

The Gravitational Wave Universe: A new window on Strong field gravity

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Gravitational Waves

- Ripples in the fabric of space time
- Accelerated mass with time varying quadrupole moment radiates gravitational waves. They encode the properties of the source.
- Travels at a speed of light

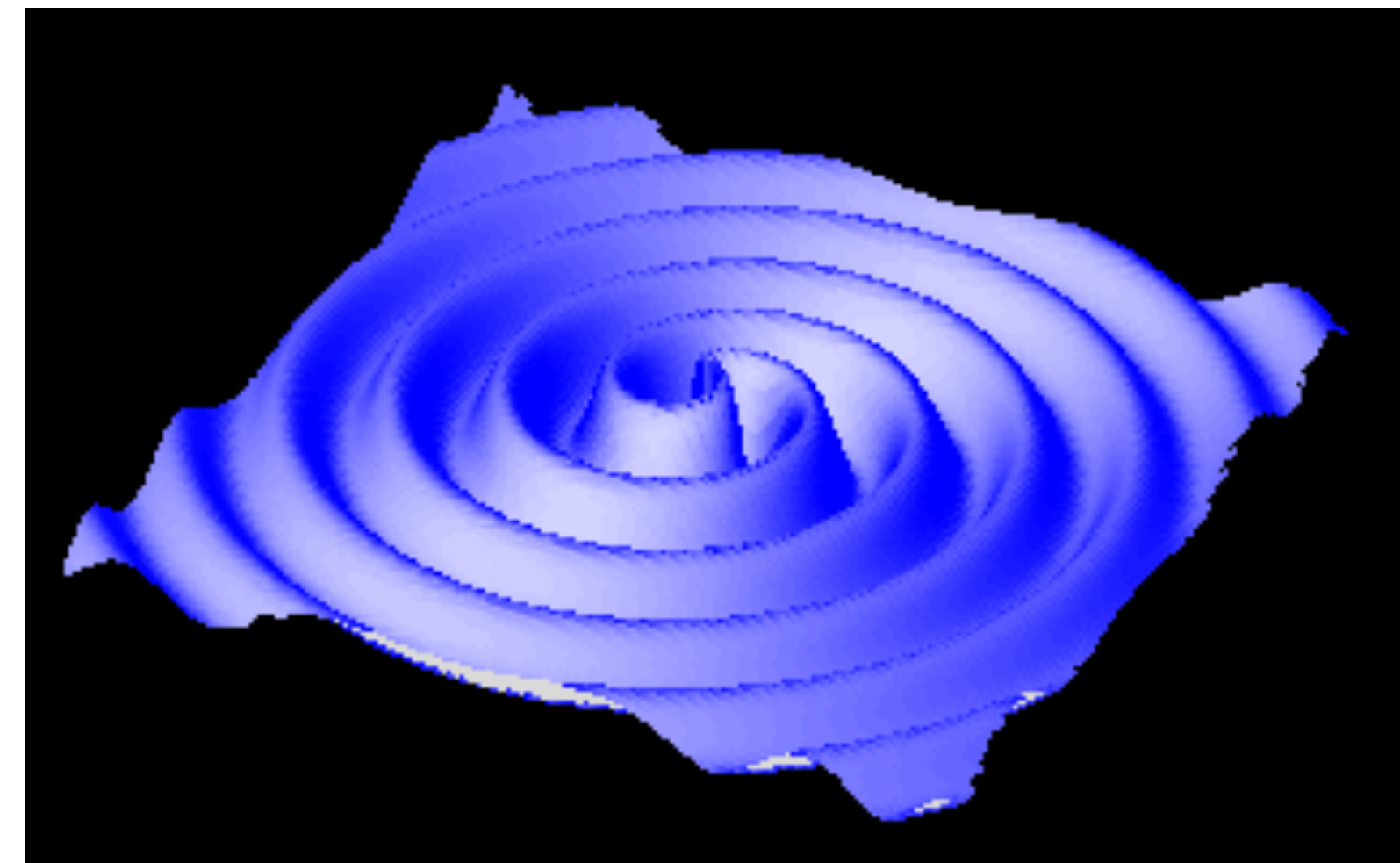
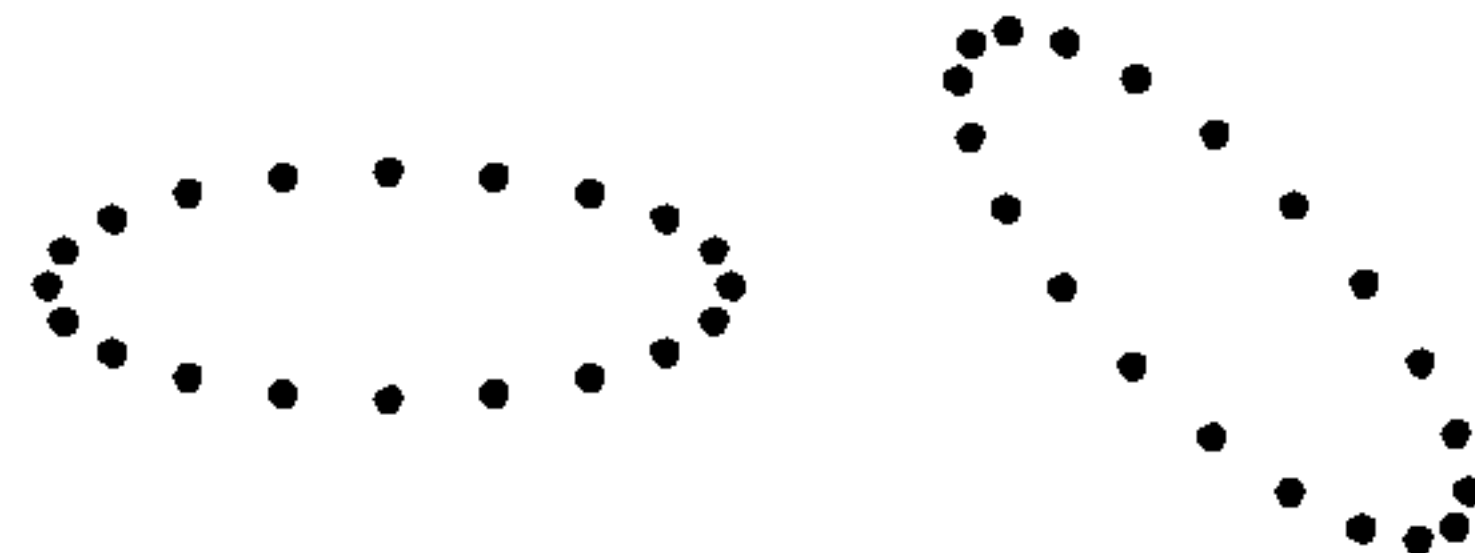


Image Credit: [Wikipedia](#)



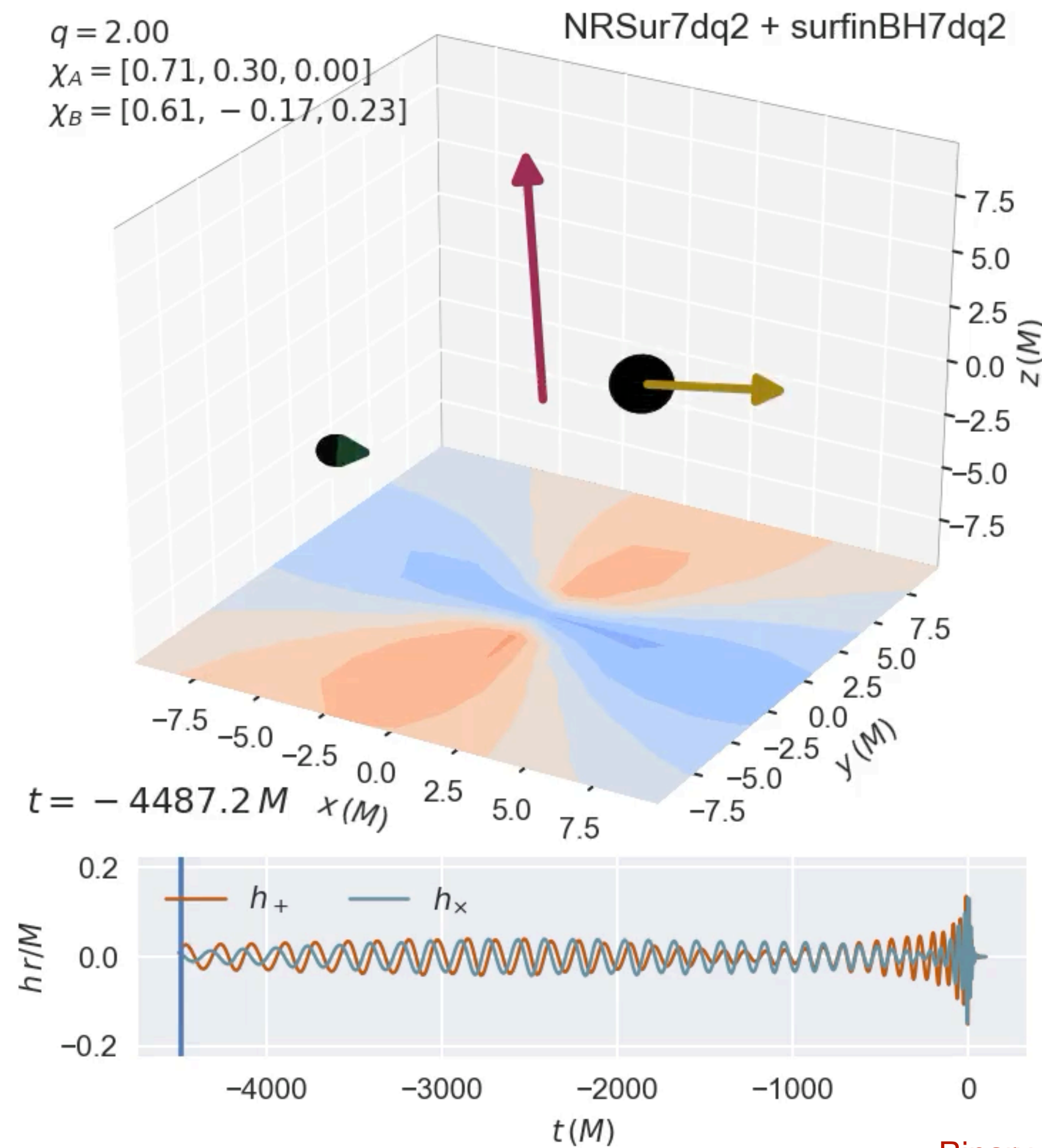
h_+

h_x

Image Credit: Animations adapted from those by MOble on [Wikipedia](#)



Gravitational Waves



Gravitational Wave Spectrum

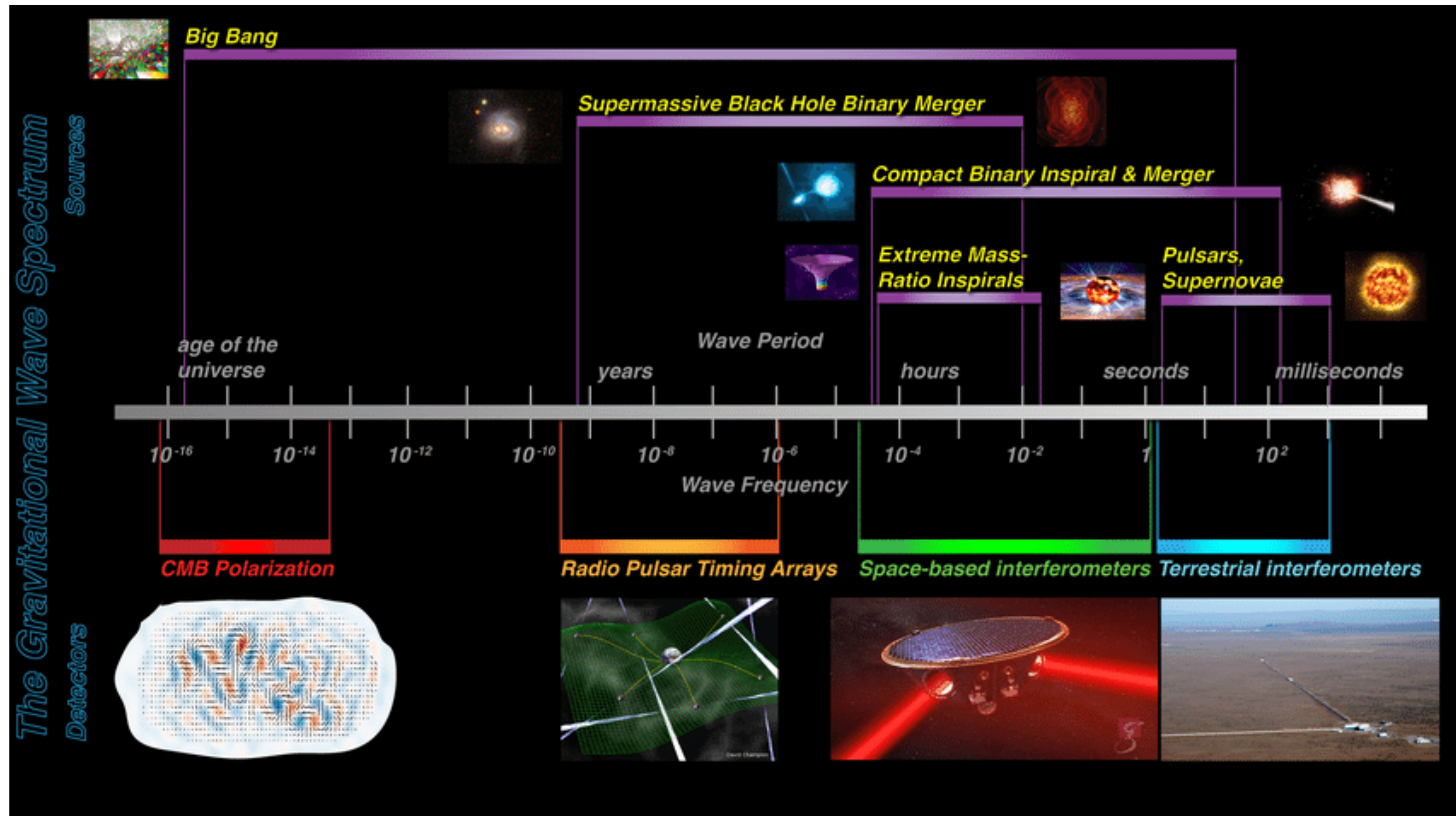


Image credit: NASA/J. I. Thorpe

GW150914

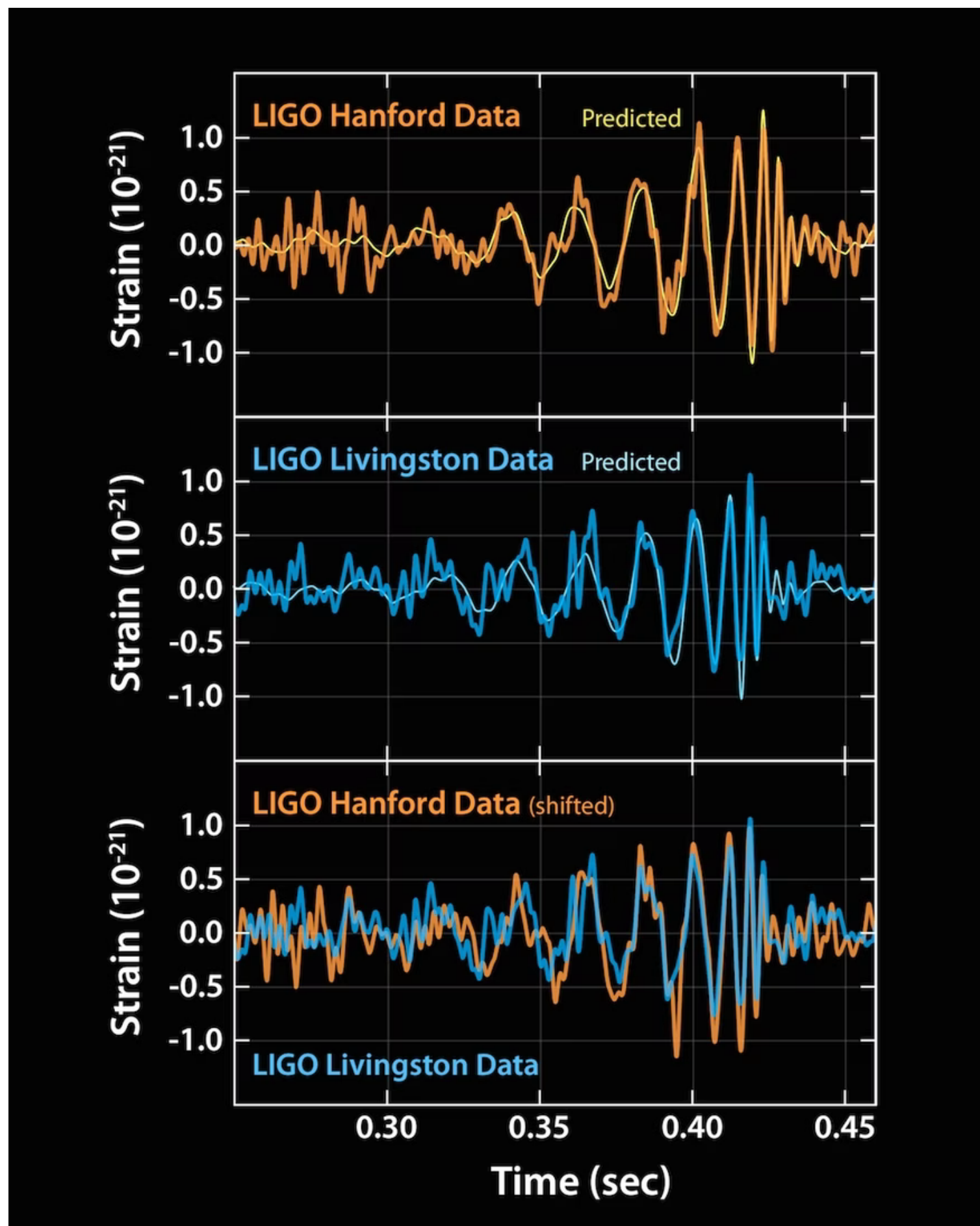
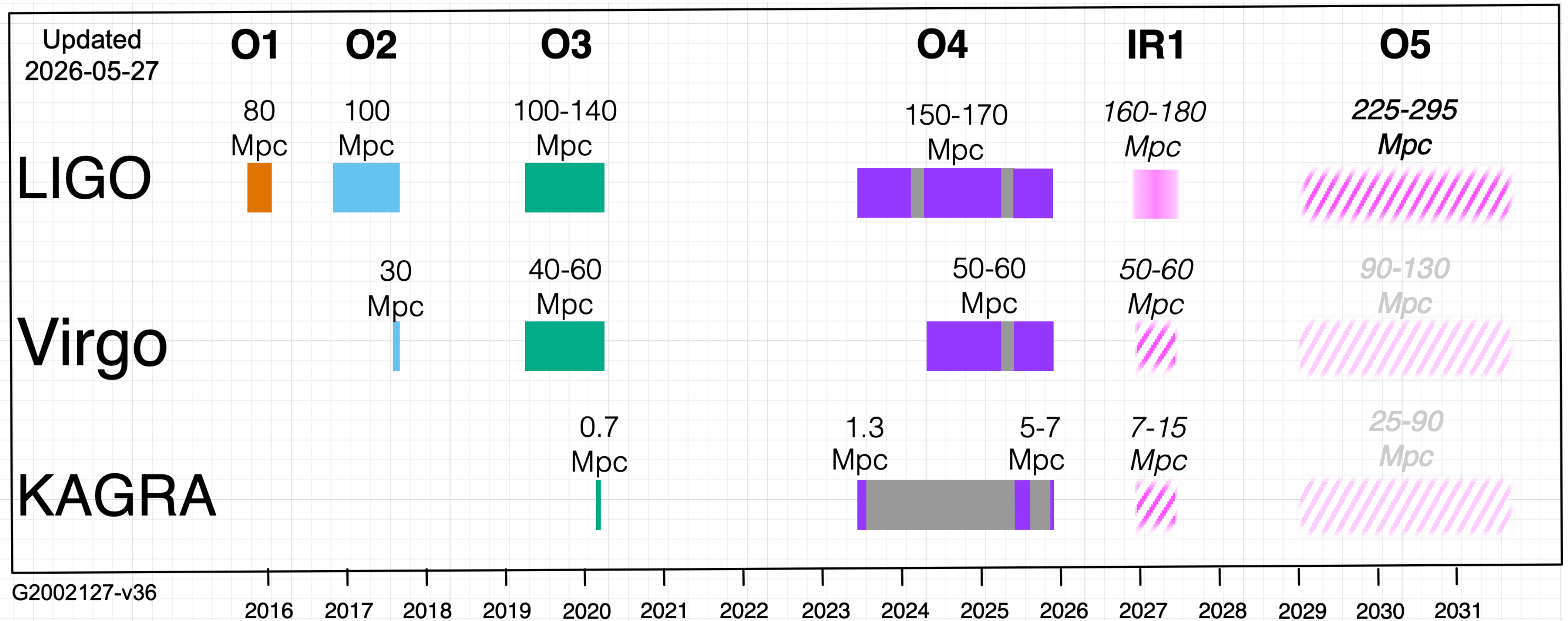


Image credit: LIGO

- First direct detection of gravitational waves.
- Observed on September 14, 2015
- The signal was seen by the Livingston detector first and then 7ms later at Hanford.
- Over about 0.2 seconds the signal increases in frequency and amplitude from 35 Hz to a peak amplitude at 150 Hz.

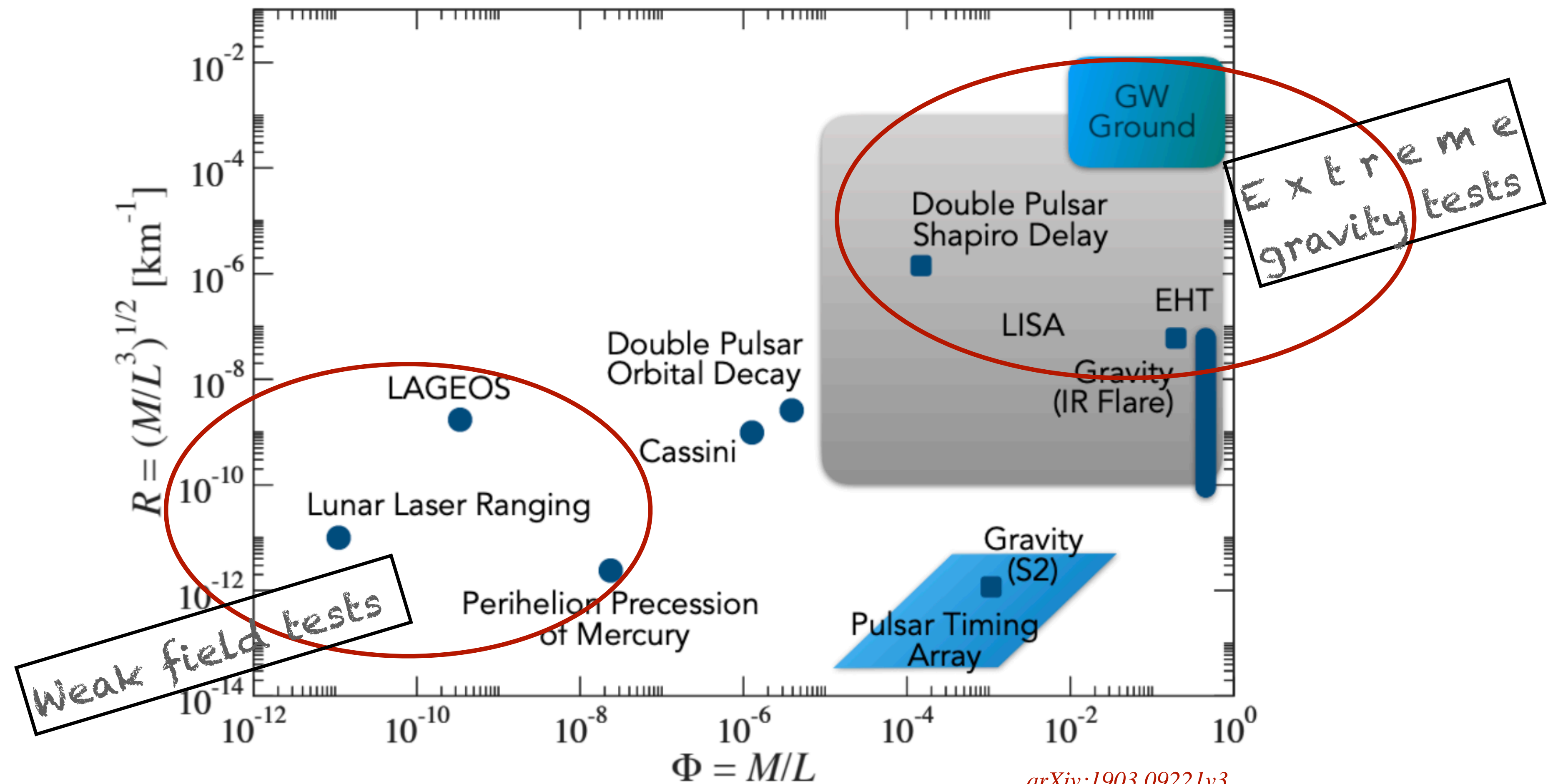
Past and future Observation period



[IGWN | Observing Plans](#)



Tests of general relativity



Tests of general relativity

Test Classification

Model dependant tests

- Pick a theory and test it.
Eg. Massive graviton theory
- Problems :
What theory do we pick?
Should we try all of them?

Model Agnostic tests

- Search for model independent GR deviations
- Introduce parametric deviations and search for them in the data.
- Map back any deviation to the physically meaningful parameters

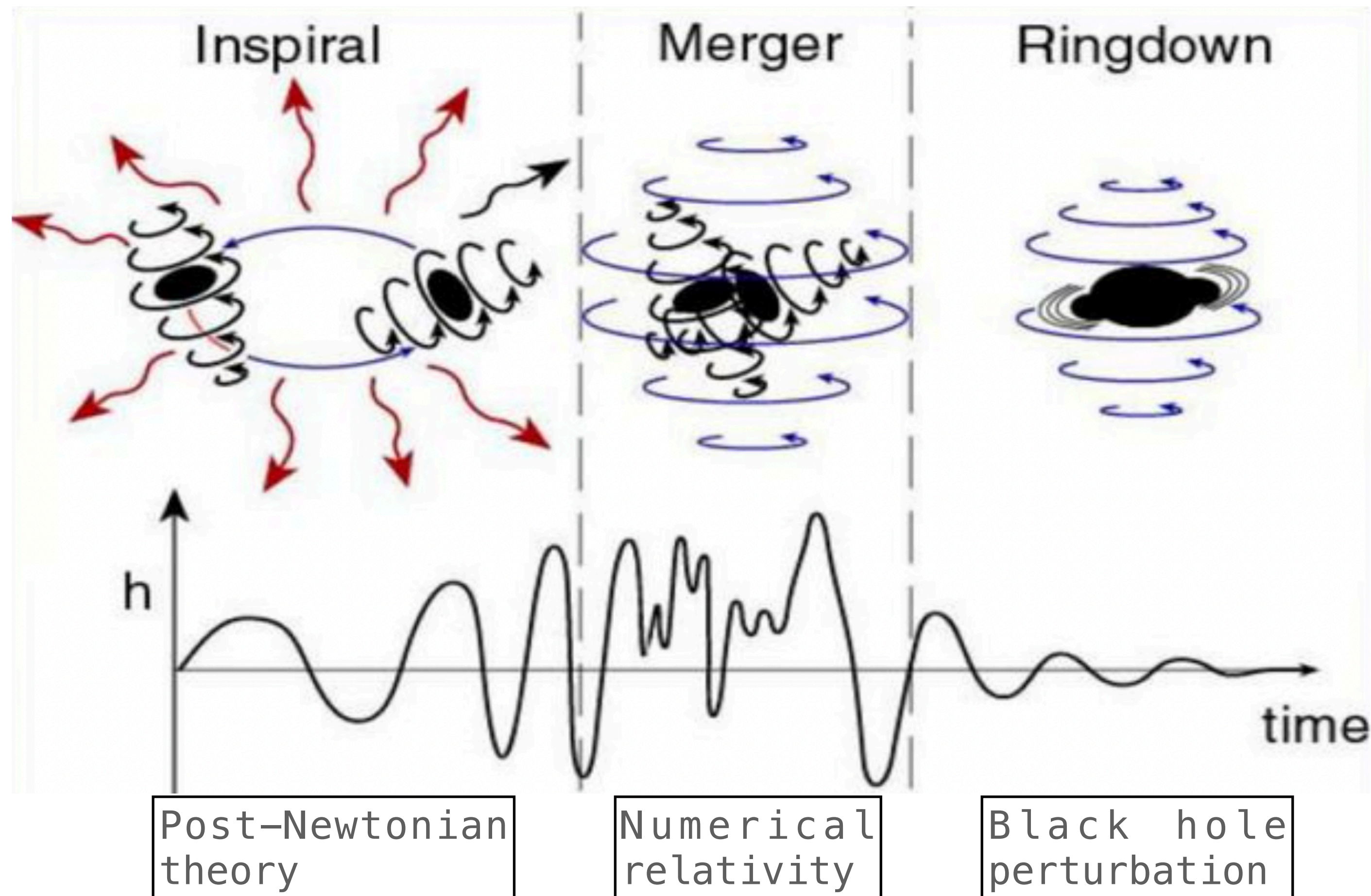
Consistency Tests

- Consistency between parts of the signal
- Check for residuals
- Consistencies between different detectors in different frequency band

GR Passes all the tests with flying colours!!



Gravitational waveform modeling



graphic courtesy: Kip Thorne

Inspiral Tests

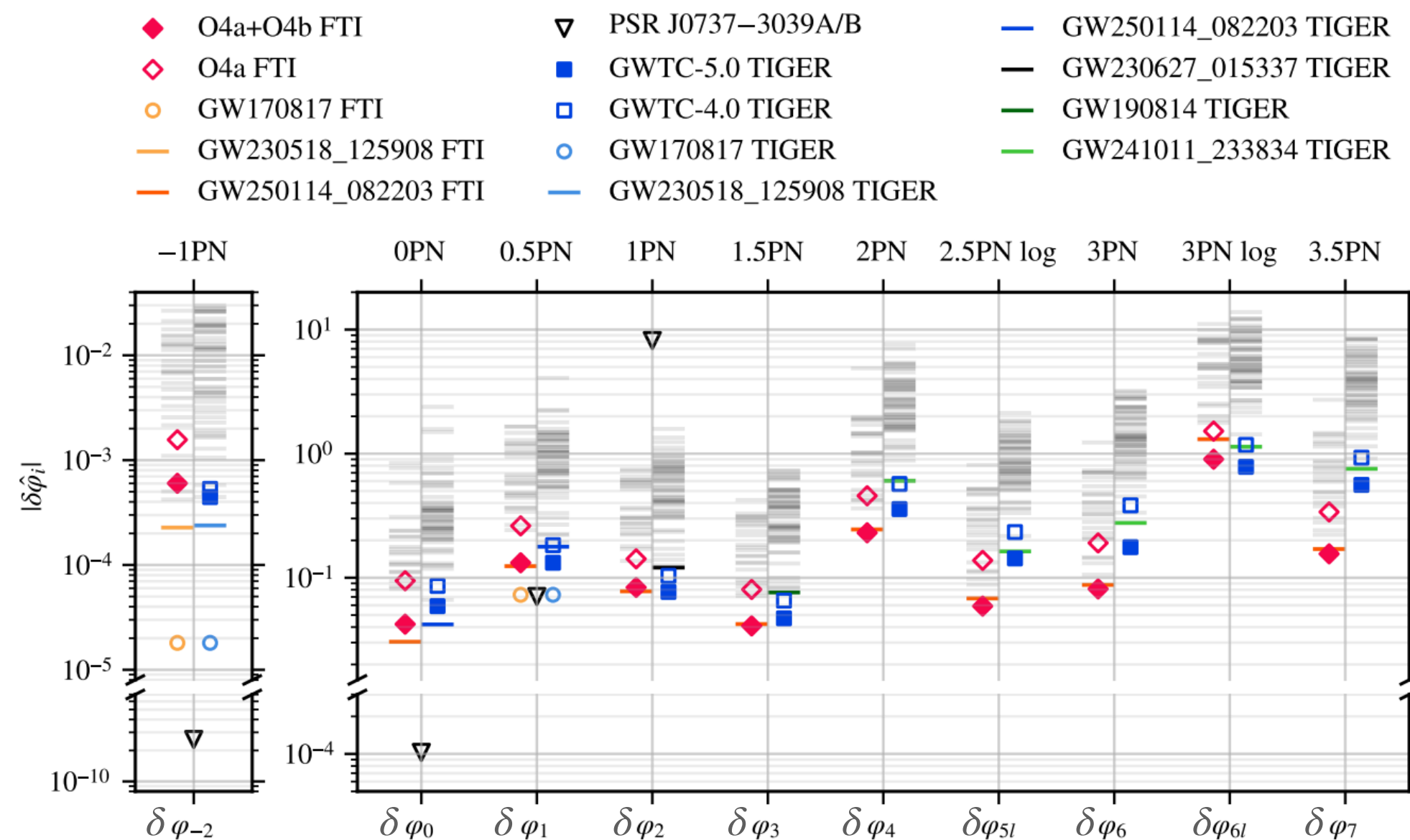


Tests of Post-Newtonian (PN) Theory

$$\Psi_{SPA} = 2\pi f t_c - \phi_c + \frac{3}{125\eta v^5} \left(\sum_{k=0}^N \phi_k \gamma^k + \sum_{kl=0}^N \phi_{kl} \gamma^{kl} \log v \right)$$

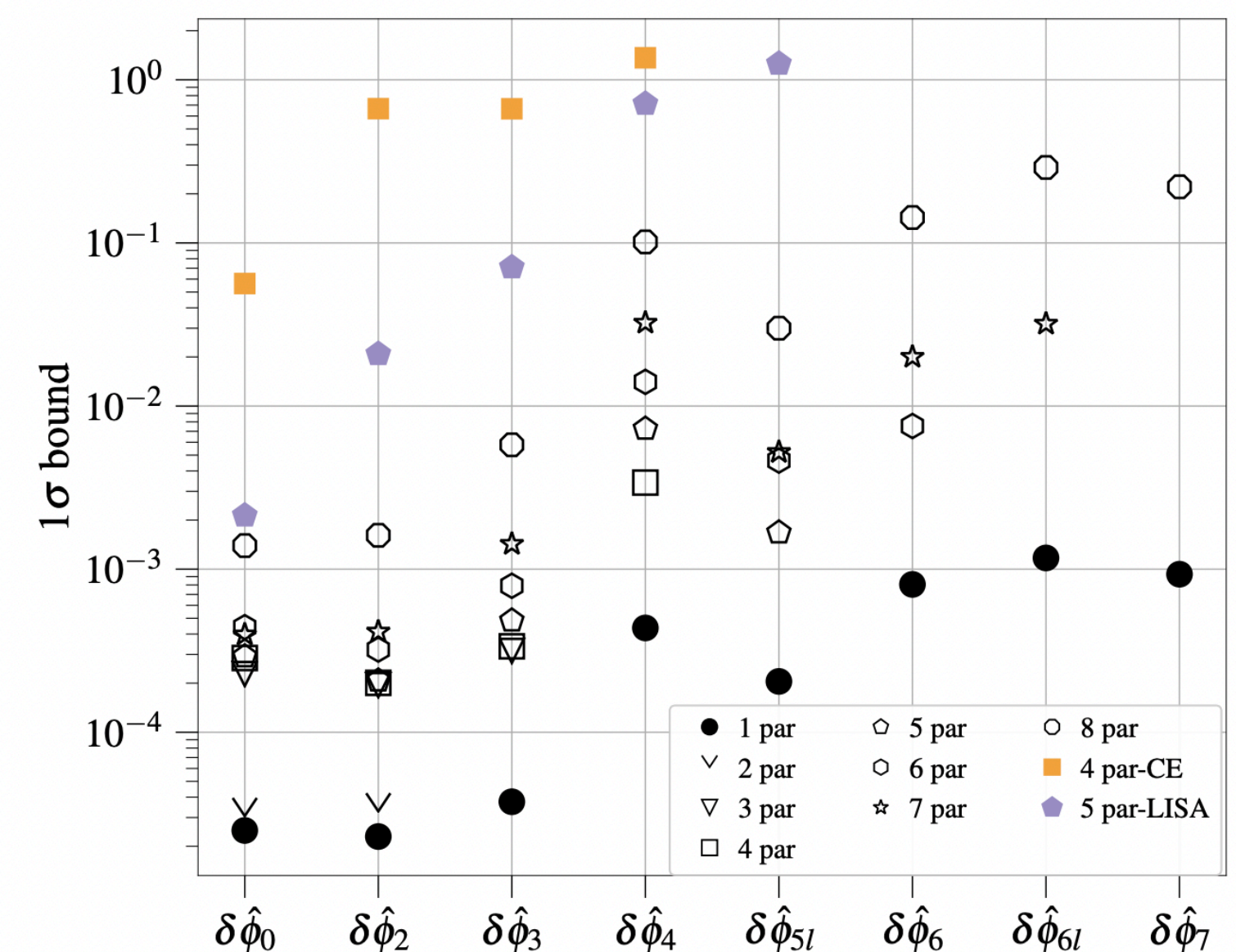
PN Coefficients

$\phi_k \rightarrow \phi_k^{GR}(1 + \delta\phi_k)$ Non-GR parametric deviations



Reported Upper limits on the absolute values of the inspiral deviation coefficients from LVK analysis on all the GW events

GWTC 5



Multi-parameter bounds from LISA+CE joint observations of 200 events

Gupta+Kastha et. al.



Tests of post-Newtonian multipolar structure

Within the PN formalism, the inspiral gravitational waveform is well described by various radiative moments.

Parametrization for modelling the possible deviations in the multipole structure



$$U_{\langle \ell \rangle} \rightarrow \mu_{\ell} U_{\langle \ell \rangle}$$

$$V_{\langle \ell \rangle} \rightarrow \epsilon_{\ell} V_{\langle \ell \rangle}$$

Modifications:

$$H_{+,\times}^{(k,n)}(\chi_1, \chi_2, \nu) \rightarrow H_{+,\times}^{(k,n)}(\chi_1, \chi_2, \nu, \mu_{\ell}, \epsilon_{\ell})$$

Modified amplitude

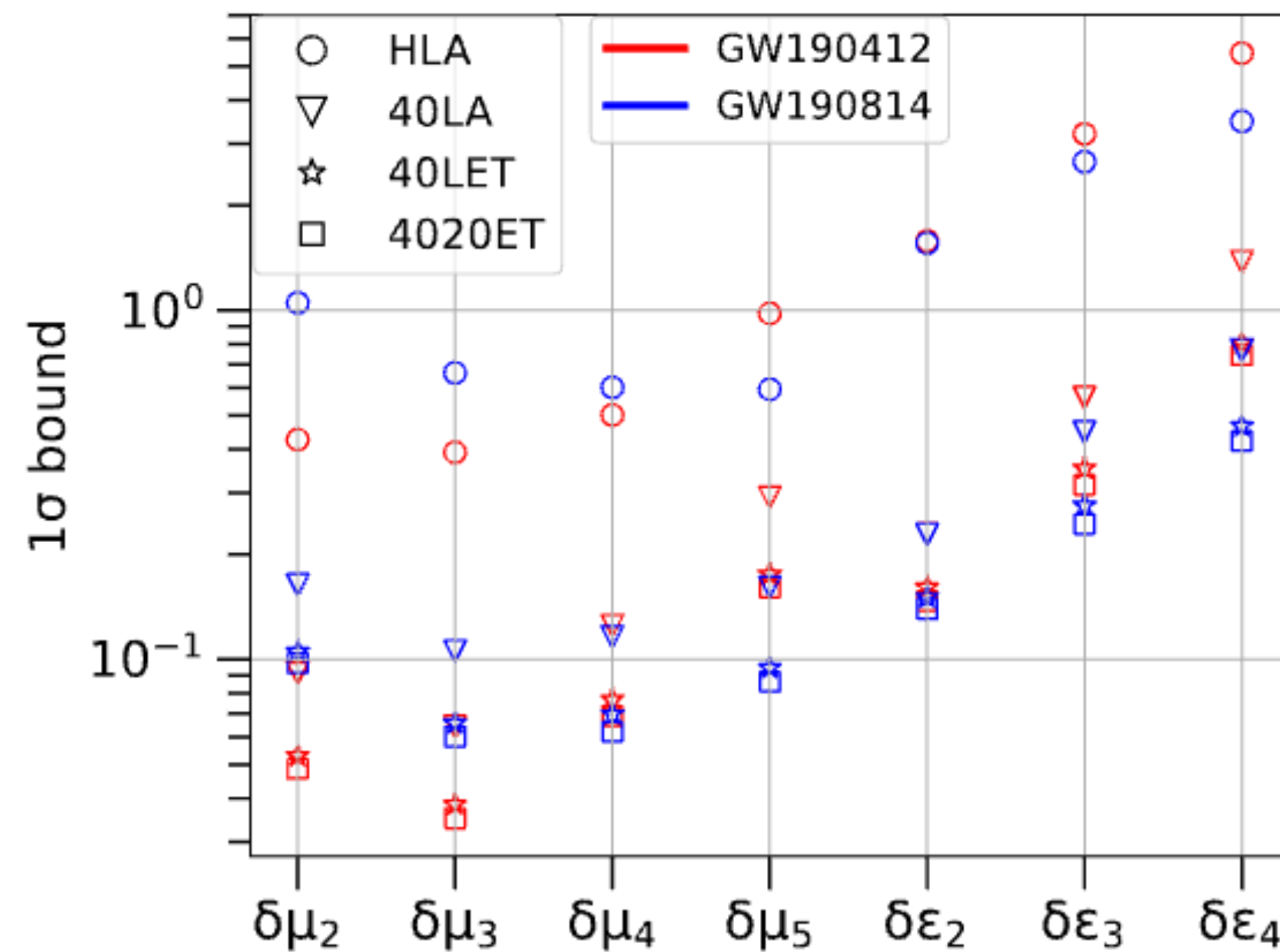
$$\Psi_{SPA}(f, \chi_1, \chi_2, \nu) \rightarrow \Psi_{SPA}(f, \chi_1, \chi_2, \nu, \mu_{\ell}, \epsilon_{\ell})$$

Modified phase

By construction, GR limit: $\mu_{\ell} = \epsilon_{\ell} = 1$



Tests of post-Newtonian multipolar structure



Mahapatra et. al.

HLA: LIGO Hanford, LIGO Livingston, LIGO Aundha
40LA: CE Washington (40 km), LIGO Livingston, LIGO Aundha
40LET: CE Washington (40 km), LIGO Livingston, ET Europe
4020ET: CE Washington (40 km), CE Texas, ET Europe



Tests of post-Newtonian multipolar structure

Within the PN formalism, the inspiral gravitational waveform is well described by various radiative moments.

$$h \equiv h_+ - ih_\times = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} h_{\ell m} Y_{-2}^{\ell m}(\Theta, \Phi) \longrightarrow \mathcal{F} = \frac{1}{16\pi} \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} |\dot{R}h_{\ell m}(t)|^2$$

$$\tilde{h}_{\ell m}^{\text{mod}}(t) = c_{\ell m} \tilde{h}_{\ell m}^{\text{GR}}(t) \longrightarrow \mathcal{F} = \mathcal{F}_{\text{NS}}(\{c_{\ell m}\}) + \mathcal{F}_{\text{spin}}(\{c_{\ell m}\}, \chi_1, \chi_2)$$

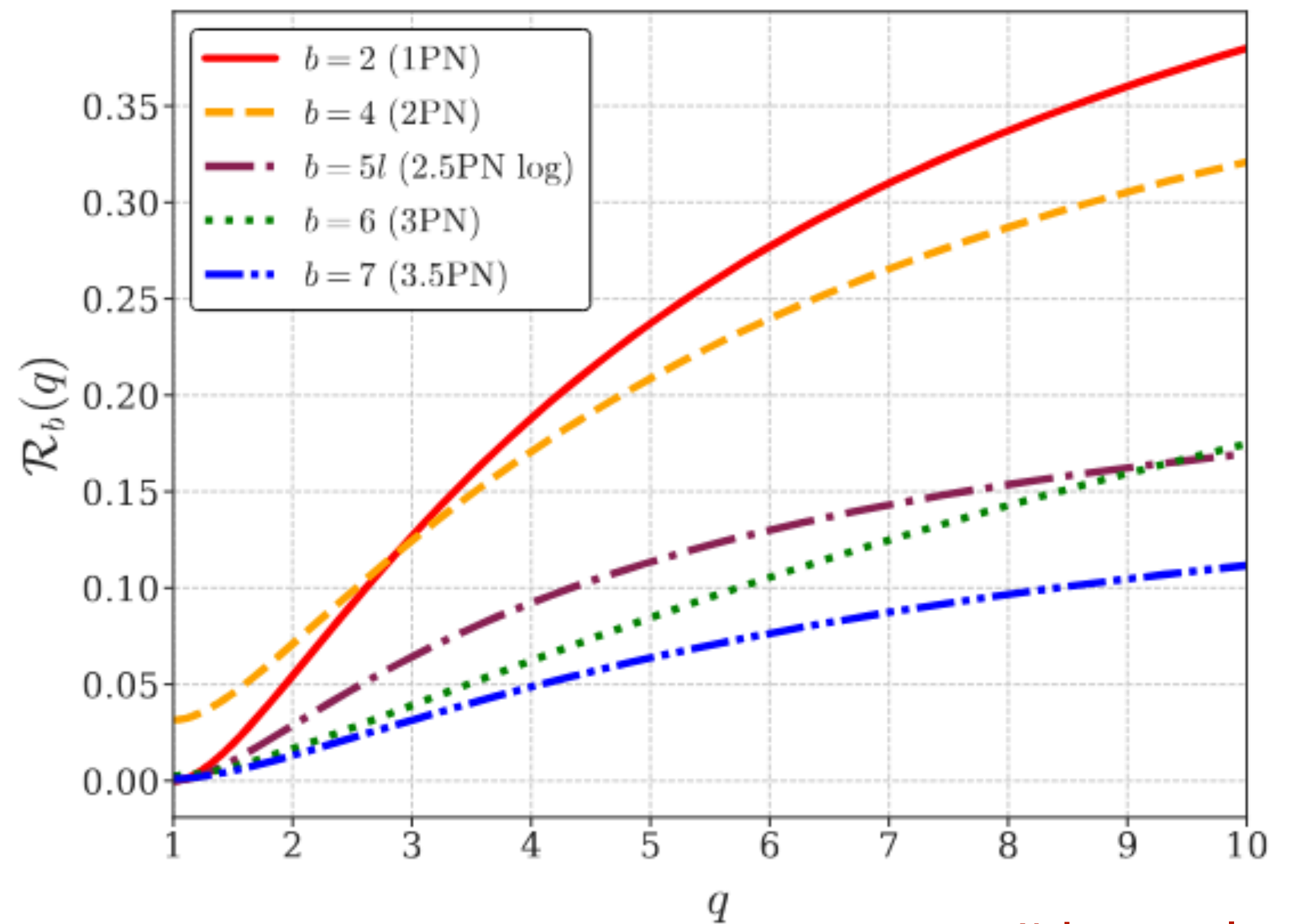
Resulting gravitational wave phase

$$\Psi(V_m) = 2\pi f t_c - \phi_c + \frac{3}{256 c_{22}^2 \nu V_m^5} \sum_{i=0}^7 \left[\psi_i(\{c_{\ell m}\}) + \psi_{iL}(\{c_{\ell m}\}) \log V_m \right] V_m^i$$

Tests of post-Newtonian multipolar structure

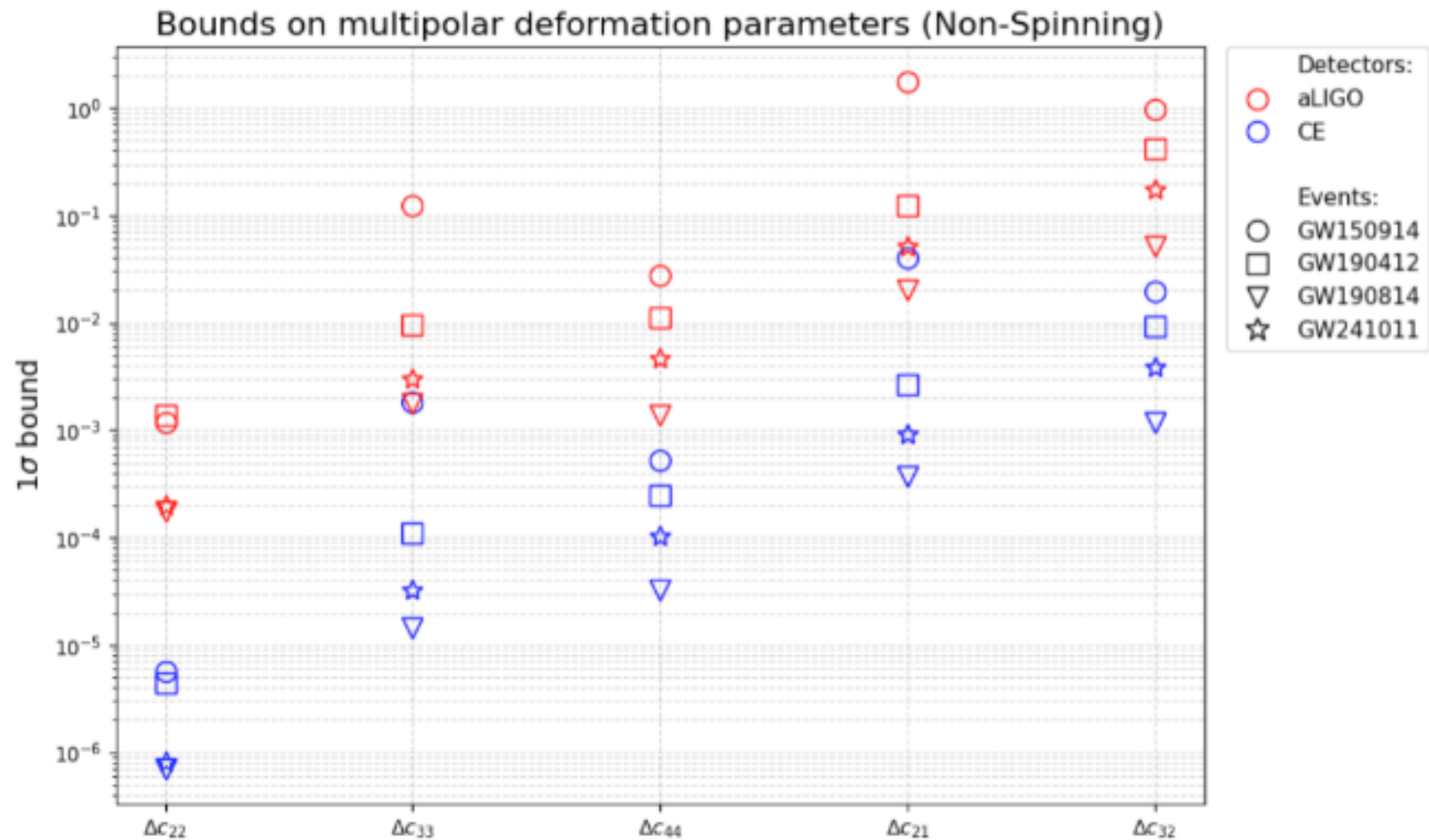
PN order	Modes
0 PN	(2,2)
1 PN	(2,2), (2,1), (3,3), (3,1)
1.5 PN	(2,2), (2,1) [†]
2 PN	(2,2), (2,1), (3,3), (3,2), (3,1), (4,4), (4,2)
2.5 PN log	(2,2), (2,1), (3,3), (3,2) [†] , (3,1)
3 PN	(2,2), (2,1), (3,3), (3,2), (3,1), (4,4), (4,3), (4,2), (4,1), (5,5), (5,3), (5,1)
3 PN log	(2,2)
3.5 PN	(2,2), (2,1), (3,3), (3,2), (3,1), (4,2)

TABLE I: Multipolar content of the parametrized GW phase to 3.5PN. Each row lists the modes (ℓ, m) contributing to ψ_k at PN order k . Entries marked with [†] denote modes whose contribution at that order originates from spin couplings and vanishes in the non-spinning limit; unmarked entries are present already for non-spinning binaries.

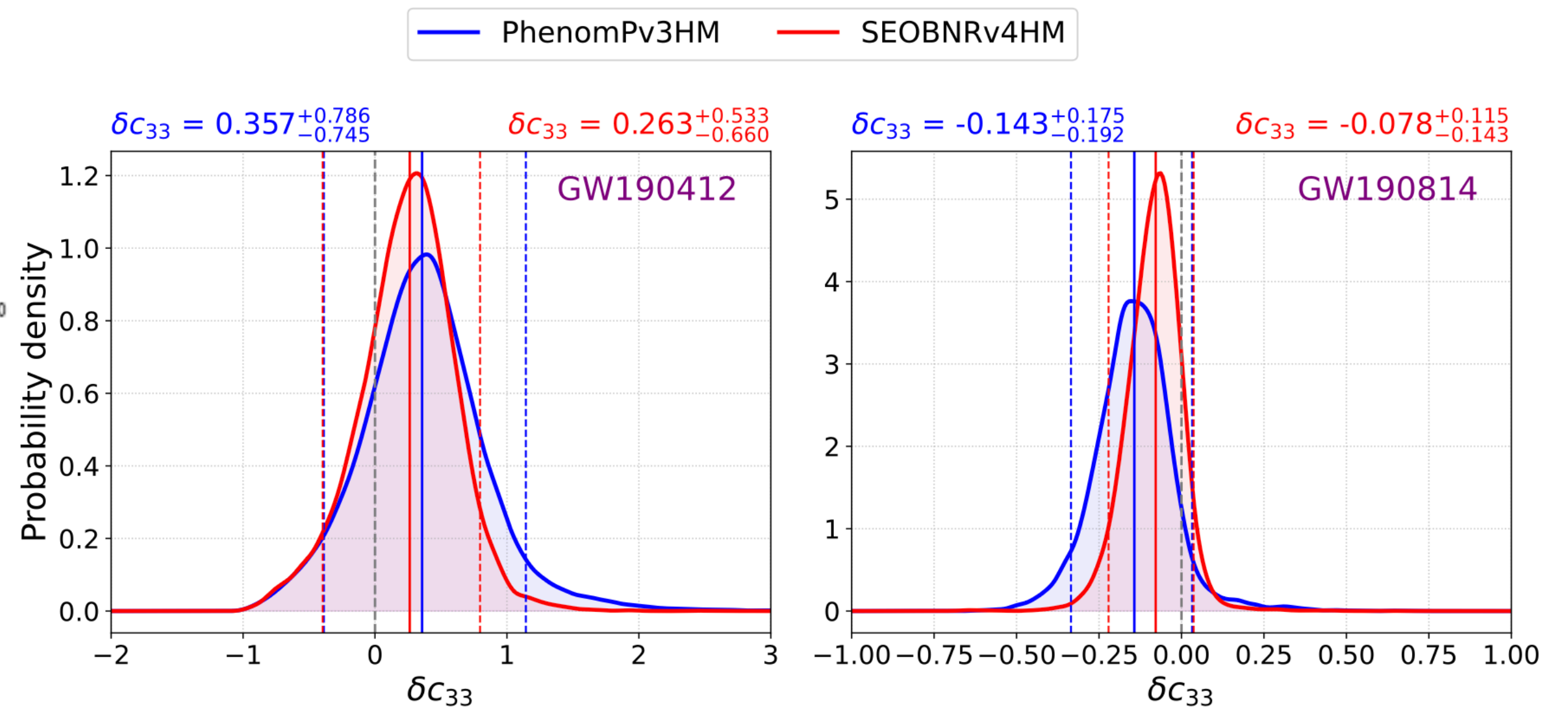
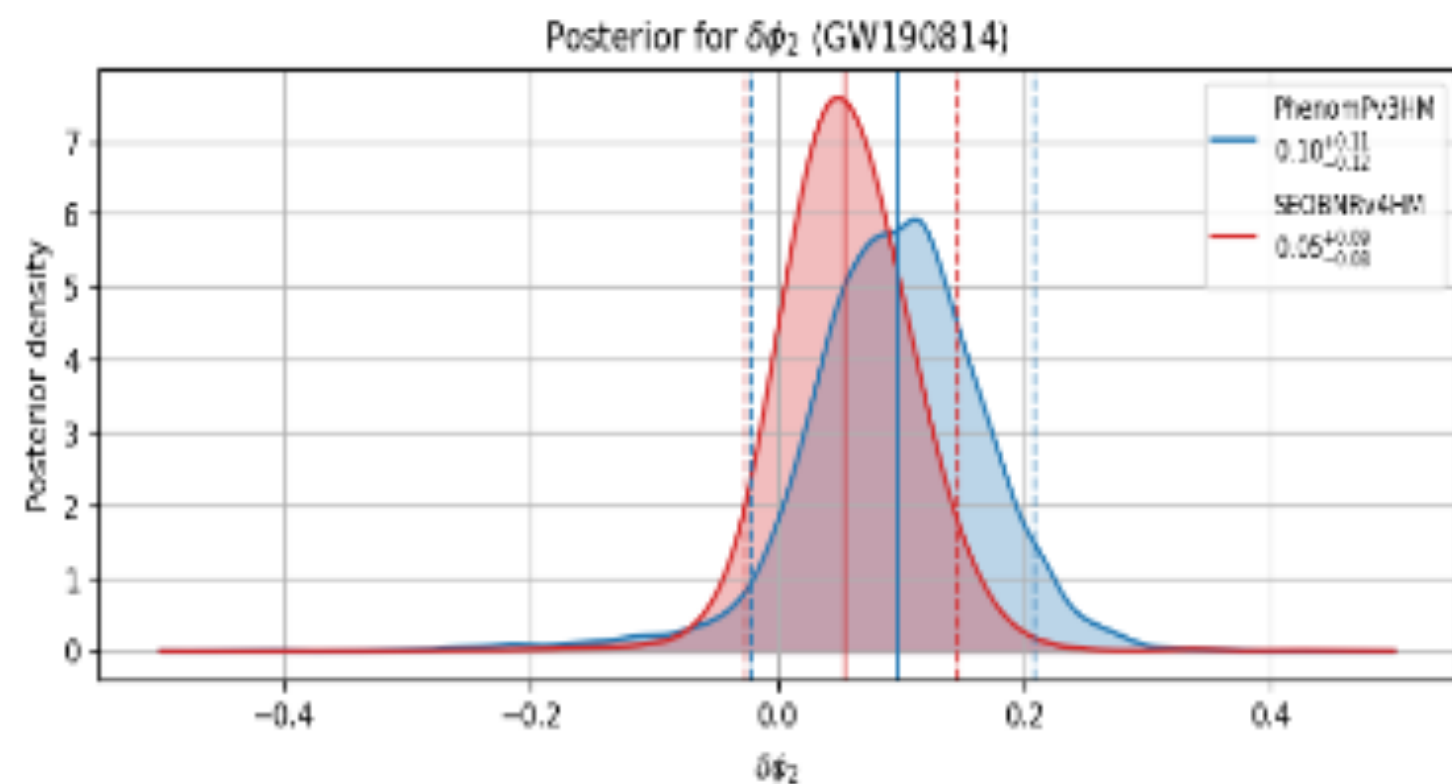
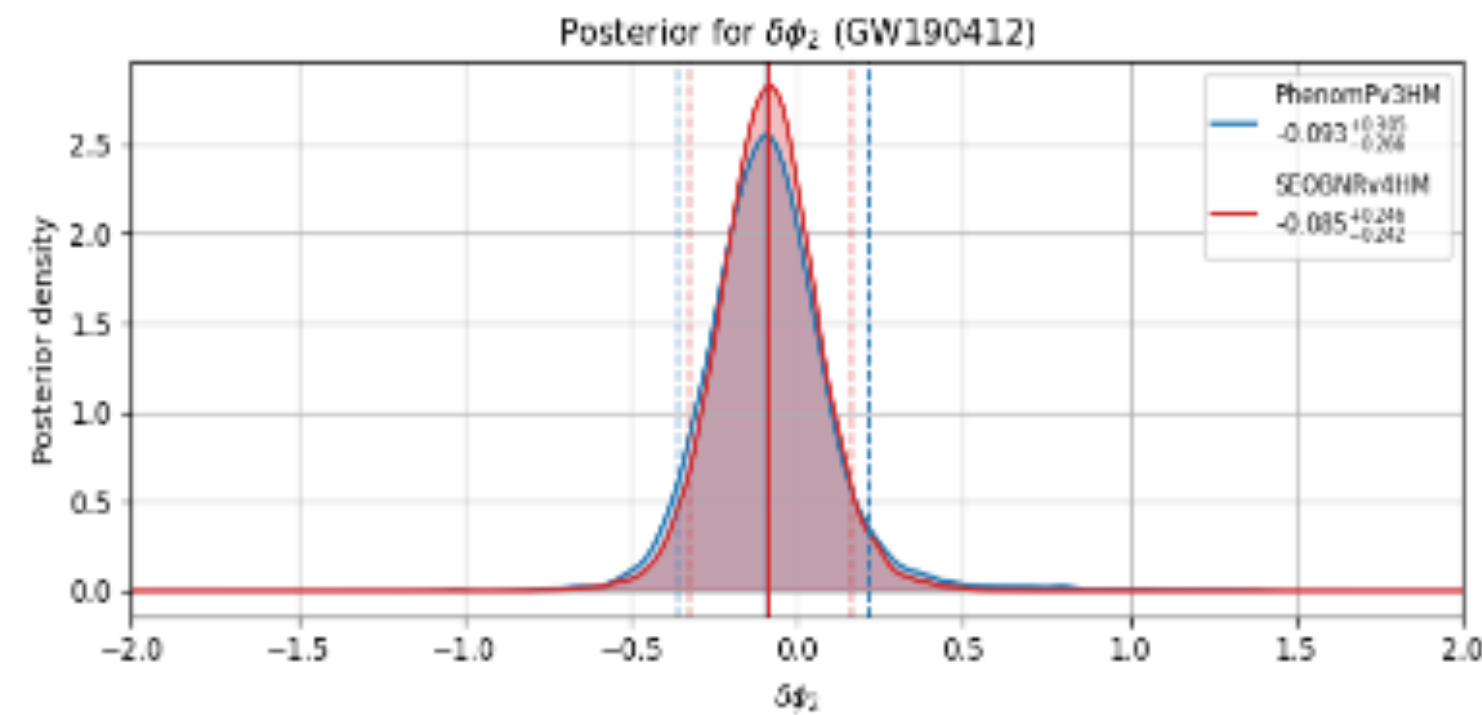


Kakran et. al.

Tests of post-Newtonian multipolar structure

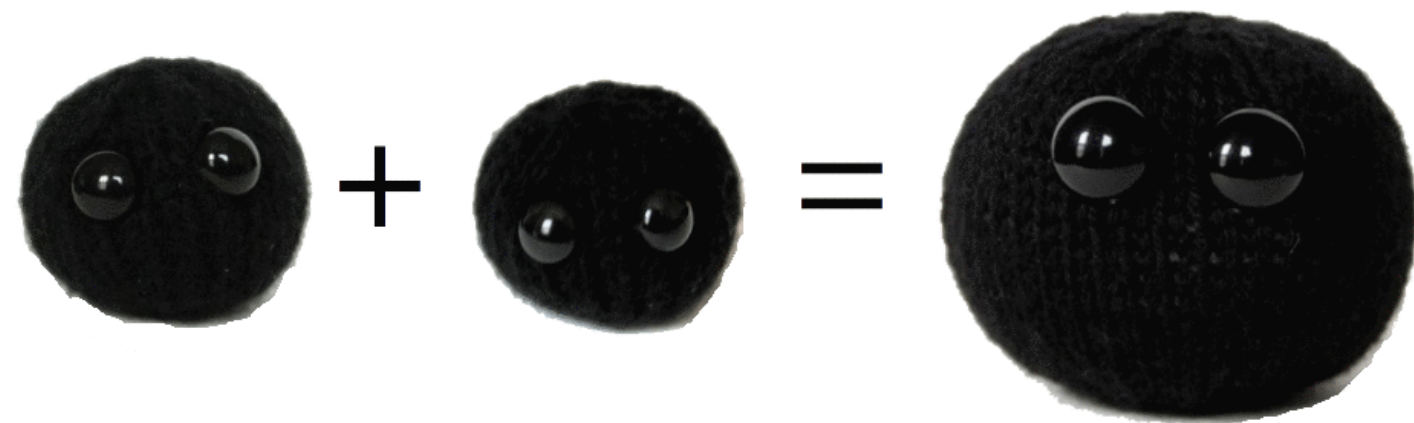


Tests of post-Newtonian multipolar structure

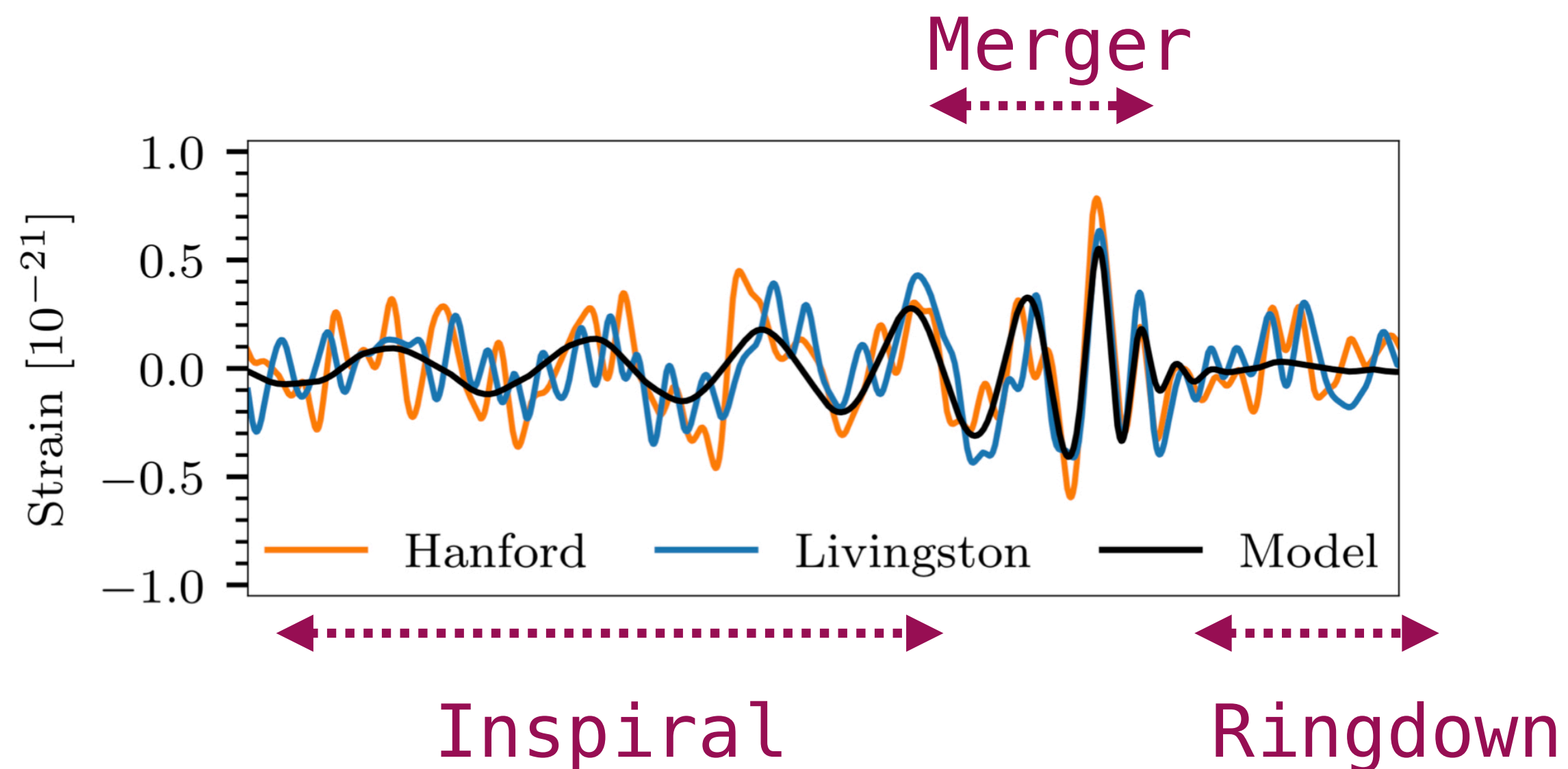


Kakran et. al.

Story so far!



- Inspiral tests:
 - Parametrised tests of PN theory
 - Parameterized test of PN multipolar structure



Gravitational waves



Growing families
of blackholes

Observation from the
3G detectors, will
reveal astounding
facts!

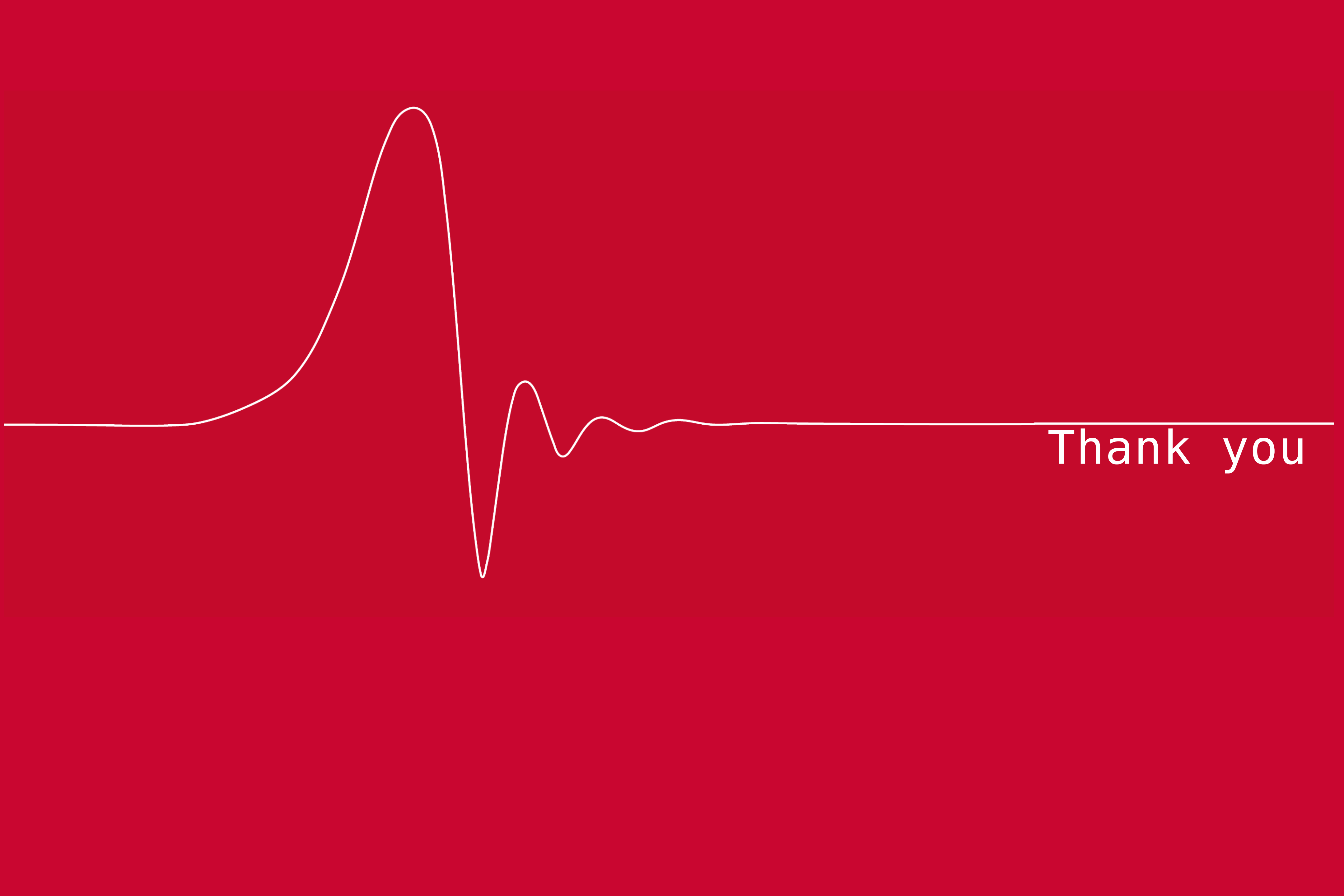
LISA joining the
party soon!!



leverage this information and
draw astrophysical
implications is our
responsibility!!

What are the questions that
are being asked?

- **Nature of the theory:** Is the Einstein's gravity correct in the strong-field?
- **Nature of black hole:** Do black holes have extra hair?



Thank you