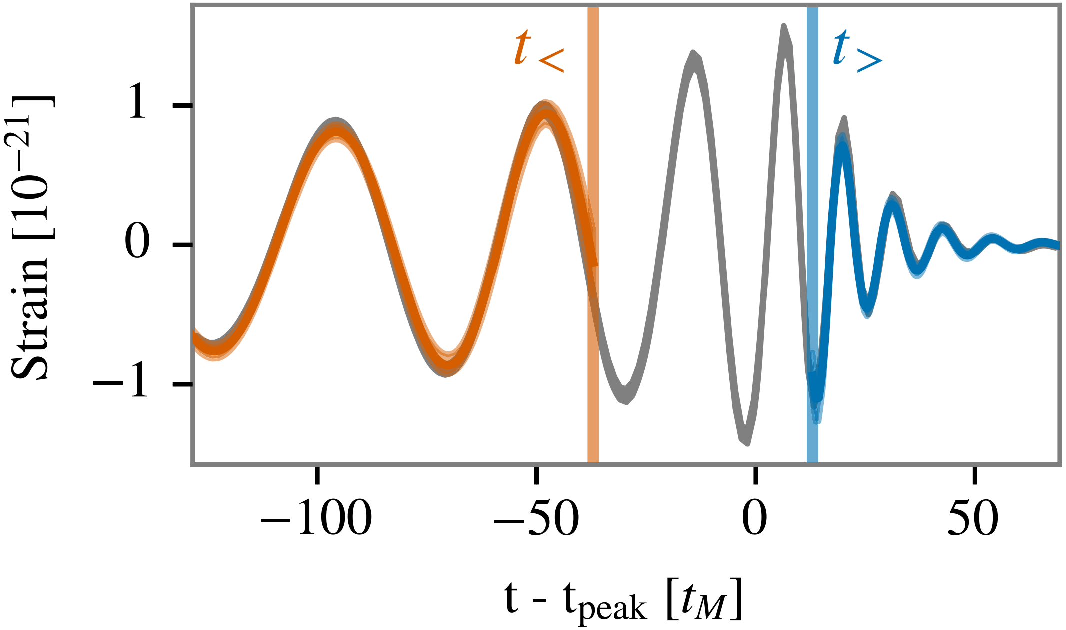
Hawking's Area Law with GW250114

[LVK, arXiv: 2509.08054]





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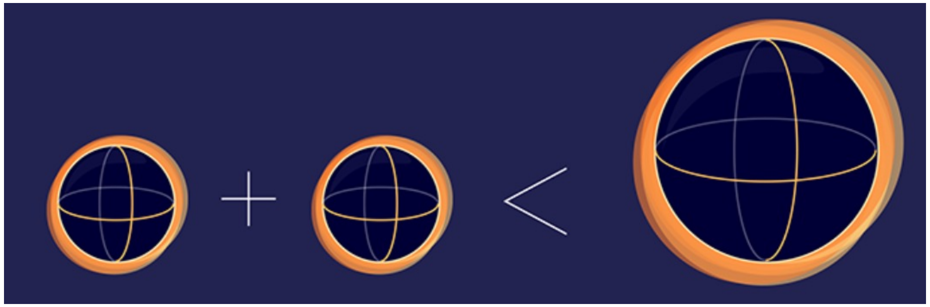

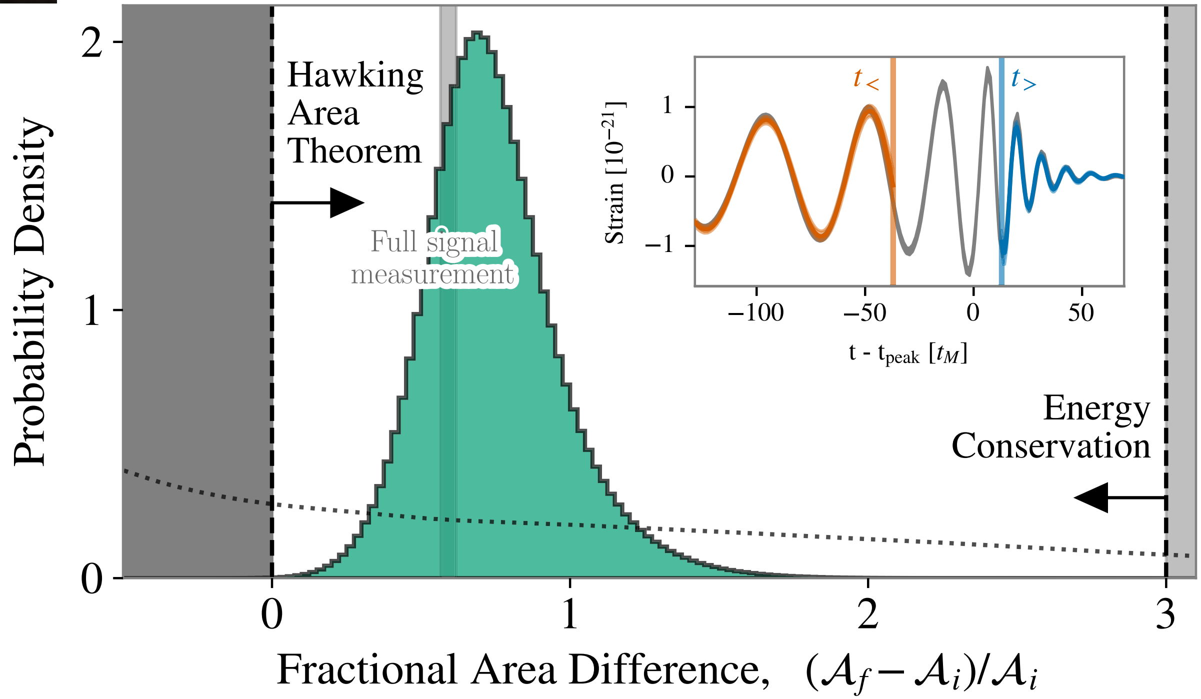

Hawking was right!

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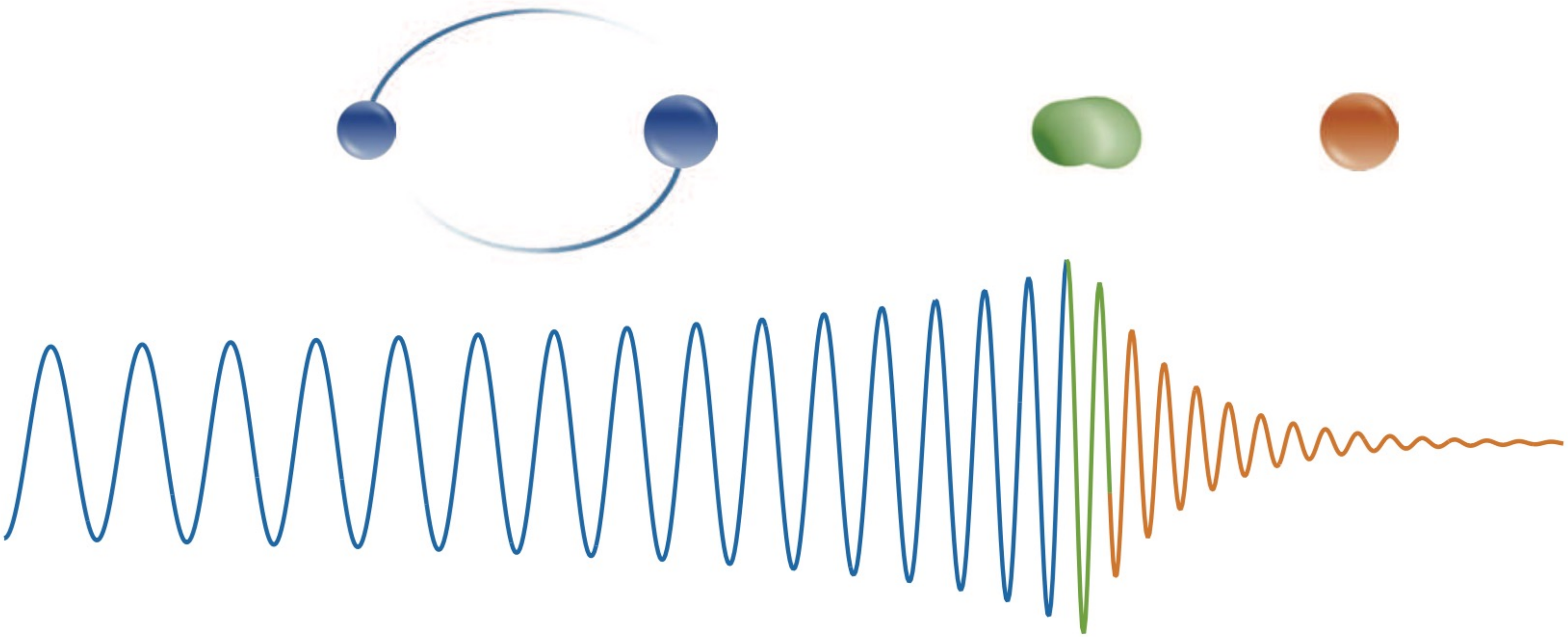

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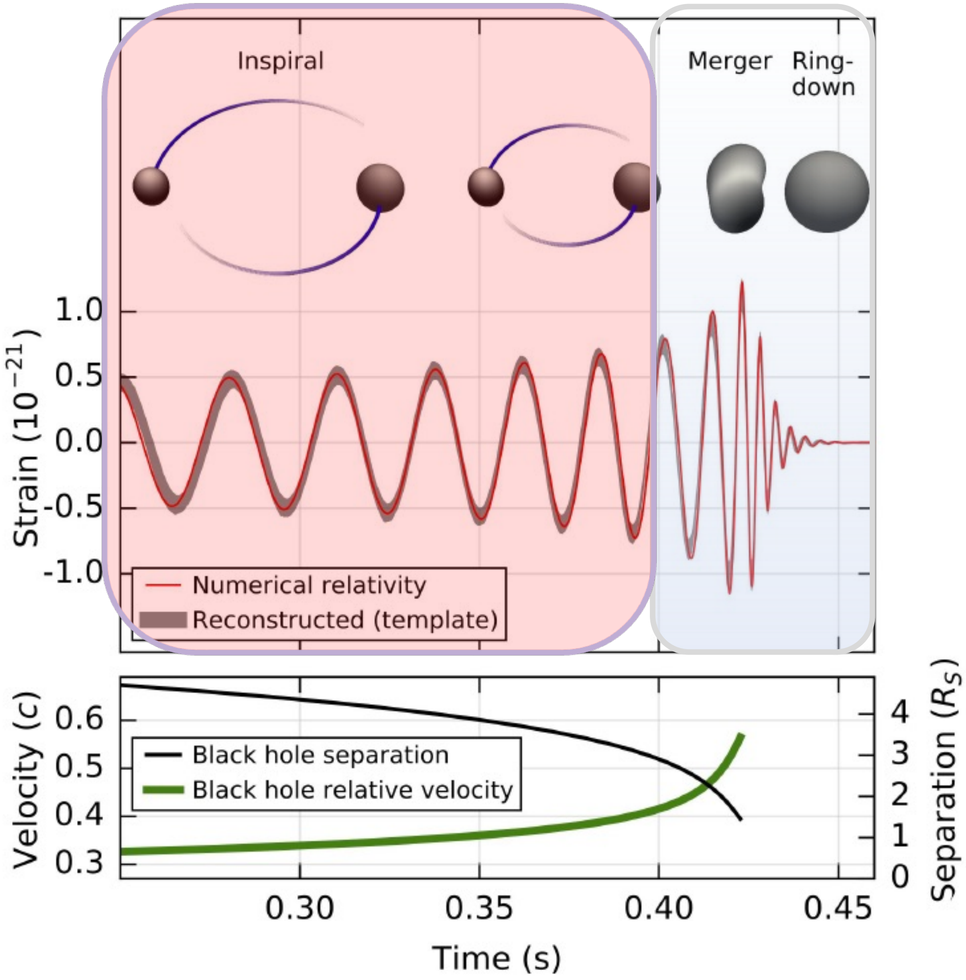
Inspiral-Merger-Ringdown Consistency Tests

initial masses & spins

$$(m_1, m_2, \chi_1, \chi_2) \Rightarrow (M_f, \chi_f)$$

final mass & spin

numerical relativity
assuming GR



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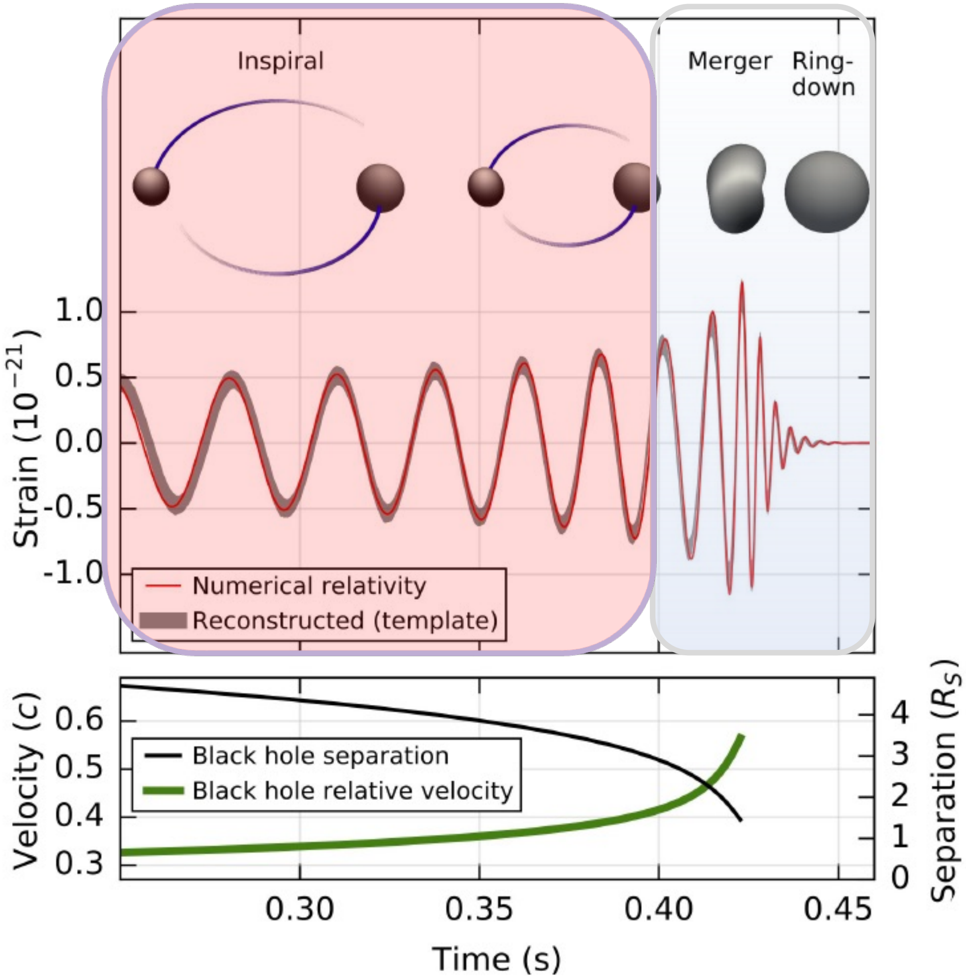

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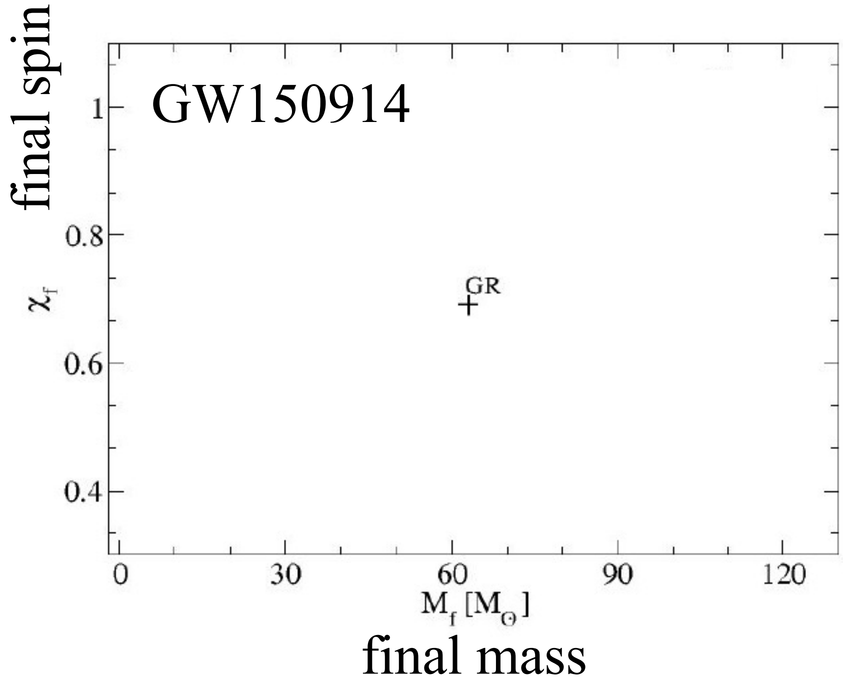

Fisher analysis

[credit: Zack Carson]

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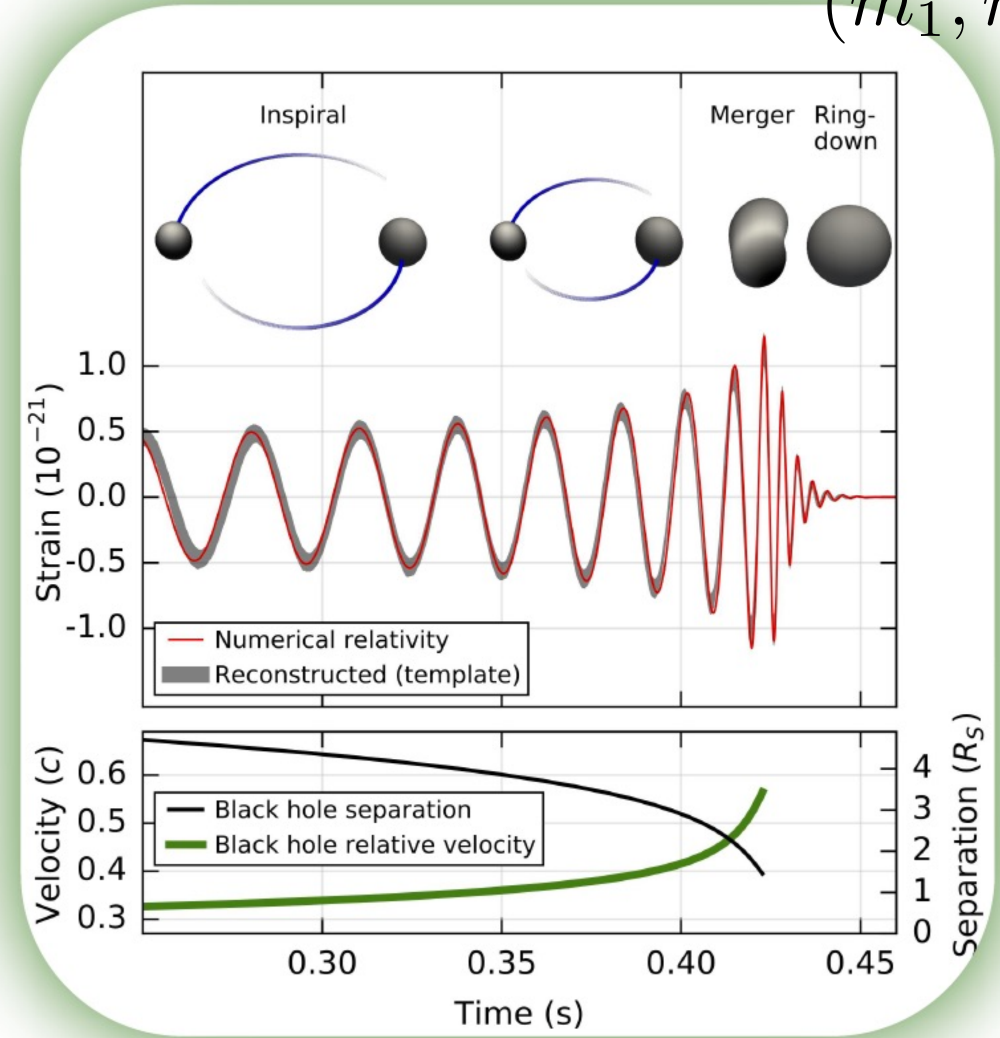

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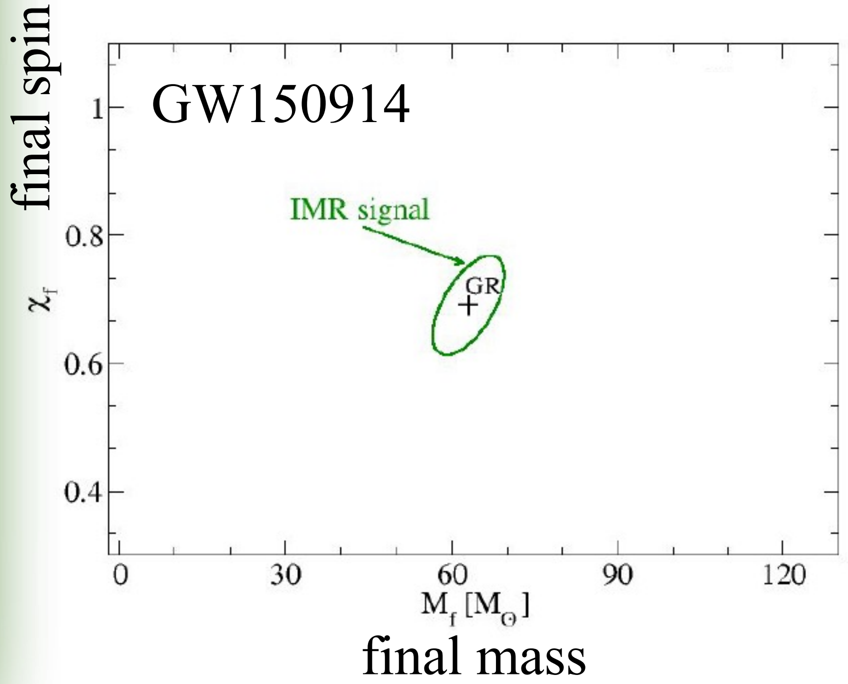

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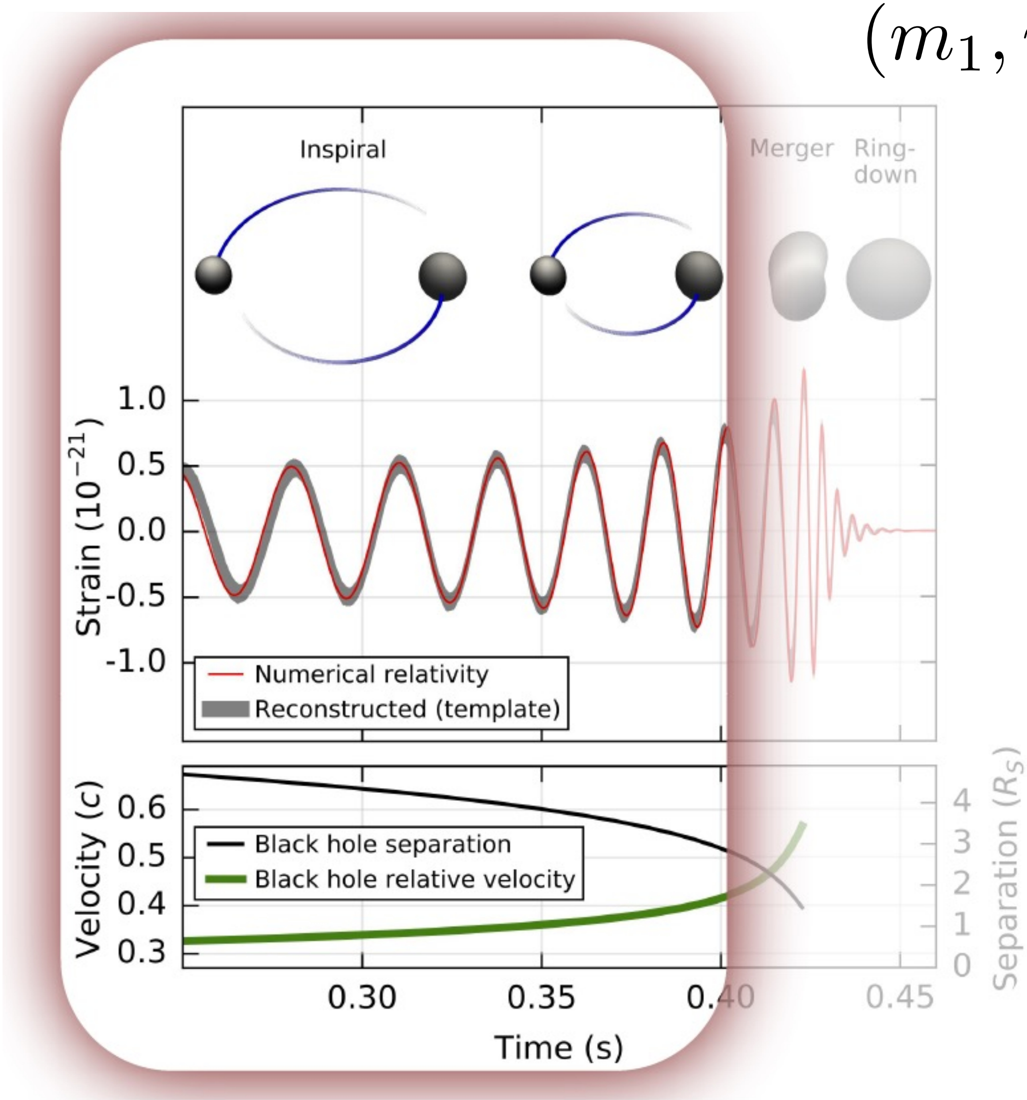

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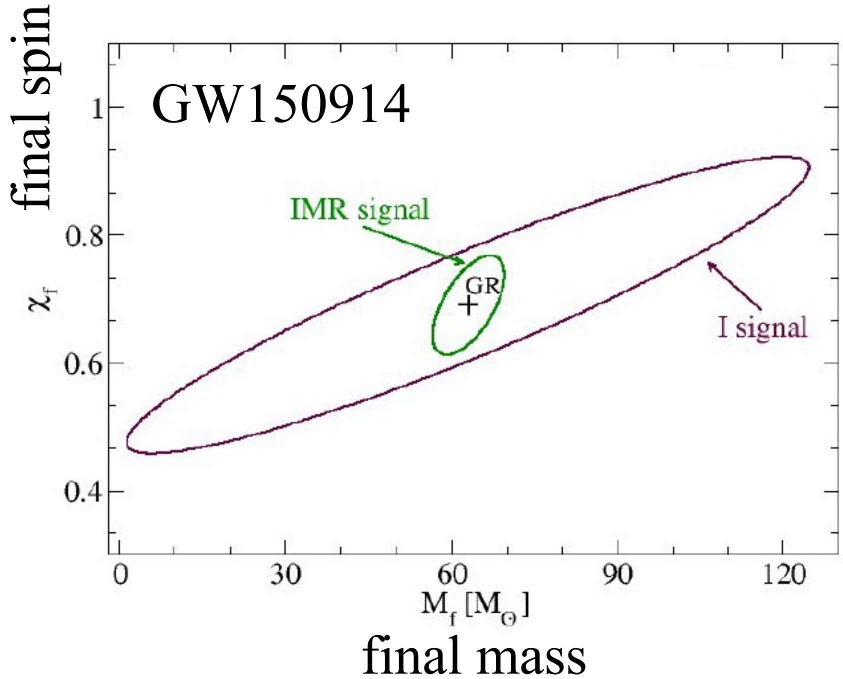

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initial masses & spins $(m_1, m_2, \chi_1, \chi_2)$ → final mass & spin (M_f, χ_f)

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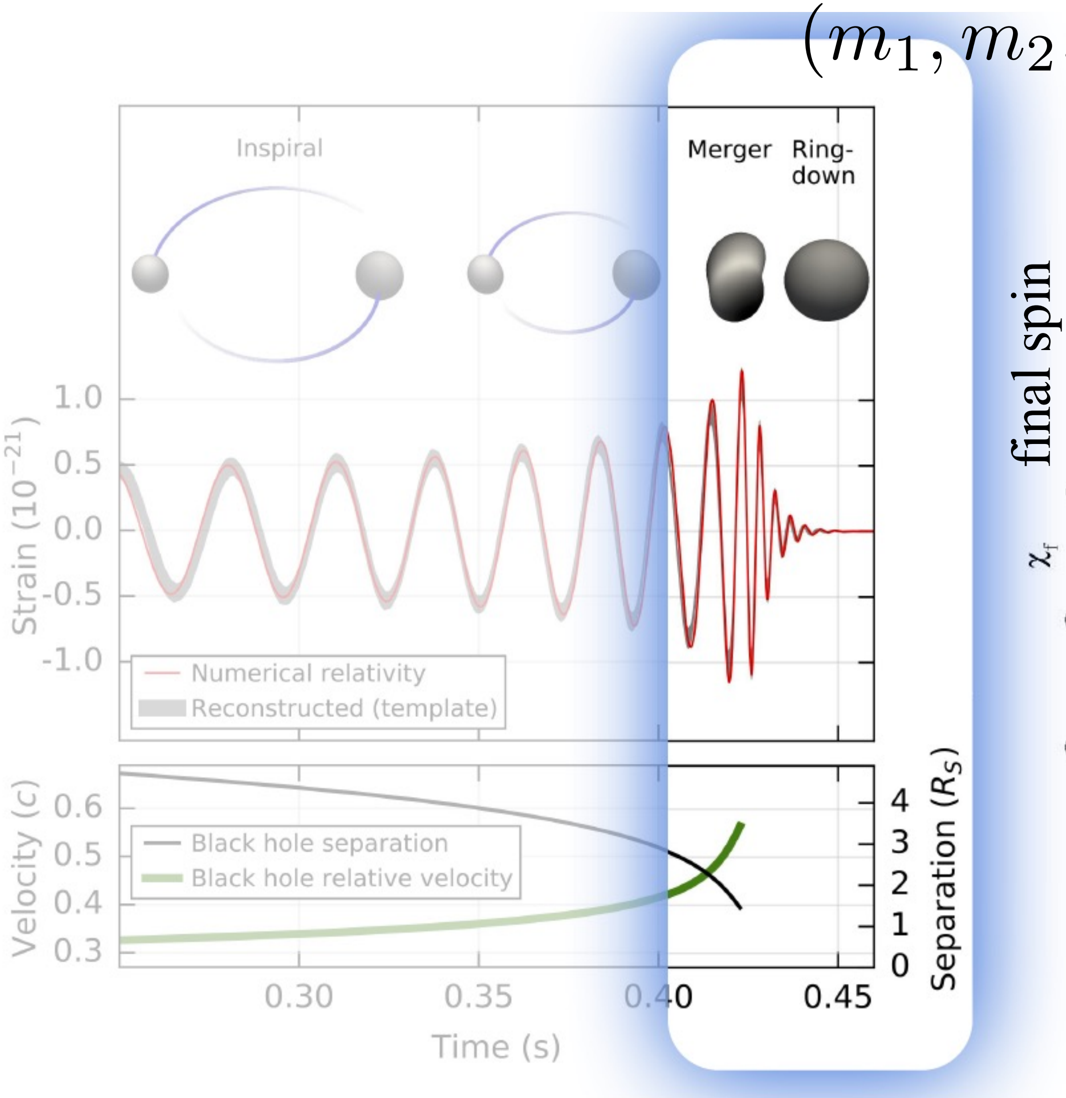
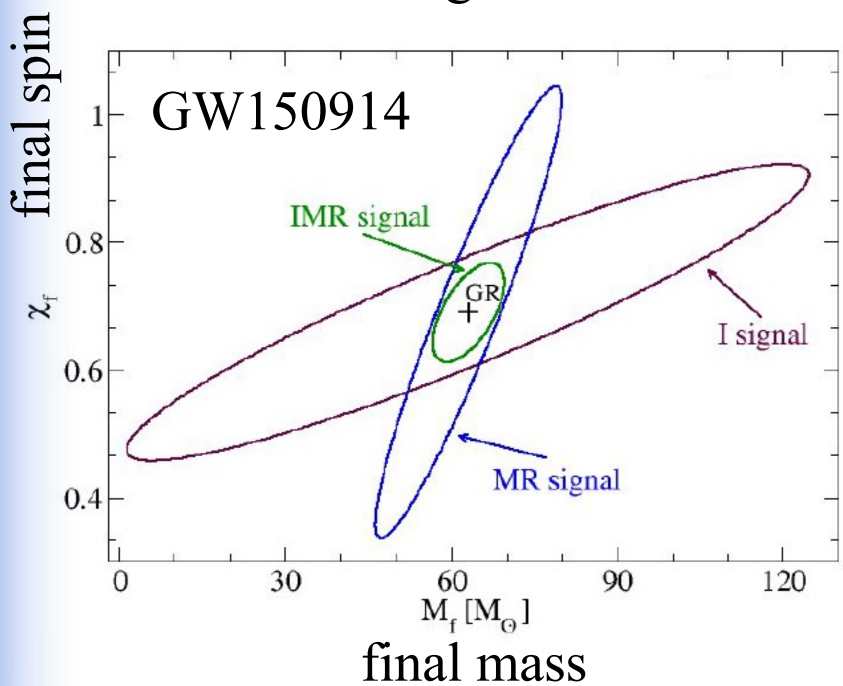
assuming GR





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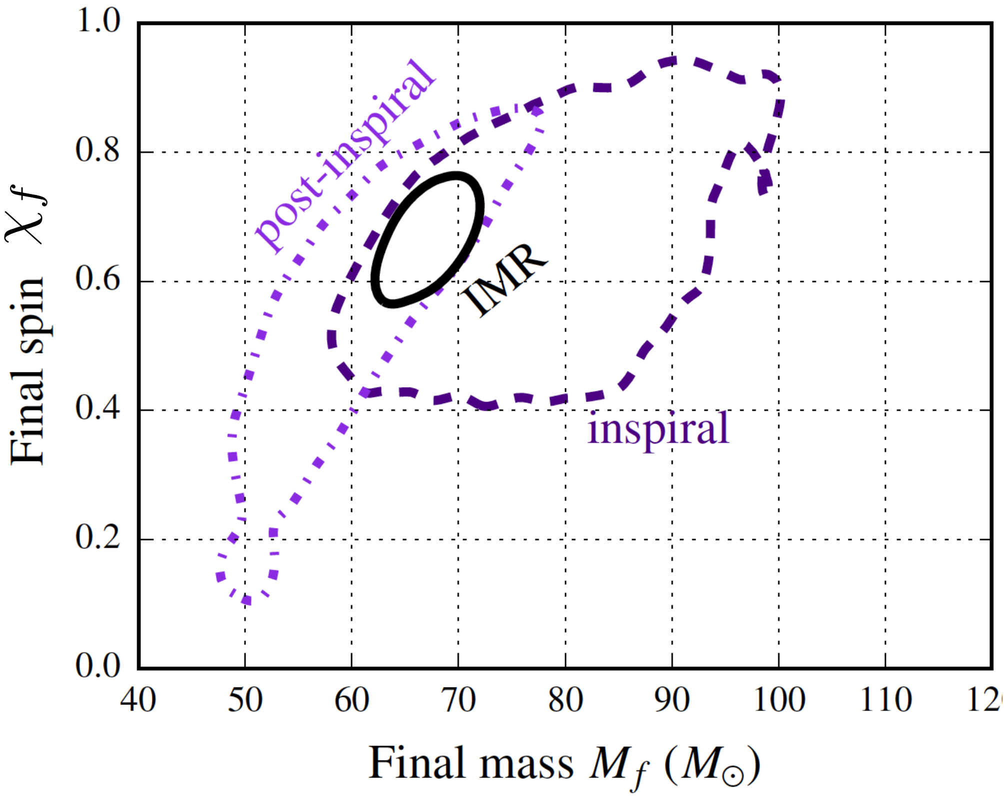
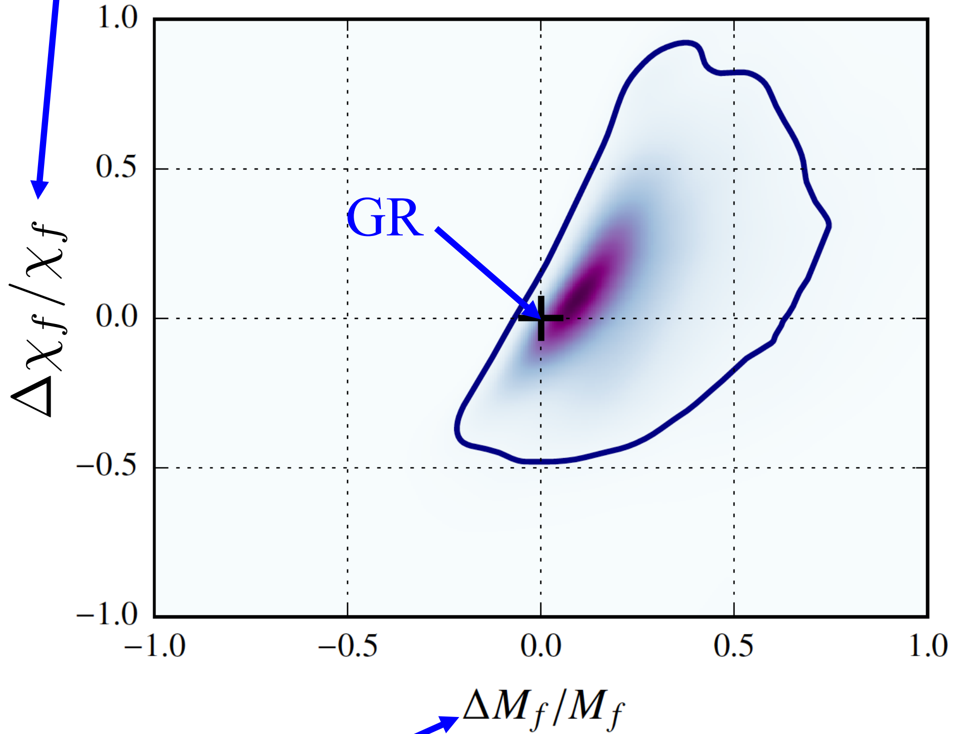
IMR Consistency Tests with GW150914

[LVC, PRL 116, 221101 (2016)]

Bayesian, actual data

$$\Delta\chi_f = \chi_f^{\mathrm{I}} - \chi_f^{\mathrm{MR}}$$

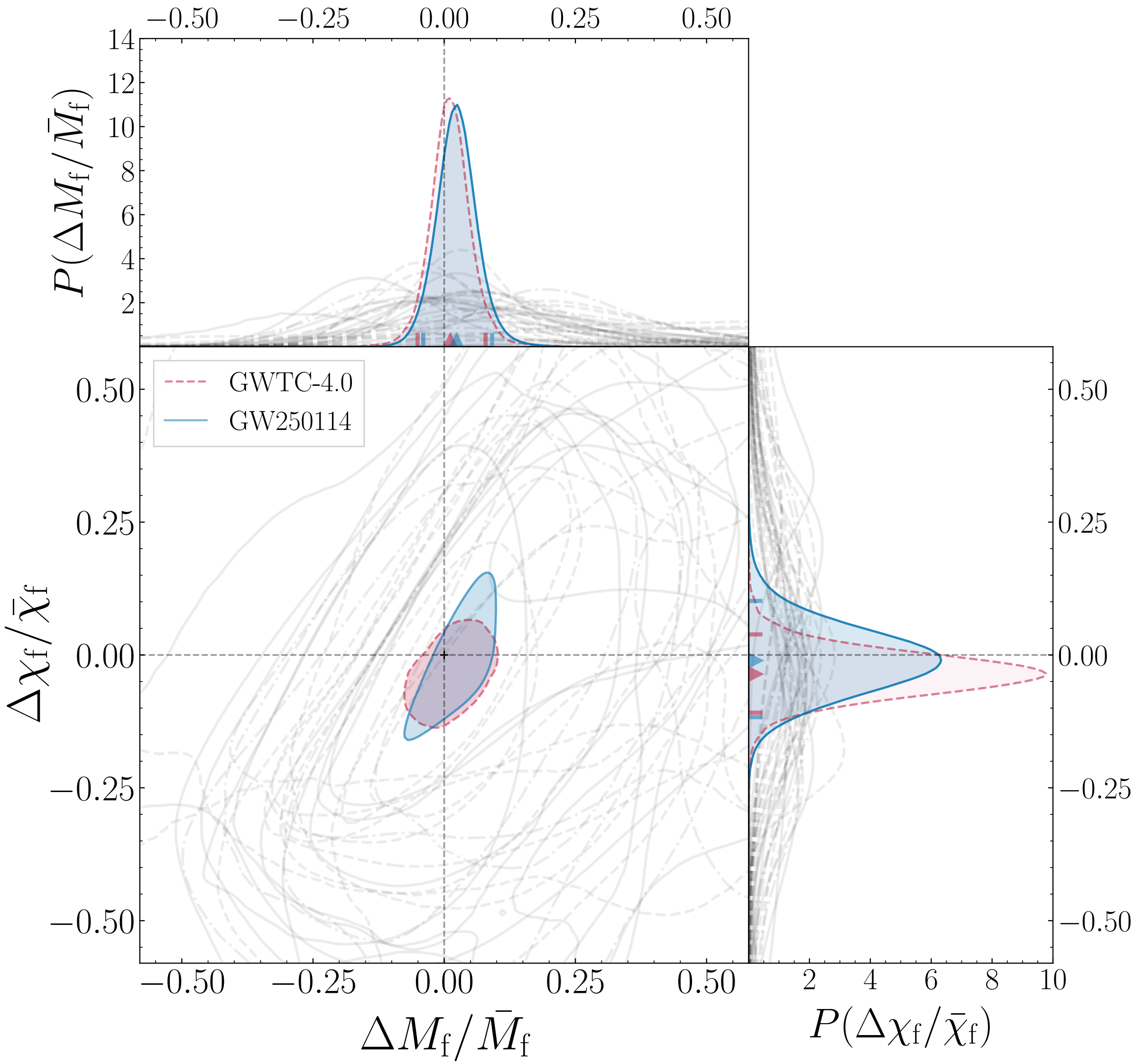




$$\Delta M_f = M_f^{\mathrm{I}} - M_f^{\mathrm{MR}}$$

IMR Consistency Tests with GWTC-4

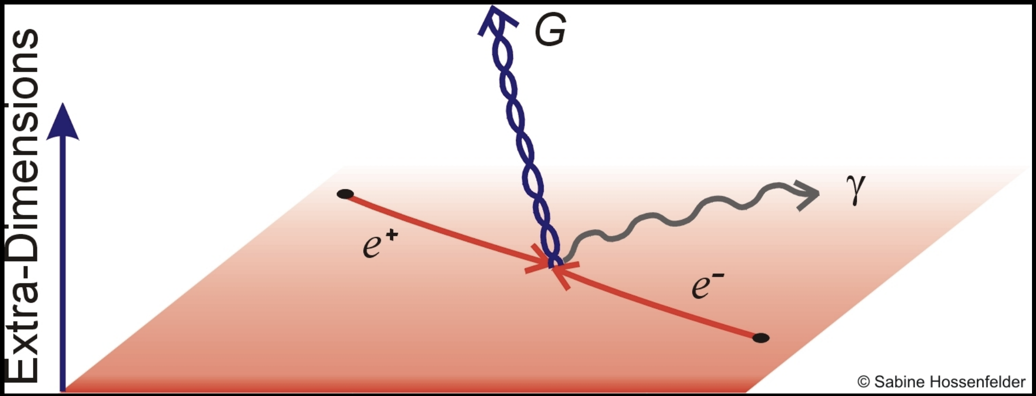
[LVK, arXiv:2509.08099]

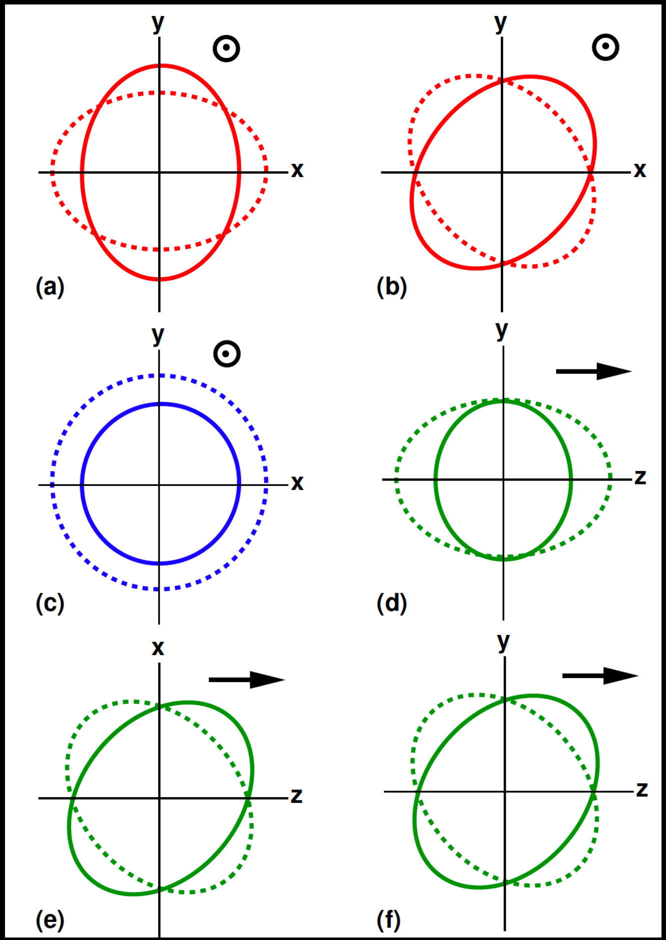


consistency can be checked to ~10% level for both final mass & spin!

Other Tests of GR with GWs

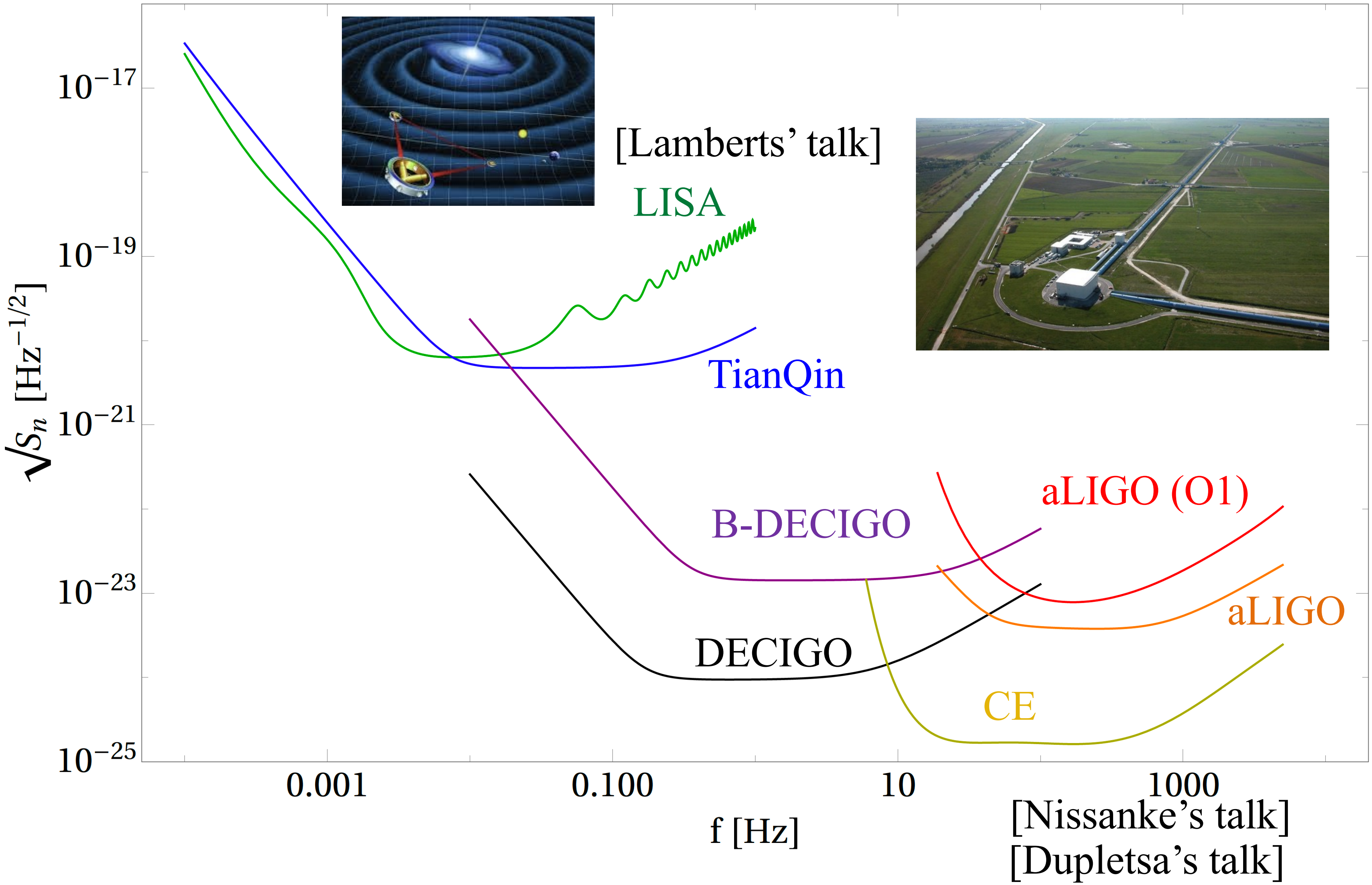
- ✓ residual signal-to-noise ratio
- ✓ non-GR polarization
- ✓ propagation speed of GWs
  dispersion relation of gravitons
- ✓ extra dimension
- ✓ …





Future Improvement

Future Detector Sensitivities



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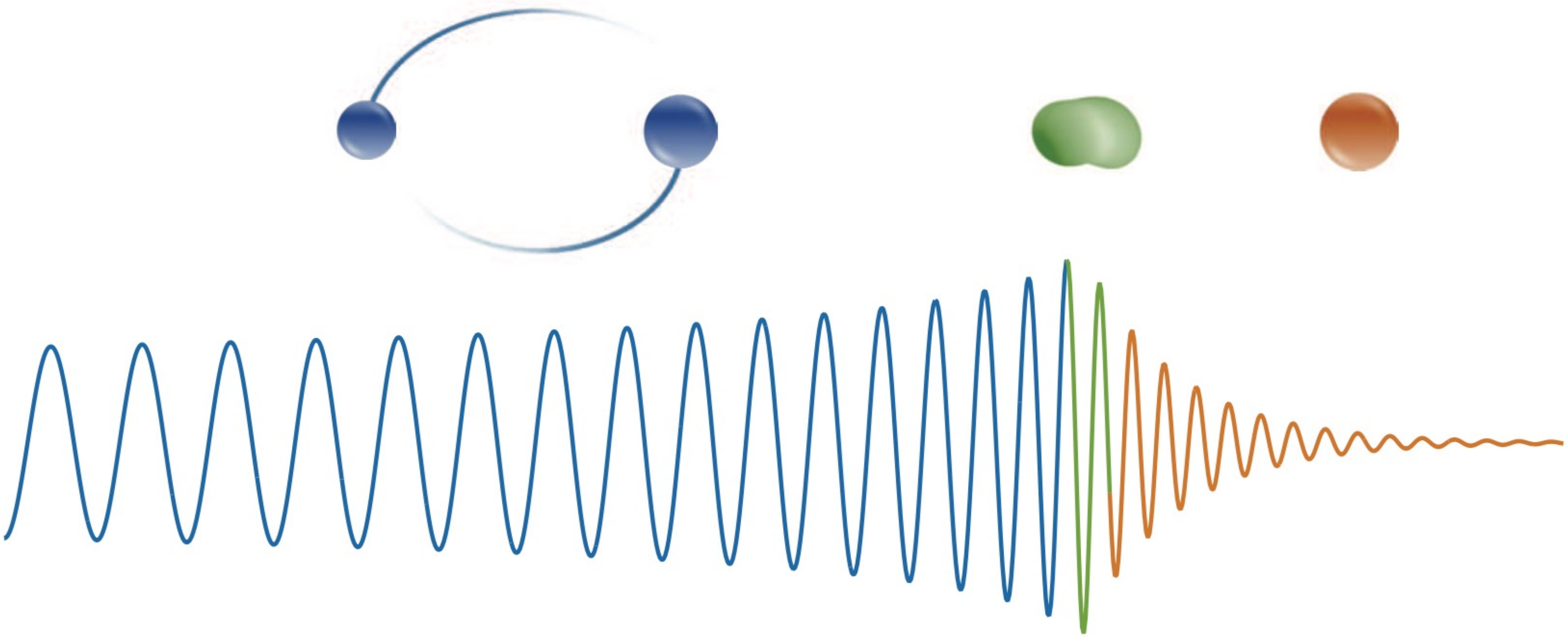

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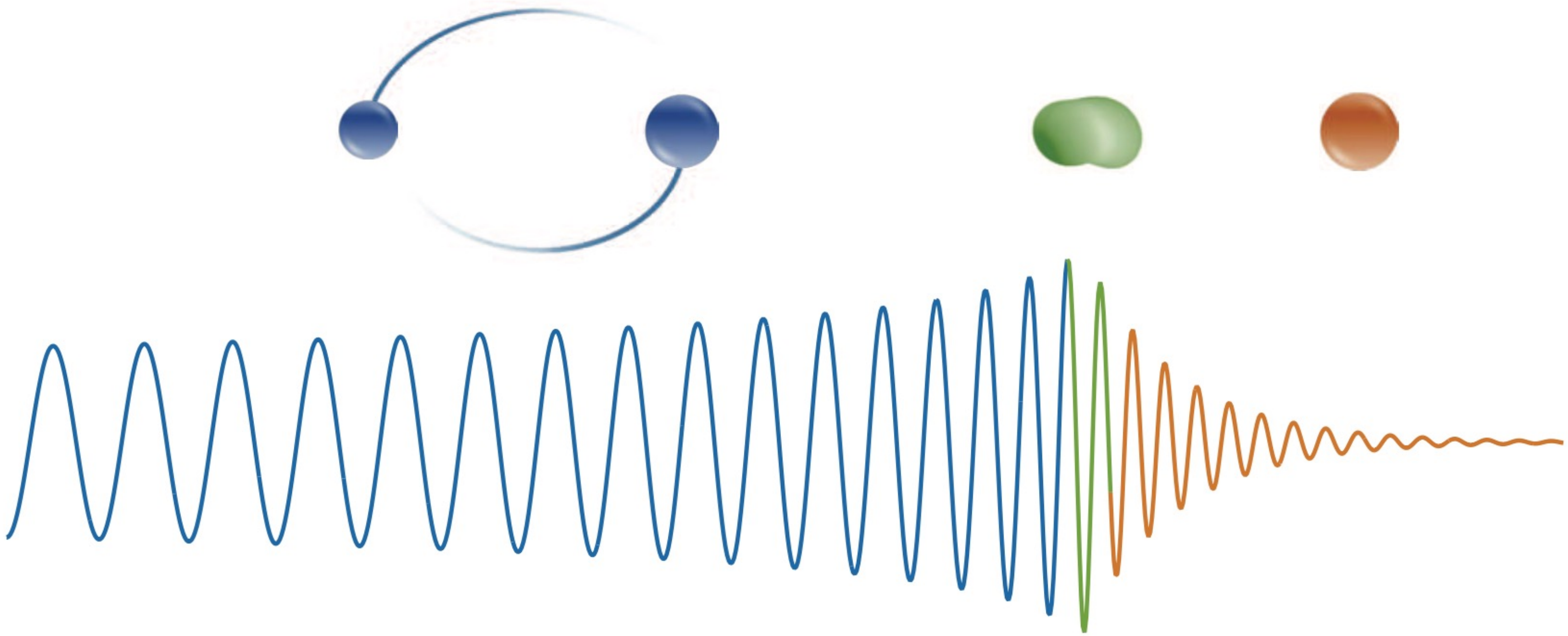

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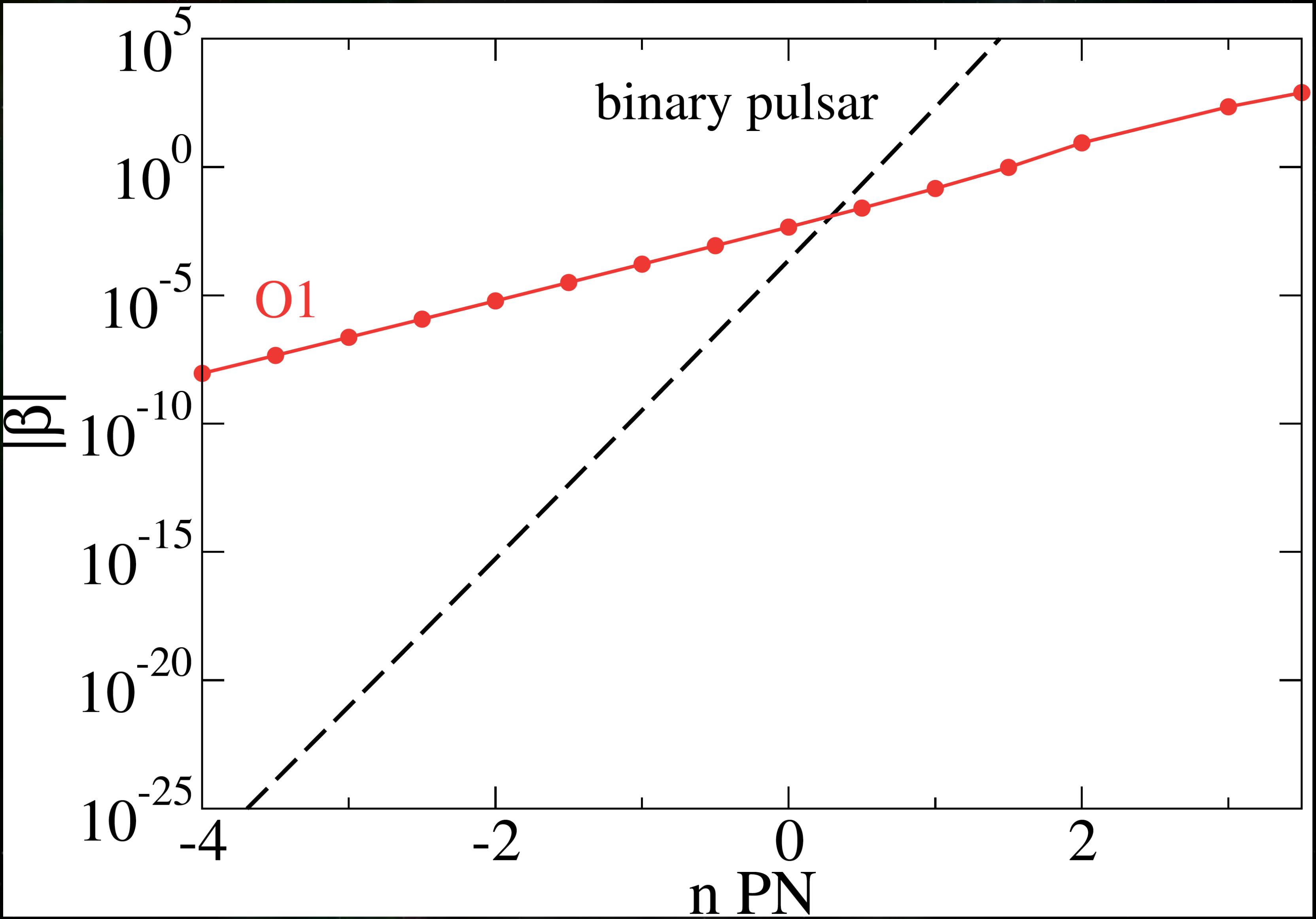
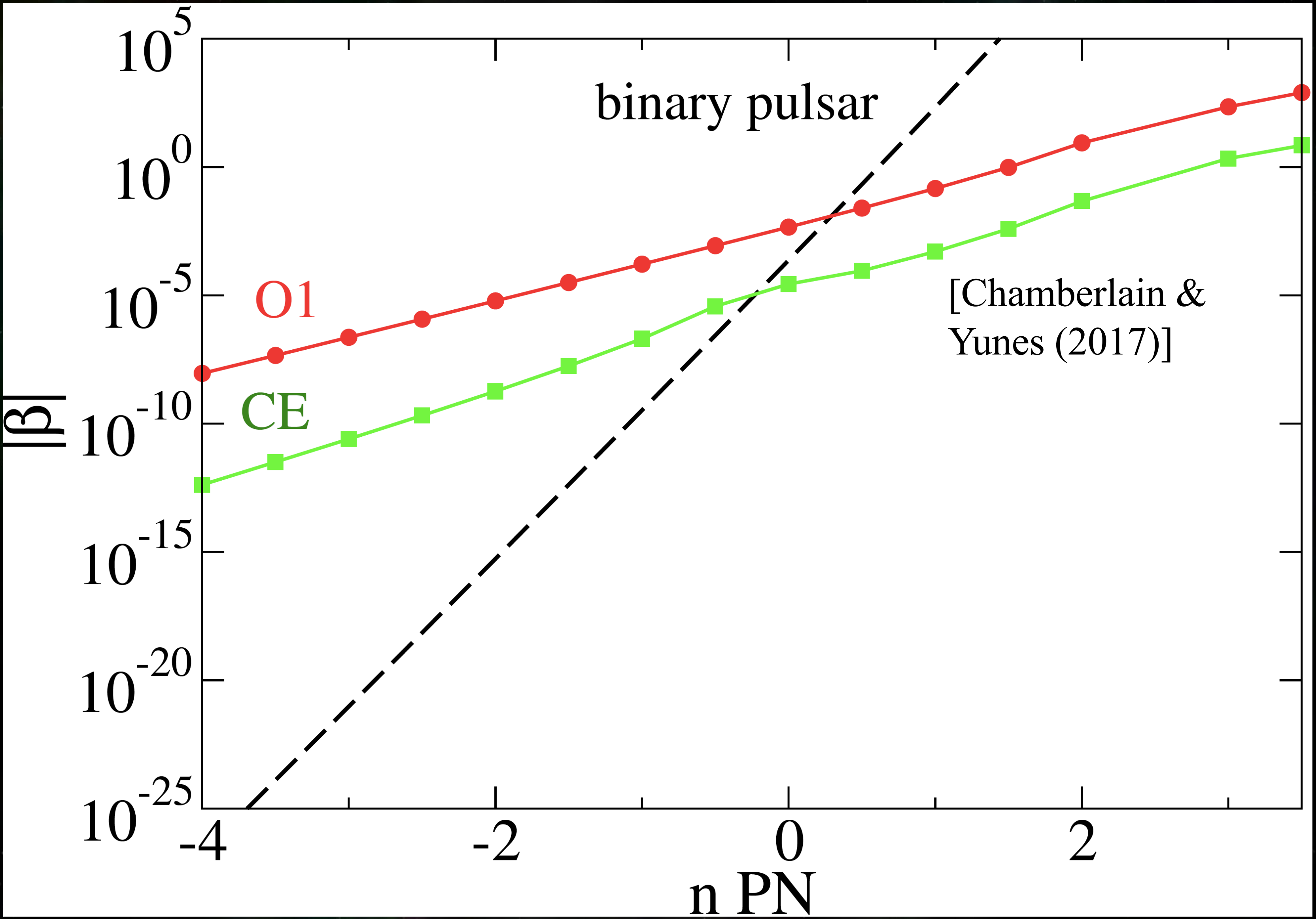
Current PPE Bounds (GW150914)



Future PPE Bounds (GW150914-like)



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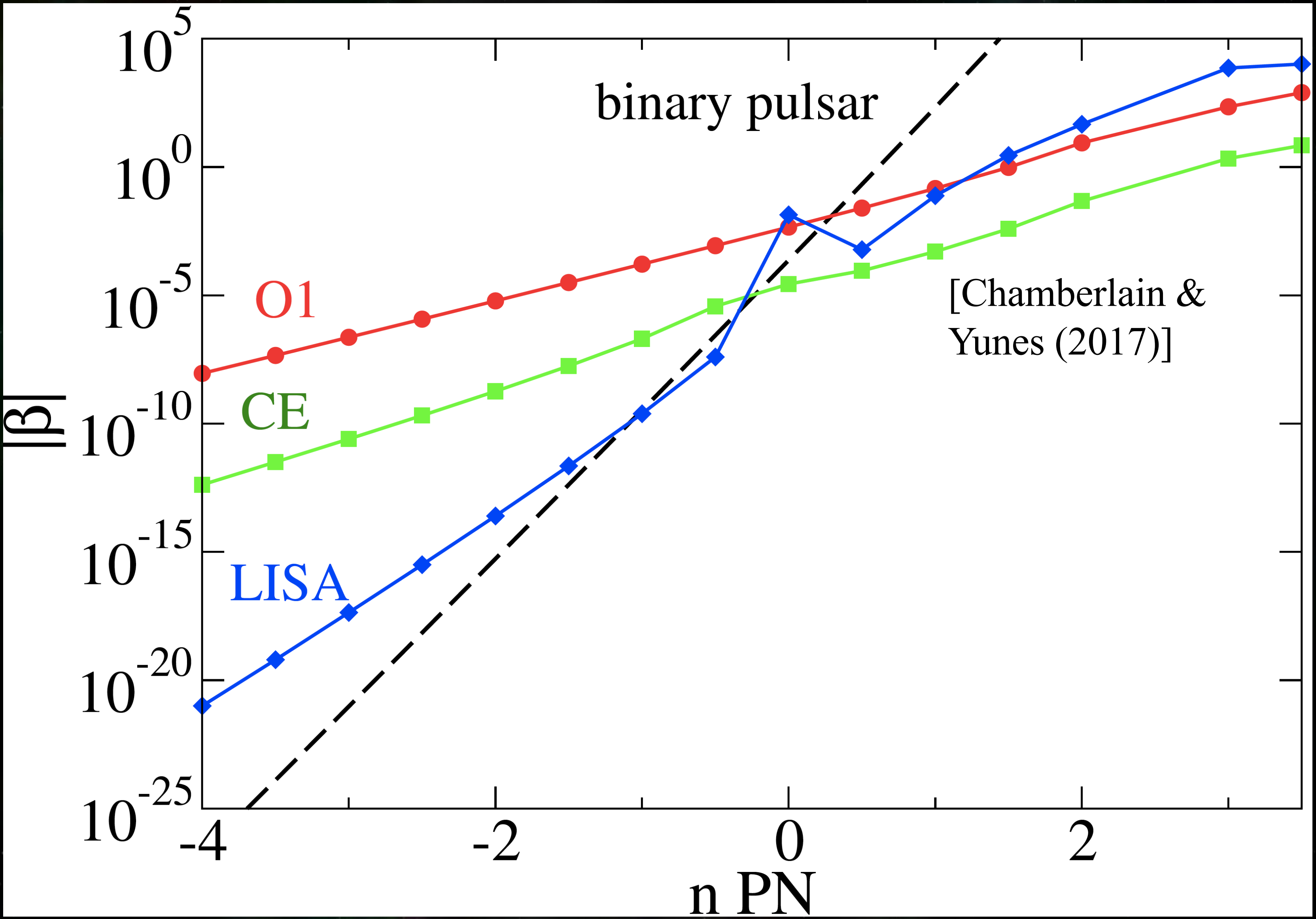

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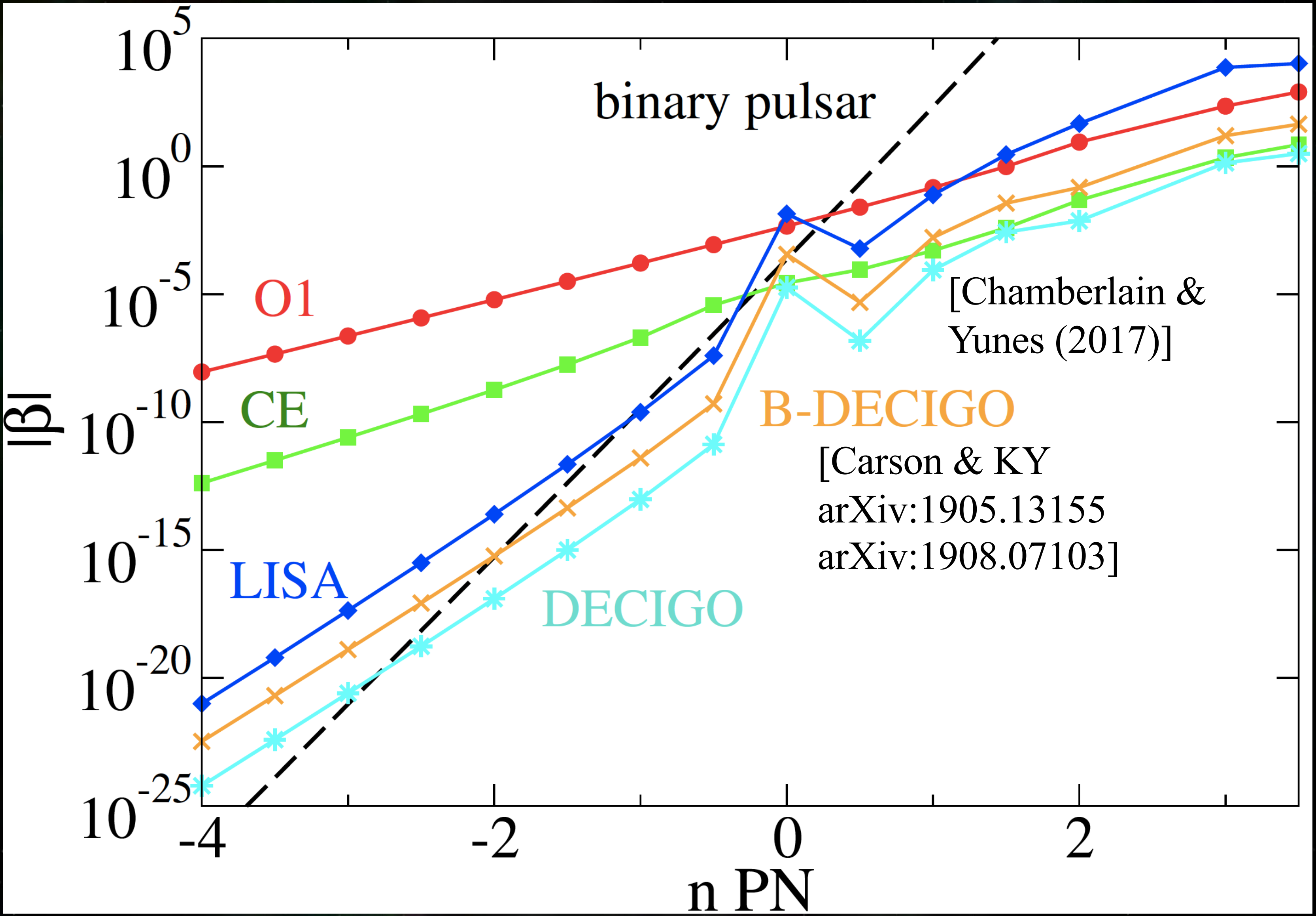
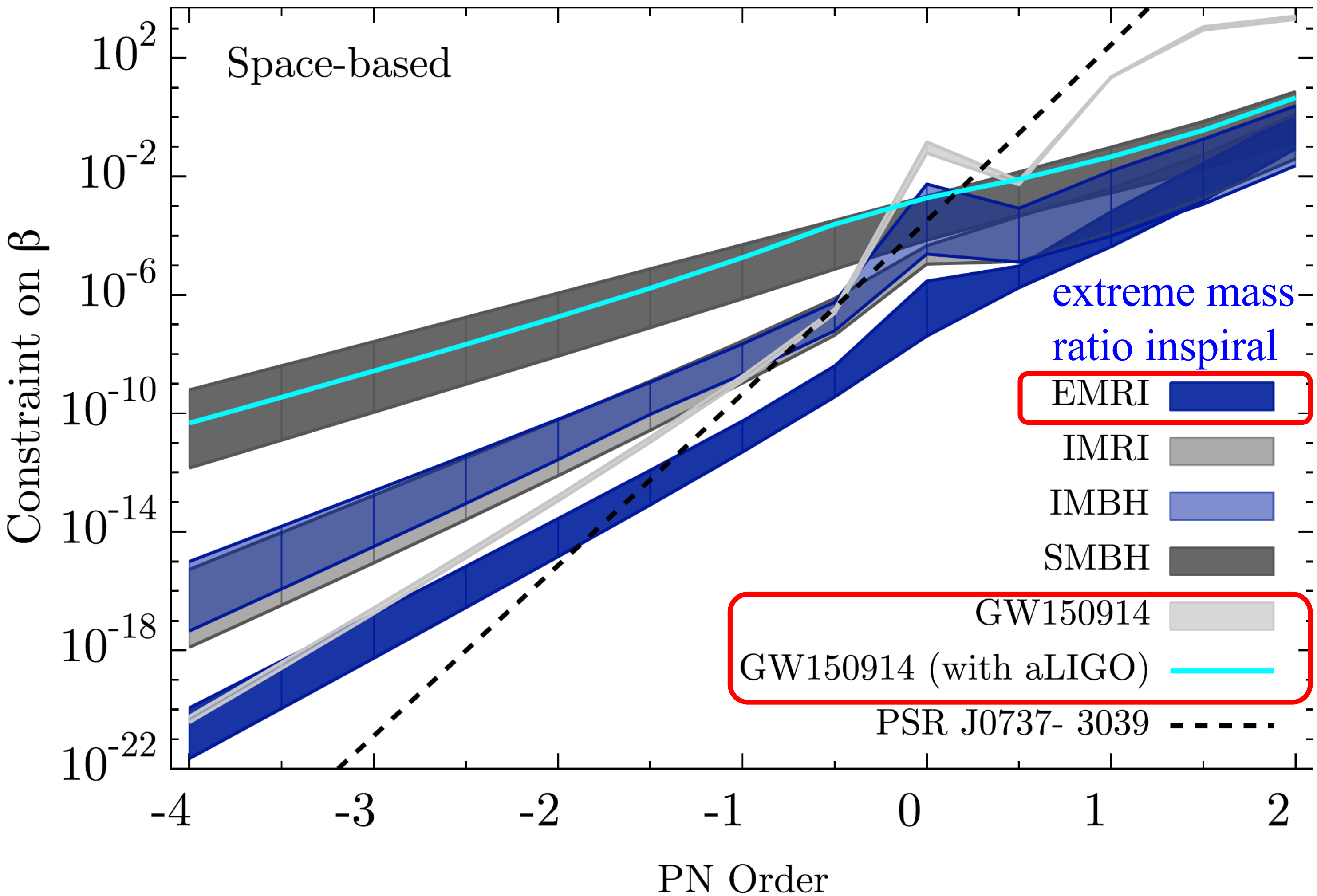
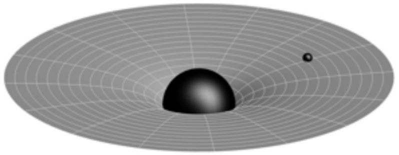


Other sources of LISA

[Chamberlain & Yunes (2017)]





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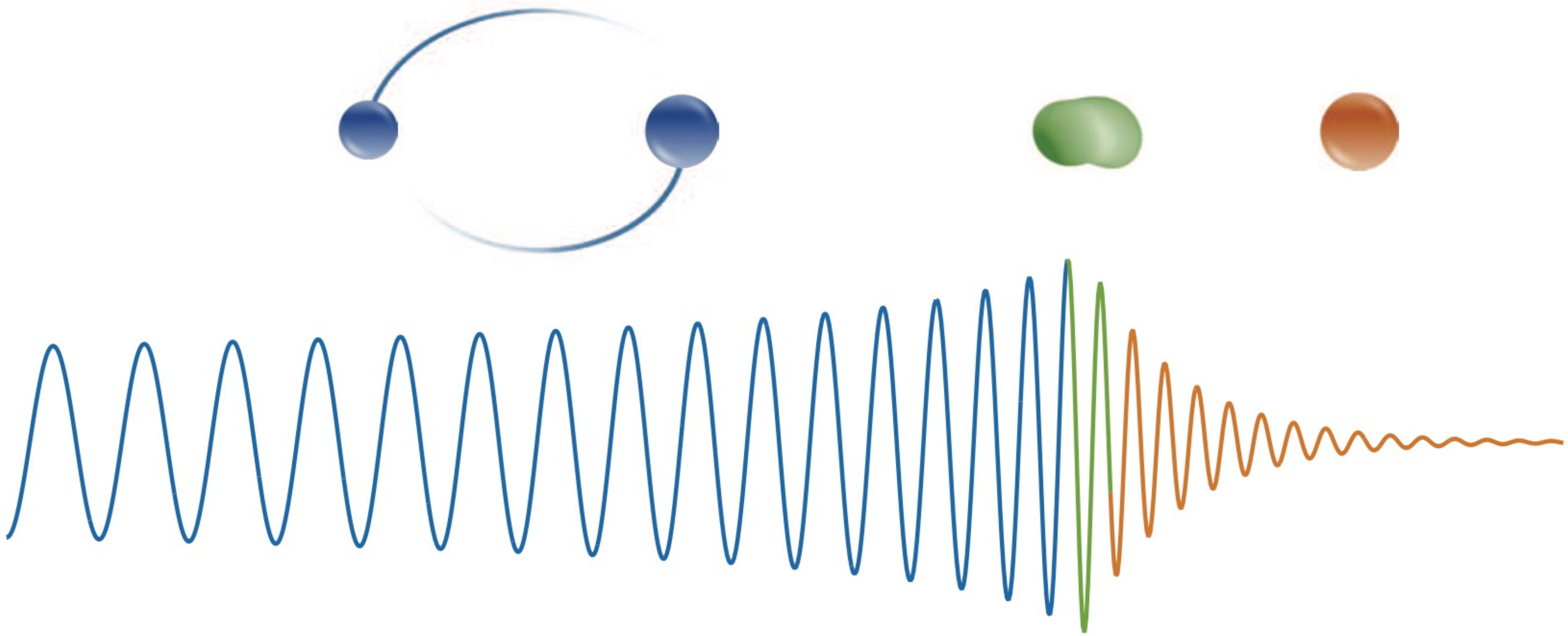

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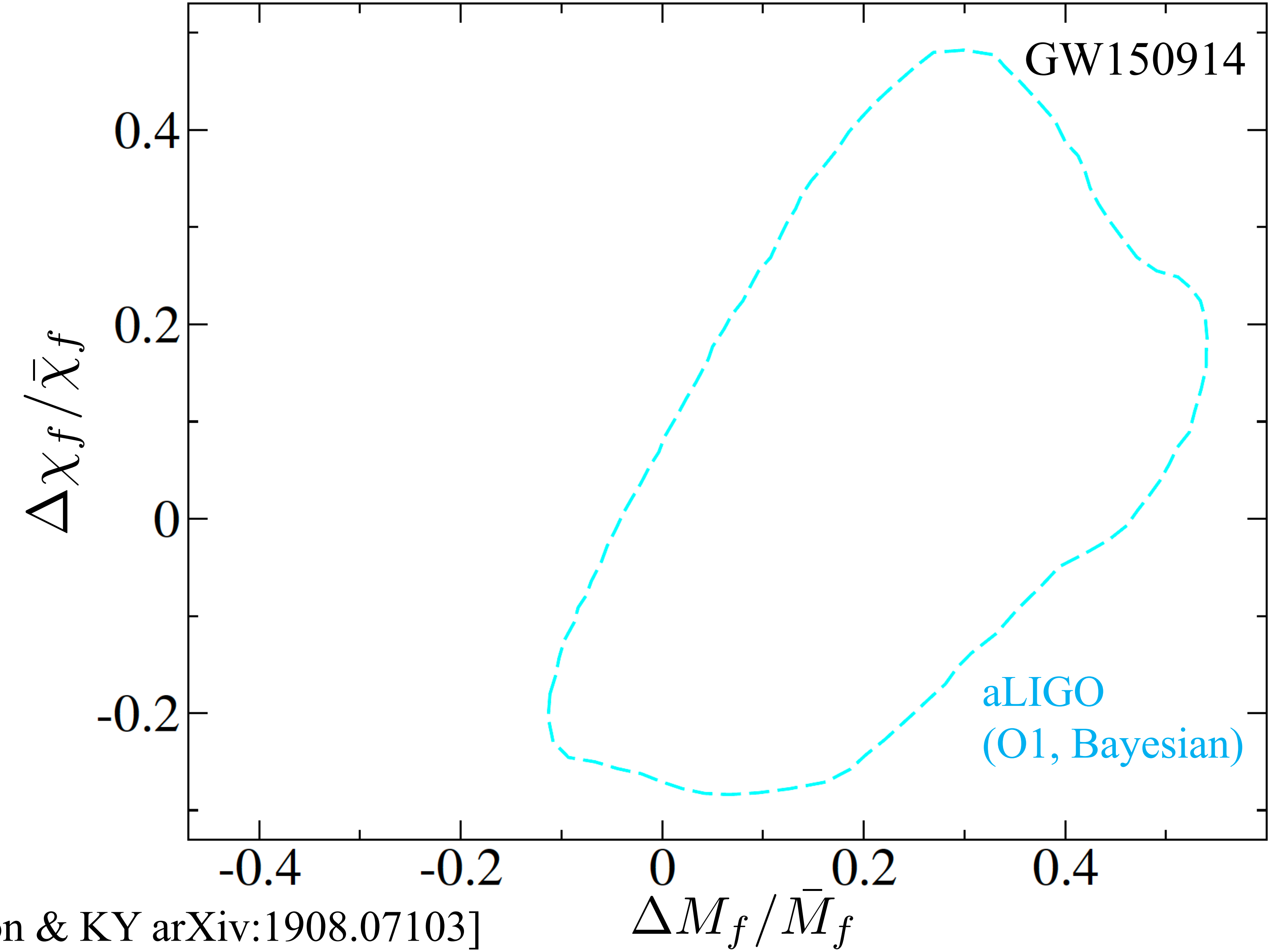
Future Improvement on IMR Consistency Tests



[Carson & KY arXiv:1908.07103]

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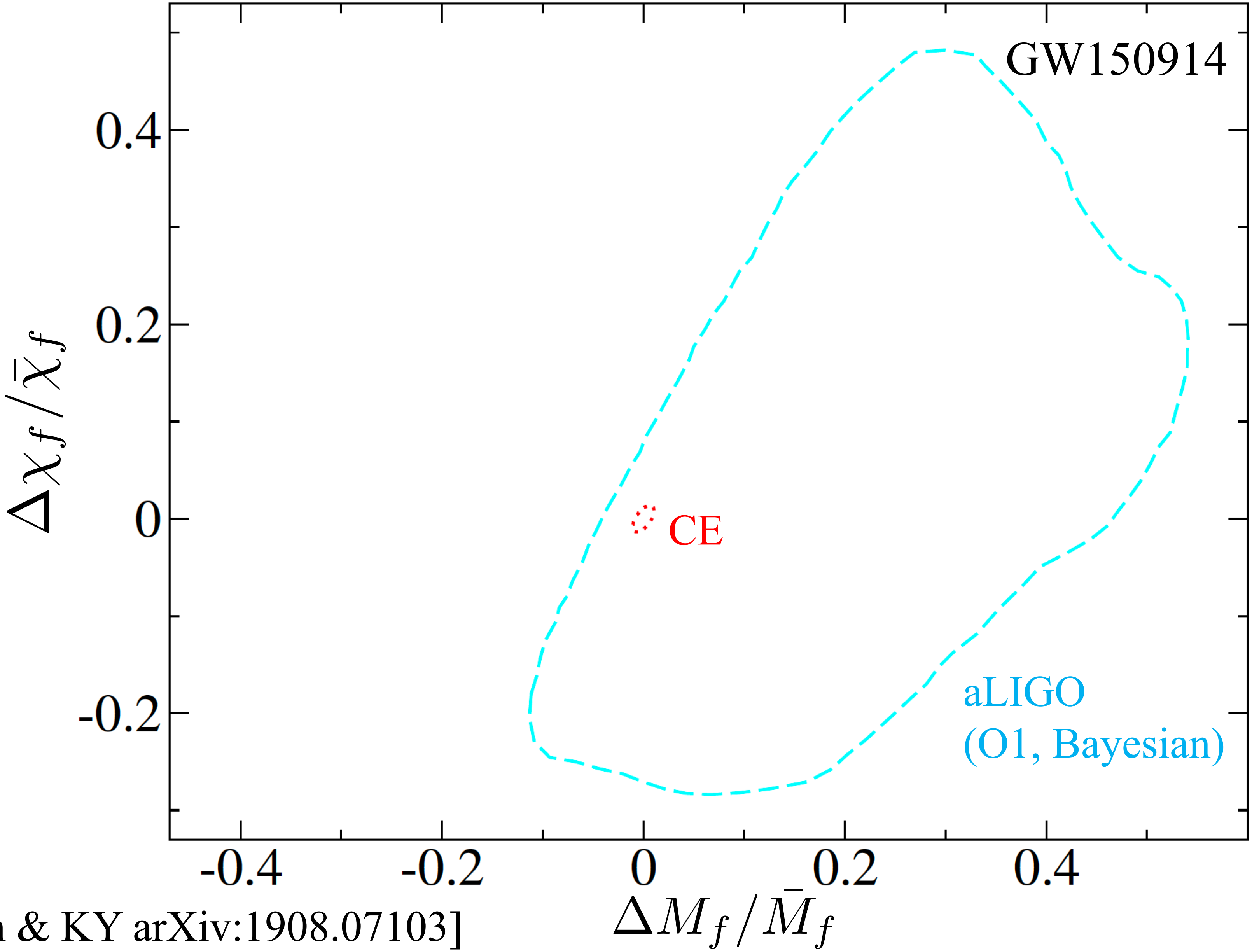

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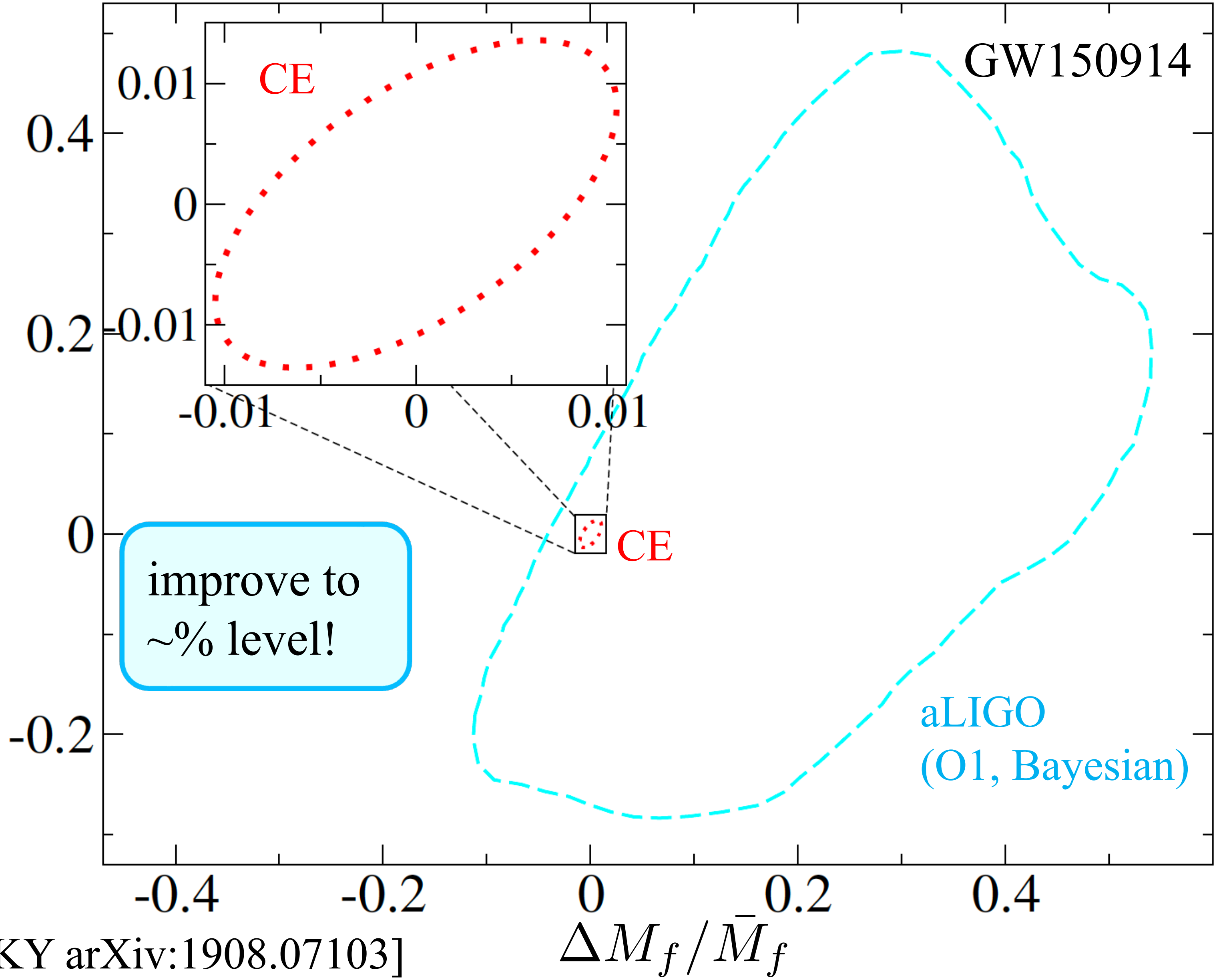

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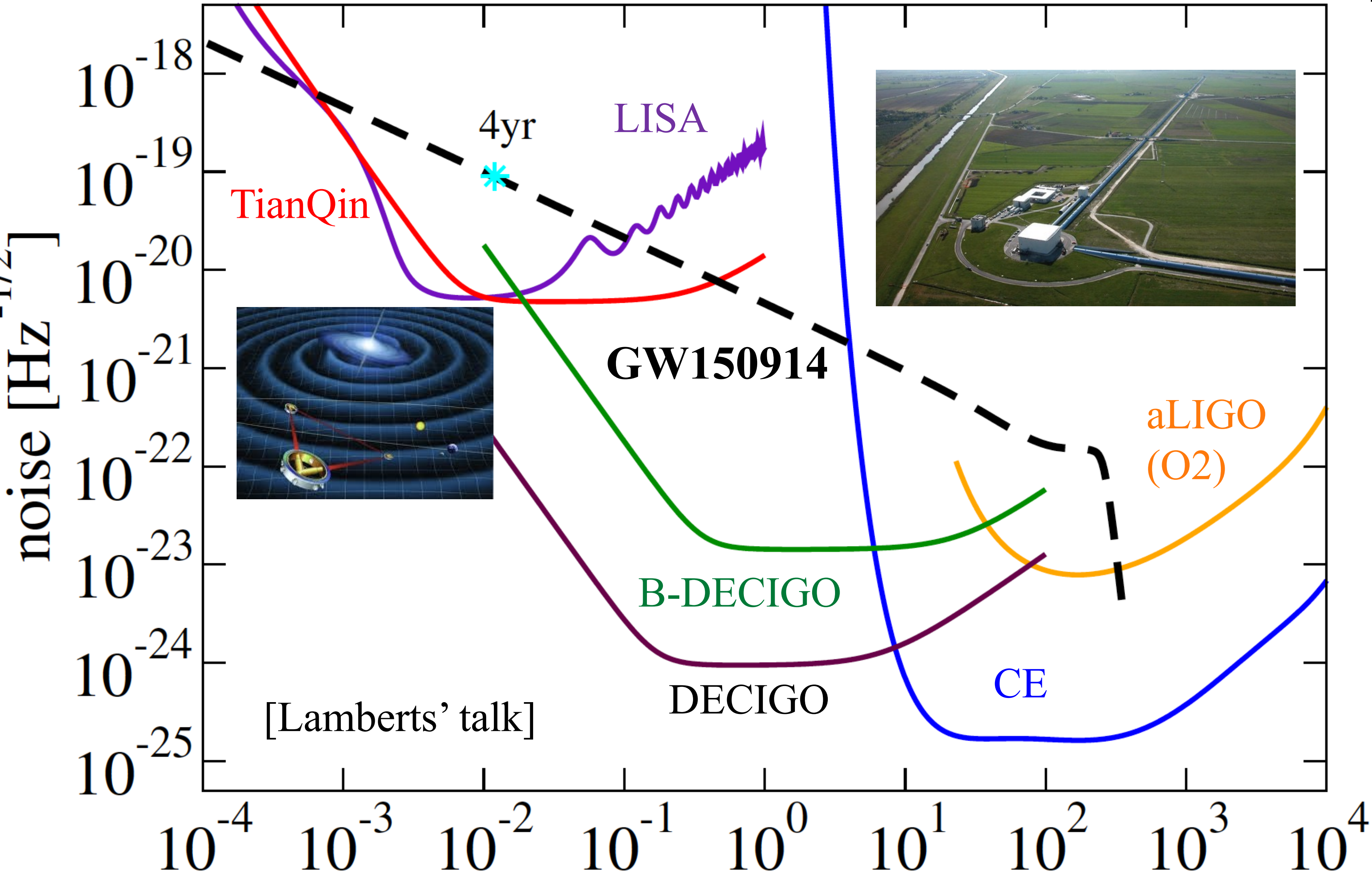
Multiband GW Astronomy

[Sesana (2016,2017)]



[Carson & KY arXiv:1905.13155]

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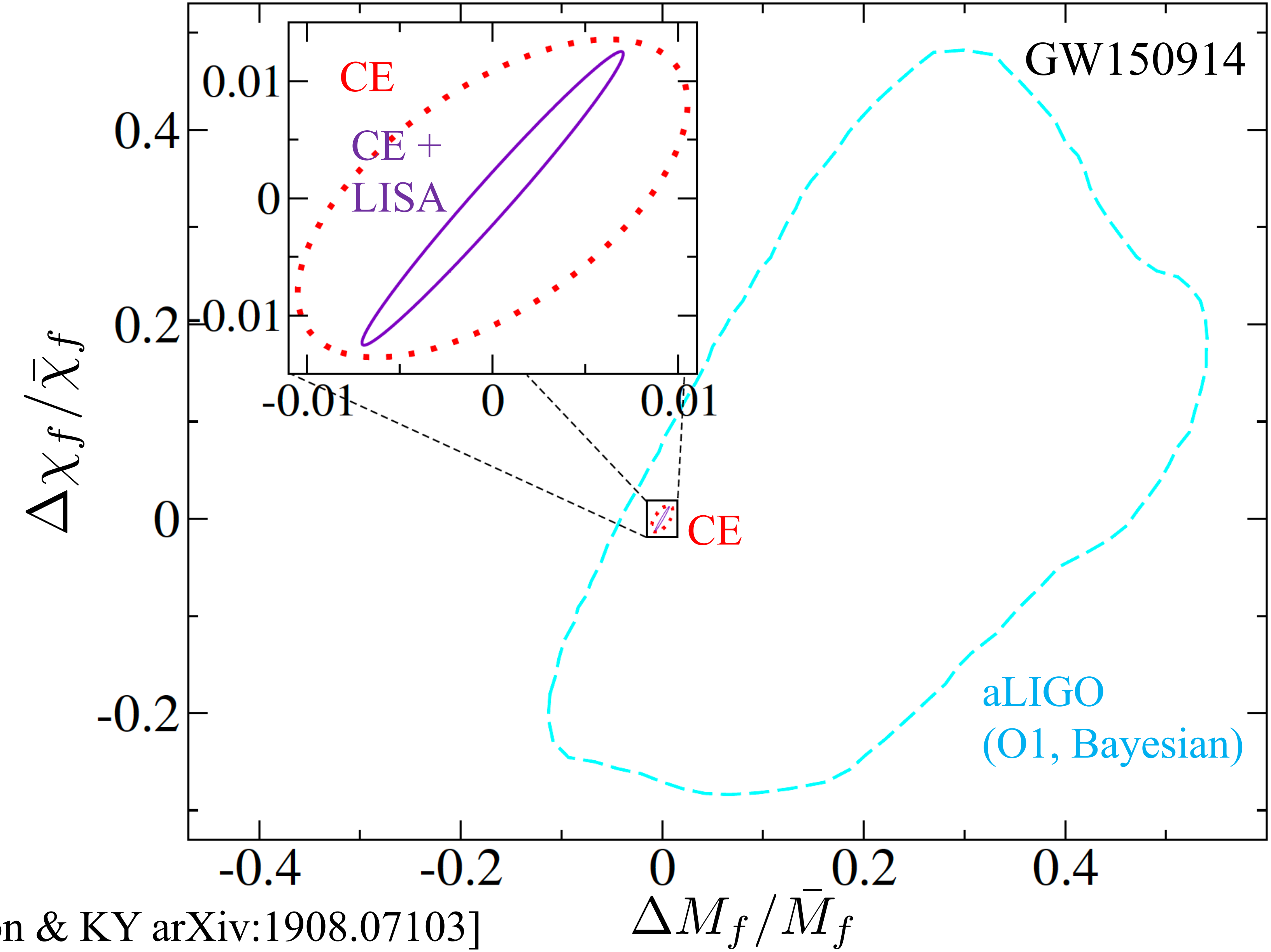


[Carson & KY arXiv:1908.07103]

Something to keep in mind…

Systematic Biases

Data in Tension with GR

Due to Noise Artifacts?	Caused by Waveform Systematics?	Due to Astrophysical Causes?
Non-Stationarity	Missing Physics Eccentricity Tides, Viscosity Kicks Ringdown Modes	Gravitational Lensing
Non-Gaussianity, Glitches		Environments
Overlapping Signals		Mistaken Source Class
Data Gaps, Detector Calibration	Inaccurate Modelling	Astrophysical Population

[Gupta et al 2405.02197]

Conclusions

Takeaway

1-1. Parameterized tests

- ✓ stringent bounds from GW170817 (-1PN) & GW250114 (pos. PN)
- ✓ orders of magnitude improvement with future detectors

1-2. No-hair tests (inspiral)

- ✓ most stringent bound on deviation from Kerr quadrupole moment with GW241011

2-1. No-hair tests (ringdown)

- ✓ first overtone mode detected with GW250114
- ✓ frequency consistent with Kerr to ~30%

3-1. Hawking's area law

- ✓ confirmed with GW250114

3-2. Inspiral-merger-ringdown consistency tests

- ✓ current accuracy of tests: ~10%
- ✓ improves to a % level with future detectors

Takeaway

1-1. Parameterized tests

- ✓ stringent bounds from GW170817 (-1PN) & GW250114 (pos. PN)
- ✓ orders of magnitude improvement with future detectors

1-2. No-hair tests (inspiral)

- ✓ most stringent bound on deviation from Kerr quadrupole moment with GW241011

2-1. No-hair tests (ringdown)

- ✓ first overtone mode detected with GW250114
- ✓ frequency consistent with Kerr to ~30%

3-1. Hawking's area law

- ✓ confirmed with GW250114

3-2. Inspiral-merger-ringdown consistency tests

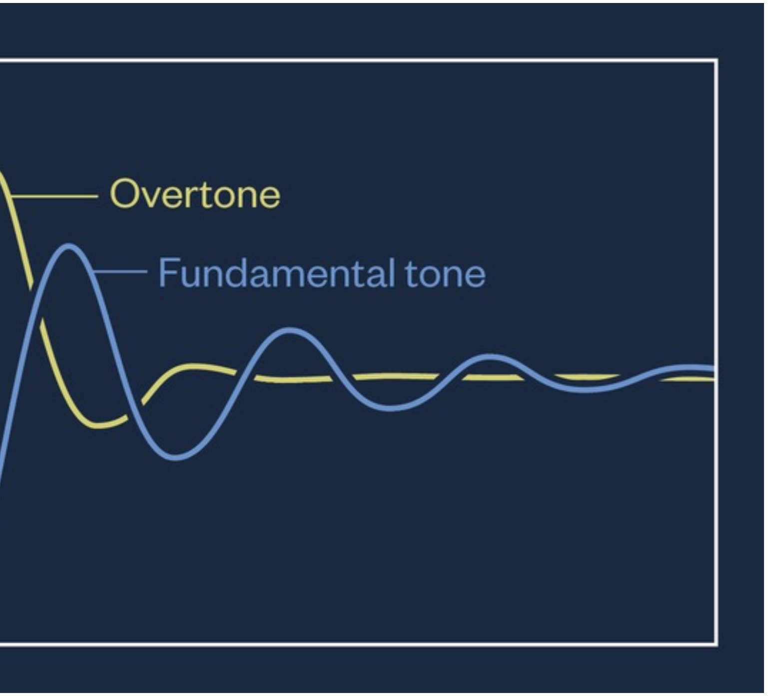
- ✓ current accuracy of tests: ~10%
- ✓ improves to a % level with future detectors

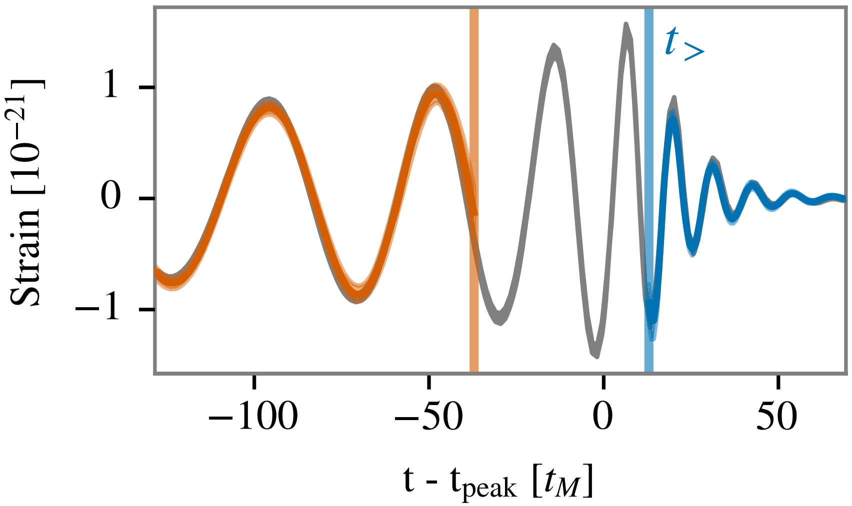
Thank You!

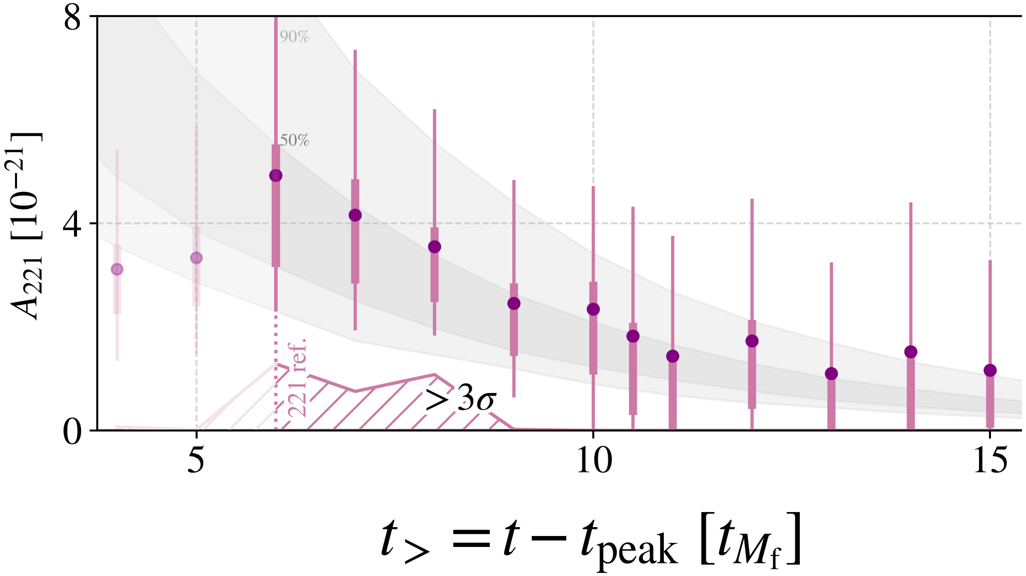
Back Up

mnant QNM Overtone Detection with GW250114

[LVK, arXiv:2509.08054]







Systematics

Cause	O4	A+	A$^{\#}$	XG
Non-Stationary Noise	✓	✓	✓	✓
Non-Gaussian Noise/Glitches	✓	✓	✓	✓
Overlapping Signals	✗	✗	✗	✓
Data Gaps	✗	✗	✗	✓
Detector Calibration	✗	✗	✗	✓
Eccentricity	✓	✓	✓	✓
Tidal Effects	✗	✓	✓	✓
Kick-induced Effects	✗	✗	✗	✓
Ringdown Modes	✓	✓	✓	✓
Precession and Higher-order Modes	✓	✓	✓	✓
Memory	✗	✗	✓	✓
Sub-optimal Waveform Calibration	✗	✗	✓	✓
Lensing	✗	✗	✗	✓
Environmental Effects	✗	✗	✗	✓
Source Misclassification	✓	✓	✓	✓
Astrophysical Population Assumptions	✓	✓	✓	✓

[Gupta et al 2405.02197]